Physics Prospects for Linear e^+e^- Colliders

Cari Cesarotti

MIT CTP Postdoctoral Fellow

C^3 Workshop @ Nikhef

What are the open questions in particle physics today?

Open Questions

Many open questions remain in the

SM & beyond

Open Questions

Many open questions remain in the SM & beyond

- Spin-0, m_h, compositeness?
- EWSB? EW Sector?
- Neutrino masses?
- Origin of Flavor?

Open Questions

Many open questions remain in the
SM & beyond

- Spin-0, m_h, compositeness?
- EWSB? EW Sector?
- Neutrino masses?
- Origin of Flavor?

- Dark matter?
- Above 10 TeV?
- Hidden Sectors?
- Anomalies?
- BAU?

Open Questions

Many open questions remain in the

SM & beyond

- Spin-0, m_h, compositeness?
- EWSB? EW Sector?
- Neutrino masses?
- Origin of Flavor?

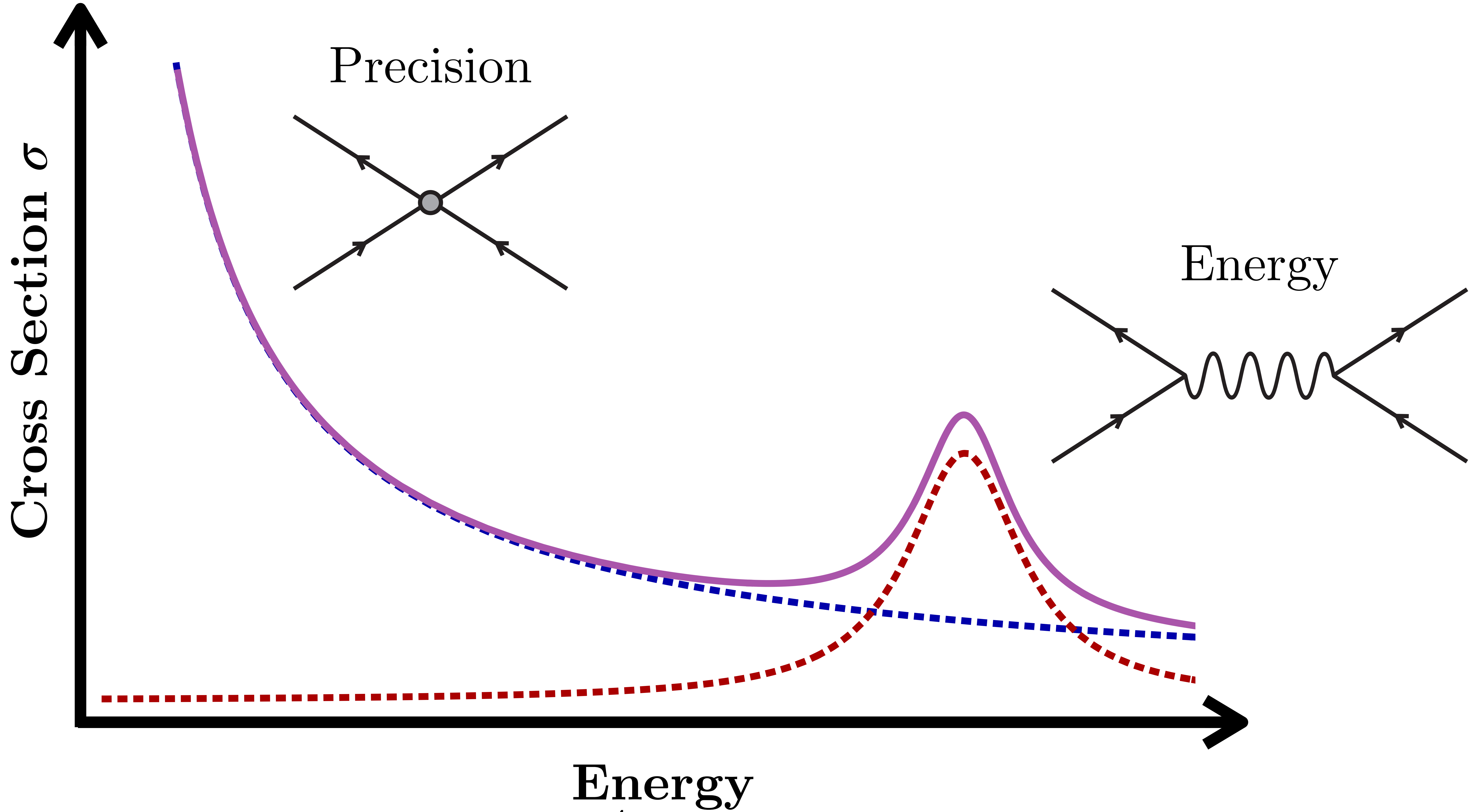
Nature of the Higgs

- Dark matter?
- Above 10 TeV?
- Hidden Sectors?
- Anomalies?
- BAU?

Open Questions

Two avenues to make progress:

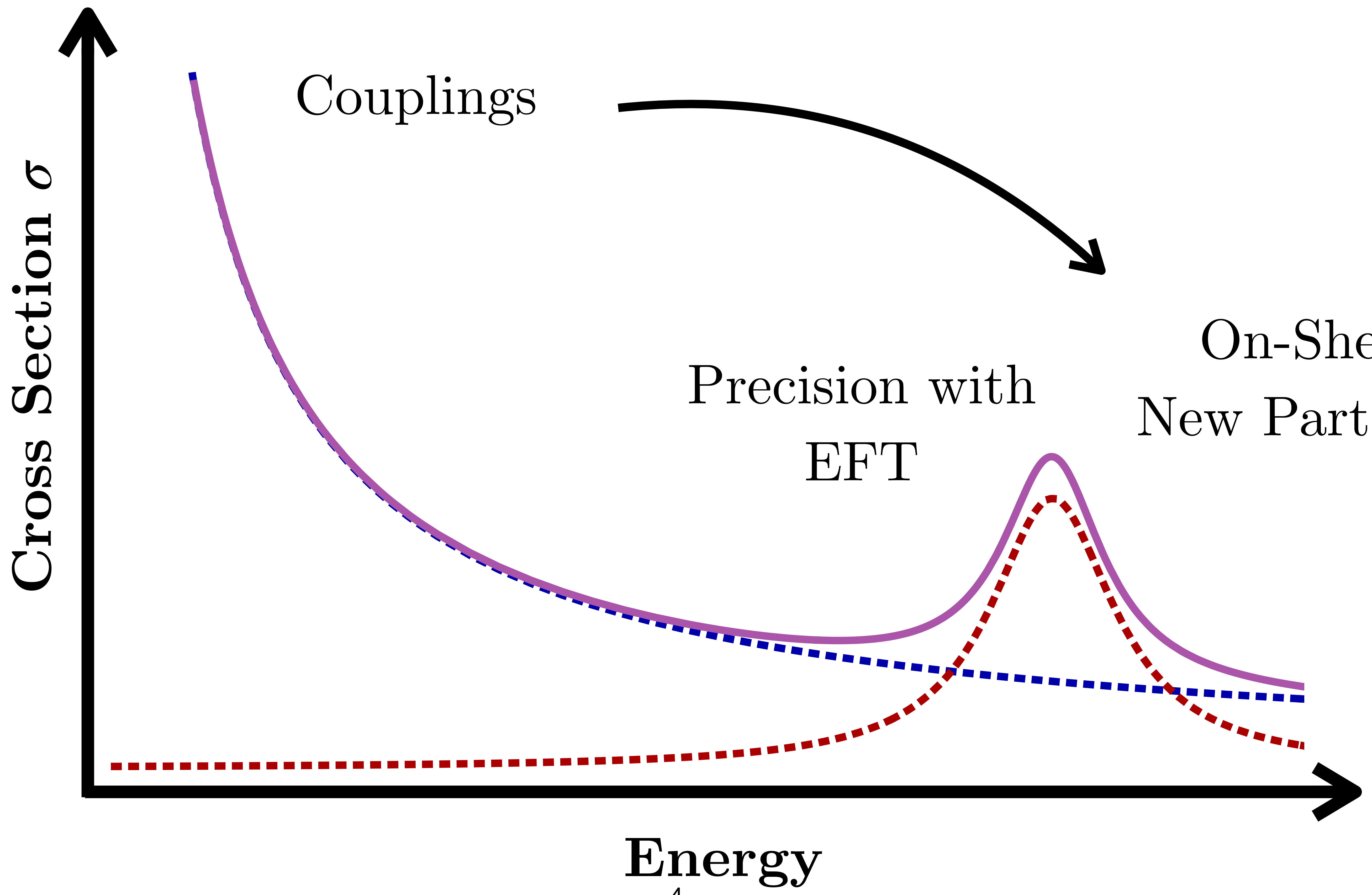
Precision & Energy



Open Questions

Two avenues to make progress:

Precision & Energy

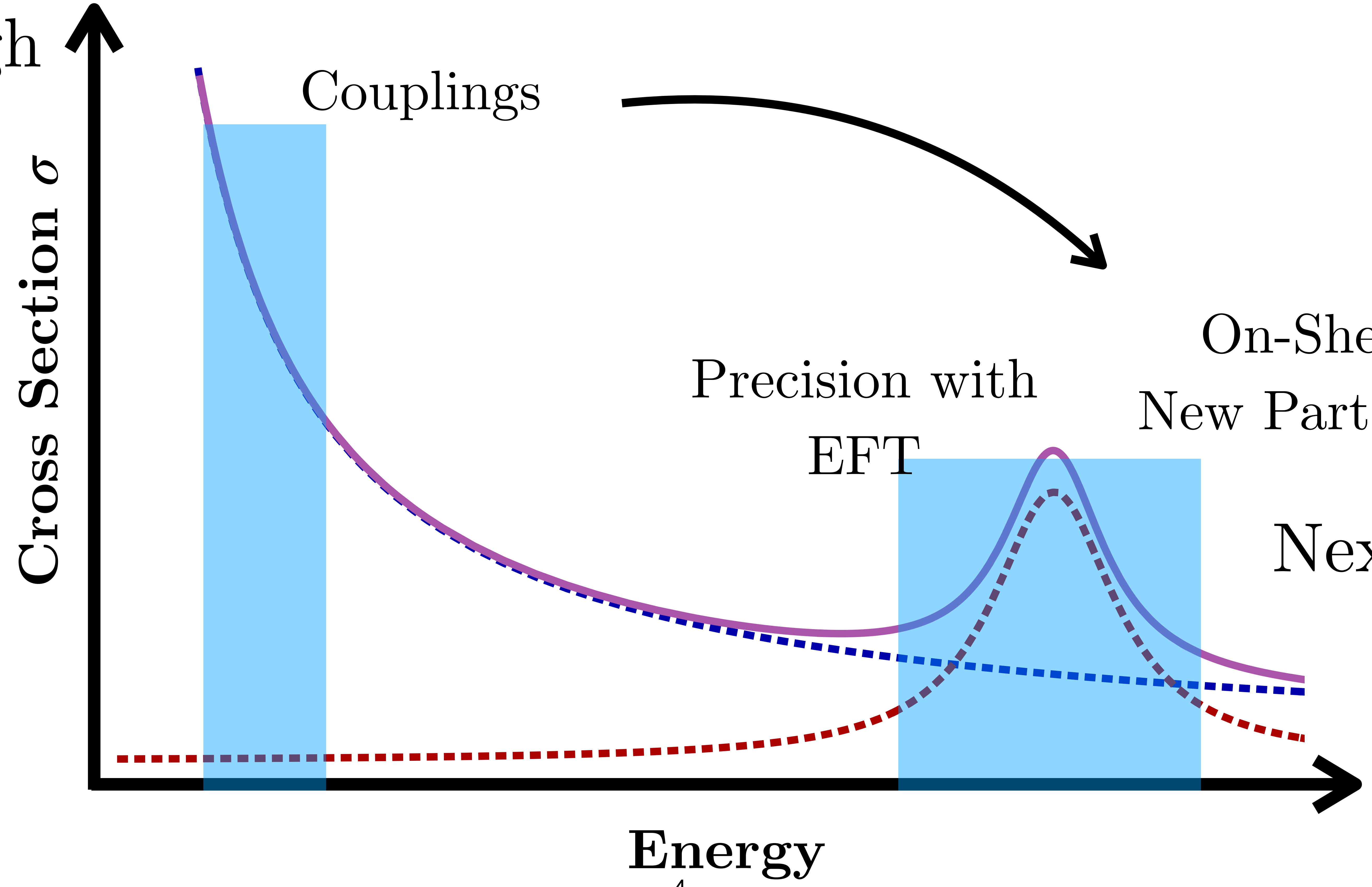


Cesarotti

Open Questions

Two avenues to make progress: Precision & Energy

Precision measurements inform where to look at high energies



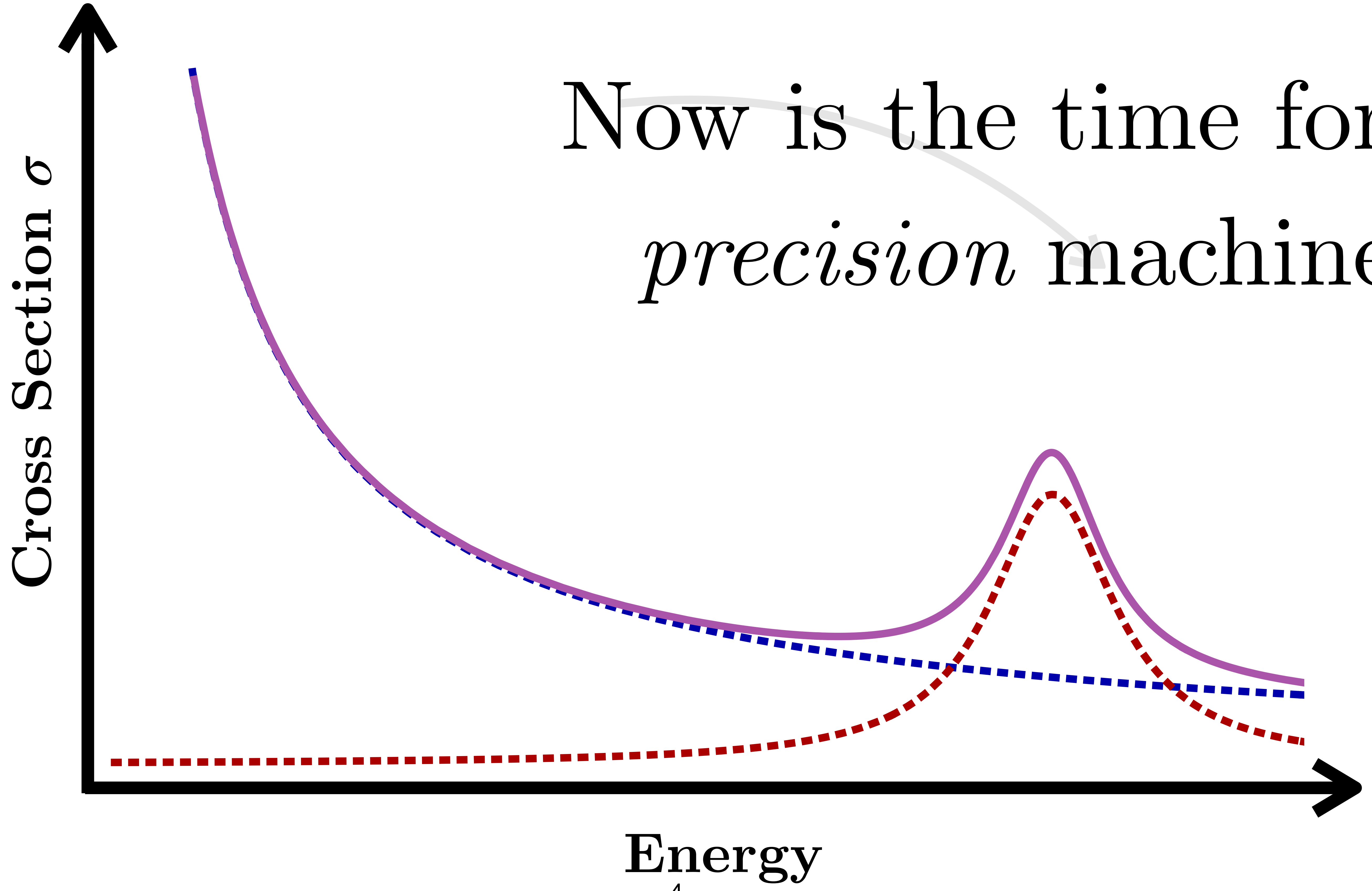
Next generation energy frontier

Cesarotti

Open Questions

Two avenues to make progress:

Precision & Energy

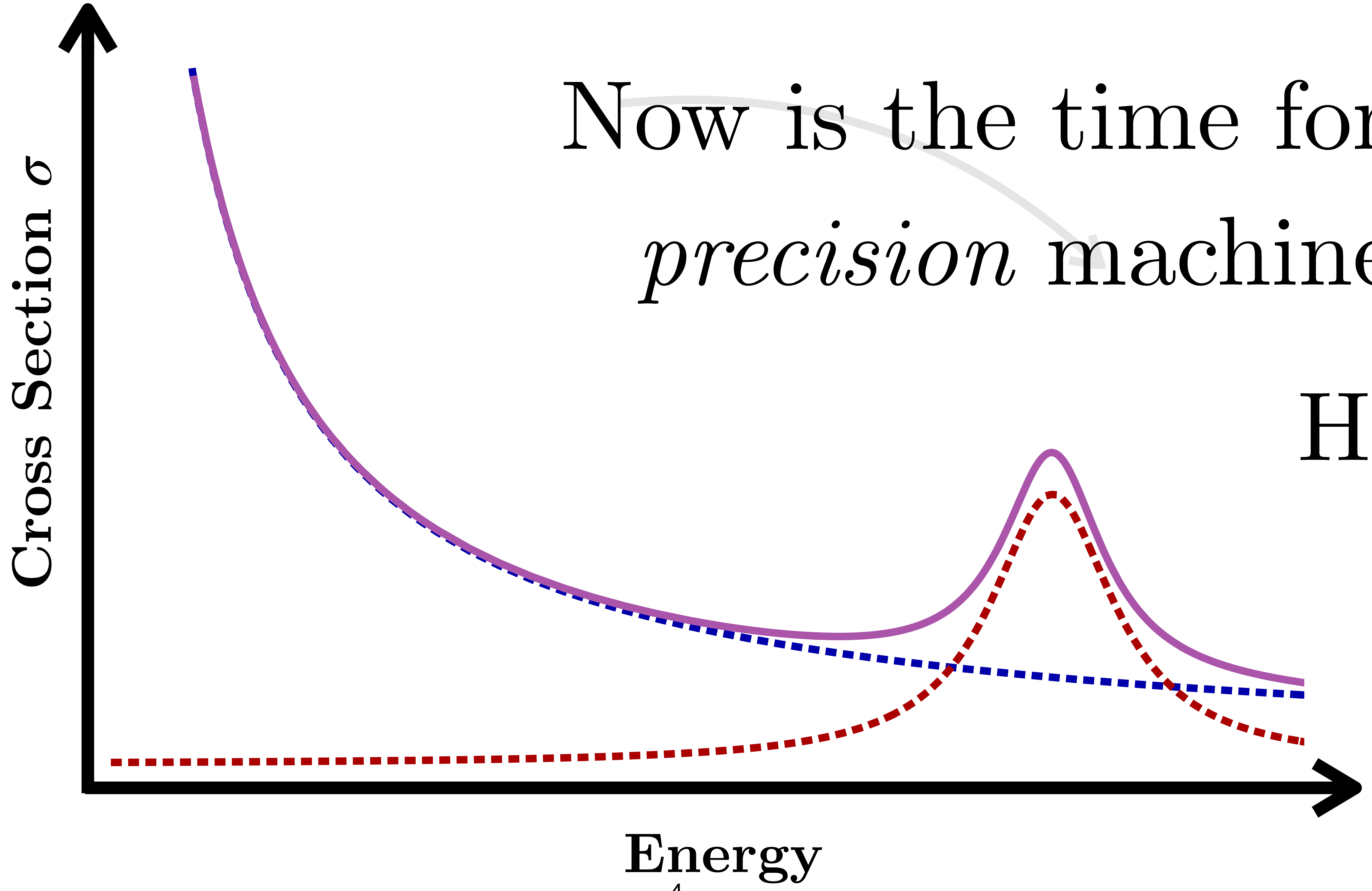


Now is the time for a *precision* machine

Open Questions

Two avenues to make progress:

Precision & Energy



Now is the time for a *precision* machine

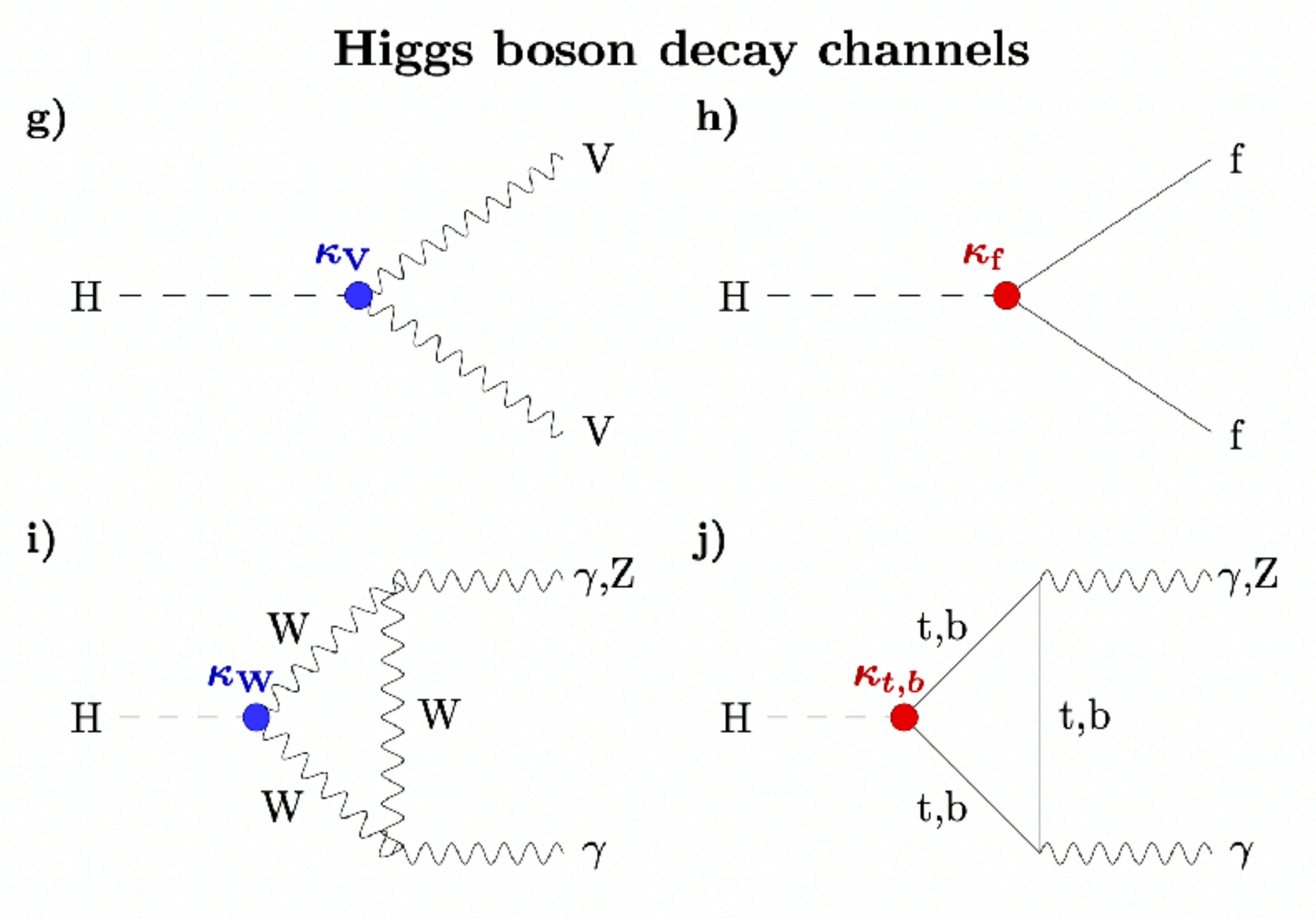
Higgs, top, & EW

Cesarotti

Higgs: Precision & Energy

Consider general scaling from EFT operators:

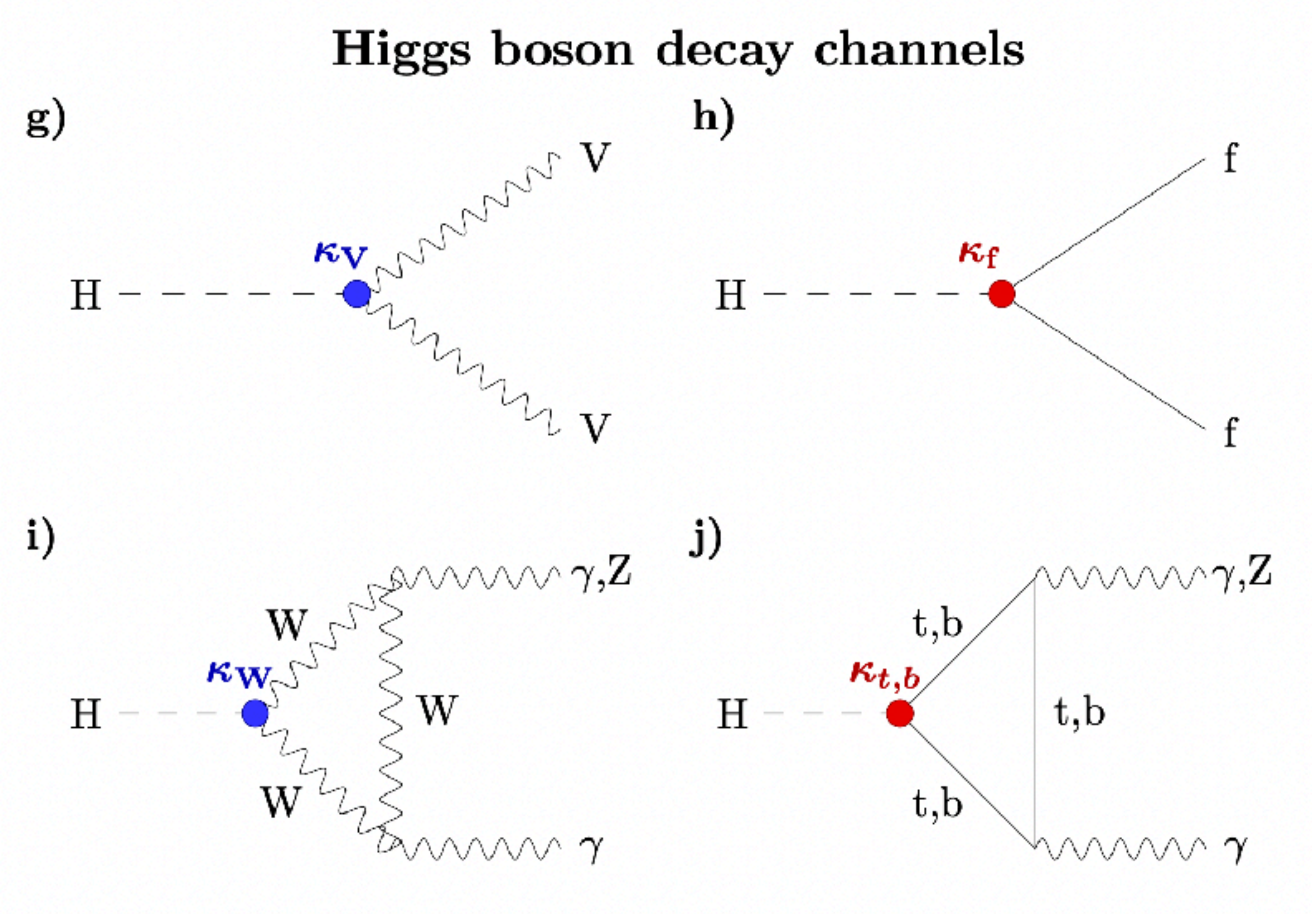
$$\mathcal{O}_{D=6} \sim H^\dagger H \mathcal{O}_{NP}$$



CMS, *Nature* '22

Higgs: Precision & Energy

Consider general scaling from EFT operators:



$$\mathcal{O}_{D=6} \sim H^\dagger H \mathcal{O}_{NP}$$

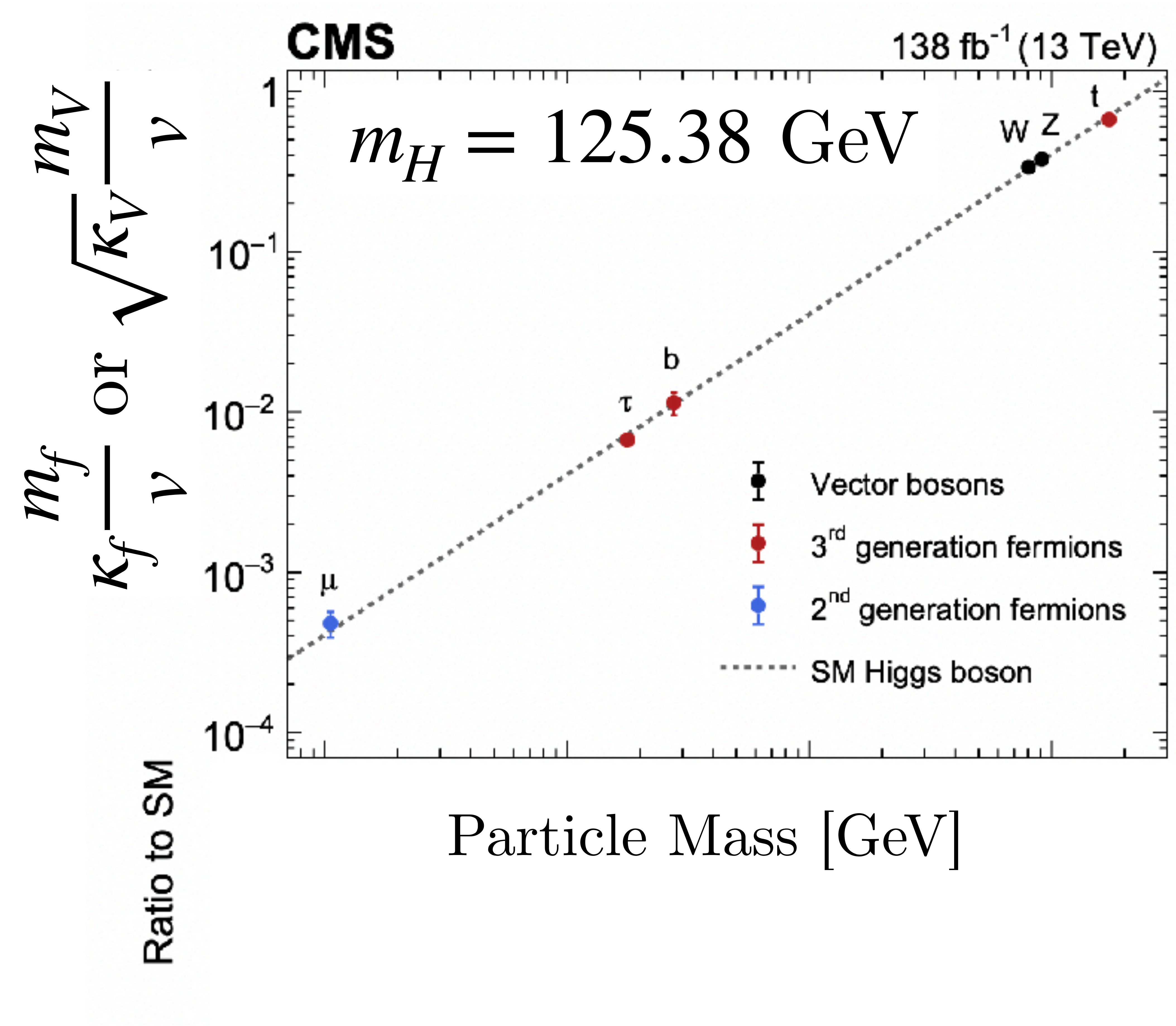
Tree Level	Loop Level
$\frac{\Delta\kappa}{\kappa} \sim \frac{v^2}{\Lambda^2}$	$\frac{\Delta\kappa}{\kappa} \sim \frac{1}{(4\pi)^2}\frac{v^2}{\Lambda^2}$

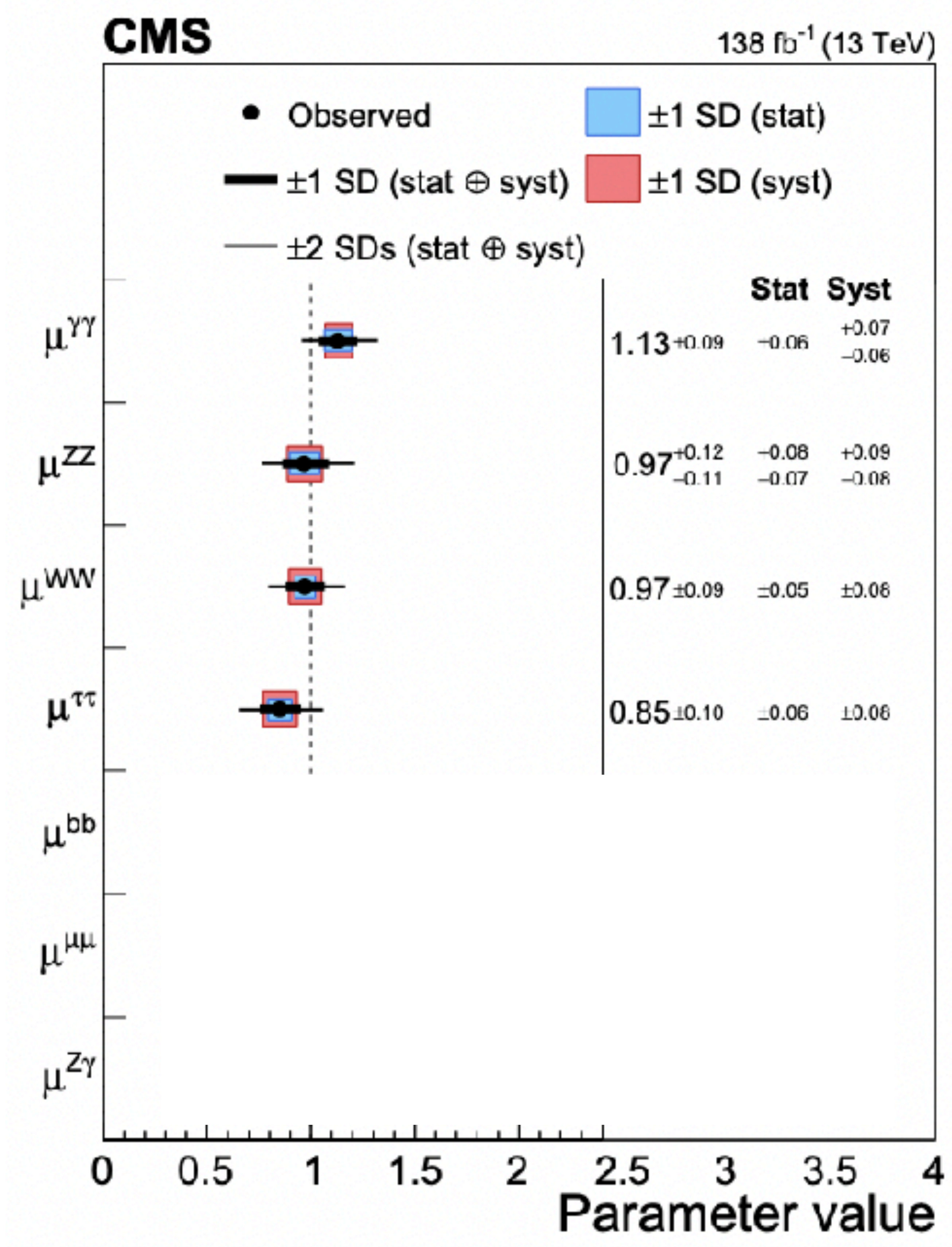
For $\sim \mathcal{O}(\,\%\,)$ Precision

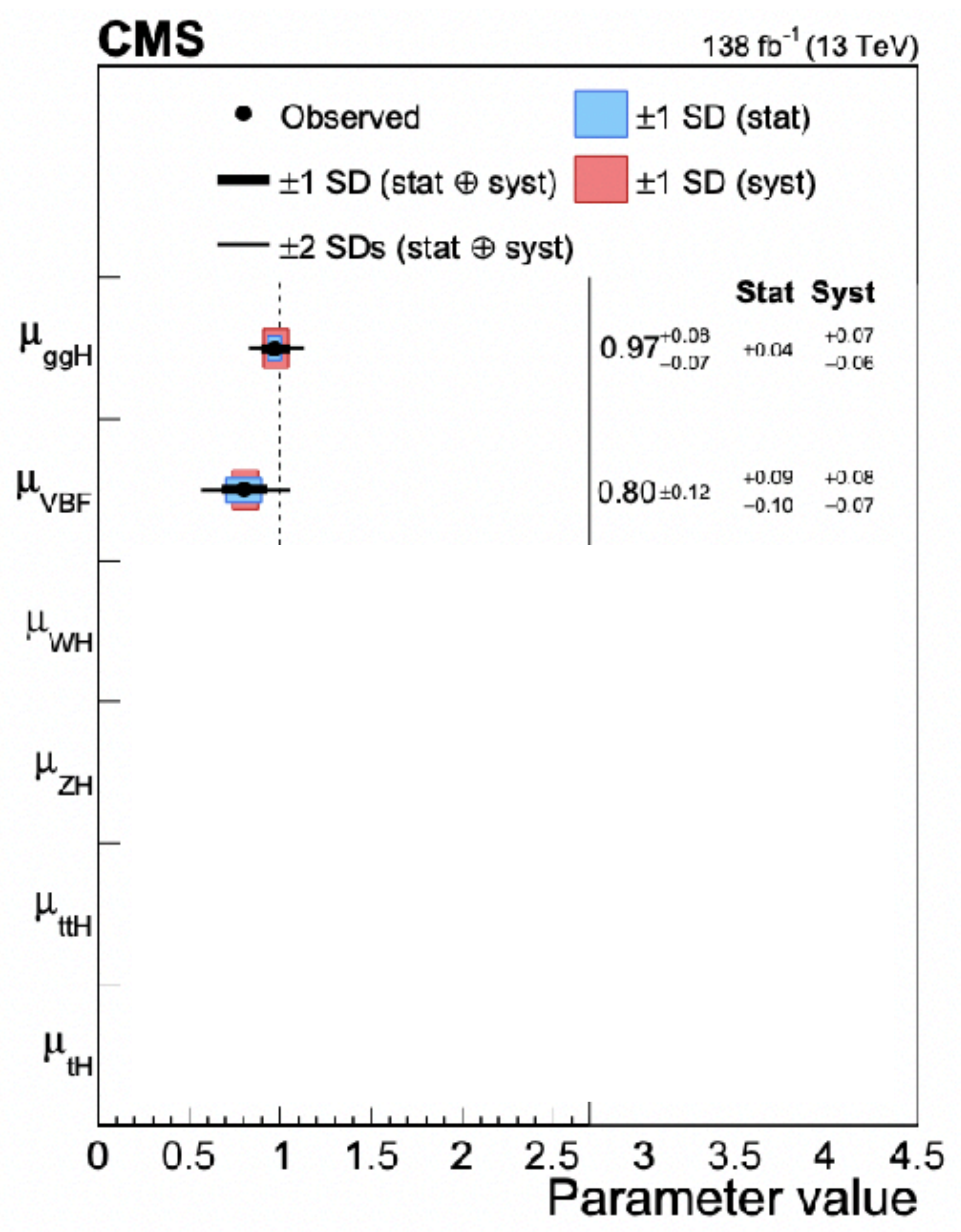
$\Lambda \sim$ TeV	$\Lambda \sim$ 10 TeV

CMS, *Nature* ‘22

Do we really know the Higgs?

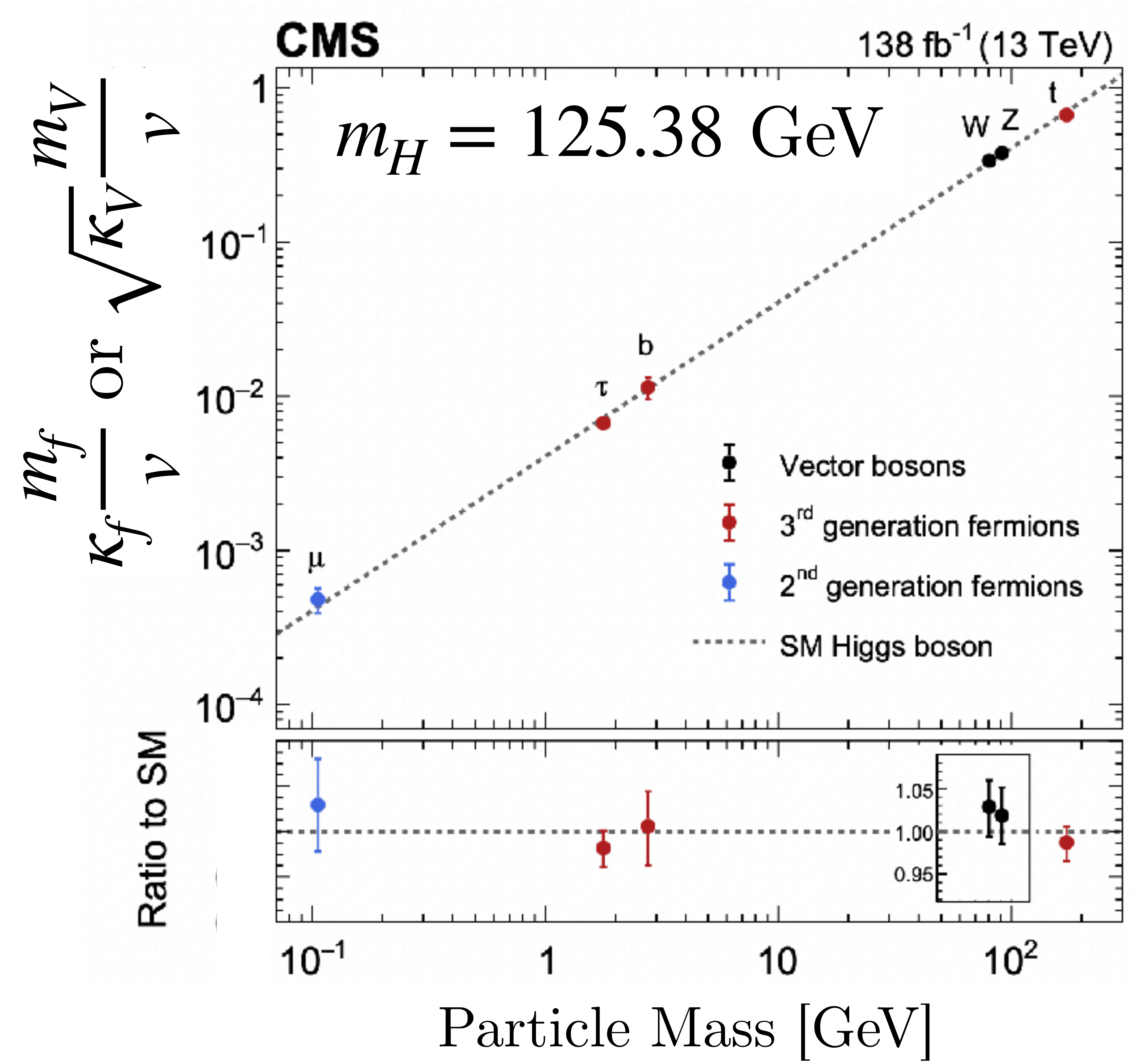


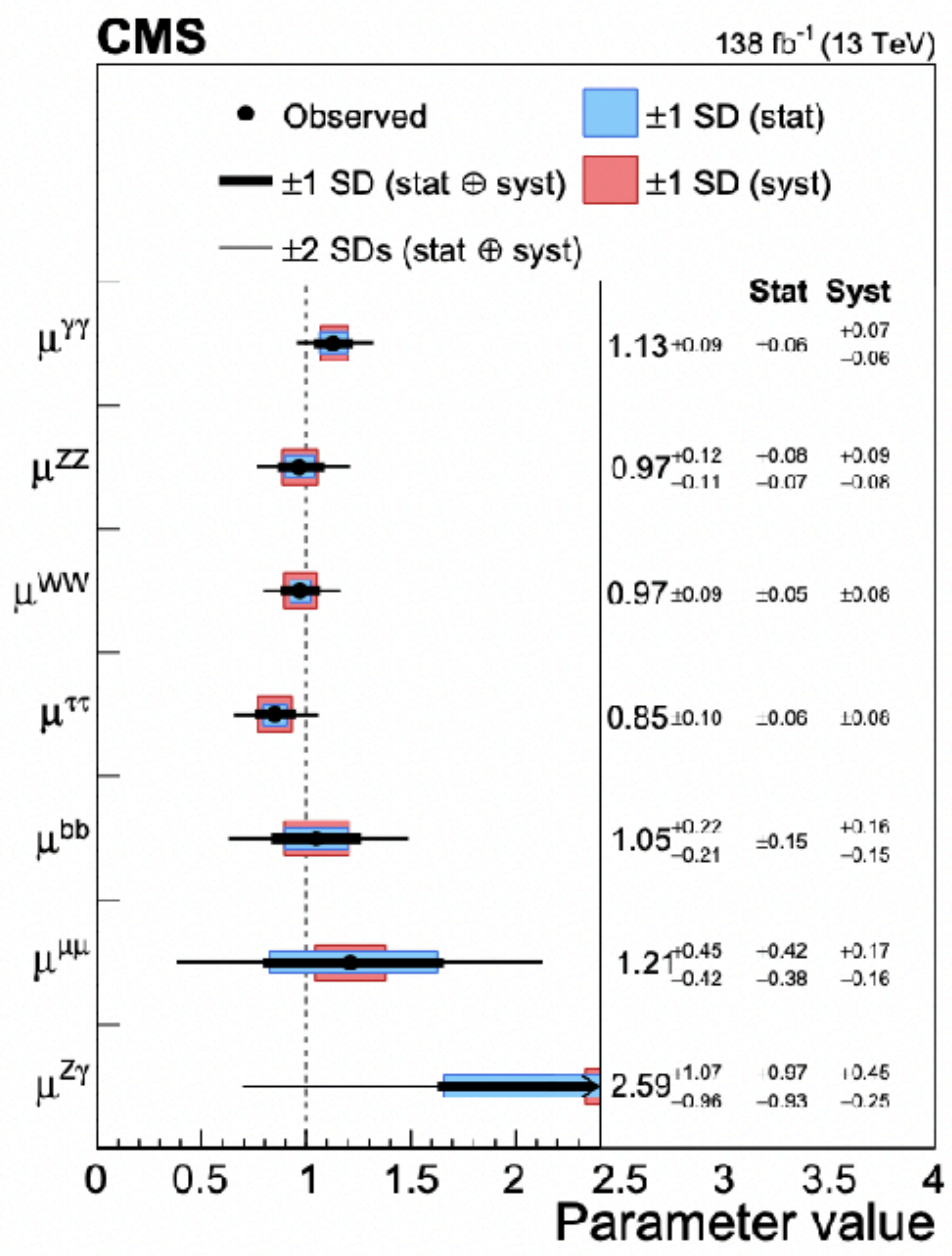


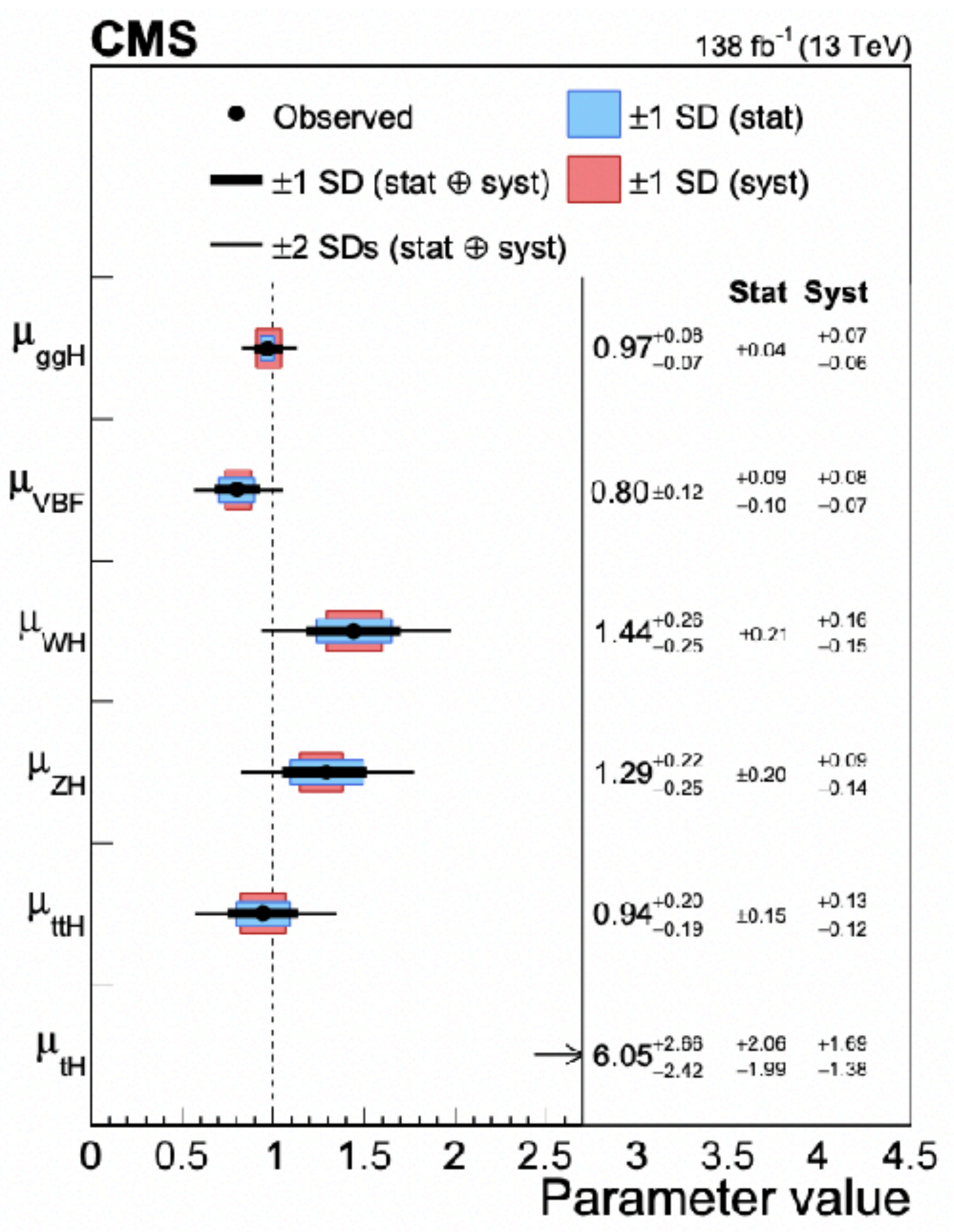


CMS, *Nature* '22

Do we really know the Higgs?





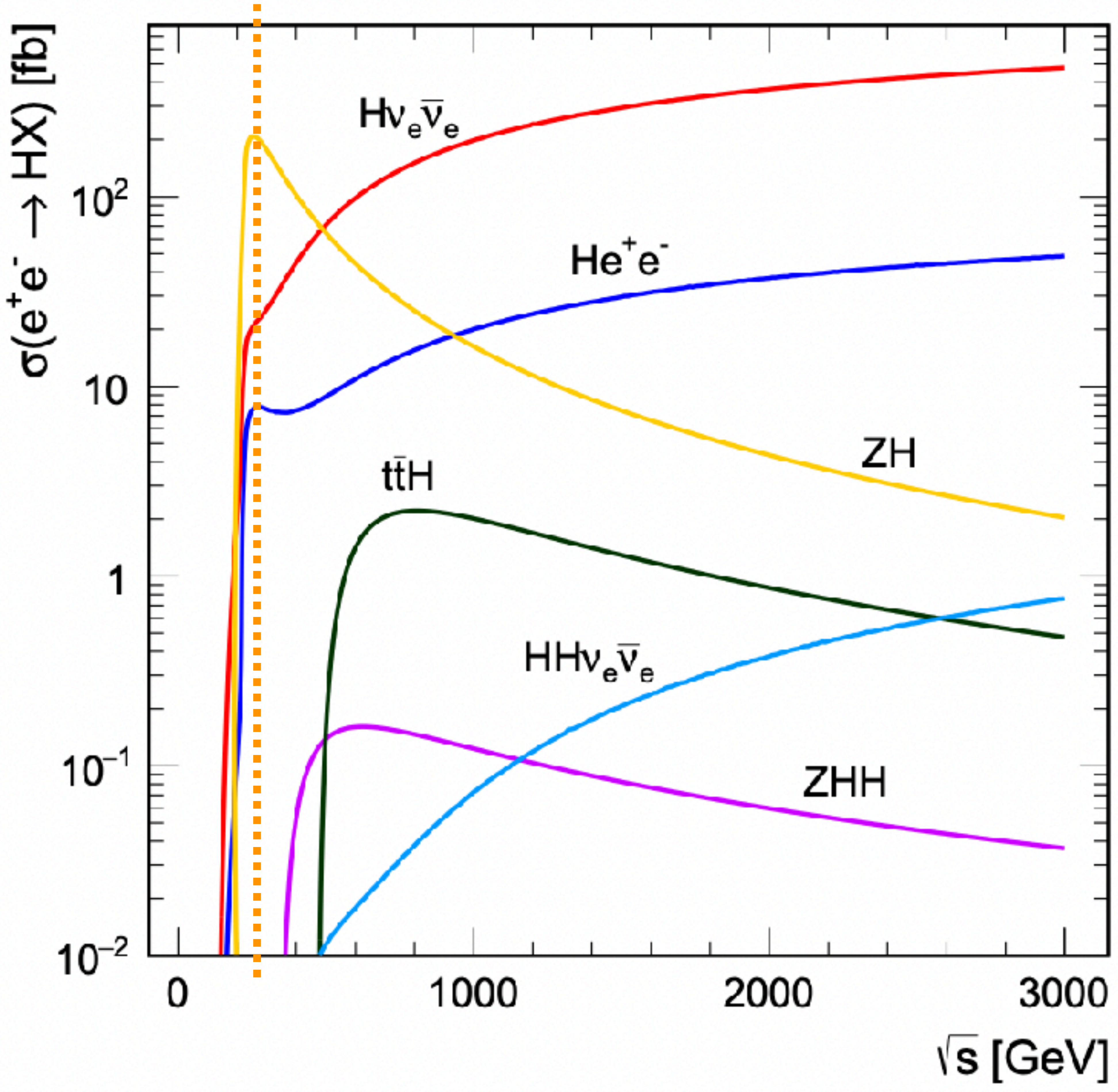


CMS, *Nature* '22

Cesarotti

Higgs Production

250 GeV

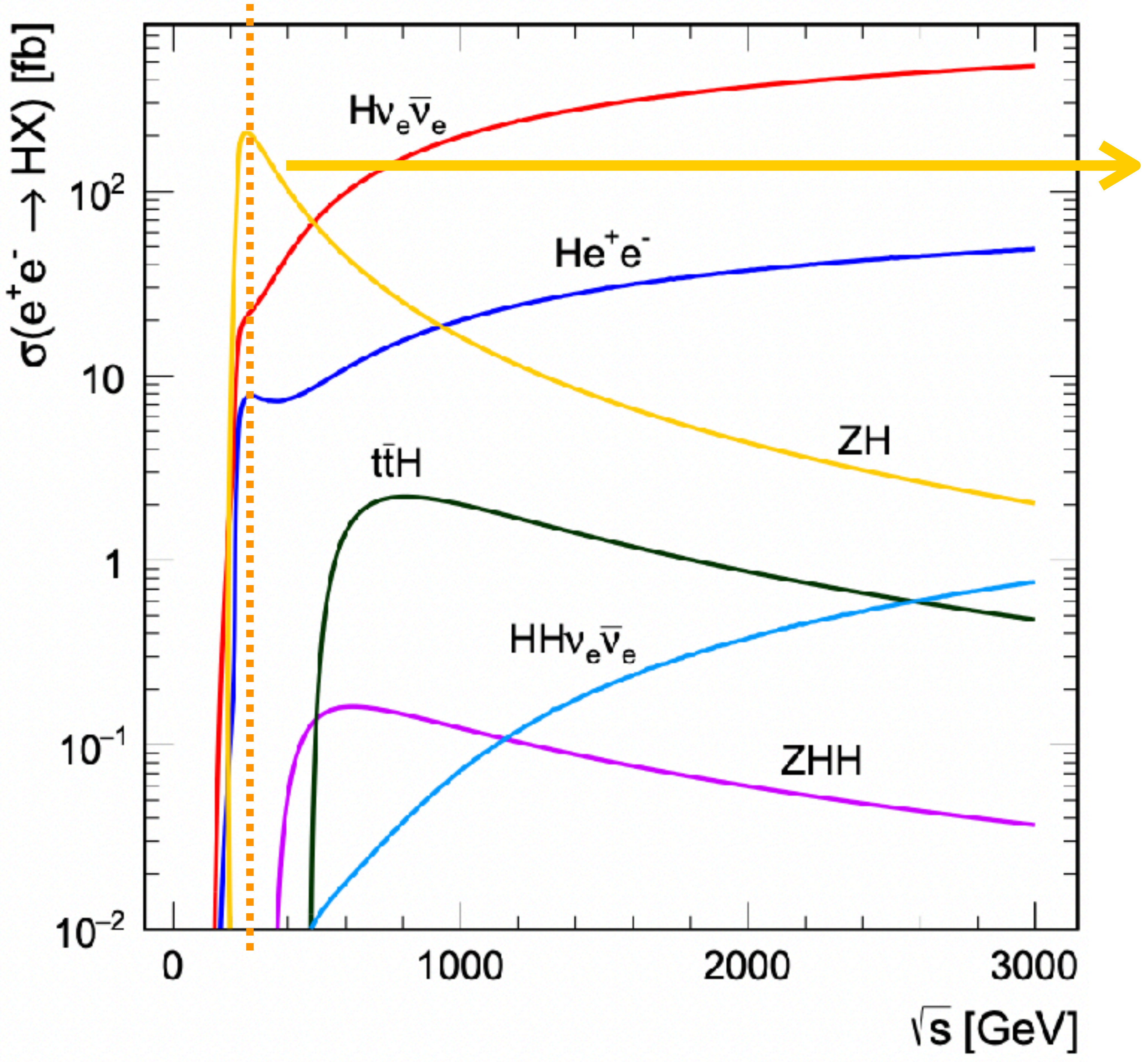


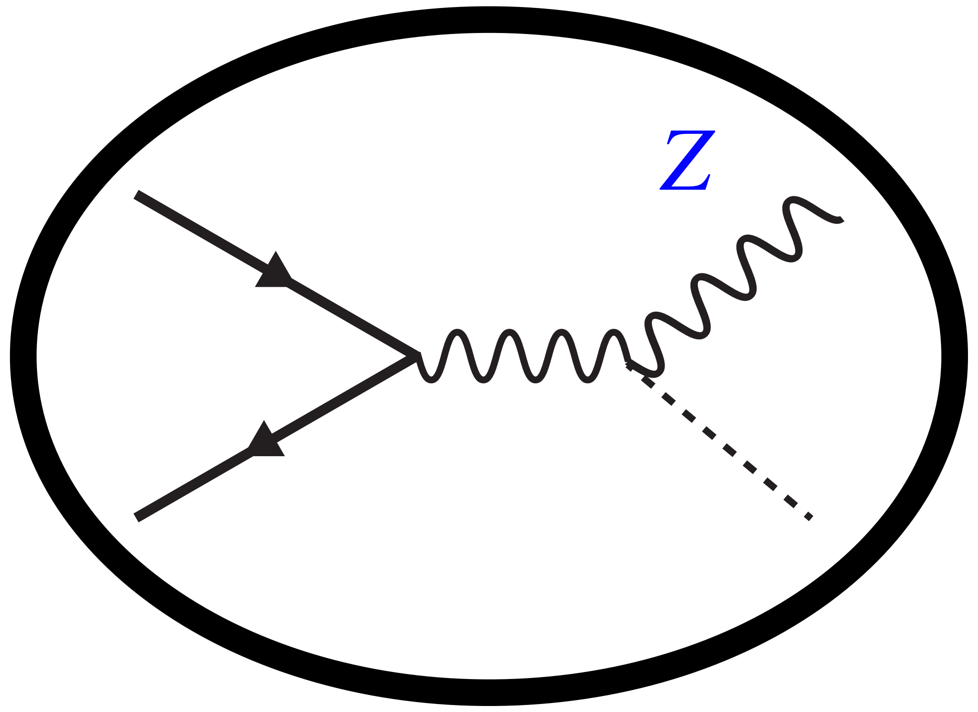
$\mathscr{L} \sim 1\ \mathrm{ab}^{-1}$

Number of Higgs is smaller, but *background* is cleaner

Higgs Production

250 GeV





$\mathscr{L} \sim 1\ \text{ab}^{-1}$

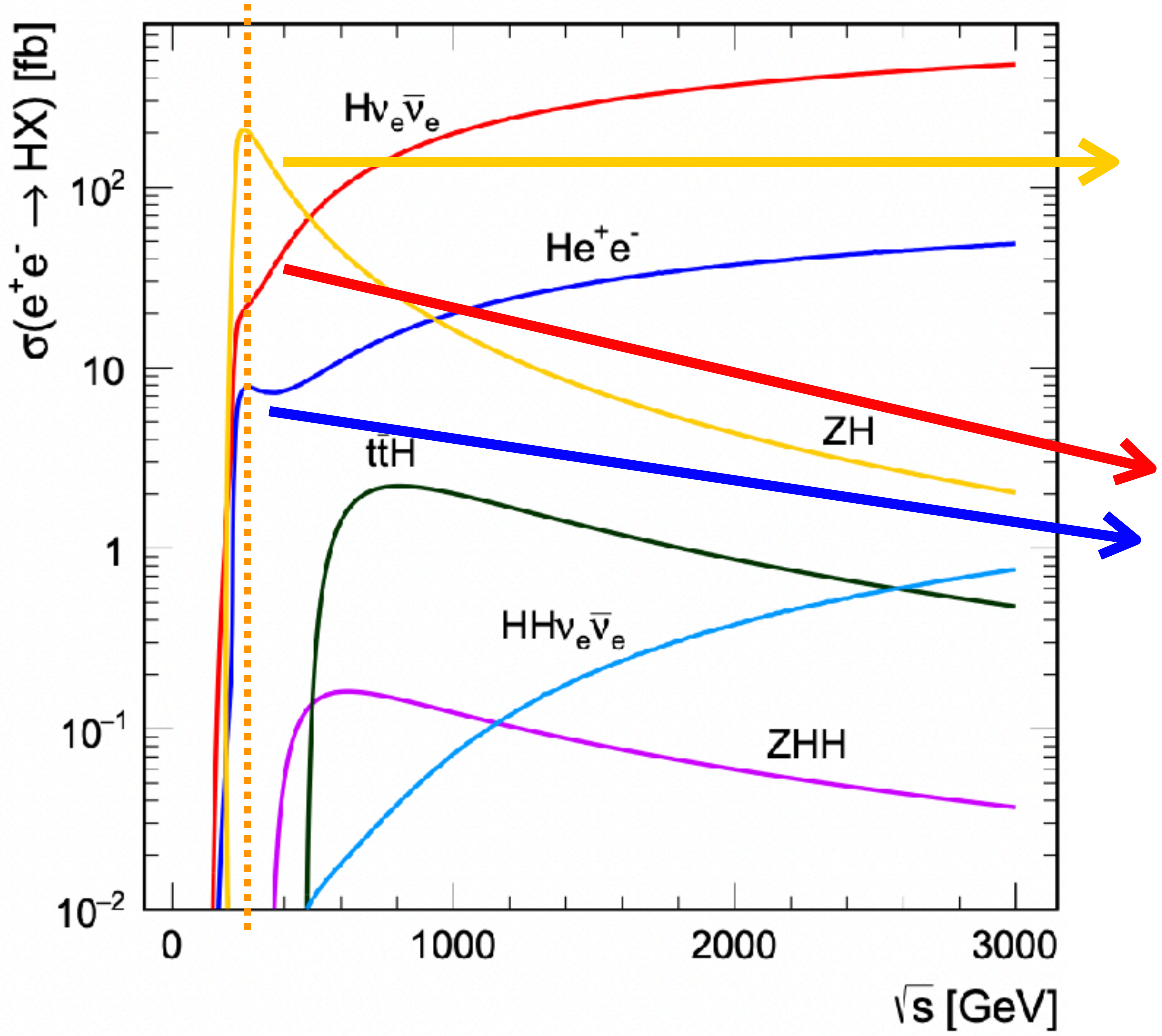
$e^+e^- \to ZH$

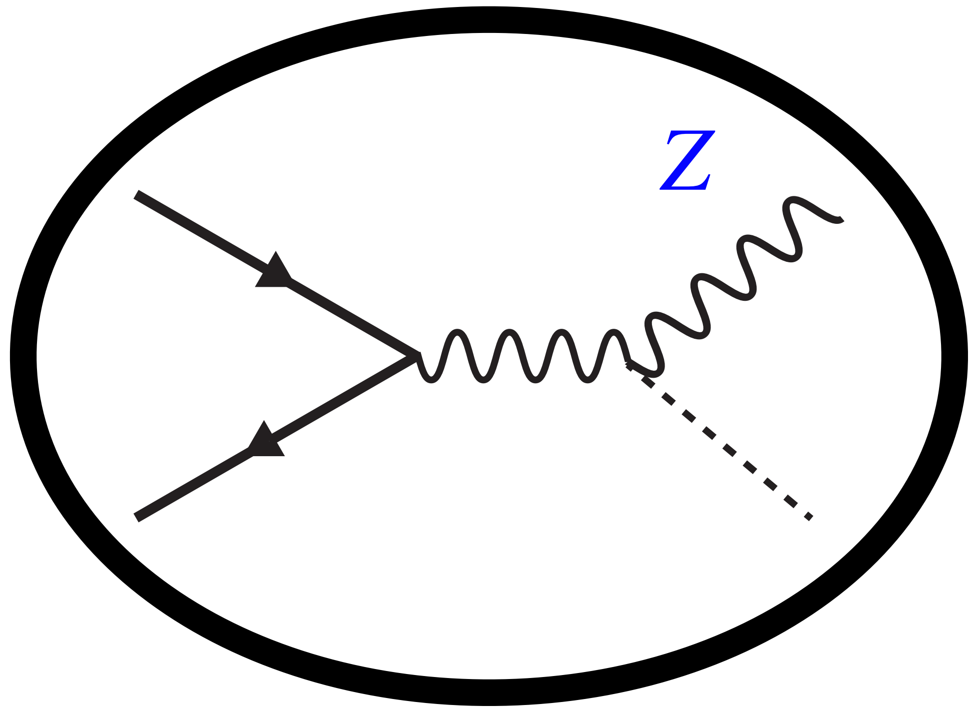
$\mathcal{O}(10^6)$ Higgs

Number of Higgs is smaller, but *background* is cleaner

Higgs Production

250 GeV

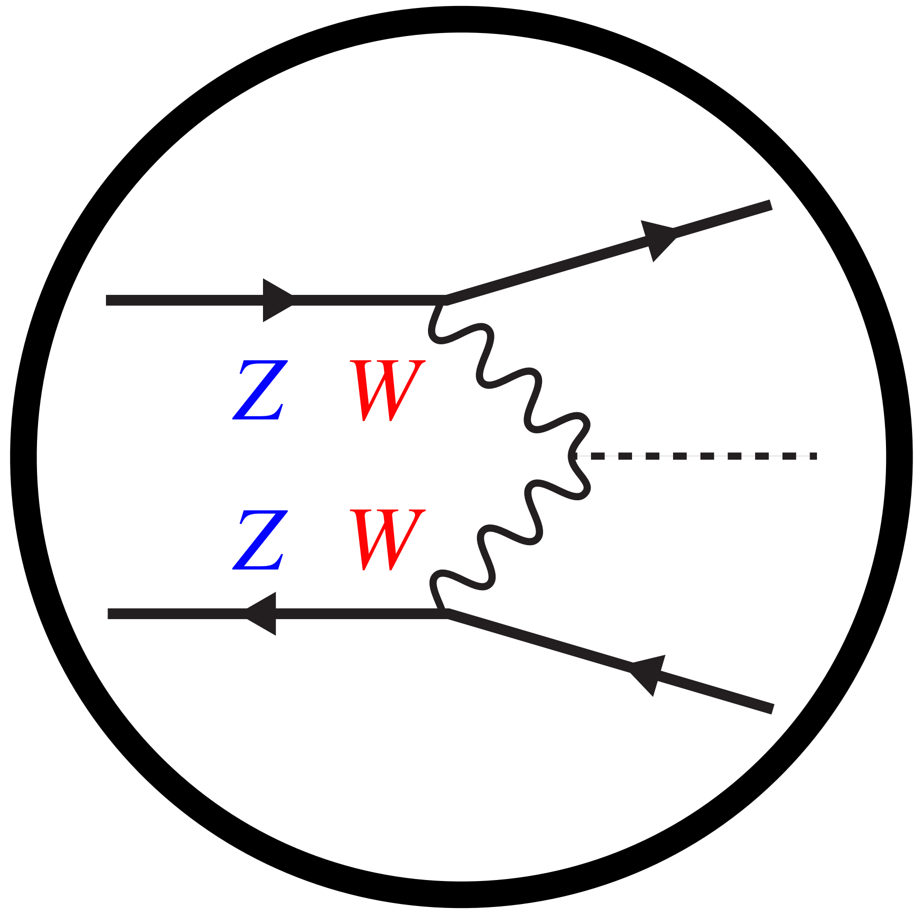




$\mathscr{L} \sim 1\ \text{ab}^{-1}$

$e^+e^- \to ZH$

$\mathcal{O}(10^6)$ Higgs



$e^+e^- \to H\nu_e\bar{\nu}_e$

$e^+e^- \to He^+e^-$

$\mathcal{O}(10^4 - 10^5)$ Higgs

Number of Higgs is smaller, but *background* is cleaner

Higgs Production

Higgs couplings can be studied in a novel way compared to the (HL)-LHC

$$\left.\begin{array}{l}\text{LHC: } \Gamma_h = 3.2^{+2.4}_{-1.7}\ \text{MeV} \\ \text{HL-LHC: } \Gamma_h = 4.1^{+0.7}_{-0.8}\ \text{MeV}\end{array}\right\}\quad h \to ZZ* \to 4l$$

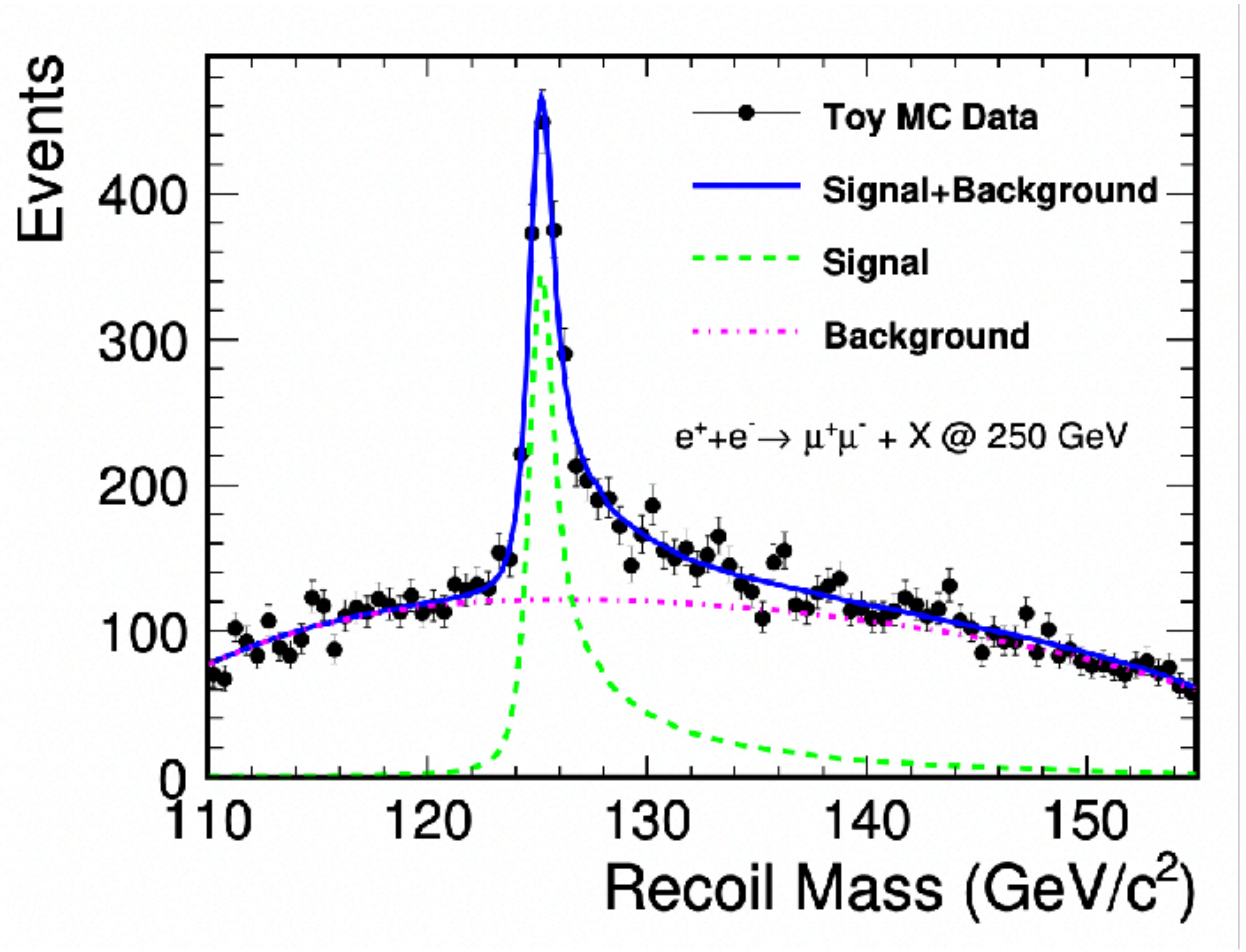
Higgs Production

Higgs couplings can be studied in a novel way compared to the (HL)-LHC

LHC: $\Gamma_h = 3.2^{+2.4}_{-1.7}$ MeV

HL-LHC: $\Gamma_h = 4.1^{+0.7}_{-0.8}$ MeV

$\Big\}$ $h \to ZZ^* \to 4l$



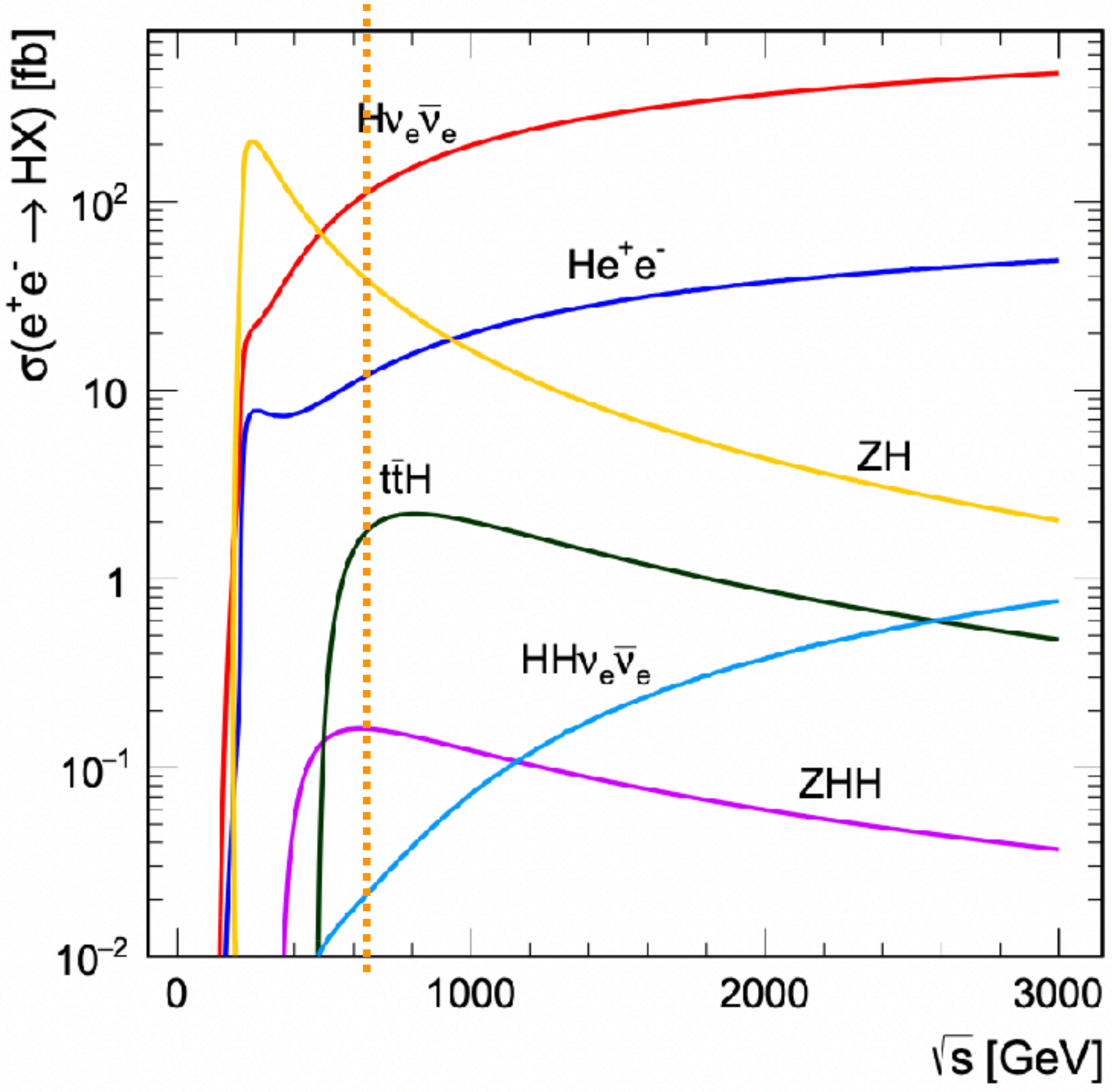
e^+e^- collisions are *clean*

$\delta\Gamma_h/\Gamma_h \sim 2\,\%$

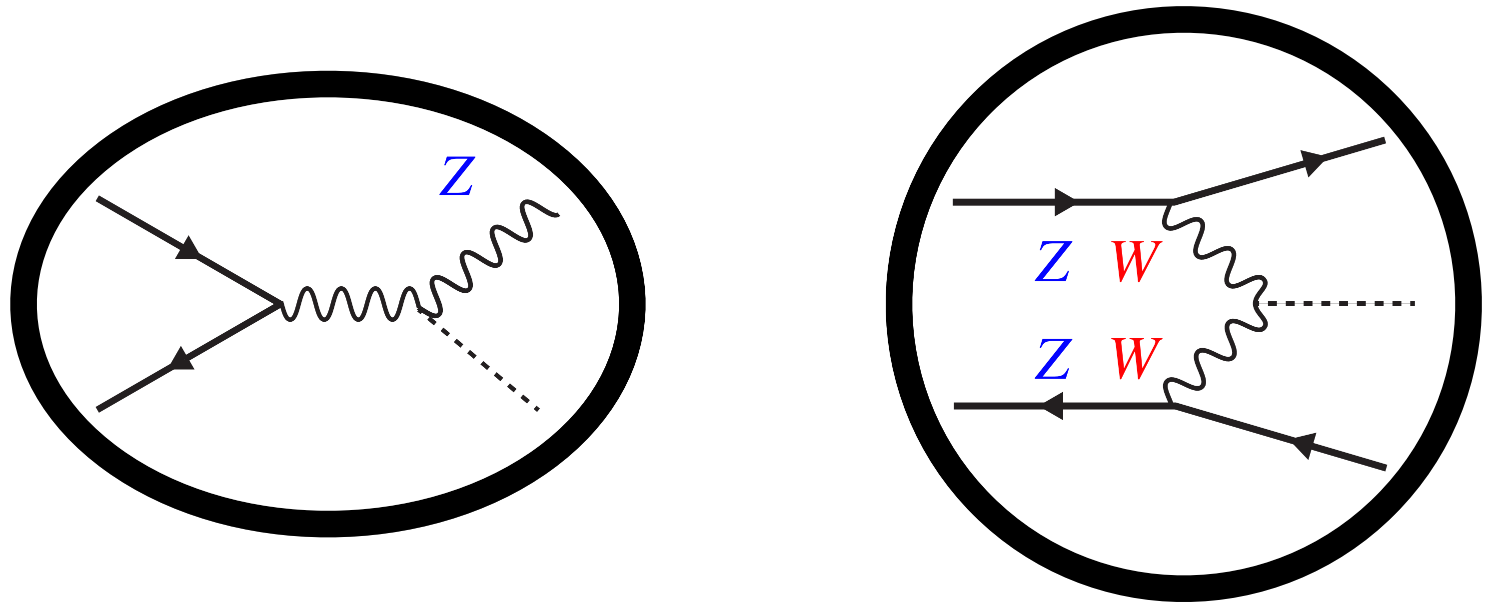
Direct measurements rather than ratios

Higgs Production

550 GeV

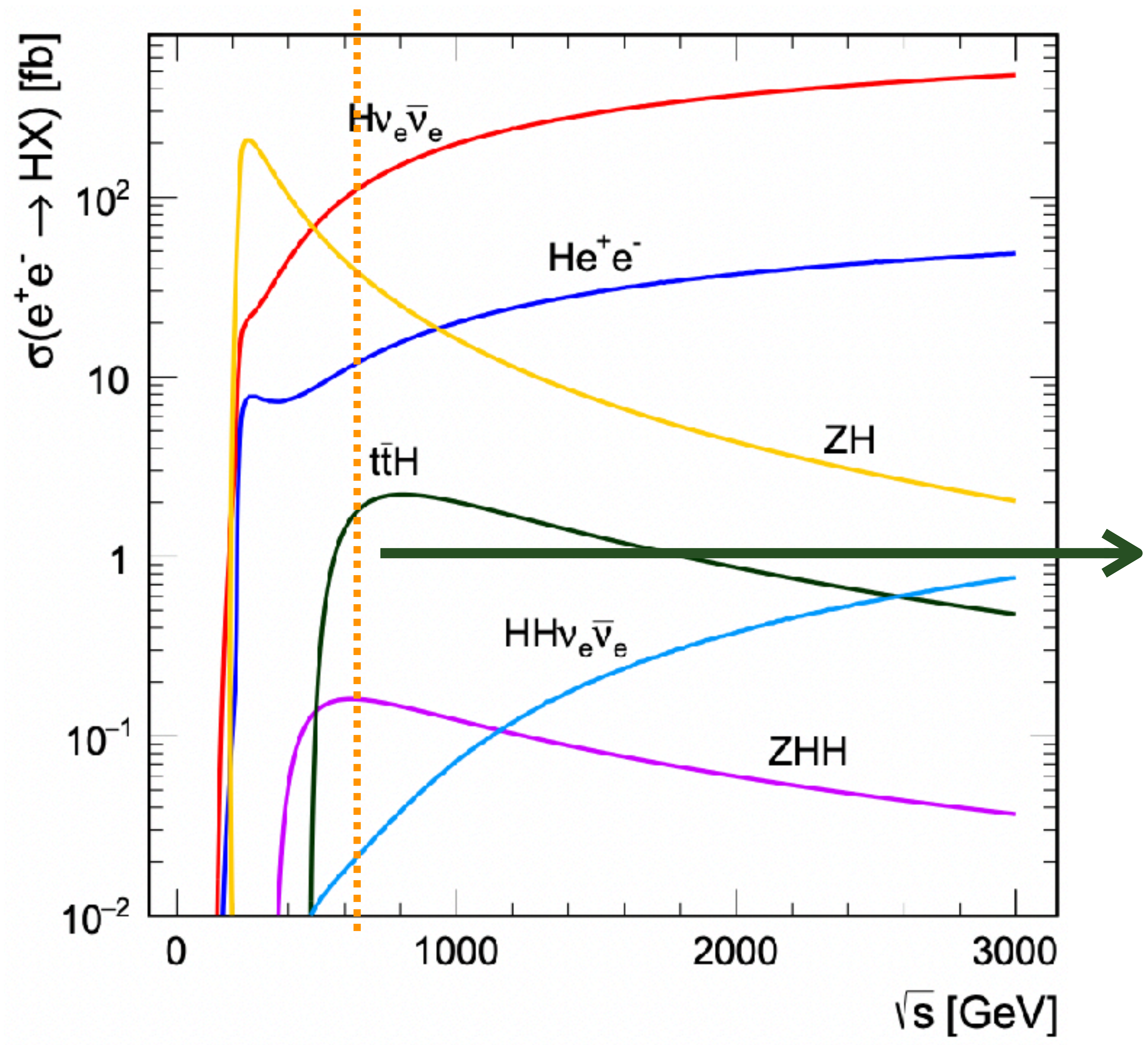


$\mathscr{L} \sim 1\ \mathrm{ab}^{-1}$

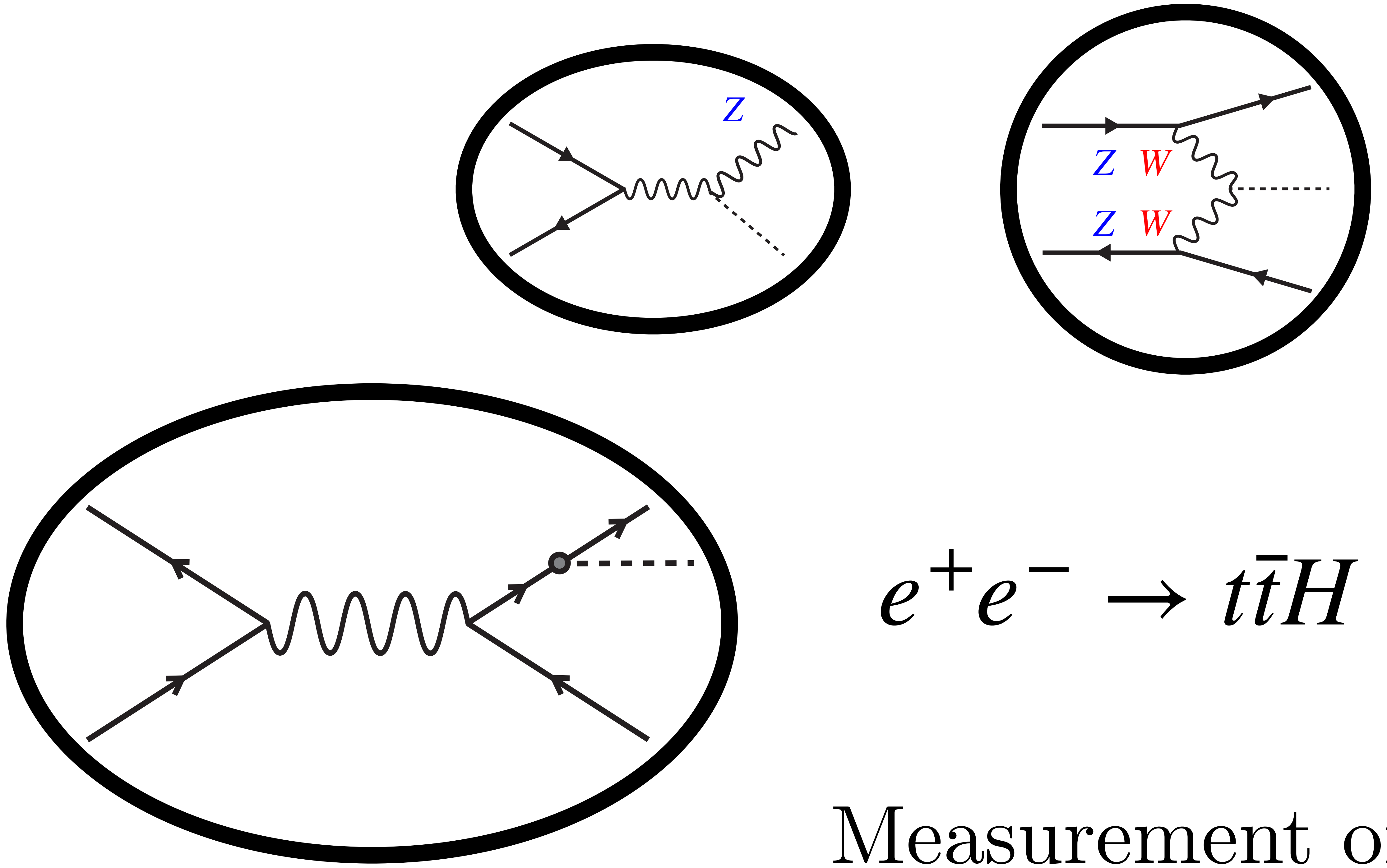


Higgs Production

550 GeV



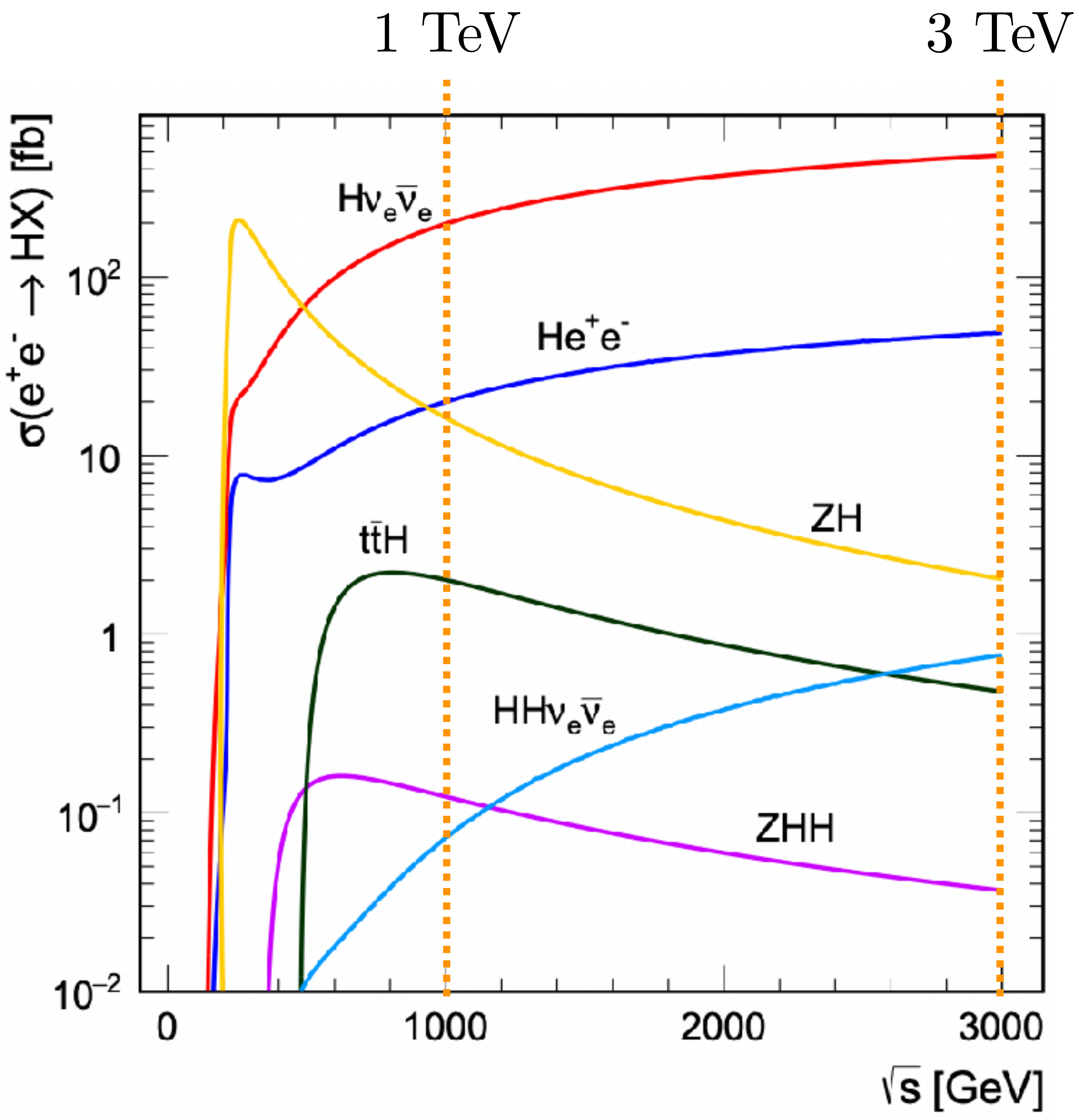
$\mathscr{L} \sim 1\ \mathrm{ab}^{-1}$



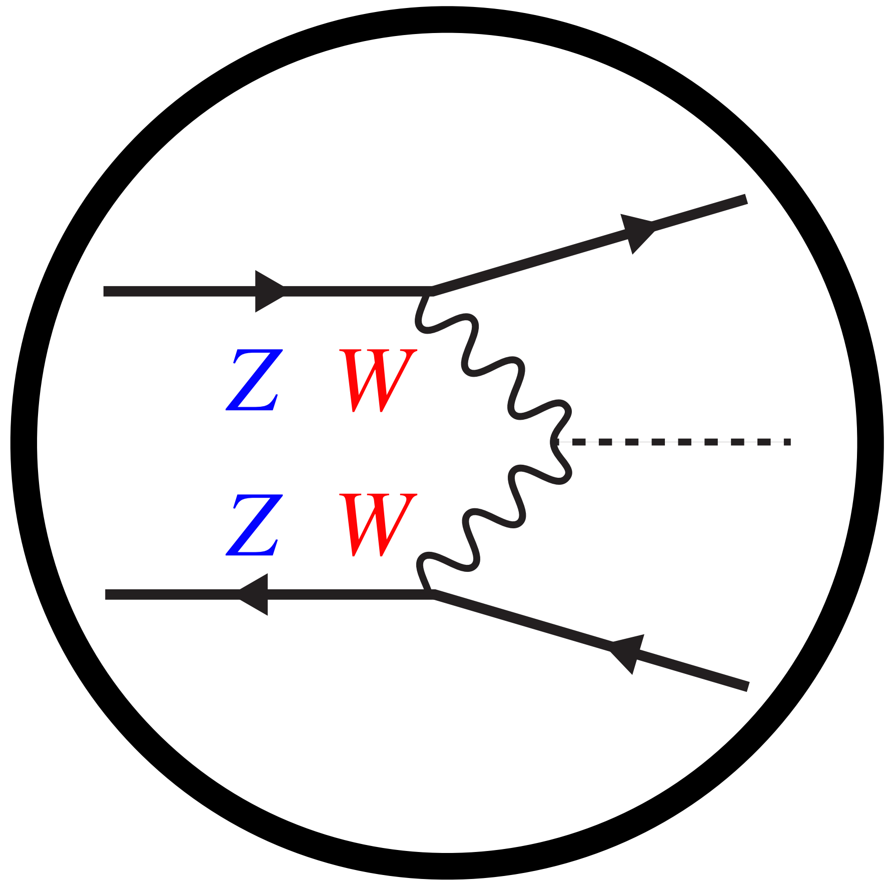
$e^+e^- \to t\bar{t}H$

Measurement of top Yukawa

Higgs Production



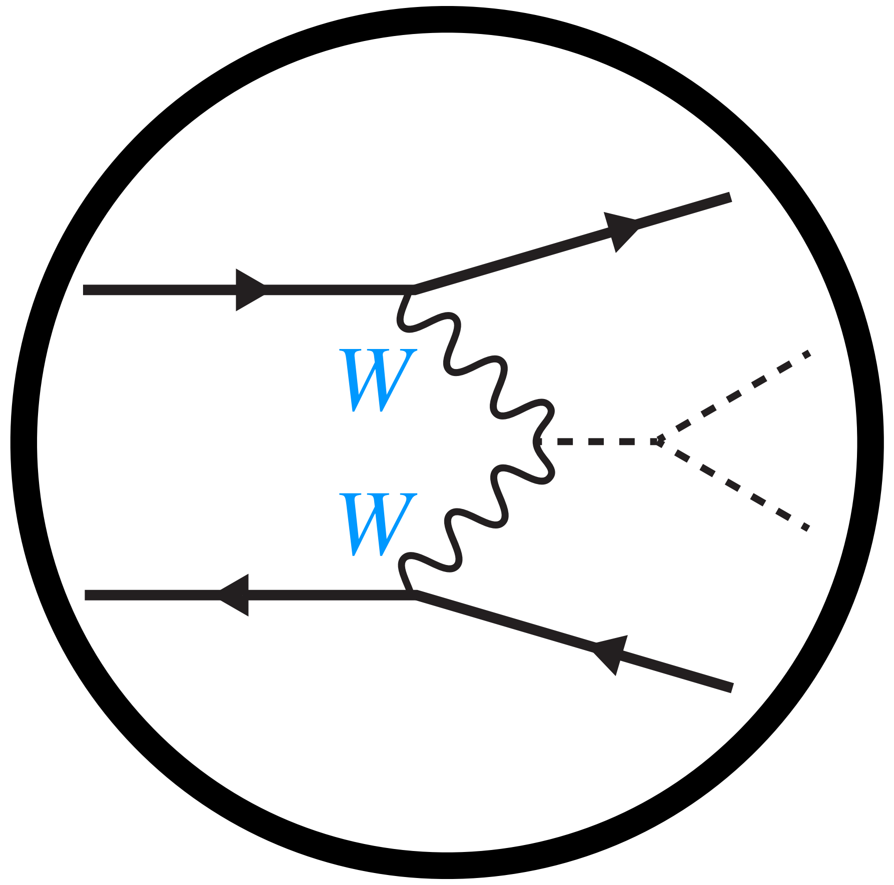
$\mathscr{L} \sim 2 - 5\ \text{ab}^{-1}$



$e^+e^- \to H\nu_e\bar{\nu}_e$

$e^+e^- \to He^+e^-$

$\mathcal{O}(10^{6+})$ VBF Higgs



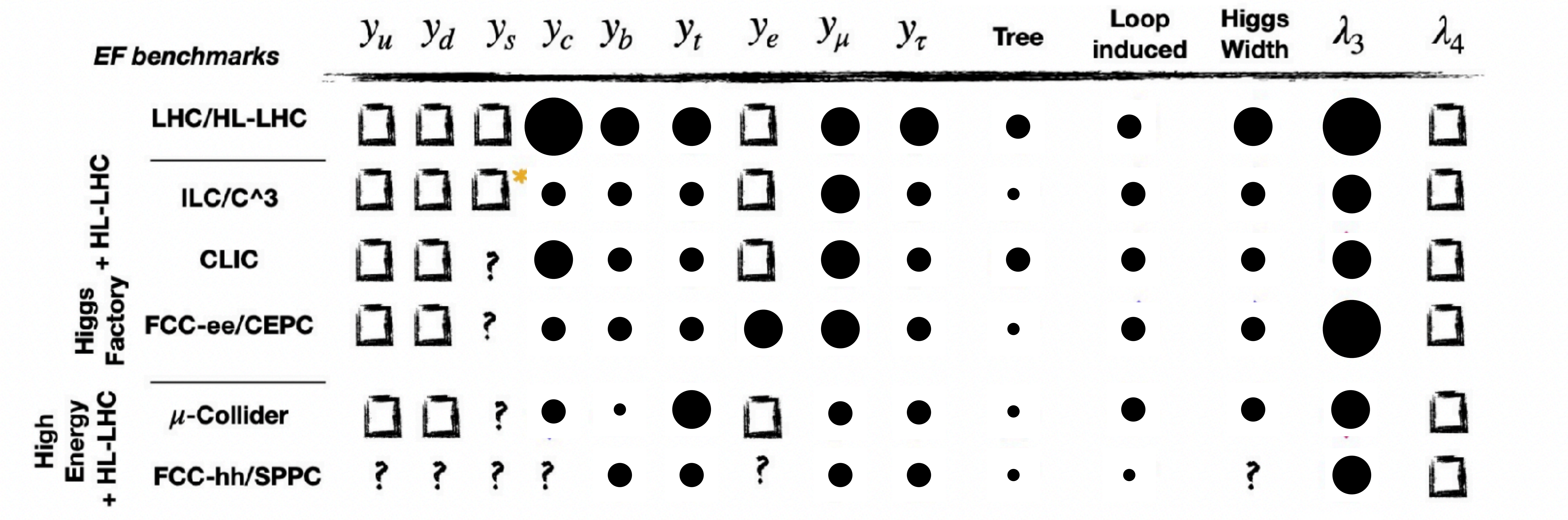
$e^+e^- \to HH\nu_e\bar{\nu}_e$

Higgs self-couplings

Overview of Uncertainties

Energy Frontier Benchmarks Integrated Staging

Gauge Couplings

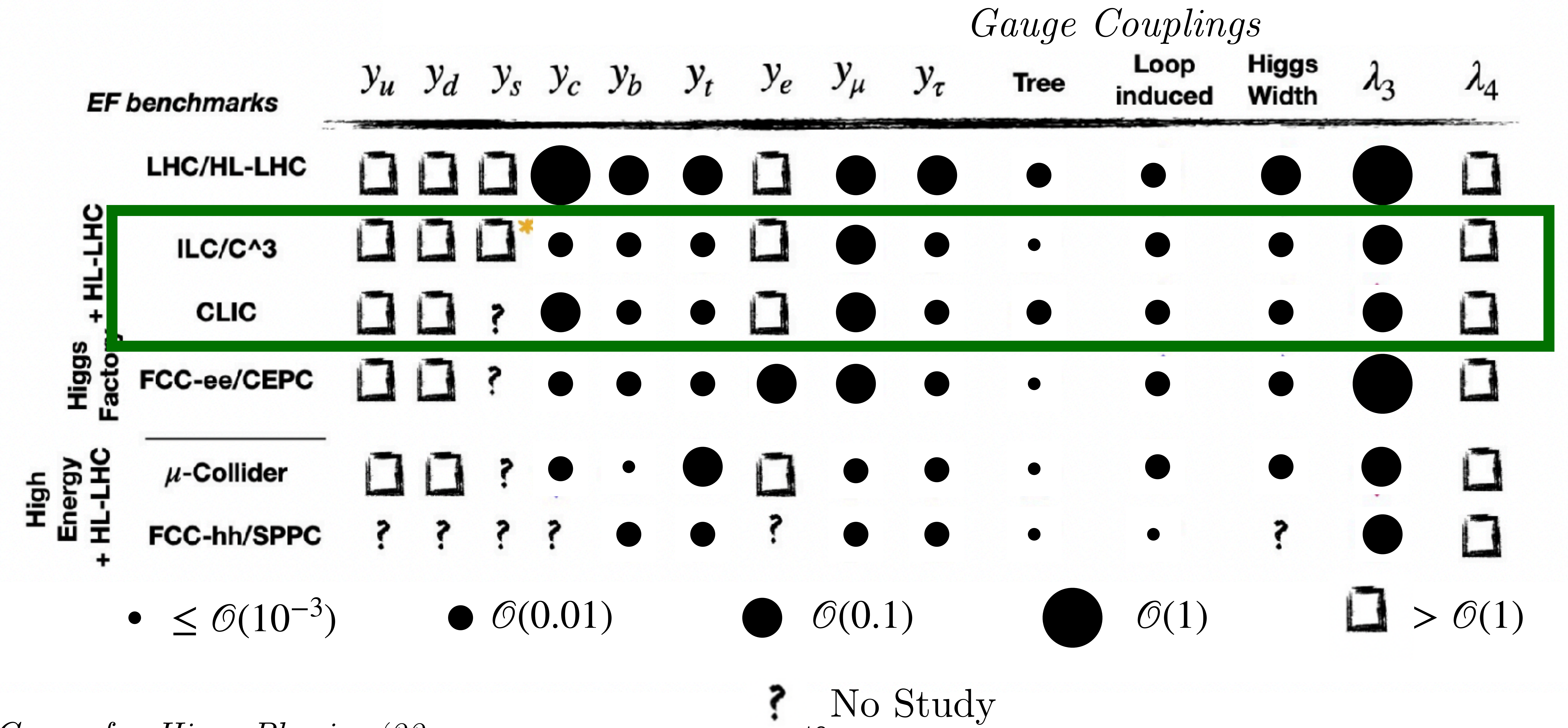


• $\leq \mathcal{O}(10^{-3})$ ● $\mathcal{O}(0.01)$ ● $\mathcal{O}(0.1)$ ● $\mathcal{O}(1)$ □ $> \mathcal{O}(1)$

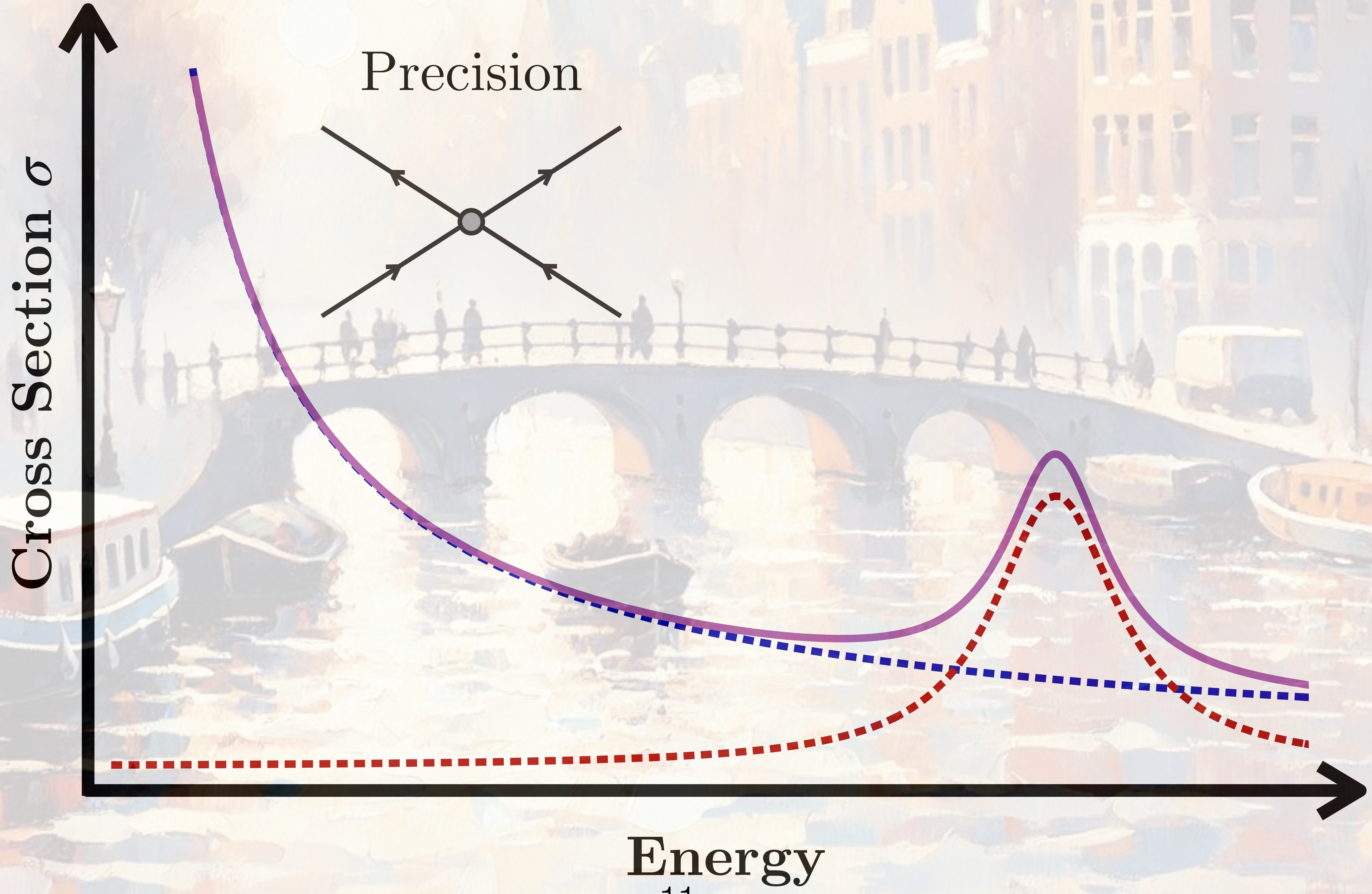
? No Study

Overview of Uncertainties

Energy Frontier Benchmarks Integrated Staging

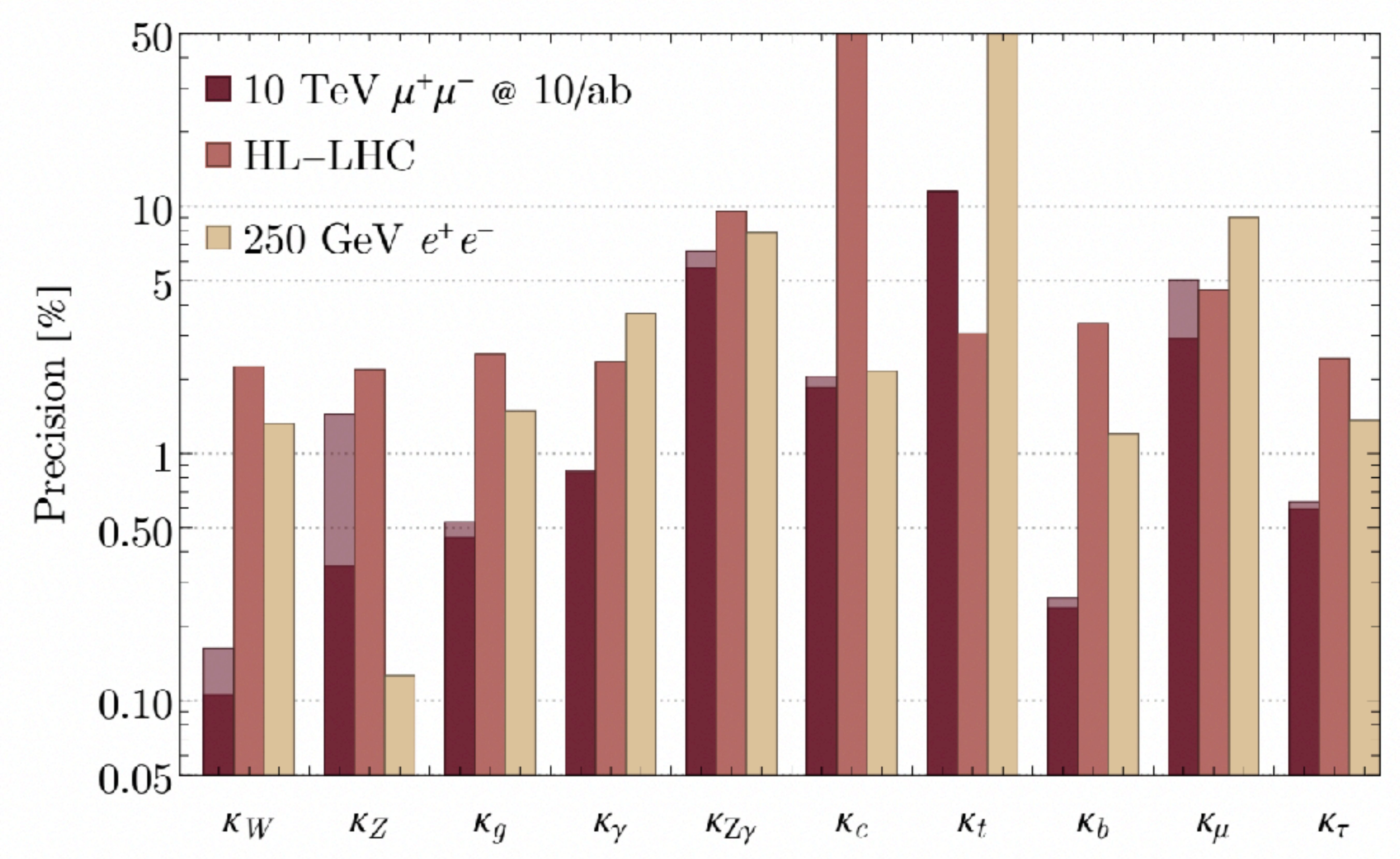


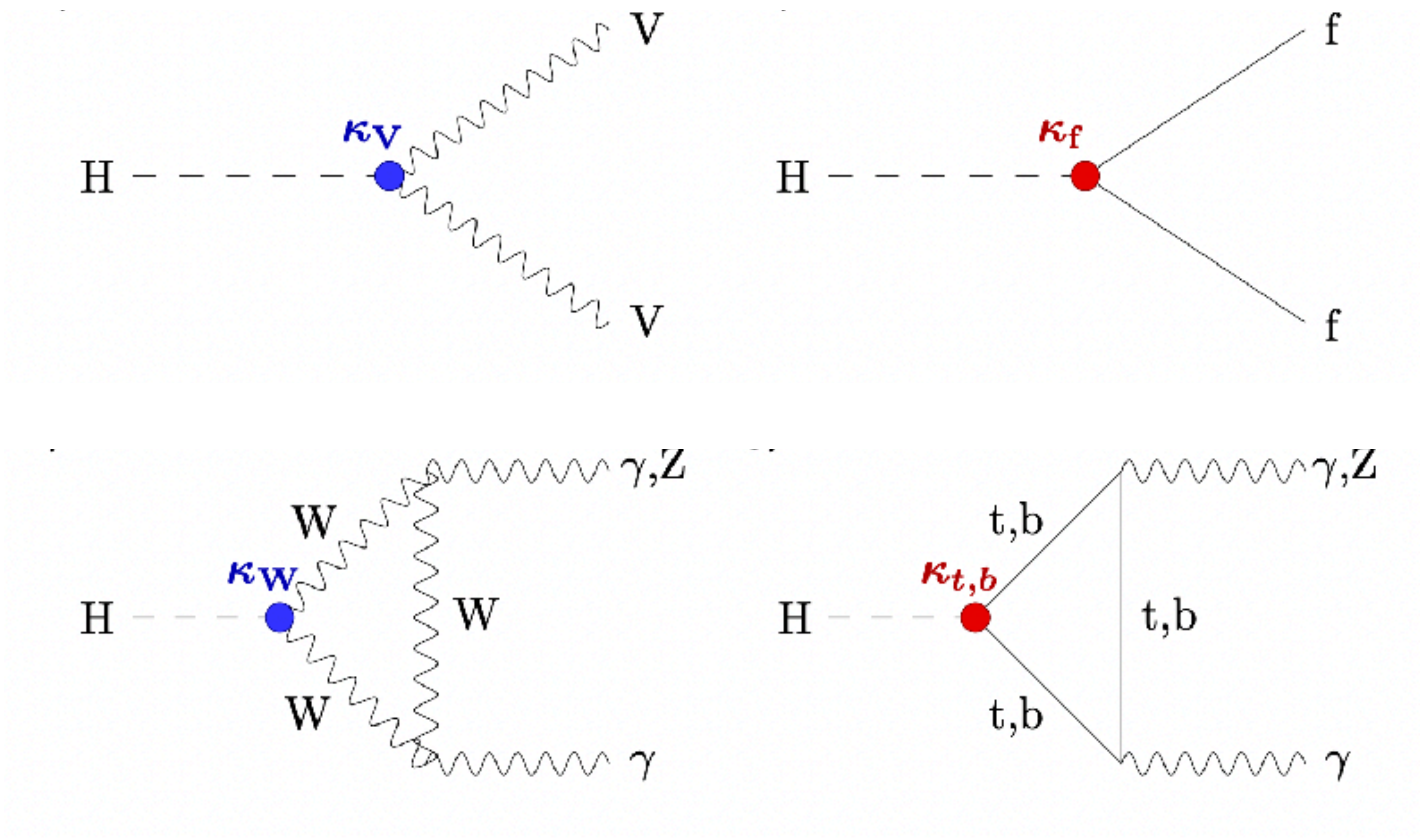
Low-Energy Deliverables



Cesarotti

Higgs Physics @ 250 GeV

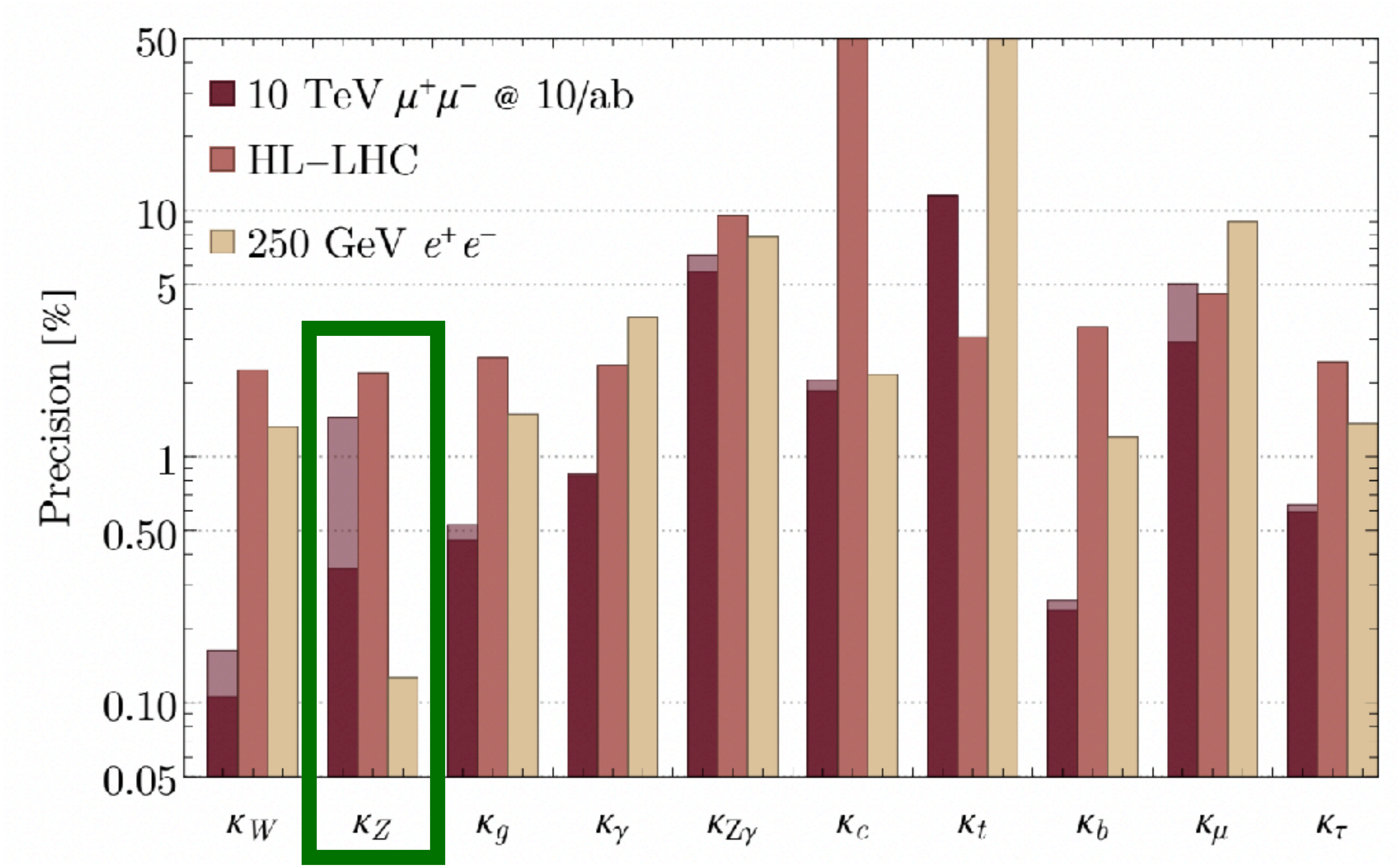


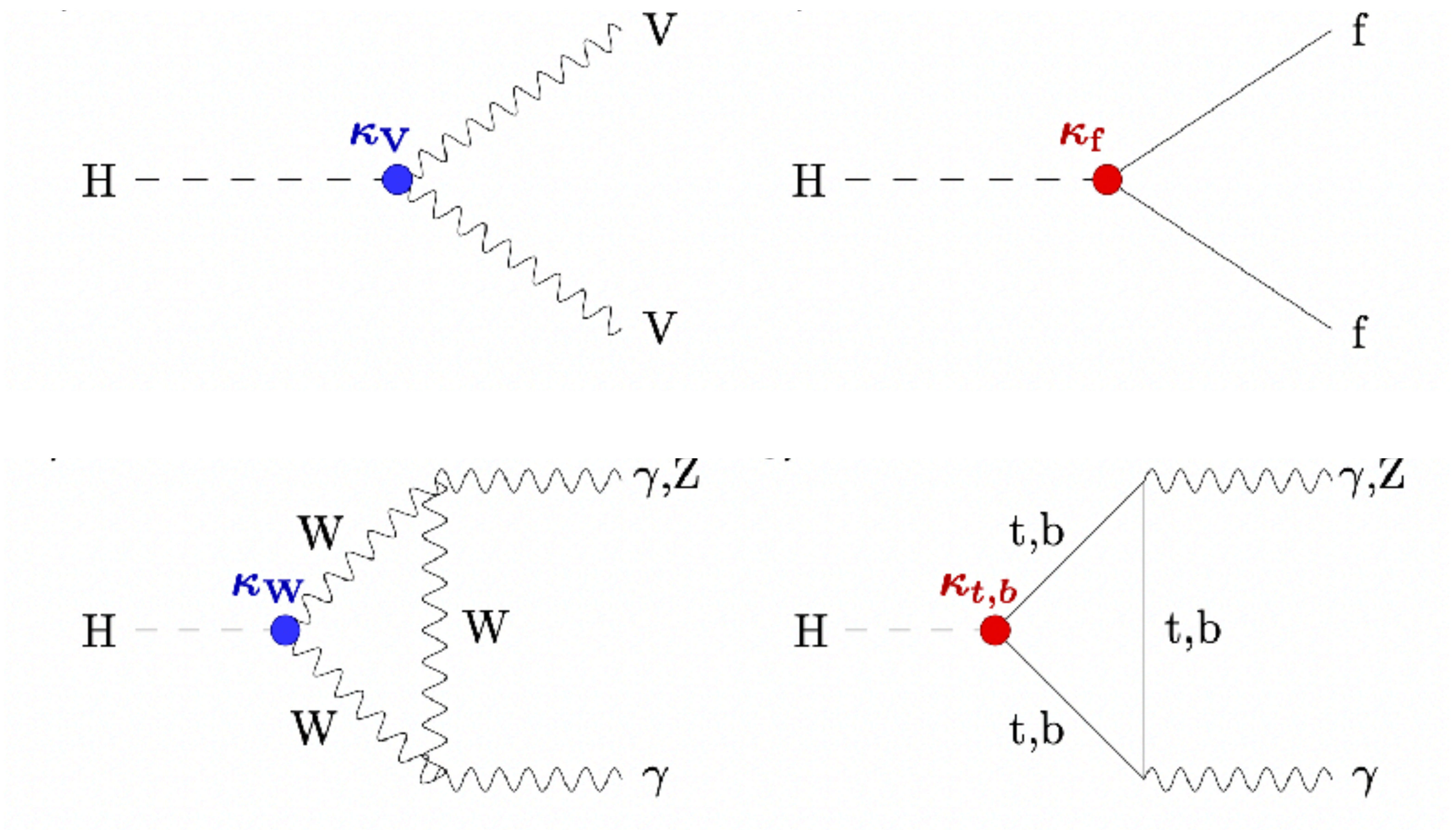


Reach of $\mathcal{O}(10^6)$ Higgs can be up to an order of magnitude more precise than HL-LHC

Forslund & Meade '23

Higgs Physics @ 250 GeV

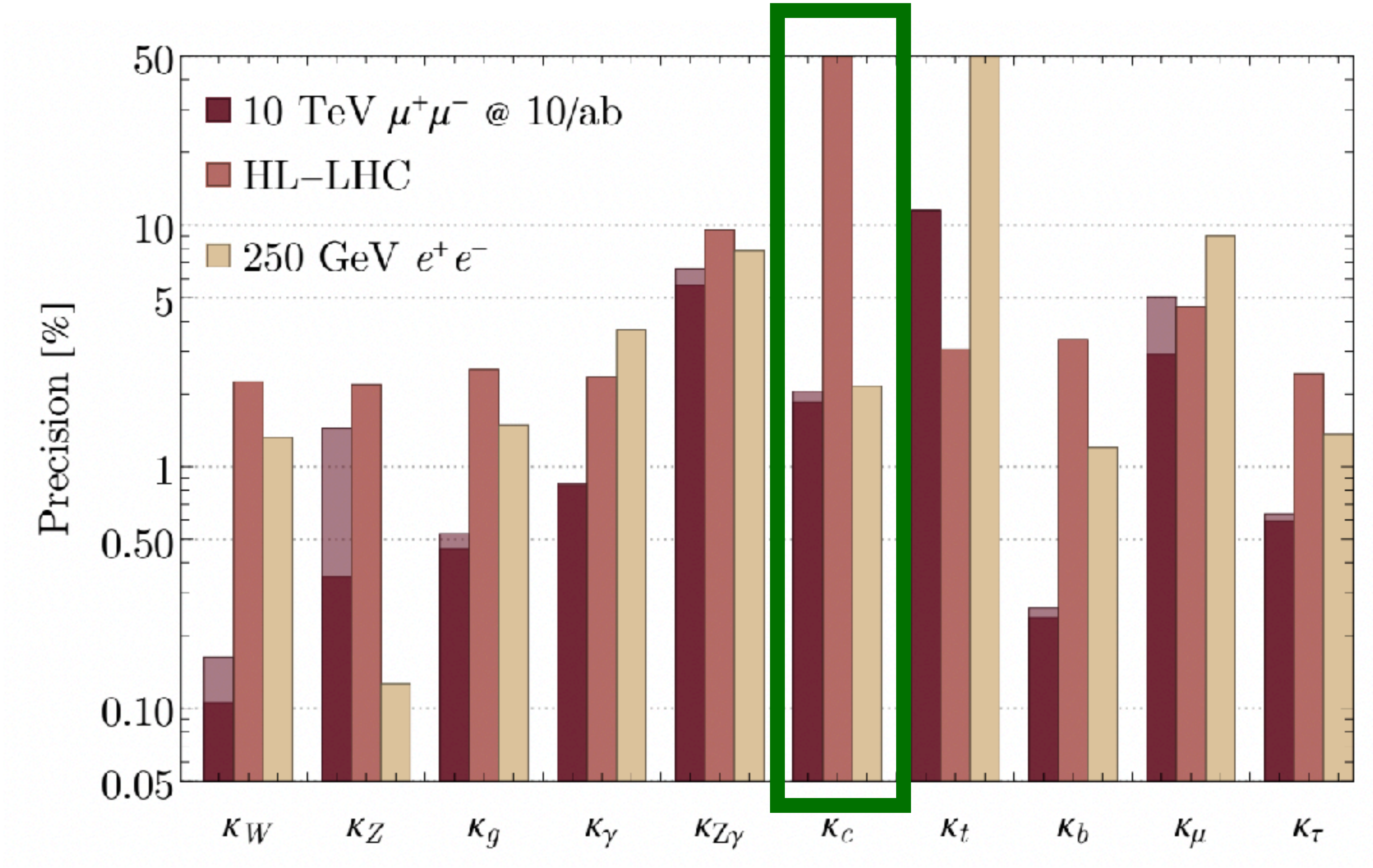




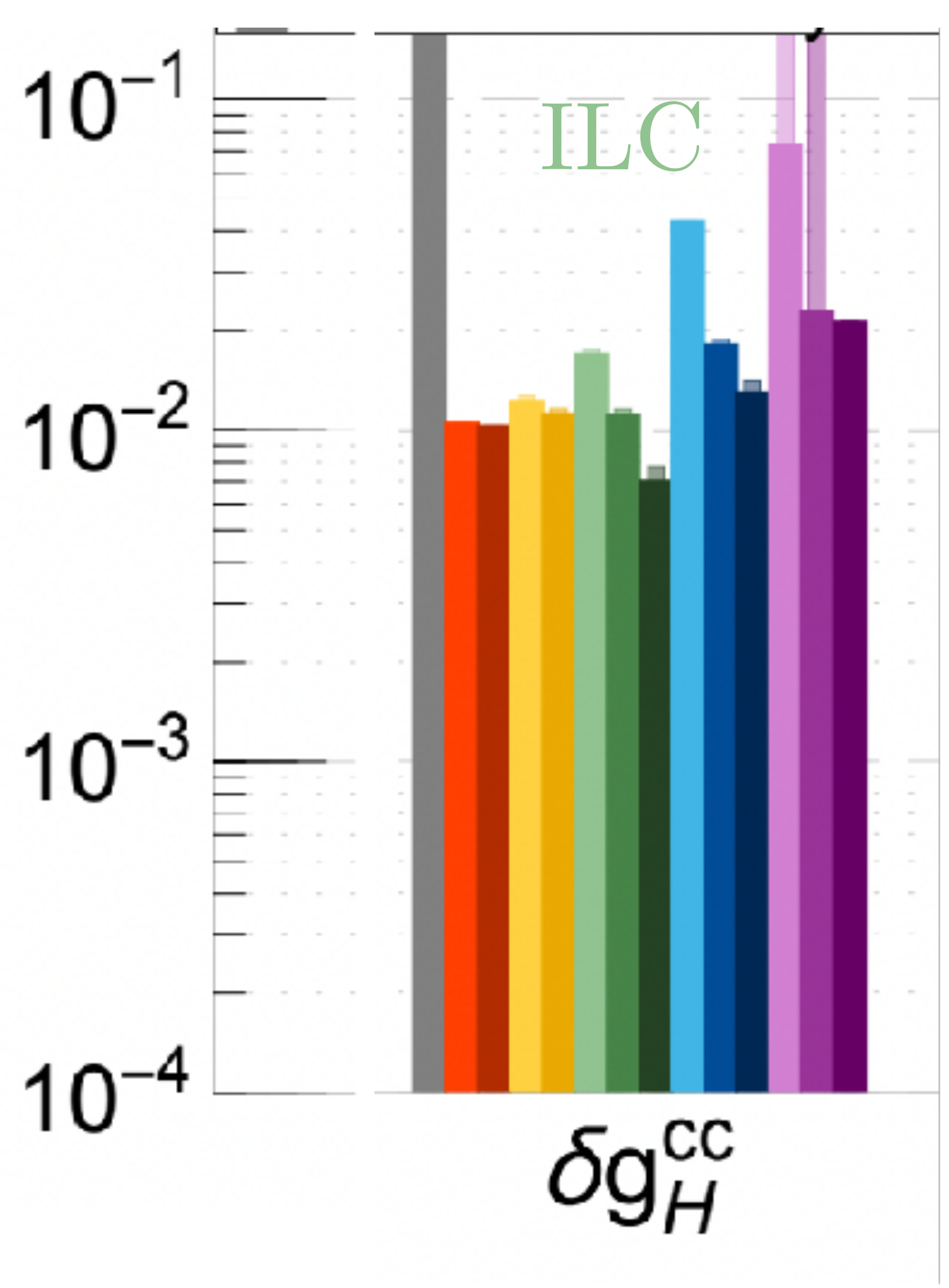
Difference in production mechanisms can improve sensitivity

Forslund & Meade '23

HIGGS PHYSICS @ 250 GEV



Forslund & Meade '23

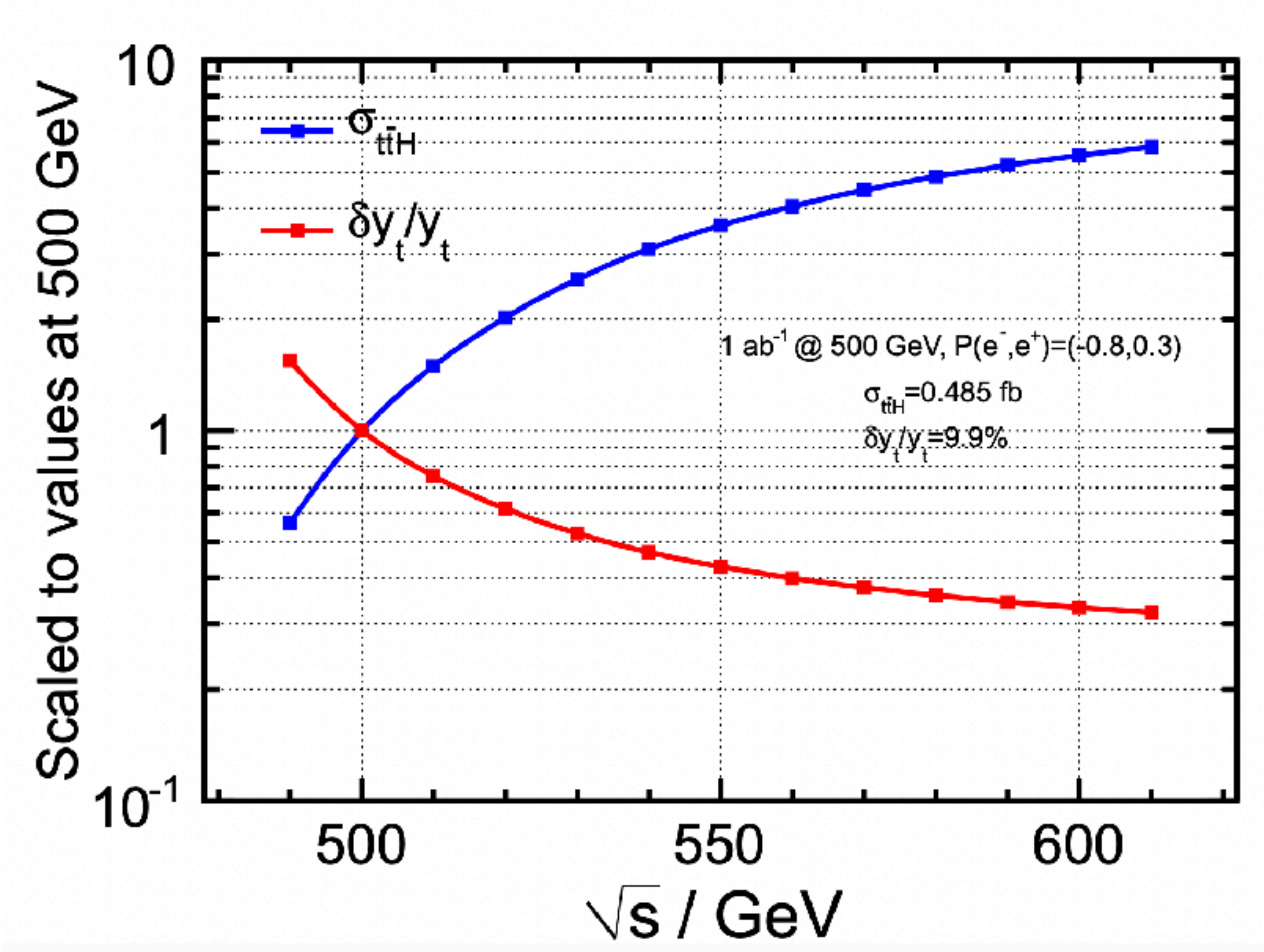


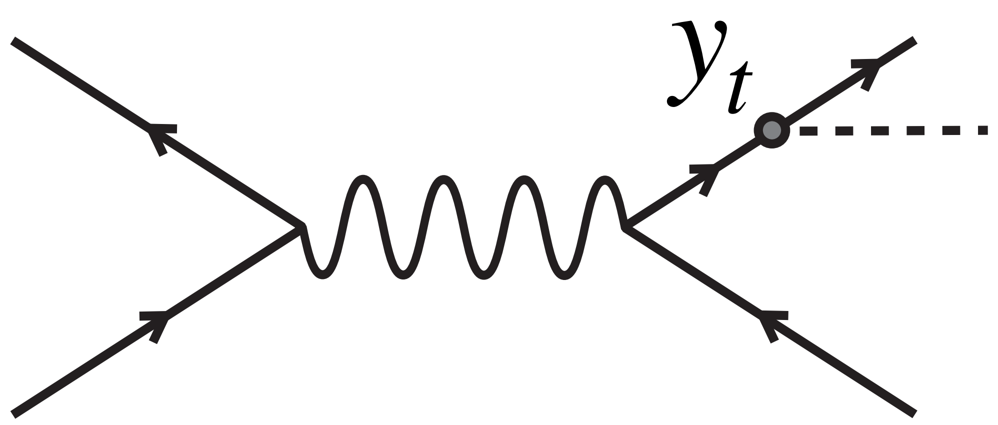
Better measurements on quark Yukawa

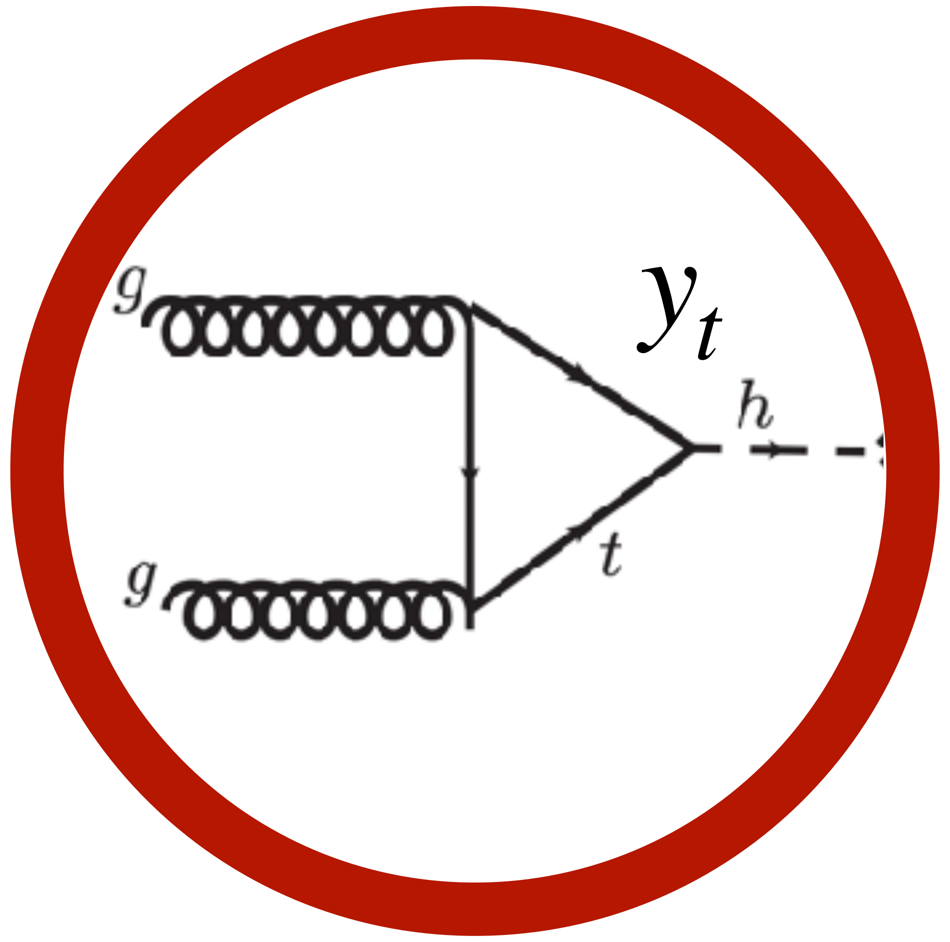
de Blas, Du, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou '22

Top Yukawa (550 GeV)

No mixing with *ggh* leads to cleaner measurement





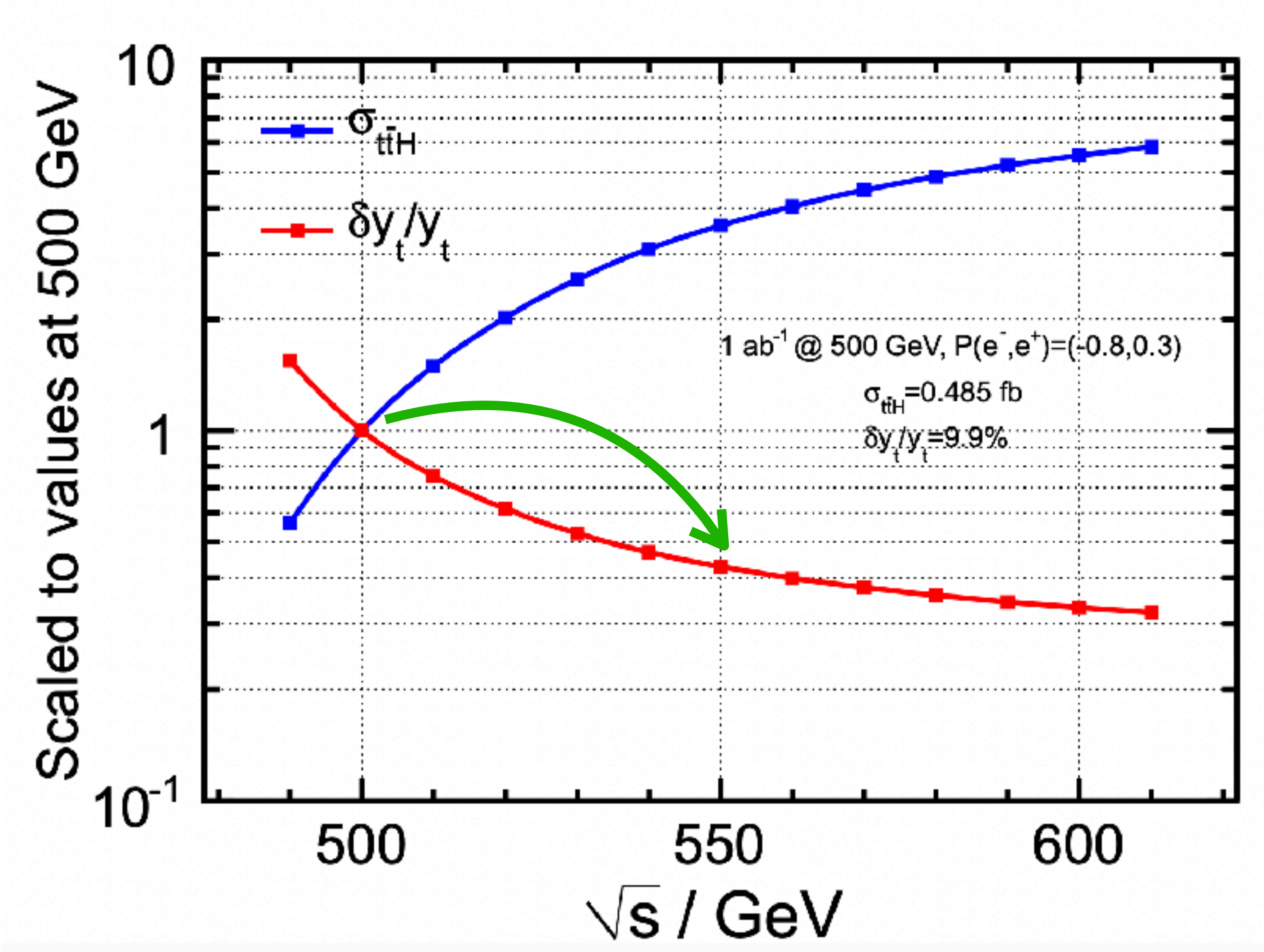


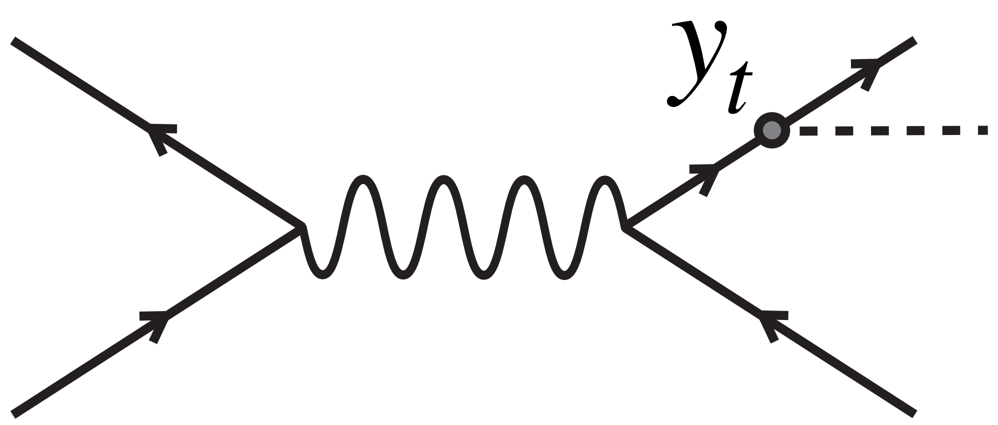
Impossible to reach with circular collider

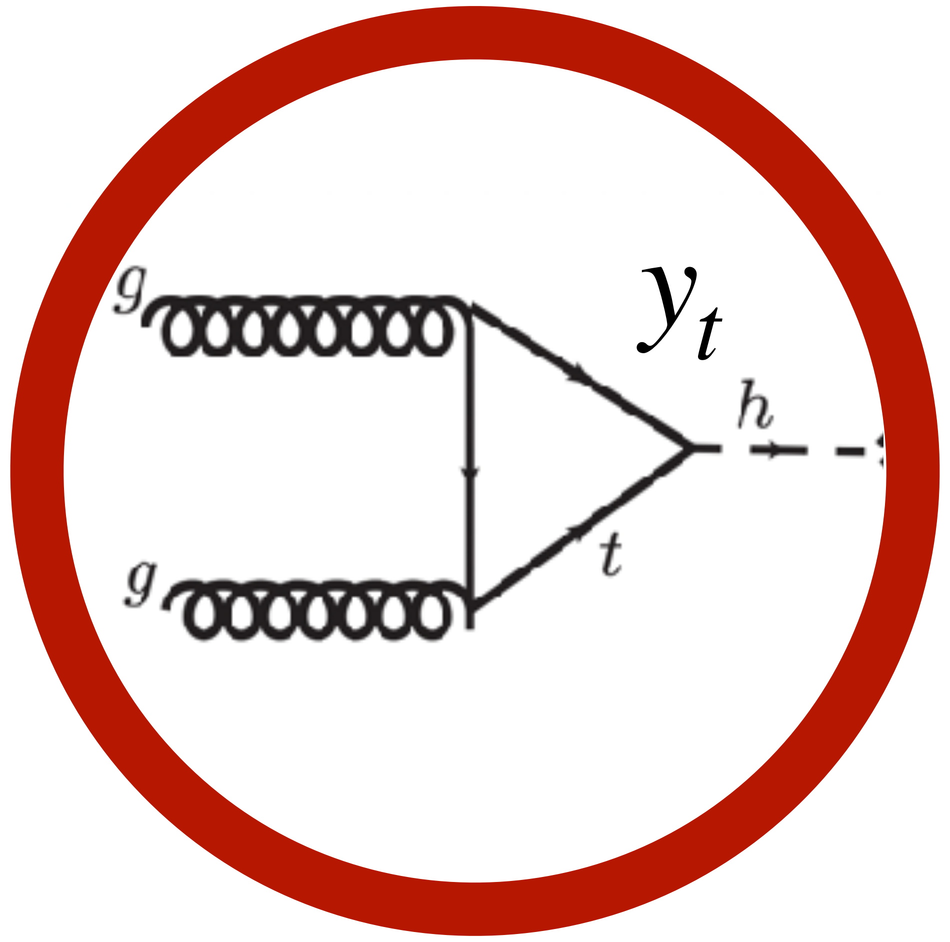
T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya '15

TOP YUKAWA (550 GEV)

No mixing with *ggh* leads to cleaner measurement





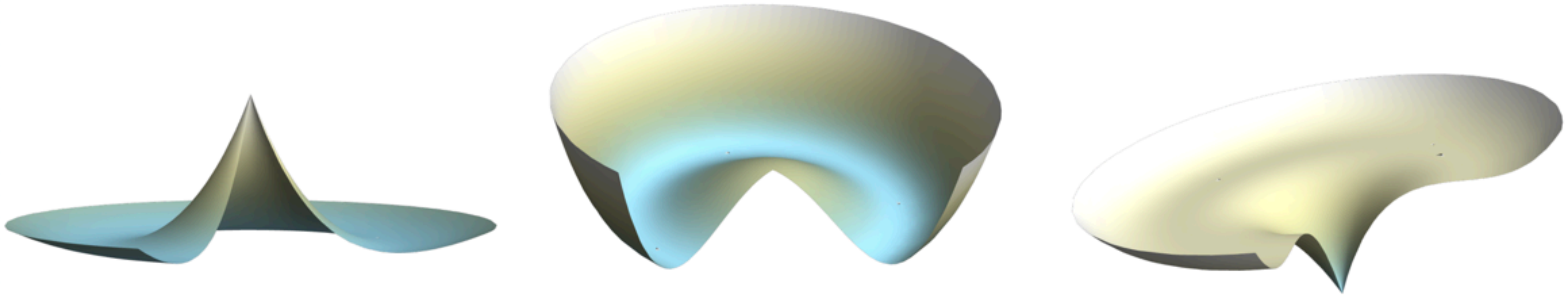


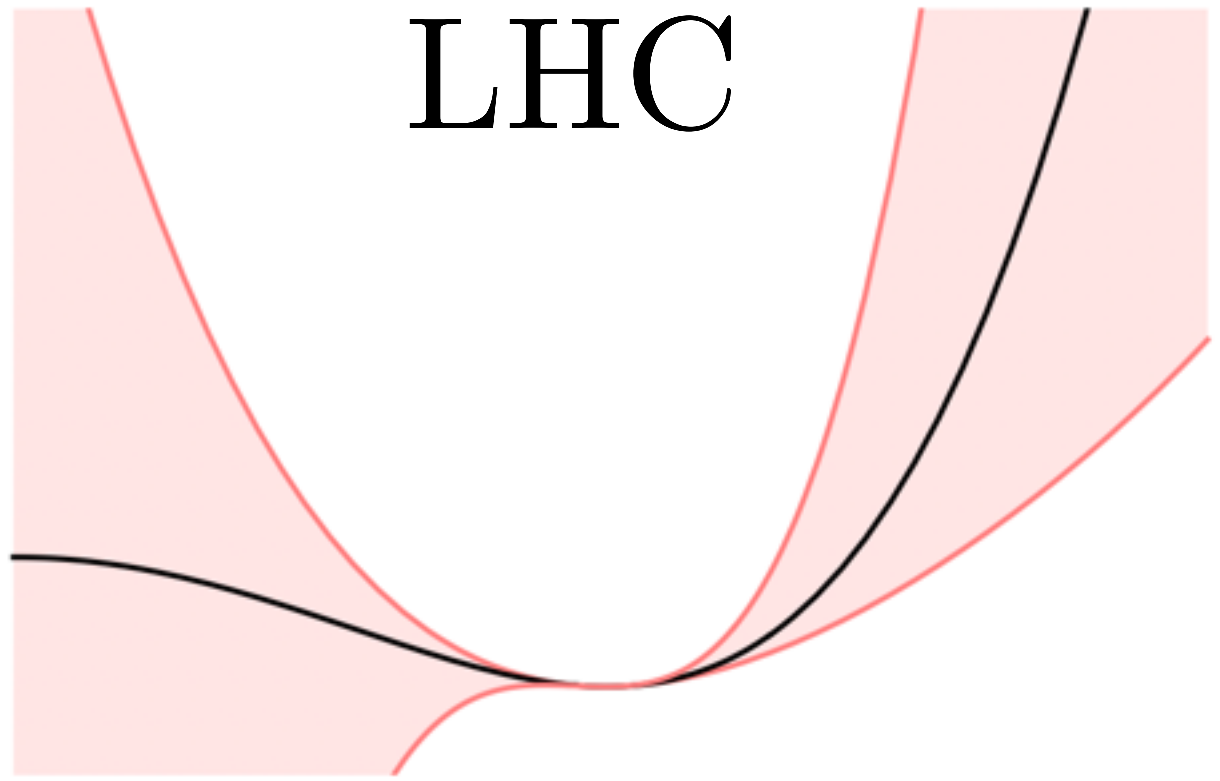
Impossible to reach with circular collider

x2 improvement with only +50 GeV!

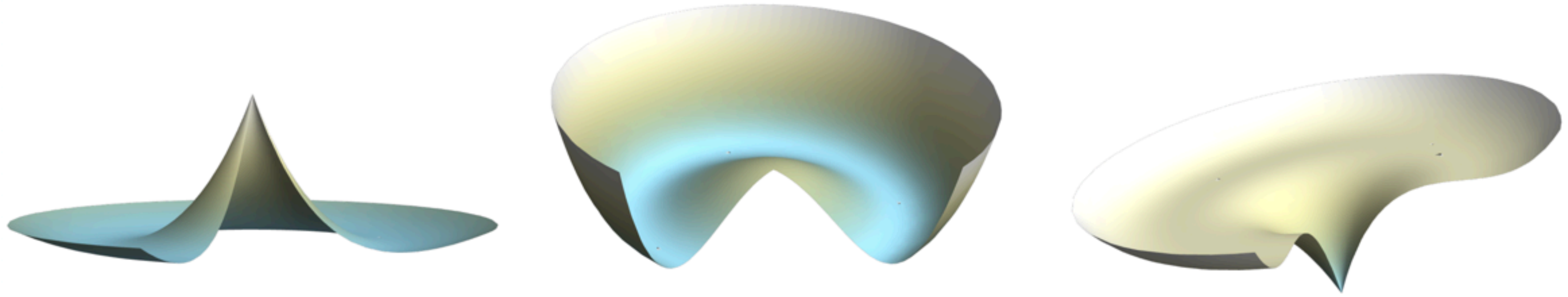
T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya '15

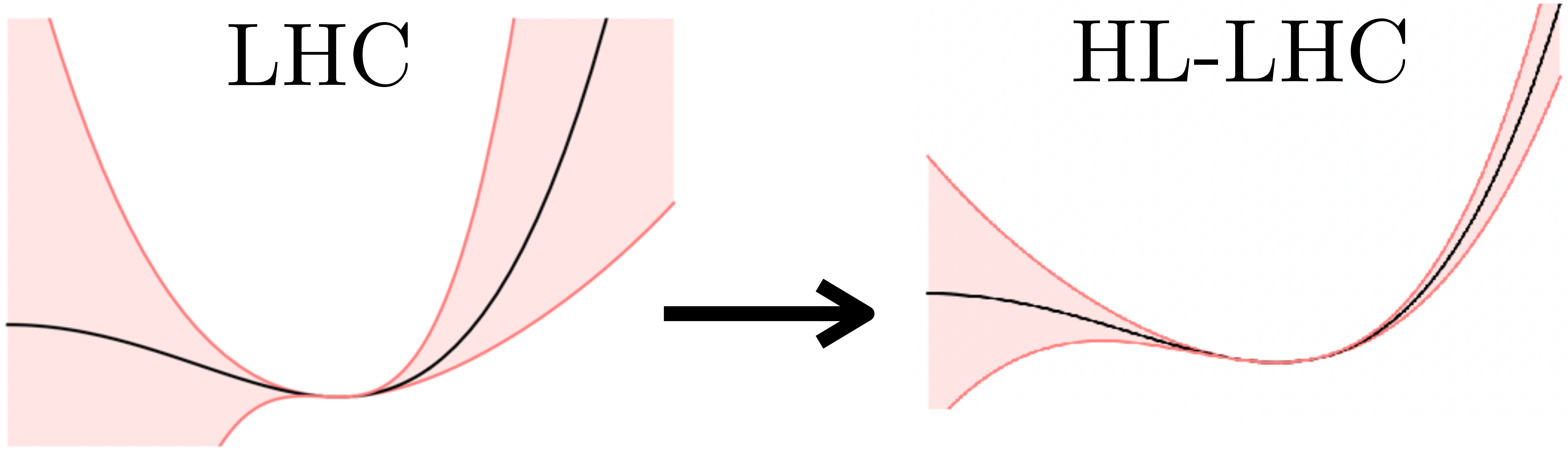
Higgs Potential





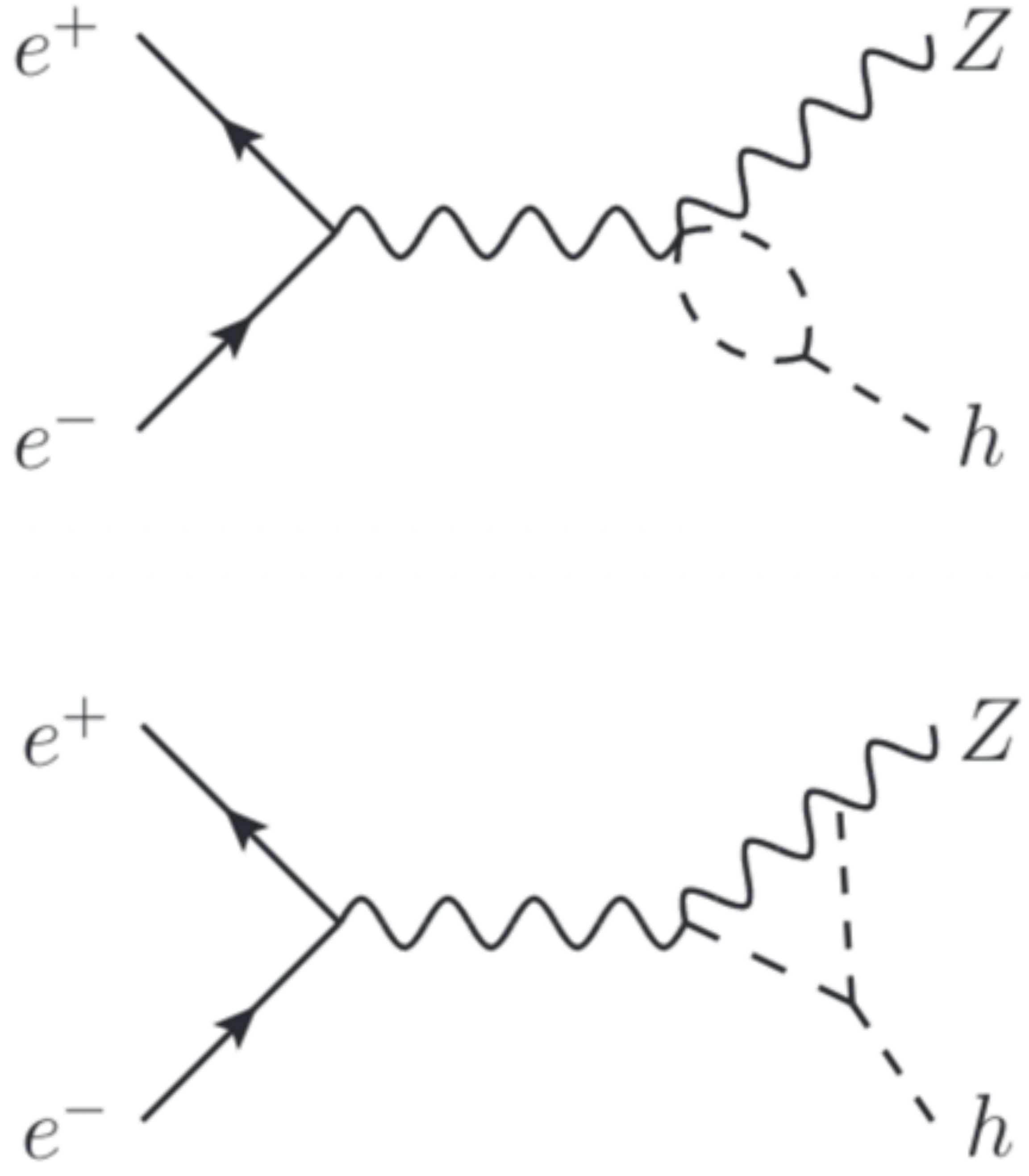
Higgs Potential



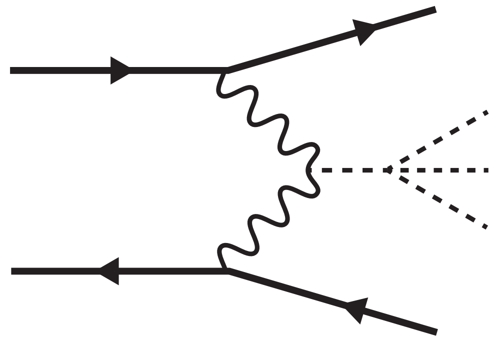


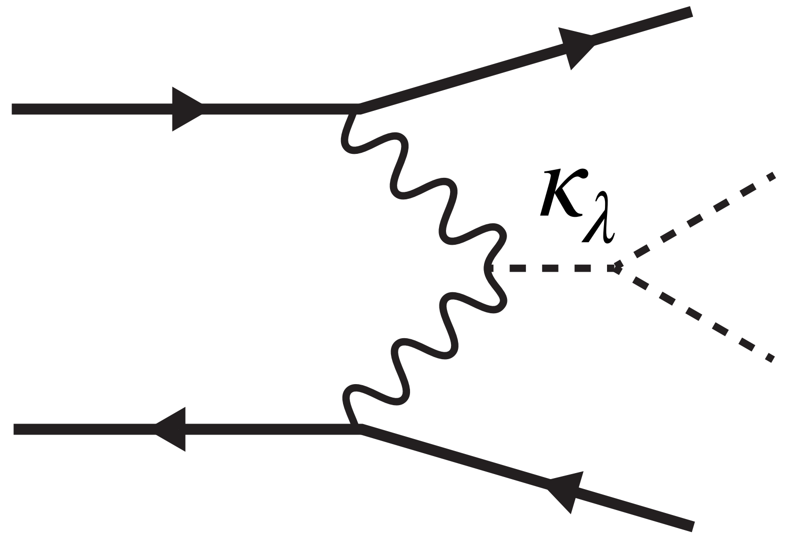
$+ \; 250 \text{ GeV } e^+e^-$

$$\delta\kappa_\lambda \sim \mathcal{O}(1)$$

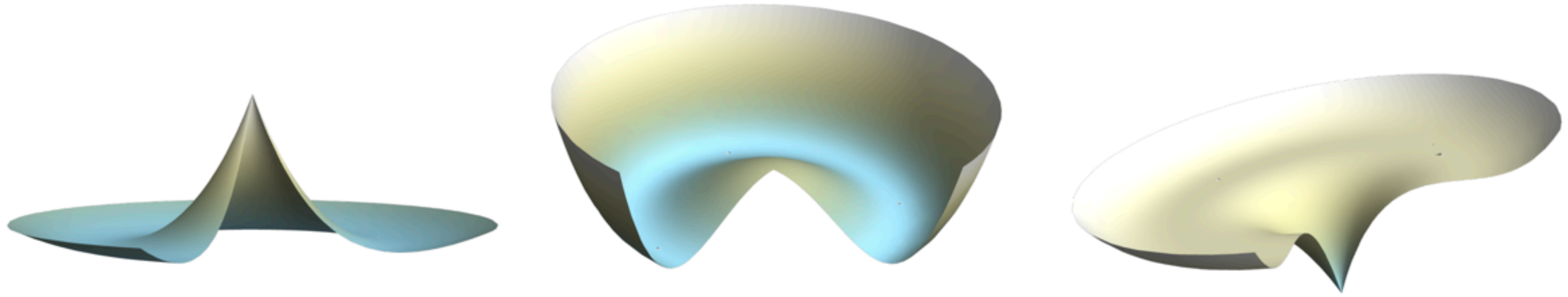


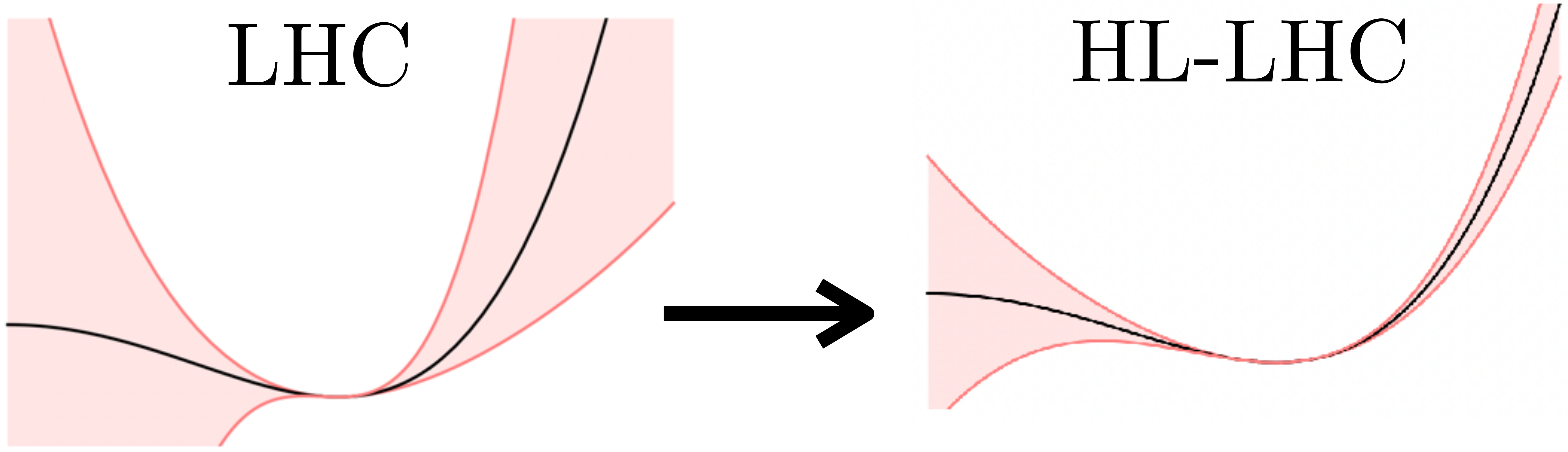
Higgs Potential

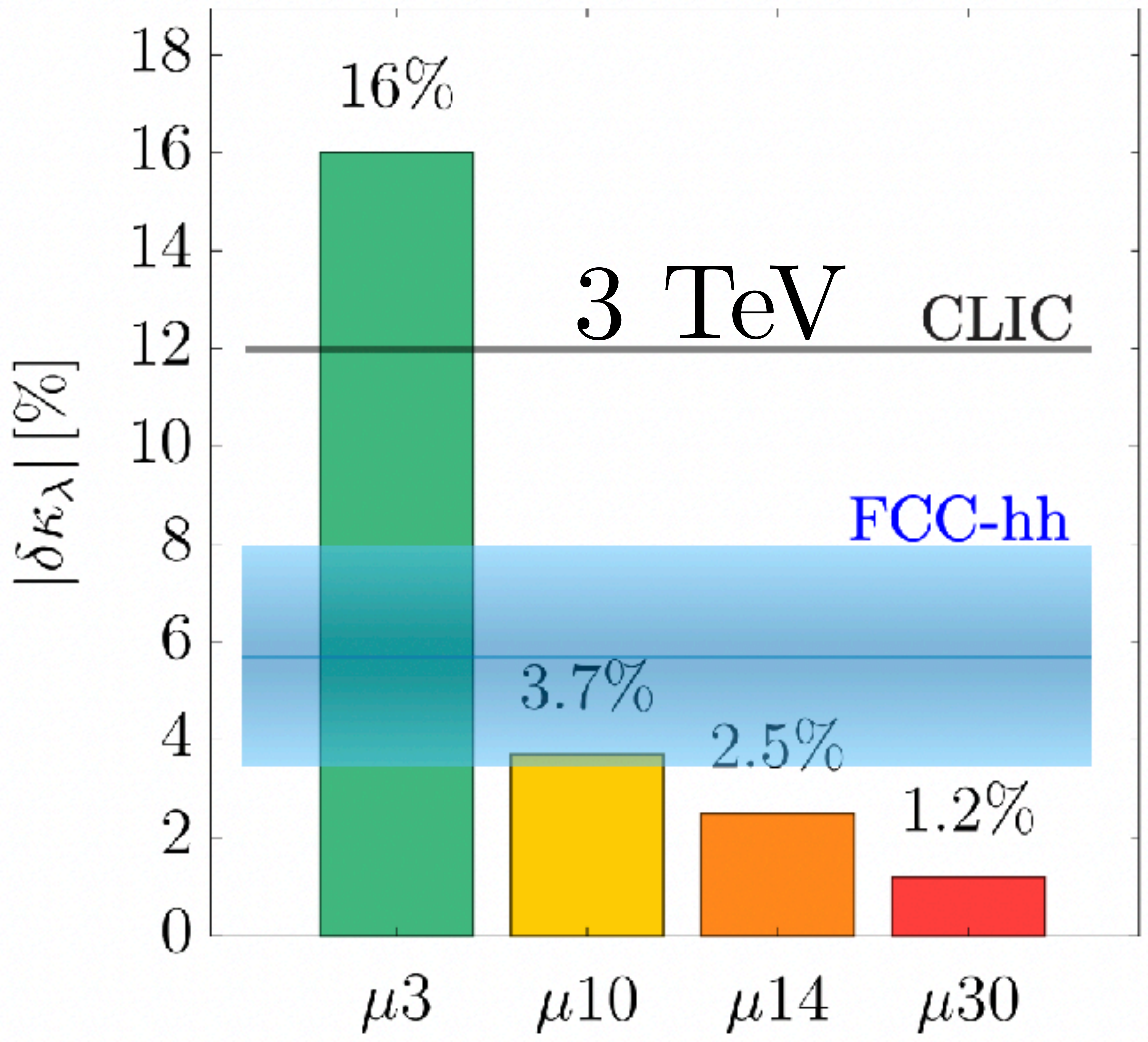




Towards a Muon Collider '23



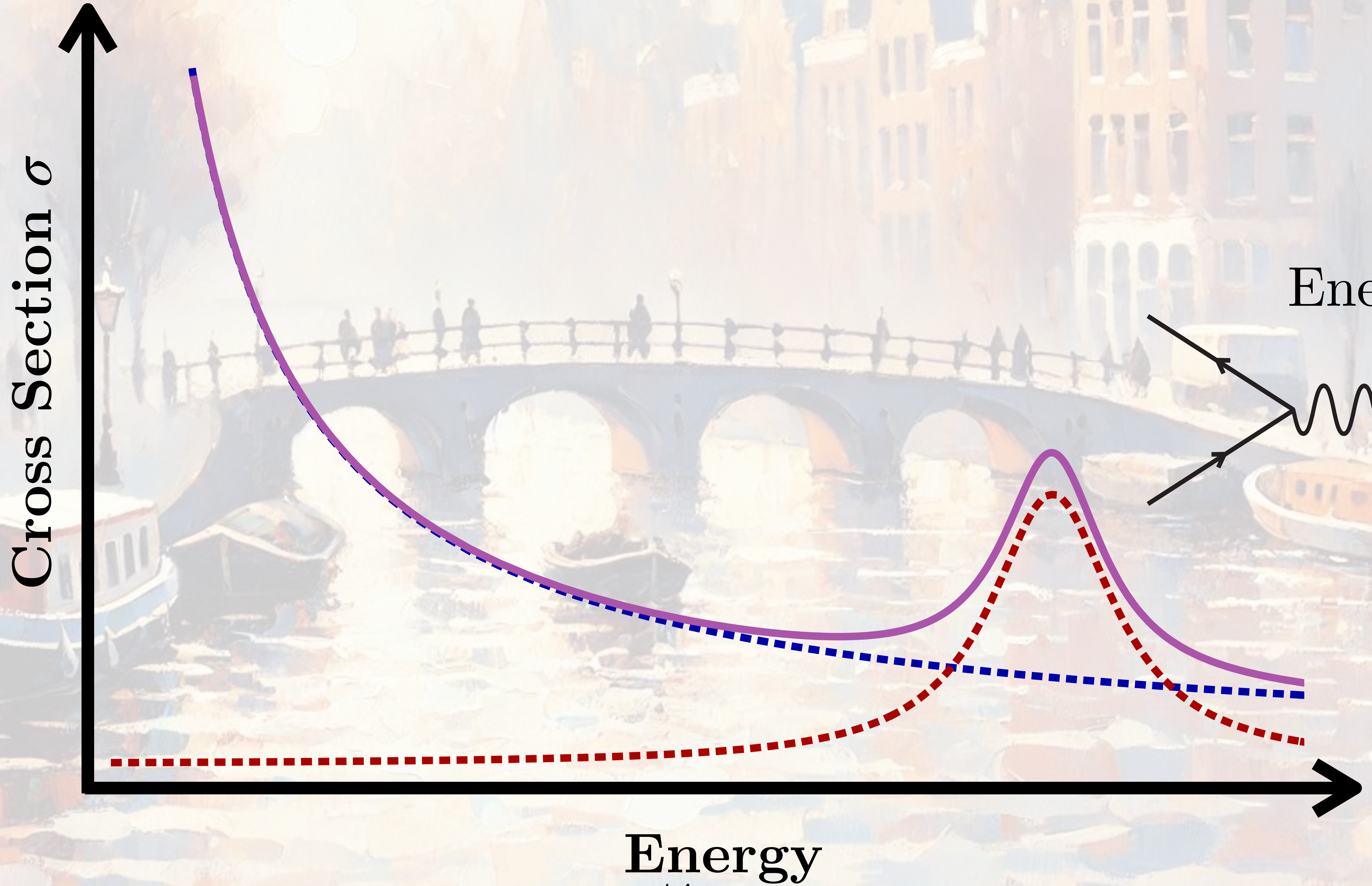


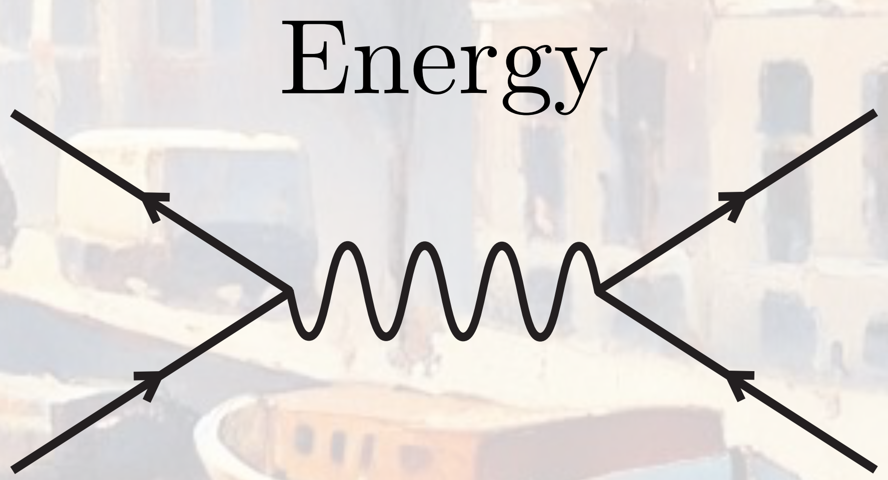


Cesarotti

Slide Credit: P Meade, N Craig, R. Petrossian Byrne

HIGH-ENERGY SEARCHES

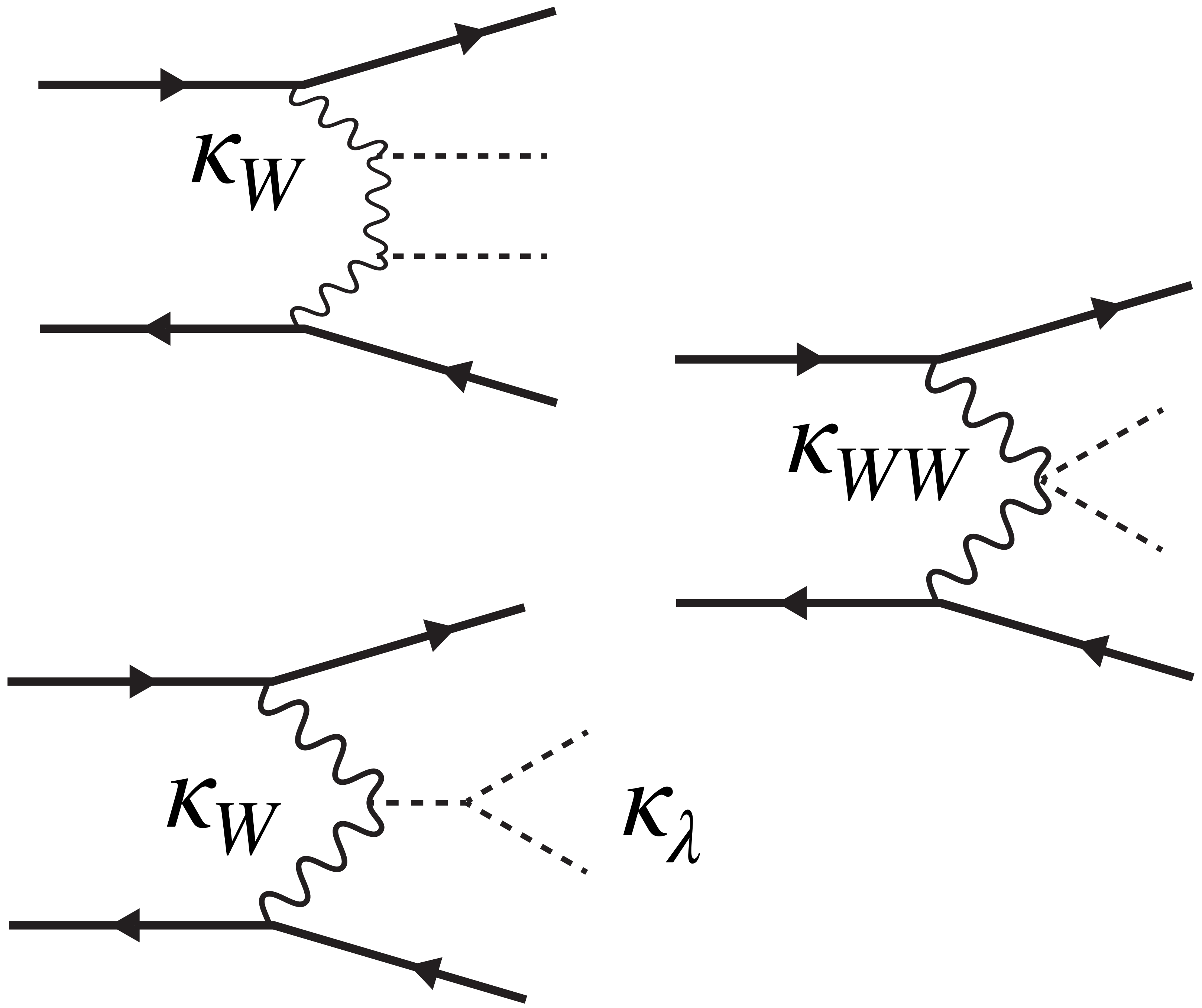




Higgs at High Energy

High energy processes can be a precision probe of new physics

Consider double Higgs production

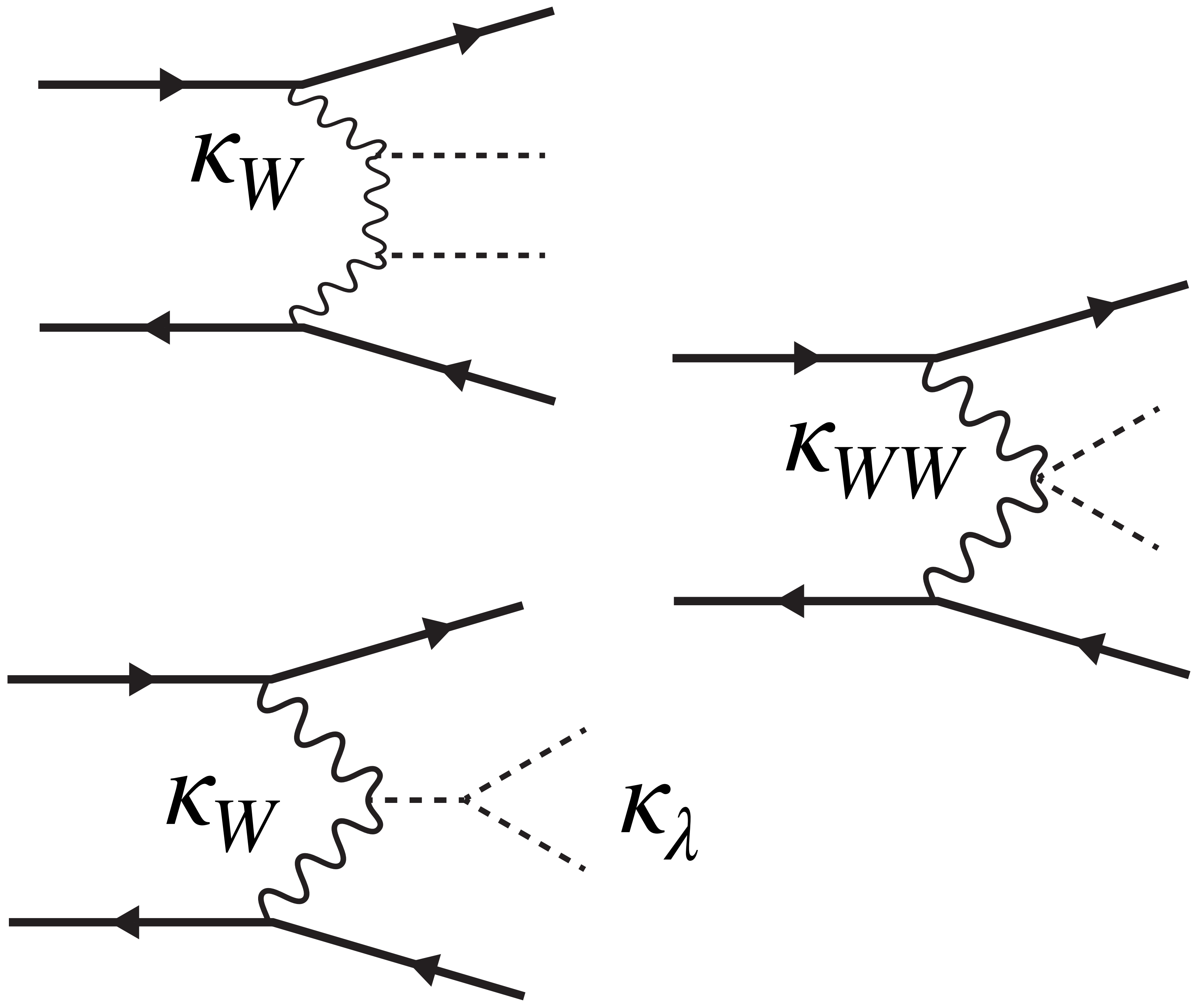


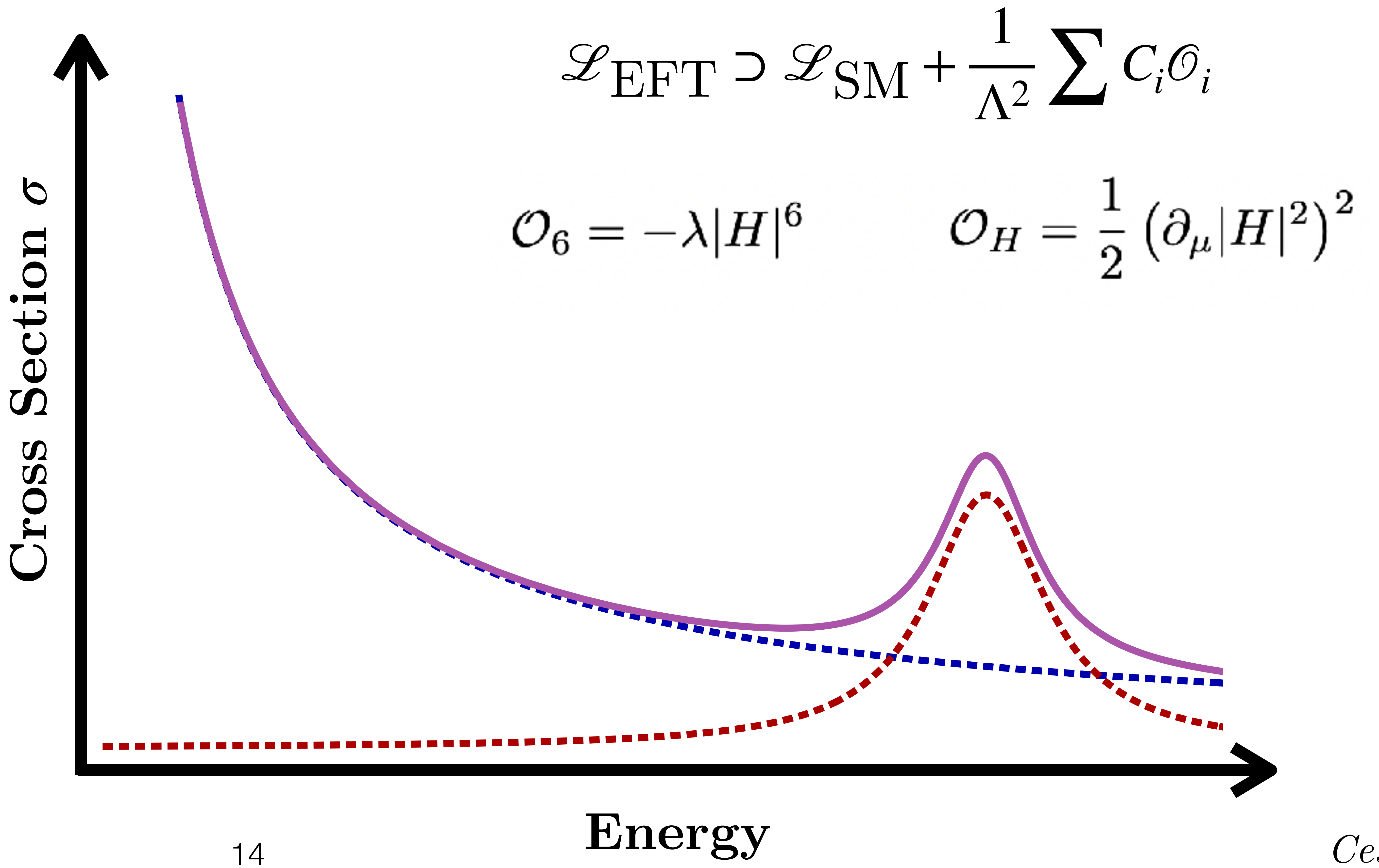
Contino et al. '13
Buttazzo, Franceschini, Wulzer '21

Higgs at High Energy

High energy processes can be a precision probe of new physics

Consider double Higgs production



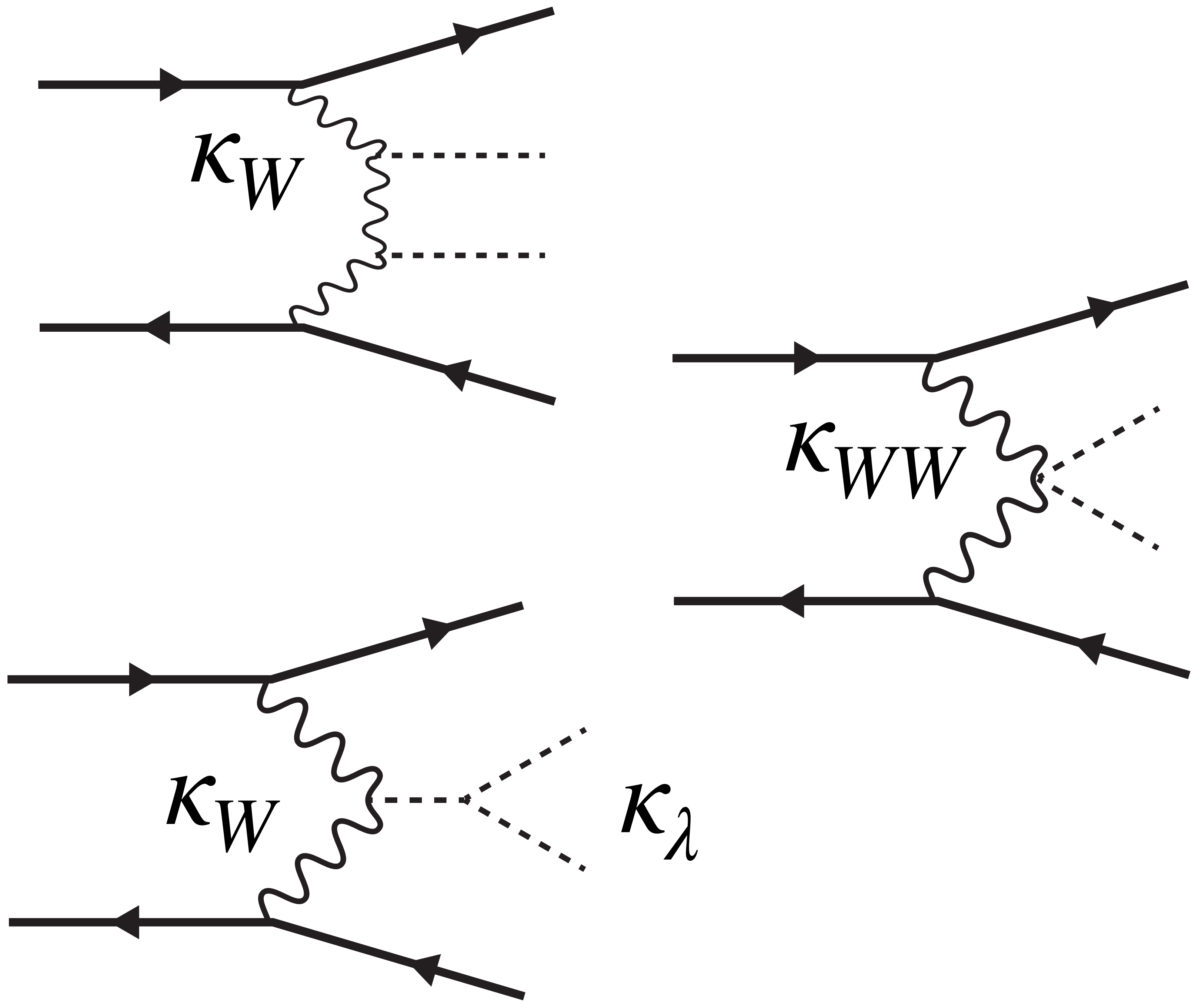


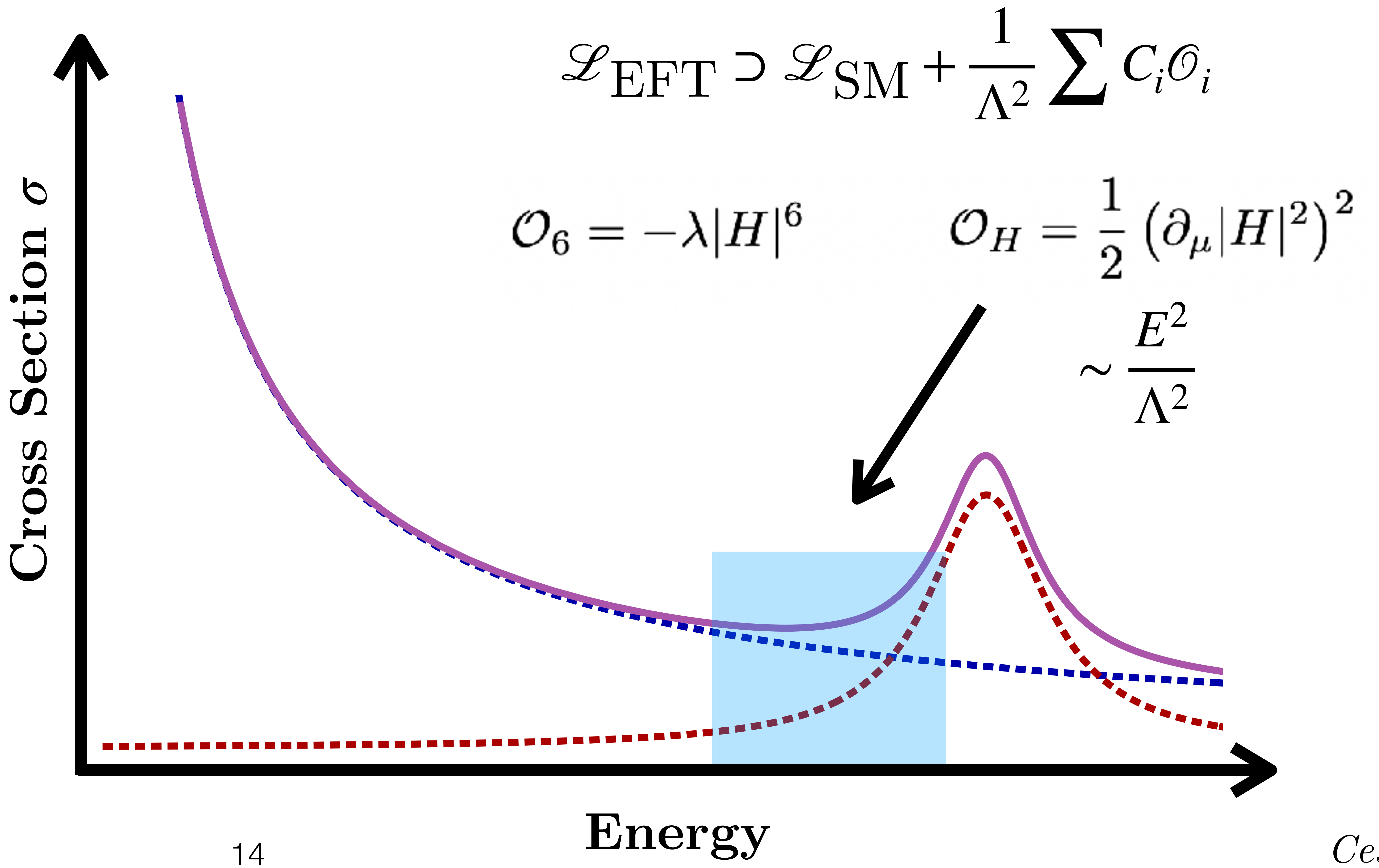
Contino et al. '13
Buttazzo, Franceschini, Wulzer '21

Higgs at High Energy

High energy processes can be a precision probe of new physics

Consider double Higgs production



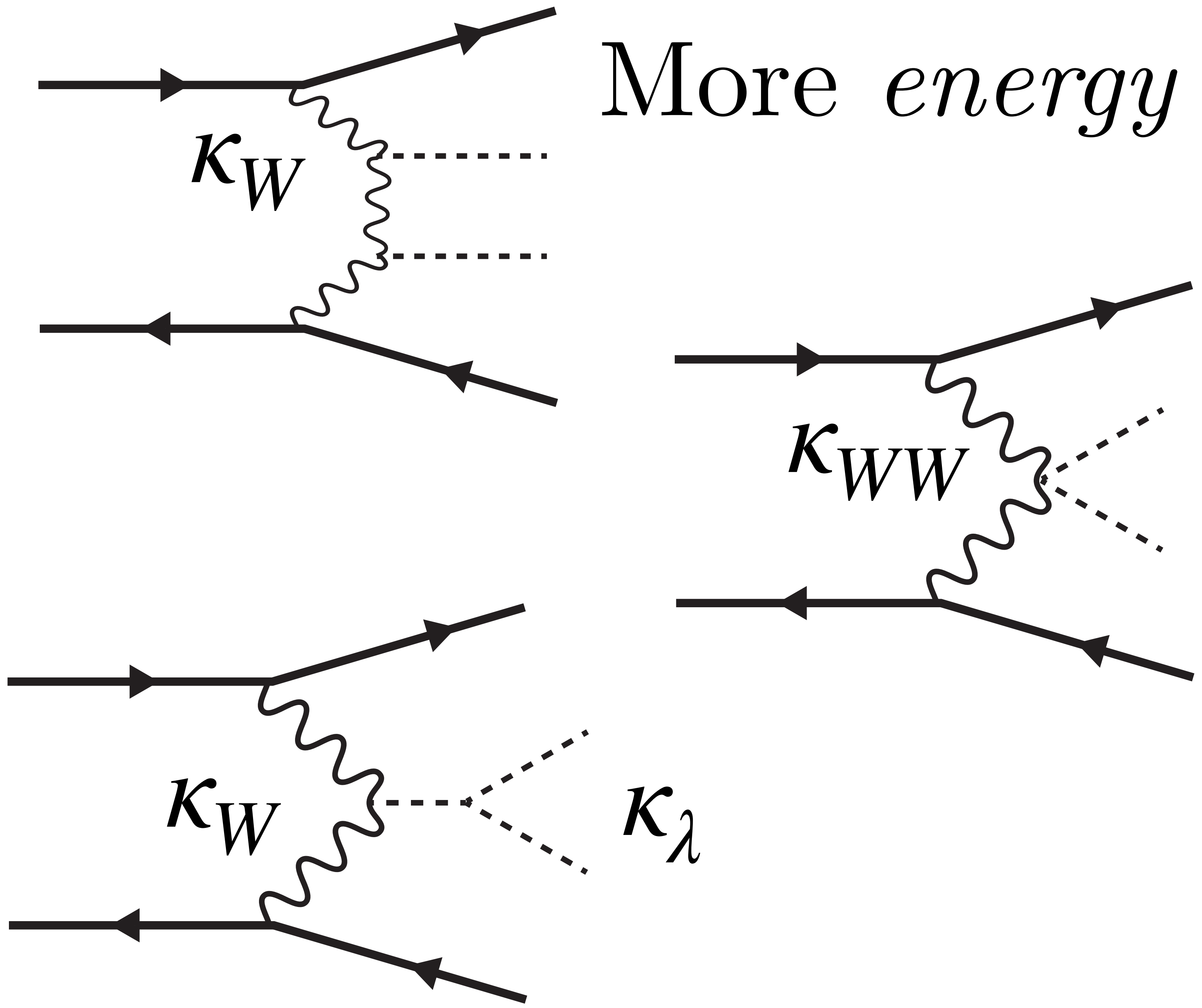


Contino et al. '13
Buttazzo, Franceschini, Wulzer '21

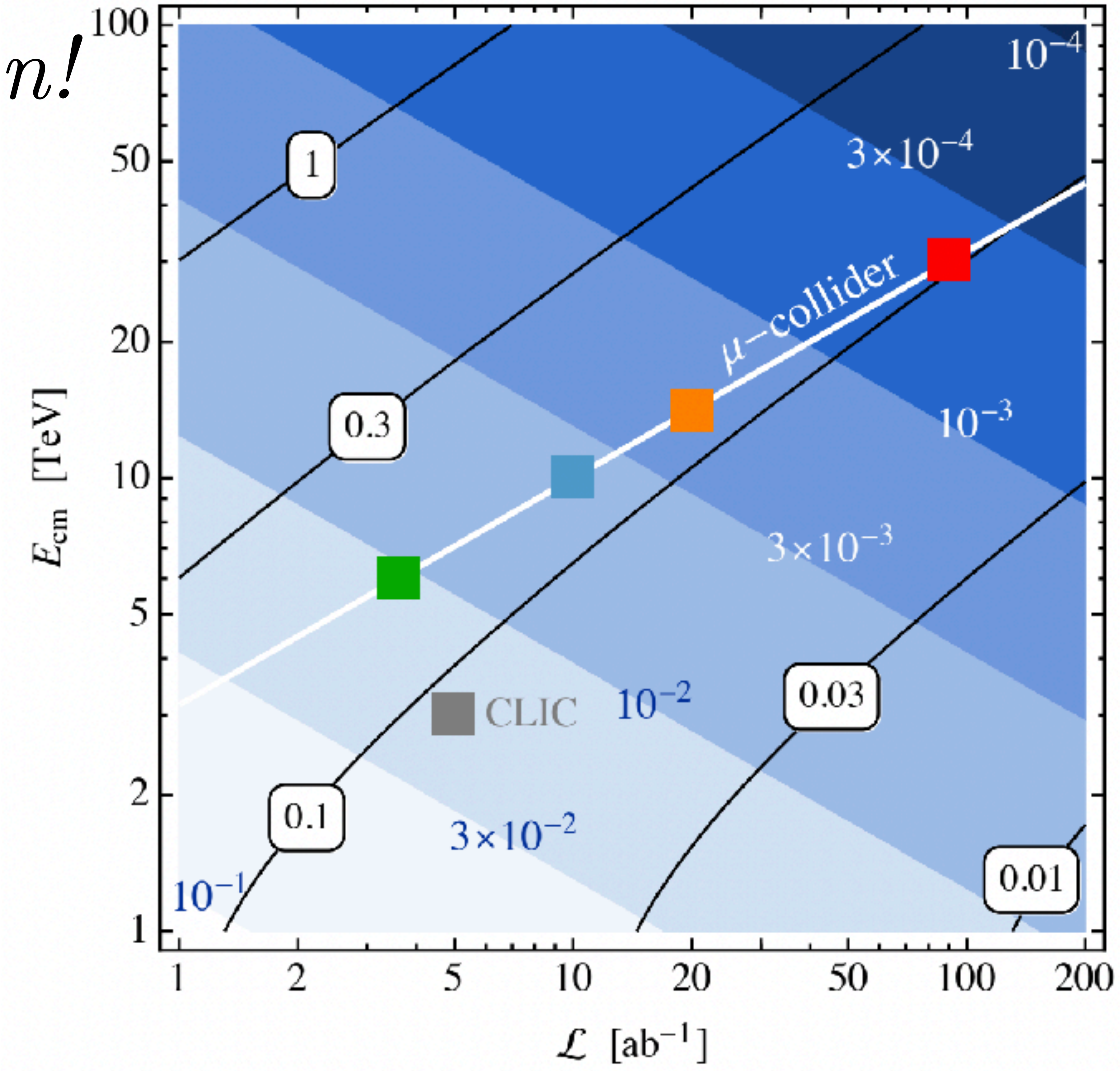
Higgs at High Energy

High energy processes can be a precision probe of new physics

Consider double Higgs production



More *energy* more *precision!*



Precision
S/B

Contino et al. '13
Buttazzo, Franceschini, Wulzer '21

BSM Example: Scalar Mixing

Benchmark model: New singlet S mixes with Higgs

$$V(S,H) = a_{HS} S|H|^2 + \frac{\lambda_{HS}}{2} S^2 |H|^2 + \frac{a_S}{3} S^3 + \frac{\lambda_S}{4} S^4 \quad \Big\} \quad \begin{aligned} h &= h_0 \cos\gamma + S \sin\gamma \\ \phi &= S\cos\gamma - h_0 \sin\gamma \end{aligned}$$

D. Buttazzo, D. Redigolo, F. Sala, A. Tesi '18

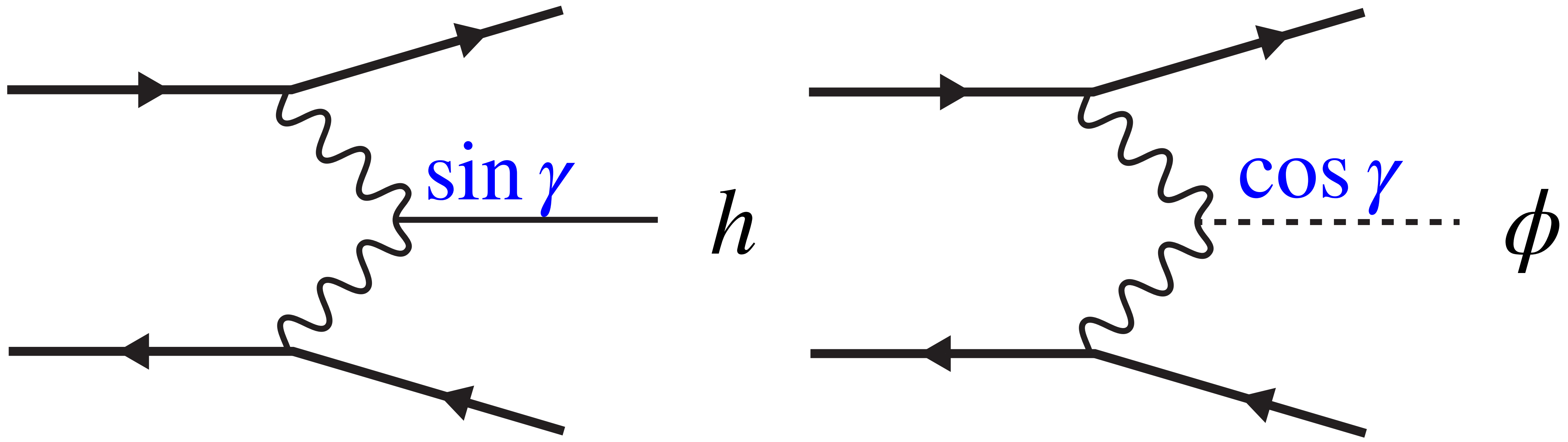
BSM Example: Scalar Mixing

Benchmark model: New singlet S mixes with Higgs

$$V(S,H) = a_{HS}S|H|^2 + \frac{\lambda_{HS}}{2}S^2|H|^2 + \frac{a_S}{3}S^3 + \frac{\lambda_S}{4}S^4 \quad \Bigg\} \quad \begin{aligned} h &= h_0\cos\gamma + S\sin\gamma \\ \phi &= S\cos\gamma - h_0\sin\gamma \end{aligned}$$

$$e^+e^- \to (h/\phi)\nu_e\bar{\nu}_e$$

$$\phi \to hh(4b)$$



D. Buttazzo, D. Redigolo, F. Sala, A. Tesi '18

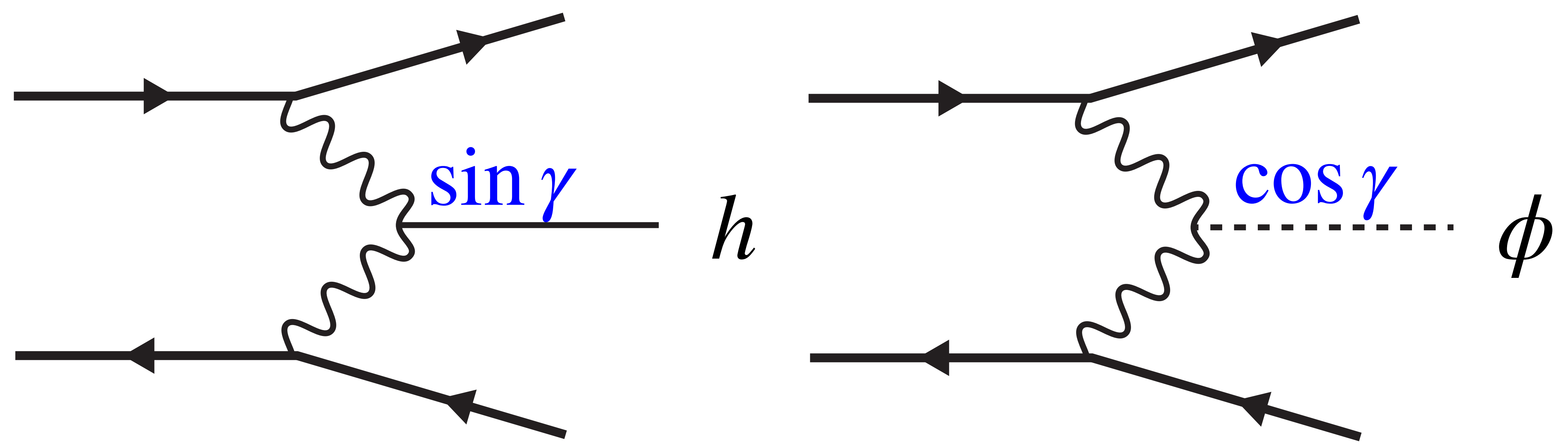
BSM Example: Scalar Mixing

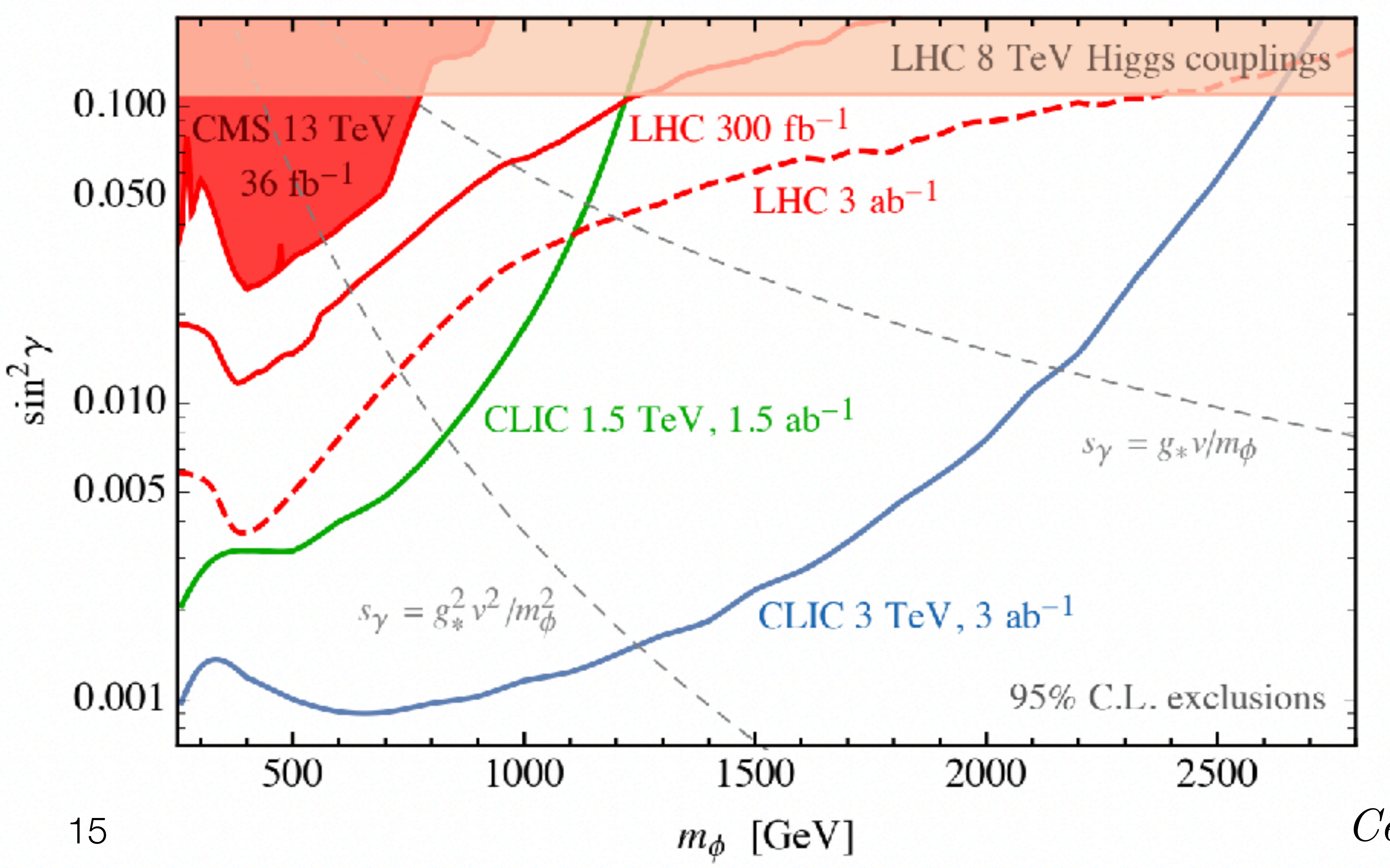
Benchmark model: New singlet S mixes with Higgs

$$V(S,H) = a_{HS} S|H|^2 + \frac{\lambda_{HS}}{2} S^2 |H|^2 + \frac{a_S}{3} S^3 + \frac{\lambda_S}{4} S^4 \quad \Big\} \quad \begin{aligned} h &= h_0 \cos\gamma + S \sin\gamma \\ \phi &= S\cos\gamma - h_0 \sin\gamma \end{aligned}$$

$$e^+e^- \to (h/\phi)\nu_e\bar{\nu}_e$$

$$\phi \to hh(4b)$$





D. Buttazzo, D. Redigolo, F. Sala, A. Tesi '18

BSM Example: 2HDM

Benchmark model: Additional SU(2) Scalar Doublet to SM

Representation and couplings can lead to remarkably different phenomenology and flavor-dependent couplings

Particles: h, H, A, $H^{\pm}$

BSM Example: 2HDM

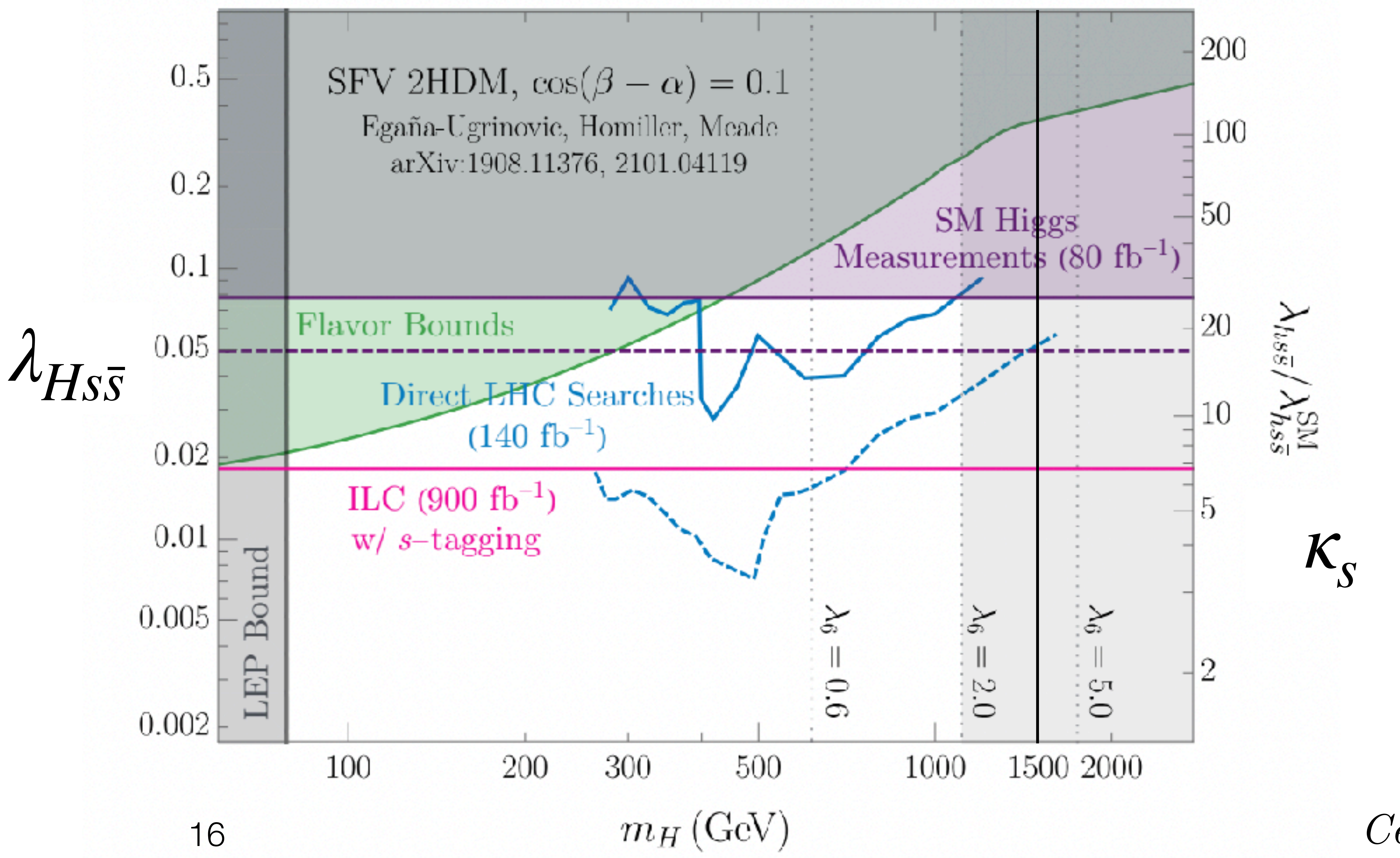
Benchmark model: Additional SU(2) Scalar Doublet to SM

Representation and couplings can lead to remarkably different phenomenology and flavor-dependent couplings

Particles: $h,\ H,\ A,\ H^{\pm}$

Example: SFV 2HDM

Only s couples to H



Egaña-Ugrinovic, Homiller, Meade '19 & '21

BSM Example: 2HDM

Benchmark model: Additional SU(2) Scalar Doublet to SM

Representation and couplings can lead to remarkably different phenomenology and flavor-dependent couplings

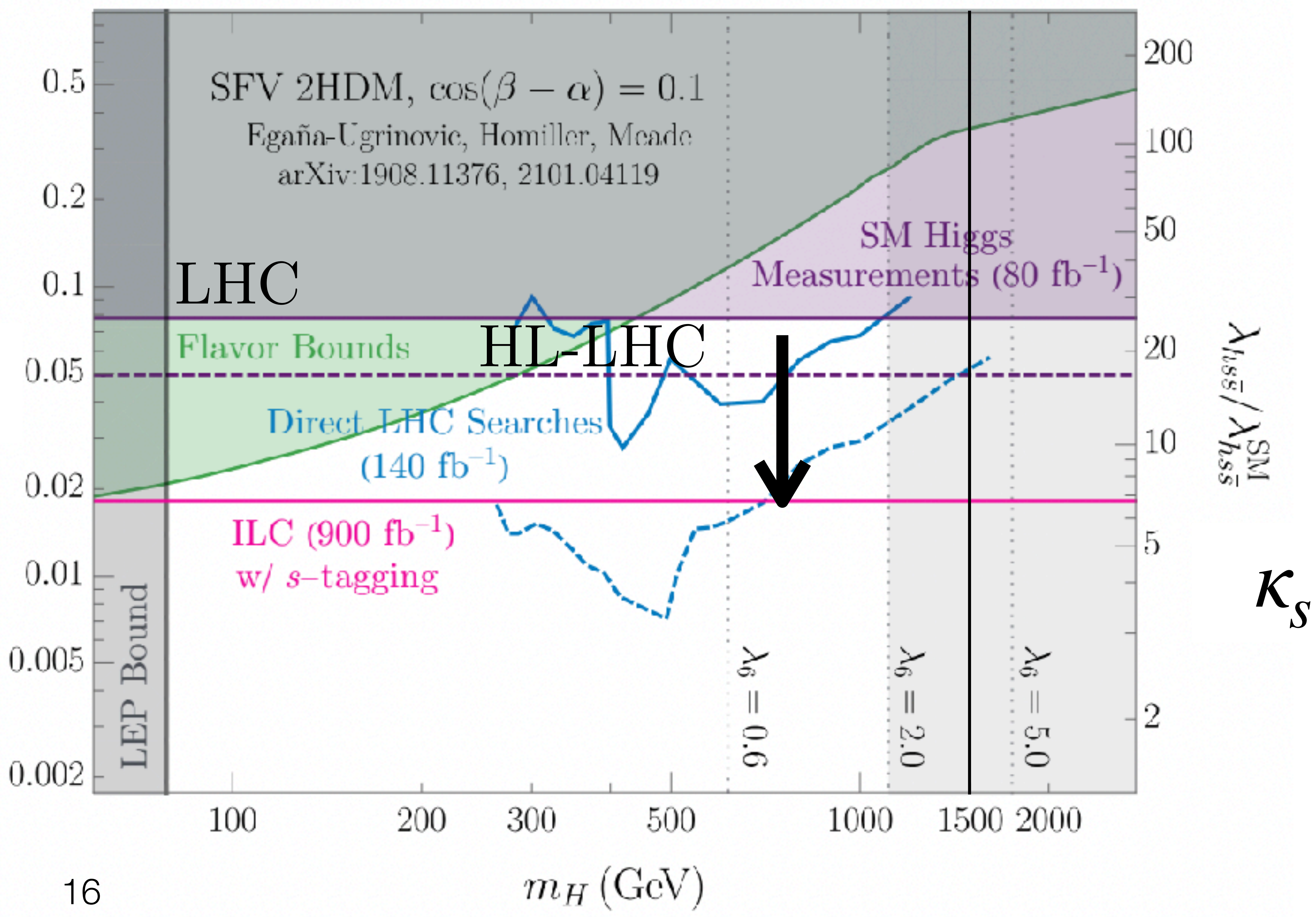
Particles: $h,\ H,\ A,\ H^{\pm}$

Example: SFV 2HDM

Only s couples to H

Improvement in Higgs coupling measurements

$\lambda_{Hs\bar{s}}$



κ_s

Egaña-Ugrinovic, Homiller, Meade '19 & '21

BSM Example: 2HDM

Benchmark model: Additional SU(2) Scalar Doublet to SM

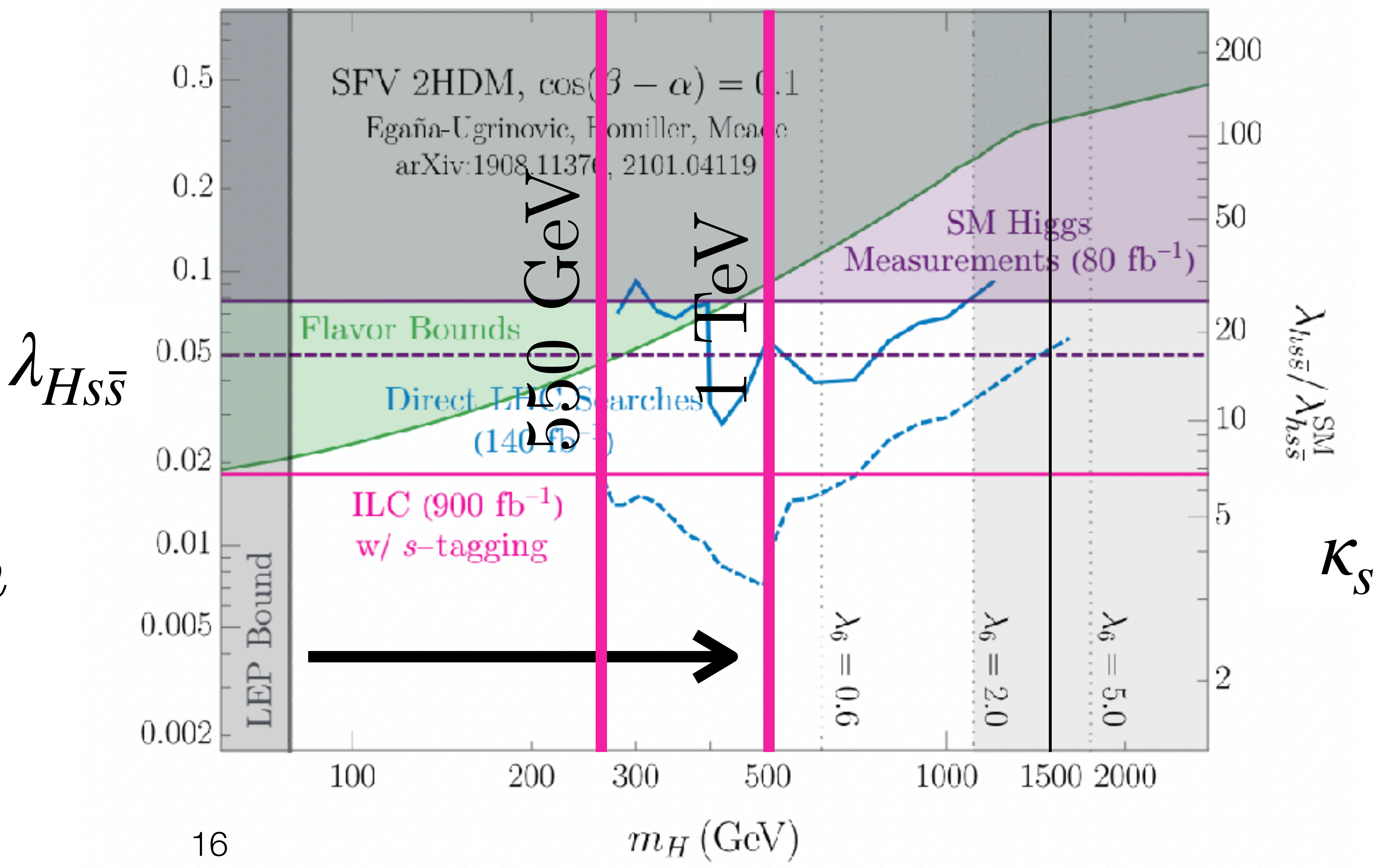
Representation and couplings can lead to remarkably different phenomenology and flavor-dependent couplings

Particles: $h,\ H,\ A,\ H^{\pm}$

Example: SFV 2HDM

Only s couples to H

Improvement in $\sqrt{s}$ *with Drell-Yan production*



Egaña-Ugrinovic, Homiller, Meade '19 & '21

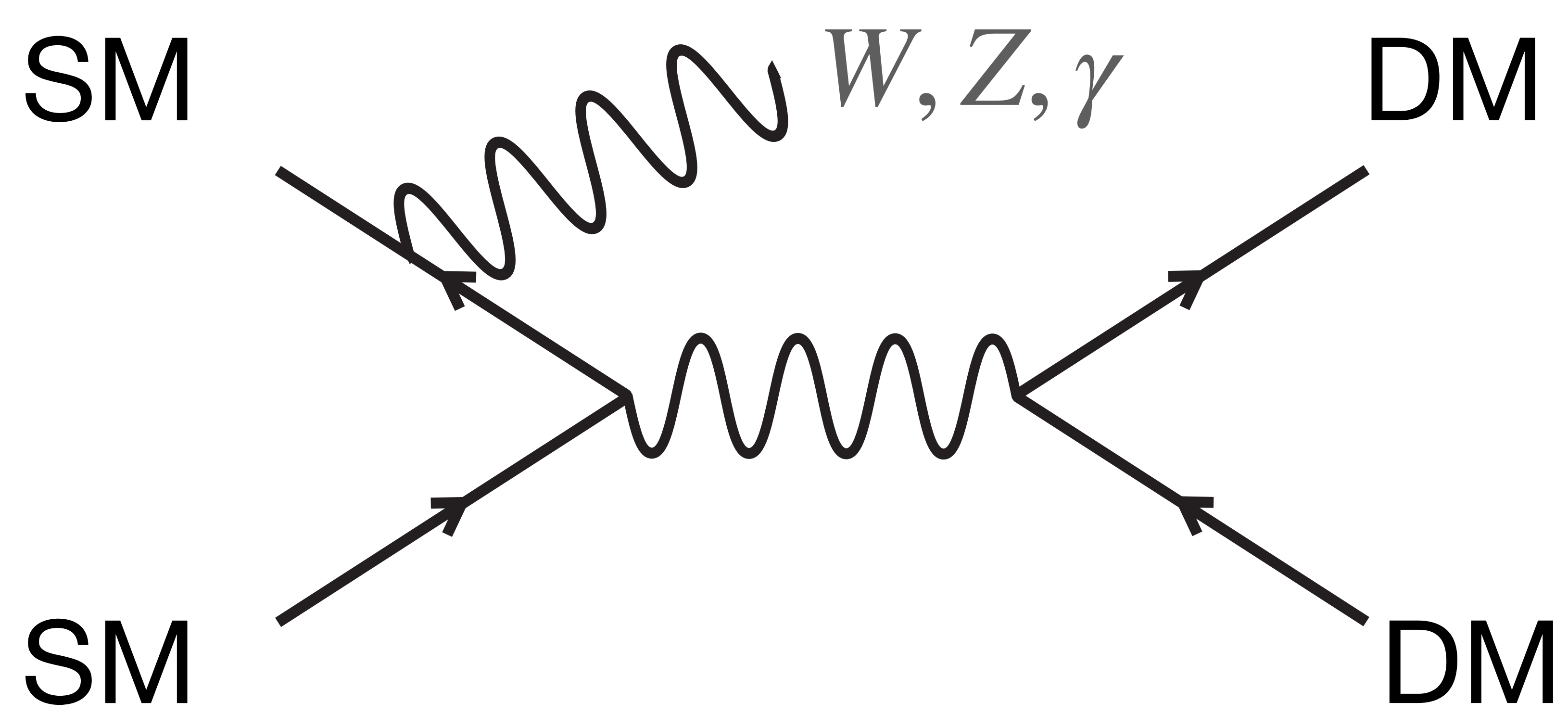
Cesarotti

BSM Example: WIMP DM

Electroweak multiplets which can arise in SUSY scenarios

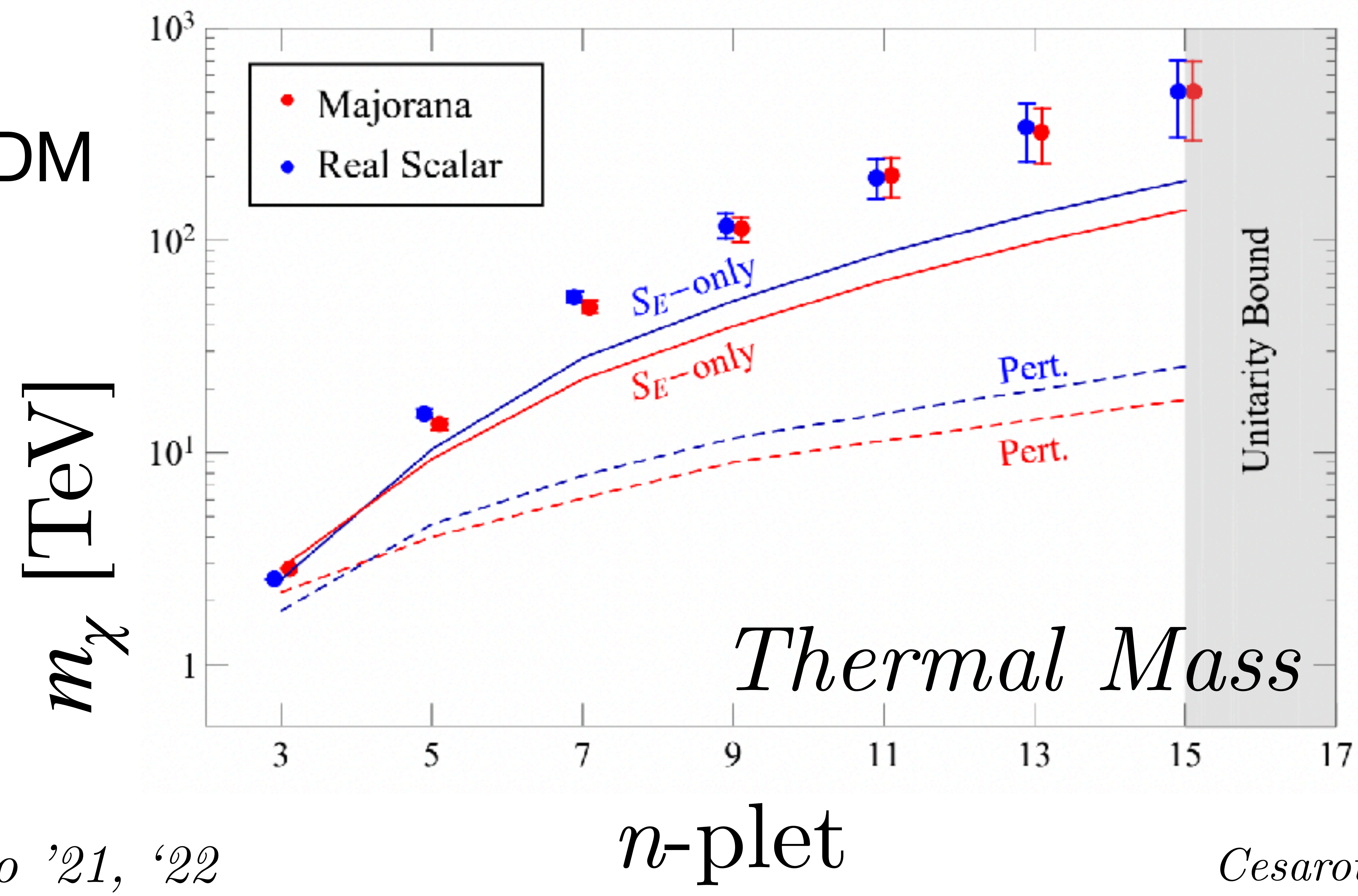
n-plet

$$\begin{pmatrix} \vdots \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \vdots \end{pmatrix}$$



Predicted at ~ TeV scale

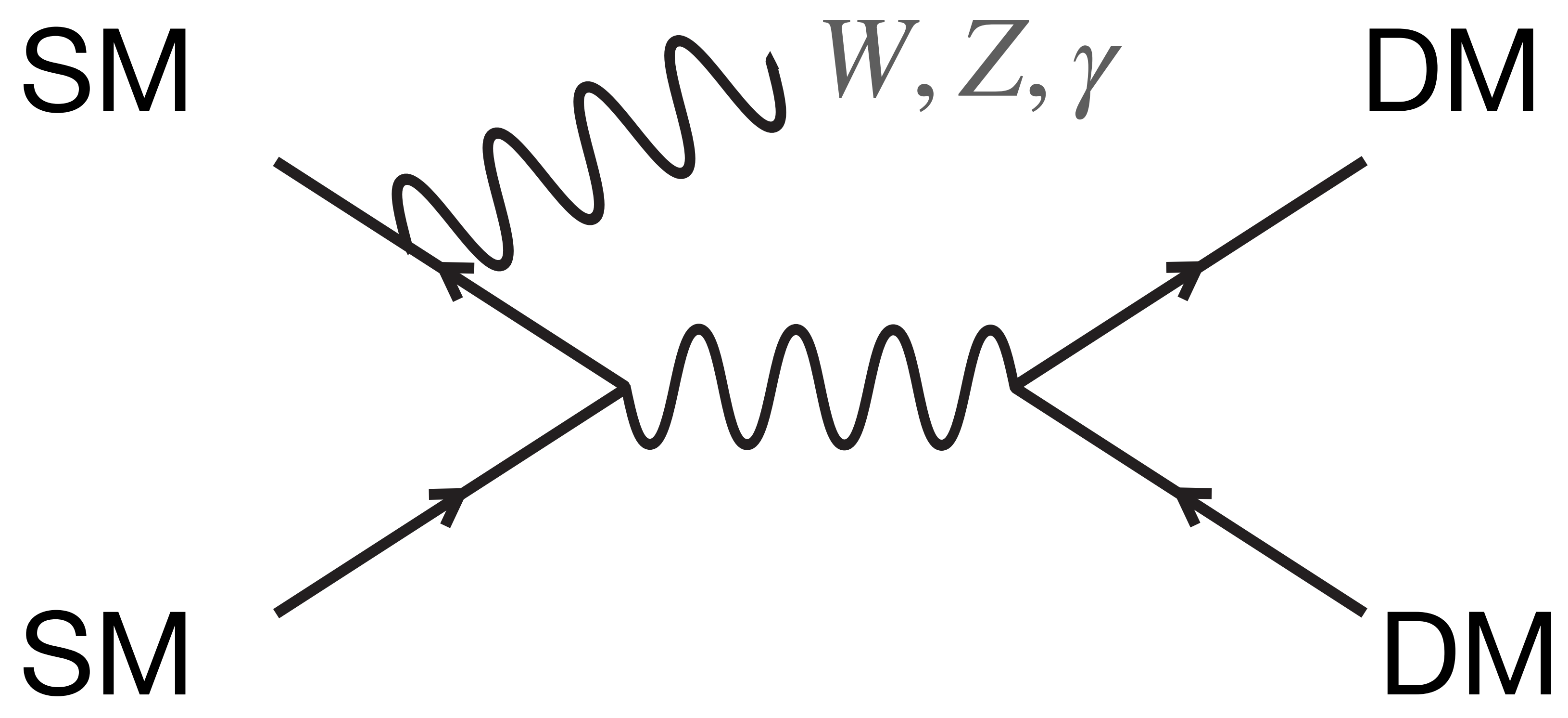
$\Delta m \sim \mathcal{O}(100)$ GeV



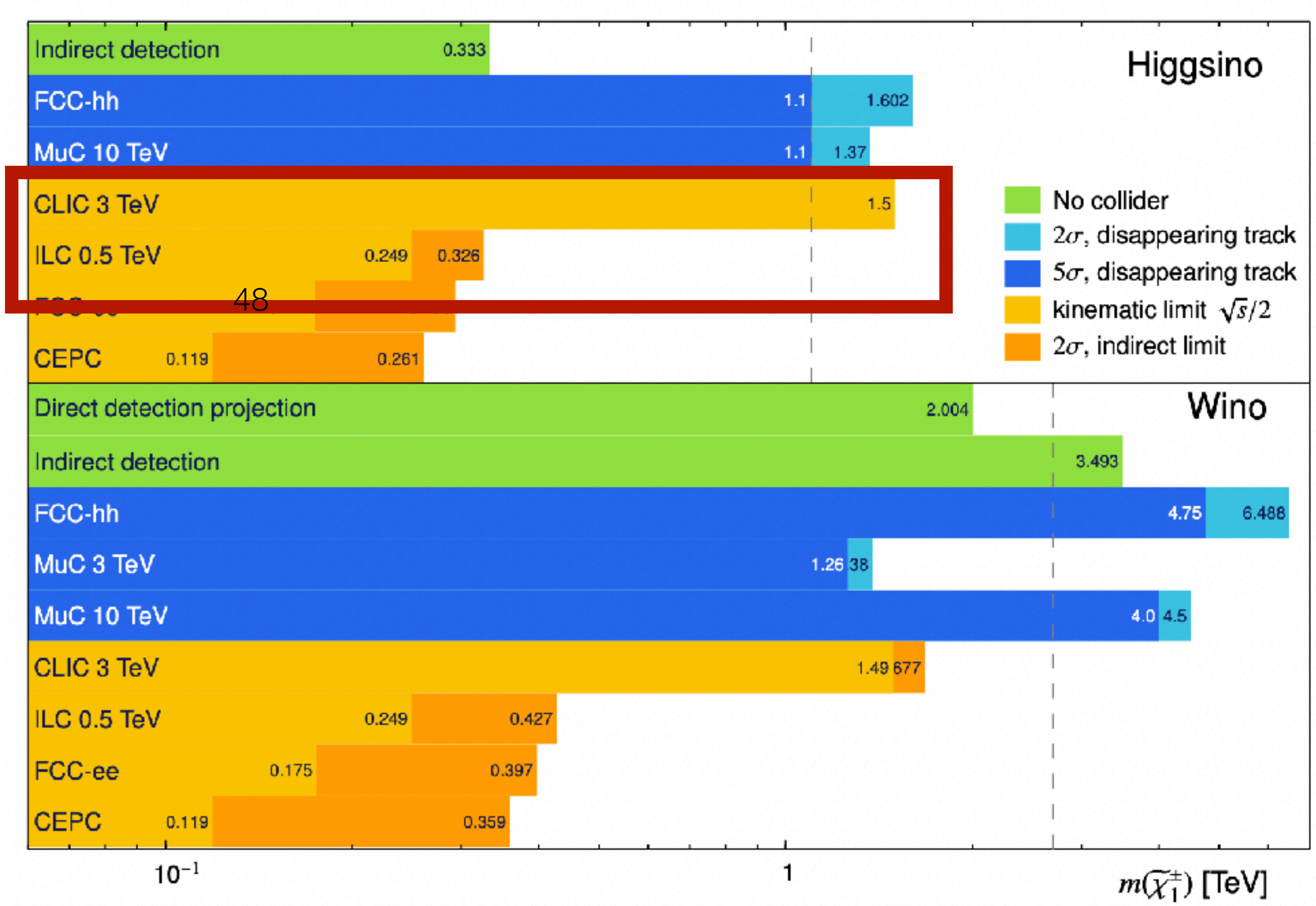
Han, Liu, Wang, Wang '20
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

BSM Example: WIMP DM

Electroweak multiplets which can arise in SUSY scenarios



Can cover Higgsino at 3 TeV



Han, Liu, Wang, Wang '20
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

Future Collider Comparison

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Future Collider Comparison

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

$\Lambda_{NP} \sim \mathcal{O}(1 - 10)$ TeV

10^6 Higgs can't measure rare decays precisely…

Future Collider Comparison

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

$\Lambda_{NP} \sim \mathcal{O}(1 - 10)$ TeV

10^6 Higgs can't measure rare decays precisely…

…but more energy improves our measurements

Future Collider Comparison

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/ eh/hh	$\mu^+\mu^-$ 10000
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

10^6 Higgs can't measure rare decays precisely…

…but more energy improves our measurements

& collider **R&D** should be prioritized as we enter the energy frontier

Outlook

Now is the time for a precision collider program

- Fastest (and cheapest?) to construct
- Inform future high-energy machines

The benefit of a linear collider is the flexibility in physics program

- Measure specific observables, then upgrade energy

Consider landscape of collider community

- Existence of other colliders should inform run parameters
- Colliders are moving target, so a flexible plan is desirable

Outlook

Now is the time for a precision collider program

- Fastest (and cheapest?) to construct
- Inform future high-energy machines

The benefit of a linear collider is the flexibility in physics program

- Measure specific observables, then upgrade energy

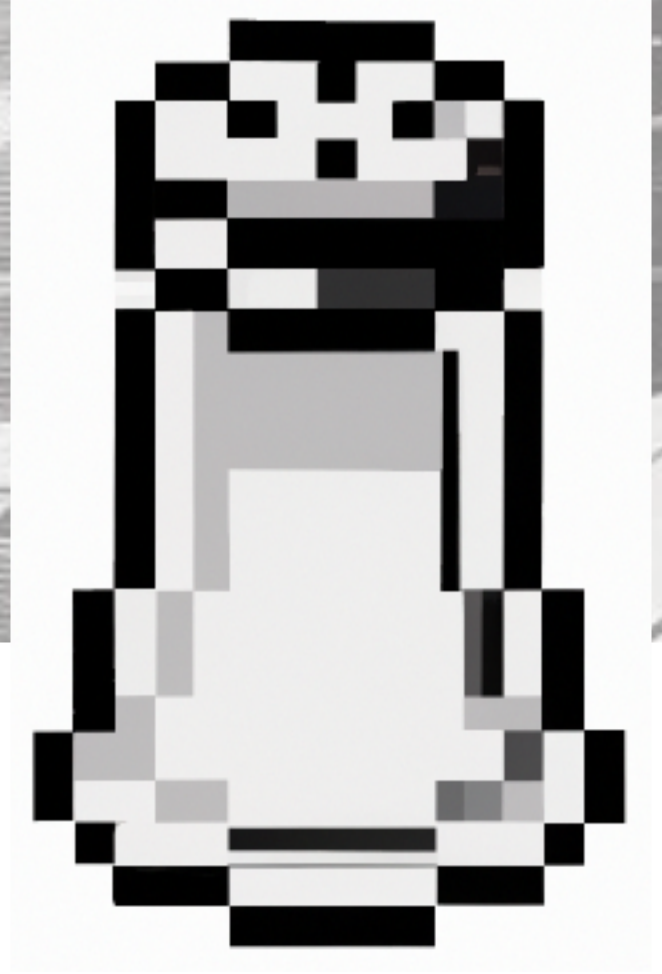
Consider landscape of collider community

- Existence of other colliders should inform run parameters
- Colliders are moving target, so a flexible plan is desirable

Collider R&D is a priority for both precision & energy frontier

Backup Slides

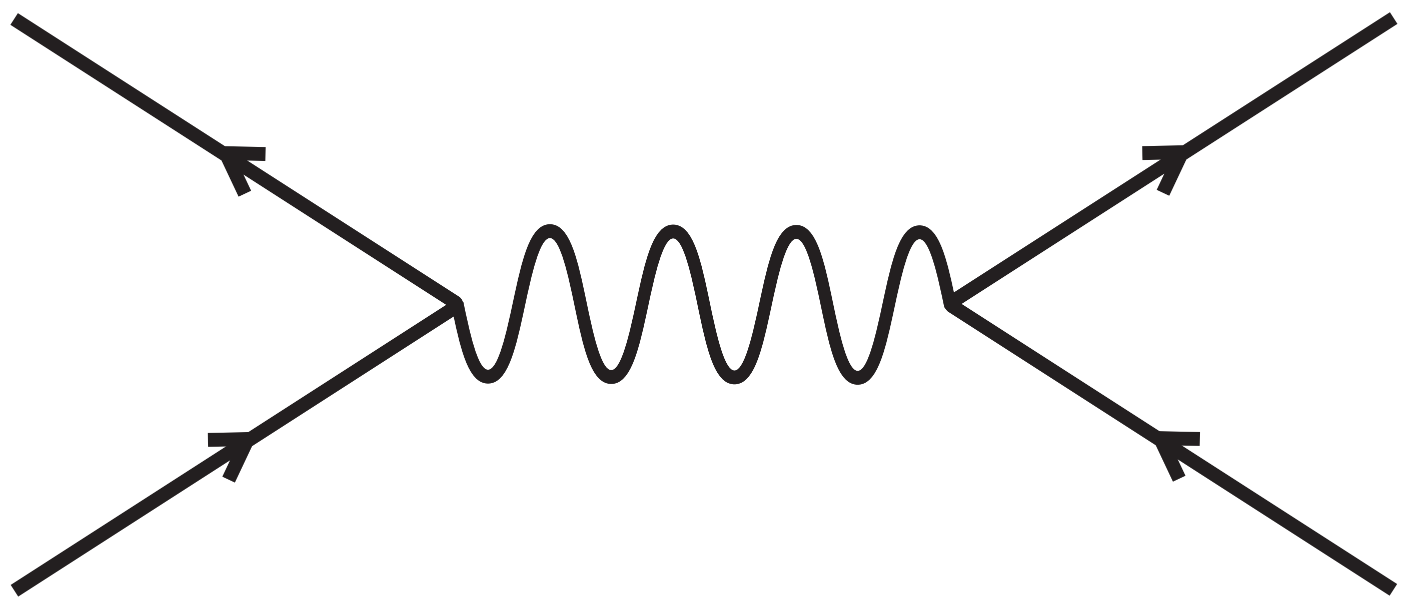
Future Collider Timescales



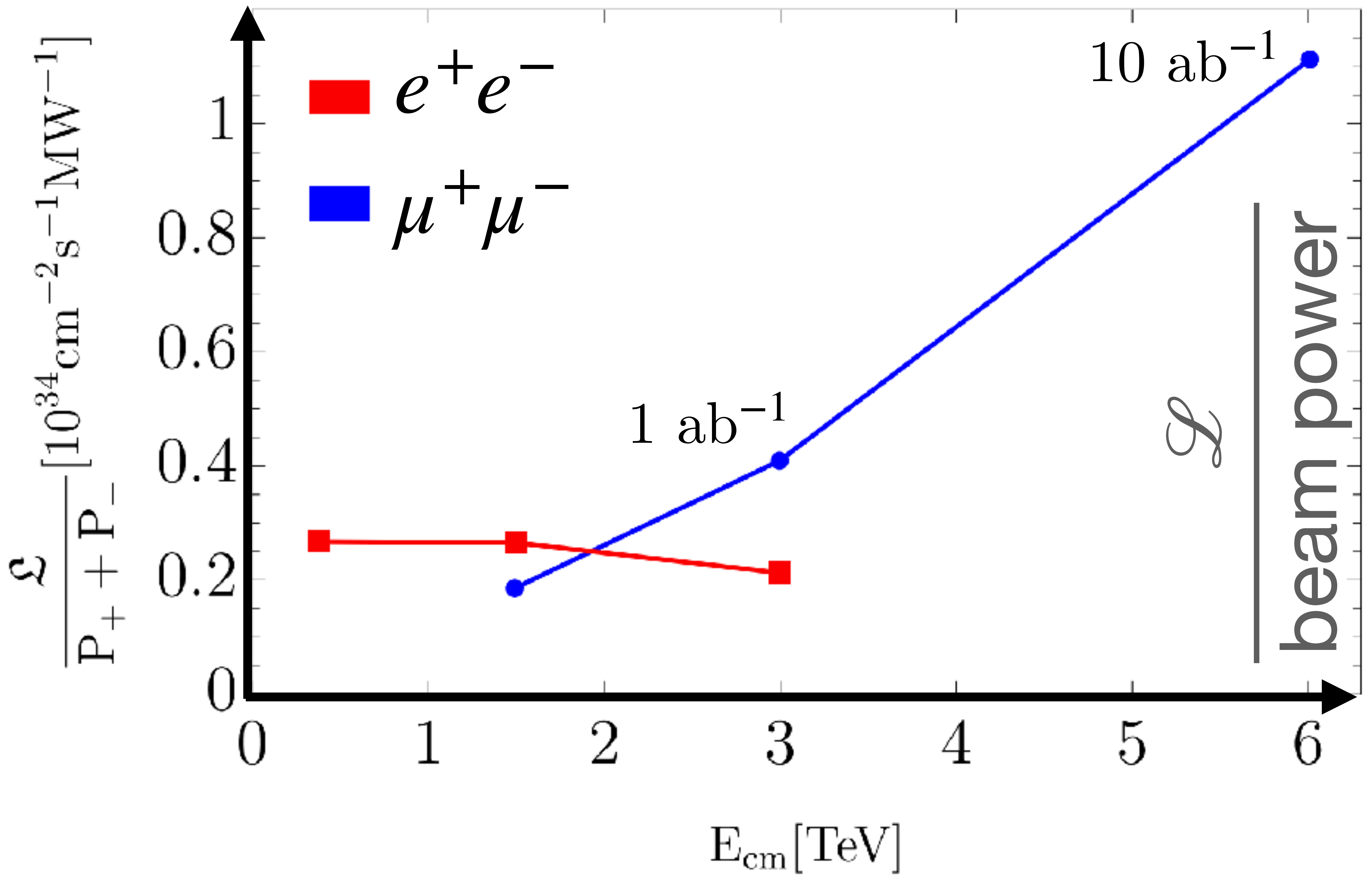
Comparison of Lepton Colliders

The higher the energy, the larger the luminosity

$$\mathscr{L} \sim \frac{N_\mu}{\text{bunch}} \times E^2$$



$$\sim \frac{1}{s}$$

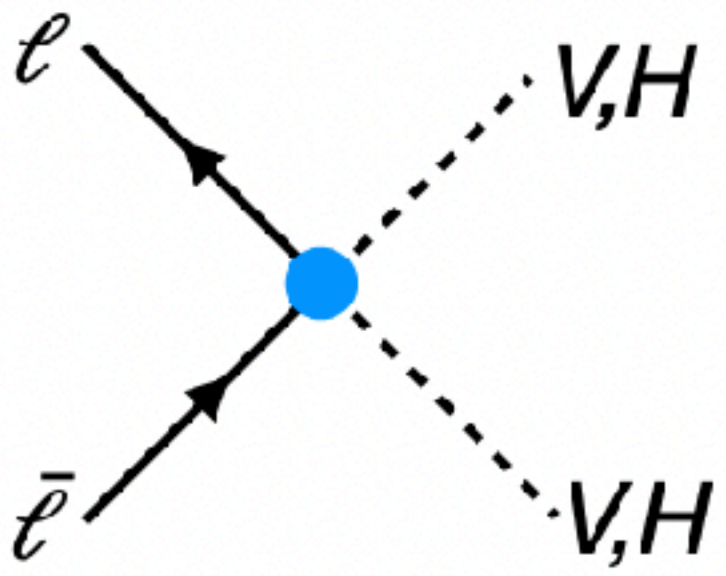


Cesarotti

Slide Credit: Buttazzo
Slide Credit: Buttazzo

Example 1: high-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:



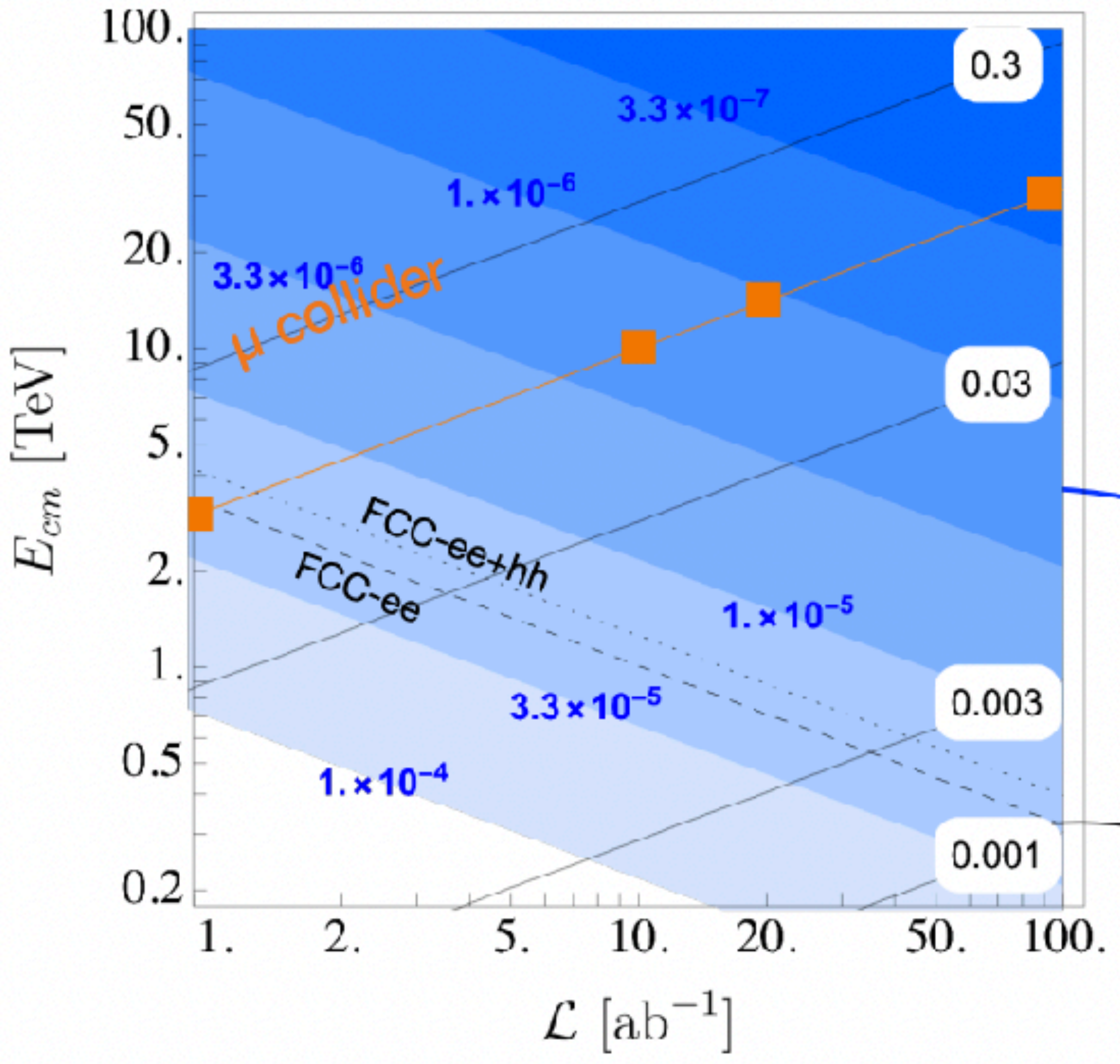
$$\ell^+\ell^- \to W_L^+ W_L^-$$
$$\ell^+\ell^- \to Z_L H$$

Determined by two dim. 6 operators (in flavor-universal theories):

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\sigma_{\mu\mu\to ZH} \approx 122\,\text{ab}\left(\frac{10\,\text{TeV}}{E_{\text{cm}}}\right)^2\left[1 + \# E^2_{\text{cm}} C_W + \# E^4_{\text{cm}} C_W^2\right]$$



related with Z-pole observables

$$\hat{S} = m_W^2(C_W + C_B)$$

LEP: 10^{-3}, FCC: few 10^{-5} **MuC:** 10^{-6}

precision of measurement

Slide Credit: de Blas

Precision physics at e^+e^- Electroweak factories

What can we do with future EW measurements?

- Precision Flavor Physics:

$5\times10^{12}\ Z$ | ~15% $Z\to bb$ | ~3.4% $Z\to\tau\tau$ | Huge sample for Flavor measurements

- E.g. B physics:

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-ee
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu$	5%	–	–	3%
$B^+ \to \tau^+\nu$	7%	–	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	–	5%

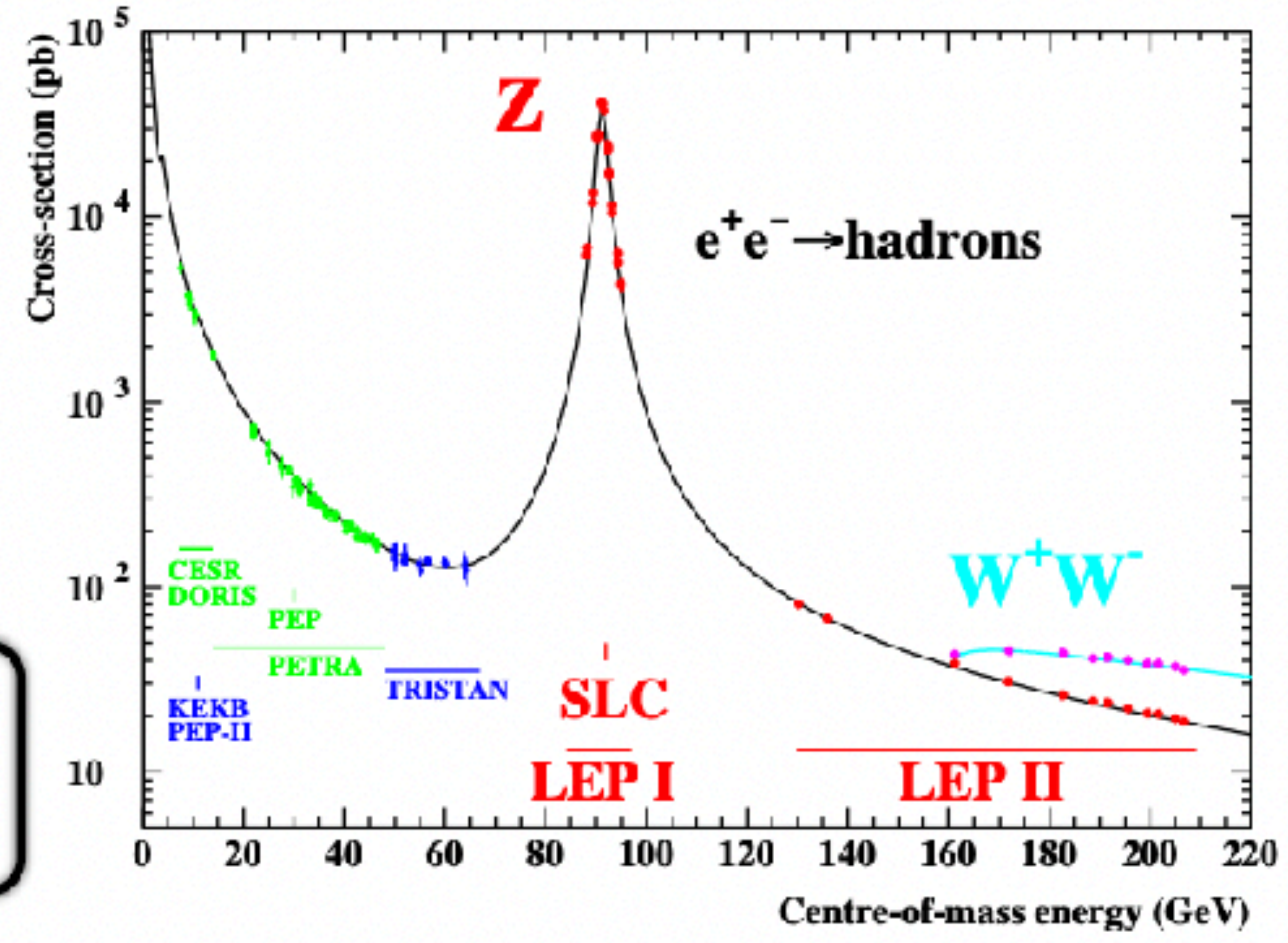
Table from S. Monteil

Precision physics at e⁺e⁻ Electroweak factories

- Future e^+e^- factories will also help us improve our knowledge of the EW interactions:
  - Improved Z pole run:
    - LEP/SLC: ~10^7 Z → O(0.1-1%)
    - FCCee/CEPC: 10^{12} Z
    - ILC (GigaZ): 10^9 Z

Z-pole EWPO:

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$



- Significantly lower stats at linear colliders but can benefit from use of polarization ⇒ Extra observables wrt unpolarized case. E.g. asymmetries

$$A_f = \frac{g^2_{Lf}-g^2_{Rf}}{g^2_{Lf}+g^2_{Rf}} \rightarrow$$

Polarized beams

Unpolarized beams

$$A^f_{FB} = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} = \frac{3}{4}A_e A_f$$

$$A_{LR} = \frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R}\frac{1}{\langle|P_e|\rangle} = A_e$$

$$A^f_{LR,FB} = \frac{3}{4}A_f$$