

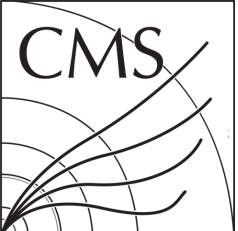


Highlights

R. Schöfbeck (Mariette Blau Institute for Particle Physics, Vienna)
for the CMS Collaboration

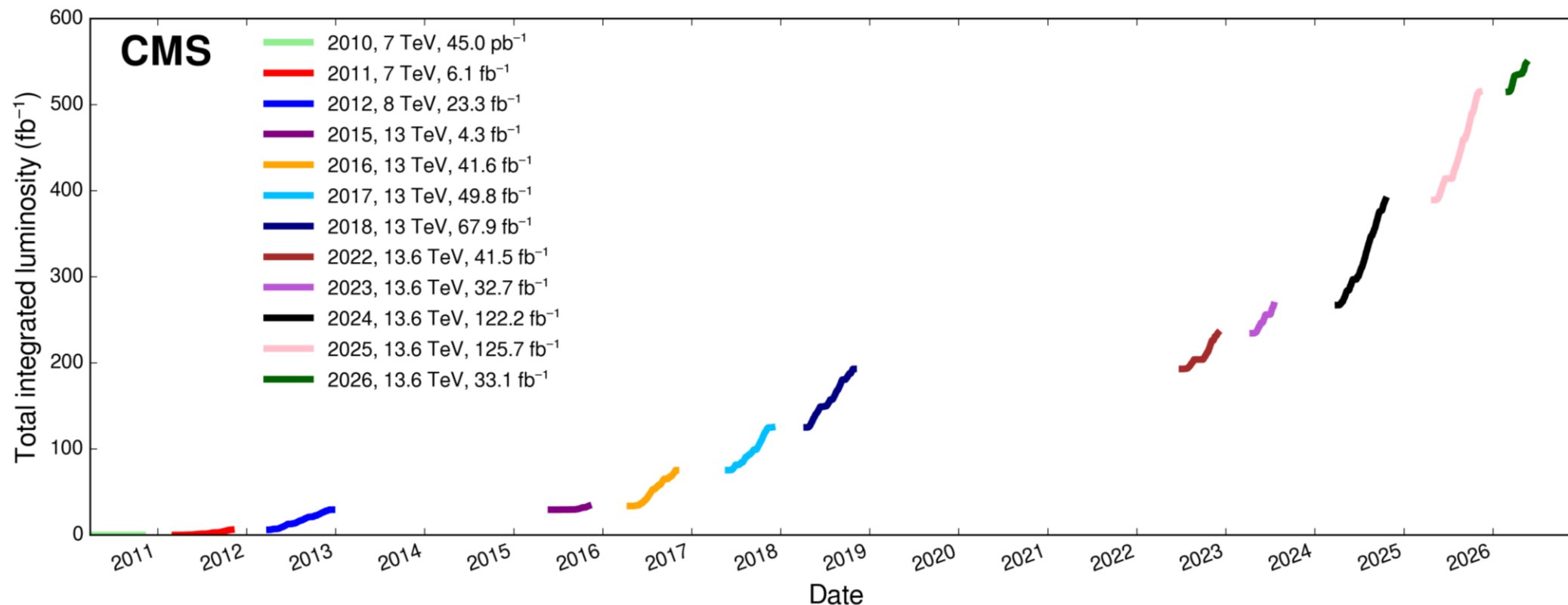
QCD@LHC, 2026, University of Oxford





LHC is over!

ÖAW



25 fb^{-1} at 7 & 8 TeV

Run 1

2009–2012

138 fb^{-1} at 13 TeV

Run 2

2015–2018

308 fb^{-1} at 13.6 TeV

Run 3

2022–2026

- 12 data taking years – Run 2 analyses done; 0.5 ab^{-1} recorded; Run 3 analyses in progress
- Next stop HL-LHC: 3 ab^{-1} with more powerful detector and trigger

Strengthened frontiers in Run 3

Standard model

Precision · QCD, electroweak & top · Higgs properties

Search frontiers

Energy · luminosity · long lifetime · low mass · anomaly detection · trigger-less data taking

Flavour factory

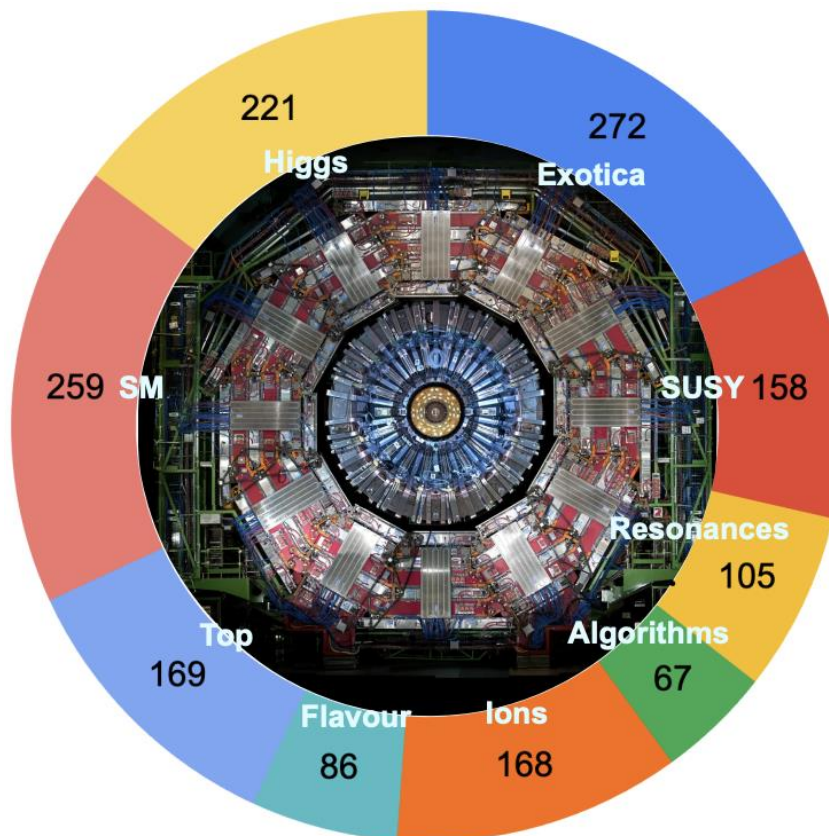
Spectroscopy · fragmentation · CP violation · Rare decays

Heavy- & light-ion physics

Medium response & quark–gluon plasma · ultra-peripheral collisions

Detector, technology & algorithms

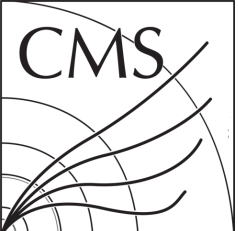
Physics performance · Machine learning · Statistical techniques



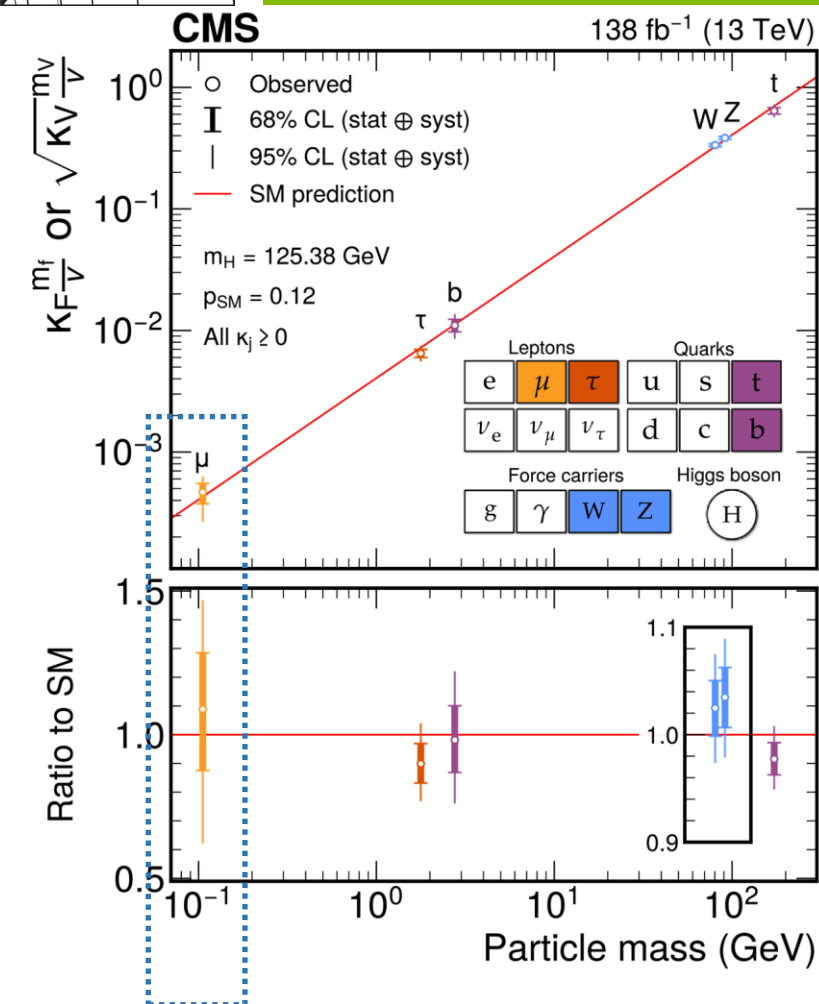
[Explore >1,500 CMS physics papers](#)

Run 3: Diverse data

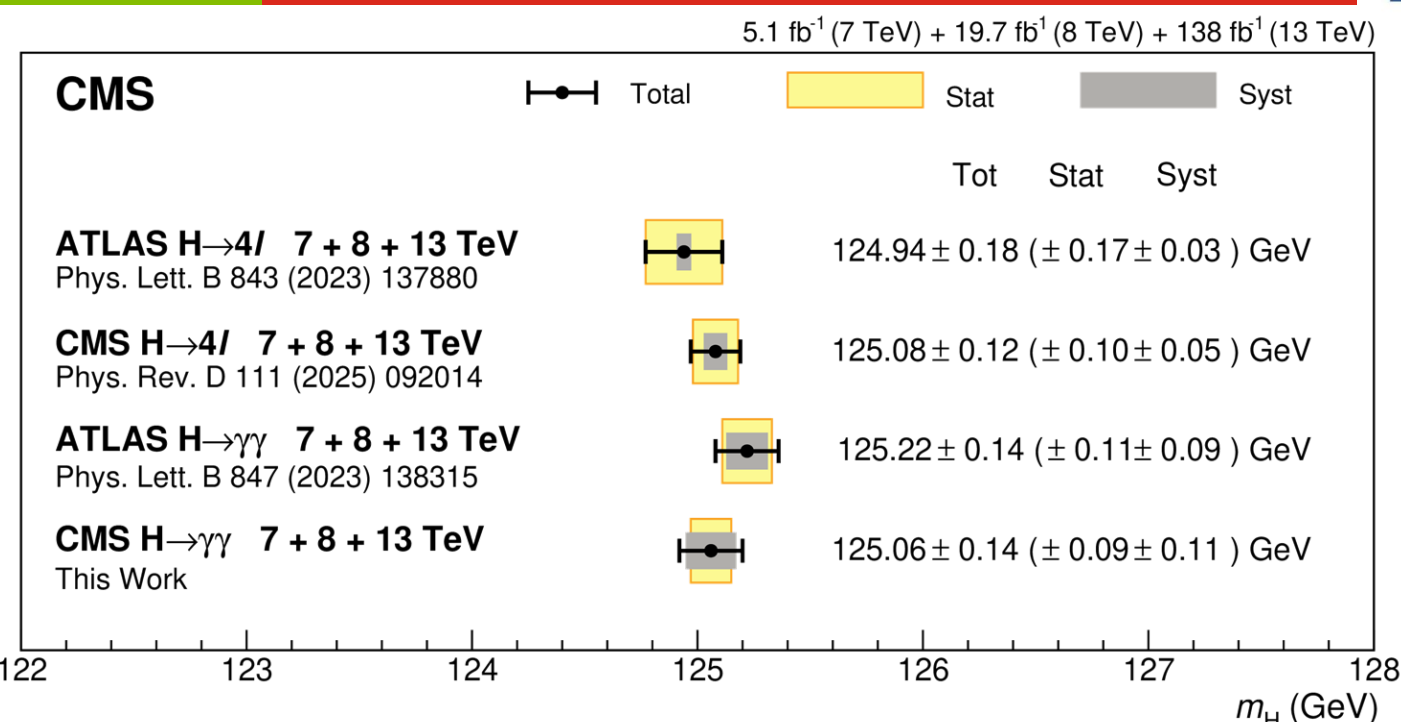
	$\sqrt{s}$ [TeV]	lumi / PU	year
pp	13.6	326 fb ⁻¹	22–26
low-PU	13.6	2 fb ⁻¹ $\mu \approx 5$	26
high-PU	13.6	$\mu \approx 150$	25
pp	2.4	3.5 pb ⁻¹	26
pp	5.36	483 pb ⁻¹	24
PbPb	5.36	≈ 8 nb ⁻¹	23–26
pO	9.62	46.5 nb ⁻¹	25
OO	5.36	9.0 nb ⁻¹	25
NeNe	5.36	0.90 nb ⁻¹	25



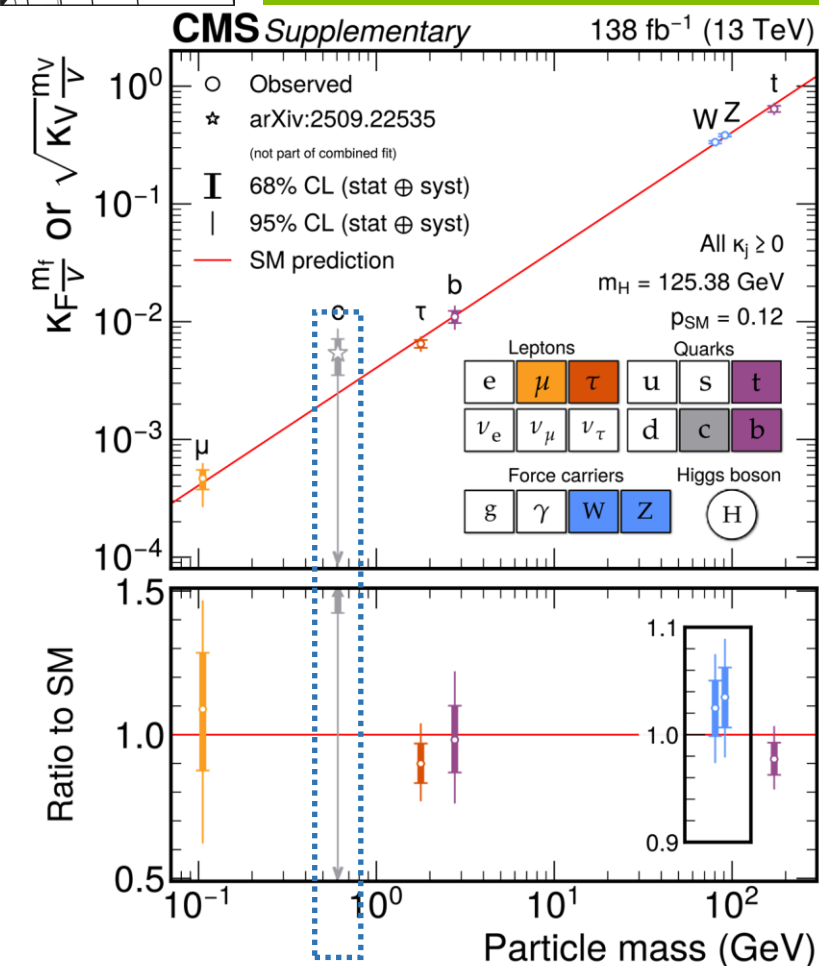
Run 2 legacy: Higgs boson measurements



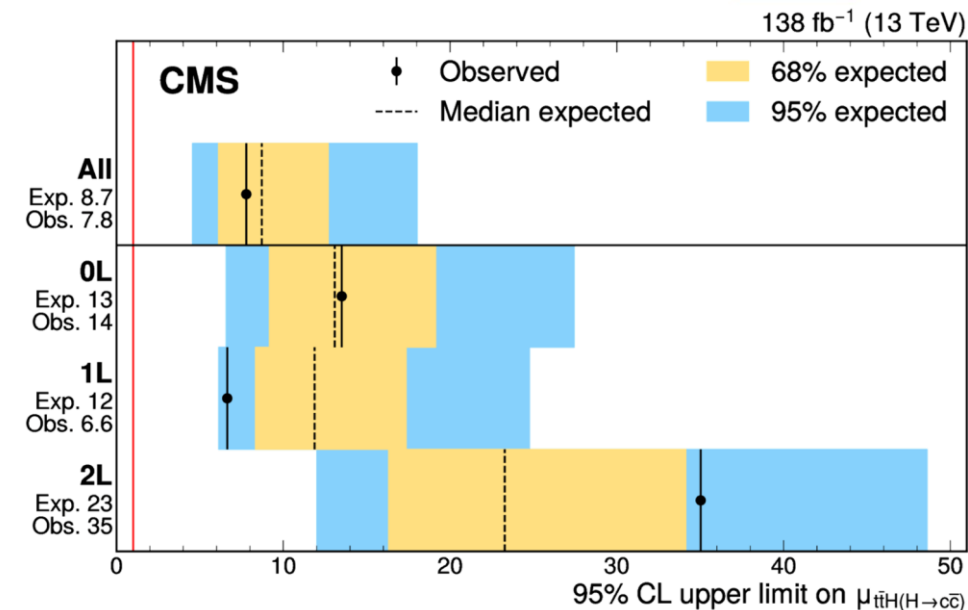
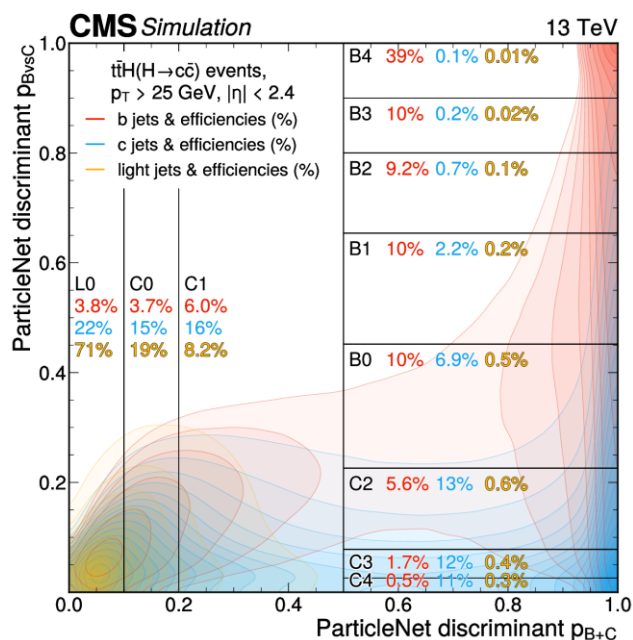
Higgs mechanism over
3 orders of magnitude



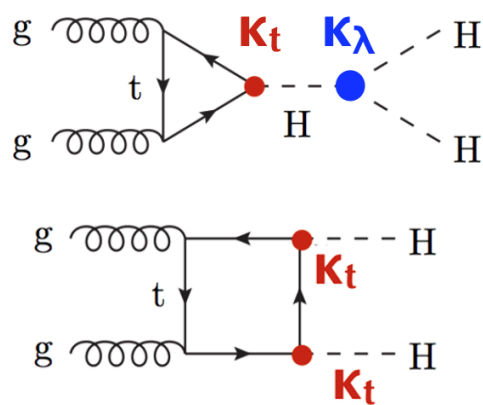
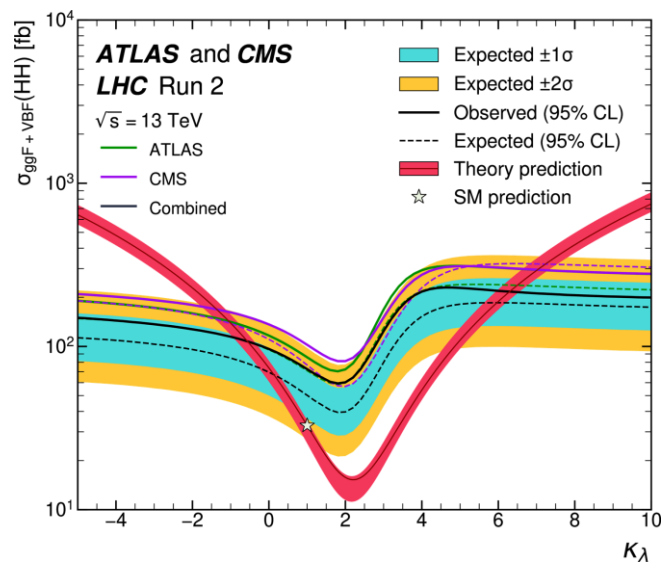
- Comprehensive Run 1+2 Higgs mass combination in $\gamma\gamma$ channel
 – $M_H(\gamma\gamma) = 125.07 \pm 0.09$ (stat) ± 0.11 (syst) GeV [[HIG-24-007](#)]
- Cross sections/couplings/2HDM constraint combination [[HIG-21-018](#)]
 – 32 kinematic regions encompassing ggH, VBF, WH, ZH: $\mu = 1.014^{+0.055}_{-0.053}$
 – Couplings follow the mass-proportional SM pattern
- Part of Run 2 legacy: 2nd generation lepton-couplings [[HIG-19-006](#)]



Coupling meas. combination

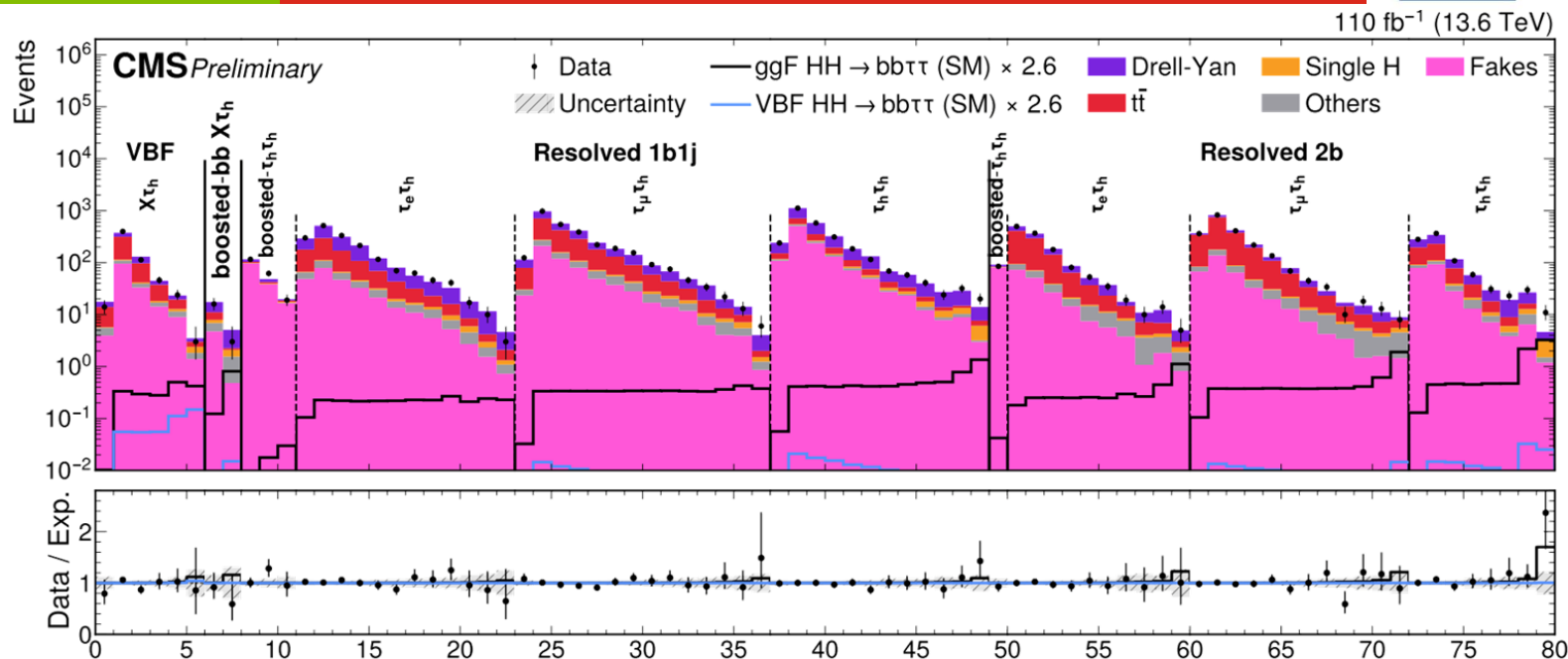


- 2nd quark generation: H→cc; considered infeasible at the LHC
 - c tagging and QCD backgrounds
- ParticleNet (dGCNN) separates b, c, and light jets, enabling a dedicated ttH(H→cc) Run 2 search [HIG-24-018]
 - 138 fb⁻¹ at 13 TeV: $\mu_{ttH(H \rightarrow c\bar{c})} < 7.8$ (8.7 expected) at 95% CL
- Combining with VH (H→cc): $|\kappa_c| < 3.5$ (2.7) obs. (exp.) [HIG-21-008]
- Expect further improvements with attention-based algorithms



ATLAS+CMS

$$\mu_{\text{HH}} = 0.8^{+0.9}_{-0.7} \text{ [[HIG-25-014](#)]}$$

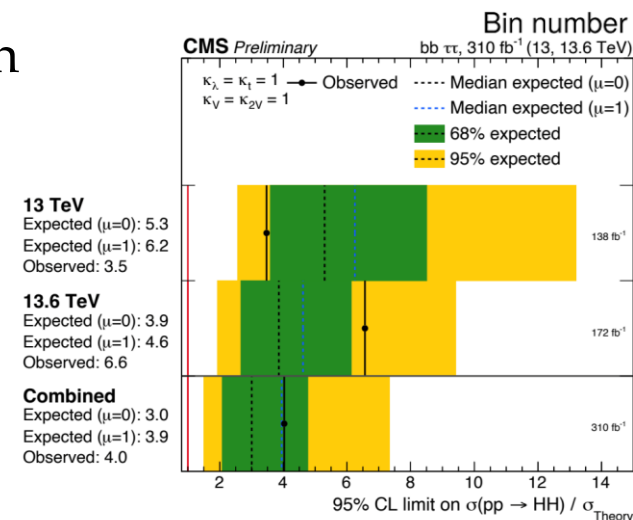


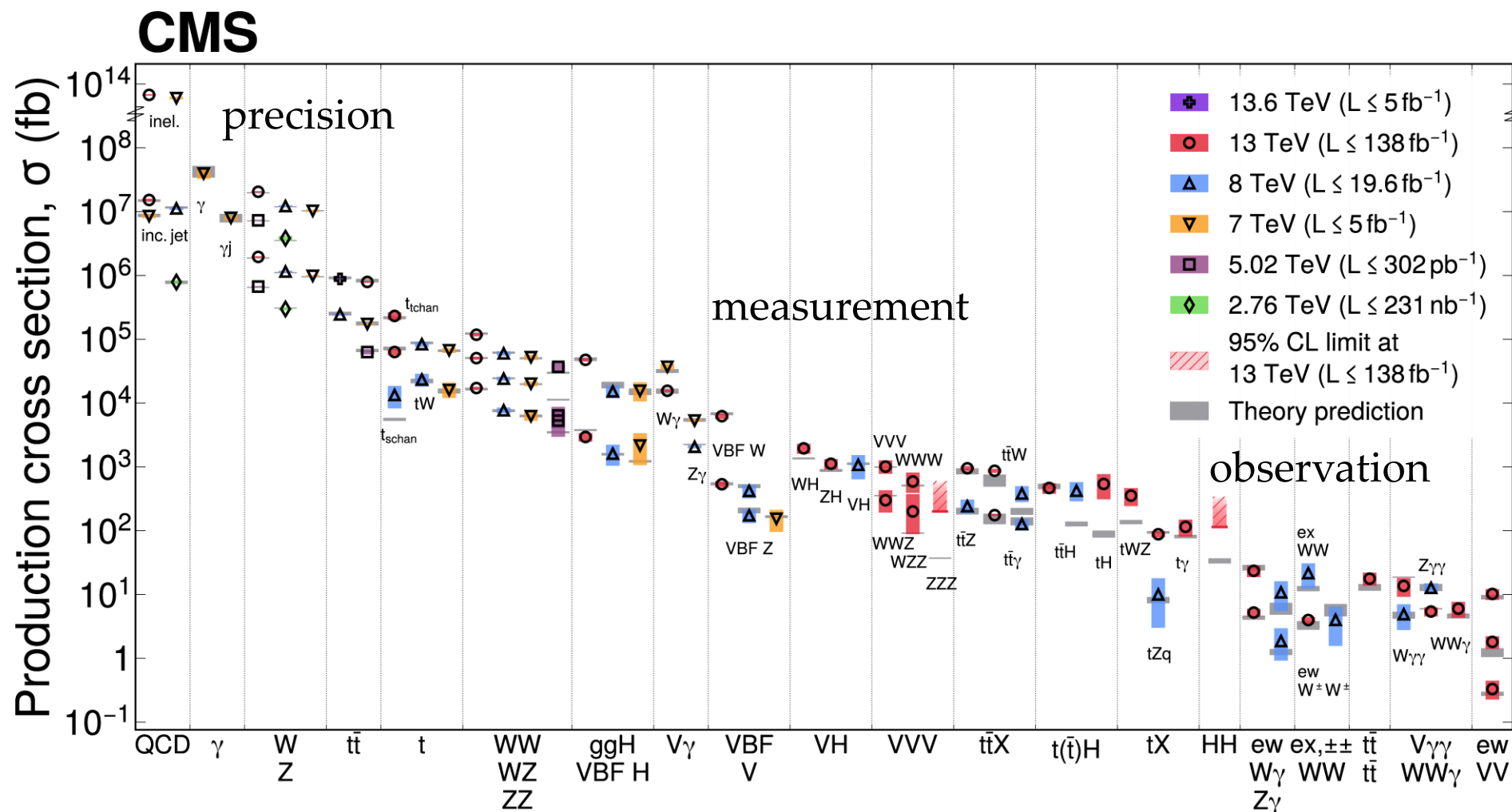
– κ_λ is *the* SM test because we little is known about the Higgs potential

- Interference with top Yukawa coupling
- ATLAS+CMS Run 2 $\mu_{\text{HH}} = 0.8^{+0.9}_{-0.7}$
- CMS results with partial Run 3 data in many channels (4b, 2b2 γ , 2b2l2 ν)

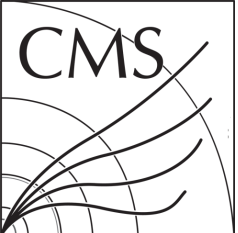
– Run 2 + Run 3 combination 0.3 ab⁻¹

- $\mu(\text{HH} \rightarrow \text{bb}\tau\tau) < 4.0$ (3.0 exp) $\times$ SM at 95% CL





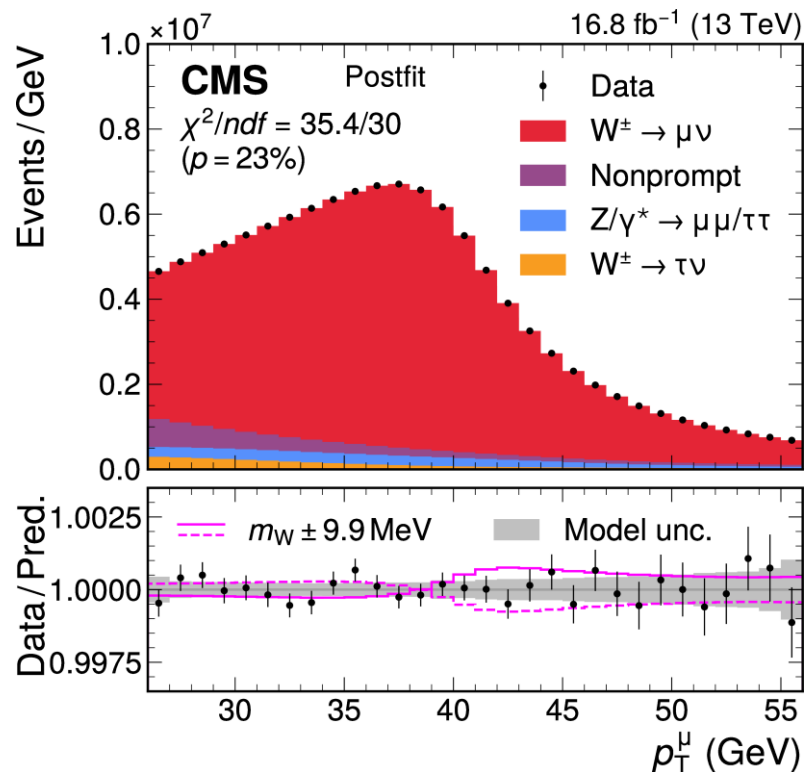
- Run 2 legacy complete; From precision measurements on SM candles to rare processes.
- $\sqrt{\mathcal{L}}$ luminosity scaling *does not dominate sensitivity!* The stairway's rungs are theory/experimental interplay.



W boson measurements

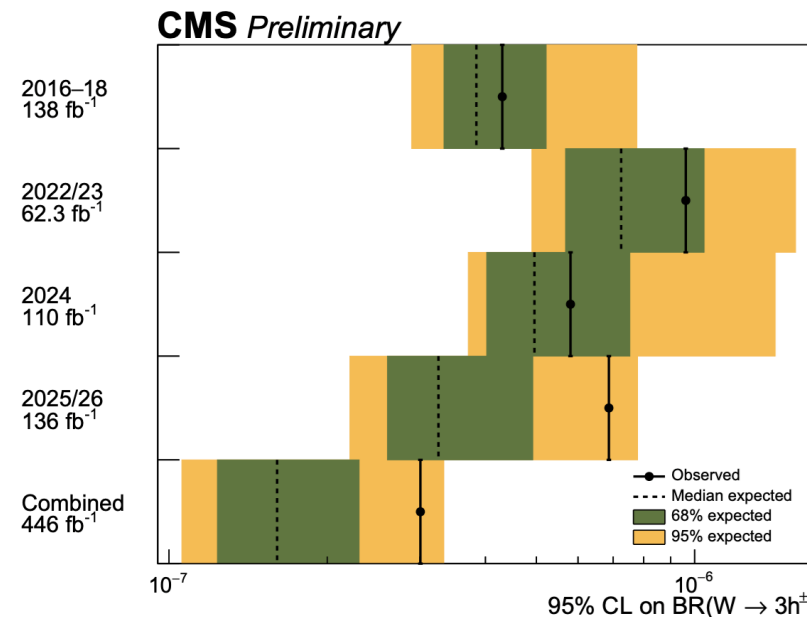
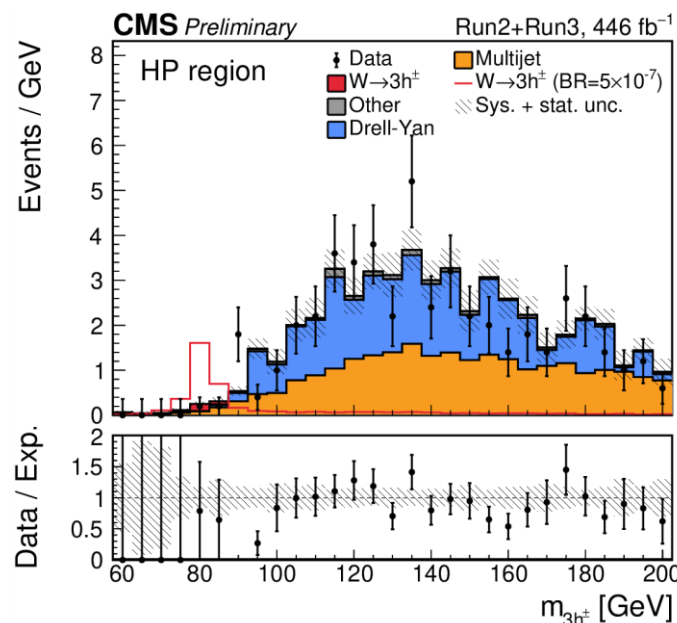
W mass measurement

[[Nature 652, 321–327 \(2026\)](#)]

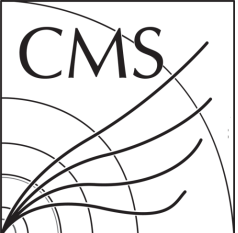


- $M_W = 80\,360.2 \pm 9.9 \text{ MeV}$ (Run 2 legacy)
- *Systematic accuracy: muon scale & PDFs*
- *PDFs profiled to 4.4 MeV, 11 MeV unprofiled*

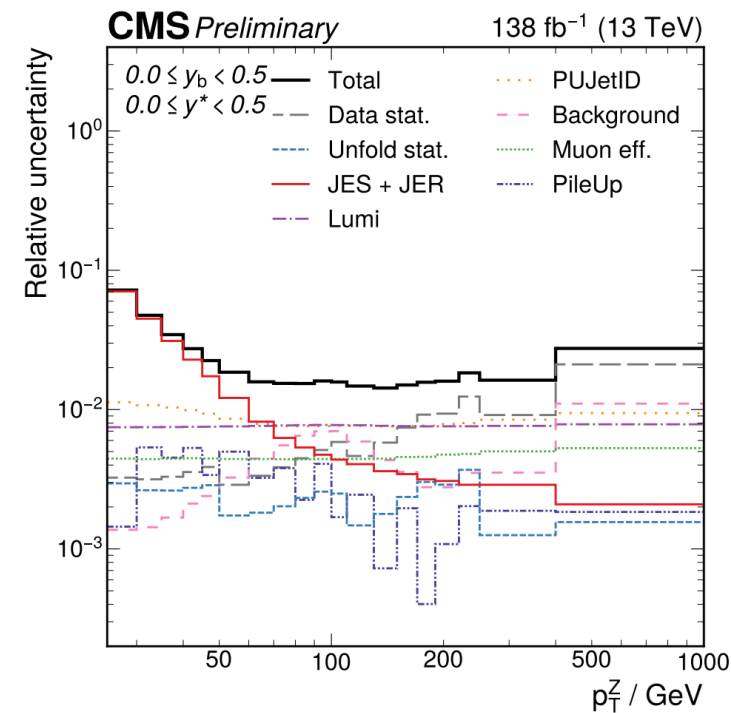
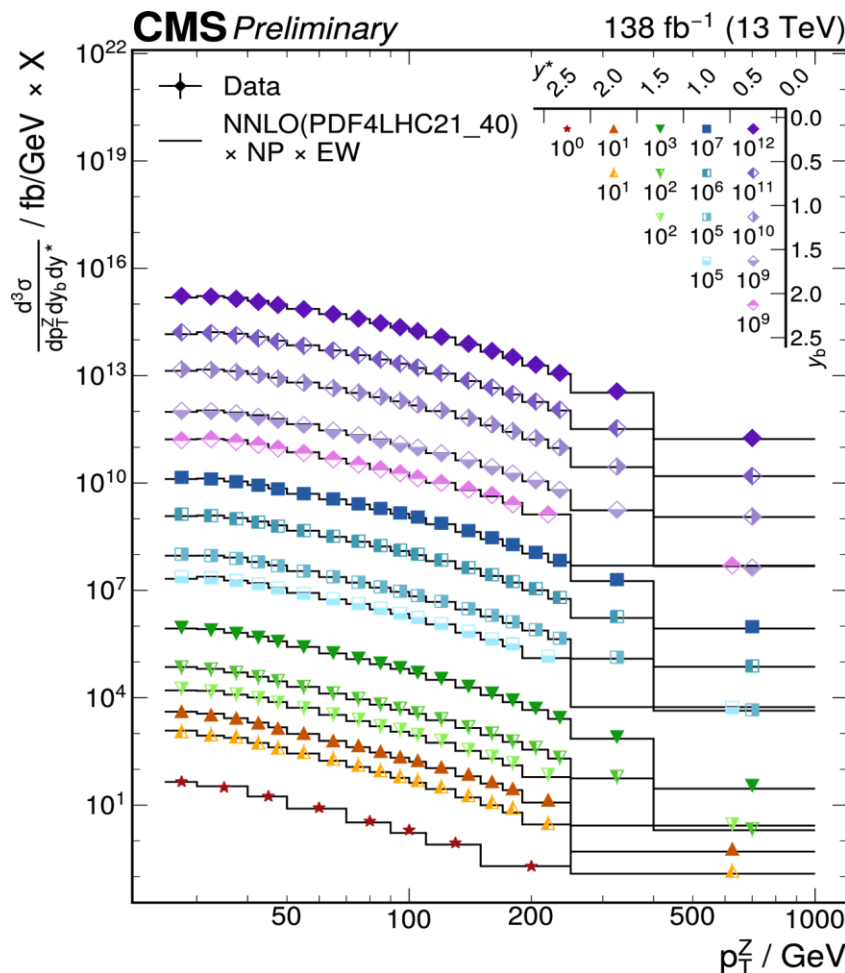
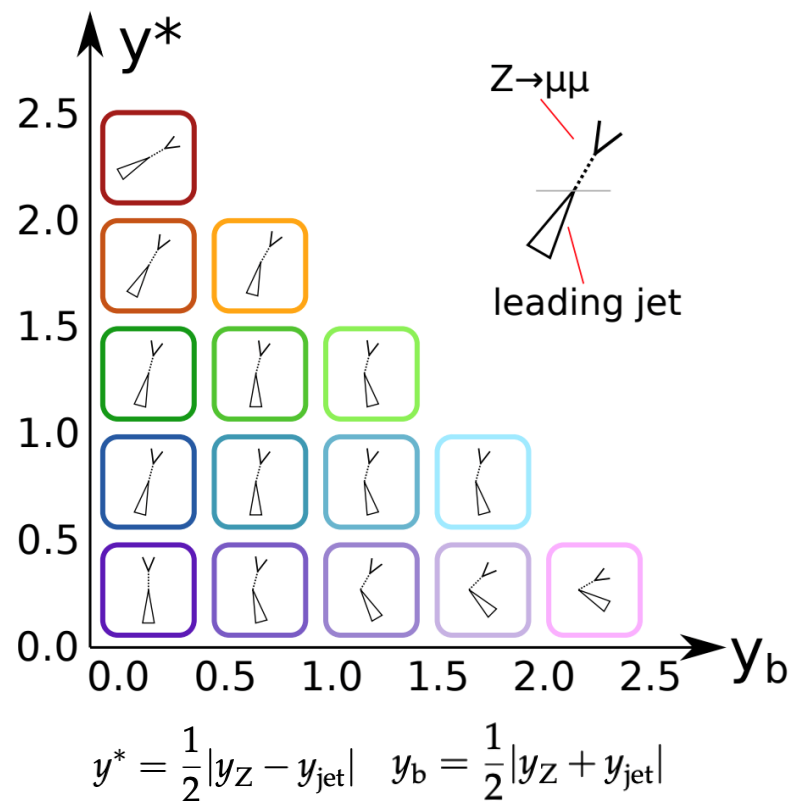
Search for $W \rightarrow 3h$ [[SMP-25-011](#)]



- Full Run 2 + Run 3 data set: 446 fb⁻¹
- $B(W \rightarrow 3h) < 2.4 \times 10^{-7}$ (95% CL)
 - $B(W^\pm \rightarrow 3\pi^\pm) \sim O(10^{-7} - 10^{-5})$ from PYTHIA
 - No dedicated calculation
- Accurate predictions for the exclusive decay would access a QCD probe at HL-LHC



Triple-differential Z+jets cross section [\[SMP-24-010\]](#)



– Unfolded in $p_{\text{T}}(\text{Z})$, y_b , and y^*

– Constrains parton density distributions

– Complementary to jet cross sections

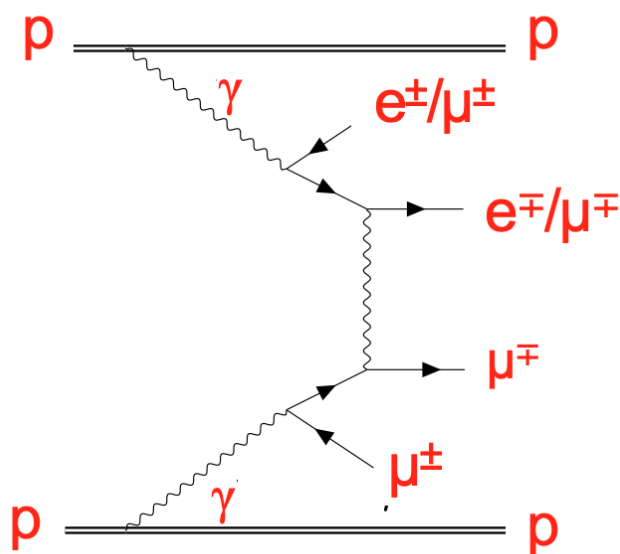
– See tomorrow's talk by Cedric Verstege

– Bulk uncertainty: 1.5%

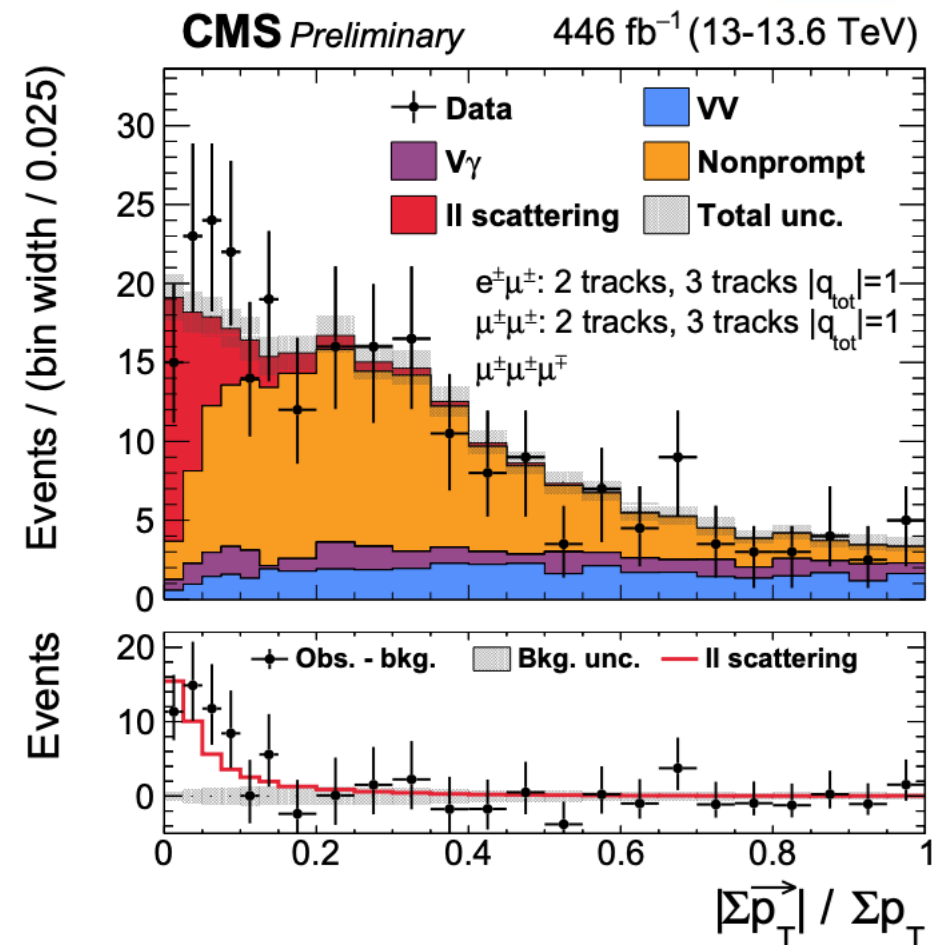
– Run 2 lumi uncertainty 0.73%
[\[LUM-20-001\]](#)

– Precise qq luminosities

- Probe QED partonic structure: γ -induced $\ell^\pm \ell^\pm$ scattering
 - 446 fb⁻¹ at $\sqrt{s} = 13$ and 13.6 TeV

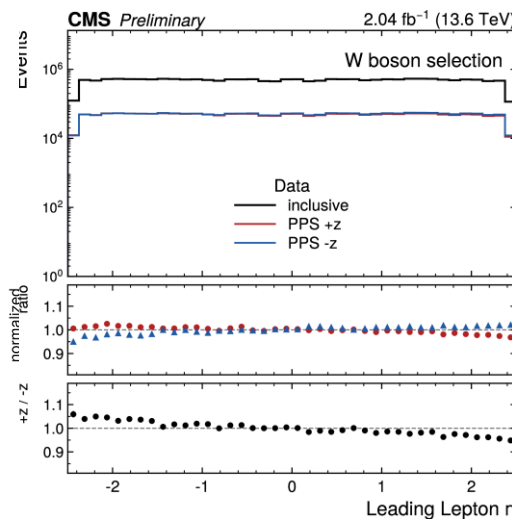
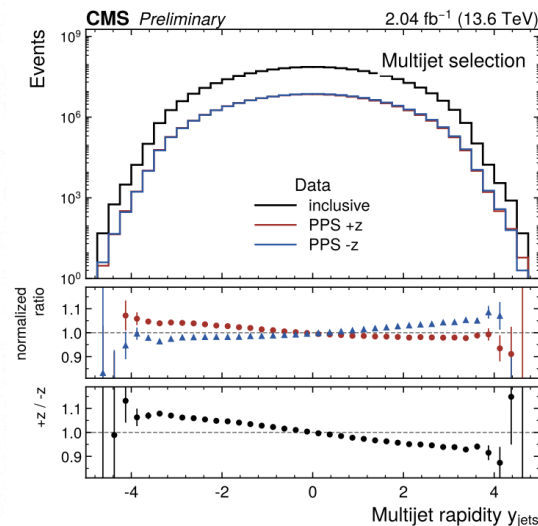
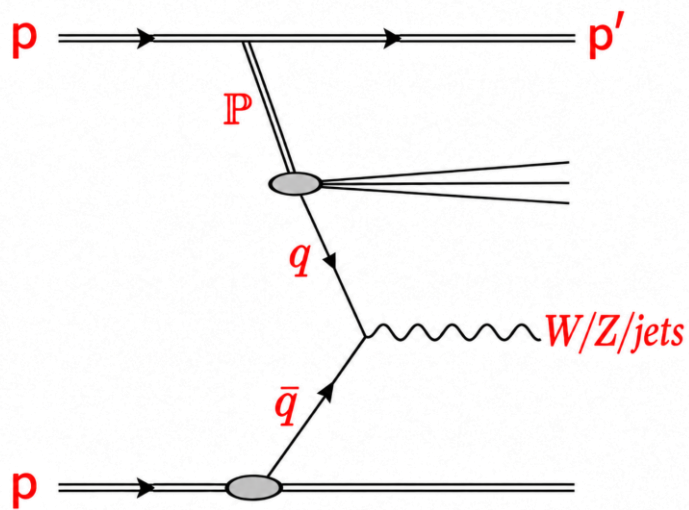
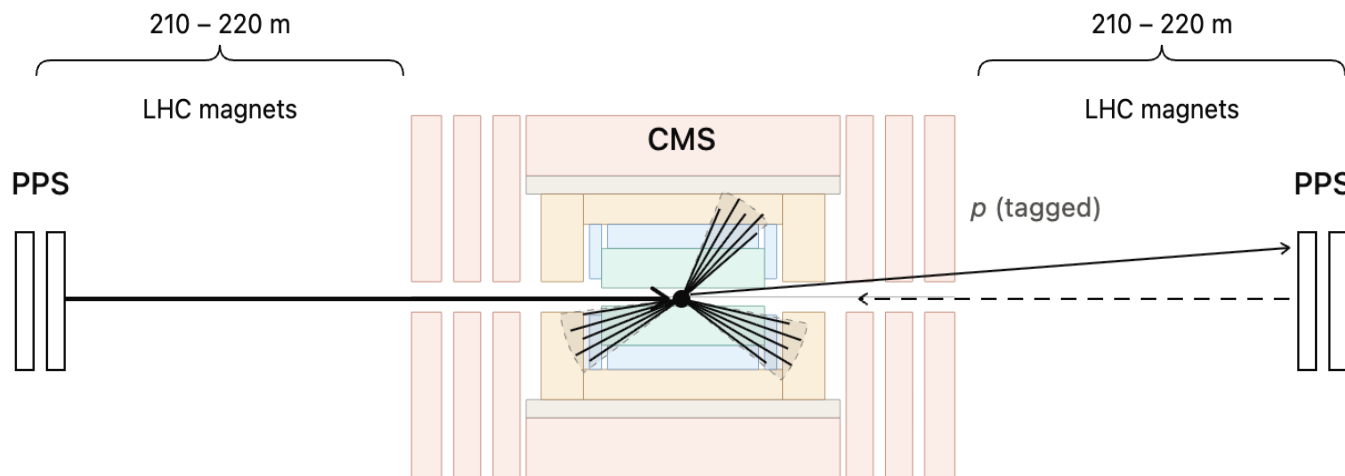


- Signal: Same-sign $e^\pm \mu^\pm$ and $\mu^\pm \mu^\pm$ pairs scatter in γ exchange
- Elastic+single-dissociative: quiet multilepton vertex
 - ≤ 4 tracks and small p_t balance, simulated with SFGen [\[PRD \(104\) 073002\]](#)
 - Categories $e^\pm \mu^\pm$, $\mu^\pm \mu^\pm$, $\mu^\pm \mu^\pm$, $\mu^\pm \mu^\pm \mu^\mp$
 - Systematics: Nonprompt/PU, survival probability at low N_{track} [\[Eur.Phys.J.C 80 \(2020\) 10\]](#)



- First observation of scattering between leptons radiated from the incoming protons
 - 5.4 σ ($\mu^\pm \mu^\pm$ at 4.0 σ)
- Protons are not tagged

- New CMS analysis: tagged $p + \text{jets}/W/Z$
- CMS Precision Proton Spectrometer
 - $\pm 220\text{m}$ from the central detector
 - PPS acceptance $3\% < \xi < 13\%$
 - $\xi \equiv 1 - p'/p$ — proton momentum loss
- Exploit low-PU run $\langle \mu \rangle = 5$, $L = 2 \text{ fb}^{-1}$
 - 20% tagging efficiency, purity 1-2%

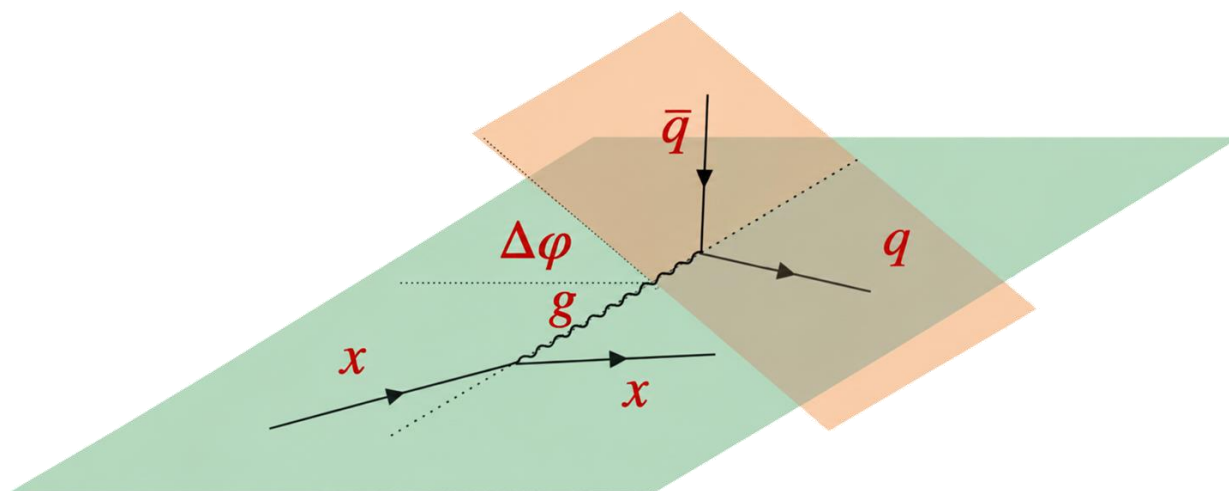


Channel	A_S
Multijet	-0.59 ± 0.03
W	-0.22 ± 0.01
Z	-0.13 ± 0.03

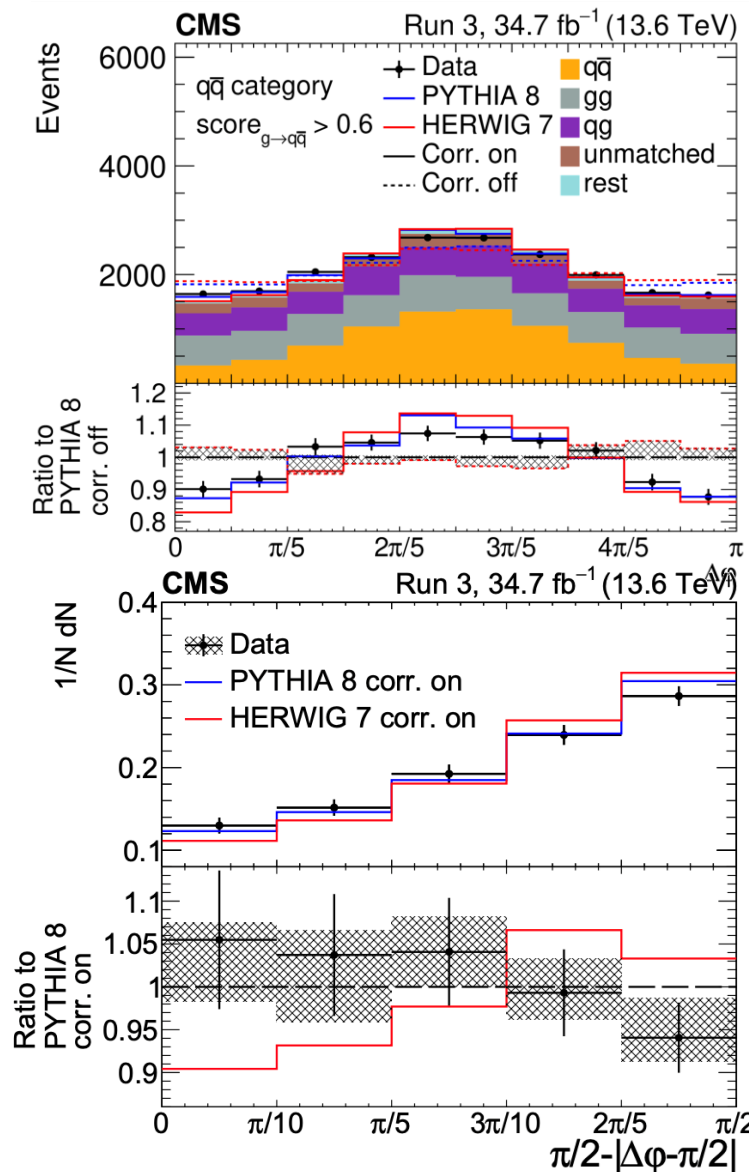
- Rapidity gap & tagged proton establish coherent color-singlet QCD at high scales

Talk by Elisabetta Manca

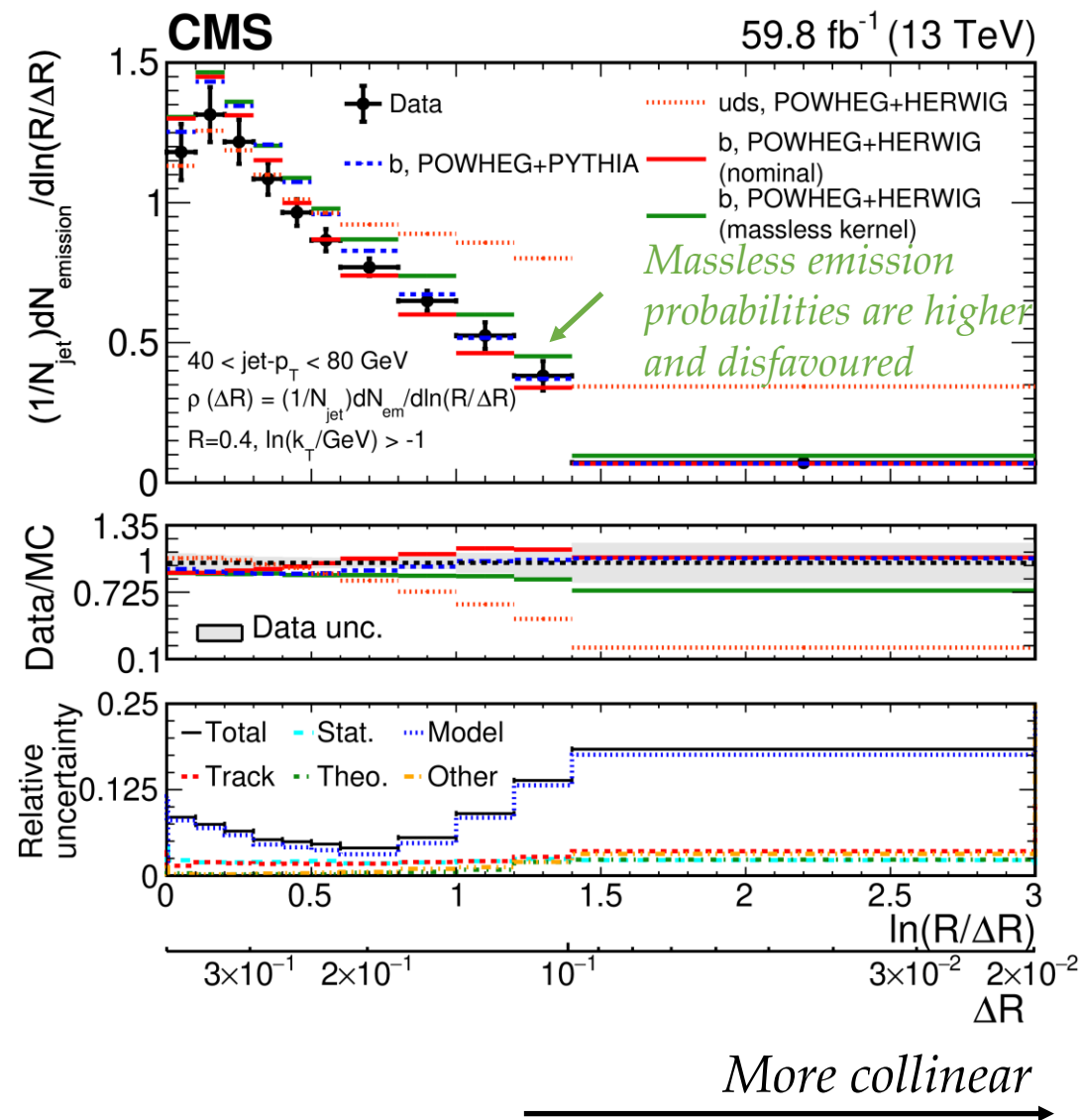
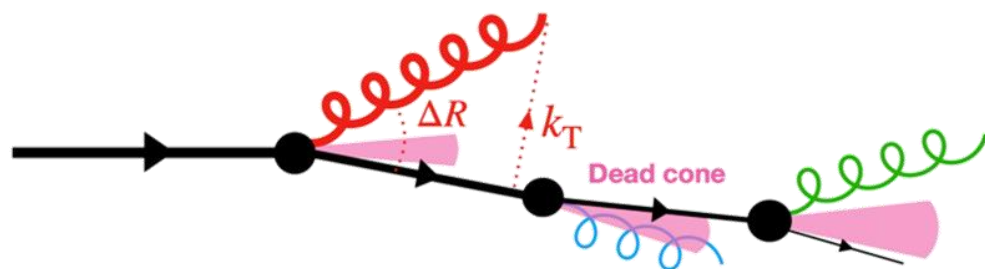
- Select $p_t > 700$ GeV AK8 jets, CA declustering
 - Observable: $\Delta\phi$ between successive splitting planes
 - Run 3 (2022): 34.7 fb^{-1} at $\sqrt{s} = 13.6$ TeV



- ML isolates $g \rightarrow qq$ splittings, where the modulation is largest
- “No correlations” is disfavored by 6.8σ ;
- Pythia within unc. (Collins–Knowles: adds modulation to the opening angle)
- Herwig (=spin density matrix) predicts stronger effect
- One step towards precision of boosted hadronic Higgs decays

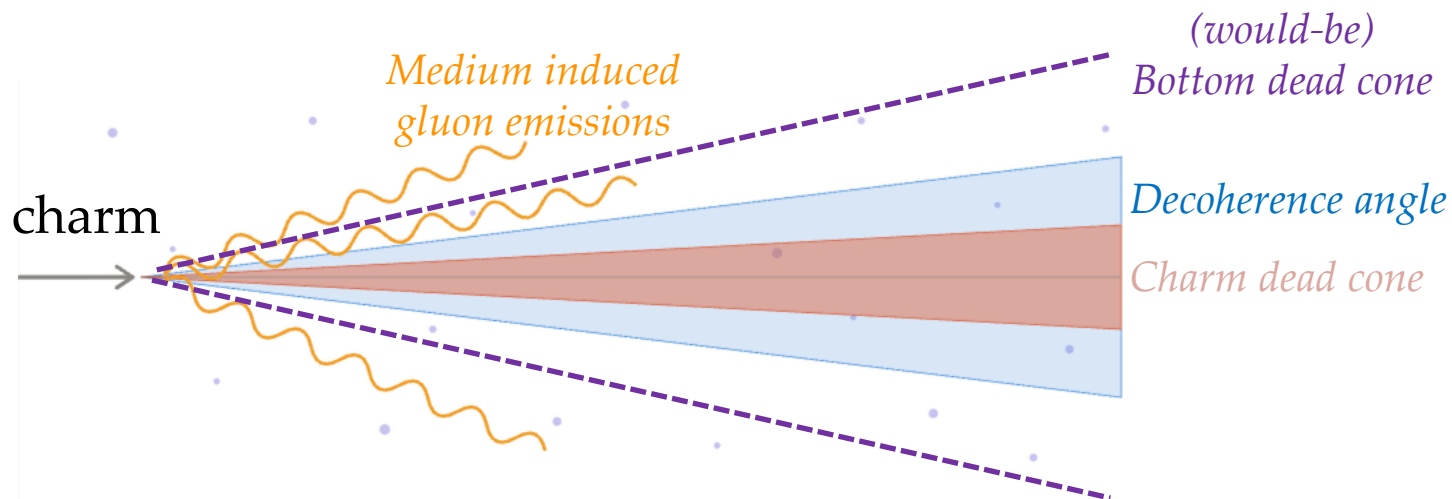


- Quark mass suppresses collinear gluon radiation within $\theta \lesssim m_b/E_b = \theta_d$ — the dead cone
 - Harder fragmentation, fewer intrajet constituents
- Top quark pairs in $e\mu$ decay channel
- Backwards traversing angular-ordered CA clustering history
 - measures the angular emission density of b jets
- A massless parton shower is disfavored by 4.3σ in the most sensitive p_t range

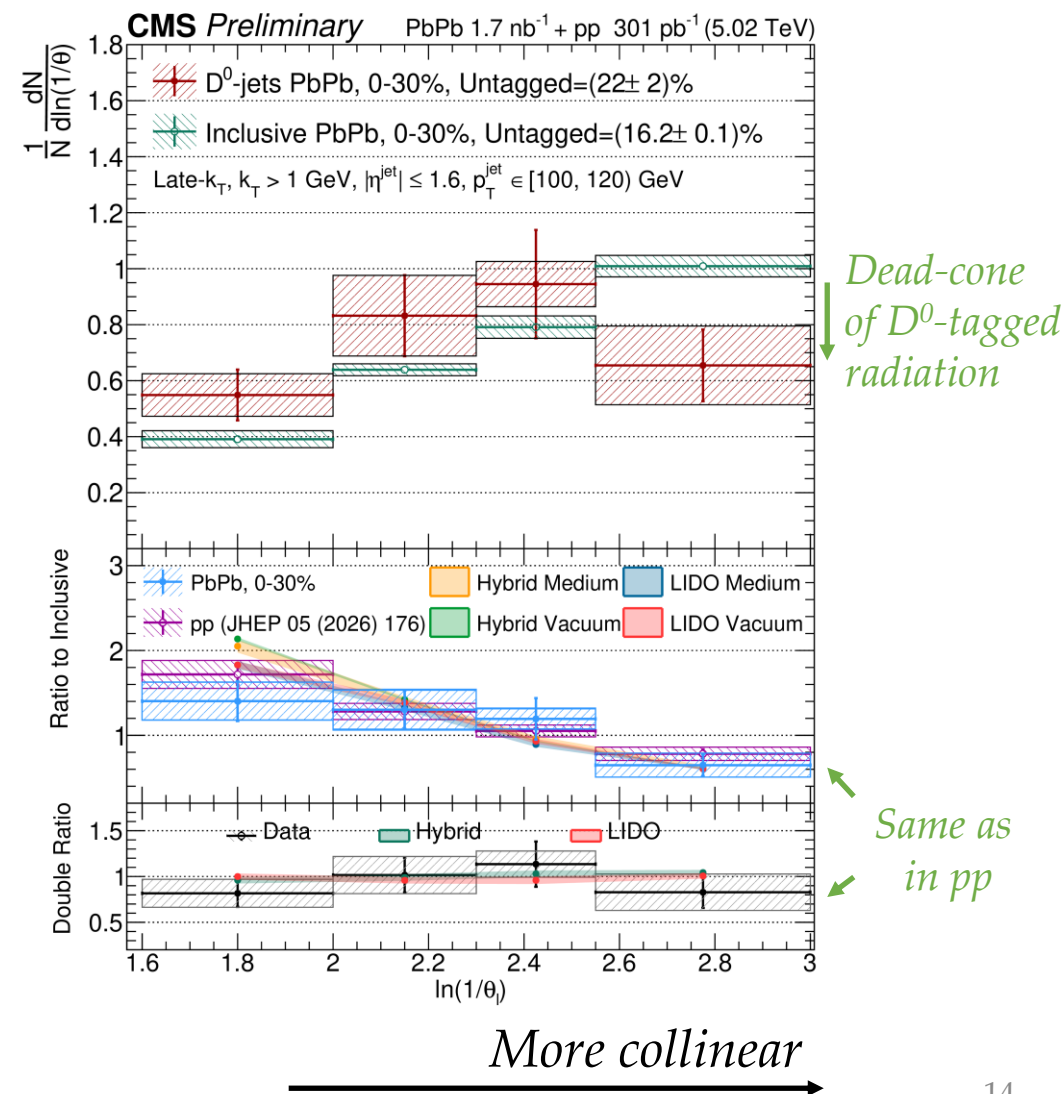


– Does the medium induce radiation that fills the dead cone of a heavy (charm) quark?

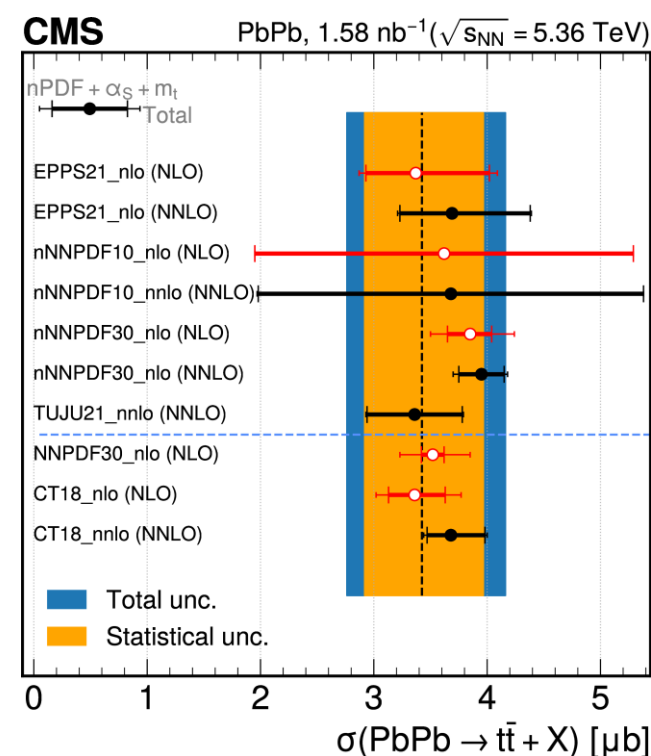
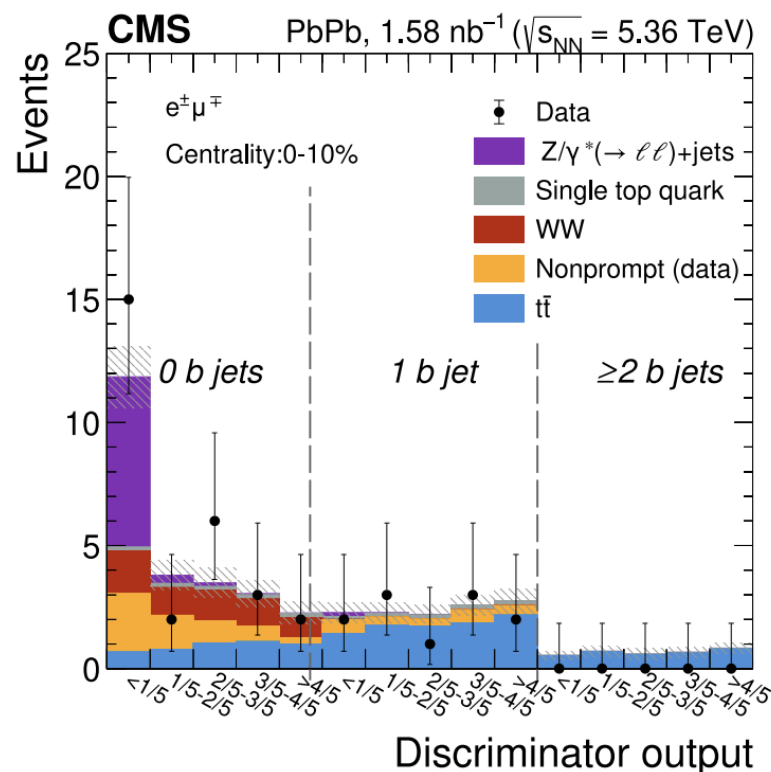
- QGP medium can not resolve angular structure below a decoherence angle



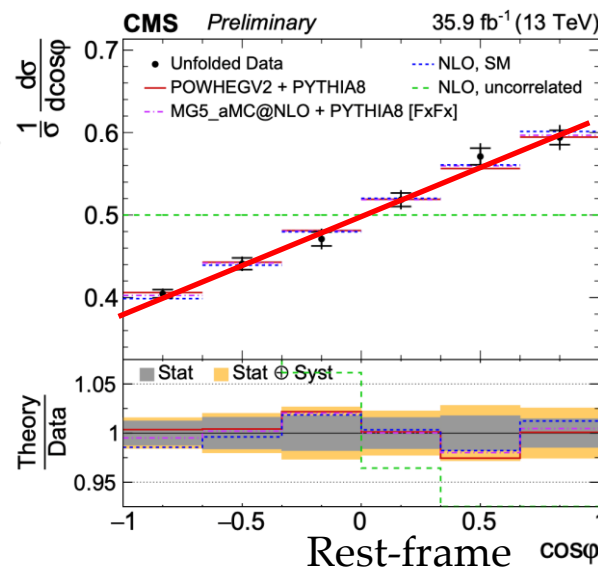
- PbPb data: 1.7 nb^{-1} at $\sqrt{s_{\text{nn}}} = 5.02 \text{ TeV}$ (2018)
- Charm quarks are identified via D^0 tags
- The small-angle suppression persists: the PbPb/pp double ratio is consistent with unity



- First measurement of $t\bar{t}$ production in PbPb collisions
 - PbPb data: 1.6 nb^{-1} at $\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV}$ (2023)
- Dilepton events and b-jet multiplicity separate $t\bar{t}$ from Drell–Yan and other backgrounds
- New techniques developed
 - electron ID (BDT)
 - lepton isolation (SoftKiller)
 - Jet energy scale calibration
 - Heavy-flavor jet identification (UPart)
- $\sigma(t\bar{t}) = 3.42^{+0.54}_{-0.51} (\text{stat})^{+0.50}_{-0.43} (\text{syst}) \mu\text{b}$
 - consistent with nuclear-PDF calculations
- $t\bar{t}/Z$ sensitive to gluon/quark nPDF ratio
 - Can discriminate nPDF sets with more data



1. Spin-correlation matrix in the tt rest-frame [Bernreuther et al., [1508.05271](#)]

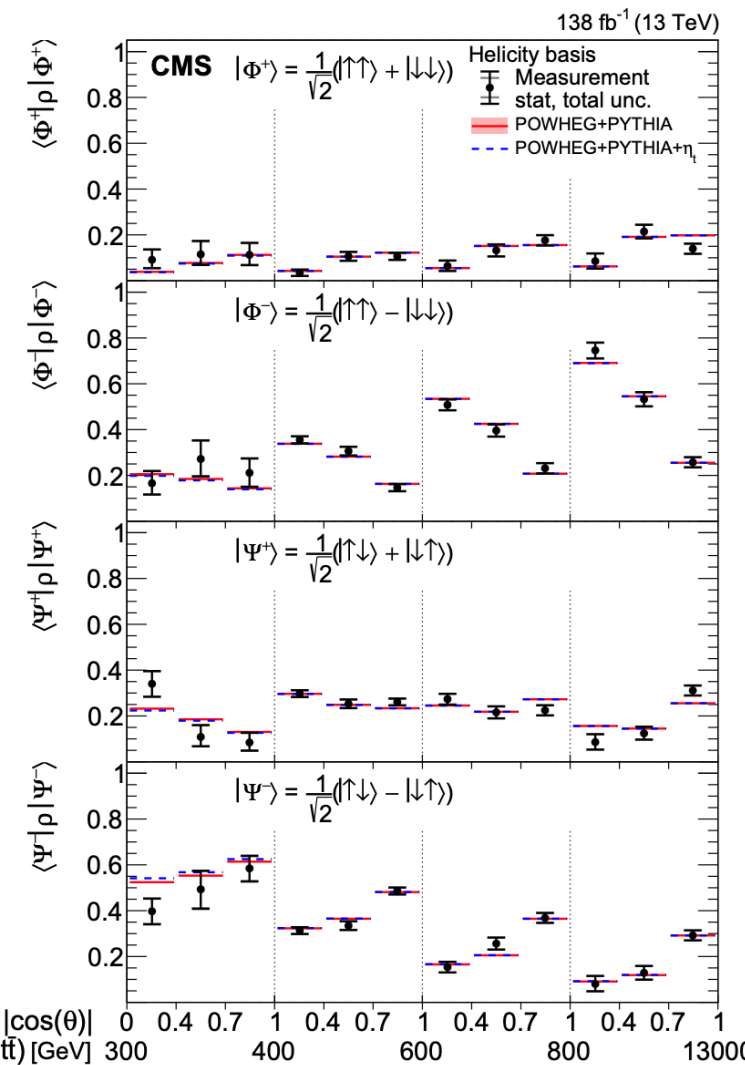


$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D \cos\varphi) \quad D = -1/3\text{Tr}[C] = -(C_{nn}+C_{rr}+C_{kk})/3$$

- Systematic description replaced earlier ad-hoc measures
- Transform observables so the parameter enters *linearly*
 - Experimentally: slope of the unfolded distribution
 - Curvature regularization: 2nd derivative; regulator $\rightarrow \infty \rightarrow \chi^2$ fit
 - Much smaller theory/modeling uncertainties than in the lab frame

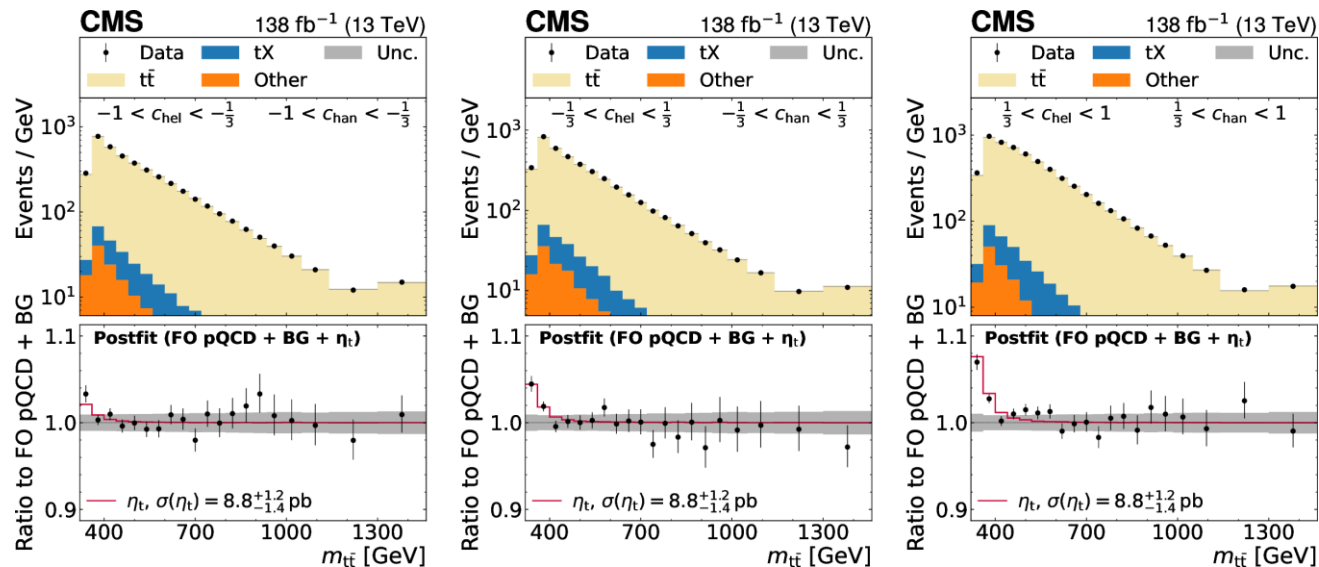
2. Enables quantum tomography in top quark pairs [[TOP-25-017](#)]

Quantum state of ttbar [\[TOP-25-017\]](#)

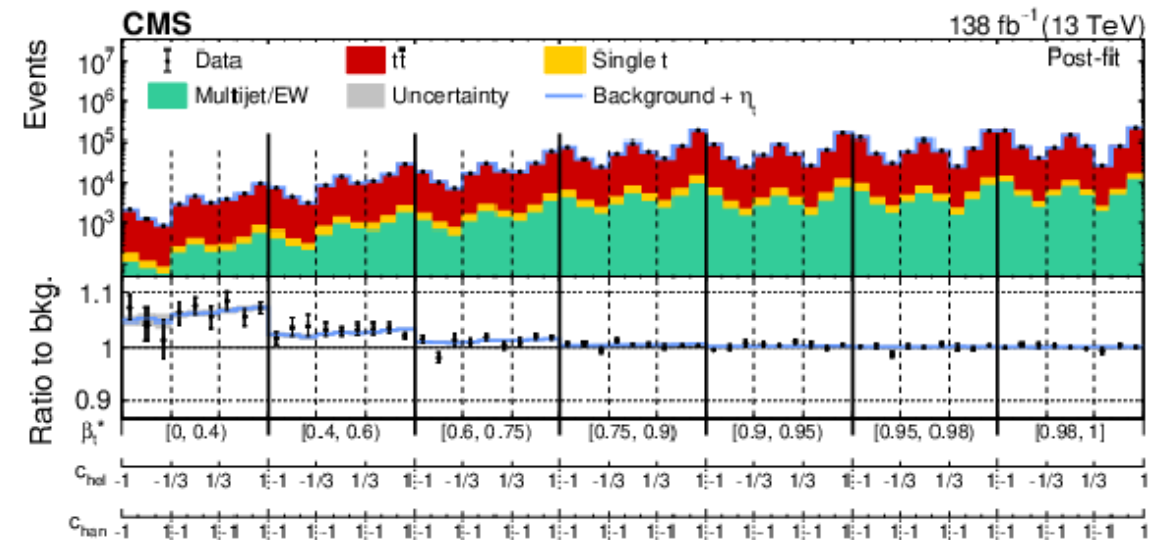


- Observed excess; pseudo-scalar enhancement close to the $t\bar{t}$ threshold, first in 2ℓ events
- Confirmed in single-lepton events using $M(t\bar{t})$, β^* and the spin observables c_{hel} and c_{chan}

Dilepton channel [TOP-24-007]



Single-lepton channel [TOP-25-002]



- Results favor pseudoscalar η_t “toponium”: $8.8^{+1.2}_{-1.4} \text{ pb}$ (2ℓ) and $5.3 \pm 0.9 \text{ pb}$ (1ℓ)

3. A theoretical challenge beyond LO; Consistent matching, shower, decay, resummation,...

Improved muon coverage and trigger

increased RPC coverage ($1.5 < |\eta| < 2.4$)

new electronics

[[CMS-TDR-016](#)]

New precision timing detector

Timing resolution of 30-40 ps for MIPs

full coverage of $|\eta| < 3.0$

[[CMS-TDR-020](#)]

New endcap calorimeters

high granularity

can reconstruct showers in 3D

[[CMS-TDR-019](#)]

Updates to calorimeter and trigger

higher granularity

electronics for trigger

New inner tracker

all silicon tracker

4 layers of pixels

5 layers of strips

coverage to $|\eta| < 4$ [[CMS-TDR-014](#)]

Upgrade to trigger and DAQ

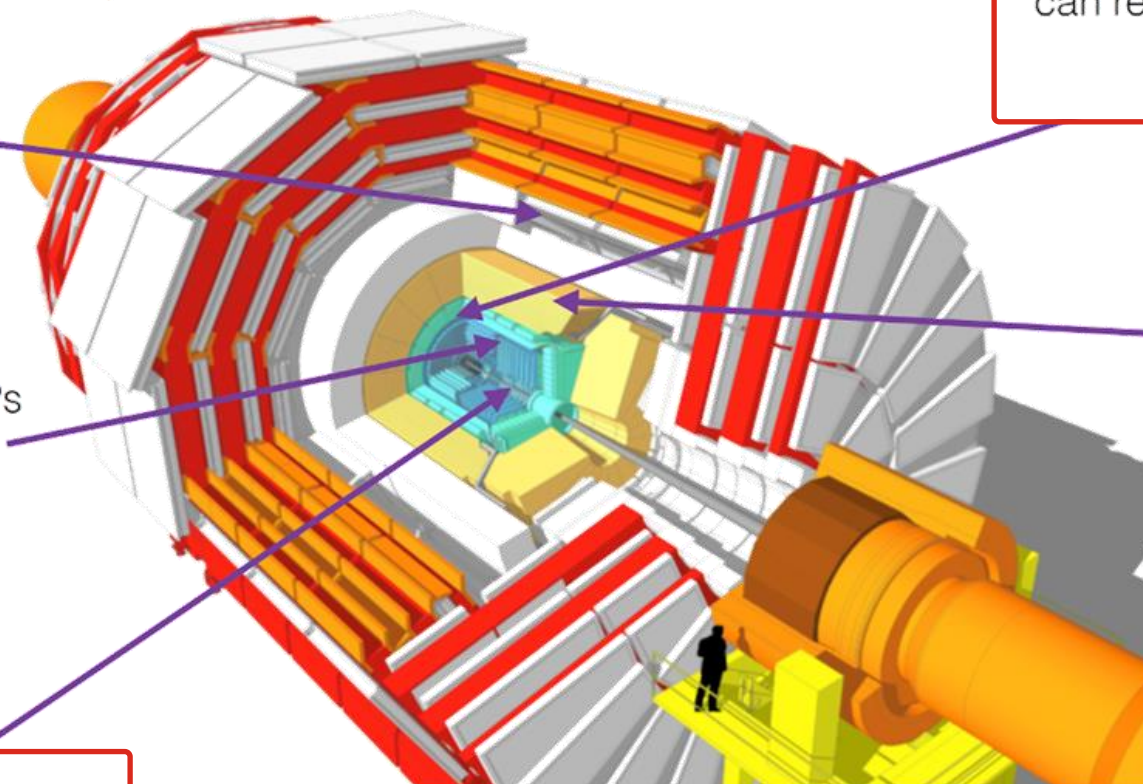
L1 rate increased to 750 kHz

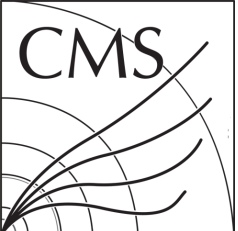
High Level trigger rate to 7.5 kHz

Track information at L1

[[L1: CMS-TDR-021](#)]

[[DAQ/HLT: CMS-TDR-022](#)]





CMS Phase-2 construction is under way

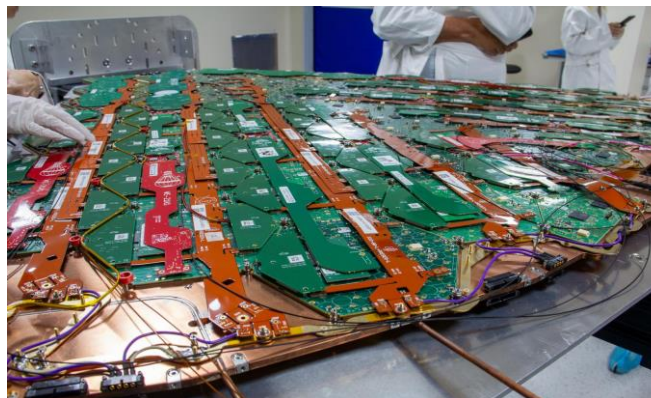
ÖAW



[Tracker barrel integration](#)



[ECAL supermodule insertion tooling](#)



[HGCal cassette assembly](#)



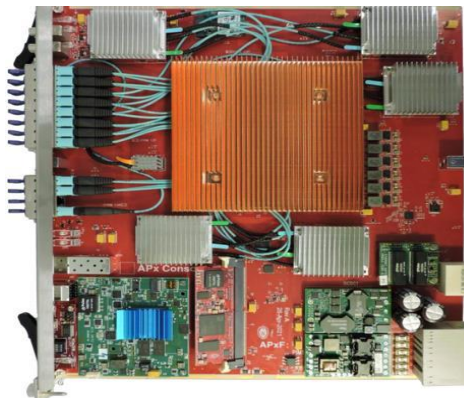
[HGCal cold tests](#)



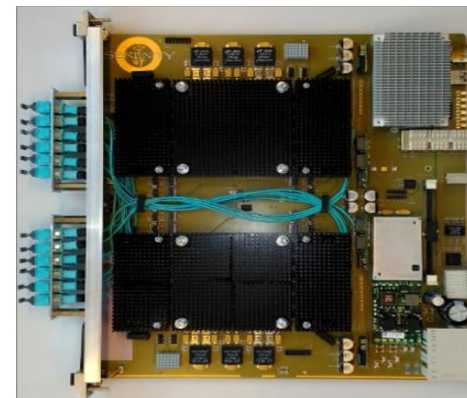
[Precision module assembly](#)



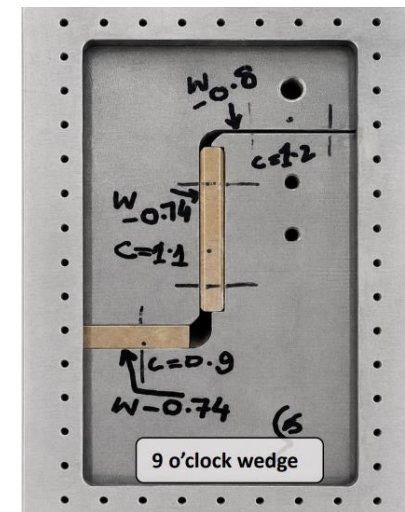
[BTL trays assembly](#)

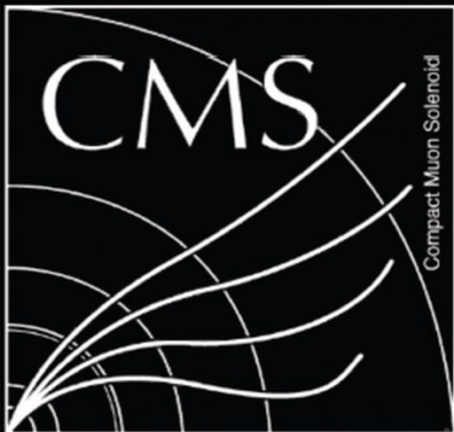


[L1 trigger-board prototype](#)

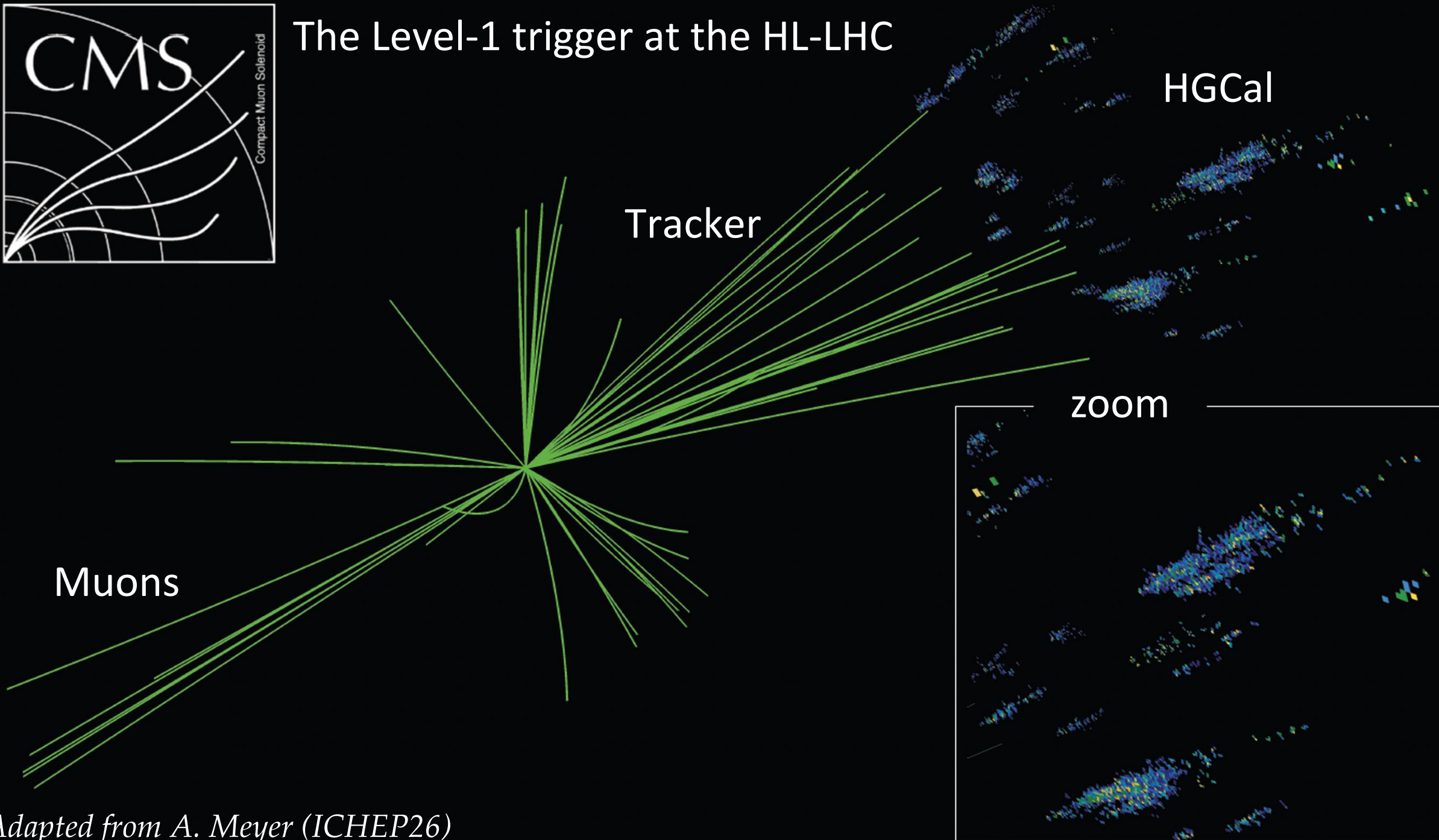


[L1 trigger-board prototype](#)

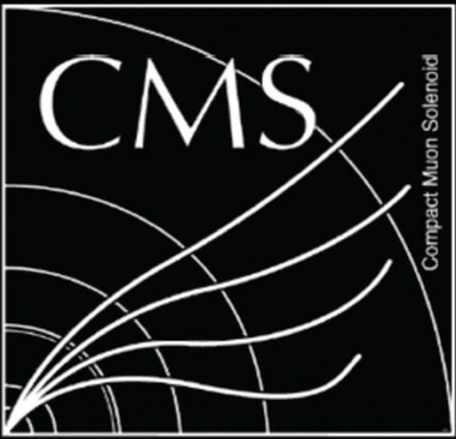




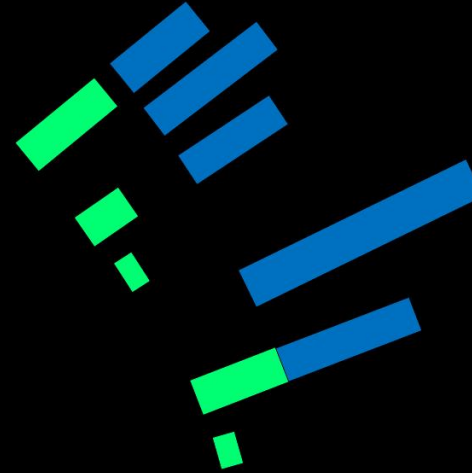
The Level-1 trigger at the HL-LHC



Adapted from A. Meyer (ICHEP26)



The Level-1 trigger today

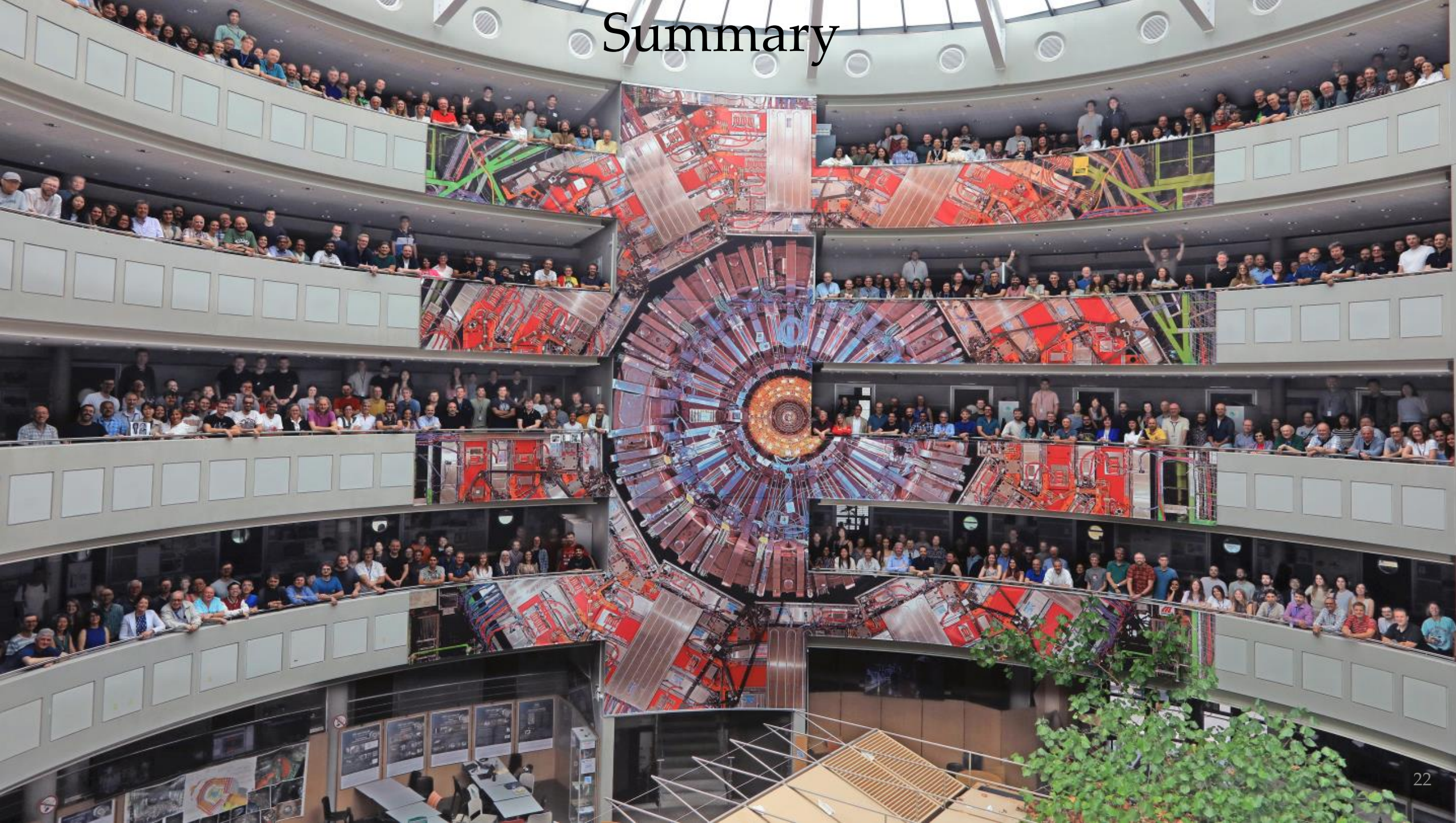


Calorimetry

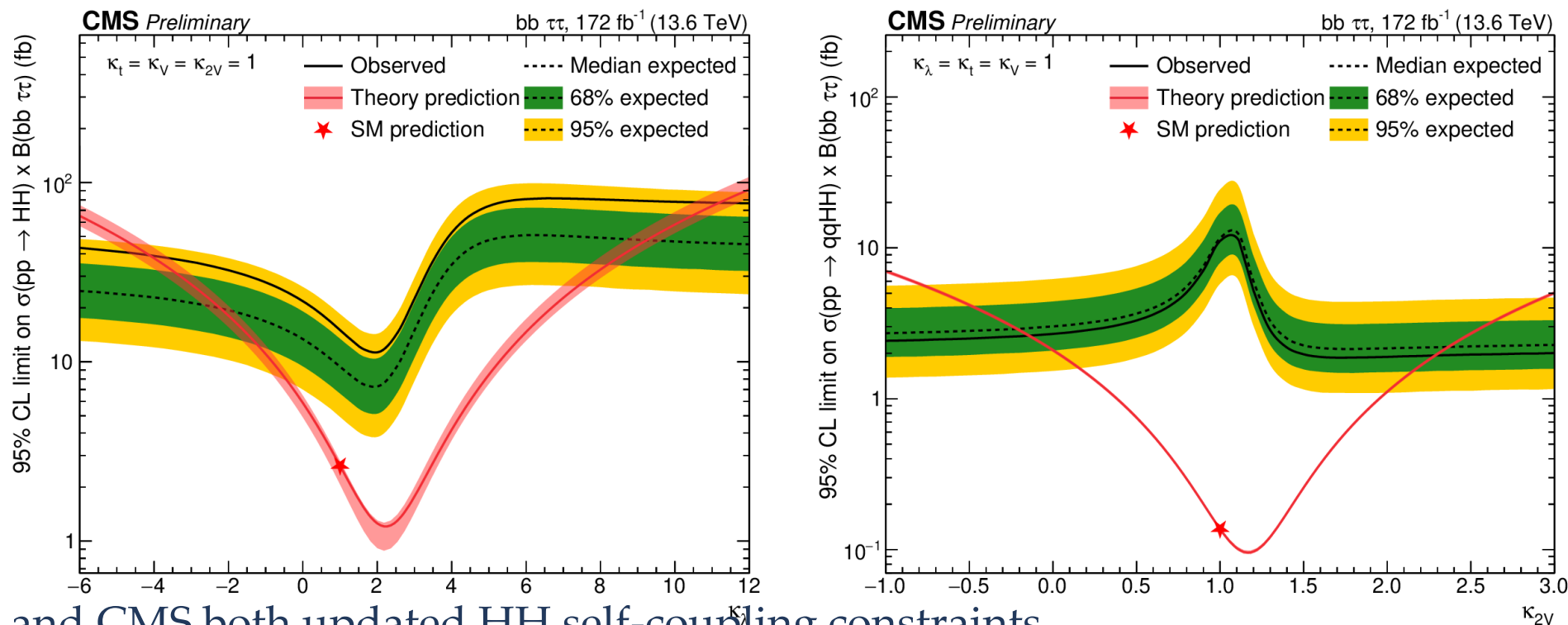
Muons

Adapted from A. Meyer (ICHEP26)

Summary

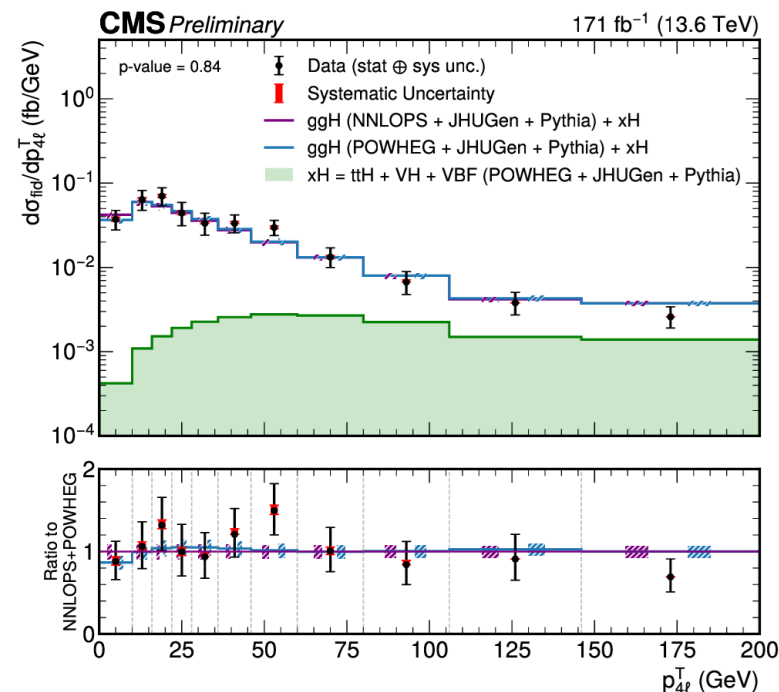
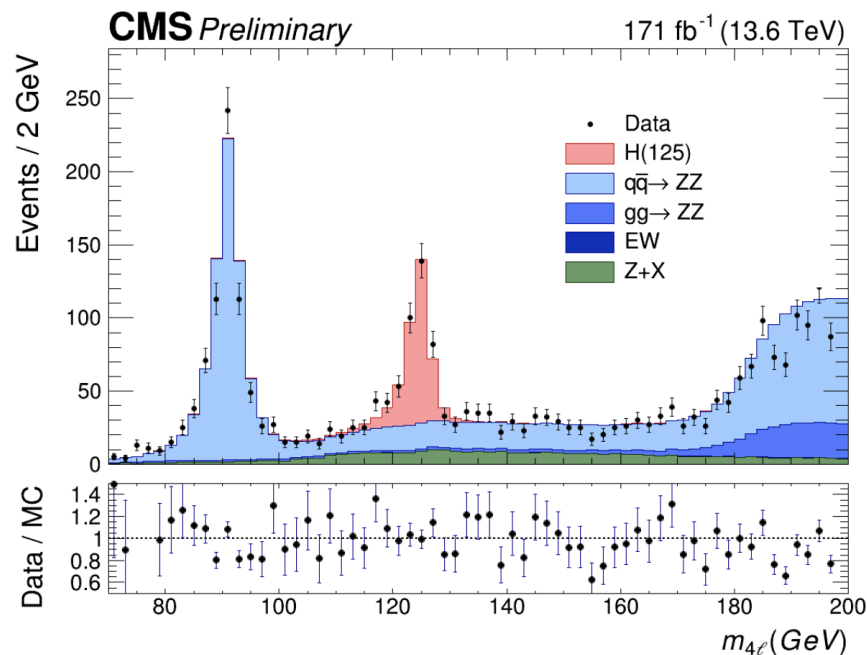


Higgs-pair production in $bb\tau\tau$ [[HIG-25-008](#)]



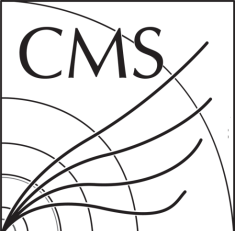
- ATLAS and CMS both updated HH self-coupling constraints
- 172 fb⁻¹ at 13.6 TeV: $\sigma(HH) < 6.6$ (3.9) $\times$ SM at 95% CL
- Run 2 + Run 3: $-2.5 < \kappa\lambda < 9.4$ at 95% CL
- QCD lever arms: b tagging sets acceptance; ggF HH theory normalisation shapes $\kappa\lambda$ limits

Differential $H \rightarrow ZZ \rightarrow 4\ell$ [[HIG-25-015](#)]

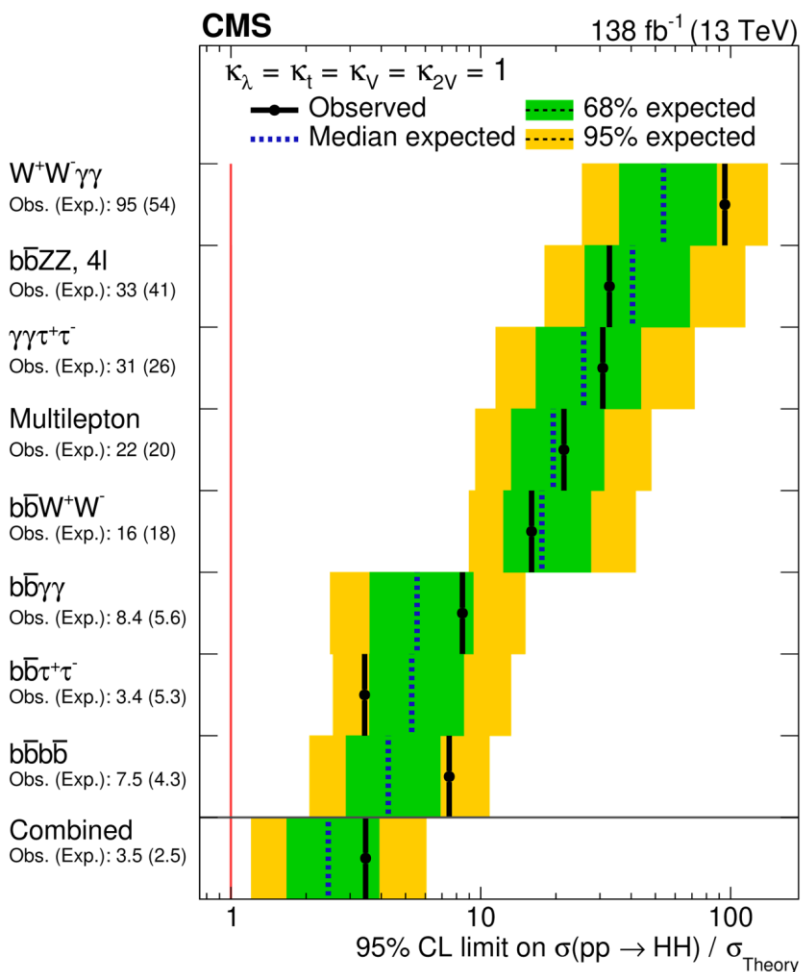


– Differential $H \rightarrow ZZ \rightarrow 4\ell$

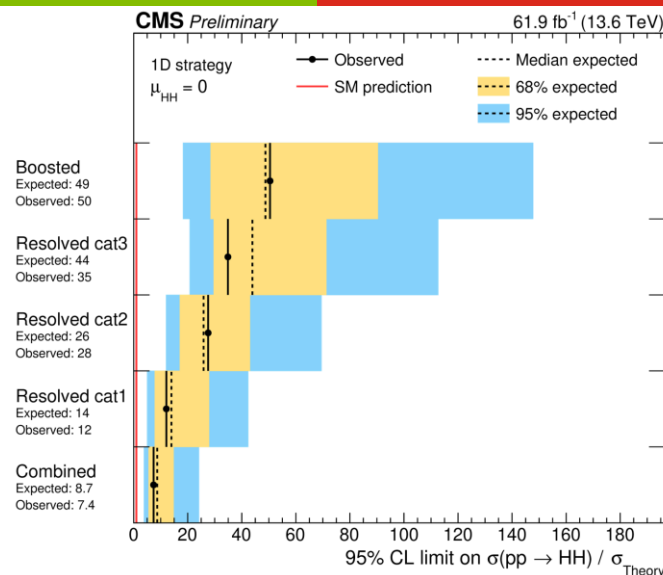
- 171 fb⁻¹ at 13.6 TeV from 2022-24: $\sigma_{\text{fid}}(H \rightarrow ZZ \rightarrow 4\ell) = 3.11 \pm 0.26$ fb (SM: 3.05)
- Fiducial p_t^H , jet, dijet and VBF measurements map the production kinematics
- p_t^H directly tests resummation and the ggF calculation; NNLOPS agrees ($p = 0.84$)



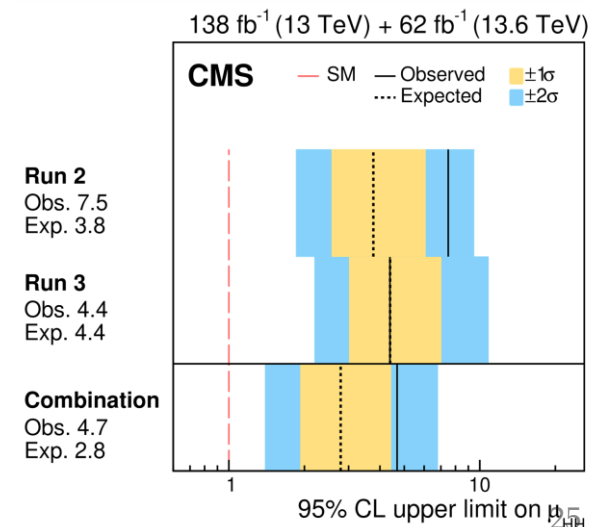
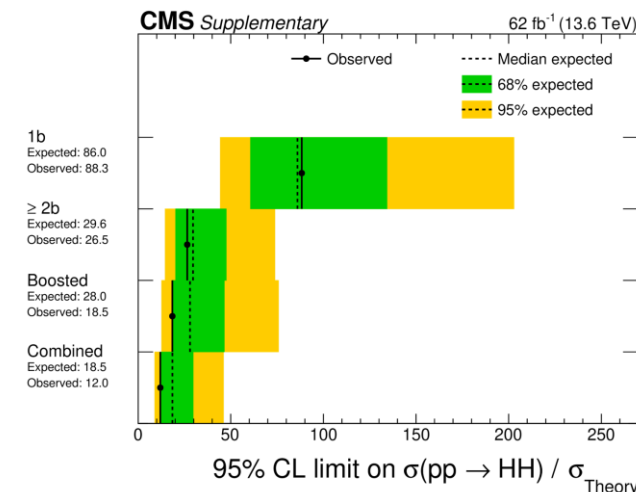
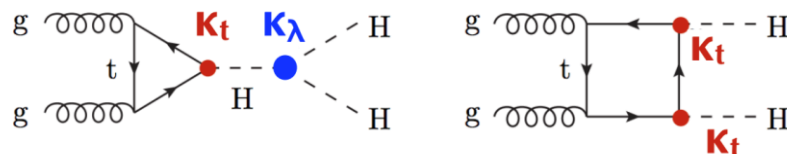
HH production: Run 2 to Run 3 [[HIG-20-011](#)]



ATLAS+CMS $\mu_{HH} = 0.8^{+0.9}_{-0.7}$
[[HIG-25-014](#)]



- κ_λ is *the* SM test because the Higgs potential is accessible and largely unconstrained
- In ggF, the κ_λ triangle and κ_t box amplitudes interfere: HH is the direct handle on the Higgs self-coupling



- 3 ab^{-1} by 2041, at up to $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- 5D reconstruction: tracker to $|\eta| \approx 4$, 30 ps timing, and high-granularity calorimetry
- Trigger at 40 MHz: tracks, vertexing, b tagging and ParticleFlow pileup suppression
- New L1 scouting makes the full collision rate available for selected low-threshold signatures

