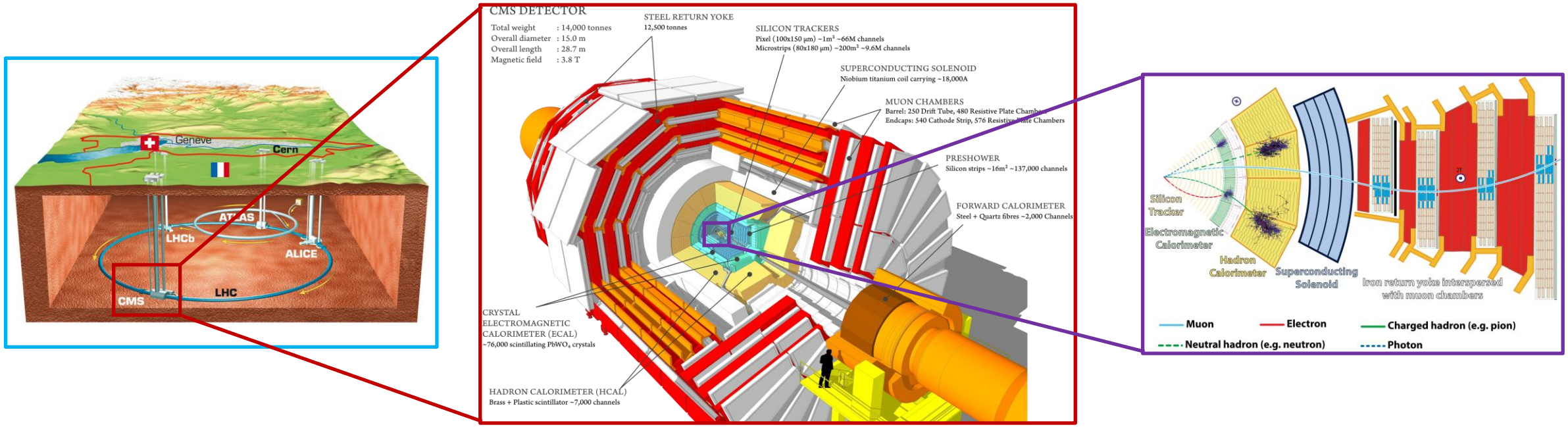
Highlights of the CMS Experiment

16th FCPPN/L Workshop, Qingdao
21-July-2025

Jie Xiao *IP2I Lyon*
On-behalf of the CMS collaboration
Refer to R. Salerno's talk in EPS 2025

The CMS experiment



CMS detector is a large general-purpose detector at the LHC, CERN

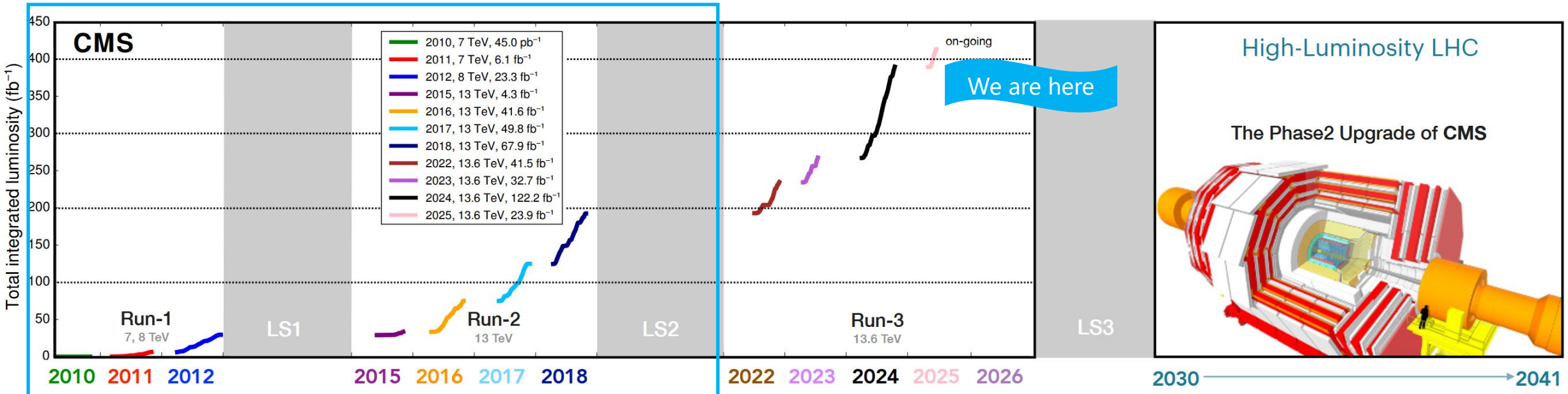
- Excellent reconstruction, identification and energy-momentum measurement of photons, electrons, muons, taus, and jets covering a wide energy range (sub-GeV to TeV)

CMS experiment aims to investigate fundamental particle interactions

- Testing the Standard Model and exploring phenomena beyond its predictions

Collecting proton-proton collisions at E_{CM} = 13.6 TeV

Milestones toward the HL-LHC



Run-1

Higgs boson discovering

Natural SUSY searches

- *Exclude large part of parameter space*

Probing QGP

Run-2

Study of Yukawa coupling

- *Observation 3rd generation*
- *Evidence 2nd generation*

Shift to precision physics

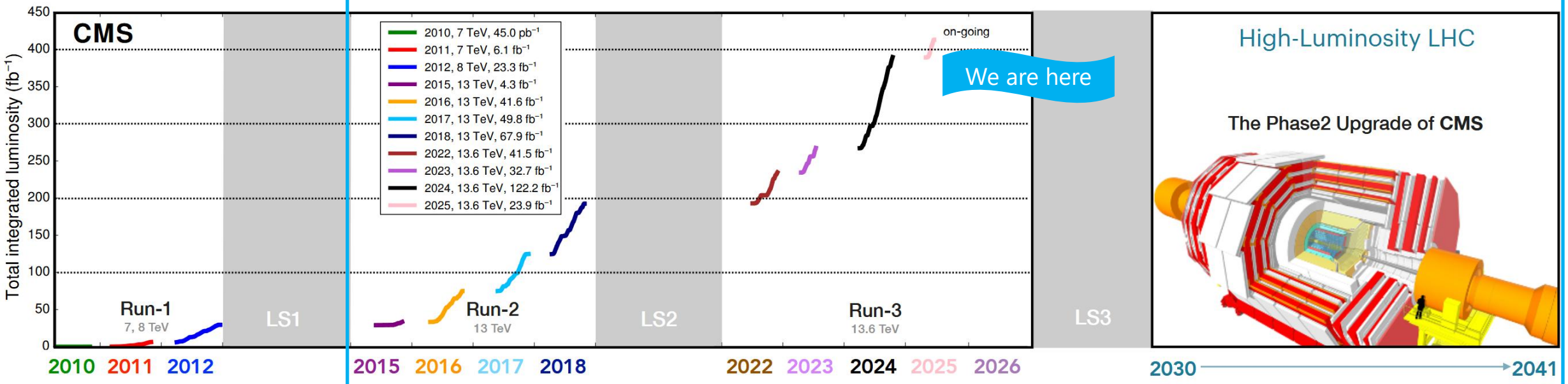
- m_W , m_{top} , $sin^2\theta_W$

Observation of VBS

Heavy flavor physics

- *Ultra-rare decay* $B_s \rightarrow \mu^+\mu^-$

Milestones toward the HL-LHC



Outline

Run-3 performance

Run-2, Run-3 analysis

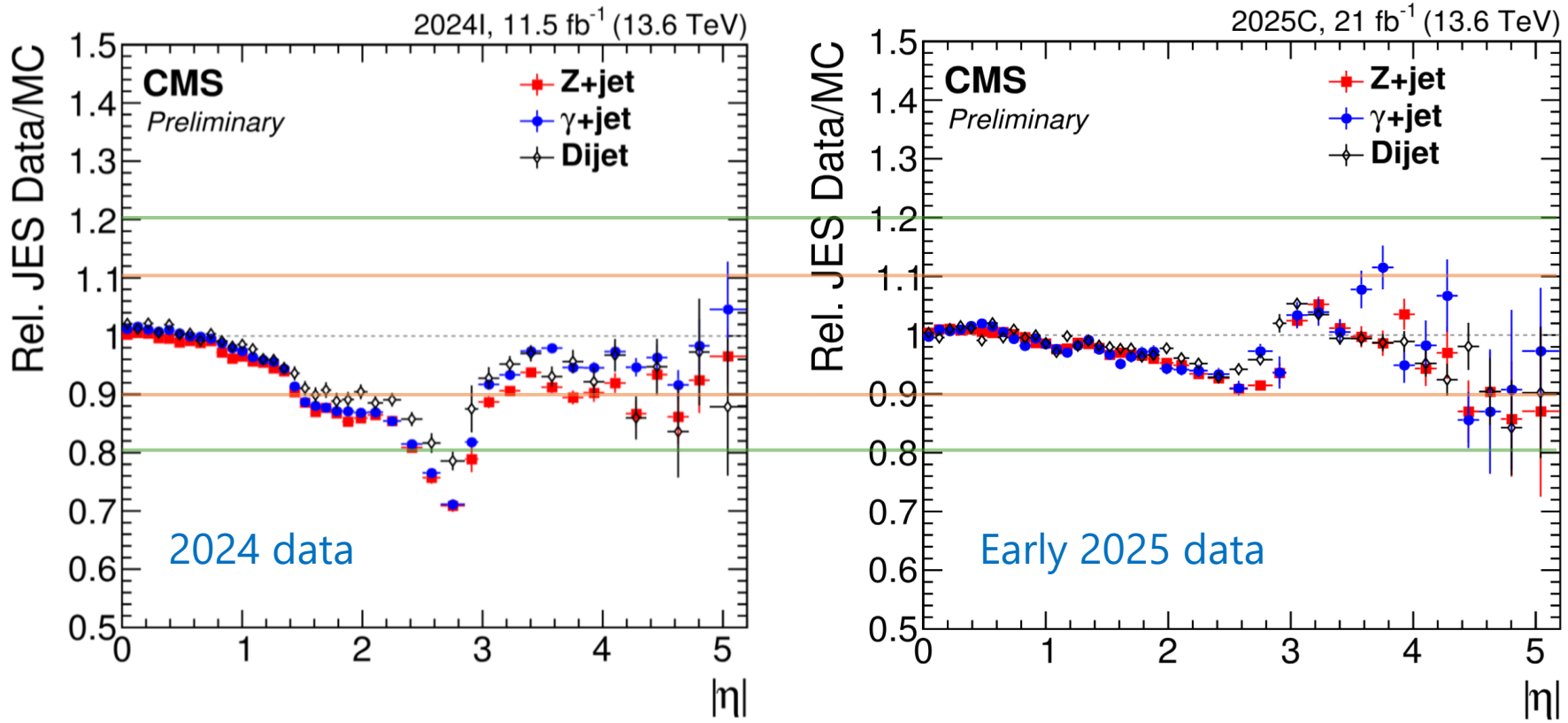
- *Precision physics*
- *Higgs boson physics*
- *top quark physics*
- *BSM searches*
- *Flavor physics*

Towards the HL-LHC

Run-3 performance

Jet reconstruction performance

❖ Reduced jet energy scale variations in early 2025 data



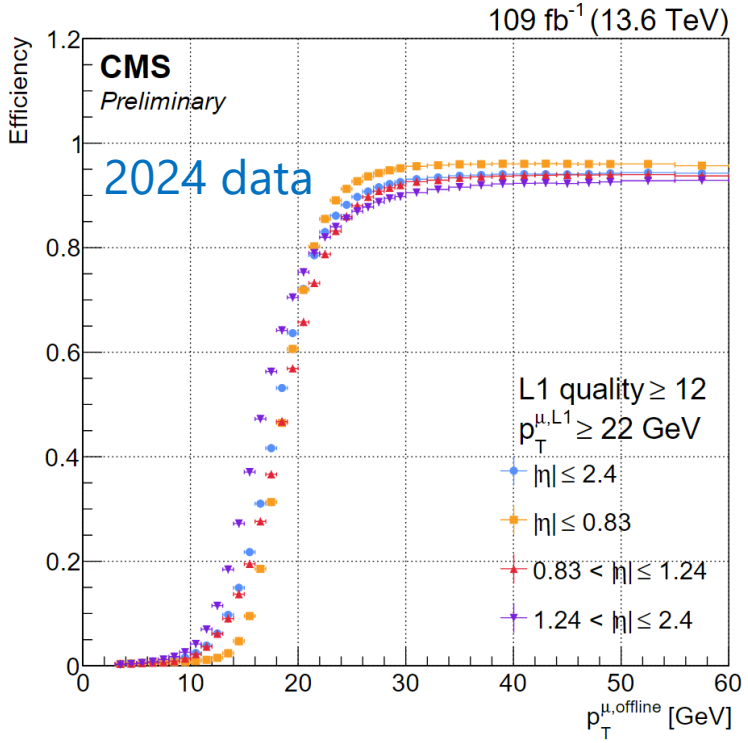
Run-3 performance

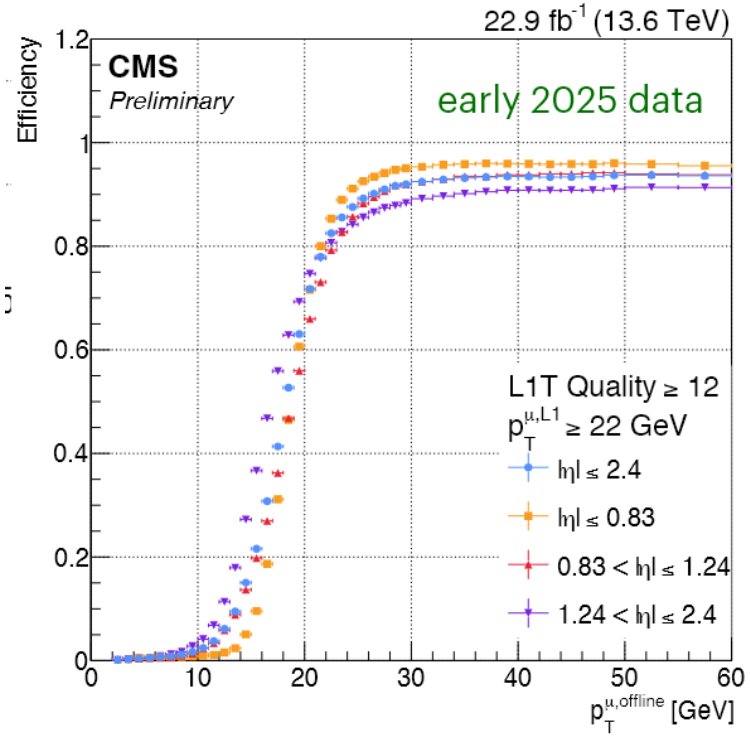
Jet reconstruction performance

- Reduced jet energy scale variations in early 2025 data

Muon trigger performance

- Similar L1 muon efficiencies in 2024 data as in early 2025 data





Run-3 performance

Jet reconstruction performance

- Reduced jet energy scale variations in early 2025 data

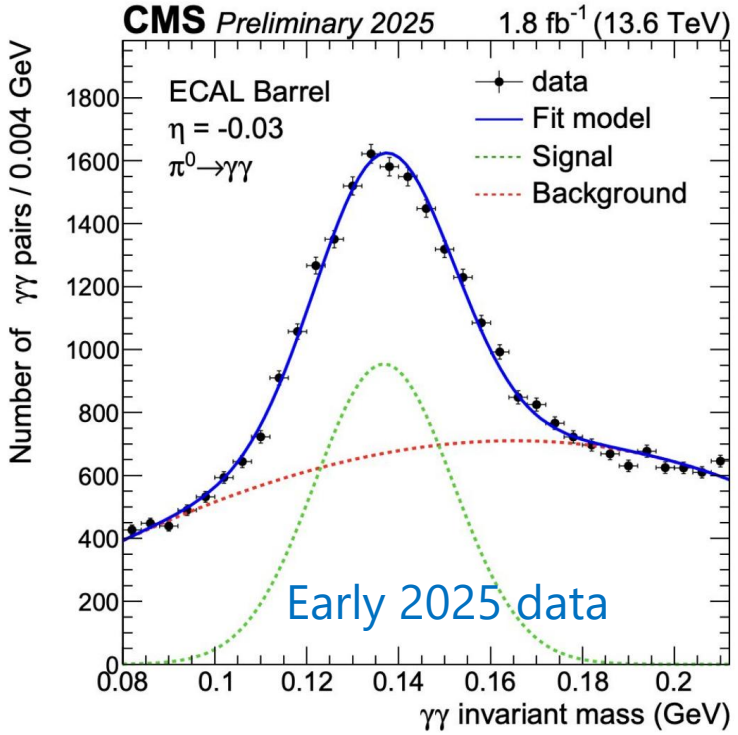
Muon trigger performance

- Similar L1 muon efficiencies in 2024 data as in early 2025 data

ECAL performance

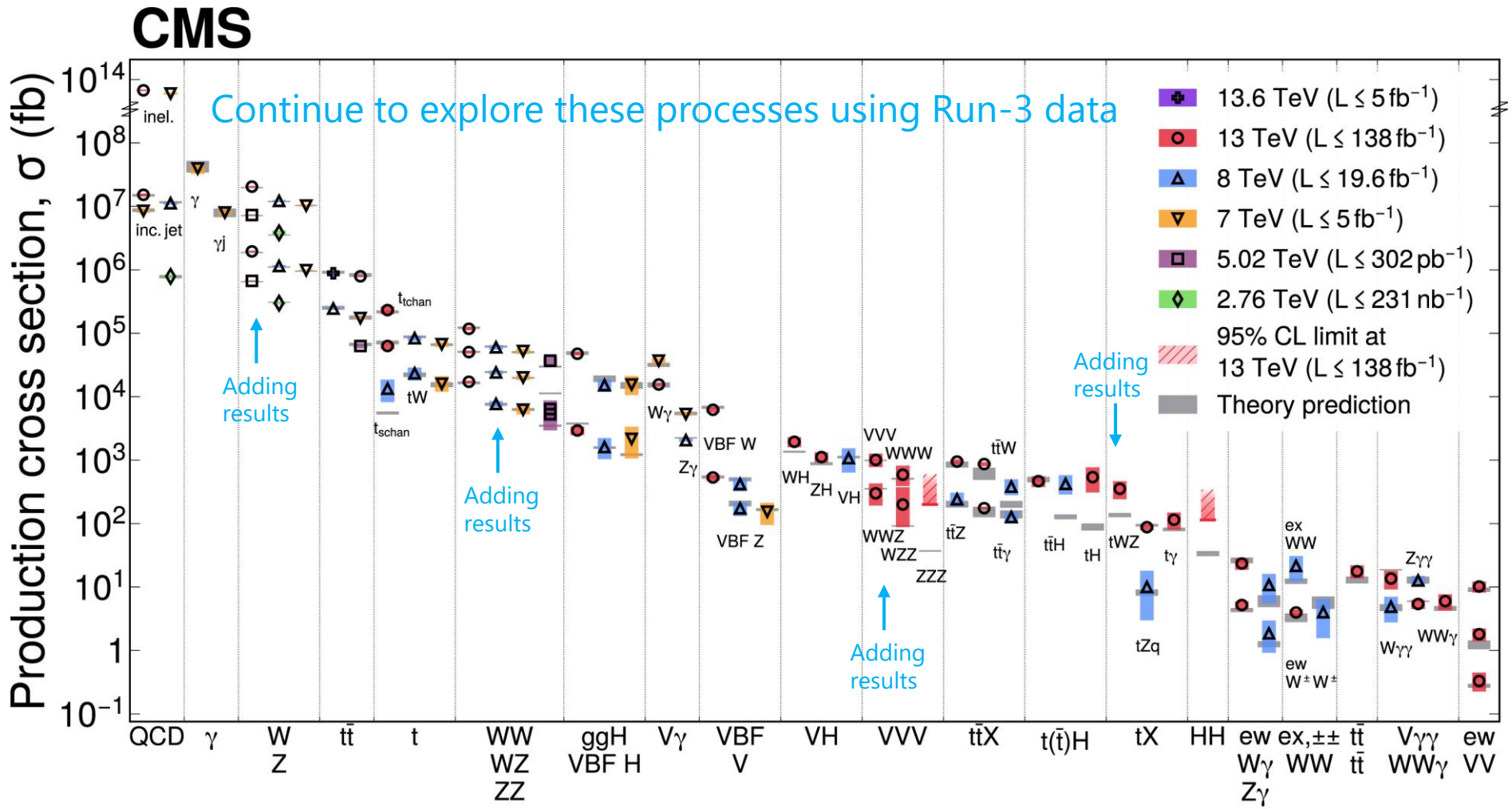
- π^0 reconstructed peak as prompt feedback to monitor the laser calibrations
- More in T. Cao's talk

π^0 reconstructed peak



Precision physics: from millibarns to femtobarns

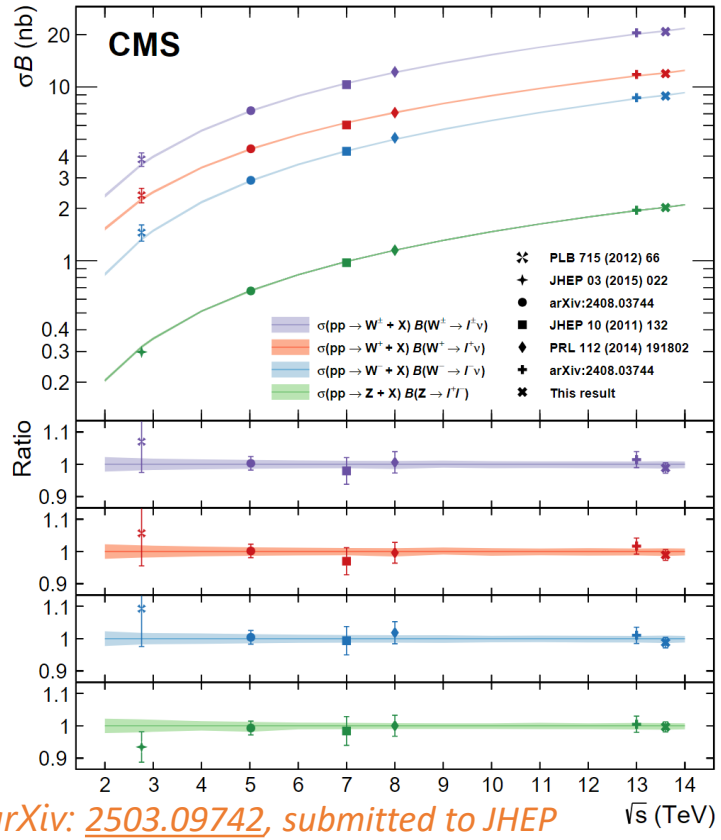
Cross-Section measurements of selected processes as of May 2024 *Phys. Rept. 1115 (2025) 3*



From millibarns to femtobarns

W and Z cross-section with Run-3 data

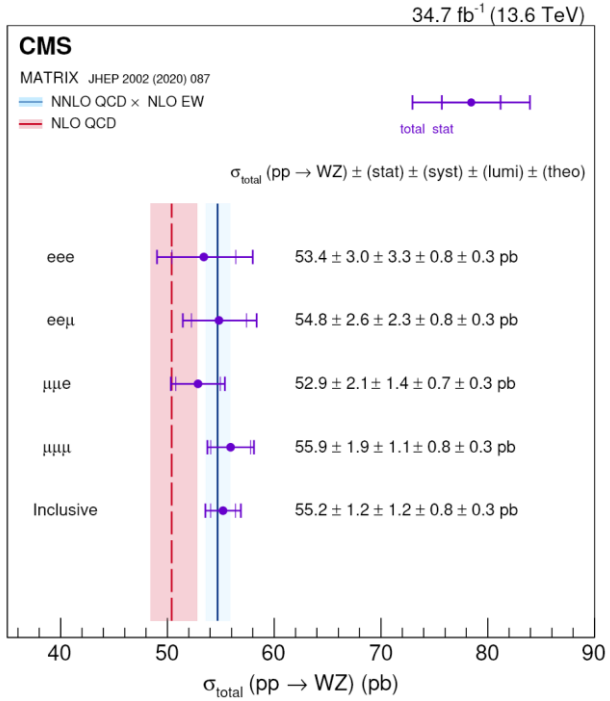
- Precision of the cross-section results exceeds that of previous measurements
- Refinement of PDF's description

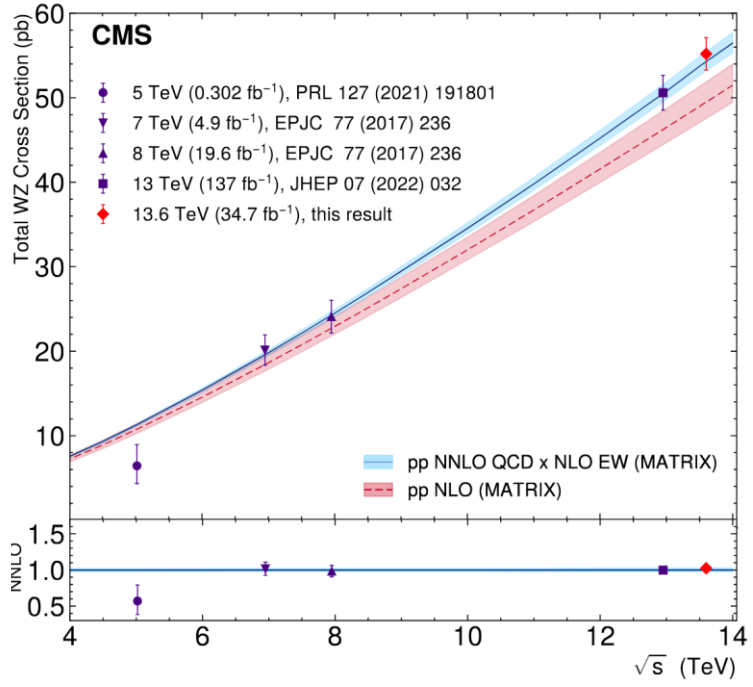


arXiv: 2503.09742, submitted to JHEP

WZ cross-section with Run-3 data

- Using improved lepton identification in Run-3
- In good agreement with the SM predictions @ NNLO QCD × NLO EW





JHEP 04 (2025) 115

WWZ and ZH cross-sections

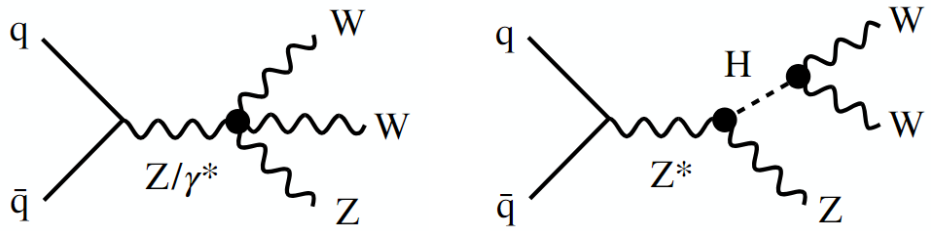
arXiv: 2505.20483, submitted to PRL

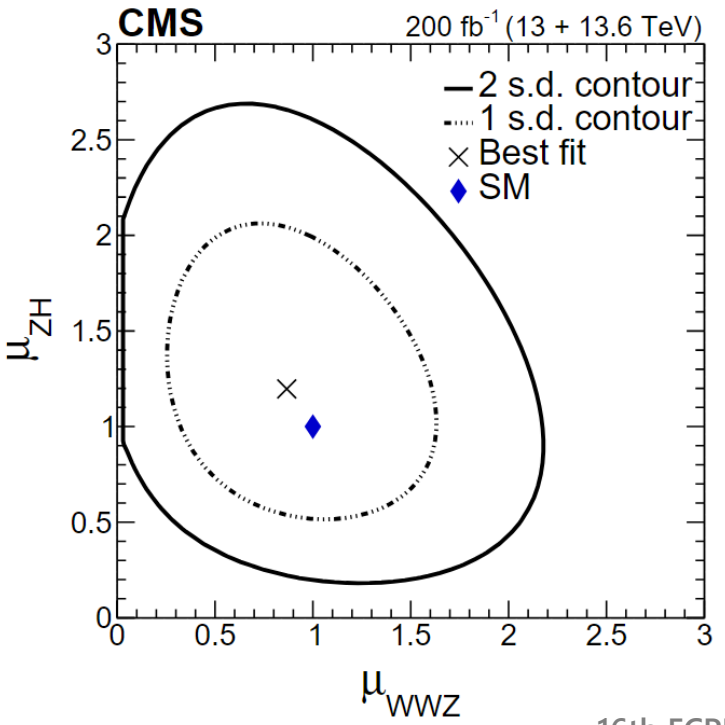
Based on full Run-2 data and Run-3 data

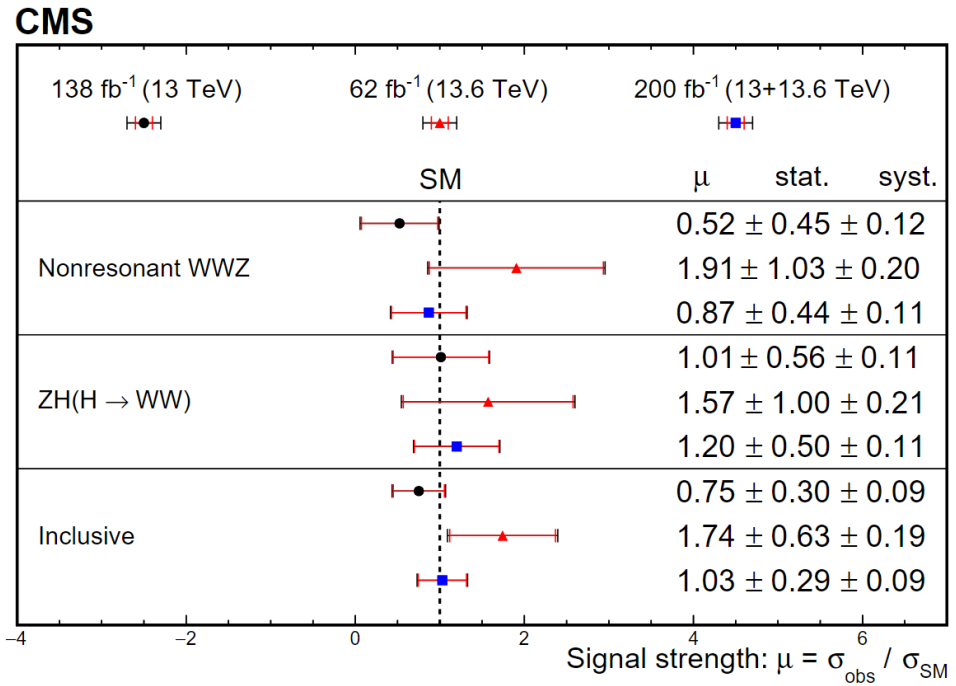
- Corresponding to an integrated luminosity of 200 fb^{-1}

Separate and simultaneous measurement of WWZ and ZH

- Observed (expected) significance of 4.5 (5.0) σ for WWZ+ZH
- Evidence for triboson production at 13.6 TeV

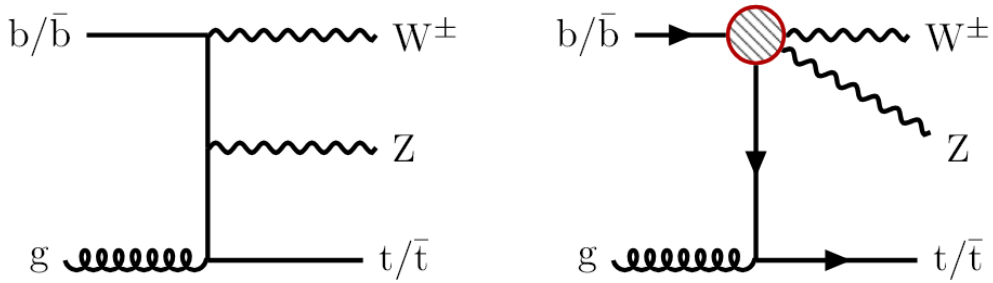






Observation of tWZ

TOP-24-009

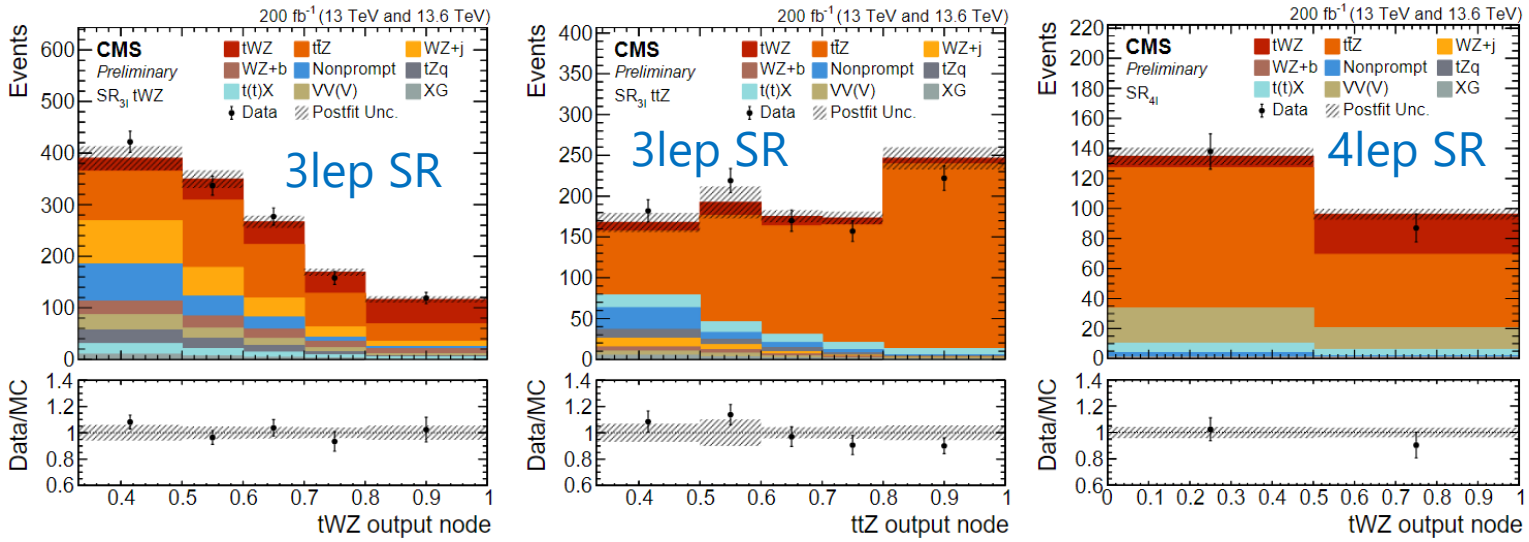


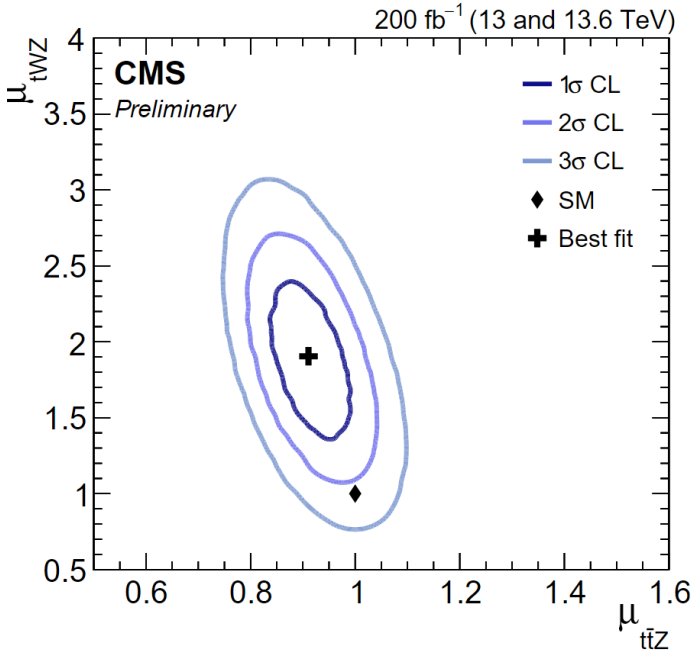
Based on full Run-2 data and Run-3 data

- Corresponding to an integrated luminosity of 200 fb^{-1}

Improved ML algorithms and reconstruction

- Measured **cross-section of tWZ**: **248±52 fb** and **244±74 fb** for **13** and **13.6 TeV**
- Observed (expected) significance of **5.8 (3.5)σ**





Higgs Sector

HIG-21-018

Combination of 16 CMS published analyses

- 7 decay channel: γγ, ZZ, WW, bb, ττ, μμ, Zγ
- 6 production channels: ggH, VBF, WH, ZH, ttH, tH
- Searches for H to invisible
- H off-shell production in the H→ZZ→4ℓ decay channel

Ultimate Precision at 13 TeV

- Signal strength inclusive

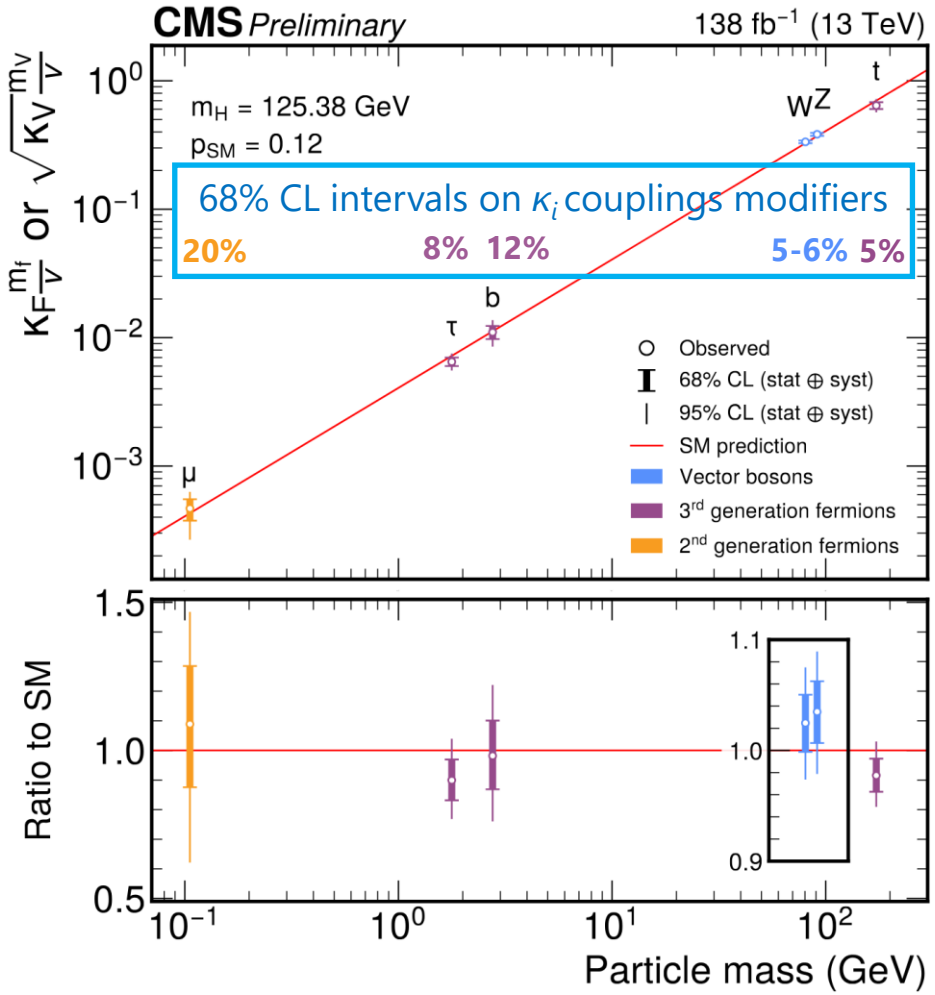
$$\sigma/\sigma_{SM} = 1.014^{+0.055}_{-0.053}(\text{total})$$

5.4%

$$= 1.014 \pm 0.028\,(\text{stat.})^{+0.025}_{-0.024}(\text{exp.})^{+0.040}_{-0.039}(\text{theo.})$$

2.7% 2.5% 3.9%

- Constraints on coupling modifiers



Probing Higgs-charm coupling via ttH

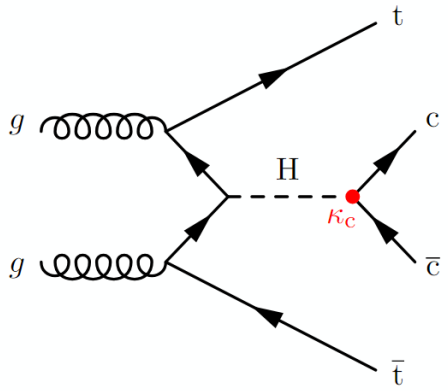
HIG-24-018

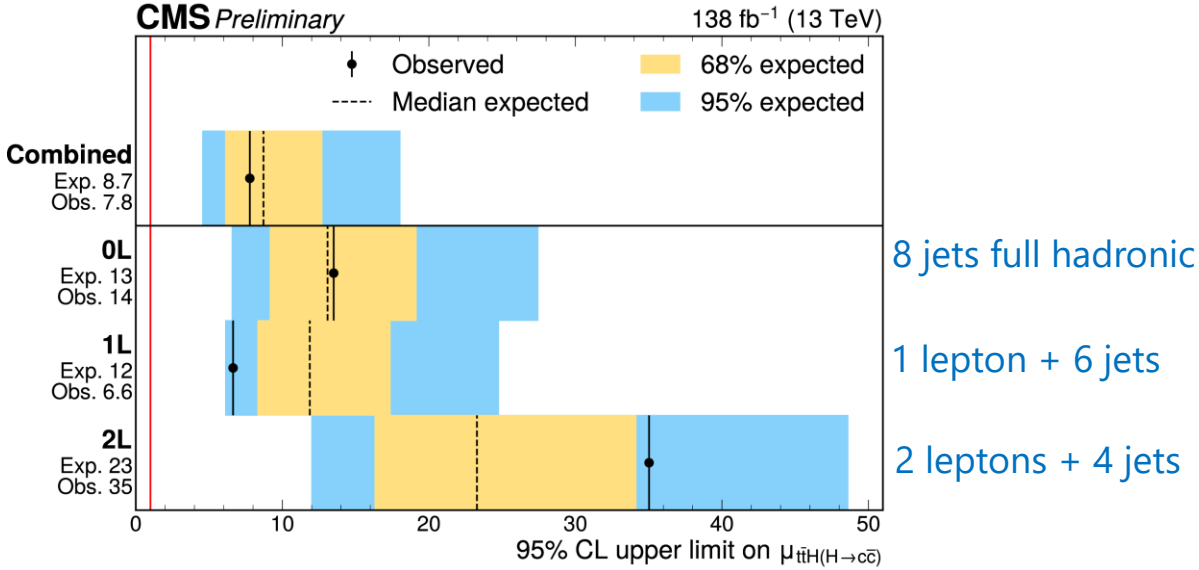
First search in ttH production channel

- With full Run-2 data, 138 fb^{-1}

Graph convolutional NN for simultaneous ID of b- and c-jets (PNet)

Multiclass event classifier-based (ParT)

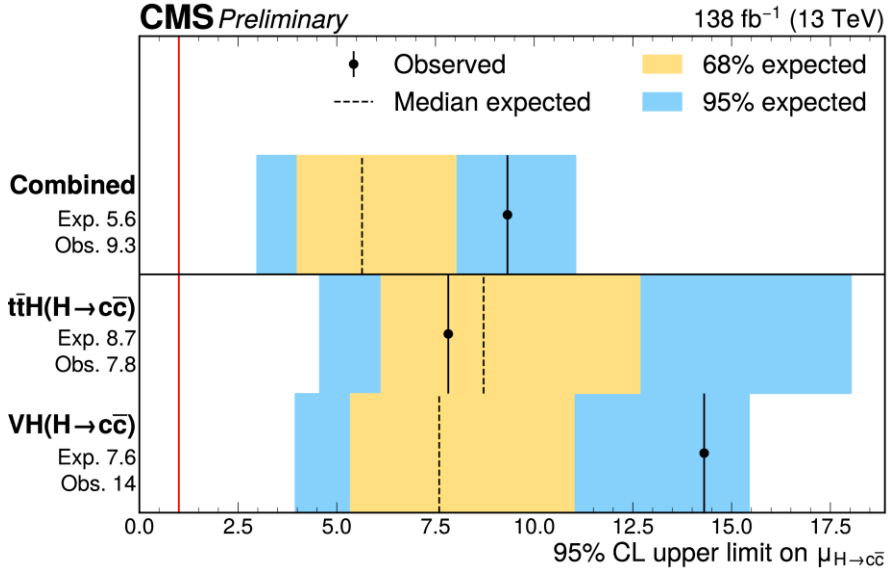




8 jets full hadronic

1 lepton + 6 jets

2 leptons + 4 jets



First ttH search
HIG-24-018

PRL 131 (2023) 061801

- Limits on $\mu_{ttH}(H\to cc)$: < 7.8 (8.7) x SM observed (expected)
- Competitive sensitivity compared to VH(cc) measurements

- In combination with VH most stringent constraint to date
- Limits on $\mu_{ttH}(H\to cc)$: < 3.5 (2.7) x SM observed (expected)

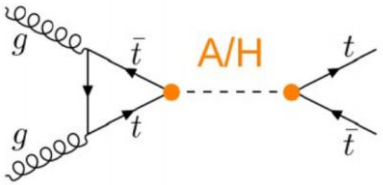
Top quark-antiquark excess

arXiv: 2503.22382, submitted to ROPP

In the search for H/A resonances into $t\bar{t}$ observed an excess of data at threshold

Measured cross section of a quasi-bound state η_t: $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb

Result well compatible with Non-Relativistic QCD (NRQCD) prediction: $\sigma(\eta_t) = 6.4$ pb

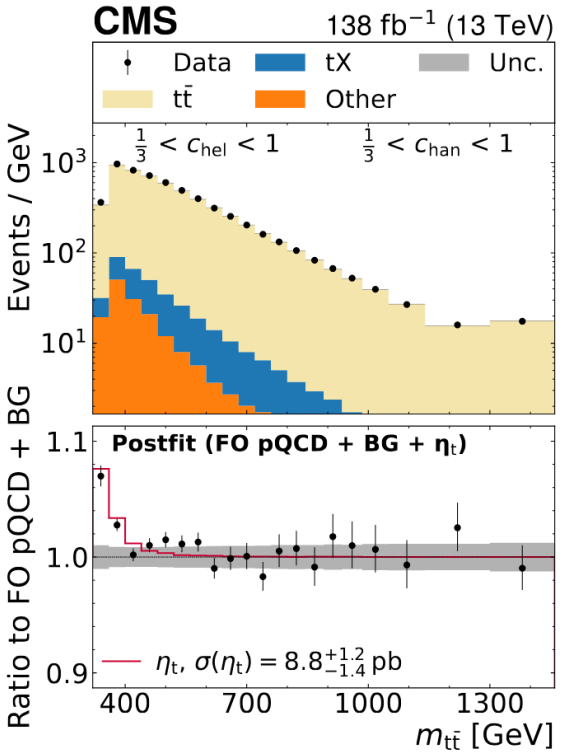


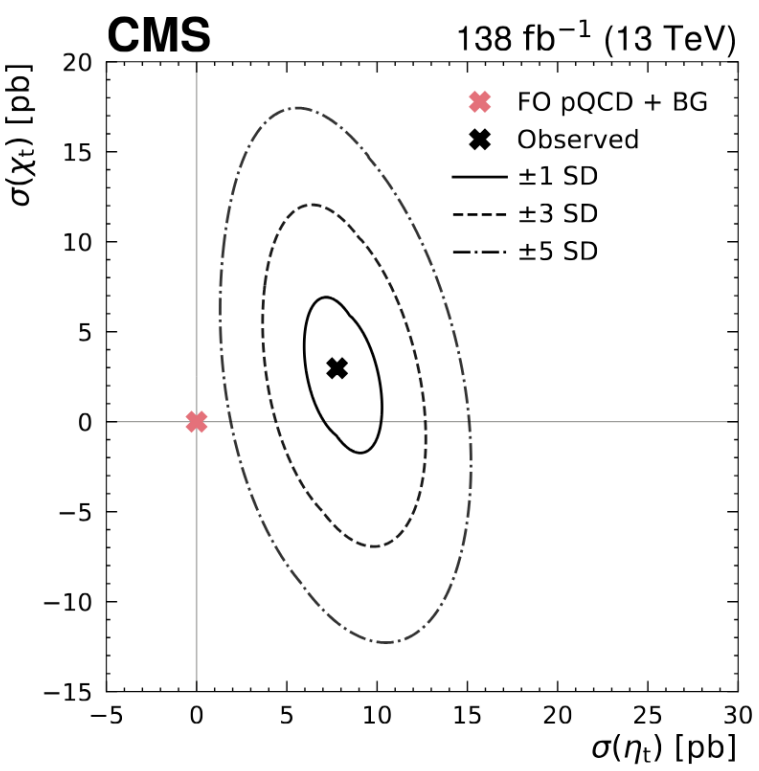
Approximating $t\bar{t}$ Quasi-Bound States with simplified η_t model prediction JHEP 03 (2024)

- Generic color-singlet, CP-odd, spin-0 particle
- Direct couplings to gluons and tops
- Mass/width from fit to NRQCD

3 search variables: m_{tt} x c_{hel} x c_{han}

- distinguish $^1S_0(A/\eta_t)$ from $^3P_0(H)$ tt spin state
  - c_{hel}: scalar product of leptons in parent top rest frame
  - c_{han}: scalar product of leptons with sign flip in top direction



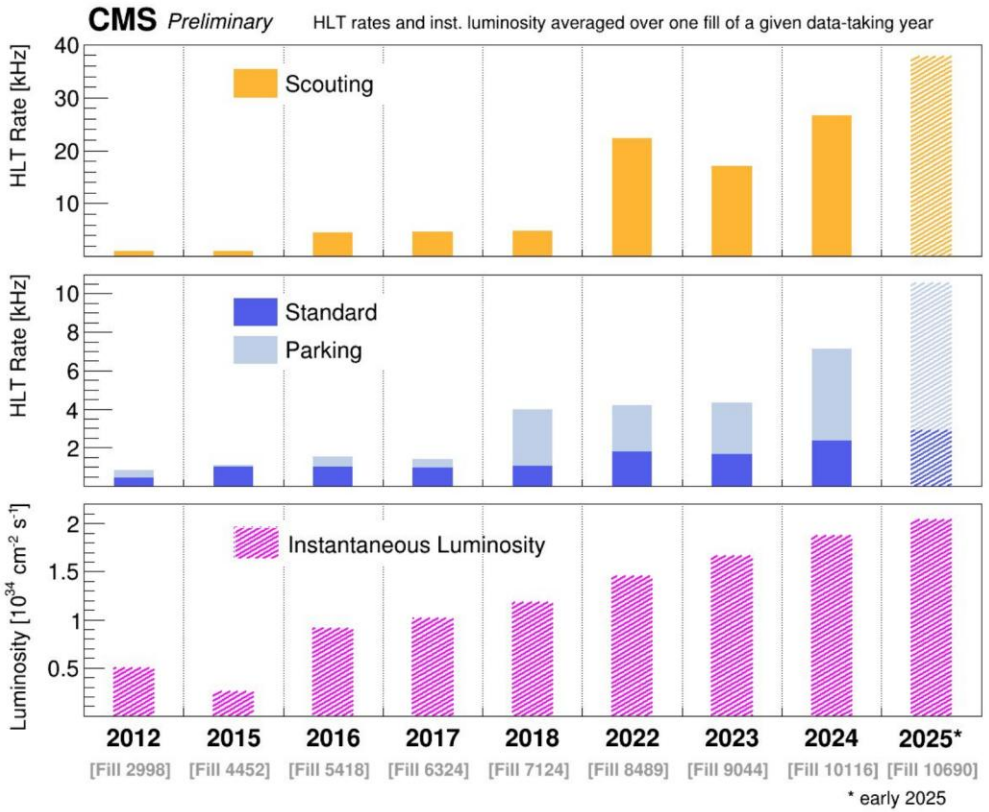


Multiple data-taking strategies in CMS

CMS-DP-2025-034

Standard, **Parking** and **Scouting** pushing CMS trigger coverage far beyond Phase-1 design values

- **Standard** streams are reconstructed offline within ~48 hours
- **Parking** streams are typically reconstructed when computing resources are available
- **Scouting** stream is taken at a higher rate with reduced event content and limited or no offline processing



Parking is now integral to the core physics program (Higgs, searches), and opens large phase space for flavor physics

HLT **scouting** runs at ~30kHz (1/3 of accepted L1T events)

- Using HLT objects for physics analyses in an even wider phase space

Low mass searches

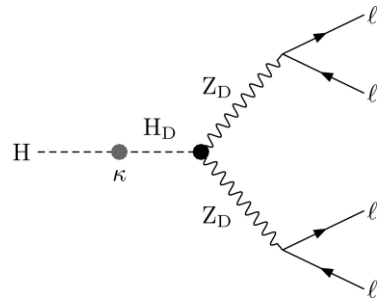
Going beyond the designed trigger constraints with the **scouting dataset**

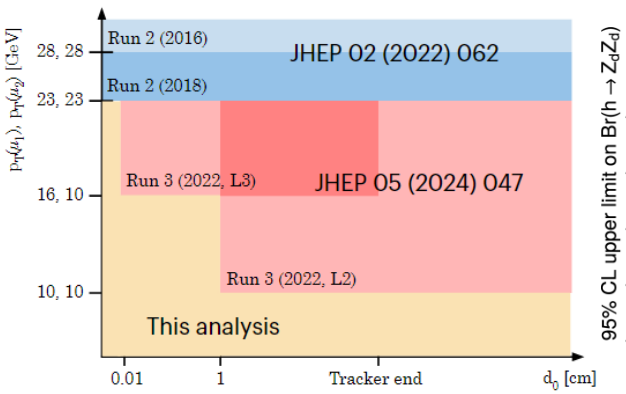
- Record reduced information at high rates, opening otherwise inaccessible low-mass phase space

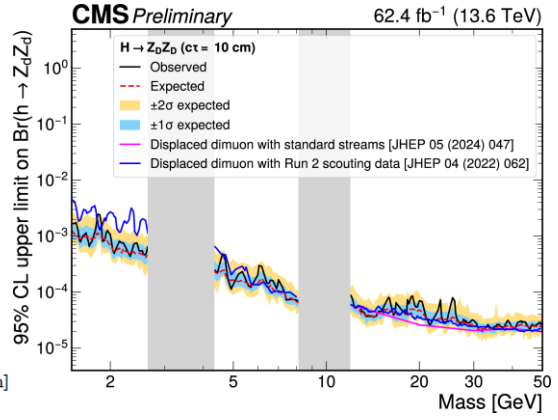
μμ resonances

- H decays to long lived dark particles with muons in the final state
- Low multimuon mass and nonzero displacement from the primary interaction vertex

EXO-24-016







Low mass searches

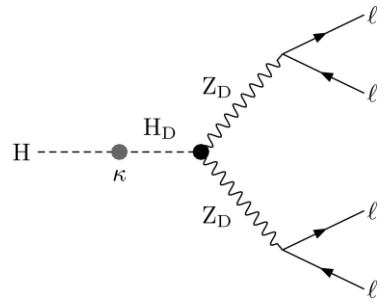
Going beyond the designed trigger constraints with the **scouting dataset**

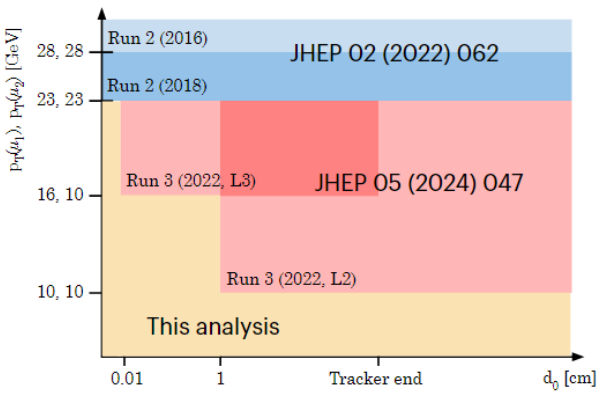
- Record reduced information at high rates, opening otherwise inaccessible low-mass phase space

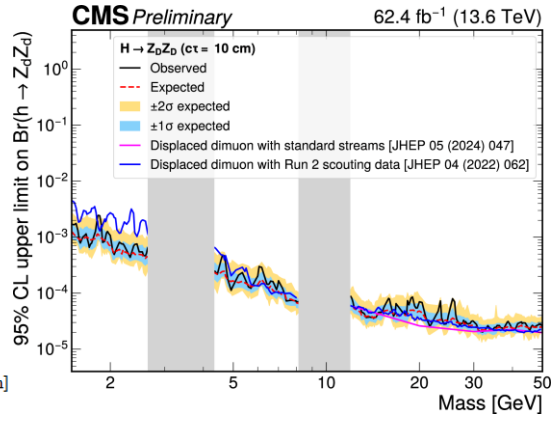
μμ resonances

EXO-24-016

- H decays to long lived dark particles with muons in the final state
- Low multimuon mass and nonzero displacement from the primary interaction vertex



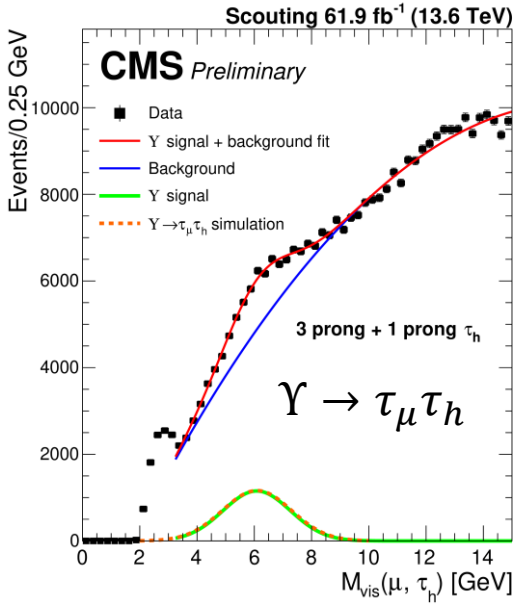


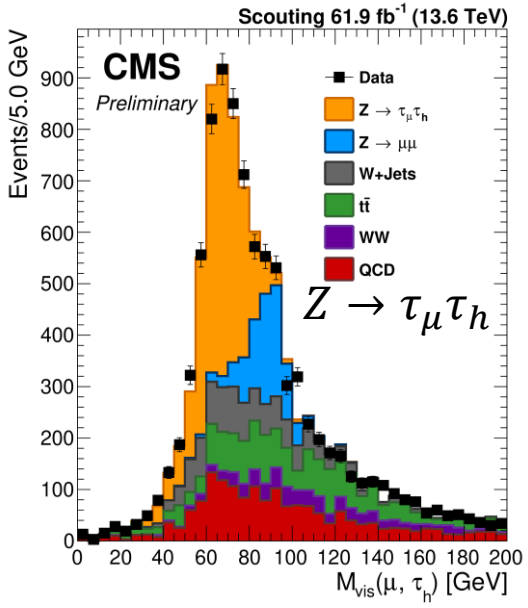


ττ resonances

EXO-24-012

- Inclusive search for a low-mass resonance Φ decaying to two τ leptons
- Resonance Υ simulation and SM candle Z are used to model continuum fit background and Z background





Low mass searches

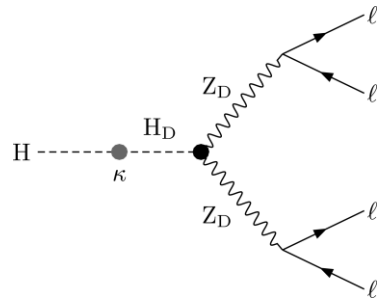
Going beyond the designed trigger constraints with the **scouting dataset**

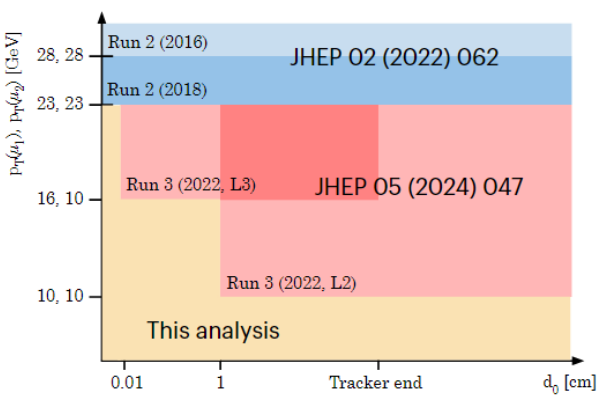
- Record reduced information at high rates, opening otherwise inaccessible low-mass phase space

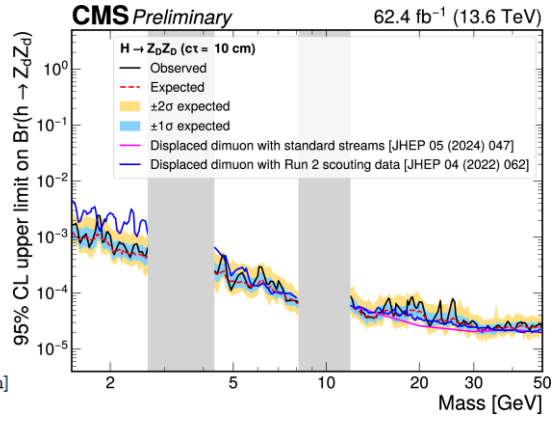
μμ resonances

EXO-24-016

- H decays to long lived dark particles with muons in the final state
- Low multimuon mass and nonzero displacement from the primary interaction vertex



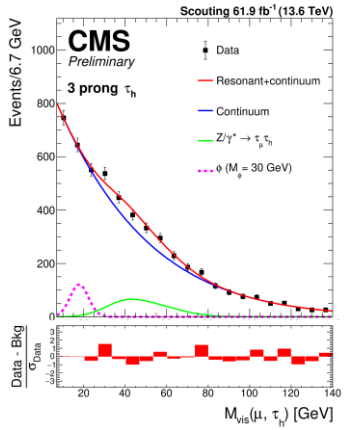


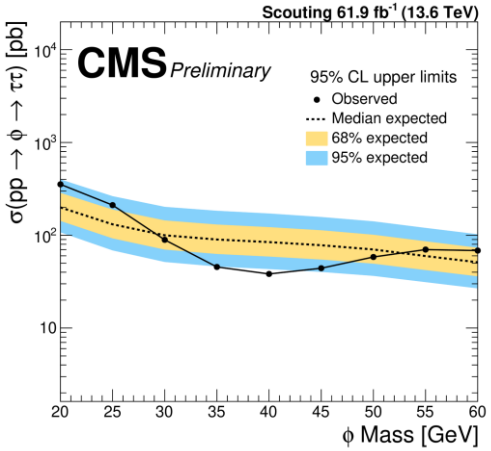


ττ resonances

EXO-24-012

- Inclusive search for a low-mass resonance ϕ decaying to two τ leptons
- Resonance Y simulation and SM candle Z are used to model continuum fit background and Z background





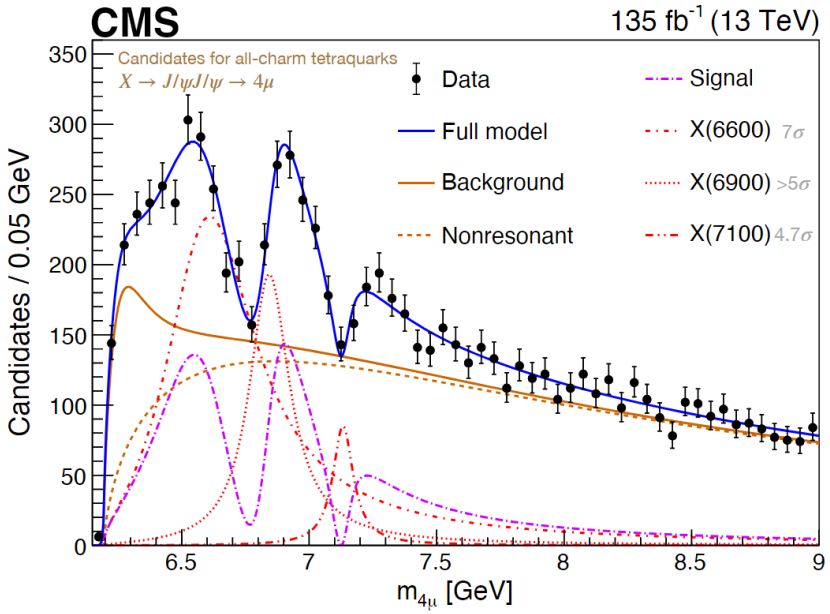
- For the first time, a scalar **ϕ boson with masses <60 GeV** in ττ decay channel have been explored at hadron colliders

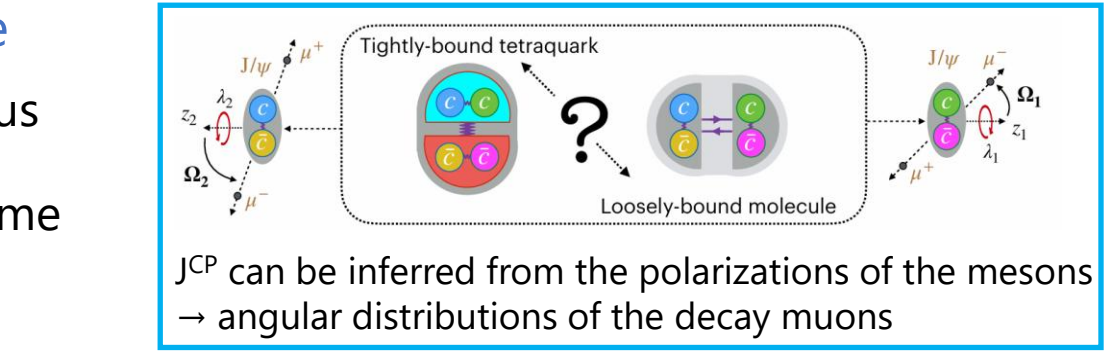
Determination of J^{CP} all-charm tetraquarks

arXiv:2506.07944, submitted to Nature

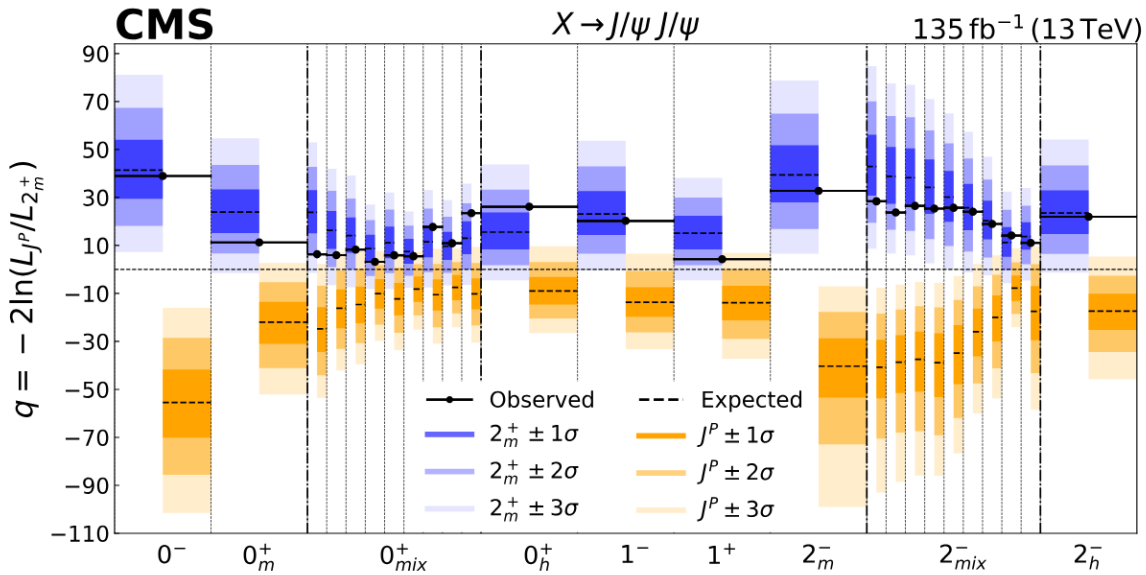
Observation of 3 X states in the $J/\psi J/\psi$ final state

- Mass spacings following a radial Regge trajectory plus interference pattern
  → the 3 particles form a family of cccc states with same quantum numbers





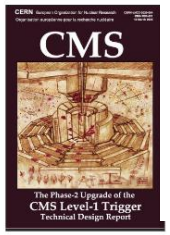
J^{CP} can be inferred from the polarizations of the mesons
→ angular distributions of the decay muons



CP = ++ established

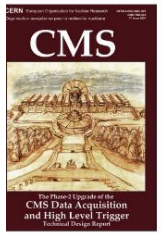
- Data consistent with 2^+_m (bound tetraquark) and inconsistent with others

CMS Upgrade Projects



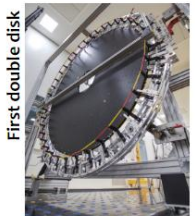
L1-Trigger

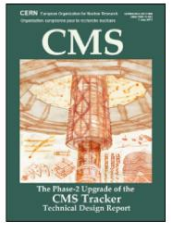
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

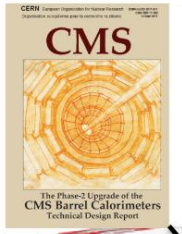
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output





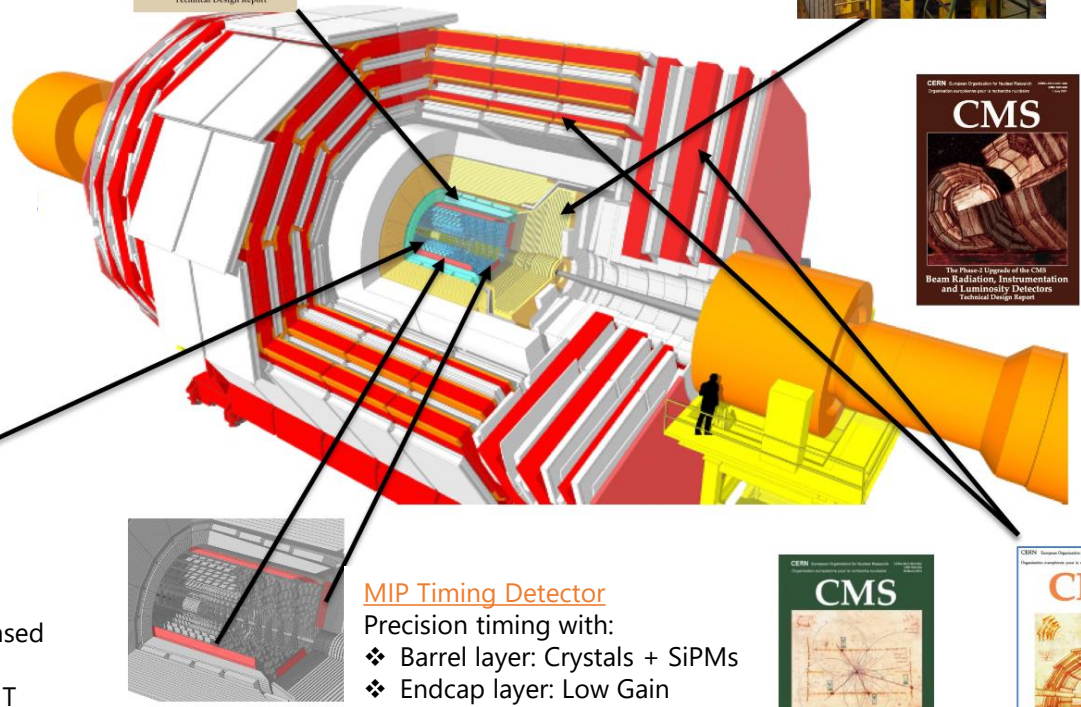
Tracker

- Si-Strip and Pixels increased granularity
- Design for tracking in L1T
- Extended coverage to 3 ≃ 3.8



Barrel Calorimeters

- ECAL crystal granularity readout at 40 MHz with precise timing for e/5 at 30 GeV
- ECAL and HCAL new Back-End boards



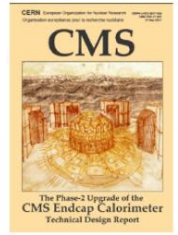
MIP Timing Detector

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

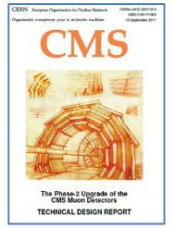
Calorimeter Endcap (HGCal)

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Beam Radiation Instr. and Luminosity

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch lumi: 1% offline, 2% online
- Neutron and mixed-field radiation monitors



Muon systems

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < 3 < 2.4 Extended coverage to 3 ≃ 3

All projects on tracks!

- Majority of ingredients in production, several finished, several procurements to finish

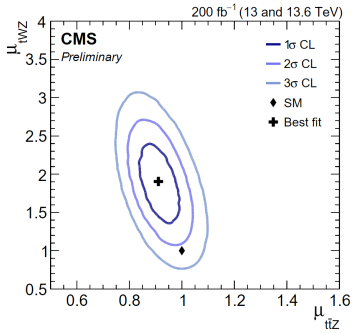
Summary

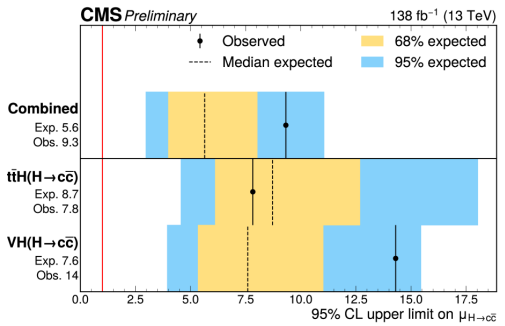
CMS Run-3 data-taking continues

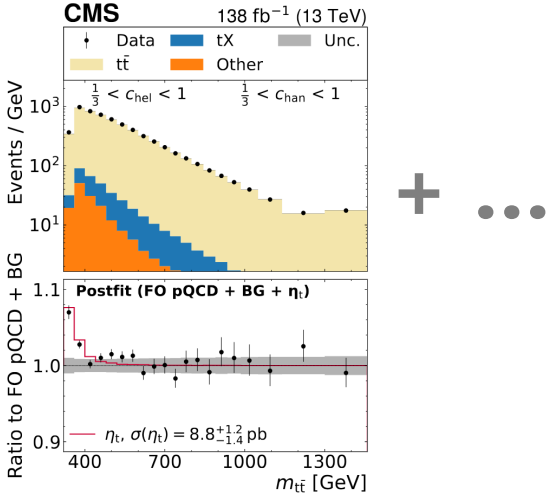
- Object performance improved in most cases

Many new analyses with Run-2 and Run-3 data

- Only cover part of the analyses, e.g.,
  - Observation of tWZ
  - Probing Higgs-charm coupling
  - Top quark-antiquark excess







+ ...

- Zγ with 2022 in T. Mu's talk
- Very lowmass diphoton resonances (10-70 GeV) in B. Massoteau' talk

CMS upgrade towards HL-LHC is on-going