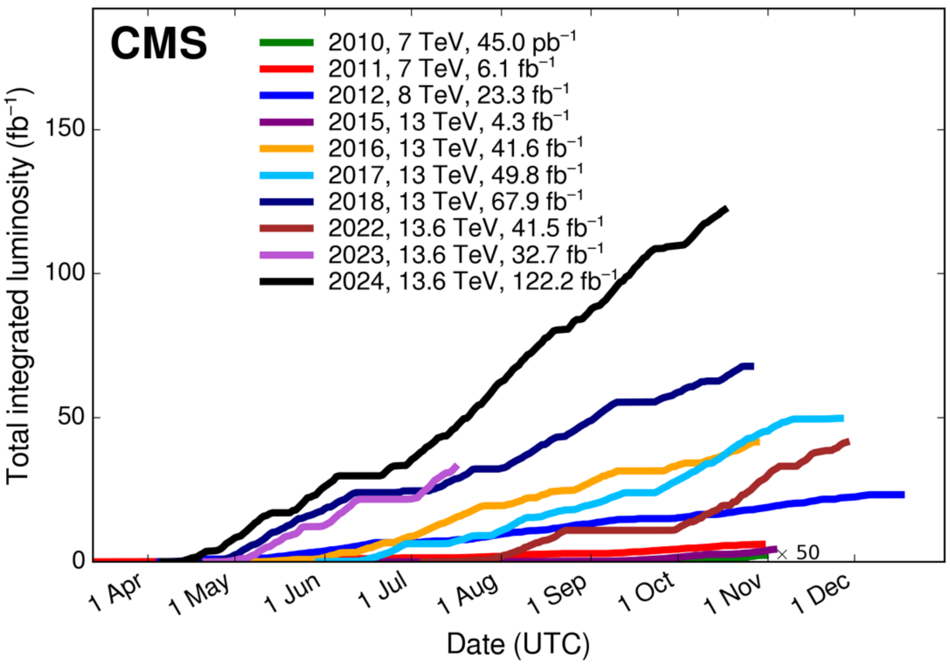
Latest results from CMS and its future upgrade

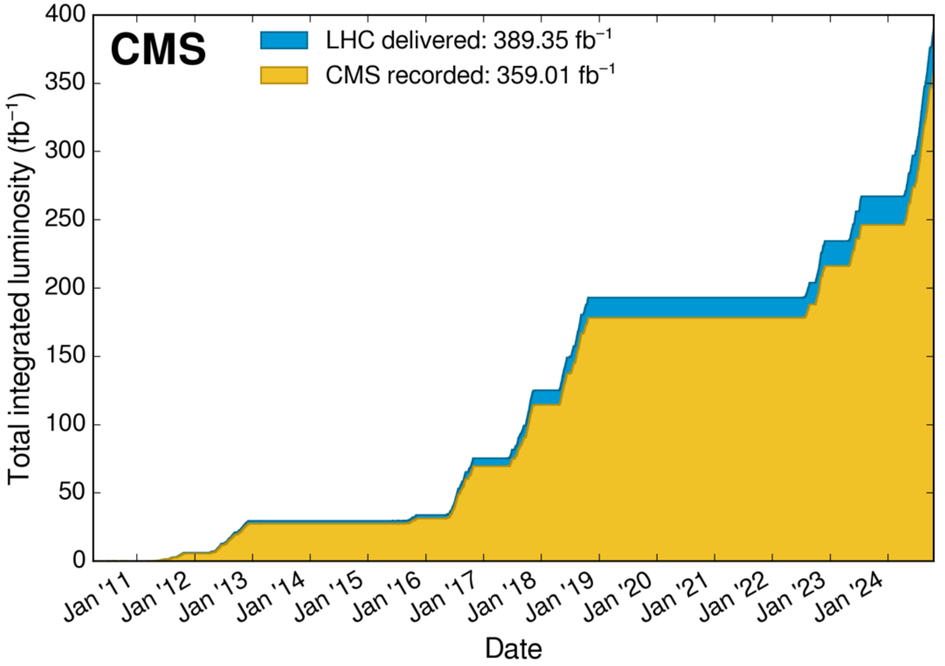
Gagan Mohanty
(on behalf of the CMS Collaboration)

Inspirations from talks of G. Landsberg (Corfu-2024) and S. Swain (PPC2024)

LHC – A spectacular running

- Has delivered close to 390 fb^{-1} of data in Runs 1-3 from 2010 until now at c.o.m. energies 7.0-13.6 TeV, exceeding our $\mathcal{L}_{int}$ projections
  - ➢ 2024 is a record year with 122 fb^{-1} of pp collision data delivered by the LHC (compare with the data size of other years in the left plot below)
- Above 90% of the delivered data are recorded and fully certified for the physics analyses
- Multiple lead-lead and proton-lead runs at various energies, augmented by the pp reference data at the same energies





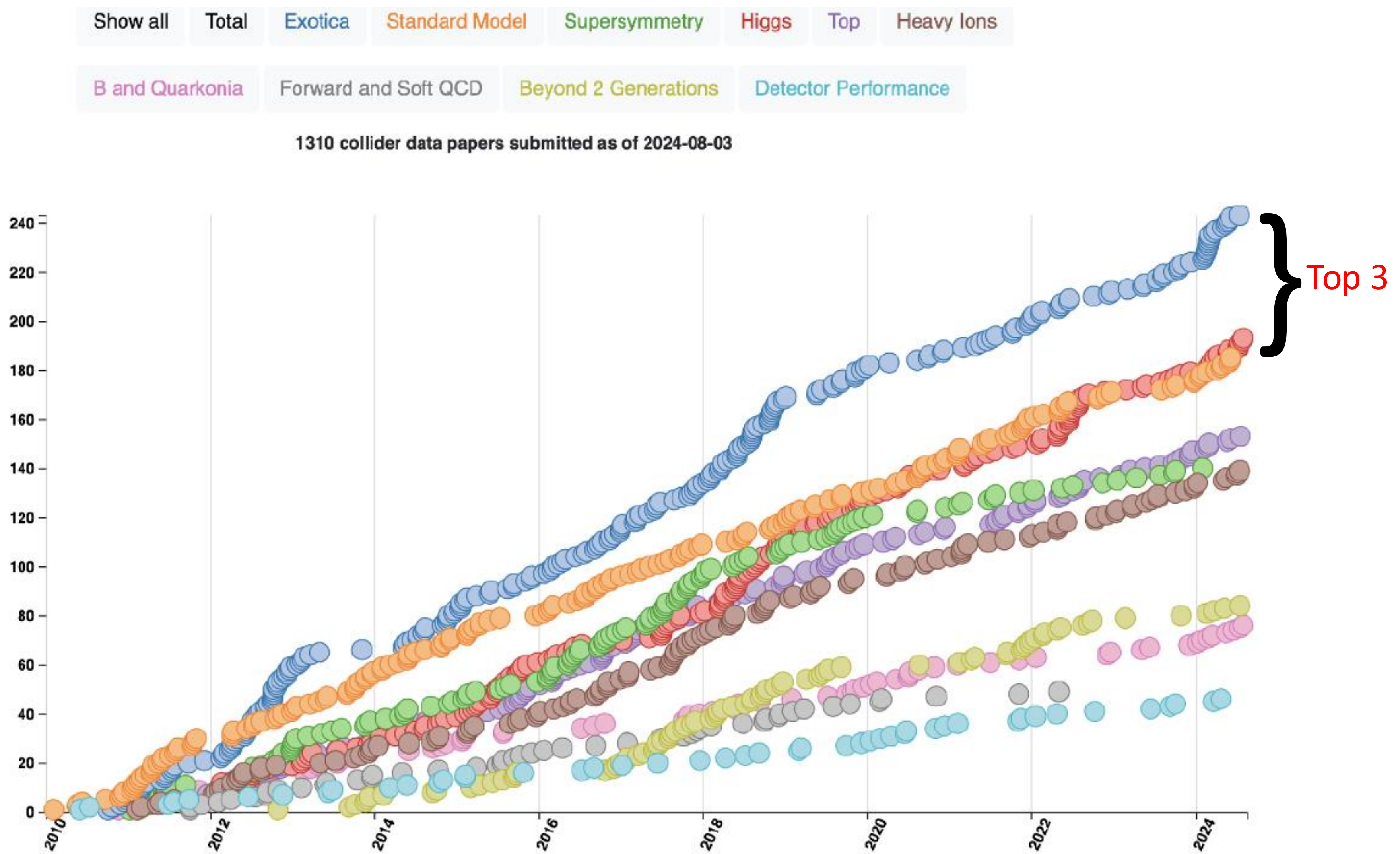
Legacy will stay on for times to come

- In one shot, the LHC has replaced following colliders:
  1) Tevatron (Higgs, BSM searches, top physics, and precision electroweak measurements)
  2) PEP-II/KEK B-factories (precision flavor physics)
  3) RHIC (heavy-ion physics)
- It has also added another one to the list:
  4) Photon-Photon collider (LbL scattering, searches for axion-like particles)
- LHC experiments, in particular ATLAS and CMS, have been extremely successful and productive in all above four areas
- Would have been impossible without phenomenological and theoretical developments of the past decade:
  - Higher-order (going up to N^3LO) calculations, advanced Monte Carlo generators, refined PDF uncertainties

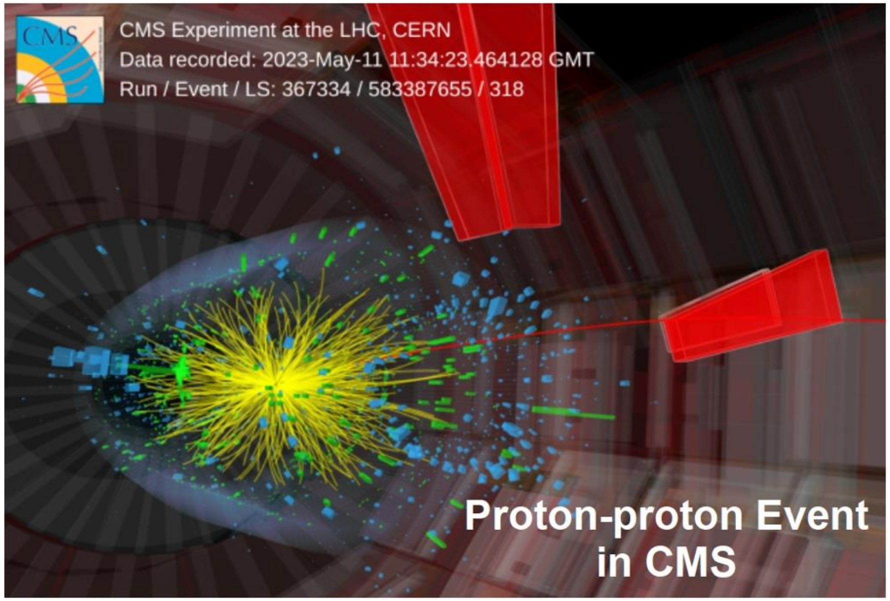
Since it is impossible to cover all aspects of the impressive experimental program in half an hour, I plan to present a few highlights of recent CMS results before concluding with its future upgrade.

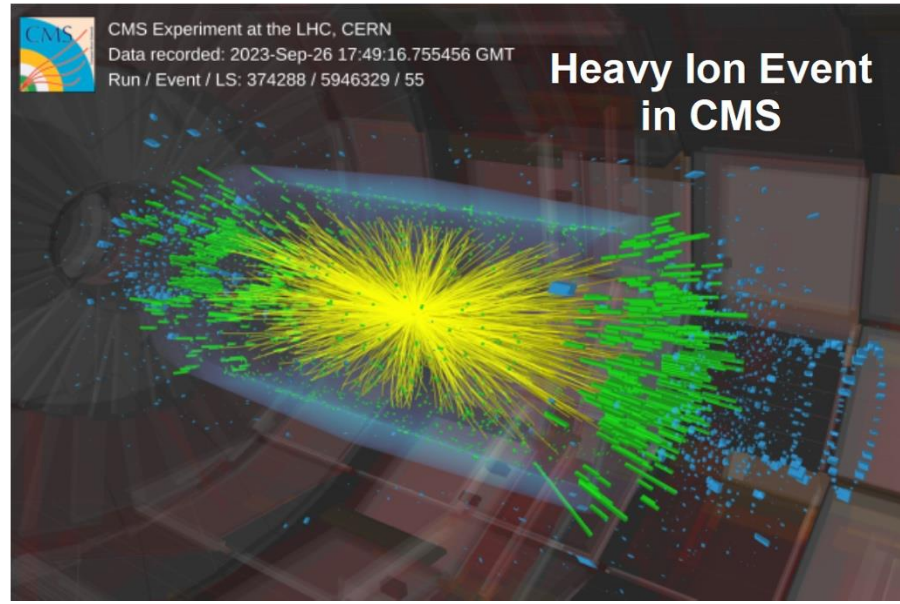
Stupendous physics harvesting

- Over 1,300 CMS physics papers submitted, with BSM searches, Higgs and SM dominating (close to 100 papers per year, i.e., two per week)



This is despite the challenge

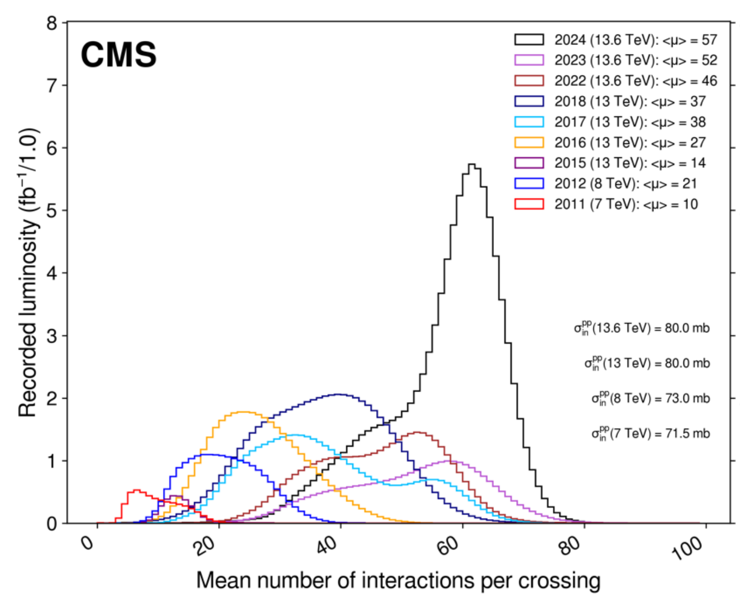




👉 A pp event at CMS looks nearly as busy as a heavy-ion one!

- Mean number of interactions per bunch crossing ('pileup') is about 50 in Run 3
  - ➢ Exceeds the original design of 20 pileup
- CMS developed state-of-the-art tools to mitigate the erroneous effects of pileup: particle-flow reconstruction and pileup-per-particle identification ('PUPPI')

[JINST 12 (2017) P10003] [JHEP 10 (2014) 059]



We already have a Higgs factory!

- LHC is a Higgs factory, the only place to study the Higgs boson today
- The Higgs production cross section, dominated by gluon-gluon fusion, is about 50 mb at 13 TeV ⇒ LHC has delivered 14M Higgs in Run 2 alone!
- That means, by now, ATLAS and CMS could have accumulated as many Higgs bosons as four LEP experiments collected Z bosons
- ➢ Triggering is the bottleneck; e.g., most of the gg → H(bb) events were never stored on tape
- Need an aggressive triggering strategy

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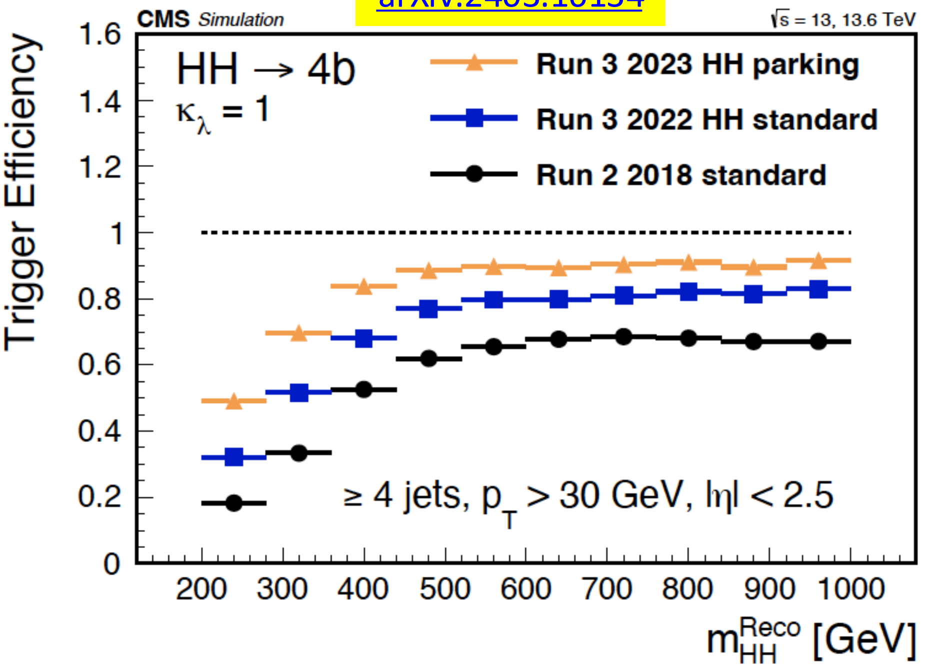
- Need an aggressive triggering strategy

- ✓ For Run 3, we raised level-1 bandwidth by 15% compared to Run 2 and rebalanced the level-1 trigger menu
- ✓ Designed high-rate b-tagged jet triggers that improved the efficiency for HH(4b, 2b2τ) events by up to 50%

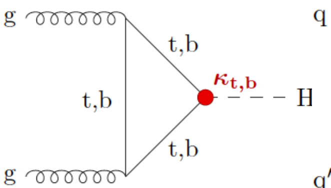
arXiv:2403.16134



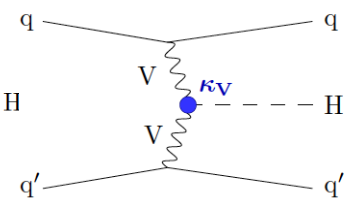
Higgs production at the LHC

- Measured cross section for different production modes agree with SM predictions

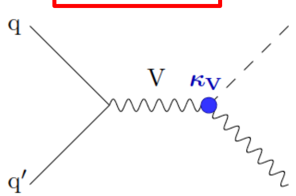
ggH



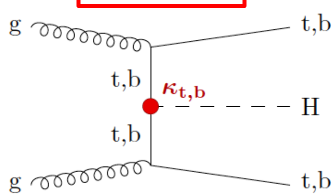
VBF



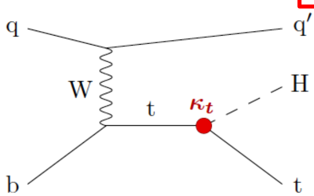
W/ZH

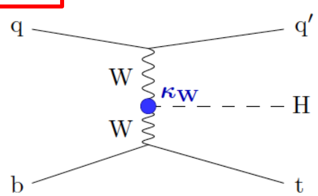


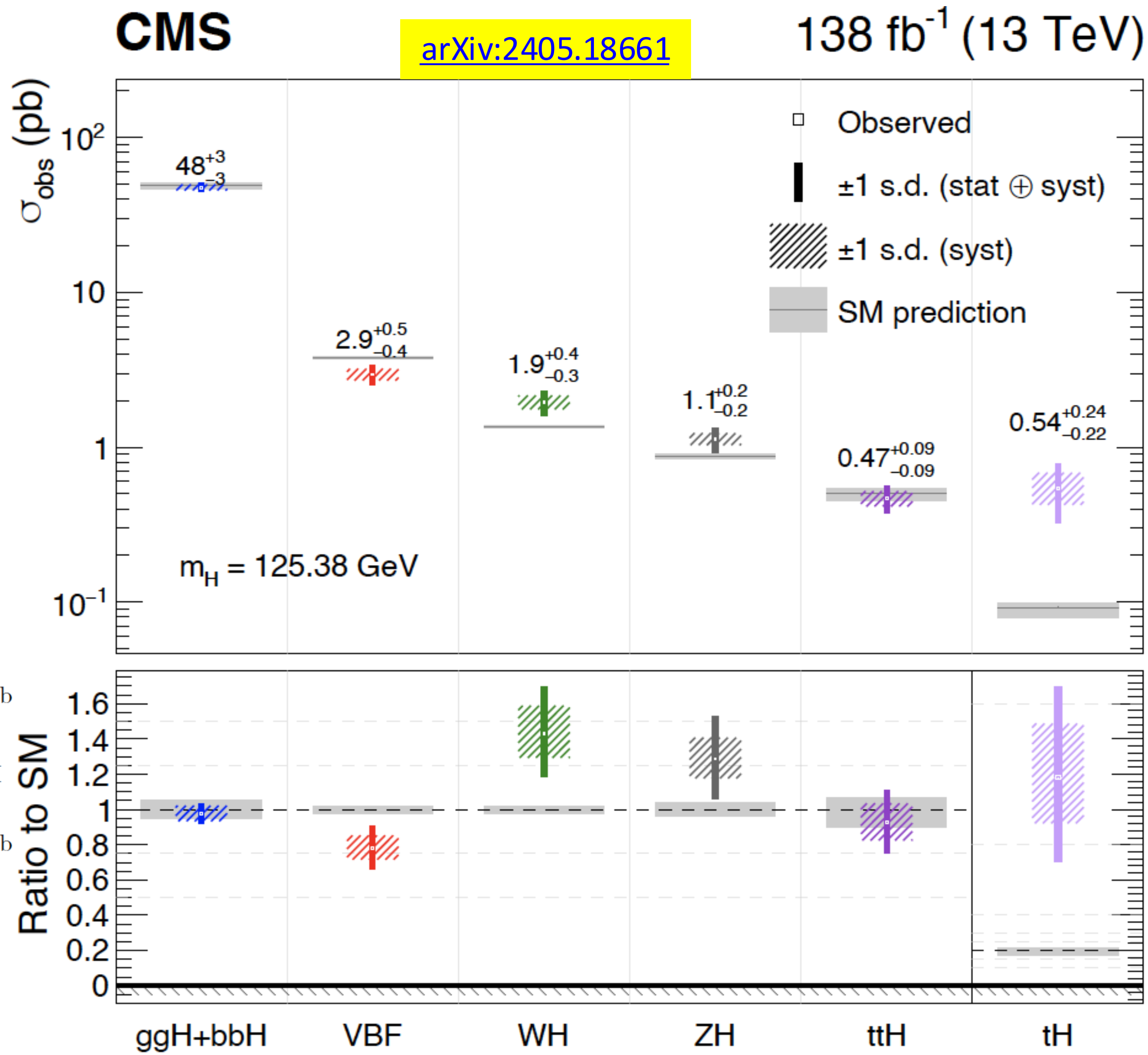
tt/bbH



tH

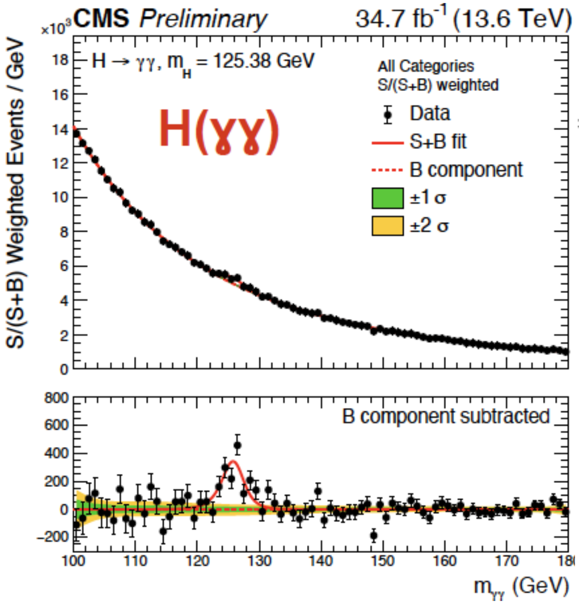


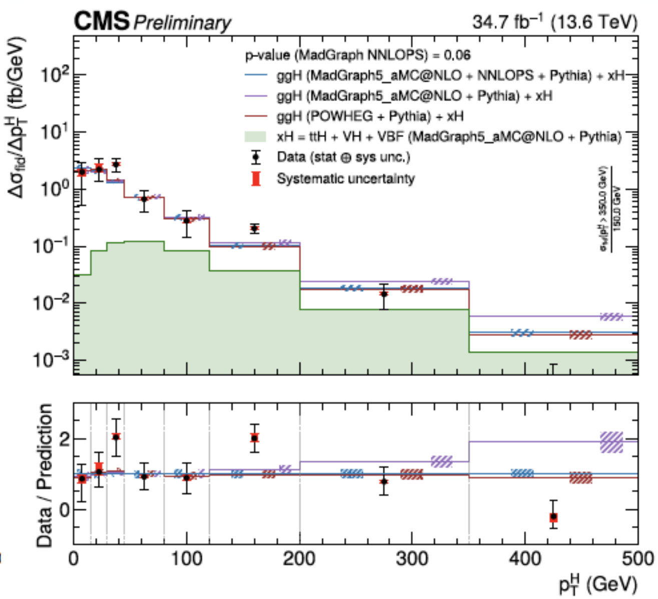


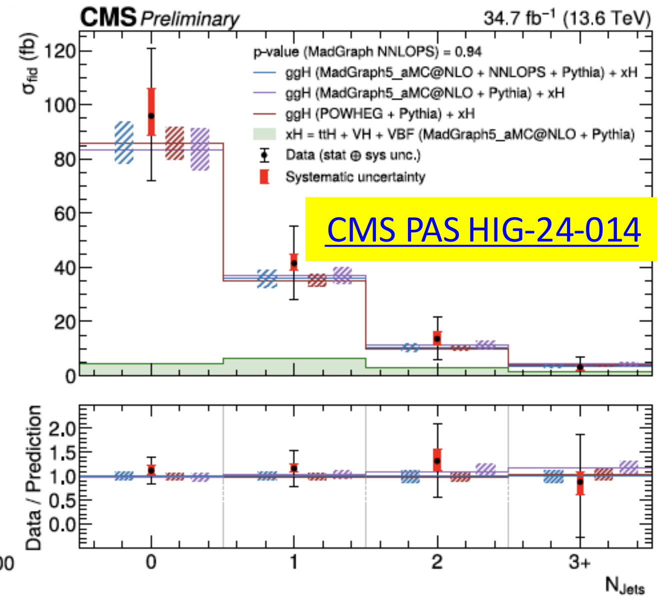


Studies at the highest energy point

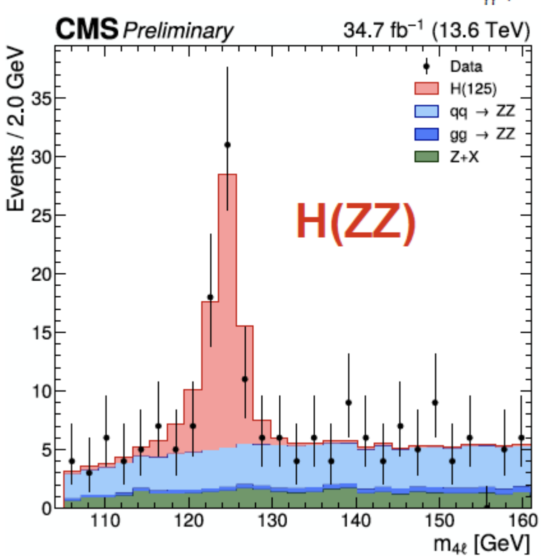
- First Higgs boson measurements with the 13.6 TeV data (Run 3) are now available in the two high-resolution decay channels

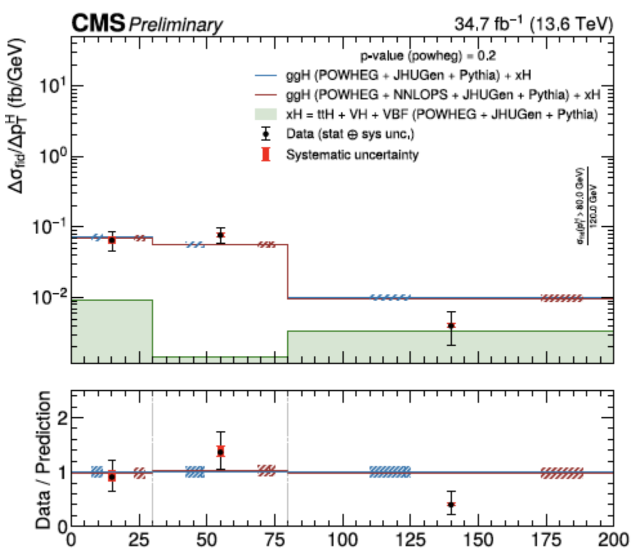


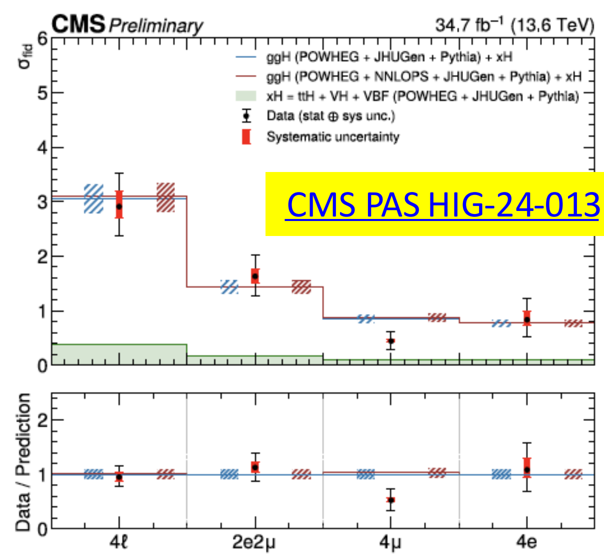




CMS PAS HIG-24-014





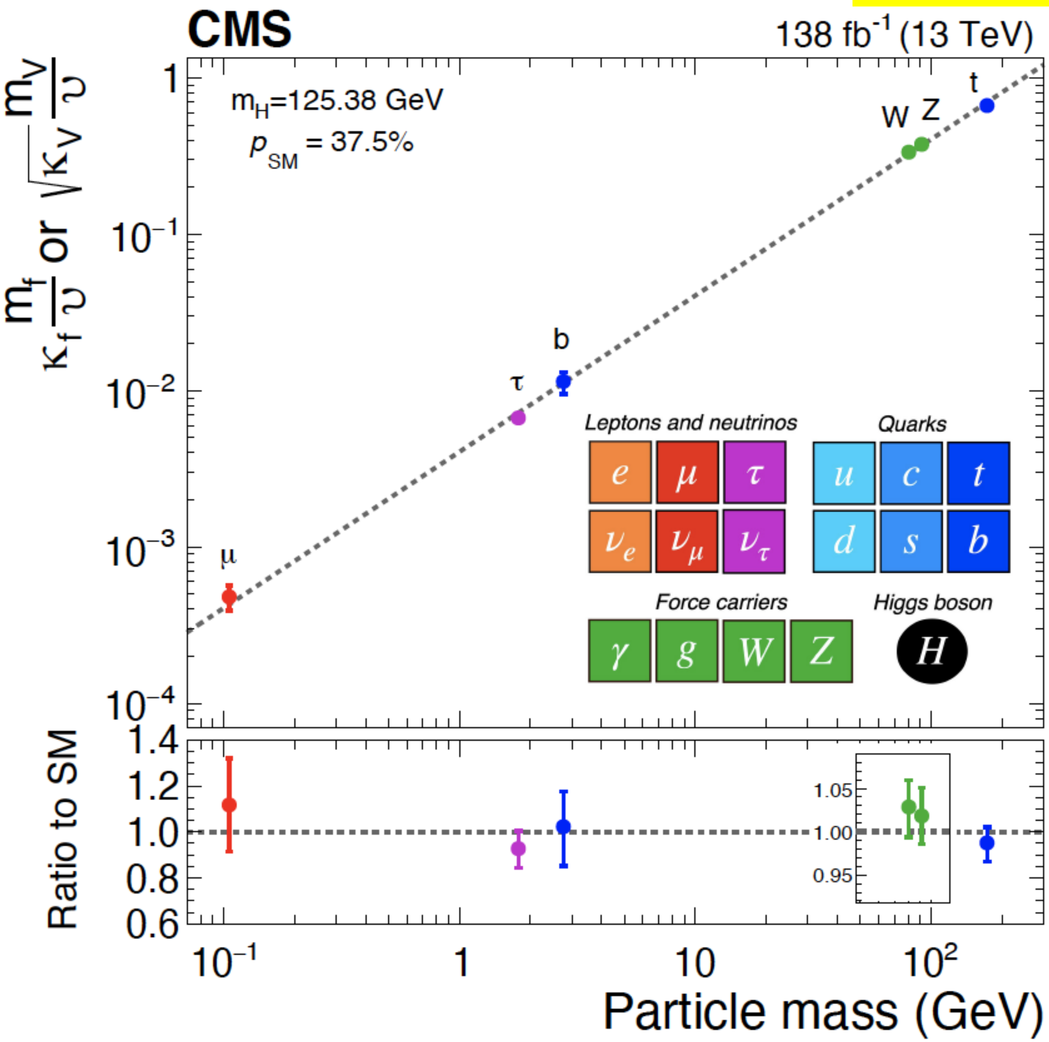


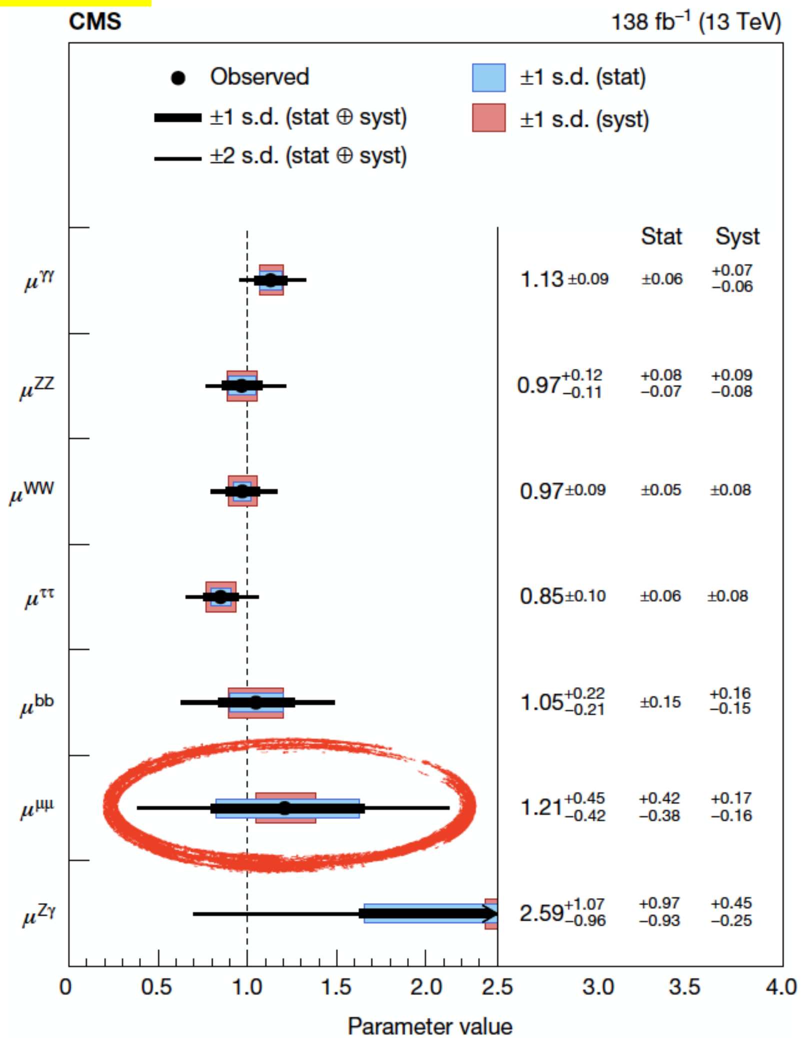
CMS PAS HIG-24-013

Higgs coupling with other SM particles

- Couplings to the third-generation fermions and electroweak bosons have been measured; first evidence for the Higgs coupling to muons has also been reported

Nature 607 (2022) 60

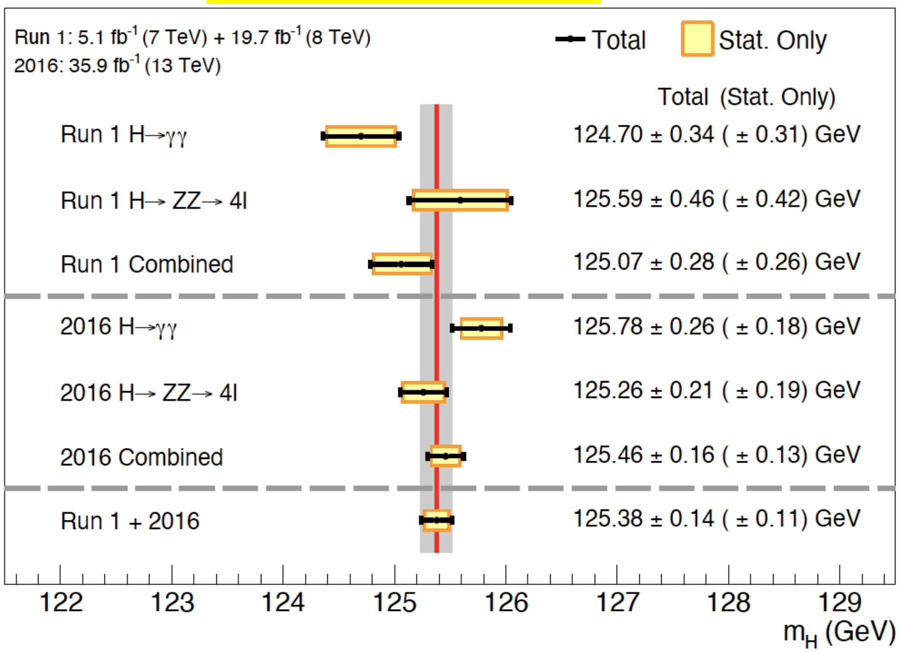




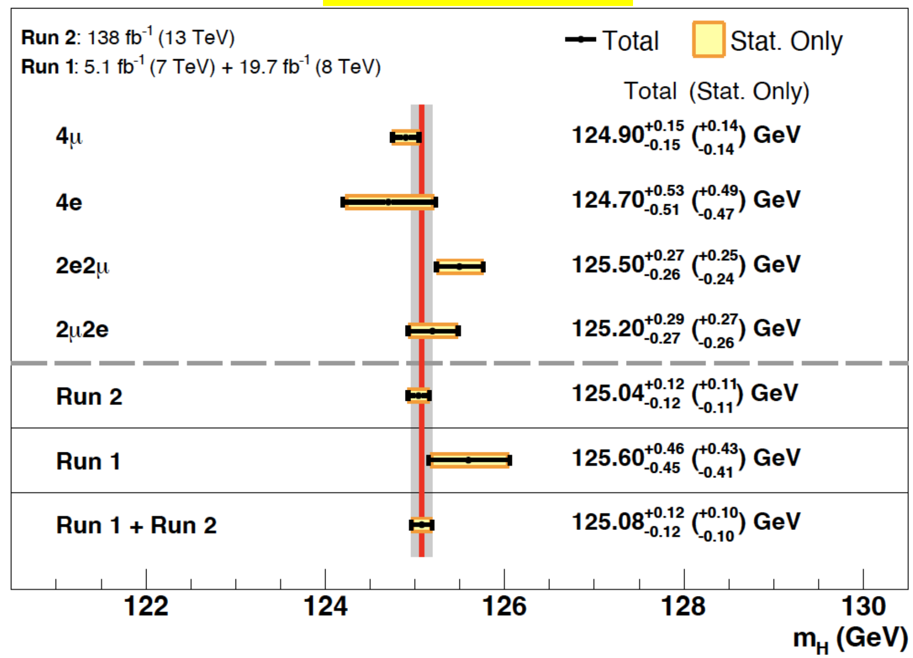
Higgs mass and width

- Measurement of the mass and width of the Higgs boson is very important
  - ✓ Higgs coupling to other elementary particles can be predicted by the SM once its mass (m_H) is known
  - ✓ Its width (Γ_H) is expected to be 4.1 MeV for an m_H value of 125 GeV
- Recent CMS measurements of m_H have achieved sub-permille precision:
  - ➢ m_H = 125.38 ± 0.14 GeV ($\mathrm{H} \to \gamma\gamma$) and 125.08 ± 0.12 GeV ($\mathrm{H} \to \mathrm{ZZ}^*$)

PLB 805 (2020) 135425



arXiv:2409.13663

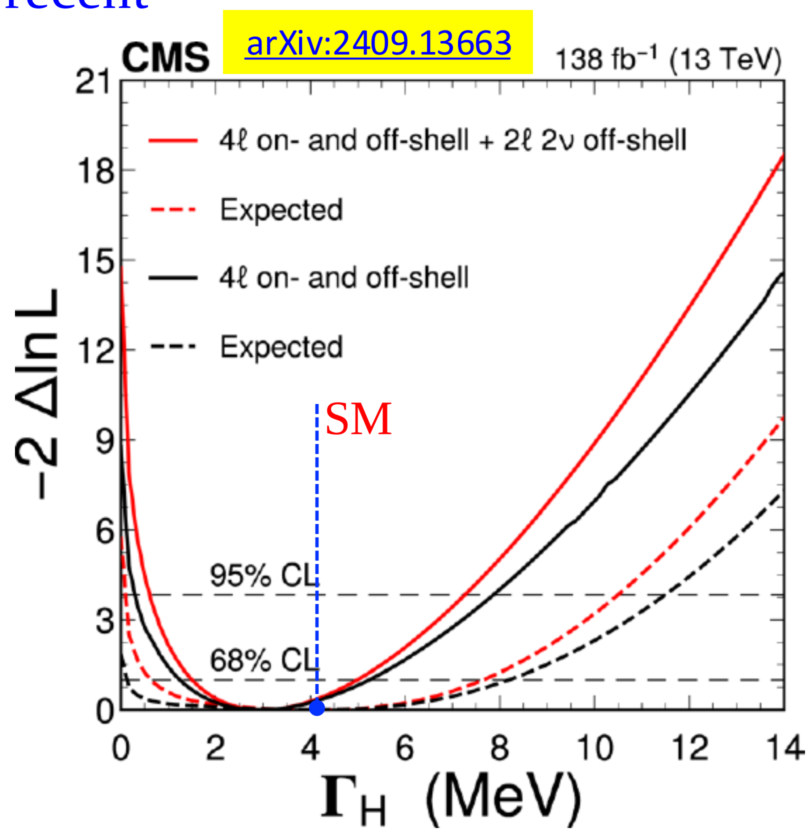


Higgs mass and width

- As Γ_H is too small, hardly discernible from the detector resolution, it is measured by comparing on-shell and off-shell Higgs production cross sections:

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}}$$

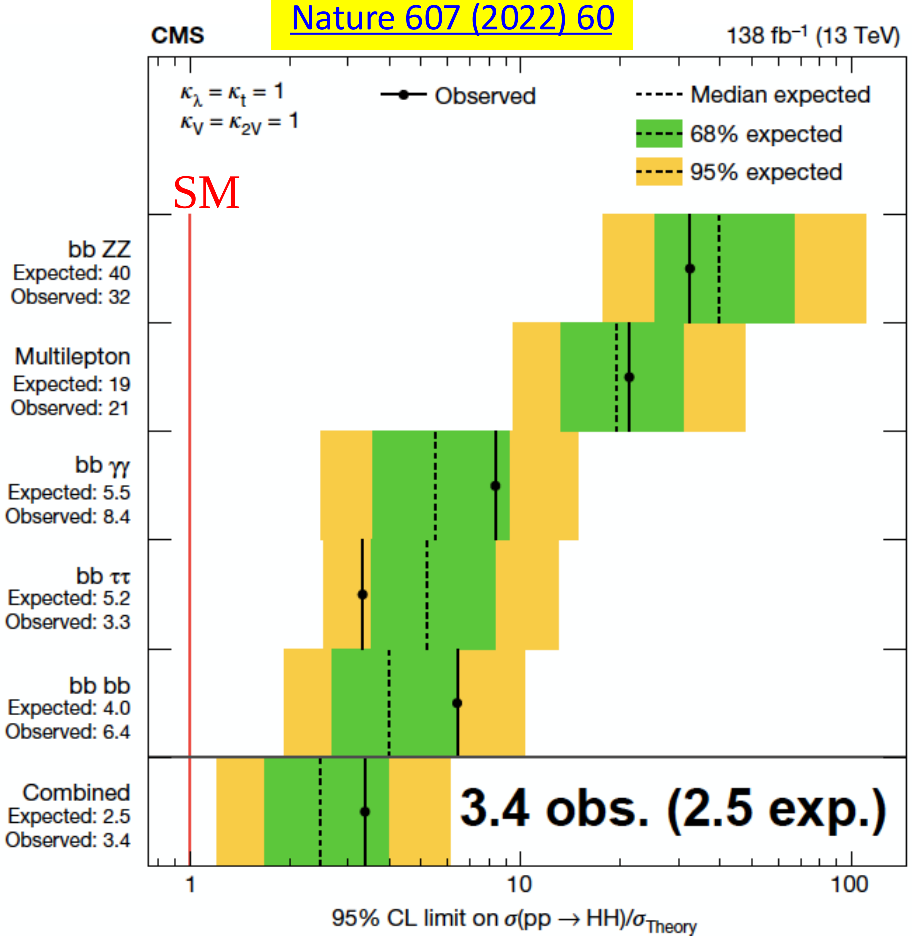
- Combining with an earlier study of the off-shell Higgs production in the $2\ell 2\nu$ channel, a recent measurement in the 4ℓ channel yielded:
  - ➢ $\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV
  - ➢ Agrees with the SM prediction

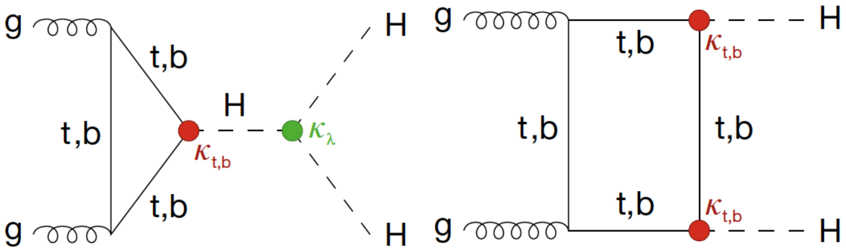


Probing Higgs self-coupling

- Measurement of the pair production of Higgs bosons can probe its self-coupling λ ⇒ ultimate goal of high-luminosity phase of LHC (HL-LHC)
- The cross section of the process is tiny due to large negative interference between the contributing diagrams

Nature 607 (2022) 60





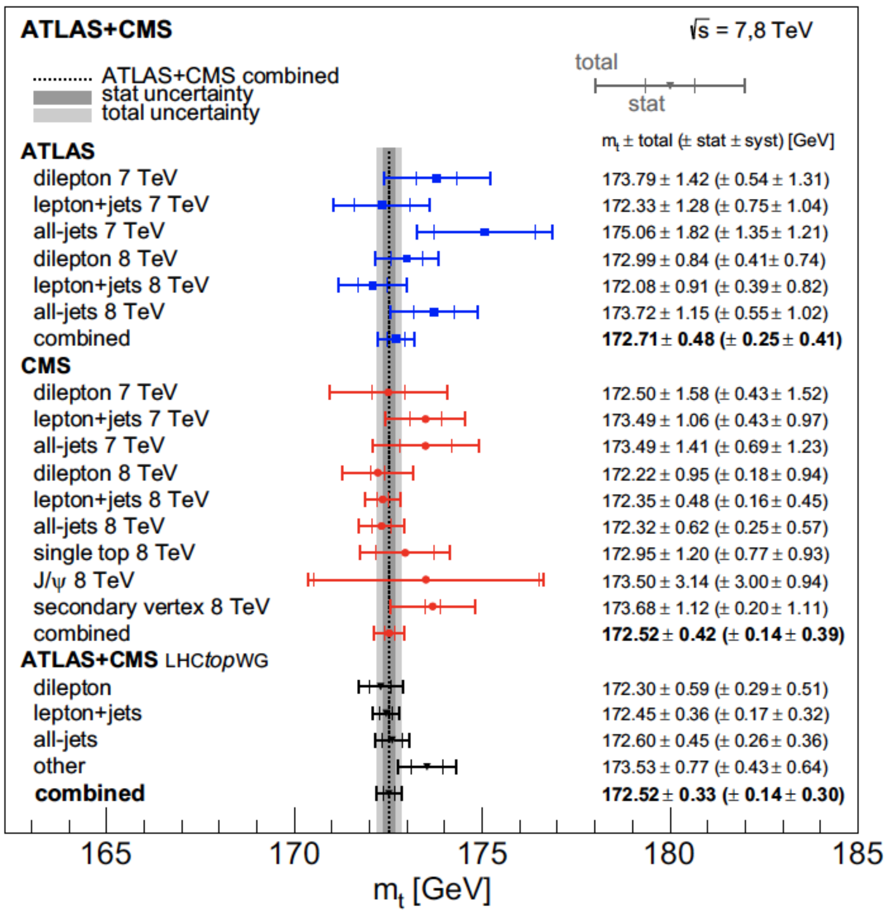
- CMS has made a significant stride in this pursuit by using ML-based b-tagging techniques, multivariate analysis methods and new triggers
- Set a 95% confidence-level upper limit on σ/σ_{SM} to be 3.4
  - ✓ Exceeds early HL-LHC projection
- Full Run 2 combination is on way

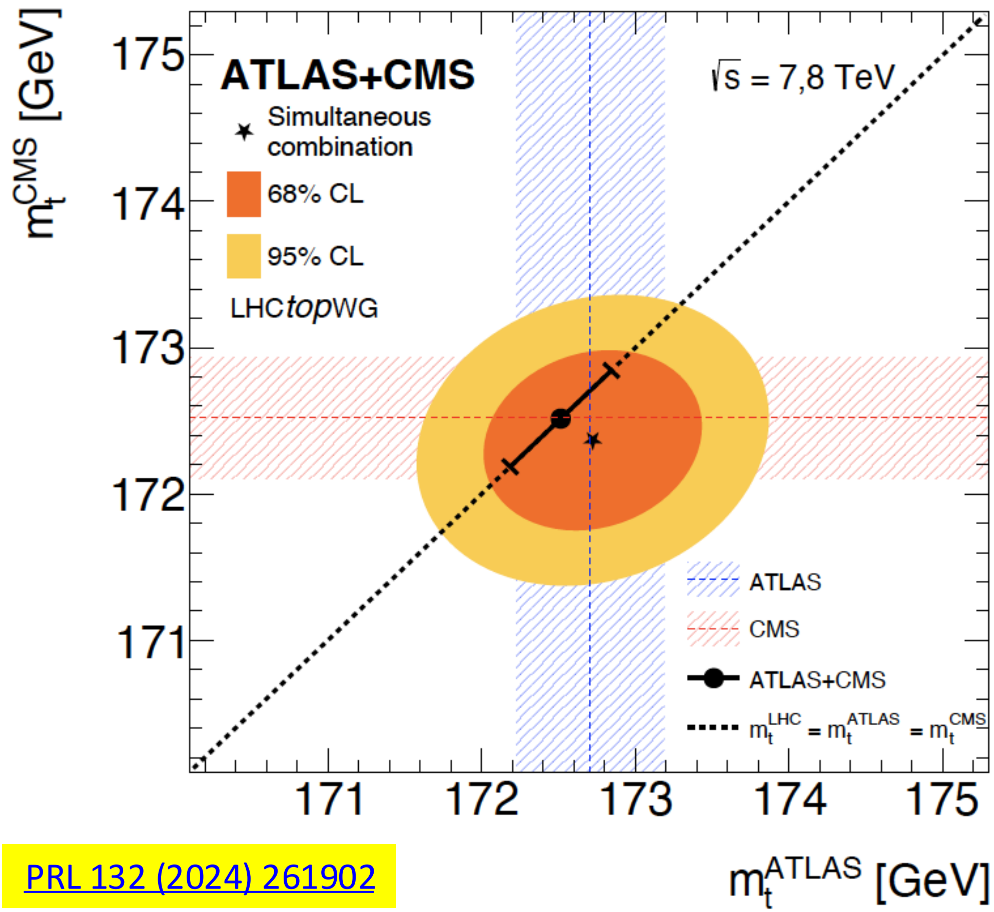
Weighing the heaviest known particle

- Most precise determination of the top quark mass comes from a recent Run 1 combination of ATLAS and CMS measurements:

  $m_t = 172.52 \pm 0.33$ GeV $\Rightarrow$ less than 2% precision

- Jet energy scale is the largest source of systematic uncertainties



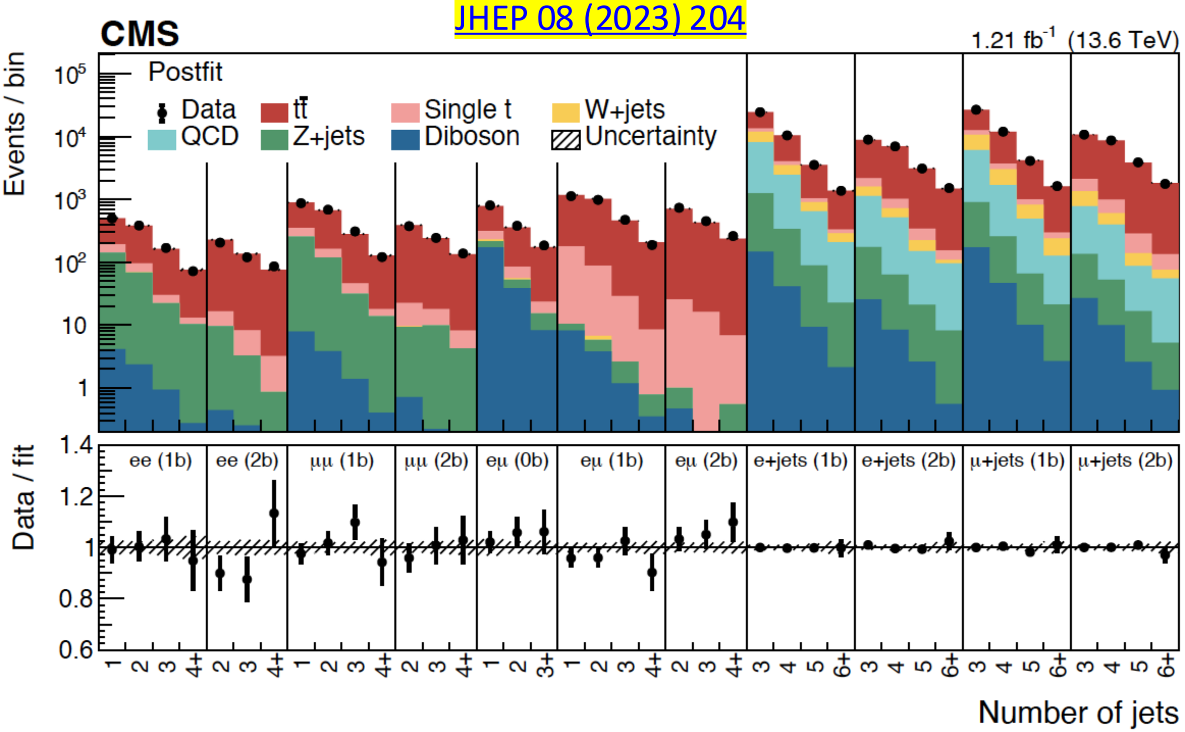


PRL 132 (2024) 261902

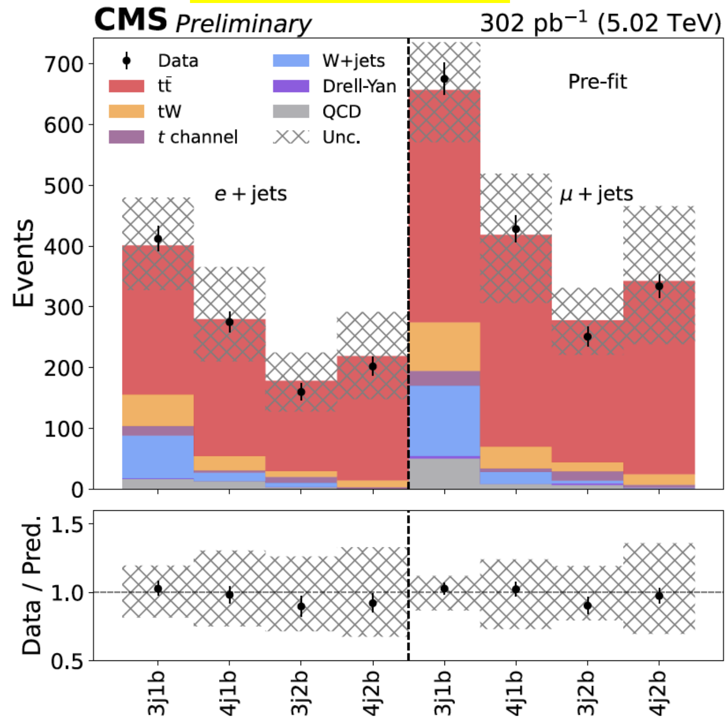
Top quark pair production

- Two recent results: measurement of top quark pair ($t\bar{t}$) production cross section at 13.6 TeV in 2ℓ+jets & ℓ+jets channels and at 5.02 TeV (low energy) in the ℓ+jets channel
  - ➢ The former is based on early Run 3 data, while the latter is done using a special low-pileup run taken in 2017
  - ➢ Performed fit to multiple event categories to control large uncertainties arising due to b-tagging and lepton efficiency in early data

JHEP 08 (2023) 204



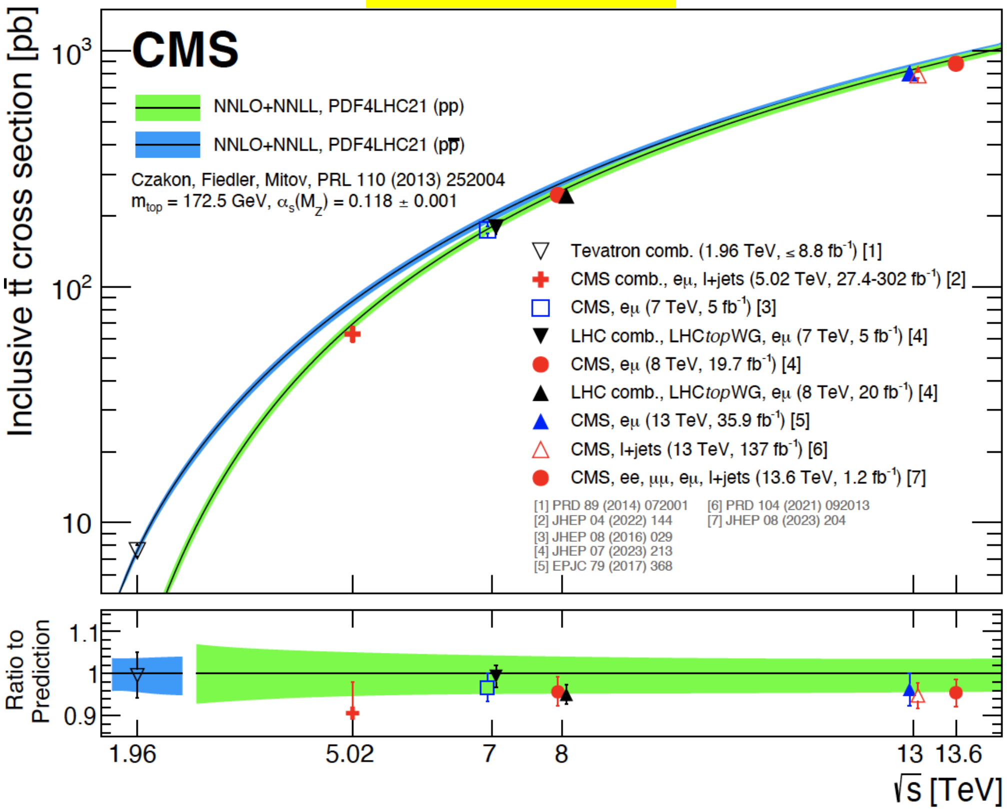
CMS PAS TOP-23-005



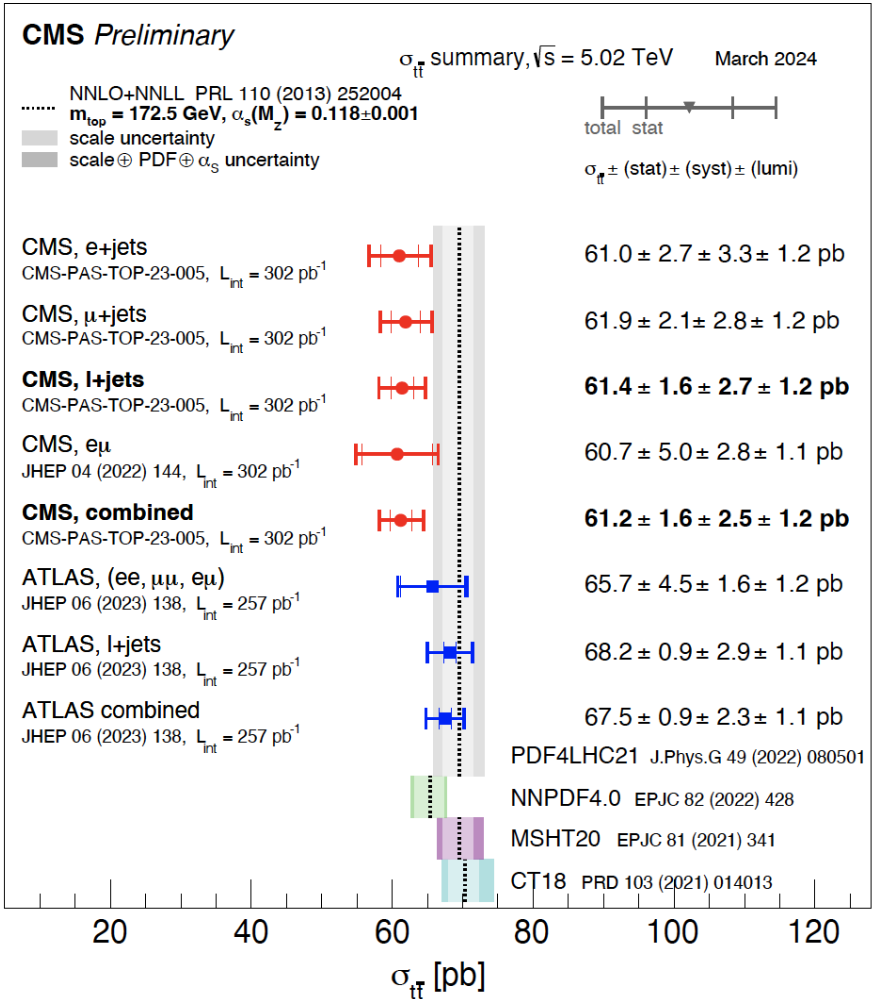
Energy dependence

👉 Below we present the inclusive $t\bar{t}$ cross section as a function of $\sqrt{s}$ and a summary of measurements performed at 5.02 TeV

arXiv:2405.18661

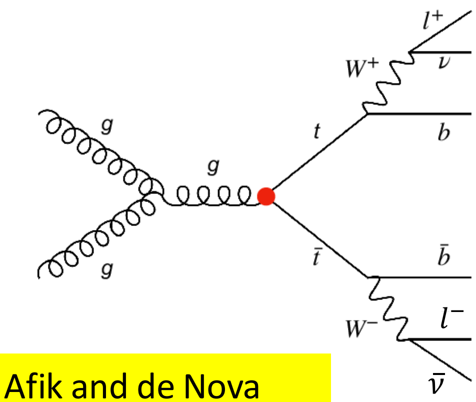


CMS PAS TOP-23-005



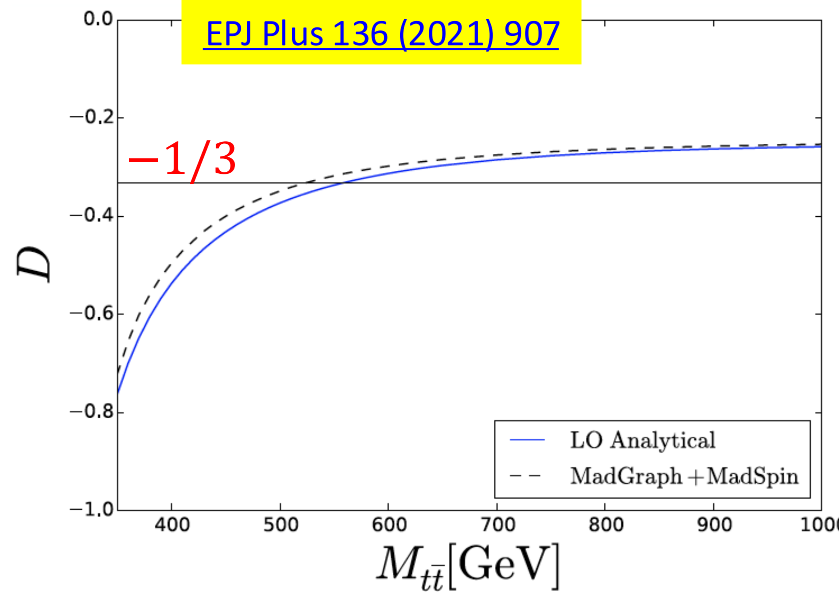
Are top quarks entangled?

- The top quark has a lifetime ($\sim 10^{-25}$s) shorter than the time scale for hadronization ($\sim 10^{-24}$s) and for spin decorrelation ($\sim 10^{-21}$s)
- Thus, the top quark decays before it can hadronize, and spins of the top quark and antiquark in the $t\bar{t}$ system as well as their decay products are correlated ⇒ sign of quantum entanglement



- Explore near-threshold $t\bar{t}$ production in the 2ℓ+jets channel
- We can use the spin correlation matrix C to define the entanglement condition
  - Entanglement marker $D = -\mathrm{Tr}[C]/3 = -3\langle\cos\phi\rangle$, where ϕ is the angle between two leptons from top quark and antiquark decays in $t\bar{t}$ rest frame
  - If $D < -1/3$, then the $t\bar{t}$ system is quantum entangled

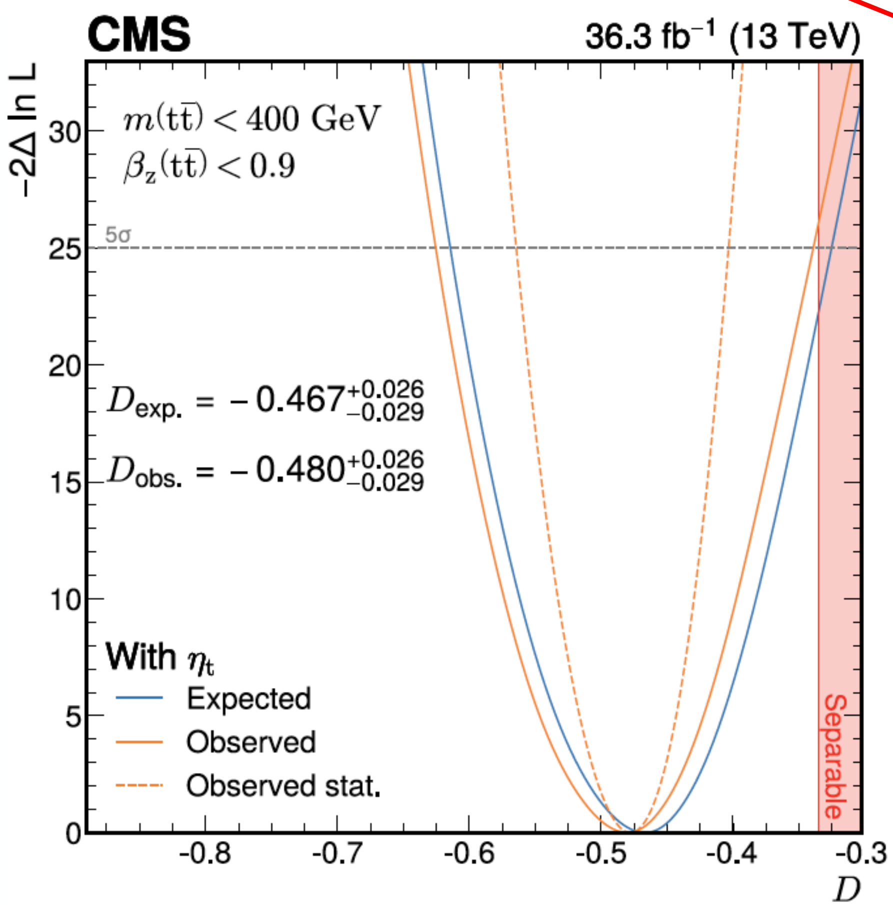
Afik and de Nova
EPJ Plus 136 (2021) 907

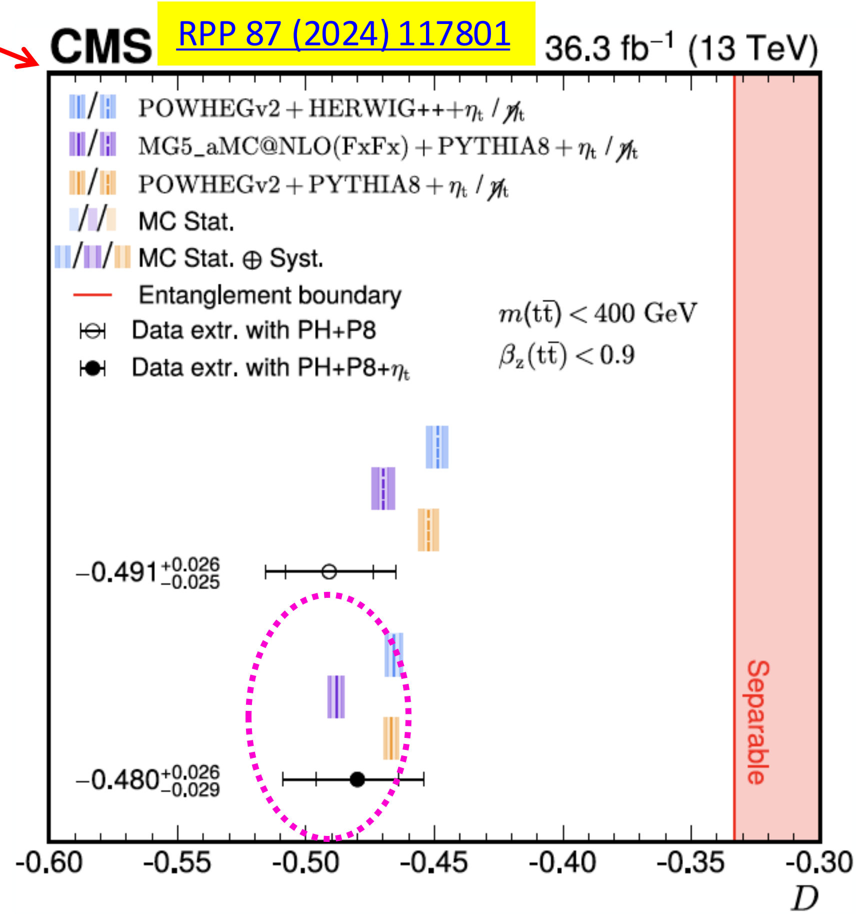


Entanglement at low mass

[Nature 633 (2024) 542]

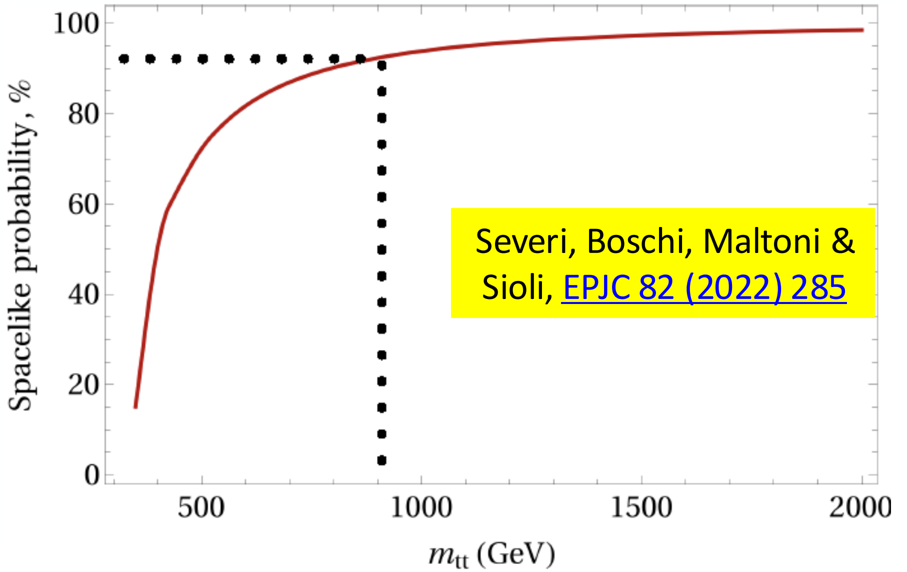
- Confirmed the first observation of quantum entanglement by ATLAS
- Observed significance of entanglement near the $t\bar{t}$ threshold is 5.1σ
- Inclusion of the below-threshold toponium resonance, a color-singlet pseudoscalar η_t, slightly improves the agreement between observed and expected entanglements



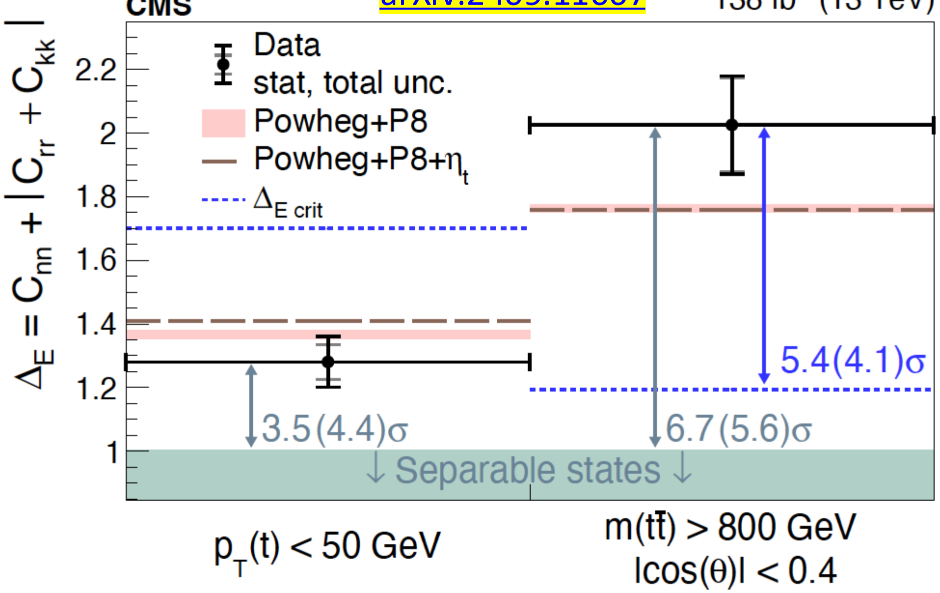


What about high mass?

- It is more challenging to detect entanglement at the high $t\bar{t}$ mass
  - Above 800 GeV, about 90% of the events have the top quark and antiquark space-like separated, i.e., their decays can't be casually connected
- Observing the entanglement in this regime is thus very interesting from quantum information point of view
- We need more copious $t\bar{t}$ production ⇒ the ℓ+jets channel is ideal for this study



arXiv:2409.11067

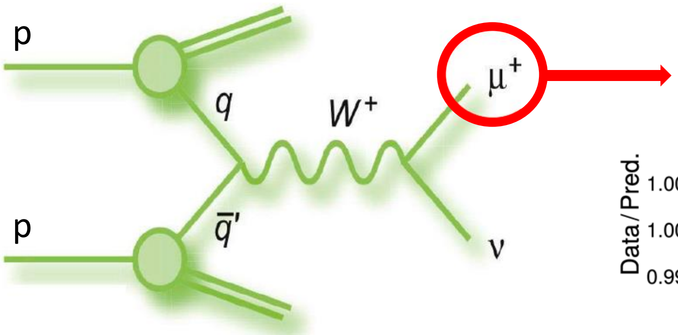


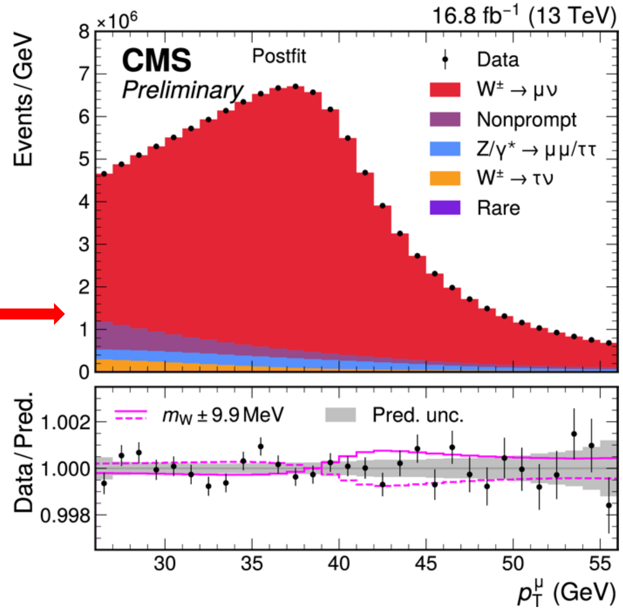
- Using Run 2 data, CMS measured entanglement at high $t\bar{t}$ mass for the first time
- Low-mass sensitivity is not as good as the 2ℓ+jets channel
- Established entanglement beyond causality connection at high mass

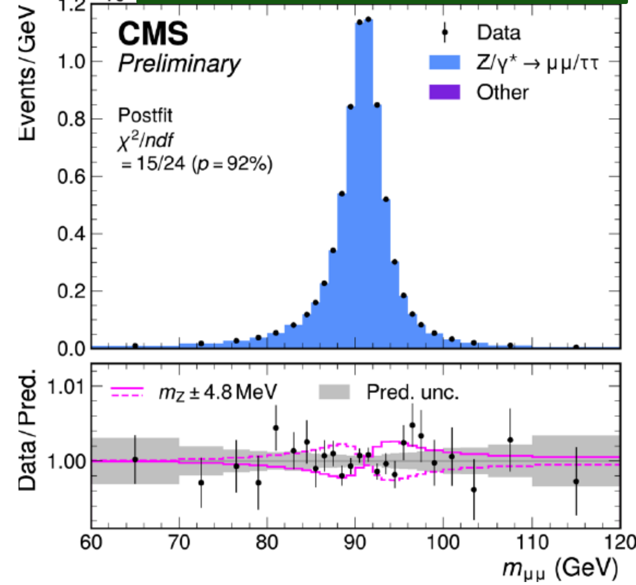
Something recent and exciting

- Used 16.8 fb^{-1} data recorded at 13 TeV in 2016
- Focused on the muon channel & kinematics
- Validate with m_Z

$m_Z - m_Z^{\mathrm{PDG}} = -2.2 \pm 4.8$ MeV







- A binned maximum-likelihood fit to the muon p_T, η and charge yields:

$$m_W = 80360.2 \pm 2.4\,(\mathrm{stat}) \pm 9.6\,(\mathrm{syst})\ \mathrm{MeV}$$
$$= 80360.2 \pm 9.9\ \mathrm{MeV}$$

Muon momentum scale	4.8
Muon reco. efficiency	3.0
W and Z angular coeffs.	3.3
Higher-order EW	2.0
p_T^V modeling	2.0
PDF	4.4
Nonprompt background	3.2
Integrated luminosity	0.1
MC sample size	1.5

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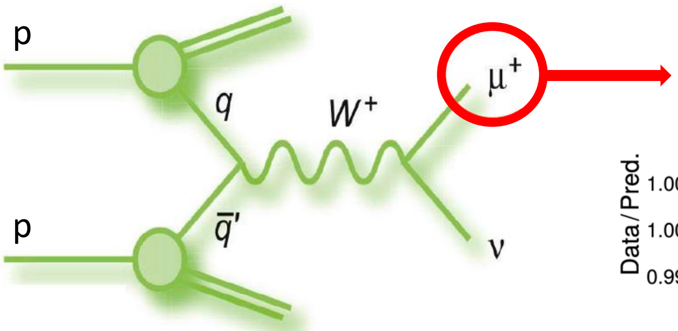

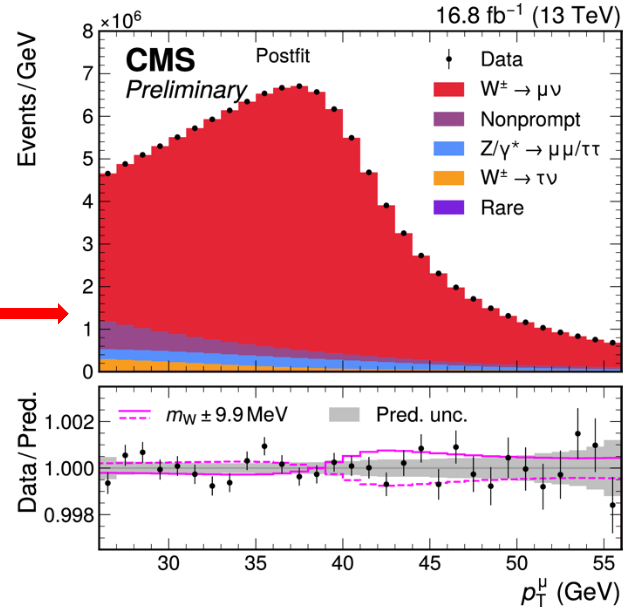

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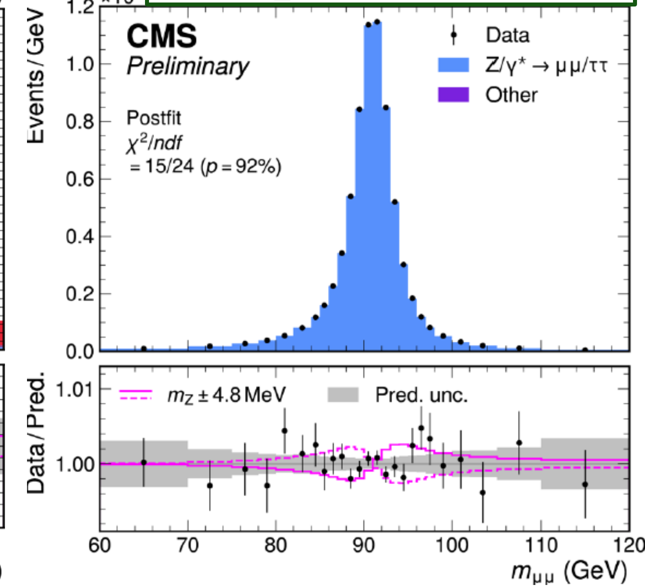

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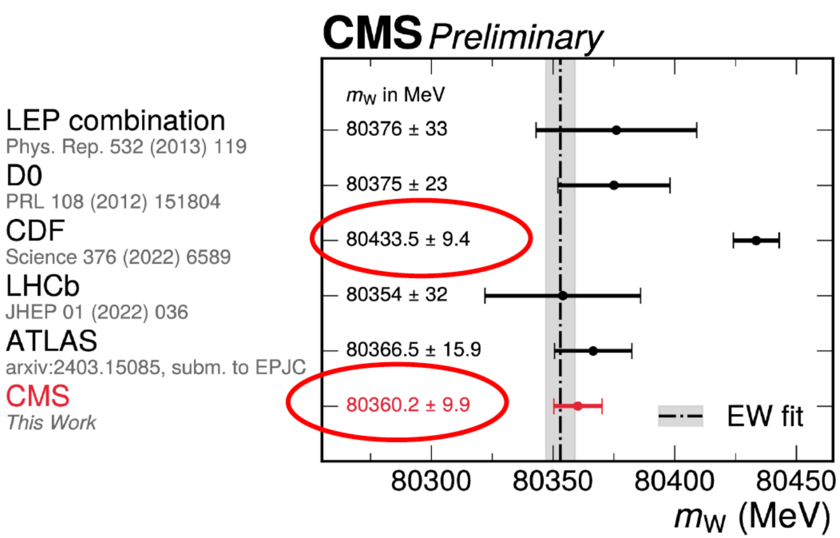

$$m_W = 80360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst})\ \text{MeV}$$
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👉 Most precise result at the LHC

👉 Comparable to CDF precision

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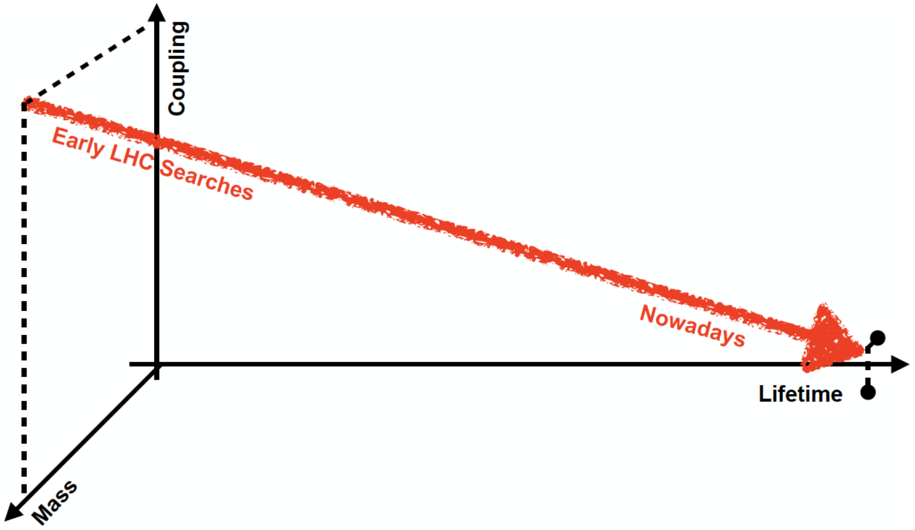
Almost 400 papers in one slide

More on the talks by Shriniketan and Subham

- Considering that the LHC has nearly reached its design c.o.m. energy, the search for heavy particles appears to be a diminishing endeavor.

➢ More complex signatures, including long-lived particles, are now our focus



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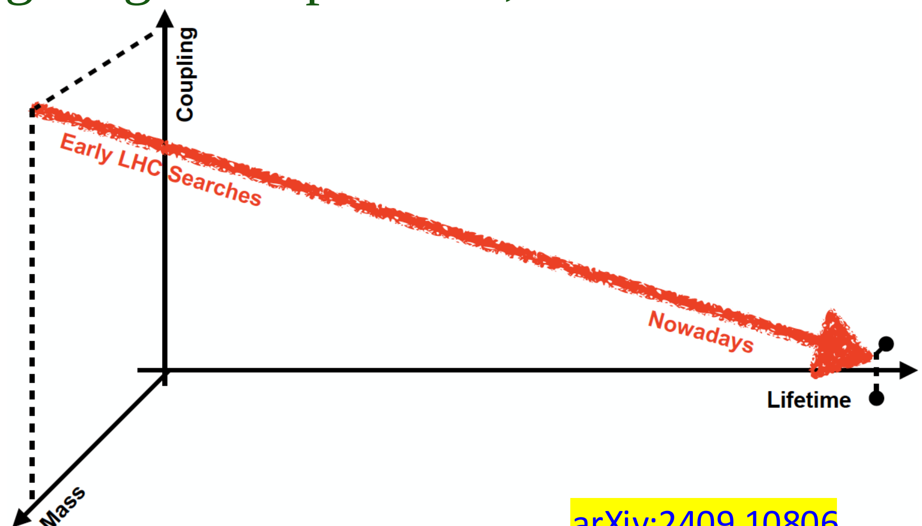
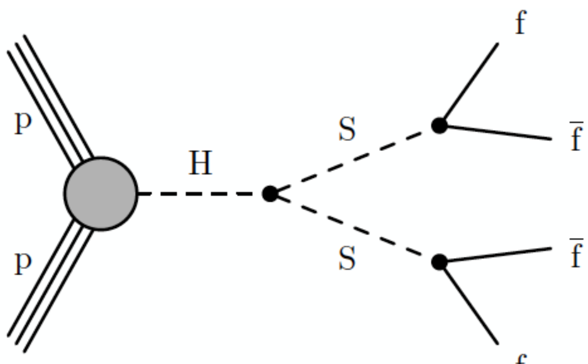
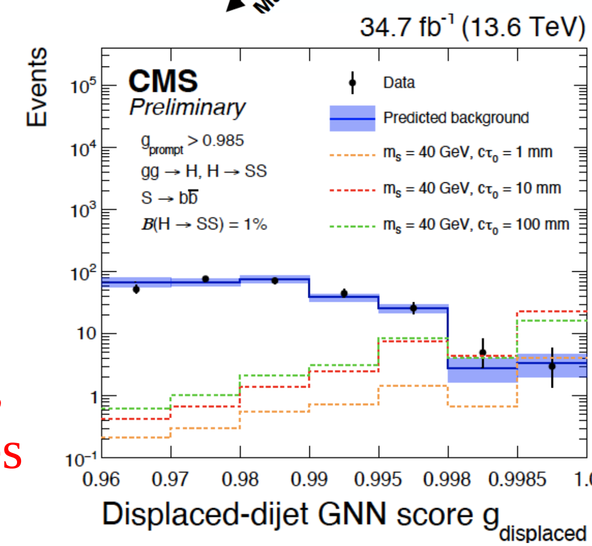
- ➢ More complex signatures, including long-lived particles, are now our focus
- An example is the exotic decay of the Higgs boson to pairs of long-lived scalars S that decay further into a pairs of jets

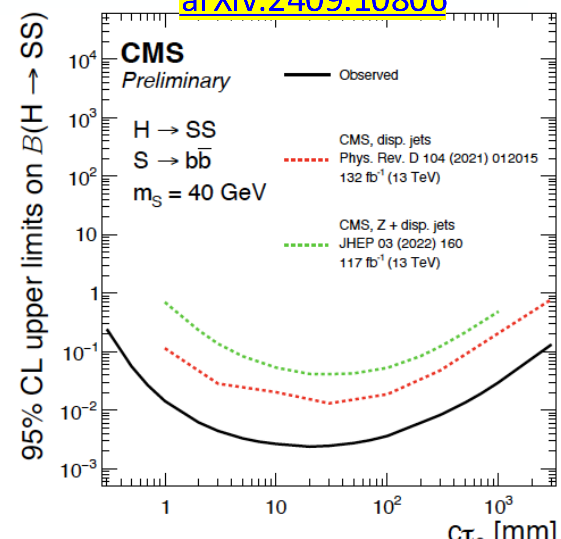




👉 Profiting from displaced-jet trigger and advanced graph NN-based bkg. suppression, the limits exceed Run-2 ones by an order of magnitude



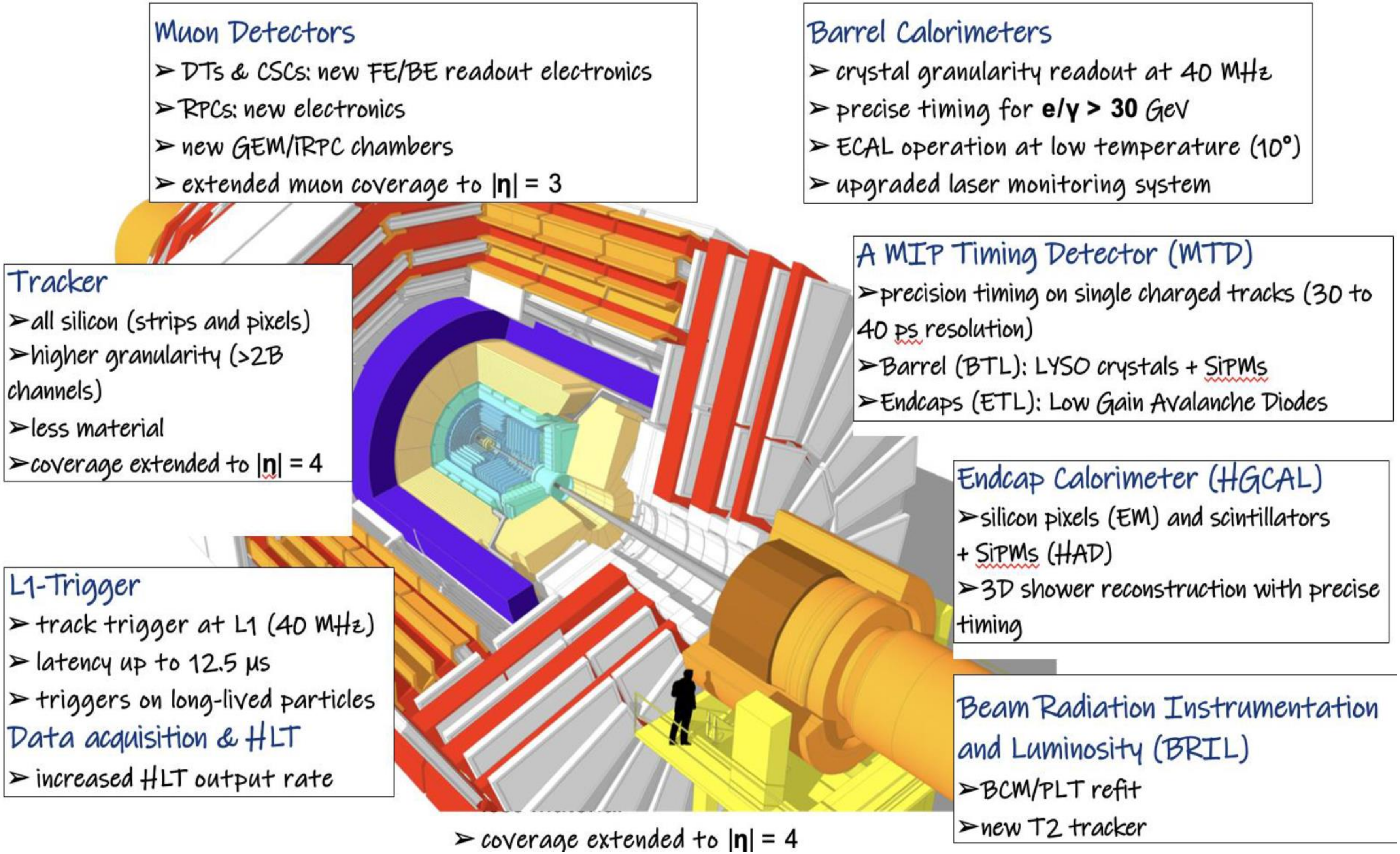
arXiv:2409.10806



What does the near-future hold?

- Key challenges at the HL-LHC:
  - ❑ Increased integrated luminosity (3-4 ab^{-1}) ⇒ huge radiation fluence
  - ❑ Increased peak luminosity (5-7.5 $\mathcal{L}_{nom}$) ⇒ higher particle and data rates
  - ❑ Increased pileup up to 200 ⇒ higher particle density in space and time

Close to full revamp of CMS

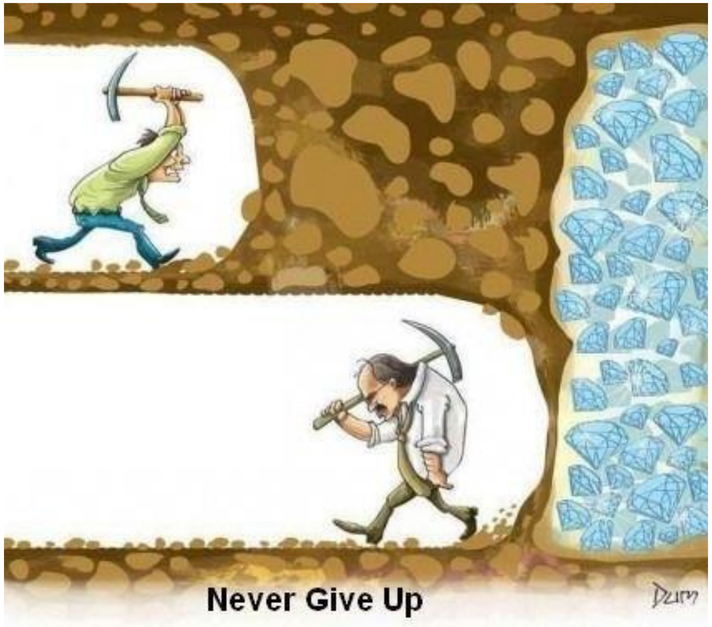


👉 Highlights: tracking info. at level-1, five-dimensional HGCAL, timing det. (mitigating pileup, adding more teeth to flavor and heavy-ion physics)

Summary

- ❑ LHC has been a dream machine, with spectacular performance
- ❑ The Nobel-prize winning discovery of the Higgs particle in 2012 completed the SM, paving an avenue of decades of exploration
- ❑ Precision SM measurements encompassing properties of top quark and vector boson continue to be very exciting
- ❑ Though nature has not been so kind on the direct BSM searches, we will march on to the more challenging, unexplored territory with more data, refined detector, and advanced analysis tools

➢ Stay tuned …



Additional information

Momentum scale uncertainty

- Largest systematic contribution to the m_W result comes from the muon momentum scale, accounting for 4.8 of the total 9.9 MeV
- Below is a breakdown of the different sources contributing to it:

Source of uncertainty	Nuisance parameters	Unc. in m_W (MeV)
J/ψ calibration stat. (with $2.1\times$ scaling)	144	3.7
Z closure stat. uncertainty	48	1.0
Z closure (LEP measurement)	1	1.7
Resolution stat. (with $10\times$ scaling)	72	1.4
Pixel multiplicity	49	0.7
Total	314	4.8

➢ As the statistics of the J/ψ calibration sample contributes the most, we expect it to reduce with larger data sample