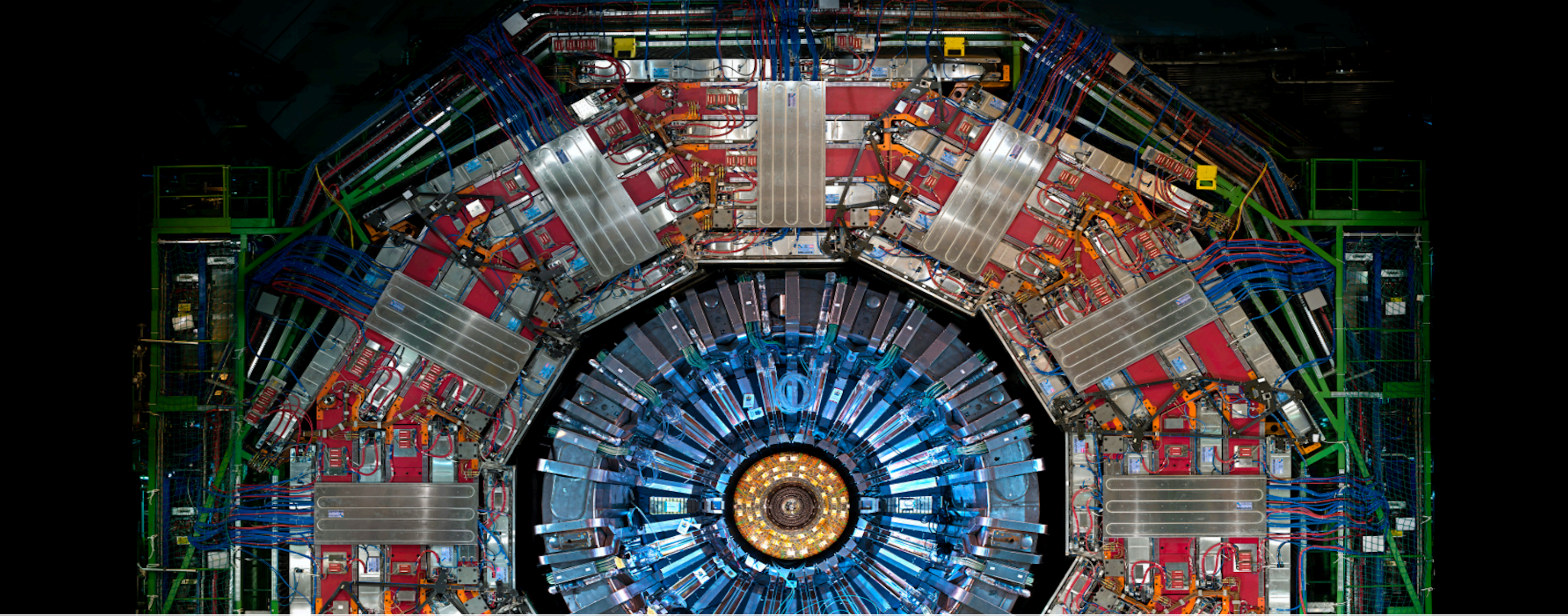


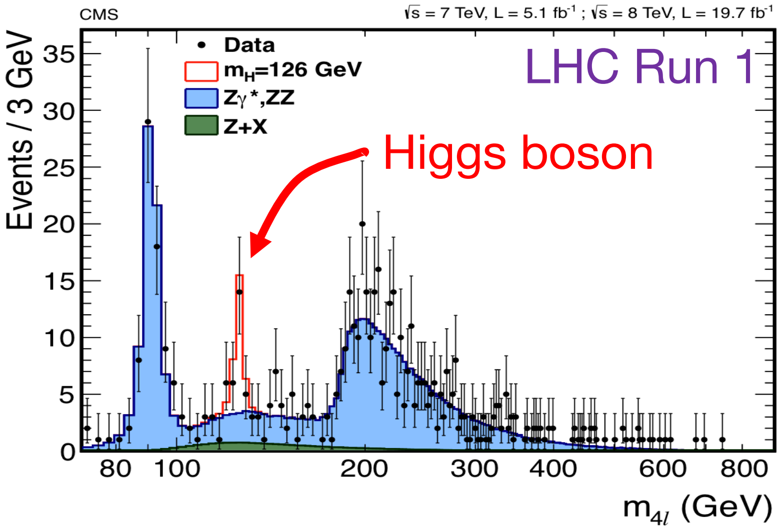
Pushing the frontiers in Higgs physics using Artificial Intelligence

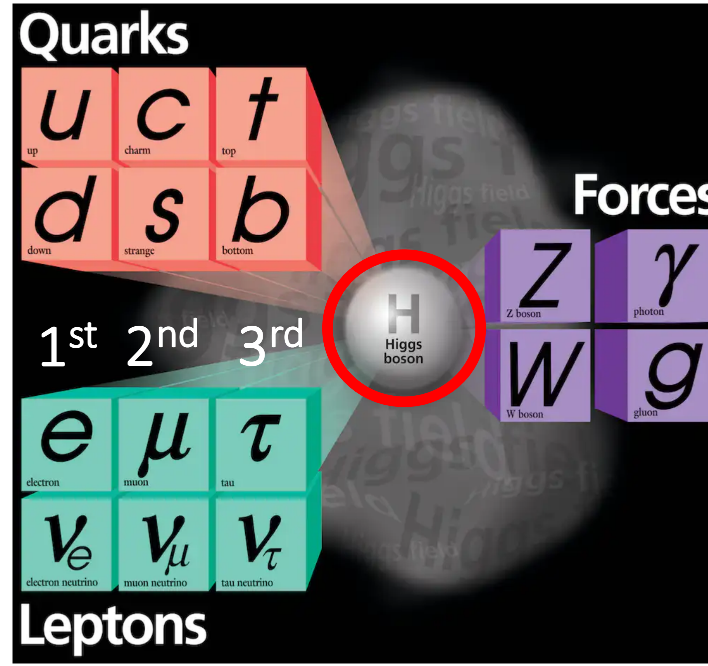
Loukas Gouskos (Brown)

Seminar @SLAC
Nov 21, 2023

July 4th 2012: Higgs discovery

- Discovery of "a/the(?)" **Higgs boson** w/ m_H=125.38±0.14 GeV (~0.2%)





- Completes the Standard Model (SM) of particle physics
- **Plays a central role**: Interacts w/ all massive particles

Higgs as an exploration tool

- “New Physics” (**BSM**) can modify Higgs properties
  - Which precision/sensitivity?

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BSM O(1TeV): Impact on H-couplings

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

Arxiv:1708.08912

$$\frac{v^2}{\Lambda^2} \sim \frac{6\%}{\Lambda^2(\mathrm{TeV})}$$

e.g. Λ=1 (5)TeV→~5 (0.1)%

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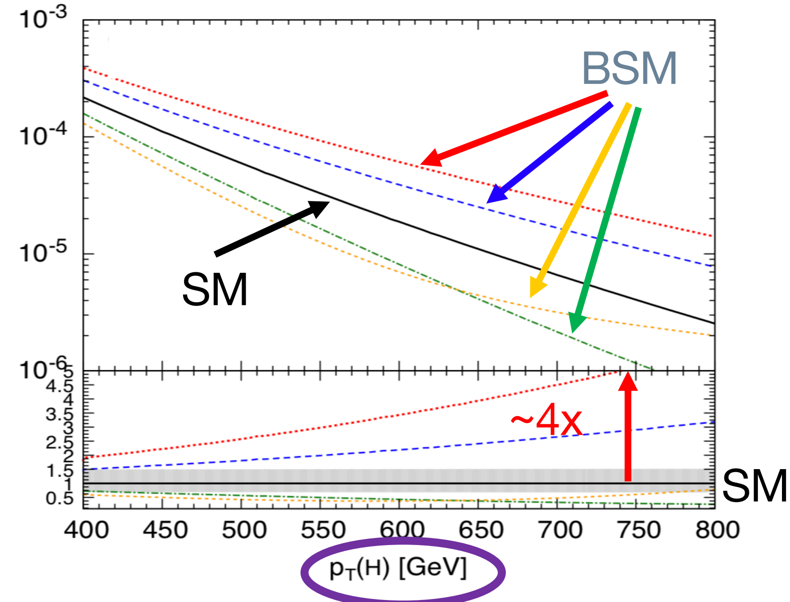
Higgs kinematics



$$\sim \left(\frac{Q}{\Lambda}\right)^2$$

e.g. $p_T(H)$~500 GeV
Λ=1 (5)TeV→~25 (1)%

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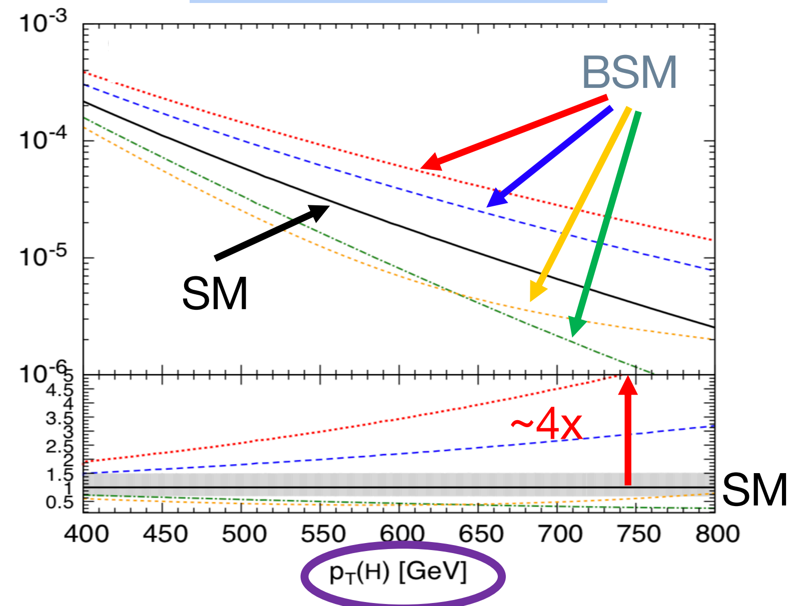


$$\sim \left(\frac{Q}{\Lambda}\right)^2$$

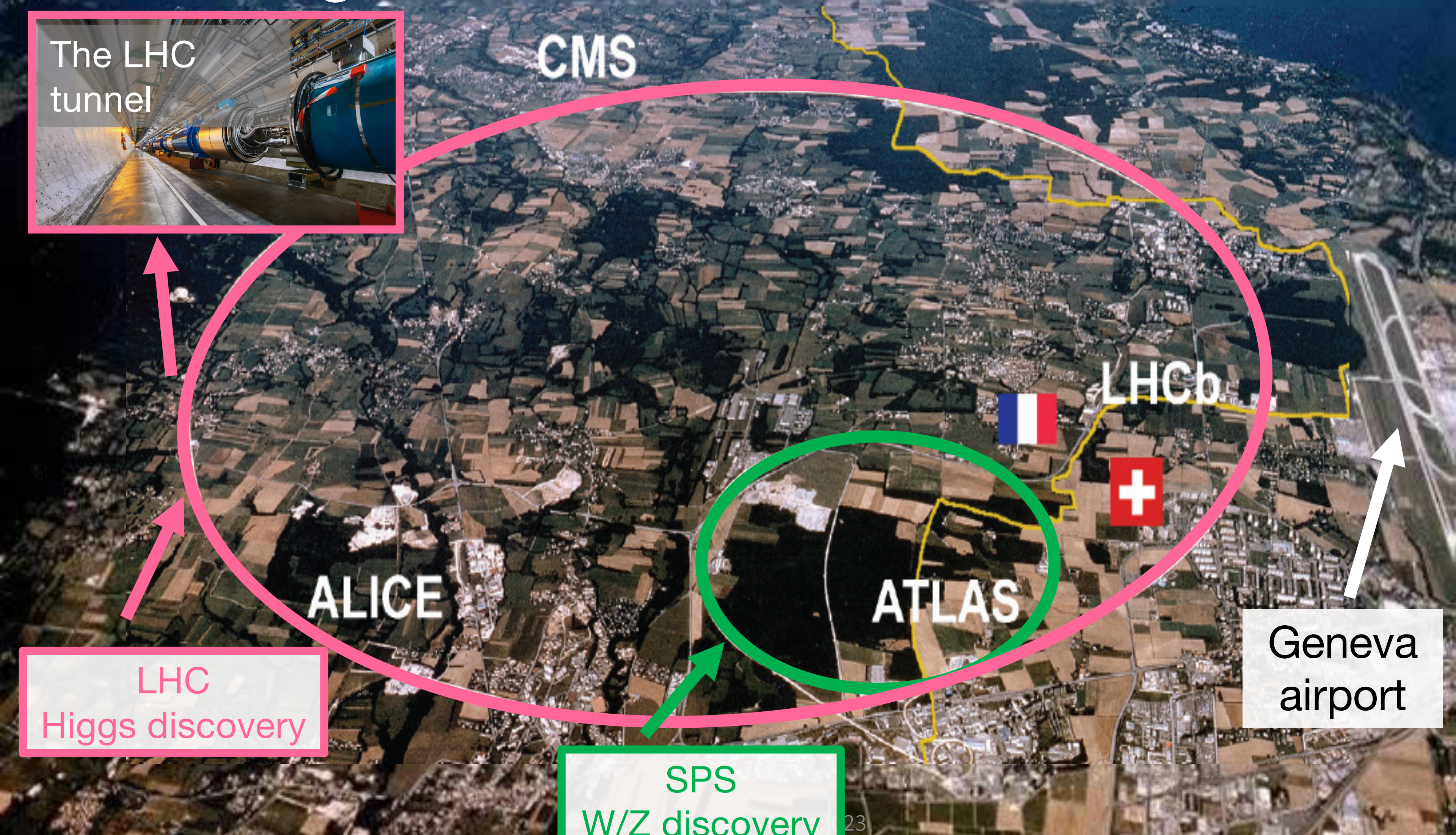
e.g. p_T(H)~500 GeV
Λ=1 (5)TeV→~25 (1)%

The discovery of the Higgs boson opens a whole new chapter of exploration

Outline:

- **Introduction:** LHC and CMS experiment
- **Higgs physics:** current status
- **Jet tools:** Review of a decade and recent developments
- **Challenging Higgs** interactions
    - Higgs-charm coupling
    - Higgs pair production
- **Summary and outlook**

The Large Hadron Collider at CERN



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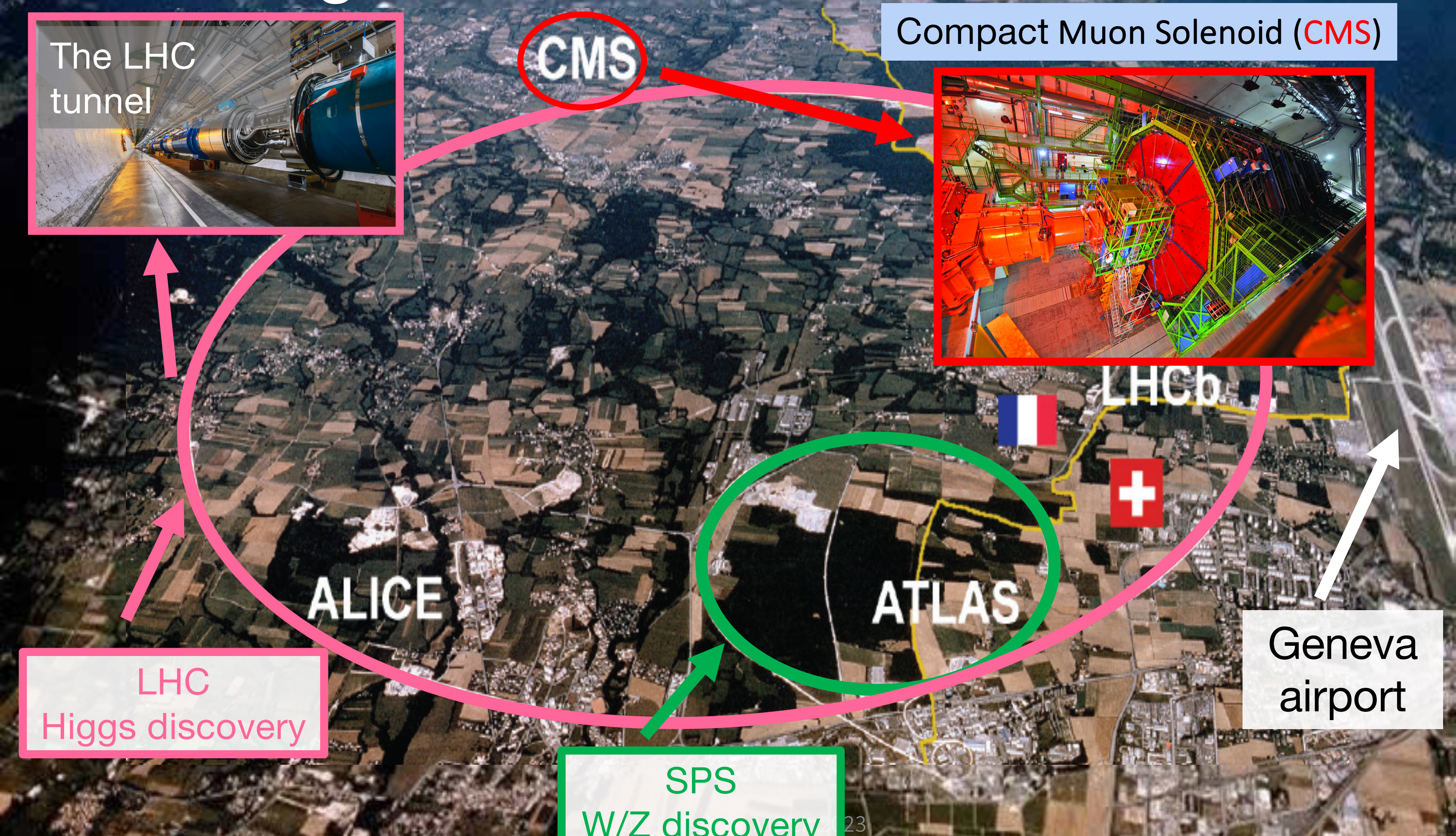
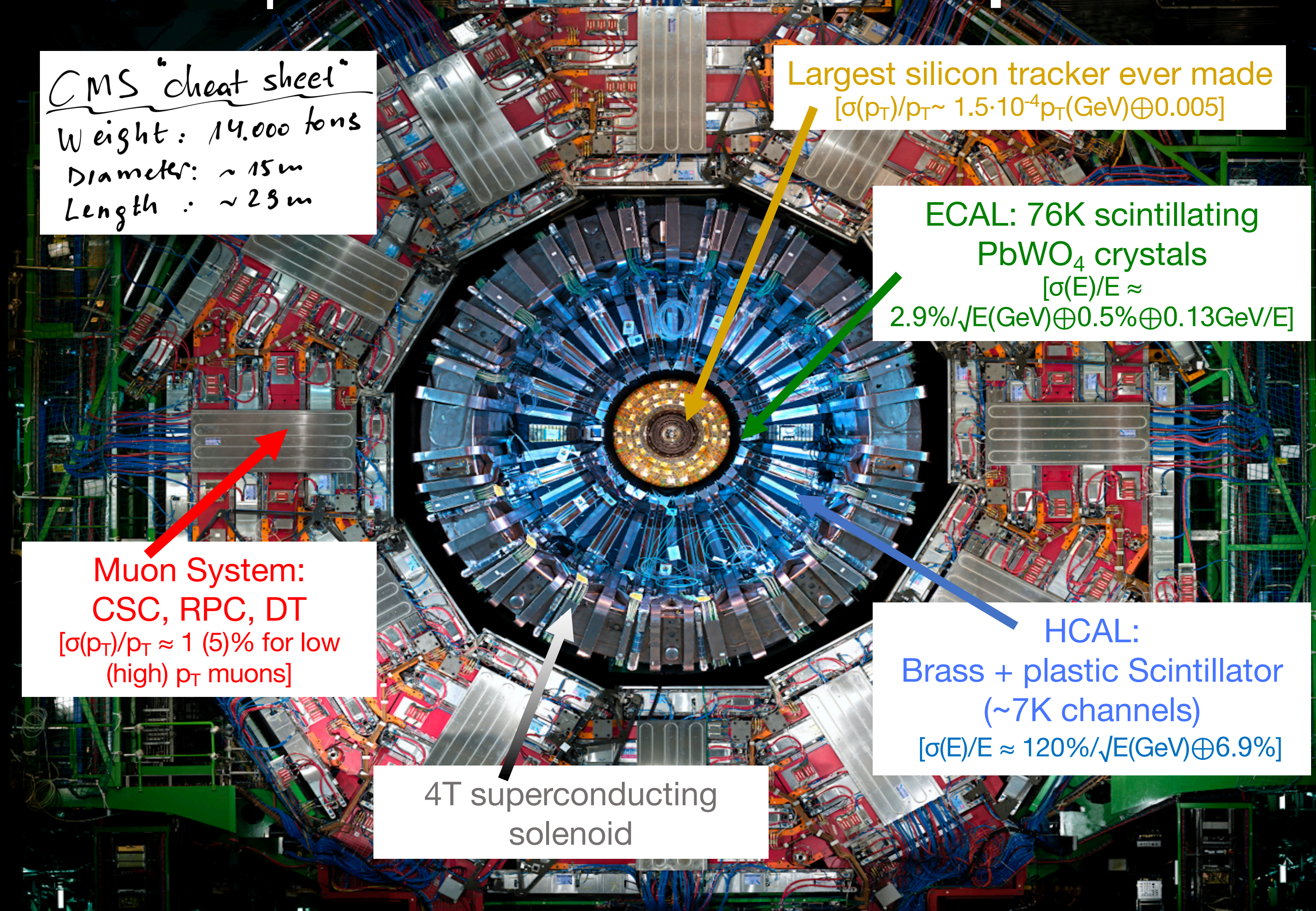
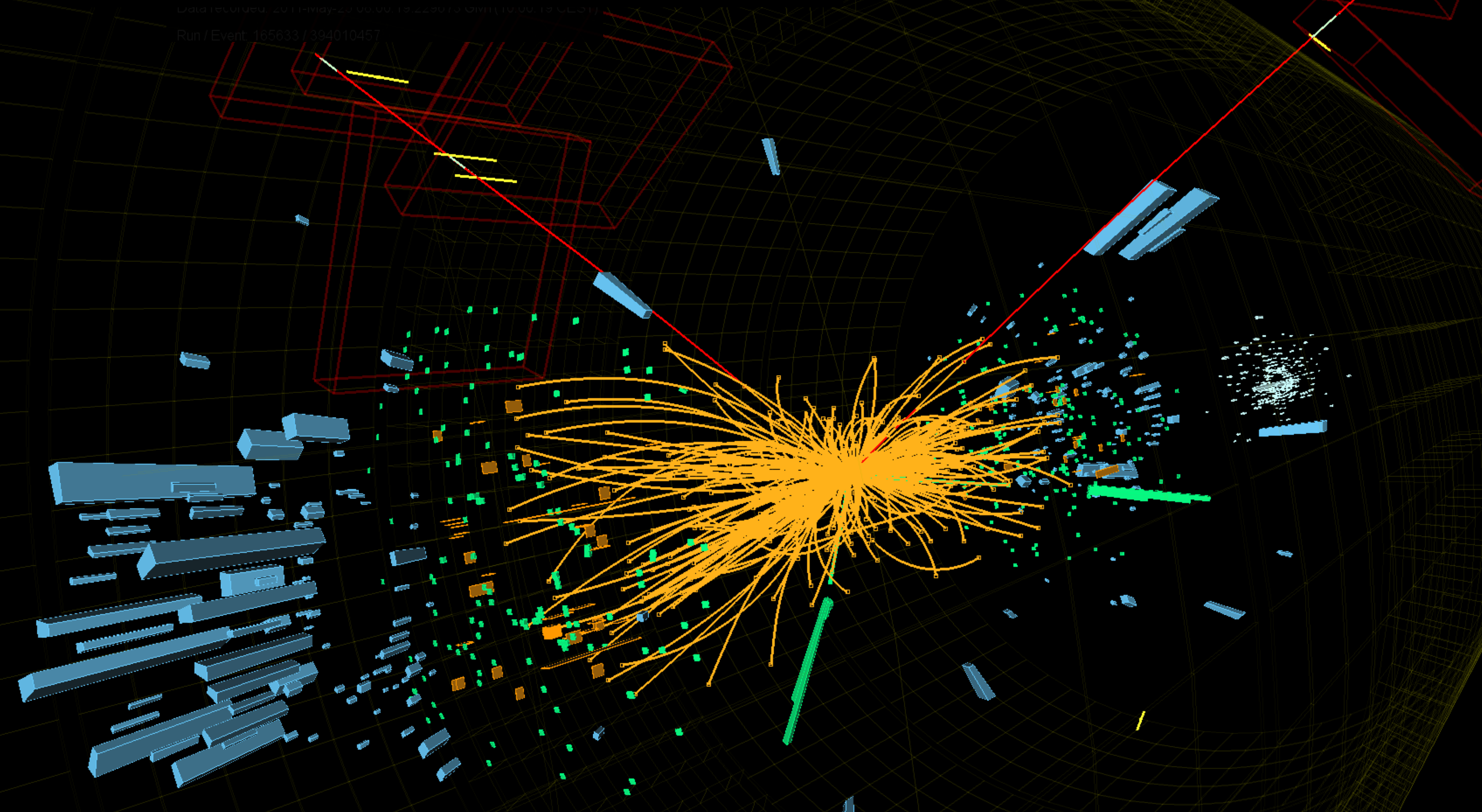


The Compact Muon Solenoid experiment

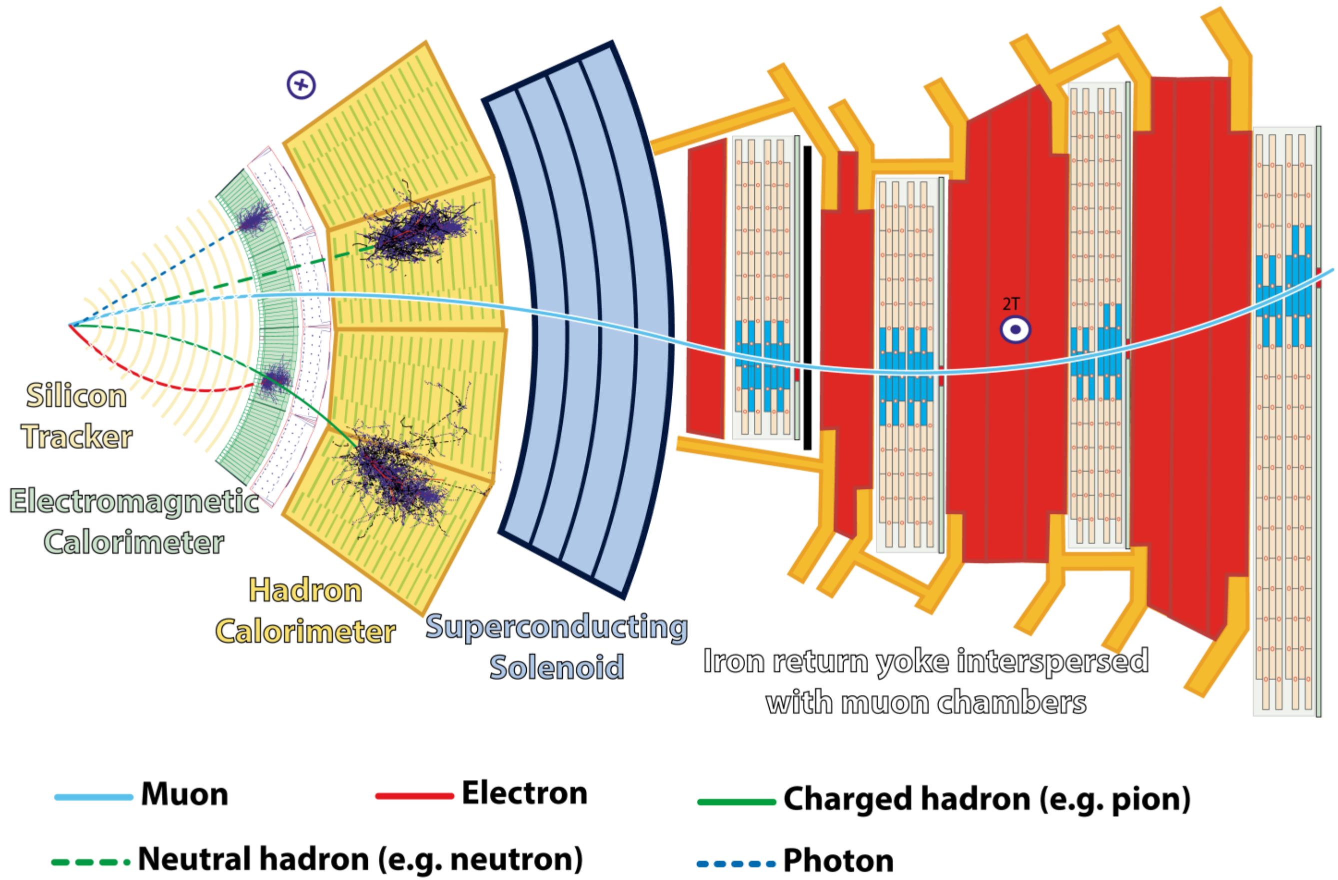


A collision event at CMS



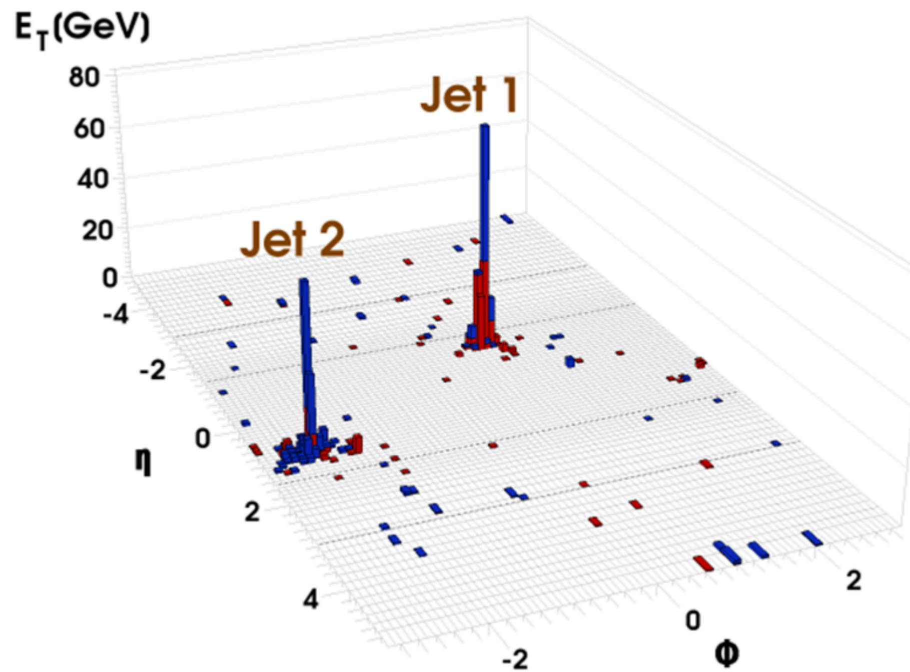
CMS event reconstruction

- Combines information from all subdetectors
  - Provides mutually exclusive list of particles



Jet reconstruction

- A Jet in theory:
  - Quarks and gluons carry color and interact via the strong force
    - QCD confinement allows only colorless states
  - Jet is seen as a spray of hadrons produced by the hadronization of quarks & gluons [forming bound states]

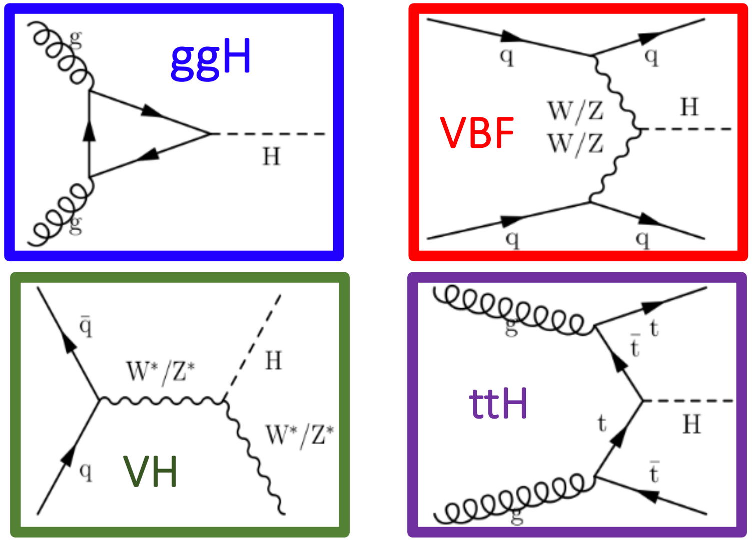


- Experimentally:
  - Cluster the reconstructed particles in the detector
  - softer-particles cluster around the hardest ones

Higgs boson:
Current status & next milestones

LHC: A Higgs factory

Production

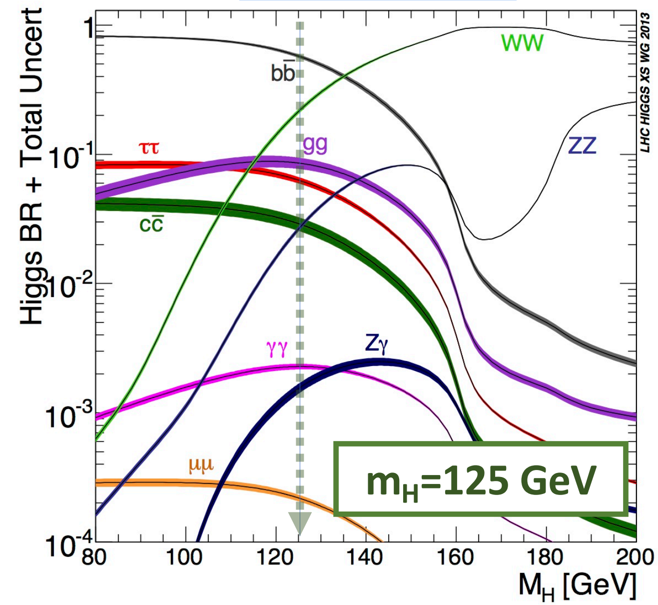


Production	#Higgs Run 2
ggH	7M
VBF	500K
VH	300K
ttH	70K

~1Higgs/sec

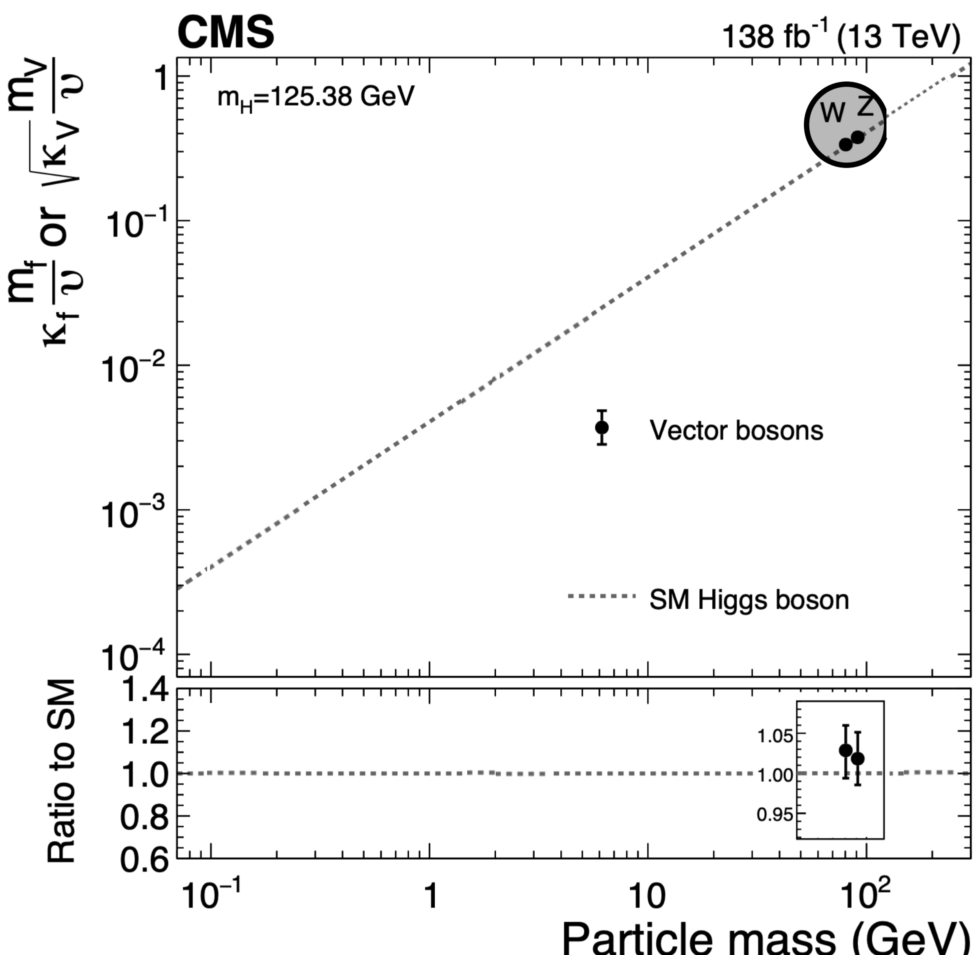
* for comparison: ttbar: 100 M, QCD: 10^{10} M

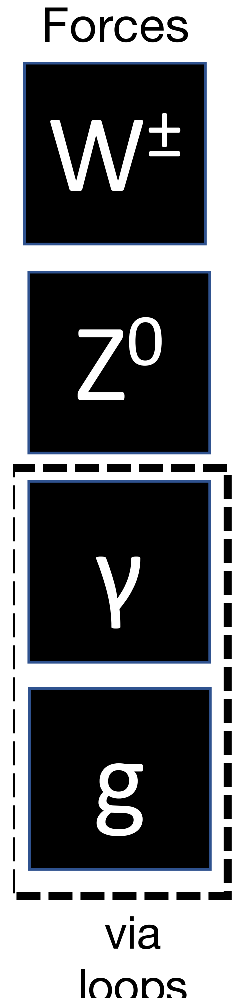
Decay



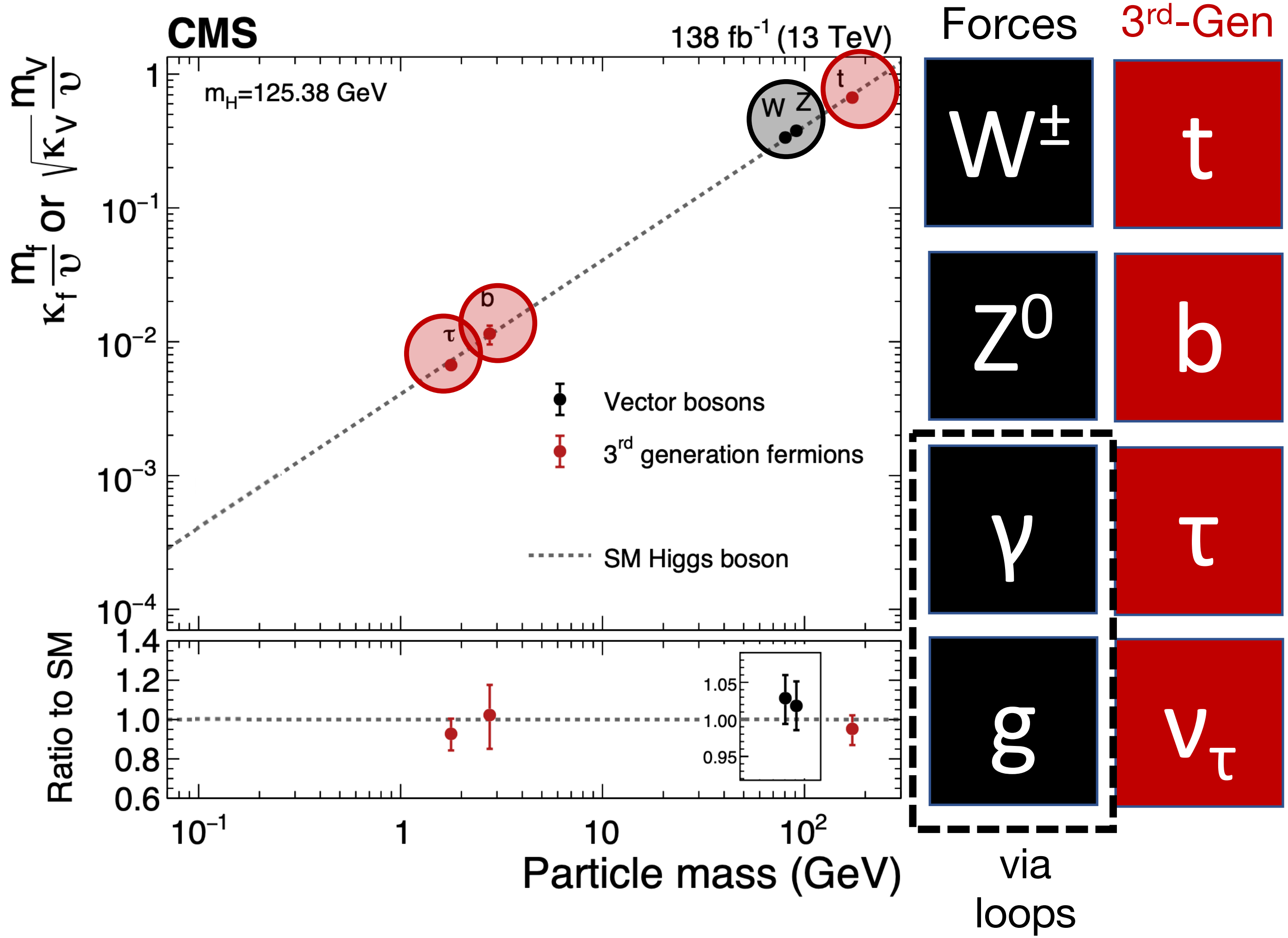
Decay	BR [%]
bb	60%
WW	20%
ττ	6%
cc	3%

Flash back: Run 1

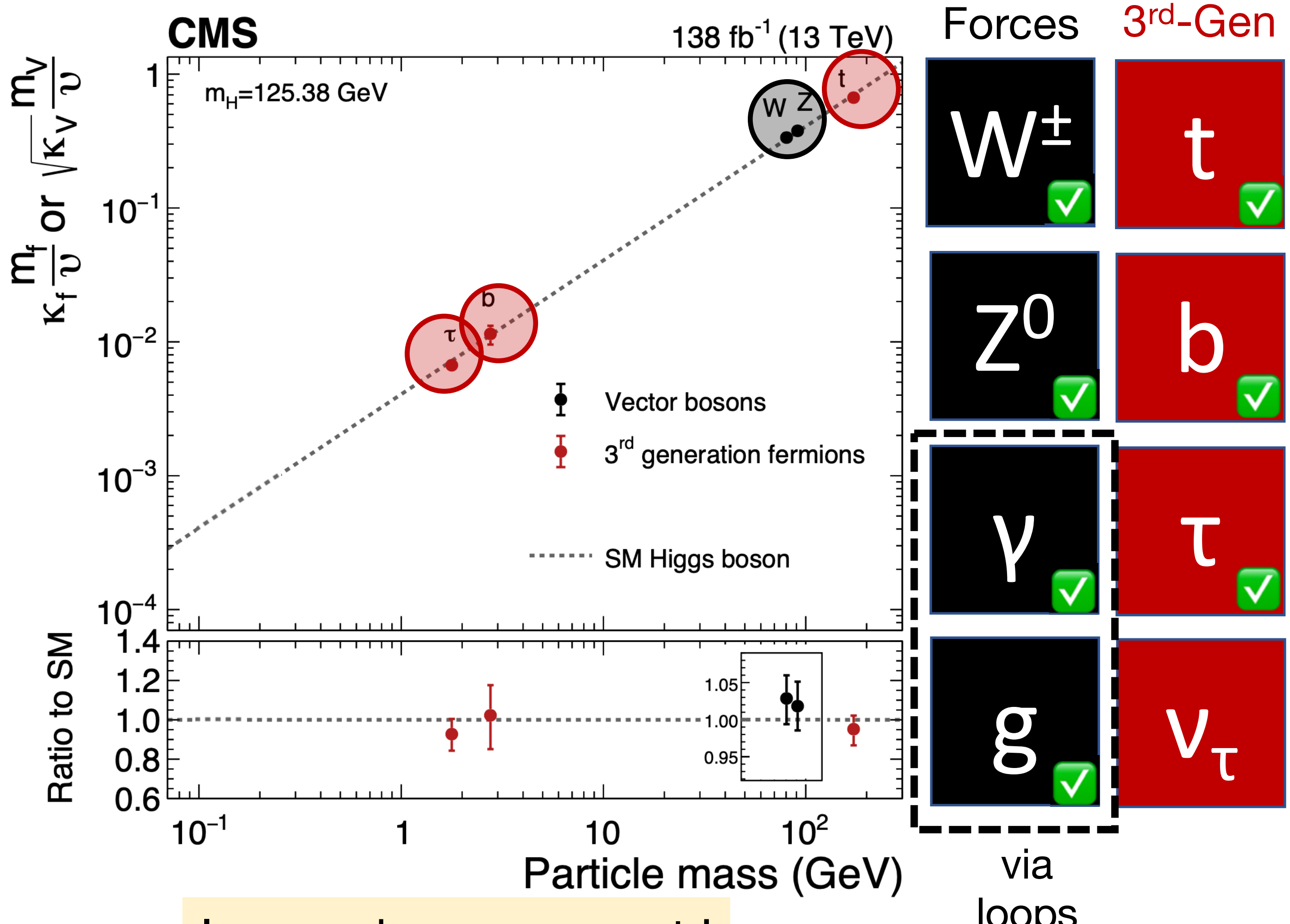




Flash back: Run 2

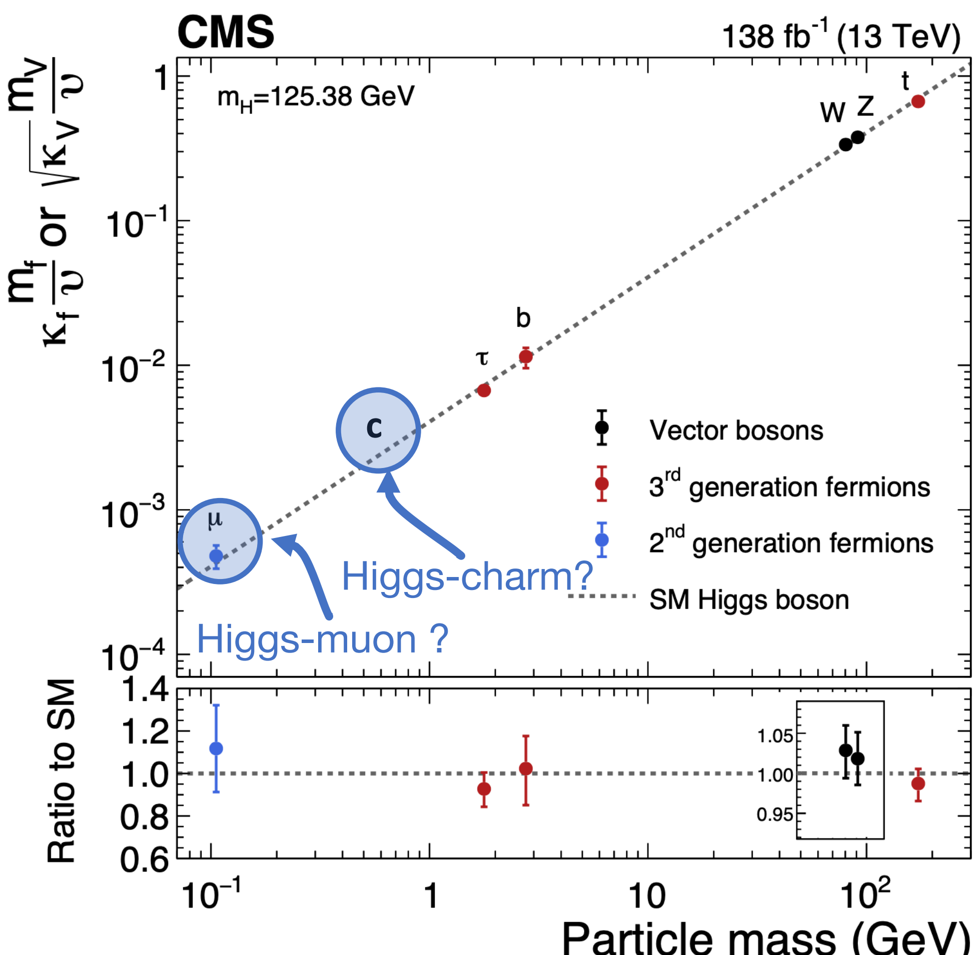


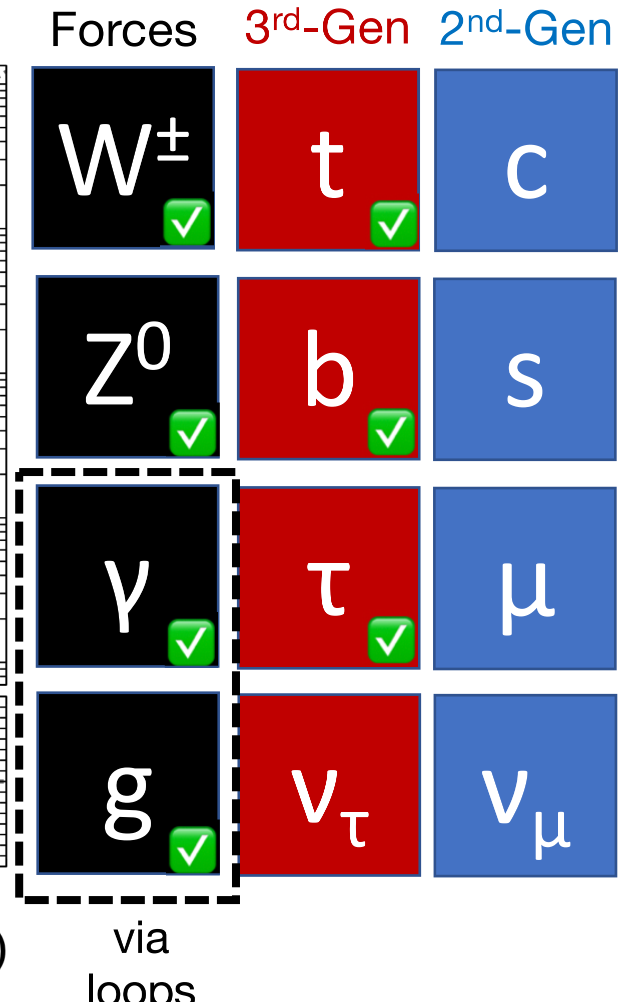
Flash back: Run 2



Impressive agreement !

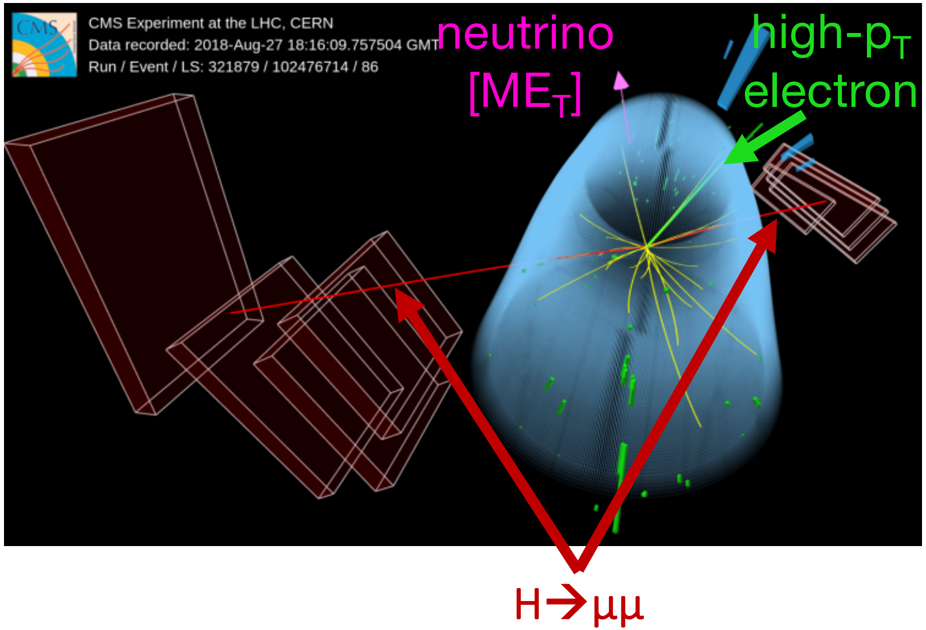
Next stop: 2nd-Gen

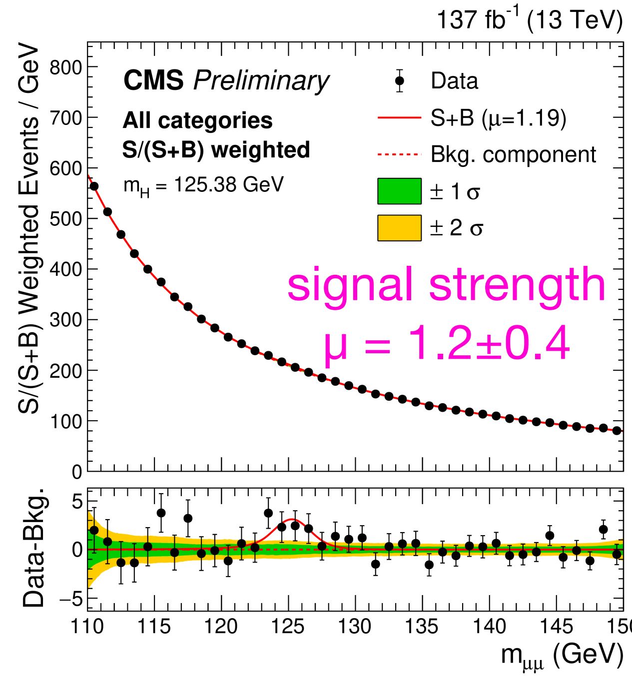




Next stop: 2^{nd}-Gen::H-μ coupling

W(→eν)H(→μμ) @13 TeV





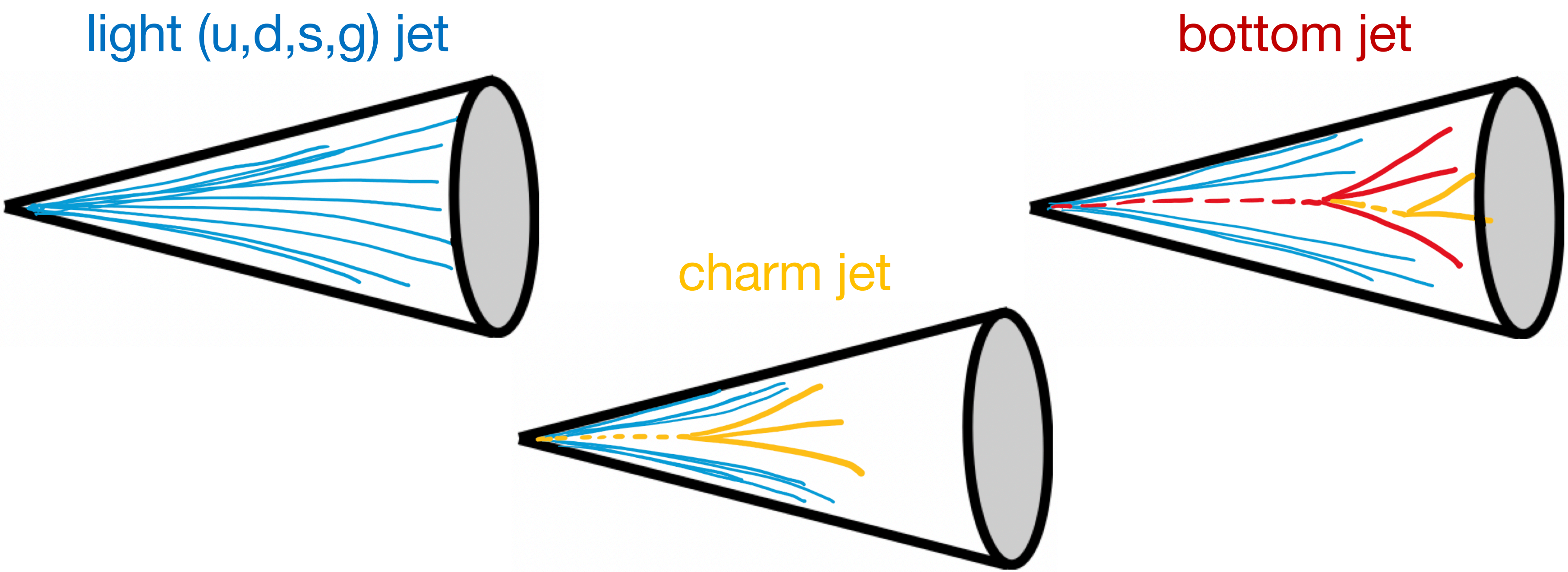
Evidence of Higgs coupling to 2^{nd} generation leptons

CMS: obs: 3σ (exp: 2.5 σ)
ATLAS: obs: 2σ (exp: 1.7 σ)

Towards Higgs-charm coupling

Mission: Impossible (?)

- Similar concept to H→bb but two big challenges
  - **Small BR (H→cc):** ~20x smaller than BR(H→bb)
  - **Charm-quark identification** much more challenging than for **b quarks**



Incredibly hard to search for @LHC
Needs novel tools and techniques [& HL-LHC]

Mission: Impossible (?)

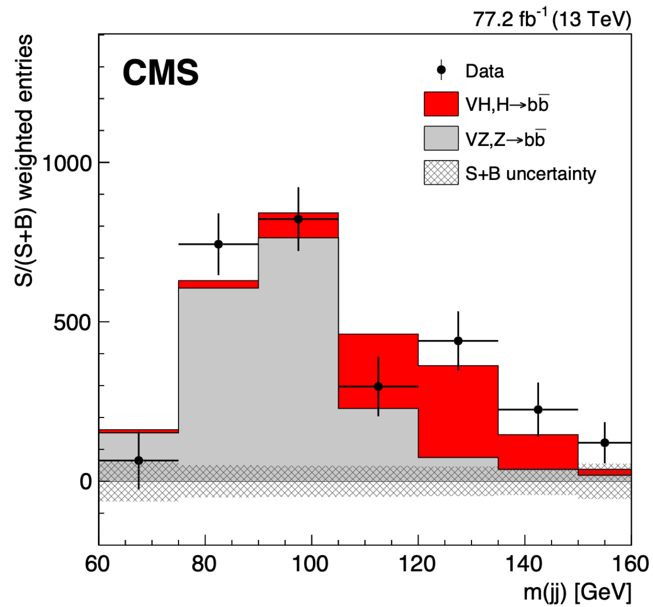
- Similar concept to H→bb but two big challenges
  - **Small BR (H→cc):** ~20x smaller than BR(H→bb)
  - **Charm-quark identification** much more challenging than for **b quarks**

But: Often exceed expectations

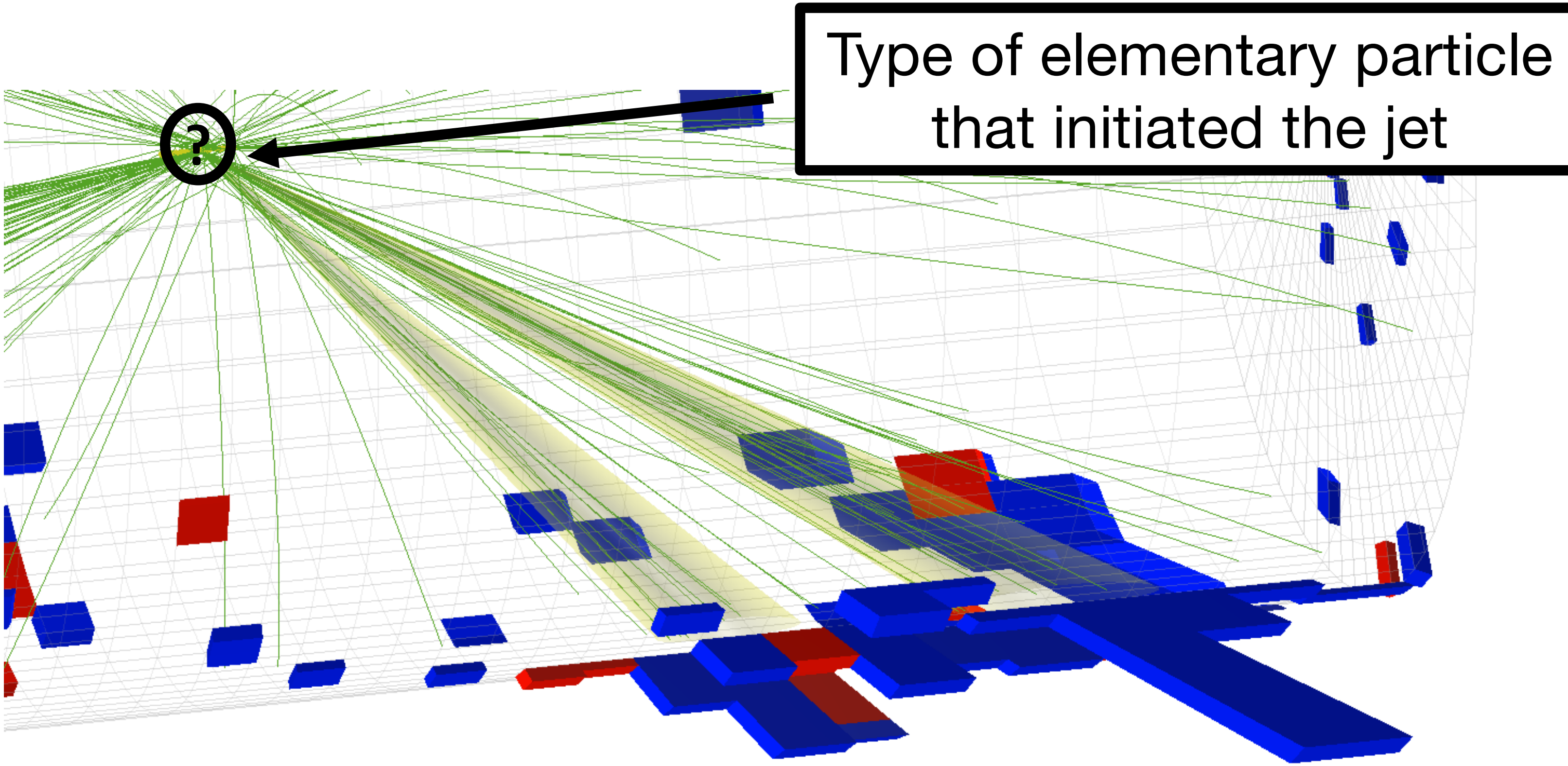
"In conclusion, the extraction of a signal from H→bb decays in the *WH* channel will be very difficult at the LHC, even under the most optimistic assumptions for the b-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself."

*ATLAS Technical Design report (1999)
- feeling not different in CMS

H→bb observation



Jet identification ("tagging")



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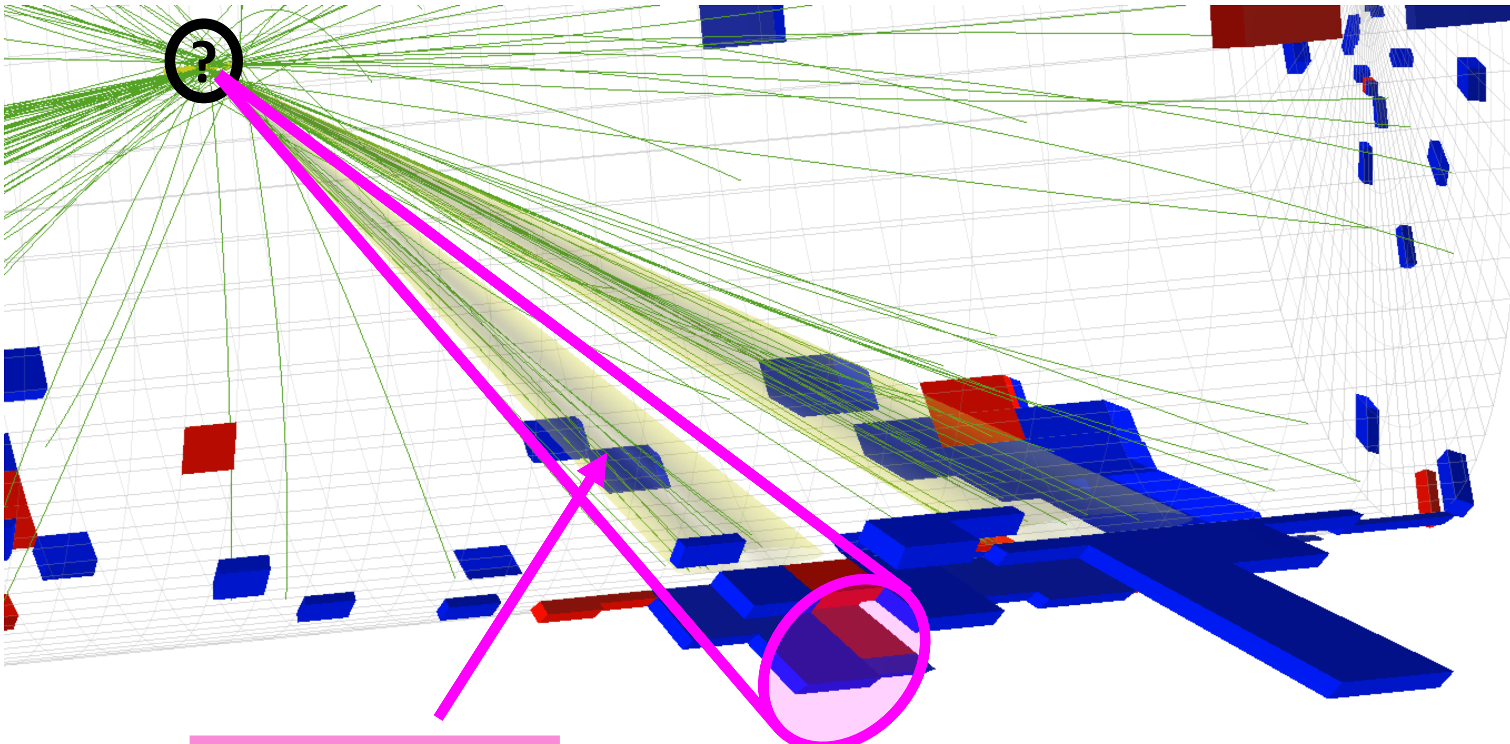
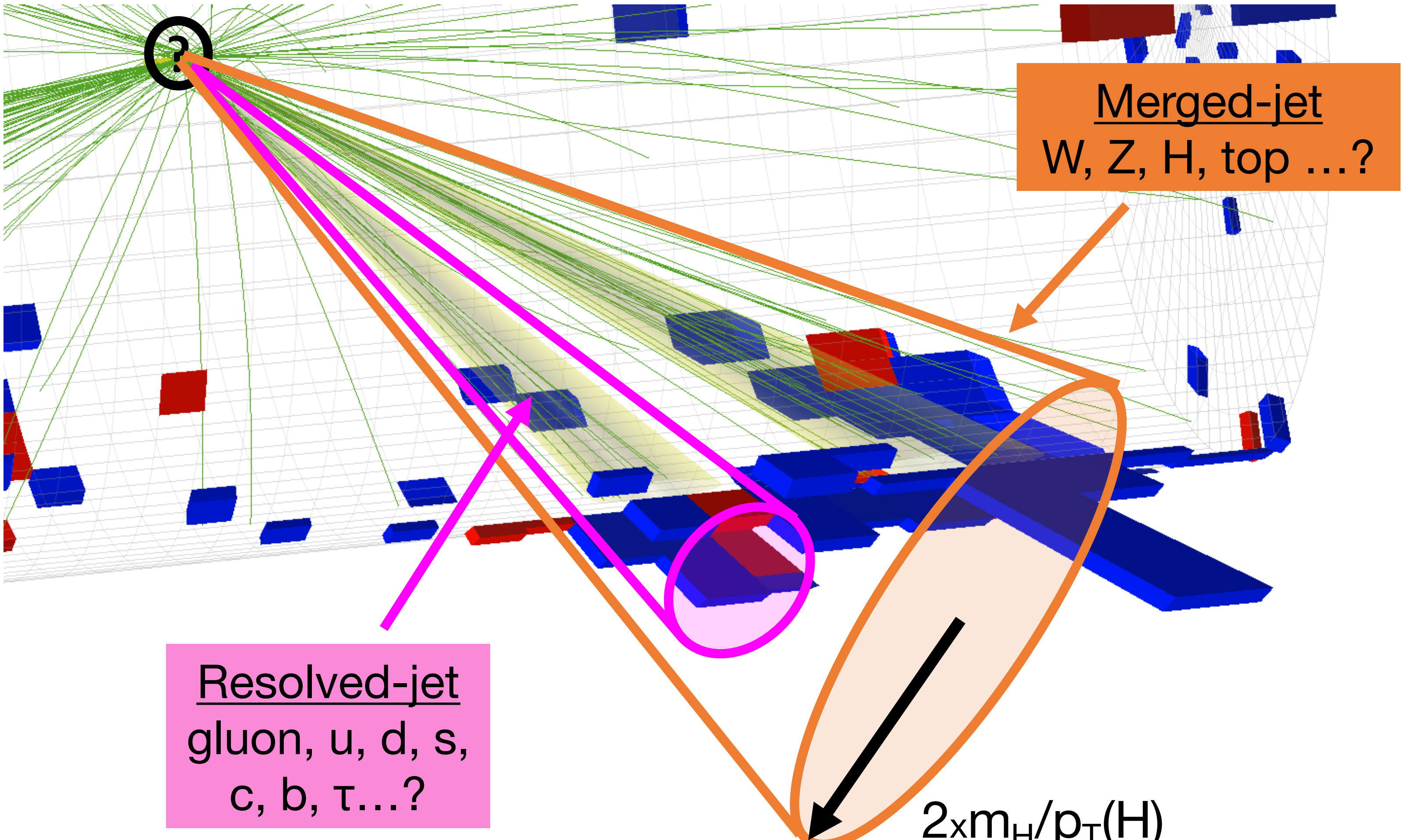
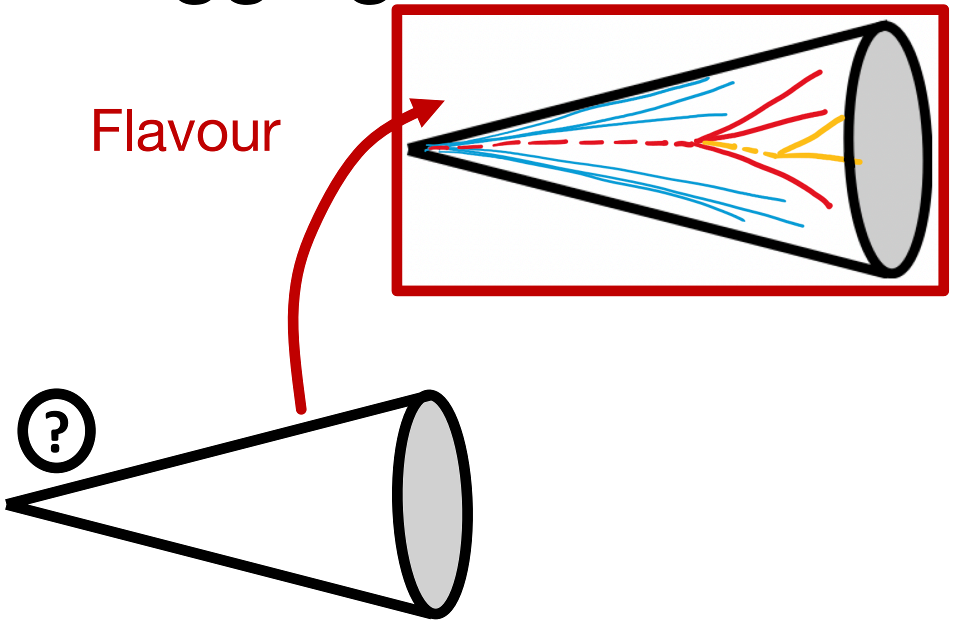


Resolved-jet
gluon, u, d, s,
c, b, τ…?

Jet identification ("tagging")

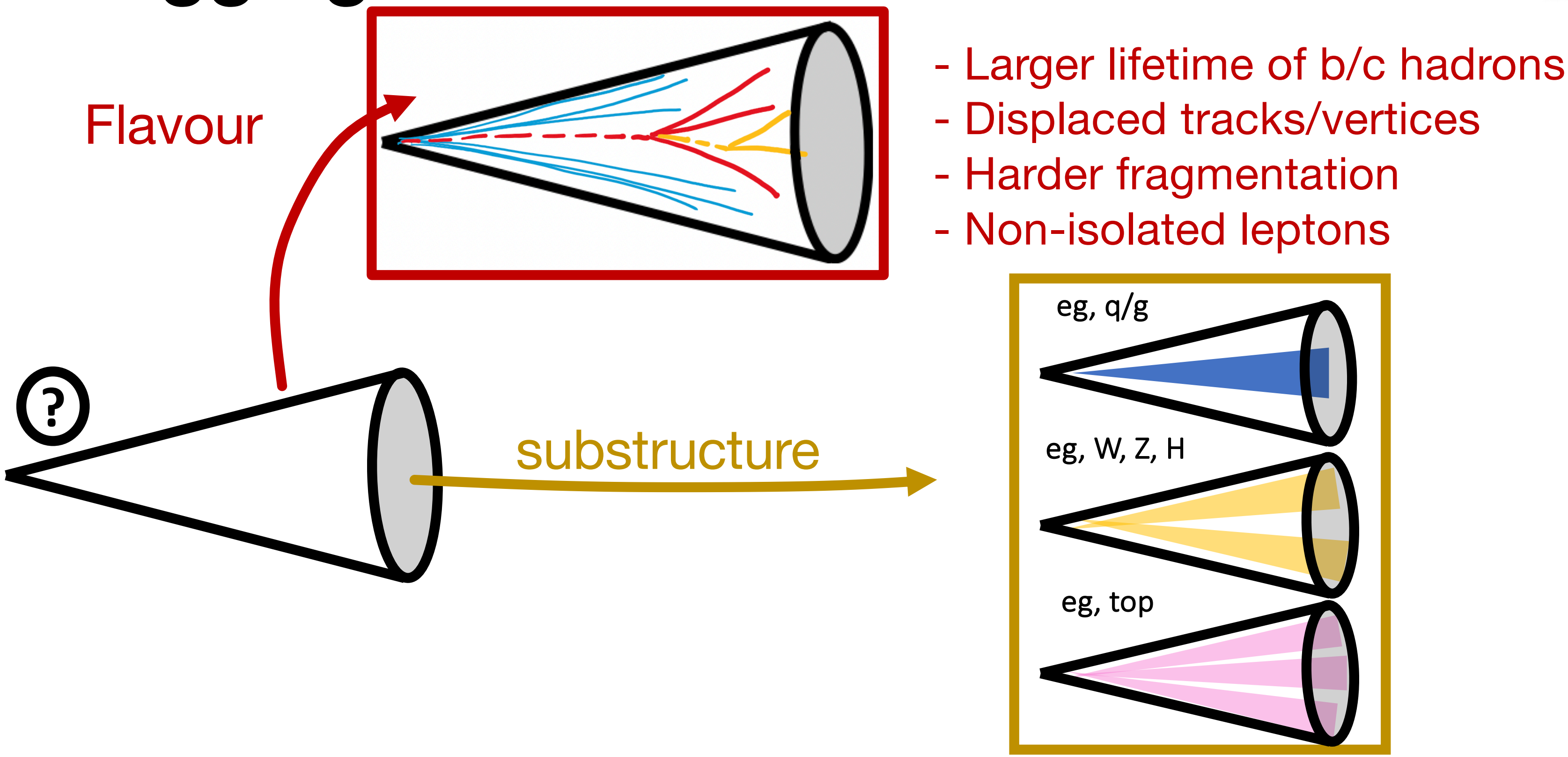


Jet tagging basics



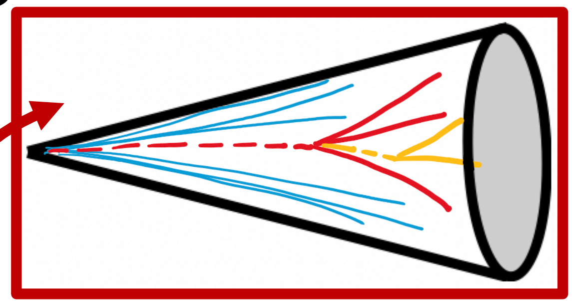
- Larger lifetime of b/c hadrons
- Displaced tracks/vertices
- Harder fragmentation
- Non-isolated leptons

Jet tagging basics



Jet tagging basics

Flavour



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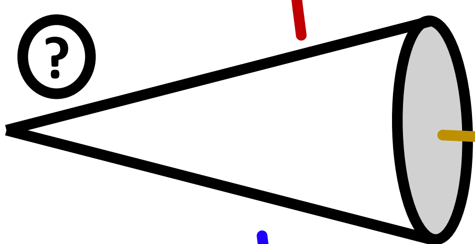
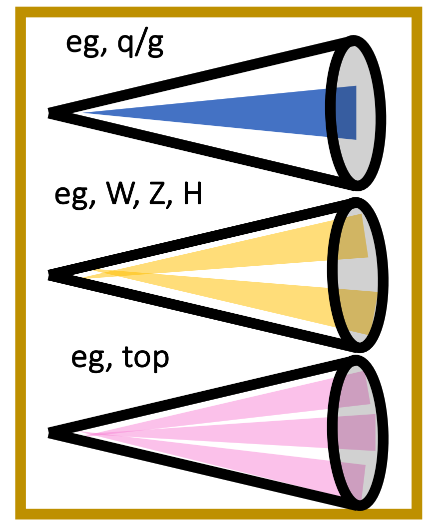
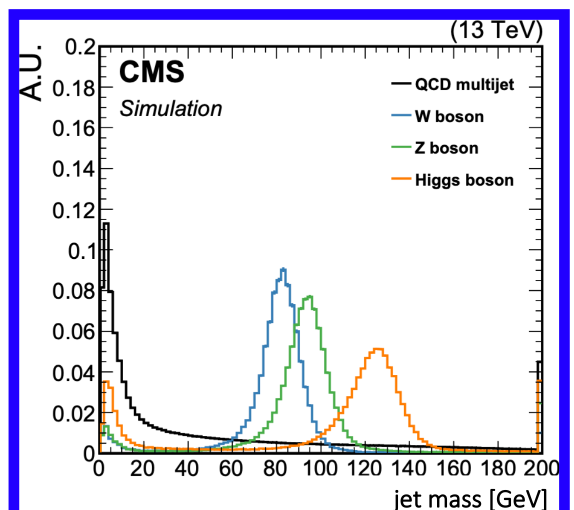


substructure



Jet mass



Light q/g: m(jet)→0 GeV

Higgs: m(jet)→125 GeV

Jet tagging basics

Flavour

- Larger lifetime of b/c hadrons
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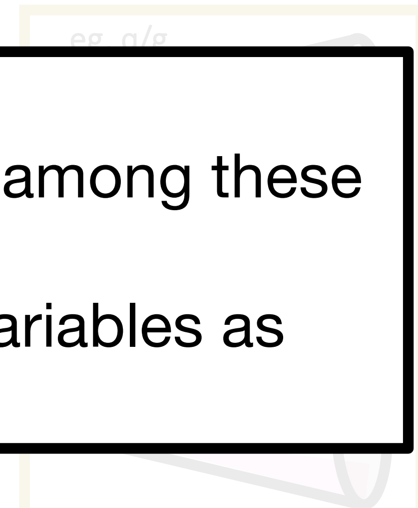
- Non-isolated leptons

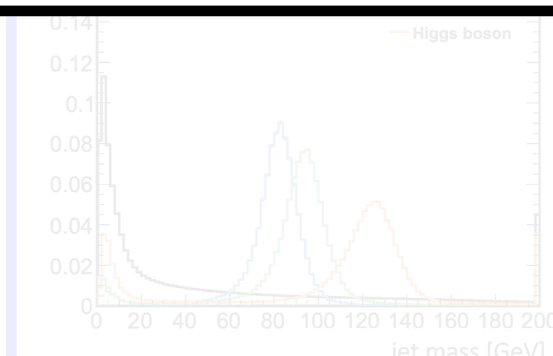


- In the beginning:
unclear <u>what correlations</u> existed among these
- Early days:
Algorithms based on High-level variables as input to simple ML

Jet mass

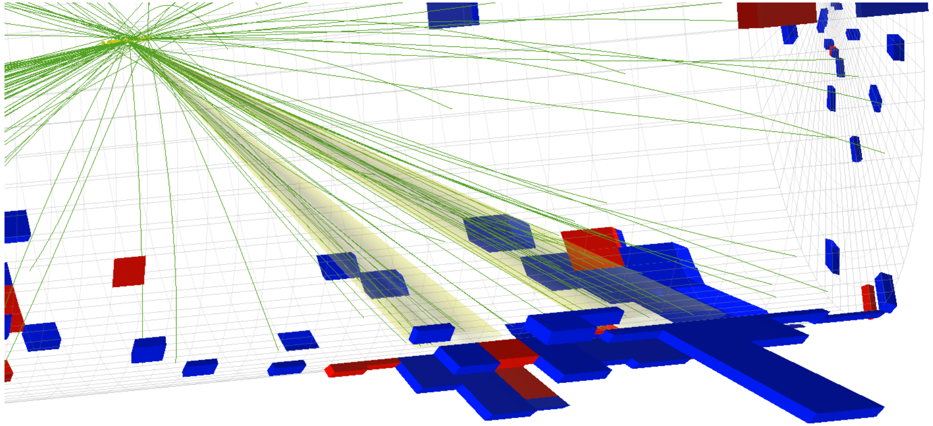
Light q/g: m(jet)→0 GeV

Higgs: m(jet)→125 GeV



Exploring more of CMS potential

- But: highly collimated decay products
  - difficult to identify patterns



- Towards **particle-based** jet tagging
  - CMS PF algo: Rich set of info / particle
    - Energy/momentum
    - Position

      → Jet substructure
    - Particle type
    - Displacement from PV
    - Reconstruction quality
    - ....

      → Flavour

Facts:
- O(50-100) particles per jet
- O (50) features per particle

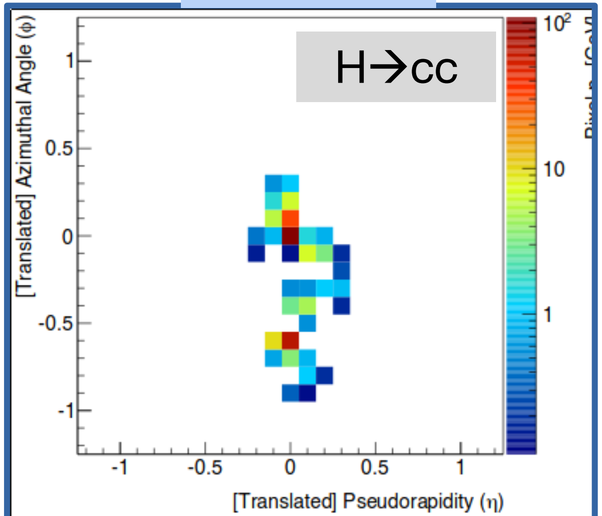
~O(1000) inputs/jet

- Ideal case for Deep Learning (DL) based algorithms with low-level inputs

Exploring more of CMS potential

- Latest approach: **Jet tagging** using jet constituents directly
- Then: use Deep Learning (DL) → Key: Jet representation

Jet Image



detector → camera
jet → image
Cons: - sparse images
- heterogeneous detectors

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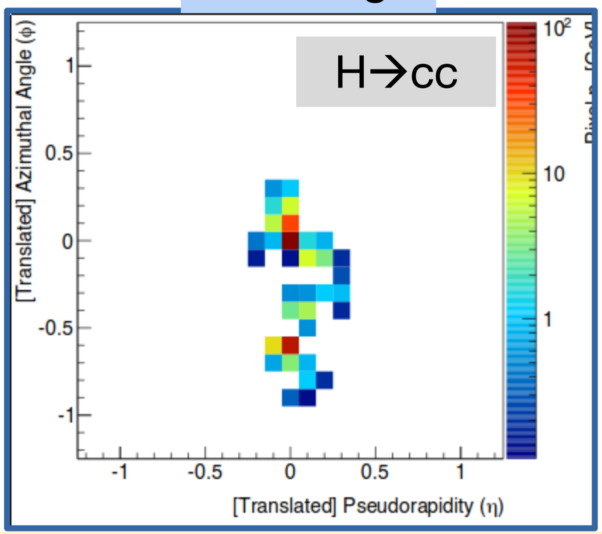

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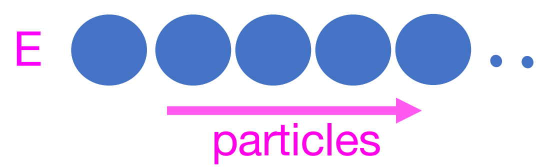
Particle Sequence



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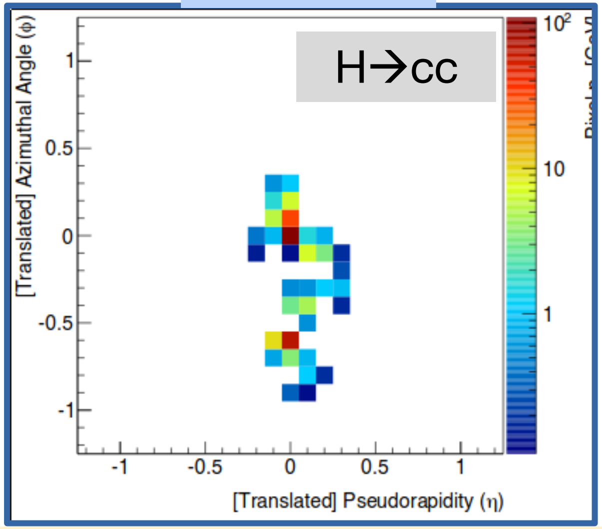

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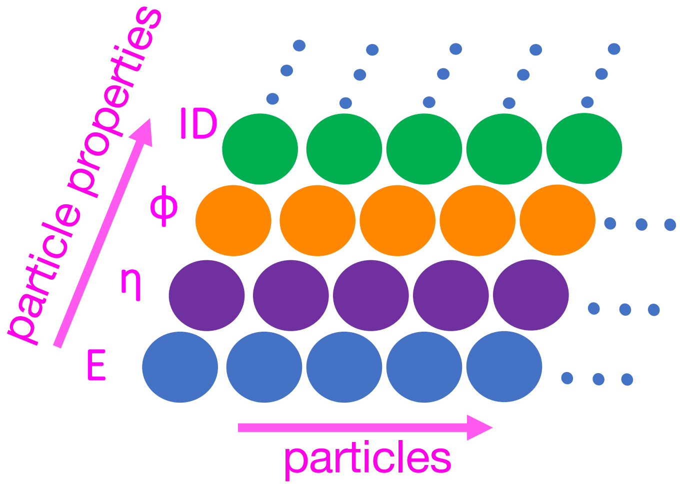
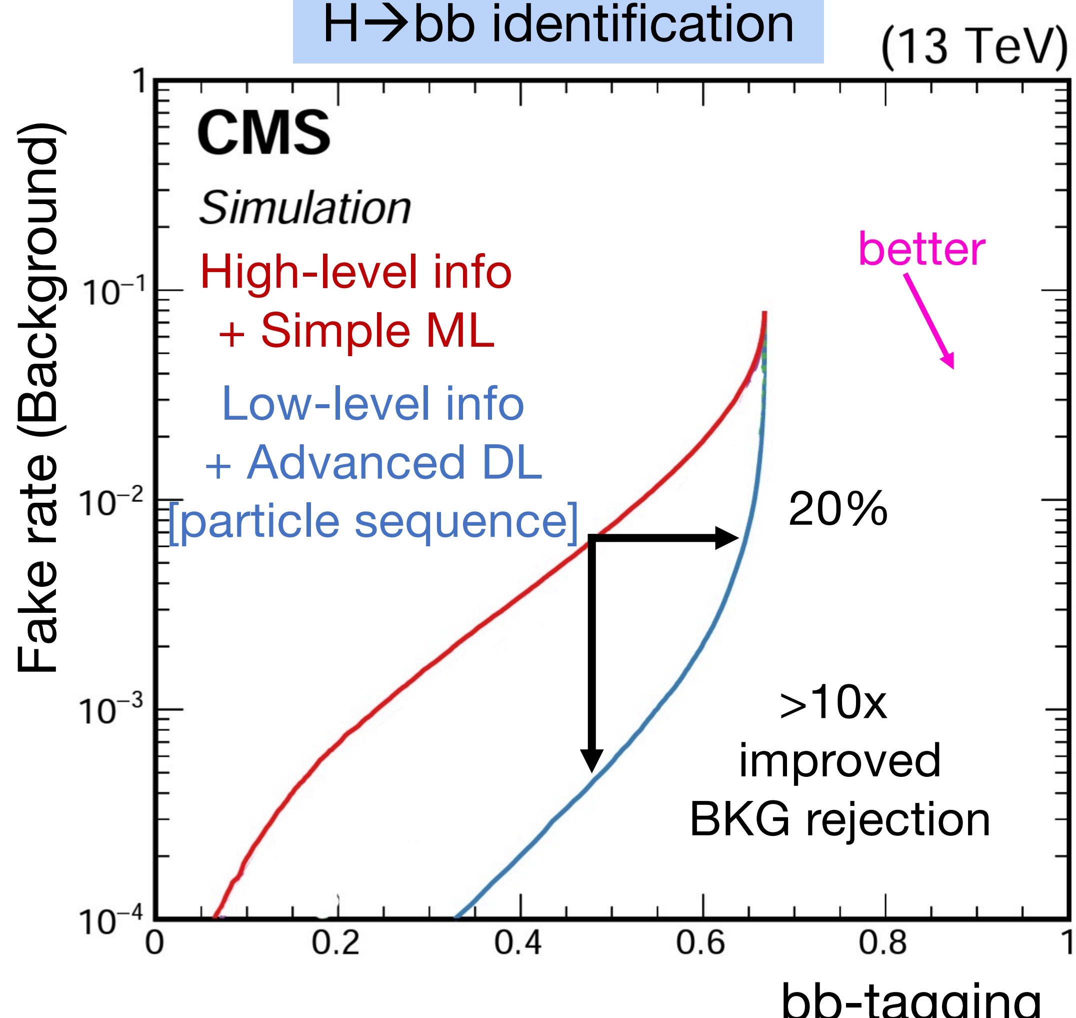


Optimal exploration of detector granularity & event reconstruction potential

A game changer

H→bb identification

NeurIPS 2017
CMS-DP-2017-049
JINST 15 (2020) P06005



Pushing the limits in jet tagging

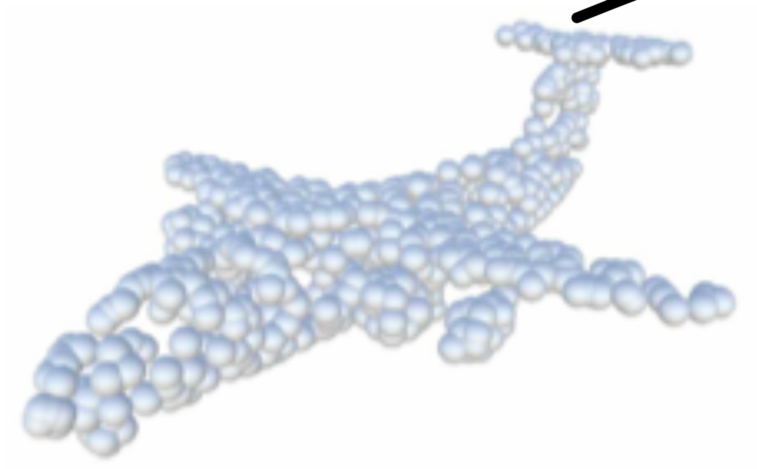
Pushing the limits in jet tagging

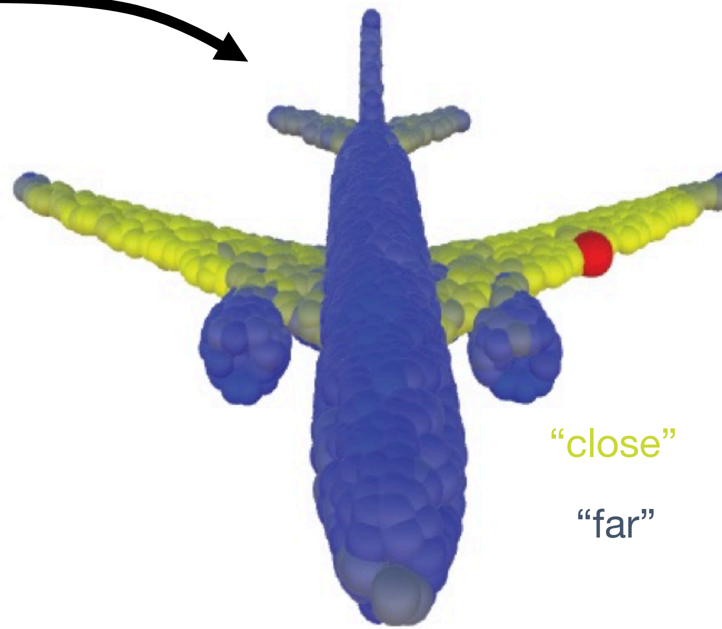
- "Point clouds": Objects represented as unordered set of points

Point clouds

Represent the object as a set of "points"

Group points based on similarity [usually using ML] e.g. Identify the wings

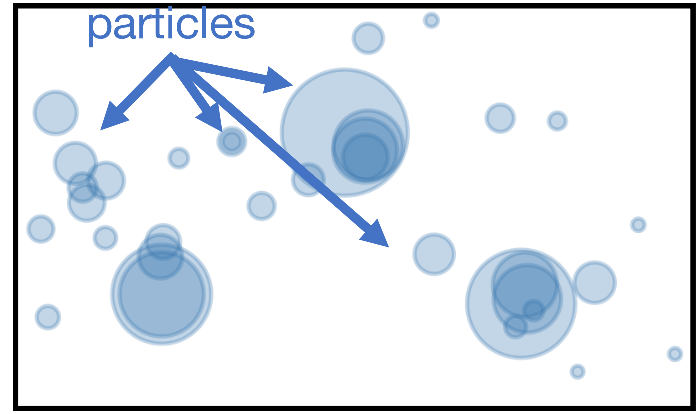




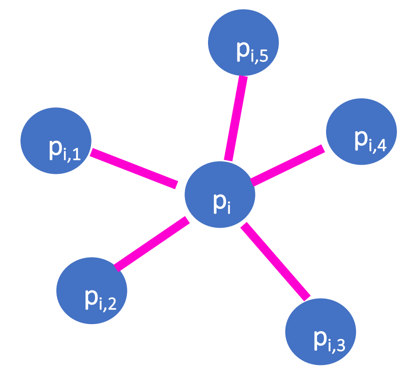
ParticleNet

H. Qu and LG
PRD 101 056019 (2020)

- Improved jet representation:
  Particle Sequences → Particle Clouds
  - Treat the jet as an unordered set of particles



- Improved Network architecture:
  Graph Neural Networks
  - Particle cloud represented as a graph
  - Each particle: **vertex** of the graph;
    Connections b/w particles: the **edges**

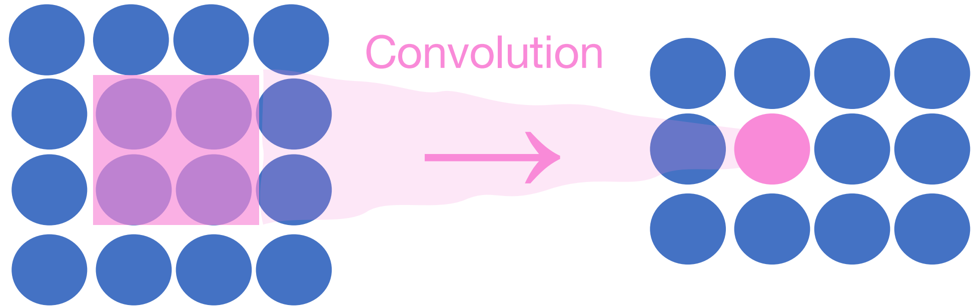


- Learn from the Graph
  Follow a hierarchical approach
  - First local structures → then more global

Extracting info from an image

- Convolution operations proven to be very powerful

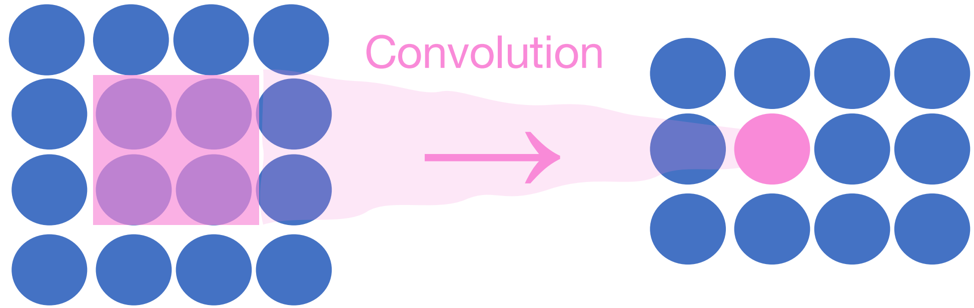
Fixed grid:



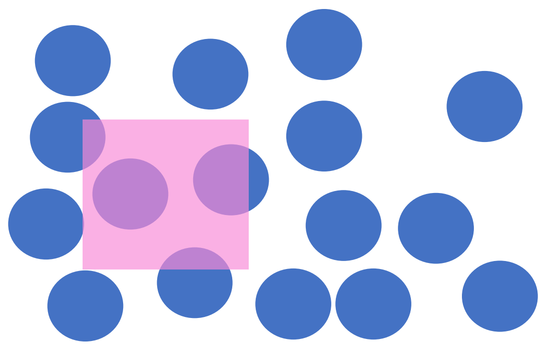
Extracting info from a cloud

- Convolution operations proven to be very powerful

Fixed grid:



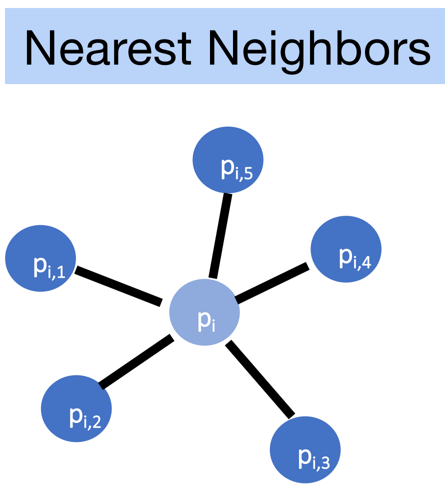
particle cloud:



not straight forward …
- Irregular and unordered sets
- Requires permutation invariant convolutional operation

Convolution on particle clouds

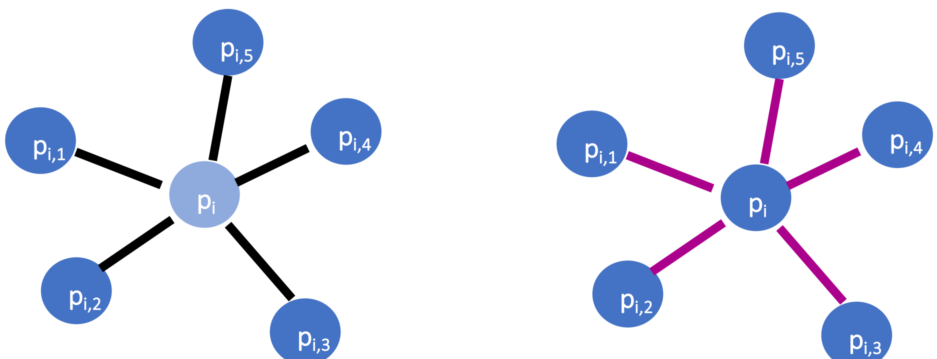
- Find the *k*-nearest **neighbors** of each particle



Convolution on particle clouds

- Find the *k*-nearest **neighbors** of each particle
- Design a permutation invariant convolution operation
  - Define **edge feature** function → **aggregate** edge feat. w/ symmetric func.

Nearest Neighbors | Convolution



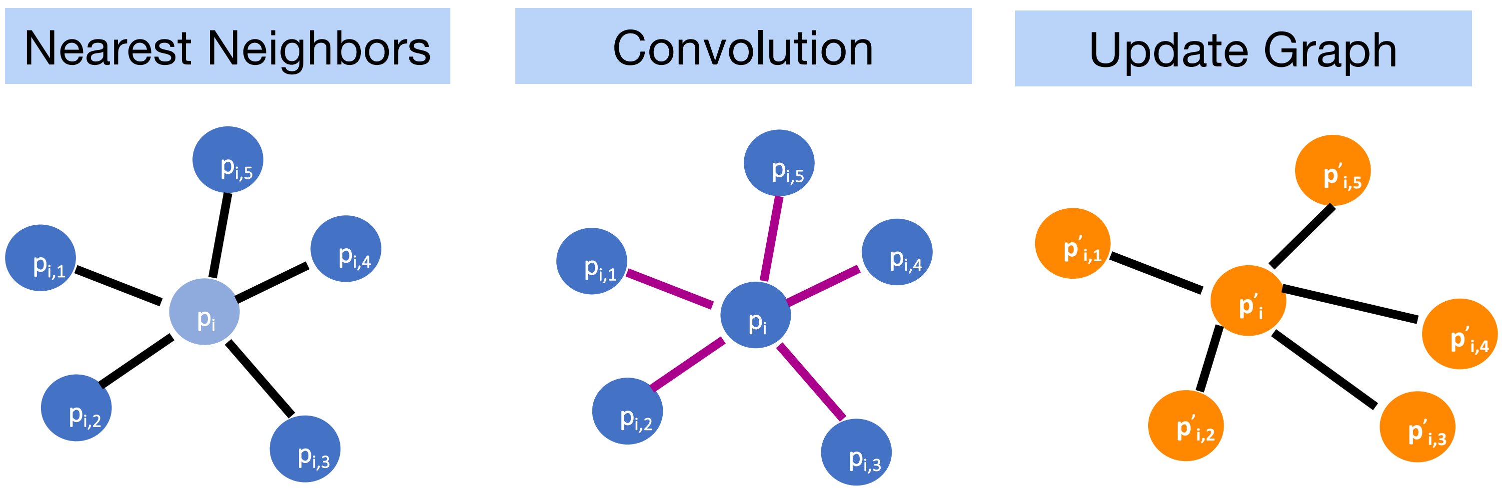
- In a nutshell:

$$p_i' = \square_{j=1}^{k} h_\Theta(p_i, p_{ij} - p_i)$$

ParticleNet:
h_Θ: MLP [shared across edges]
□ : average over all k-NN

Convolution on particle clouds

- Find the *k*-nearest **neighbors** of each particle
- Design a permutation invariant convolution operation
  - Define **edge feature** function → **aggregate** edge feat. w/ symmetric func.
- Update Graph: Use feature space produced after convolution
  - i.e. a mapping from one particle cloud to another



- In a nutshell:

$$p_i' = \underset{j=1}{\overset{k}{\square}} h_\Theta(p_i, p_{ij} - p_i)$$

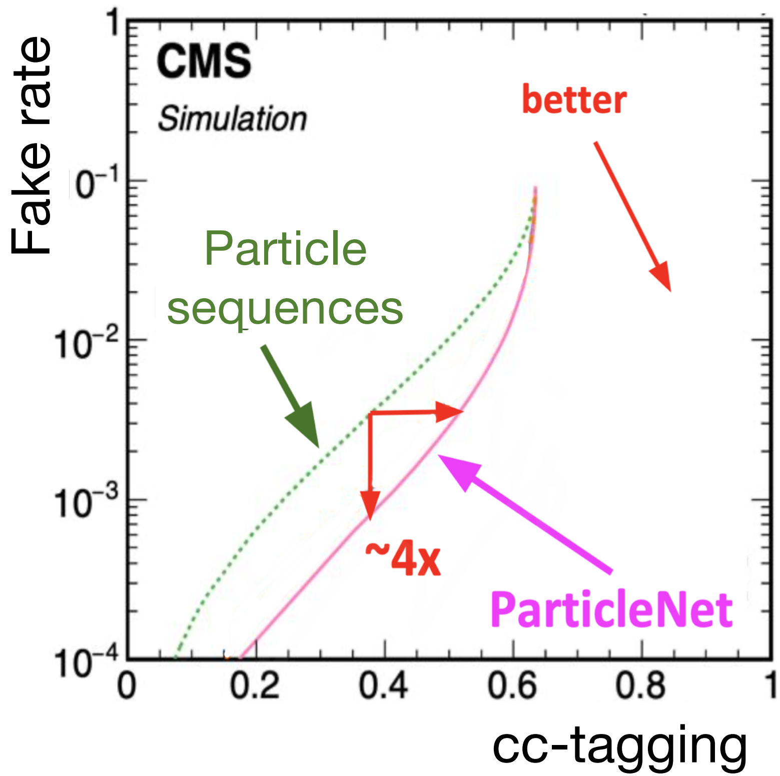
ParticleNet:
h_Θ: MLP [shared across edges]
$\square$: average over all k-NN

ParticleNet in action

JINST 15 (2020) P06005

CMS-DP-2022-005

H→cc identification

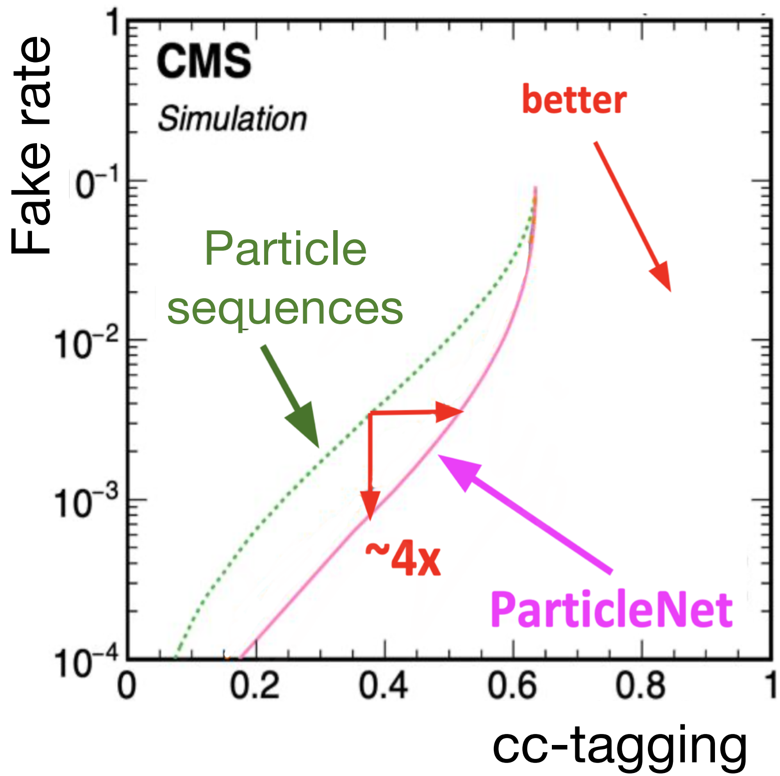


ParticleNet in action

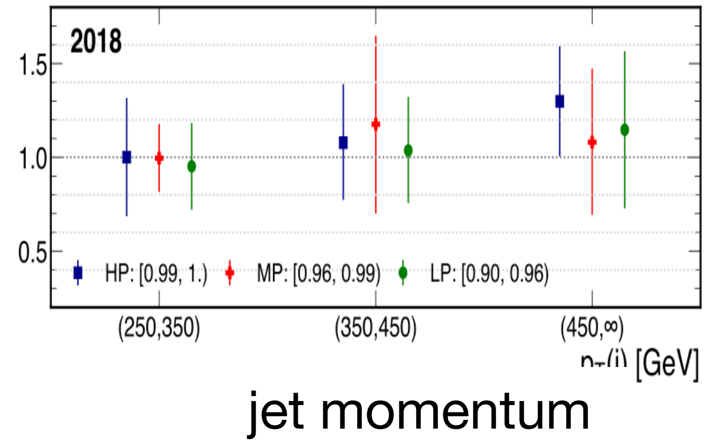
JINST 15 (2020) P06005

CMS-DP-2022-005

H→cc identification



Confirmed in data

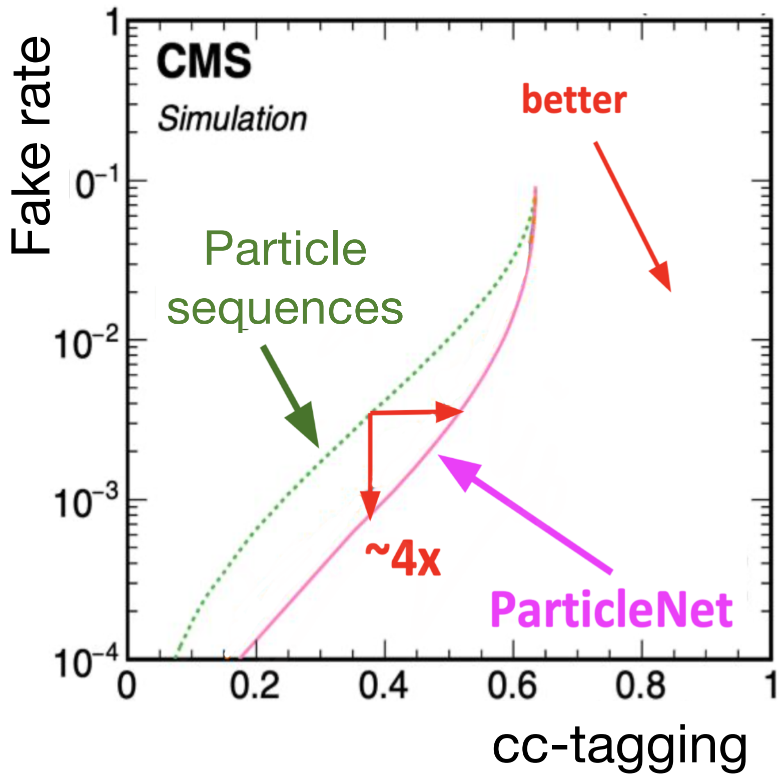


ParticleNet in action

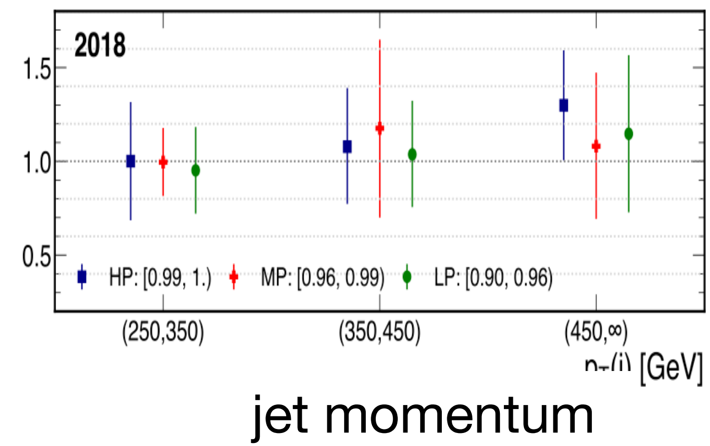
[JINST 15 (2020) P06005](#)

[CMS-DP-2022-005](#)

H→cc identification



Confirmed in data

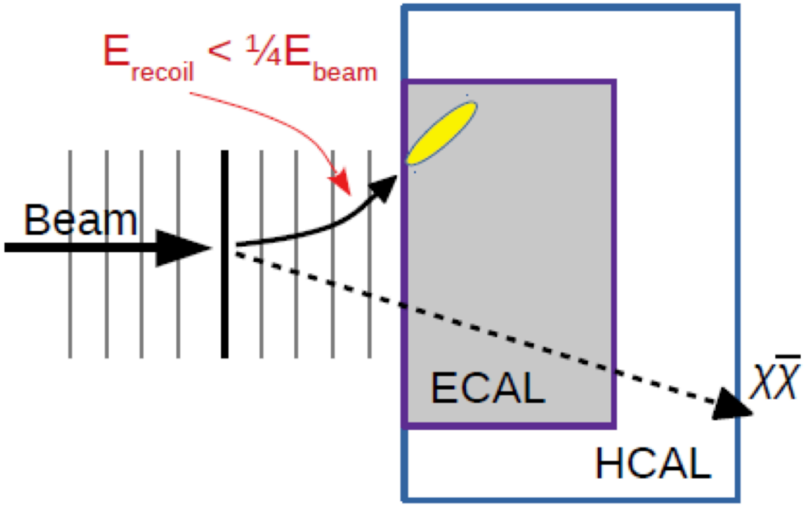


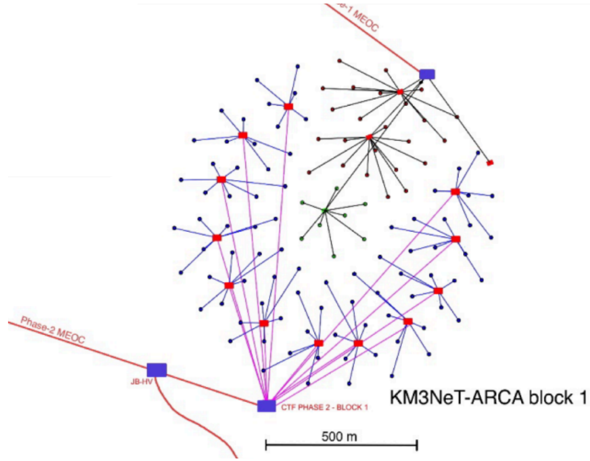
Other ParticleNet applications [in CMS]:
- jet mass reconstruction
- event reconstruction/clustering
- real-time selection [since Run 3]

ParticleNet … beyond colliders

Dark Matter [e.g. LDMX]

Neutrino physics [e.g. KM3Net]





End-to-end calorimetry reconstruction

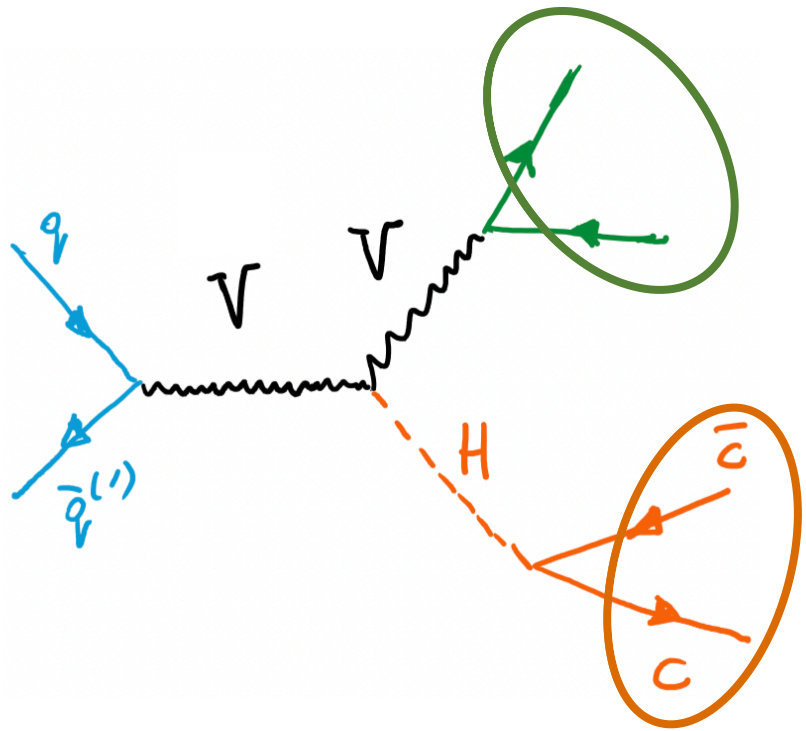
Pattern recognition of comics-rays direction

- And other experiments: in DM and Astroparticle physics

Back to H→cc

The H→cc analysis

- Target VH production
  - Smaller production cross-section but clean signature

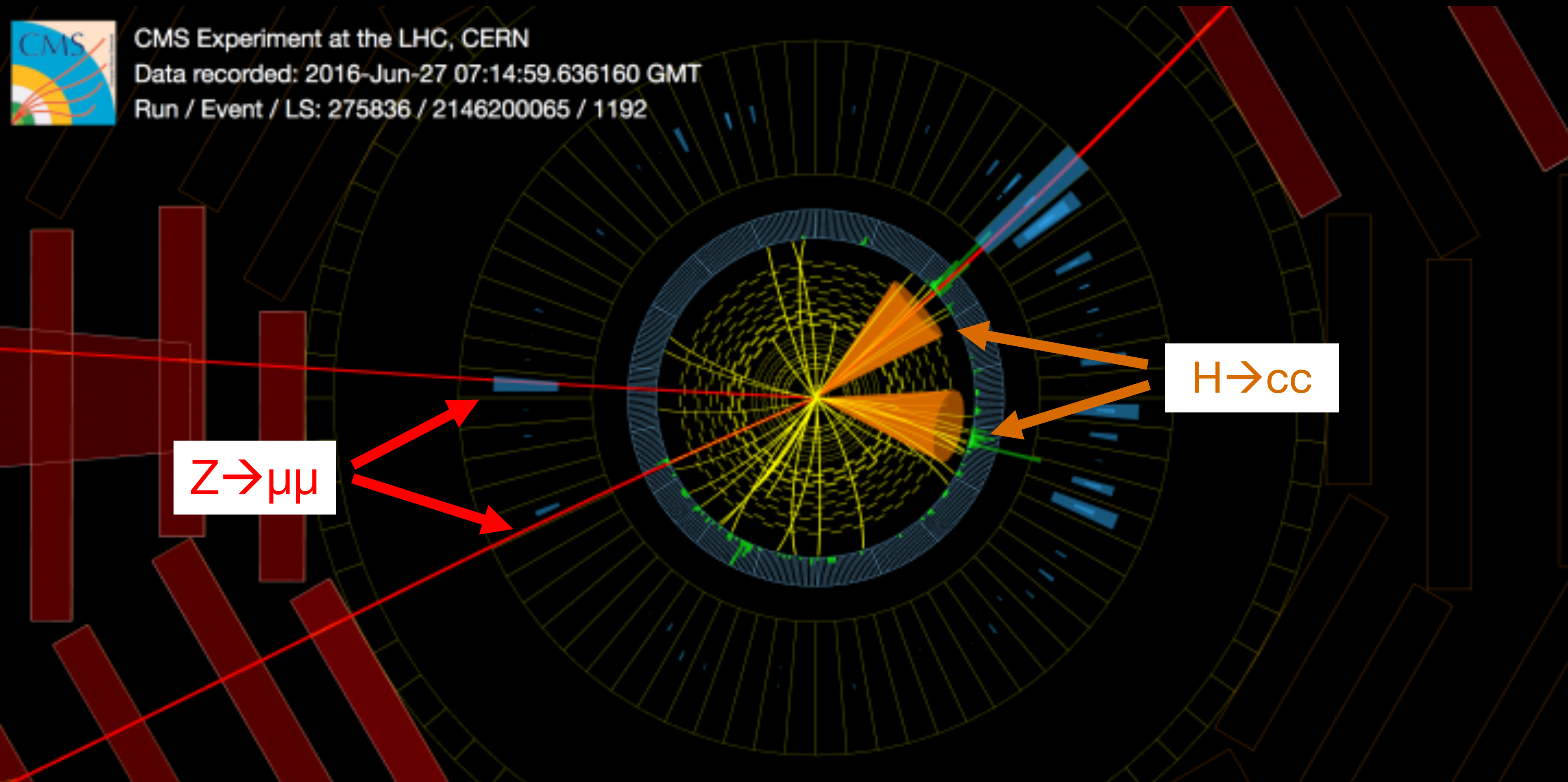


- Target leptonic decays of V boson
  - Suppress QCD background
  - Main backgrounds: ttbar, W/Z+jets

- Challenges [reminder]:
  - Small BR
  - Charm tagging

Fully explore Higgs decay topology

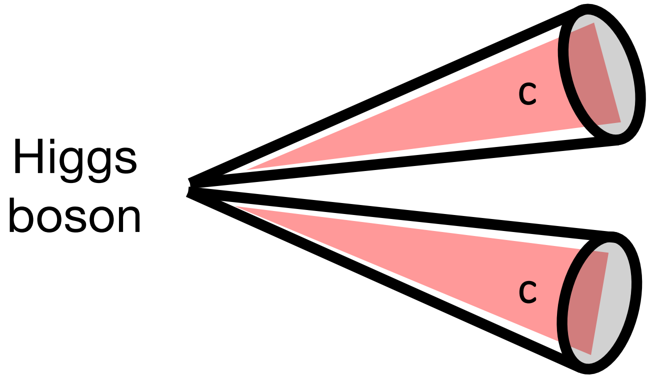
H→cc candidate



Analysis strategy

- Two complementary approaches for Higgs reconstruction

Traditional approach: Resolved-jet

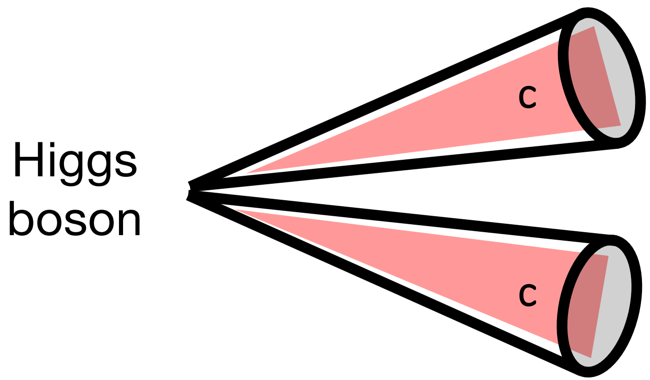


- Larger signal acceptance
- but also larger BKGs..

Analysis strategy

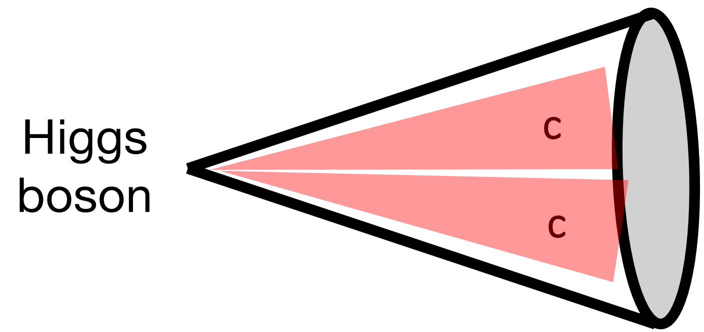
- Two complementary approaches for Higgs reconstruction

Traditional approach: Resolved-jet



- Larger signal acceptance
- but also larger BKGs..

Novel approach: Merged-jet



- Improved signal purity
- Better exploit correlations between charm quarks
- Use state-of-the-art tools [i.e., ParticleNet]

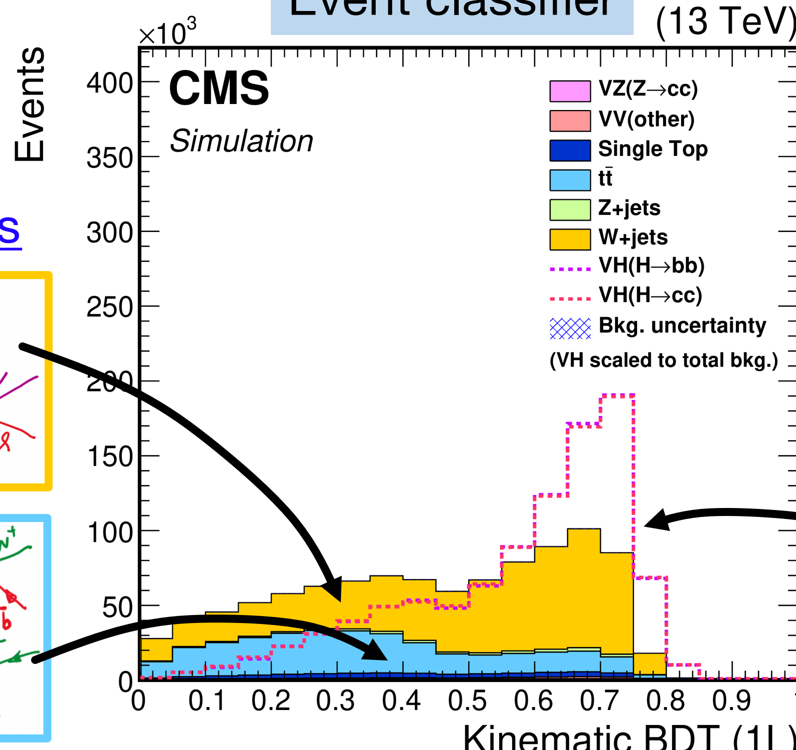
Boost (p_T [jet]) →

Final result: Combination of two topologies

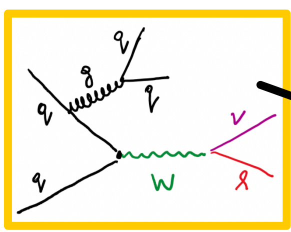
Event-level separation

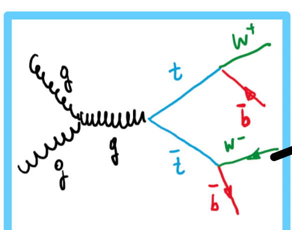
- Large and complex backgrounds against small signal
  - Need powerful discrimination power → “***Machine Learning***”
  - Small systematic uncertainties

Event classifier



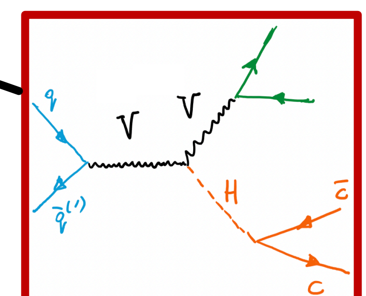
Backgrounds





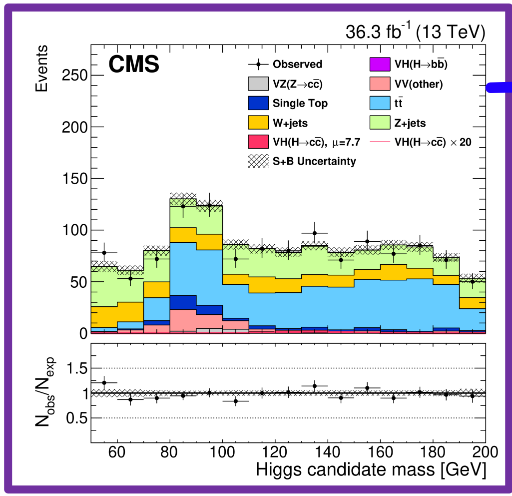
Tip:
- Classifier designed allowing “in-situ” ParticleNet calibration
- ~30% reduced systematics

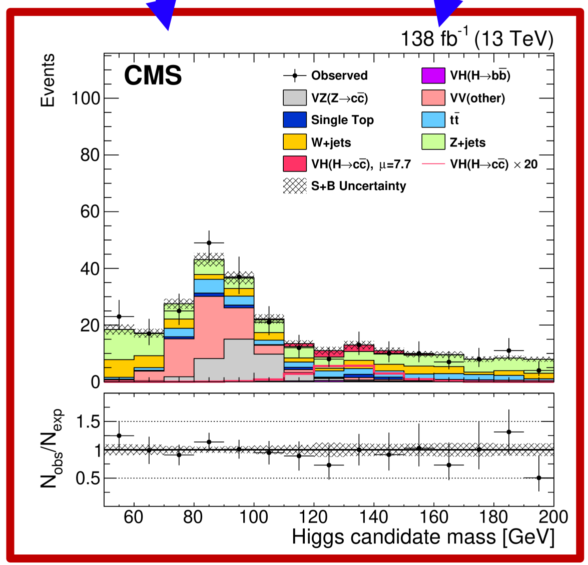
Signal

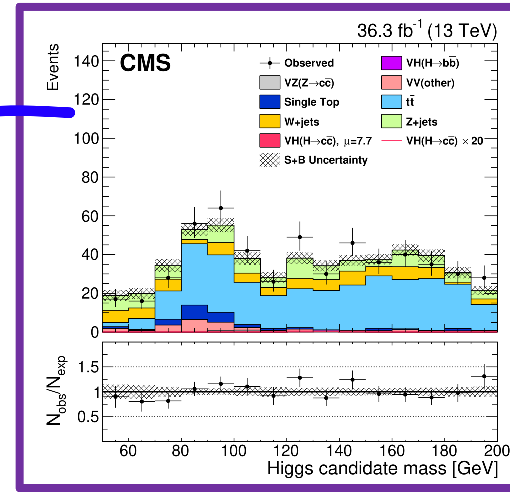


Background estimation

- Complex backgrounds → data-driven approach:
  - Design a **data control region** / BKG process
  - Measure the process and **extract corrections**
  - Transfer them to the **search region** to correct BKGs

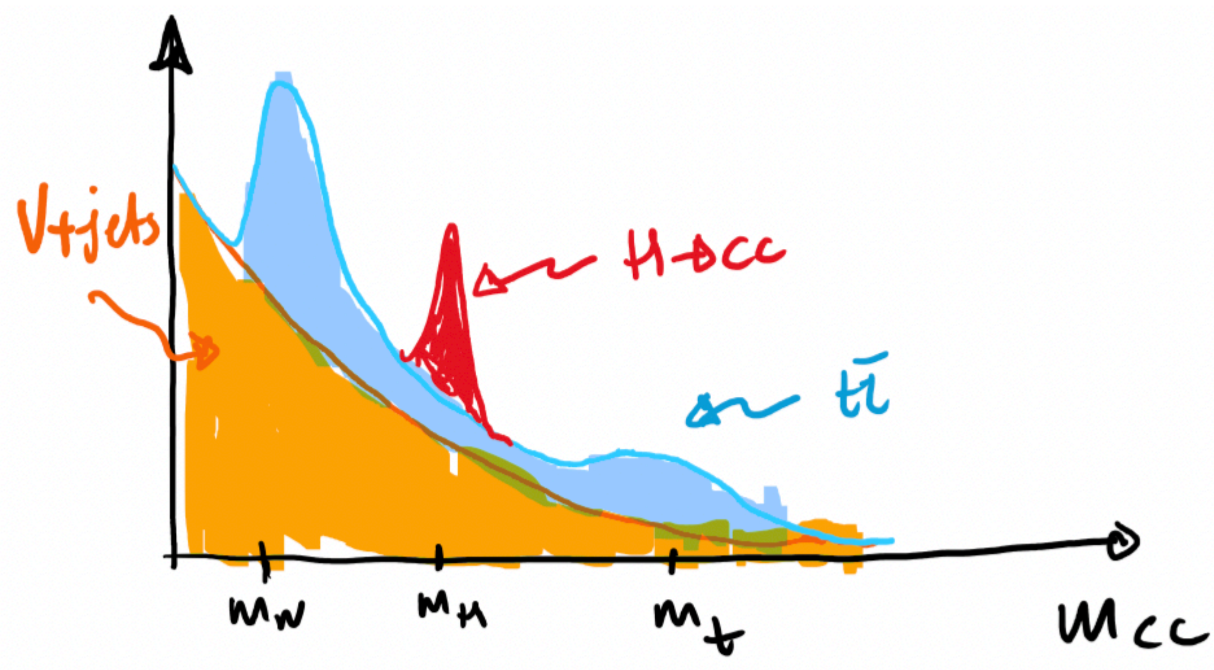






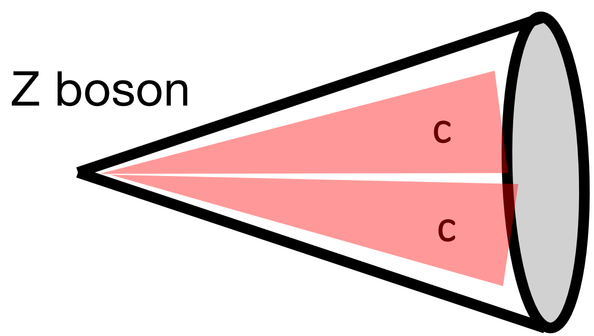
Signal extraction

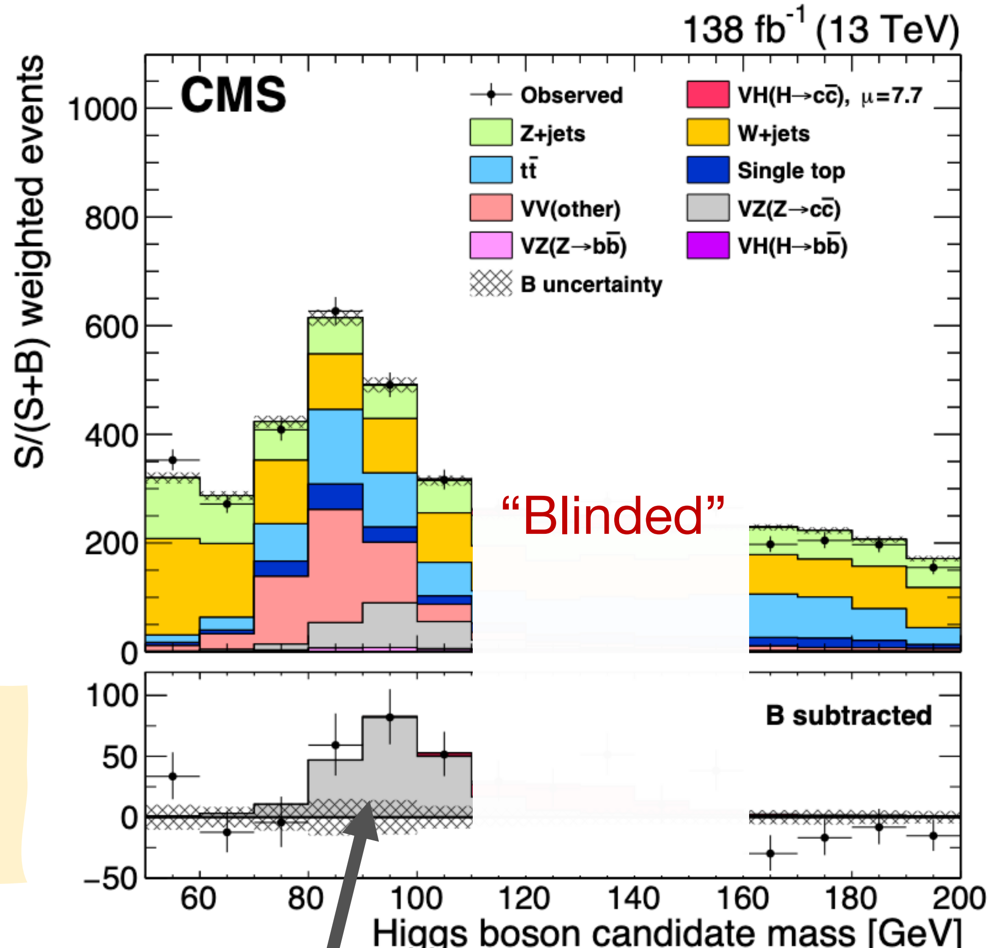
- Look for an excess in data compatible with H→cc
  - **IF no excess:**
    set limits on the maximum possible H→cc rate allowed by the data



How all these work in data?

Golden candle



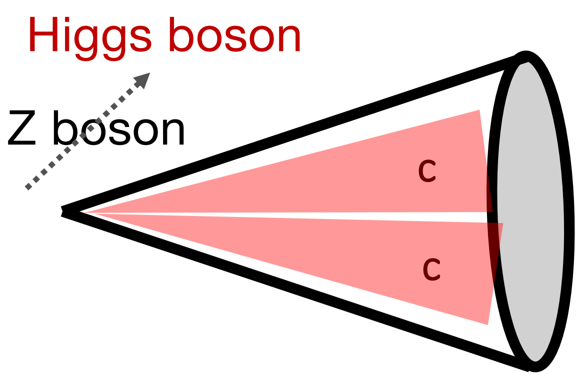


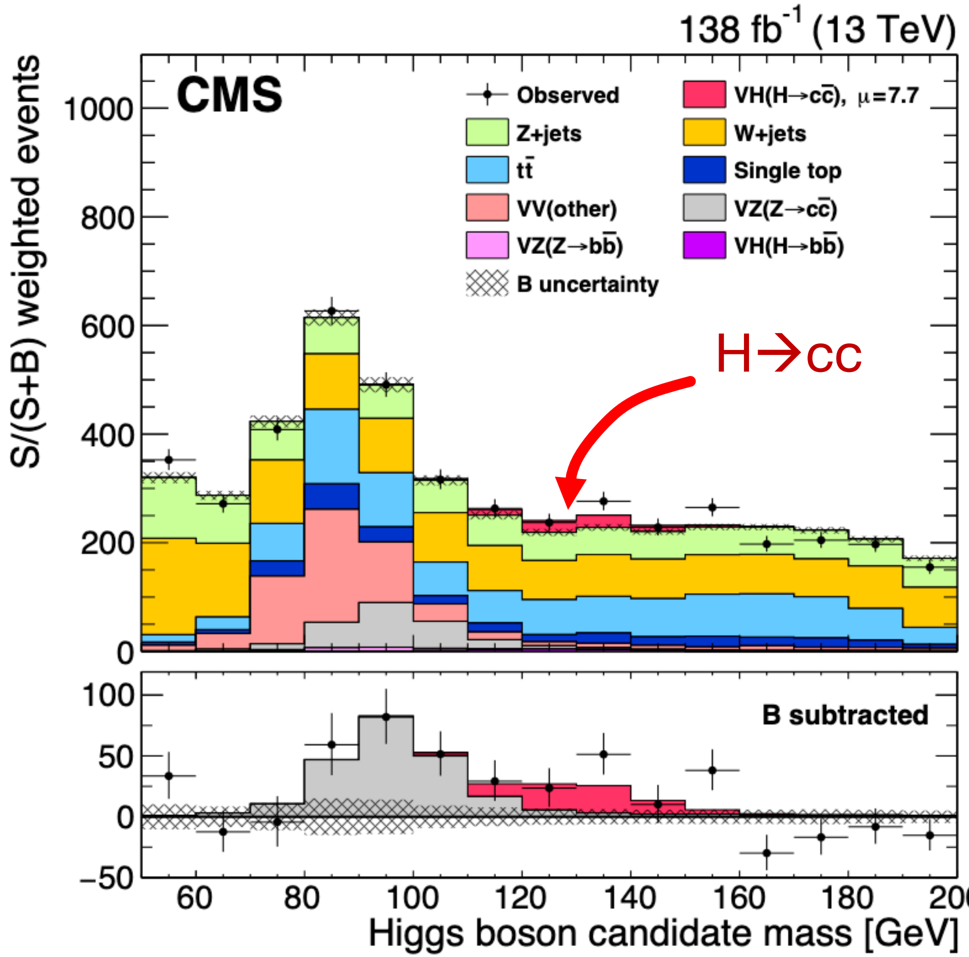
<u>Technique proven on VZ(→cc)</u>
5.7σ (5.9σ) Obs (Exp)
μ = 1.01 ± 0.22

Z→cc: 1st observation at hadron colliders!

Look for VH→cc

"Unblind" Higgs mass



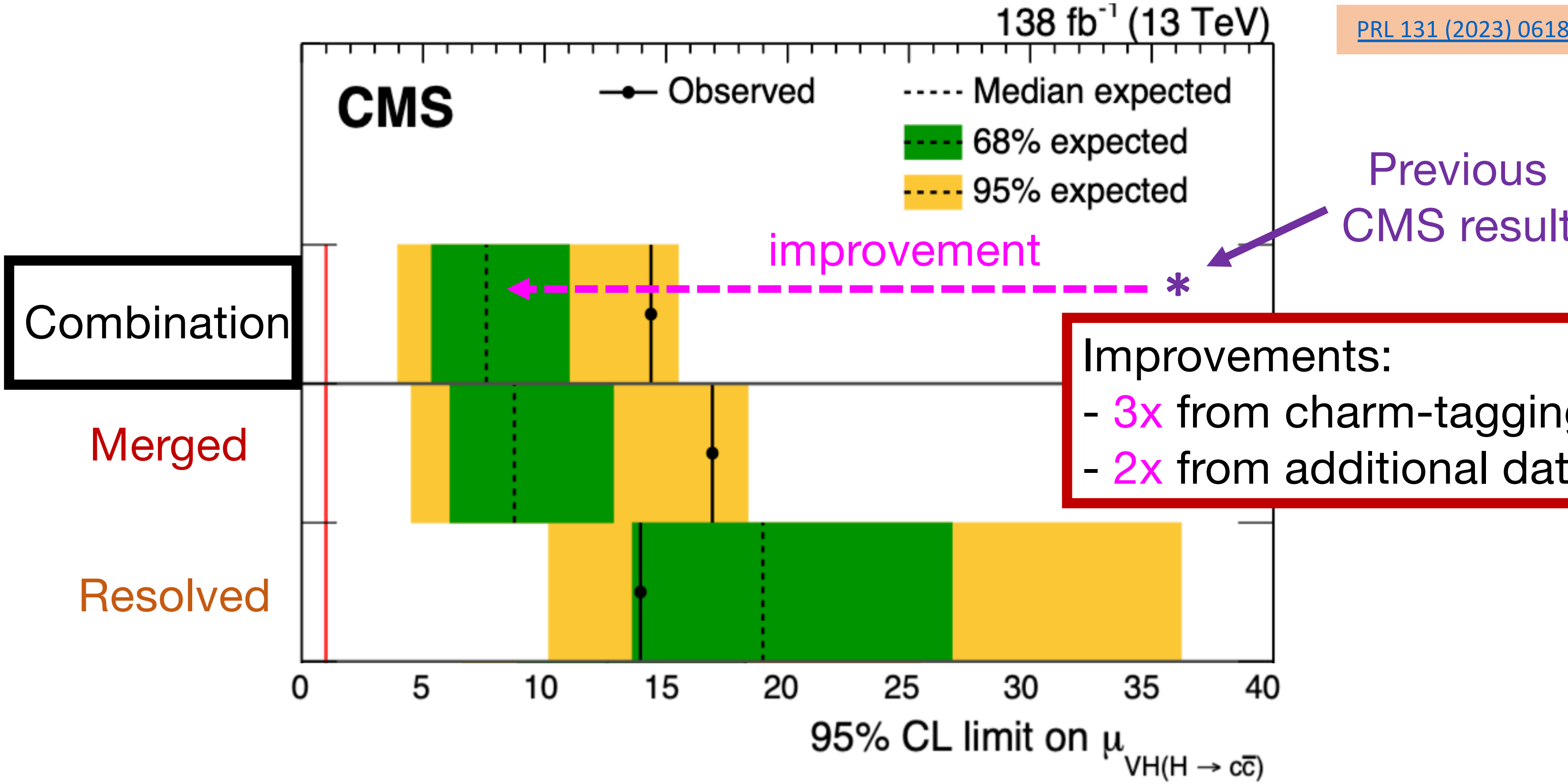


H→cc signal strength

$\mu = 7.7^{+3.8}_{-3.5}$

VH(→cc) results

[PRL 131 (2023) 061801](PRL 131 (2023) 061801)

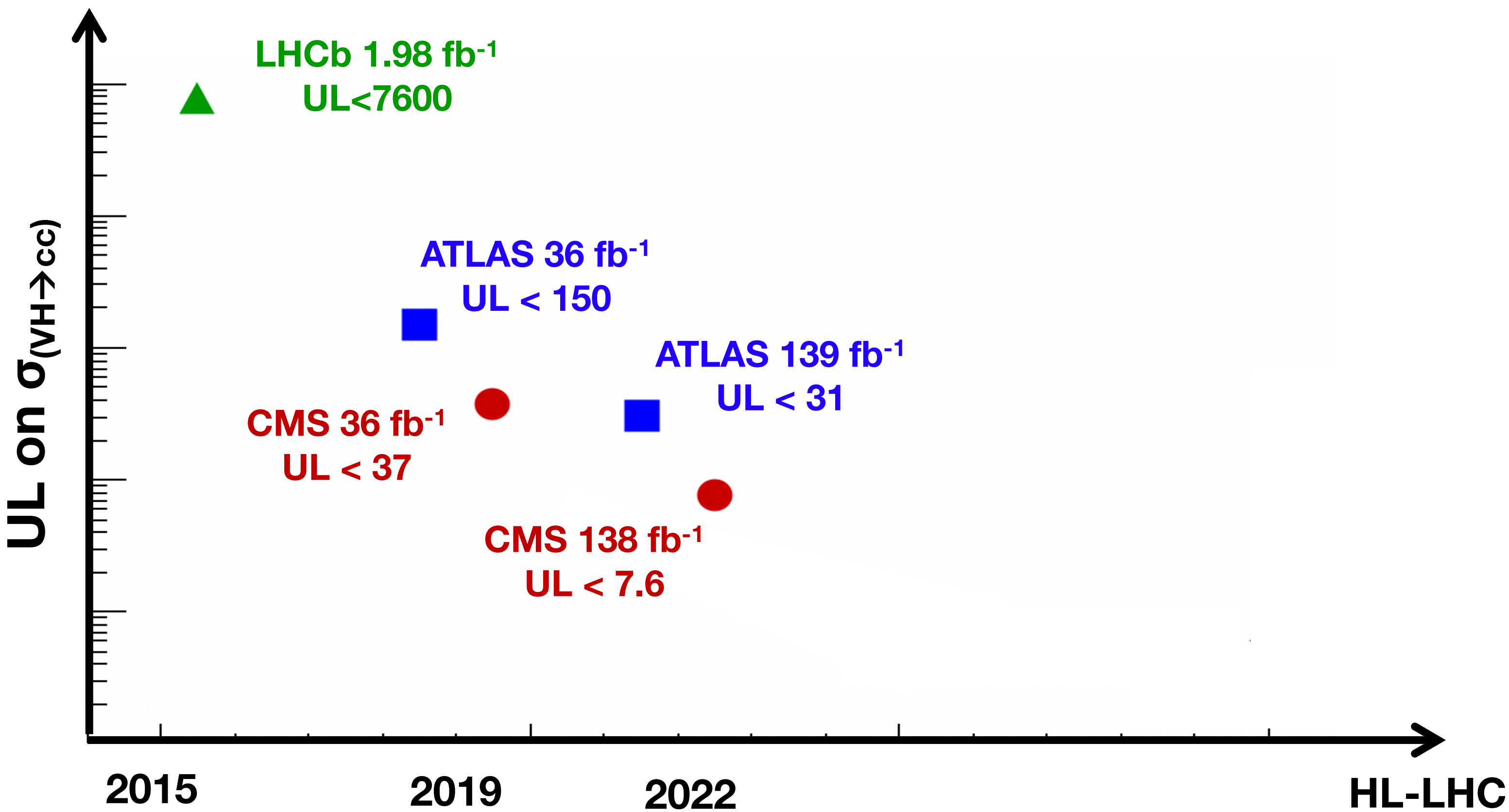


Improvements:
- 3x from charm-tagging
- 2x from additional data

Strongest limits to date @LHC:
- CMS: obs: 14 (exp: 7)

Constraints on Higgs-charm coupling
obs: $1.1<|\kappa_C|<5.5$ (exp: $|\kappa_C|<3.4$)
Comparable to previous (ATLAS, LHCb) projections for HL-LHC [i.e. 20x more data]

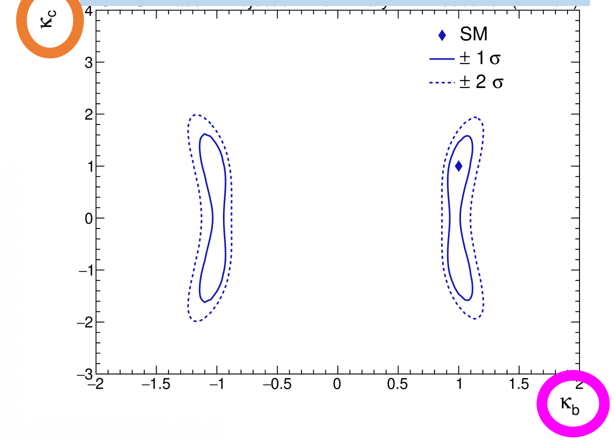
Intermediate summary



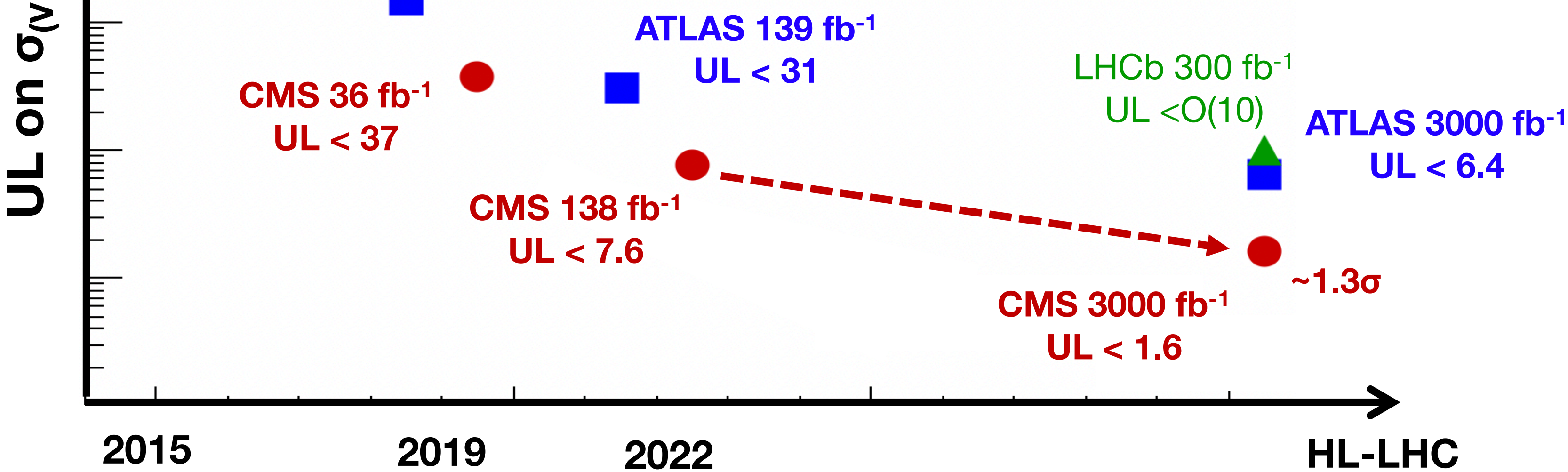
<u>O(10000)→….→ O(10) in ~5 years</u>
Lot’s of effort & ingenuity in multiple areas

Intermediate summary

Looking ahead: HL-LHC



Simultaneous extraction of H-c and H-b coupling



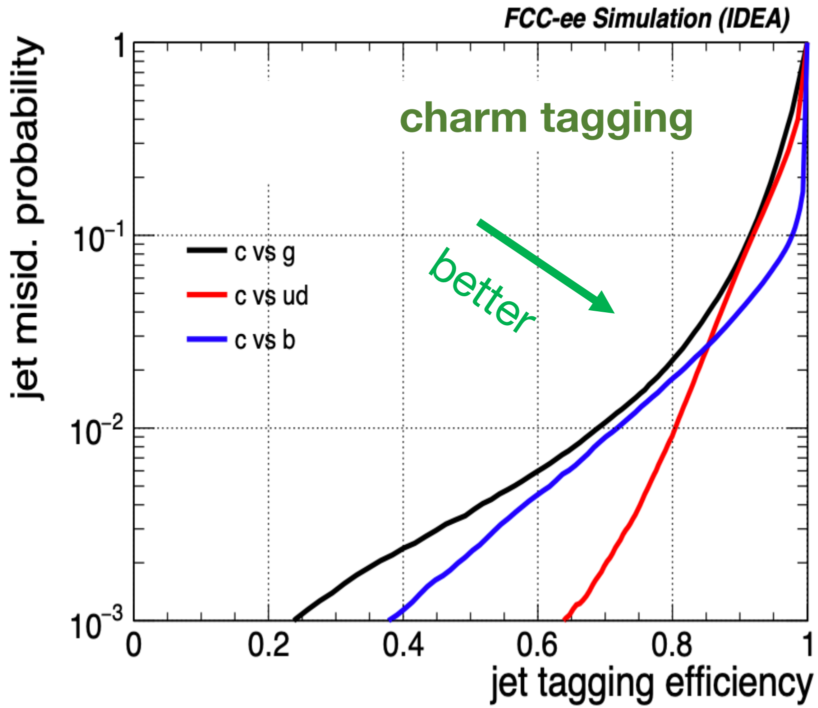
O(10000)→….→ O(10) in ~5 years
Lot's of effort & ingenuity in multiple areas

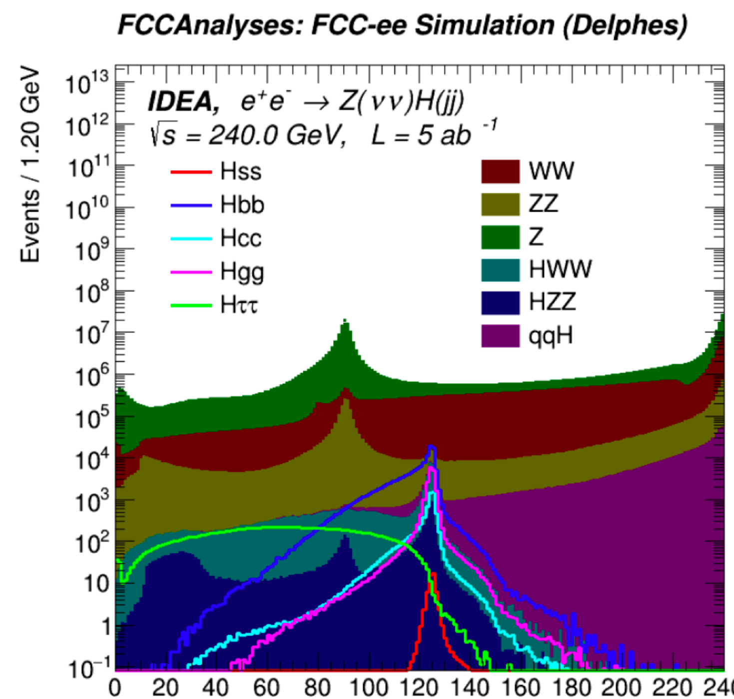
Reach SM sensitivity!

Still a long way ahead

- HL-LHC: potentially **evidence [3σ]** of Higgs-charm coupling
  - Only a future e^+e^- machine can **guarantee observation**

ParticleNet@FCCee

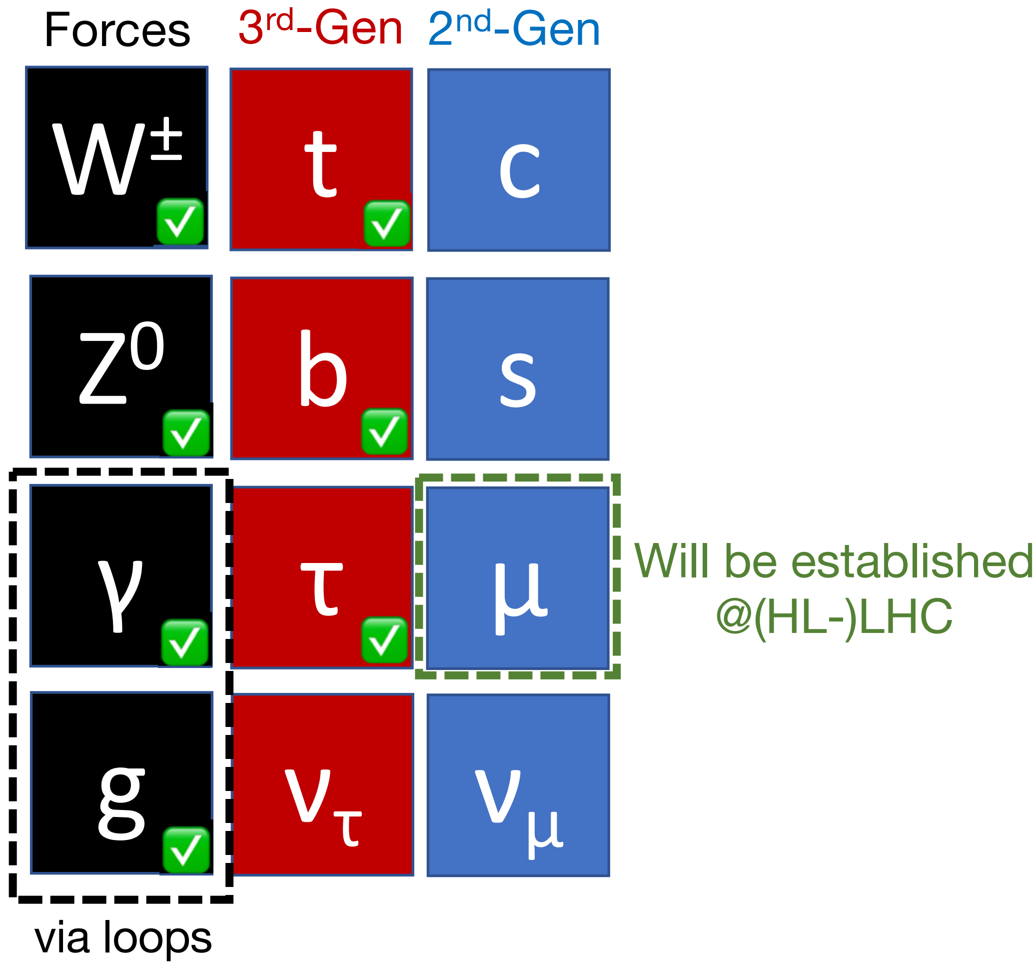




Z(→νν) H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.3	2.1	100	0.8

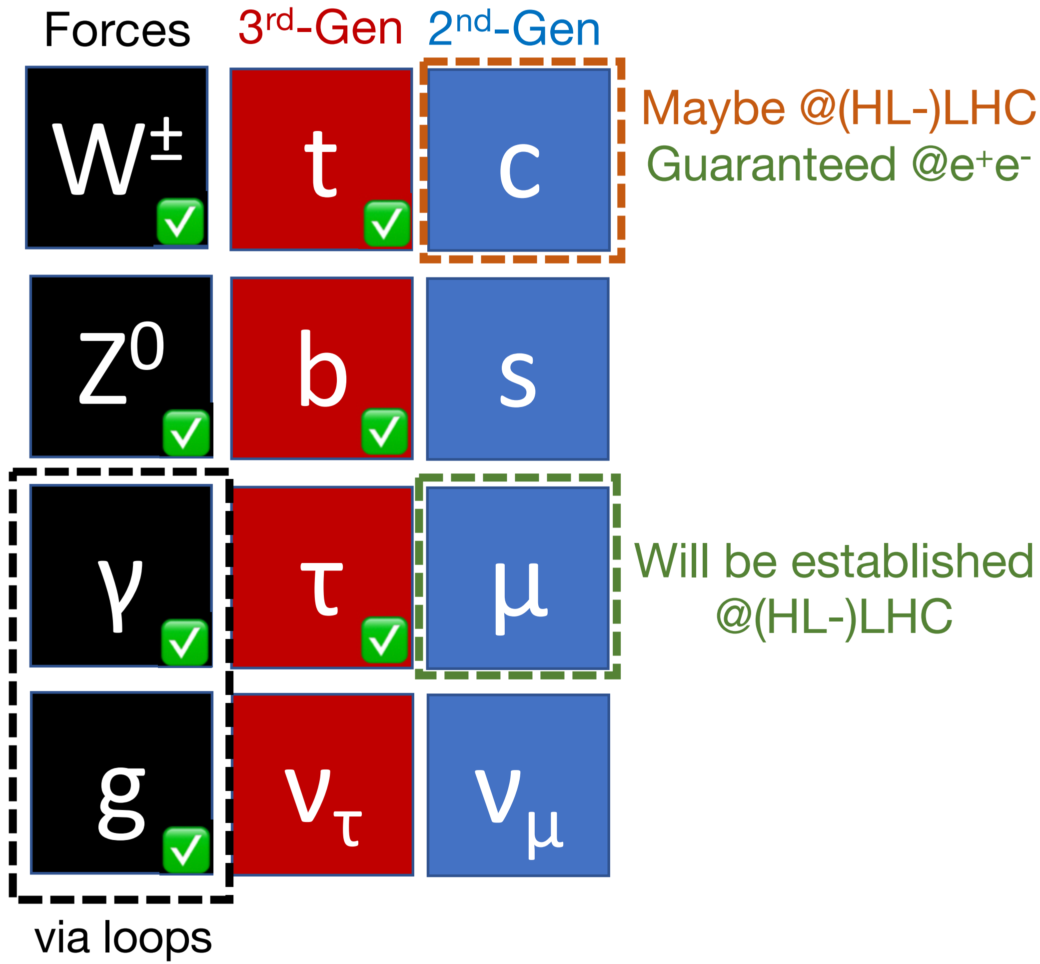
The big picture

Z(→νν) H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.3	2.1	100	0.8



The big picture

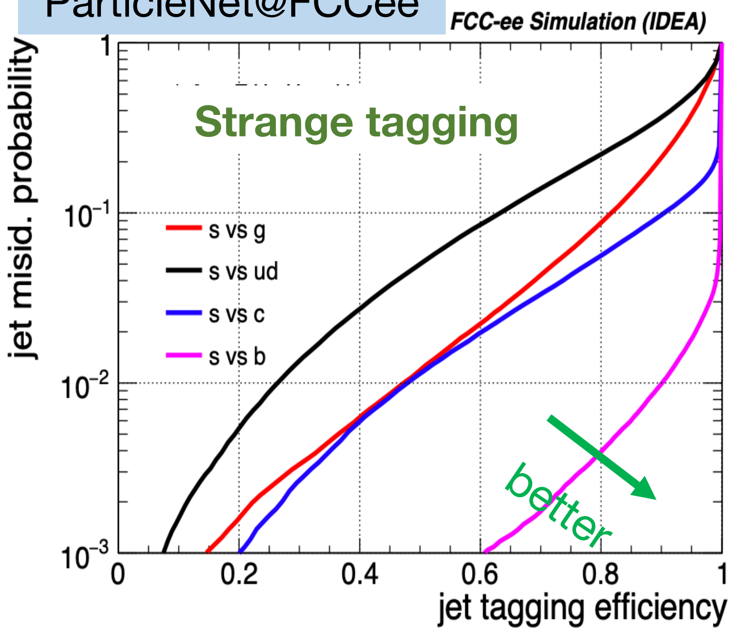
$Z(\rightarrow\nu\nu)$ $H(\rightarrow qq)$	bb	cc	ss	gg
$\delta\mu/\mu$ (%)	0.3	2.1	100	0.8

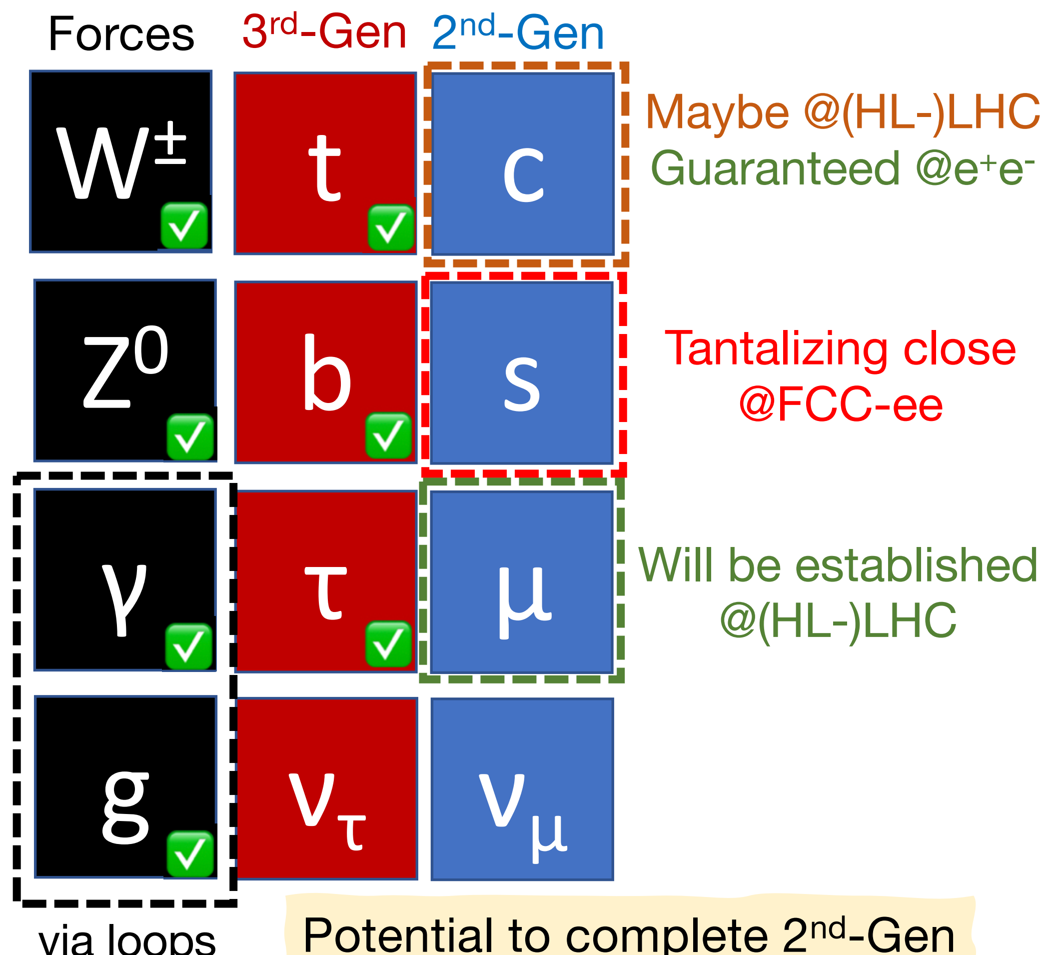


The big picture

Z(→νν) H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.3	2.1	100	0.8

ParticleNet@FCCee





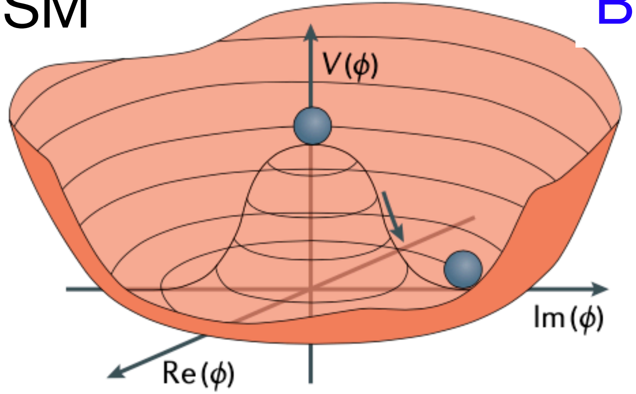
Potential to complete 2nd-Gen Yukawa couplings

Interactions with two Higgs bosons

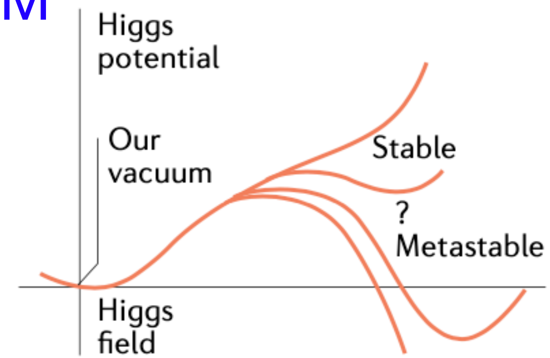
The nature of the Higgs potential

- Big milestone towards fully exploring the Higgs properties
  - Understand how electroweak symmetry broke in the early universe
  - Is generation of masses connected to the matter-antimatter asymmetry

SM

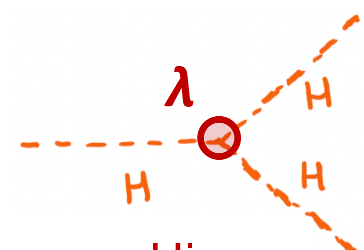


BSM



$$V(h) = \frac{1}{2}M_H^2 H^2 + \frac{1}{3!}\sqrt{3\lambda_H}M_H H^3 + \frac{1}{4!}\lambda_H H^4$$

Higgs mass — Shape of potential

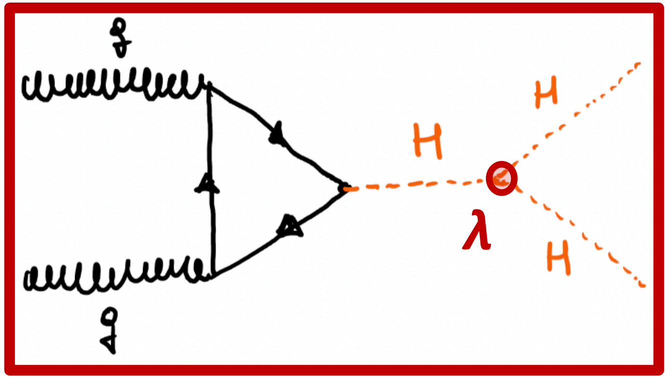


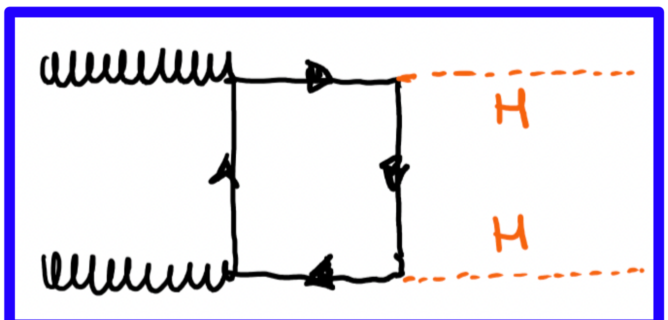
Measure Higgs self-coupling

Higgs pair production at the LHC

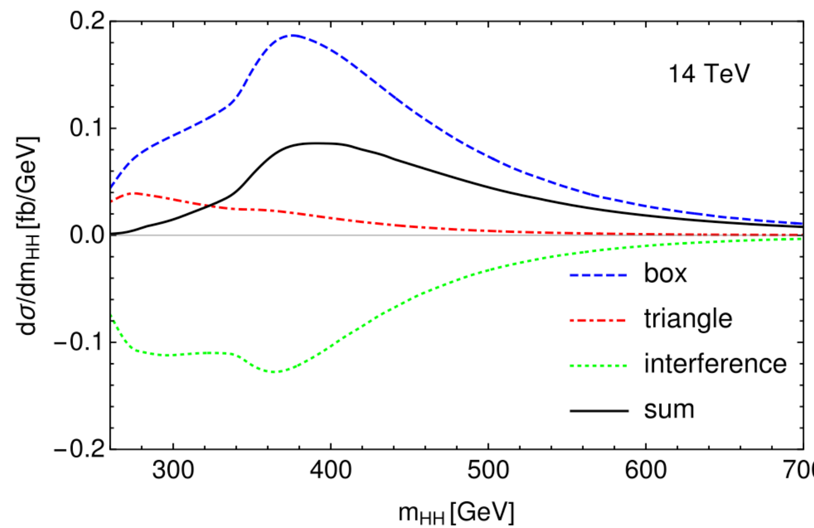
- Direct access to self-coupling: via Higgs pair production (HH)

Dominant production: ggF





Interference [assuming SM]



triangle: lower m_{HH}

box: larger m_{HH}

- Very rare (σ ~31fb): **1/1000 of single-H**; ~4K HH during Run 2

HH experimental signatures

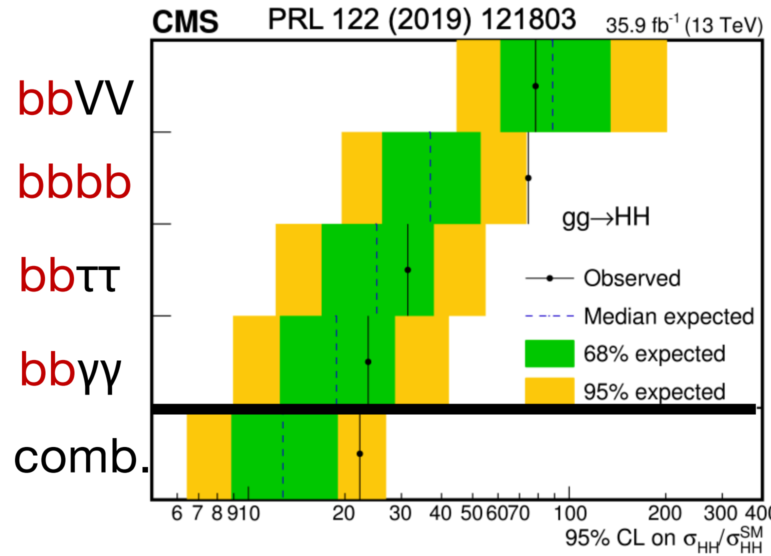
Final states

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Largest BR ↑

Cleaner signature →

Main drivers (early Run2)



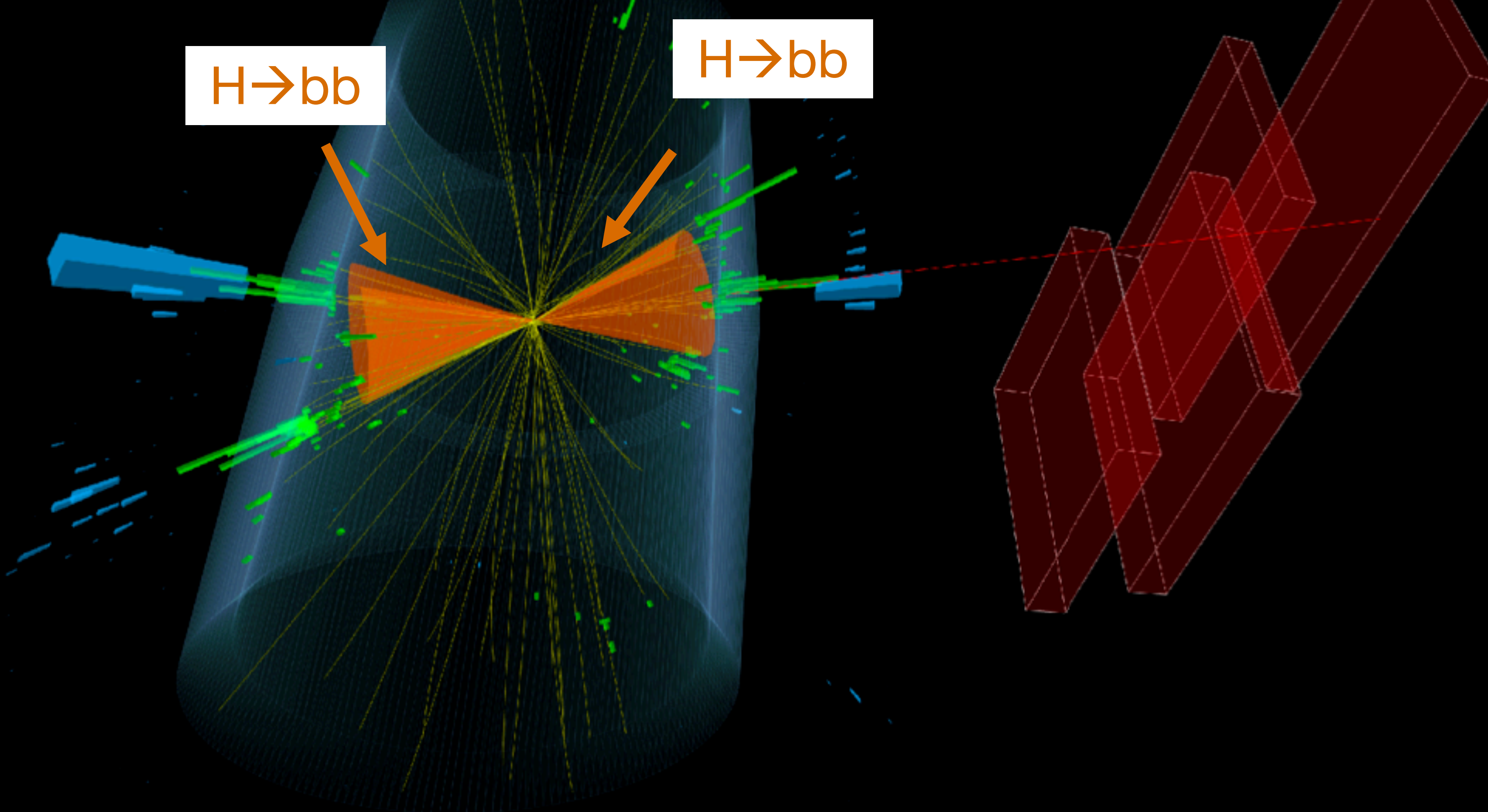
General strategy

- Explore several final states
- No golden channel [as in single-H]

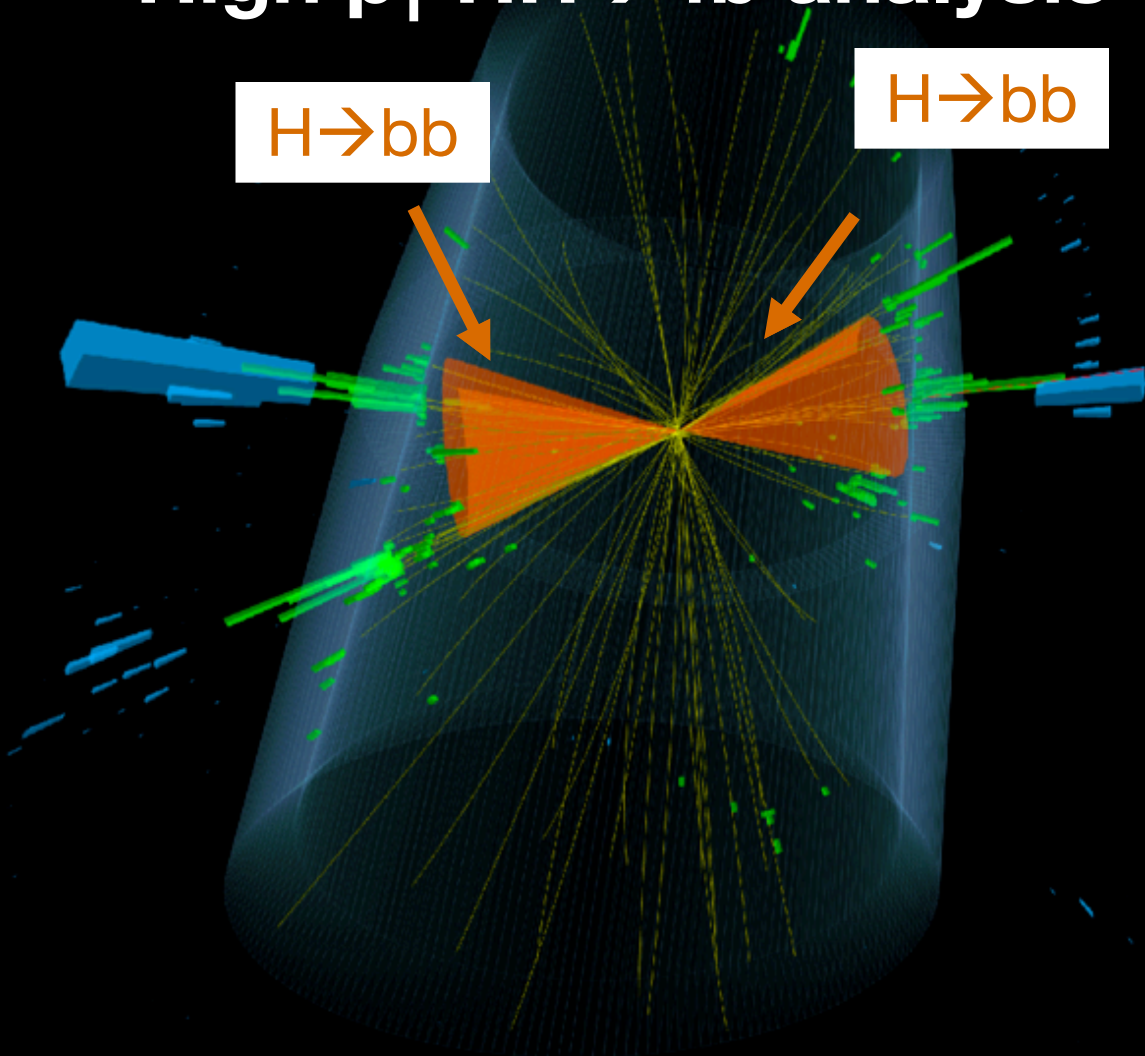
Most sensitive channels:
at least one H→bb

- Good compromise b/w signal purity and acceptance
- Clearly: Jet tagging is critical

High p_T HH→4b analysis



High p_T HH→4b analysis



Advantages:

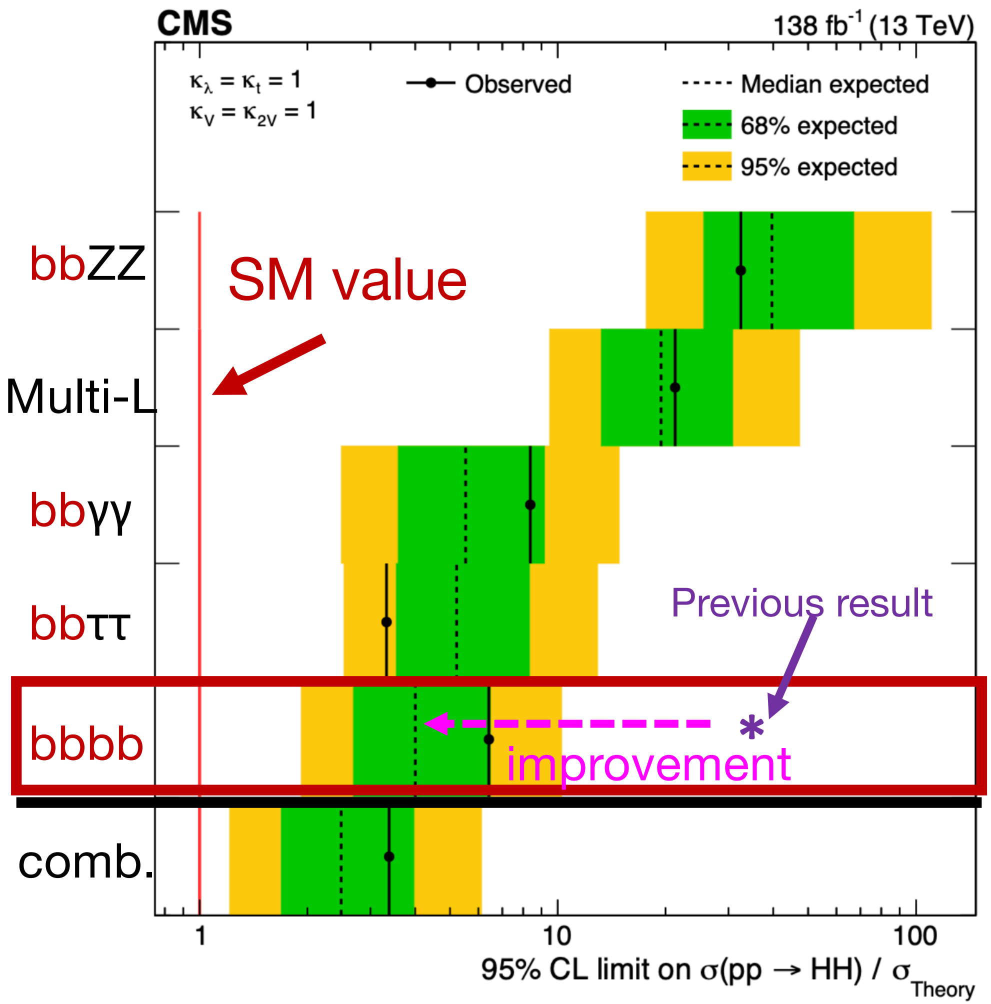
- Largest BR
- High momentum Higgs bosons
  - Reduced combinatorial BKG
  - Improved signal purity

Challenges:

- Huge QCD background
  - H→bb identification
  - ParticleNet H→bb tagger
- Background estimation [e.g. QCD, ttbar]
  - data-driven approach

Sensitivity on HH production

PRL 131 (2023) 041803



Improvements:
- 4x from b-tagging
- 2x from additional data

HH→4b: drives sensitivity

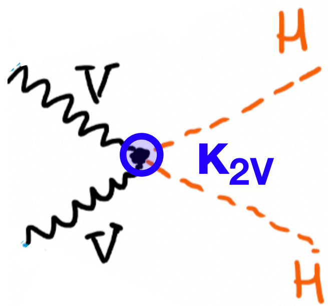
Results

Strongest limits to date @LHC:
- CMS: obs: 6.4 (exp: 4.0)

Higgs self coupling (κ_λ):
- CMS: obs: $-3.0<|\kappa_\lambda|<9.9$
  (exp: $-1.8<|\kappa_\lambda|<8.8$)

En route to self-coupling: HHVV

- **HHVV** coupling: not established [until recently]



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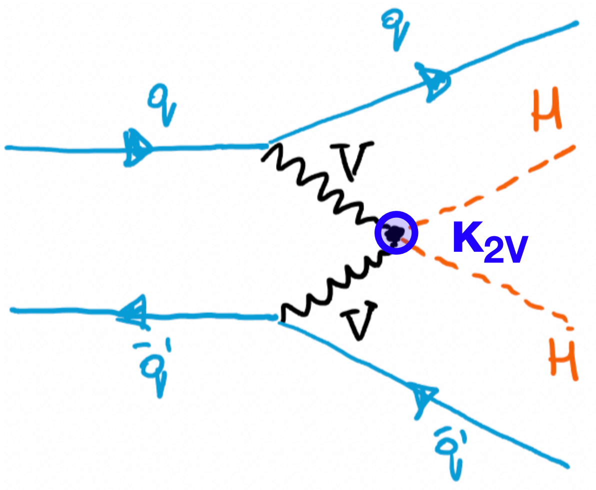
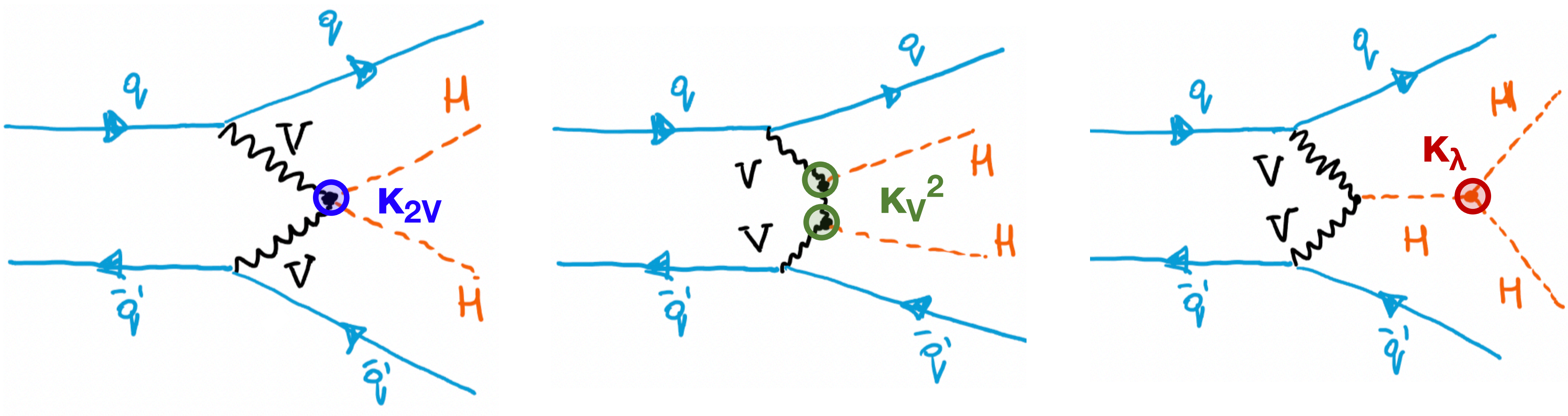


- Turning the LHC to a VV collider
  - Direct sensitivity to VVHH (**κ_{2V}**) coupling
    - but: Extremely rare [σ~1.7 fb]

En route to self-coupling: HHVV

- **HHVV** coupling: not established [until recently]



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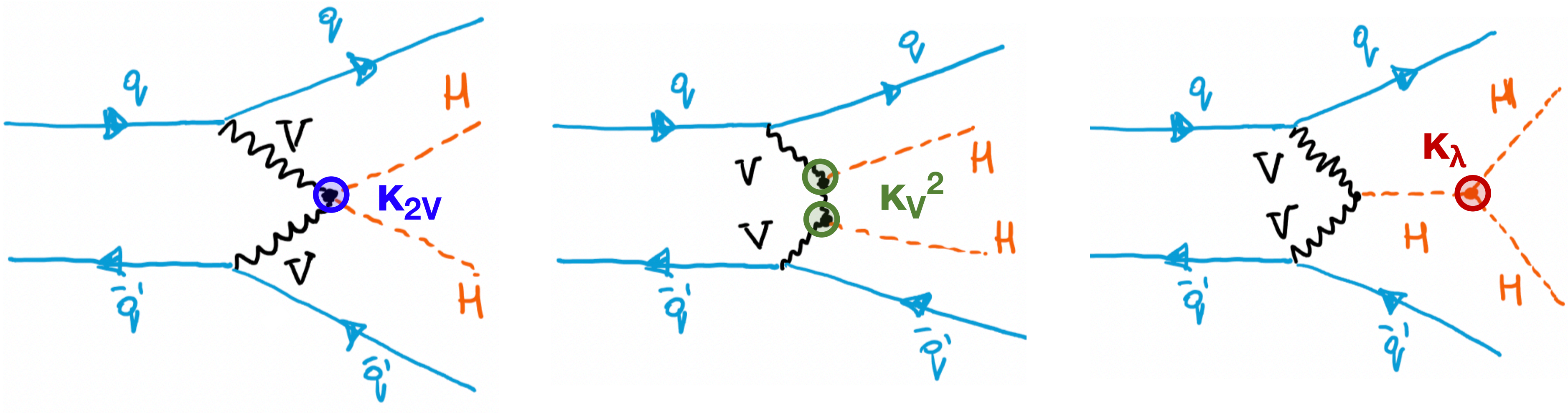

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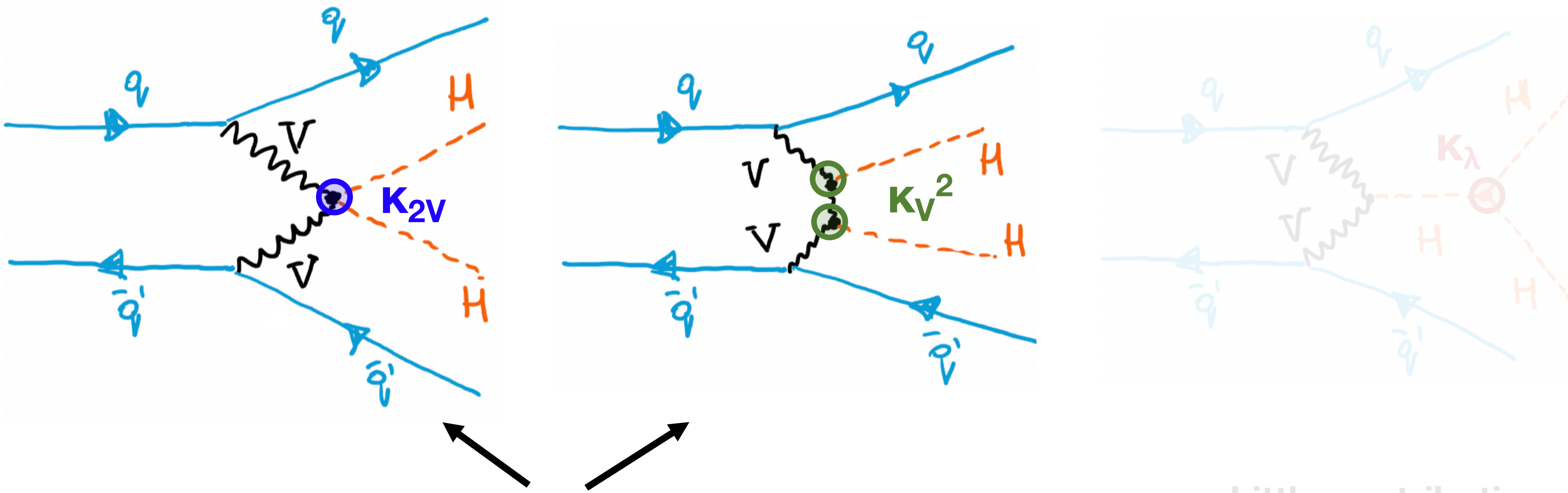

SM: large cancelation

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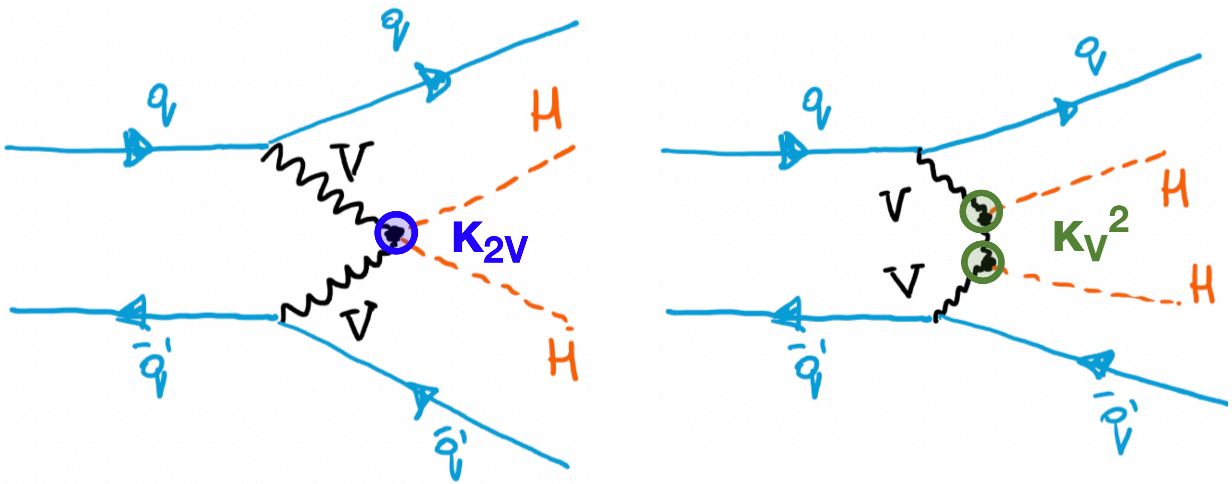
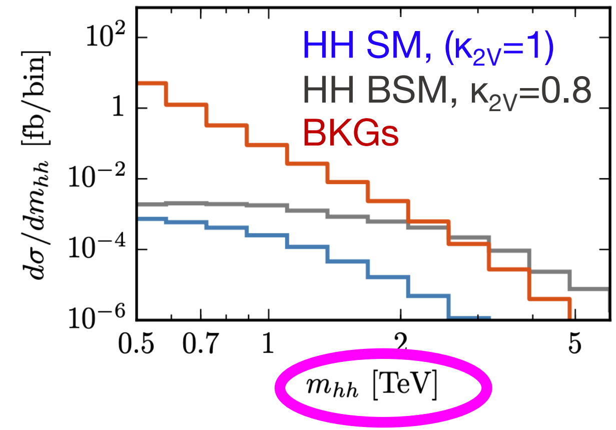




SM: large cancelation

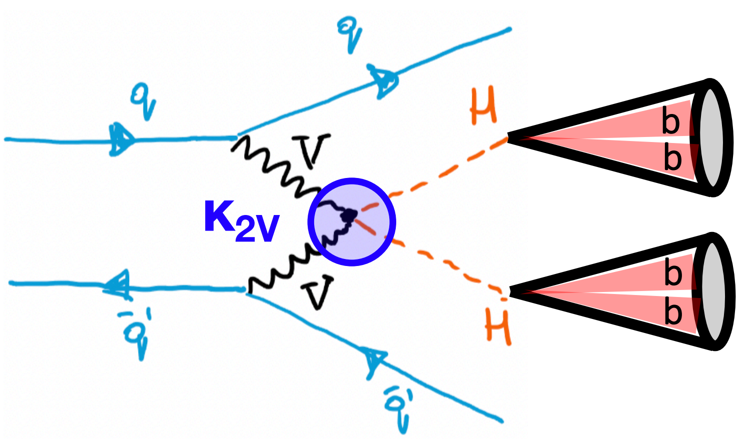
Powerful probe of BSM

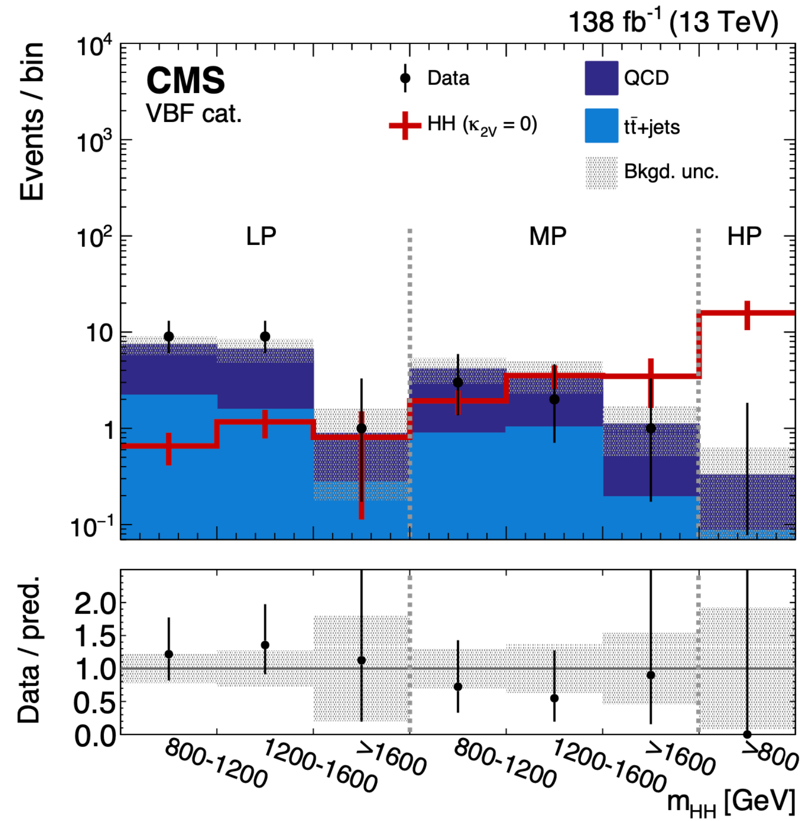
- BSM: striking effect on m_{HH}
- **Signature:** high p_T Higgs bosons

- Turning the LHC to a VV collider
  - Direct sensitivity to VVHH (**κ_{2V}**) coupling
    - but: Extremely rare [σ~1.7 fb]

Analysis strategy in a nutshell

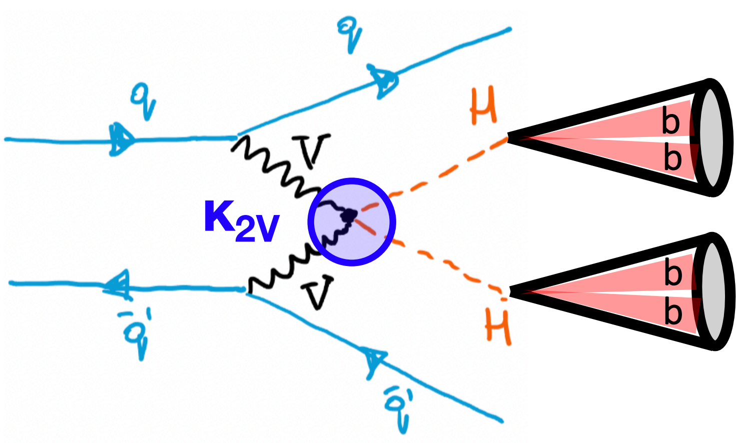
- Same tools as ggF HH→4b, but also exploit VBF signature
  - high p_T(H) regime
  - ParticleNet H→bb tagging
  - Data-driven BKG estimation

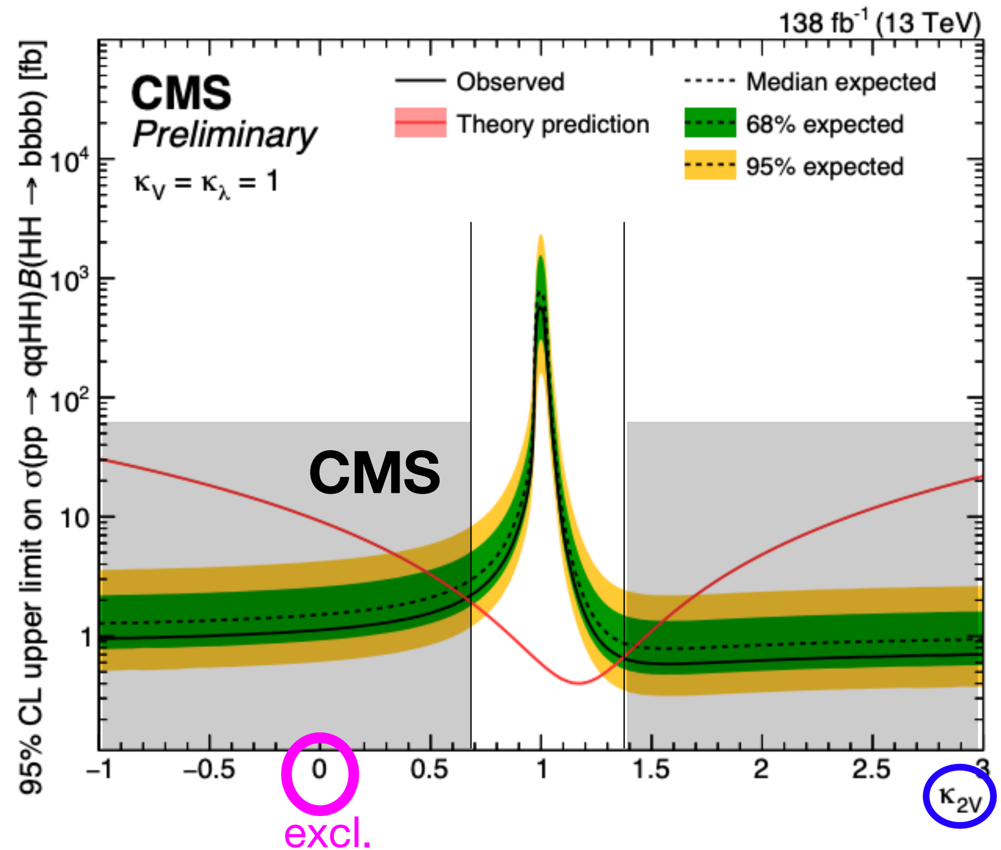




Results on HH-VV coupling

PRL 131 (2023) 041803



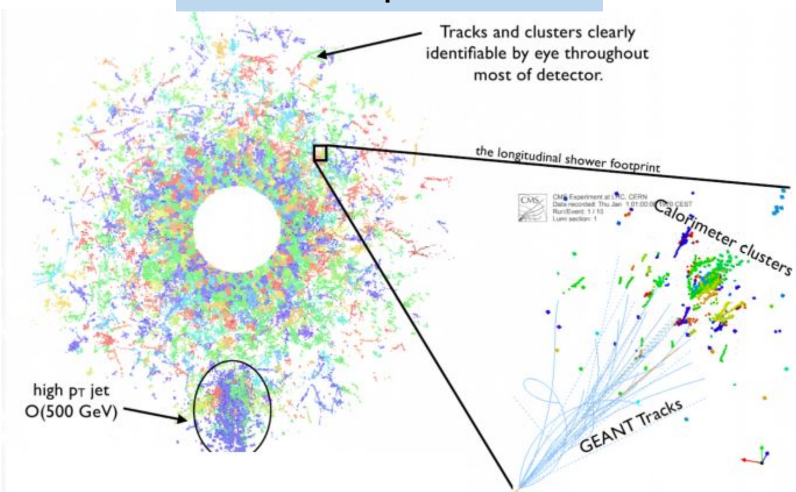


- Tightest constraints to date @LHC
- κ_{2V}=0 excluded by > 6σ → 1st confirmation of HH-VV coupling

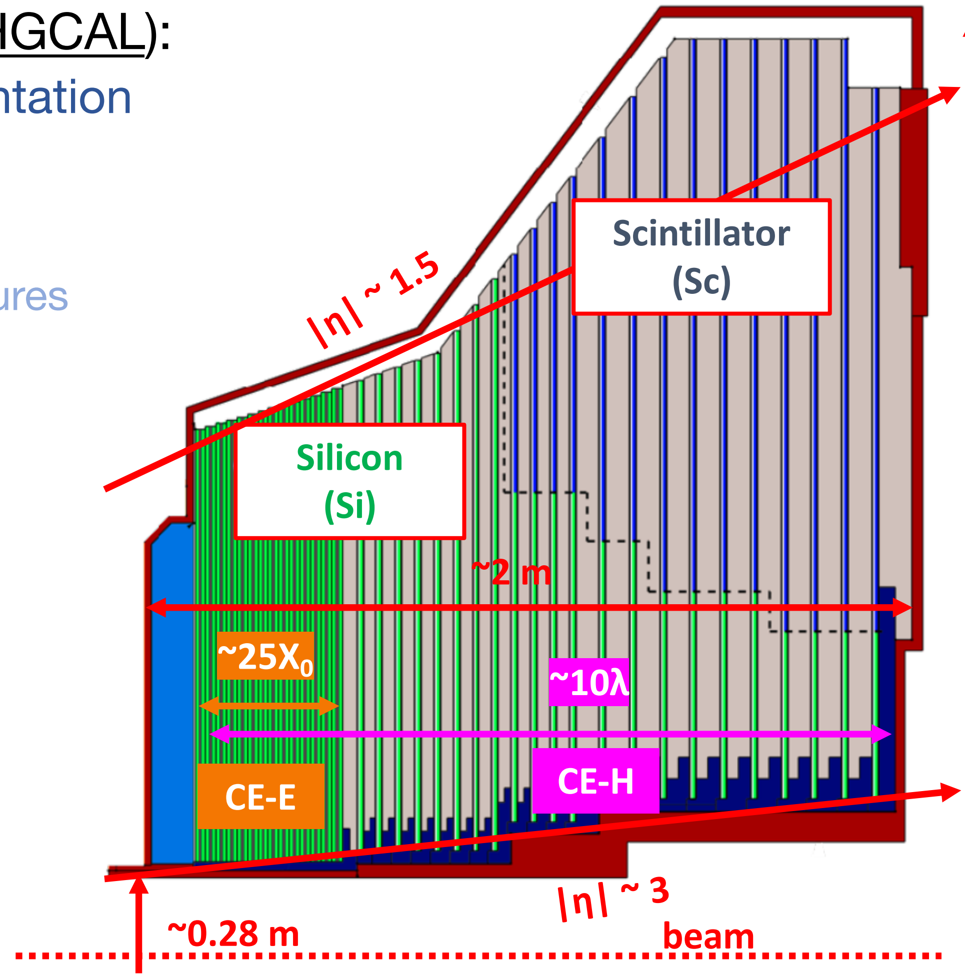
Mid-term future: HL-LHC

- CMS High Granularity Calorimeter (HGCAL):
  - fine lateral and longitudinal segmentation
  - precision timing capabilities
- Physics-driven design
  - particularly relevant for VBF signatures

Lot's of potential



Natural playground for developing cutting-edge AI-based algorithms



Summary and outlook

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- The discovery of the Higgs boson completes a remarkable theory: The Standard Model of Particle Physics
  - Clearly the biggest highlight of the 1st decade of the LHC
- Since then: Enormous progress in understanding the Higgs particle
  - Both from the Experiment and Theory communities
  - Cutting-edge techniques [e.g., AI] in several areas brought substantial improvements in sensitivity
    - Often **reaching sensitivity expected at the end of HL-LHC** program
- Still: Everything looks very SM like

Summary and outlook

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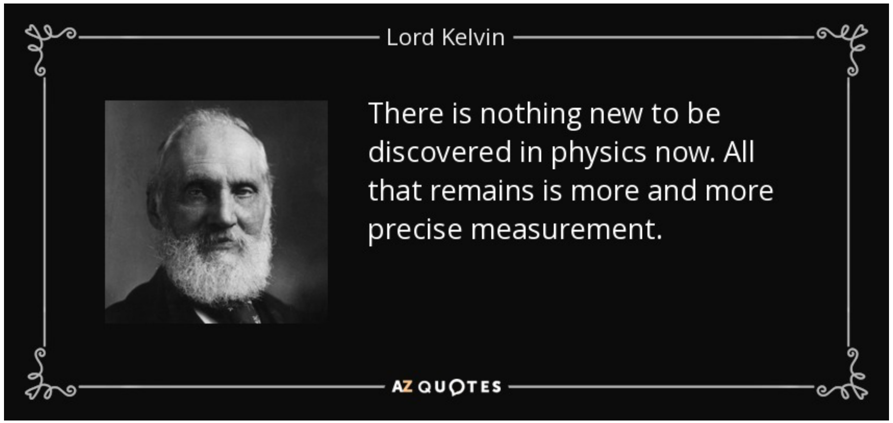
- Still: Everything looks very SM like, but…

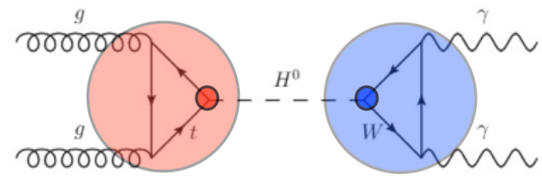


.. and we all know what followed after this statement

Back-ups

Interpretation [i.e. look for deviations]

- Signal strength (μ)
  := Production cross-section x BR



- *Coupling modifiers (κ)*:

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

  - Simplest framework to probe deviations from SM [express "***μ***" to "***κ***"]
  - no need of BSM calculations; but simplifications [e.g., blind to polarization, etc..]

- *Effective Field Theory (EFT)*:

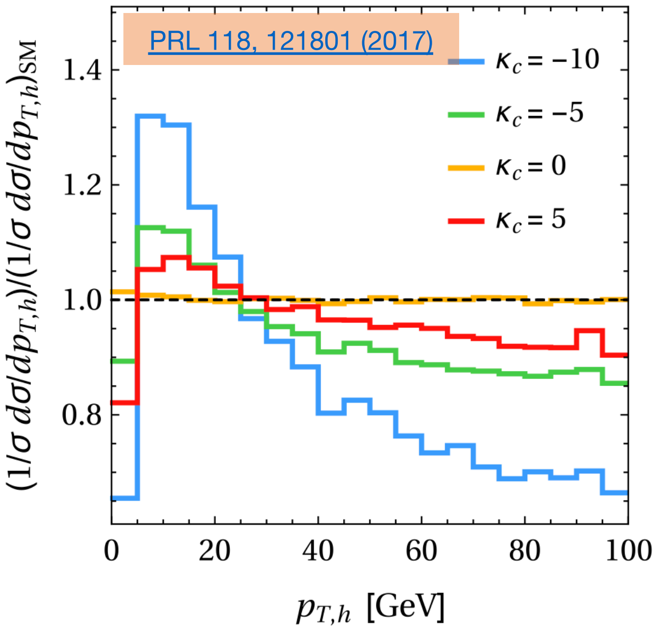
$$\mathscr{L}_d = \sum_i c_i^{(d)} \mathscr{O}_i^{(d)}$$

  - Extension of *κ*–framework: probe helicity structure and polarization
  - sensitive to higher-order effects [via operators]

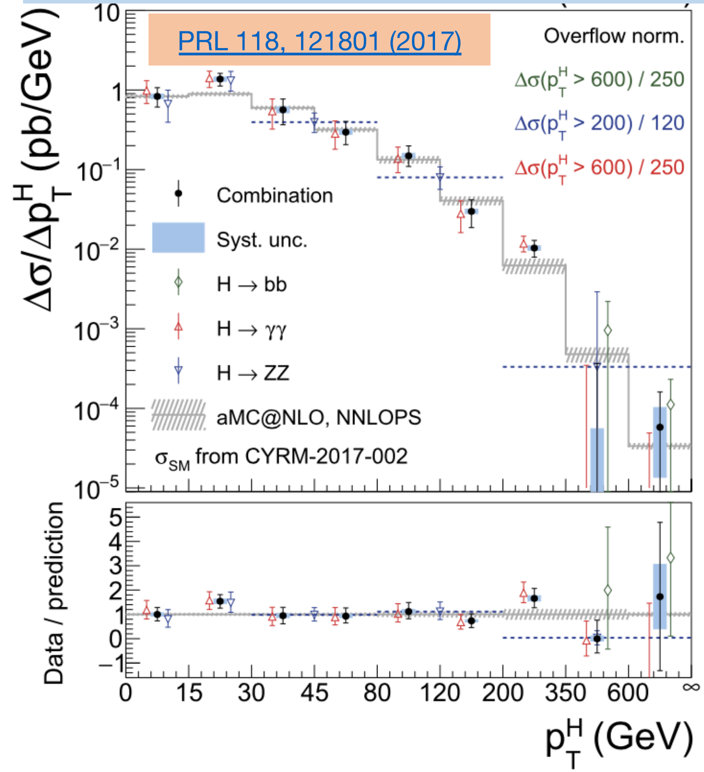
Indirect bounds

- New physics can modify Higgs kinematics [e.g. $p_T(H)$]

Impact on $p_T(H)$: Theory



Measurement of $p_T(H)$: Experiment
.. and look for deviations



Constraints on H-c coupling (κ_C):

-4.9 (-6.1) < κ_C < 4.8 (6.0) OBS (EXP)

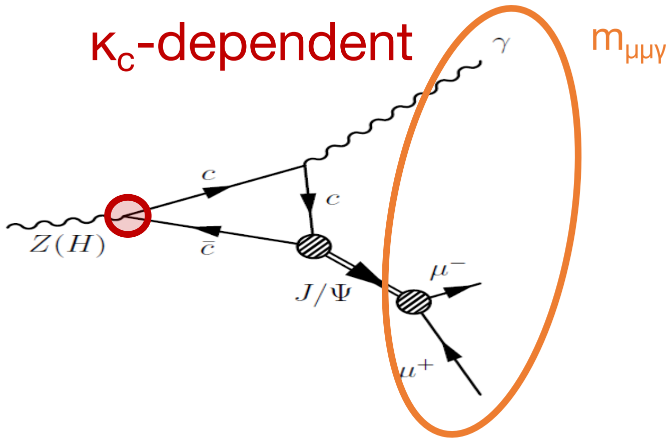
IF both κ_b and κ_C float:

-33 (31) < κ_C < 38 (36) OBS (EXP)

Strong model–dependence ☹

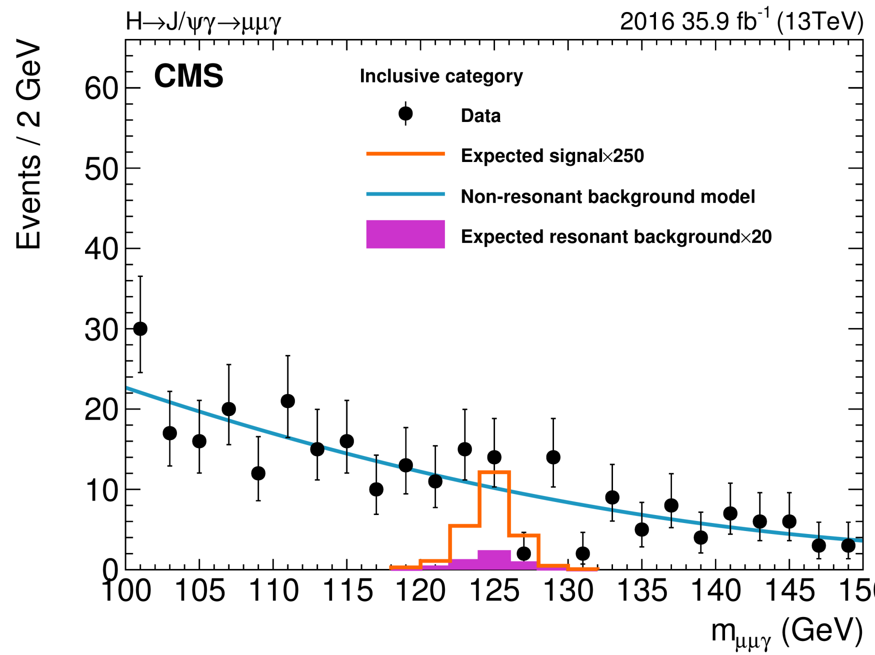
Exclusive decay modes

- Access κ_c via charmonium decays:



- Very clean signature
- **but:** Very rare
  BR(H→J/ψ γ) ~ $3\text{x}10^{-6}$

- Analysis strategy:
  - μμ final state
  - Fit $m_{\mu\mu\gamma}$ to extract signal



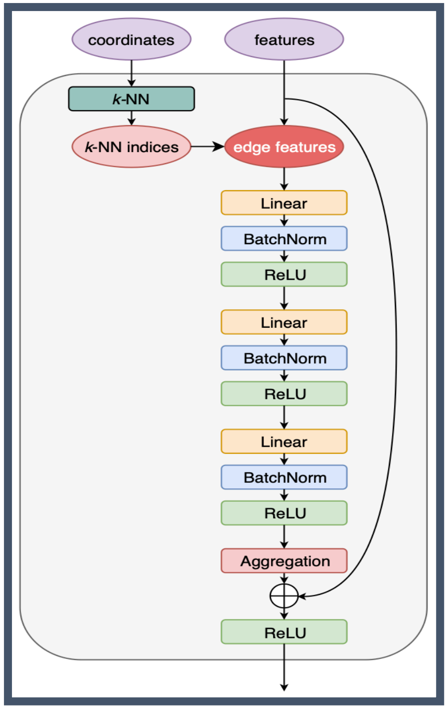
- Constraints on κ_C O(100xSM)
- Far weaker than indirect ones

ParticleNet architecture

- Based on EdgeConv and DGCNN
  - but customized for the jet tagging task

H. Qu and LG
[PRD 101 056019 (2020)]

EdgeConv block



Introduced:
- features beyond spatial coordinates
- residual connections
- MLP conf.

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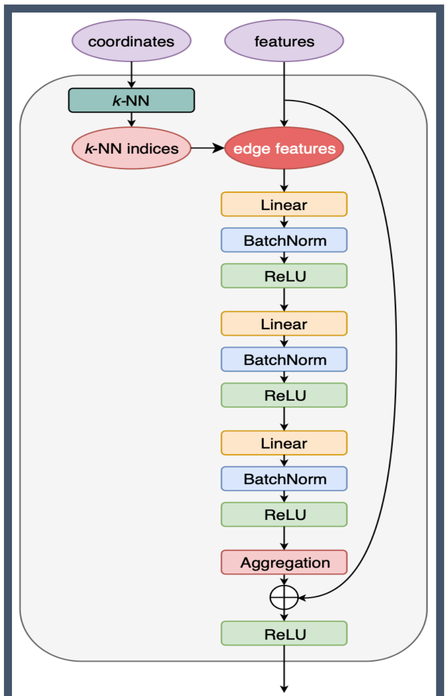

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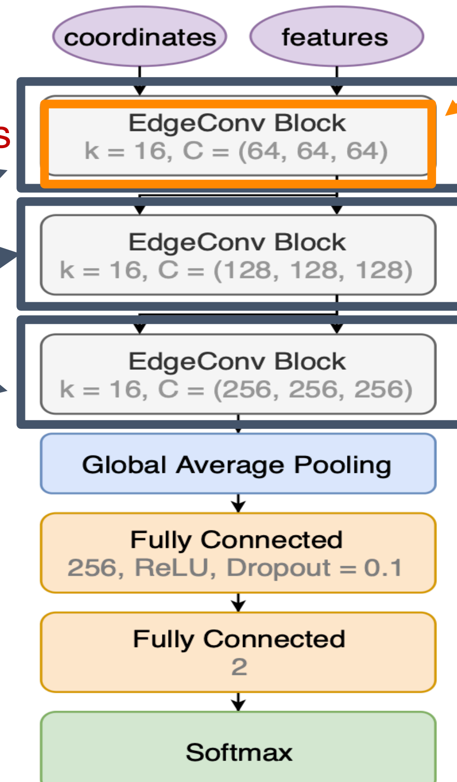


particles distributed in η-ϕ

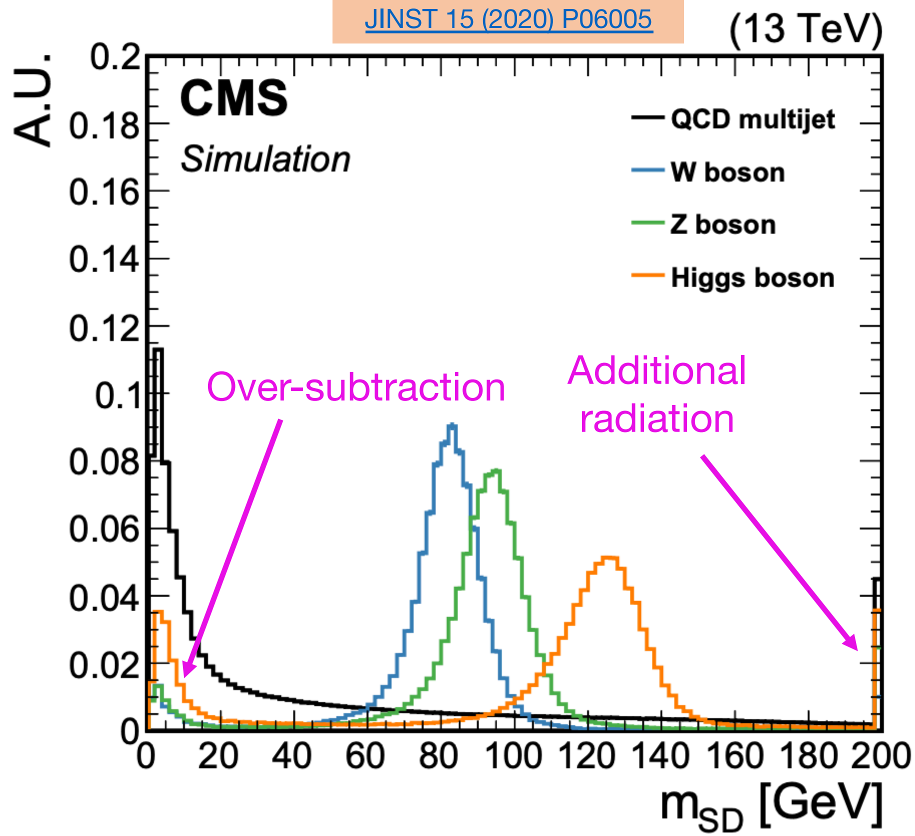
From local to more global structures

A closer look to the jet mass

- Traditional approach: Jet "grooming"
  - Pros: - simple
    - well tested in data
  - Cons: some inefficiency

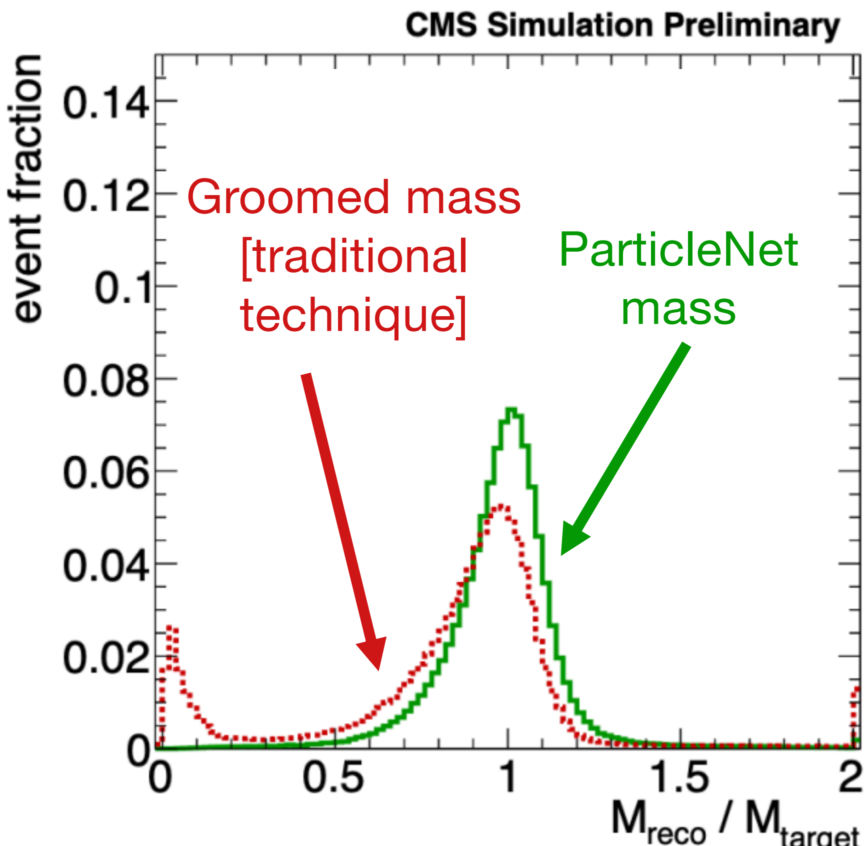
- Additional challenge: Decays to bb/cc Energy loss via (undetected) neutrinos

JINST 15 (2020) P06005



Improving jet mass reconstruction

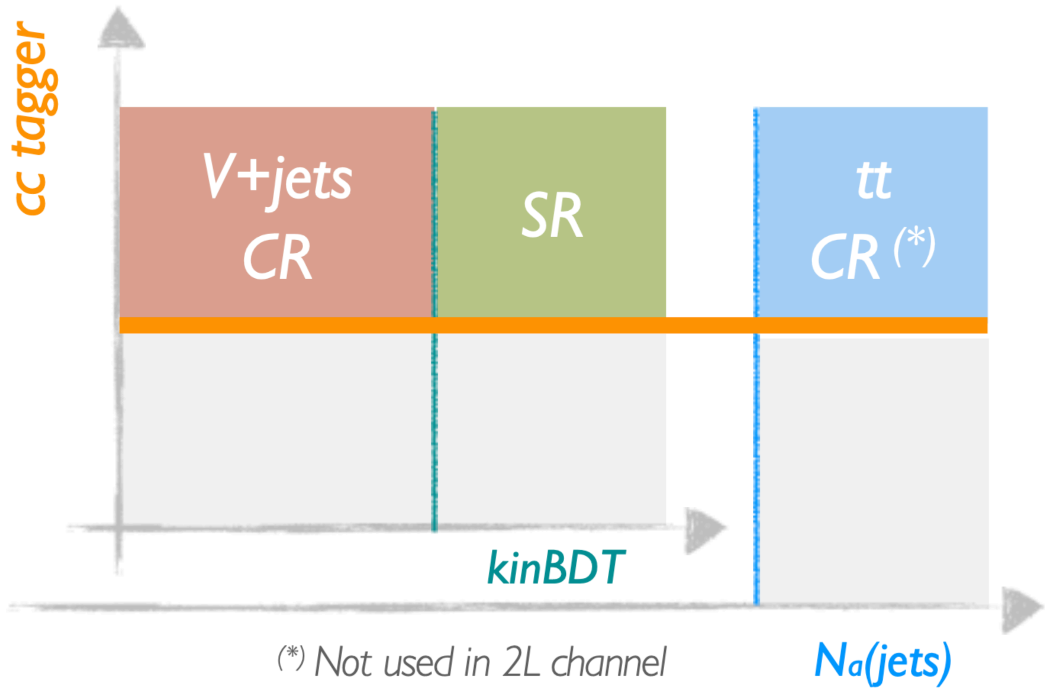
- ParticleNet: to predict the jet mass from its constituents



> 2x improvement in jet mass resolution

Merged-jet: BKG estimation

- Major backgrounds (i.e. V+jets and ttbar) estimated from data CRs
  - CRs are designed to have similar flavor composition as SRs
    - Extract cc-tagging efficiency **directly from data**
    - No need to split V+jets BKG → reduced systematic uncertainties

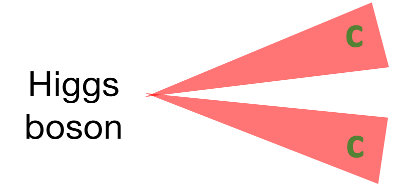


Simple and robust BKG estimation stragegy

Full analysis validated in two data samples:
→ Low $p_T(V)$
→ Low values of the cc-discriminant

Resolved-jet: Analysis strategy

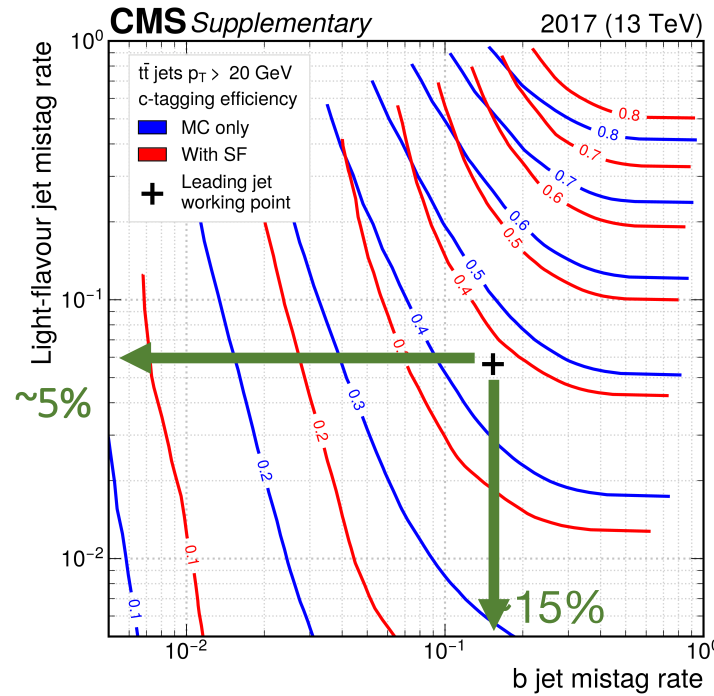
- Recover signal acceptance by including the “traditional” resolved jet topology



- Higgs candidate (H_{cand}) selection
  - Define two discriminants
    - **“CvsL”**: P(c) / [P(c) + P(light)]
    - **“CvsB”**: P(c) / [P(c) + P(b)]
- H_{cand}:
  - two highest “CvsL” small-*R* jets
- Search region (SR)
  - Leading “CvsL” jet pass WP:

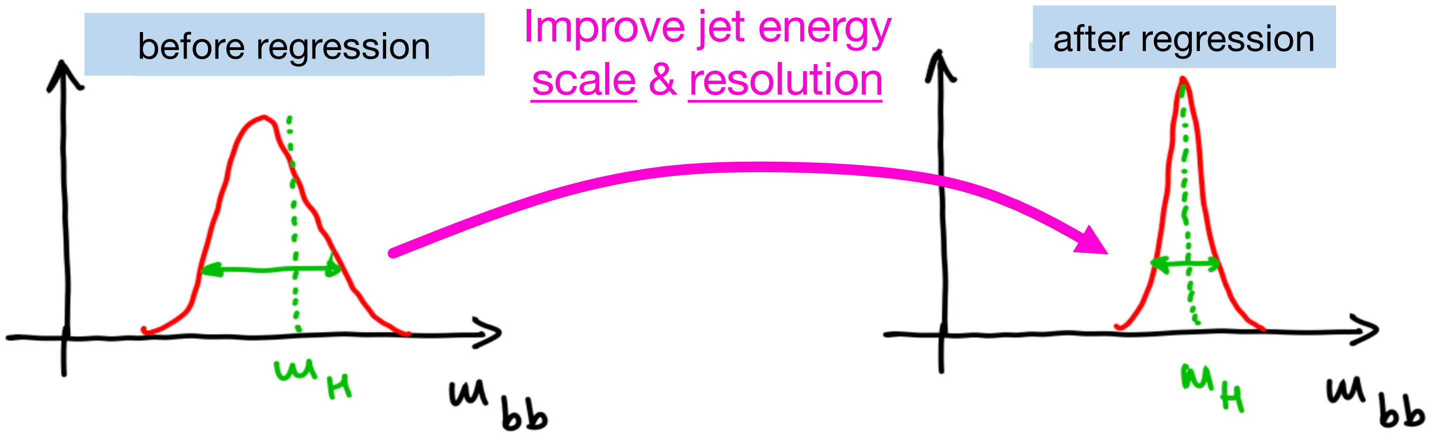
Flavor	Efficiency
c-jet	43%
light-jet	5%
b-jet	15%

DeepFLavour/DeepJet



Resolved-jet: c-jet regression

- Precise estimation of the b/c-quark energy challenging
  - energy loss via (undetected) neutrinos from semileptonic decays (~20%)
  - mis-reconstructed tracks and/or tracks outside jet cone, etc..



DNN-based regression algorithm

Inspired by:
CSBS 4 (2020) 10

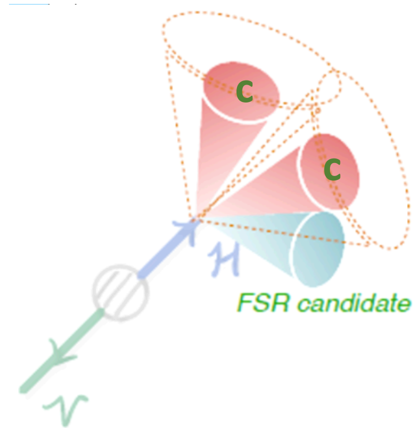
Inputs (43 in total):
- Jet kinematics
- Jet composition
- PU information
- Info about leptonic decays
- Secondary vertex (SV) info

DNN architecture
- Fully connected network
- 6 Layers

Outputs:
- scale correction
- 25% quantile
- 75% quantile

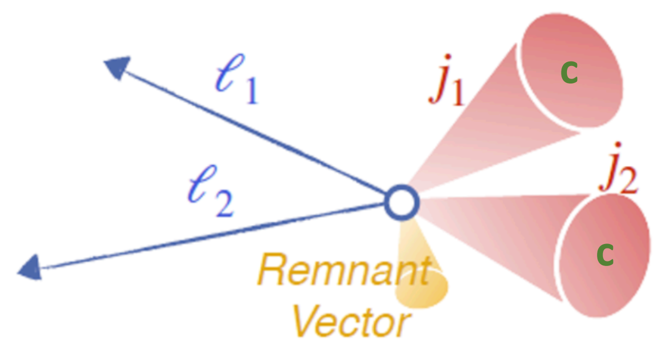
Resolved-jet: Further improvements

- *"FSR Recovery"*:
  Recover jets from Final State Radiation:
  - Jets close [i.e. $\Delta R<0.8$] to H_{cand} included in Higgs 4-vector



Up to ~5% improvement in $m(H_{cand})$ resolution

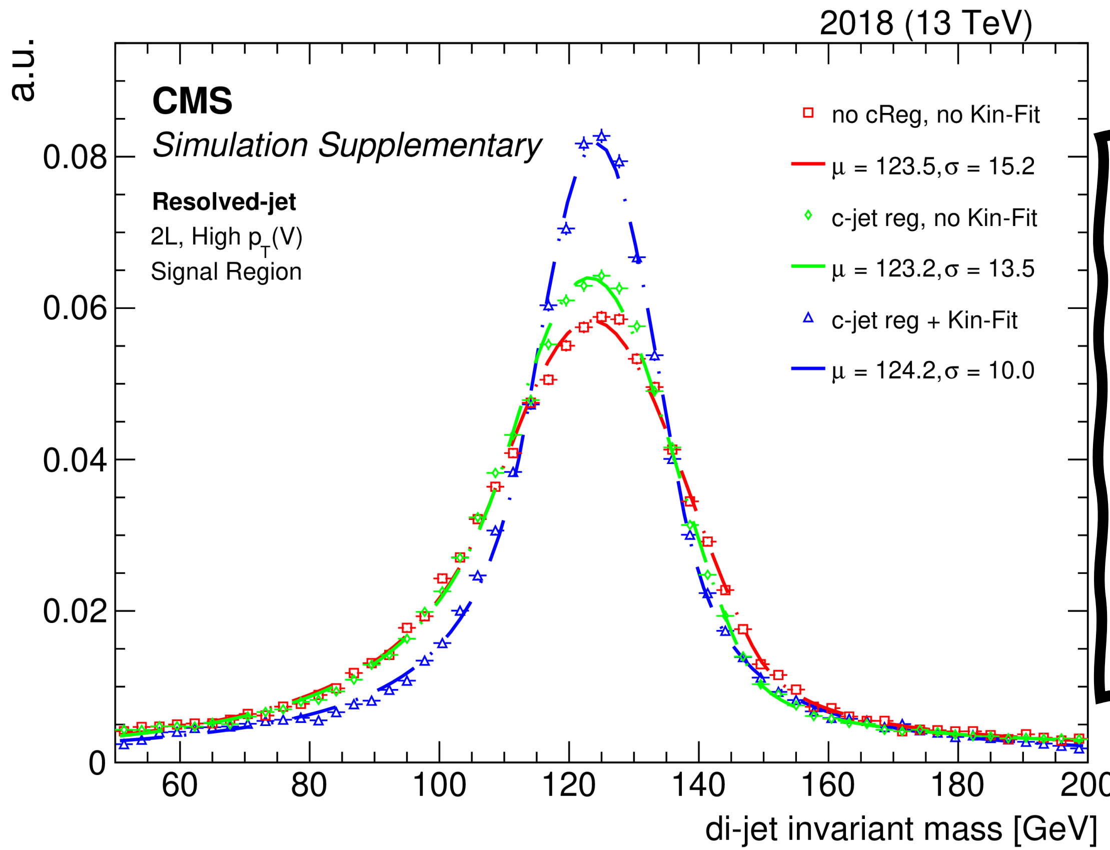
- *"Kinematic Fit"*:
  - 2L channel i.e. Z(→LL)H(→cc): no genuine sources of missing energy
  - Improve p_T(jet) measurement via a kinematic fit
    - Constraint 2L system to Z mass
    - Balance LL+cc+jets in transverse plane
    - Adjust jet energies within EXP resolution



Up to ~30% improvement in $m(H_{cand})$ resolution

Resolved-jet: $m(H_{cand})$ performance

2L channel, $p_T(V)$> 150 GeV



$m(H_{cand})$ resolution

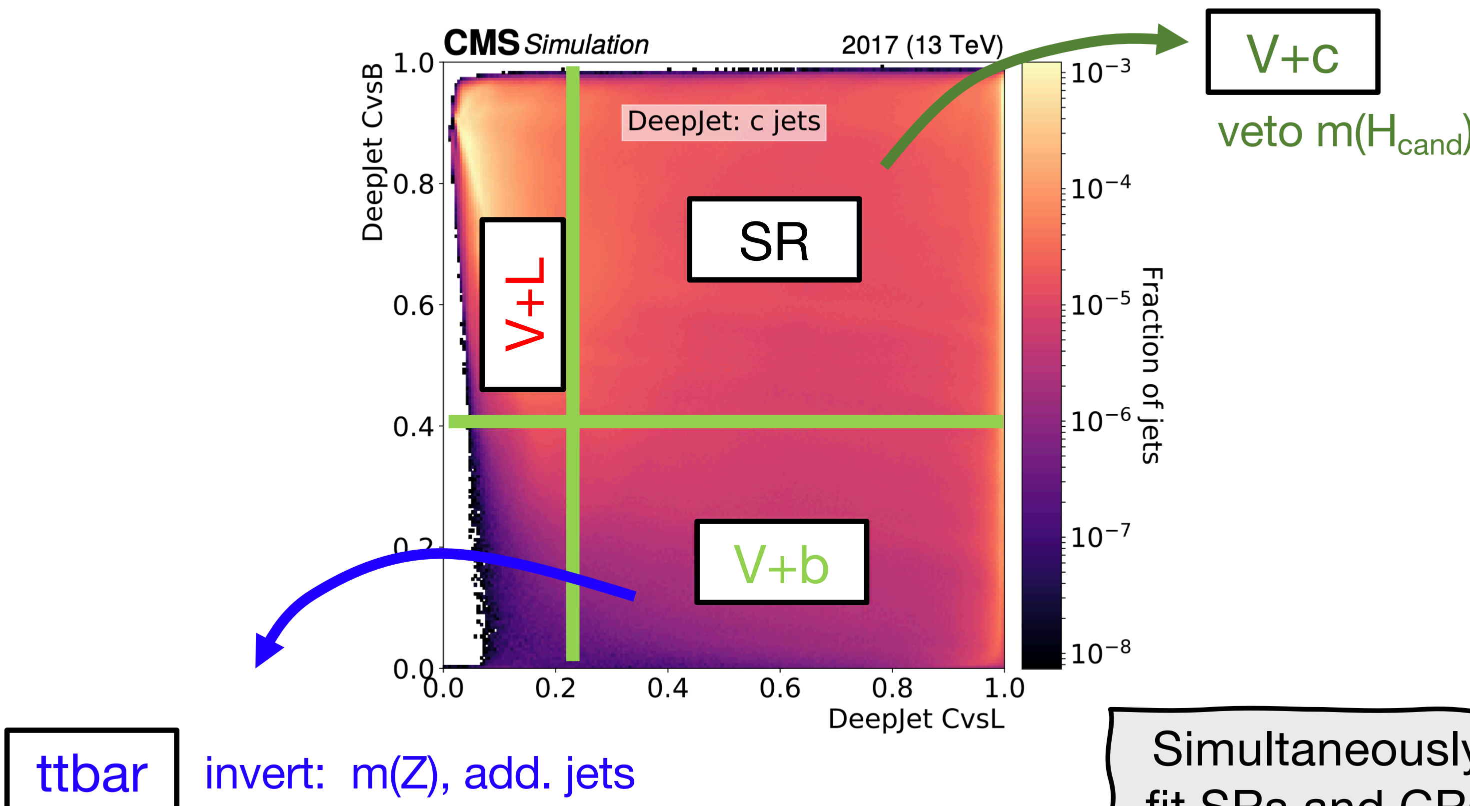
- FSR recovery: 12.3 %

- c-jet regression: 10.9 %

- Kinematic Fit [2L]: 8%

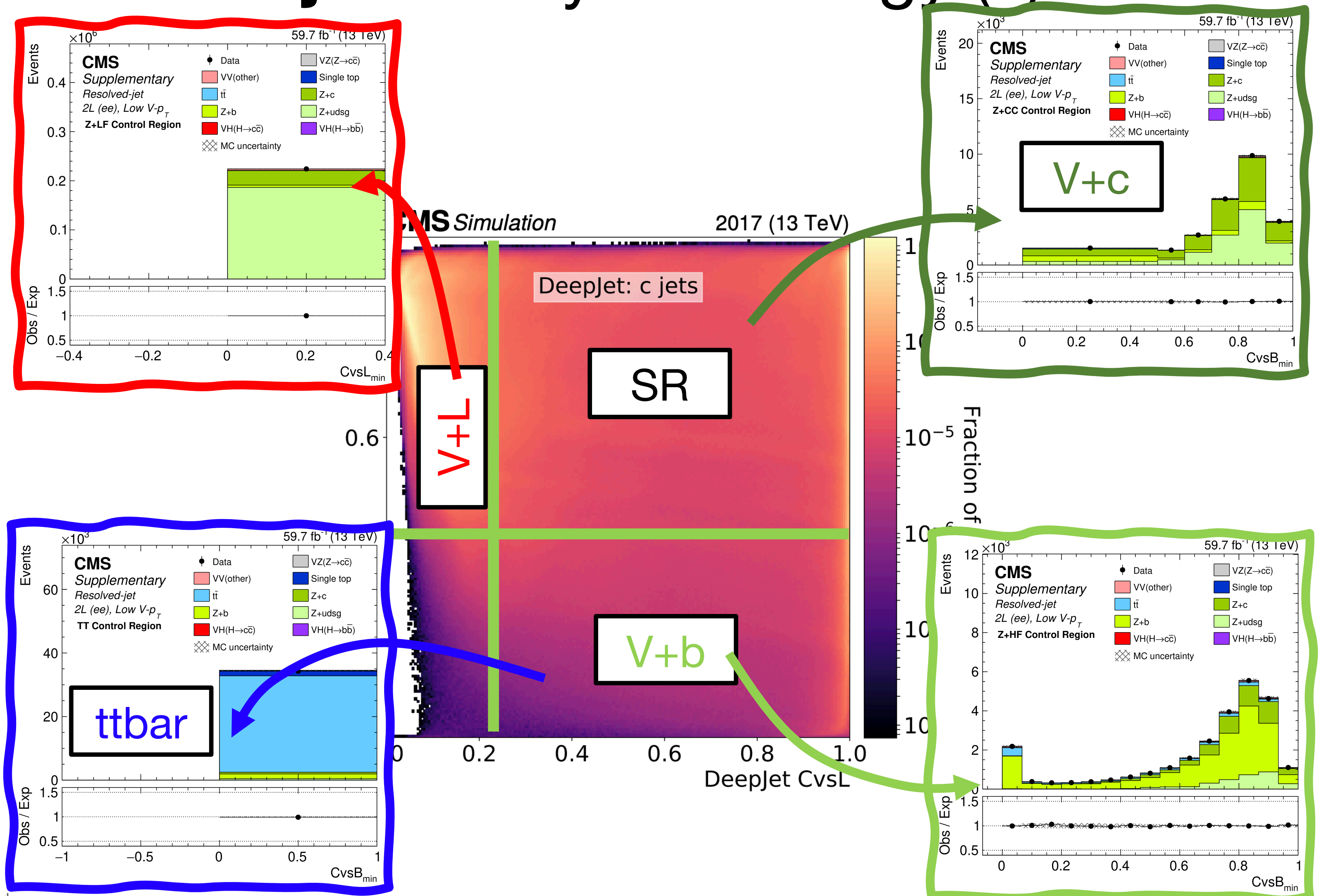
Resolved-jet: Analysis strategy (II)

- Precise estimation main BKGs [i.e. V+jets and ttbar] vital
  - Estimated from dedicated **data** control regions [CRs]
    - N.B.: V+jets split based on flavor composition: (V+c(c), V+b(b)/bc, V+udsg)



Simultaneously fit SRs and CRs

Resolved-jet: Analysis strategy (II)



VH(→cc): Results

- Final result: combination of two topologies
  - IFF p_T(Large-*R*)>300 GeV → **merged-jet**, else **resolved-jet**
    - Maximize expected sensitivity

- Systematics scheme:
  - mostly correlated
    but: c/cc-tagging efficiency
    & PDF, μ_R, μ_F for V+jets

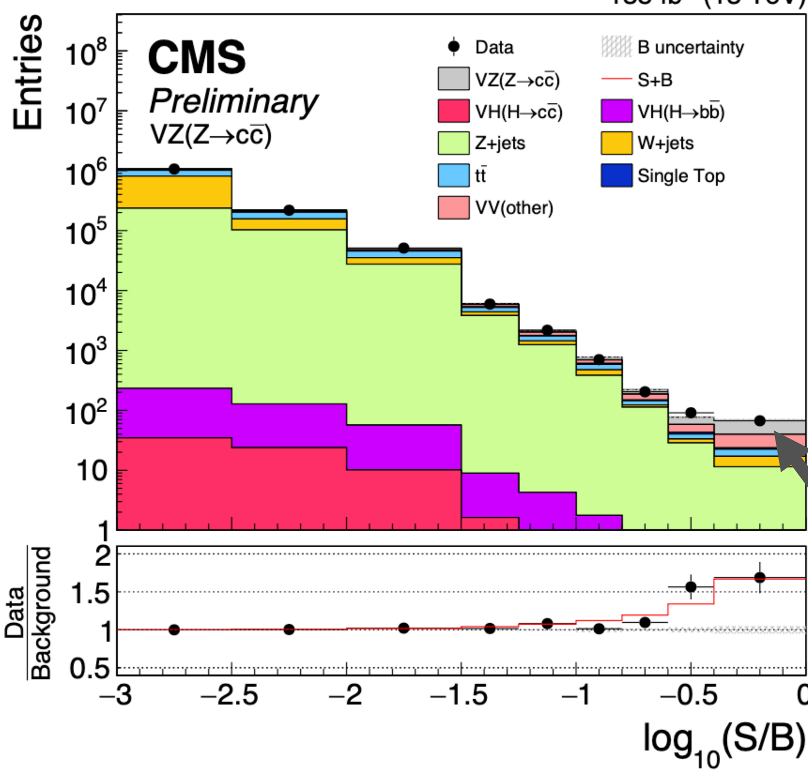
- Dominant sources:
  - Stats of CRs
  - Statistical power of MC samples

Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	**85%**
Background normalizations	37%
Experimental	**48%**
Sizes of the simulated samples	37%
c jet identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Integrated luminosity	6%
Lepton identification efficiencies	4%
Theory	**22%**
Backgrounds	17%
Signal	15%

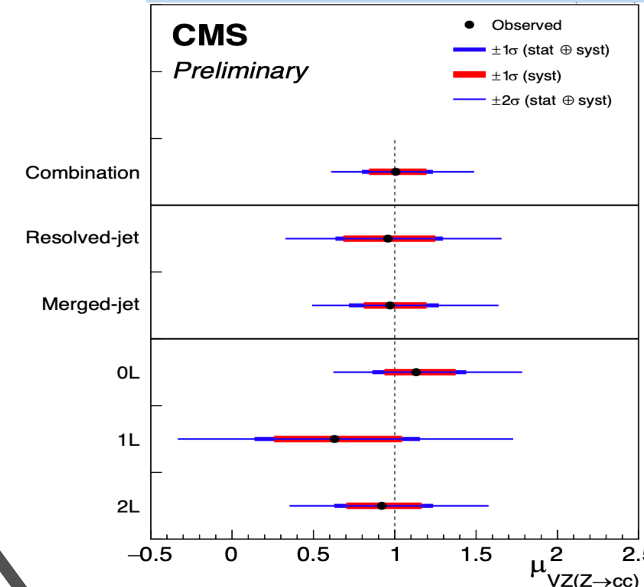
Validation using VZ(→cc)

- Final result: combination of both topologies
- But first … Validation by measuring VZ(→cc)

Combination



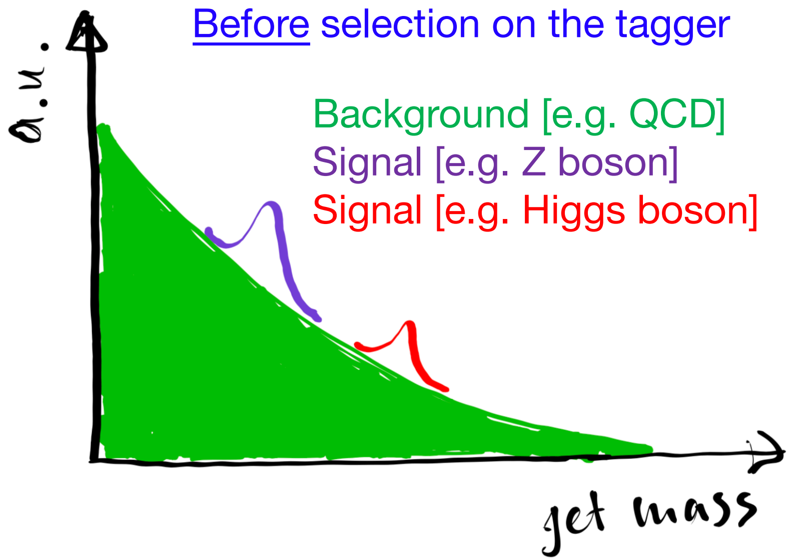
VZ(→cc) signal strength

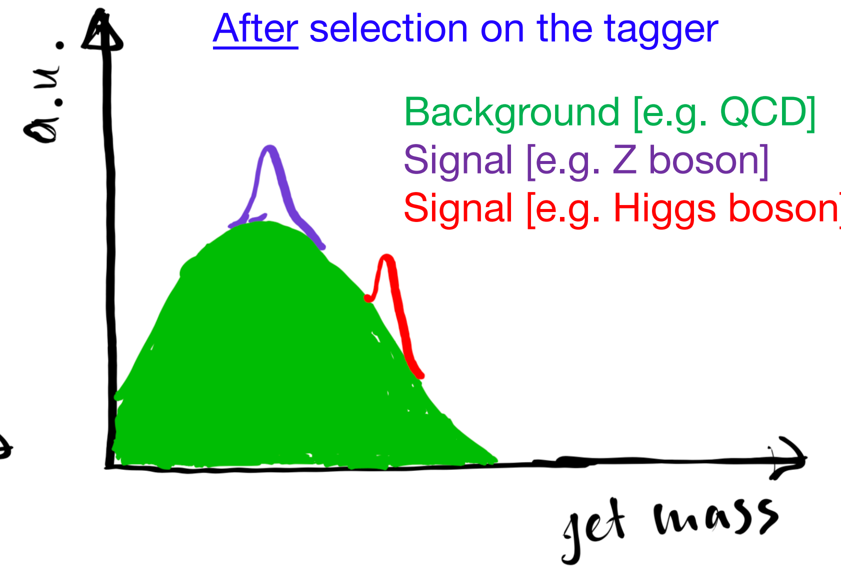


Technique proven on VZ(→cc)
5.7σ (5.9σ) Obs (Exp)
μ = 1.01 ± 0.22
[1st observation at hadron colliders]

Jet mass (de-)correlation

- Jet taggers are correlated with jet mass





Jet Mass distribution in Background jets becomes similar to that from signal:
"Mass sculpting"

- Depending on the analysis this may not be welcome

Jet mass (de-)correlation methods

- Several jet mass decorrelation techniques explored so far

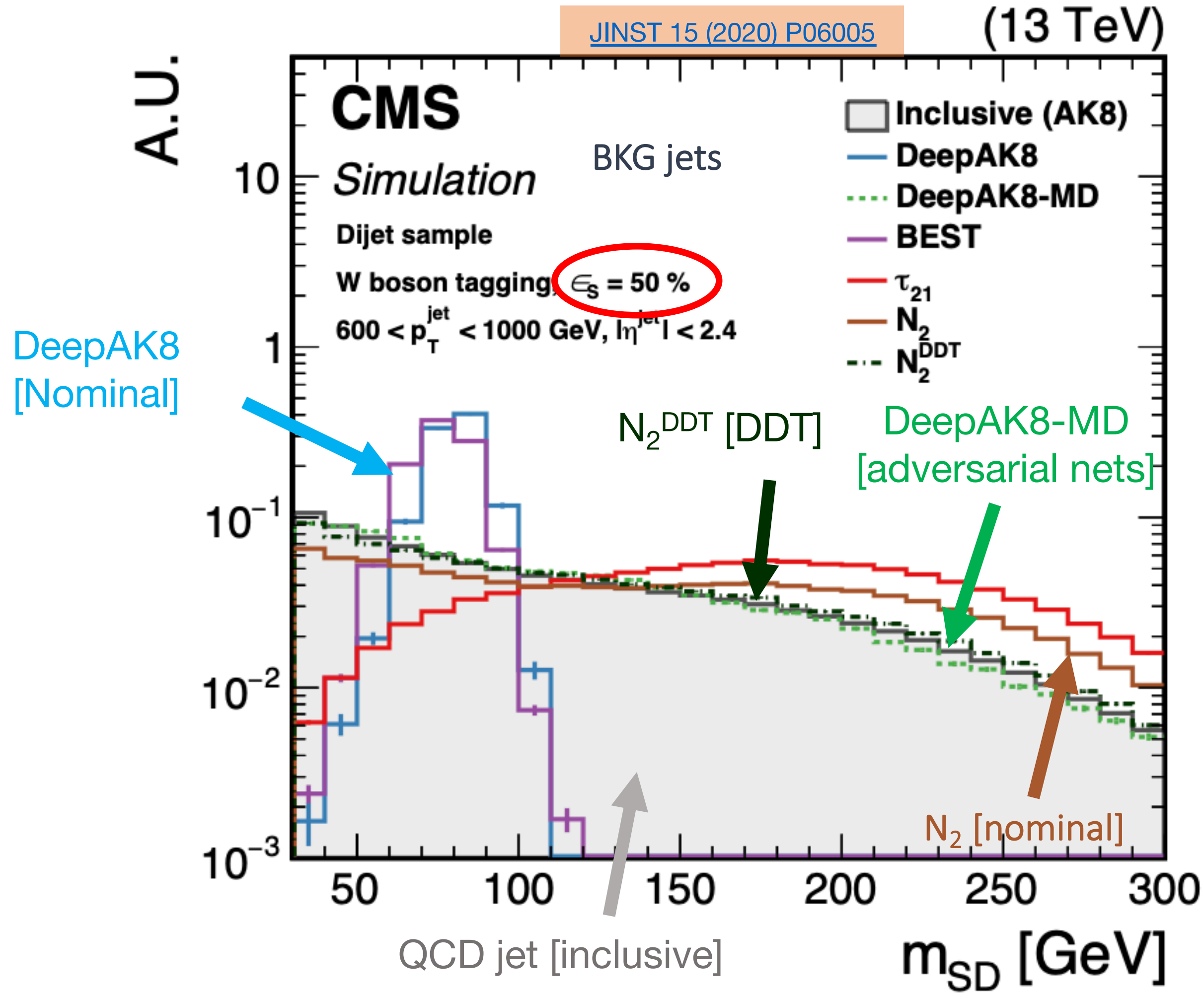
- **Sample reweighting:**
  - reweight QCD m(j) to match the signal one

- **D**esign **D**ecorrelated **T**agger **(DDT):**
  - Define a metric e.g., $\rho = \ln(m_{SD}^2 / p_T^2)$ to capture correlation m(jet)
  - **Then:** transform response to preserve constant BKG rejection across m(j): **$\text{Tagger}^{DDT} = \text{Tagger} - X_{(\%)}$**

- Adversarial networks:
  - Introduce an NN to predict m(jet) from the features extracted by the nominal network
  - Acts as penalty term in classifier network

Jet mass (de-)correlation methods

JINST 15 (2020) P06005



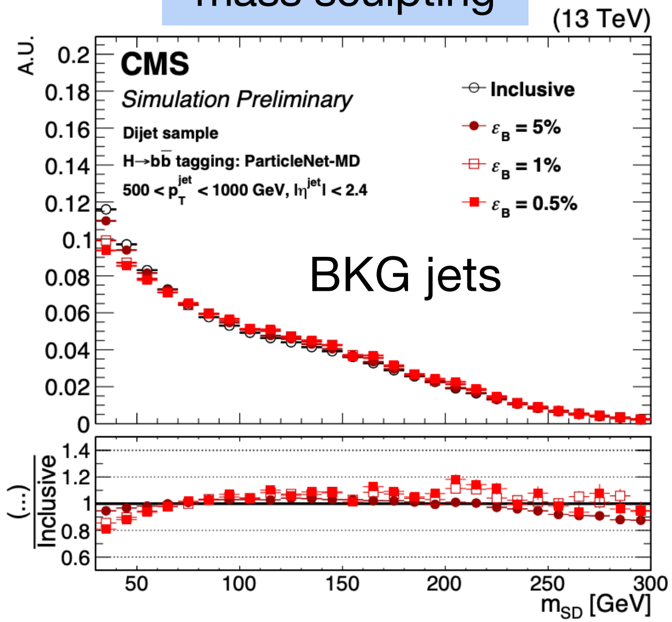
Mass sculpting greatly reduced but not perfect …

Jet mass (de-)correlation methods (II)

CMS-DP-2020-002

- A new jet mass de-correlation method for 2-prong tagging
  - Developed in the context of ParticleNet [applicable to any tagger]
- Strategy:
  - Design dedicated “signal” samples w/ flat m(X) [X: spin-0 particle]
    - hadronic decays of X → bb, cc, qq [on equal fractions]
  - **Signal** and **BKG** jets **re-weighted to a flat distribution** in m(jet) & p_T(jet)

mass sculpting



→ Improved mass decorrelation
No indication of mass sculpting
- even for very tight WPs

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[CMS-DP-2020-002]

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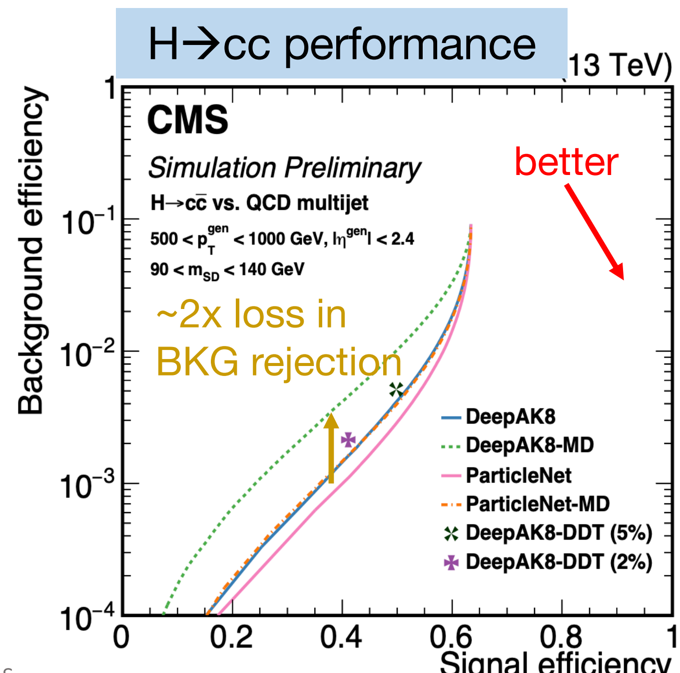


→ Improved mass decorrelation
No indication of mass sculpting
- even for very tight WPs

→ Minimal performance loss compared to the nominal ParticleNet
- ~2x improved performance compared to DeepAK8—MD (ie adversarial training)

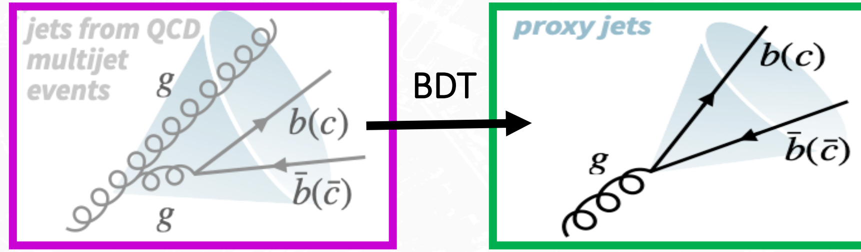
→ Training significantly easier

MD := mass decorrelated

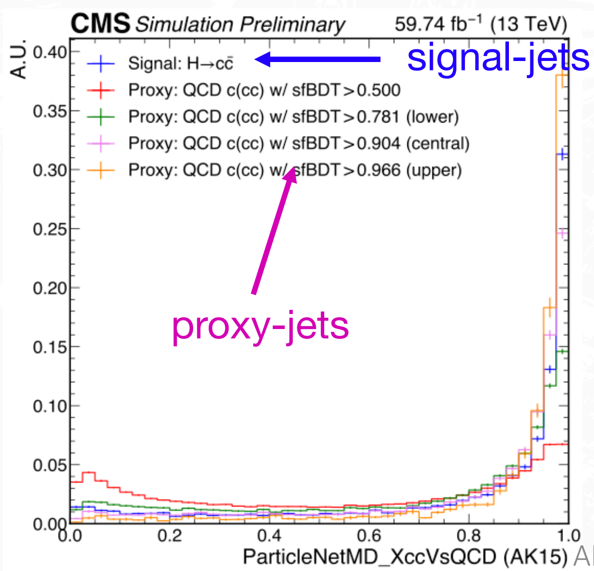
ParticleNet calibration

CMS-DP-2022-005

- **Challenge:** No pure H/Z→bb,cc sample; rely on proxy jets from g→bb,cc
  - Yet: difficult to select proxy jets w/ similar characteristics to signal jets
- **New method:** Develop a BDT to distinguish *hard 2-prong* splittings, from *soft-bb/cc* radiations

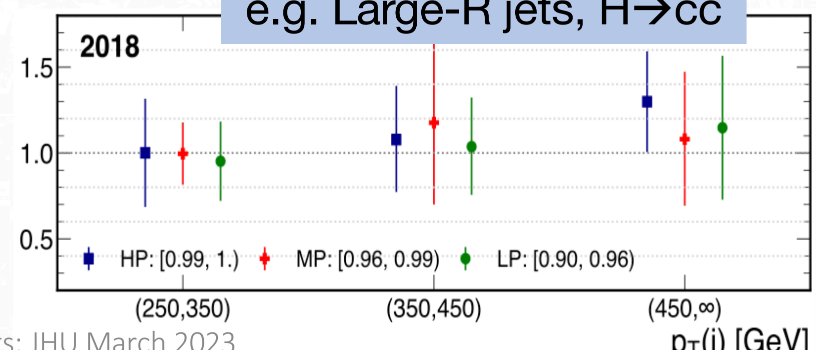


e.g. AK15 jets, H→cc



- Extract SFs from simultaneous fit of m(SV) in "pass" and "fail" categories
- For different values of the BDT

e.g. Large-R jets, H→cc



Performance comparison

SciPost Phys. 7, 014 (2019)

- Comparison against various DL-based jet tagging algorithms
  - tested on a common top-tagging dataset

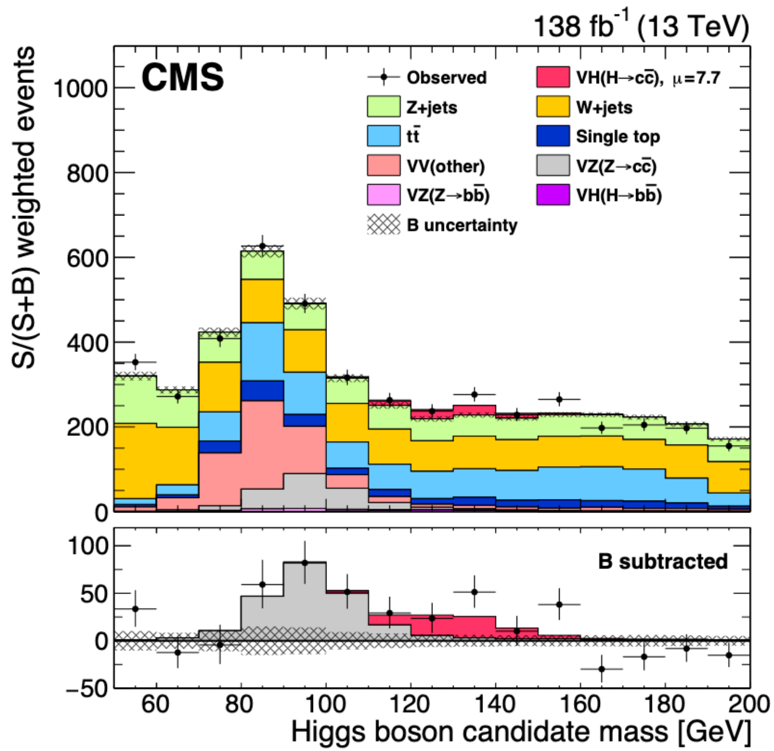
	AUC	Acc	$1/\epsilon_B$ ($\epsilon_S = 0.3$) single	mean	median	#Param
CNN [16]	0.981	0.930	914±14	995±15	975±18	610k
ResNeXt [31]	0.984	0.936	1122±47	1270±28	1286±31	1.46M
TopoDNN [18]	0.972	0.916	295±5	382± 5	378 ± 8	59k
Multi-body N-subjettiness 6 [24]	0.979	0.922	792±18	798±12	808±13	57k
Multi-body N-subjettiness 8 [24]	0.981	0.929	867±15	918±20	926±18	58k
TreeNiN [43]	0.982	0.933	1025±11	1202±23	1188±24	34k
P-CNN (DeepAK8)	0.980	0.930	732±24	845±13	834±14	348k
ParticleNet [47] (v1)	0.985	0.938	1298±46	1412±45	1393±41	498k
LBN [19]	0.981	0.931	836±17	859±67	966±20	705k
LoLa [22]	0.980	0.929	722±17	768±11	765±11	127k
LDA [54]	0.955	0.892	151±0.4	151.5±0.5	151.7±0.4	184k
Energy Flow Polynomials [21]	0.980	0.932	384			1k
Energy Flow Network [23]	0.979	0.927	633±31	729±13	726±11	82k
Particle Flow Network [23]	0.982	0.932	891±18	1063±21	1052±29	82k
GoaT (Ensemble of all taggers)	0.985	0.939	1368±140		1549±208	35k
ParticleNet	0.986	0.940	1615 ± 93			**366k**

DeepAK8

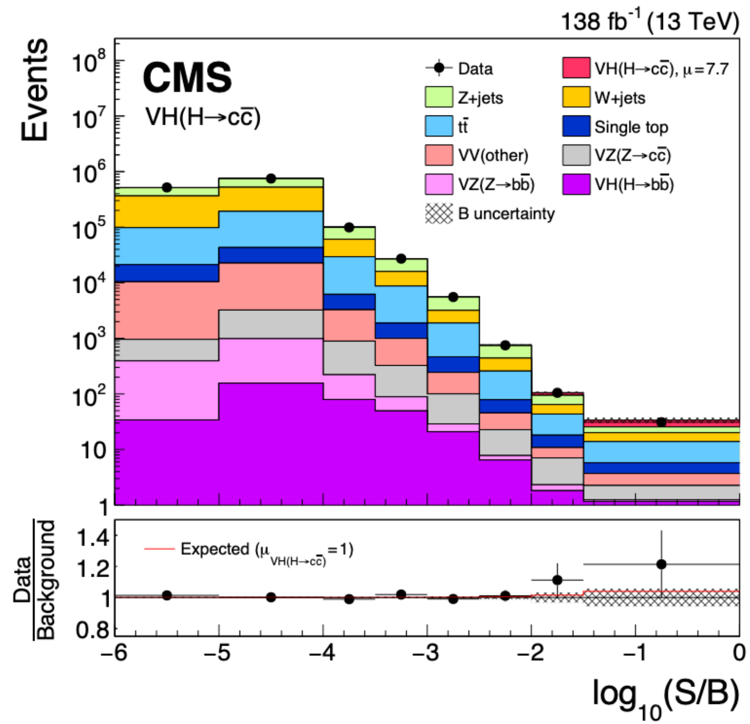
Ensemble of all taggers:

Look for VH(→cc)

“Unblinding” Higgs mass



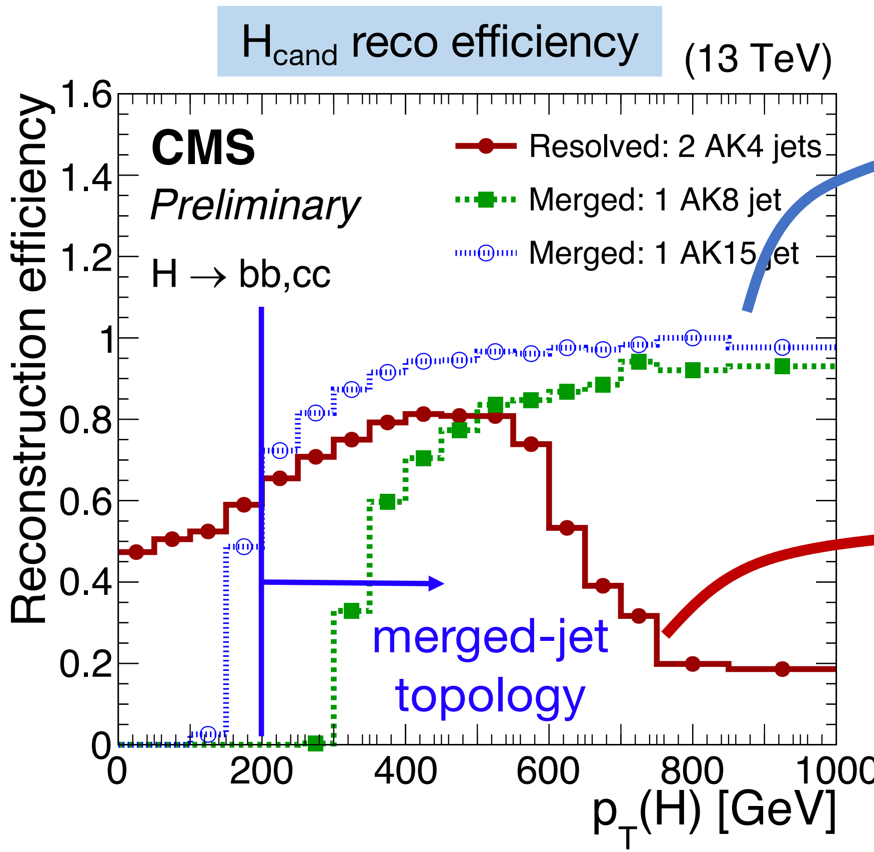
Resolved + merged topologies



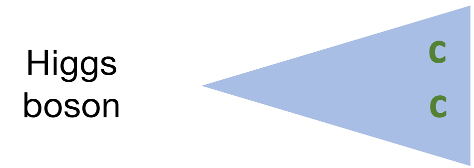
signal strength (μ) = $7.7^{+3.8}_{-3.5}$

Cornerstone: H_{cand} reconstruction & ID

- Two complementary approaches

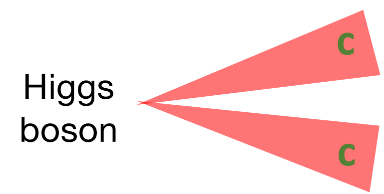


Merged-jet (R=1.5)



- Better exploit correlations b/w the two c-quarks

Traditional approach:
Resolved-jet

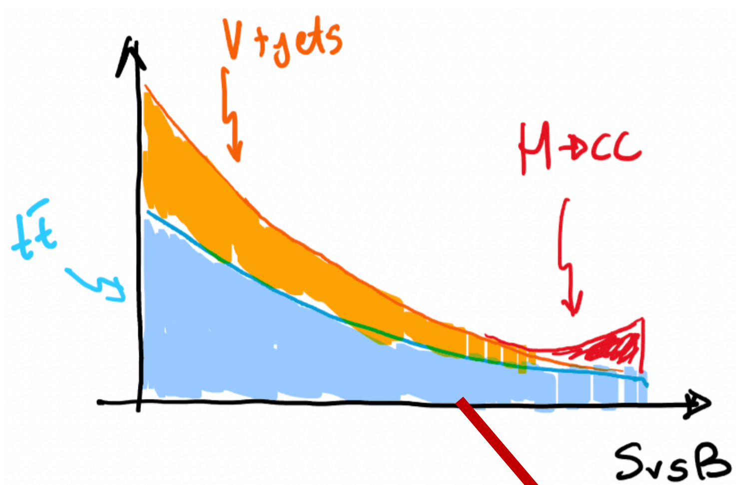


- Larger σ(VH→cc) [but also BKGs ☹]

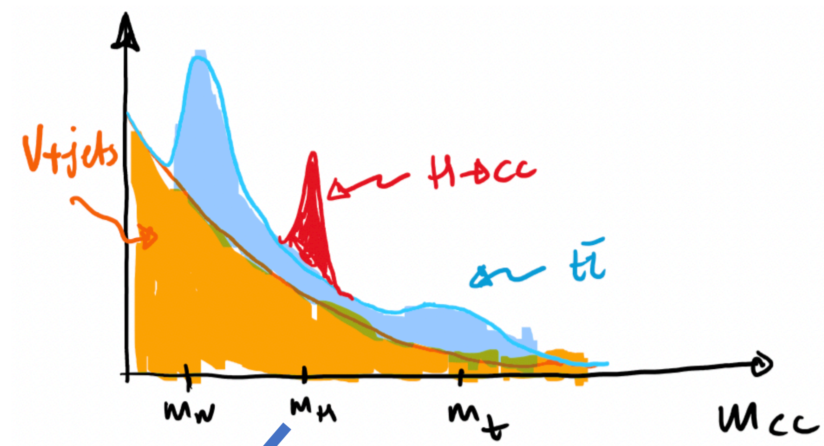
Signal extraction

- Look for an excess in data compatible with H→cc
  - **IF no excess:**
    set limits on the maximum possible H→cc rate allowed by the data

Resolved-jet
Use discriminant



Merged-jet
Use H_{cand} mass



Final result: Combination

HH extra

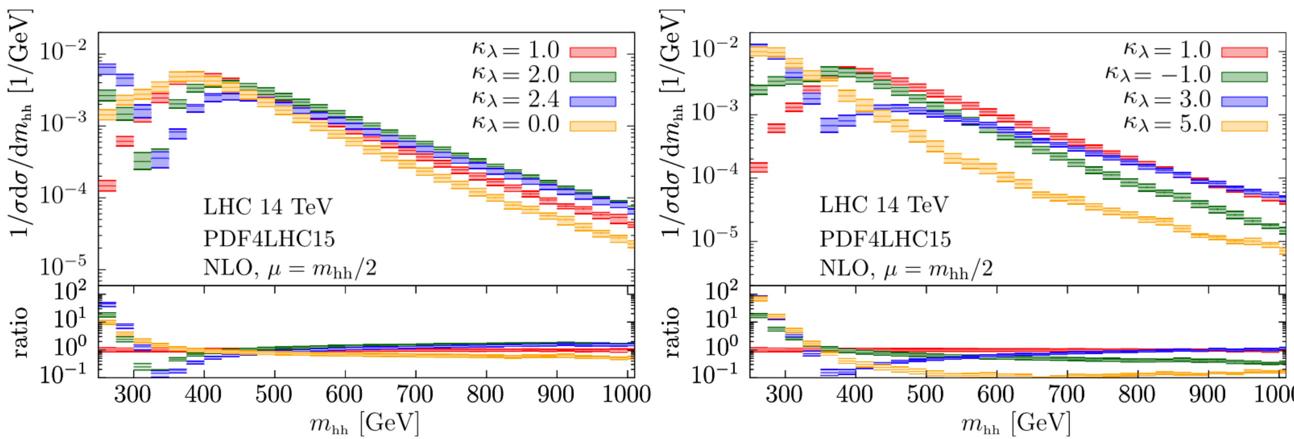
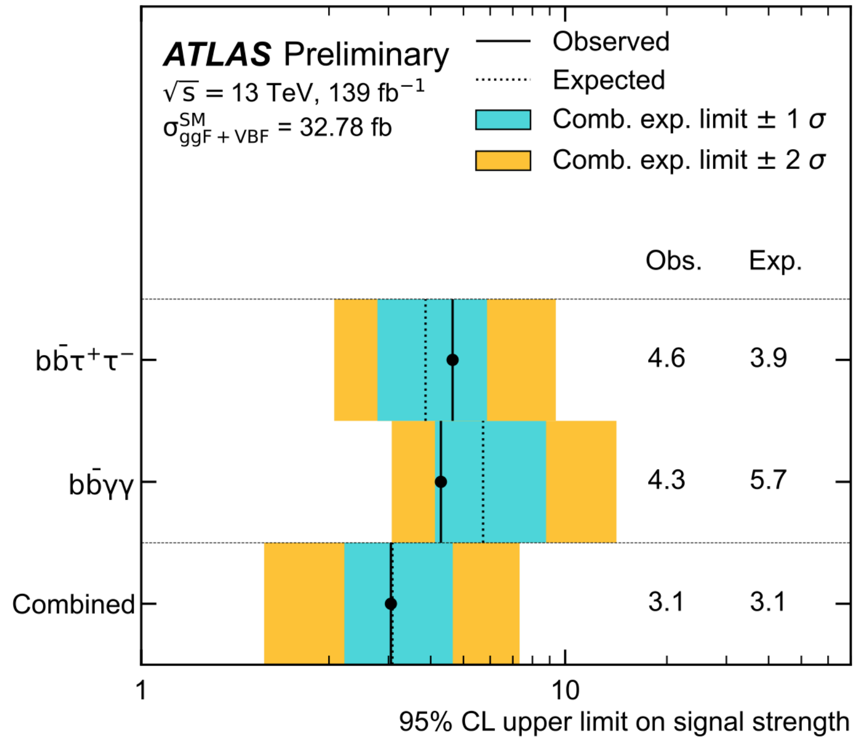


Fig. 11. Normalised Higgs boson pair invariant mass distributions at 14 TeV for (left) positive small values of κ_λ and (right) larger or negative values of κ_λ [64].

HH ATLAS Full Run 2

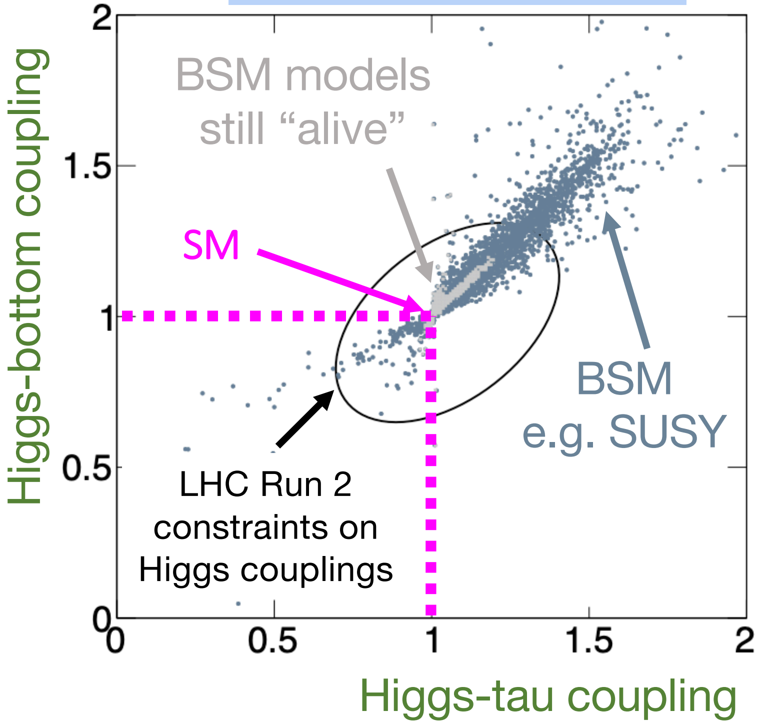
	Obs.	-2σ	-1σ	Exp.	1σ	2σ
$b\bar{b}\gamma\gamma$	4.3	3.1	4.1	5.7	8.8	14.3
$b\bar{b}\tau^+\tau^-$	4.6	2.1	2.8	3.9	5.9	9.4
Combined	3.1	1.7	2.2	3.1	4.7	7.3



Higgs as an exploration tool

- "New Physics" (**BSM**) can modify Higgs properties:

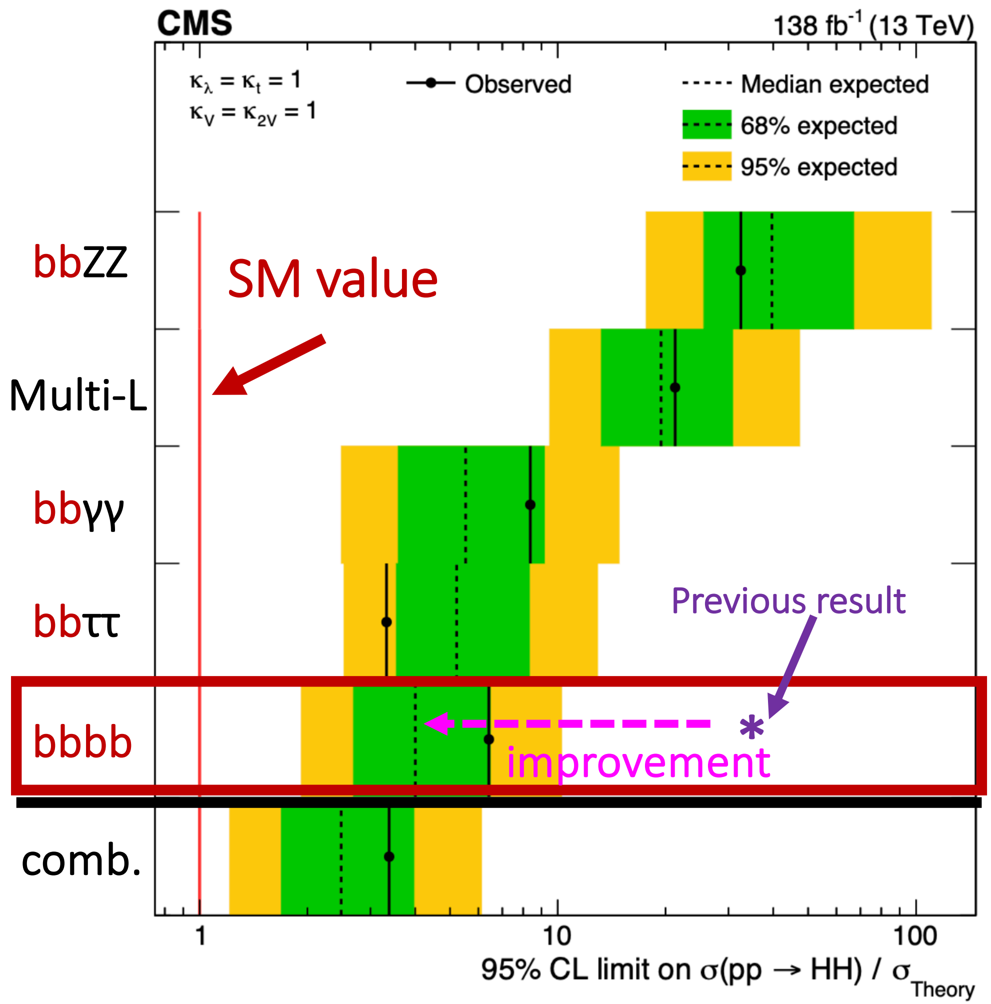
Higgs couplings



Parameter	Range
$\tan\beta$	[1, 60]
M_A	[50, 6000]
M_1	[-5000, 6000]
M_2	[-5000, 6000]
M_3	[50, 6000]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-6000, 6000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[50, 6000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[50, 6000]
$M_{\tilde{\tau}_L}$	[50, 6000]
$M_{\tilde{\tau}_R}$	[50, 6000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[50, 6000]
$M_{\tilde{q}_{3L}}$	[50, 6000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[50, 6000]
$M_{\tilde{t}_R}$	[50, 6000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 6000]
$M_{\tilde{b}_R}$	[50, 6000]

Sensitivity on HH production

PRL [accepted]



Improvements:
- 4x from b-tagging
- 2x from additional data

HH→4b: drives sensitivity

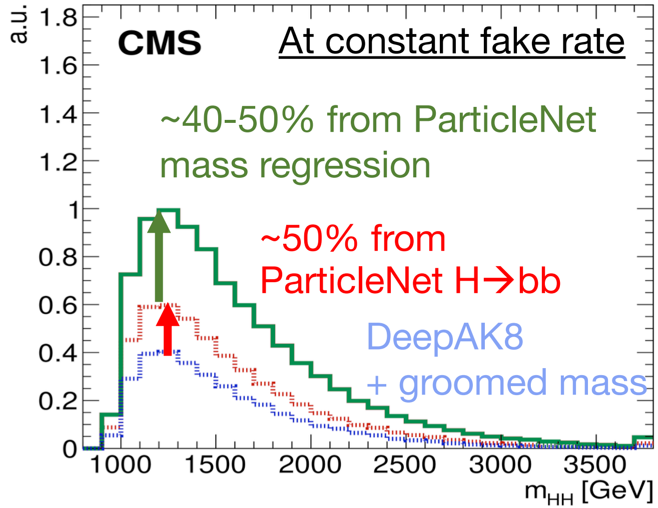
Results

Strongest limits to date:
- **CMS:** obs: 6.4 (exp: 4.0)
- ATLAS: obs: 5.4 (exp:8.1)

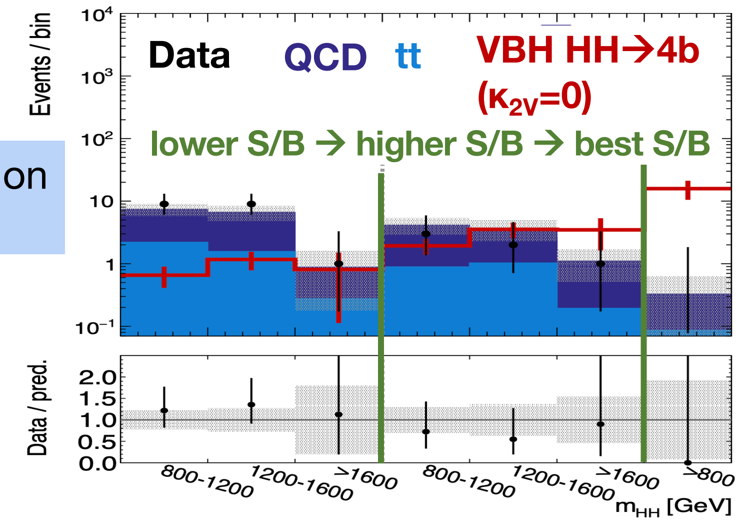
Higgs self coupling (κ_λ):
- CMS: obs: $-3.0<|\kappa_\lambda|<9.9$
  (exp: $-1.8<|\kappa_\lambda|<8.8$)
- 2x better than ATLAS

Higgs pair production (VBF)

ParticleNet in action



Signal extraction (m_{HH})



VBF HH: Results