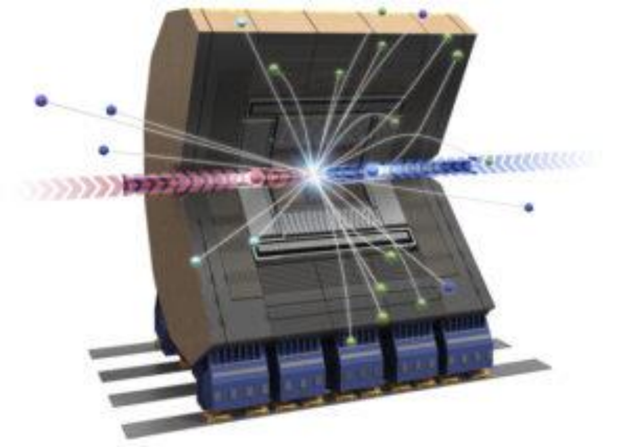
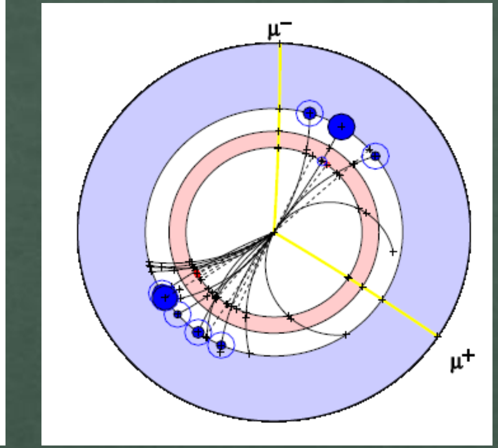
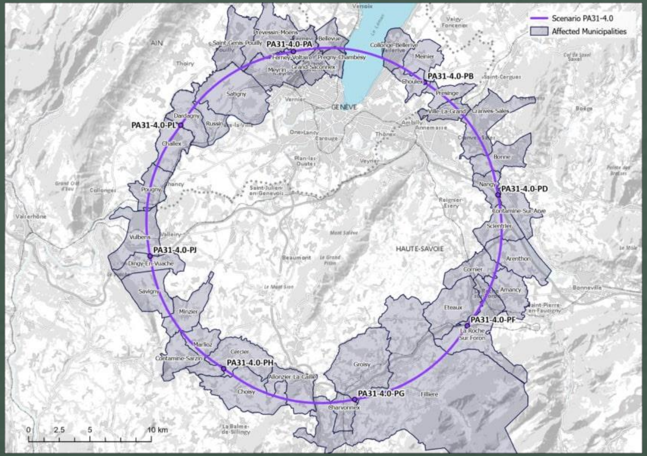
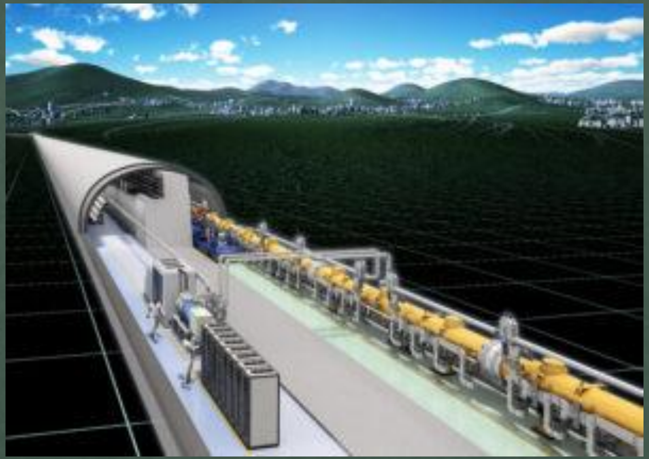








Higgs at e^+e^- Colliders

Sarah Eno
U. Maryland

Bias alert

- I am the US representative to the FCC "Physics, Detectors, Experiments" executive committee.
- I am a member of the US DOE/NSF Higgs factory steering committee (4 members)
- I am very excited about the physics of future electron-positron colliders.

About me:

- B.A. Gettysburg college 1984
- PhD U. Rochester AMY experiment at KEK in Japan
- Postdoc U. Chicago CDF experiment at Tevatron
- Faculty at Maryland since 1993 working on the D0 experiment at the Tevatron, the **CMS** experiment at the LHC, and FCC.

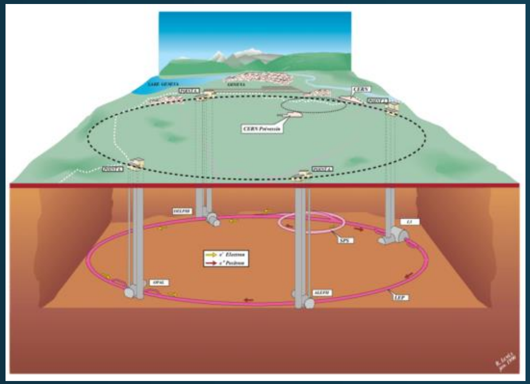
Known for my work in

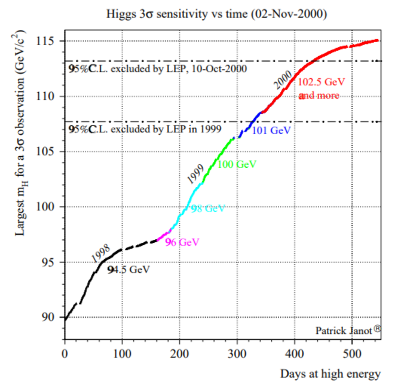
- Studies of QCD using W and Z bosons
- W mass, W width
- New particle searches (4th generation quarks, leptoquarks, dark matter with a QCD-like dark sector)
- Radiation damage in plastic scintillators
- Calorimetry (especially dual-readout crystal calorimetry)

I love both ATLAS and ILC but will often forget to show them my love. I have only two slides on CEPC, although I think it is also great.

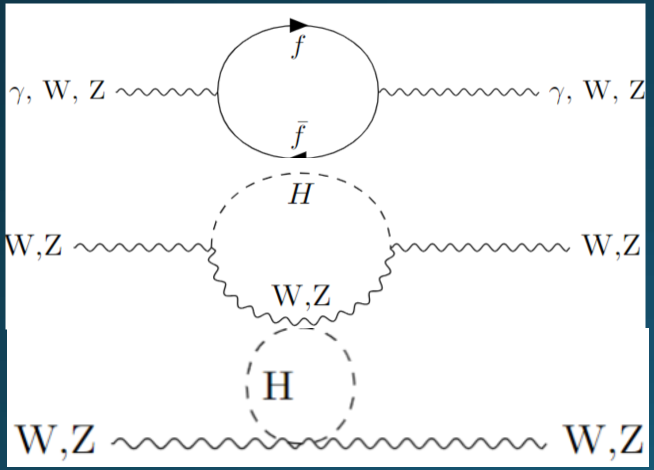
Also I'm vice chair of the DPF division of APS so please join now so we can have our fair number of fellows.

e^+e^- colliders have long been a leading source of our knowledge of the Higgs boson



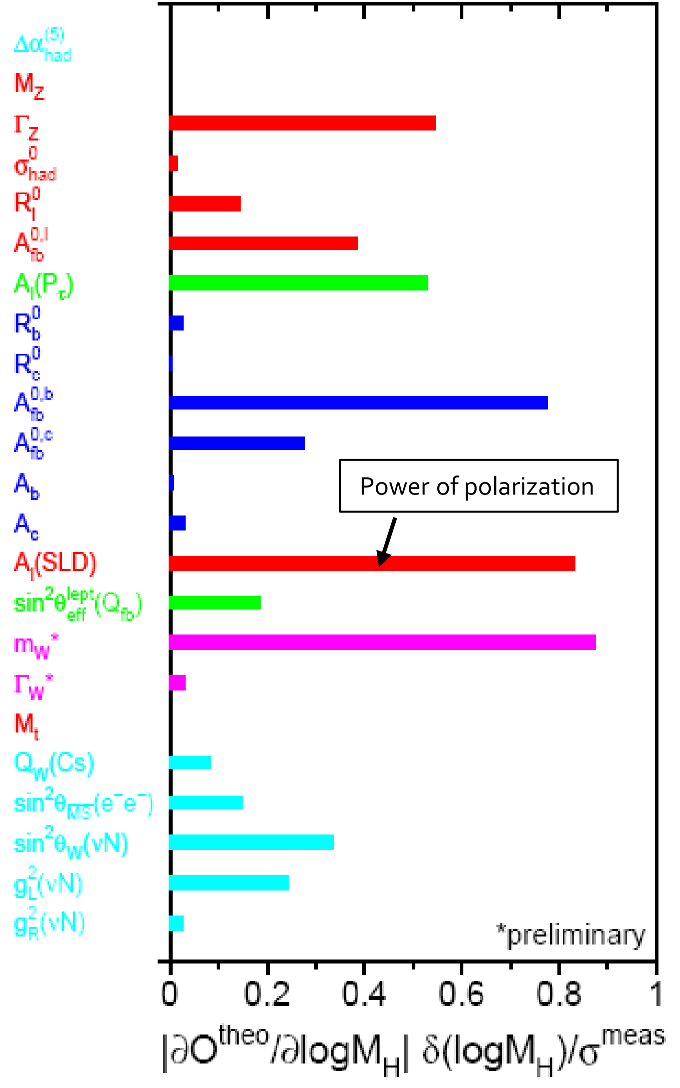


https://cds.cern.ch/record/567226/files/10-1-ra.pdf

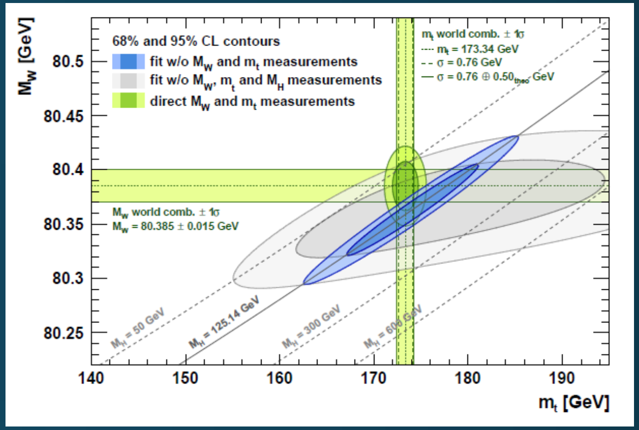


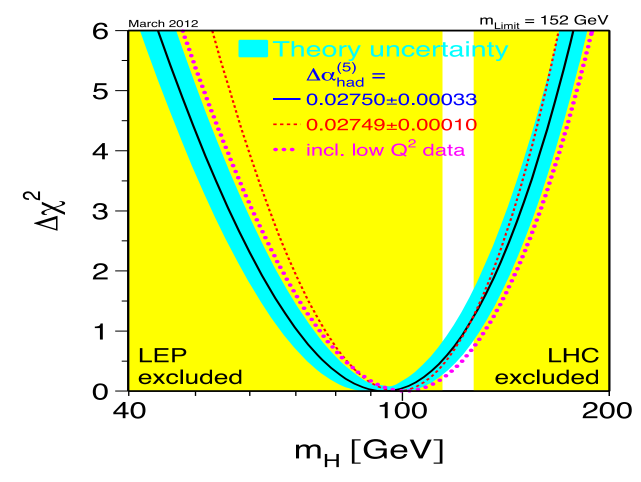
$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?



Power of polarization

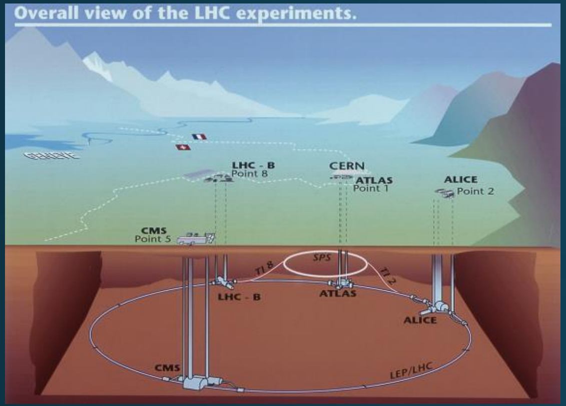


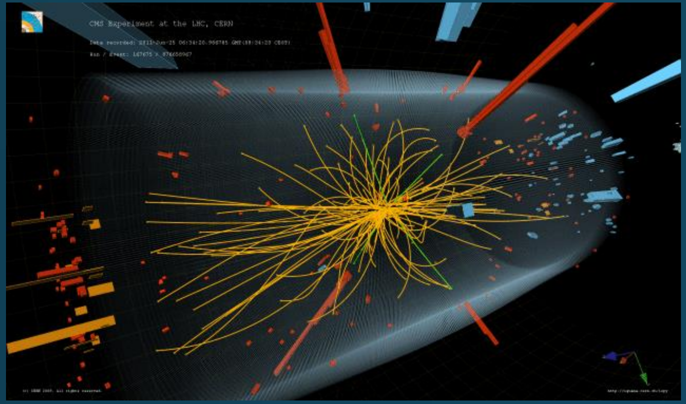


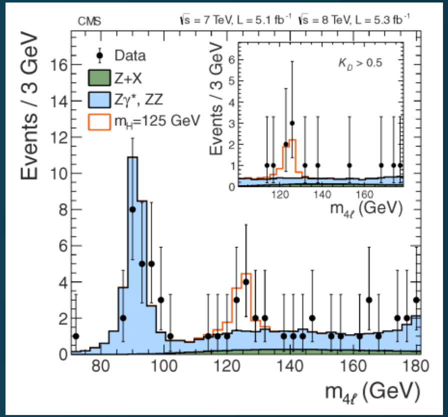
The previous denizen of the LHC tunnel told us exactly where to look. LEP 1989 – 2000.

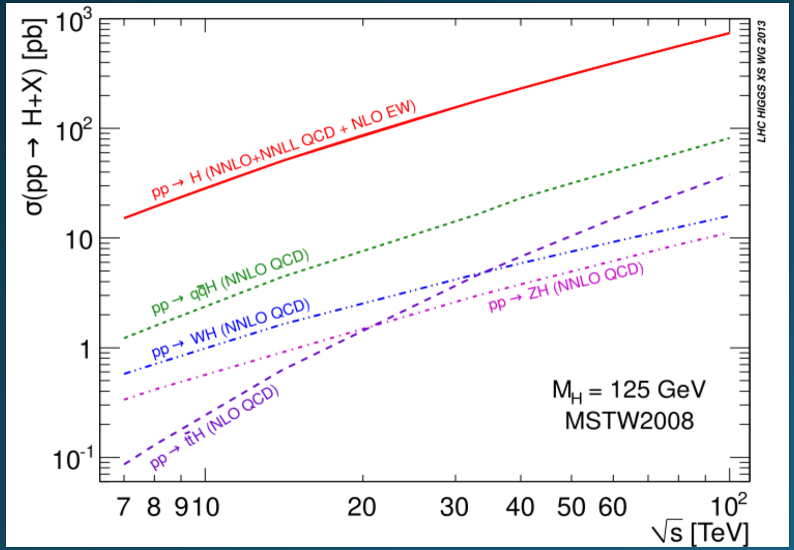
And since its discovery at LHC, we have learned a lot more

Higgs cross section at 14 TeV is ~60 pb (arXiv:2209.07510). 300 fb^{-1} yields about 2E7 Higgs

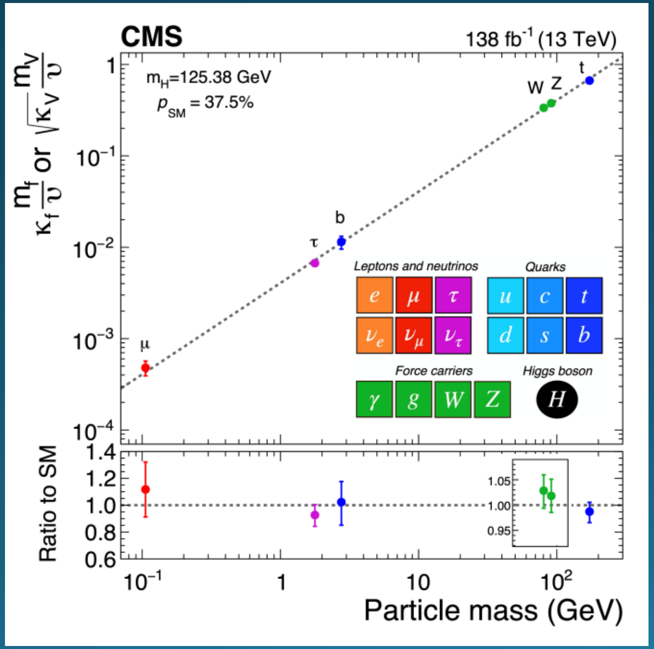


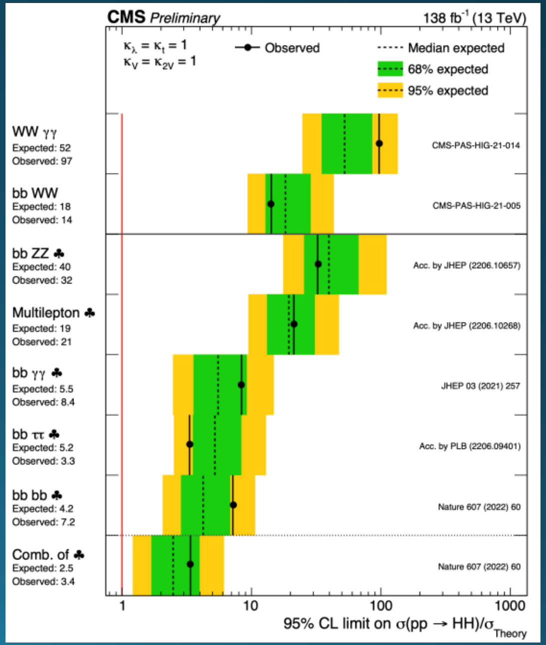






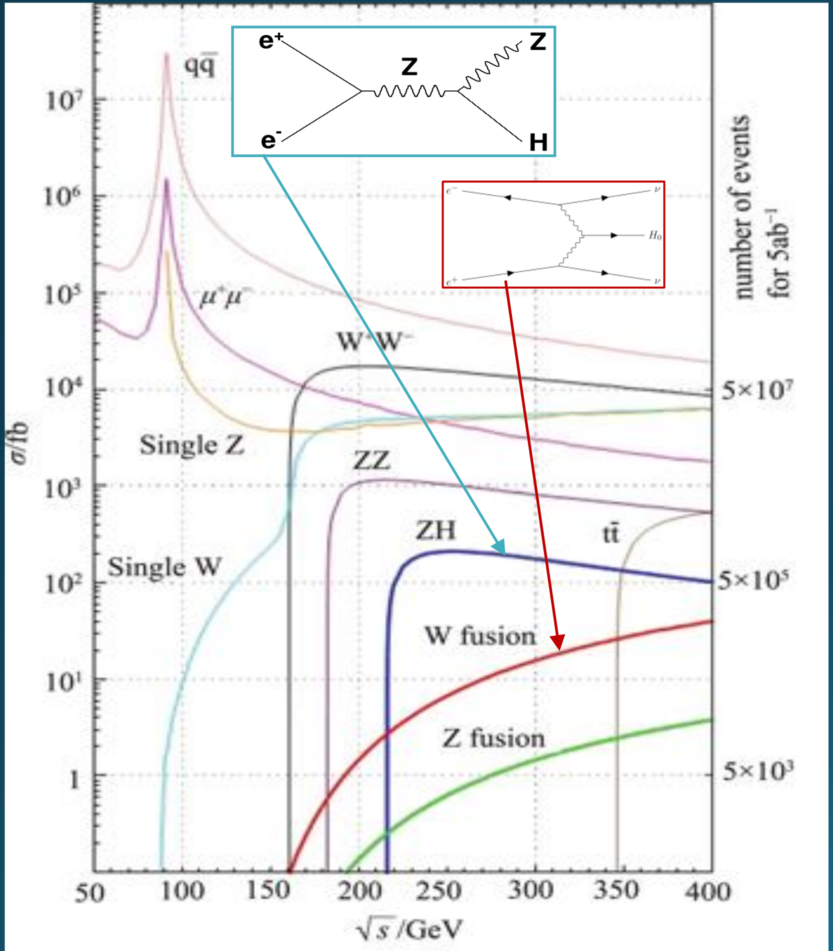
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

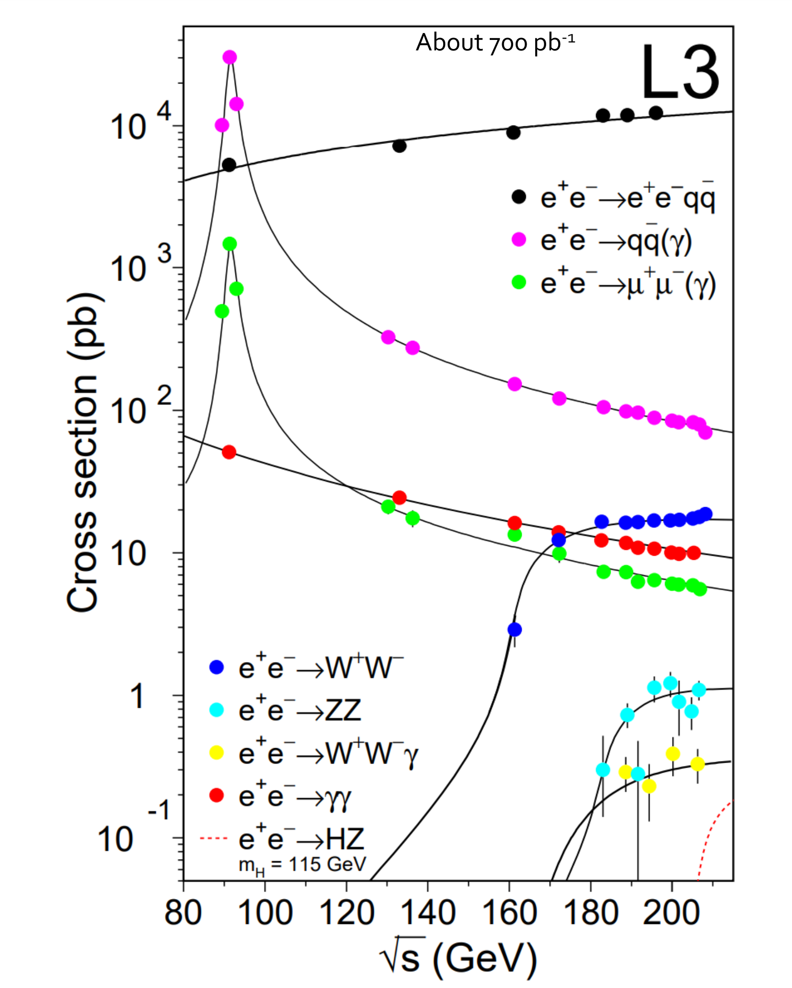




A historical aside…

The history of our field would have been very different if LEP 2 had been able to go just a little higher

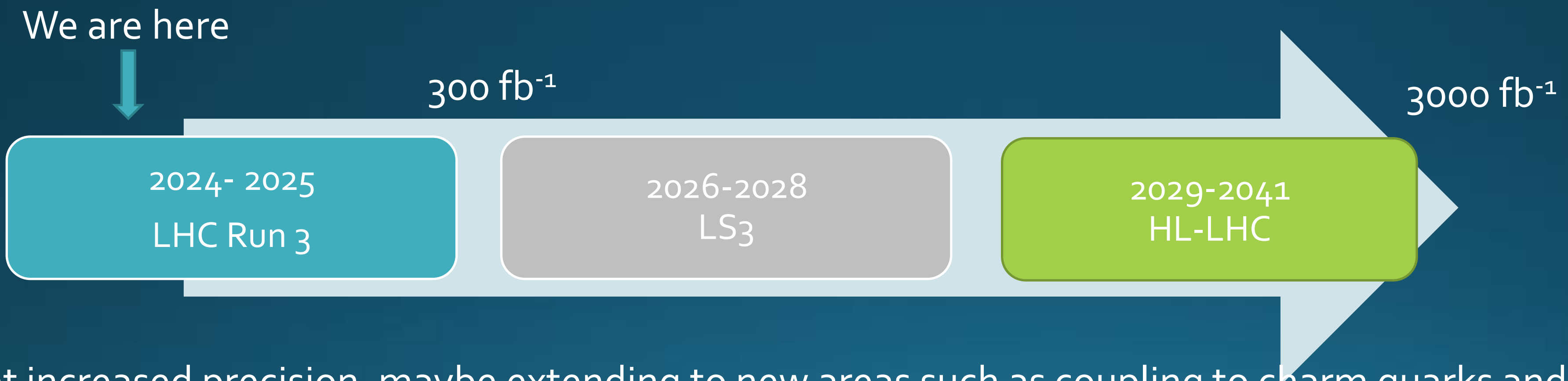




Higgs

So far, it may be that the EWK symmetry is broken via the textbook version of the Higgs mechanism
But we do not know

- if Higgs gives mass to first and second generation quarks.
- what sets its Yukawa couplings
- what gives neutrinos their mass?
- if dark matter is indeed a massive particle, what gives it its mass?
- Since the Higgs determines the CKM matrix, it is the source of SM CP violation in the quark sector. Is there more to this interesting fact?
- Are there any new particles that affect its couplings to the known particles via loop corrections? (or even at tree level through mixing)


We are here

300 fb^{-1}

3000 fb^{-1}

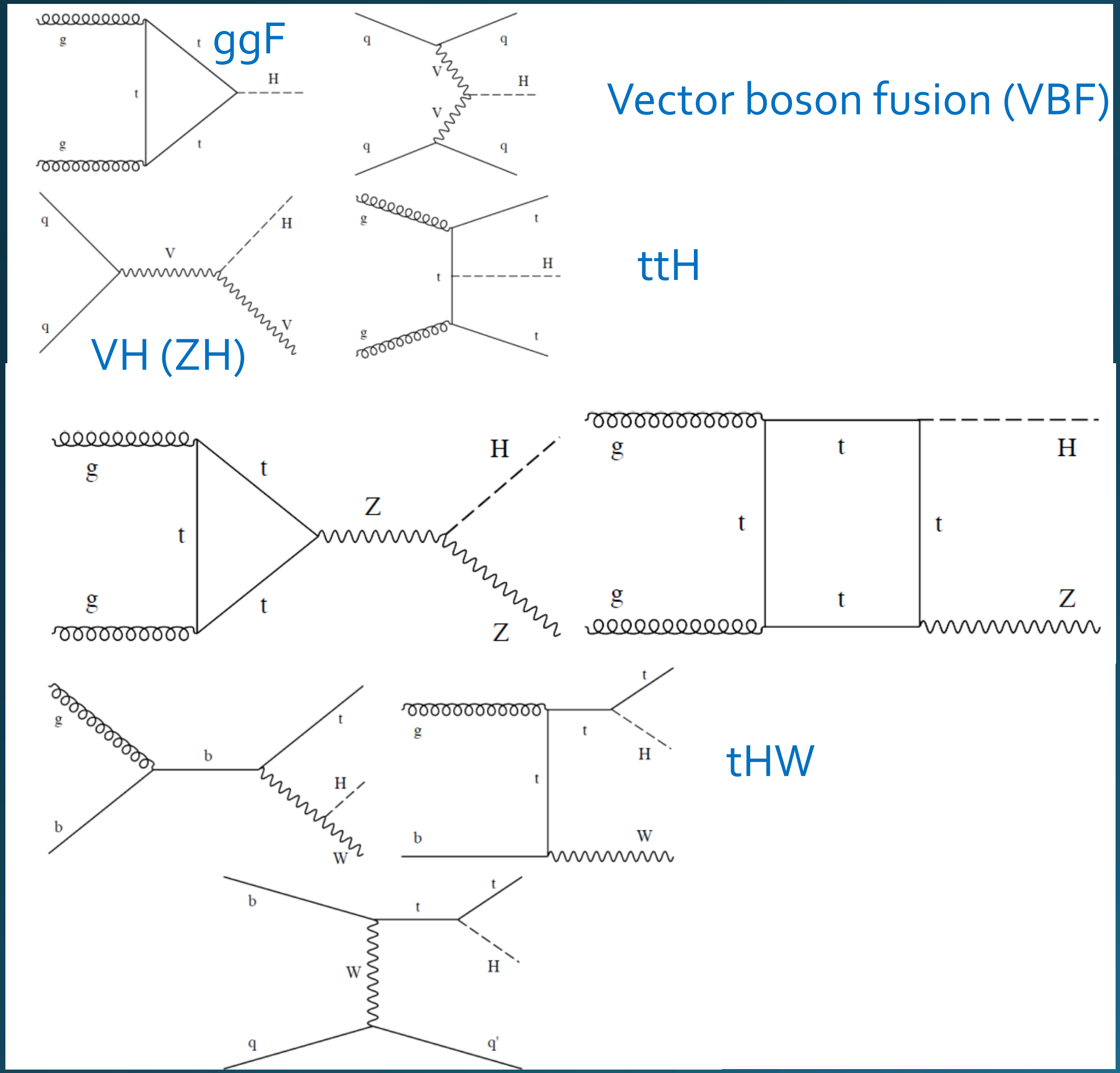
2024- 2025
LHC Run 3

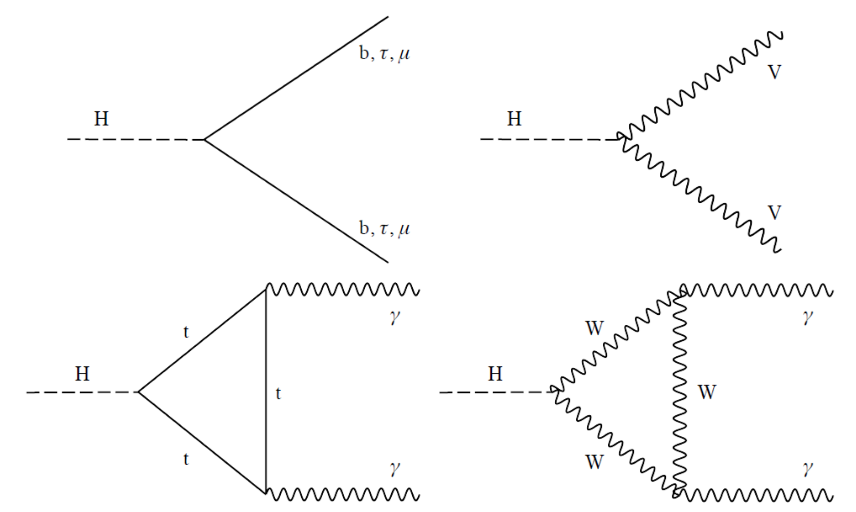
2026-2028
LS3

2029-2041
HL-LHC

We will get increased precision, maybe extending to new areas such as coupling to charm quarks and the Higgs triple coupling, during the HL-LHC running.
What will remain to learn at a new e^+e^- machine? What are some challenges with what we will be learning at HL-LHC.

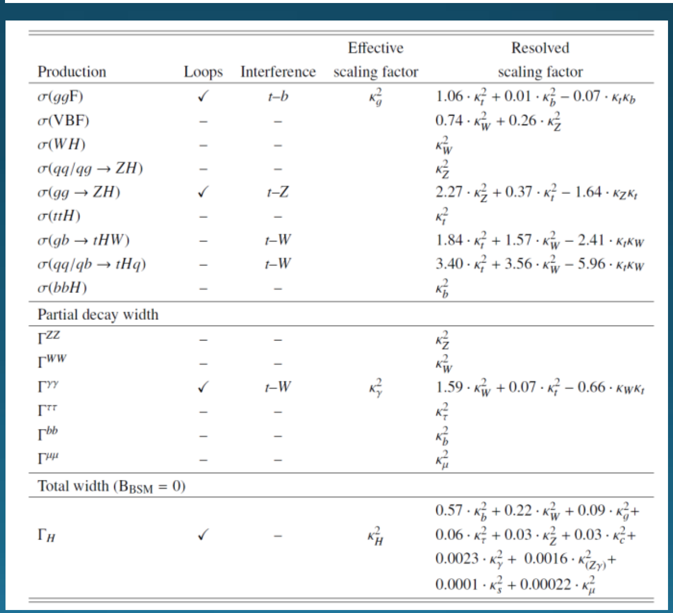
Higgs nomenclature





$$\kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{\mathrm{SM}}}$$

Sometimes κ
sometimes μ



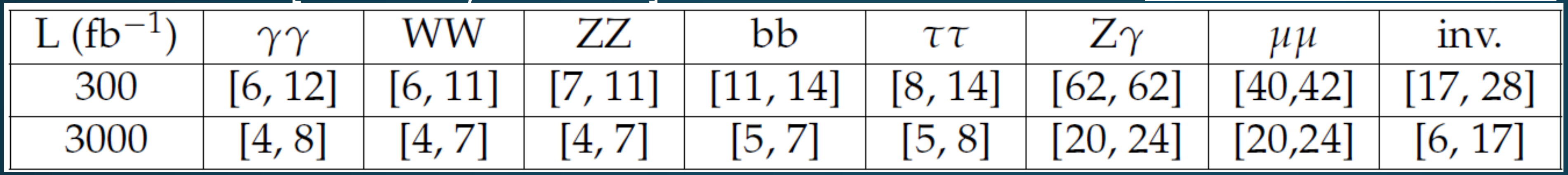
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(gg\mathrm{F})$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{\mathrm{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

At the LHC, each measurable is a product of terms related to production and to decay. Some of these contain more than one κ. We'll discuss e^+e^- later.

What will we know by the end of the HL-LHC run?

$$\mu = \sigma / \sigma_{SM}$$

Precision in %: [scenario 2, scenario 1]

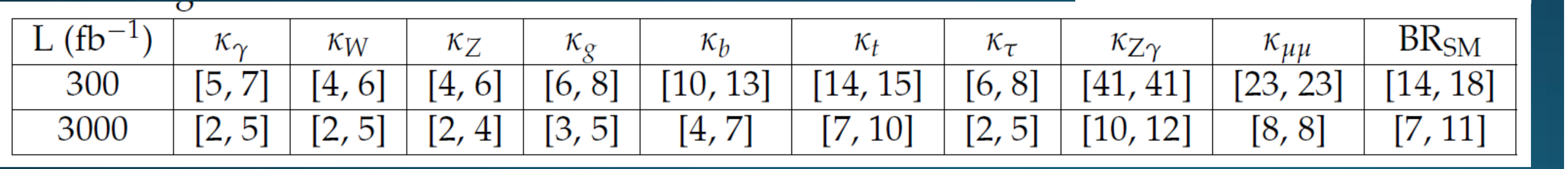


L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

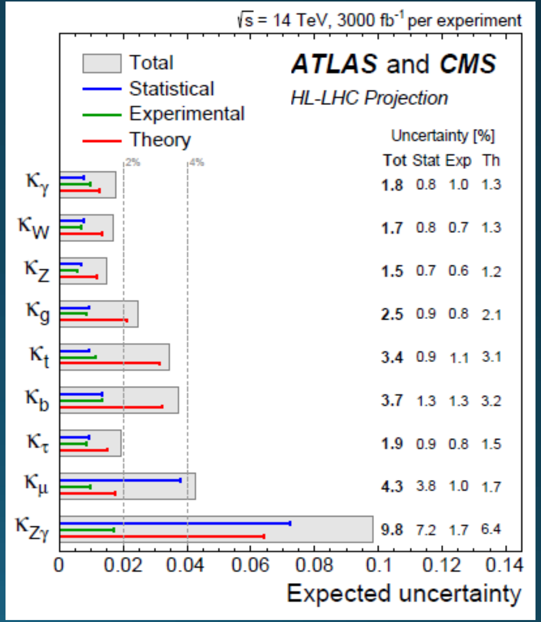
sqrt(10) ~3.2 [1.5,1.5] [1.5,1.6] [1.7,1.6] [2.2,2] [1.6,1.7] [3.1,2.6] [2,1.7] [2.8,1.6]

In Scenario 1, all systematic uncertainties are left unchanged. In Scenario 2, the theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity.

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$$



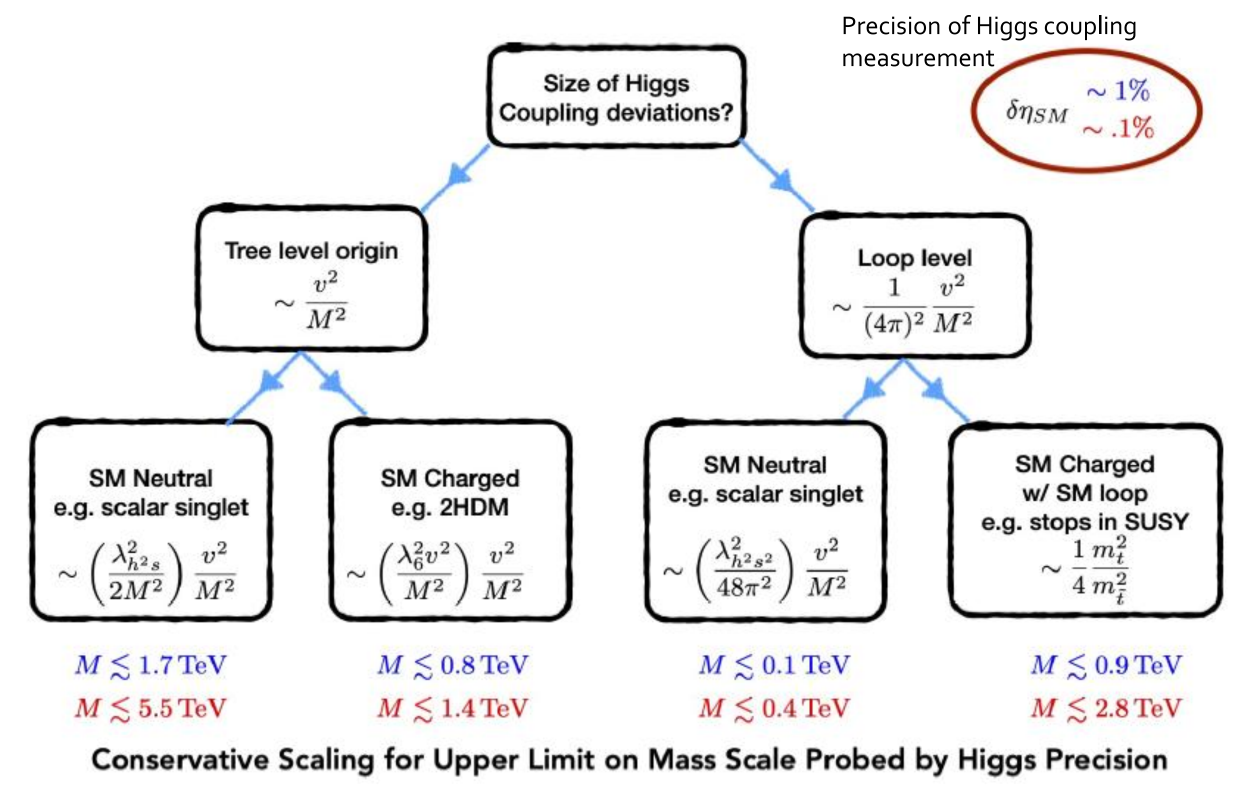
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]



Surely will gain a factor of 1.5 to 2. May gain more (hard to know) Maybe at 2-10%?

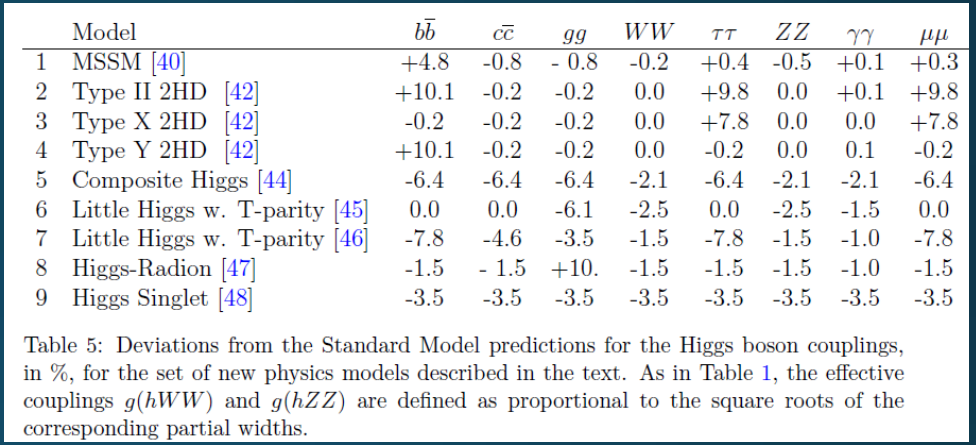
arXiv:1307.7135

What these precisions mean…



Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

Report of the Topical Group on Higgs Physics for Snowmass 2021:
The Case for Precision Higgs Physics
https://arxiv.org/abs/2209.07510



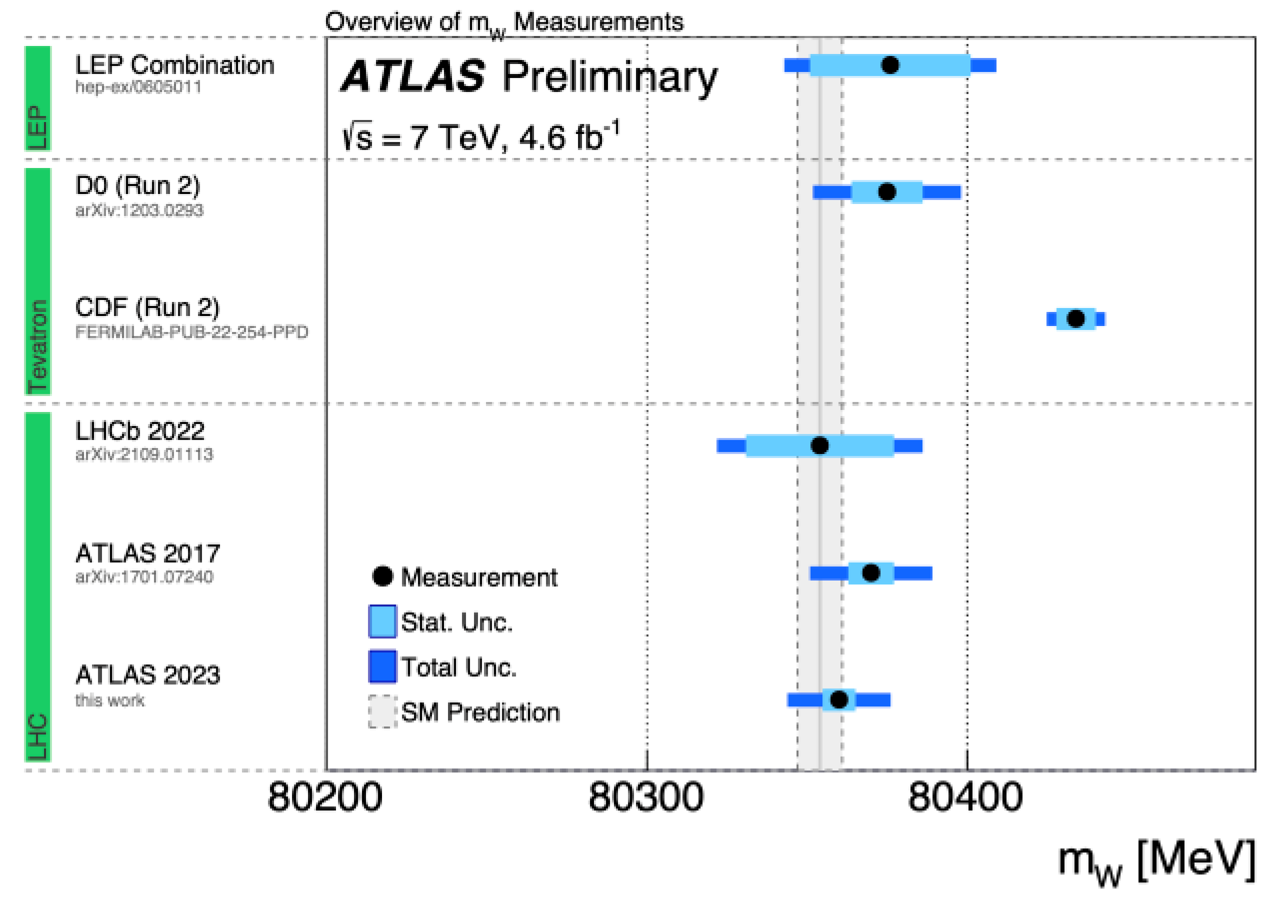
	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

Often, the reach goes as $\sqrt{p}$
Factor 10 is factor of 3

Some models do exceed these reaches for a given precision.
HL-LHC puts us at 2-10%
Maybe enough. Or…

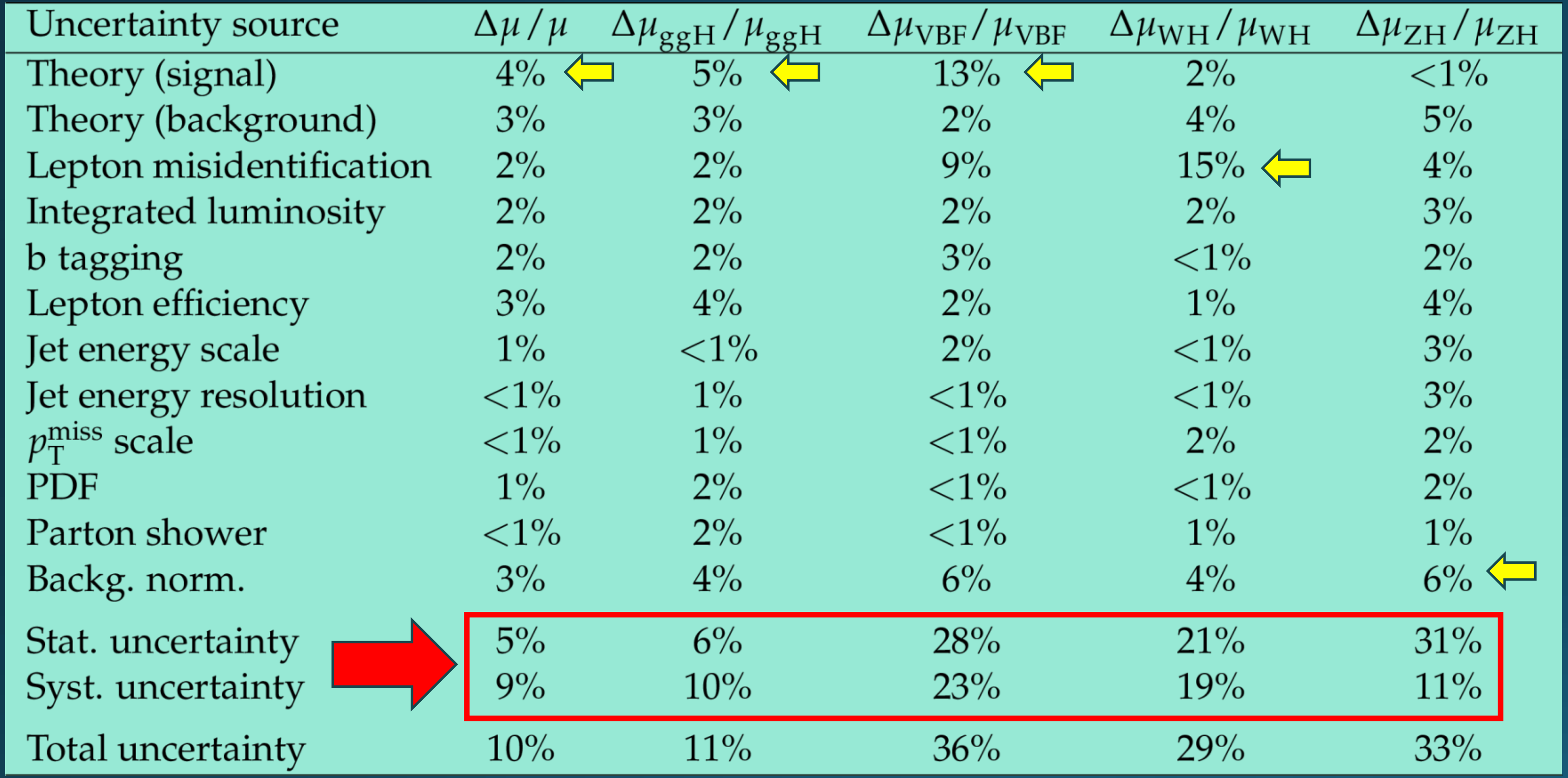
Or we may end up here.



CDF: 80433±9 MeV
(0.01% measurement)

Pushing down systematic uncertainties can be done, but it requires cross checks. Some systematics can be reduced more reliably than others.

Systematics on Higgs measurements



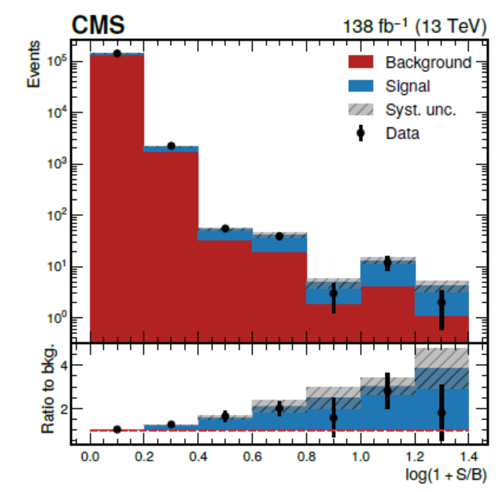
Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{\mathrm{ggH}}/\mu_{\mathrm{ggH}}$	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$	$\Delta\mu_{\mathrm{WH}}/\mu_{\mathrm{WH}}$	$\Delta\mu_{\mathrm{ZH}}/\mu_{\mathrm{ZH}}$
Theory (signal)	4%	5%	13%	2%	<1%
Theory (background)	3%	3%	2%	4%	5%
Lepton misidentification	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b tagging	2%	2%	3%	<1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	<1%	2%	<1%	3%
Jet energy resolution	<1%	1%	<1%	<1%	3%
$p_{\mathrm{T}}^{\mathrm{miss}}$ scale	<1%	1%	<1%	2%	2%
PDF	1%	2%	<1%	<1%	2%
Parton shower	<1%	2%	<1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

Measurements of the Higgs boson production cross section and couplings in the WW boson pair decay channel in proton-proton collisions at √s=13 TeV
https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-013/index.html

Chart shows clearly the need for the emphasis of this school. This will also apply to FCCee.

Getting the experimental uncertainties down in a high pileup environment will give experimentalists lots of fun. Not a trivial challenge.

CMS H->WW



A new hope

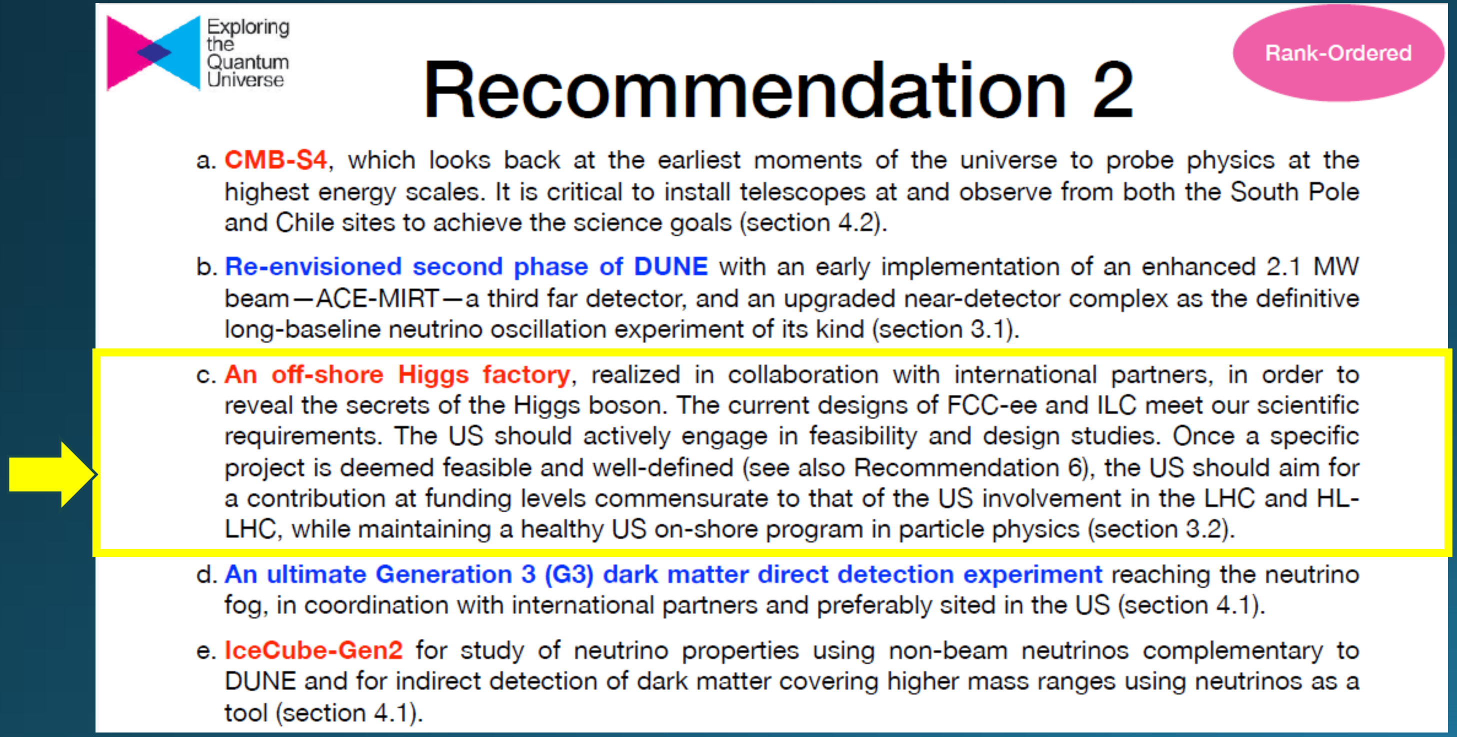
We are here

2024- 2025
LHC Run 3

2026-2028
LS3

2029-2041
HL-LHC

All good things must end. 2041 is only 17 years from now.



Recommendation 2

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

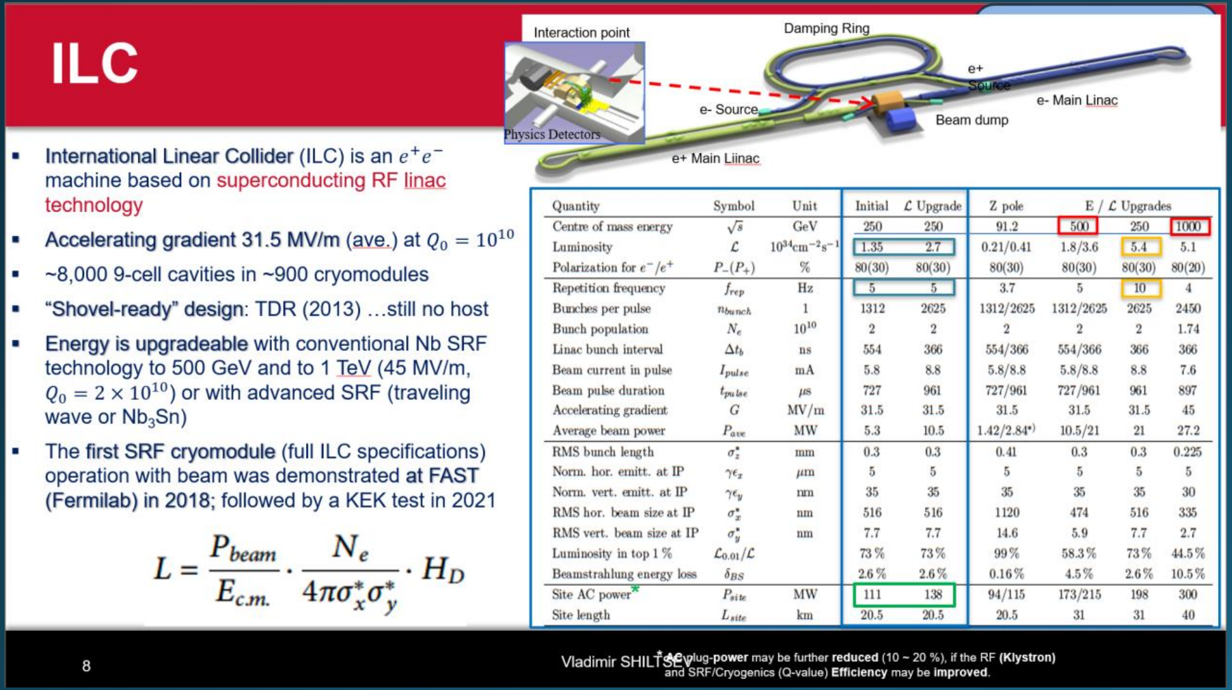
e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

Given our other scientific commitments, an "affordable" path to make sure there is no gap in having a running high energy collider.

ILC and FCC-ee

Seventeen years is a short time. Luckily we have two options that we have a high confidence can be made to work on this time scale that can produce large, clean Higgs samples.

Shiltsev, DPF-Pheno 2024



ILC

- International Linear Collider (ILC) is an e^+e^- machine based on superconducting RF linac technology
- Accelerating gradient 31.5 MV/m (ave.) at $Q_0 = 10^{10}$
- ~8,000 9-cell cavities in ~900 cryomodules
- "Shovel-ready" design: TDR (2013) …still no host
- Energy is upgradeable with conventional Nb SRF technology to 500 GeV and to 1 TeV (45 MV/m, $Q_0 = 2\times10^{10}$) or with advanced SRF (traveling wave or Nb_3Sn)
- The first SRF cryomodule (full ILC specifications) operation with beam was demonstrated at FAST (Fermilab) in 2018; followed by a KEK test in 2021

$$L = \frac{P_{beam}}{E_{c.m.}} \cdot \frac{N_e}{4\pi\sigma_x^*\sigma_y^*} \cdot H_D$$

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	10^{34}cm^{-2}s^{-1}	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	µs	727	961	727/961	727/961	961	897
Accelerating gradient	G	MV/m	31.5	31.5	31.5	31.5	31.5	45
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_z^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	µm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_x^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power*	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

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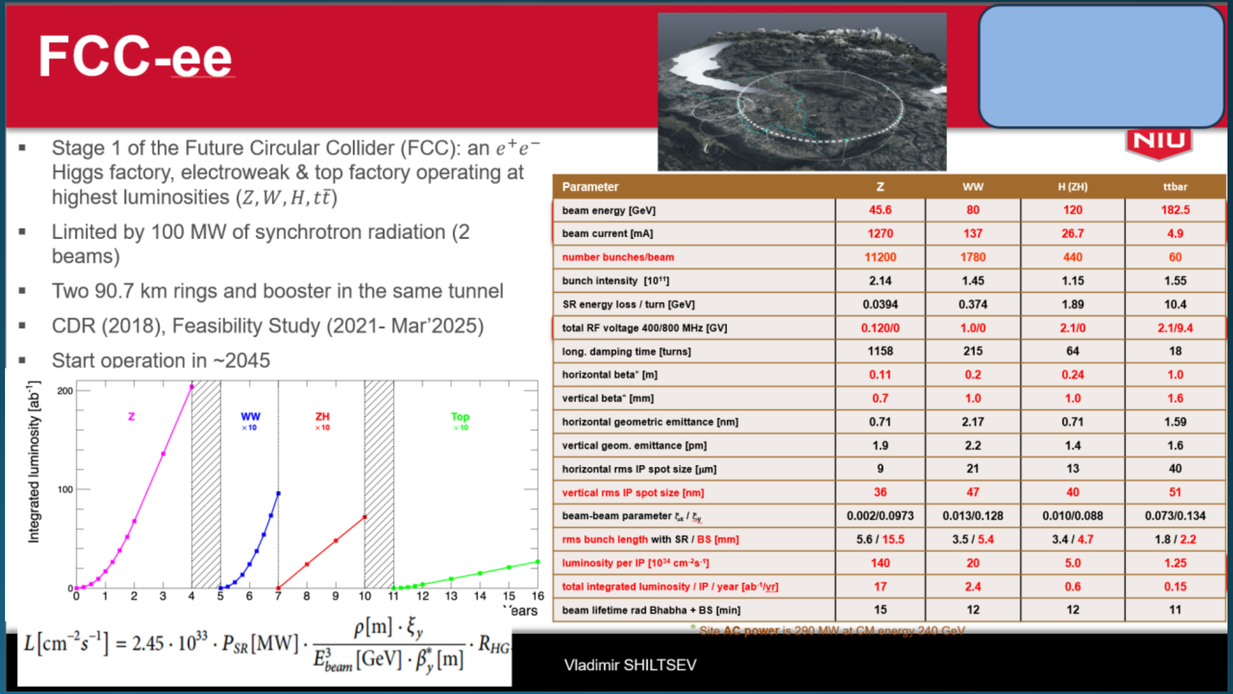
*AC plug-power may be further reduced (10 ~ 20 %), if the RF (Klystron) and SRF/Cryogenics (Q-value) Efficiency may be improved.



FCC-ee

- Stage 1 of the Future Circular Collider (FCC): an e^+e^- Higgs factory, electroweak & top factory operating at highest luminosities $(Z, W, H, t\bar{t})$
- Limited by 100 MW of synchrotron radiation (2 beams)
- Two 90.7 km rings and booster in the same tunnel
- CDR (2018), Feasibility Study (2021- Mar'2025)
- Start operation in ~2045

$$L[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = 2.45\cdot10^{33}\cdot P_{SR}[\mathrm{MW}]\cdot\frac{\rho[\mathrm{m}]\cdot\xi_y}{E_{beam}^3[\mathrm{GeV}]\cdot\beta_y^*[\mathrm{m}]}\cdot R_{HG}$$

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [µm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

* Site AC power is 290 MW at CM energy 240 GeV

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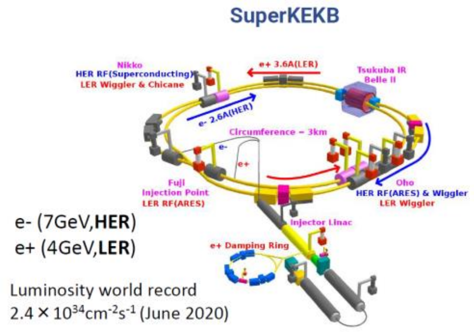
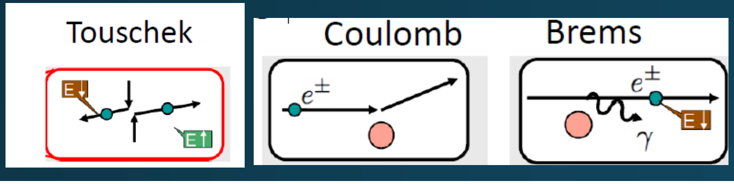
Any new machine is hard

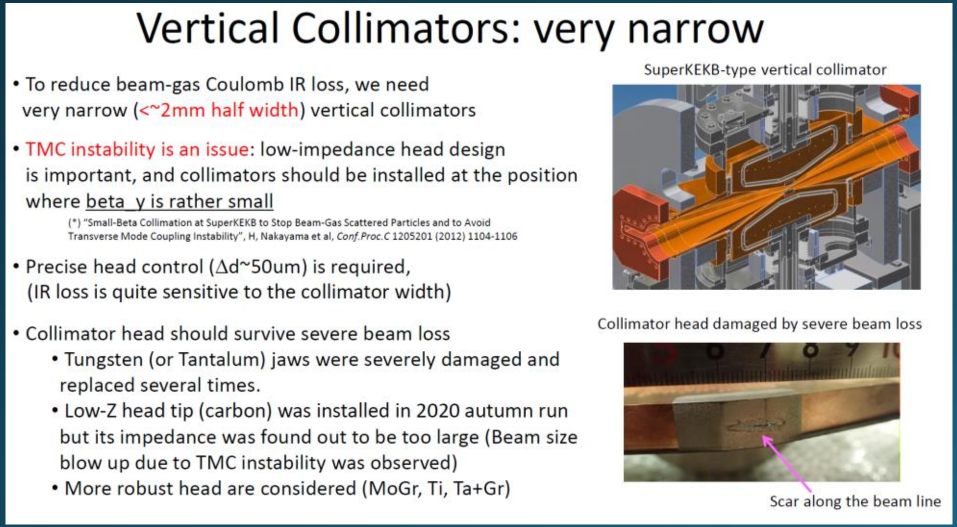
Nakayama, London



e- (7GeV,**HER**)
e+ (4GeV,**LER**)

Luminosity world record
2.4×10^{34} cm^{-2}s^{-1} (June 2020)





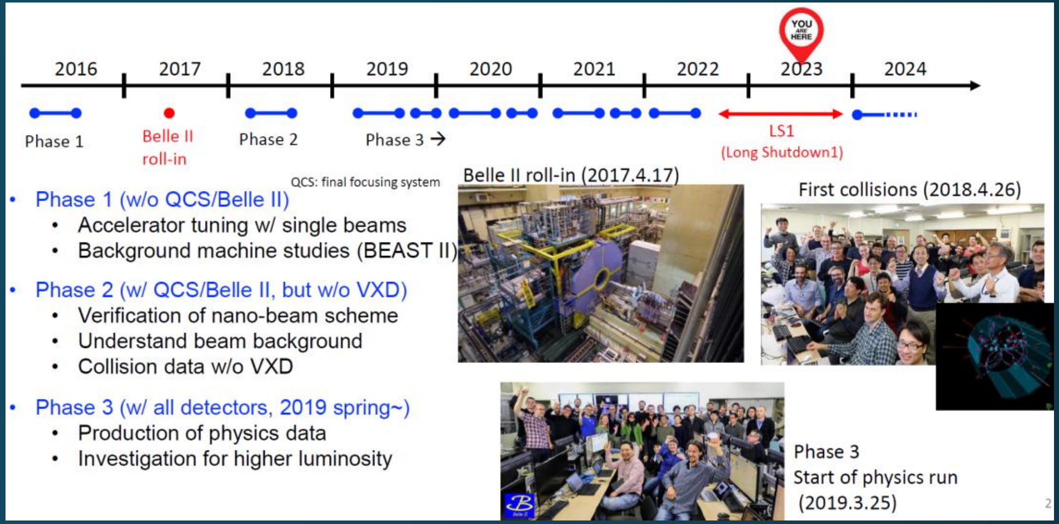
Vertical Collimators: very narrow

- To reduce beam-gas Coulomb IR loss, we need very narrow (<~2mm half width) vertical collimators
- TMC instability is an issue: low-impedance head design is important, and collimators should be installed at the position where beta_y is rather small
  (*) "Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability", H, Nakayama et al, *Conf.Proc.C* 1205201 (2012) 1104-1106
- Precise head control (Δd~50um) is required, (IR loss is quite sensitive to the collimator width)
- Collimator head should survive severe beam loss
  - Tungsten (or Tantalum) jaws were severely damaged and replaced several times.
  - Low-Z head tip (carbon) was installed in 2020 autumn run but its impedance was found out to be too large (Beam size blow up due to TMC instability was observed)
  - More robust head are considered (MoGr, Ti, Ta+Gr)

SuperKEKB-type vertical collimator

Collimator head damaged by severe beam loss

Scar along the beam line



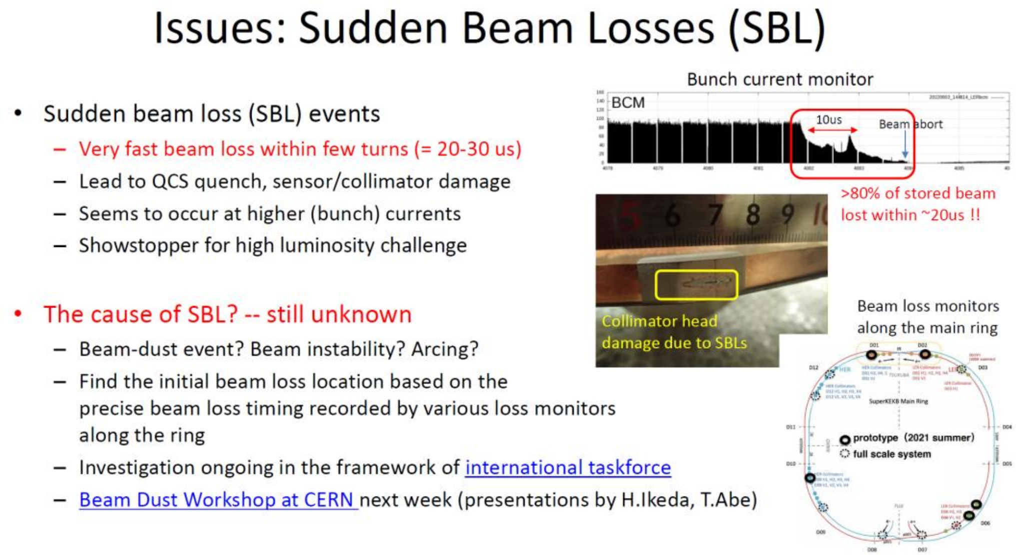
QCS: final focusing system

- Phase 1 (w/o QCS/Belle II)
  - Accelerator tuning w/ single beams
  - Background machine studies (BEAST II)
- Phase 2 (w/ QCS/Belle II, but w/o VXD)
  - Verification of nano-beam scheme
  - Understand beam background
  - Collision data w/o VXD
- Phase 3 (w/ all detectors, 2019 spring~)
  - Production of physics data
  - Investigation for higher luminosity

Belle II roll-in (2017.4.17)

First collisions (2018.4.26)

Phase 3
Start of physics run
(2019.3.25)



Issues: Sudden Beam Losses (SBL)

- Sudden beam loss (SBL) events
  - Very fast beam loss within few turns (= 20-30 us)
  - Lead to QCS quench, sensor/collimator damage
  - Seems to occur at higher (bunch) currents
  - Showstopper for high luminosity challenge
- The cause of SBL? -- still unknown
  - Beam-dust event? Beam instability? Arcing?
  - Find the initial beam loss location based on the precise beam loss timing recorded by various loss monitors along the ring
  - Investigation ongoing in the framework of international taskforce
  - Beam Dust Workshop at CERN next week (presentations by H.Ikeda, T.Abe)

Bunch current monitor

>80% of stored beam lost within ~20us !!

Collimator head damage due to SBLs

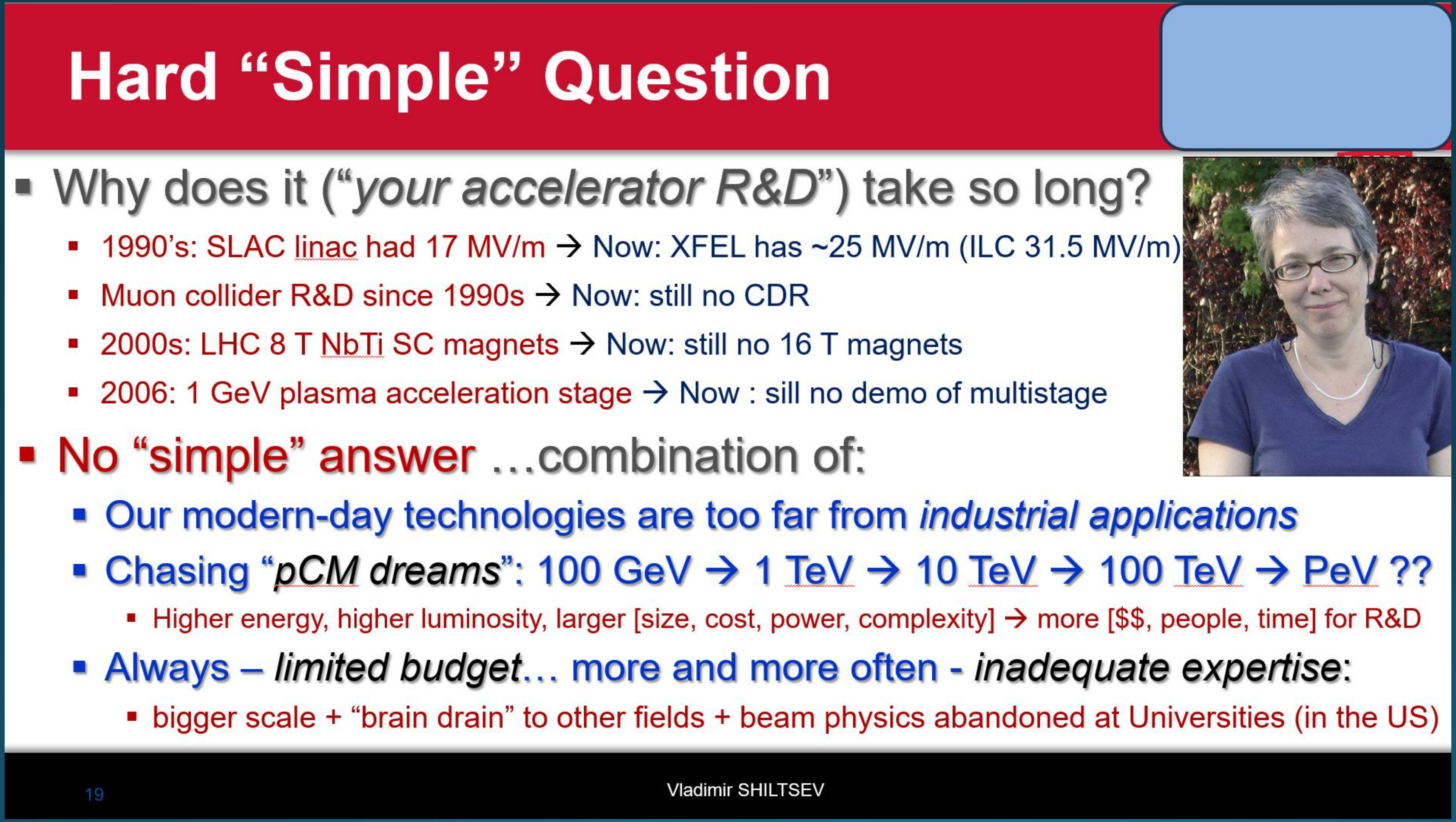
Beam loss monitors along the main ring

All accelerator physics is hard, even "relatively straightforward" plans. This can happen at any option.

seventeen years is a short time

accelerator physics is a very challenging highly technical area

Vladimir Shiltsev: DPF/Pheno 2024 in Pittsburg



Hard “Simple” Question

- Why does it (“*your accelerator R&D*”) take so long?
  - 1990’s: SLAC linac had 17 MV/m → Now: XFEL has ~25 MV/m (ILC 31.5 MV/m)
  - Muon collider R&D since 1990s → Now: still no CDR
  - 2000s: LHC 8 T NbTi SC magnets → Now: still no 16 T magnets
  - 2006: 1 GeV plasma acceleration stage → Now : sill no demo of multistage
- No “simple” answer …combination of:
  - Our modern-day technologies are too far from *industrial applications*
  - Chasing “*pCM dreams*”: 100 GeV → 1 TeV → 10 TeV → 100 TeV → PeV ??
    - Higher energy, higher luminosity, larger [size, cost, power, complexity] → more [$$, people, time] for R&D
  - Always – *limited budget*… more and more often - *inadequate expertise*:
    - bigger scale + “brain drain” to other fields + beam physics abandoned at Universities (in the US)

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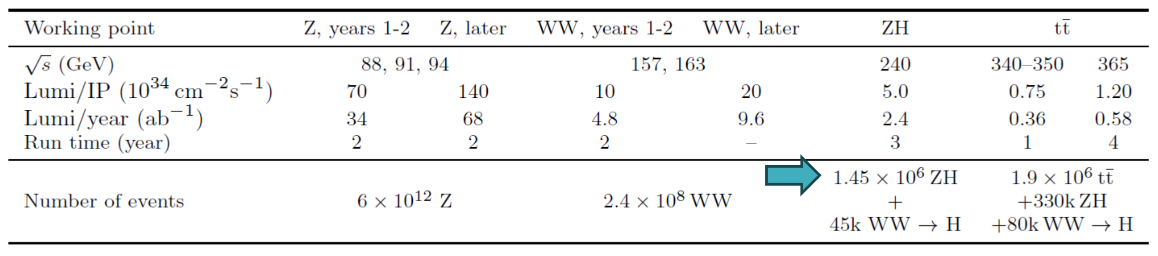
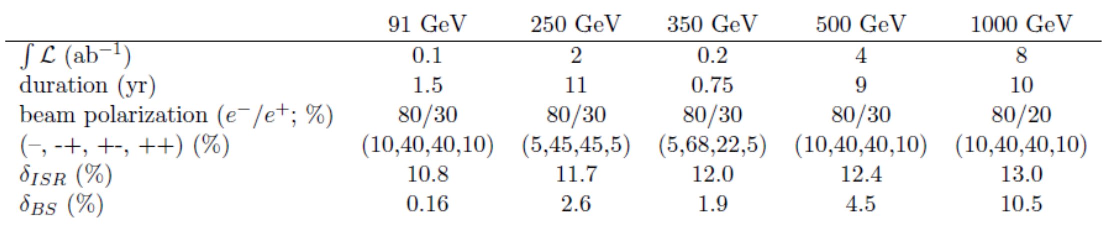
Higgs and so much more

FCC-ee nominal strawman run plan

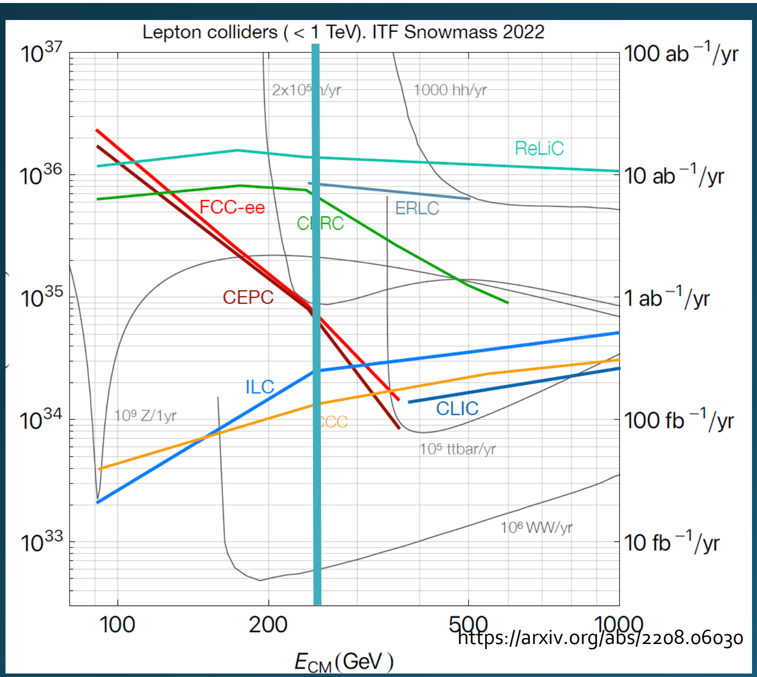


Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW → H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW → H	

ILC nominal strawman run plan

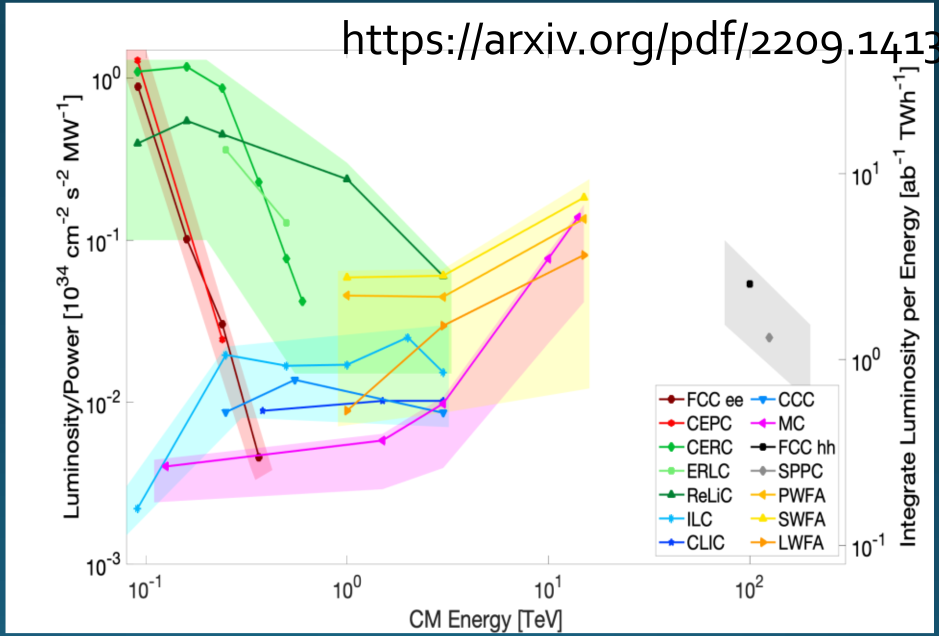


	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L}$ (ab^{-1})	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(−, -+, +-, ++) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
δ_{ISR} (%)	10.8	11.7	12.0	12.4	13.0
δ_{BS} (%)	0.16	2.6	1.9	4.5	10.5



https://arxiv.org/abs/2208.06030

https://arxiv.org/pdf/2209.14136



For more on these machines, see https://arxiv.org/abs/2209.14136

- It is interesting to note that HL-LHC gives about 2E8 Higgs while FCCee will give about 1E6 Higgs
- Linear colliders allow polarization, which is a great asset for exploring EWK physics due to its V-A structure

Higgs at e^+e^-

- Model independent coupling measurements
- Measurement of loop corrections to the Higgs couplings
- “Closure” tests of the standard model
- Decay channels too difficult to handle in hadron collider environment

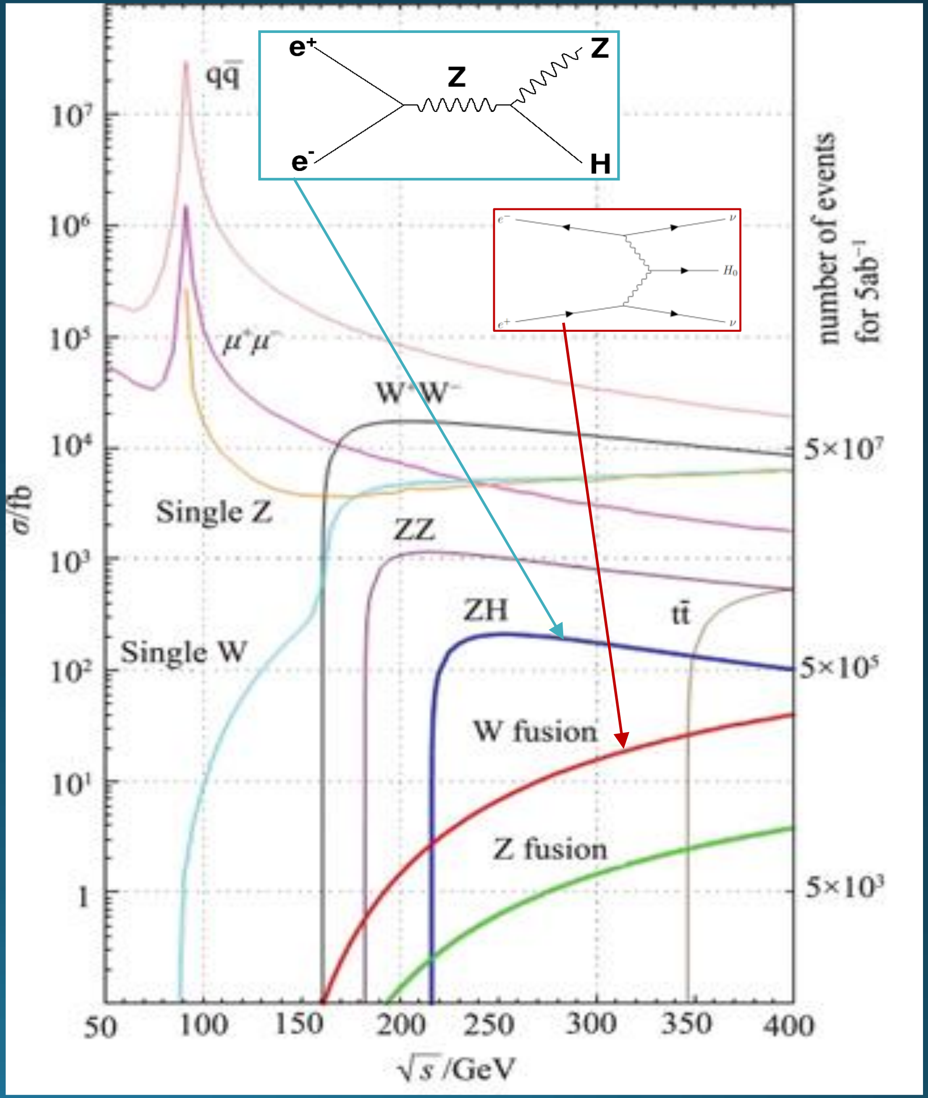
I’ve always been a fan of closure tests.
But of course observing Higgs to dark matter would also be super cool.

Higgs production

One of the strengths of the LHC program is the access to so many Higgs production diagrams. This benefit can also be accessed at FCCee.

Run plan for optimal Higgs studies involves two energies, 240 and 365 to pick up the two main diagrams (365lso gives us the tt sample)

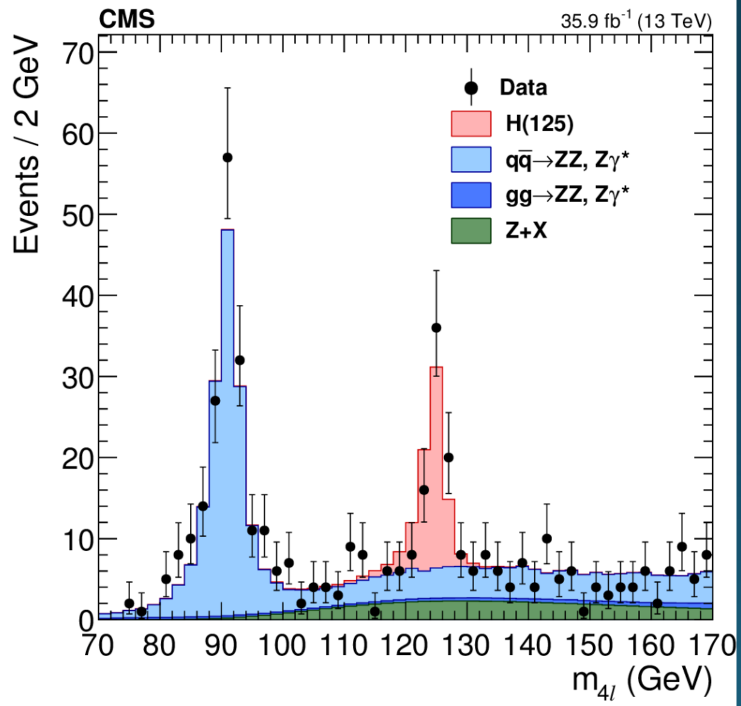
We can also see there are *in principle* non-trivial backgrounds (it is a log plot).



Higgs mass

At the LHC, the Higgs mass is measured in ZZ to 4 leptons and $\gamma\gamma$ final states
Current measurement (pdg) is 125.20 ± 0.11 GeV using 25 fb^{-1} of data
Projected HL-LHC should roughly scale as 1/sqrt(2500/25)=1/10 (about 0.01 GeV)

https://new-cds.cern.ch/doi/10.17181/jfb44-sod81



To see the new physics beyond the Higgs loop, need mass to about 10 MeV or better

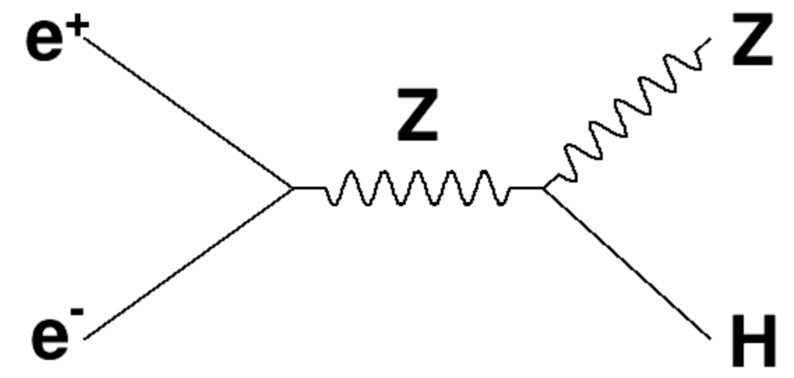
$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

If we want to measure the Higgs coupling to electrons, need to know this number to about 4 MeV.

Might guess you would measure it in e^+e^- collisions in a similar way.

e^+e^- to ZH magic



$$m_{recoil} = s + m_{f\bar{f}} - 2\sqrt{s}(E_f + E_{\bar{f}})$$

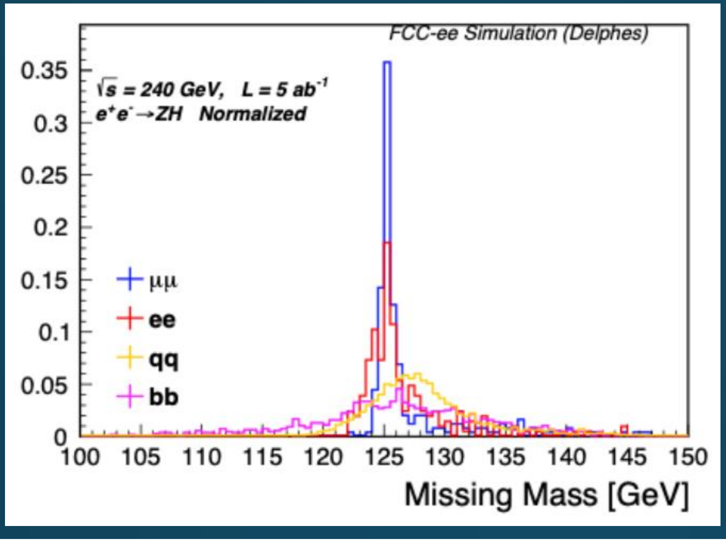
“missing mass” or “recoil mass” or “recoil” or “leptonic recoil” (for the most commonly used Z decay mode)

Higgs can be identified independent of decay mode using the “missing mass “ or “boson recoil mass” method. If an event has an identified Z boson, use its 3-momentum as the 3-momentum of the recoil particle and the center-of-mass collision energy to calculate the mass of whatever is recoiling against the Z.

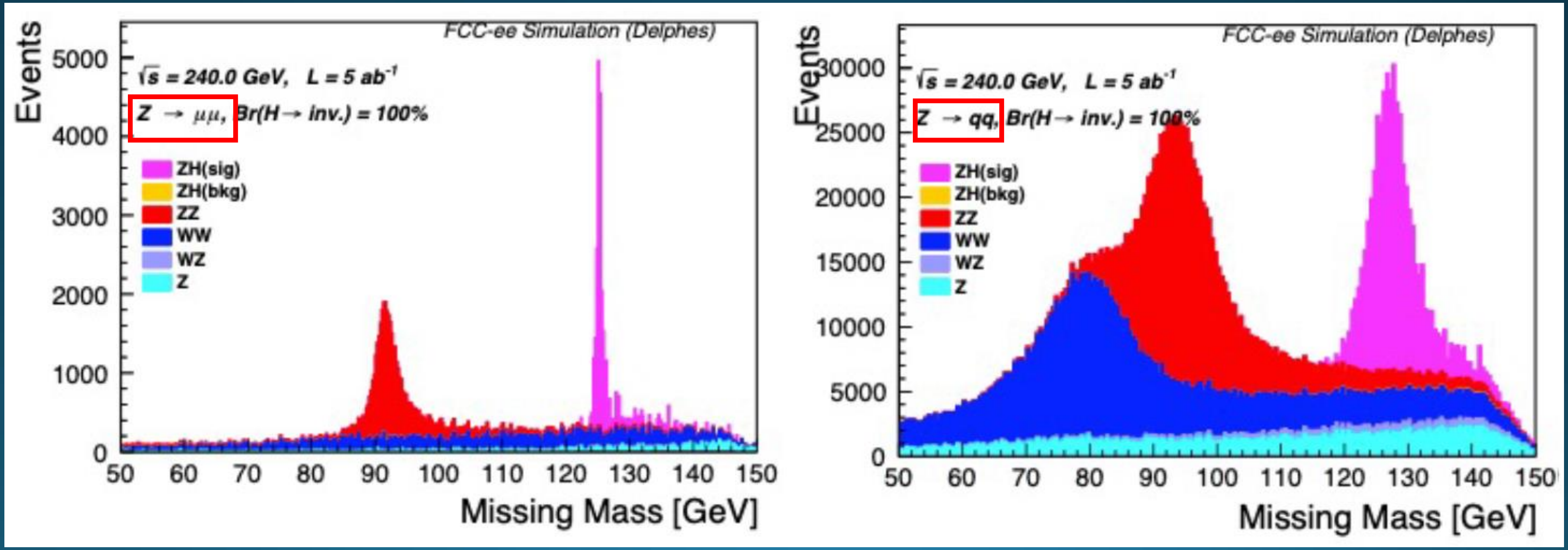
The ZZ background is not negligible, so works best if you can use a Z decay with excellent resolution, generally Z to muons (with a really great tracker).

Missing mass

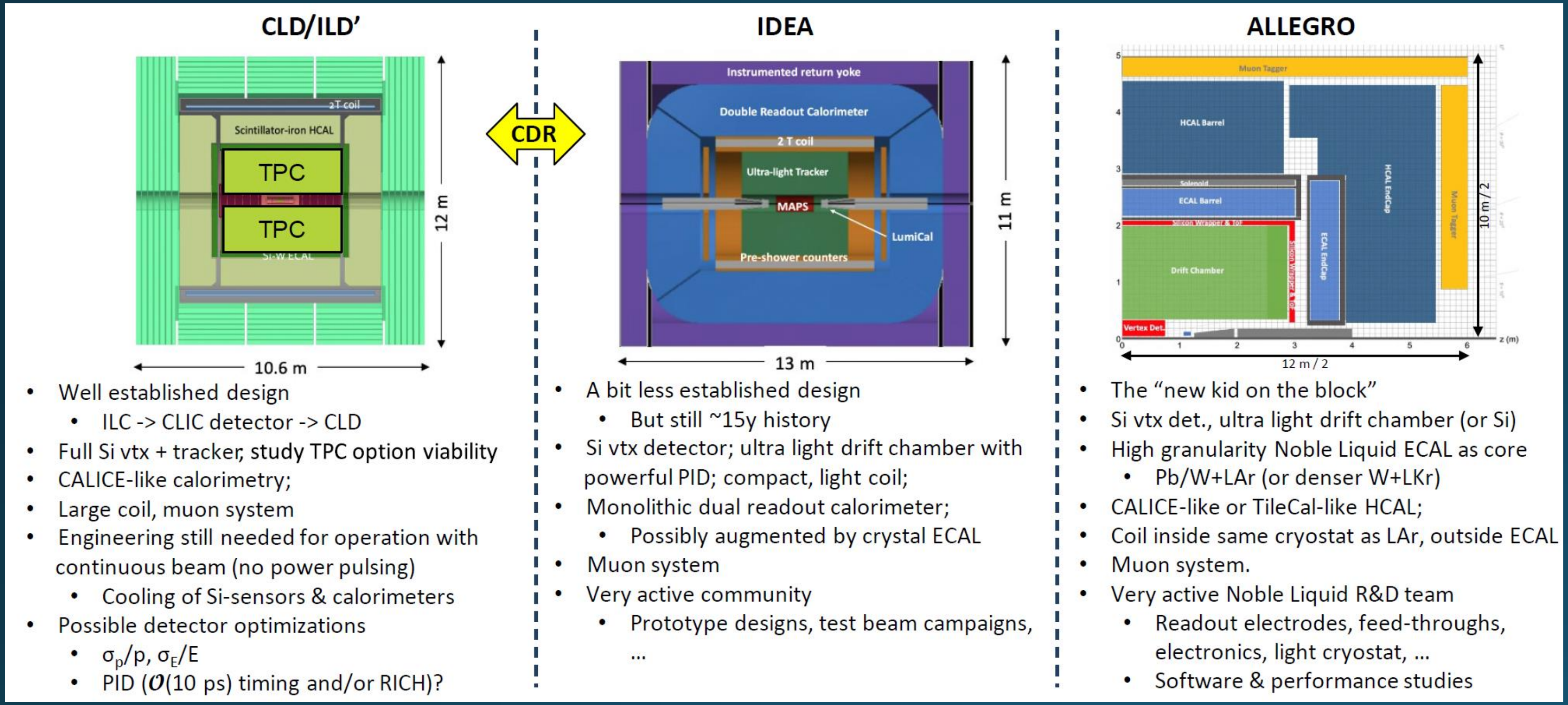
Muons!



Although the jet channel is certainly usable



trackers



CLD/ILD'

- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker, study TPC option viability
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

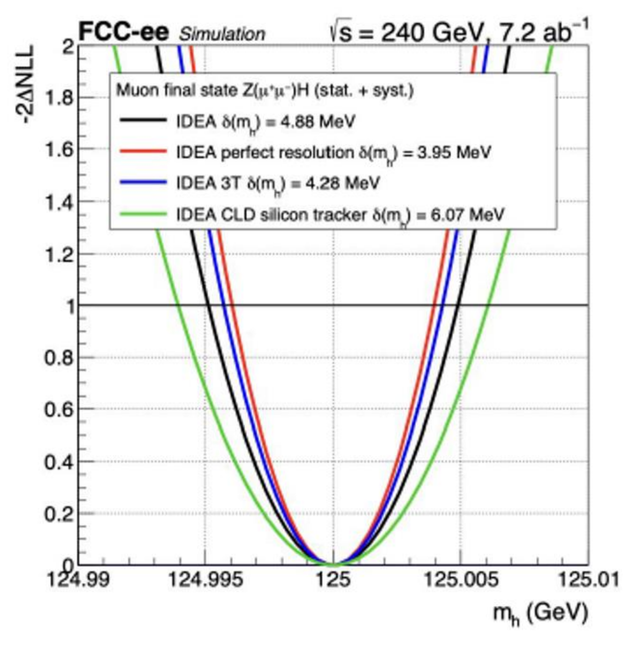
IDEA

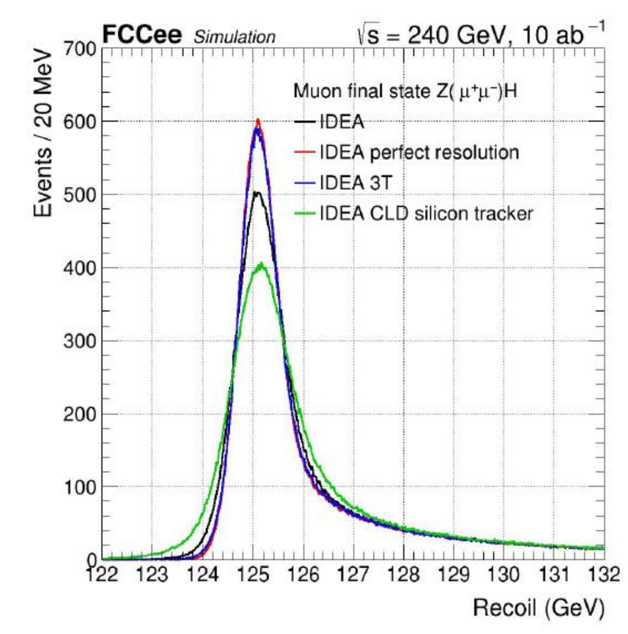
- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO

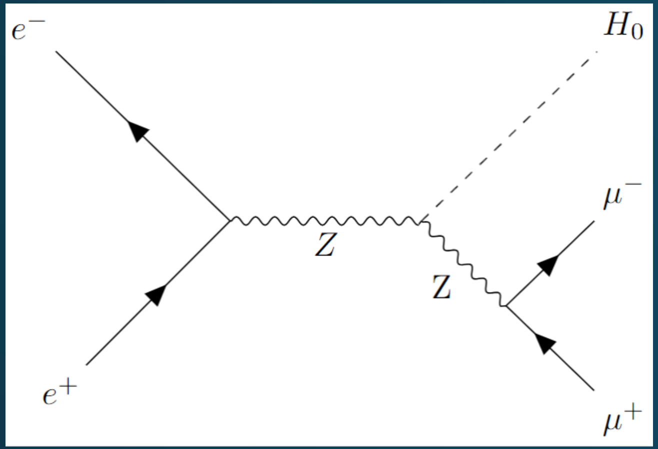
- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

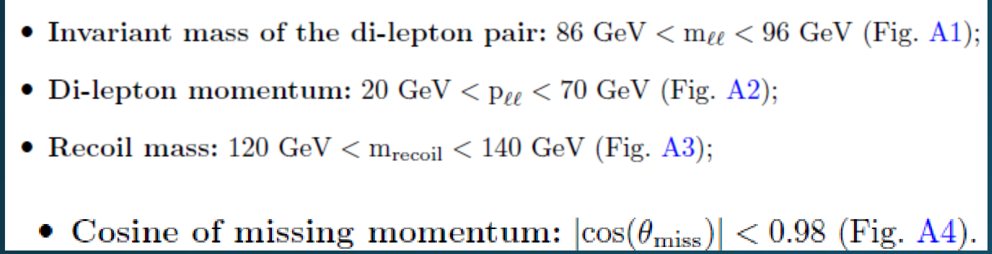
Note that for FCCee Z pole running, the magnetic field is limited to 2T to achieve luminosity goals. Not a requirement at ZH, although designing magnets and detectors to work well at different fields can be challenging.





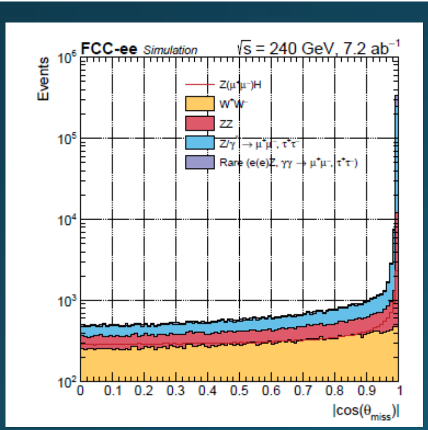
Missing mass and H mass





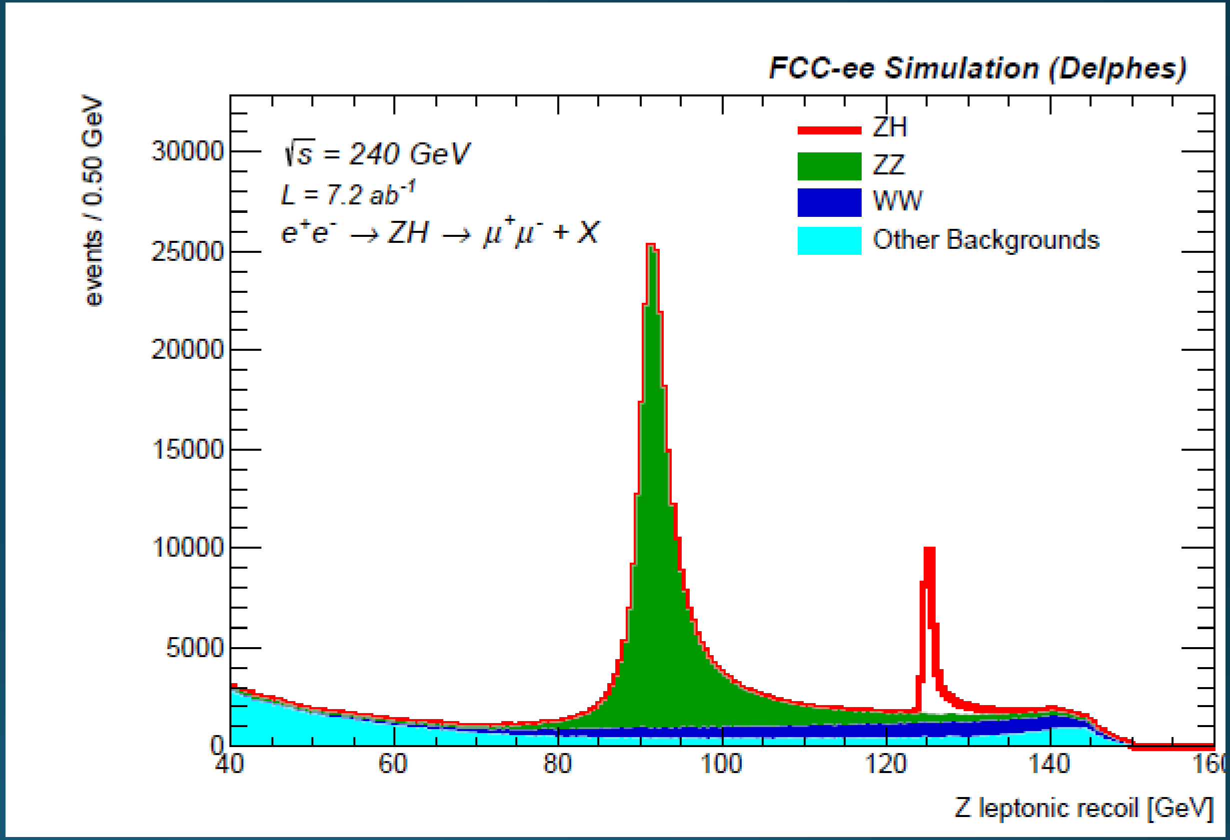
- **Invariant mass of the di-lepton pair:** 86 GeV $< m_{\ell\ell} <$ 96 GeV (Fig. A1);
- **Di-lepton momentum:** 20 GeV $< p_{\ell\ell} <$ 70 GeV (Fig. A2);
- **Recoil mass:** 120 GeV $< m_{recoil} <$ 140 GeV (Fig. A3);

- **Cosine of missing momentum:** $|\cos(\theta_{miss})| < 0.98$ (Fig. A4).



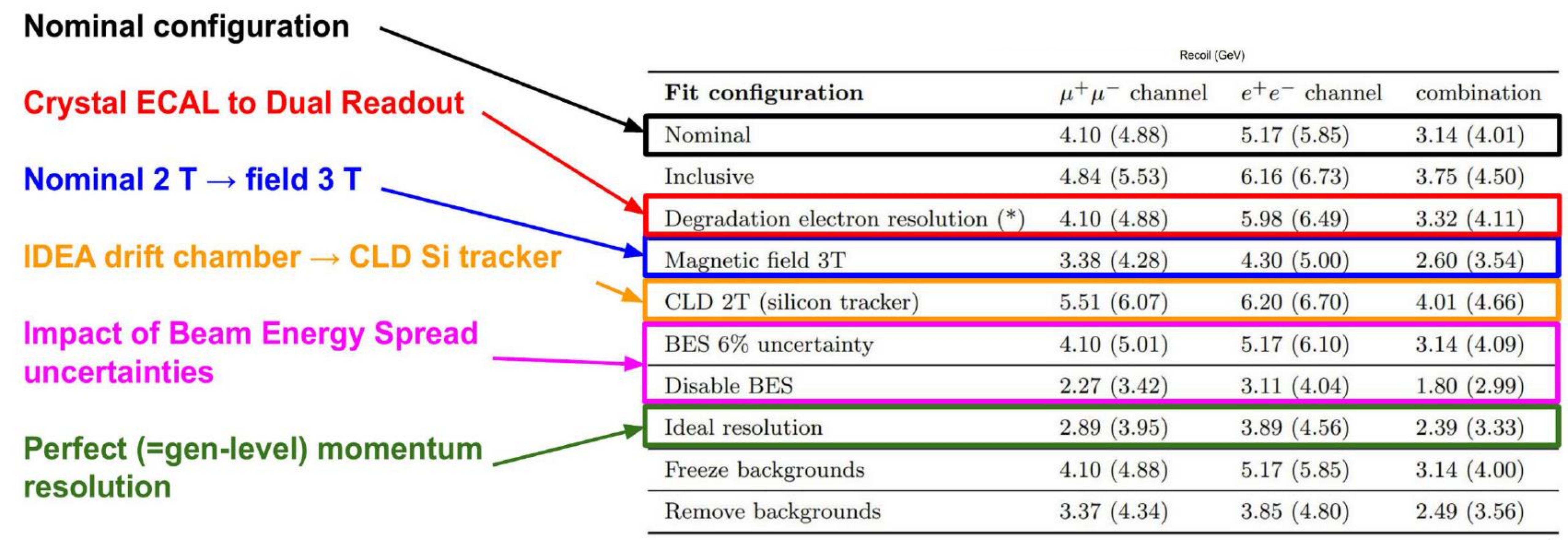
For Higgs, this last cut has a decay-mode dependency (but is very good at getting rid of the Z (not ZZ) background)

https://new-cds.cern.ch/records/a68b8-3mt57



Expected uncertainty combining all channels and energies around 0.0038 GeV

Extreme care needed



Nominal configuration

Crystal ECAL to Dual Readout

Nominal 2 T → field 3 T

IDEA drift chamber → CLD Si tracker

Impact of Beam Energy Spread uncertainties

Perfect (=gen-level) momentum resolution

Recoil (GeV)

Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	4.10 (4.88)	5.17 (5.85)	3.14 (4.01)
Inclusive	4.84 (5.53)	6.16 (6.73)	3.75 (4.50)
Degradation electron resolution (*)	4.10 (4.88)	5.98 (6.49)	3.32 (4.11)
Magnetic field 3T	3.38 (4.28)	4.30 (5.00)	2.60 (3.54)
CLD 2T (silicon tracker)	5.51 (6.07)	6.20 (6.70)	4.01 (4.66)
BES 6% uncertainty	4.10 (5.01)	5.17 (6.10)	3.14 (4.09)
Disable BES	2.27 (3.42)	3.11 (4.04)	1.80 (2.99)
Ideal resolution	2.89 (3.95)	3.89 (4.56)	2.39 (3.33)
Freeze backgrounds	4.10 (4.88)	5.17 (5.85)	3.14 (4.00)
Remove backgrounds	3.37 (4.34)	3.85 (4.80)	2.49 (3.56)

Work needed on resolution measurements, beam energy spread

Cross sections

At a future Higgs factor, cross section measurements are the key.
These are the measurements that give us the access to the partial widths (and thus the loops).

These need to be measured as precisely as possible

- A precision measurement of the total Higgs cross section in a model-independent way using the missing mass.
- Excellent control over luminosity calculation
- Excellent control acceptance/efficiency
- Compare to a highly precise theory calculation

Results often reported using the kappa framework (there are variations regarding how possible non-SM decays are included).

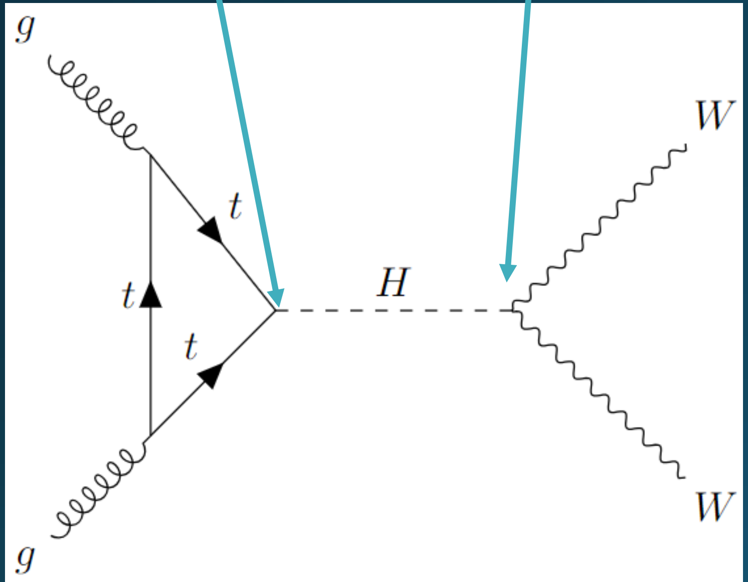
$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

(sometimes μ is used instead of κ)

High precision on the calculated SM value in the denominator is required.

Cross sections at LHC

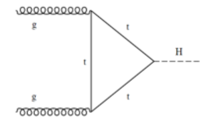
What we measure is a cross section for a production mode and a decay

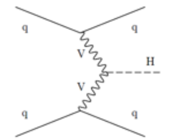


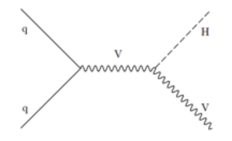
And not really even that, since each set of selection criteria is only enriched in a single production+decay diagram. For this analysis, at least the VH seems clean.

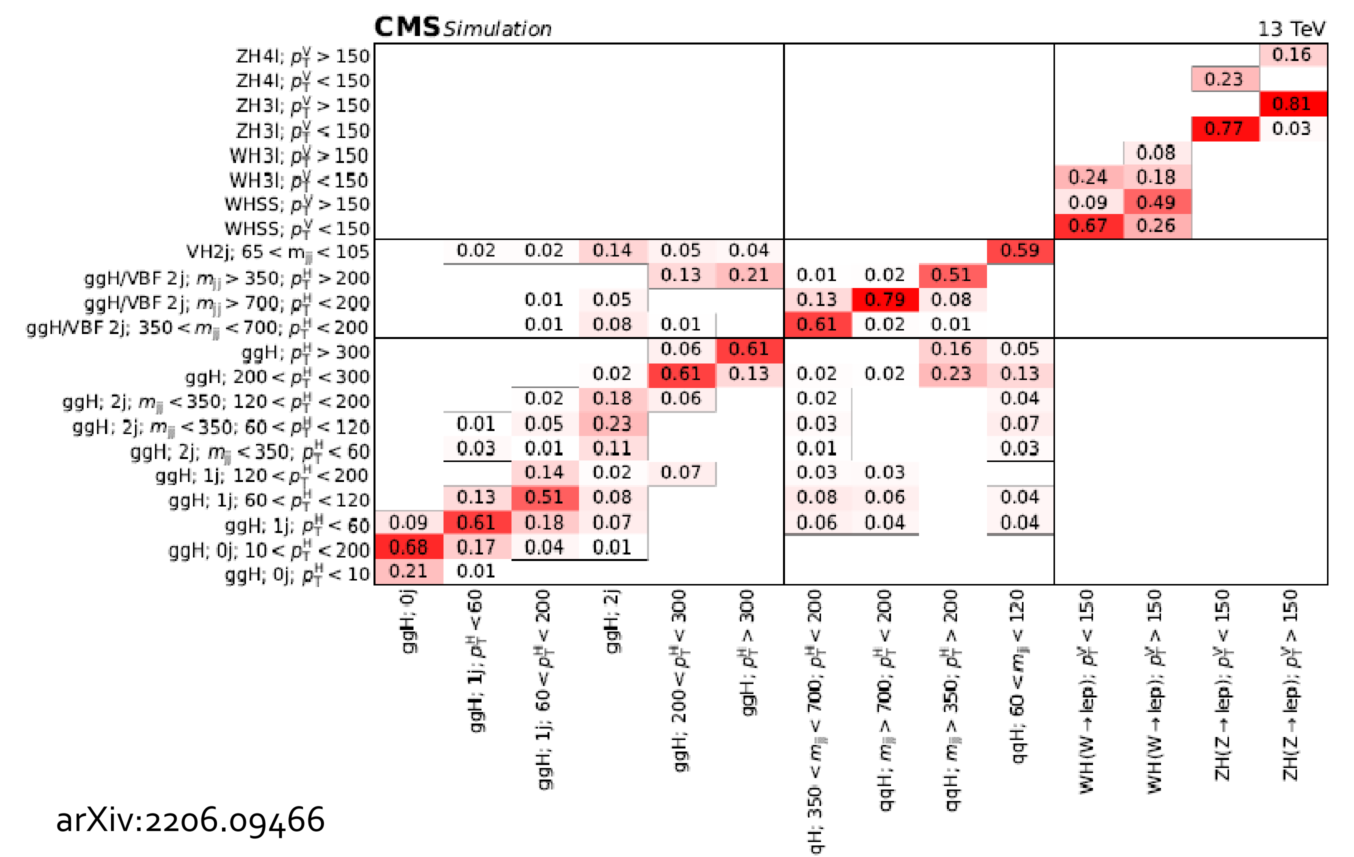
Higgs to WW

Expected signal composition in each STXS bin. Generator-level bins are reported in the horizontal axis, and the corresponding analysis categories on the vertical axis.





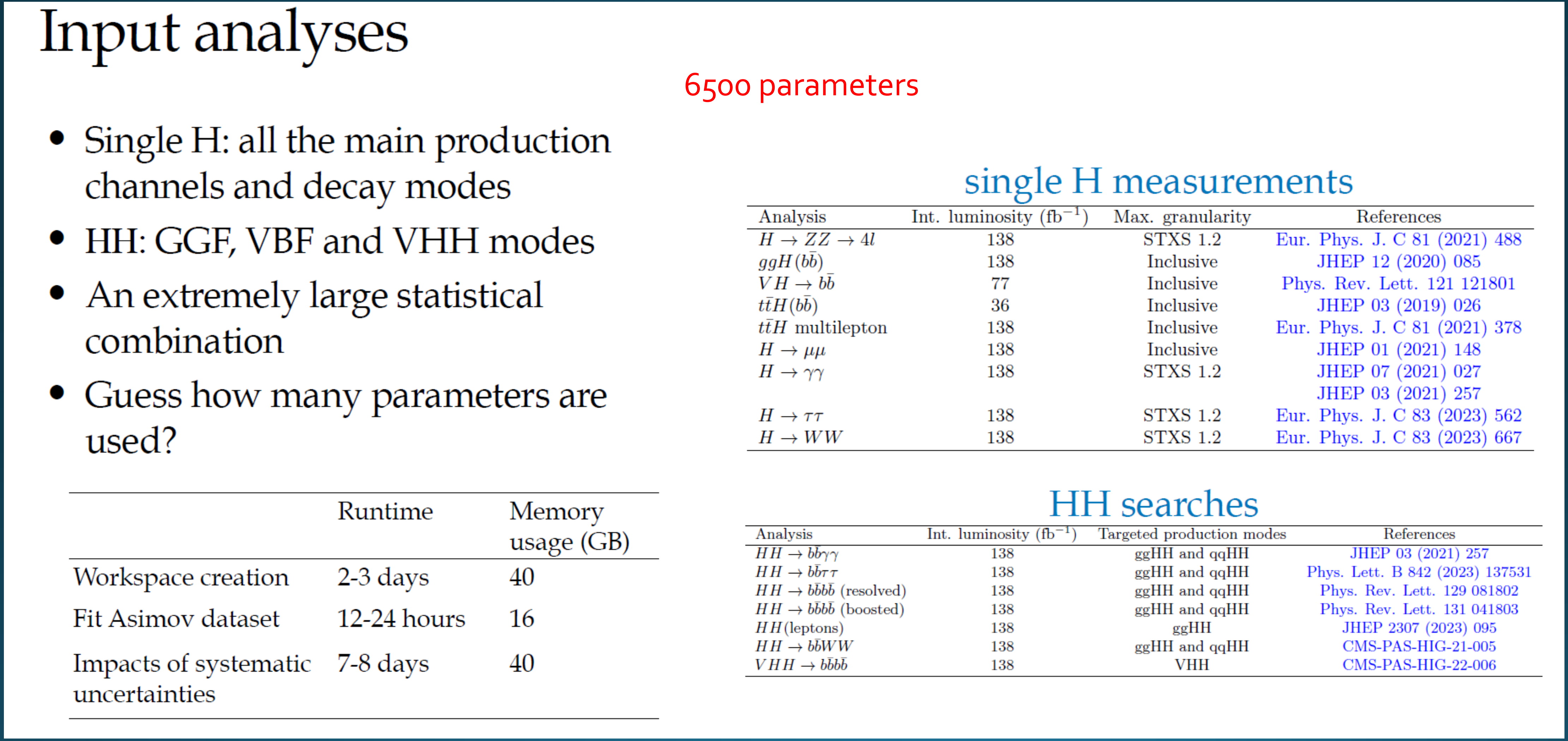




	ggH; 0j	ggH; 1j; $p_T^H < 60$	ggH; 1j; $60 < p_T^H < 200$	ggH; 2j	ggH; $200 < p_T^H < 300$	ggH; $p_T^H > 300$	qqH; $350 < m_{jj} < 700$; $p_T^H < 200$	qqH; $m_{jj} > 700$; $p_T^H < 200$	qqH; $m_{jj} > 350$; $p_T^H > 200$	qqH; $60 < m_{jj} < 120$	WH(W → lep); $p_T^V < 150$	WH(W → lep); $p_T^V > 150$	ZH(Z → lep); $p_T^V < 150$	ZH(Z → lep); $p_T^V > 150$
ZH4l; $p_T^V > 150$														0.16
ZH4l; $p_T^V < 150$													0.23	
ZH3l; $p_T^V > 150$														0.81
ZH3l; $p_T^V < 150$													0.77	0.03
WH3l; $p_T^V > 150$												0.08		
WH3l; $p_T^V < 150$											0.24	0.18		
WHSS; $p_T^V > 150$											0.09	0.49		
WHSS; $p_T^V < 150$											0.67	0.26		
VH2j; $65 < m_{jj} < 105$		0.02	0.02	0.14	0.05	0.04				0.59				
ggH/VBF 2j; $m_{jj} > 350$; $p_T^H > 200$					0.13	0.21	0.01	0.02	0.51					
ggH/VBF 2j; $m_{jj} > 700$; $p_T^H < 200$			0.01	0.05			0.13	0.79	0.08					
ggH/VBF 2j; $350 < m_{jj} < 700$; $p_T^H < 200$			0.01	0.08	0.01		0.61	0.02	0.01					
ggH; $p_T^H > 300$					0.06	0.61			0.16	0.05				
ggH; $200 < p_T^H < 300$				0.02	0.61	0.13	0.02	0.02	0.23	0.13				
ggH; 2j; $m_{jj} < 350$; $120 < p_T^H < 200$			0.02	0.18	0.06		0.02			0.04				
ggH; 2j; $m_{jj} < 350$; $60 < p_T^H < 120$		0.01	0.05	0.23			0.03			0.07				
ggH; 2j; $m_{jj} < 350$; $p_T^H < 60$		0.03	0.01	0.11			0.01			0.03				
ggH; 1j; $120 < p_T^H < 200$			0.14	0.02	0.07		0.03	0.03						
ggH; 1j; $60 < p_T^H < 120$		0.13	0.51	0.08			0.08	0.06		0.04				
ggH; 1j; $p_T^H < 60$	0.09	0.61	0.18	0.07			0.06	0.04		0.04				
ggH; 0j; $10 < p_T^H < 200$	0.68	0.17	0.04	0.01										
ggH; 0j; $p_T^H < 10$	0.21	0.01												

arXiv:2206.09466

Giant fit



Input analyses

6500 parameters

- Single H: all the main production channels and decay modes
- HH: GGF, VBF and VHH modes
- An extremely large statistical combination
- Guess how many parameters are used?

	Runtime	Memory usage (GB)
Workspace creation	2-3 days	40
Fit Asimov dataset	12-24 hours	16
Impacts of systematic uncertainties	7-8 days	40

single H measurements

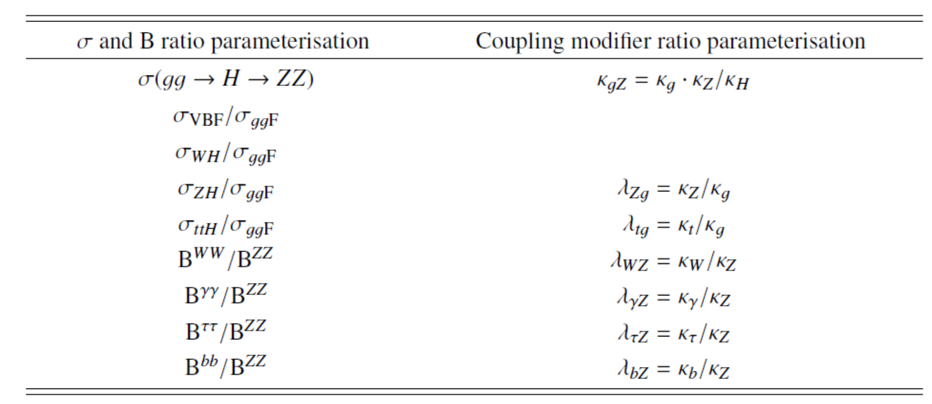
Analysis	Int. luminosity (fb^{-1})	Max. granularity	References
$H \to ZZ \to 4l$	138	STXS 1.2	Eur. Phys. J. C 81 (2021) 488
$ggH(b\bar{b})$	138	Inclusive	JHEP 12 (2020) 085
$VH \to b\bar{b}$	77	Inclusive	Phys. Rev. Lett. 121 121801
$t\bar{t}H(b\bar{b})$	36	Inclusive	JHEP 03 (2019) 026
$t\bar{t}H$ multilepton	138	Inclusive	Eur. Phys. J. C 81 (2021) 378
$H \to \mu\mu$	138	Inclusive	JHEP 01 (2021) 148
$H \to \gamma\gamma$	138	STXS 1.2	JHEP 07 (2021) 027 JHEP 03 (2021) 257
$H \to \tau\tau$	138	STXS 1.2	Eur. Phys. J. C 83 (2023) 562
$H \to WW$	138	STXS 1.2	Eur. Phys. J. C 83 (2023) 667

HH searches

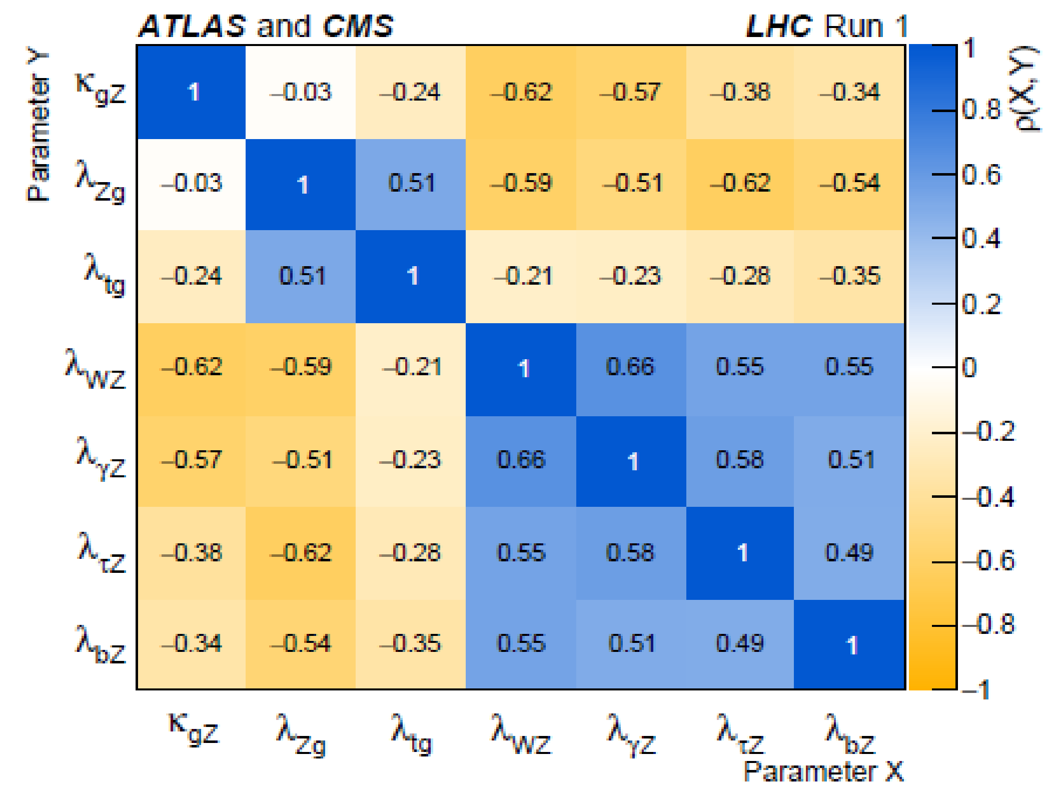
Analysis	Int. luminosity (fb^{-1})	Targeted production modes	References
$HH \to b\bar{b}\gamma\gamma$	138	ggHH and qqHH	JHEP 03 (2021) 257
$HH \to b\bar{b}\tau\tau$	138	ggHH and qqHH	Phys. Lett. B 842 (2023) 137531
$HH \to b\bar{b}b\bar{b}$ (resolved)	138	ggHH and qqHH	Phys. Rev. Lett. 129 081802
$HH \to b\bar{b}b\bar{b}$ (boosted)	138	ggHH and qqHH	Phys. Rev. Lett. 131 041803
HH(leptons)	138	ggHH	JHEP 2307 (2023) 095
$HH \to b\bar{b}WW$	138	ggHH and qqHH	CMS-PAS-HIG-21-005
$VHH \to b\bar{b}b\bar{b}$	138	VHH	CMS-PAS-HIG-22-006

Cross sections at LHC

arXiv: 1606.02266



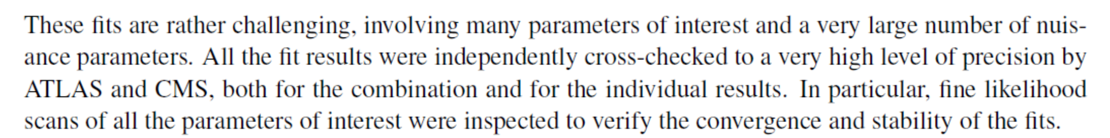
σ and B ratio parameterisation	Coupling modifier ratio parameterisation
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{\mathrm{VBF}}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
$\mathrm{B}^{WW}/\mathrm{B}^{ZZ}$	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$\mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$\mathrm{B}^{\tau\tau}/\mathrm{B}^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
$\mathrm{B}^{bb}/\mathrm{B}^{ZZ}$	$\lambda_{bZ} = \kappa_b/\kappa_Z$



	κ_{gZ}	λ_{Zg}	λ_{tg}	λ_{WZ}	$\lambda_{\gamma Z}$	$\lambda_{\tau Z}$	λ_{bZ}
κ_{gZ}	1	−0.03	−0.24	−0.62	−0.57	−0.38	−0.34
λ_{Zg}	−0.03	1	0.51	−0.59	−0.51	−0.62	−0.54
λ_{tg}	−0.24	0.51	1	−0.21	−0.23	−0.28	−0.35
λ_{WZ}	−0.62	−0.59	−0.21	1	0.66	0.55	0.55
$\lambda_{\gamma Z}$	−0.57	−0.51	−0.23	0.66	1	0.58	0.51
$\lambda_{\tau Z}$	−0.38	−0.62	−0.28	0.55	0.58	1	0.49
λ_{bZ}	−0.34	−0.54	−0.35	0.55	0.51	0.49	1

At the LHC, each measurable involves at least two couplings (production and decay). By measuring several processes, the individual couplings can be disentangled, but with substantial correlations.

And anybody who has ever done this kind of fit will surely agree with the quoted text from the paper.

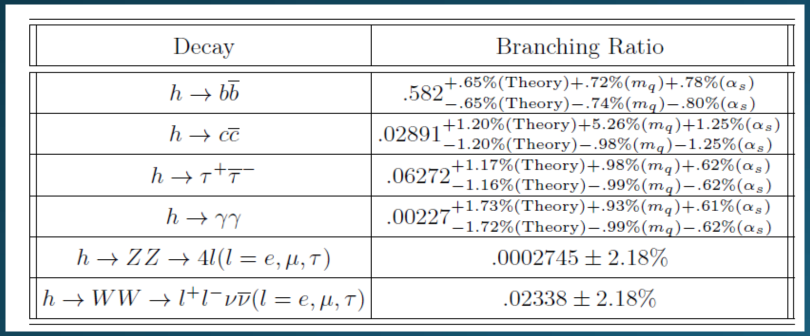


These fits are rather challenging, involving many parameters of interest and a very large number of nuisance parameters. All the fit results were independently cross-checked to a very high level of precision by ATLAS and CMS, both for the combination and for the individual results. In particular, fine likelihood scans of all the parameters of interest were inspected to verify the convergence and stability of the fits.

Theory status

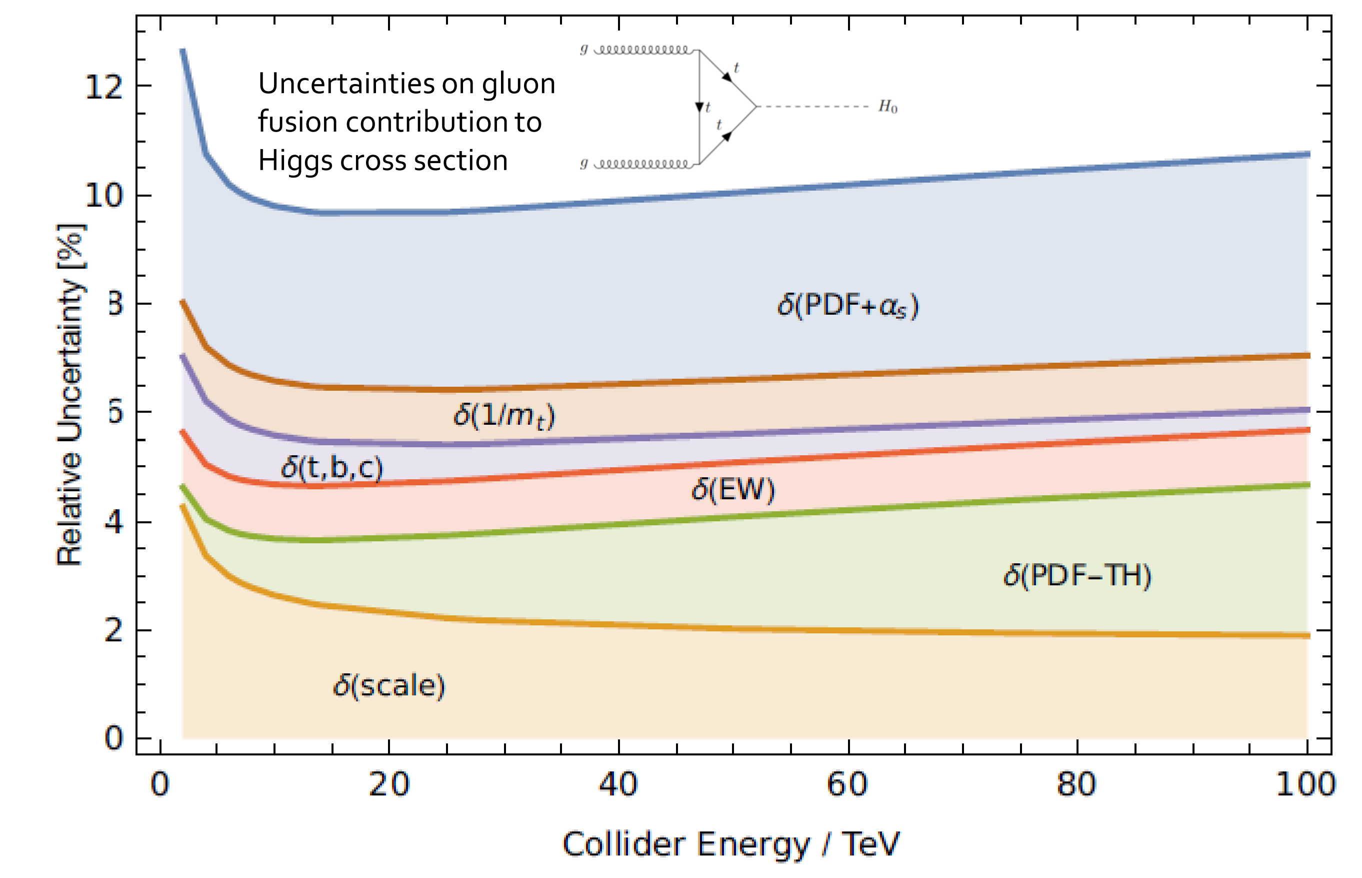
Right now, uncertainties on cross sections at hadron colliders can be substantial.

Uncertainties on branching fractions tend to be around 2%.



Decay	Branching Ratio
$h \to b\bar{b}$	$.582^{+.65\%(\text{Theory})+.72\%(m_q)+.78\%(\alpha_s)}_{-.65\%(\text{Theory})-.74\%(m_q)-.80\%(\alpha_s)}$
$h \to c\bar{c}$	$.02891^{+1.20\%(\text{Theory})+5.26\%(m_q)+1.25\%(\alpha_s)}_{-1.20\%(\text{Theory})-.98\%(m_q)-1.25\%(\alpha_s)}$
$h \to \tau^+\overline{\tau}^-$	$.06272^{+1.17\%(\text{Theory})+.98\%(m_q)+.62\%(\alpha_s)}_{-1.16\%(\text{Theory})-.99\%(m_q)-.62\%(\alpha_s)}$
$h \to \gamma\gamma$	$.00227^{+1.73\%(\text{Theory})+.93\%(m_q)+.61\%(\alpha_s)}_{-1.72\%(\text{Theory})-.99\%(m_q)-.62\%(\alpha_s)}$
$h \to ZZ \to 4l(l = e, \mu, \tau)$	$.0002745 \pm 2.18\%$
$h \to WW \to l^+l^-\nu\overline{\nu}(l = e, \mu, \tau)$	$.02338 \pm 2.18\%$

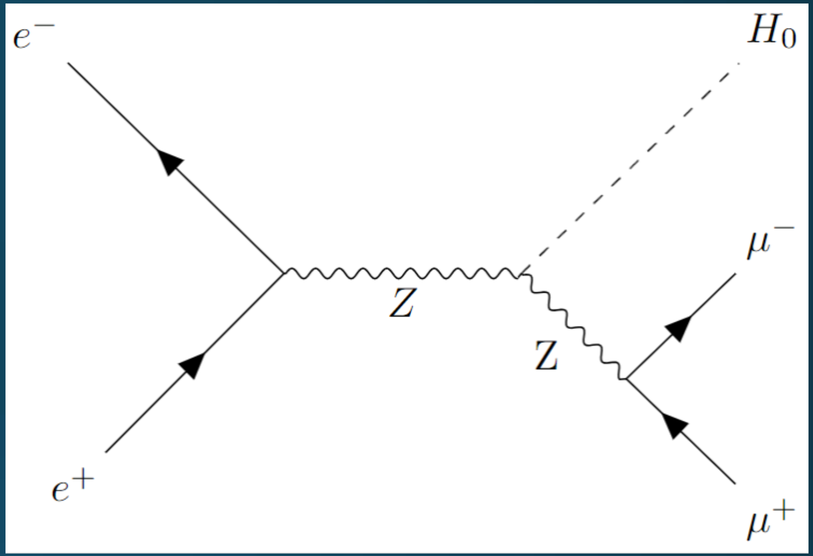
arXiv:2209.07510

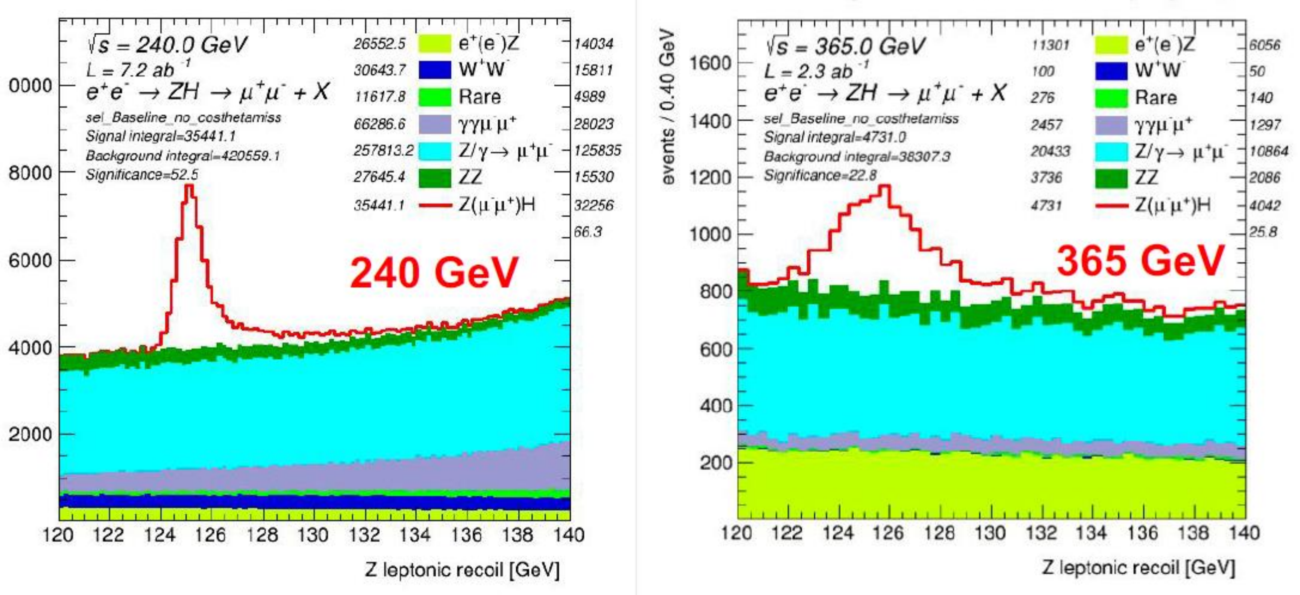


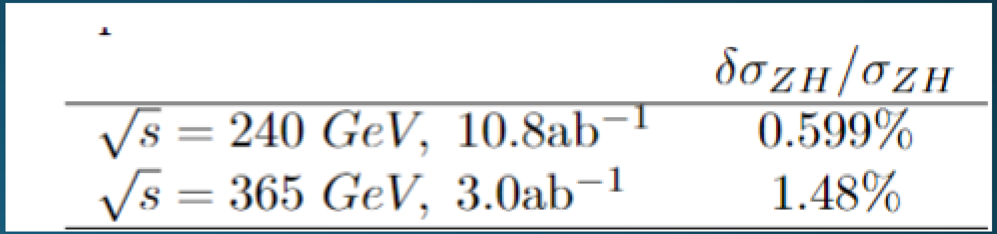
Uncertainties on gluon fusion contribution to Higgs cross section

At e^+e^-, again use the missing mass magic

e^+e^- collisions allows a very pure extraction of the ZH cross section.







	$\delta\sigma_{ZH}/\sigma_{ZH}$
$\sqrt{s} = 240\ GeV,\ 10.8\text{ab}^{-1}$	0.599%
$\sqrt{s} = 365\ GeV,\ 3.0\text{ab}^{-1}$	1.48%

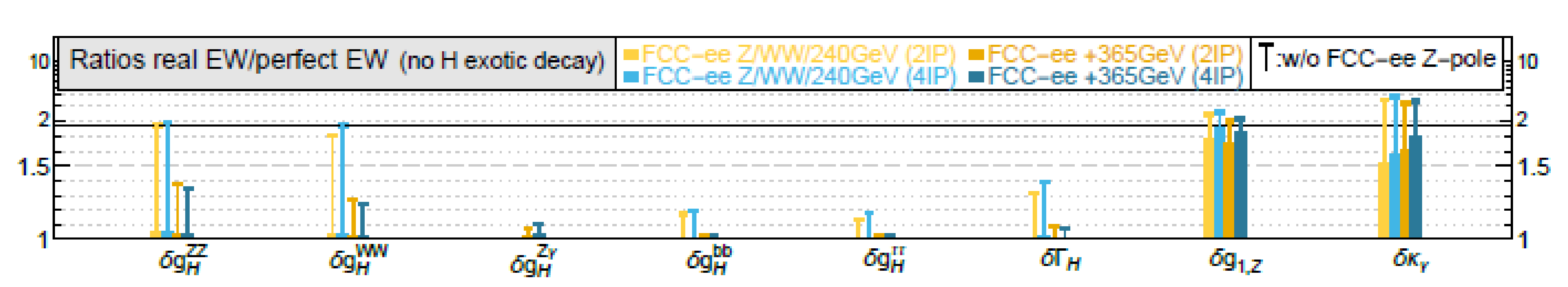
Removing the Z suppression cut to remove virtually all dependence on Higgs decay mode at the cost of additional backgrounds.

https://new-cds.cern.ch/records/a68b8-3mt57

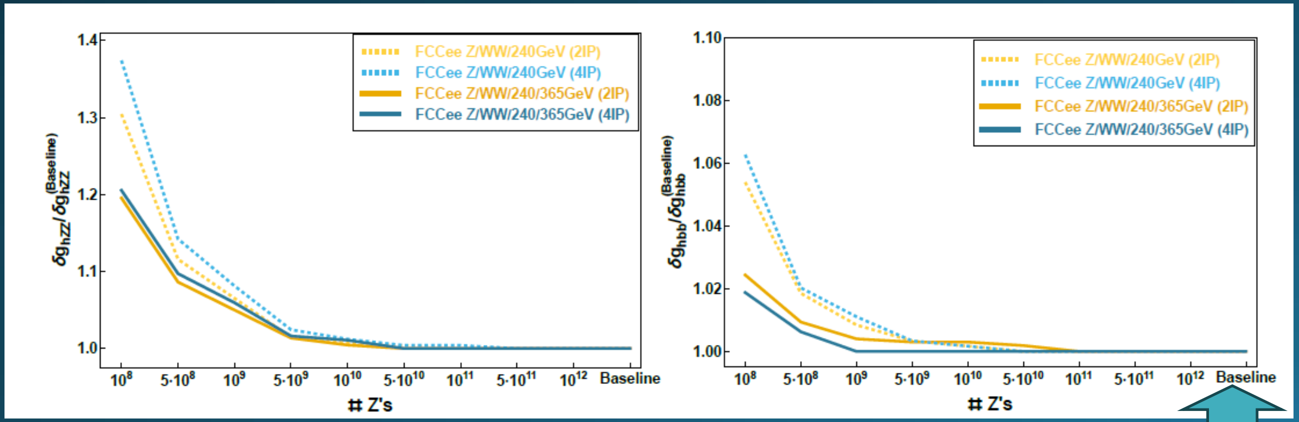
but

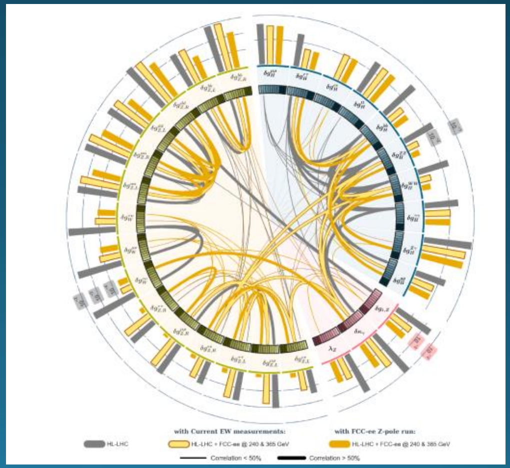
But we still need to compare to the predicted values. And the theory calculations require input of measured SM parameters.

To understand Higgs, need to understand the Z



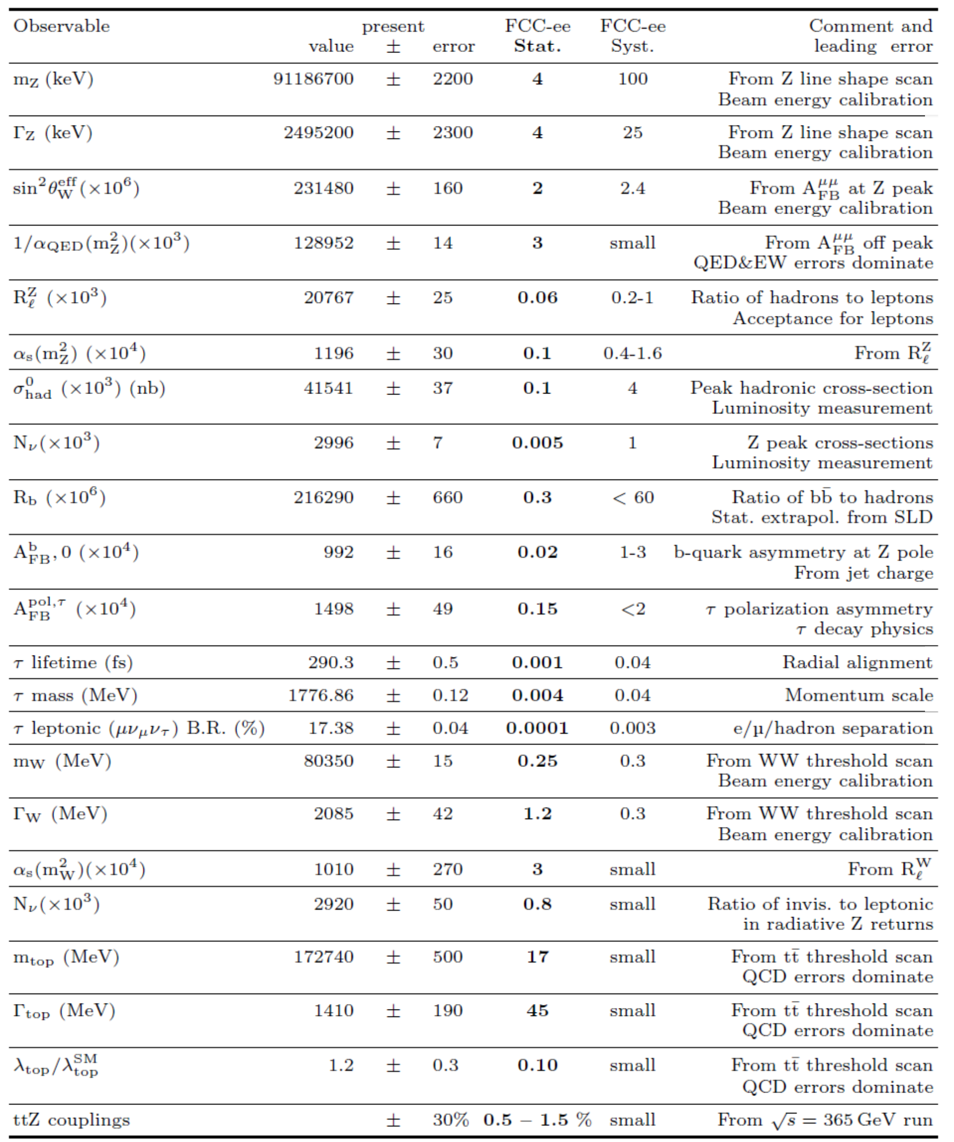
This plot shows the ratio of the uncertainty in a scenario to that if all EWK parameters were known to infinite precision. As you can see, reducing the uncertainties on fundamental EWK parameters at the Z running has a strong impact error bars on all measurements. (take say the turquoise δg_H^{ZZ}… with Z running the uncertainty is just over than 1. without it is almost 2.





No orange line connects the Higgs to the EWK, illustrating broken correlation

Orders of magnitude



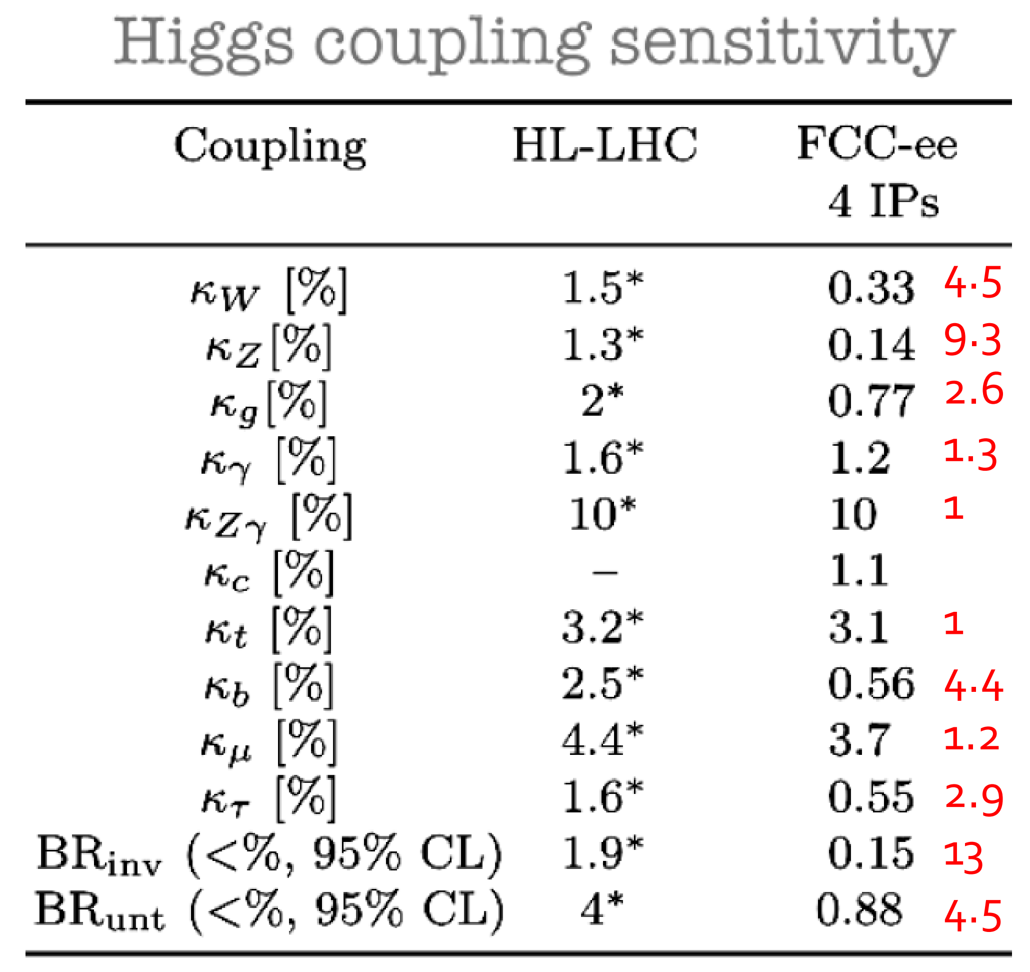
Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error	total FCC error/past	FCC sys/stat
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration	20	25
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration	90	6
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	50	1
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate	5	0
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons	25	17
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z	20	16
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement	10	40
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement	7	200
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD	10	200
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge	5	150
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics	25	13
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment	10	40
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale	3	10
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/µ/hadron separation	15	30
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration	40	1.2
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration	35	
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W	90	
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns	60	
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate	30	
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate	4	
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate		
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run		

Higgs Couplings

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$$

https://new-cds.cern.ch/records/511pr-rd590

Once we have the ZH cross section regardless of branching ratio, each decay mode directly measures only one coupling.



Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee 4 IPs	
κ_W [%]	1.5*	0.33	4.5
κ_Z [%]	1.3*	0.14	9.3
κ_g [%]	2*	0.77	2.6
κ_γ [%]	1.6*	1.2	1.3
$\kappa_{Z\gamma}$ [%]	10*	10	1
κ_c [%]	–	1.1	
κ_t [%]	3.2*	3.1	1
κ_b [%]	2.5*	0.56	4.4
κ_μ [%]	4.4*	3.7	1.2
κ_τ [%]	1.6*	0.55	2.9
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.15	13
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	0.88	4.5

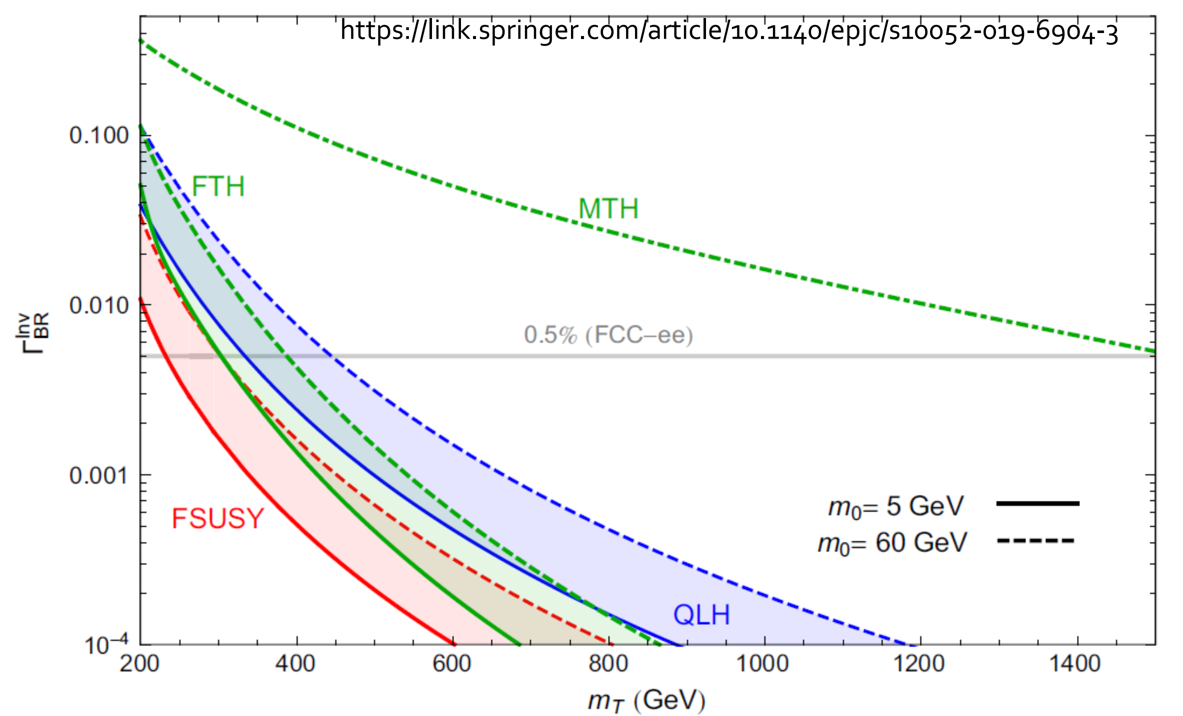
Not a surprise that we improve most regarding the coupling to the Z at what is essentially a Z factory.

Higgs width

Non standard modeling decay modes of the Higgs give an increased width.

Could the Higgs provide dark matter mass? a portal to a dark sector? or to other light or long-lived particles? Or to particles whose backgrounds are too large to allow detection?

Standard model prediction for the Higgs width is 4.07 MeV ±4% (pdg)
Standard model prediction for BR to invisible is the negligible contribution from ZZ to four neutrinos (10^{-3}).



https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3

SUSY-based "glueballs" model as function of top partner mass.

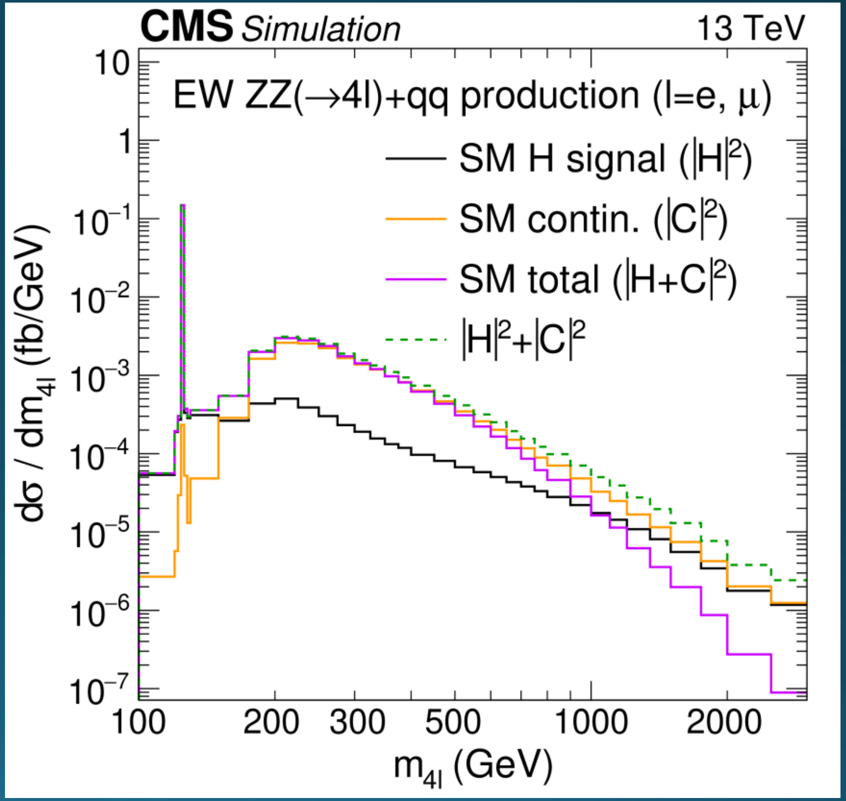
At LHC

Current measurement at LHC is $3.7^{+1.9}_{-1.4}$ Mev (pdg) (50% measurement)
After HL-LHC, maybe 14% measurement? (including invisible decays in the model-dependent fit to all cross sections gives 6-17% uncertainty)

$$\sigma^{on-shell\ (105-140\ GeV)} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_p$$

$$\sigma^{off-shell\ (>220\ GeV)} \propto g_p^2 g_d^2 \propto \mu_p \Gamma_H$$

Measurement also done in llνν channel



Note the interference term between continuum and signal is destructive.

Higgs width at e^+e^-

Much easier, much less model dependent at a Higgs factory
Two ways:

- Both start with ZH cross section at 240 GeV
  - First uses ZH->ZZZ* at 240 GeV (about a 4.6% measurement)
  - Second uses ννH->bb at 370 GeV (about a 3.2% measurement)
- These two plus other channels for the second method could lead to about 1% measurement

Although combining many few percent measurements to get a 1% measurement is never a trivial thing to do

$$\sigma_{\mathrm{ZH}} \propto \mathrm{g}_{\mathrm{Z}}^2$$

$$\sigma_{ZH,H(ZZ^*)} \propto \frac{\mathrm{g}_{\mathrm{Z}}^2 \times \mathrm{g}_{\mathrm{Z}}^2}{\Gamma_H}$$

$$\Gamma_H \propto \frac{\sigma_{ZH}^2}{\sigma_{ZH,H(ZZ^*)}}$$

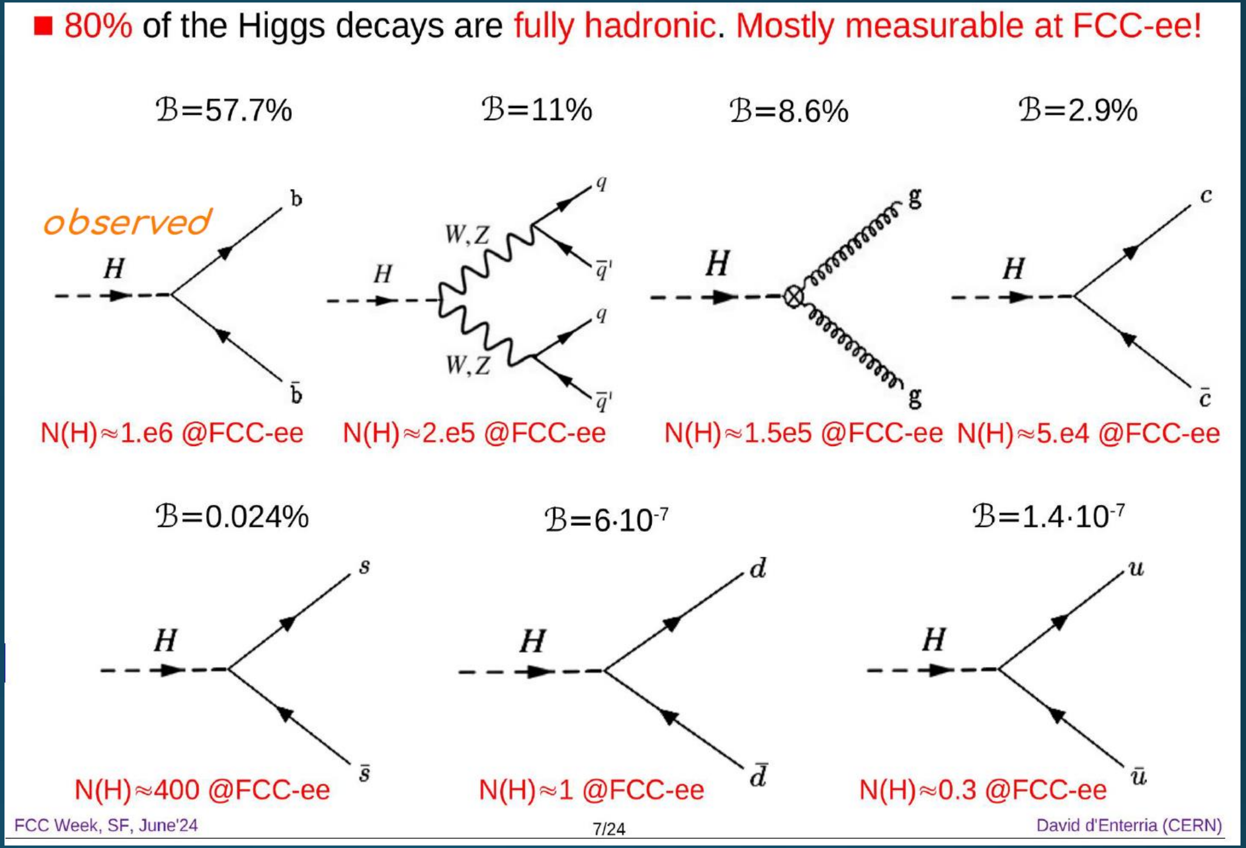
or

$$\Gamma_H \propto \frac{\sigma_{ZH}^2 \sigma_{H\nu_e\bar{\nu}_e,H(bb)}}{\sigma_{ZH,H(bb)}\sigma_{ZH,H(WW^*)}}$$

Back to couplings

Well, maybe these things are harder than I'm implying.

Many of the decay modes we want to measure are hadronic.



■ 80% of the Higgs decays are fully hadronic. Mostly measurable at FCC-ee!

$\mathcal{B}$=57.7% — N(H)≈1.e6 @FCC-ee

$\mathcal{B}$=11% — N(H)≈2.e5 @FCC-ee

$\mathcal{B}$=8.6% — N(H)≈1.5e5 @FCC-ee

$\mathcal{B}$=2.9% — N(H)≈5.e4 @FCC-ee

$\mathcal{B}$=0.024% — N(H)≈400 @FCC-ee

$\mathcal{B}=6\cdot10^{-7}$ — N(H)≈1 @FCC-ee

$\mathcal{B}=1.4\cdot10^{-7}$ — N(H)≈0.3 @FCC-ee

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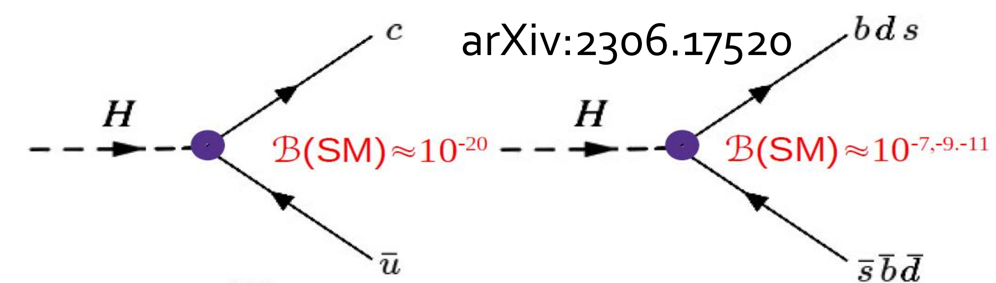
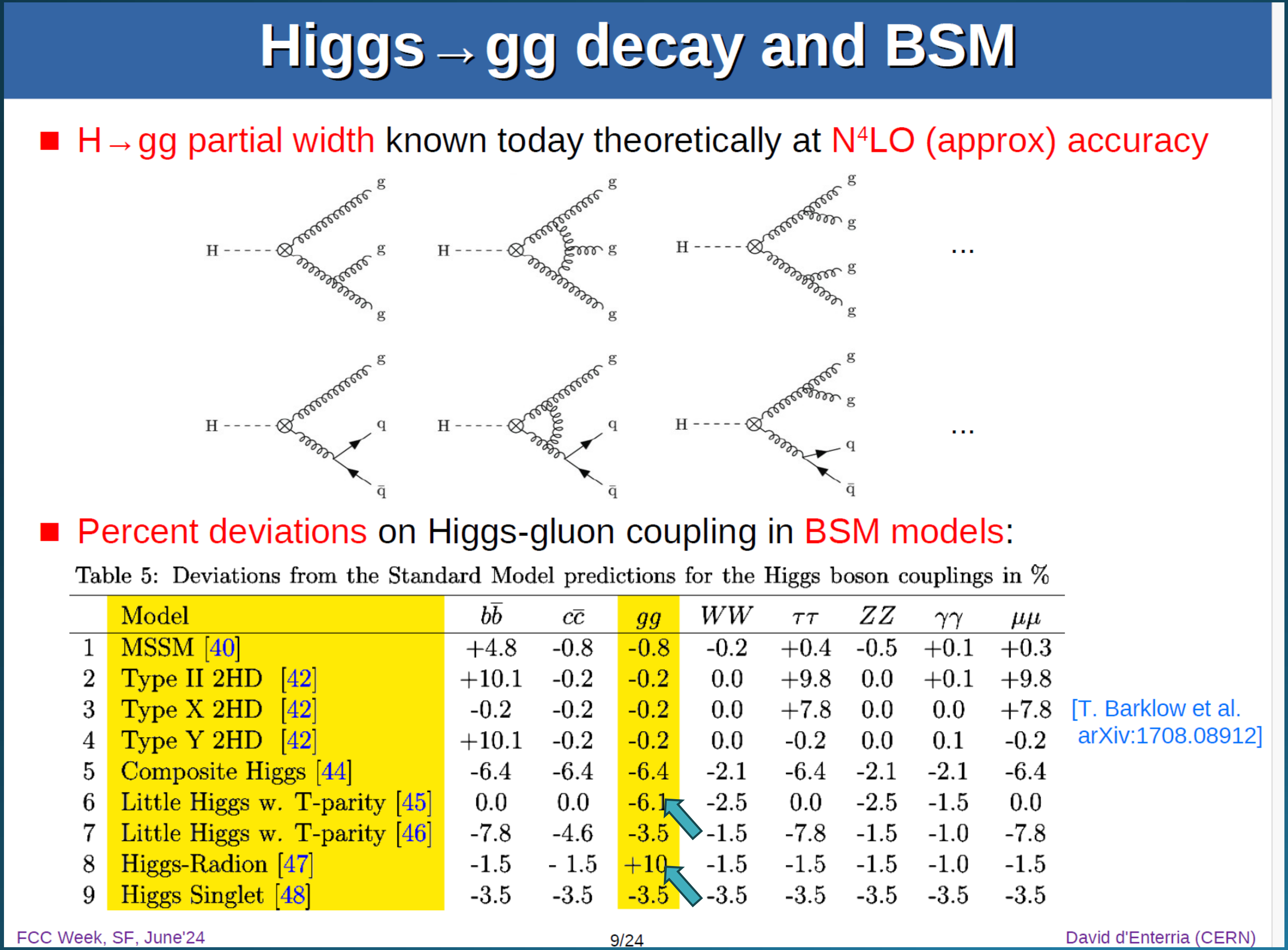
And surely we'll want to look for flavor violating decays as well



arXiv:2306.17520

These are interesting. Consider Higgs to gluon



Higgs → gg decay and BSM

- H → gg partial width known today theoretically at N^4LO (approx) accuracy

- Percent deviations on Higgs-gluon coupling in BSM models:

Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings in %

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	-0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

[T. Barklow et al. arXiv:1708.08912]

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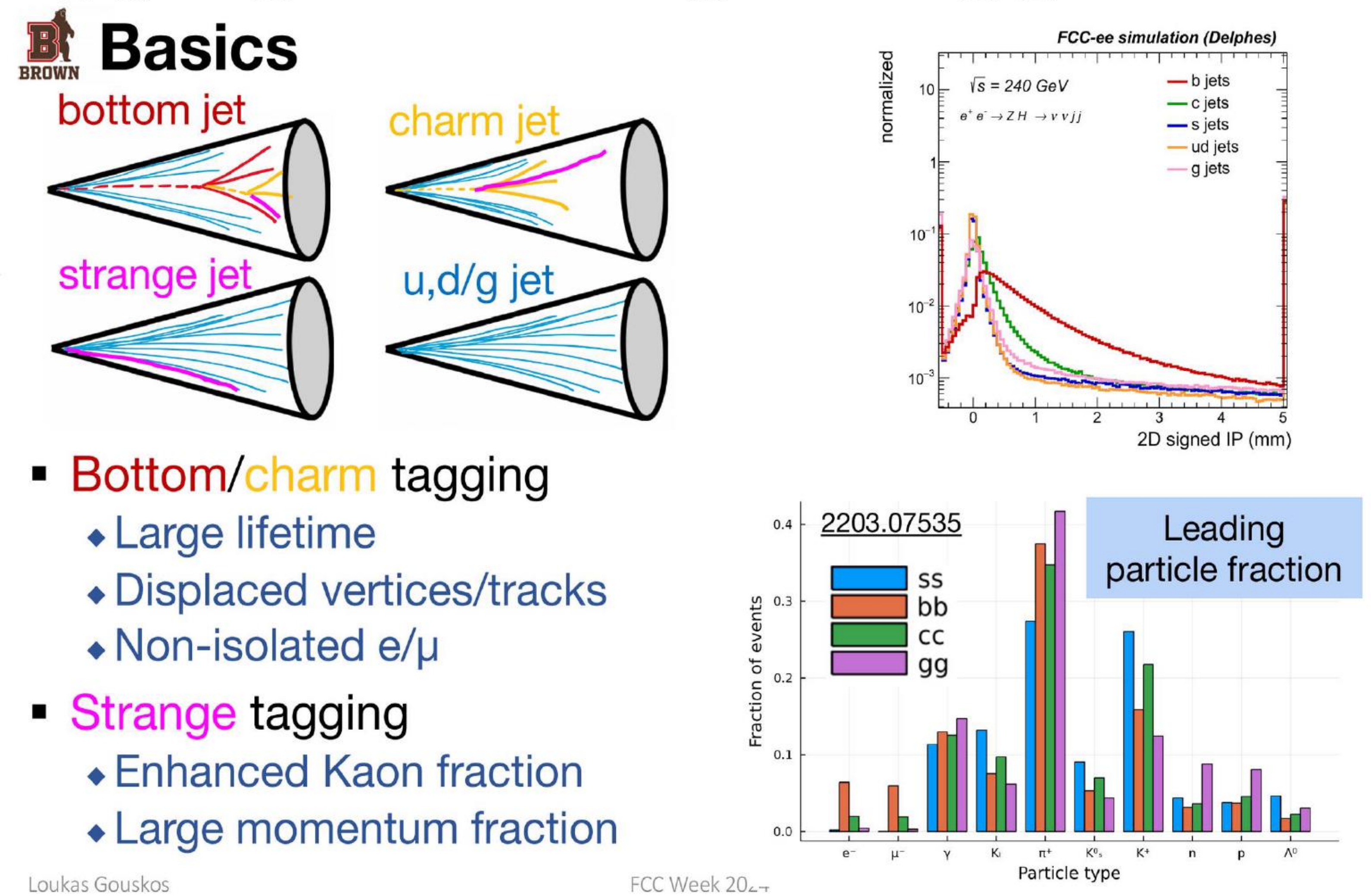
Biggest change for some model.

Also pattern can help distinguish between different models.

So need to ID jet flavor

Kaon (strange) tagging could be key to this program

Although note that this is not easy. The differences in the kaon content are not large, and training on MC could lead to biases due to uncertainties in fragmentation.



Basics

- Bottom/charm tagging
  - Large lifetime
  - Displaced vertices/tracks
  - Non-isolated e/μ
- Strange tagging
  - Enhanced Kaon fraction
  - Large momentum fraction

Loukas Gouskos

FCC Week 20

arXiv:2310.03440

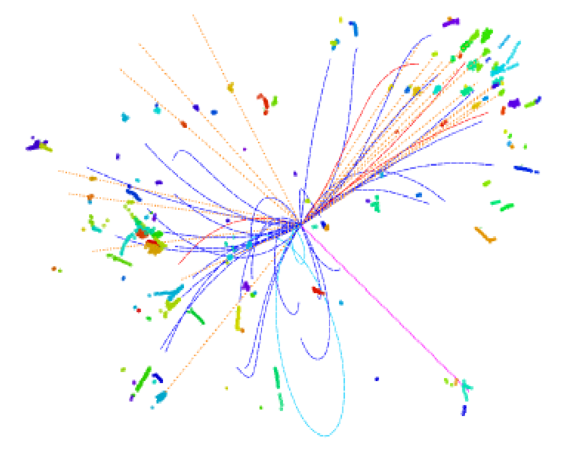
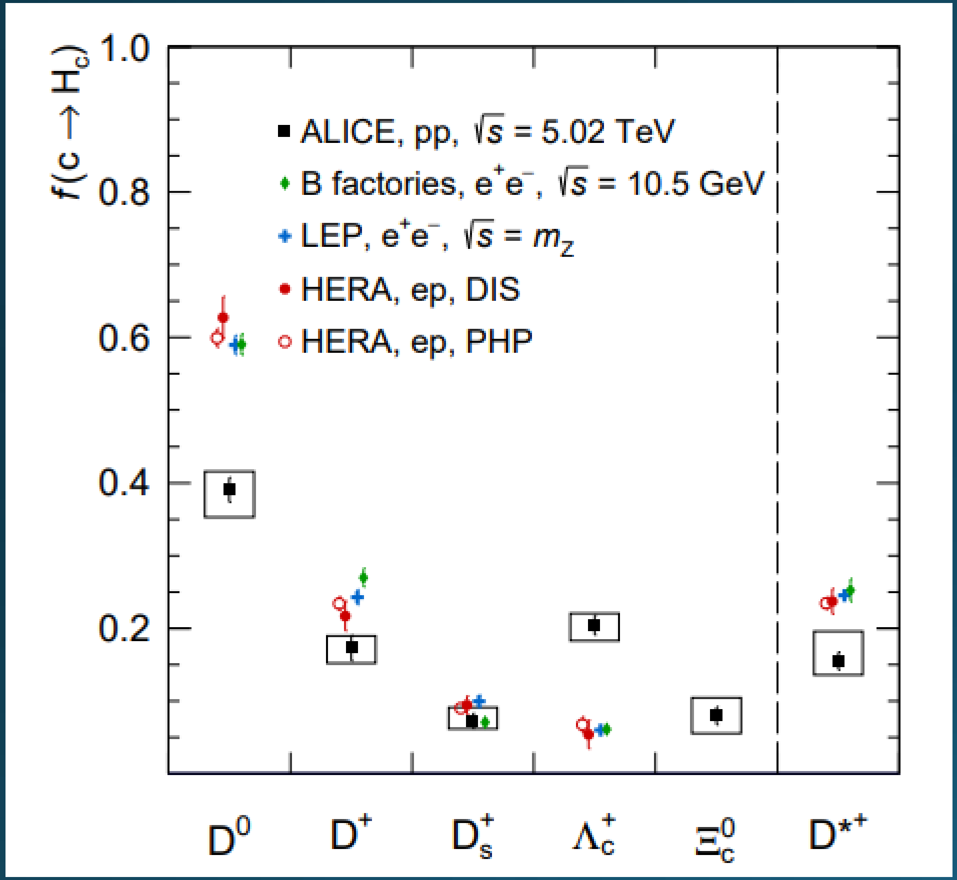


FIG. 1. Event display of an $e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}gg$ ($\sqrt{s}$ = 240 GeV) event simulated and reconstructed with the CEPC baseline detector [17]. Different particles are depicted with colored curves and straight lines: red for $e^\pm$, cyan for $\mu^\pm$, blue for $\pi^\pm$, orange for photons, and magenta for neutral hadrons.

Charm fragmentation

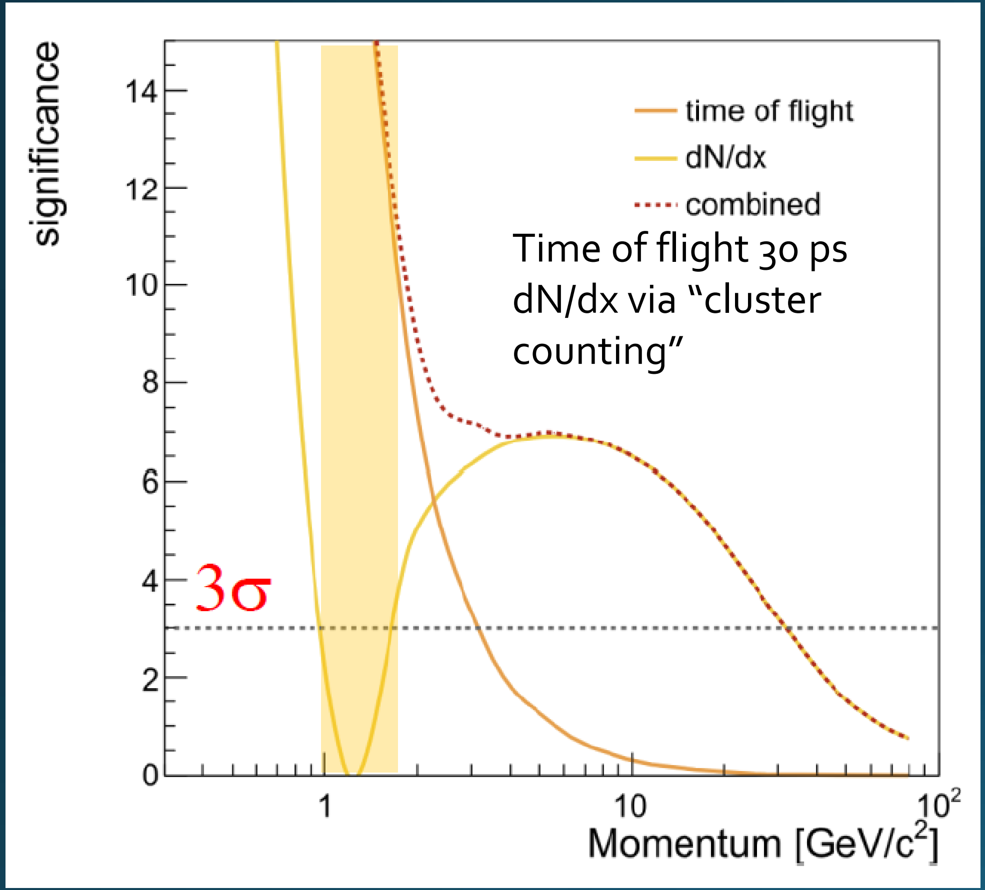
https://arxiv.org/abs/2105.06335



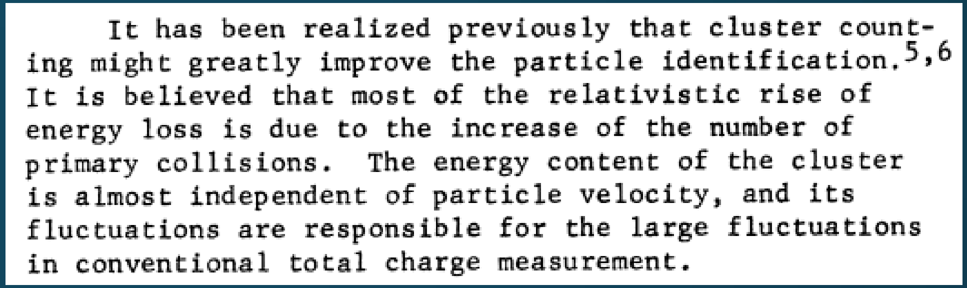
Charm-quark fragmentation fractions into charm hadrons measured in pp collisions at √ s = 5.02 TeV in comparison with experimental measurements performed in e+e – collisions at LEP and at B factories, and in ep collisions at HERA

Some disagreement between LEP and b factories. Considerable disagreement between these and pp.

Unlike at ATLAS/CMS, kaon ID will be available

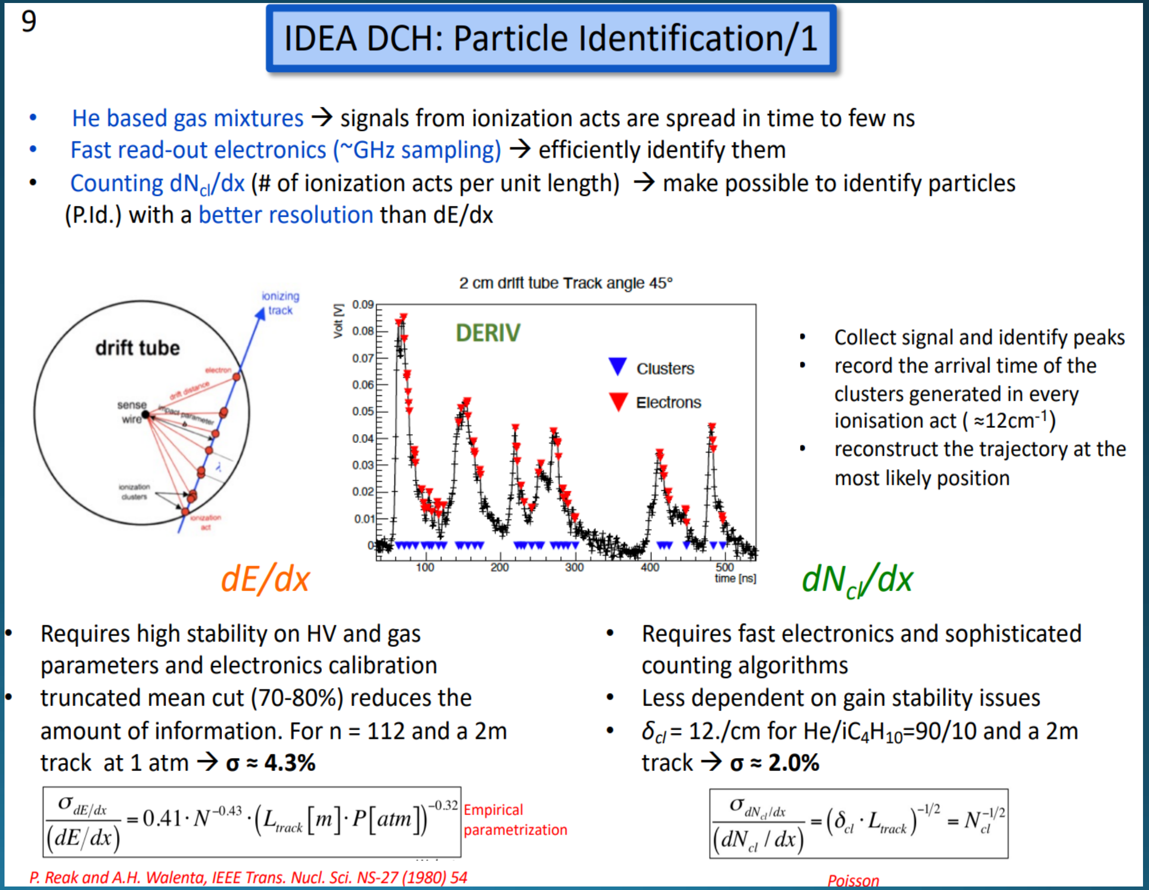


Time of flight 30 ps
dN/dx via "cluster counting"



It has been realized previously that cluster counting might greatly improve the particle identification.[5,6] It is believed that most of the relativistic rise of energy loss is due to the increase of the number of primary collisions. The energy content of the cluster is almost independent of particle velocity, and its fluctuations are responsible for the large fluctuations in conventional total charge measurement.

https://ieeexplore.ieee.org/abstract/document/4330801 (1980)



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IDEA DCH: Particle Identification/1

- He based gas mixtures → signals from ionization acts are spread in time to few ns
- Fast read-out electronics (~GHz sampling) → efficiently identify them
- Counting dN_{cl}/dx (# of ionization acts per unit length) → make possible to identify particles (P.Id.) with a better resolution than dE/dx

- Collect signal and identify peaks
- record the arrival time of the clusters generated in every ionisation act (≈12cm^{-1})
- reconstruct the trajectory at the most likely position

dE/dx

- Requires high stability on HV and gas parameters and electronics calibration
- truncated mean cut (70-80%) reduces the amount of information. For n = 112 and a 2m track at 1 atm → **σ ≈ 4.3%**

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot N^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

Empirical parametrization

P. Reak and A.H. Walenta, IEEE Trans. Nucl. Sci. NS-27 (1980) 54

dN_{cl}/dx

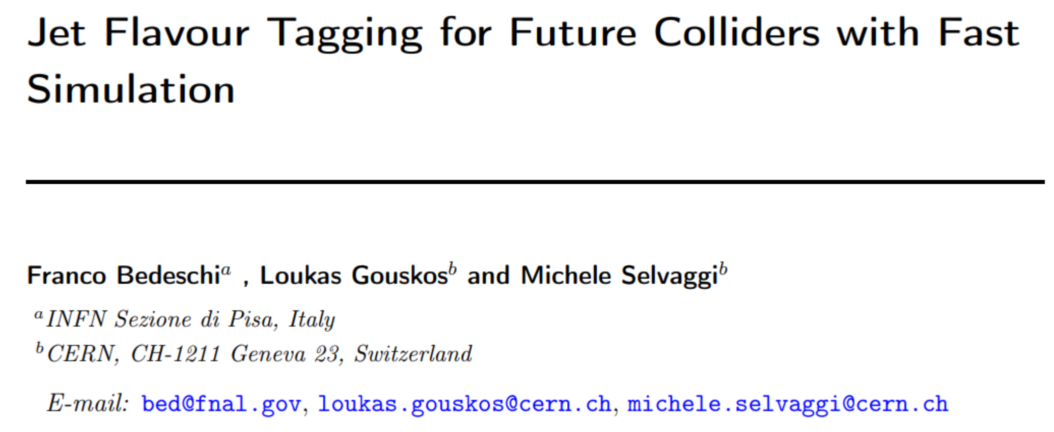
- Requires fast electronics and sophisticated counting algorithms
- Less dependent on gain stability issues
- δ_{cl} = 12./cm for He/iC$_4$H$_{10}$=90/10 and a 2m track → **σ ≈ 2.0%**

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2} = N_{cl}^{-1/2}$$

Poisson

Two taggers

arXiv:2202.03285



Jet Flavour Tagging for Future Colliders with Fast Simulation

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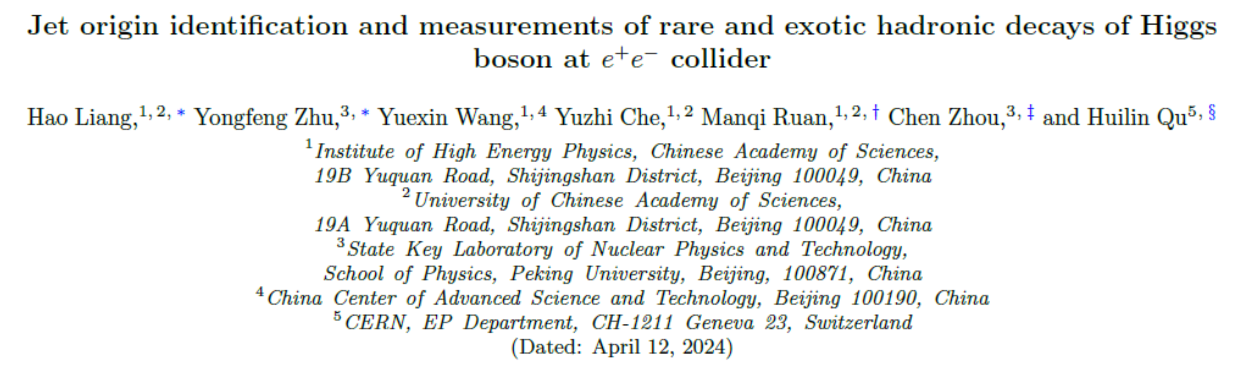
arXiv:2310.0344



Jet origin identification and measurements of rare and exotic hadronic decays of Higgs boson at e^+e^- collider

Hao Liang,[1,2,*] Yongfeng Zhu,[3,*] Yuexin Wang,[1,4] Yuzhi Che,[1,2] Manqi Ruan,[1,2,†] Chen Zhou,[3,‡] and Huilin Qu[5,§]

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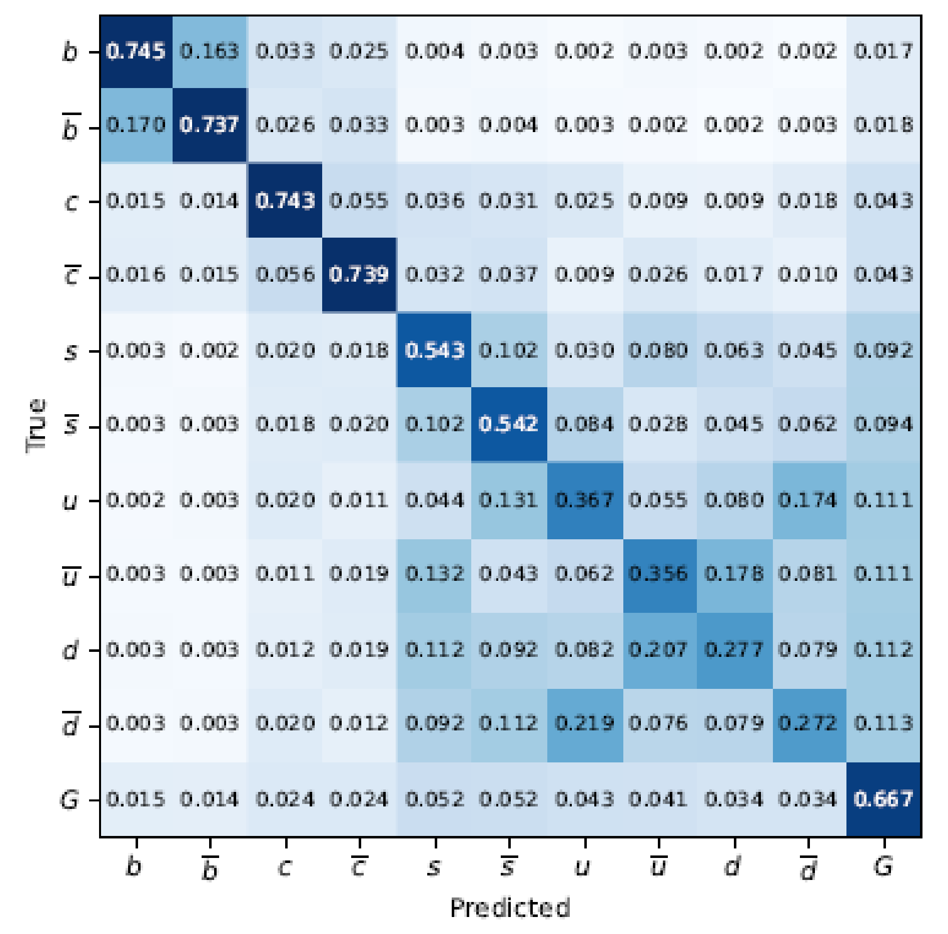
(Dated: April 12, 2024)

To enhance the scientific discovery power of high-energy collider experiments, we propose and

Both use graph neural nets.

Liang et al



True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.745	0.163	0.033	0.025	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.170	0.737	0.026	0.033	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.014	0.743	0.055	0.036	0.031	0.025	0.009	0.009	0.018	0.043
$\bar{c}$	0.016	0.015	0.056	0.739	0.032	0.037	0.009	0.026	0.017	0.010	0.043
s	0.003	0.002	0.020	0.018	0.543	0.102	0.030	0.080	0.063	0.045	0.092
$\bar{s}$	0.003	0.003	0.018	0.020	0.102	0.542	0.084	0.028	0.045	0.062	0.094
u	0.002	0.003	0.020	0.011	0.044	0.131	0.367	0.055	0.080	0.174	0.111
$\bar{u}$	0.003	0.003	0.011	0.019	0.132	0.043	0.062	0.356	0.178	0.081	0.111
d	0.003	0.003	0.012	0.019	0.112	0.092	0.082	0.207	0.277	0.079	0.112
$\bar{d}$	0.003	0.003	0.020	0.012	0.092	0.112	0.219	0.076	0.079	0.272	0.113
G	0.015	0.014	0.024	0.024	0.052	0.052	0.043	0.041	0.034	0.034	0.667

Non-trivial correlations

For strange, non-trivial charge mis-id. Lots of mis-id to u,d,g (30%)

Even b's only correctly id'd 90% of the time (ignoring charge misid)

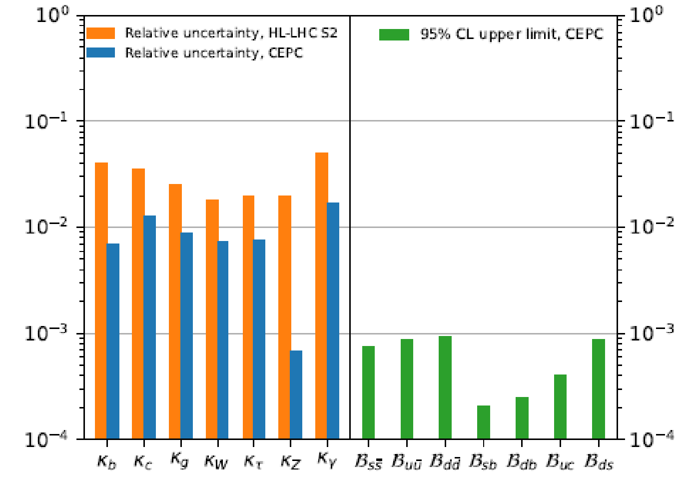
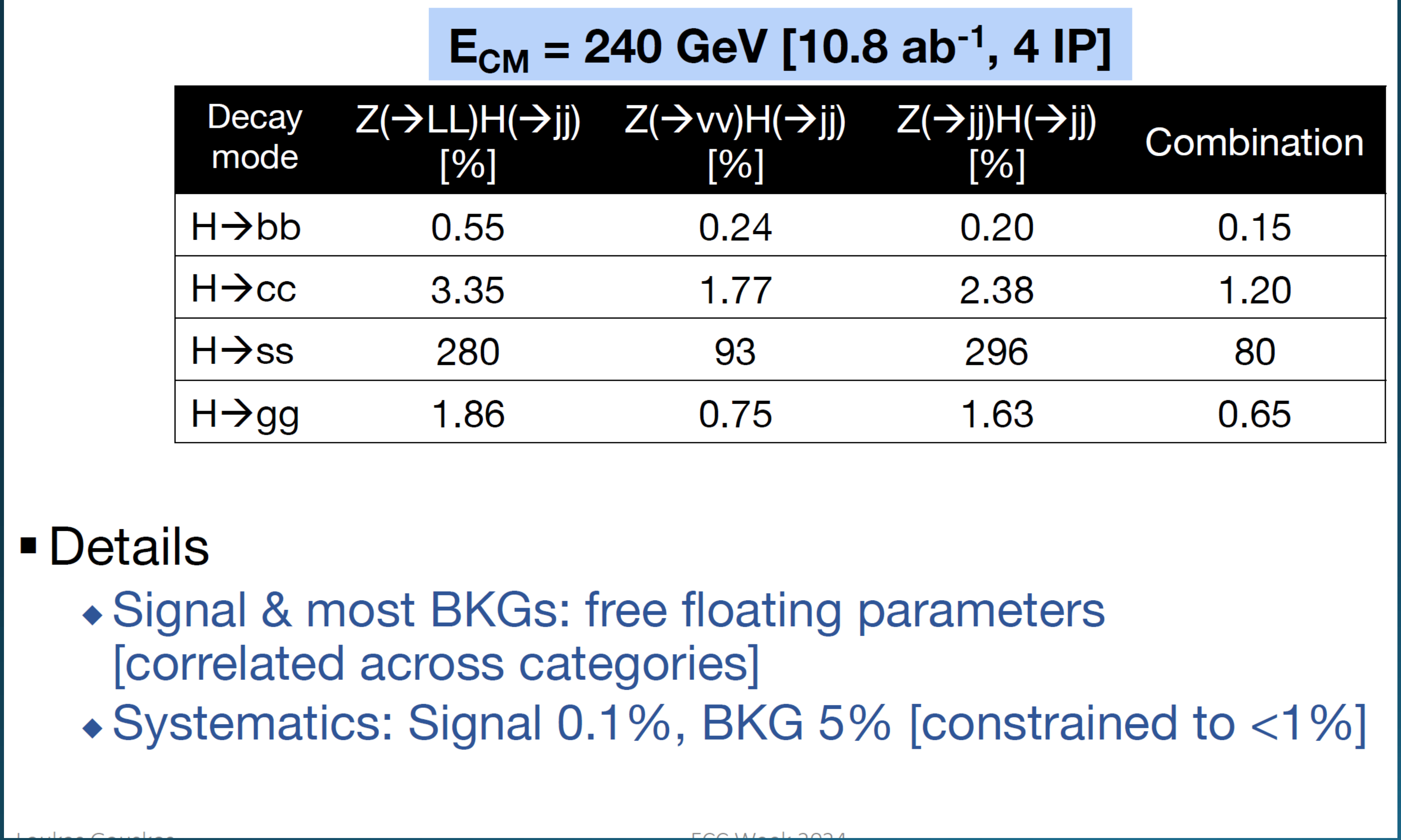


FIG. 5. Expected upper limits on the branching ratios of Higgs rare decays from this work (green) and the relative uncertainties of Higgs couplings anticipated at CEPC [20] (blue) and HL-LHC [43] (orange) under the kappa-0 fit scenario [54] and scenario S2 of systematics [55], as cited in Ref. [20].

Results (FCCee)

Work in progress



E_{CM} = 240 GeV [10.8 ab^{-1}, 4 IP]

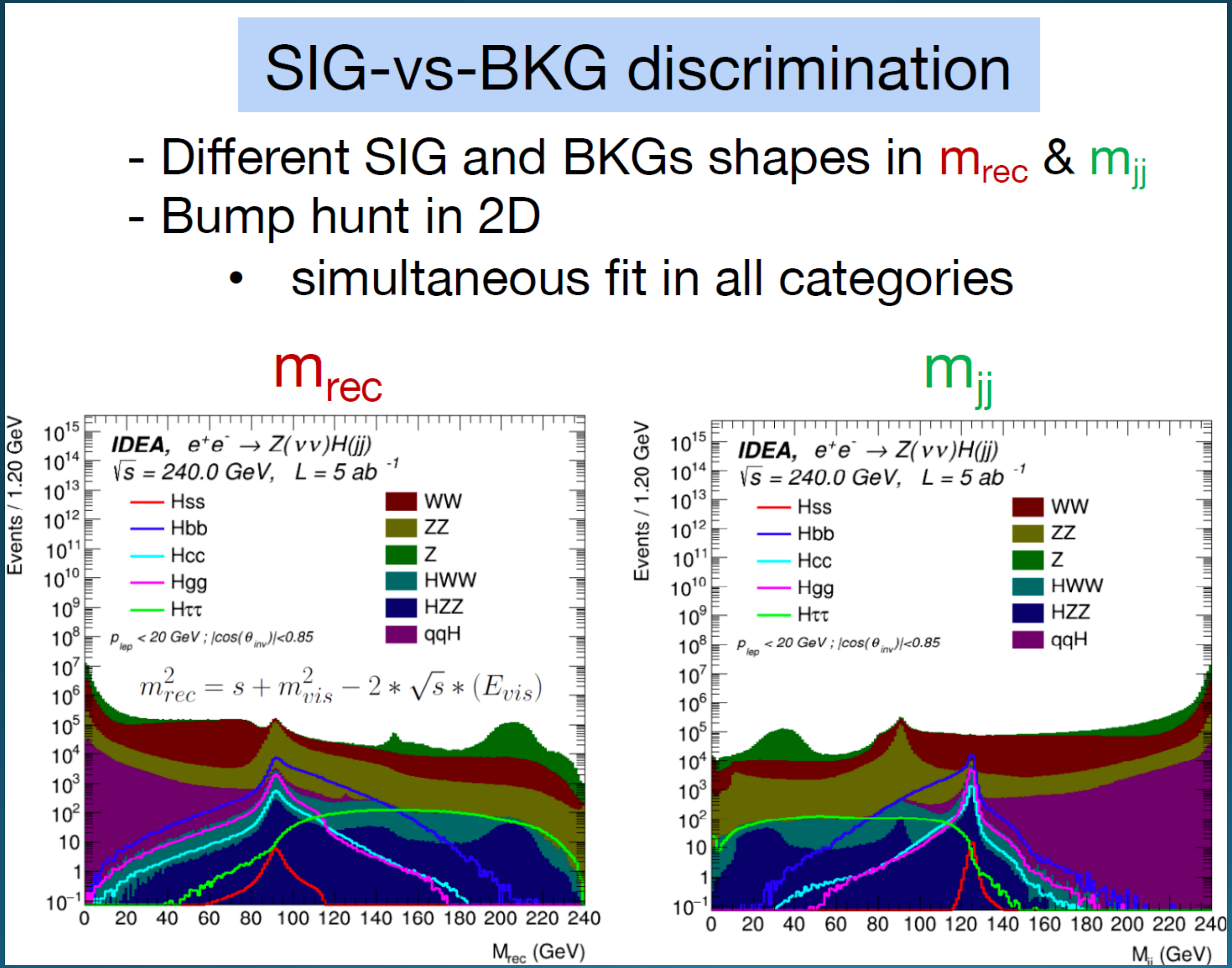
Decay mode	Z(→LL)H(→jj) [%]	Z(→vv)H(→jj) [%]	Z(→jj)H(→jj) [%]	Combination
H→bb	0.55	0.24	0.20	0.15
H→cc	3.35	1.77	2.38	1.20
H→ss	280	93	296	80
H→gg	1.86	0.75	1.63	0.65

- Details
  - Signal & most BKGs: free floating parameters [correlated across categories]
  - Systematics: Signal 0.1%, BKG 5% [constrained to <1%]

Can see we really do not get a measurement of the strange coupling yet. More work and clever ideas needed!

Also the measurement of the charm coupling relies strongly on the Z to invisible, but…

Loukas Goukas, FCC week, San Francisco



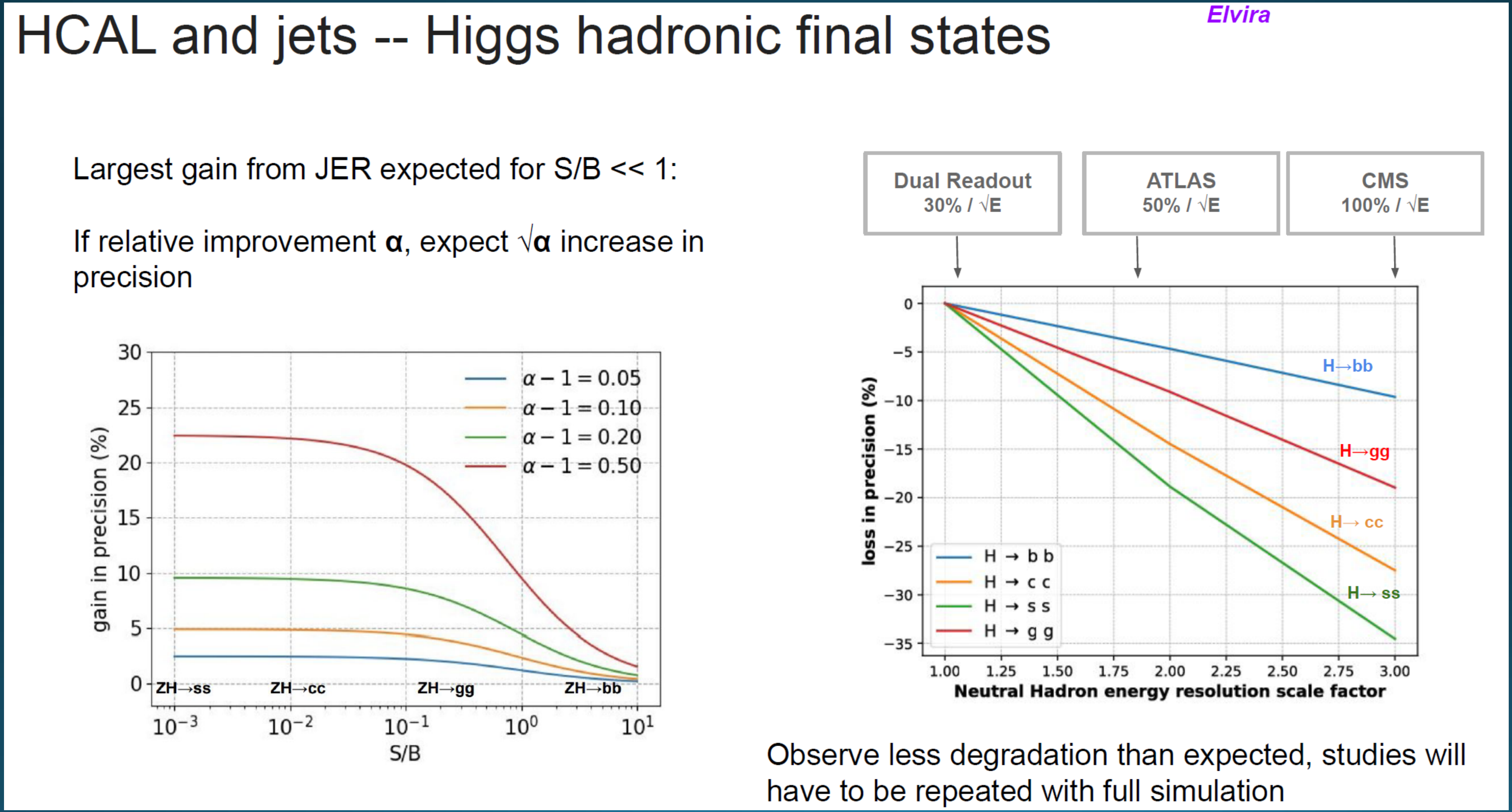
SIG-vs-BKG discrimination

- Different SIG and BKGs shapes in m_{rec} & m_{jj}
- Bump hunt in 2D
  - simultaneous fit in all categories

m_{rec}

m_{jj}

Detector implications (beyond kaon tagging)



HCAL and jets -- Higgs hadronic final states

Elvira

Largest gain from JER expected for S/B << 1:

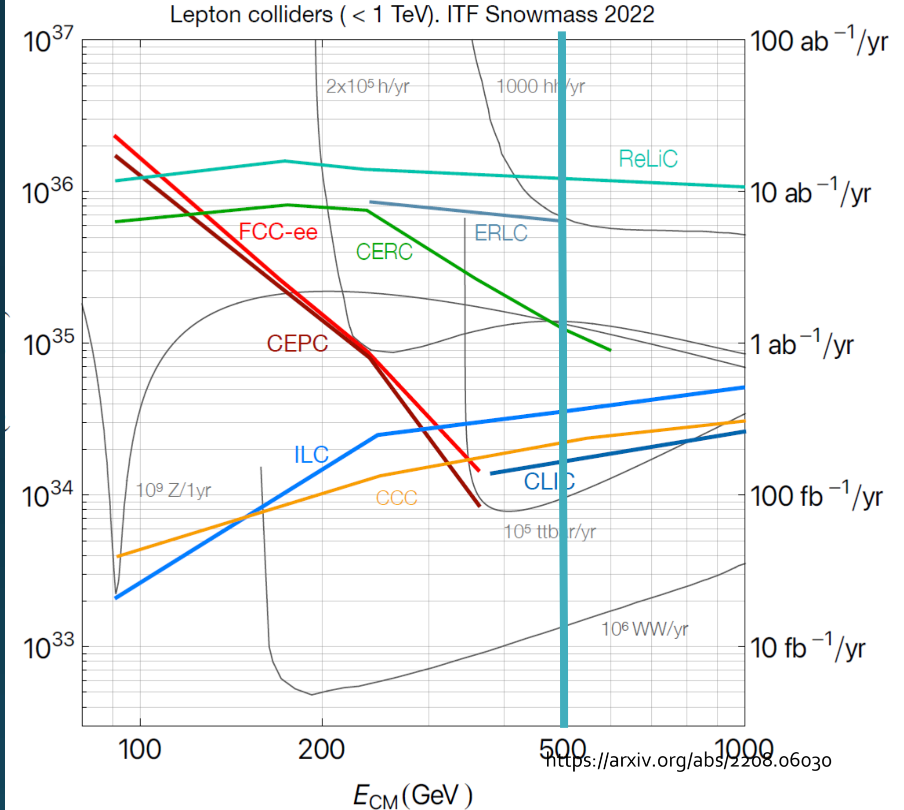
If relative improvement **α**, expect √**α** increase in precision

Observe less degradation than expected, studies will have to be repeated with full simulation

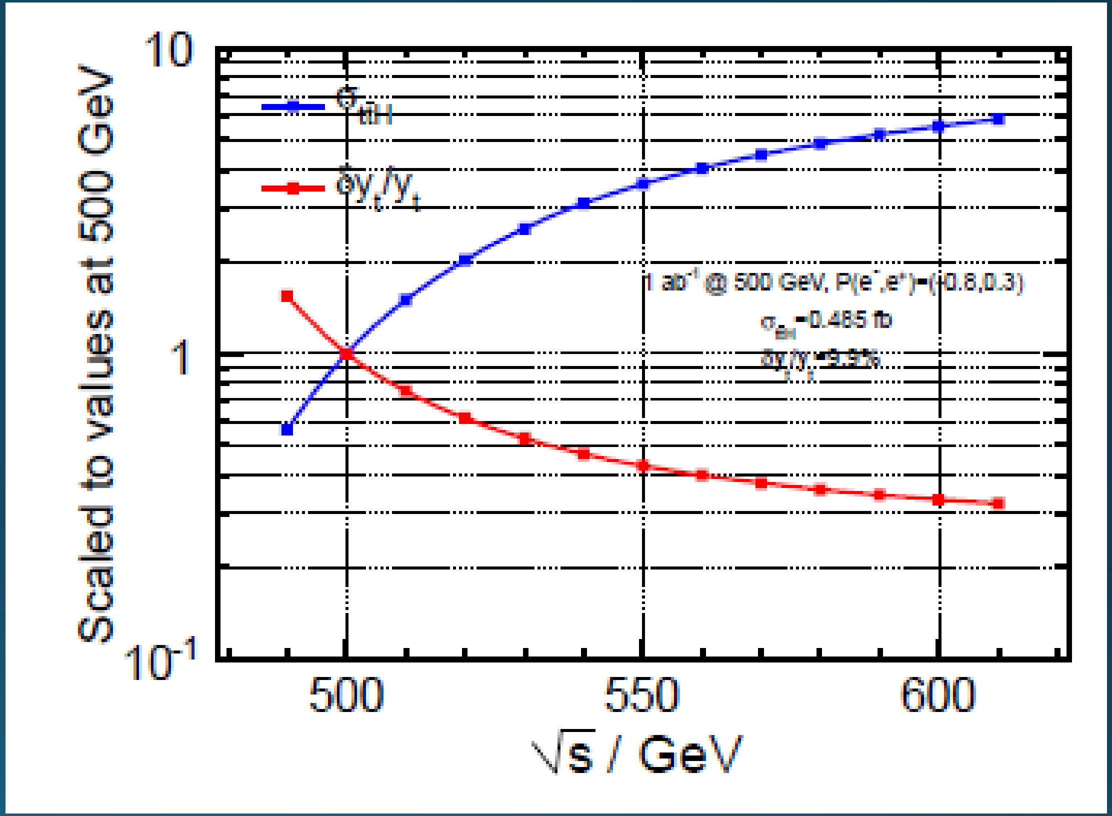
Higgs top coupling

Really cannot be done at FCCee. 3% measurement at ILC/CLIC/C3. Also hl-lhc expects 3% measurement

arXiv:2209.07510

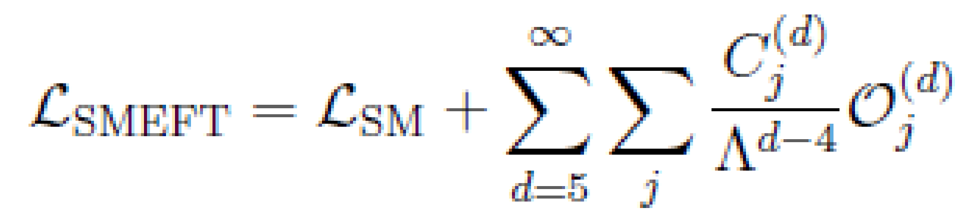


https://arxiv.org/abs/2208.06030



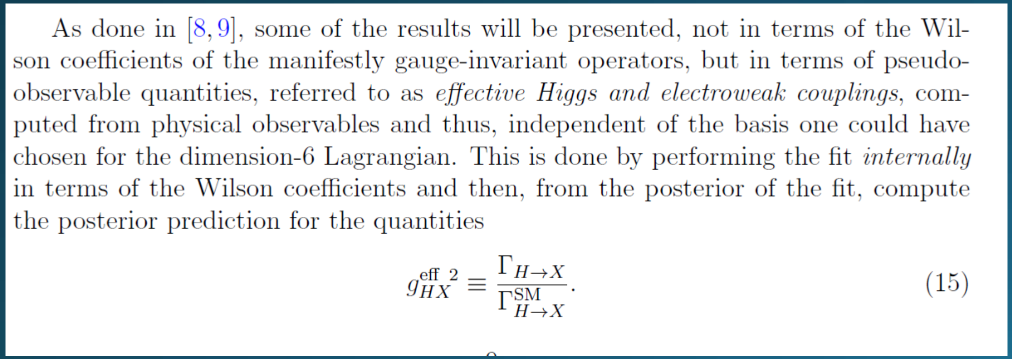
Beyond the kappa framework

The Higgs coupling measurements have been widely studied in the corresponding design studies through global fits in the so-called κ framework. While very helpful in illustrating the precision reach of Higgs measurements, this κ framework can miss interactions of Lorentz structure different from that of the SM. This method is a more realistic way of including potential effects of new physics.



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_{j} \frac{C_j^{(d)}}{\Lambda^{d-4}} \mathcal{O}_j^{(d)}$$

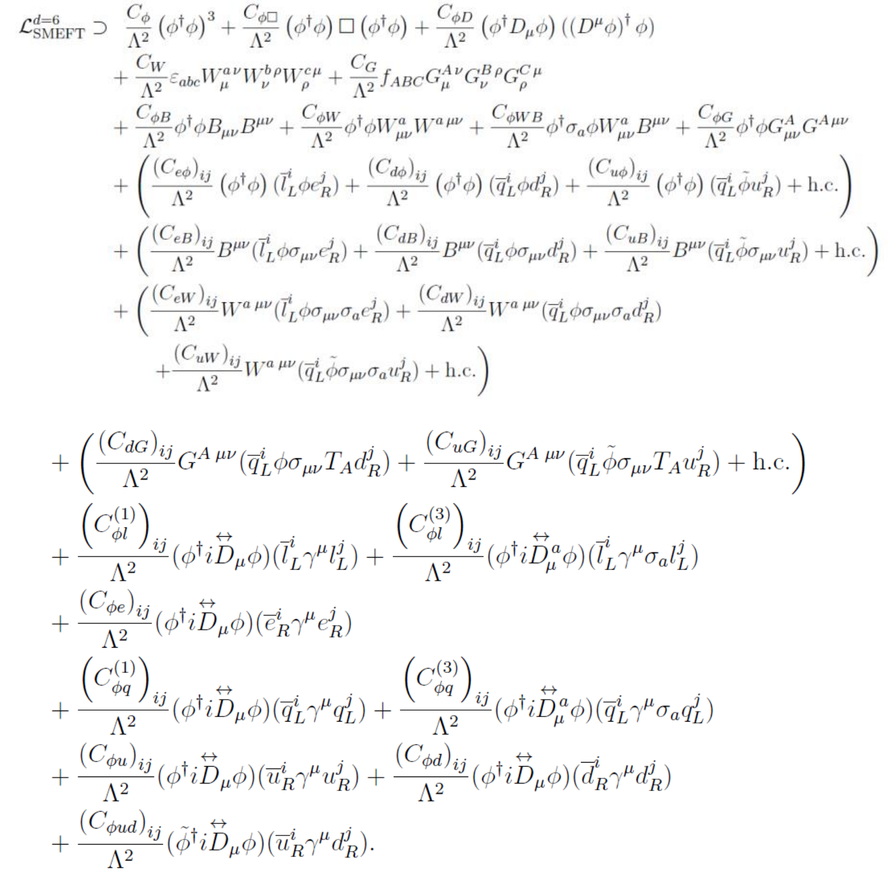
These can include the relations between the longitudinal components of the WZ to higgs couplings.



As done in [8,9], some of the results will be presented, not in terms of the Wilson coefficients of the manifestly gauge-invariant operators, but in terms of pseudo-observable quantities, referred to as *effective Higgs and electroweak couplings*, computed from physical observables and thus, independent of the basis one could have chosen for the dimension-6 Lagrangian. This is done by performing the fit *internally* in terms of the Wilson coefficients and then, from the posterior of the fit, compute the posterior prediction for the quantities

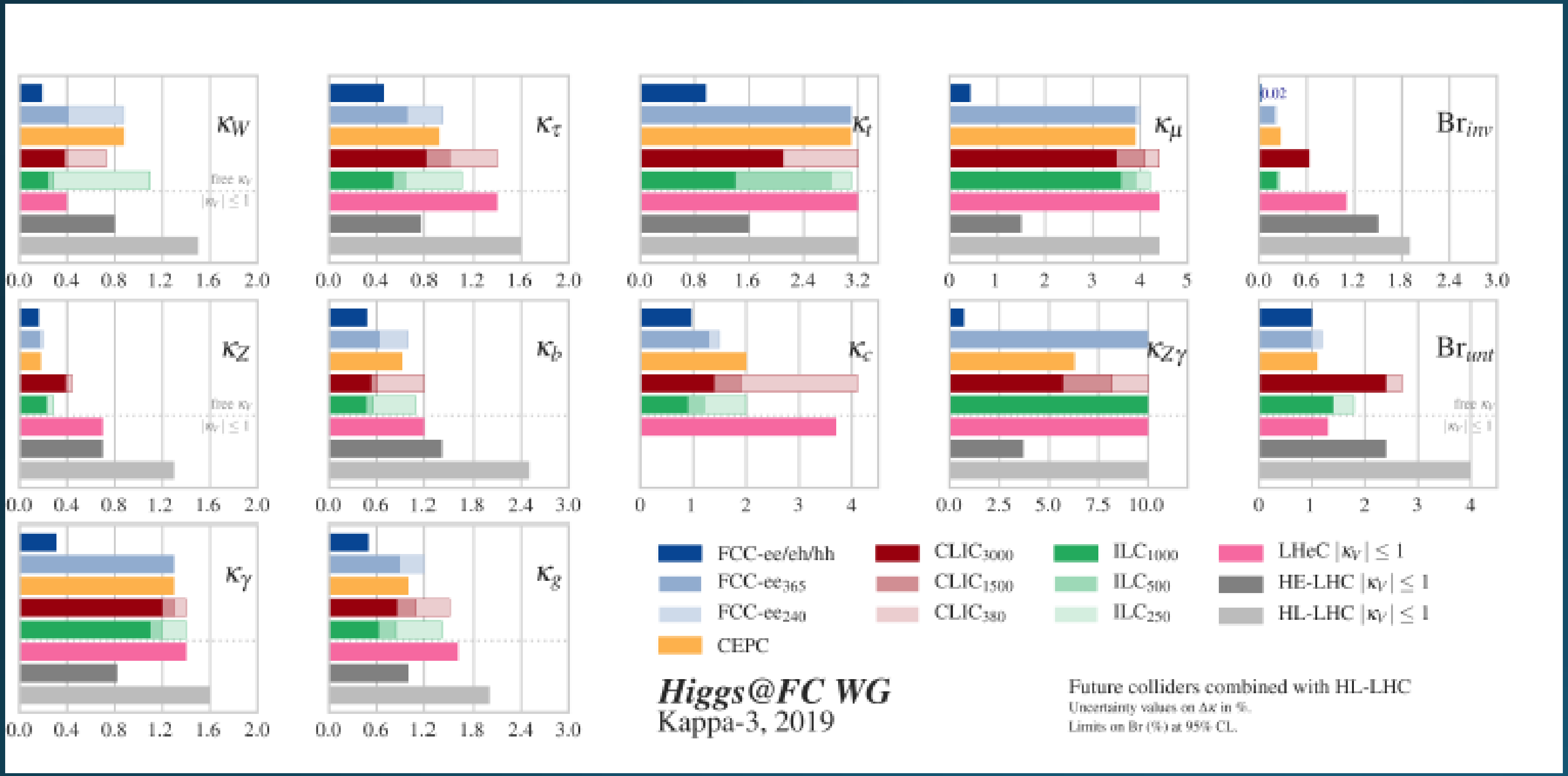
$$g_{HX}^{\mathrm{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}. \qquad (15)$$

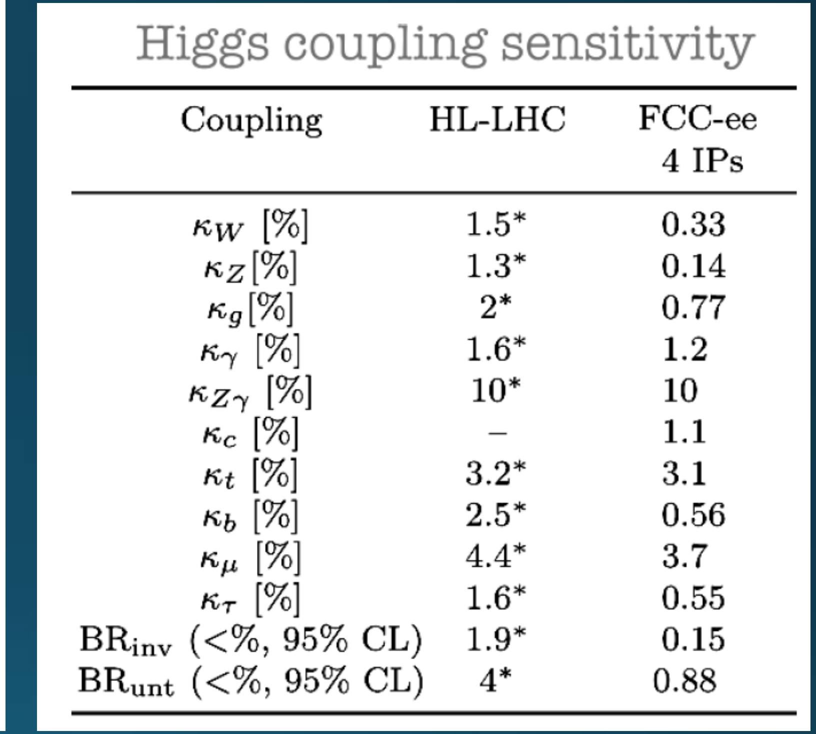
https://arxiv.org/abs/2206.08326



$$\begin{aligned}
\mathcal{L}_{\mathrm{SMEFT}}^{d=6} \supset\ & \frac{C_\phi}{\Lambda^2}\left(\phi^\dagger\phi\right)^3 + \frac{C_{\phi\Box}}{\Lambda^2}\left(\phi^\dagger\phi\right)\Box\left(\phi^\dagger\phi\right) + \frac{C_{\phi D}}{\Lambda^2}\left(\phi^\dagger D_\mu\phi\right)\left(\left(D^\mu\phi\right)^\dagger\phi\right) \\
& + \frac{C_W}{\Lambda^2}\varepsilon_{abc}W_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu} + \frac{C_G}{\Lambda^2}f_{ABC}G_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu} \\
& + \frac{C_{\phi B}}{\Lambda^2}\phi^\dagger\phi B_{\mu\nu}B^{\mu\nu} + \frac{C_{\phi W}}{\Lambda^2}\phi^\dagger\phi W_{\mu\nu}^a W^{a\,\mu\nu} + \frac{C_{\phi WB}}{\Lambda^2}\phi^\dagger\sigma_a\phi W_{\mu\nu}^a B^{\mu\nu} + \frac{C_{\phi G}}{\Lambda^2}\phi^\dagger\phi G_{\mu\nu}^A G^{A\,\mu\nu} \\
& + \left(\frac{(C_{e\phi})_{ij}}{\Lambda^2}\left(\phi^\dagger\phi\right)\left(\bar{l}_L^i\phi e_R^j\right) + \frac{(C_{d\phi})_{ij}}{\Lambda^2}\left(\phi^\dagger\phi\right)\left(\bar{q}_L^i\phi d_R^j\right) + \frac{(C_{u\phi})_{ij}}{\Lambda^2}\left(\phi^\dagger\phi\right)\left(\bar{q}_L^i\tilde{\phi}u_R^j\right) + \mathrm{h.c.}\right) \\
& + \left(\frac{(C_{eB})_{ij}}{\Lambda^2}B^{\mu\nu}(\bar{l}_L^i\phi\sigma_{\mu\nu}e_R^j) + \frac{(C_{dB})_{ij}}{\Lambda^2}B^{\mu\nu}(\bar{q}_L^i\phi\sigma_{\mu\nu}d_R^j) + \frac{(C_{uB})_{ij}}{\Lambda^2}B^{\mu\nu}(\bar{q}_L^i\tilde{\phi}\sigma_{\mu\nu}u_R^j) + \mathrm{h.c.}\right) \\
& + \left(\frac{(C_{eW})_{ij}}{\Lambda^2}W^{a\,\mu\nu}(\bar{l}_L^i\phi\sigma_{\mu\nu}\sigma_a e_R^j) + \frac{(C_{dW})_{ij}}{\Lambda^2}W^{a\,\mu\nu}(\bar{q}_L^i\phi\sigma_{\mu\nu}\sigma_a d_R^j)\right. \\
& \qquad \left. + \frac{(C_{uW})_{ij}}{\Lambda^2}W^{a\,\mu\nu}(\bar{q}_L^i\tilde{\phi}\sigma_{\mu\nu}\sigma_a u_R^j) + \mathrm{h.c.}\right) \\
& + \left(\frac{(C_{dG})_{ij}}{\Lambda^2}G^{A\,\mu\nu}(\bar{q}_L^i\phi\sigma_{\mu\nu}T_A d_R^j) + \frac{(C_{uG})_{ij}}{\Lambda^2}G^{A\,\mu\nu}(\bar{q}_L^i\tilde{\phi}\sigma_{\mu\nu}T_A u_R^j) + \mathrm{h.c.}\right) \\
& + \frac{\left(C_{\phi l}^{(1)}\right)_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}_L^i\gamma^\mu l_L^j) + \frac{\left(C_{\phi l}^{(3)}\right)_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu^a\phi)(\bar{l}_L^i\gamma^\mu\sigma_a l_L^j) \\
& + \frac{(C_{\phi e})_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_R^i\gamma^\mu e_R^j) \\
& + \frac{\left(C_{\phi q}^{(1)}\right)_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_L^i\gamma^\mu q_L^j) + \frac{\left(C_{\phi q}^{(3)}\right)_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu^a\phi)(\bar{q}_L^i\gamma^\mu\sigma_a q_L^j) \\
& + \frac{(C_{\phi u})_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_R^i\gamma^\mu u_R^j) + \frac{(C_{\phi d})_{ij}}{\Lambda^2}(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_R^i\gamma^\mu d_R^j) \\
& + \frac{(C_{\phi ud})_{ij}}{\Lambda^2}(\tilde{\phi}^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_R^i\gamma^\mu d_R^j).
\end{aligned}$$

Kappa frame work



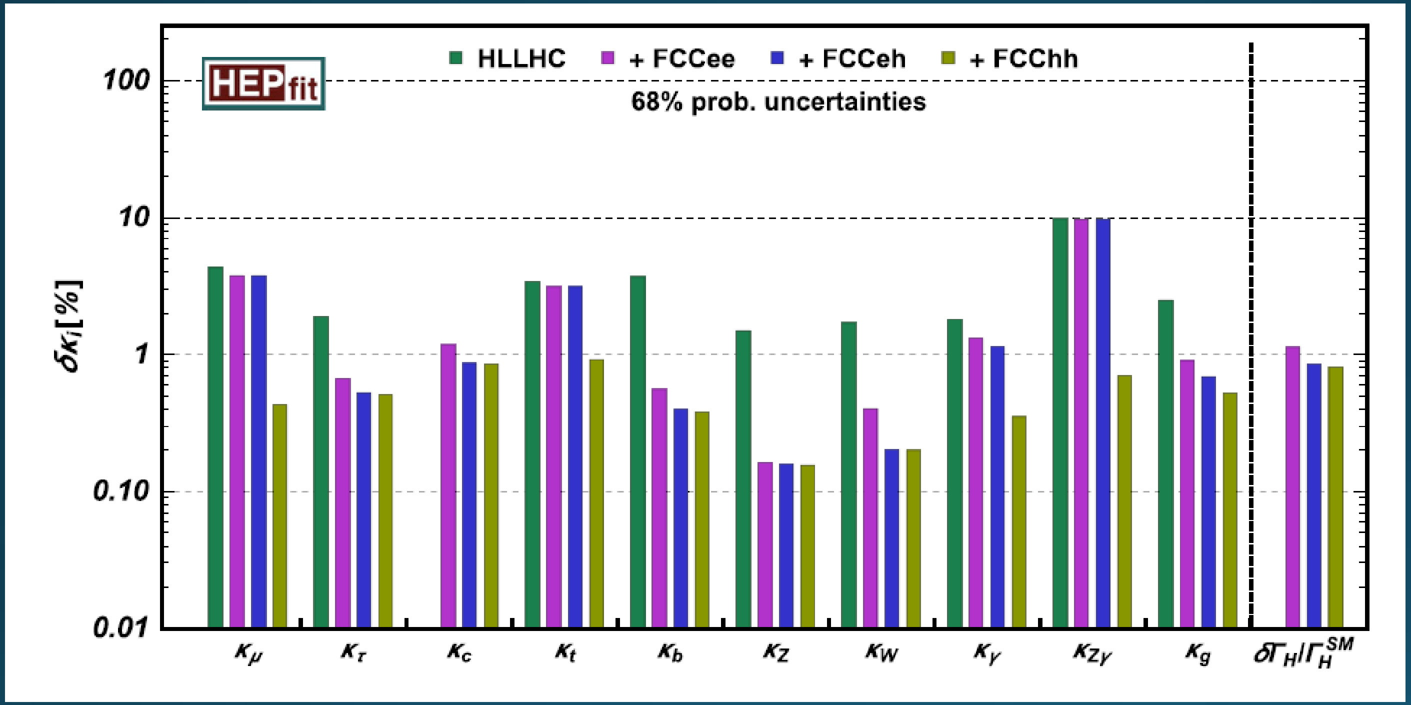


Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee 4 IPs
κ_W [%]	1.5*	0.33
κ_Z [%]	1.3*	0.14
κ_g [%]	2*	0.77
κ_γ [%]	1.6*	1.2
$\kappa_{Z\gamma}$ [%]	10*	10
κ_c [%]	–	1.1
κ_t [%]	3.2*	3.1
κ_b [%]	2.5*	0.56
κ_μ [%]	4.4*	3.7
κ_τ [%]	1.6*	0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	0.88

EFT framework

HL-LHC κ_W precision goes from 1.5 to 2%



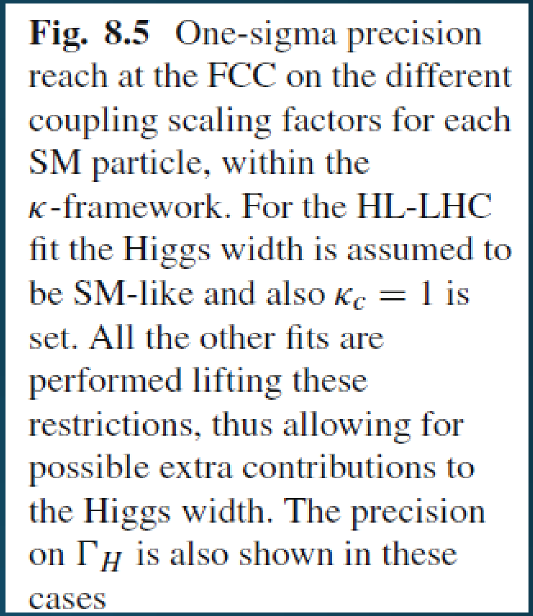
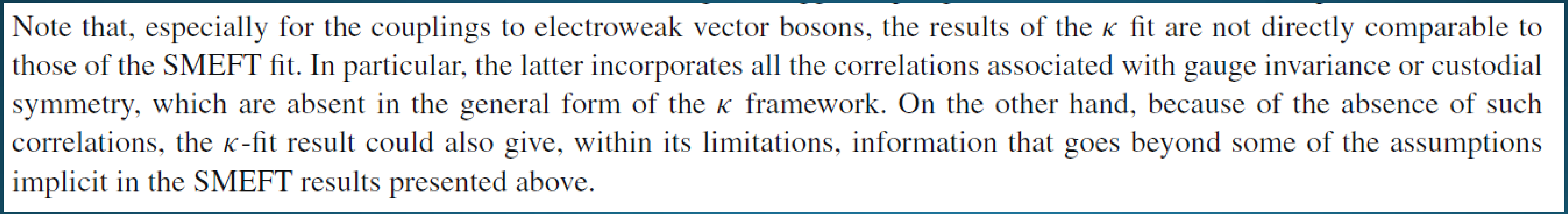
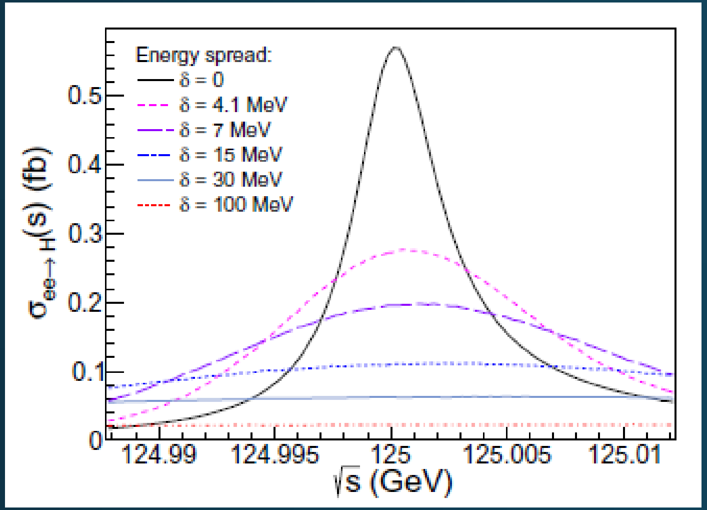


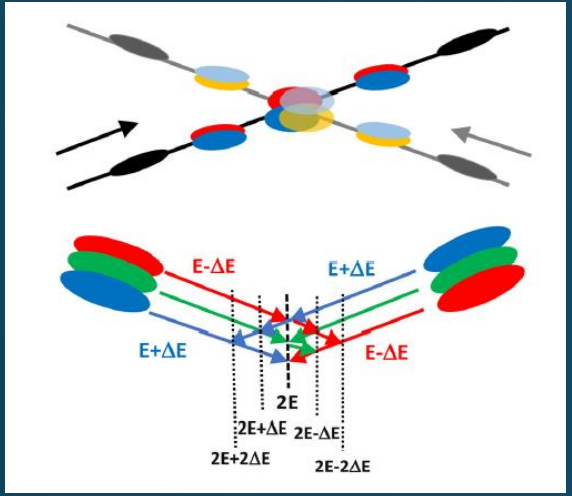
Fig. 8.5 One-sigma precision reach at the FCC on the different coupling scaling factors for each SM particle, within the κ-framework. For the HL-LHC fit the Higgs width is assumed to be SM-like and also $\kappa_c = 1$ is set. All the other fits are performed lifting these restrictions, thus allowing for possible extra contributions to the Higgs width. The precision on Γ_H is also shown in these cases

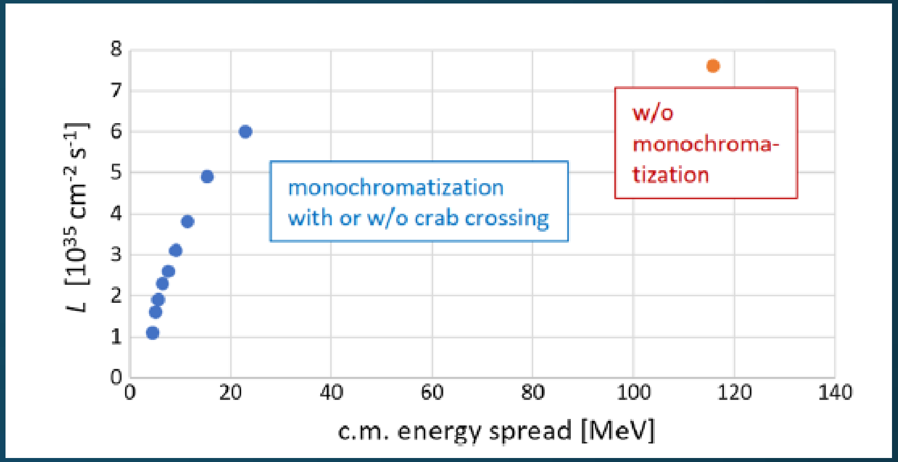

Note that, especially for the couplings to electroweak vector bosons, the results of the κ fit are not directly comparable to those of the SMEFT fit. In particular, the latter incorporates all the correlations associated with gauge invariance or custodial symmetry, which are absent in the general form of the κ framework. On the other hand, because of the absence of such correlations, the κ-fit result could also give, within its limitations, information that goes beyond some of the assumptions implicit in the SMEFT results presented above.

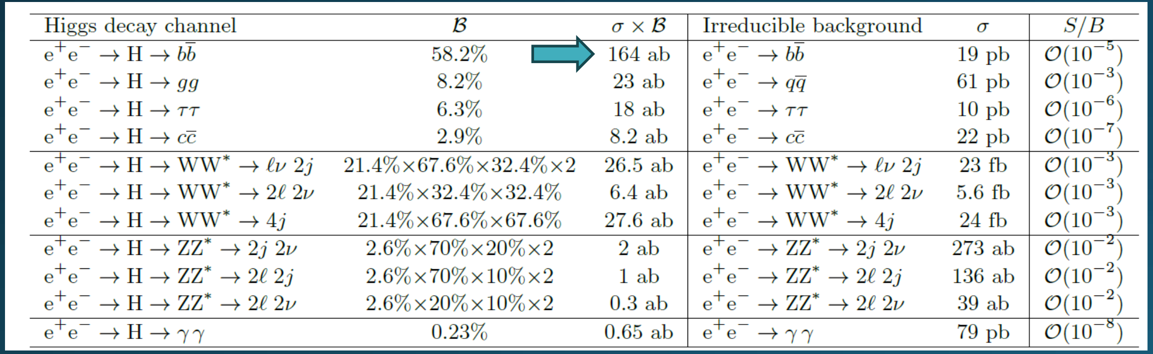
Higgs coupling to electron

PLB755(2016)58





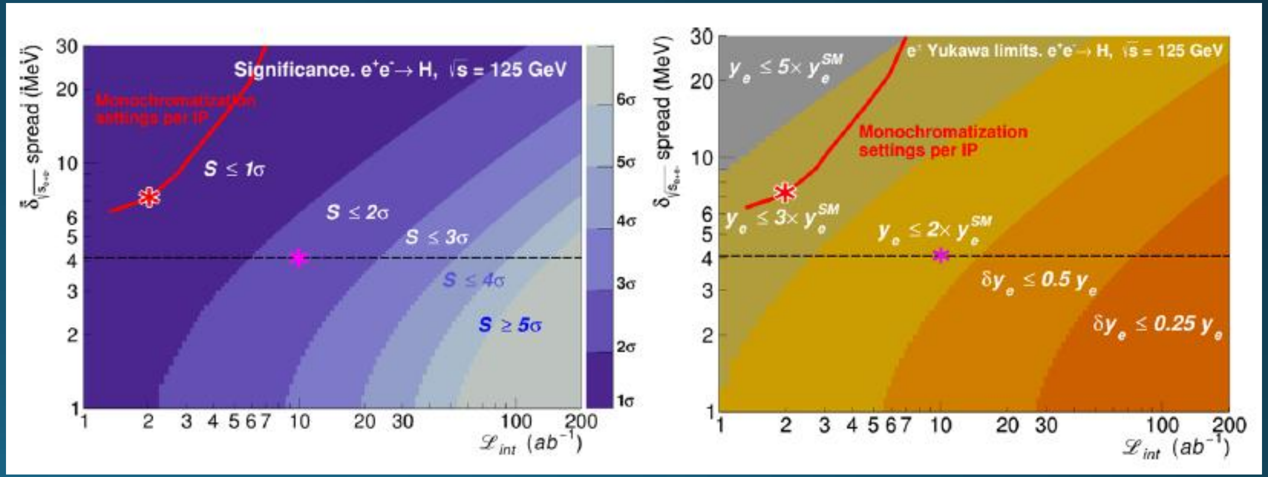




Higgs decay channel	$\mathcal{B}$	$\sigma\times\mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \to H \to b\bar{b}$	58.2%	164 ab	$e^+e^- \to b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \to H \to gg$	8.2%	23 ab	$e^+e^- \to q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to \tau\tau$	6.3%	18 ab	$e^+e^- \to \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \to H \to c\bar{c}$	2.9%	8.2 ab	$e^+e^- \to c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \to H \to WW^* \to \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^- \to WW^* \to \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^- \to WW^* \to 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^- \to WW^* \to 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to ZZ^* \to 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^- \to ZZ^* \to 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to \gamma\gamma$	0.23%	0.65 ab	$e^+e^- \to \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

https://link.springer.com/article/10.1140/epjp/s13360-021-02204-2
https://accelconf.web.cern.ch/ipac2017/papers/wepik015.pdf
https://arxiv.org/abs/2107.02686

YIKES!!



Would take a couple of years, so not clear this would ever happen, but a fun idea. LEP did run at this energy, but not enough int lum to make an event.

CP violation

arXiv:2406.03557
JHEP 03, 050 (2016)
Konstantin Asteriadis et al

$$A_{\text{CP}} = \frac{\sigma(\cos\theta < 0) - \sigma(\cos\theta > 0)}{\sigma_{\text{SM,NLO}}}$$

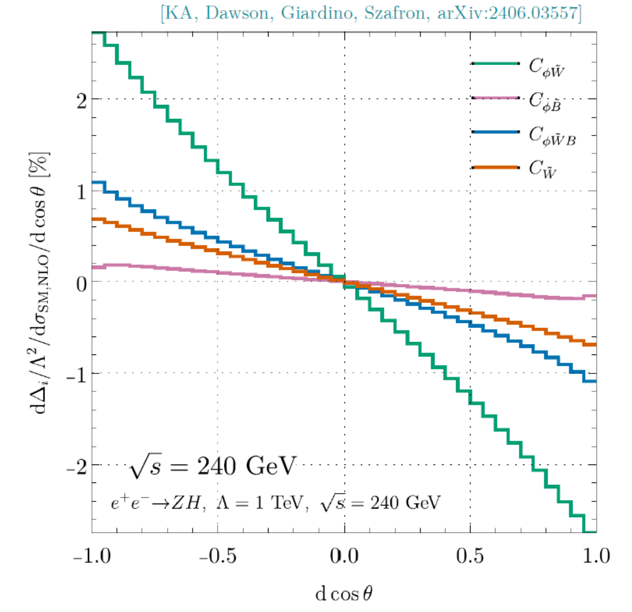
Θ is the angle between the incoming electron and the outgoing Higgs

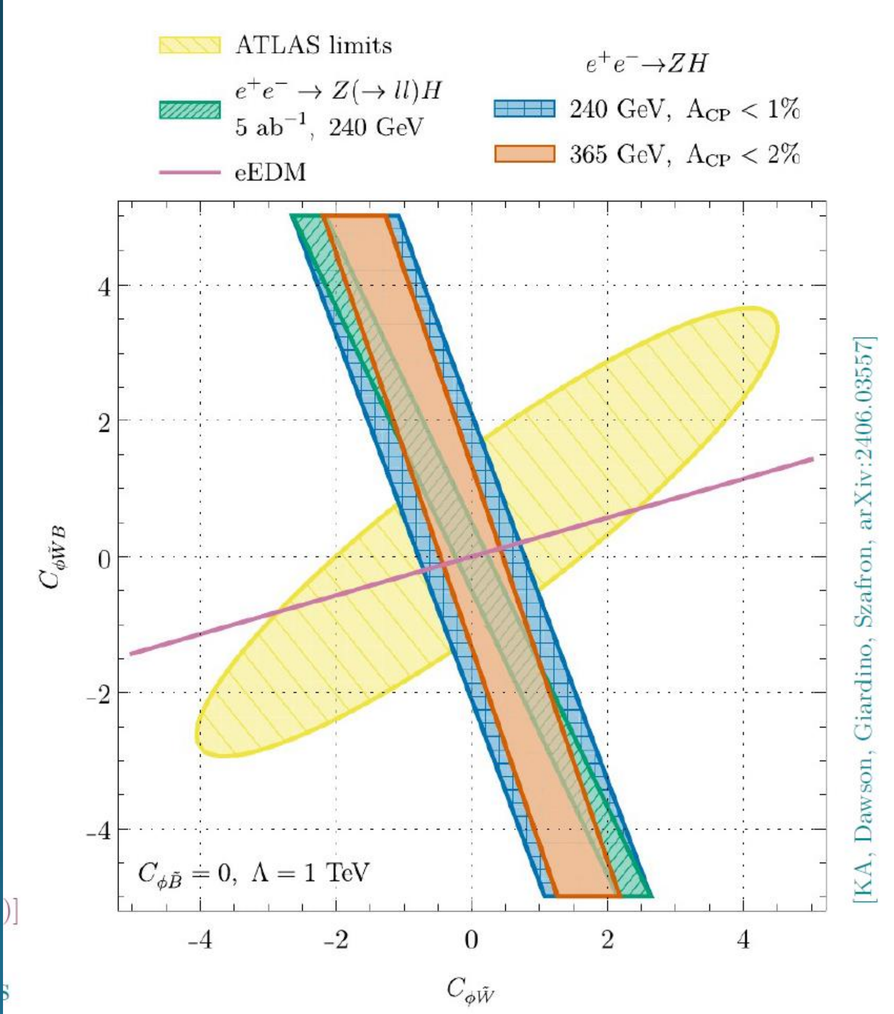
- Four CP violating operators

$$\begin{aligned} O_{\tilde{W}} &= \epsilon_{abc}\tilde{W}^{a\nu}_{\mu}W^{b\rho}_{\nu}W^{c,\mu}_{\rho} \\ O_{\phi\tilde{W}} &= \tilde{W}^{a}_{\mu\nu}W^{\mu\nu b}(\phi^{\dagger}\phi) \\ O_{\phi\tilde{B}} &= \tilde{B}_{\mu\nu}B^{\mu\nu}(\phi^{\dagger}\phi) \\ O_{\phi\tilde{W}B} &= \tilde{W}^{a}_{\mu\nu}B^{\mu\nu}(\phi^{\dagger}\sigma^{a}\phi) \end{aligned}$$

- Assuming $\Lambda = 1$ TeV, $C_i = 1$ and $\sqrt{s} = 240$ GeV (FCC-ee)

$$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{SM,NLO}}} = 1 + \sum_i \frac{C_i(\mu)}{\Lambda^2}\left\{\Delta_i + \bar{\Delta}_i \log\frac{\mu^2}{s}\right\}$$


[KA, Dawson, Giardino, Szafron, arXiv:2406.03557]



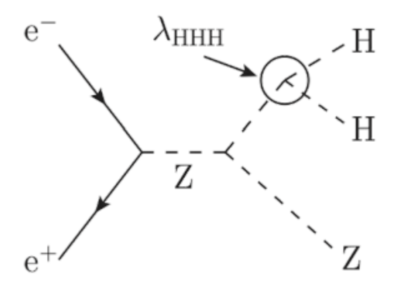
Higgs self coupling

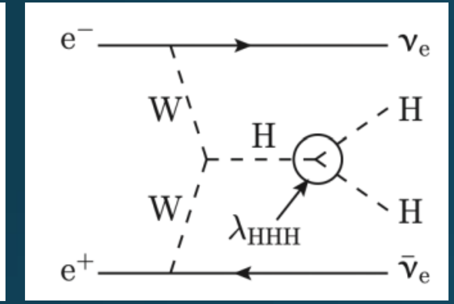
One of the main drivers of the length of the HL-LHC run

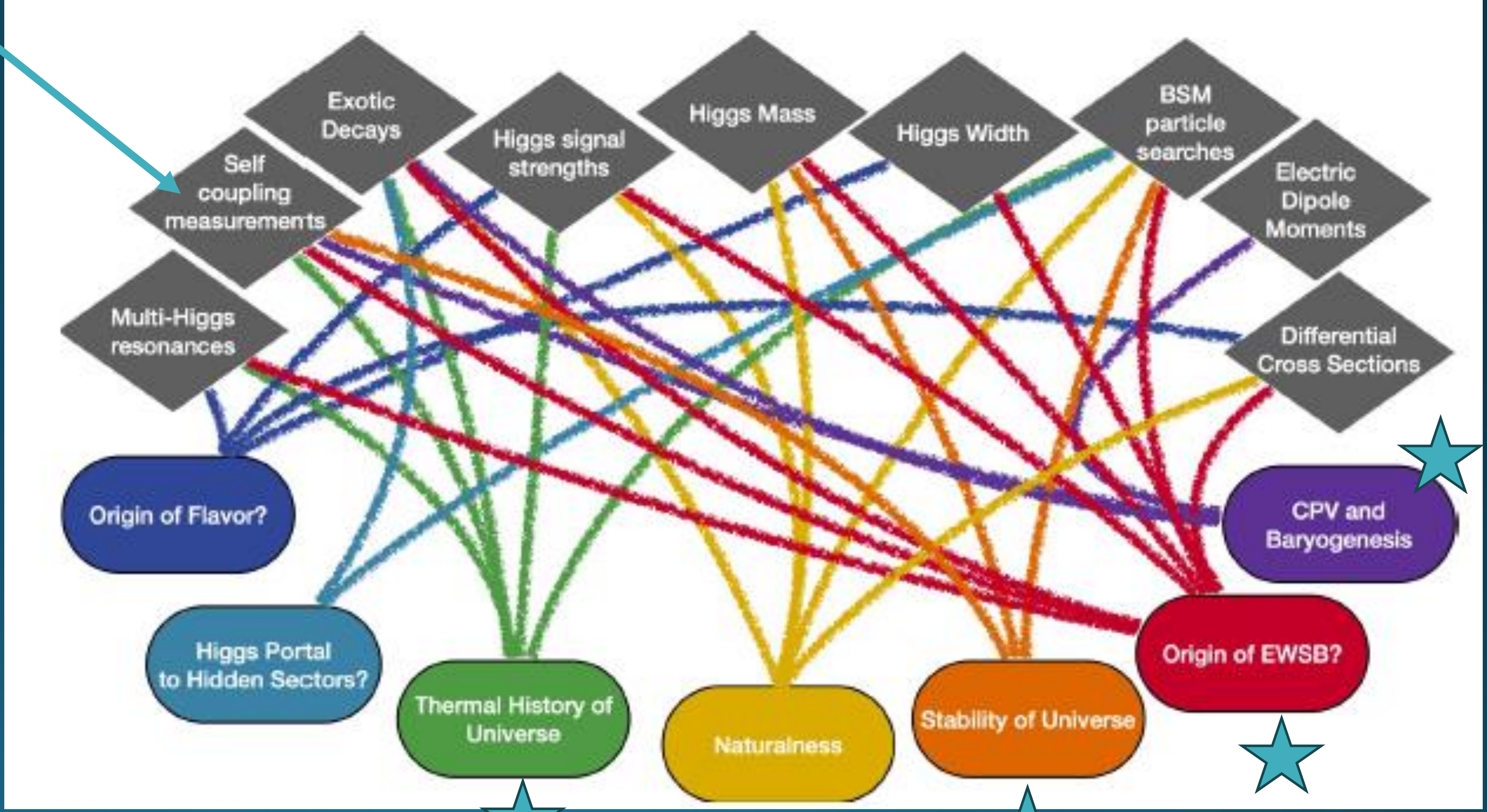
$$V(H) = \mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2$$

$$m_H = \lambda v \quad M_W = \frac{ev}{2\sin^2\theta_W}$$

Predicted in the SM







Requires a center-of-mass energy of 500 GeV, which FCC-ee can't really do, although linear colliders could with enough money. FCChh could also access these energies once magnets are developed (and money found)

https://arxiv.org/abs/2307.16515

https://cds.cern.ch/record/2805993?ln=en

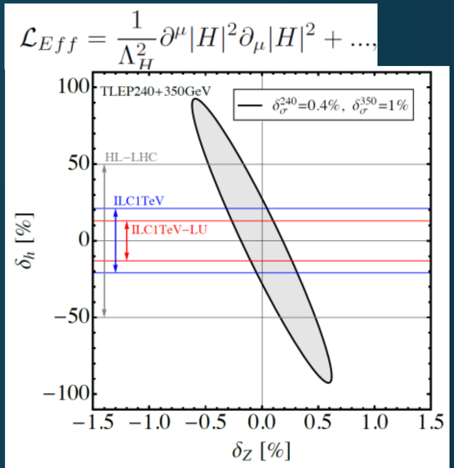
Higgs self coupling

Can be measured indirectly at FCC-ee to about 30%

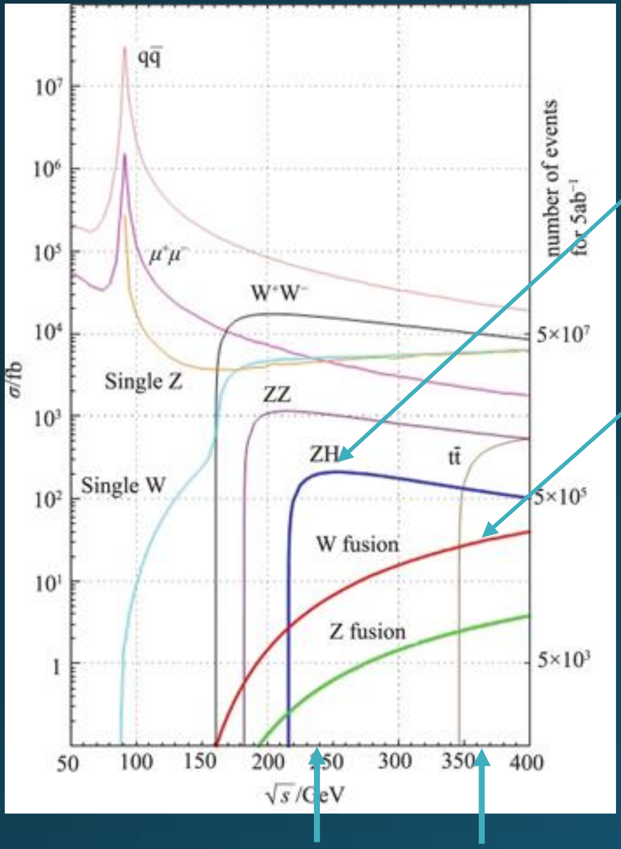
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{3!}\delta_h A_{h,SM} h^3$$

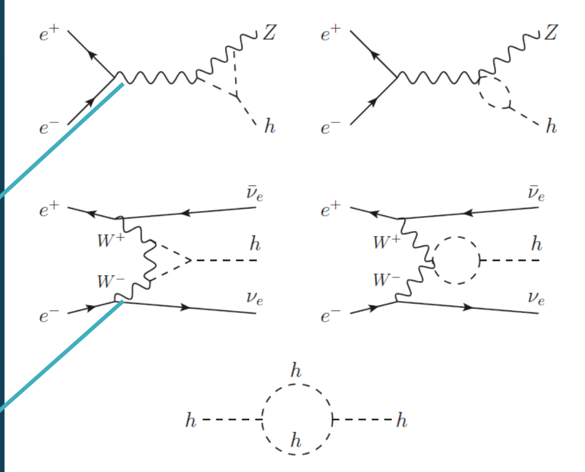
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

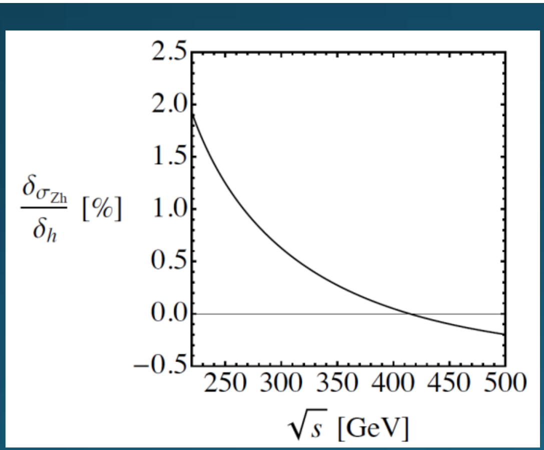
$$\delta_\sigma^{240,350,500} = 1.4, 0.3, -0.2 \times \delta_h \%$$



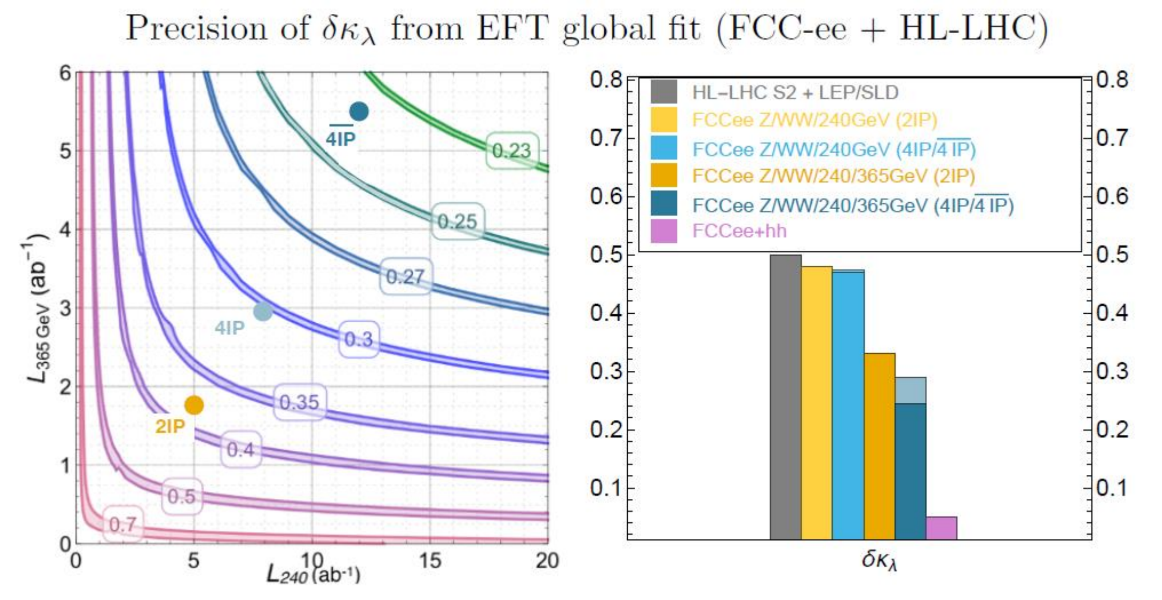
$$\mathcal{L}_{Eff} = \frac{1}{\Lambda_H^2}\partial^\mu |H|^2 \partial_\mu |H|^2 + \ldots$$







How to distinguish modifications to hZZ and hhh



Precision of $\delta\kappa_\lambda$ from EFT global fit (FCC-ee + HL-LHC)

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.015001

https://link.springer.com/article/10.1007/JHEP02(2018)178

Extended higgs-like sectors

Through their effects on the couplings

arXiv:1910.11775

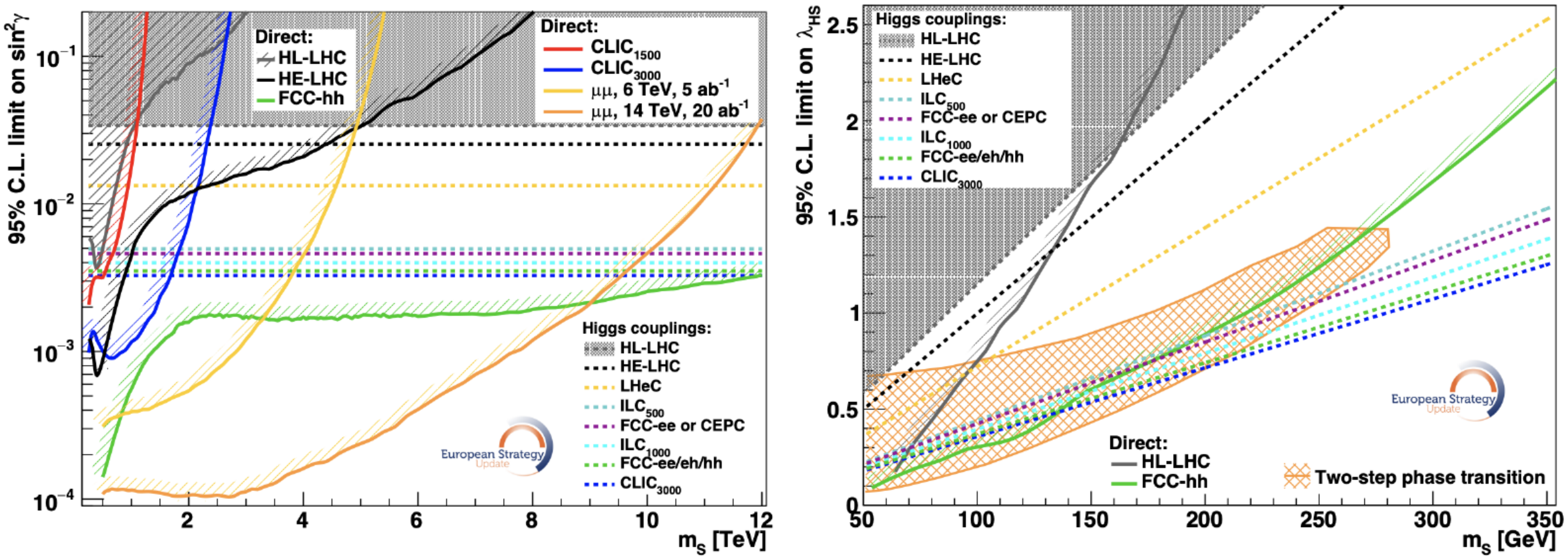
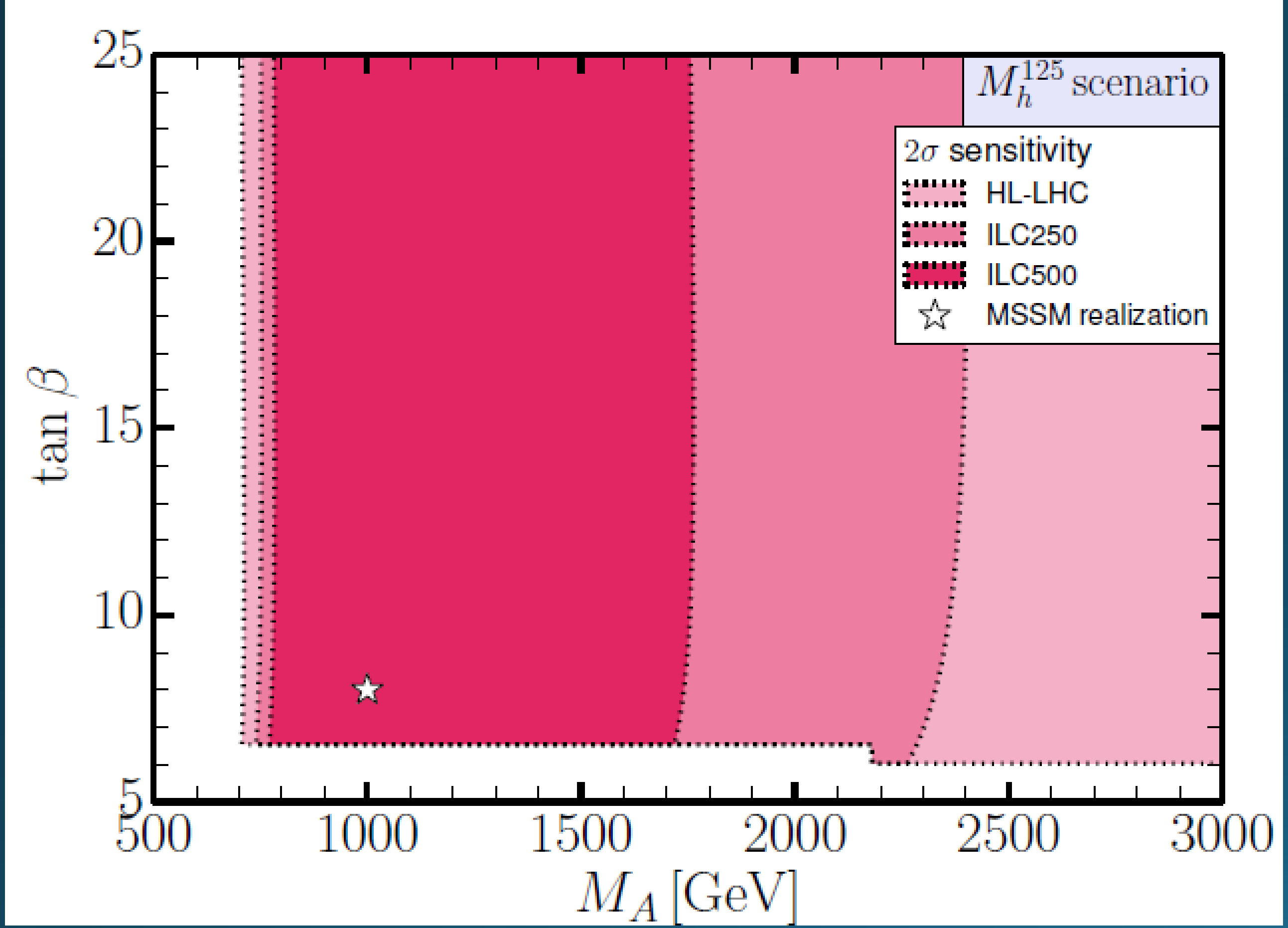


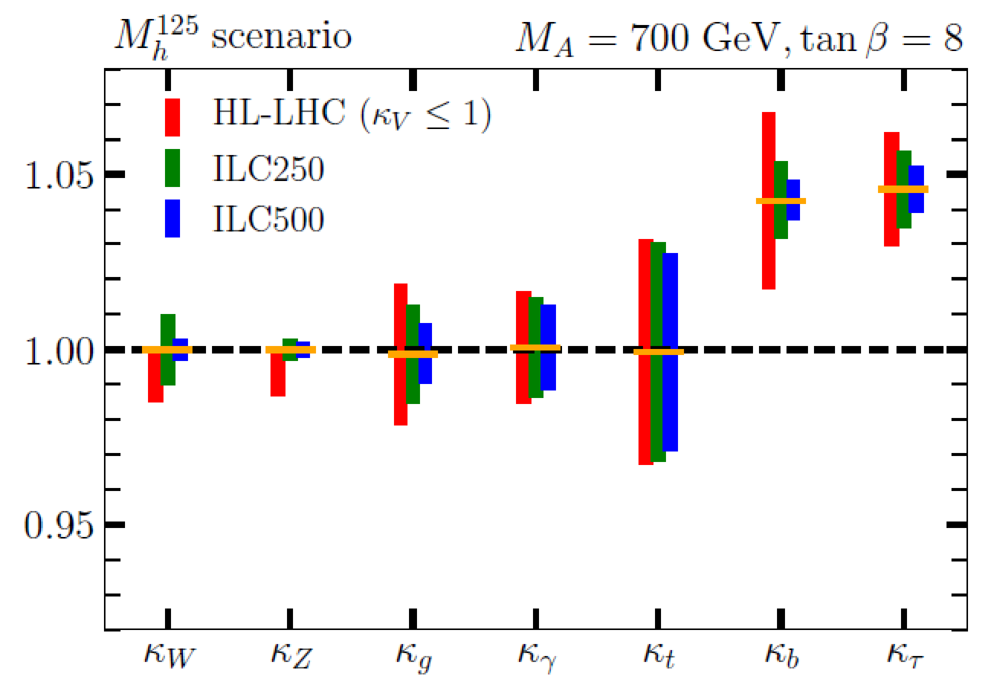
FIG. 34: This figure is from [88] Figure 8.11, where the LHS shows the direct and indirect sensitivity to a singlet which mixes with the SM Higgs, while the RHS shows the limit of no-mixing, but overlaid with regions of parameter space where a strong first-order phase transition is allowed.

Extended higgs-like sectors

doublet

arXiv:2005.14536





Direct searches in Higgs decays

arXiv:2209.07510

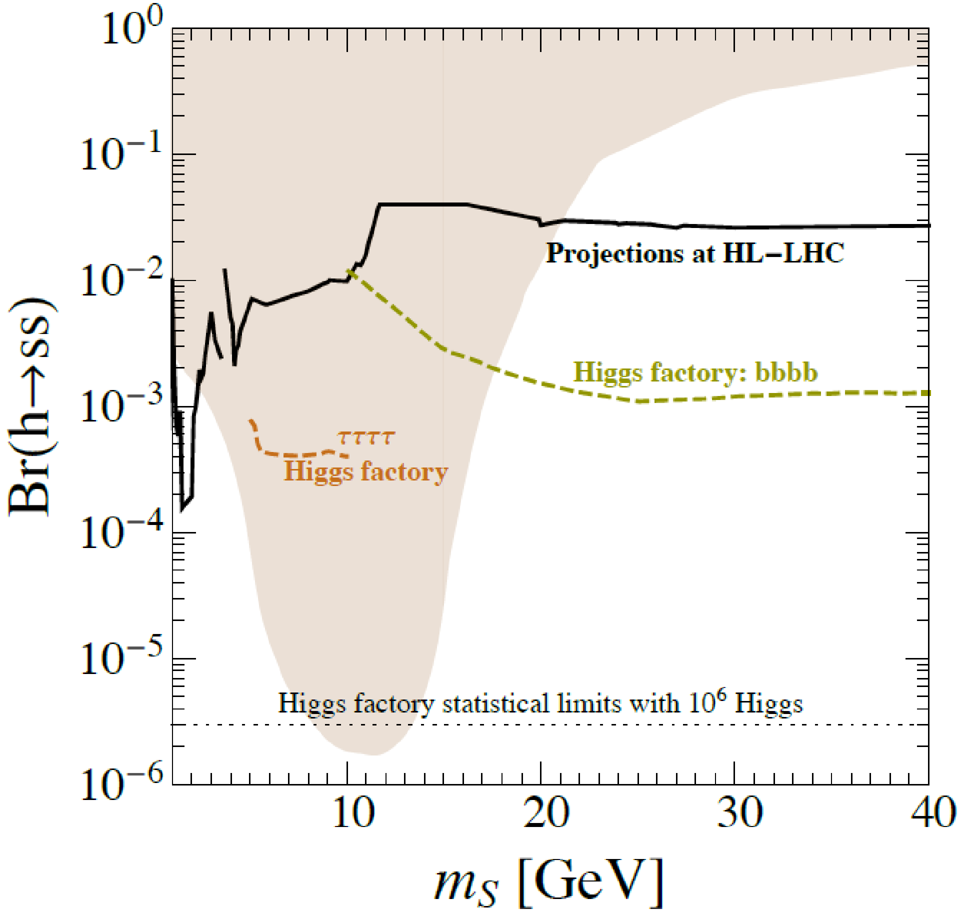
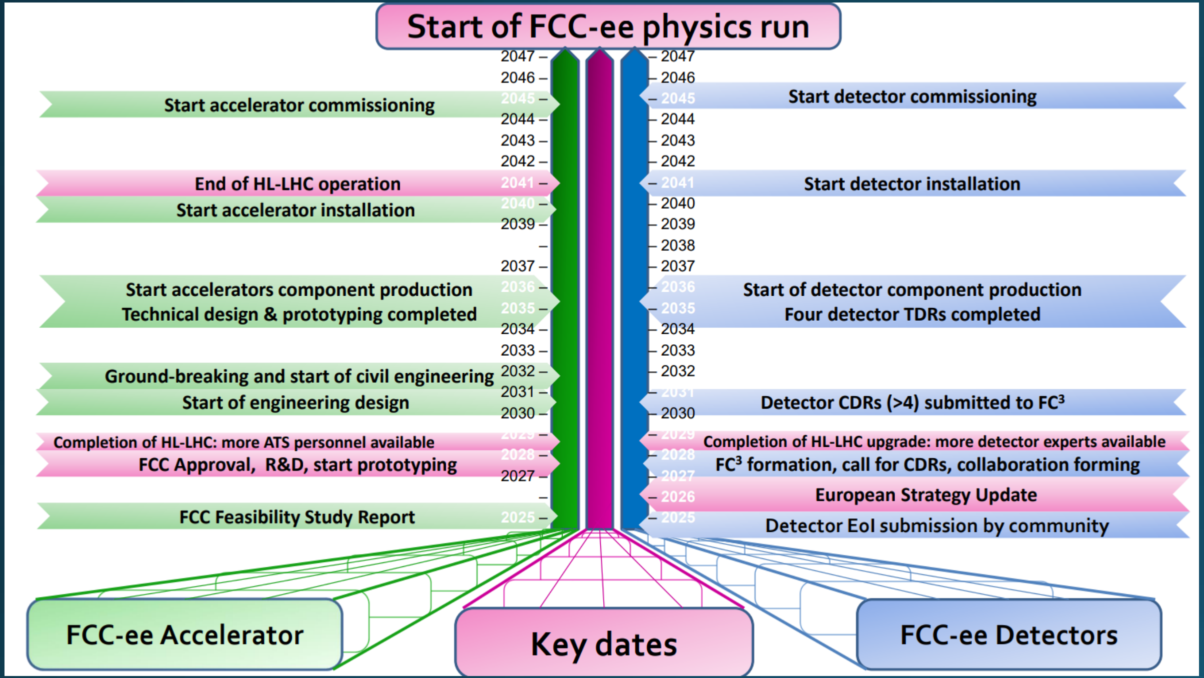


FIG. 40: Higgs portal model with $h \to SS$. The shaded region allows for an electroweak phase transition. From Ref [93]. See also [128]

Can I avoid thinking about this?



Start of FCC-ee physics run

Start accelerator commissioning

End of HL-LHC operation

Start accelerator installation

Start accelerators component production

Technical design & prototyping completed

Ground-breaking and start of civil engineering

Start of engineering design

Completion of HL-LHC: more ATS personnel available

FCC Approval, R&D, start prototyping

FCC Feasibility Study Report

Start detector commissioning

Start detector installation

Start of detector component production

Four detector TDRs completed

Detector CDRs (>4) submitted to FC^3

Completion of HL-LHC upgrade: more detector experts available

FC^3 formation, call for CDRs, collaboration forming

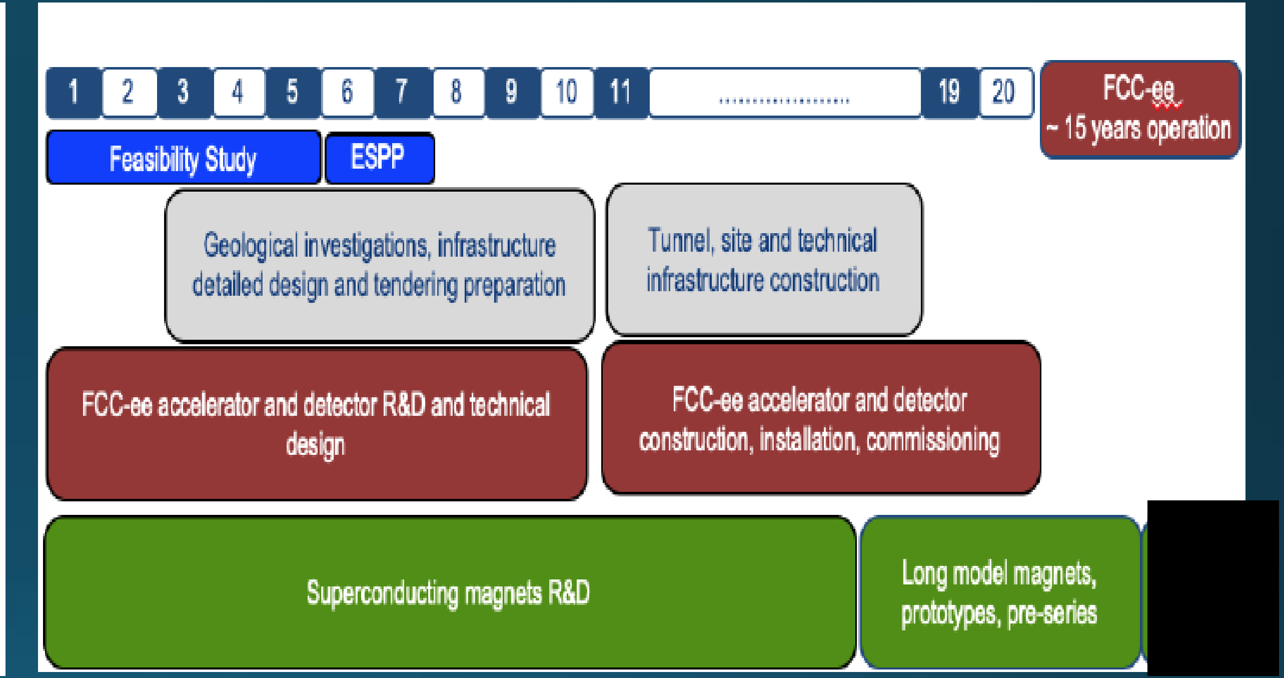
European Strategy Update

Detector EoI submission by community

FCC-ee Accelerator

Key dates

FCC-ee Detectors



FCC-ee
~ 15 years operation

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

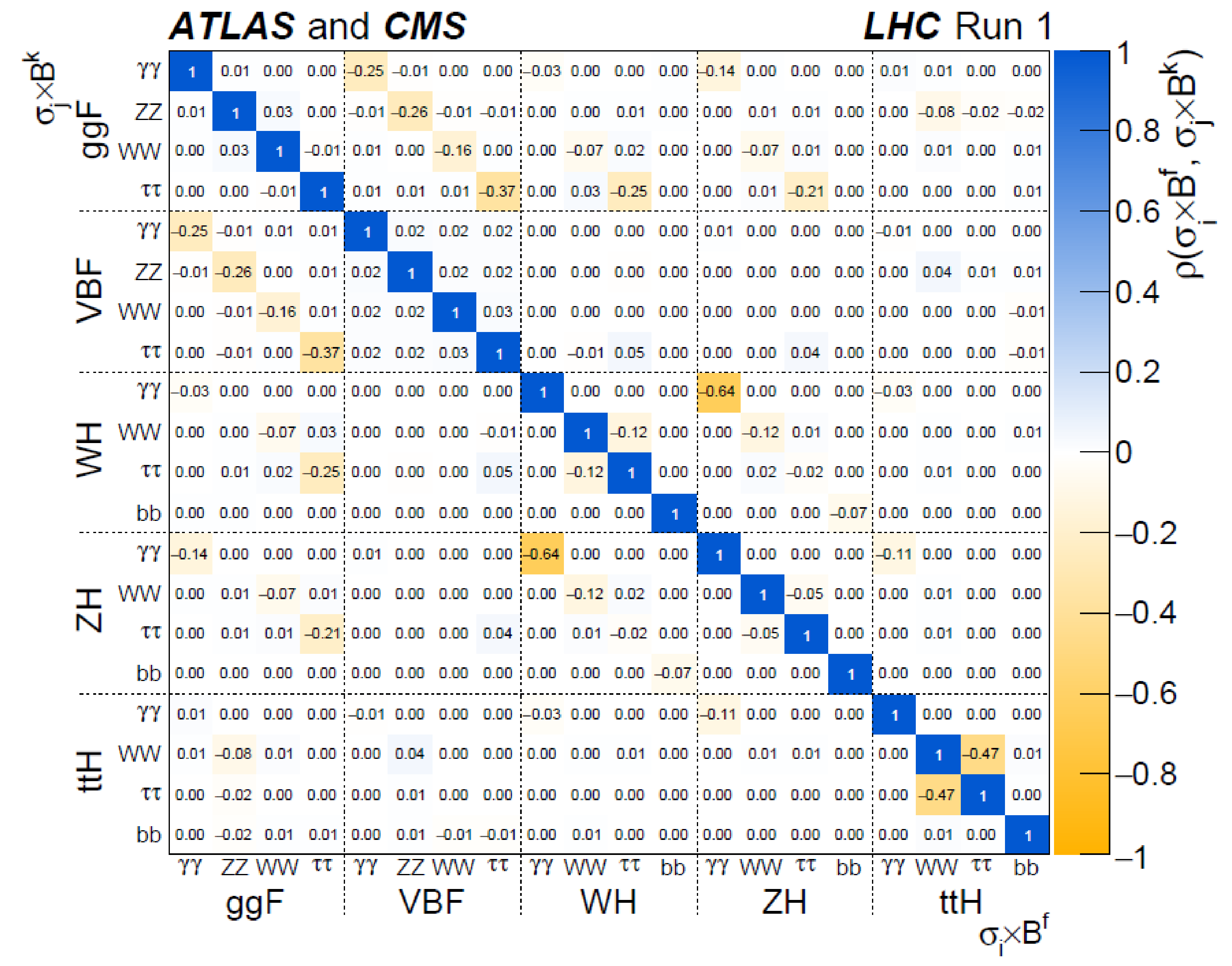
Superconducting magnets R&D

Long model magnets, prototypes, pre-series

[redacted]

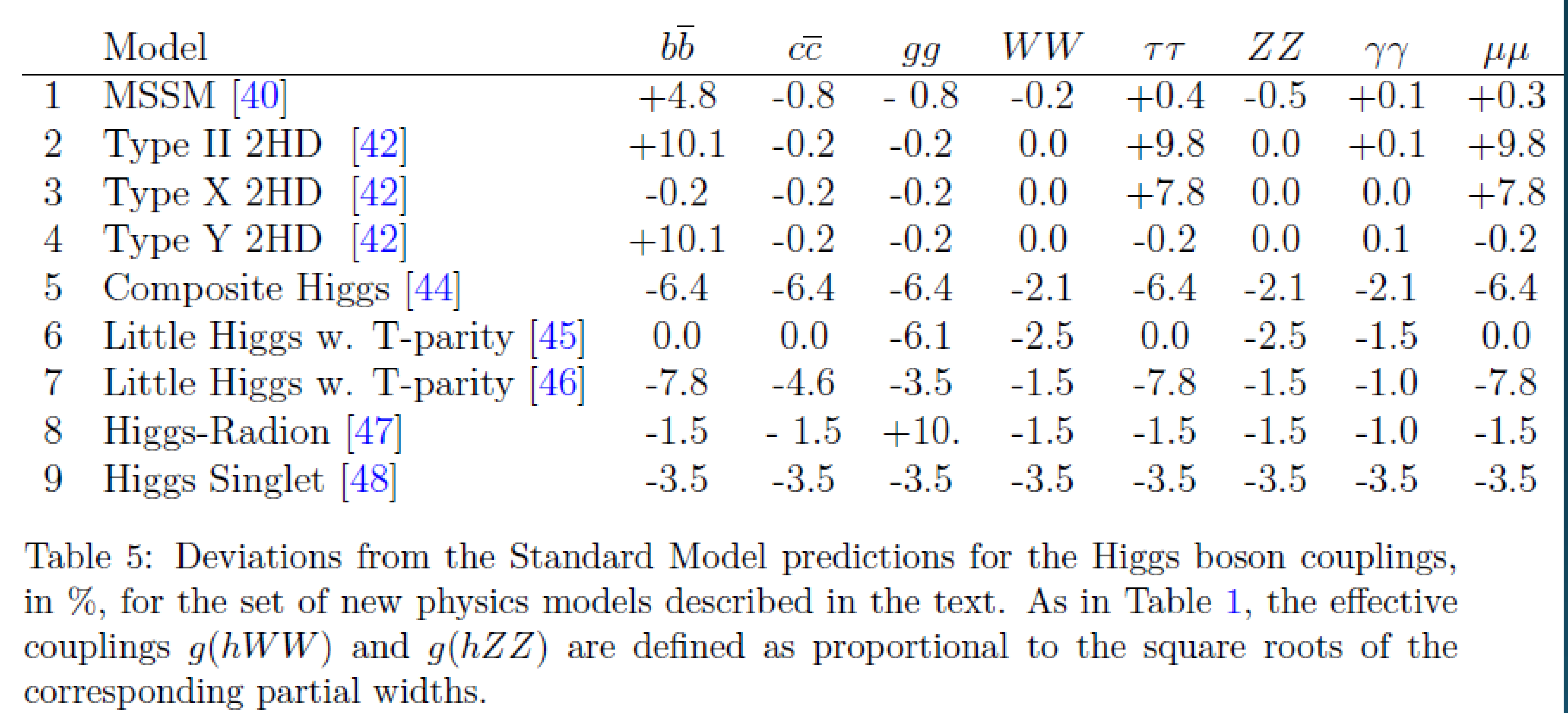
summary

- A Higgs factory will give us precision information about what is both the oddest part, and the part that sets most of the physics, of the standard model
- The required work is challenging and fun
- However, none of the three possibilities will happen if the world particle physics community doesn't push.



		ggF				VBF				WH				ZH				ttH			
		γγ	ZZ	WW	ττ	γγ	ZZ	WW	ττ	γγ	WW	ττ	bb	γγ	WW	ττ	bb	γγ	WW	ττ	bb
ggF	γγ	1	0.01	0.00	0.00	−0.25	−0.01	0.00	0.00	−0.03	0.00	0.00	0.00	−0.14	0.00	0.00	0.00	0.01	0.01	0.00	0.00
	ZZ	0.01	1	0.03	0.00	−0.01	−0.26	−0.01	−0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	−0.08	−0.02	−0.02
	WW	0.00	0.03	1	−0.01	0.01	0.00	−0.16	0.00	0.00	−0.07	0.02	0.00	0.00	−0.07	0.01	0.00	0.00	0.01	0.00	0.01
	ττ	0.00	0.00	−0.01	1	0.01	0.01	0.01	−0.37	0.00	0.03	−0.25	0.00	0.00	0.01	−0.21	0.00	0.00	0.00	0.00	0.01
VBF	γγ	−0.25	−0.01	0.01	0.01	1	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	−0.01	0.00	0.00	0.00
	ZZ	−0.01	−0.26	0.00	0.01	0.02	1	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01
	WW	0.00	−0.01	−0.16	0.01	0.02	0.02	1	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.01
	ττ	0.00	−0.01	0.00	−0.37	0.02	0.02	0.03	1	0.00	−0.01	0.05	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	−0.01
WH	γγ	−0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	−0.64	0.00	0.00	0.00	−0.03	0.00	0.00	0.00
	WW	0.00	0.00	−0.07	0.03	0.00	0.00	0.00	−0.01	0.00	1	−0.12	0.00	0.00	−0.12	0.01	0.00	0.00	0.00	0.00	0.01
	ττ	0.00	0.01	0.02	−0.25	0.00	0.00	0.00	0.05	0.00	−0.12	1	0.00	0.00	0.02	−0.02	0.00	0.00	0.01	0.00	0.00
	bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	−0.07	0.00	0.00	0.00	0.00
ZH	γγ	−0.14	0.00	0.00	0.00	0.01	0.00	0.00	0.00	−0.64	0.00	0.00	0.00	1	0.00	0.00	0.00	−0.11	0.00	0.00	0.00
	WW	0.00	0.01	−0.07	0.01	0.00	0.00	0.00	0.00	0.00	−0.12	0.02	0.00	0.00	1	−0.05	0.00	0.00	0.01	0.00	0.00
	ττ	0.00	0.01	0.01	−0.21	0.00	0.00	0.00	0.04	0.00	0.01	−0.02	0.00	0.00	−0.05	1	0.00	0.00	0.01	0.00	0.00
	bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.07	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00
ttH	γγ	0.01	0.00	0.00	0.00	−0.01	0.00	0.00	0.00	−0.03	0.00	0.00	0.00	−0.11	0.00	0.00	0.00	1	0.00	0.00	0.00
	WW	0.01	−0.08	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	1	−0.47	0.01
	ττ	0.00	−0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.47	1	0.00
	bb	0.00	−0.02	0.01	0.01	0.00	0.01	−0.01	−0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	1

arXiv:1708.08912

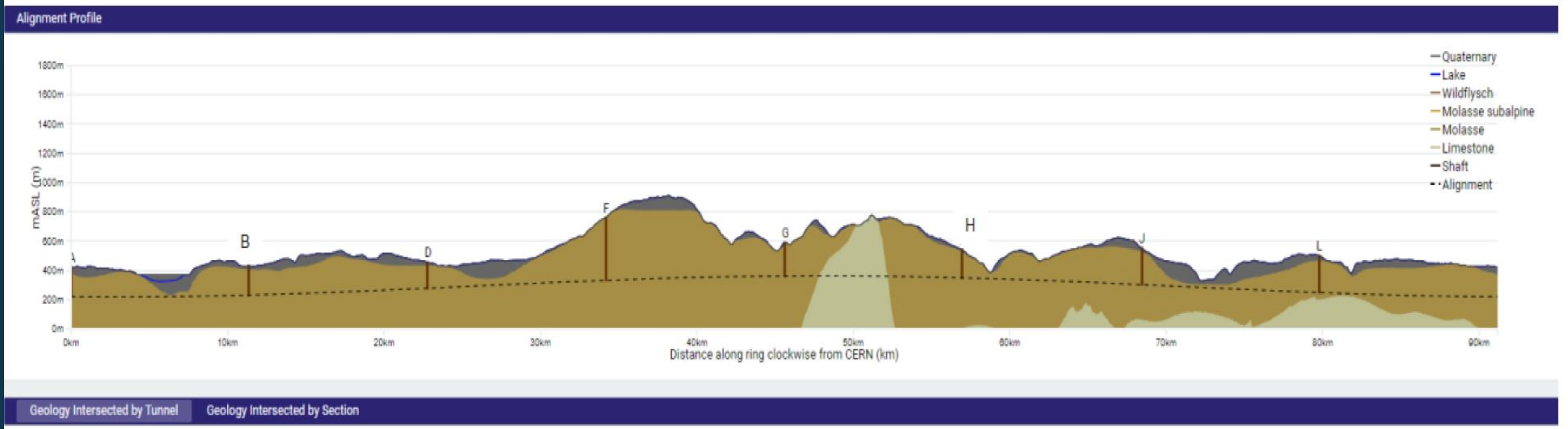


	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

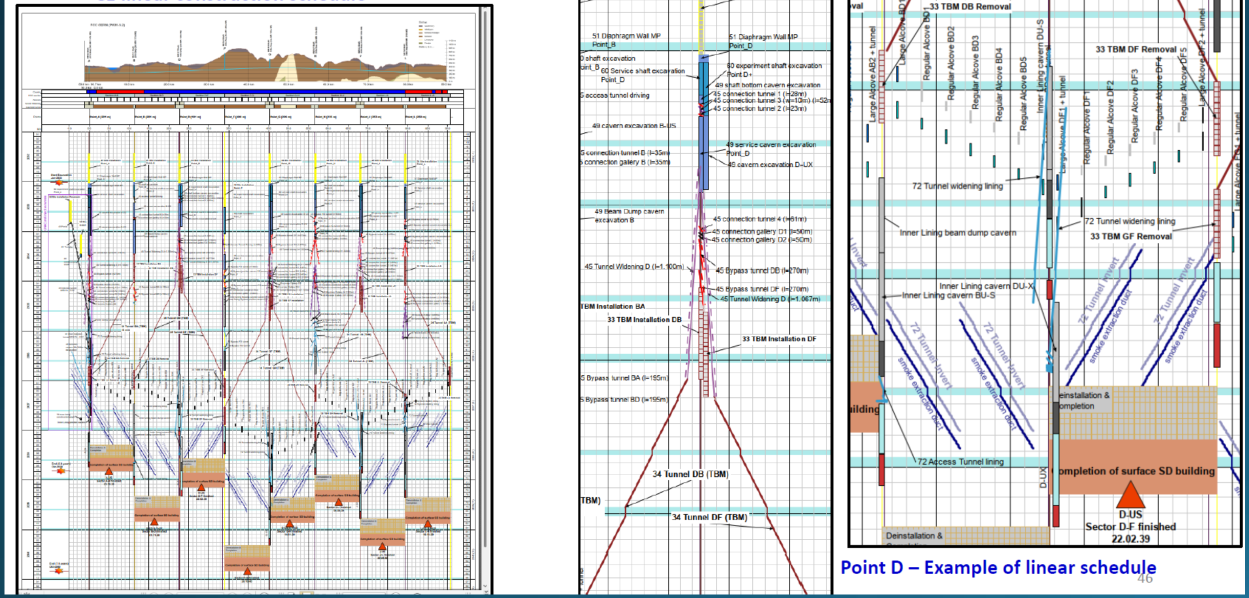
Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

backup

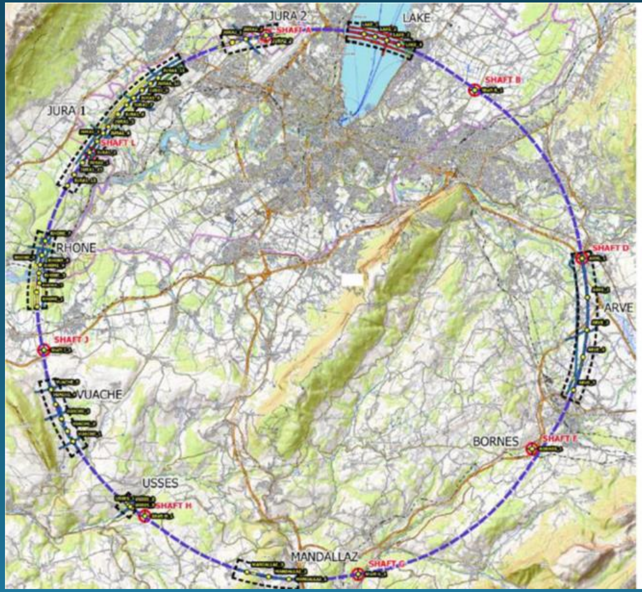
Timely progress on understanding the tunnel



CE linear construction schedule



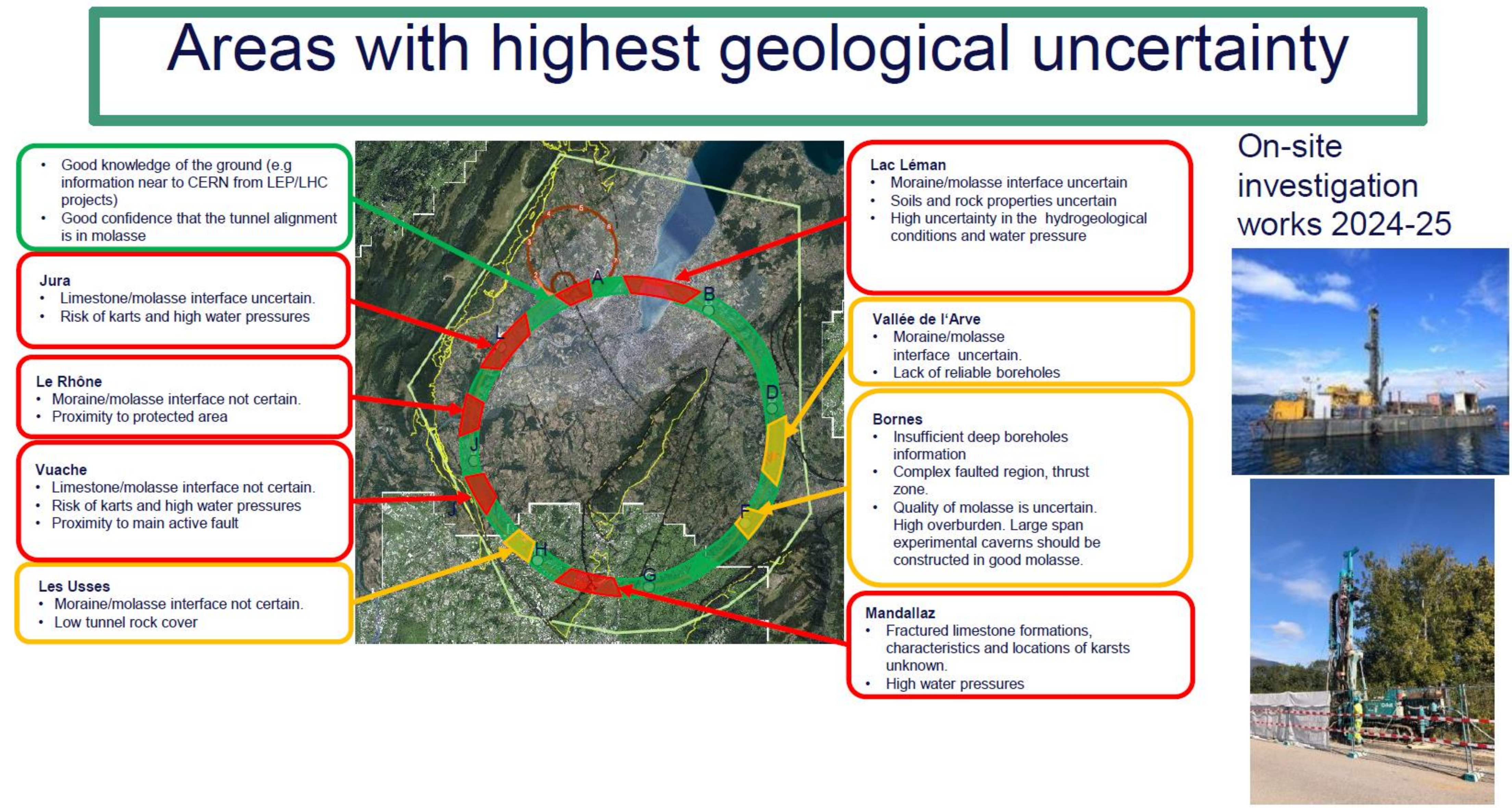
Point D – Example of linear schedule



- Site investigations in areas with uncertain geological conditions:
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022
  - **Alignment with FR and CH on the process for obtaining authorisation procedures. Planned start of drillings in Q2/2024**
- **Contract Status:**
  - Engineering service contracts since July 2022
  - Site investigation tendering ongoing
  - **Contract placement approved by Council in December 2023 and mobilization after contracts are signed**

Drilling works on the lake

Slides M. Benedikt



Areas with highest geological uncertainty

- Good knowledge of the ground (e.g information near to CERN from LEP/LHC projects)
- Good confidence that the tunnel alignment is in molasse

Jura
- Limestone/molasse interface uncertain.
- Risk of karts and high water pressures

Le Rhône
- Moraine/molasse interface not certain.
- Proximity to protected area

Vuache
- Limestone/molasse interface not certain.
- Risk of karts and high water pressures
- Proximity to main active fault

Les Usses
- Moraine/molasse interface not certain.
- Low tunnel rock cover

Lac Léman
- Moraine/molasse interface uncertain
- Soils and rock properties uncertain
- High uncertainty in the hydrogeological conditions and water pressure

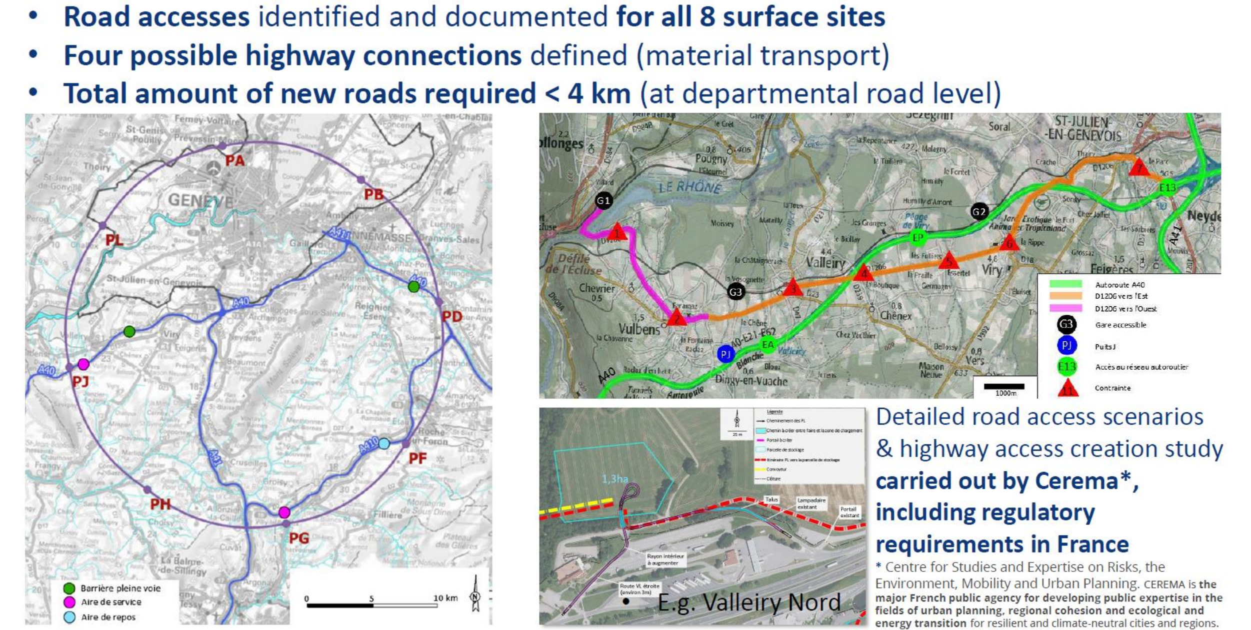
Vallée de l'Arve
- Moraine/molasse interface uncertain.
- Lack of reliable boreholes

Bornes
- Insufficient deep boreholes information
- Complex faulted region, thrust zone.
- Quality of molasse is uncertain. High overburden. Large span experimental caverns should be constructed in good molasse.

Mandallaz
- Fractured limestone formations, characteristics and locations of karsts unknown.
- High water pressures

On-site investigation works 2024-25

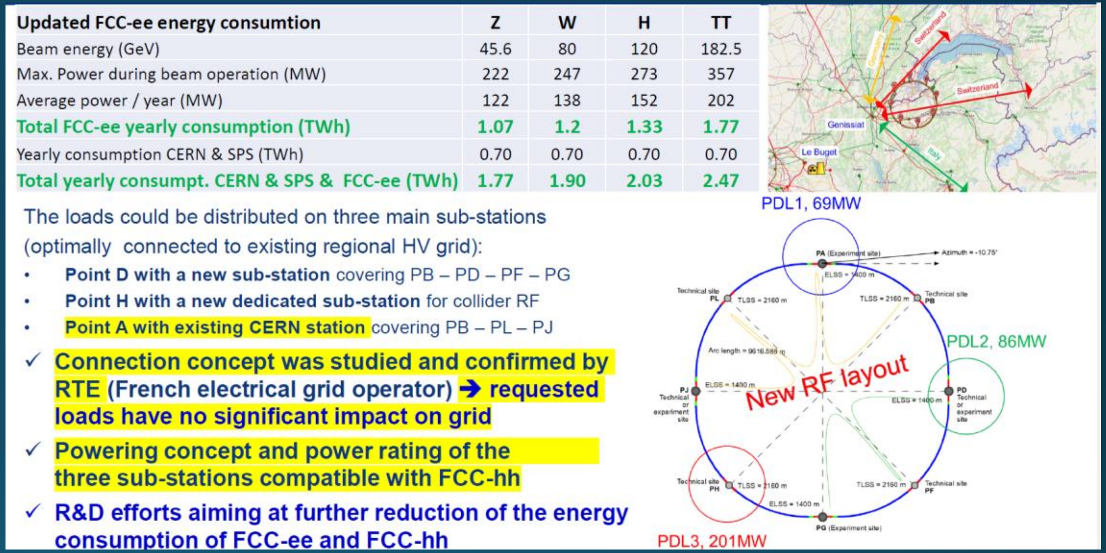
All details being scrutinized



- **Road accesses** identified and documented **for all 8 surface sites**
- **Four possible highway connections** defined (material transport)
- **Total amount of new roads required < 4 km** (at departmental road level)

Detailed road access scenarios & highway access creation study **carried out by Cerema*, including regulatory requirements in France**

* Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning. CEREMA is **the major French public agency for developing public expertise in the fields of urban planning, regional cohesion and ecological and energy transition** for resilient and climate-neutral cities and regions.



Updated FCC-ee energy consumtion	**Z**	**W**	**H**	**TT**
Beam energy (GeV)	45.6	80	120	182.5
Max. Power during beam operation (MW)	222	247	273	357
Average power / year (MW)	122	138	152	202
Total FCC-ee yearly consumption (TWh)	**1.07**	**1.2**	**1.33**	**1.77**
Yearly consumption CERN & SPS (TWh)	0.70	0.70	0.70	0.70
Total yearly consumpt. CERN & SPS & FCC-ee (TWh)	**1.77**	**1.90**	**2.03**	**2.47**

The loads could be distributed on three main sub-stations (optimally connected to existing regional HV grid):

- **Point D with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- **Point A with existing CERN station** covering PB – PL – PJ

✓ **Connection concept was studied and confirmed by RTE (French electrical grid operator) ➔ requested loads have no significant impact on grid**

✓ **Powering concept and power rating of the three sub-stations compatible with FCC-hh**

✓ **R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-hh**

Cool things about the machine

Machine calibration

One of the things I find most fascinating about this machine is the possibility to do an extremely precise energy calibration via "resonant depolarization", used to measure the spin precession frequency, which is related to the beam energy via: $\Omega = \Omega_C(1 + \frac{g-2}{2}\frac{E}{m_e})$

where the cyclotron frequency is: $\Omega_c = \frac{-e}{\gamma m} B_y$ y is vertical

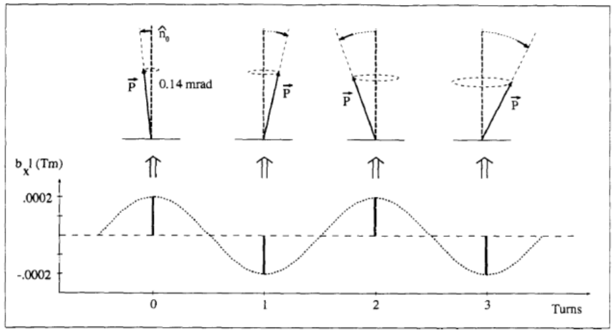
So the "spin tune" or number of spin processions in one turn, the part beyond 1 :

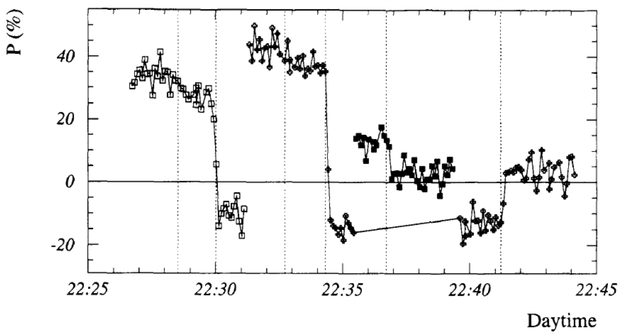
$$\nu = \frac{g_e - 2}{2}\gamma = \frac{E[MeV]}{440.6486}$$

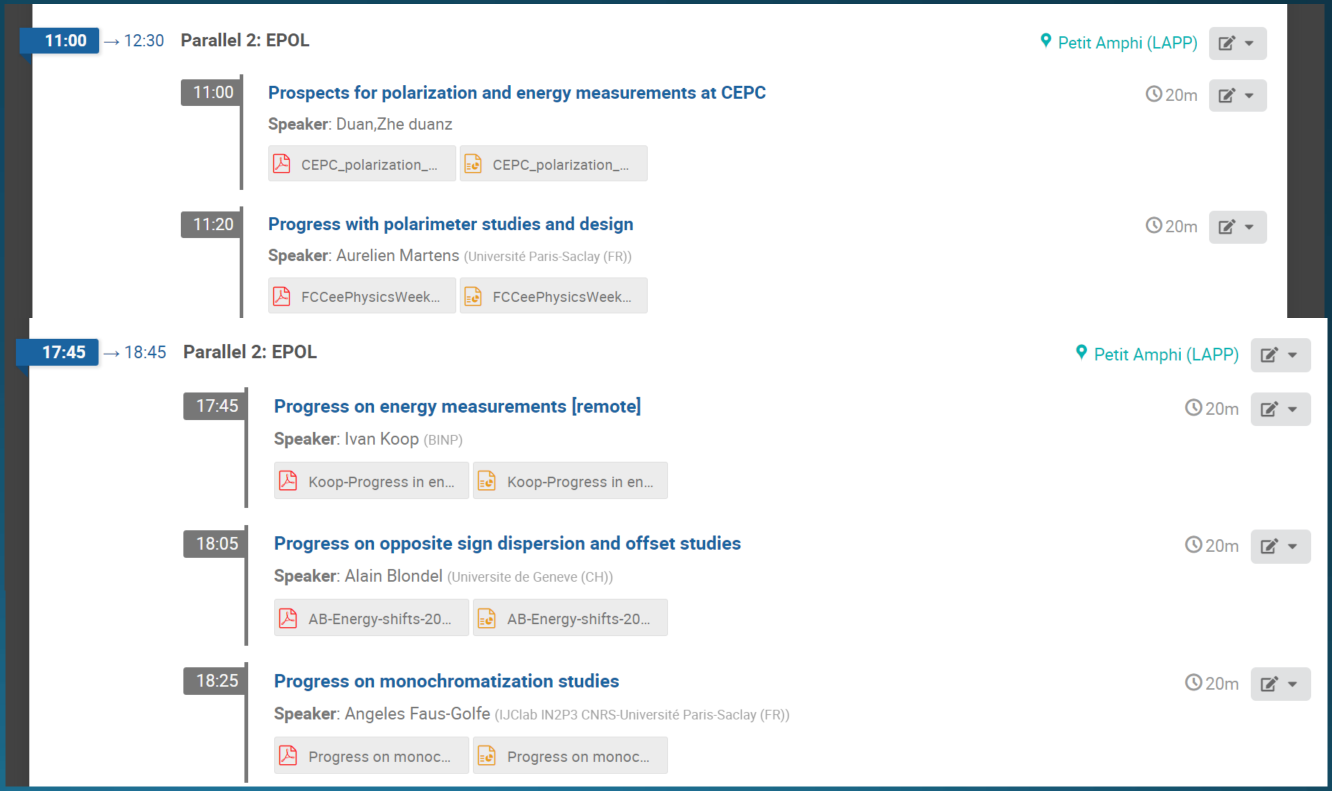
If the beam is excited by a magnetic field perpendicular to the beam axis, it rotates the spin around the radial direction. If this kick is in phase with the spin progression, you can push the spin into the horizonal plane and then flip it.

$$\nu = \frac{g_e - 2}{2}\frac{E_B}{m_e c^2}$$

Each time moves a bit farther away







11:00 → 12:30 **Parallel 2: EPOL** Petit Amphi (LAPP)

11:00 **Prospects for polarization and energy measurements at CEPC** 20m
Speaker: Duan,Zhe duanz
CEPC_polarization_... CEPC_polarization_...

11:20 **Progress with polarimeter studies and design** 20m
Speaker: Aurelien Martens (Université Paris-Saclay (FR))
FCCeePhysicsWeek... FCCeePhysicsWeek...

17:45 → 18:45 **Parallel 2: EPOL** Petit Amphi (LAPP)

17:45 **Progress on energy measurements [remote]** 20m
Speaker: Ivan Koop (BINP)
Koop-Progress in en... Koop-Progress in en...

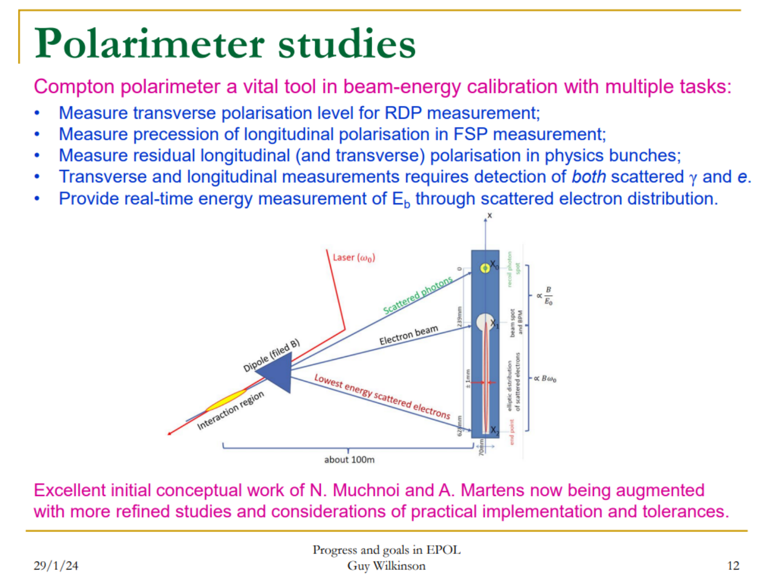
18:05 **Progress on opposite sign dispersion and offset studies** 20m
Speaker: Alain Blondel (Universite de Geneve (CH))
AB-Energy-shifts-20... AB-Energy-shifts-20...

18:25 **Progress on monochromatization studies** 20m
Speaker: Angeles Faus-Golfe (IJClab IN2P3 CNRS-Université Paris-Saclay (FR))
Progress on monoc... Progress on monoc...

https://inspirehep.net/literature/1650329
https://www.sciencedirect.com/science/article/pii/037026939290457F
https://cds.cern.ch/record/267514/

Resonant depolarization

Wilkinson, Annecy and Krakow



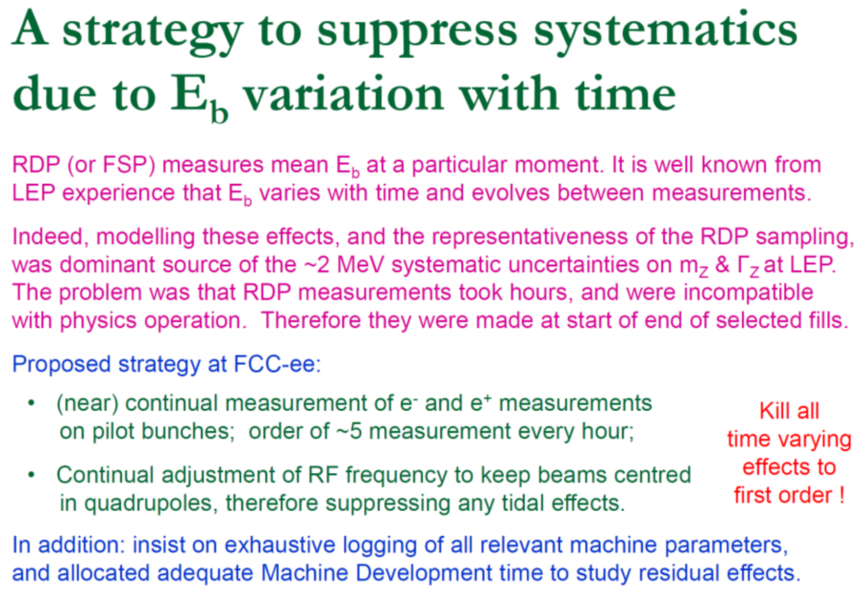
Polarimeter studies

Compton polarimeter a vital tool in beam-energy calibration with multiple tasks:

- Measure transverse polarisation level for RDP measurement;
- Measure precession of longitudinal polarisation in FSP measurement;
- Measure residual longitudinal (and transverse) polarisation in physics bunches;
- Transverse and longitudinal measurements requires detection of *both* scattered γ and *e*.
- Provide real-time energy measurement of E_b through scattered electron distribution.

Excellent initial conceptual work of N. Muchnoi and A. Martens now being augmented with more refined studies and considerations of practical implementation and tolerances.

29/1/24 Progress and goals in EPOL
Guy Wilkinson 12



A strategy to suppress systematics due to E_b variation with time

RDP (or FSP) measures mean E_b at a particular moment. It is well known from LEP experience that E_b varies with time and evolves between measurements.

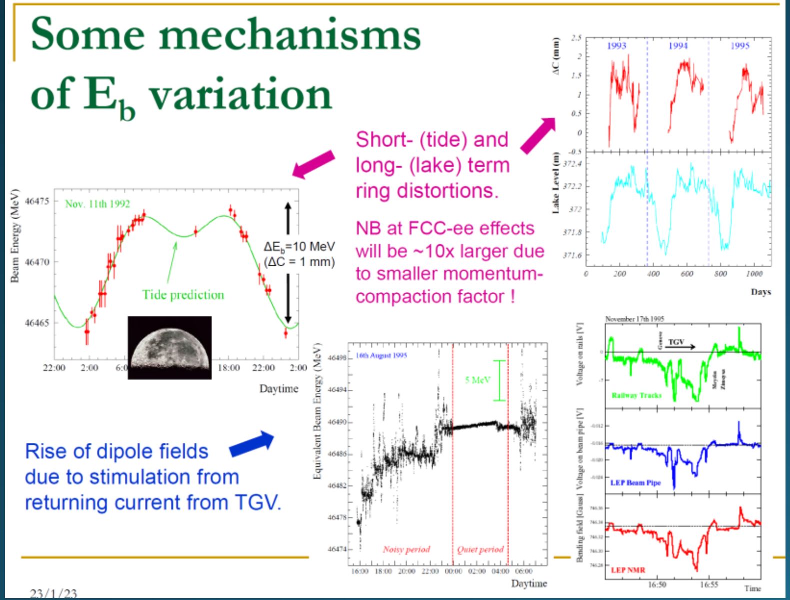
Indeed, modelling these effects, and the representativeness of the RDP sampling, was dominant source of the ~2 MeV systematic uncertainties on m_Z & Γ_Z at LEP. The problem was that RDP measurements took hours, and were incompatible with physics operation. Therefore they were made at start of end of selected fills.

Proposed strategy at FCC-ee:

- (near) continual measurement of e^- and e^+ measurements on pilot bunches; order of ~5 measurement every hour;
- Continual adjustment of RF frequency to keep beams centred in quadrupoles, therefore suppressing any tidal effects.

Kill all time varying effects to first order !

In addition: insist on exhaustive logging of all relevant machine parameters, and allocated adequate Machine Development time to study residual effects.



Some mechanisms of E_b variation

Short- (tide) and long- (lake) term ring distortions.

NB at FCC-ee effects will be ~10x larger due to smaller momentum-compaction factor !

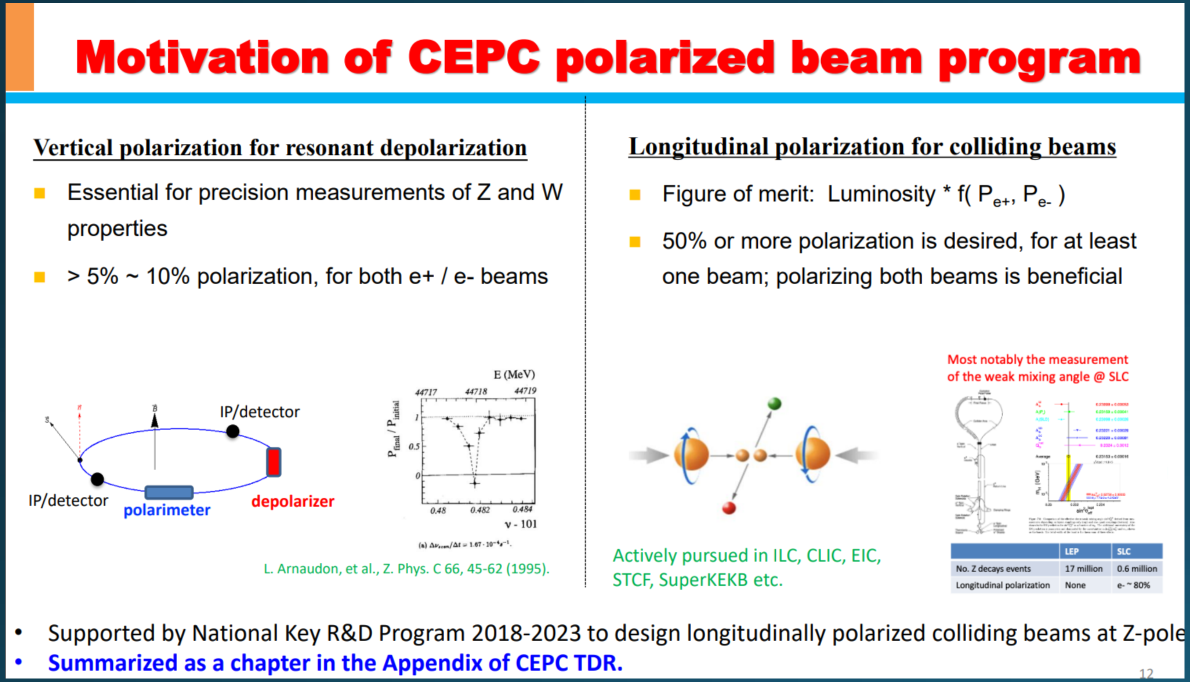
Rise of dipole fields due to stimulation from returning current from TGV.

23/1/23

Goal is 4 keV. LEP measurement was 1.2-1.7 MeV

This process requires strong collaboration between accelerator and machine physicists

Interesting news from CEPC on longitudinal polarization
Zhe Duan's talk



Motivation of CEPC polarized beam program

Vertical polarization for resonant depolarization

- Essential for precision measurements of Z and W properties
- > 5% ~ 10% polarization, for both e+ / e- beams

L. Arnaudon, et al., Z. Phys. C 66, 45-62 (1995).

Longitudinal polarization for colliding beams

- Figure of merit: Luminosity * f(P_{e+}, P_{e-})
- 50% or more polarization is desired, for at least one beam; polarizing both beams is beneficial

Actively pursued in ILC, CLIC, EIC, STCF, SuperKEKB etc.

Most notably the measurement of the weak mixing angle @ SLC

	LEP	SLC
No. Z decays events	17 million	0.6 million
Longitudinal polarization	None	e- ~ 80%

- Supported by National Key R&D Program 2018-2023 to design longitudinally polarized colliding beams at Z-pole
- **Summarized as a chapter in the Appendix of CEPC TDR.**

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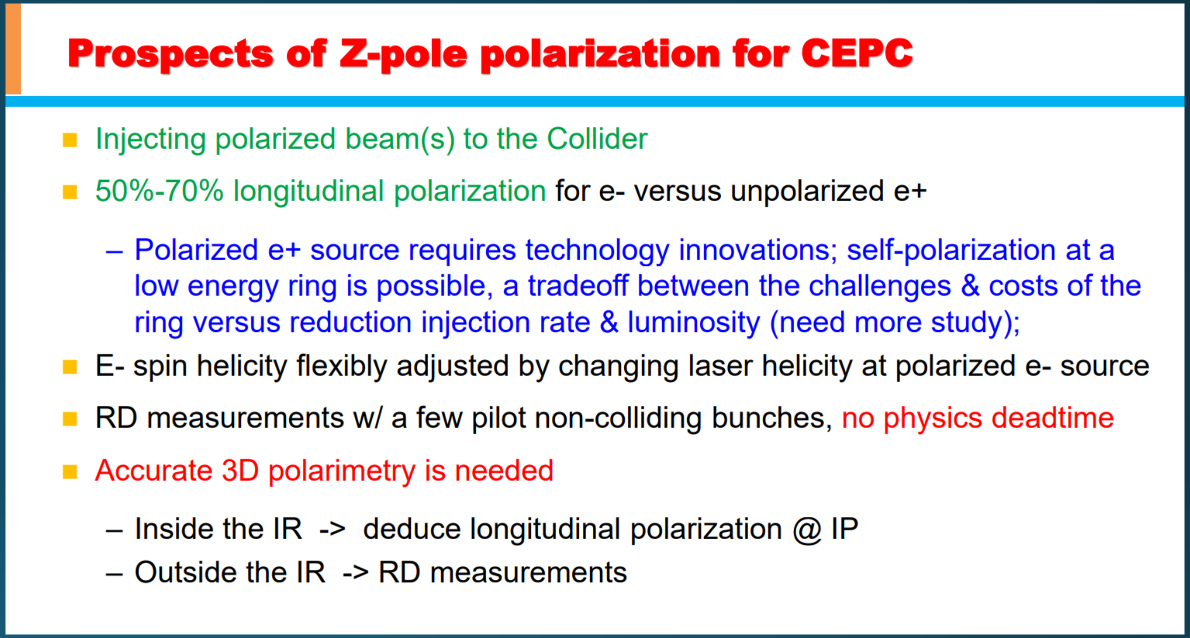
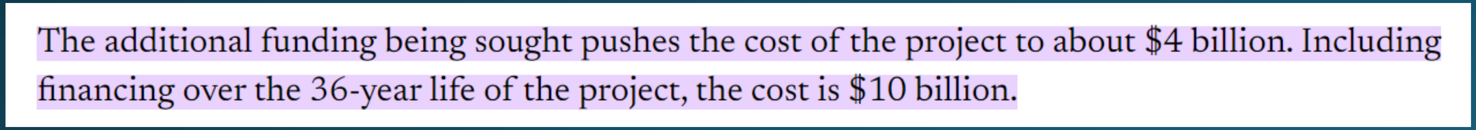


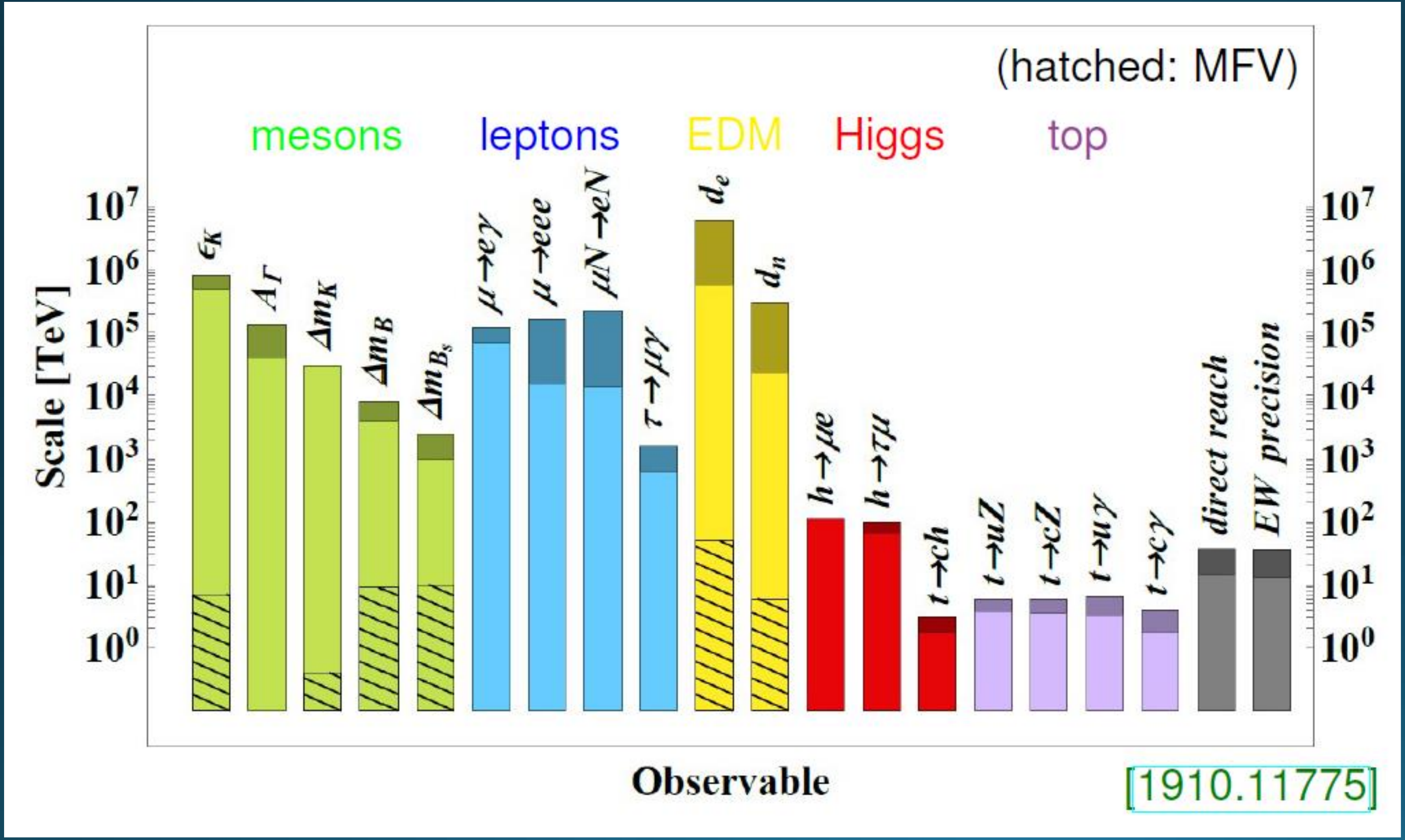
Prospects of Z-pole polarization for CEPC

- Injecting polarized beam(s) to the Collider
- 50%-70% longitudinal polarization for e- versus unpolarized e+
  - Polarized e+ source requires technology innovations; self-polarization at a low energy ring is possible, a tradeoff between the challenges & costs of the ring versus reduction injection rate & luminosity (need more study);
- E- spin helicity flexibly adjusted by changing laser helicity at polarized e- source
- RD measurements w/ a few pilot non-colliding bunches, no physics deadtime
- Accurate 3D polarimetry is needed
  - Inside the IR -> deduce longitudinal polarization @ IP
  - Outside the IR -> RD measurements

Purple line



The additional funding being sought pushes the cost of the project to about $4 billion. Including financing over the 36-year life of the project, the cost is $10 billion.



[1910.11775]

Physics briefing book, European strategy 2019

$$\delta\Sigma \equiv \frac{\Sigma_{\mathrm{NLO}}}{\Sigma_{\mathrm{NLO}}(\kappa_\lambda = 1)} - 1 \simeq (C_1 + 2\delta Z_H)\delta\kappa_\lambda + \delta Z_H \delta\kappa_\lambda^2$$

Change in an observable with an single external higgs line with change in hhh delta kappa lambda