Recent Results from CMS

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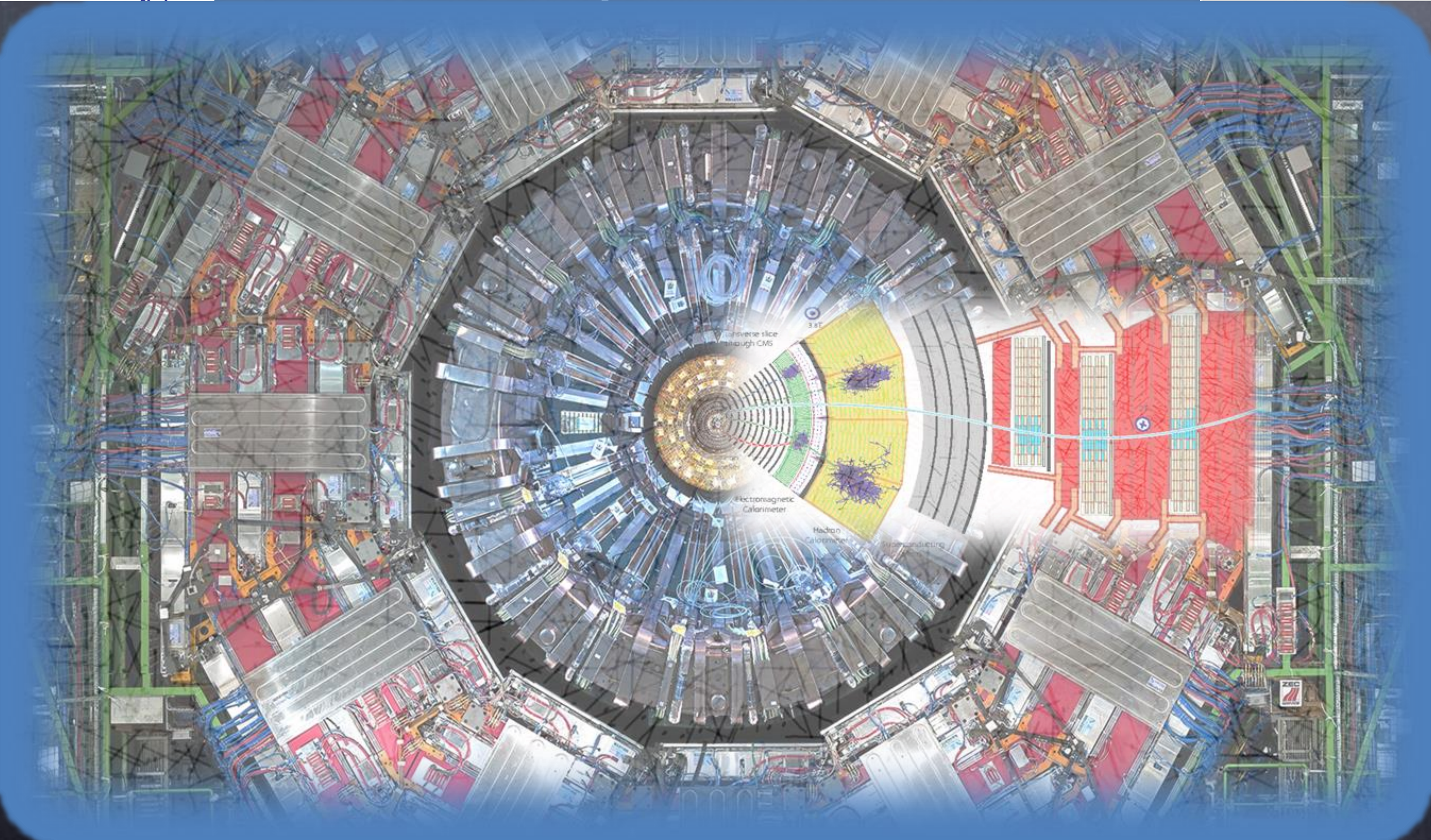
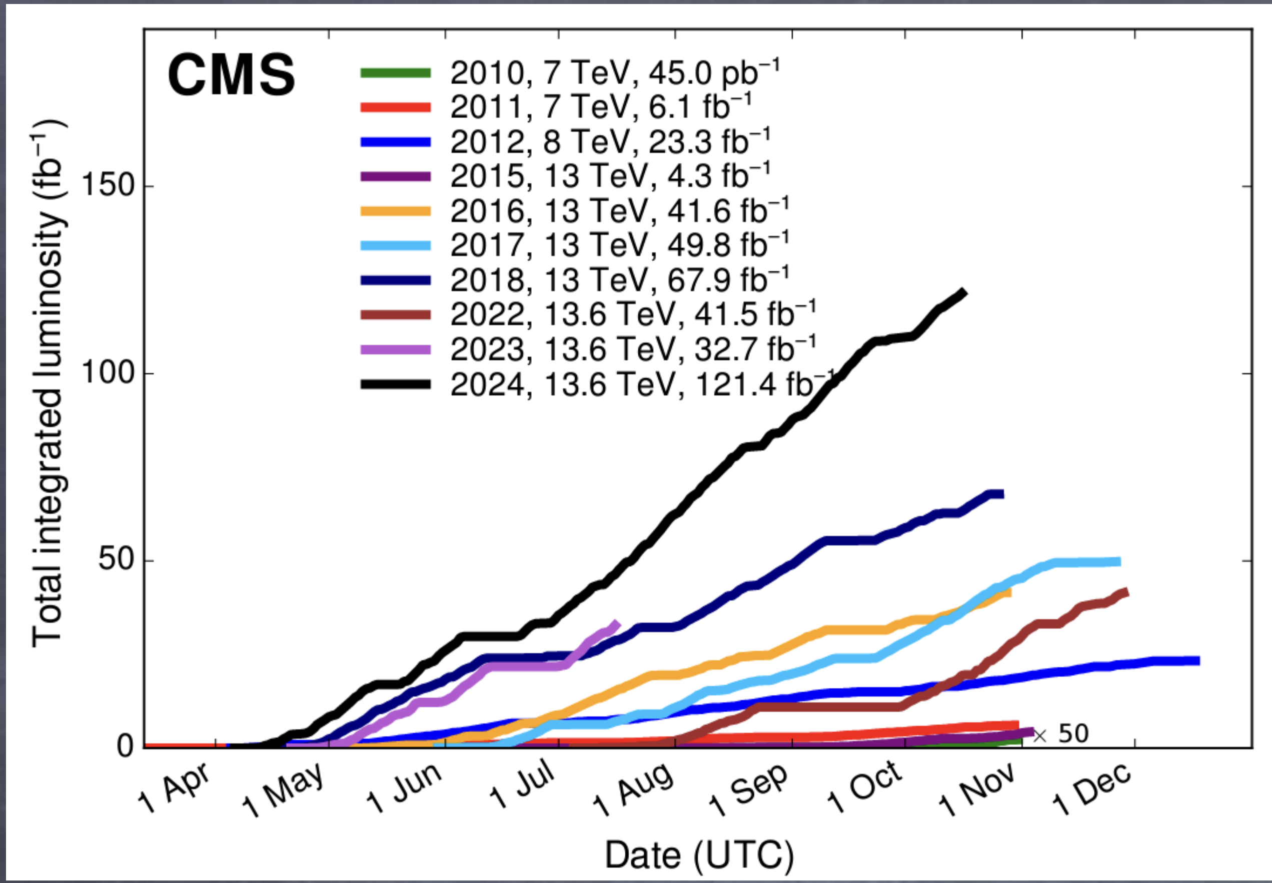
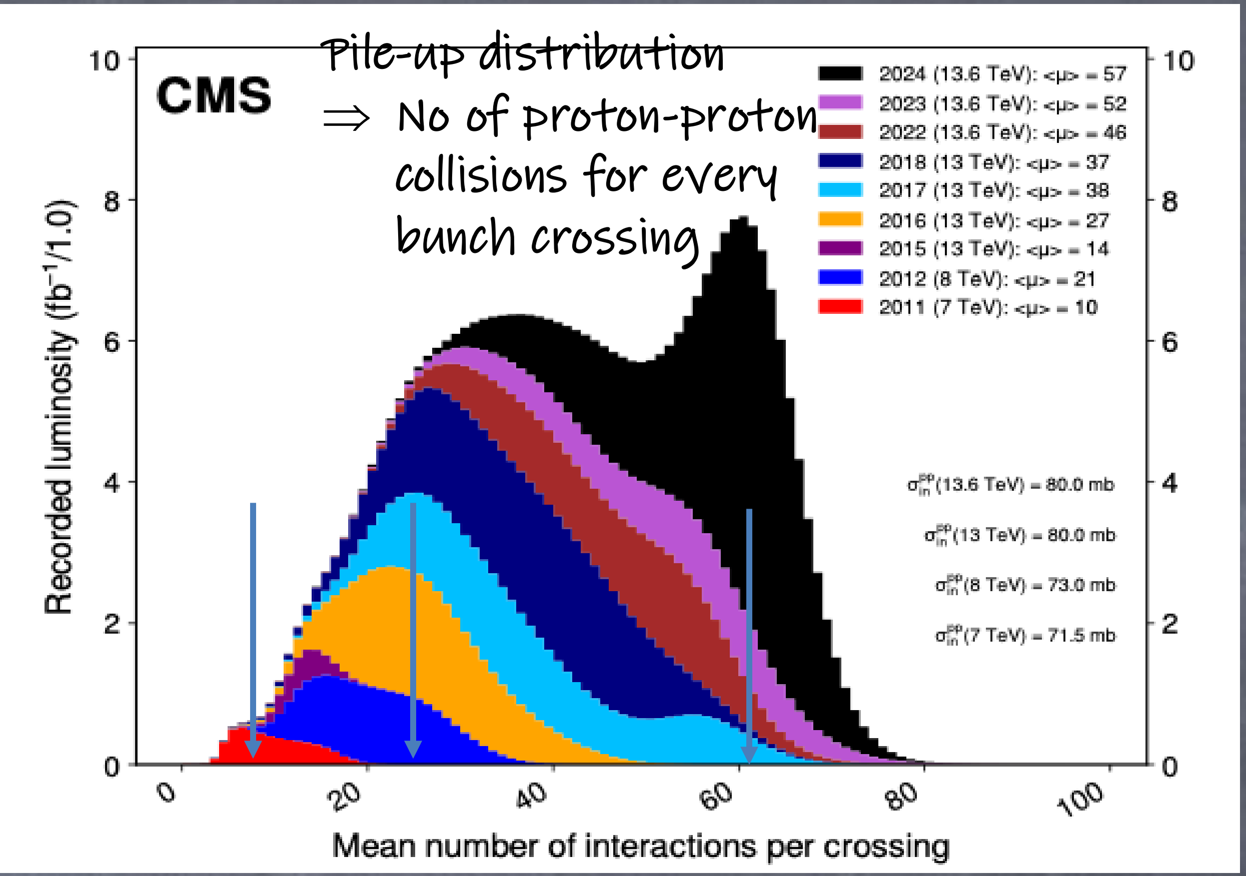
On behalf of the CMS Collaboration

(PPC 2024, IIT Hyderabad, Oct 14-18, 2024)

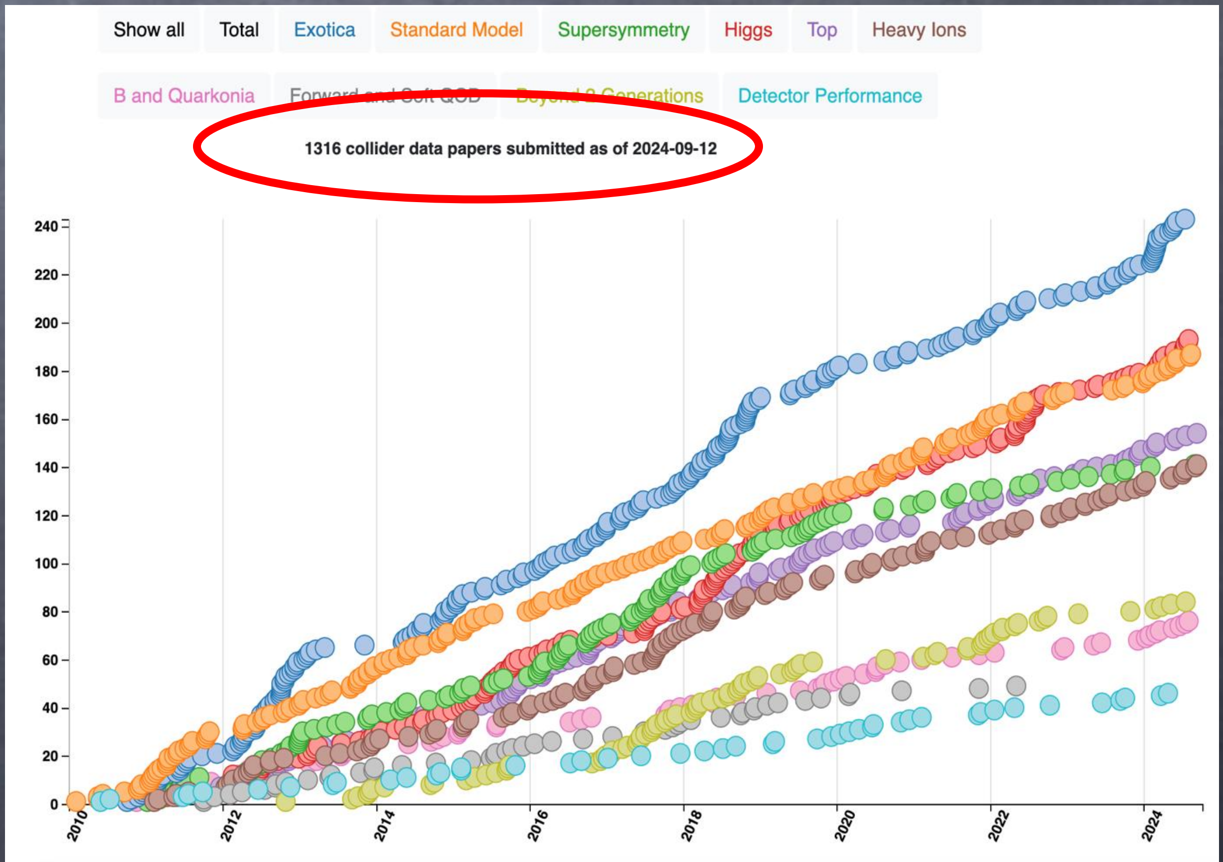


LHC and CMS performance





- ✓ The LHC has provided more than 390 fb^{-1} data out of which CMS recorded ~360 fb^{-1} (93%)
- ✓ We have now 13.6 TeV collision energy, however moving to higher luminosity leading to more pile up is an experimental issue. Will require detector upgrade (also to survive till ~4000fb^{-1})
- ✓ CMS produced more than 1400 papers (on physics data analysis, hardware, etc.)
- ✓ The following slides provide a few recent results (can not cover all) from CMS collaboration.



W mass measurement with the CMS data

- The precision measurement of W mass very important for SM internal consistency.

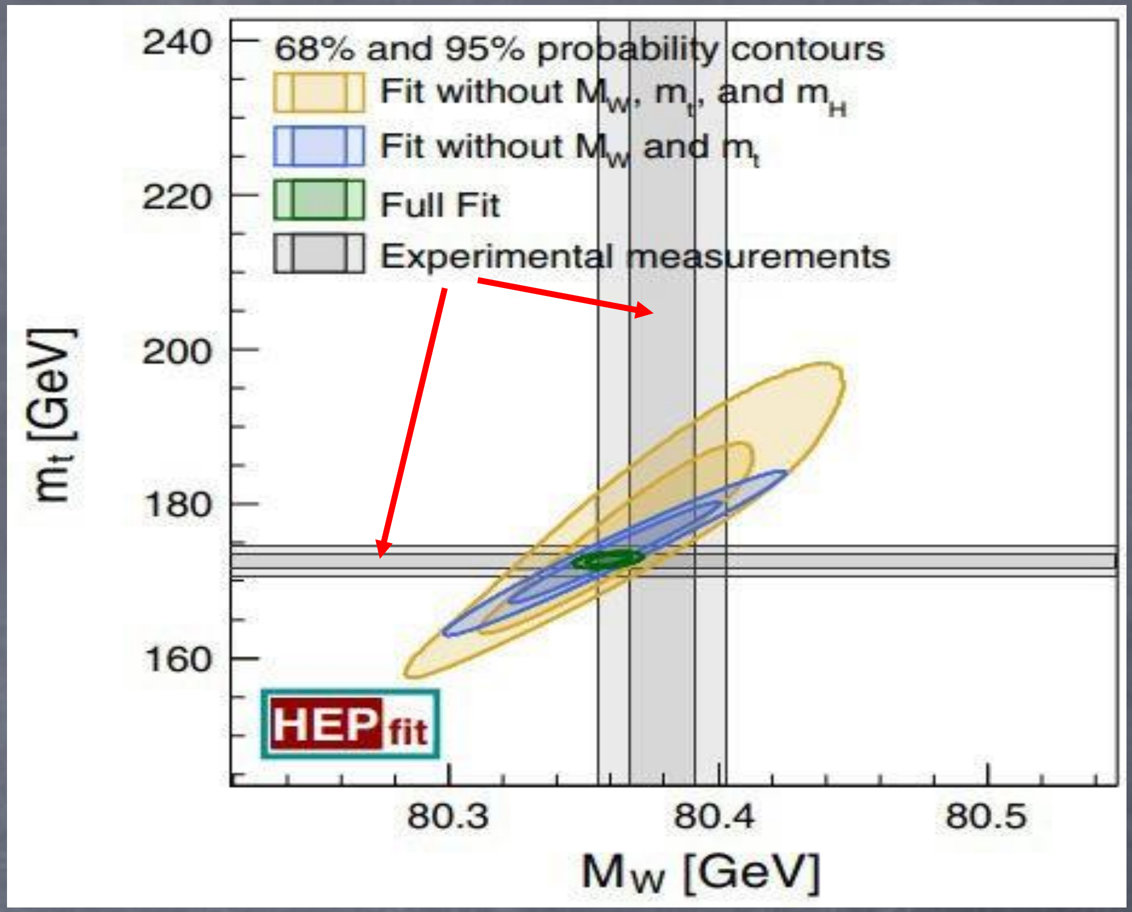
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{1-\Delta r}$$

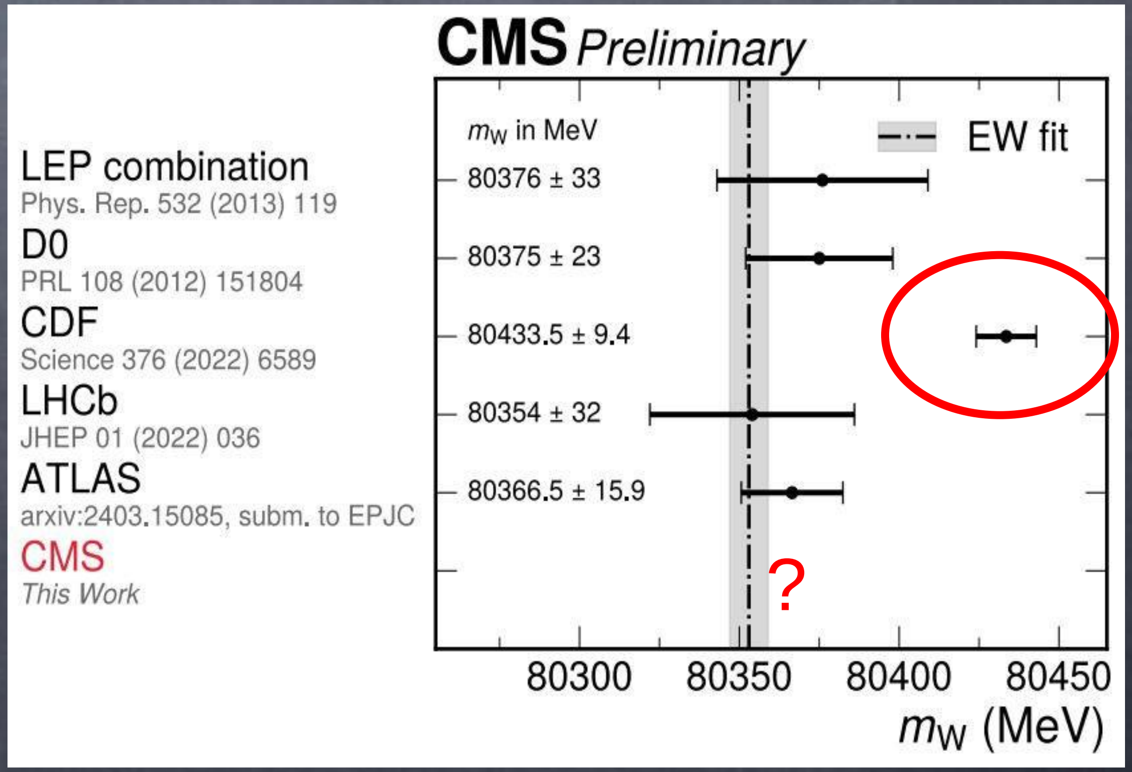
- The EW global fit results in the W-mass to be 80353 ± 6 MeV, more precise than the direct experimental measurement

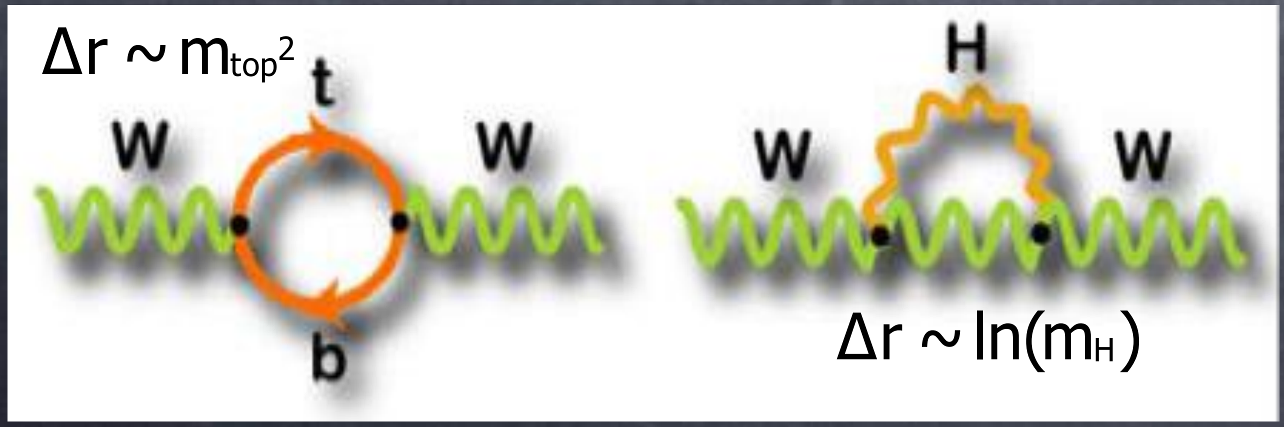
✓ The world average: 80369.2 ± 13.3 MeV

✓ In 2022 CDF measured the mass of W mass to be 80433.5 ± 9.4 MeV (~ 7σ discrepancy with SM prediction)

✓ Is there new physics? Possible BSM in the loop can change the W mass.



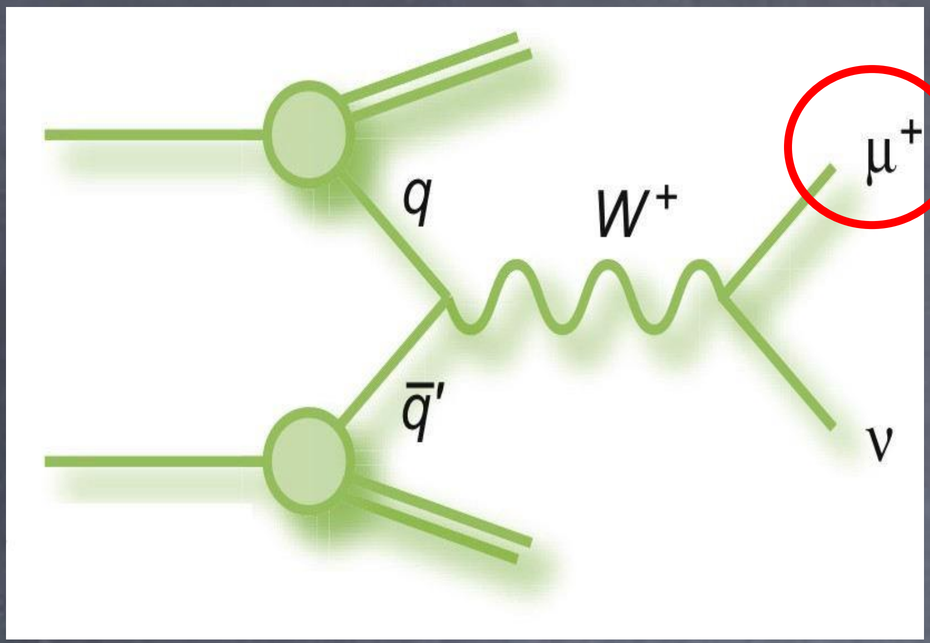


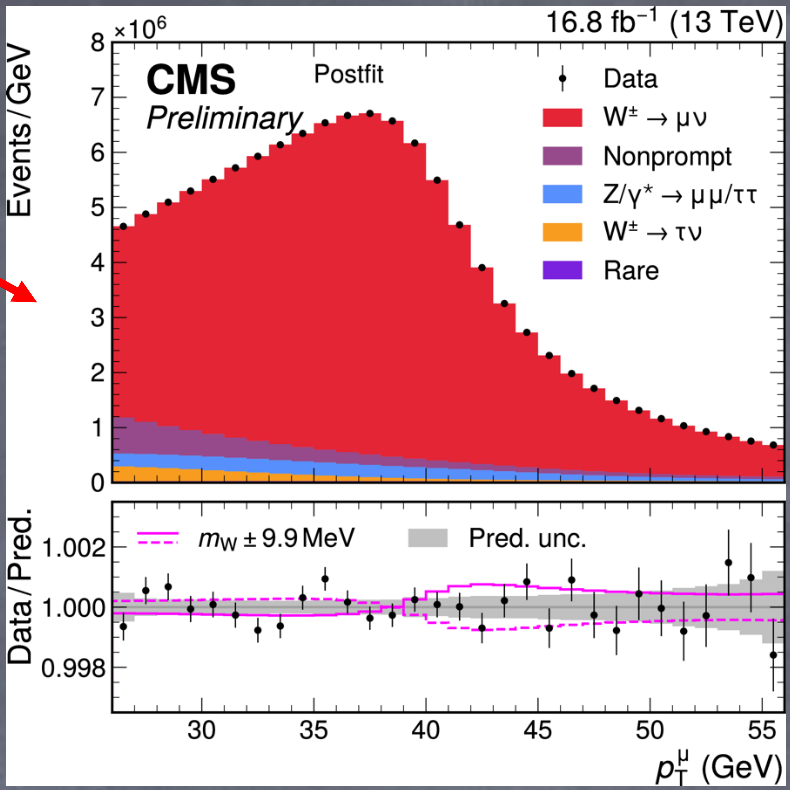


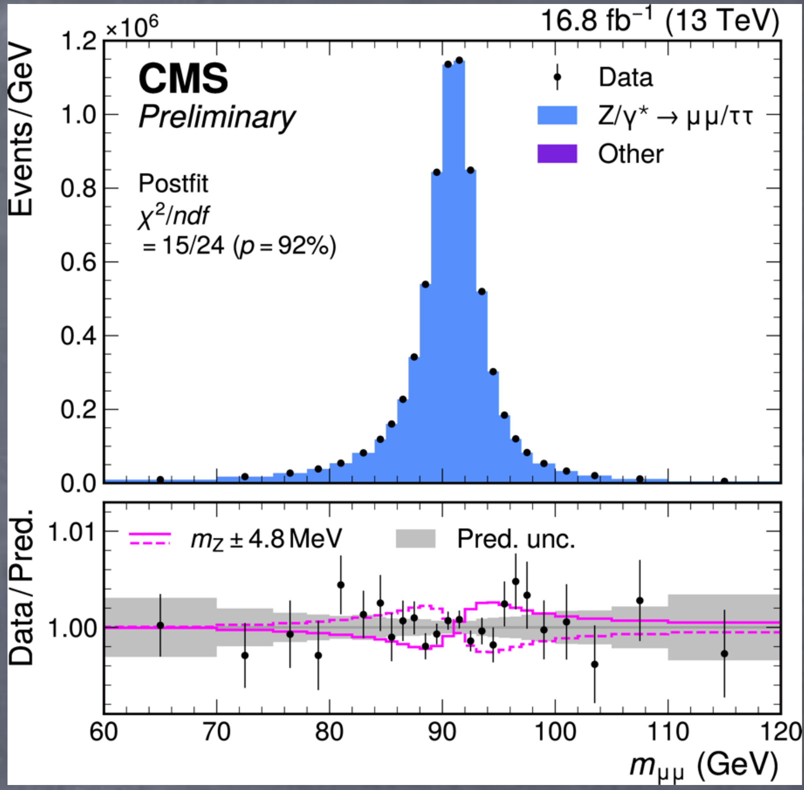
Strategy to measure W-mass in hadron machines

- ✓ The W mass measurement relies on the leptonic decays of W boson, $W^{\pm} \rightarrow l^{\pm}\nu$
- ✓ The CMS experiment uses muon decay channel of W as it provides better experimental precision
- ✓ Due to presence of neutrino, one can not fully reconstruct W boson, so the W-mass is measured indirectly using transverse P_T^l of muon (sensitive to m_W via Jacobian peak), or transverse mass $(m_T) = \sqrt{2p_T^{\ell}p_T^{\rm miss}(1-\cos\Delta\phi_{\ell\nu})}$, where $\Delta\phi$ is the azimuthal angle between lepton and the missing P_T^{miss} due to neutrino.
- ✓ In high luminosity conditions of LHC, using M_T is not preferred as the resolution of P_T^{miss} degrades due to large number of pp collisions (pile-ups) when two proton bunches cross each other.
- ✓ CMS measures W mass by fitting three distributions: (i) muon transverse momentum, (ii) muon pseudo-rapidity, η, and (iii) muon charge, q^{μ}; using template shapes for signal and background processes

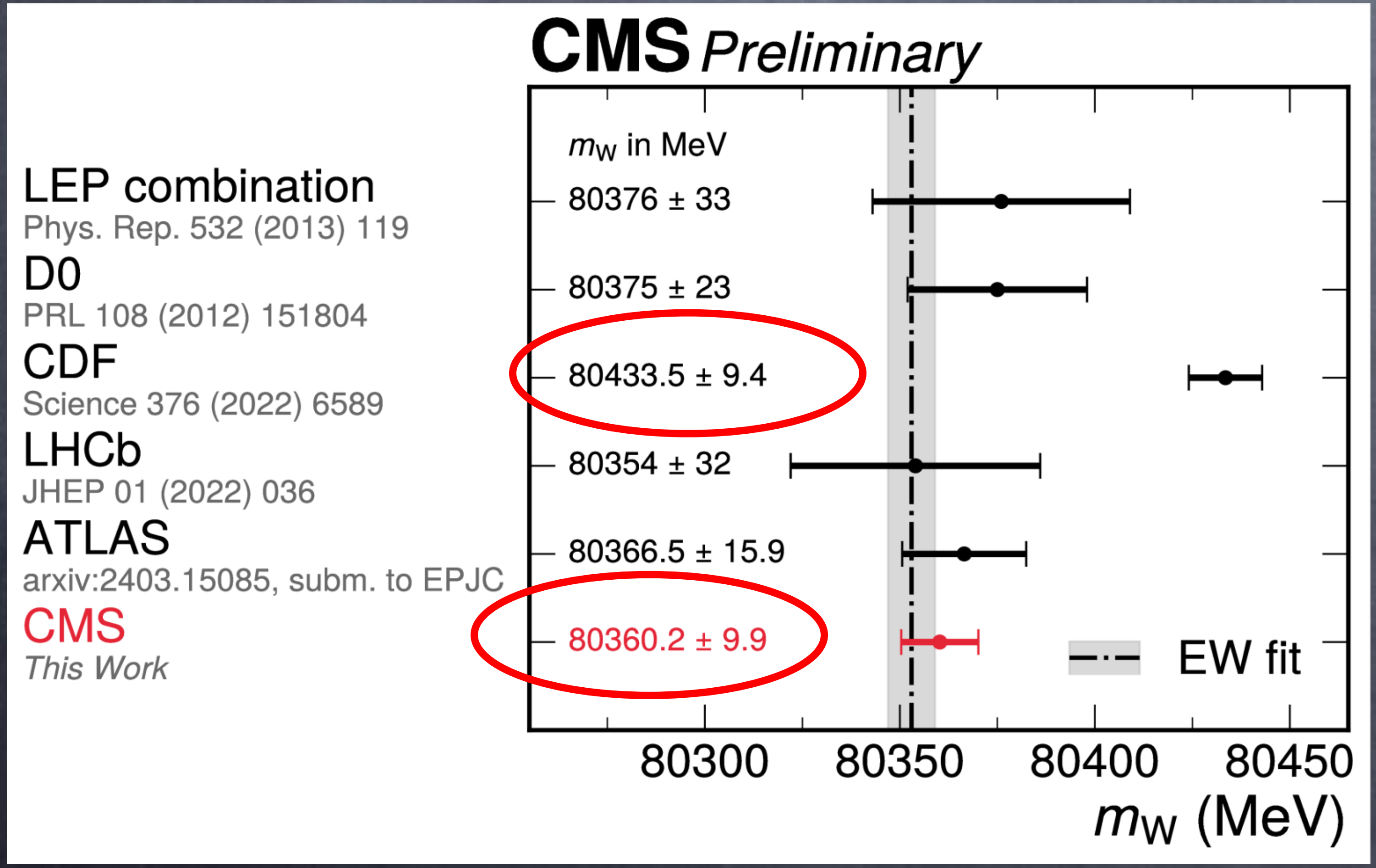
W mass measurement result with CMS data







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



- ✓ CMS used 16.8 fb^{-1} (2016) data collected at 13TeV COM energy.
- ✓ A binned maximum likelihood template fit p_T^{μ}, η^{μ}, and q^{μ} gives the value of m_W as:

$$m_W = 80\,360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst})$$
$$= 80\,360.2 \pm 9.9\,\text{MeV}$$

Understanding W mass measurement and outlook

- ✓ Several checks have been performed and constrains h on the kinematic variable applied
- ✓ As cross check, an alternate analysis approach is developed to reduce the sensitivity to theoretical inputs to m_W measurement. => m_W is extracted simultaneously with W angular distribution. The procedure is based on spin-1 particle decaying to leptons in terms of helicity states.

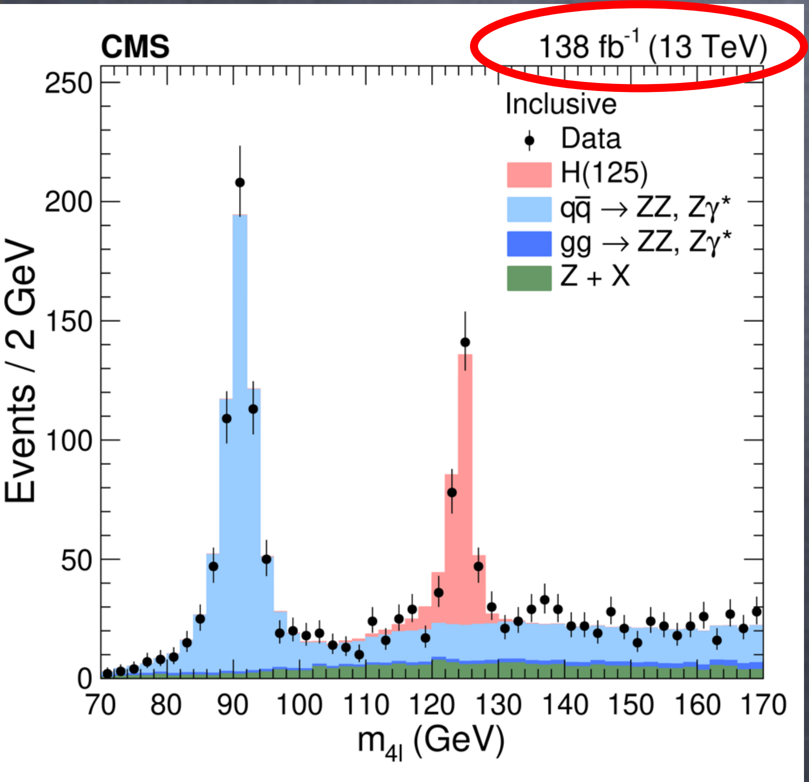
Source of uncertainty	Impact (MeV) Nominal	Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9

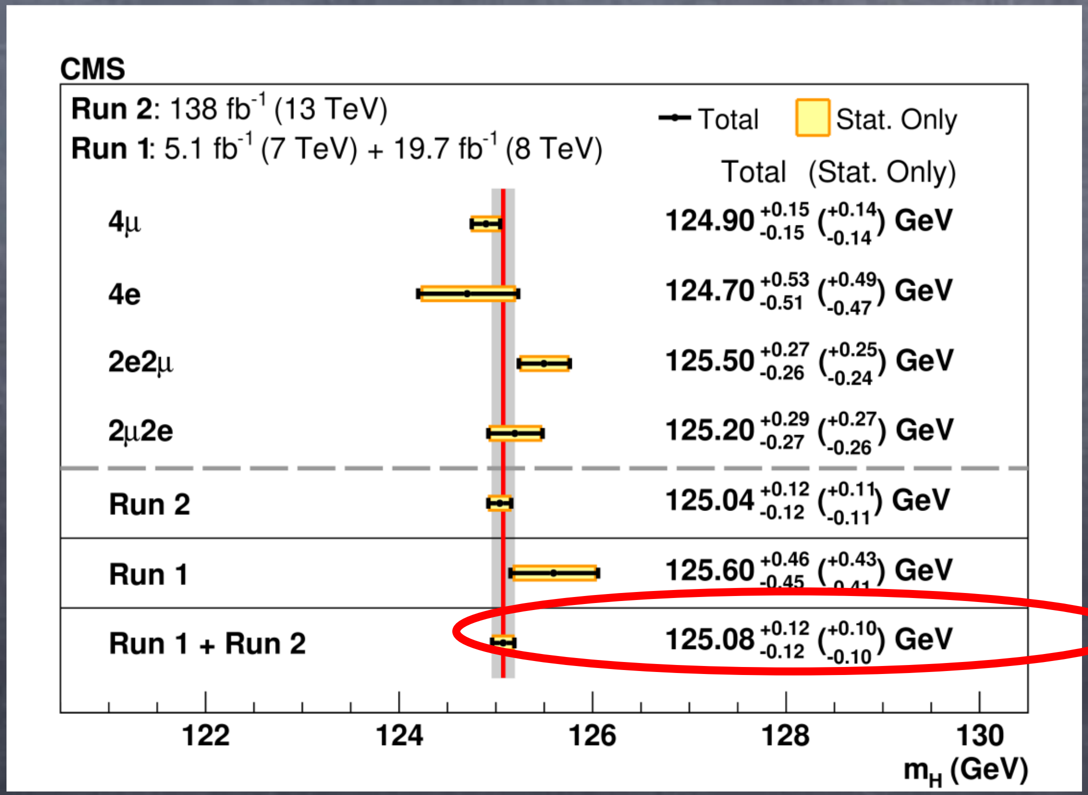
For details, please see CMS-PAS-SMP-23-002

- ✓ First measurement of W mass from the CMS experiment
- ✓ Most precise at LHC
- ✓ Agreement with SM and other experimental measurements, except CDF one
- ✓ Future measurements, with better precision would be very important.

Higgs boson mass and width measurement via $H \rightarrow 4l$, with CMS Run-2 data

- ✓ Higgs discovery has been one of the spectacular successes of SM
- ✓ Precision test of its mass and width is very important, e.g. the Higgs coupling to vector bosons strongly dependent on Higgs mass.
- ✓ The recent measurement from CMS with 2016 data, using $H \rightarrow 4l$, results in m_H to be 125.26 ± 0.21 (±0.19) GeV
- ✓ The width (in SM) is predicted to be 4.1 MeV corresponding to m_H=125 GeV
- ✓ The CMS experiment also measured the width to be, $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV (Nature Physics 18(2022), 1329)
- ✓ The result is now updated by CMS experiment using full Run-2 data (138 fb^{-1})



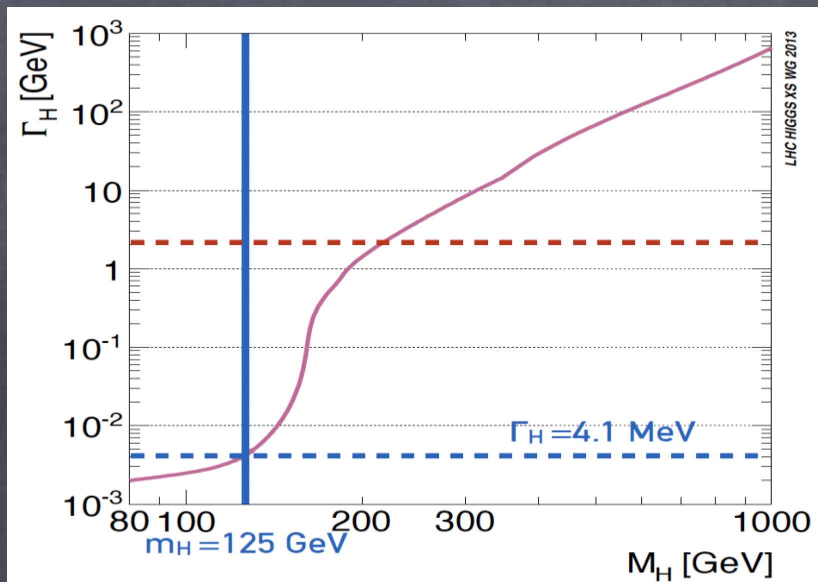


The current precision is ~120 MeV (0.09%). Most precise single measurement of m_H

Expect to go down to ~30MeV with HL-LHC (20 x data) and better upgraded detector

Γ_H<330 MeV at 95%CL

Higgs boson width measurement via H→4l with CMS Run-2 data



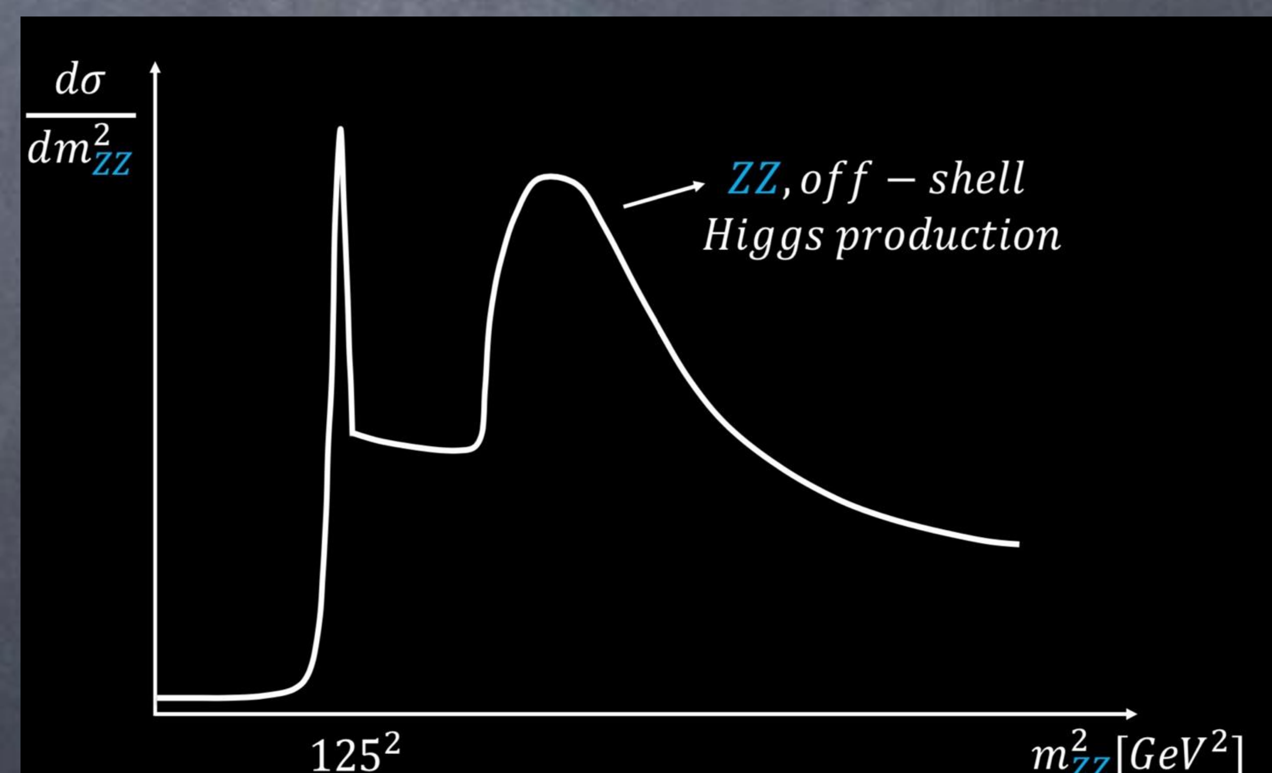
✓ The SM predicts the Higgs width to be 4.1 MeV (corresponding to lifetime of 1.6 x 10^{-22} sec) at m_H = 125GeV. Remember the similar parameter (width) for EW vector boson (W and Z) ~ 2GeV

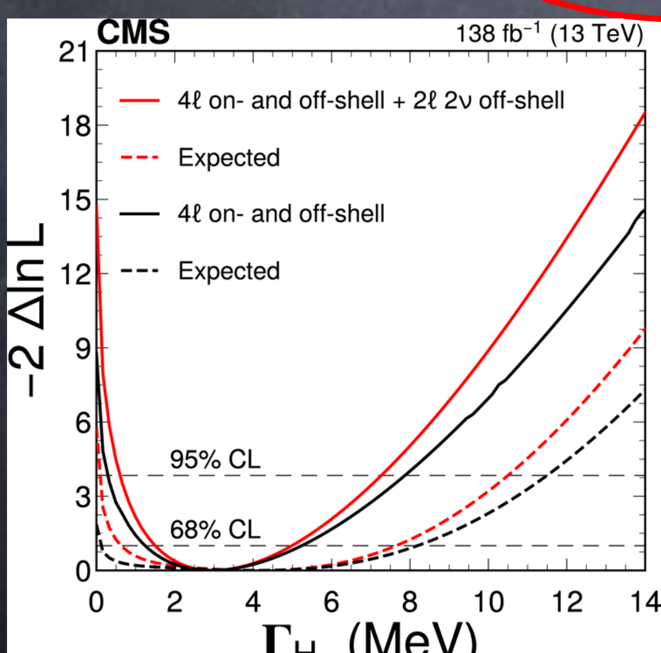
✓ The standard procedure to obtain the Higgs width is by comparing the on-shell and off-shell Higgs production

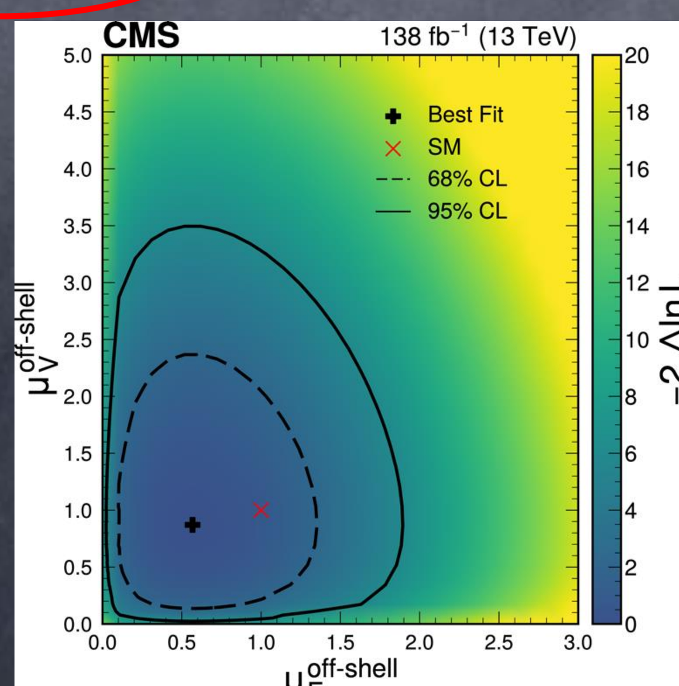
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

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

Parameter	Observed	Expected
m_H (GeV)	125.08 ± 0.12	± 0.12
on-shell Γ_H (MeV)	<50 [<330]	<320 [<640]
off-shell Γ_H (MeV)	$3.0^{+2.0}_{-1.5}$ [0.6, 7.3]	4.1 ± 3.5 [0.1, 10.5]

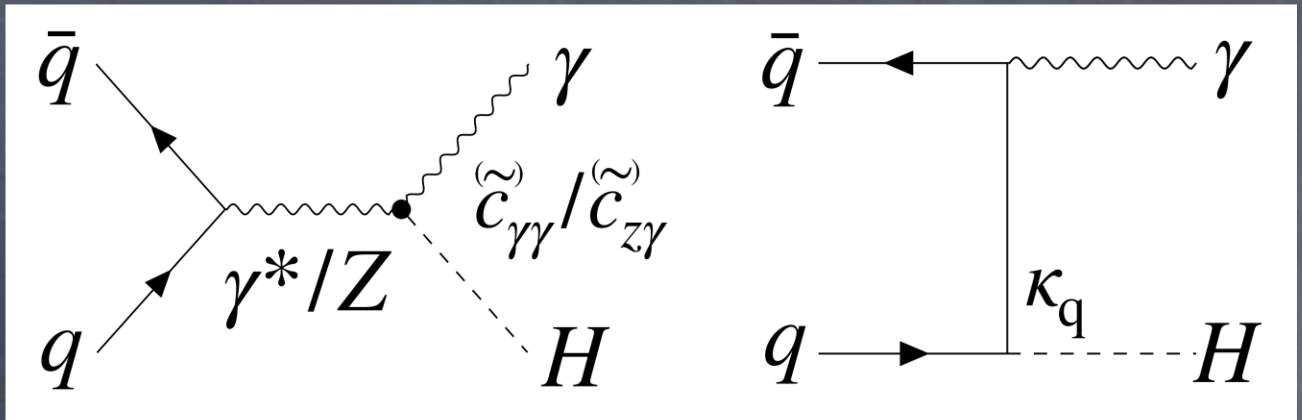






arXiv: 2409.13663 (submitted to PRD)

Search for γH production and constrain on quark-H Yukawa coupling



✓ One can have γH similar to ZH or WH (H->bb, 4l decay modes are considered)

✓ This production has not been directly explored in LHC.

✓ The SM cross section $\sigma_{\gamma H}$ is expected to be very small, <5fb at 14TeV collision energy (beyond current experimental reach). However new anomalous interactions (HZγ , Hγγ) may enhance such production.

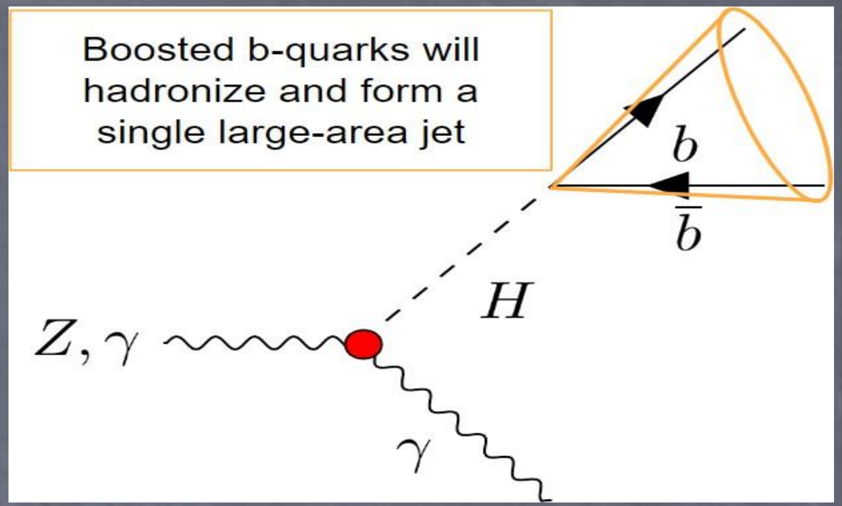
✓ CMS primarily focused production mechanisms generated by the effective HZγ and Hγγ vertices(Fig shown on top left). These could be generated by heavy particle in loop leading to EFT operators. Measure cross section and constrain the operators.

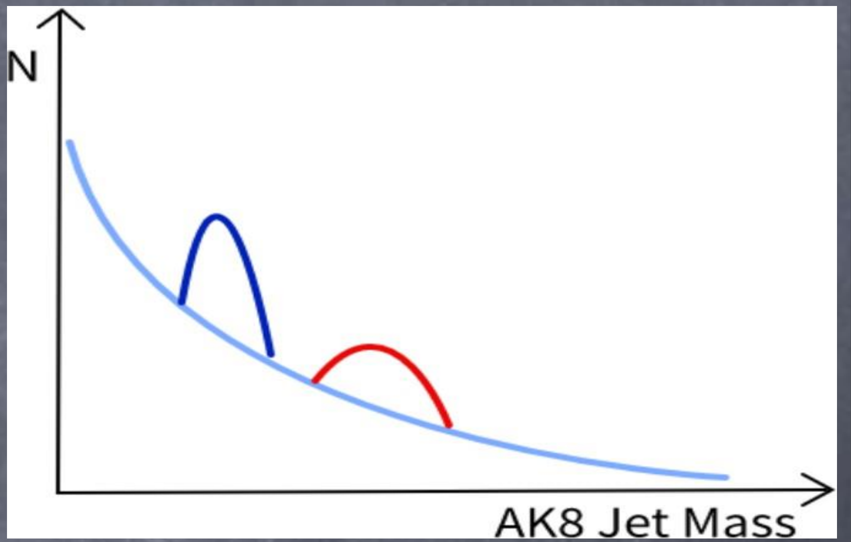
$$\frac{\sigma(qq \to \gamma H)}{\sigma_{\rm ref}^{\gamma H}} = (c_{z\gamma})^2 + (\tilde{c}_{z\gamma})^2 + 0.0982\,(c_{\gamma\gamma})^2 + 0.0982\,(\tilde{c}_{\gamma\gamma})^2 - 0.243\, c_{z\gamma}c_{\gamma\gamma} - 0.243\,\tilde{c}_{z\gamma}\tilde{c}_{\gamma\gamma}$$

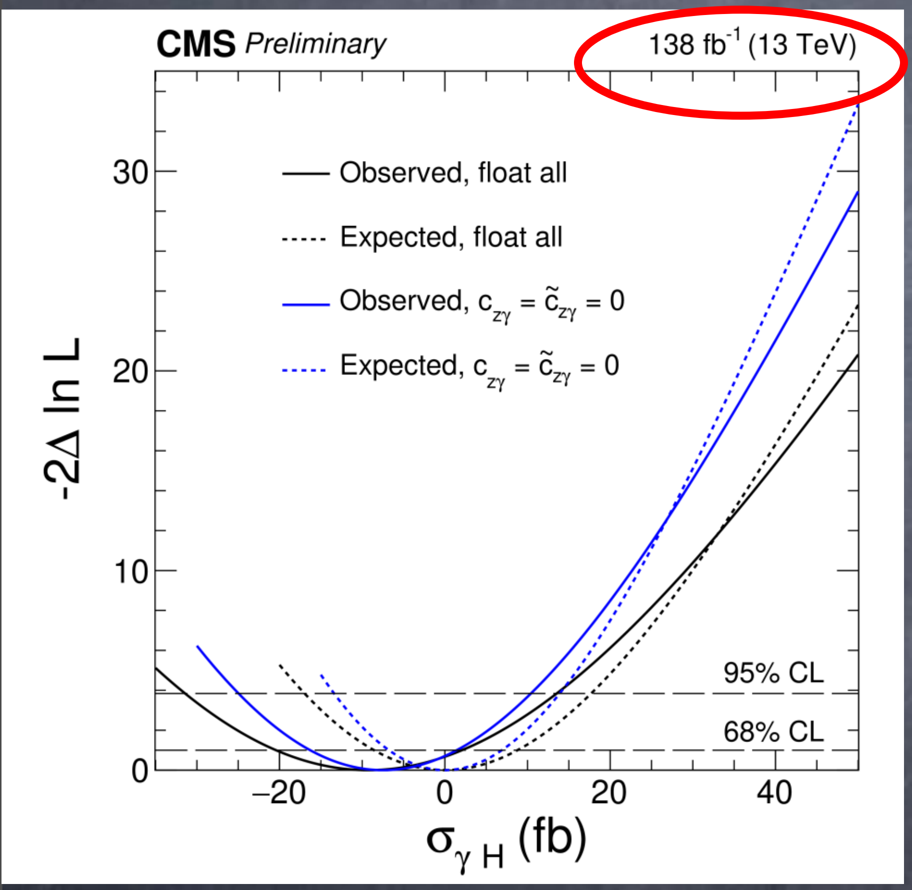
$\sigma_{\rm ref}^{\gamma H}$ = 180.3 fb

Constrain on light-quark H Yukawa coupling

- ✓ Look for H-decay to b-pairs/ 4-leptons
- ✓ Select one photon + high P_T jet (high P_T, >300GeV, dramatically reduces non-resonant backgrounds)
- ✓ Fit the jet mass distribution, search for H_{bb} signal bump



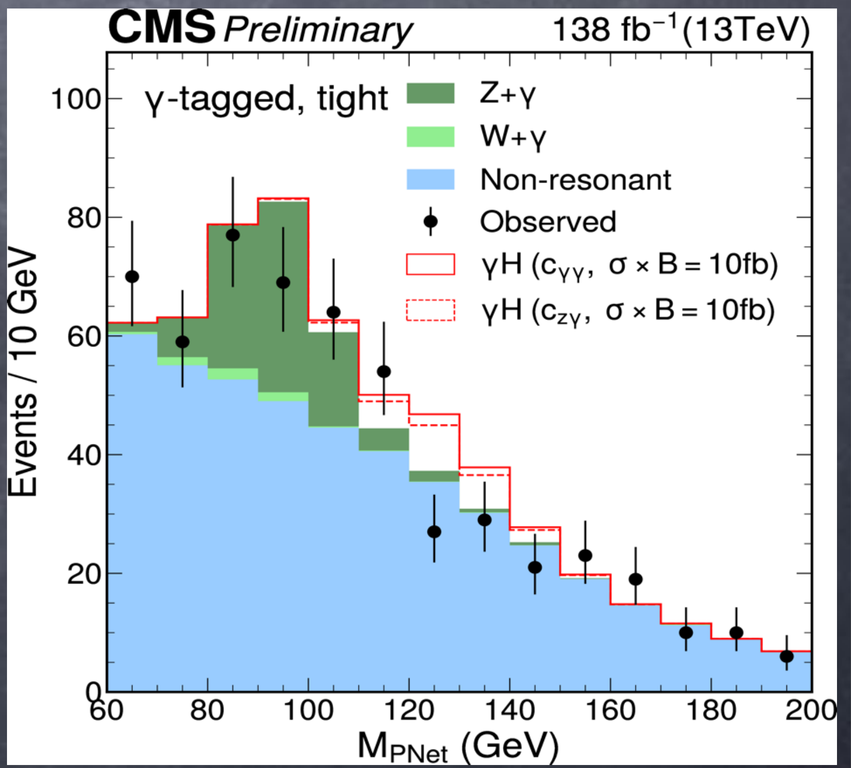




No significant excess seen γH events in either channels

The γH production cross section is constrained to be <15.7 fb at 95%CL

The production of H->4l Was used to check Yukawa coupling of Higgs with lighter quarks.



At 95% CL: $\kappa_u = (0.0 \pm 1.5) \times 10^3$, $\kappa_d = (0.0 \pm 7.1) \times 10^2$, $\kappa_s = 0^{+33}_{-34}$, and $\kappa_c = 0.0^{+2.7}_{-3.0}$

CMS-PAS-HIG-23-011

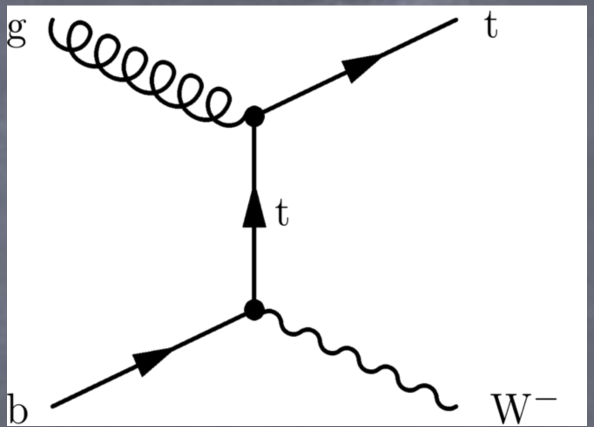
Differential X-section of single top with W-boson

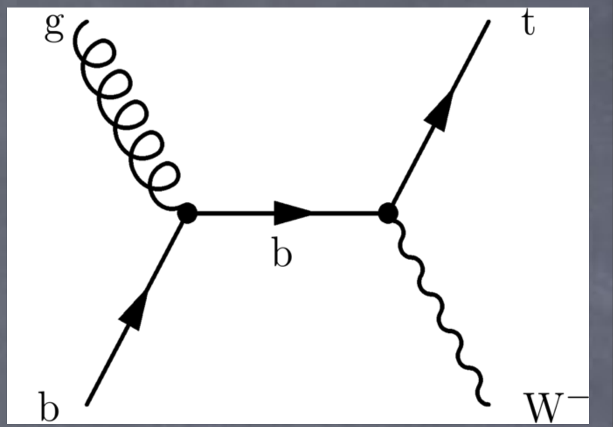
arXiv: 2409.06444
(submitted to JHEP

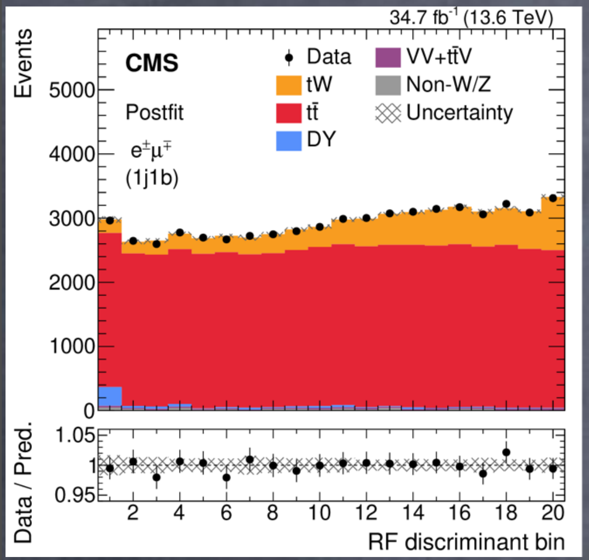
- ✓ First measurement of inclusive and differential production X-section with Run-3 data (34.5fb-1)
- ✓ Signal: tW, where t -> bW. Both W's decay leptonically leading to dilepton ($e^{\pm}\mu^{\mp}$) final state along with jets. Measured inclusive X-section is:

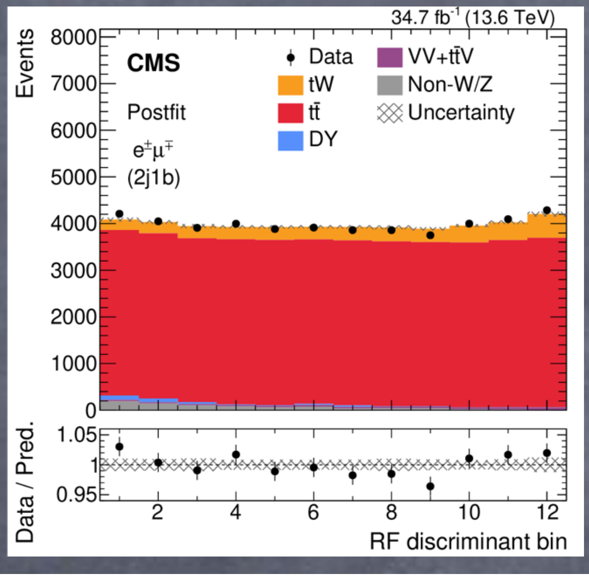
$$\sigma_{tW} = 82.3 \pm 2.1\,(\text{stat})\,^{+9.9}_{-9.7}\,(\text{syst}) \pm 3.3\,(\text{lumi})\,\text{pb}$$

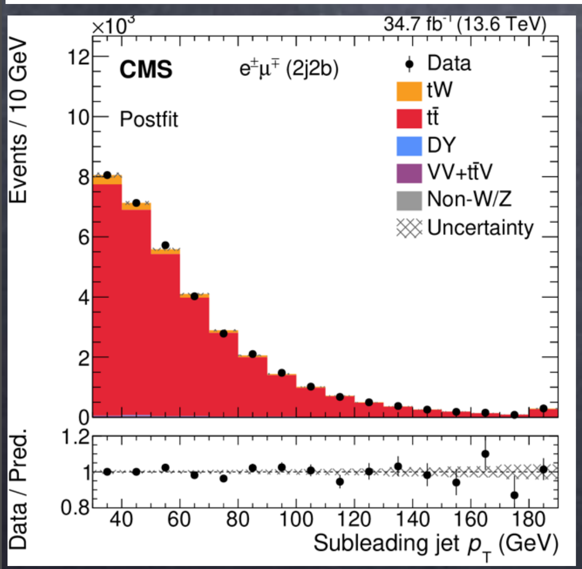
SM prediction: $87.9^{+2.0}_{-1.9}\,(\text{scale}) \pm 2.4\,(\text{PDF+}\alpha_S)\,\text{pb}$

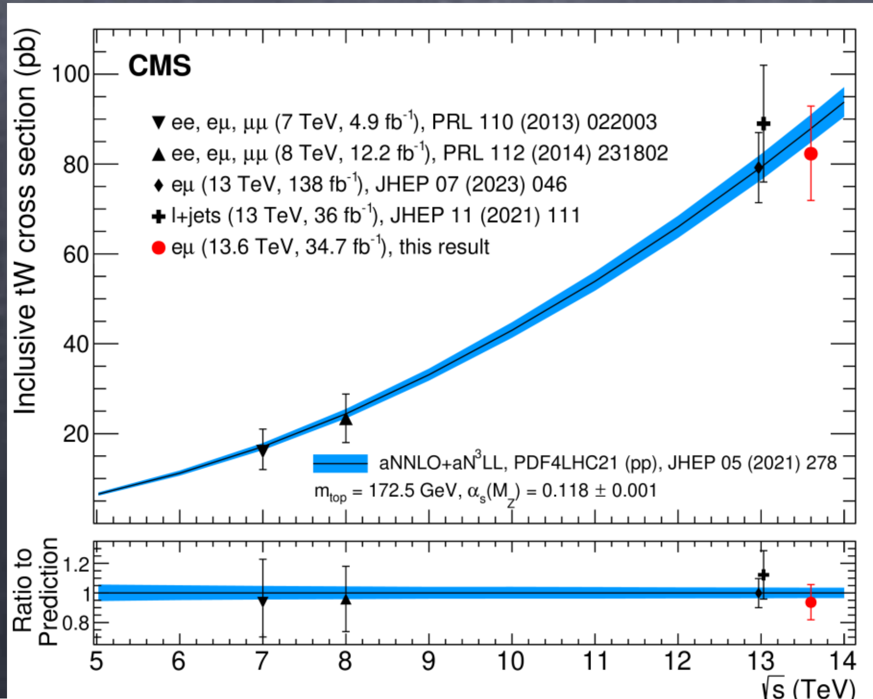


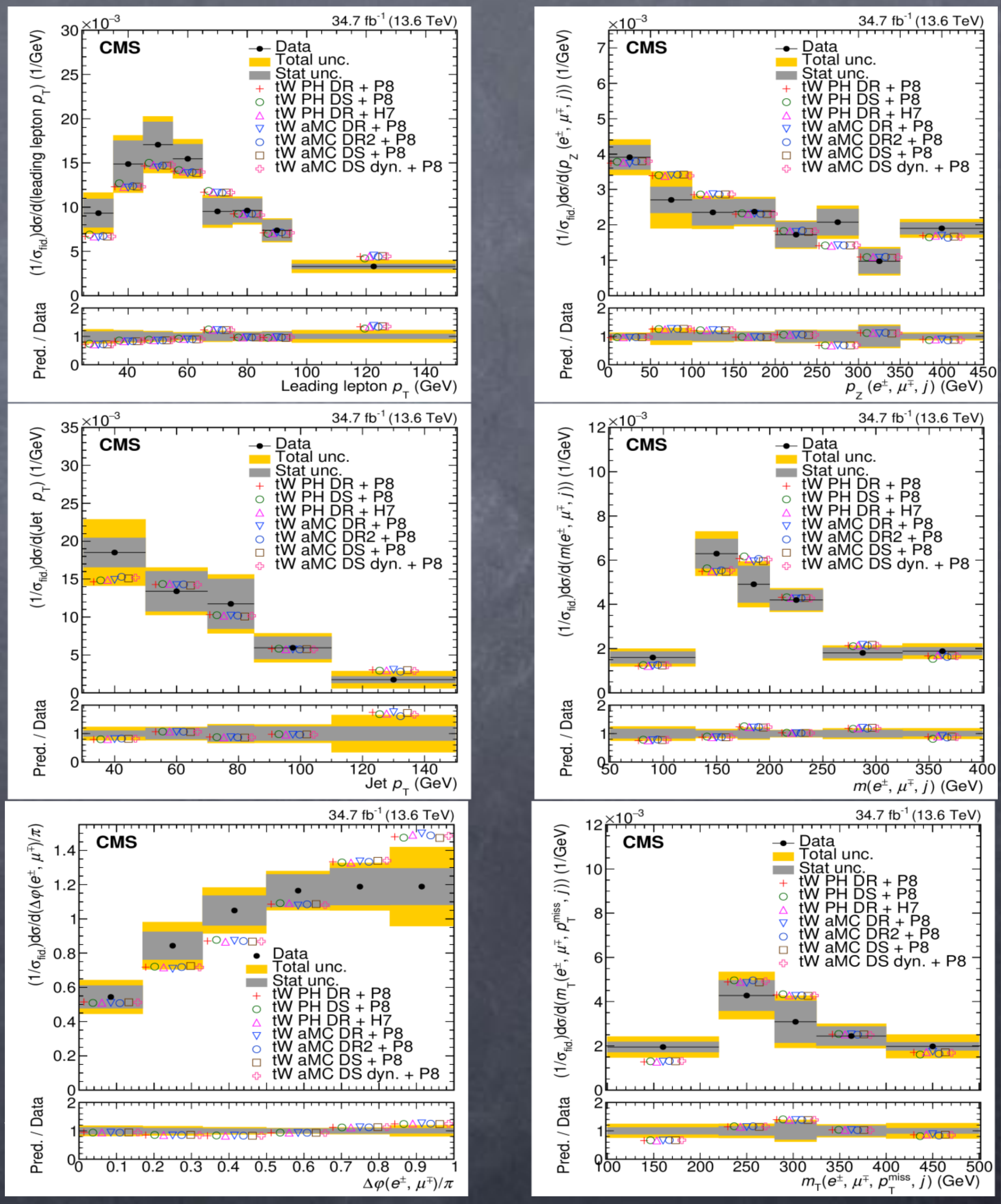




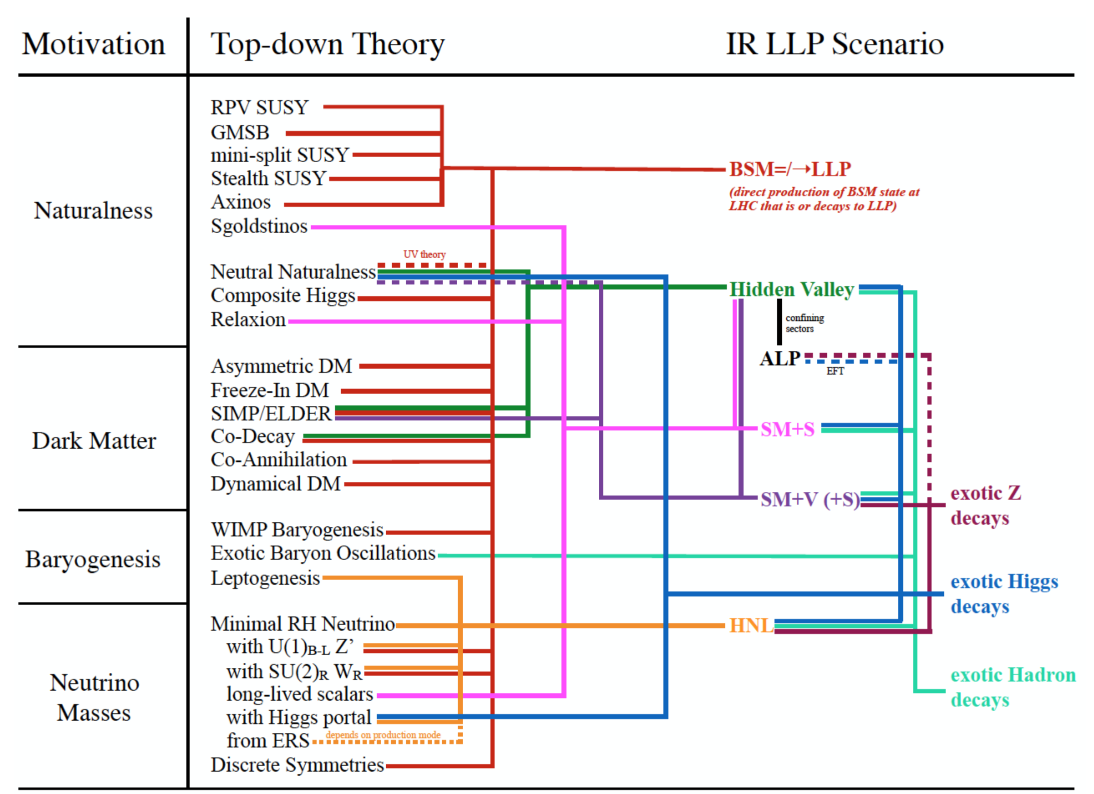


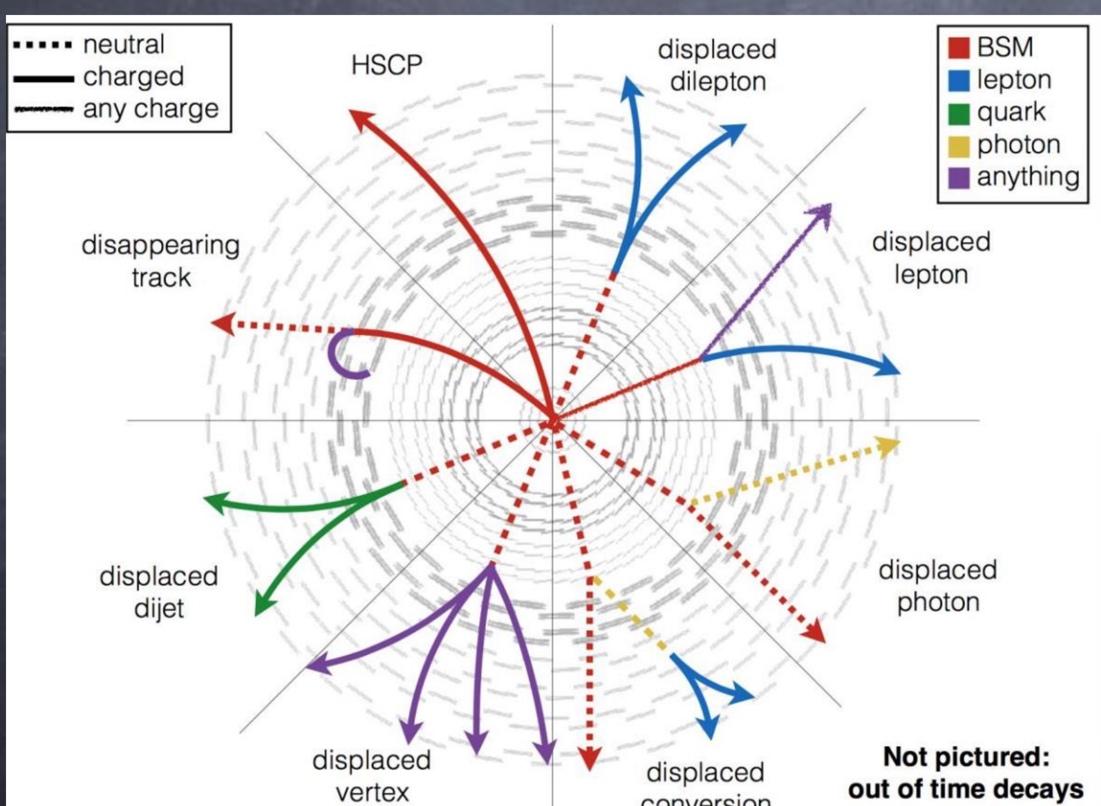






Search for BSM through LLPs

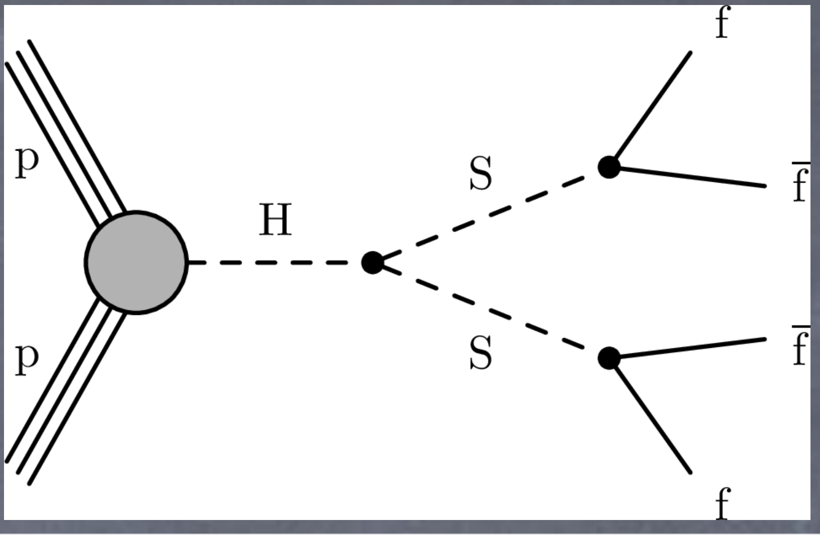


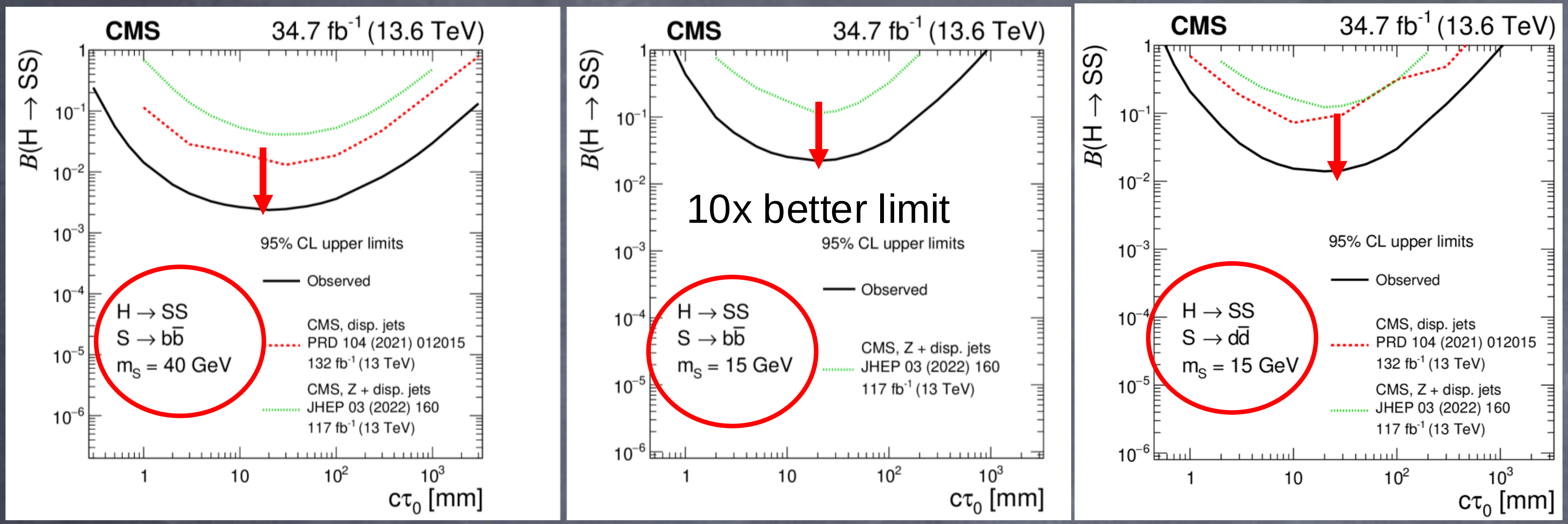


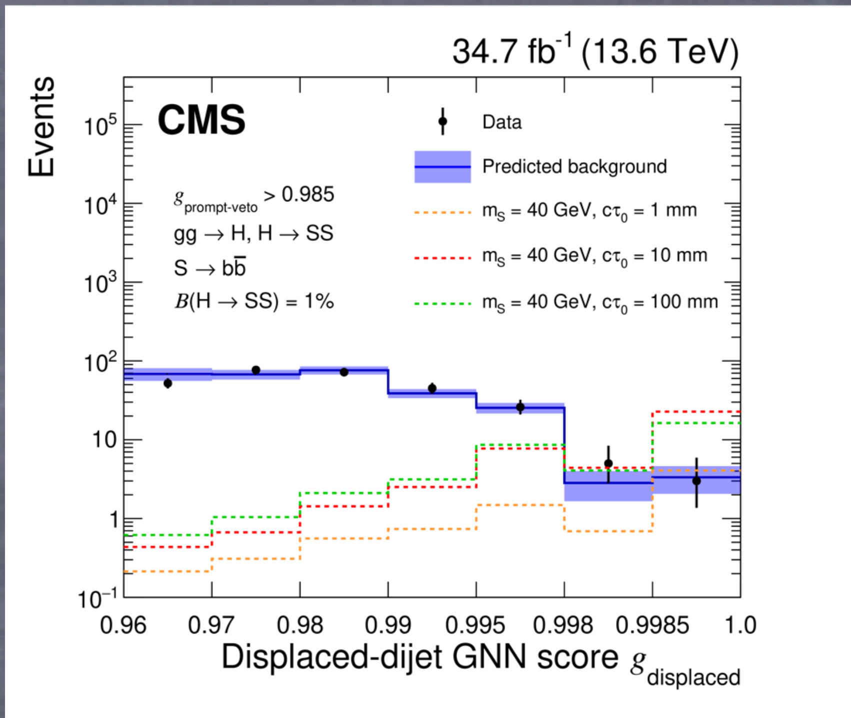
- ✓ Several BSM theories tries to explain hierarchy problem, dark matter, baryogenesis, non-zero neutrino masses, etc.
  => No BSM found till date
- ✓ Most BSM searches focus on heavy states that promptly decay to high energy visible particles such as jets, leptons, photons etc.
- ✓ A generic and much less explored alternative is that BSM shows up as new Long Lived Particles (LLPs) decaying to SM particle at some macroscopic distance away from production points.
- ✓ Several such displaced signatures (shown on the left figure) are being searched at LHC
- ✓ The lifetime of the LLPs are in general free parameters of the model (can live up to 10^7m).
- ✓ CMS searched for low mass LLPs (< 60GeV) produced with 34.7fb^{-1} (2022) Run-3 data.

Search for low mass LLPs with di-jet final state

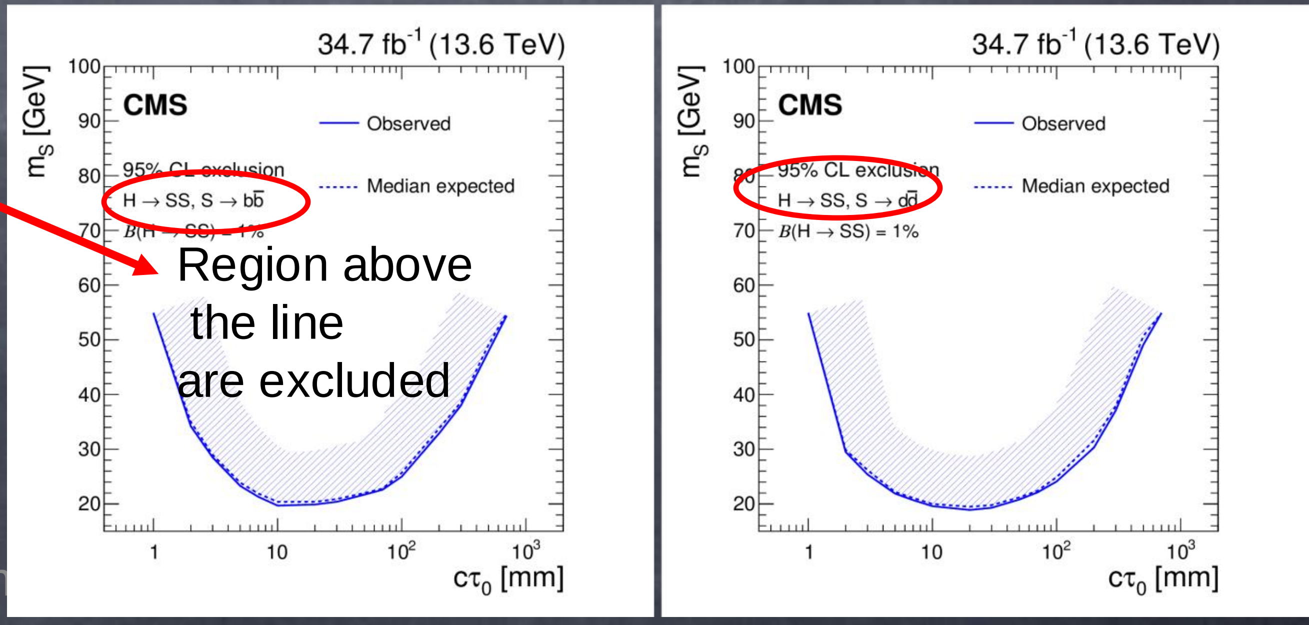
- ✓ Signature is exotic decay of 125 GeV Higgs (H) to two long lived neutral scalars(S) which further decay to Pair of SM fermions (quark pairs or tau lepton pairs)
- ✓ Look for di-jets with displaced vertex, reconstructed using the displaced tracks associated with jets





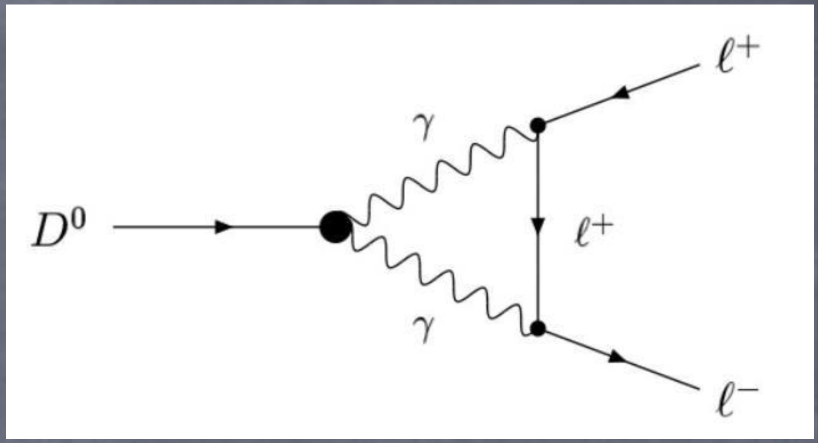


- ✓ The observed data events are consistent with background expectation (no significant excess).
- ✓ Limit on masses are set at 95% CL.
- ✓ The measurement also set the lower limit on top quark partner mass within fraternal twin Higgs and folded SUSY model to be 350 GeV and 250 GeV, respectively.



CMS-EXO-23-013
(submitted to Rep on Prog in Phys)

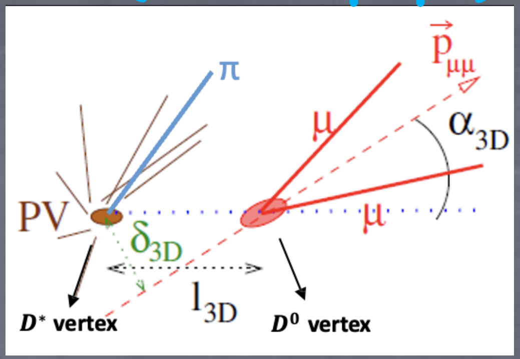
Rare Charm decaying to two opposite sign muons ($D^0 \to \mu^+\mu^-$)



- Rare decays of hadrons is one of the most promising place to look for new physics beyond SM.
- Easy to see even the small NP effects against smaller SM contributions.
- In particular, the FCNC (Flavor Changing Neutral Current) processes, which are forbidden at tree level, are preferred.
- $D^0 \to \mu\mu$ is one such process and the goal is to measure its branching fraction
- Compared to "$b \to s$" (B_s meson decays), rare charm decays mediated by "$c \to u$" transition, are not explored much.
  - SM Prediction: BF($D^0 \to \mu\mu$) > ~3×10^{-13} (Long distance) – PRD 66 (2002) 014009
  - Most stringent experimental search BF < 3.5×10^{-9} at 95% CL from LHCb, PRL 131, 041804, which is 4 orders of magnitude larger than SM prediction

- CMS searches for this decay mode using 64.5 fb^{-1} data collected during 2022-2023 at the Center-of-mass energy of 13.6 TeV

Rare Charm decaying to two opposite sign muons ($D^0 \to \mu^+\mu^-$)



- Look for $D^0 \to \mu^+\mu^-$ through cascade decay of $D^{*+} \to D^0\pi^+$

✓ The extra soft pion reduces the background by orders of magnitude, although it reduces signal yield also.

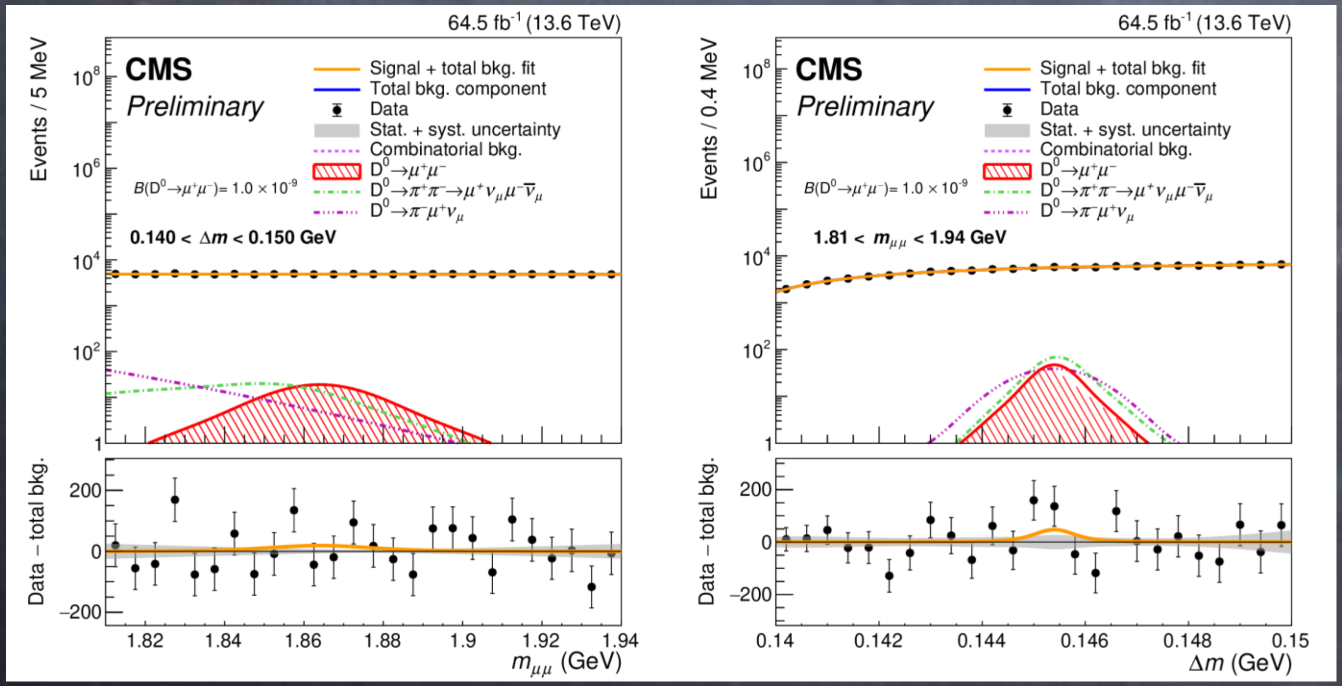
- Signal yield extracted with 2D fit to: $D^0(\mu^+\mu^-)$ mass and Δm ($m_{D^{*+}}$ - m_{D^0})
- $D^0 \to \pi^+\pi^-$ is used as normalization channel, which has close kinematics with $D^0 \to \mu^+\mu^-$
- The normalization channel helps in cancellation of most of the systematic uncertainties

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \mathcal{B}(D^0 \to \pi^+\pi^-)\frac{N_{D^0\to\mu^+\mu^-}}{N_{D^0\to\pi^+\pi^-}}\frac{\varepsilon_{D^0\to\pi^+\pi^-}}{\varepsilon_{D^0\to\mu^+\mu^-}}$$

$\varepsilon \to$ Signal efficiency obtained from MC

$N_{D0 \to \mu+\mu-} \to$ Signal Yield from data

Range	Signal	Comb	Peak	Semi	Total	Data
Full range	139 ± 123	126185 ± 366	220 ± 58	207 ± 40	126751 ± 355	126752
$0.145 < \Delta m < 0.146$ GeV	92 ± 81	14044 ± 63	141 ± 37	91 ± 17	14367 ± 81	14412
$1.84 < m_{\mu\mu} < 1.89$ GeV	120 ± 106	48553 ± 204	123 ± 33	55 ± 11	48851 ± 211	48798



No significant excess over background expectation is found

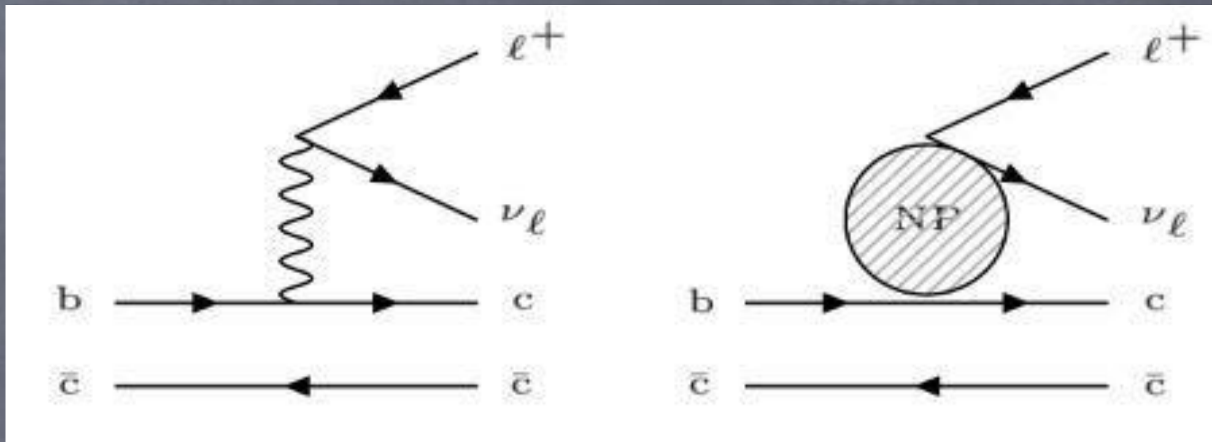
$B(D^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9}$ at 95% CL

30% improvement over the previous limit

CMS-PAS-BPH-23-008

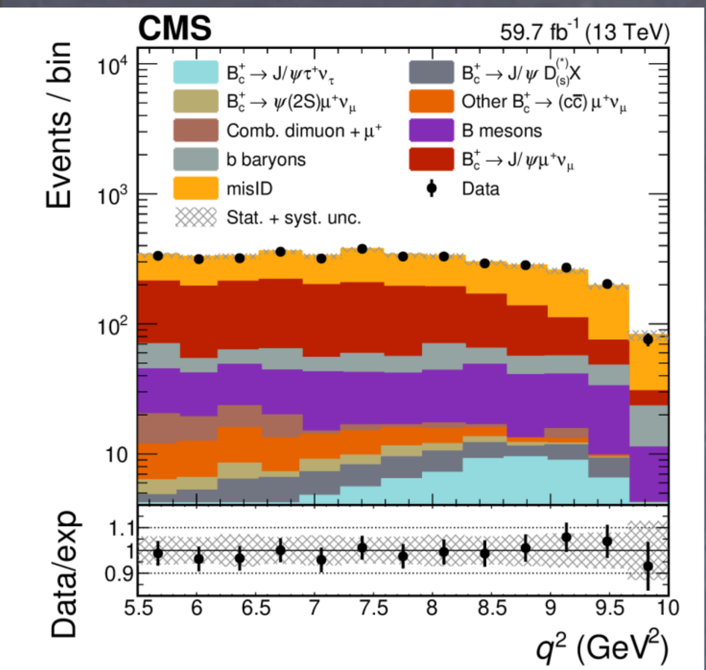
Test of LFU with R(J/ψ) measurement

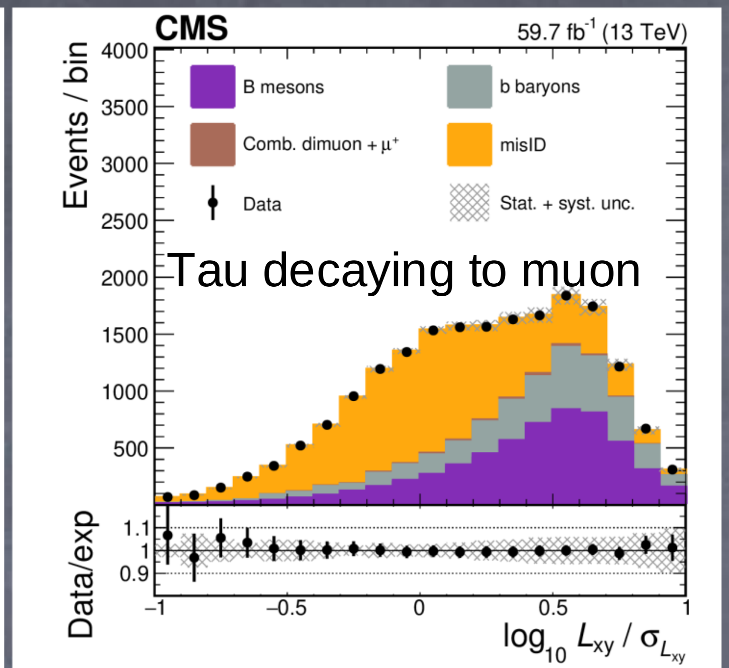
- ✓ In SM, three lepton families have same coupling for electroweak interaction, known as,
  -> Lepton Flavor Universality (LFU)



- ✓ LFU has been confirmed in leptonic decays of W and Z boson at per-mil level.
- ✓ In recent years, the LFU has been tested in the semi-leptonic decays of b-hadrons, e.g. $R(D^*)$ which has 3.2σ deviation above SM expectation.
  [Measured $R(D^*)$ = 0.295± 0.014, SM expectation =0.254± 0.005]
- ✓ Several BSM models that contains additional particles and non-trivial flavor interactions, can give rise to LFU violation.
- ✓ CMS looked for LFU with semi-leptonic decays: $R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu})}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})}$
- ✓ SM prediction for R(J/ψ) = 0.2582 ± 0.0038. PRL 125 (2020) 222003
- ✓ LHCb measurement: 0.71 ± 0.17 (stat) ± 0.18 (syst) PRL 120, 121801 (2018)
- ✓ CMS measures R(J/ψ) with partial/full Run-2 data collected at 13TeV COM energy
  using $\tau \to \mu\, \nu_\mu\, \nu_\tau$ channel, we use 59.7 fb^{-1} data collected during 2018
  using $\tau \to \pi^+\pi^-\pi^+ (\pi^0)\, \nu_\tau$ channels, we use 138 fb^{-1} data collected during full Run-2

R(J/ψ) results with CMS data



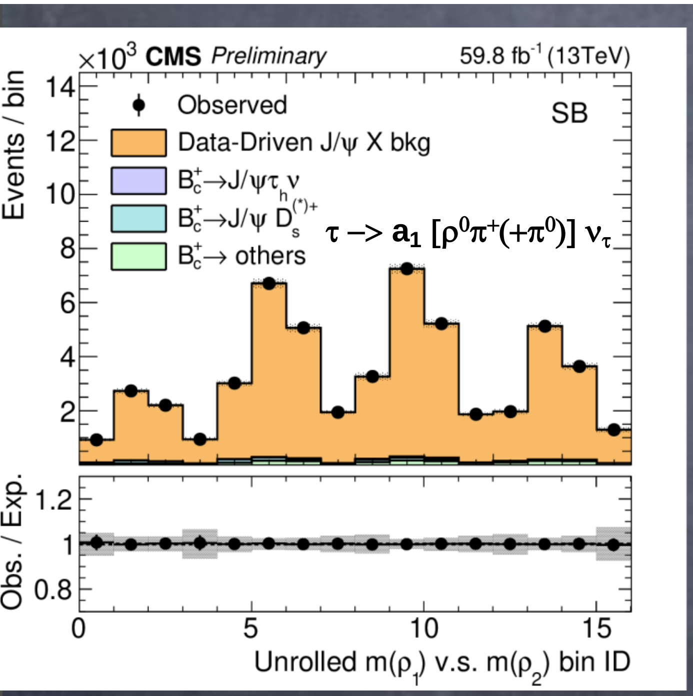


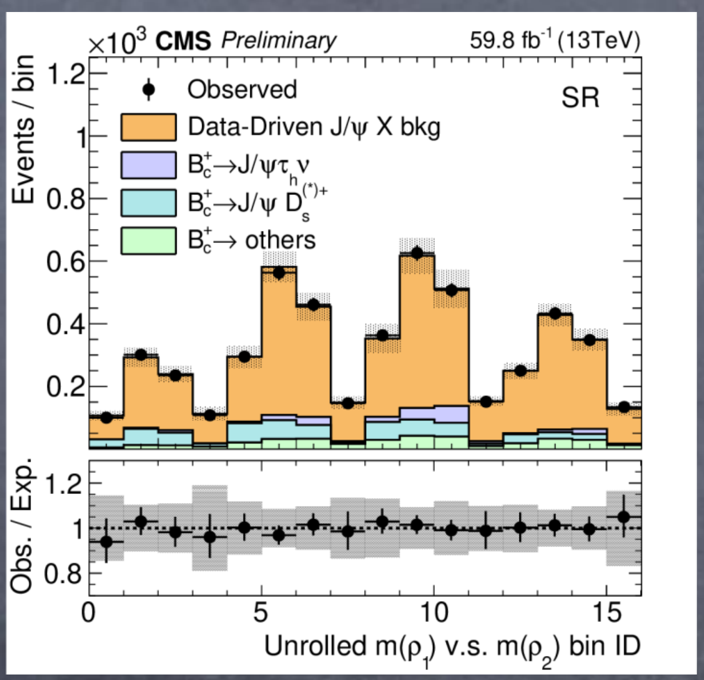
$q^2 = (P_{B_c} - P_{J/\psi})^2$

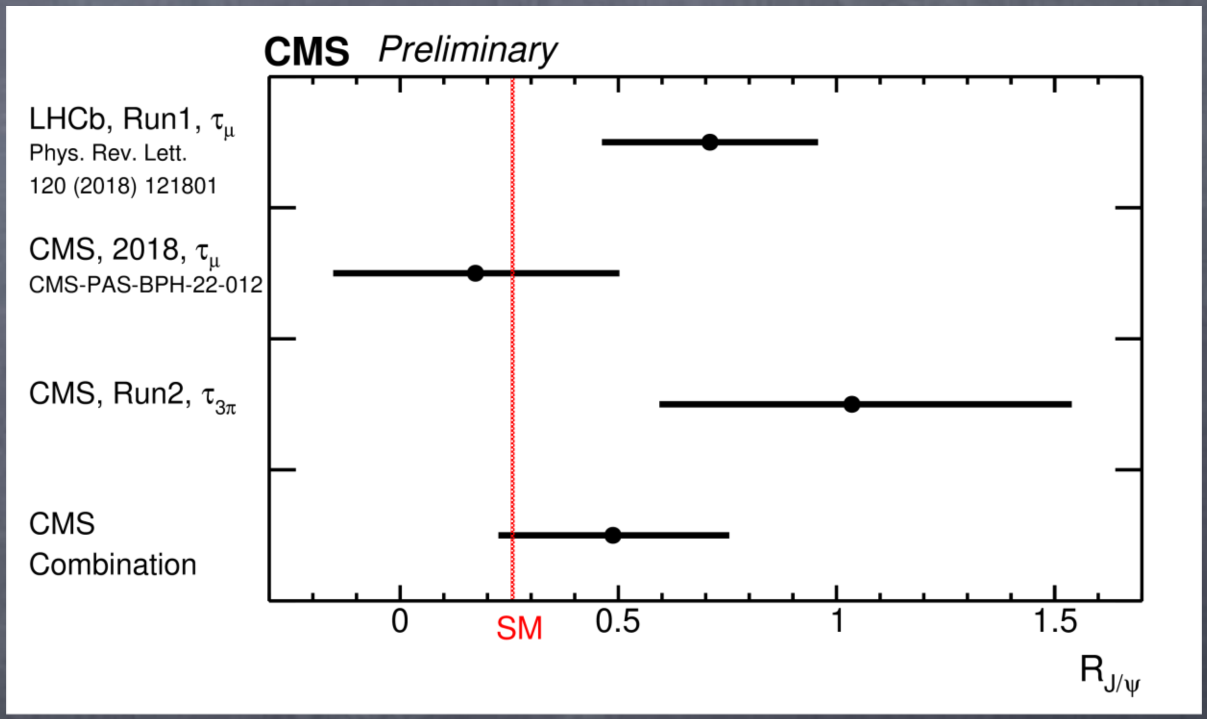
L_{xy}: The distance between J/ψ decay vertex and the beamline in transverse plane

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.17 \pm 0.33$$

arXiv:2408.00678 (submitted to PRL)







Using full Run-2 data for hadronic τ-decay:

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 1.04^{+0.50}_{-0.44}$$

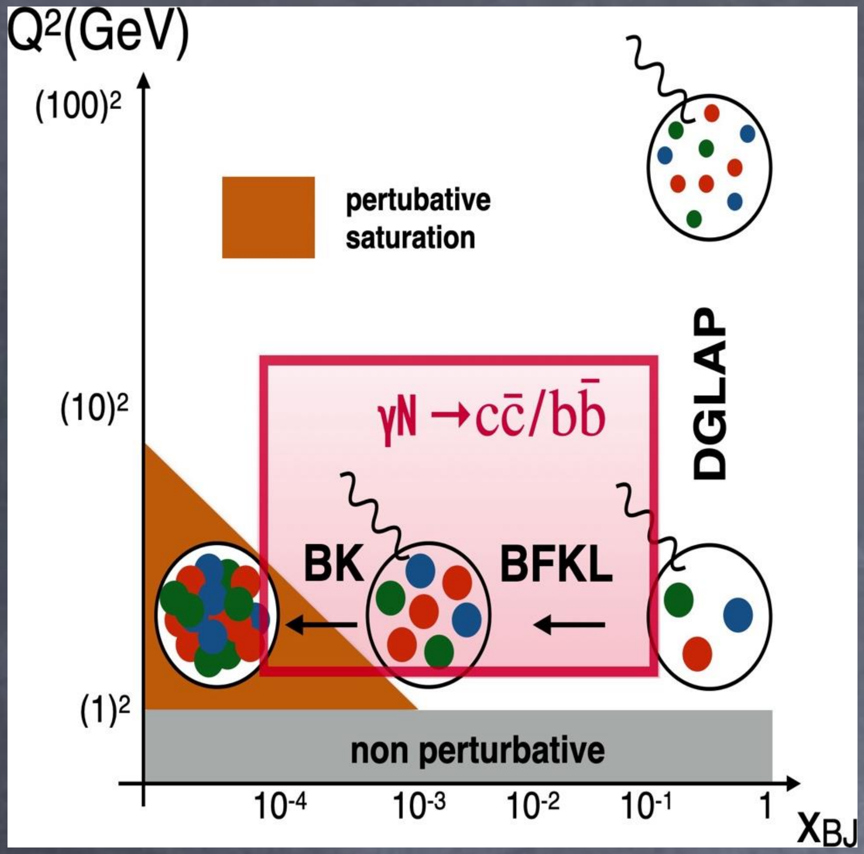
Combined leptonic and hadronic channels:

$$\mathcal{R}_{J/\psi} = 0.49 \pm 0.25\,(\text{stat}) \pm 0.09\,(\text{syst})$$

Consistent with SM prediction of 0.258 ±0.004

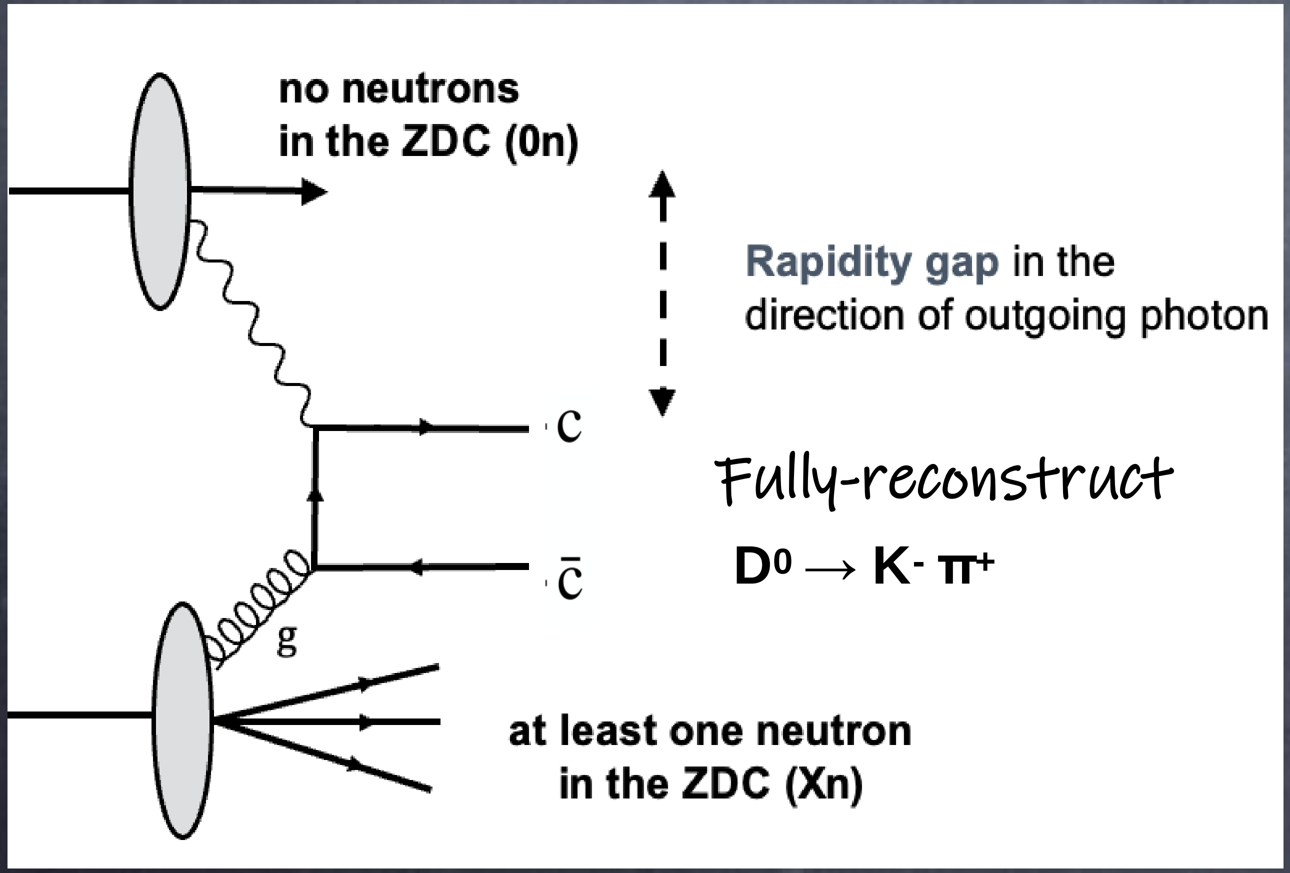
CMS-PAS-BPH-23-001

D^0 photoproduction in UPC PbPb Collisiom at 5.36TeV



- ✓ The partonic structure of protons/nuclei are described by parton (quark and gluon) distribution functions (PDFs)
  => Expressed in terms of parton momentum fraction(Bjorken-x) and virtuality (Q^2). The pdfs are extracted from global data fit.

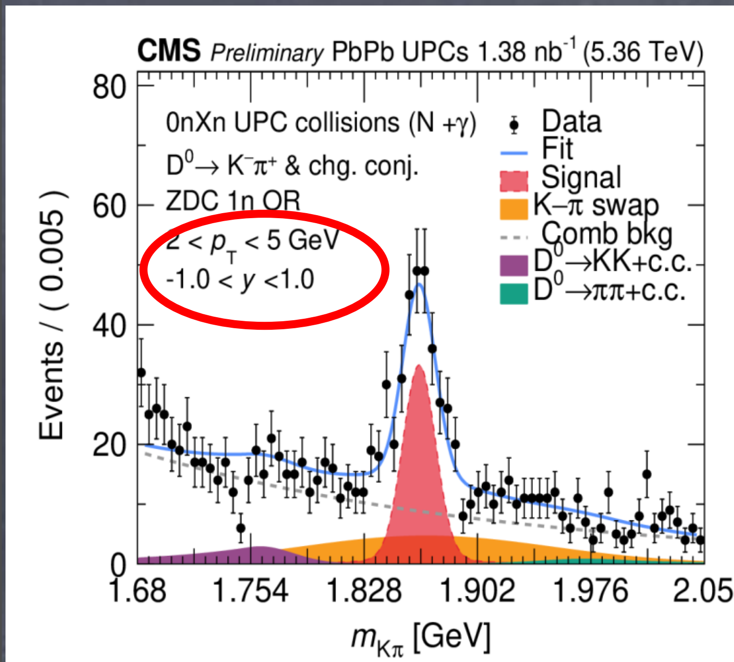
- ✓ The UPC collisions are dominated by photons exchange due to strong EM fields created by ultra-relativistic heavy ions.
- ✓ One of the two nuclei breaks up due to in-elastic hard scattering and other remains intact (XnOn).
- ✓ Provides access to a wide range of x, Q^2 region down to low x

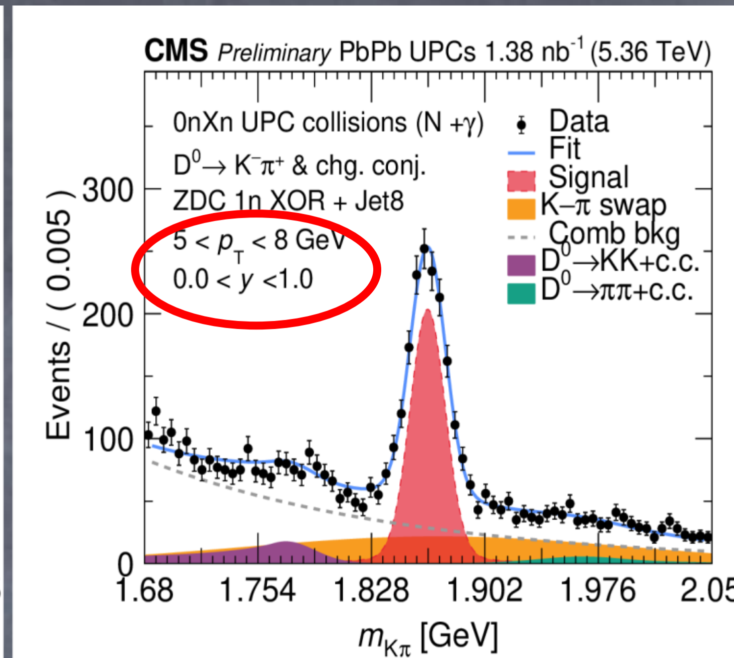


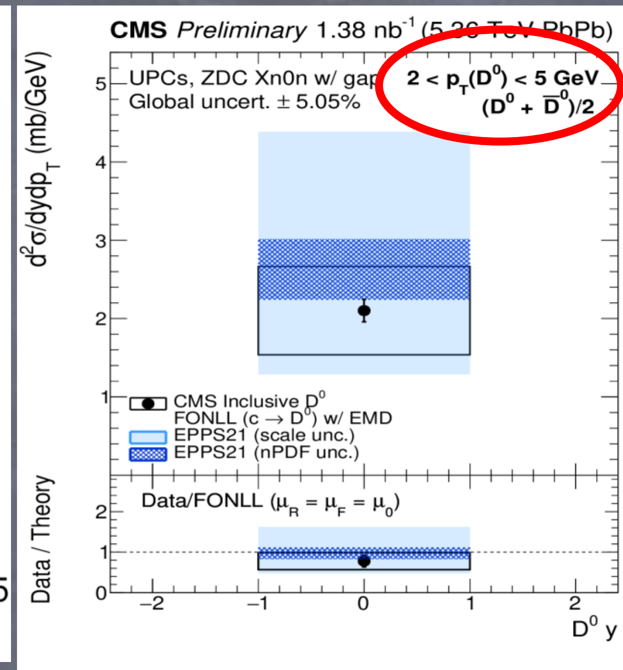
- ✓ CMS made first measurement of photonuclear X-section of D^0 mesons in UPC collisions using 1.38 nb^{-1} PbPb collision data.
  Includes both prompt (c->D^0) and non-prompt (b->D^0) decays

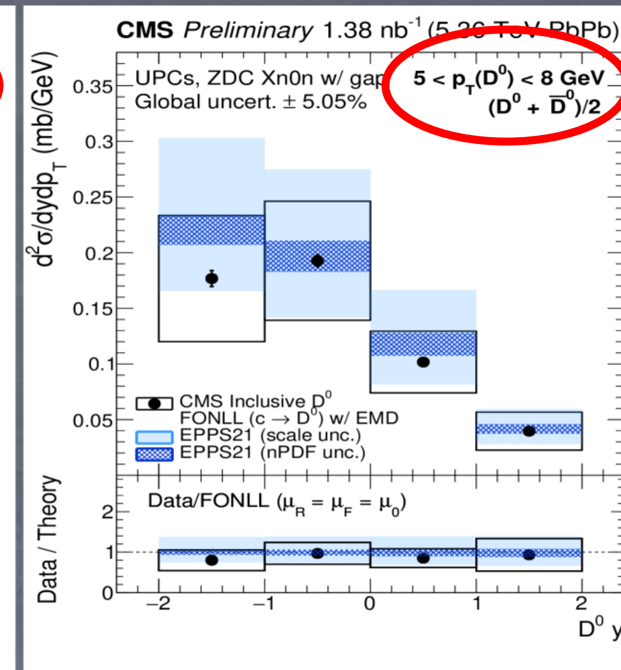
- ✓ Observables: D^0 production as a function of P_T and η, primarily double differential X-section

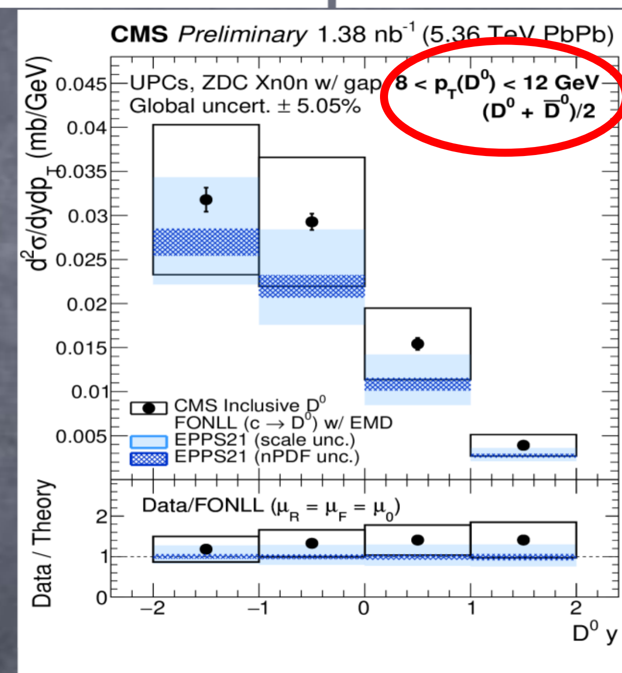
Differential Production X-section for D^0







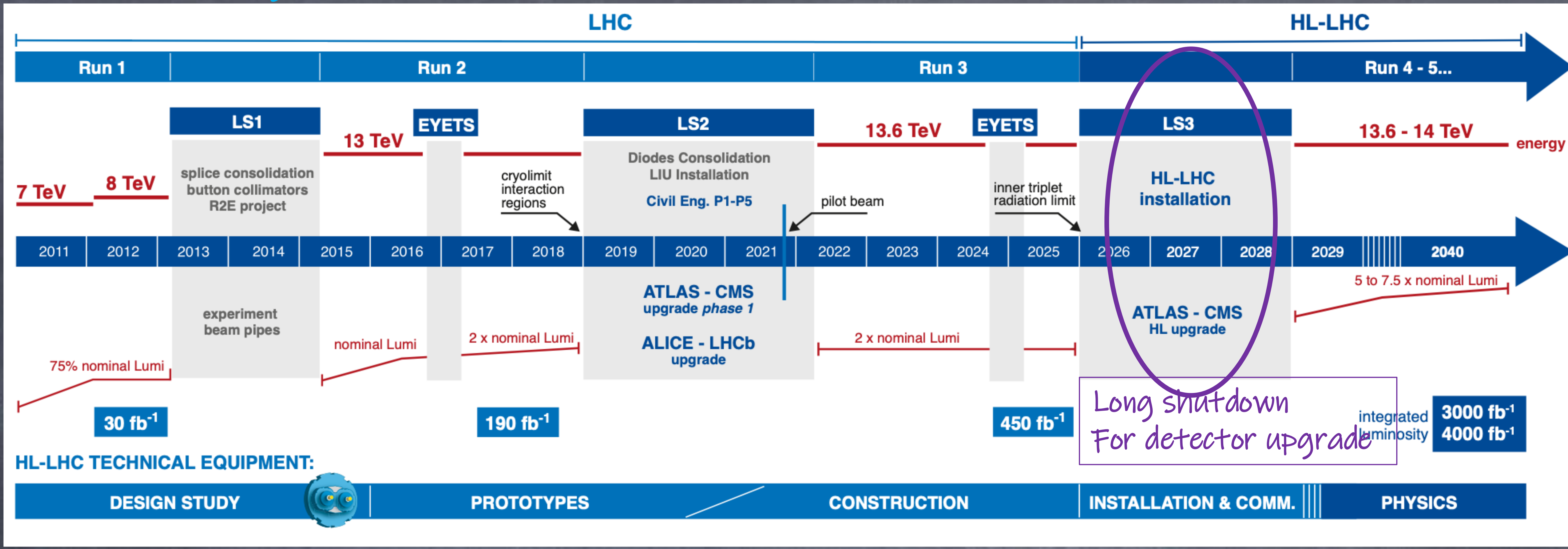




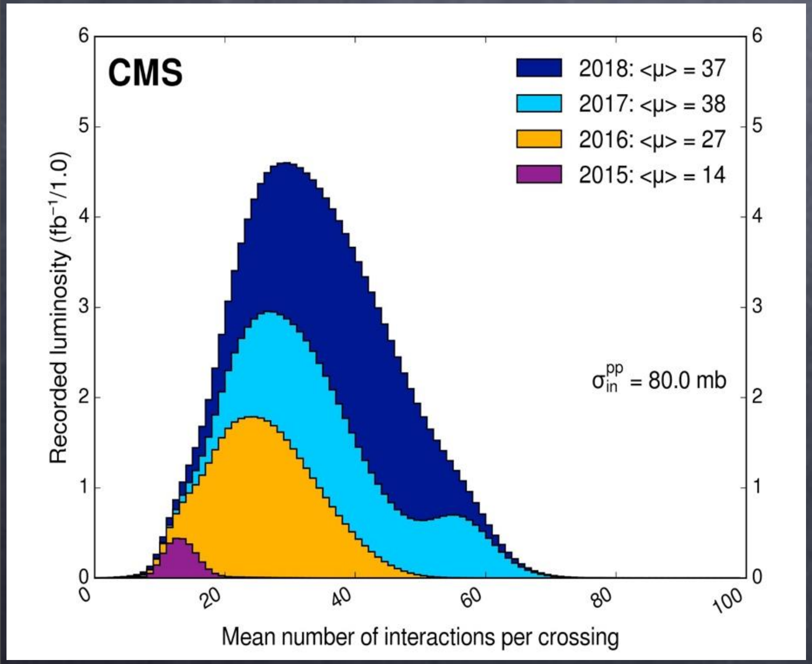
- ✓ The cross –section measurement for D^0 production as a function of P_T and η is performed (+ve rapidity corresponds to low-x and –ve rapidity to high-x region)
- ✓ The results are compared to theoretical calculations at next-to-leading order using recent parameterizations of nuclear PDFs.
- ✓ Good agreements with data within uncertainties
- ✓ This measurement provides new experimental constrains on nuclear matter with heavy quark observables over a large range of x and Q^2.

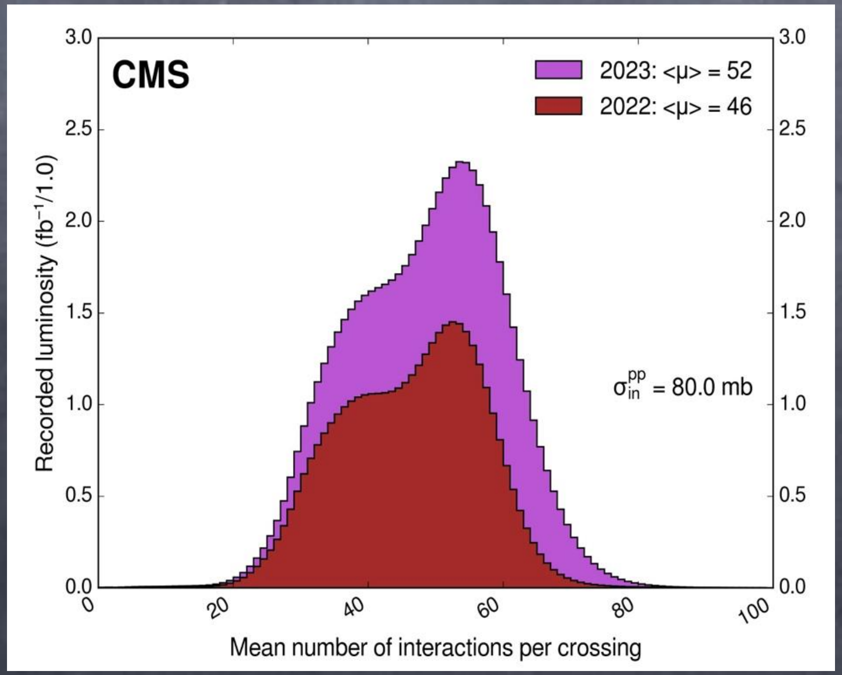
CMS-PAS-HIN-24-003

New upgraded detector with better performance to come soon

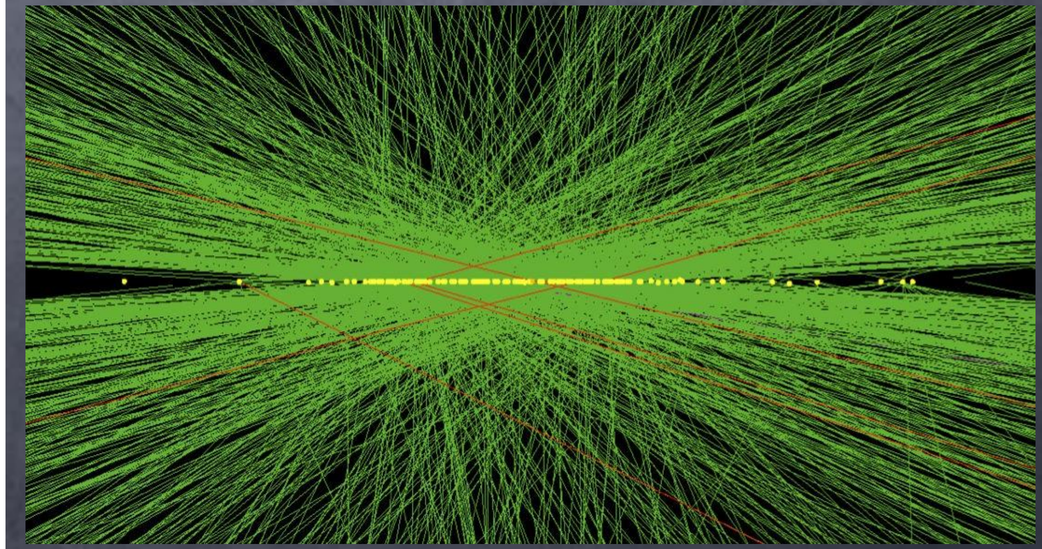


Pileup conditions: <# pp collisions> / bunch crossing





HL-LHC: <PU> 140-200



Which ones to be upgraded?

✓ Almost all detector part/related electronic to be upgraded to deal with intense beam condition

Muon Detectors
- DTs & CSCs: new FE/BE readout electronics
- RPCs: new electronics
- new GEM/iRPC chambers
- extended muon coverage to |η| = 3

Barrel Calorimeters
- crystal granularity readout at 40 MHz
- precise timing for e/γ > 30 GeV
- ECAL operation at low temperature (10°)
- upgraded laser monitoring system

Tracker
- all silicon (strips and pixels)
- higher granularity (>2B channels)
- less material
- coverage extended to |η| = 4

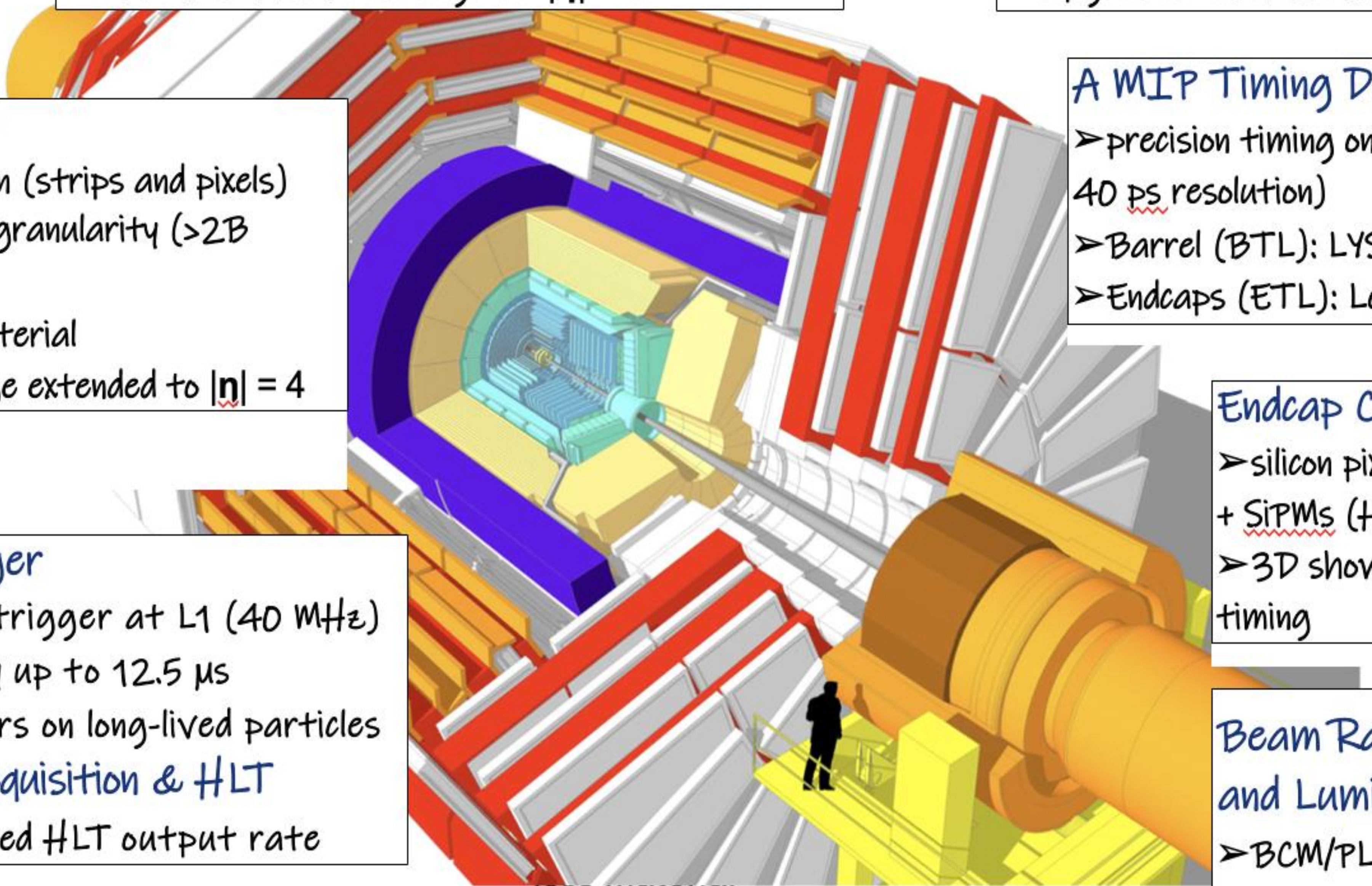
A MIP Timing Detector (MTD)
- precision timing on single charged tracks (30 to 40 ps resolution)
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes

Endcap Calorimeter (HGCAL)
- silicon pixels (EM) and scintillators + SiPMs (HAD)
- 3D shower reconstruction with precise timing

L1-Trigger
- track trigger at L1 (40 MHz)
- latency up to 12.5 μs
- triggers on long-lived particles

Data acquisition & HLT
- increased HLT output rate

Beam Radiation Instrumentation and Luminosity (BRIL)
- BCM/PLT refit
- new T2 tracker



➢ coverage extended to |η| = 4

Summary and Outlook

- ✓ LHC has provided greater insight and understanding of Standard Model of particle Physics.
- ✓ Higgs discovery was tremendous success towards it.
- ✓ More precision measurements are needed on all the areas: Higgs, top, W, flavor sector, etc. This gives handle to look for NP (New Physics) indirectly.
- ✓ LHC looks for NP directly also. Absence of NP, SUSY for example so far, creates more challenges (where and how to find) in future to look for NP.
- ✓ However, we will collect 15-20 times more data by 2040, with new upgraded CMS detector.
- ✓ Look forward to wonderful years ahead with many more new precise measurements on different SM parameters as well as BSM searches.