RECENT HIGHLIGHTS FROM CMS

Greg Landsberg

Corfu, Greece, 26.08.24

Corfu 2024 Workshop on the SM & Beyond

Outline

- ✦ LHC Performance: Four Machines in One
- ✦ 30,000 Feet Highlights:
  - Standard Model Measurements
  - Searches for New Physics
- ✦ Conclusions: Quo Vadis?

- ✦ Disclaimer: these are selected highlights of a large number of CMS results, with clear personal bias: they tell a story, rather than simply make up a shopping list... All the links are clickable!

- ✦ For a full physics analysis landscape at CMS, please refer to:
  - https://cms-results-search.web.cern.ch/

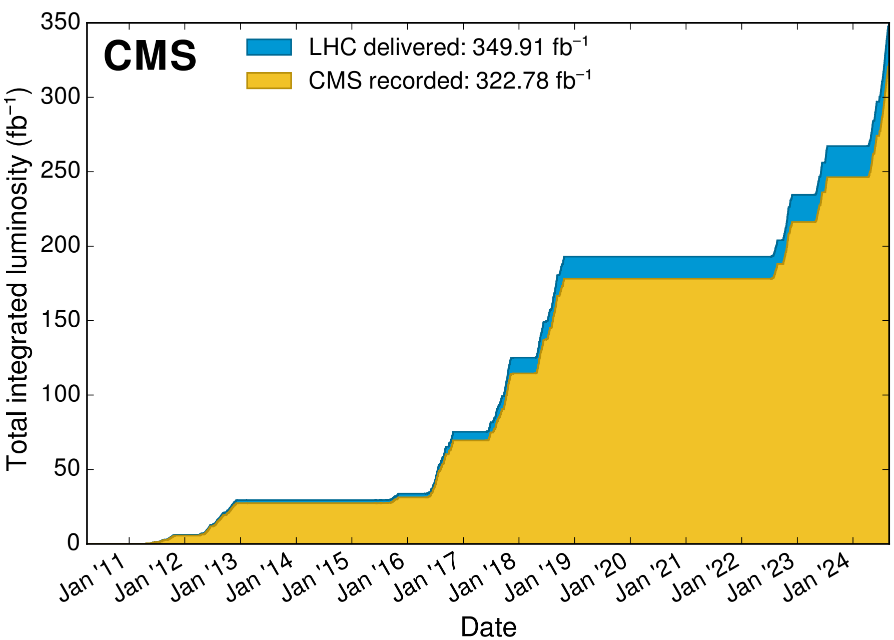
Dedication: I'd like to dedicate this talk to the memory of Peter Ware Higgs (29.05.29-08.04.24), whose transformative and groundbreaking ideas laid the foundation for the physics of the standard model and the very particle named after him

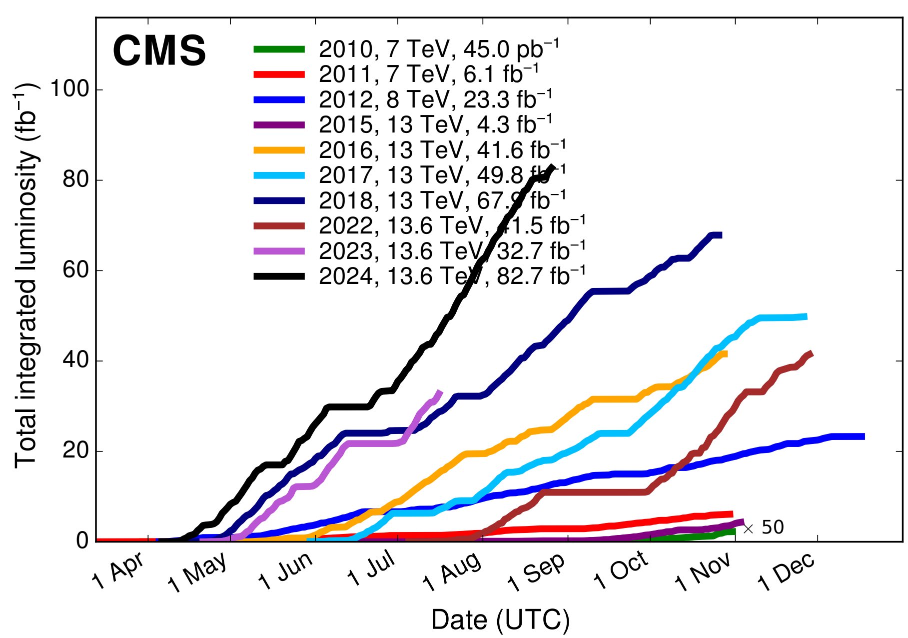
The LHC Legacy

See also Yannis Papaphilippou's talk on Tuesday next week

LHC - a Big Success!

- Nearly 350/fb of data have been delivered by the LHC in Runs 1-3 (2010-now), at a c.o.m. of 7-13.6 TeV, exceeding the integrated luminosity projections
  - 2024 is a record year with 83/fb already delivered and more data coming!
- About 90% of the delivered data are recorded and fully certified for physics analyses
- Several heavy-ion and proton-lead runs at various energies, augmented by the proton-proton reference data at the same energies
- Thank you, LHC, for the spectacular running!





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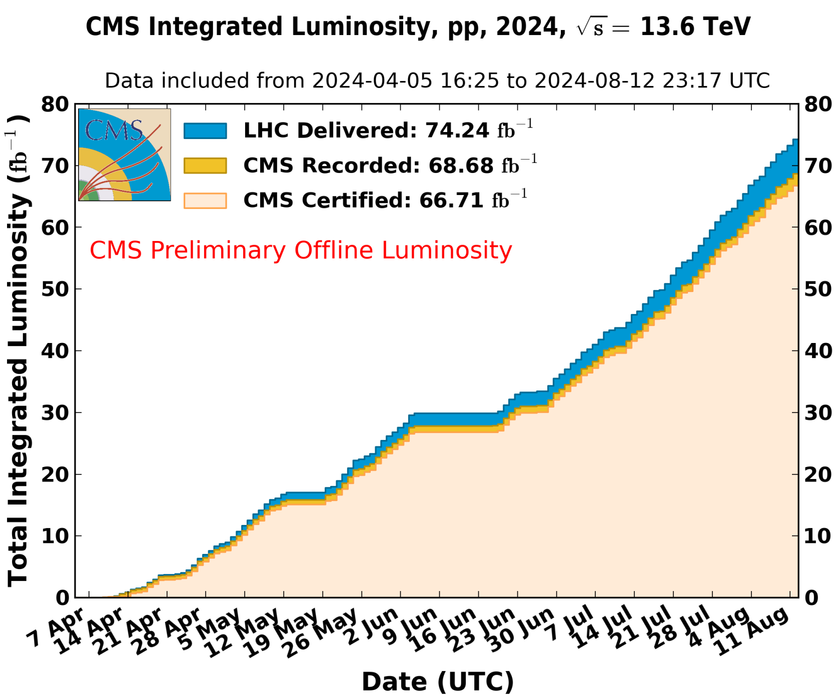

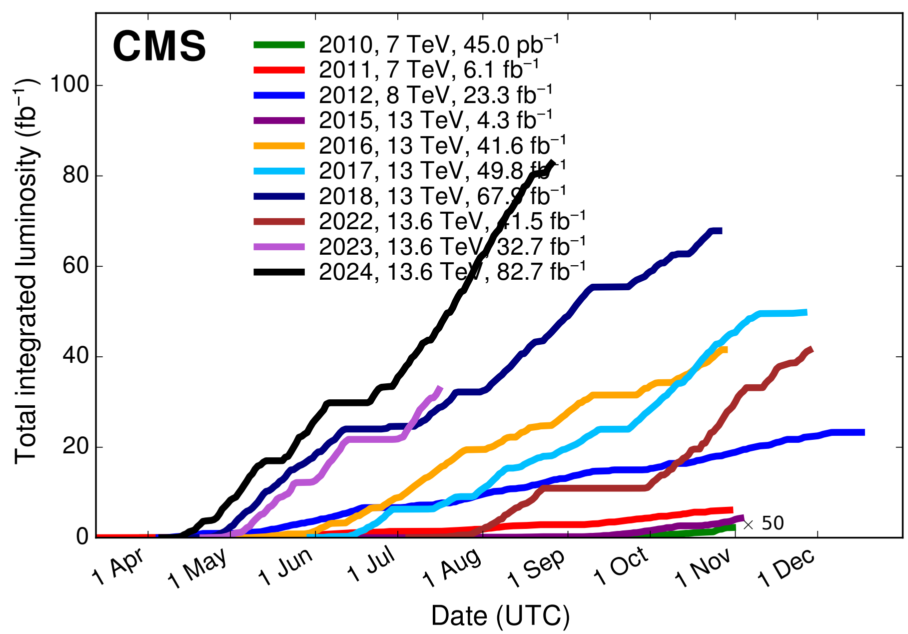


Four Machines in One!
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4-in-1 print, copy, scan, fax
Bluetooth® Smart
Dual Band Wi-Fi
35-page auto document feede
HP OfficeJet 5255
Handmade Goods Retail Store Revenue Projection
handmade
HP OfficeJet 5255
Print Photos
Print From Dropbox
Print Documents
Print Settings

The LHC Legacy

- The LHC has figuratively replaced three machines in one go:
  - Tevatron (Higgs, BSM searches, top physics, and precision EW measurements)
  - BaBar/Belle B factories (precision B physics)
  - RHIC (heavy-ion physics)
- It also added one more machine:
  - $\gamma\gamma$ collider (LbL scattering, Breit-Wheeler processes, searches for ALPs)
- The LHC experiments in general, and CMS in particular, are very successful and productive in all these four areas
- Would not be possible without theoretical and phenomenological breakthroughs of the past decade:
  - Higher-order calculations ("NLO revolution" → N^3LO), modern Monte Carlo generators, reduced and better estimated PDF uncertainties
- Since it's impossible to cover all the aspects of this impressive program in one talk, I'll present a few highlights of recent CMS results in Higgs physics, SM physics, flavor physics, heavy-ion physics, and the discovery program, somewhat geared to the topics of this workshop

Challenge: Big Data

- The amount of data produced by each LHC experiment is truly enormous: ~10 PB/year
- It takes some time to fully calibrate and align the detectors, and then reconstruct the data with the best possible calibrations
- As a result, most of the results presented in these talk are based on Run 2 (2015-2018, 13 TeV, ~140/fb) data
- First results from Run 3 dataset at 13.6 TeV started to appear and will be highlighted as well
- Overall, a very fast turn-around compared to earlier generations of HEP experiments!

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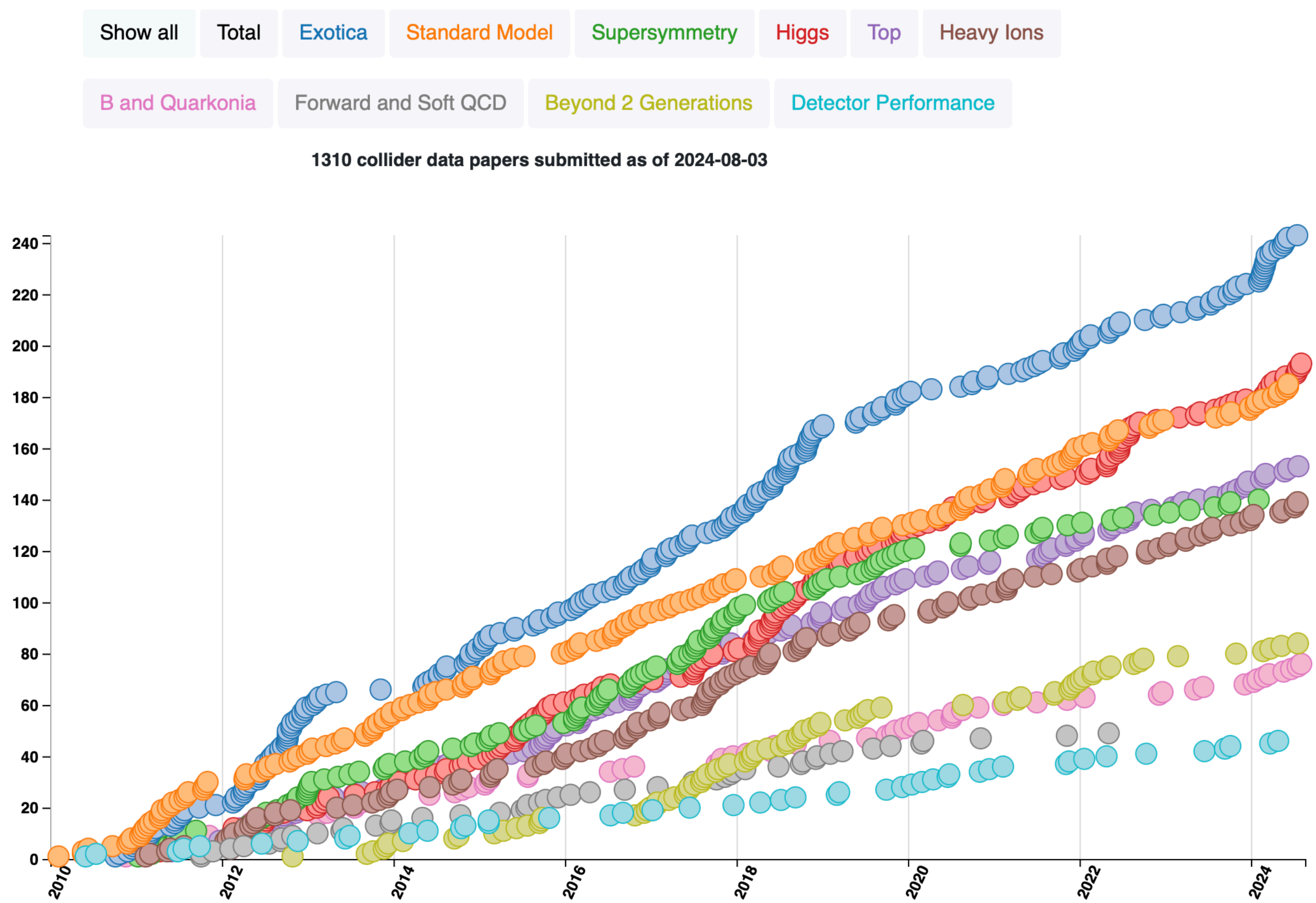
Publish or Perish!

✦ CMS: over 1,300 papers submitted, with searches, Higgs, and SM dominating (~100 papers/year, i.e., 2/week)

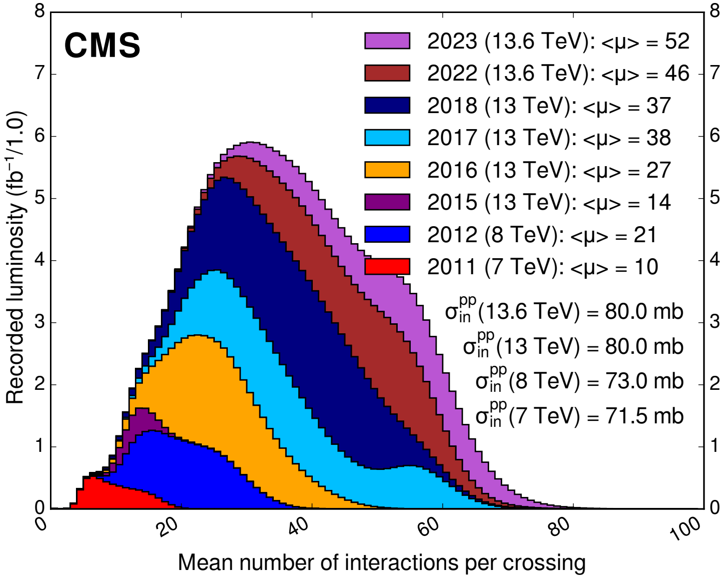


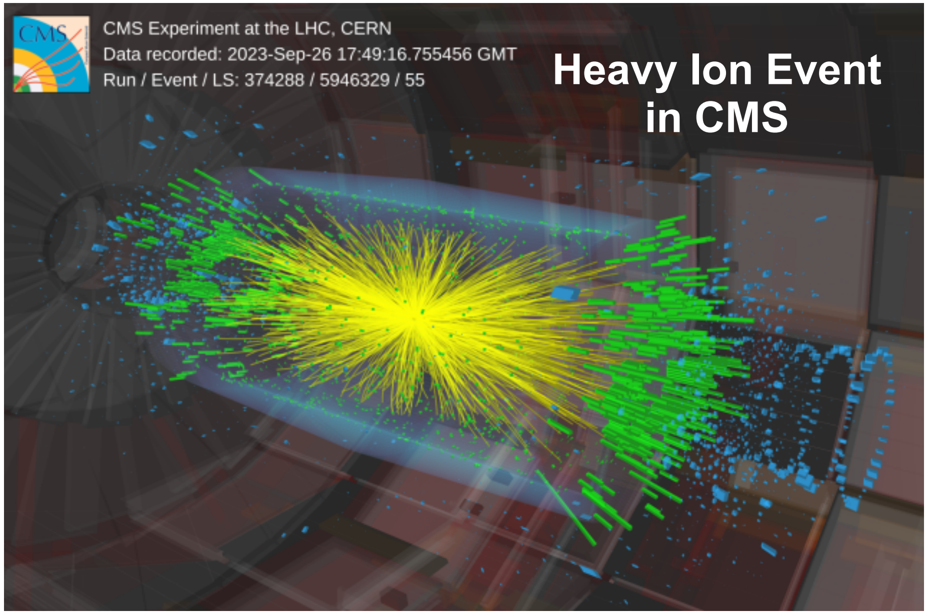
ATLAS+CMS Physics Reports

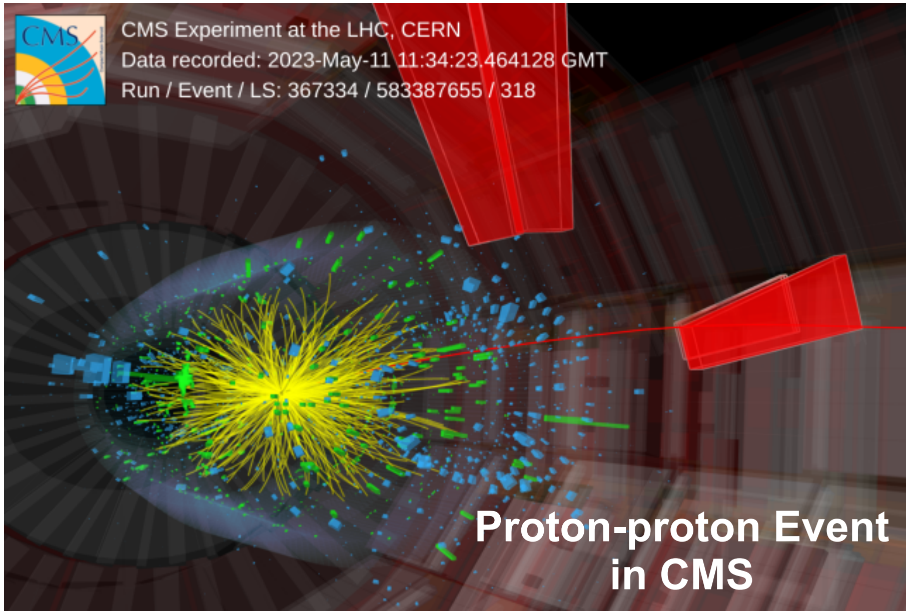
- CMS (ATLAS) just submitted 7 (6) Phys. Rept. articles on various aspects of the LHC physics program
  - These are legacy Run 2 papers and a valuable resource on experimental techniques and results
- CMS:
  - arXiv:2403.01313, Review of top quark mass measurements in CMS
  - arXiv:2403.16926, Searches for Higgs boson production through decays of heavy resonances
  - arXiv:2403.16134, Enriching the physics program of the CMS experiment via data scouting and data parking
  - arXiv:2405.10785, Overview of high-density QCD studies with the CMS experiment at the LHC
  - arXiv:2405.13778, Dark sector searches with the CMS experiment
  - arXiv:2405.17605, Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV at the CMS experiment
  - arXiv:2405.18661, Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns

Challenge: Pileup

- In CMS now a proton-proton event looks nearly as busy as a heavy-ion one!
- Average number of simultaneous interactions per bunch crossing (pileup, PU) is about 50 in Run 3
    - This by far exceeds the original LHC design PU number of 20
- Developed sophisticated tools to mitigate the effects of the PU: particle-flow reconstruction, machine-learning techniques



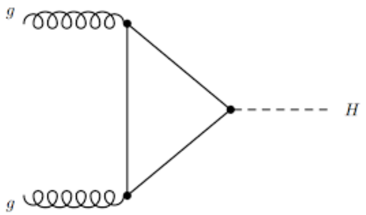




See also Sandra Kortner's talk tomorrow

Higgs Physics Highlights

Higgs Factory

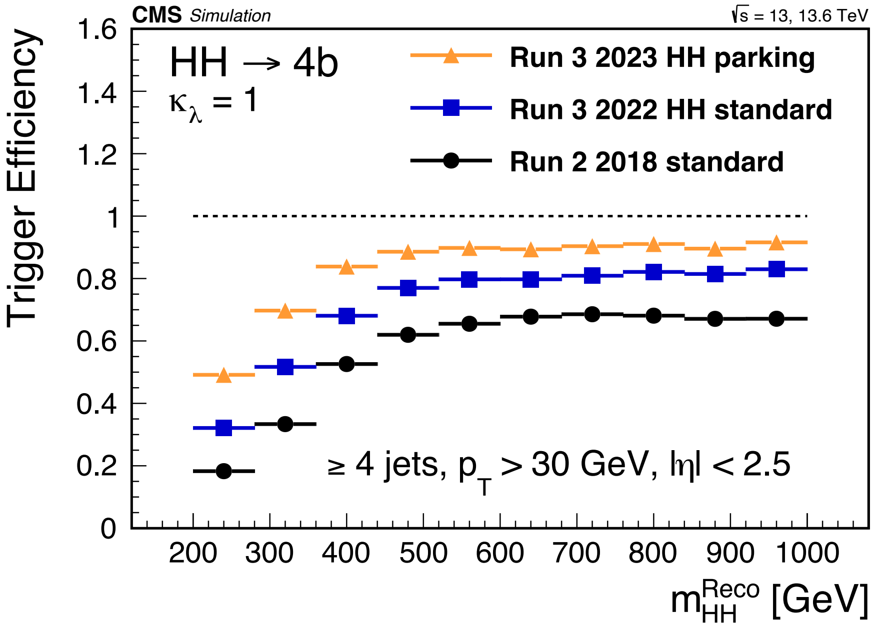


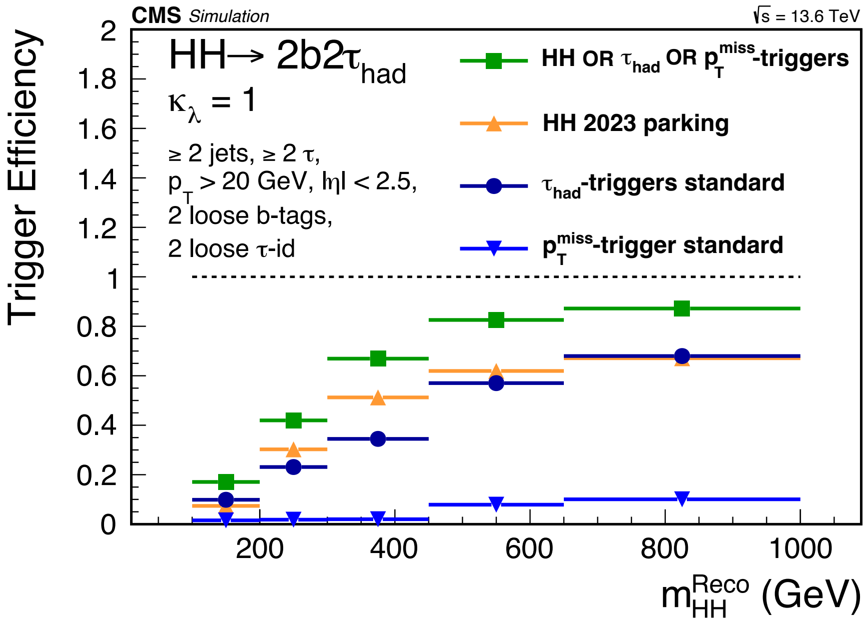
- LHC is the Higgs factory and the only place to study Higgs physics directly today
- At 13 TeV, the production cross section for the Higgs boson, dominated by gluon-gluon fusion, is ~50 pb
  - 14M Higgs bosons delivered by the LHC in Run 2!
  - By now ATLAS and CMS could have accumulated as many Higgs bosons as four LEP experiments accumulated Z bosons
  - With the cross section @13.6 TeV of ~60 pb another 9M have been already delivered in Run 3!
- But: triggering is a big challenge:
  - Most of gg → H(bb) events were never put on tape, which is how half of the Higgs bosons are produced and decay
- Need to pursue aggressive triggering strategies and go for lower cross section production mechanisms to observe all possible Higgs boson decays and couplings

Old Challenges, New Triggers

- Increased the L1 bandwidth by 15% compared to Run 2 and rebalanced the L1 trigger menu
- Designed high-rate b-tagged jet triggers for Run 3
  - Improved the efficiency for HH(4b) and HH(2b2τ) by up to 50% in 2023 compared to Run 2, and even more so for 2024 running

CMS arXiv:2403.16134





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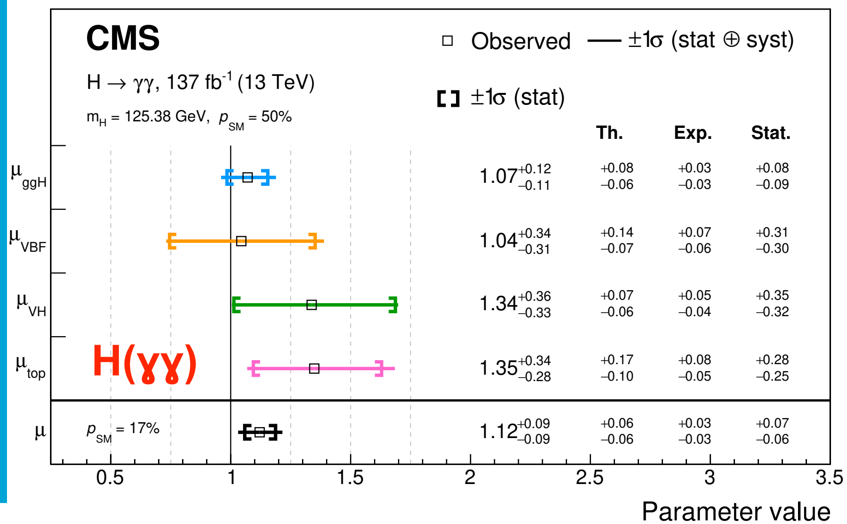
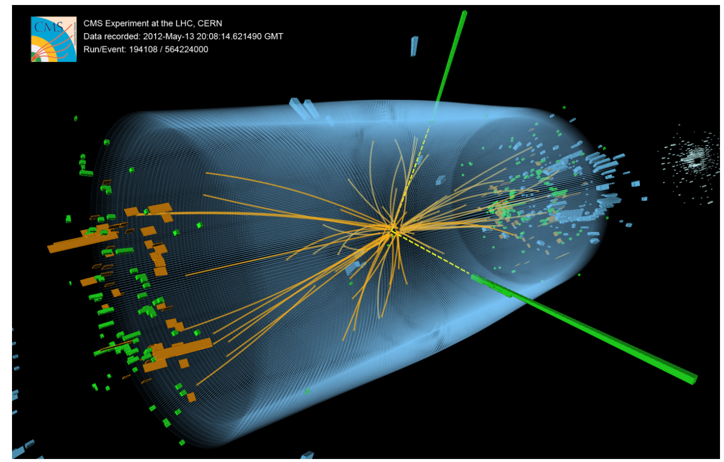
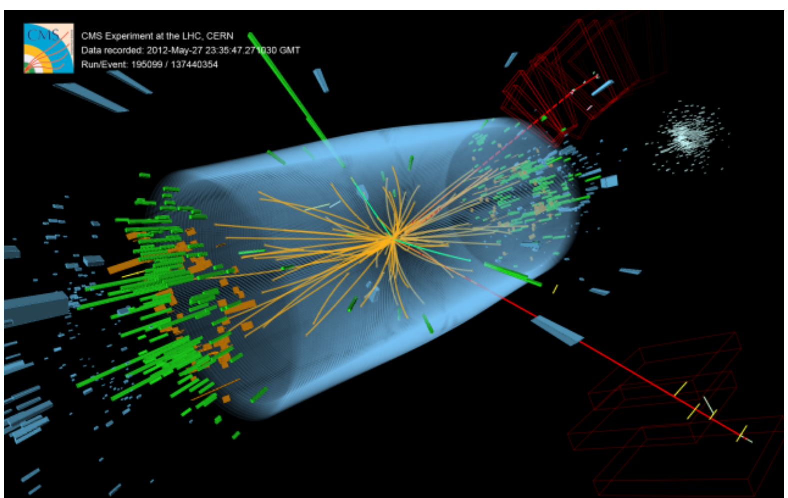
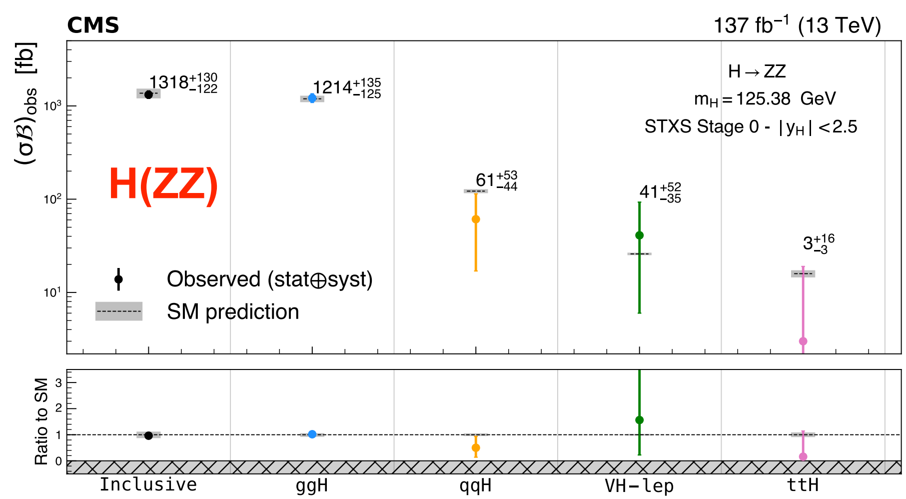
Higgs Boson Cross Sections

- ✦ Inclusive and fiducial cross section in multiple production modes have been measured and broadly agree with the SM predictions







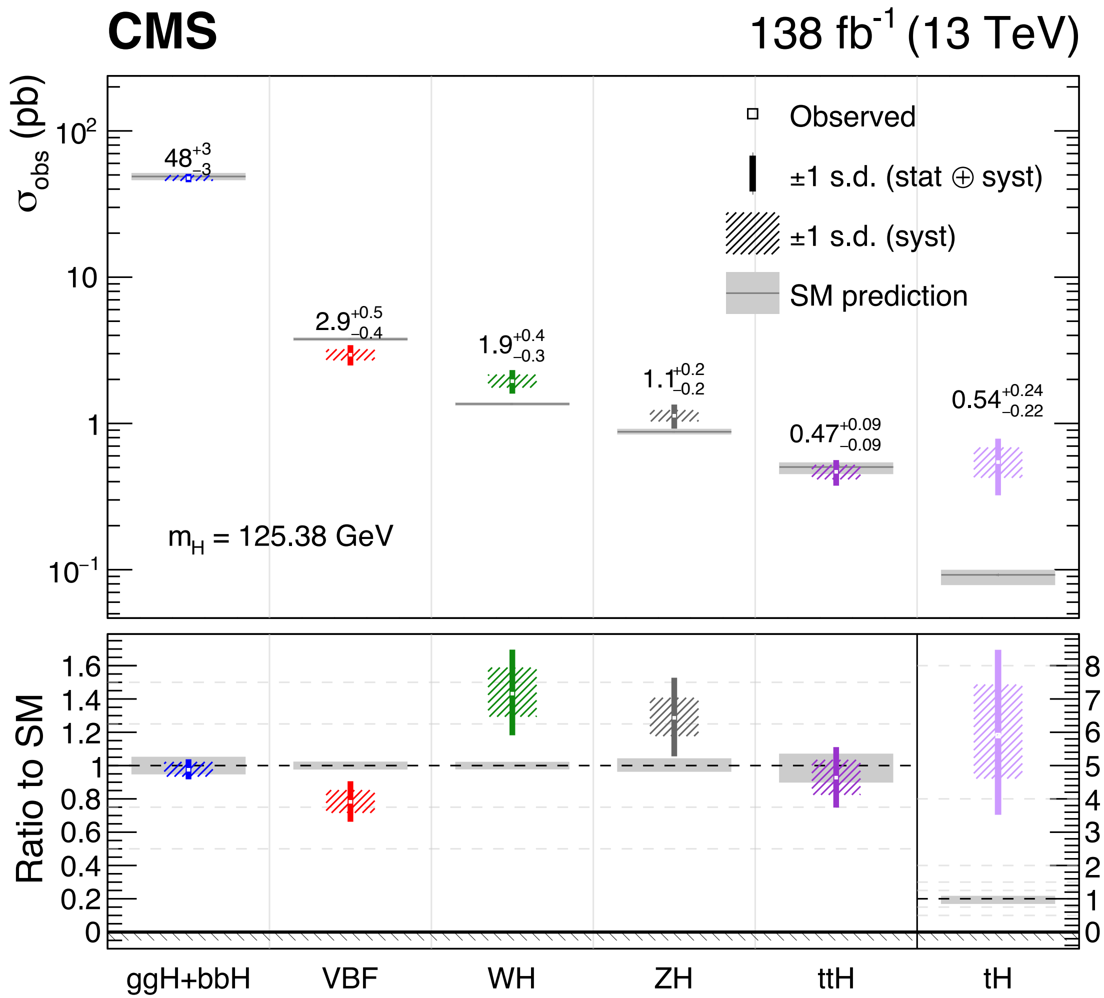


CMS JHEP 07 (2021) 027

CMS EPJC 81 (2021) 488

Production Modes Combination

✦ The combined cross section results per production mode are also now available and are in good agreement with the SM predictions



CMS arXiv:2405.18661

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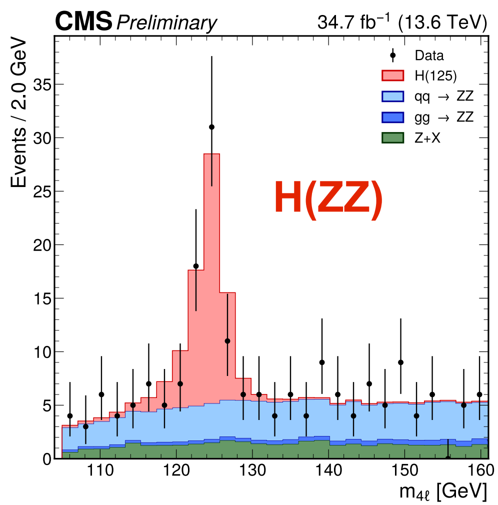
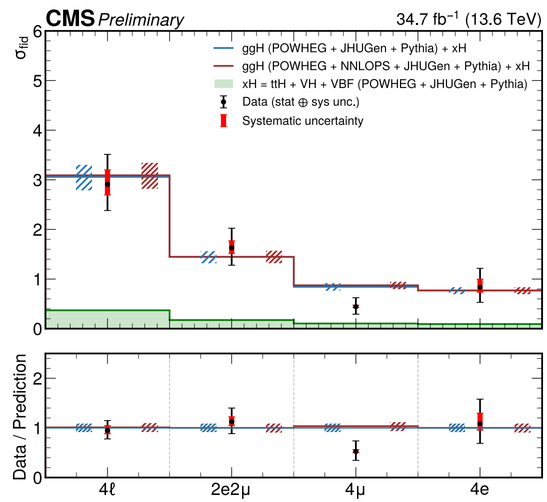
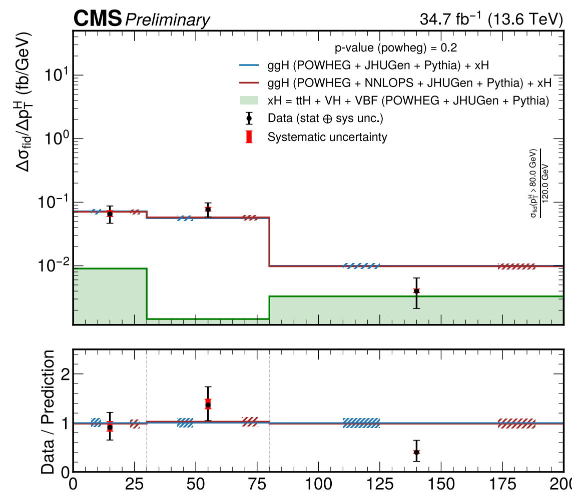
H(ZZ/γγ) at 13.6 TeV

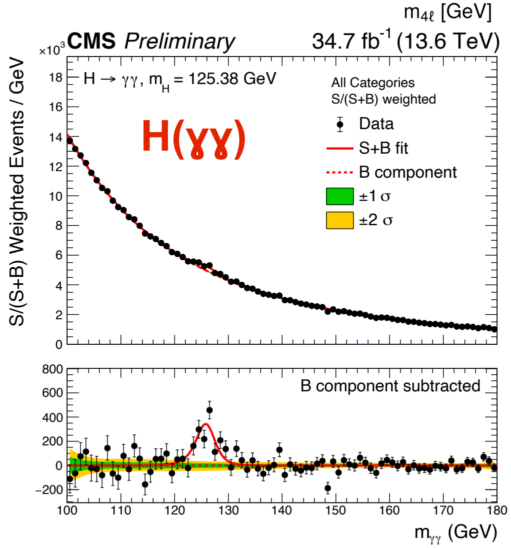
- ✦ First Higgs boson production properties measurements with 13.6 TeV data are now available in H(ZZ) and H(γγ) channels

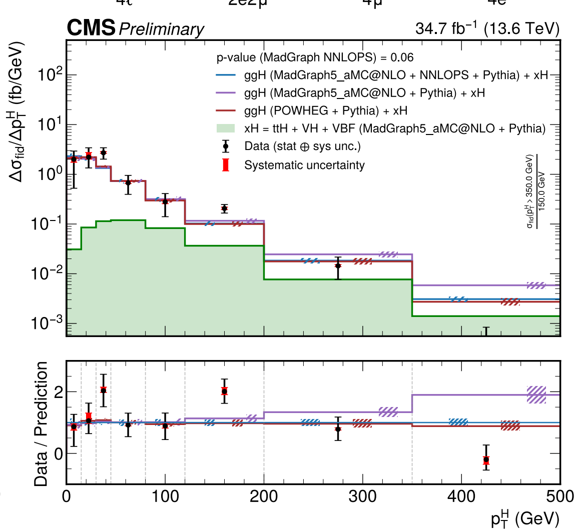


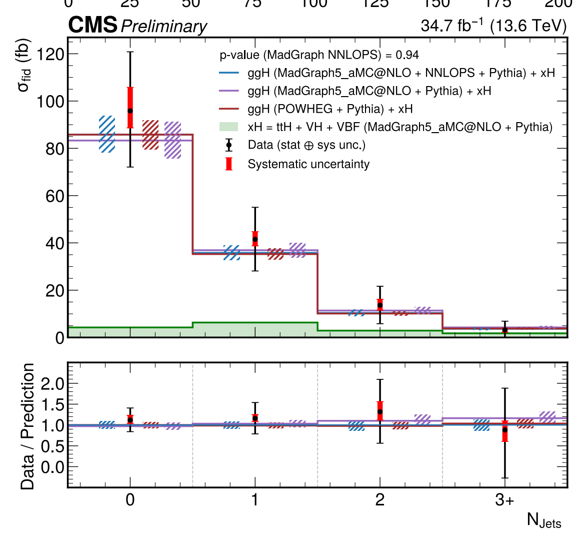




CMS PAS HIG-24-013

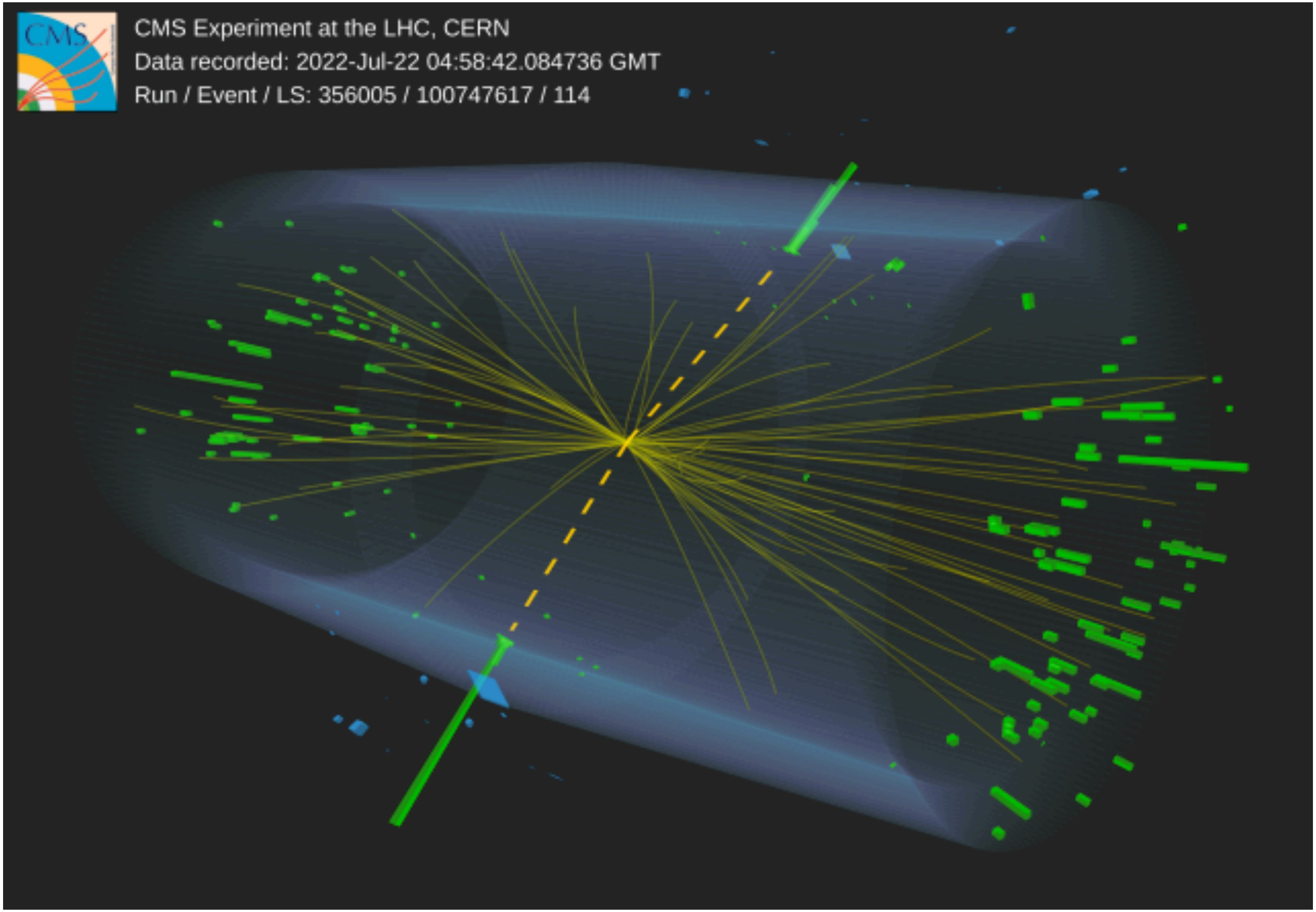




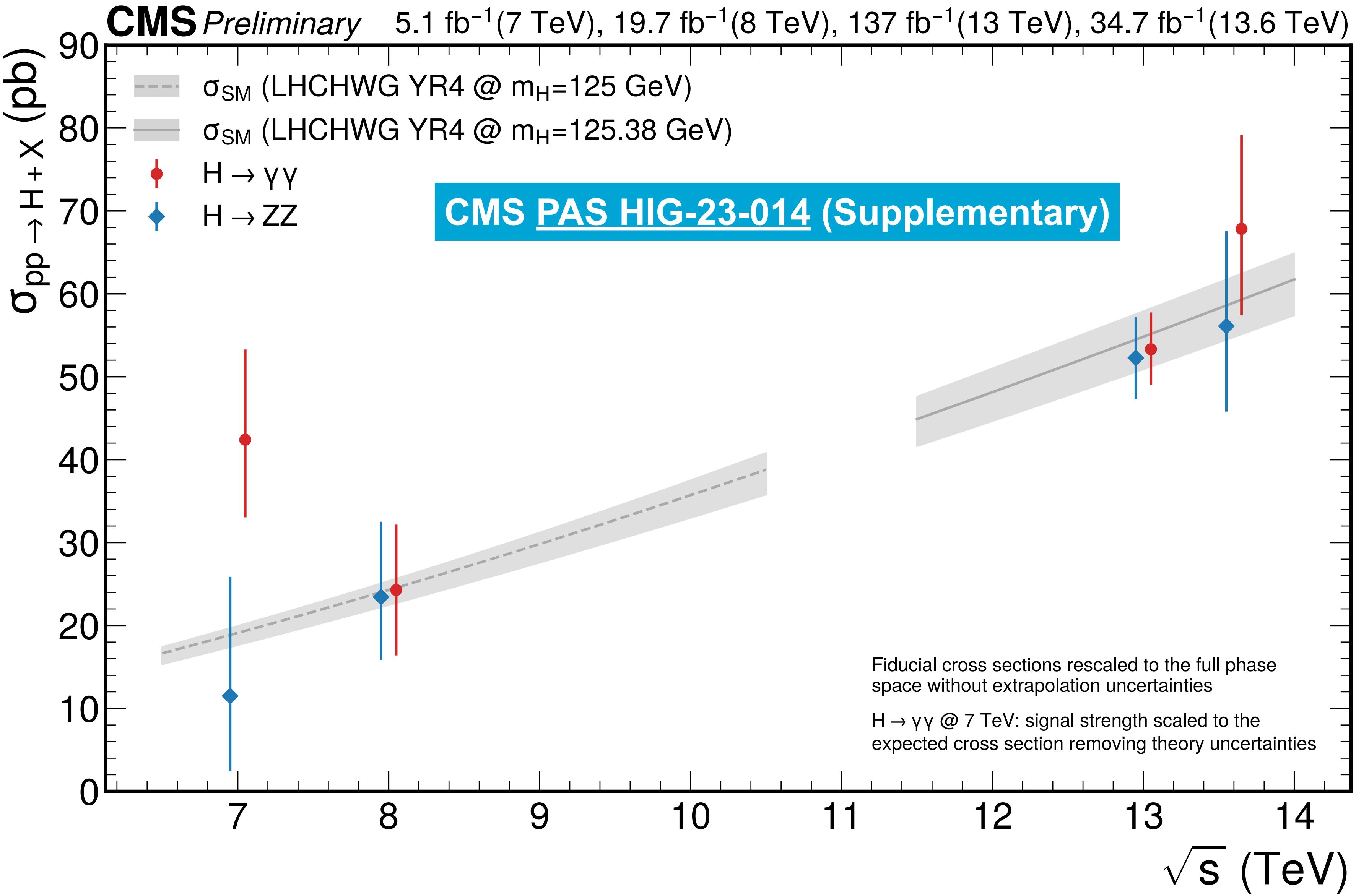


CMS PAS HIG-23-014

Higgs at 13.6 TeV

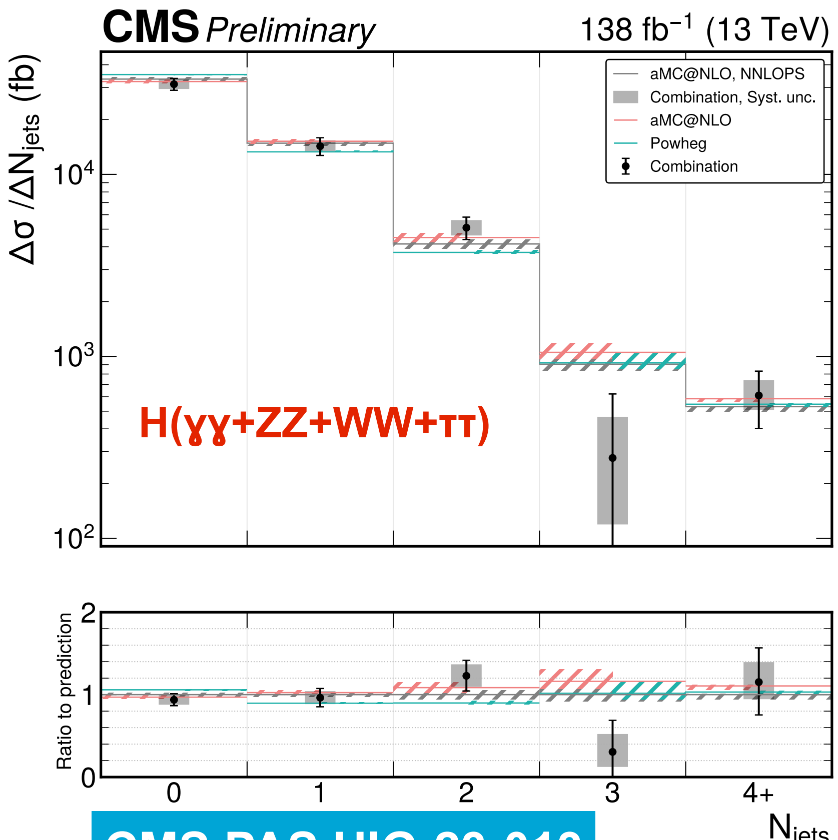


Energy Dependence

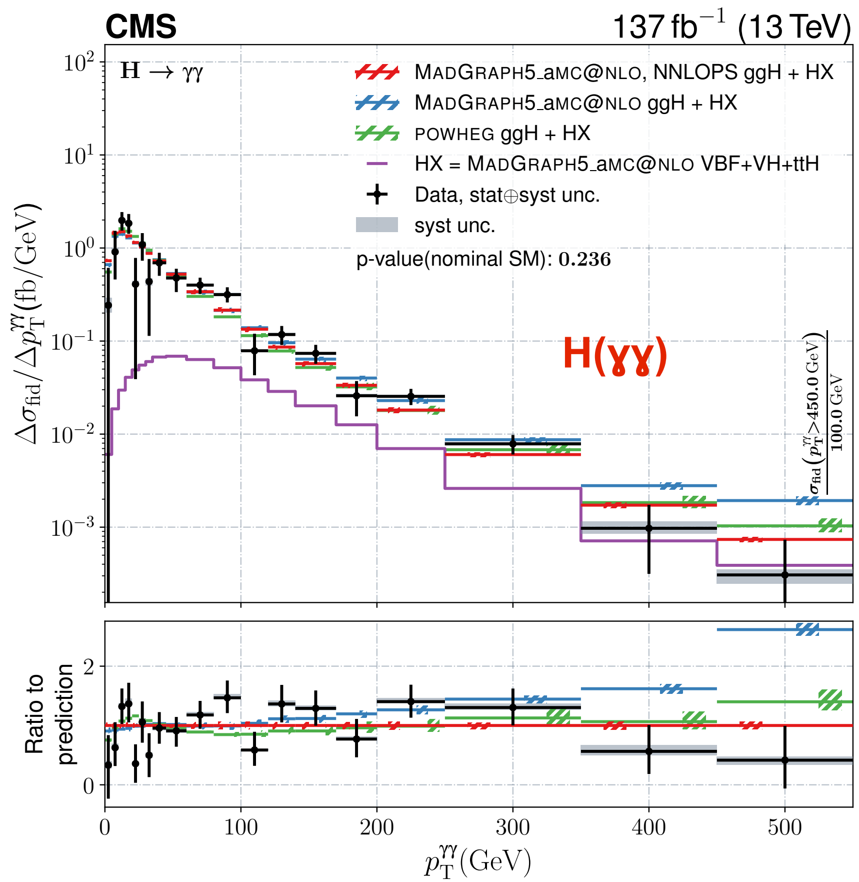


Going Differential

- By now the number of recorded Higgs bosons is large enough to start measuring differential cross sections
- Stress tests of higher-order theoretical calculations and parton shower generators



CMS PAS HIG-23-013

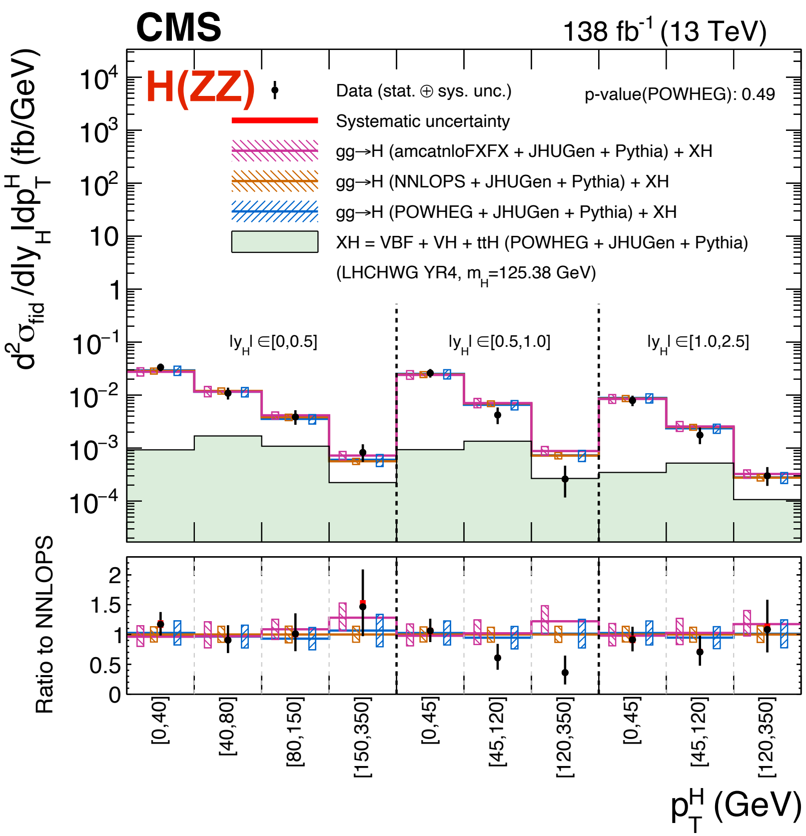


CMS JHEP 07 (2023) 091

Going Doubly Differential

- Already started probing double-differential cross sections with reasonable precision (e.g., ZZ channel, $d^2\sigma/dp_T d|y|$)
- Important for testing theory prediction at high p_T(H), high associated jet multiplicity, high rapidity, etc.

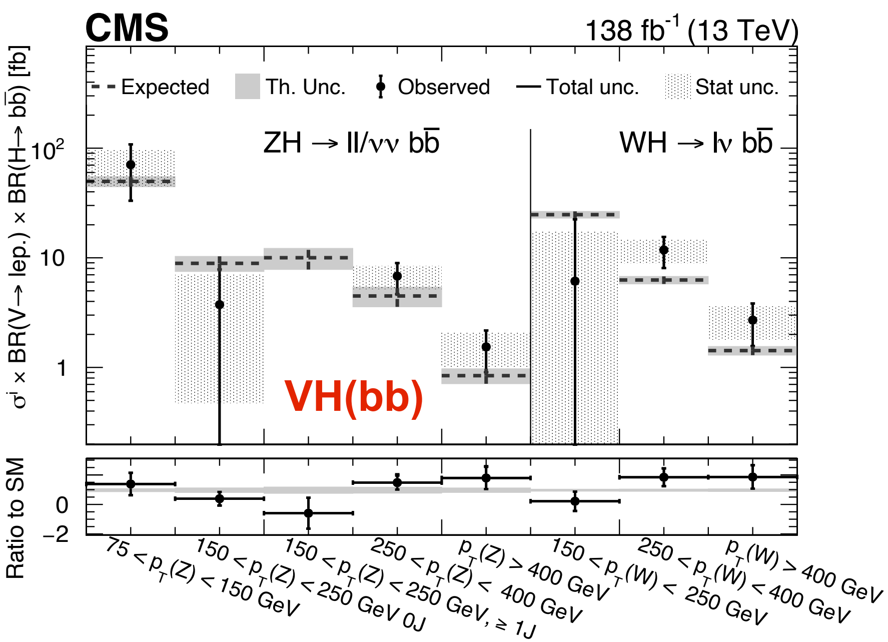
CMS JHEP 08 (2023) 040



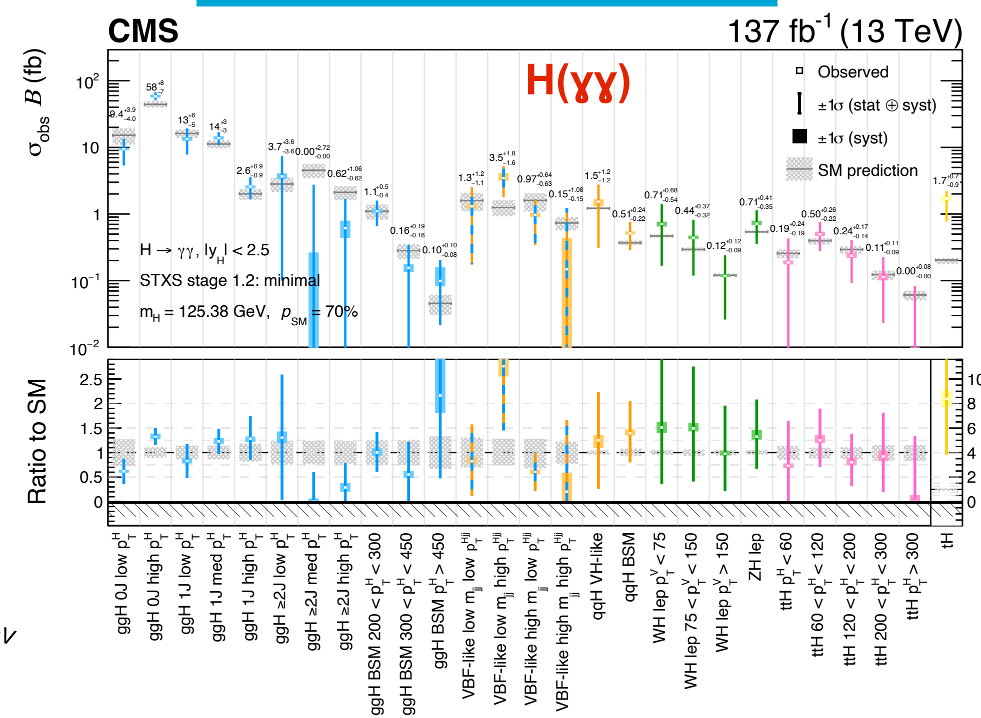
Going STXS

- More and more results are being interpreted in the Simplified Template Cross Section (STXS) framework, which is somewhat in between fully inclusive and fully differential measurements
- Allows for a straightforward SMEFT reinterpretation and setting constraints on various Wilson coefficients, thus providing sensitivity to BSM physics

CMS PRD 109 (2024) 092011



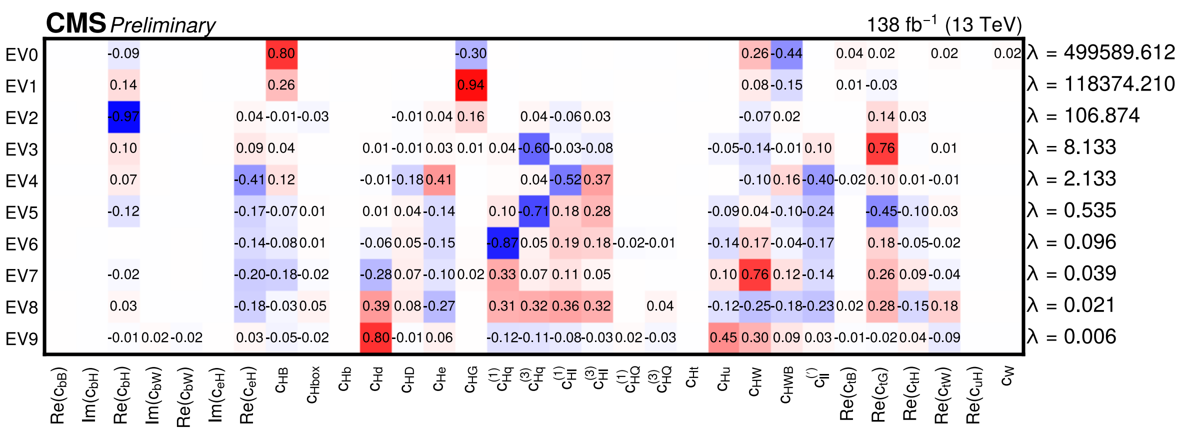
CMS JHEP 07 (2021) 027

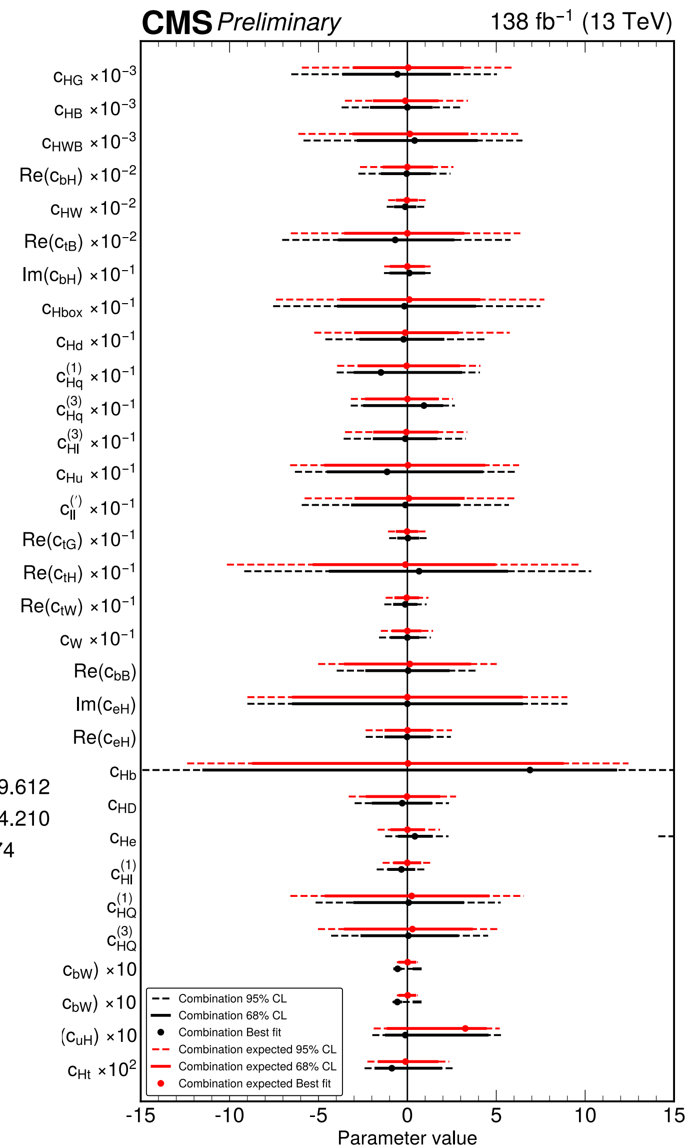


SMEFT Interpretations

- ✦ SMEFT principal component analysis of the combined H(γγ, ZZ, WW, ττ) differential cross section measurements
- ✦ Decompose the covariance matrix in 10 principal eigenvectors and translate the limits on these eigenvectors into limits on Wilson coefficients

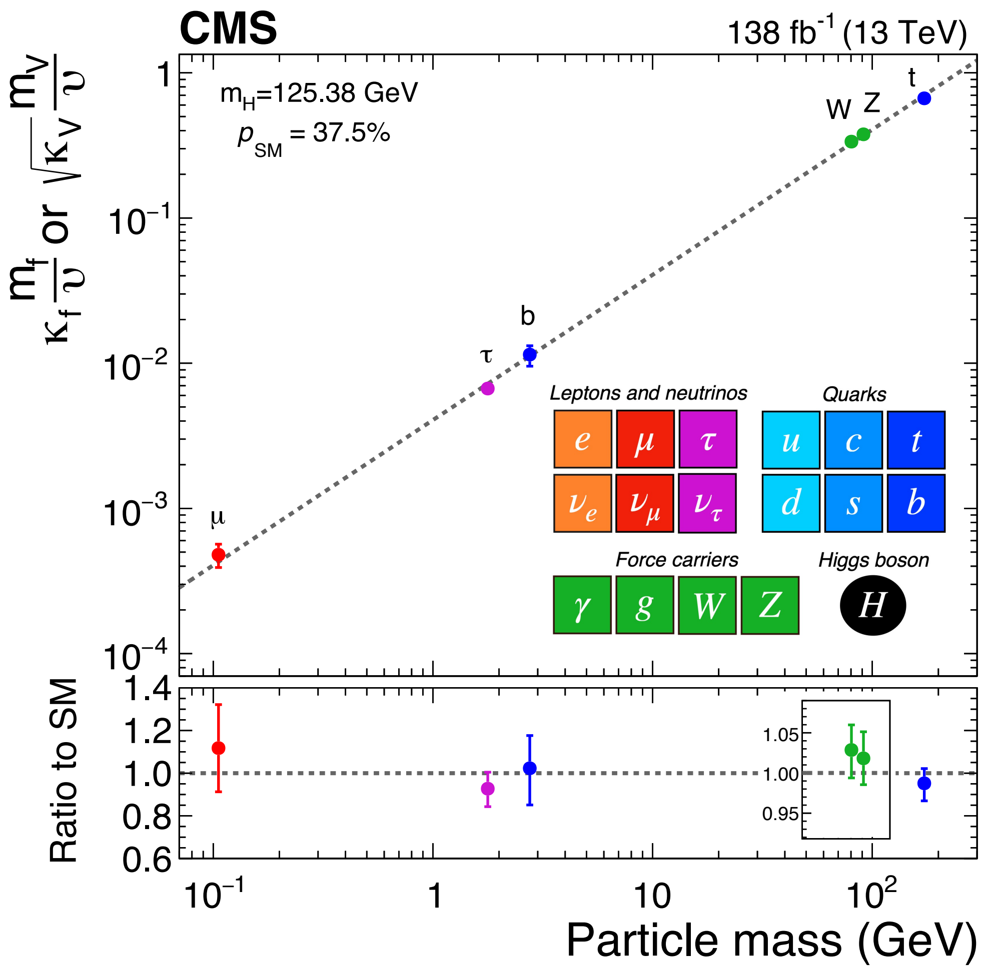
CMS PAS HIG-23-013



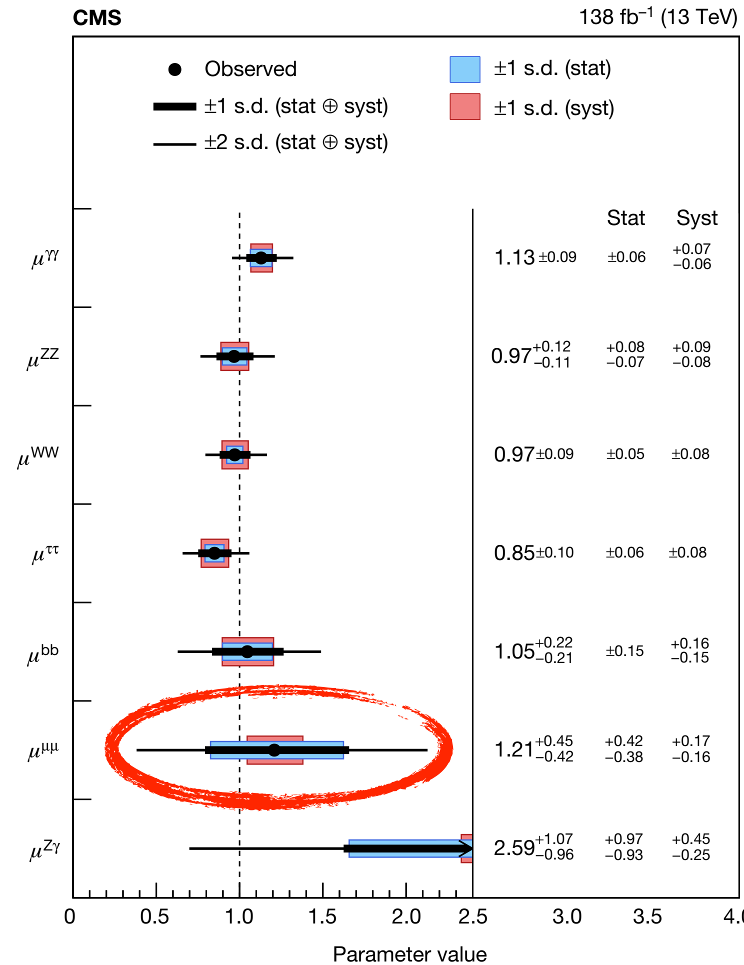


Higgs Boson Couplings

- Couplings to third-generation fermions and EW bosons have been measured; first evidence for coupling to muons

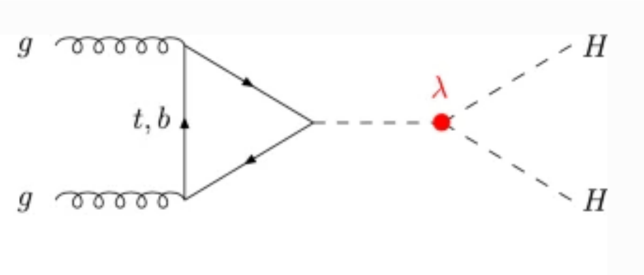


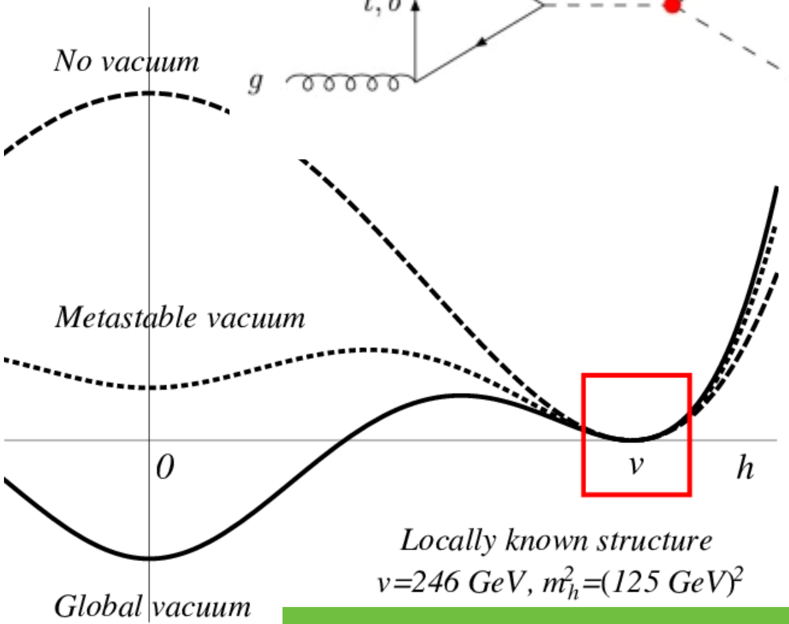
CMS Nature 607 (2022) 60



Exploring Higgs Potential

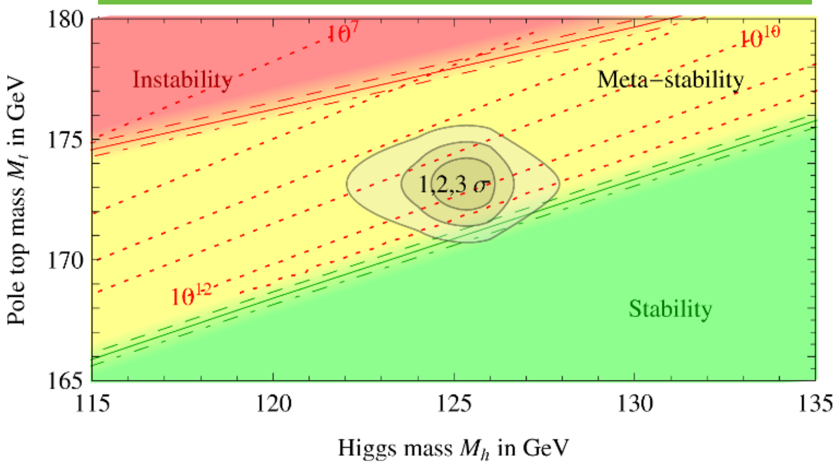
- One of the most important couplings is a Higgs boson self-coupling, λ
- Directly affects the shape of the Higgs potential, with implications for both early and late universe (e.g., EW vacuum stability)
- Depends on λ (or, in the SM, $m_H = \sqrt{2\lambda}v$), m_t, and α_s
- Important to precisely measure all these parameters, including λ, to test the predictions of the Higgs mechanism





Bai et al. JHEP 07 (2021) 225

Degrassi et al. JHEP 08 (2012) 098



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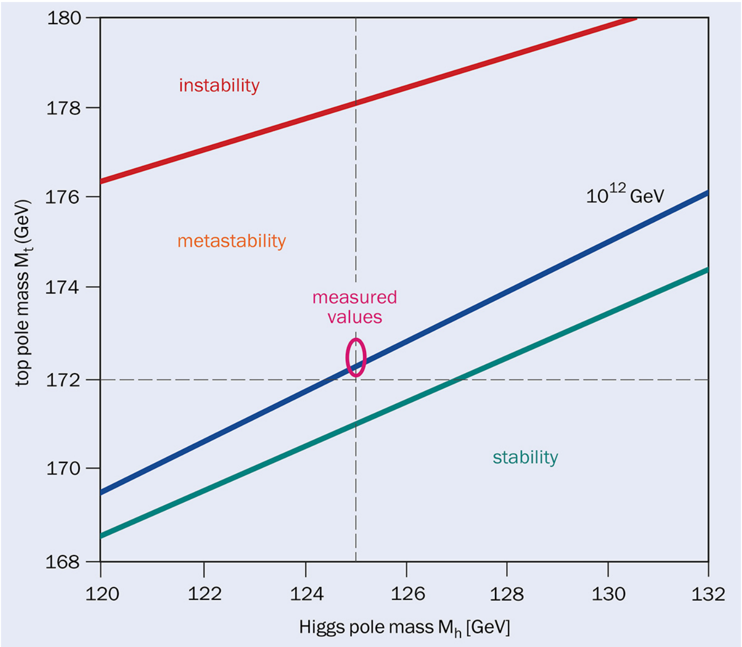
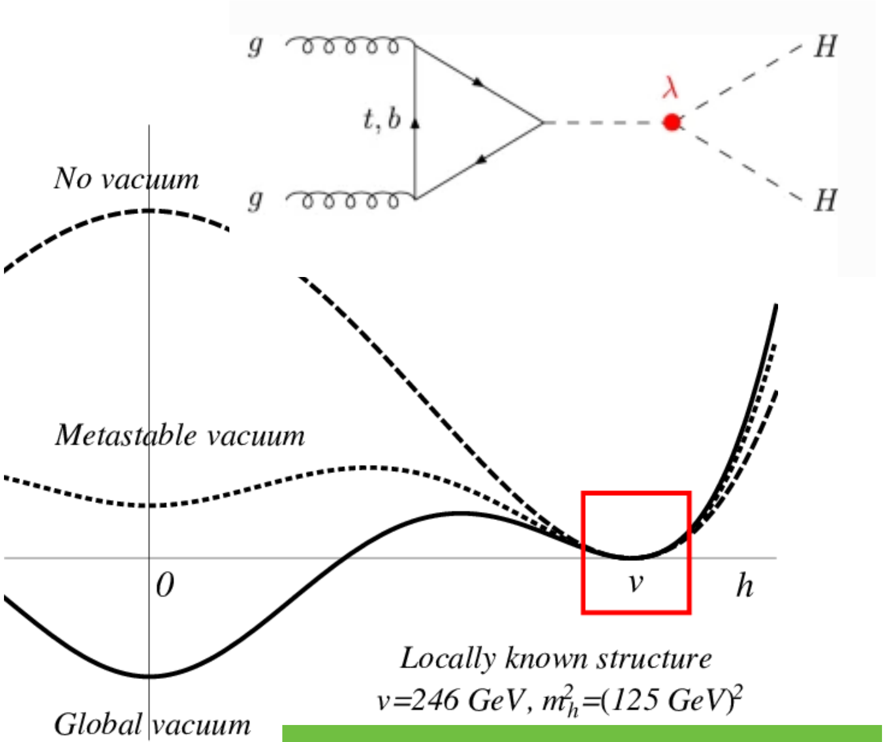
J. Ellis, CERN Courier 62 (2022) 59



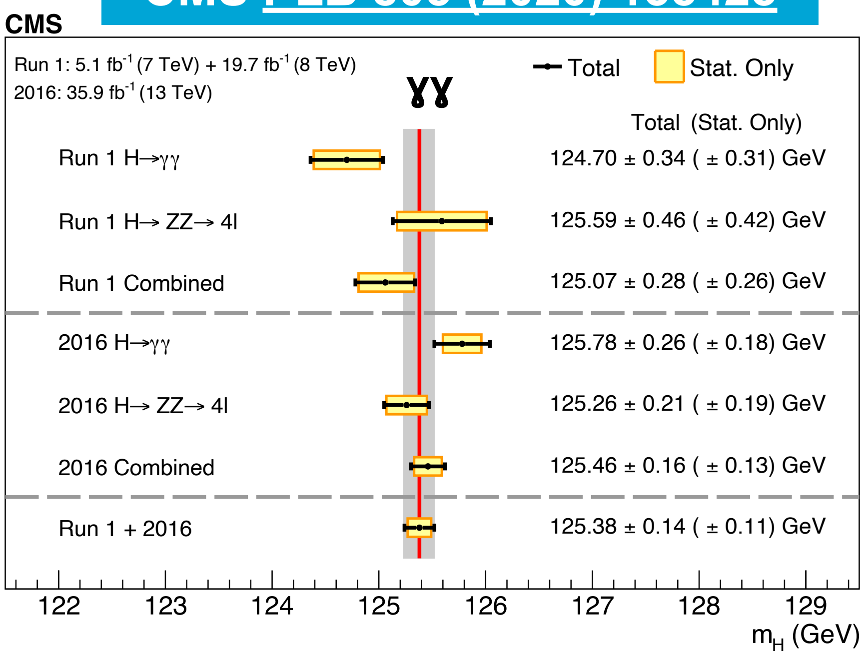


Bai et al. JHEP 07 (2021) 225

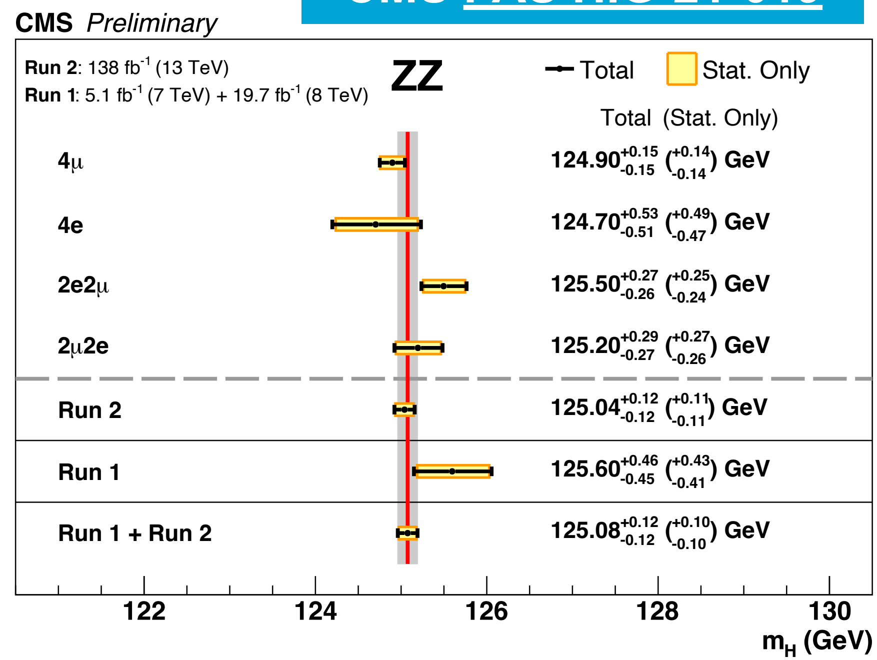
Higgs Boson Mass and Width

- New, more precise measurements of the Higgs boson mass with sub-permille precision have been achieved!
  - $M_H = 125.38 \pm 0.14$ GeV ($H \to \gamma\gamma$) and **125.08 ± 0.12 GeV** ($H \to ZZ$)
  - CMS also measured the Higgs boson width by combining on-shell and off-shell production of H(ZZ) with
    - $\Gamma_H =$ **$3.2^{+2.4}_{-1.7}$ MeV** [CMS, Nat. Phys. **18** (2022) 1329]
- Measurements are in agreement with the SM prediction of $\Gamma_H = 4.1$ MeV

CMS PLB 805 (2020) 135425



CMS PAS HIG-21-019



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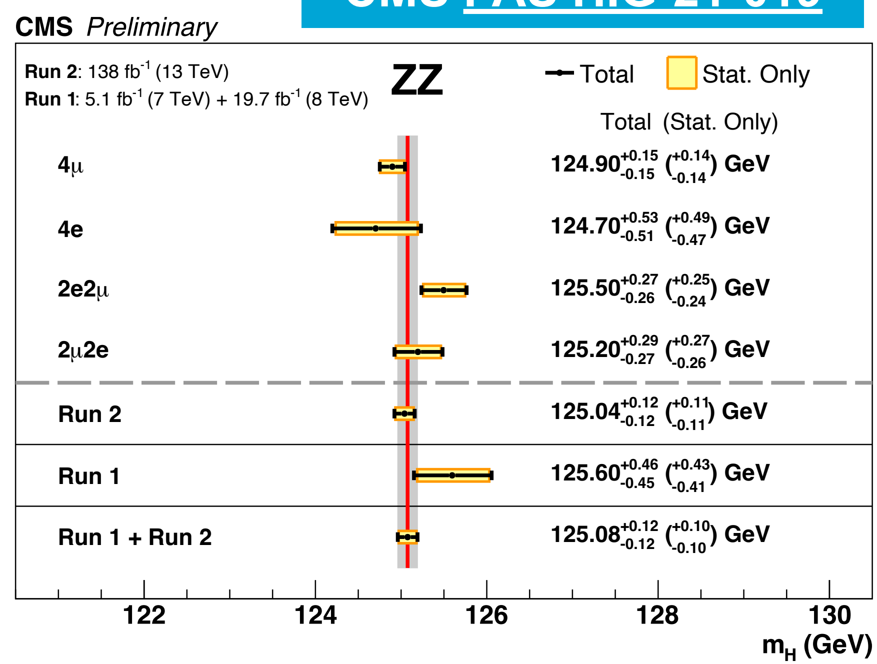
CMS PAS HIG-21-019

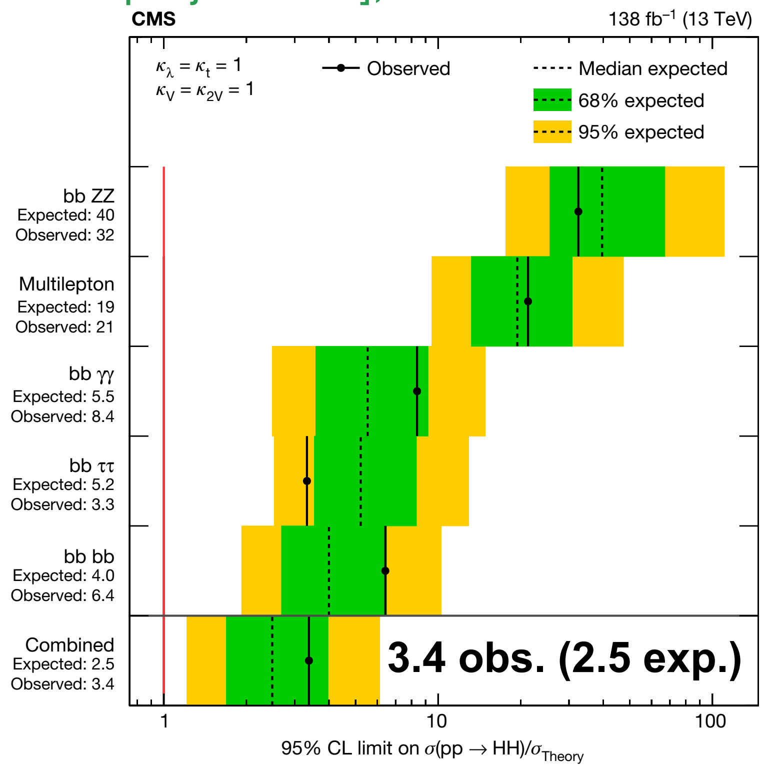
γγ



Probing Self-Coupling

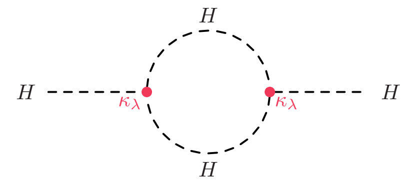
- Measurement of Higgs boson self-coupling λ is an ultimate goal of HL-LHC
- The cross section is very low, due to large negative interference between the diagrams contributing to Higgs boson pair production
- Enormous progress has been achieved using ML b tagging techniques, multivariate methods, and new triggers; first Run 3 results are coming soon
- Current CMS 95% CL limits on $\mu = \sigma/\sigma_{SM}$ for HH production are <3.4 (2.5) [already exceeded early HL LHC projections!]; full Run 2 combination is on its way

CMS Nature 607 (2022) 60



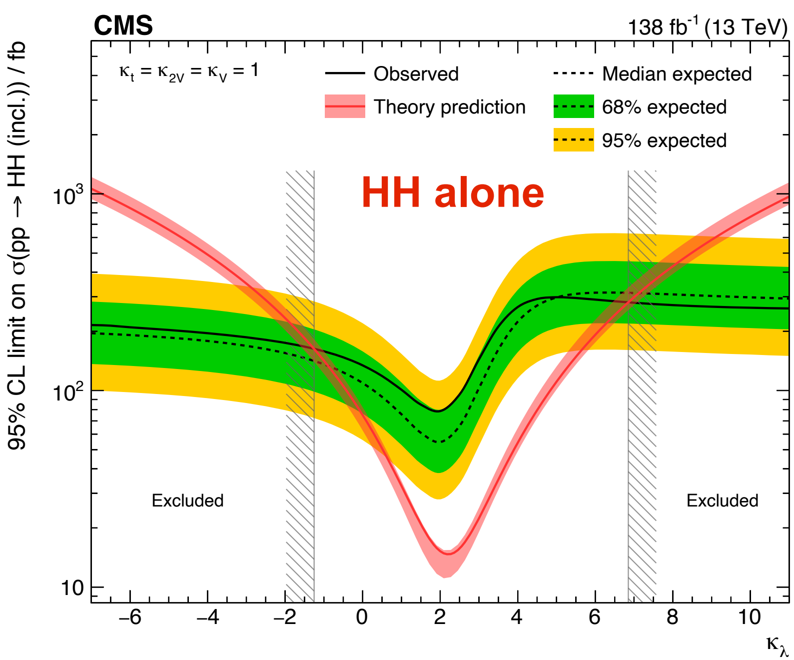
Sensitivity to λ

- ✦ Because of the negative interference, sensitivity to λ is non-trivial
  - ◉ Combination of single and double Higgs production helps to constrain the self-coupling in a more model-independent way

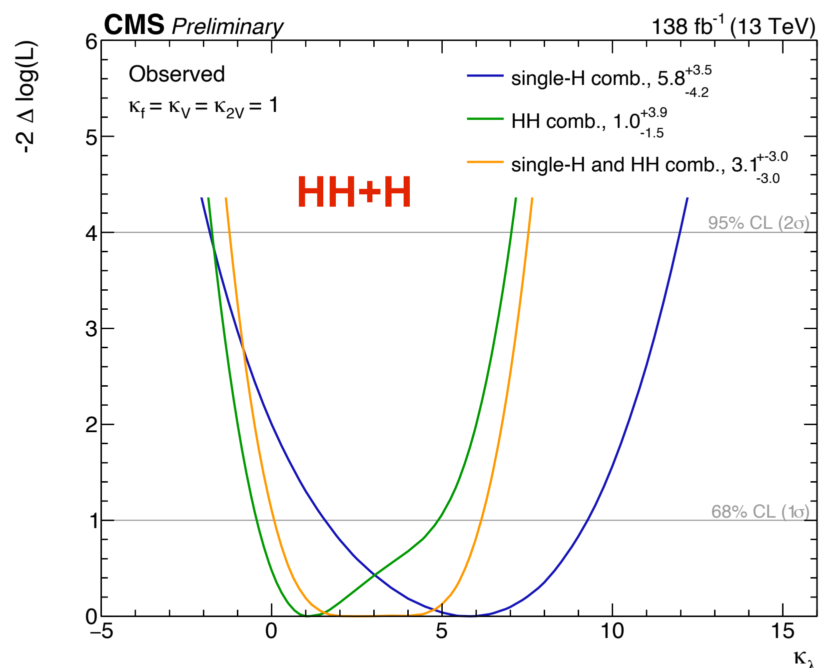


$-1.24 < \kappa_\lambda < 6.9$ @ 95% CL
$0.67 < \kappa_{2V} < 1.38$ @ 95% CL
$\kappa_{2V} = 0$ is excluded at 6.6σ!

$-1.2 < \kappa_\lambda < 7.5$ @ 95% CL
$-2.3 < \kappa_\lambda < 7.88$ @ 95% CL if κ_{2V}, κ_V, κ_f are left unconstrained



CMS Nature 607 (2022) 60



CMS PAS HIG-23-006

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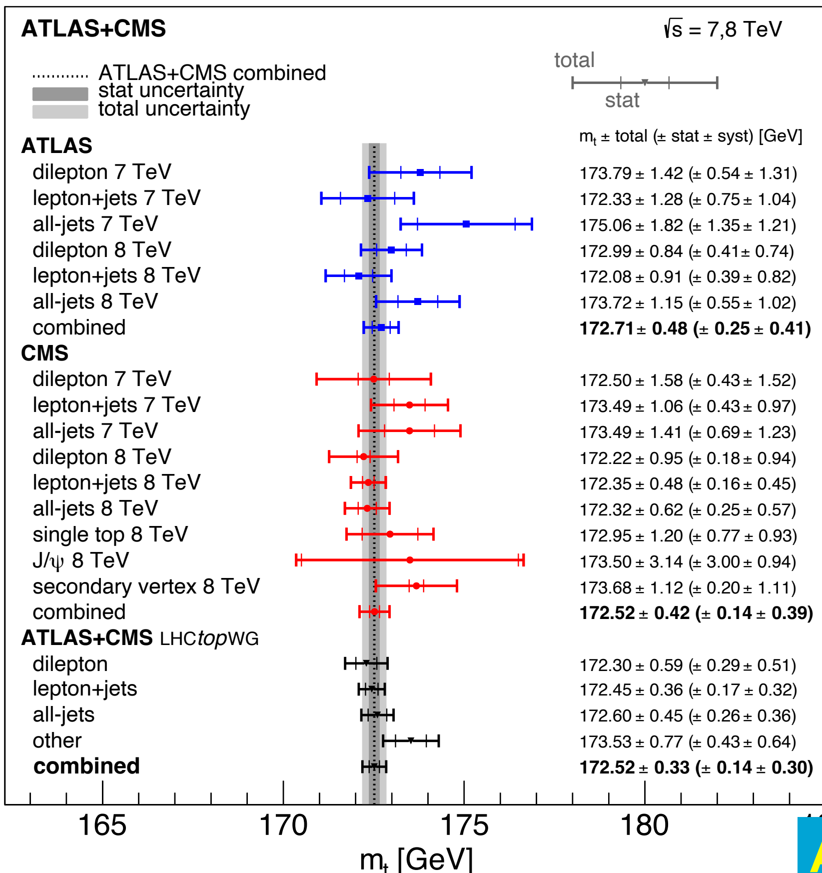
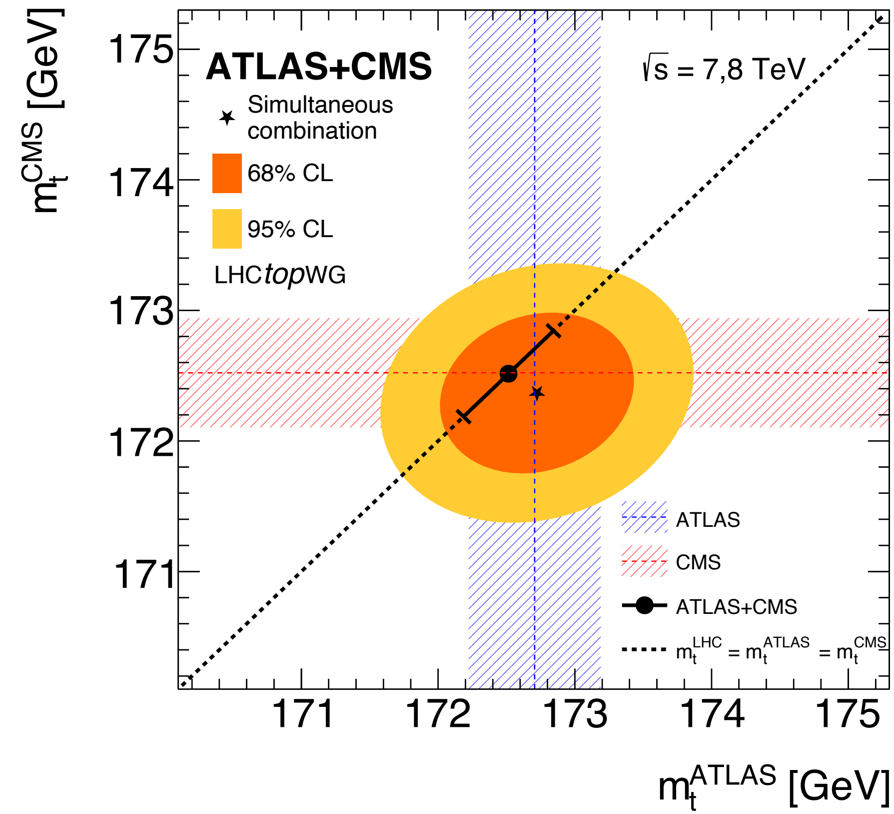
Top Quark Mass Measurement

- The most precise measurement of the top quark mass is currently from a recent Run 1 combination of ATLAS and CMS measurements: $m_t = 172.52 \pm 0.33$ GeV, with <2‰ precision
  - The most precisely measured quark mass!





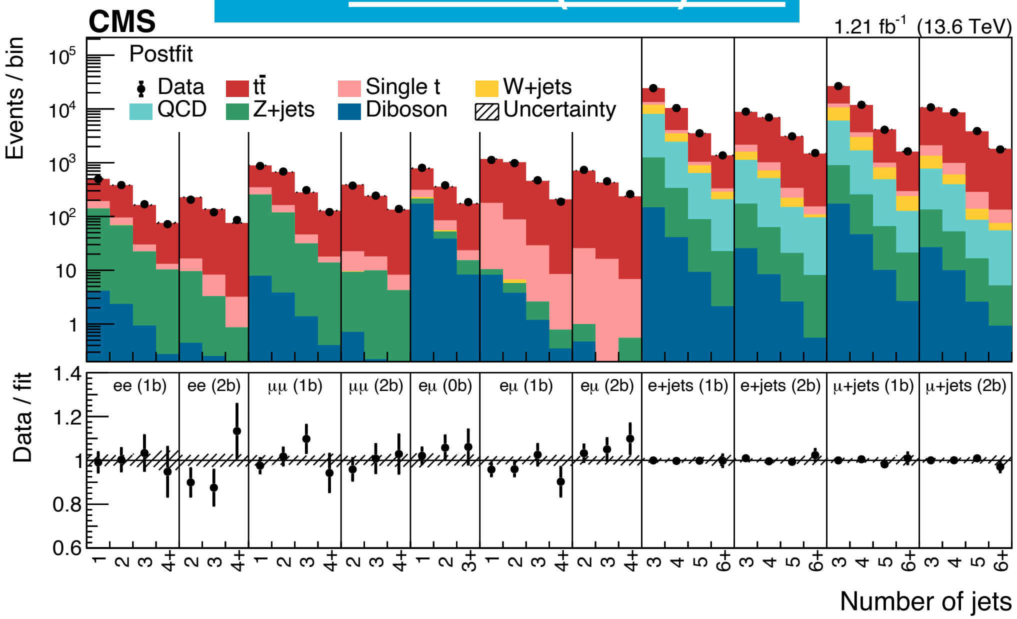
ATLAS & CMS PRL 132 (2024) 261902

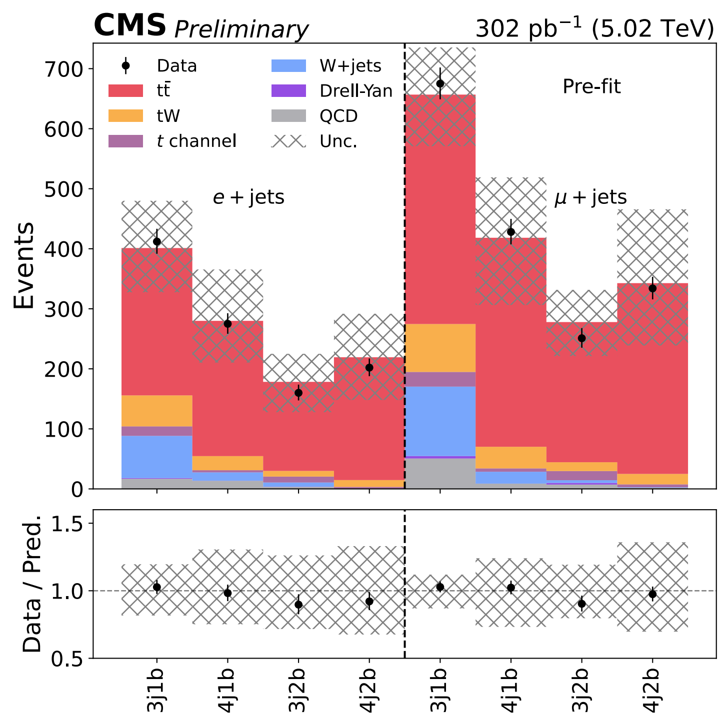
BROWN

tt Cross Section Measurements

- ✦ Two recent results from CMS: first measurement of the tt cross section at 13.6 TeV in dilepton and ℓ+jets, and at 5.02 TeV in ℓ+jets channels
  - ◉ The former is done using early Run 3 data, while the latter is based on a special low-pileup run of 2017
  - ◉ Fit to multiple categories in data is performed to reduce large uncertainty in b tagging and lepton efficiency in early data

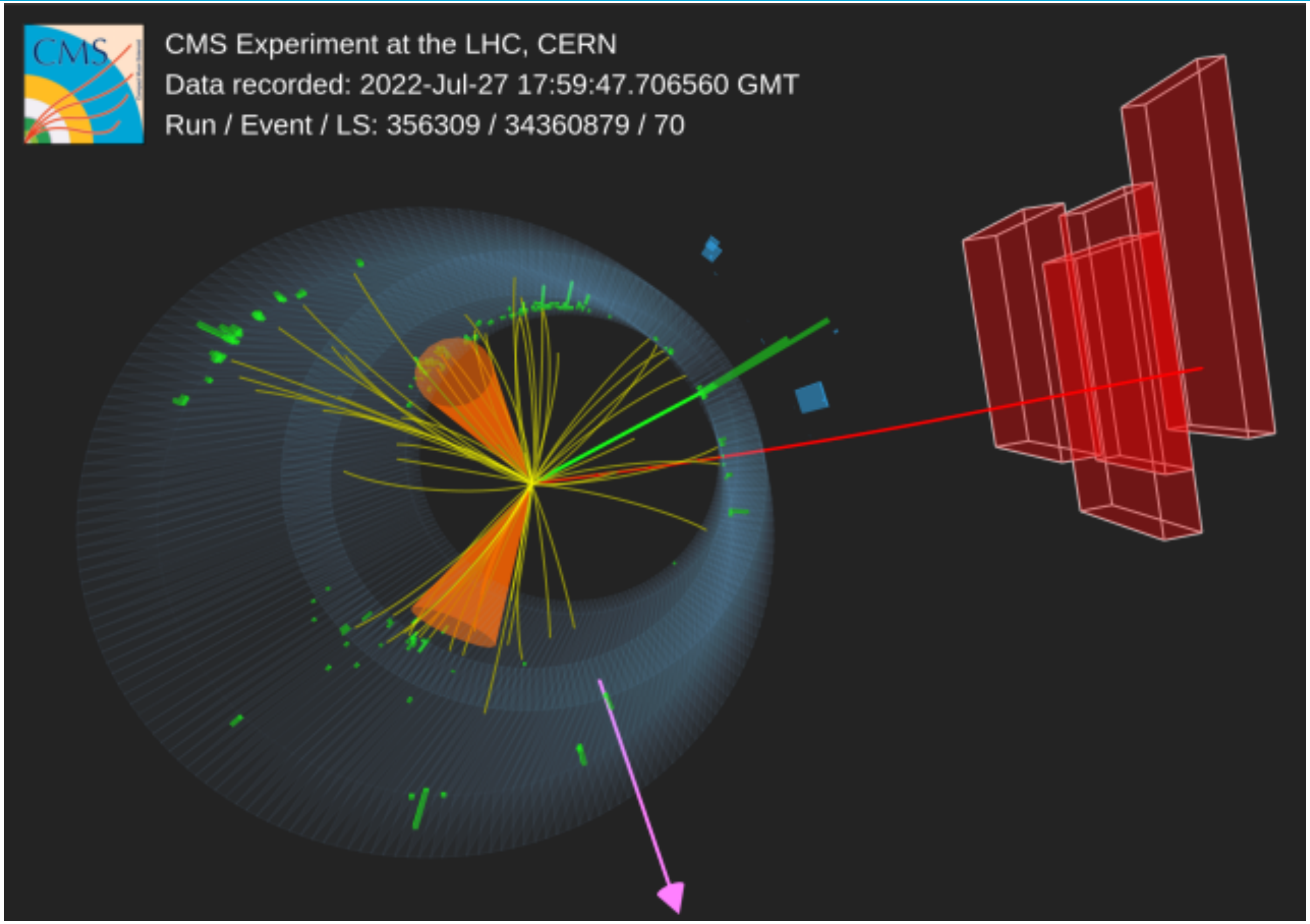
CMS JHEP 08 (2023) 204





CMS PAS TOP-23-005

tt Candidate at 13.6 TeV

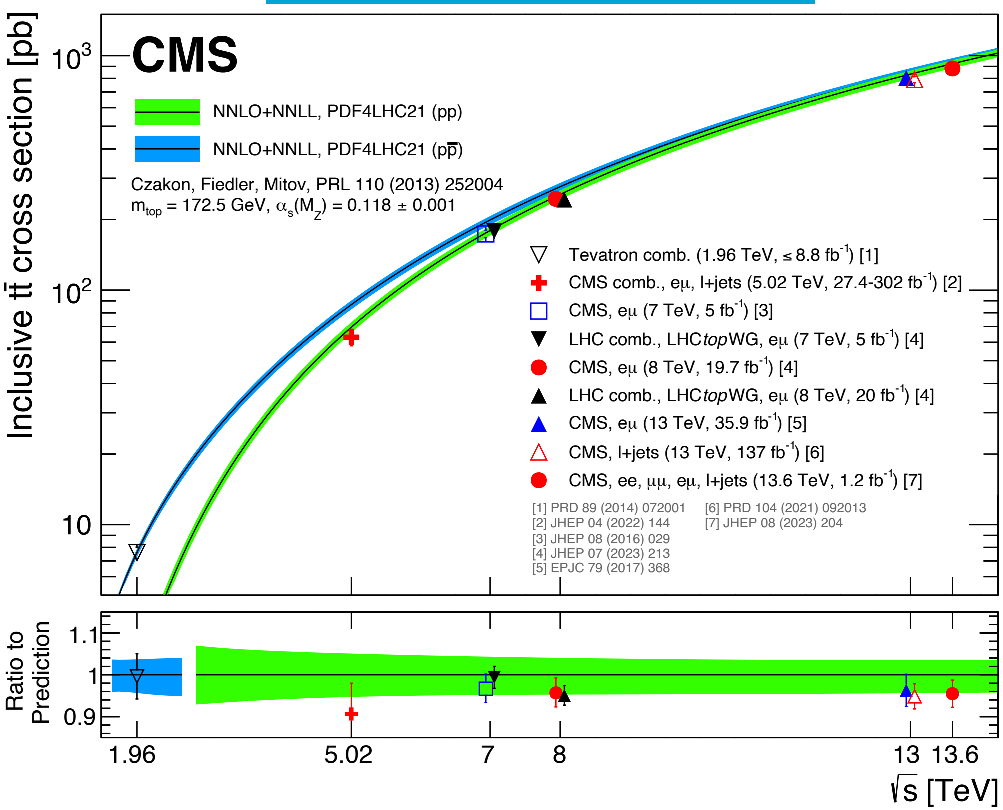


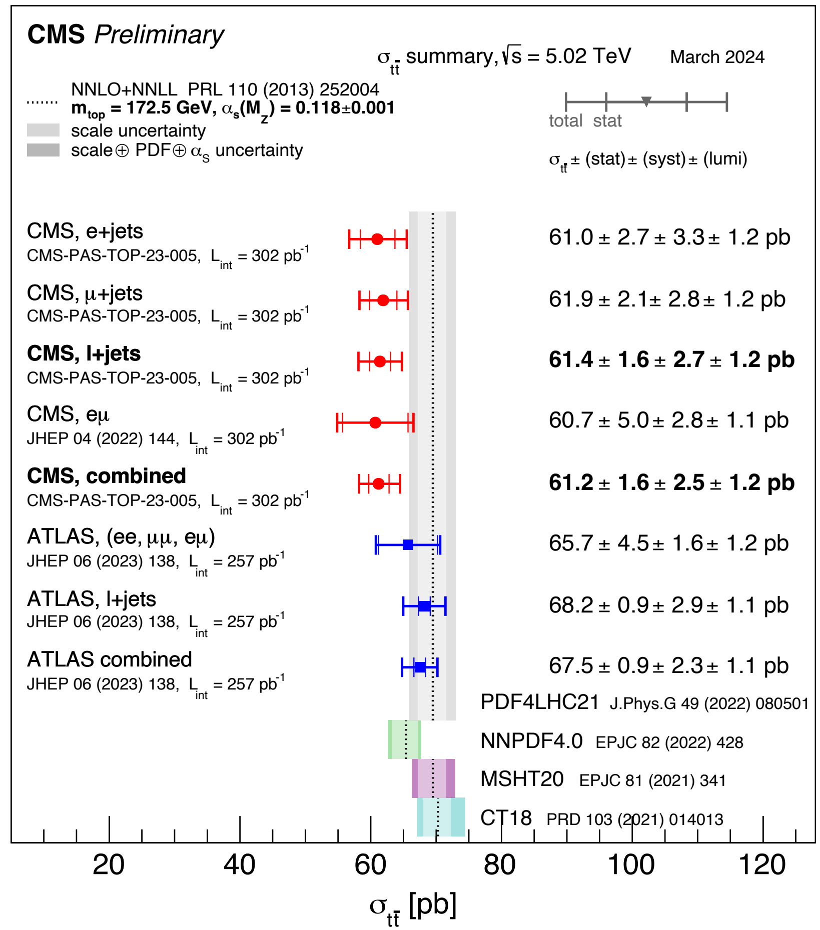
A candidate event in which a top quark pair is produced. Each top quark decays to a b quark and a W boson. Each b quark produces a jet, shown by the orange cones. One W boson decays to a neutrino (not seen) and a muon (shown by the red lines). The other W boson decays to a neutrino and an electron (shown by the green line). The missing transverse energy from the two neutrinos is represented by the magenta arrow.

Energy Dependence

- Dependence of the tt cross section on √s and a summary of 5.02 TeV measurements

CMS arXiv:2405.18661

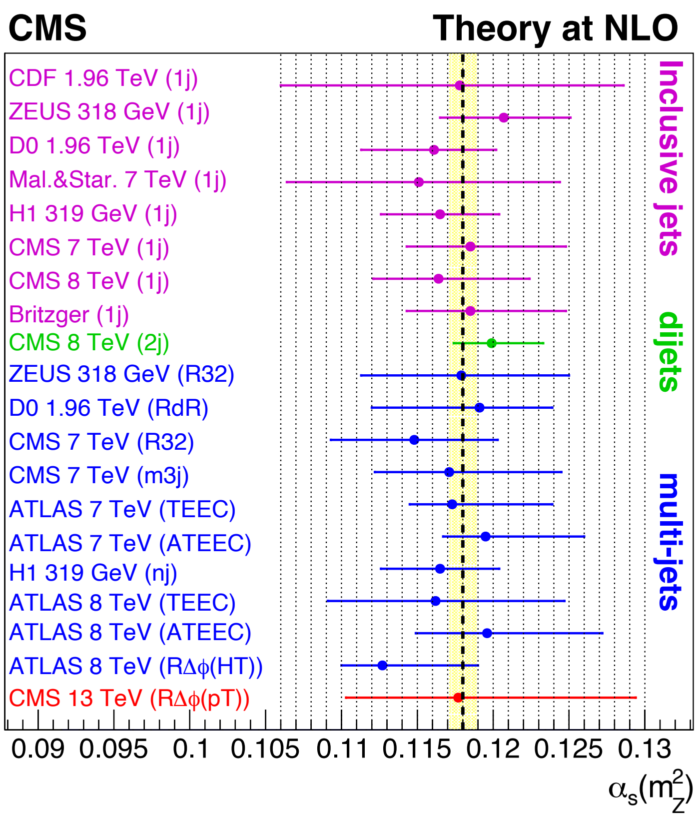




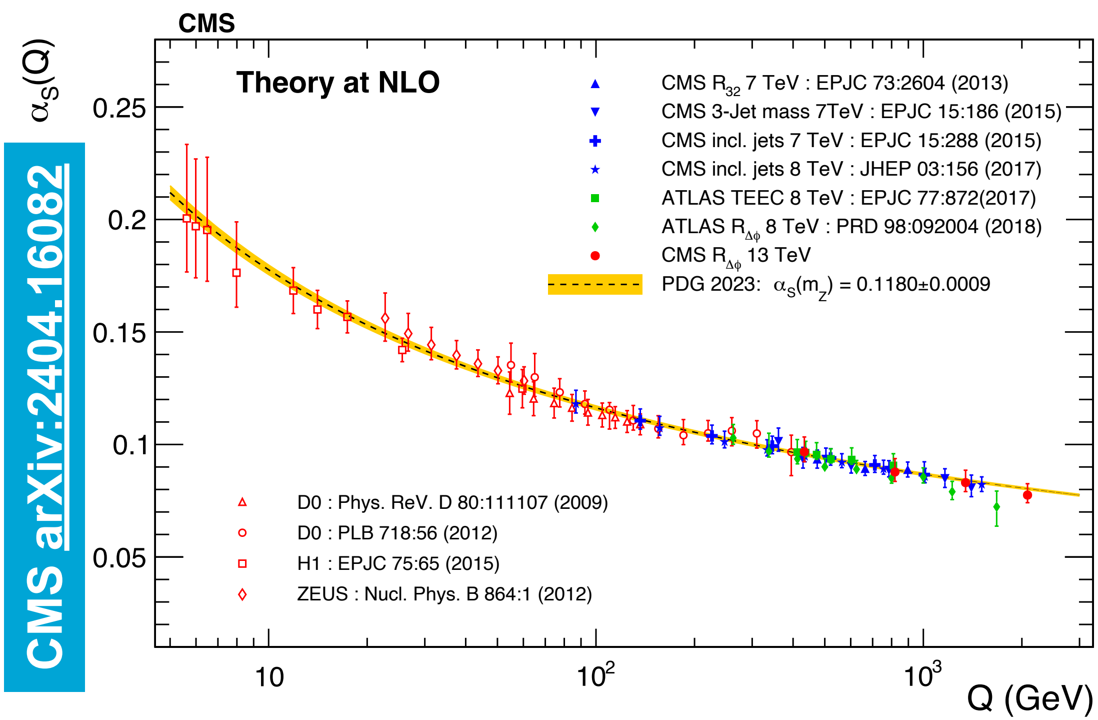
CMS PAS TOP-23-005

Strong Coupling Measurement

- ✦ A new 13 TeV result from CMS using azimuthal correlations in multijet production
- ✦ The running of $\alpha_S(Q)$ has been probed at the LHC over nearly 3 orders of magnitude in Q and agrees very well with the QCD NLO RGE evolution
- ✦ Moving toward NNLO/NNLL and N^{3}LO extraction
  - ◉ NNLO extraction from double-deferential inclusive jet cross sections at 13 TeV $\alpha_S(m_Z) = 0.1166 \pm 0.0017$ [JHEP 02 (2022) 142 and Addendum JHEP 12 (2022) 035]



CMS arXiv:2404.16082



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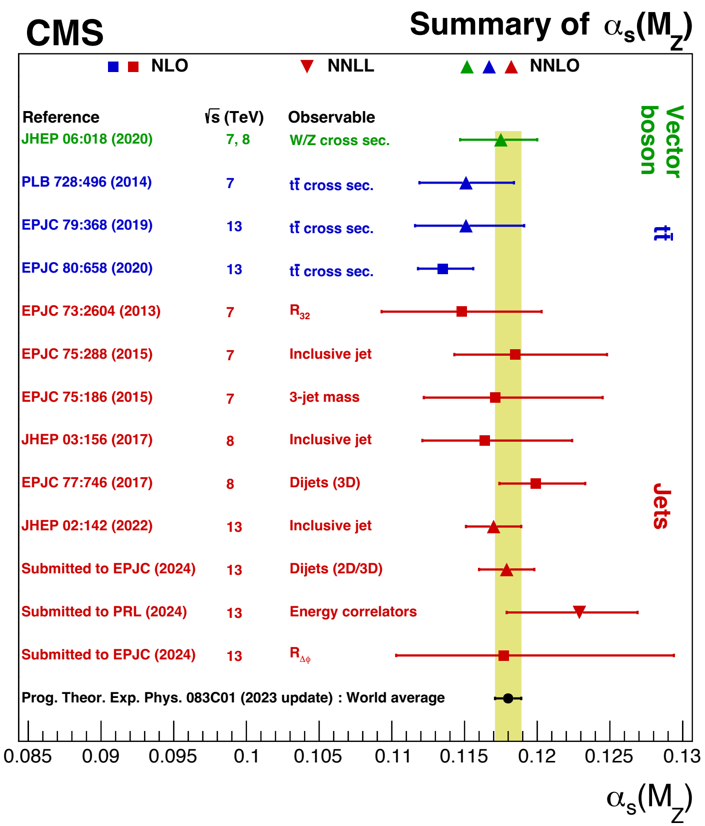
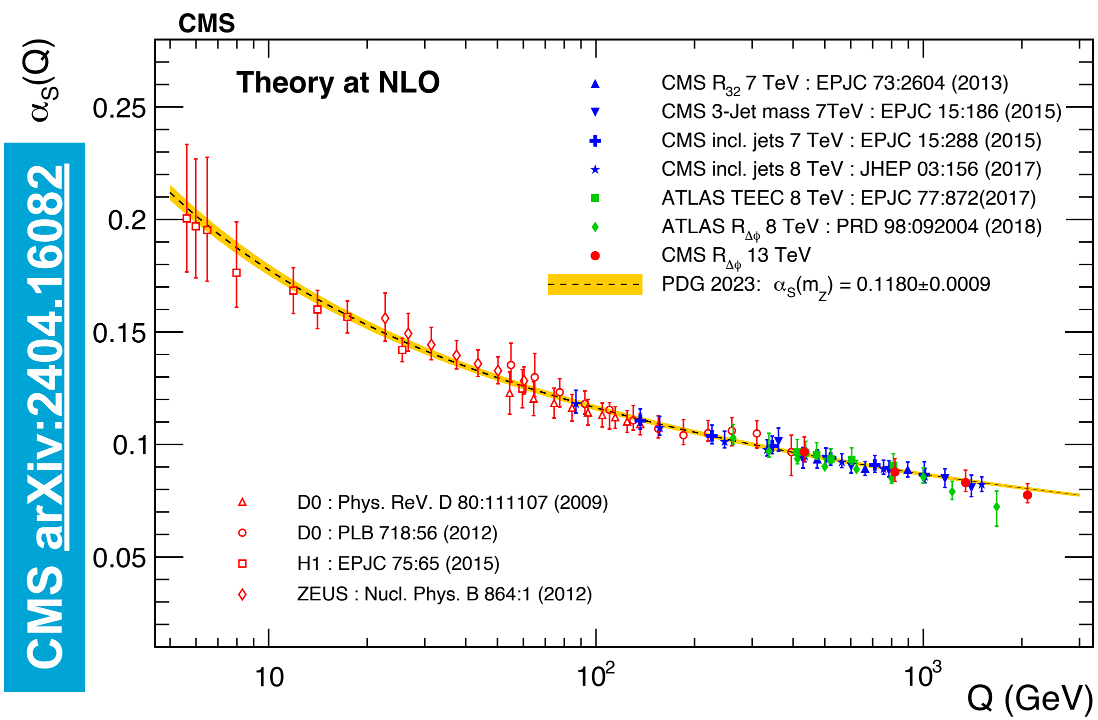
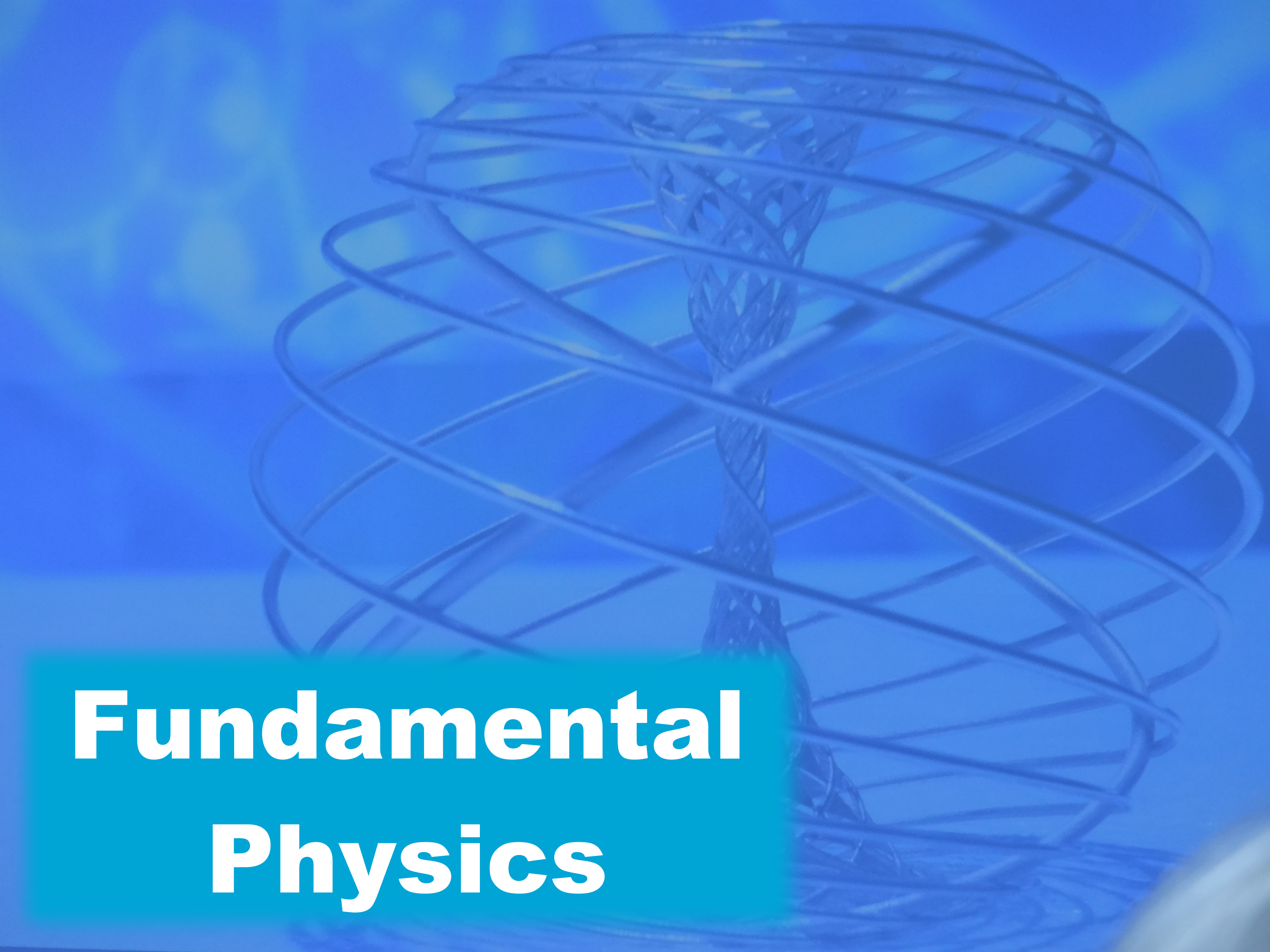


CMS arXiv:2405.18661

CMS arXiv:2404.16082

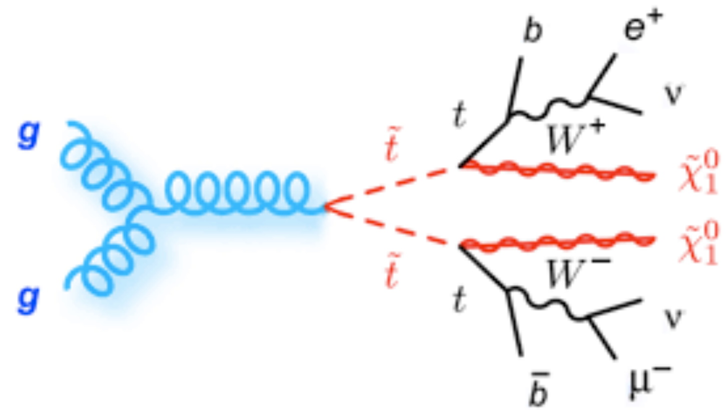


Fundamental Physics



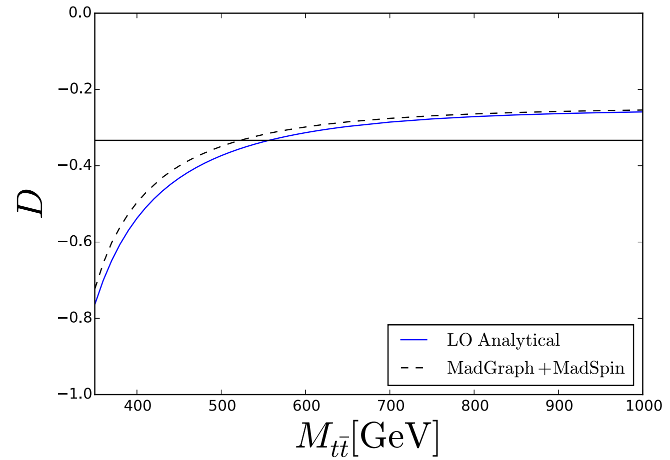
Top Quark Entanglement

- Top quark pair production is an excellent laboratory to look for fundamental QM effects, such as quantum entanglement
- Top quark decays before it hadronizes and the spins of the two top quarks and their decay products are therefore correlated, leading to an entanglement



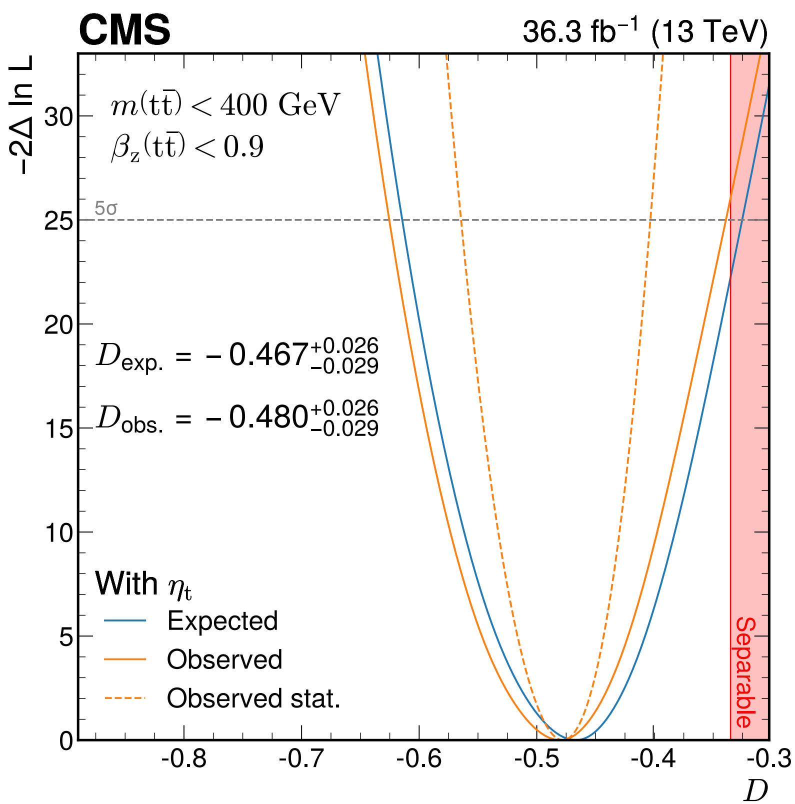
- Explore near-threshold tt production in the dilepton+jets final state
- The spin correlation matrix C can be used to define the entanglement condition [Peres–Horodecki condition, similar to Bell's inequality]
  - Entanglement marker D = -Tr[C]/3 = -3⟨cosϕ⟩, where ϕ is the angle between two leptons from the top quark decays in the tt rest frame
  - If D < -1/3, the tt system is entangled

Afik, de Nova, EPJ+ 136 (2021) 907

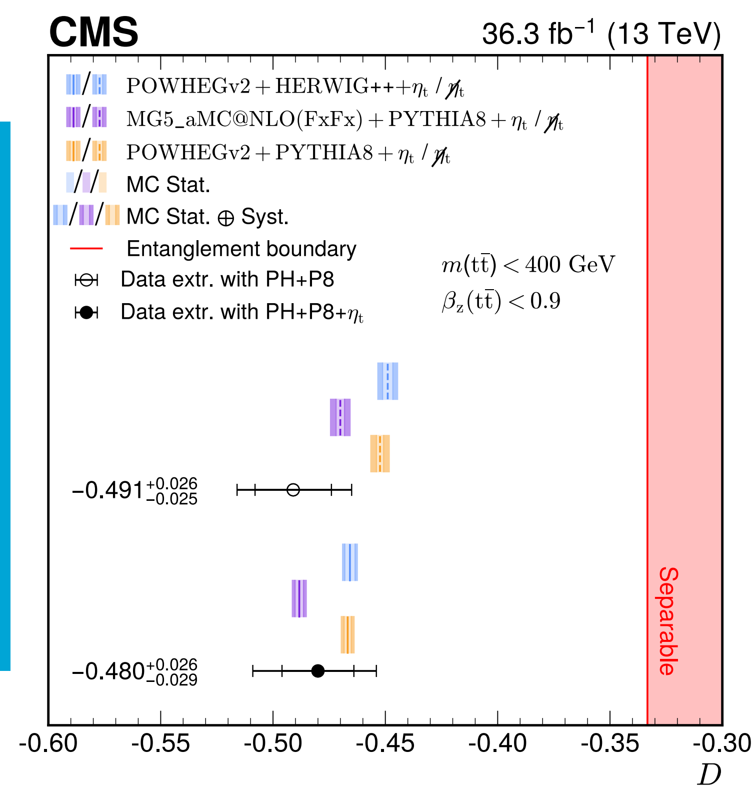


Entanglement at Low Mass

- ✦ Following the first observation of quantum entanglement in the tt system by ATLAS: D = -0.547 ± 0.002 (stat) ± 0.021 (syst) [arXiv:2311.07288], recently CMS confirmed this result and further showed that the inclusion of the below-threshold toponium resonance (a color-singlet pseudoscalar η_t) slightly improves the agreement between the observed and predicted entanglement
- ✦ The entanglement near the threshold (m(tt) < 400 GeV) is observed (expected) with a significance of 5.1 (4.7)σ



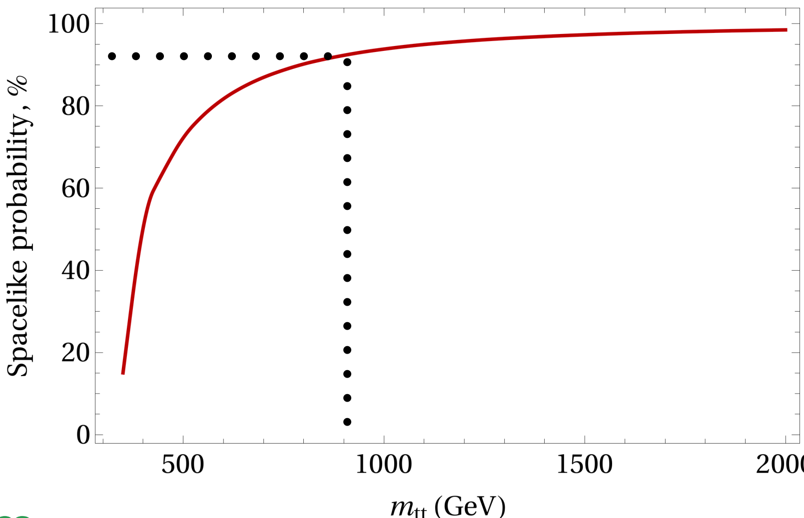
CMS arXiv:2406.03976



Entanglement at High Mass

- While the entanglement at the threshold is enhanced, especially in the presence of a toponium bound state, the two top quarks are mainly time-like separated during the decay (as they are non-relativistic)
- While entanglement is harder to detect at high tt masses, above 800 GeV about 90% of events have the two top quarks that are space-like separated (essentially each has β > 0.5), meaning that the two decays can't be casually connected

Severi et al, EPJC 82 (2022) 285

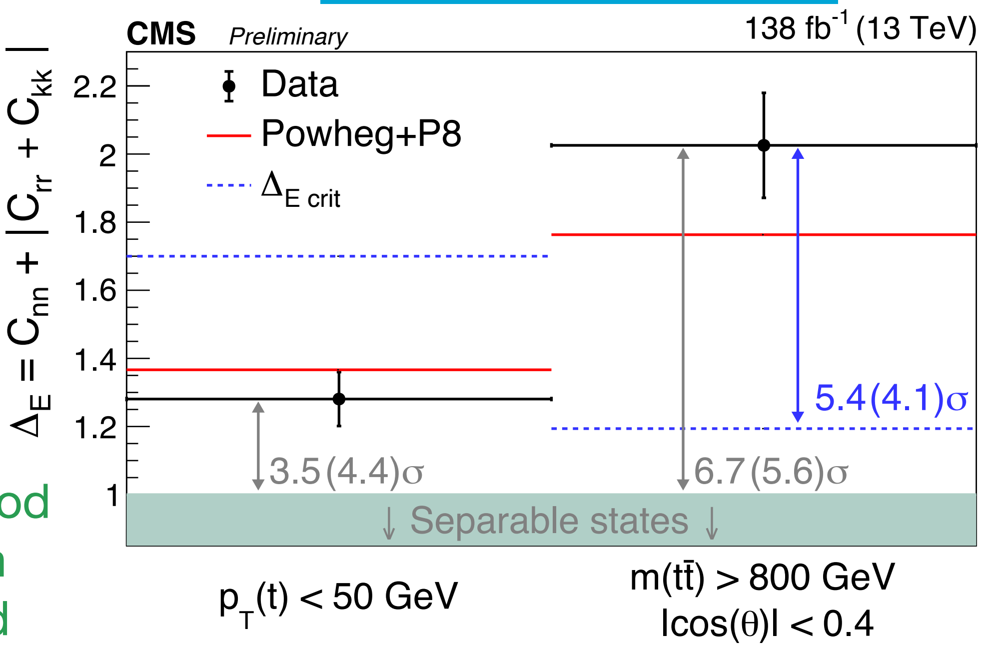


- Observing the entanglement in this regime is therefore very interesting from the quantum information point of view
- However, one needs more copious production, so the lepton+jets channel is ideal for such a measurement

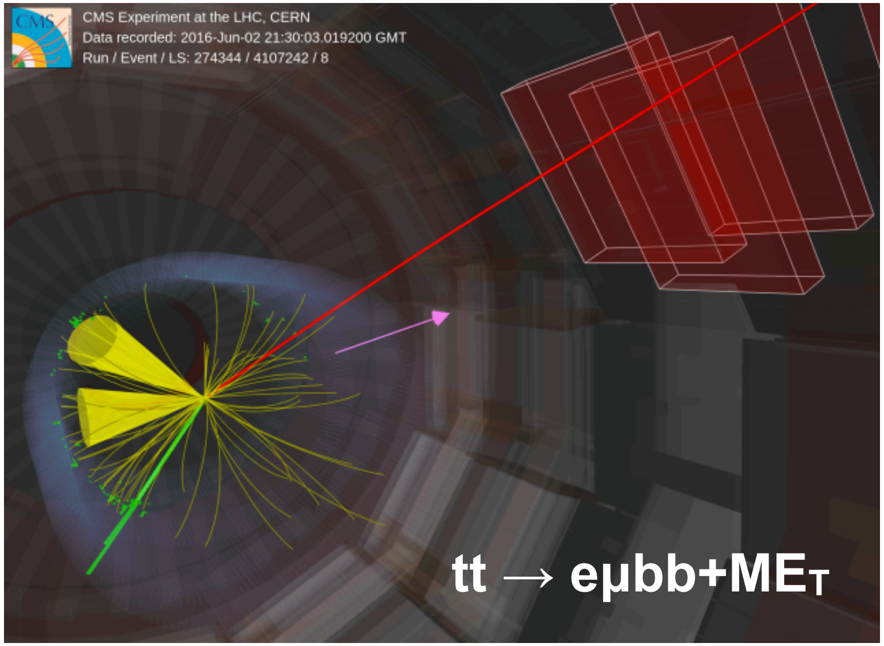
Entanglement at High Mass

- A new CMS analysis in the lepton+jets channel measured the entanglement at high mass for the first time using Run 2 data set
- Uses $\Delta_E = -3D > 1$ as the entanglement criterion and selects events at high tt mass and large scattering angle in the c.o.m. frame, $|\cos\theta| < 0.4$
- Also defines $\Delta_{E\ crit} = f + 3(1 - f)$, where f is the fraction of space-like separated events
- An excess above 1 ($\Delta_{E\ crit}$) is a measure of entanglement (beyond the one that can be explained by a causality connection)
  - For f = 90%, $\Delta_{E\ crit} = 1.2$
- For m(tt) > 800 GeV and $|\cos\theta| < 0.4$, observed an excess above 1 of 6.7 (5.6 expected)σ and an excess above $\Delta_{E\ crit} = 1.2$ of 5.4 (4.1 expected)σ, thus establishing an entanglement beyond causality connection
- Sensitivity at low masses is not as good as in the dilepton channel and only an evidence of entanglement is observed

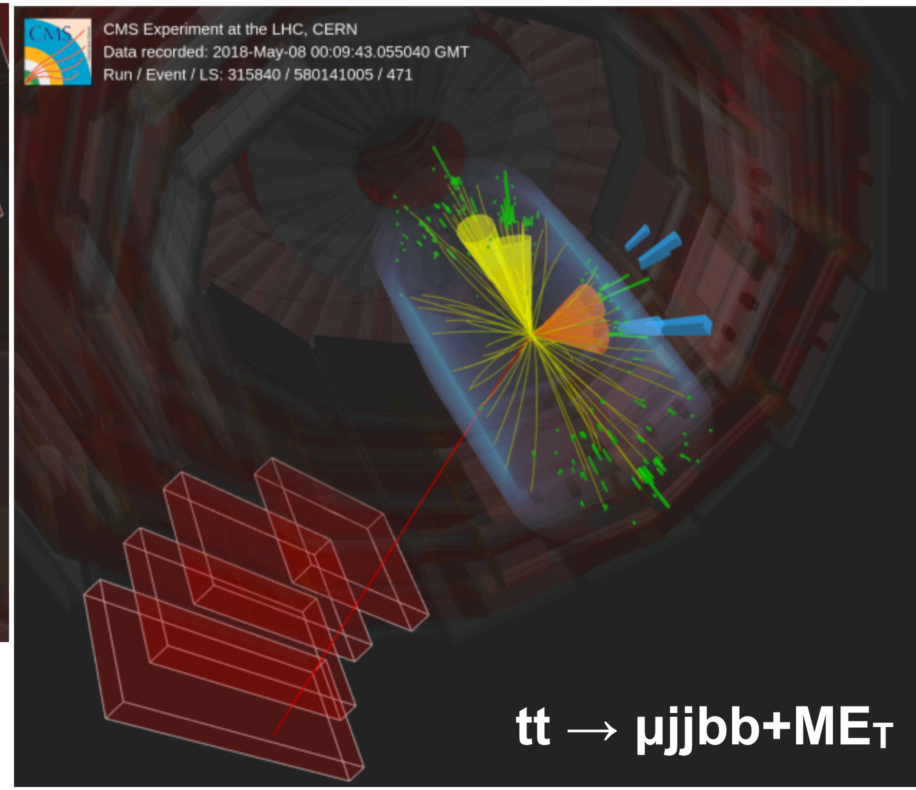
CMS PAS TOP-23-007



Entangled



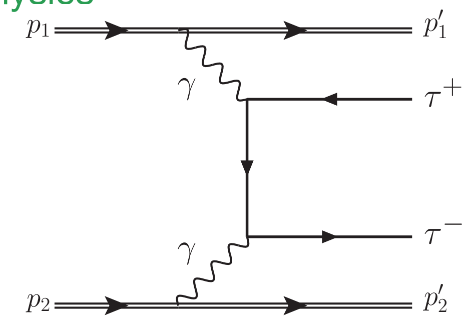
Entangled top quark pair candidate seen in the CMS detector. Each top quark decays to a b quark and a W boson. Each b-tagged jet is represented by the yellow cones. One W boson decays to an electron (green line) and a neutrino. The other W boson decays to a muon (red line) and a neutrino. The neutrinos are not seen and the missing transverse energy from them is represented by the magenta arrow.

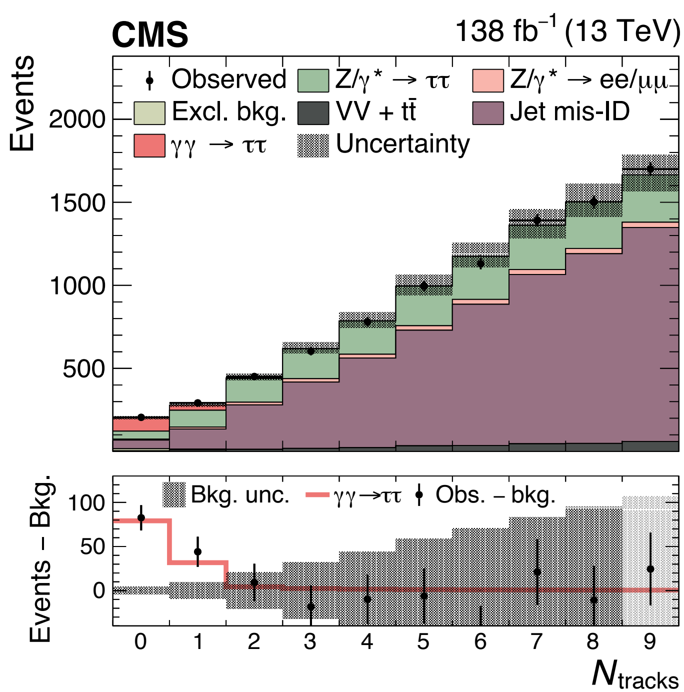


Entangled top quark pair candidate seen in the CMS detector. Each top quark decays to a b quark and a W boson and each b quark produces a jet (orange cones). One W boson decays to a neutrino (not seen) and a muon (red line) and the other to two jets (yellow cones).

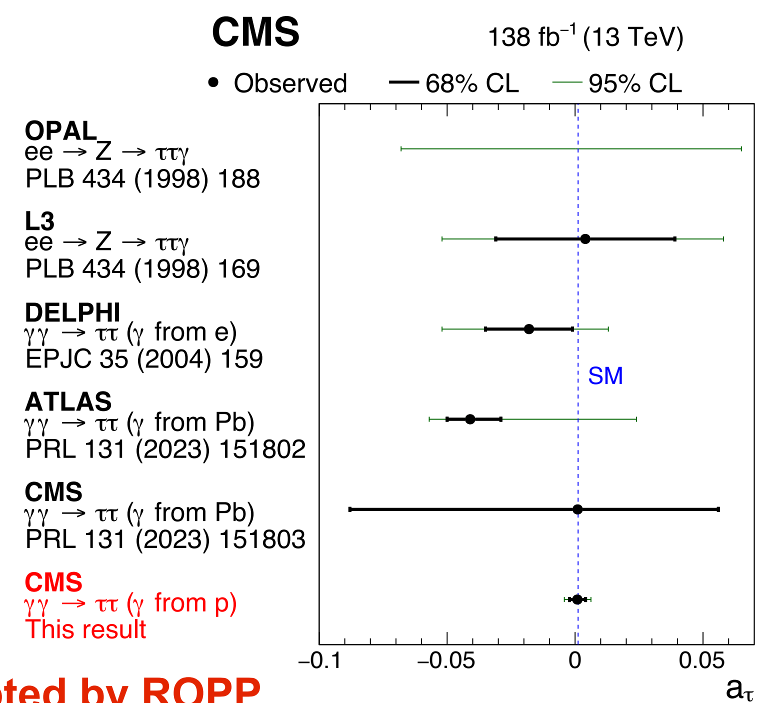
g-2 of the Tau Lepton

- Anomalous magnetic moments are fundamental parameters sensitive to new physics
  - Cf. Paride Paradisi's talk on the muon g-2 saga this afternoon
- The magnetic moment of the tau lepton is known rather poorly
- New CMS analysis using photon-photon collisions [LHC as a photon collider!] in pp running to probe exclusive photoproduction of tau lepton pairs, which is sensitive to g-2
  - Based on the combination of hadronic and leptonic tau decays
  - Exclusivity is ensured by requiring primary vertex with no more than one extra track
- First observation of exclusive ττ production and the most stringent limit on g_τ - 2: [-0.0042,0.0062], approaching sensitivity to the Schwinger term $\alpha/2\pi = 0.00116$



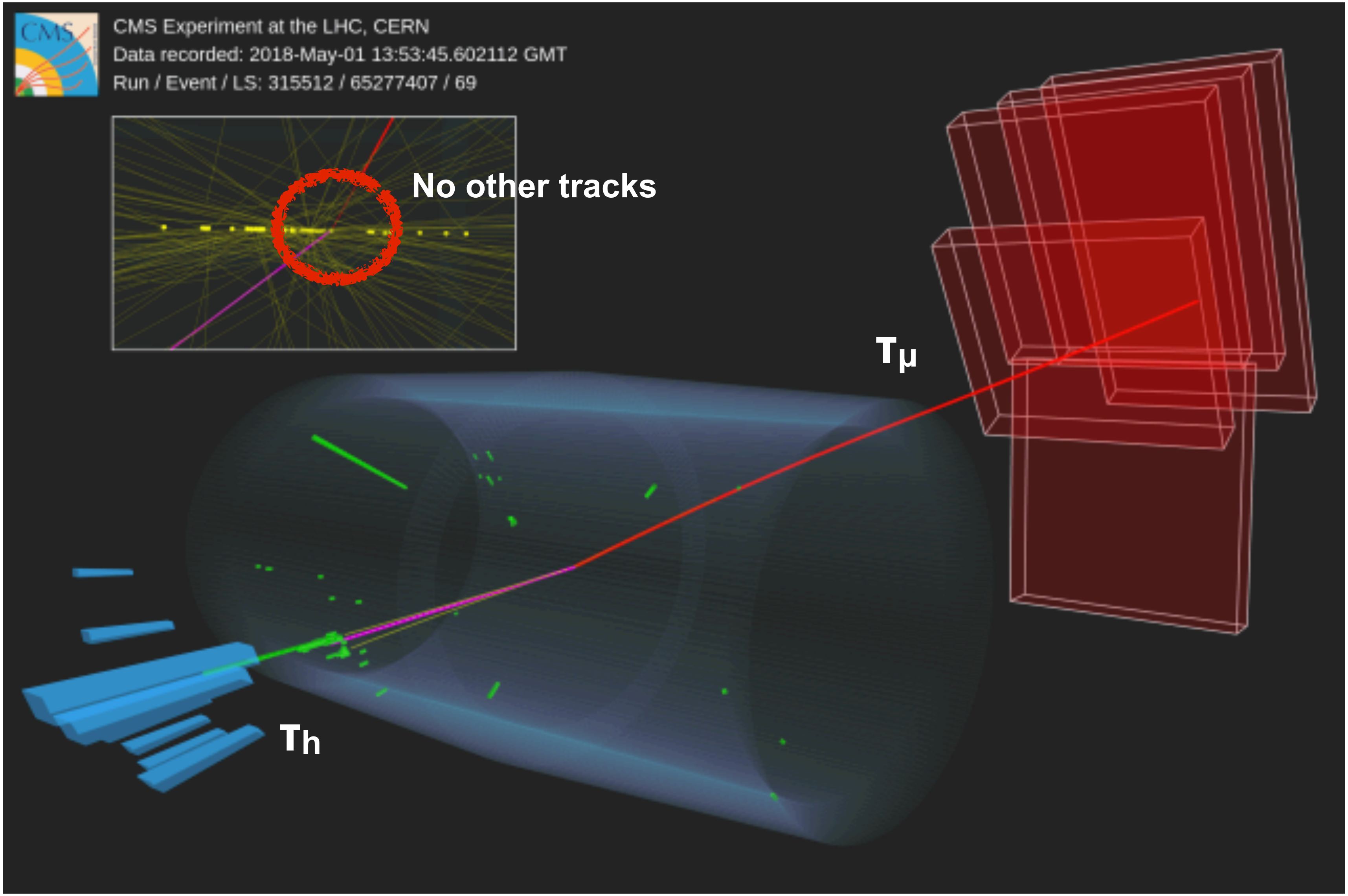


CMS arXiv:2406.03975



Accepted by ROPP

Exclusive ττ Candidate

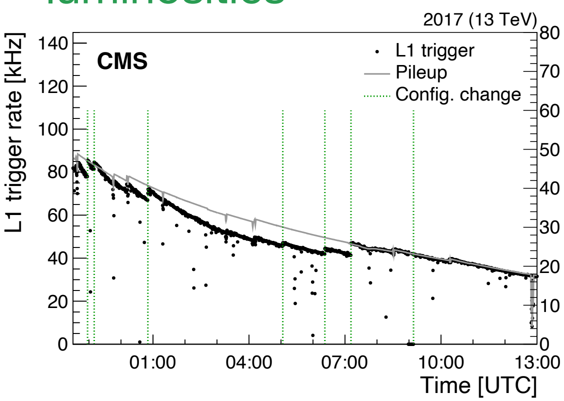


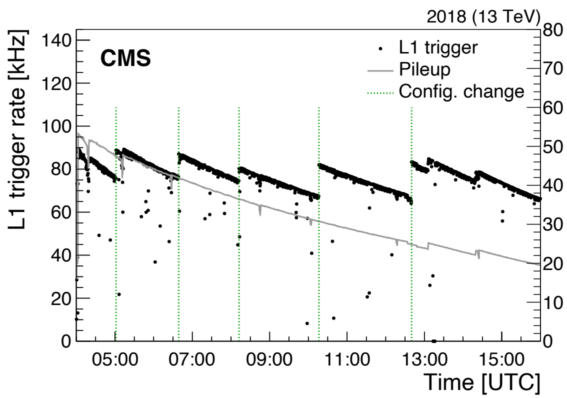
Lepton Flavor Universality Tests

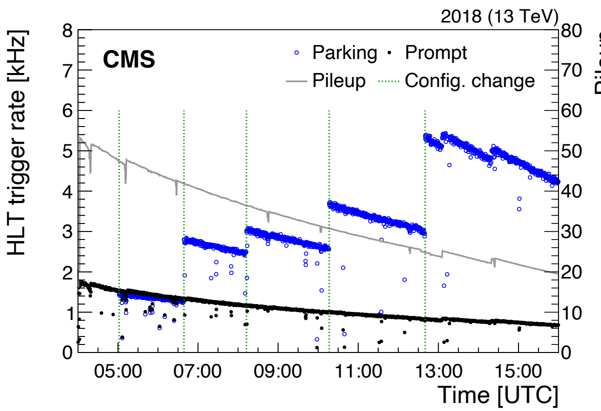
- In the SM, couplings of gauge bosons to fermions are universal, which is an accidental symmetry of the SM
- Recent interest in lepton flavor universality (LFU) violation sparkled by the LHCb claims of LFU violation in $b \to sl^+l^-$ transitions [by now understood to be due to a missing background]
  - Higgs boson is the only known particle with non-flavor-universal couplings to leptons
- In 2018, CMS mounted a special data parking campaign with the goal of putting 10^{10} unbiased b hadron decays on tape, thus enabling the R(K) measurement, defined as $R(\mathrm{K}) = \dfrac{\mathrm{B}^\pm \to \mathrm{K}^\pm \mu^+ \mu^-}{\mathrm{B}^\pm \to \mathrm{K}^\pm \mathrm{e}^+ \mathrm{e}^-}$

CMS B Parking Campaign

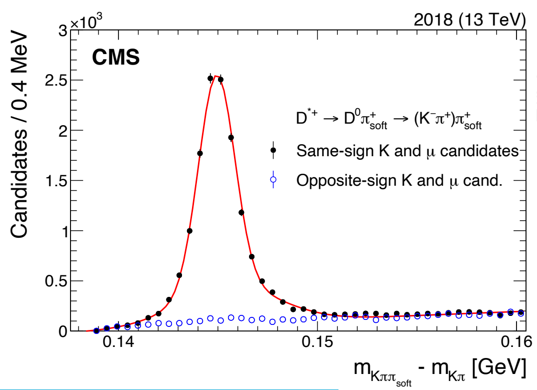
- ✦ Set of single-muon triggers to tag a semileptonic b hadron decay on one side and record an unbiased probe on the other
- ✦ Relies on unused L1 resources and increased HLT rate at lower instantaneous luminosities

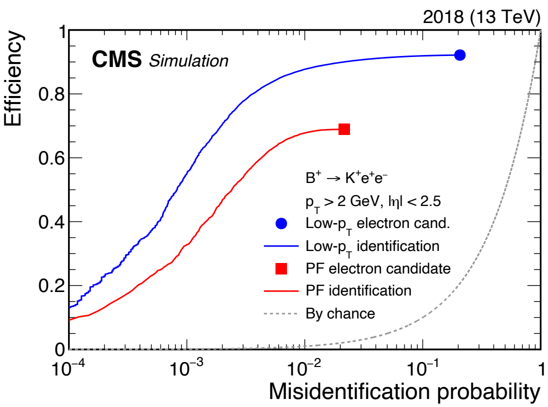






- ✦ Simultaneously developed a new electron ID for p_T as low as 1 GeV (standard one stops at 3 GeV)
- ✦ Purity in b hadrons of ~80% is estimated using D^{*+} meson decays
- ✦ While it took a while to understand these unique data, they are now being used for many B physics and search analyses





CMS arXiv:2403.16134

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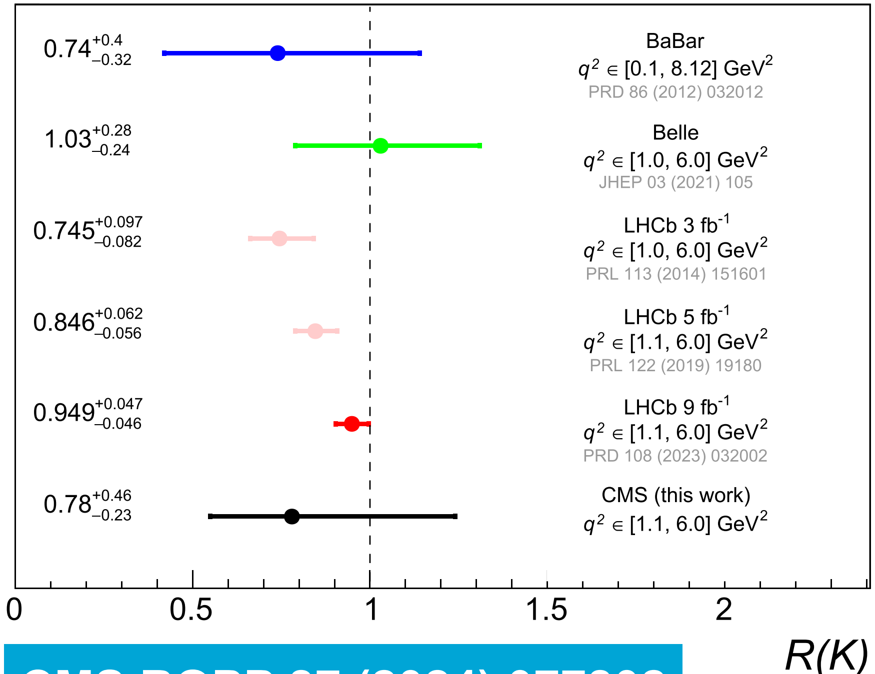
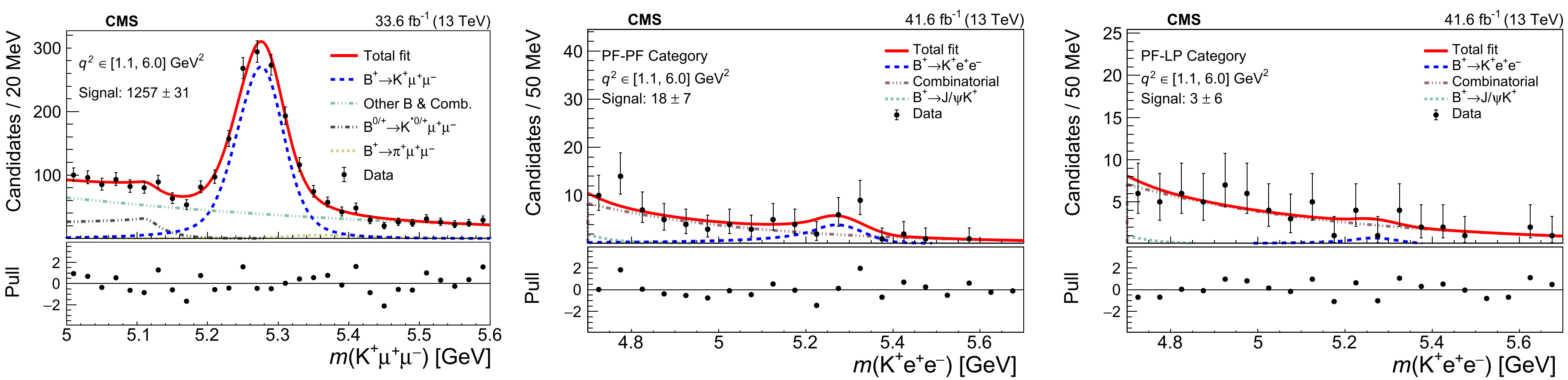
R(K) Measurement

- Despite a very large sample, it's a difficult analysis with many backgrounds
- The efficiency for the signal in the electron channel is therefore small, despite all the improvements
- Normalize to the $B^\pm \to K^\pm J/\psi(l^+l^-)$ channel with established LFU to reduce the uncertainties
- The electron channel uses PF-PF and PF-LP electron combinations, but the signal yield is only ~20 events
- Still managed to keep all the backgrounds under control and measure $R(K) = 0.78^{+0.46}_{-0.23}$
- Similar to the BaBar precision

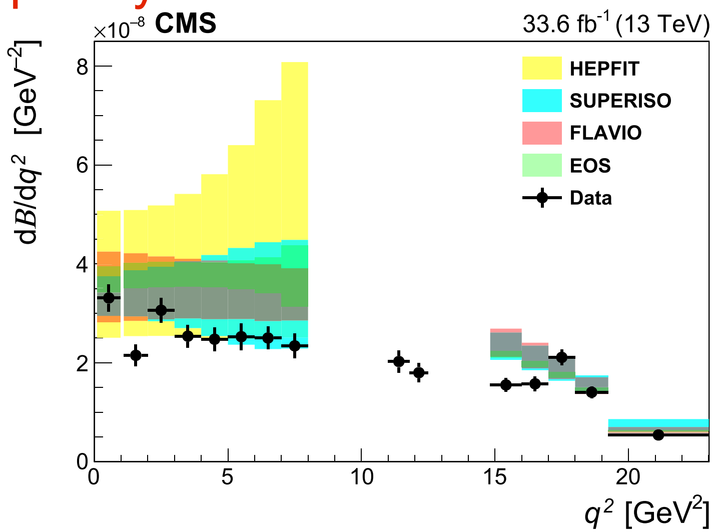


CMS ROPP 87 (2024) 077802



Next Steps

- Also, measured the differential branching fraction in $q^2 = m(\mu^+\mu^-)^2$ with the precision similar to the world average
  - Confirmed the LHCb observation that the muonic branching fraction is suppressed compared to the SM predictions
  - Caveat: poorly known contributions from charm loops could be the reason



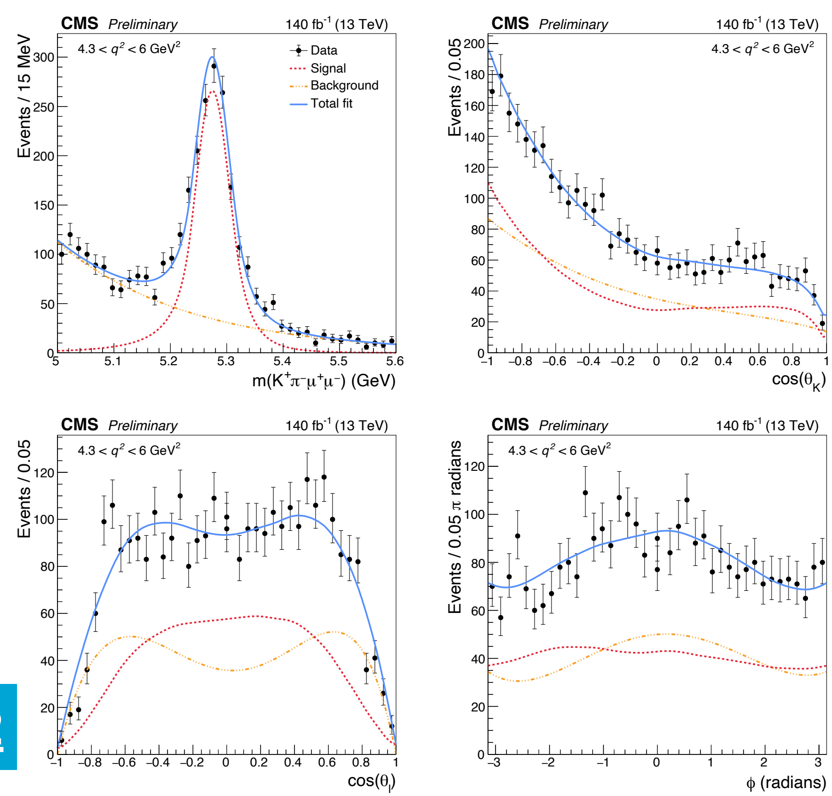
CMS ROPP 87 (2024) 077802

- Based on the experience with the first R(K) analysis, reoptimized the trigger for 2022-2023 data taking, with the goal to increase the signal yield by an order of magnitude
  - The analysis is ongoing; expect results in early 2025

Angular Analysis of the B → K*μμ Decay

- Completed the Run 2 analysis of angular distributions in the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays, where a tension with the SM predictions has been observed by LHCb
- The analysis is done via a 3D fit to three decay angles and the $K^+\pi^-\mu^+\mu^-$ invariant mass in bins of $q^2 = m(\mu\mu)^2$
- Eight angular coefficients: F_L, P_1-P_3, P_4'-P_6', P_8' are extracted

Fit example in the $4.3 < q^2 < 6$ GeV^2 bin

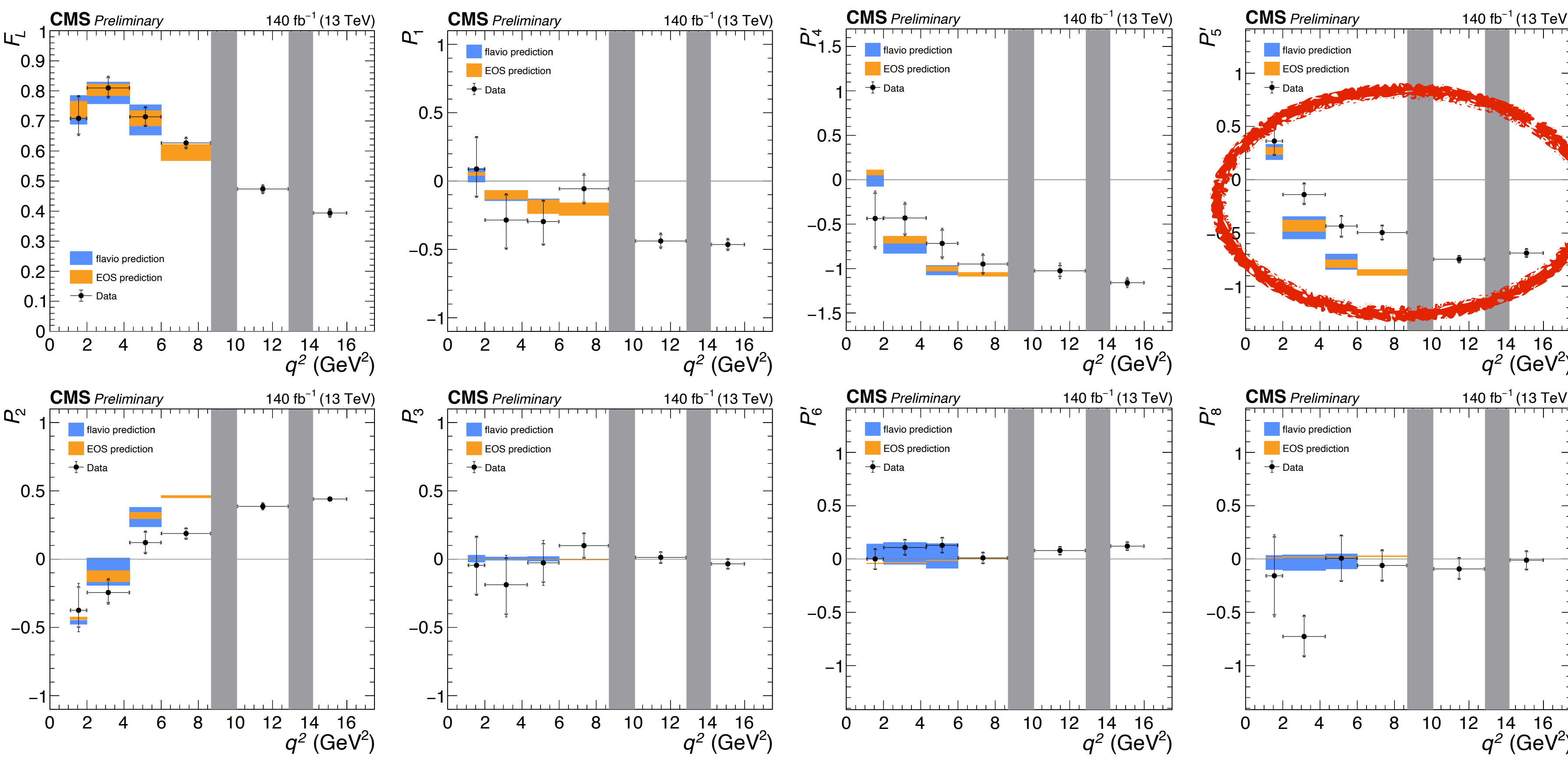


CMS PAS BPH-21-002

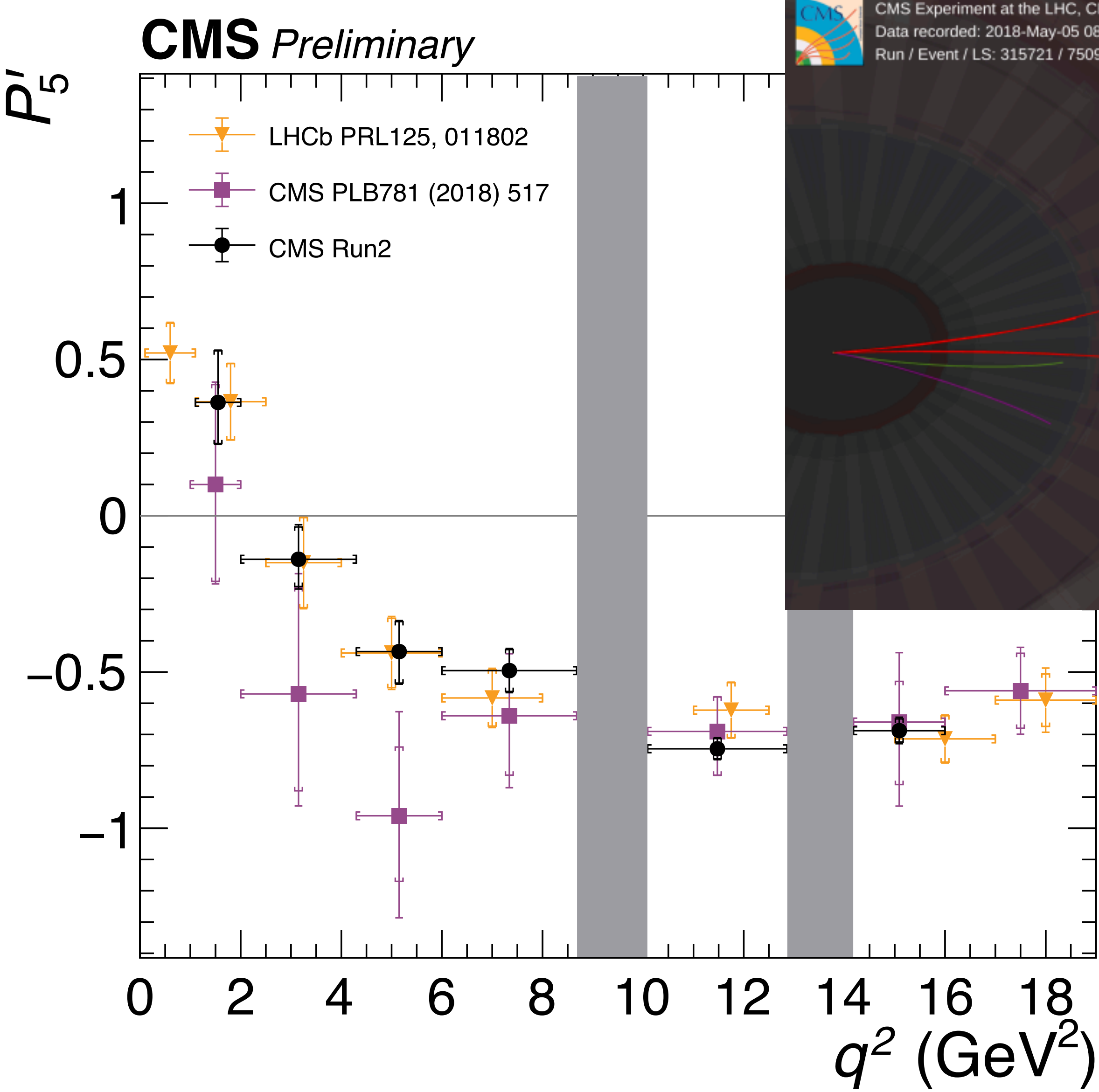
$B^0 \to K^{*0}\mu^+\mu^-$ Results

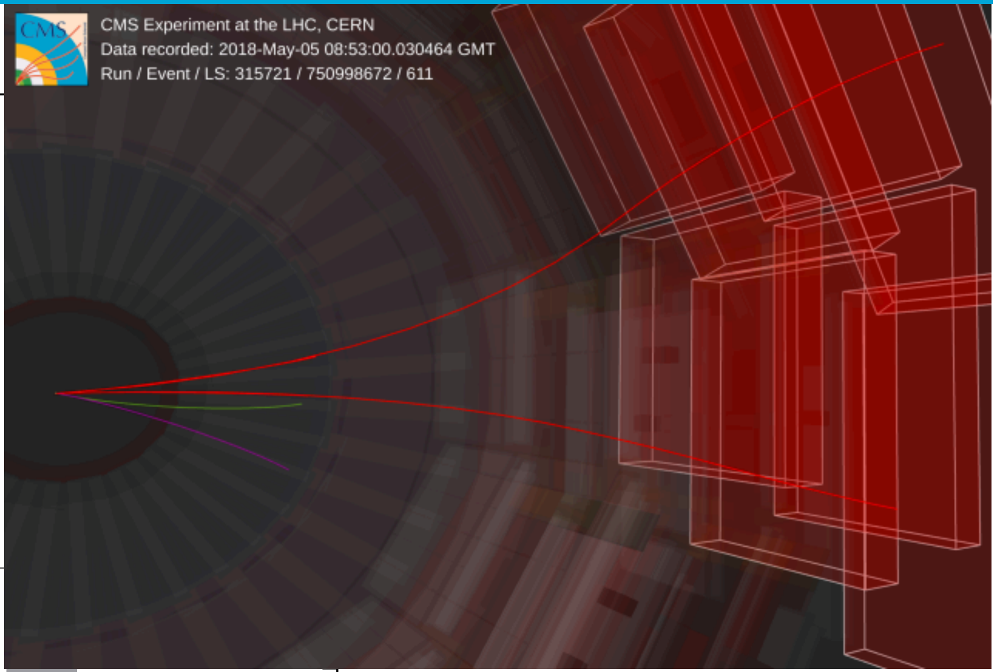
- While most of the coefficients agree with the SM, P5' shows a sizable deviation, similar to the LHCb claim

CMS PAS BPH-21-002



CMS vs LHCb





CMS PAS BPH-21-002

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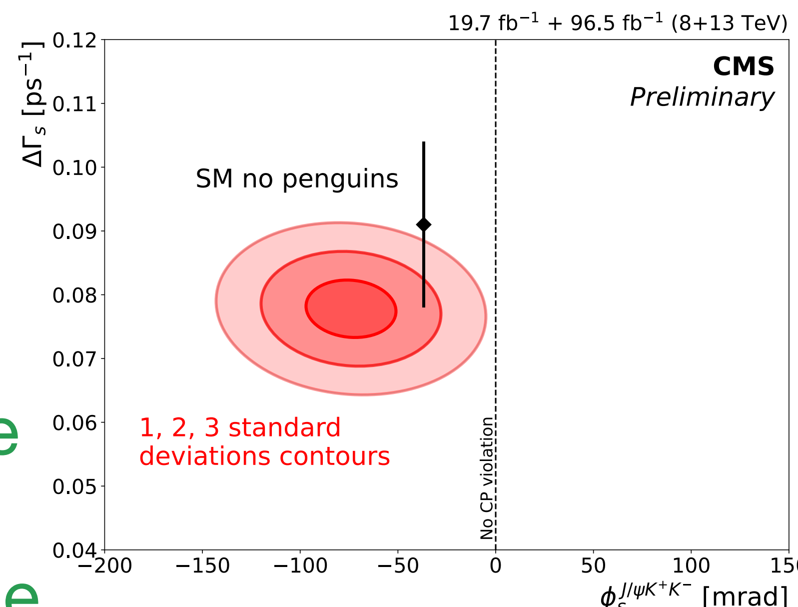
CP Violation in $B_s \rightarrow J/\psi\varphi$ Decays

- CP violation (CPV) is one of three Sakharov conditions for creation of matter-antimatter asymmetry in the universe
- Recent result from CMS is based on the most performant flavor tagger to date, allowed to establish CPV in $B_s \rightarrow J/\psi\phi$ decays
  - New tagger, based on DNNs achieved unprecedented tagging efficiency of 55.9% with the dilution factor of 10%, for a tagging power of 5.6%
- The result is consistent with the SM and LHCb measurement, and established for the first time >3σ evidence for the CPV phase ϕ_s to be non-zero

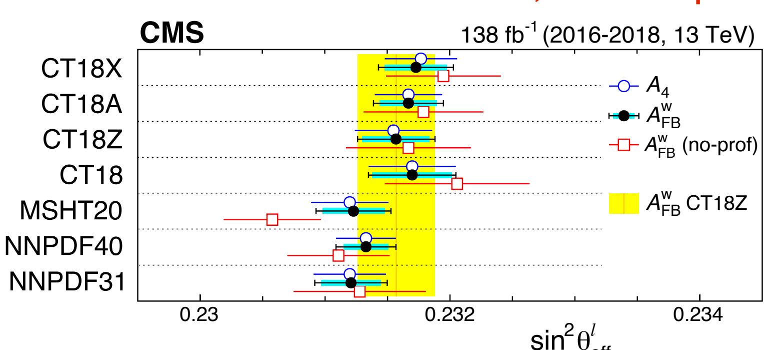
CMS PAS BPH-23-004

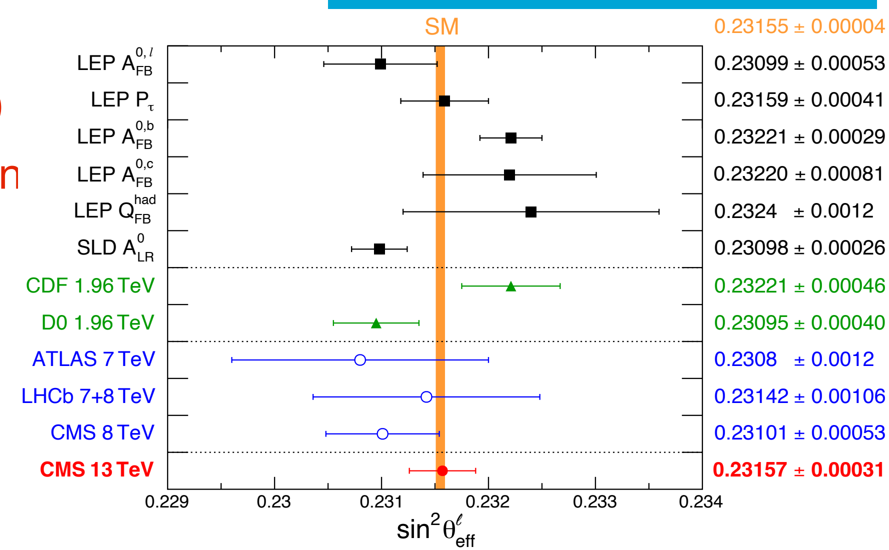


$\sin^2\theta_W$ Measurement

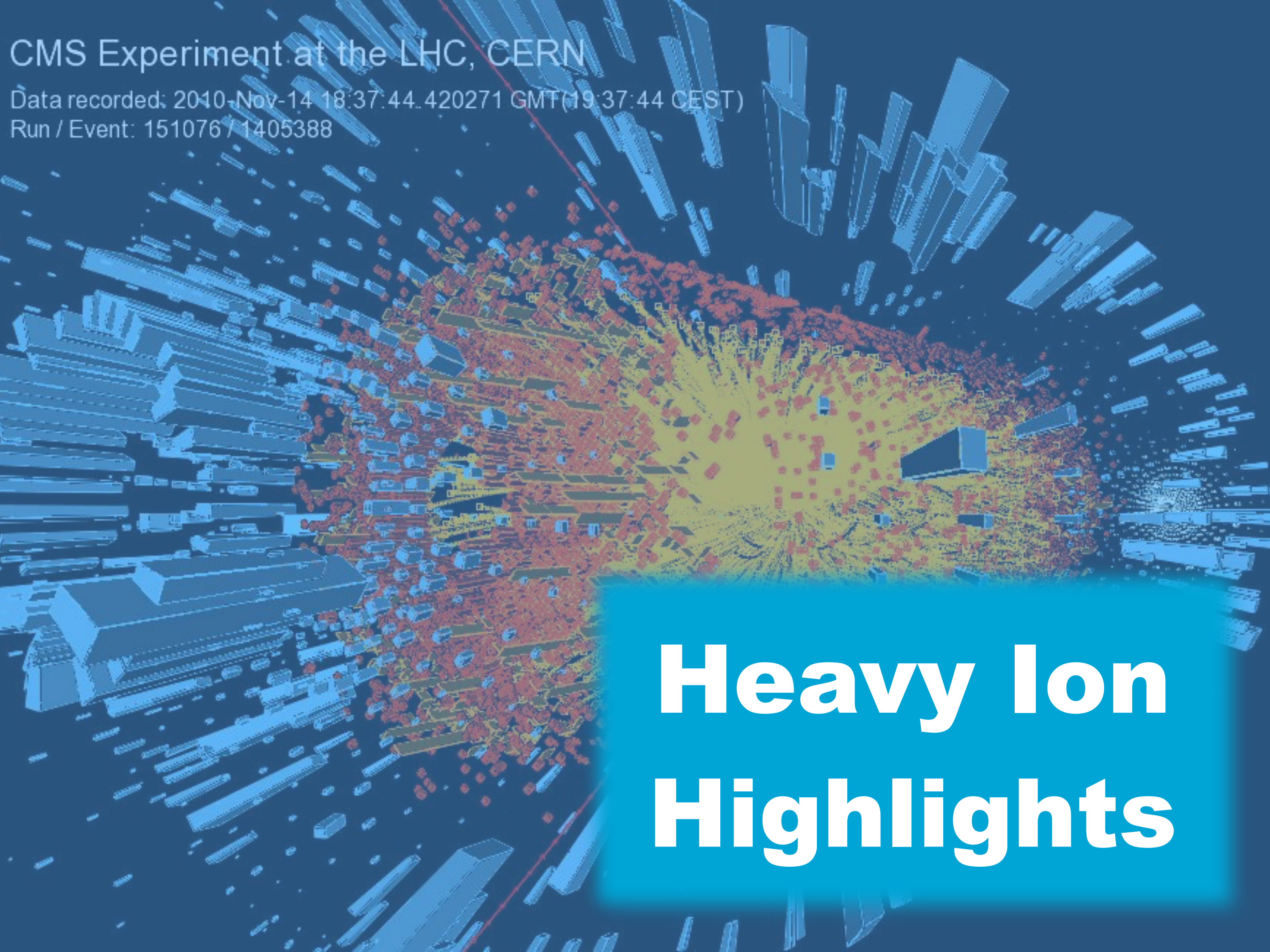
- New measurement of effective weak leptonic mixing angle $\sin^2\theta^{\ell}_{eff}$ using $Z(\ell\bar{\ell})$ events
- Long-standing tension between the LEP and SLC results: 0.23221 ± 0.00029 (LEP, FB asymmetry) and 0.23098 ± 0.00026 (SLD, LR asymmetry), which differ by 3.2σ
  - Current prediction from global EW fits $\sin^2\theta^{\ell}_{eff} = 0.23155 \pm 0.00004$
- Measurement is performed using leptonic angular distributions θ in the Collins-Soper frame and calculating FB asymmetry weighted by y and cosθ
  - The analysis is done in both e and μ channels, with the electron |η| coverage up to 4.36 (HF calorimeter)
  - An alternative method is using an unfolded A_4 coefficient
  - Several sets of PDFs are considered
  - $\sin^2\theta^{\ell}_{eff} = 0.23157 \pm 0.00031$ (A_{FB}, CT18Z)
  - In between LEP and SLD, similar precision

CMS arXiv:2408.07622





Heavy Ion Highlights



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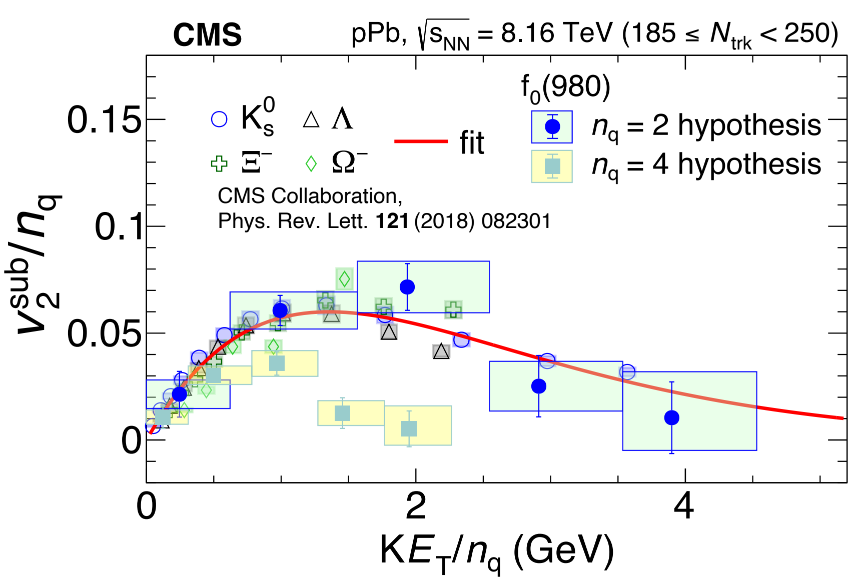
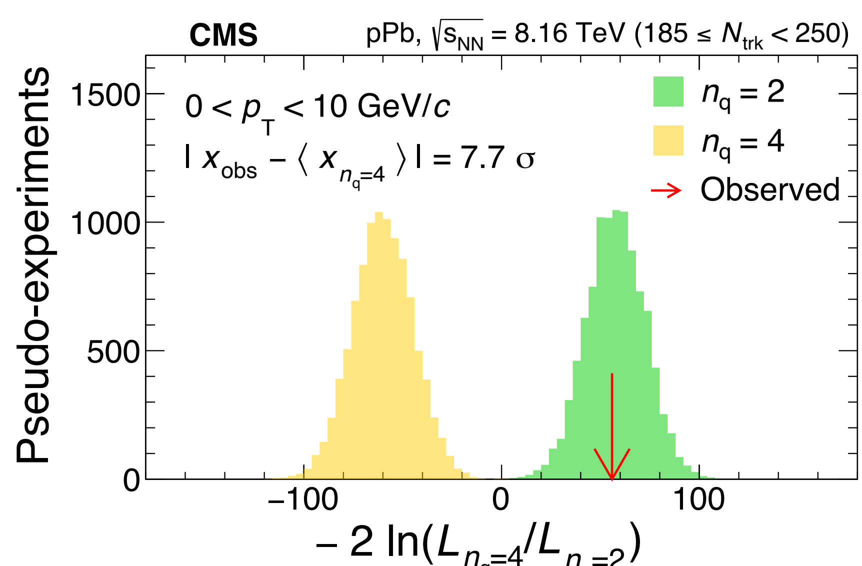
Resolving f_0(980) Puzzle

- For the first time, heavy ion collisions were used to probe the particle content of a potentially exotic state
- Since the 60-ies, the f_0(980) state, which is rather broad was speculated to be a tetraquark candidate, a molecular state, or an ordinary meson
- This is possible through the coalescence picture of bound state formation in nuclear collisions
  - Bound states are formed from particle with similar momenta and spatial positions
  - The elliptic flow of a state thus inherits the elliptic flow of the constituents, $v_2(p_T) \approx n_q v_{2,q}(p_T/n_q)$
- Consequently, measuring the elliptic flow of a specific state can tell how many quarks it contains
- CMS measurement excluded $n_q = 4$ over $n_q = 2$ by 7.7σ, thus solving a half-a-century old puzzle! [Submitted to Nature Comm.]

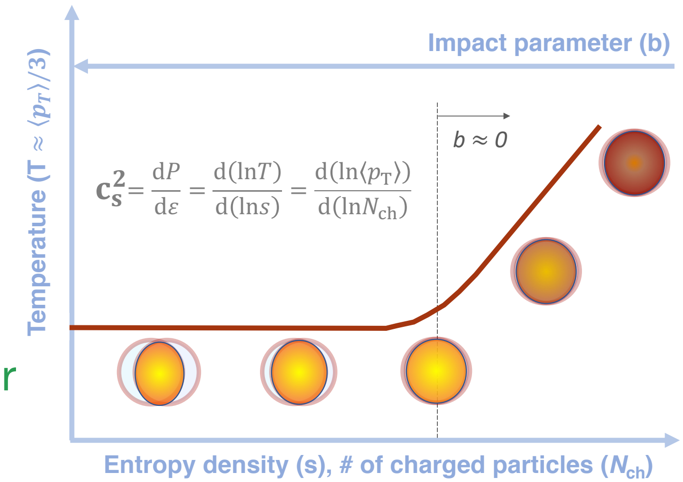


CMS arXiv:2312.17092

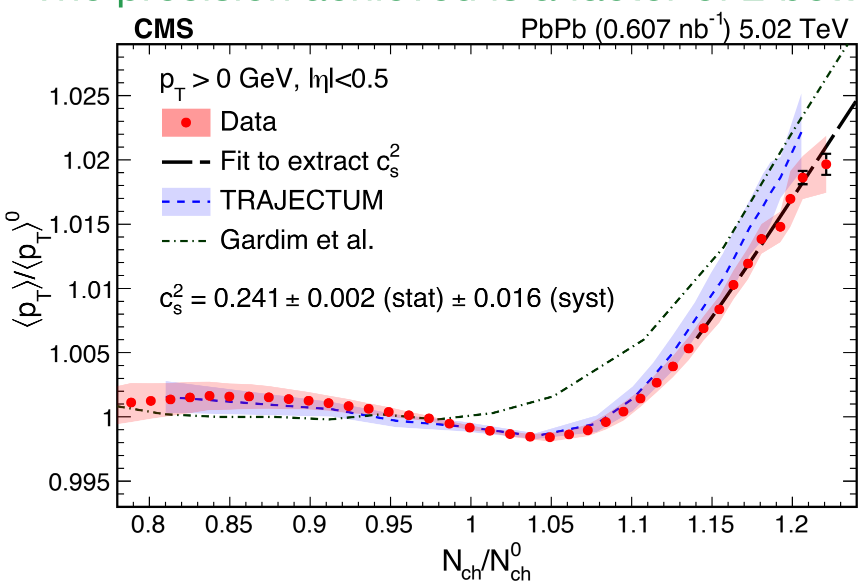


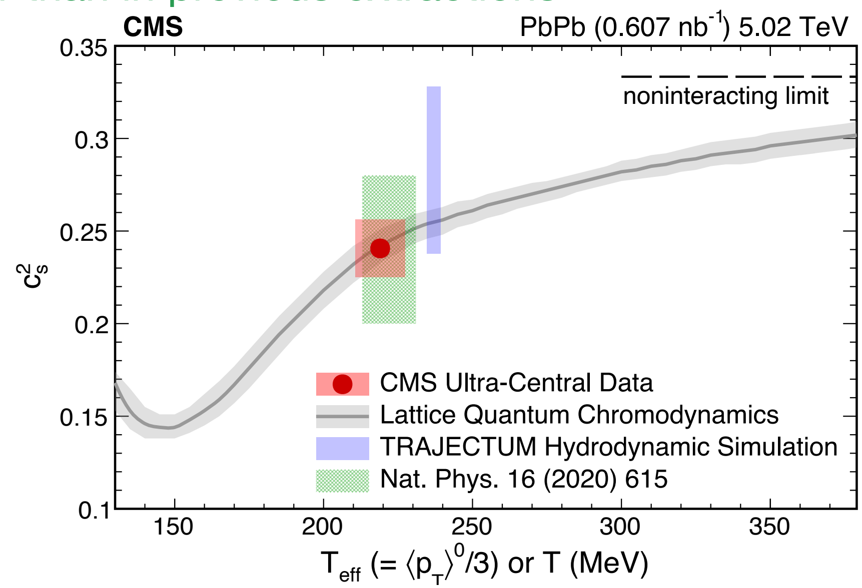
Speed of Sound in QGP

- Based on using thermodynamic equation in heavy ion collisions to extract speed of sound c_s in the QGP using its equation of state: $c_s^2 = dP/d\varepsilon$, where P is pressure and ε is energy density
- Relies on a novel method [Gardim et al., PLB 809 (2020) 135749] of connecting $dP/d\varepsilon$ in heavy ion collisions with nearly 0 impact parameter with the change in the average p_T of charged particles as a function of their multiplicity N_{ch}
- In practice normalize both $\langle p_T \rangle$ and N_{ch} to their average values in a reference sample [0-5% centrality]
- The precision achieved is a factor of 2 better than in previous extractions



CMS ROPP 87 (2024) 077801

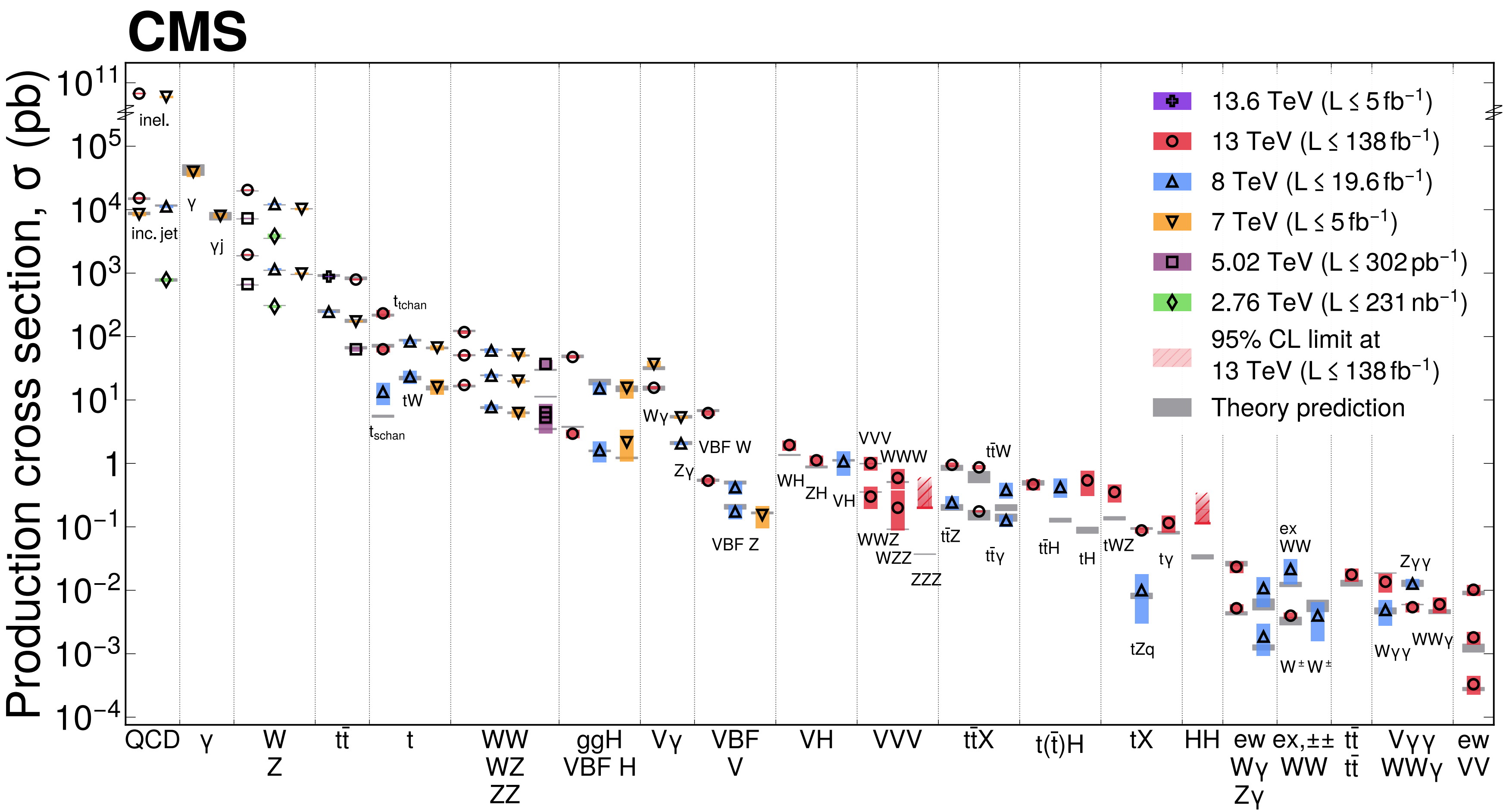




Standard Model Highlights

"Stairway to Heaven"

✦ Mind-boggling precision on so many SM processes!



CMS arXiv:2405.18661

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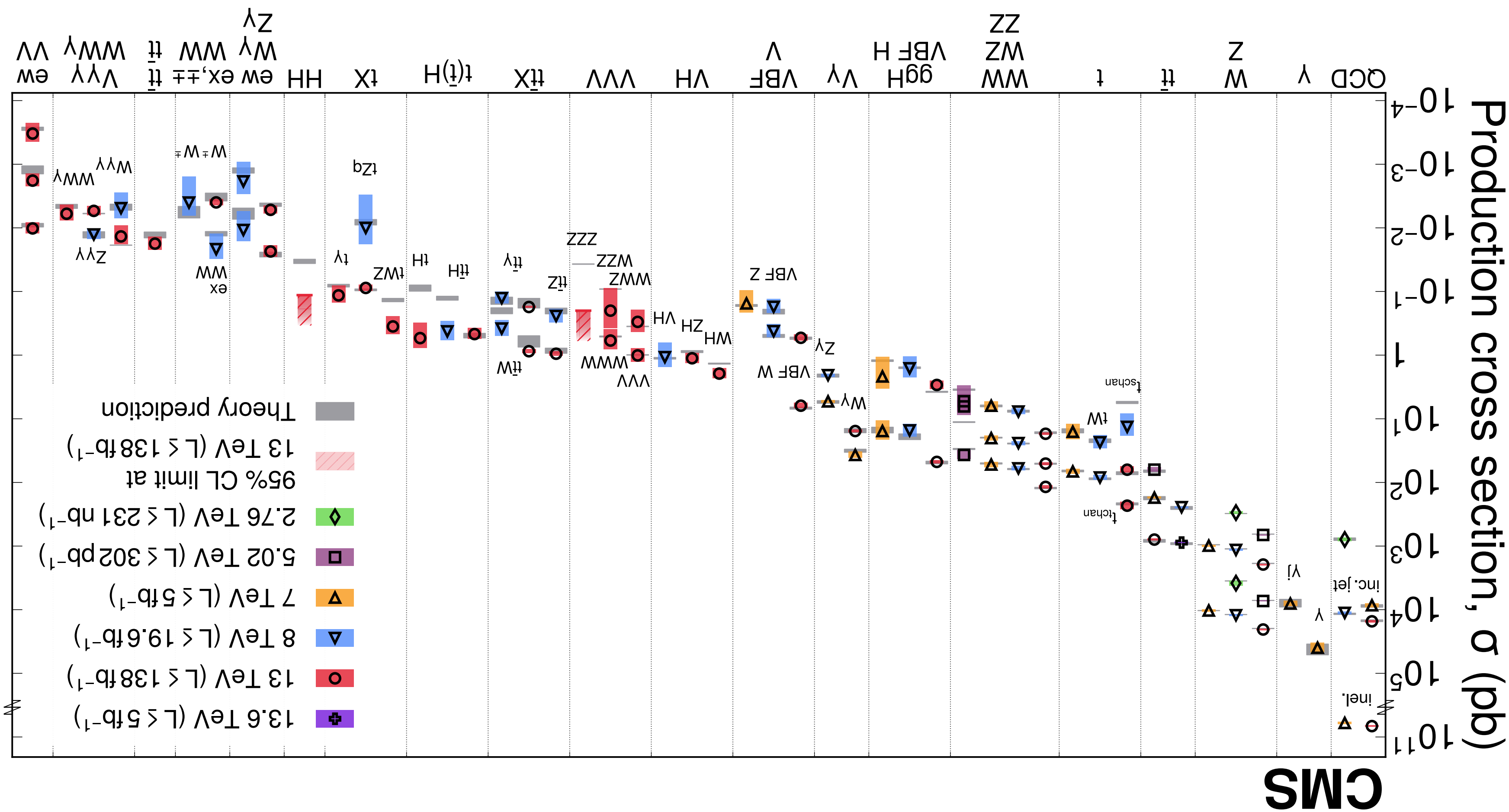
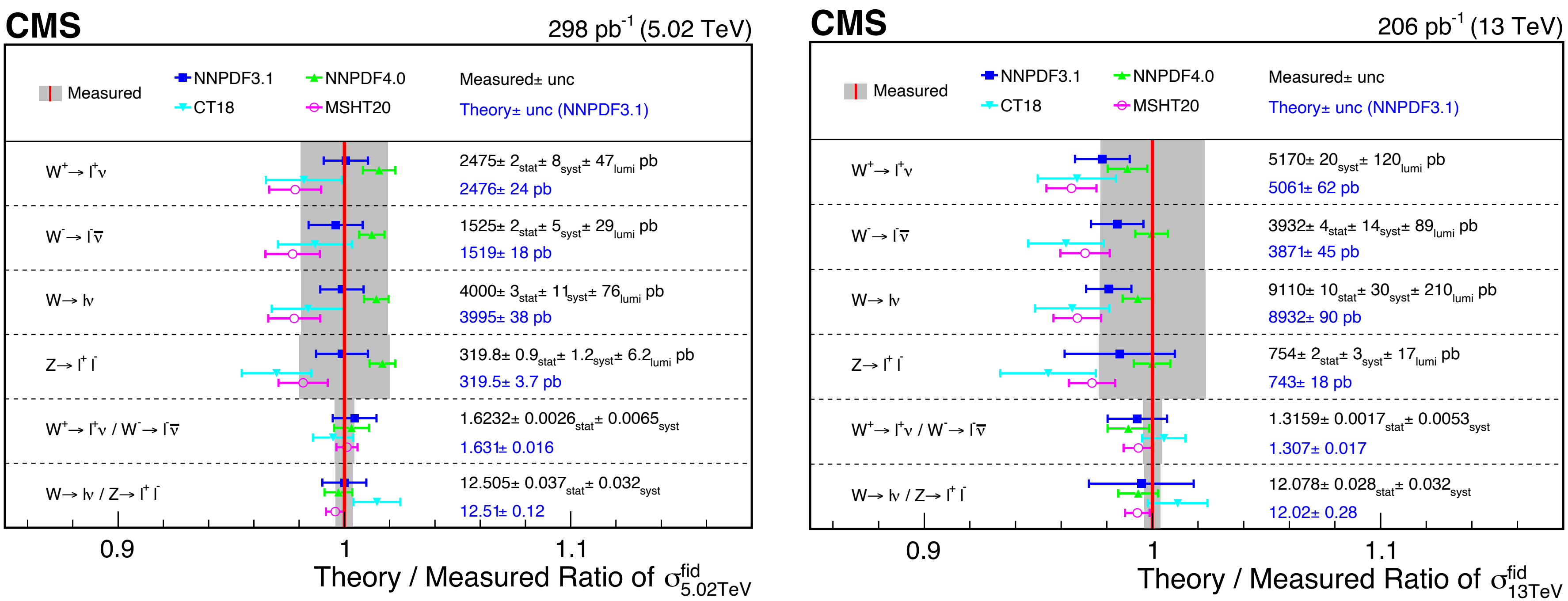


CMS [arXiv:2405.18661](https://arxiv.org/abs/2405.18661)

W/Z Cross Section at 13 TeV

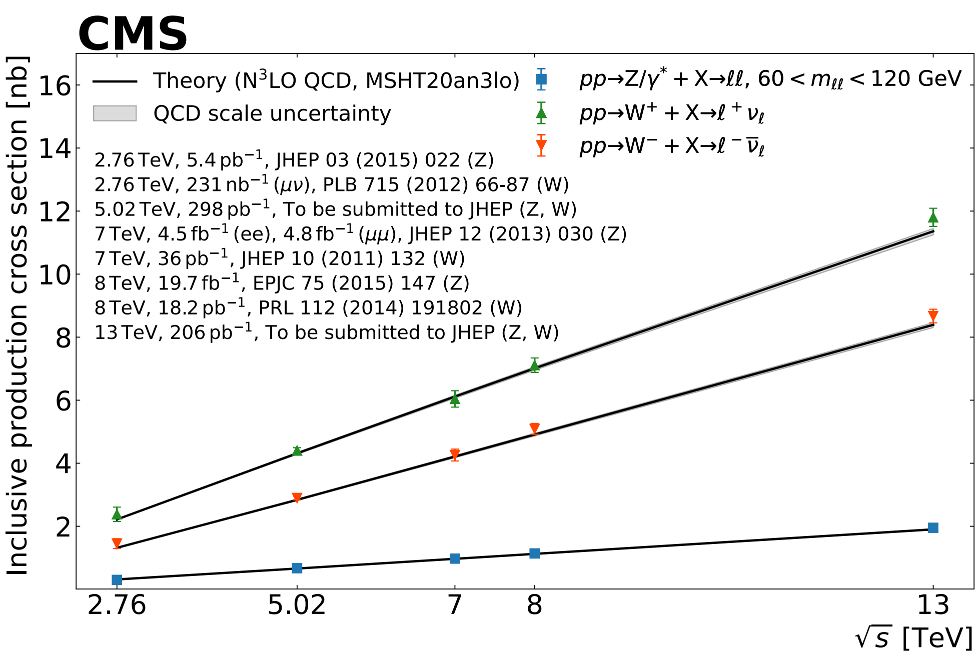
✦ Recent measurement of the W/Z cross section at 5.02 and 13 TeV in special low-pileup runs

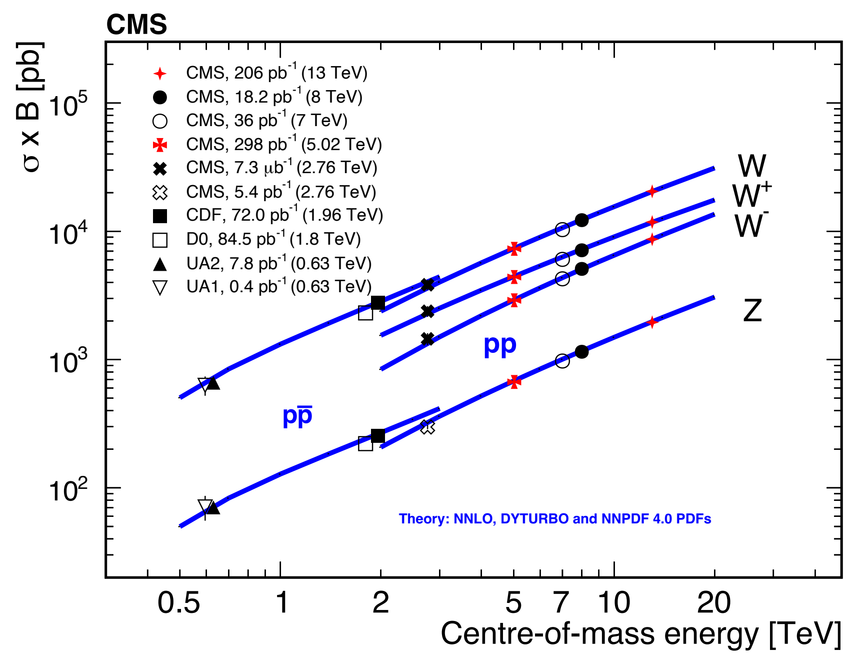


CMS arXiv:2408.03744

Energy Dependence

✦ Excellent agreement with theoretical predictions via DITurbo at N³LO and NNLO



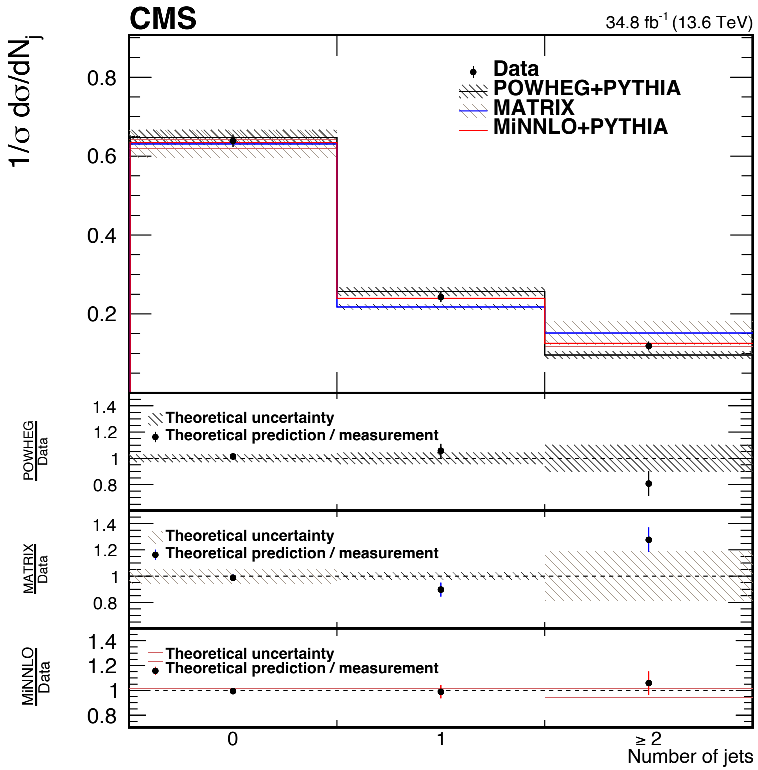


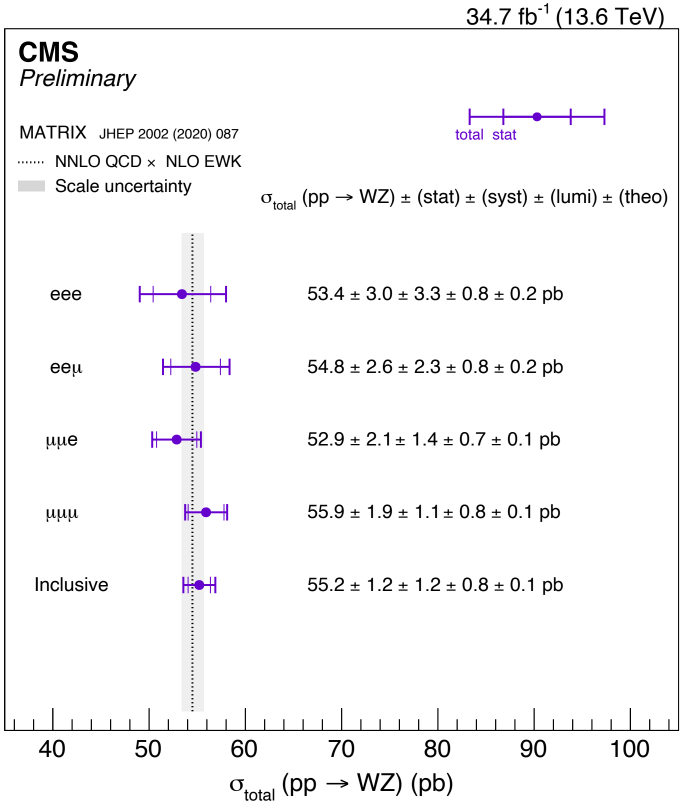
CMS arXiv:2405.18661

Cross Sections at 13.6 TeV

- Recently measured W^+W^- and WZ cross sections at 13 TeV
  - The WW cross section measurement uses eμ channel and defines several control regions (CRs) to constrain the backrounds and extracts the differential cross section $d\sigma/dN_j$
  - The WZ cross section measurement is performed in trilepton channel and also defines several CRs
  - Both measurements are in good agreement with theory at NNLO QCD + NLO EW

CMS arXiv:2406.05101



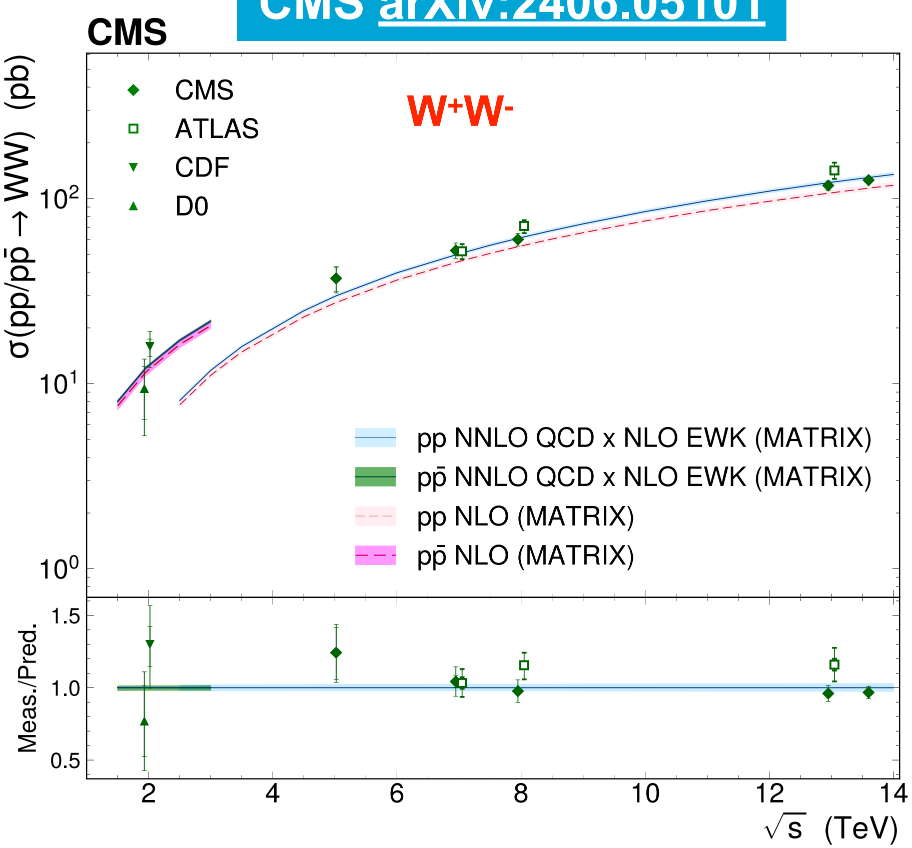


CMS PAS SMP-24-005

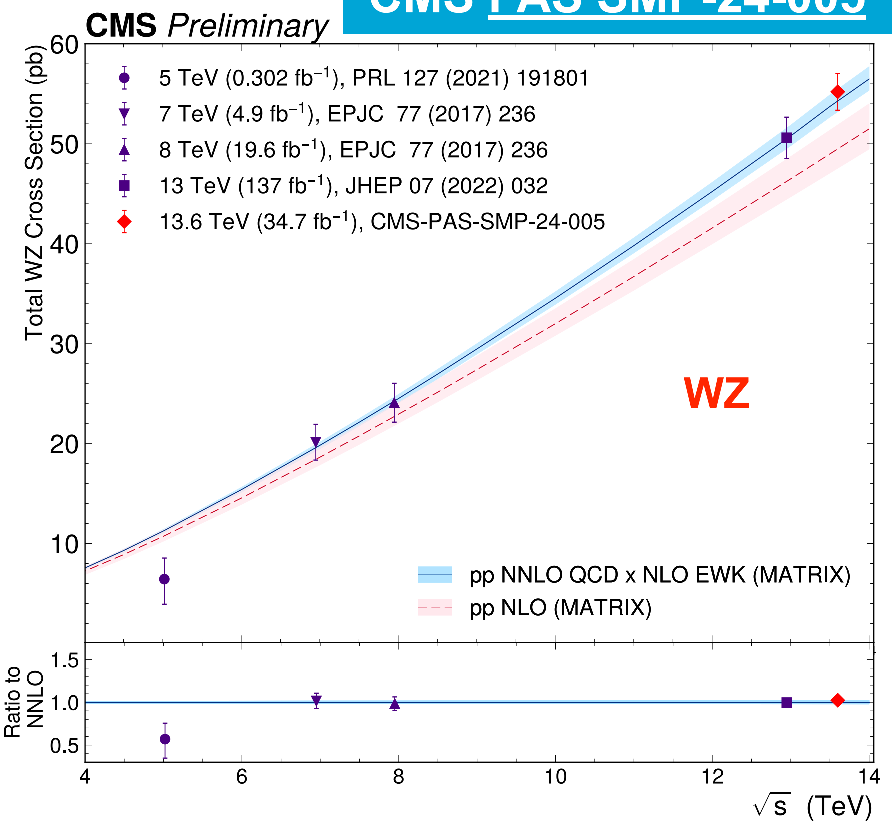
Energy Dependence

- Good agreement with the NNLO QCD X NLO EW SM predictions
- Clear deviation from NLO QCD is seen at high energies

CMS arXiv:2406.05101



CMS PAS SMP-24-005



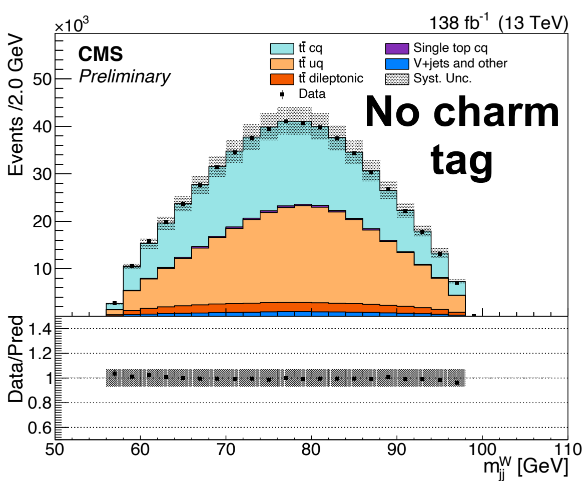
W → cq over W → qq'

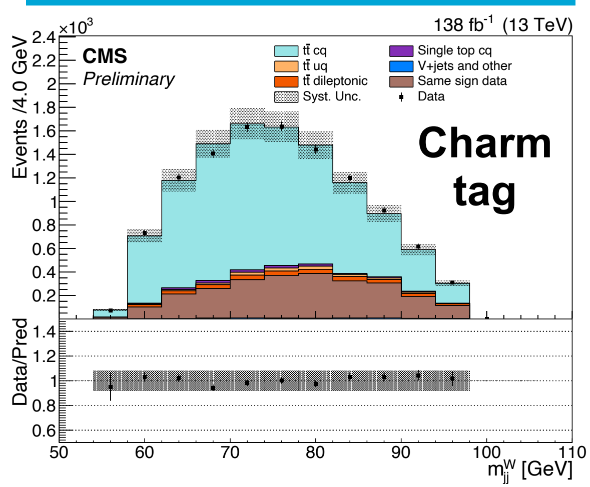
- Measurement of the W → cq over W → qq' (and charge-conjugate) cross section ratio gives access to the $|V_{cs}|$ CKM matrix element
- Indeed $R_c^W = \dfrac{\mathcal{B}(W \to cq)}{\mathcal{B}(W \to uq) + \mathcal{B}(W \to cq)}$ can be expressed as $R_c^W = \dfrac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2} = 0.5,$ assuming the CKM matrix unitarity
- The current best R_c^W measurement comes from LEP $R_c^W = 0.49 \pm 0.04$
- We used a sample of tt events as the "tagged" source of W bosons, with one decaying leptonically and the other one hadronically
- Charm jets are identified using muon tagging, with the muon of an opposite sign (OS) to that of a lepton from the other W boson decay; the backgrounds have equal fractions of OS and SS events, so we used OS-SS subtraction to extract the signal

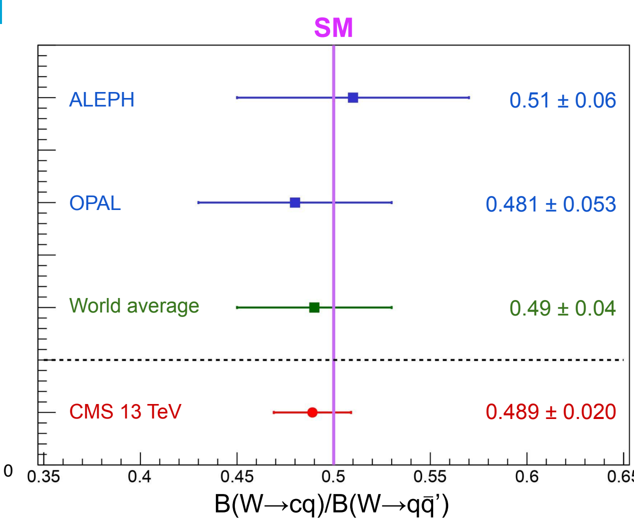
$|V_{cs}|$ Measurement

- The dijet invariant mass spectra are well reproduced by simulation
- Charm tag + SS subtraction are effective in removing backgrounds
- Precision twice that of the LEP result has been achieved:
  - $R_c^W = 0.489 \pm 0.005\ (\text{stat}) \pm 0.019\ (\text{syst}) = 0.489 \pm 0.020$
- Using measurement of the leptonic branching fractions we obtain the sum of squared second row CKM elements of $\Sigma = 0.970 \pm 0.041$
- Subtracting world-average $|V_{cd}|^2$ and $|V_{cb}|^2$ values, we obtain $|V_{cs}| = 0.959 \pm 0.021$ [to be compared with the 0.975 ± 0.006 world average]

CMS PAS SMP-24-009



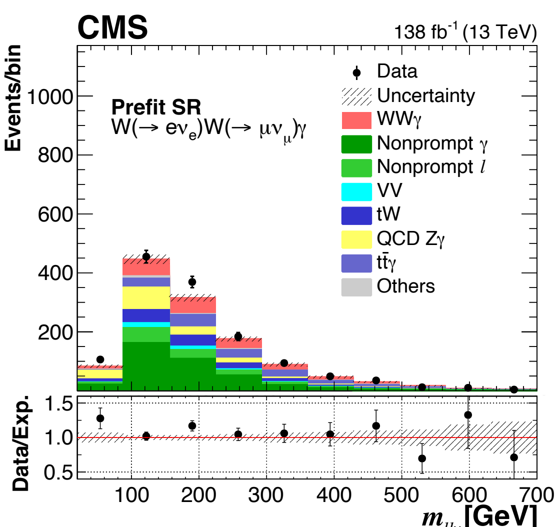


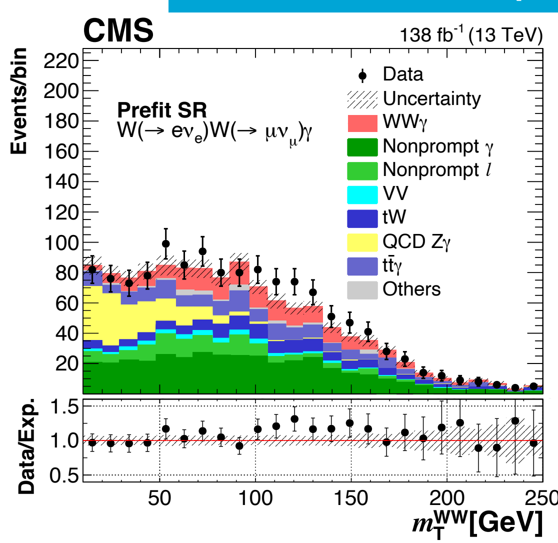


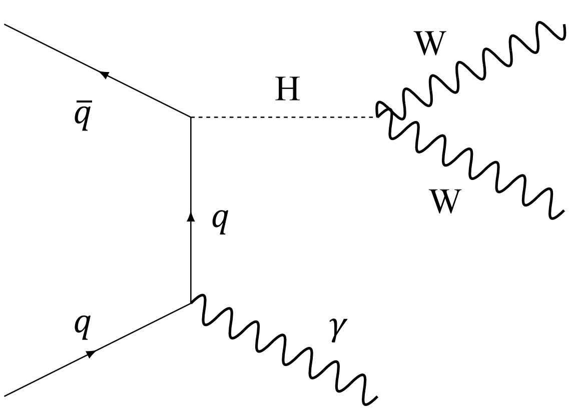
Observation of WWγ Production

- CMS reported the first observation of the WWγ production
- The process is sensitive to both TGCs and QGCs, as well as H(WW)+γ
- Search is performed in the eμγ+ME_T final state using m(eμγ) vs. m_T(WW) 2D distribution
- σ_{fid} = 5.9 ± 1.3 fb is observed, in agreement with the 5.33 ± 0.34 (scale) ± 0.05 (PDF) fb NLO QCD prediction
- The WWγ signal is observed with 5.6 (5.1 expected)σ
- Limits at 95% CL on Hγ production initiated by c quarks are set at 88 fb, corresponding to $|\kappa_c| < 190$

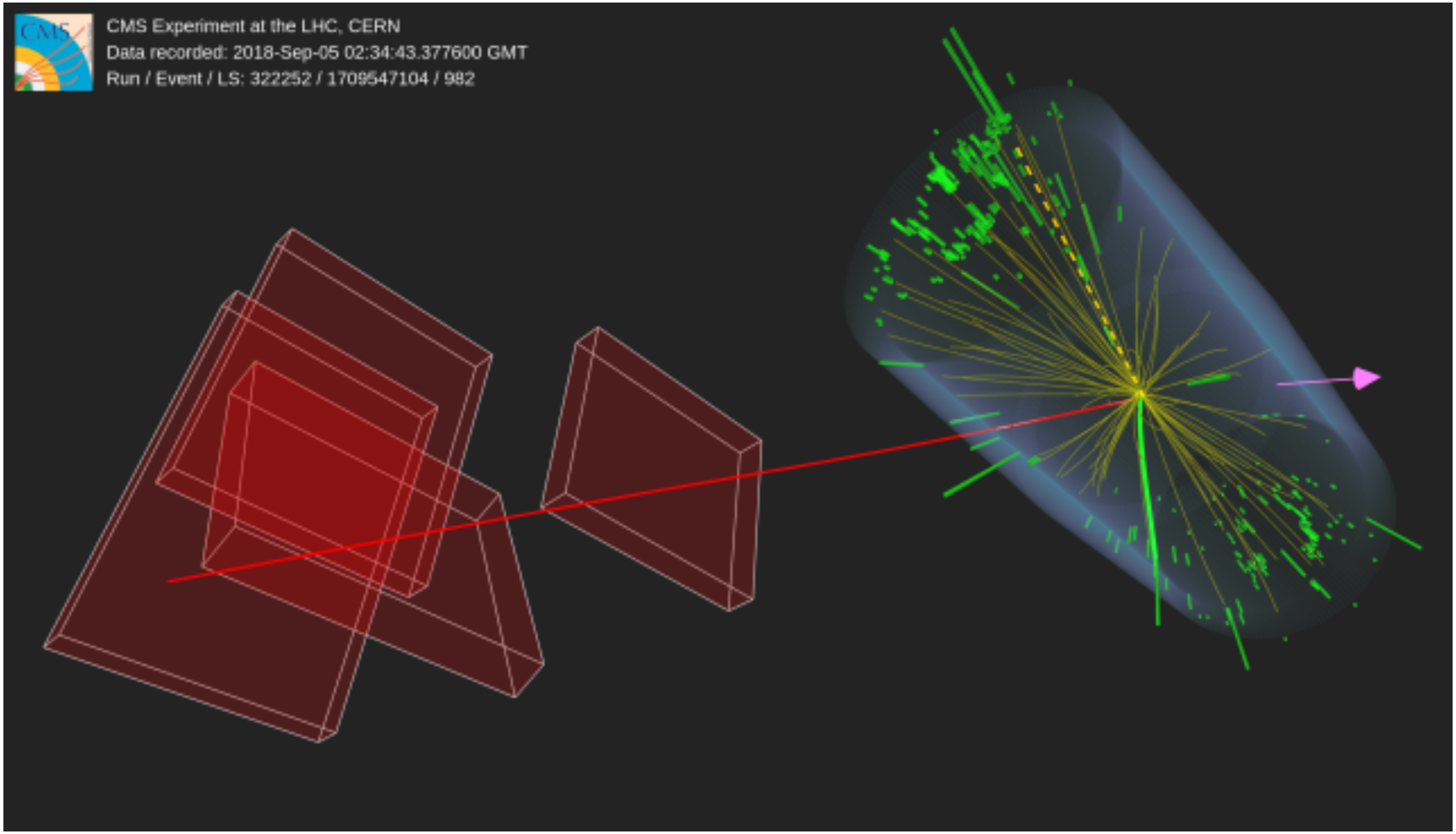
CMS PRL 132 (2023) 123901







WWγ Candidate



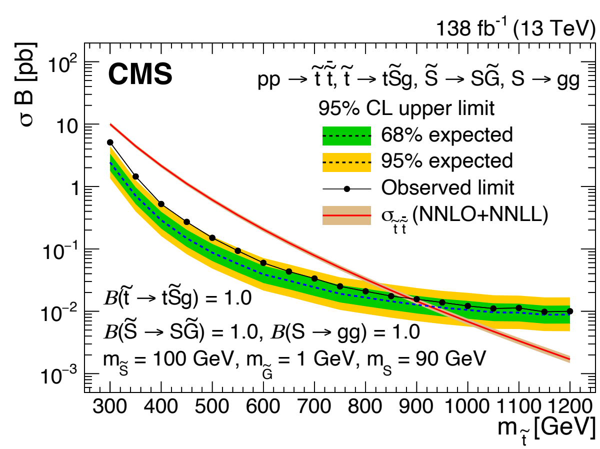
A candidate event in which two W bosons and a photon are produced. One W boson decays to a muon (represented by the red line) and a neutrino and the other to an electron (represented by the green line) and a neutrino. The photon is represented by the dashed line pointing to the energy deposit in the calorimeter (represented by the green boxes).

Searches for New Physics

See also Albert De Roeck's and Andrea Perrotta's talks on Wednesday

Looking for Unknown

- The LHC has been successfully operating for nearly 15 years, transforming the entire landscape of searches for new physics
- Despite a number of tantalizing hints seen by ATLAS, CMS, and LHCb over the years, apart from the observation of the Higgs boson and a number of QCD states, none of them raised to the discovery level yet; many are now gone
- So, why are we still looking for new physics at the LHC and where should we look for it if we are to continue?
- Why are we still covering something like a territory of Brazil with the "Brazilian flag" exclusion plots?



The Why

- Many things are missing from the standard model (SM), hinting that it is likely incomplete
  - Physics issues: no gravity; no dark matter; no connection between the three generations of quarks and leptons; no quantitative explanation of the matter-antimatter asymmetry in the universe; no neutrino oscillations
  - Math issues: naturalness, which became a real problem since the discovery of the Higgs boson; "arbitrary" fermion masses; strong CP problem
- Most of viable SM extensions that cure some of the above problems require new particles, dimensions, symmetries
- Many lead to the phenomenology within the reach of the LHC, although there is no guarantee anymore
- Many exclusions, while appear strong, are based on simplifying assumptions, which are often arbitrary (e.g., Br = 1) - read the fine print!

The Why

Read the fine print!

The Where

- Given that the LHC has reached its ultimate energy, looking for heavy particles is a game of a diminishing return - it will take many years to discover something in this regime, if we haven't seen a hint so far
  - No more low-hanging fruit!

- The focus shifts to much more complicated signatures, which haven't been exploited thus far, as well as significantly more sophisticated analyses than we pursued during the earlier years
- Doubling time has doubled since Run 2; it is now about three years
  - Compatible with a "lifetime" of a graduate student in an LHC experiment, allowing for a well-designed and sophisticated analysis rather than a "luminosity chase"

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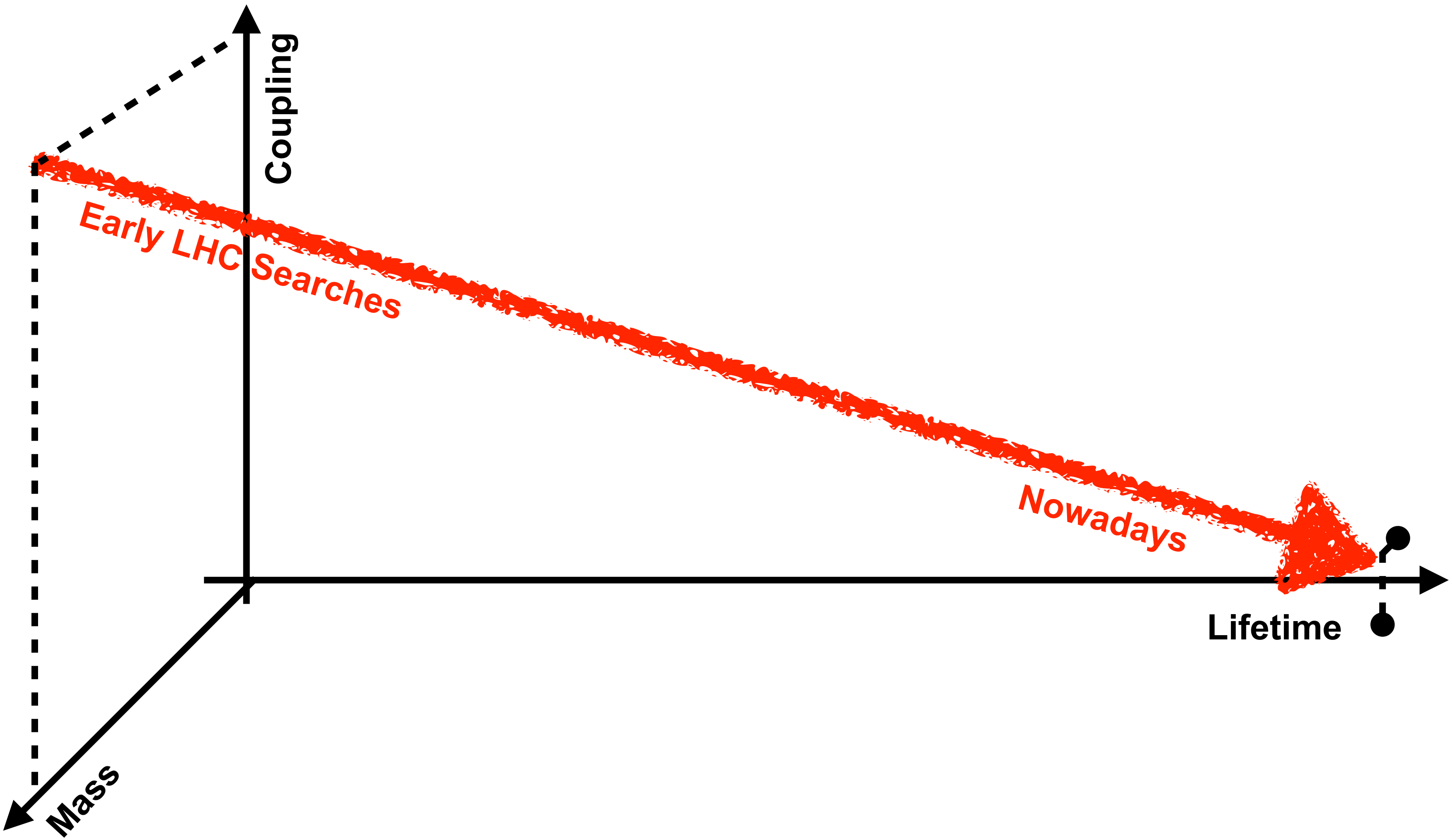
Stairway to Hell

✦ The paradigm shift

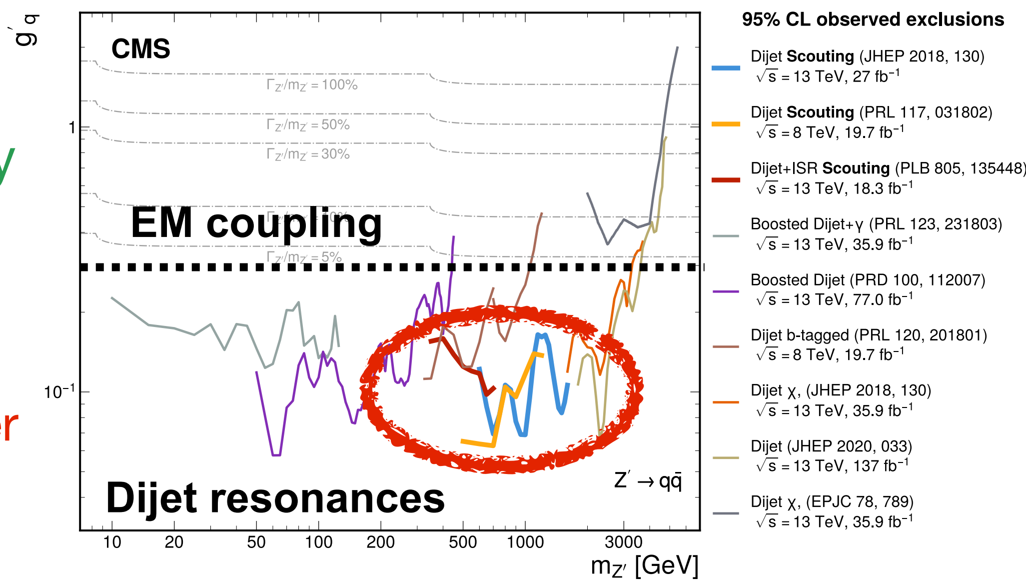


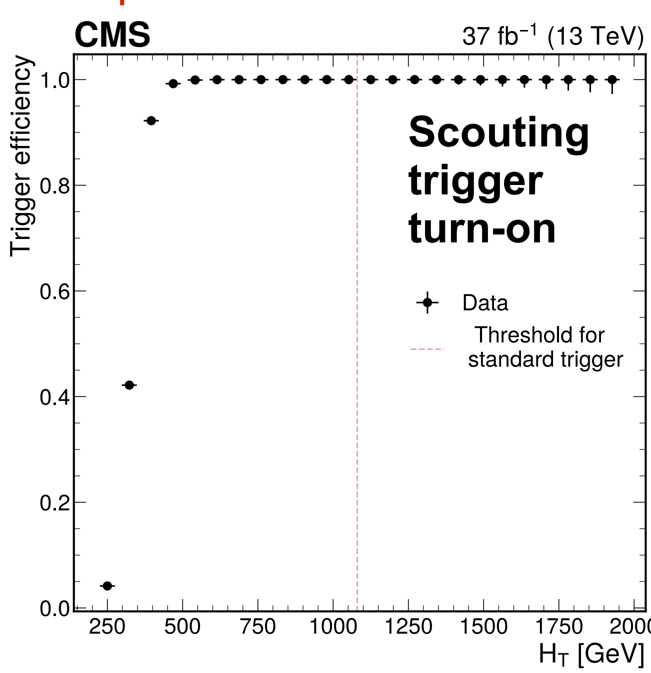
New Tools for the New Paradigm

- Use of new triggers not available earlier in the LHC running
  - A variety of triggers optimized for long-lived particles
  - Data scouting
  - Extensive use of GPU in the trigger
  - ISR-based triggers with jet substructure and mass-decorrelated subjet taggers
  - Data parking
- Novel approaches with machine learning (ML) techniques: weakly supervised and unsupervised ML

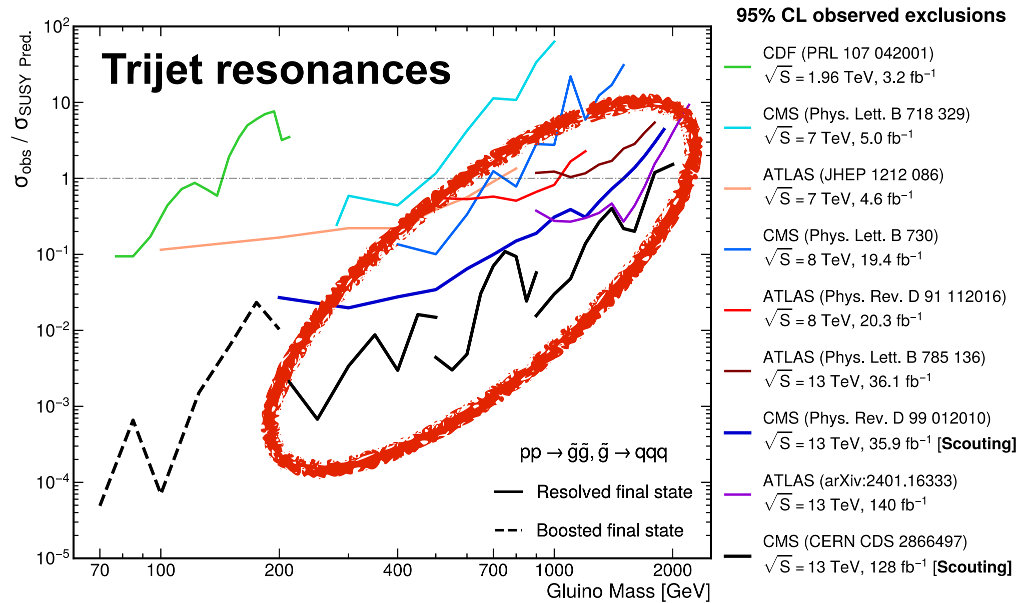
Toward Small Masses: Scouting

- Scouting analysis is based only on the high-level trigger (HLT) objects resulting in a very compact event size and vastly increased rate per bandwidth for the scouting data stream
  - Avoids the use of (large) trigger prescales



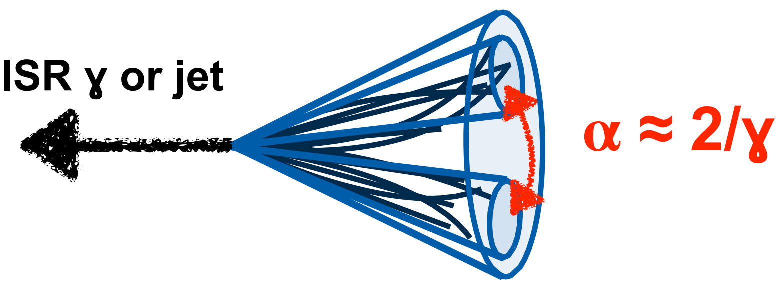


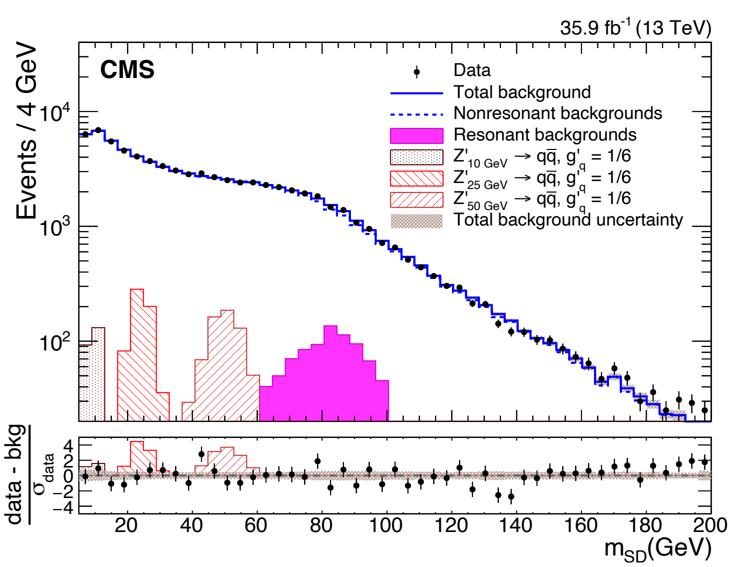
CMS arXiv:2403.16134



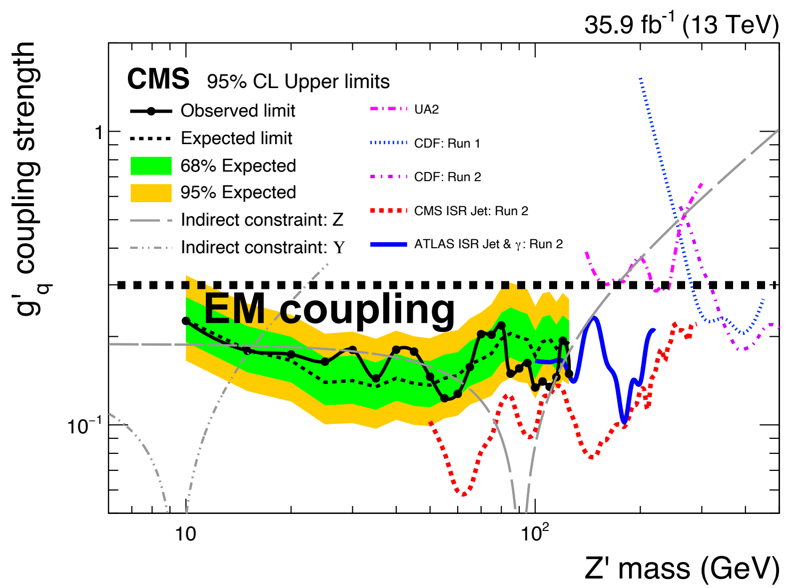
Toward Small Masses: ISR

- Use high-p_T single-photon or single-jet triggers to record the events, require a substructure in the recoiling AK8 jet, and search for narrow resonances in the recoiling jet trimmed mass spectrum
- Allows to go as low as 10 GeV in the resonance mass!





CMS PRL 123 (2019) 231803



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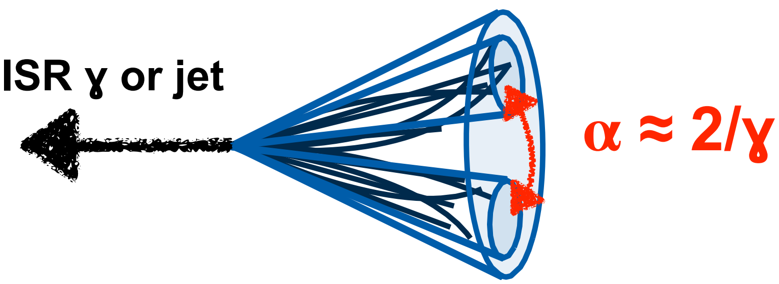
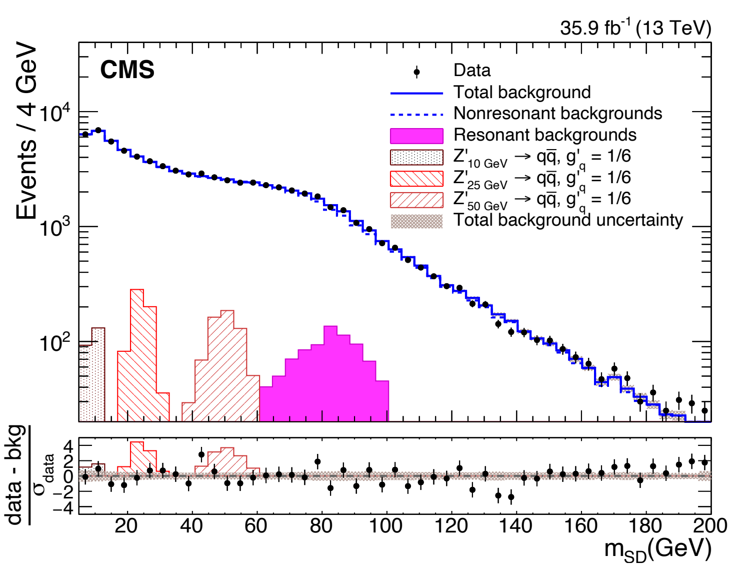


p_T(ISR) ~ 100 GeV
m(X) ~ 25 GeV
γ ~ 4, α ~ 0.5 - a single jet



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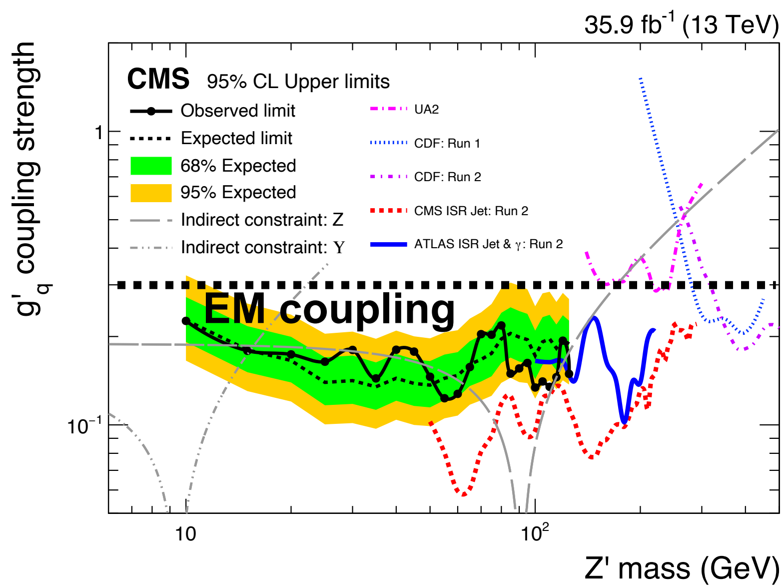

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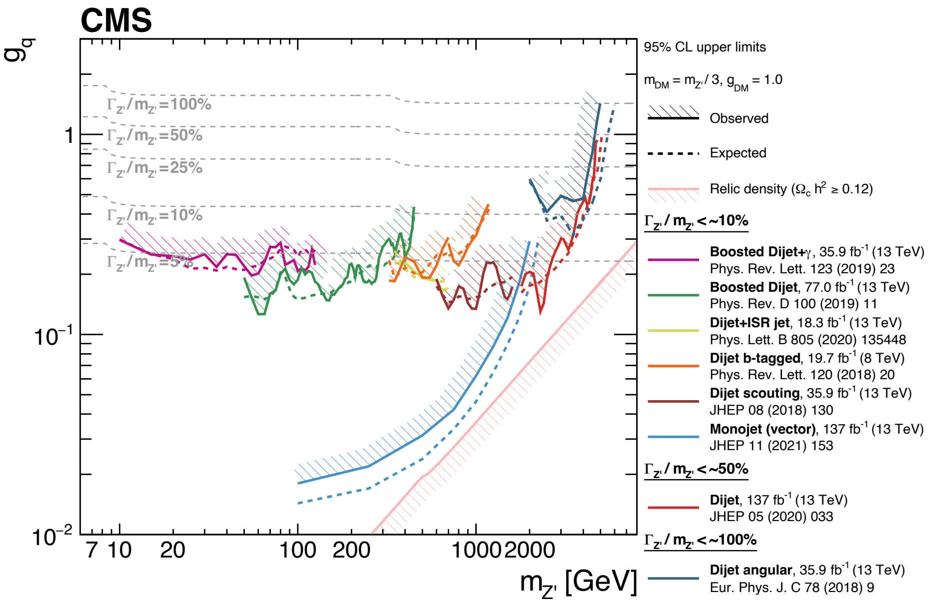

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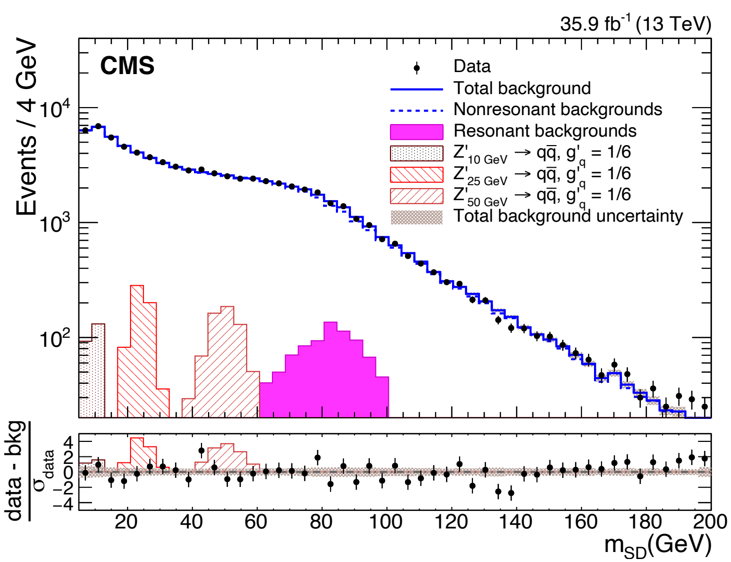
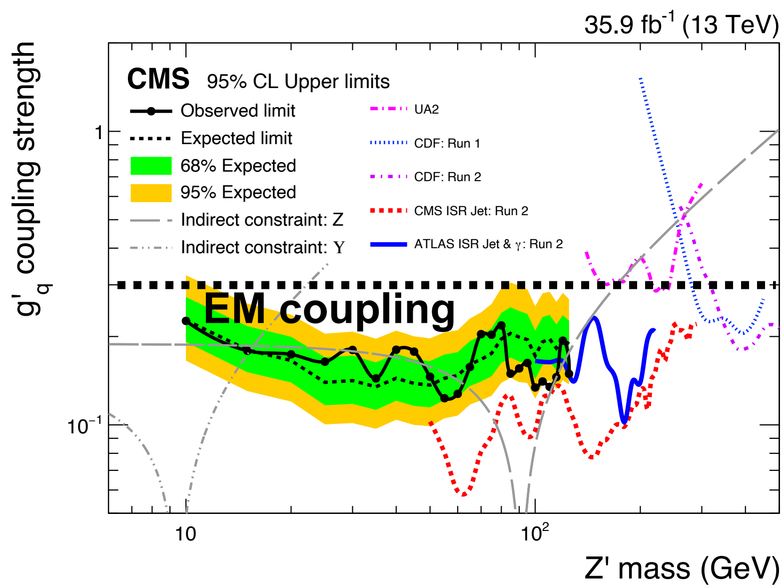


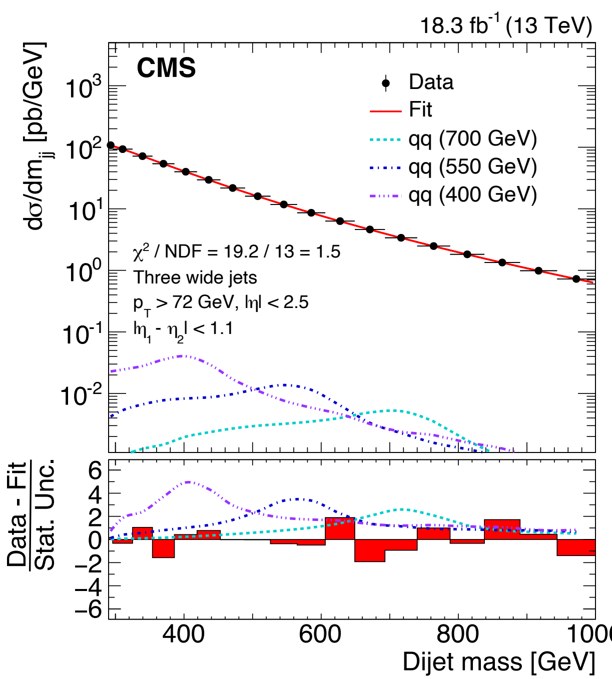


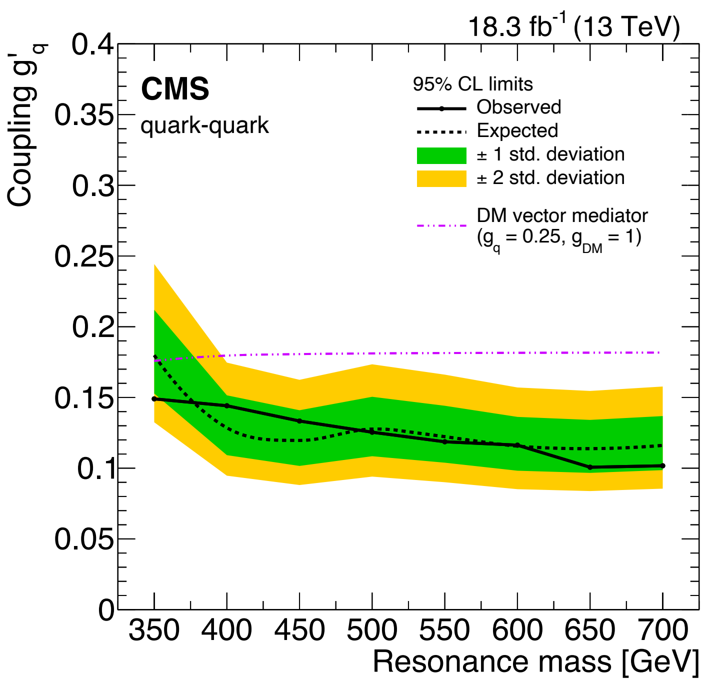
BROWN

Toward Low Masses: ISR+Scouting

- One could also combine the two techniques, adding extra sensitivity
  - The idea behind a CMS search for dijet resonances in three-jet events collected by a low-H_T scouting trigger (4 kHz @ 10^{34} $cm^{-2}s^{-1}$) available for ~half of 2016 data taking (18 fb^{-1})
  - Use large-R (1.1) jets offline to improve resolution and acceptance
  - Limits set in the 350-700 GeV range as low as 1/3 of EM coupling

CMS PLB 805 (2020) 135448





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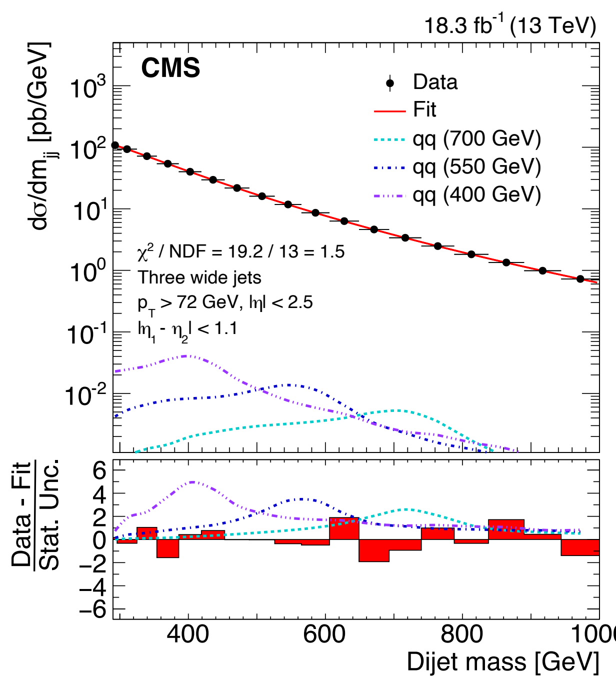
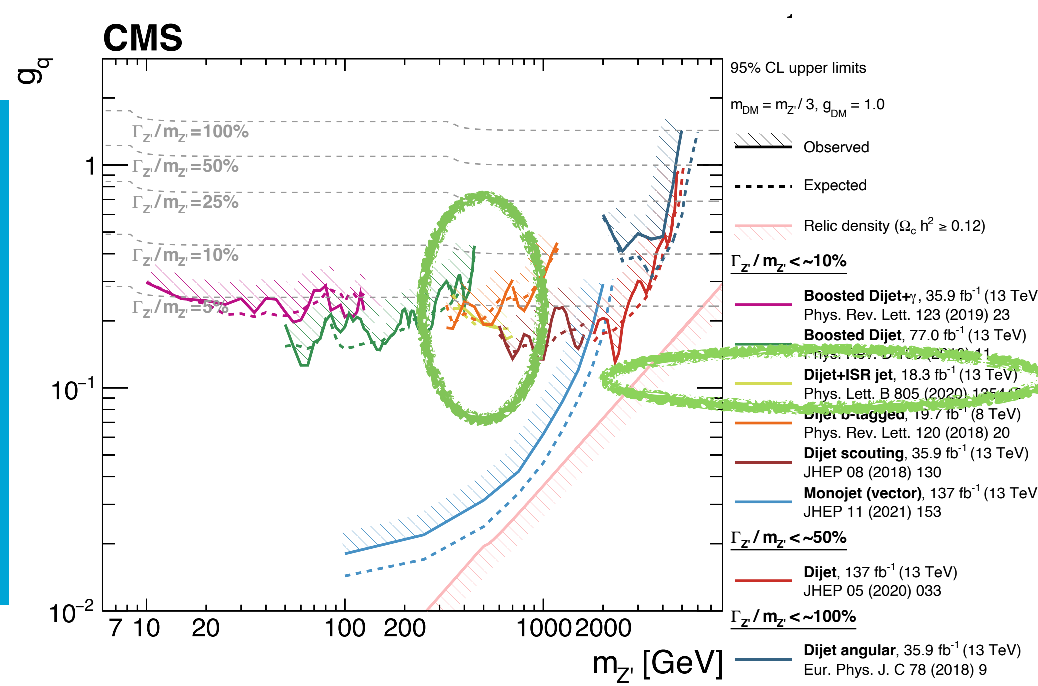
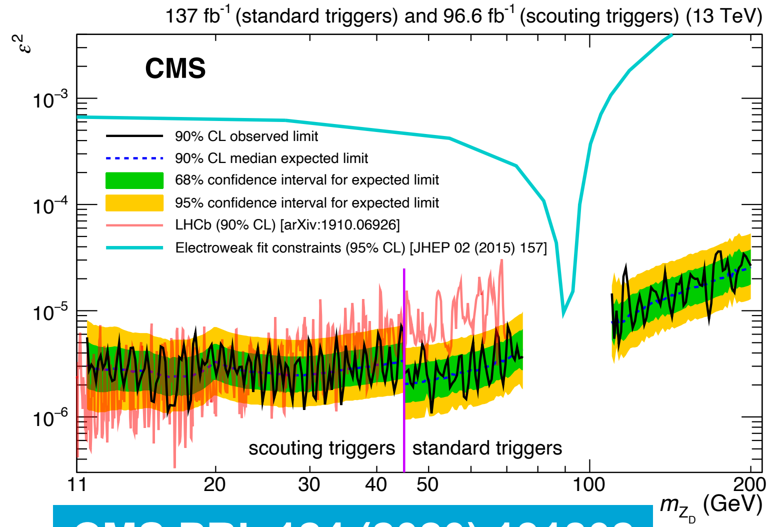


CMS arXiv:2403.16134

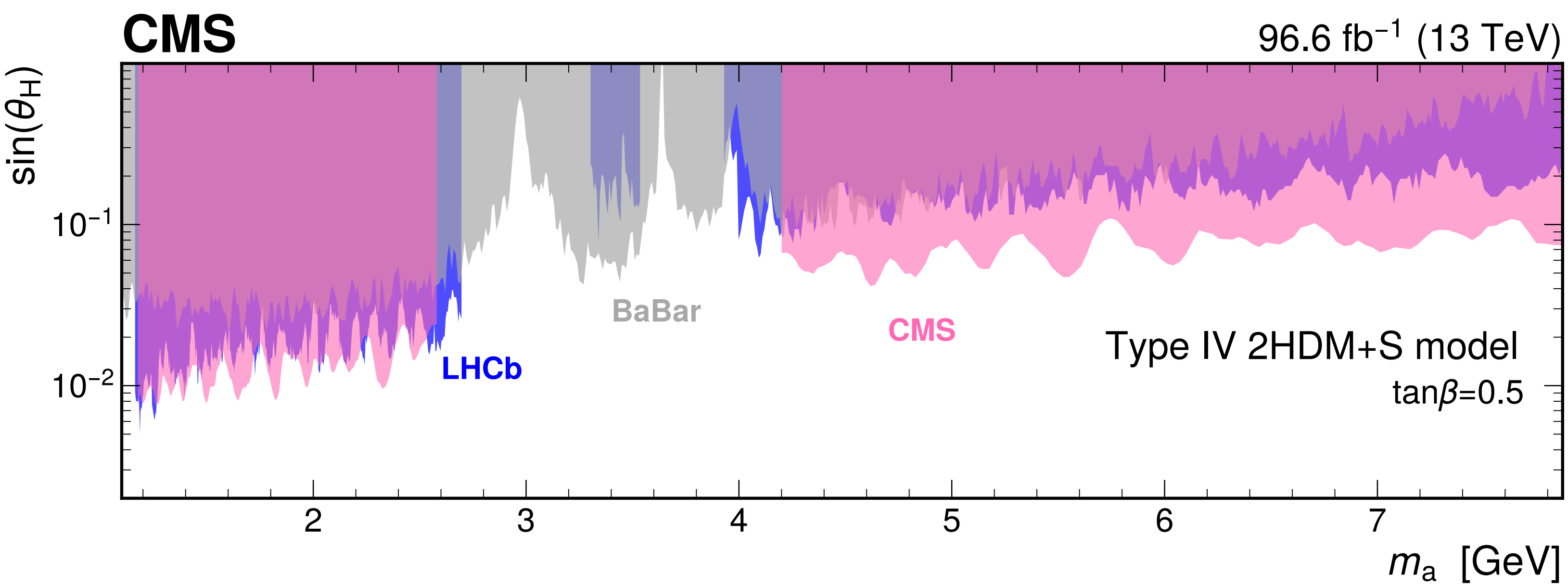


Low-Mass Dimuon Resonances

- CMS searches based on the dimuon regular and scouting triggers
- Nice complementarity between the two sets of results, interpreted as dark Z boson or in the context of 2HDM + complex singlet model w/ H-a mixing
- New search based entirely on a scouting trigger allowed to lower the mass reach below the Υ resonances in the same models

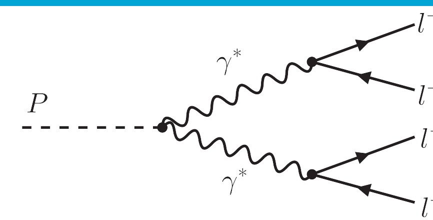


CMS PRL 124 (2020) 131802

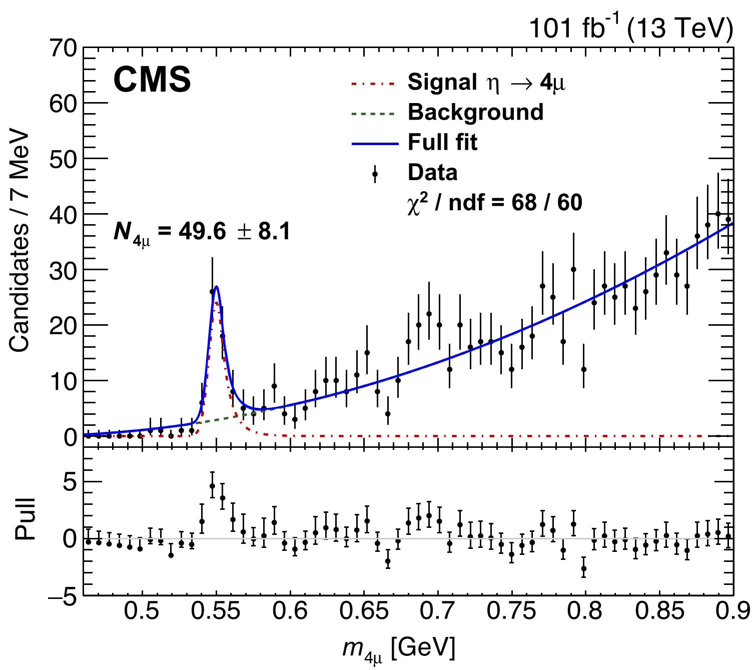


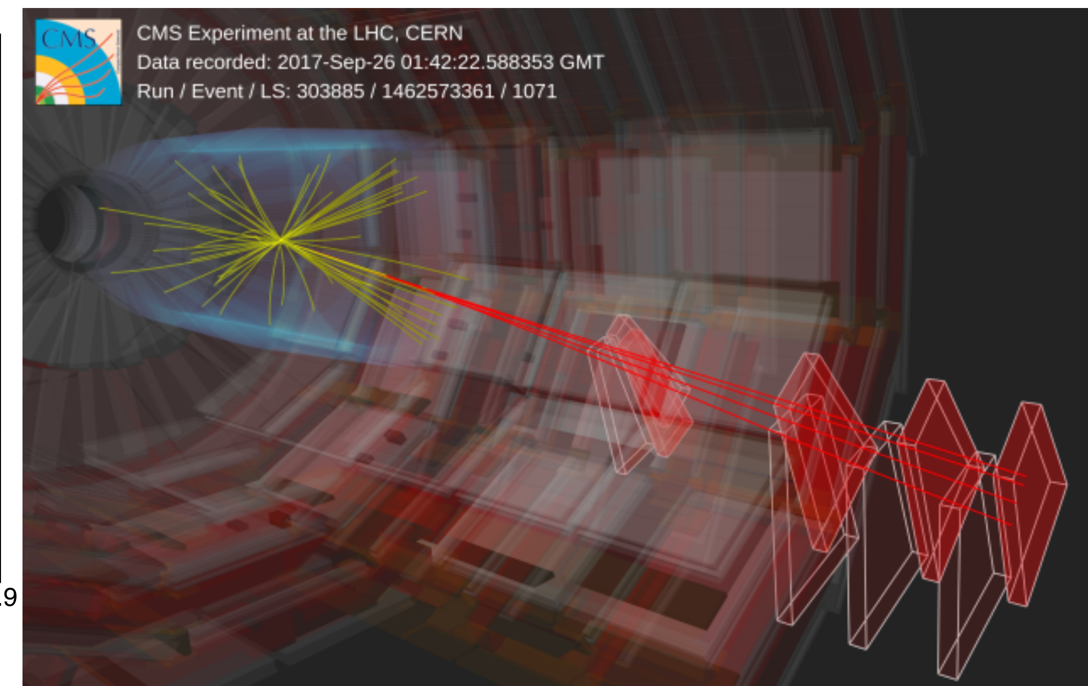
CMS JHEP 12 (2023) 070

Searches in Parked Data



- ✦ Observation of a rare η → 4μ Dalitz decay with high-rate dimuon triggers
  - $\mathcal{B}(\eta \to 4\mu) = [5.8 \pm 0.8\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 0.7\ (\mathcal{B})] \times 10^{-9}$
  - Consistent with the SM prediction of $[3.98 \pm 0.15] \times 10^{-9}$

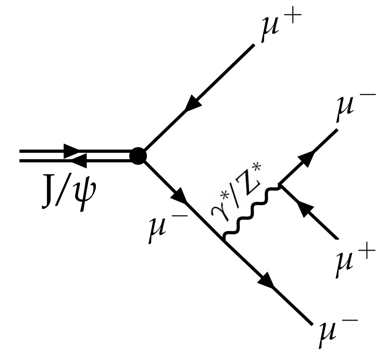




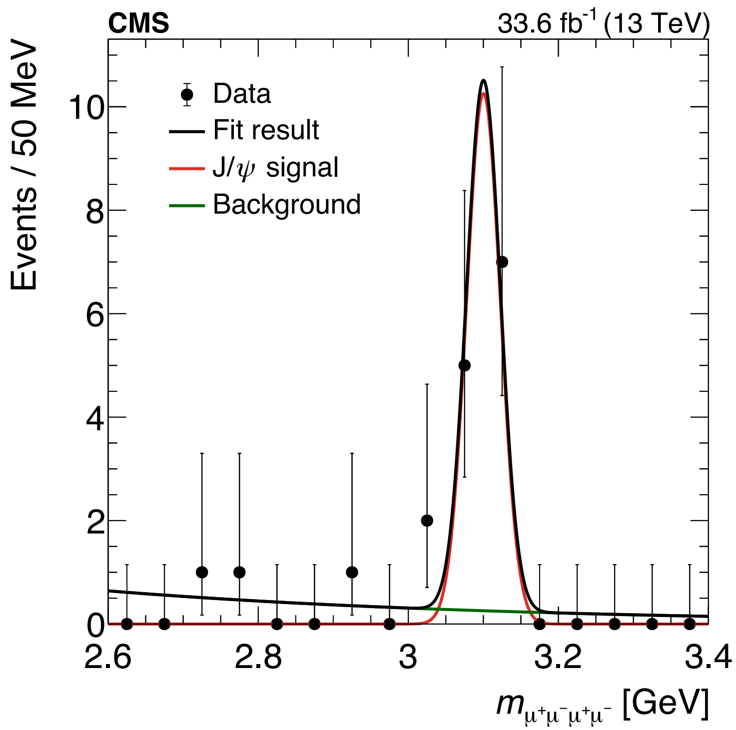
CMS PRL 131 (2023) 091903

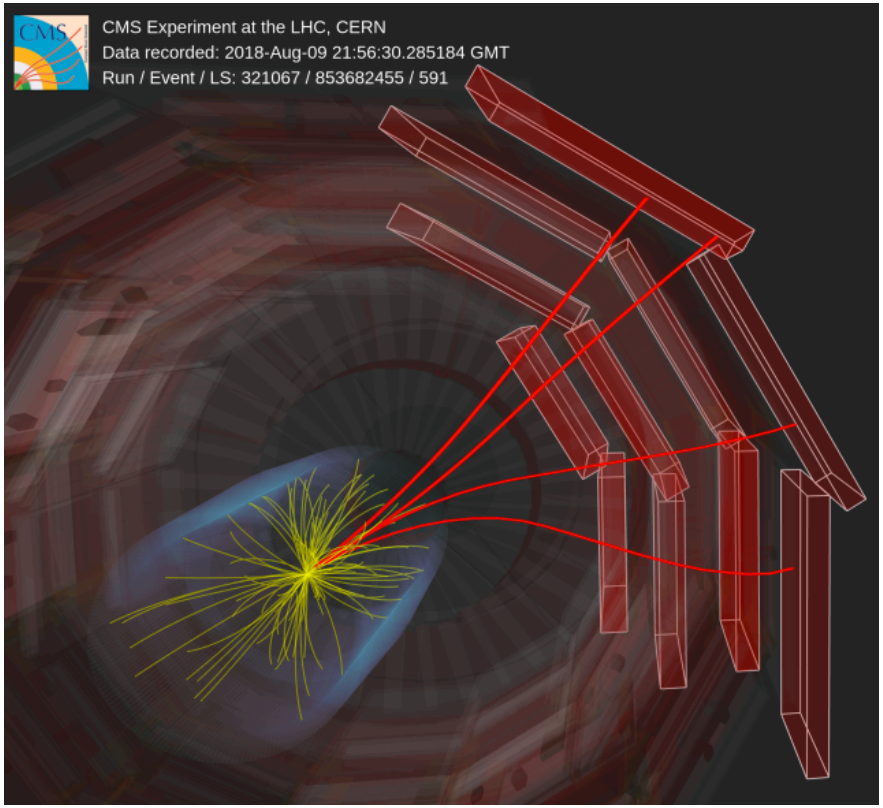
Observation of J/ψ → 4μ

- Observation of the J/ψ → 4μ decay using B parked data
- Based on a displaced muon trigger
  - $\mathcal{B}(J/\psi \to 4\mu) = [10.1^{+3.3}_{-2.7}\,(\text{stat}) \pm 0.4\,(\text{syst})]\times10^{-7}$
  - Consistent with the SM prediction of $[9.74 \pm 0.05]\times10^{-7}$



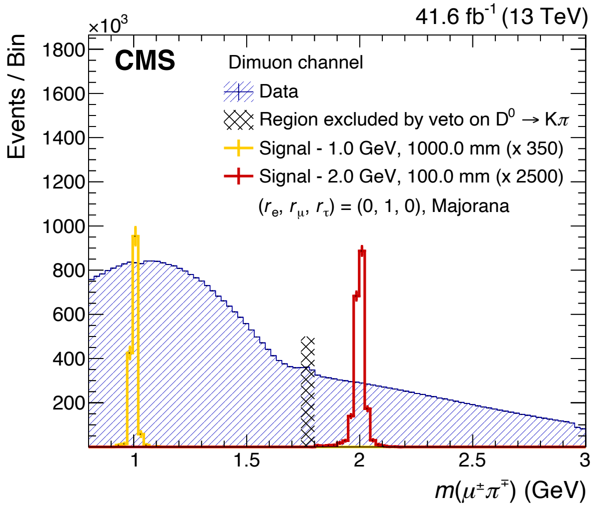
CMS PRD 109 (2024) L111101

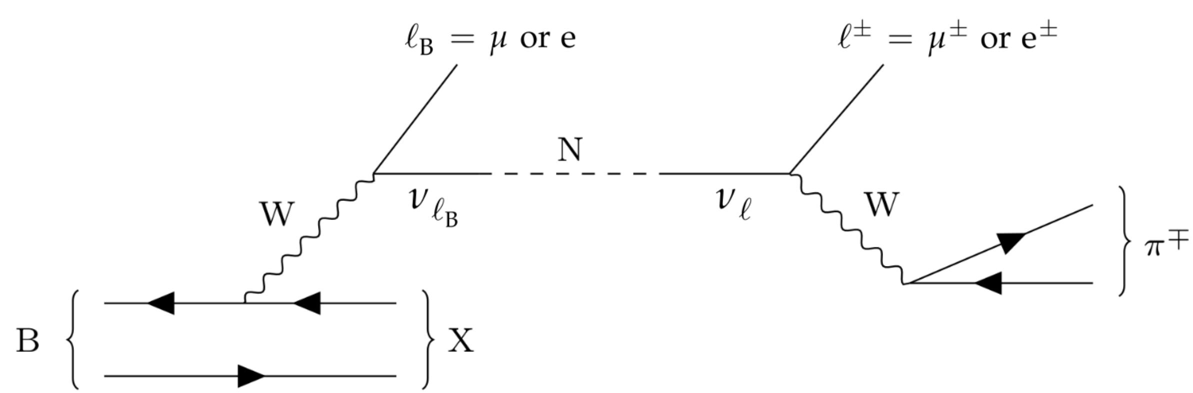




Search for HNLs in Parked Data

- Heavy neutral leptons are present in many models explaining neutrino masses
- CMS parked data made it possible to make a search for HNL in b hadron decays
- Consider generic case of mixing with all three neutrino families: $|V_N|^2 = |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$, with $r_\ell = |V_{\ell N}|^2/|V_N|^2$
- Consider different combinations of r_ℓ
- Look for a peak in the $\ell^\pm\pi^\mp$ mass spectrum in a number of categories based on the displacement, relative sign of two leptons, and the three-body mass

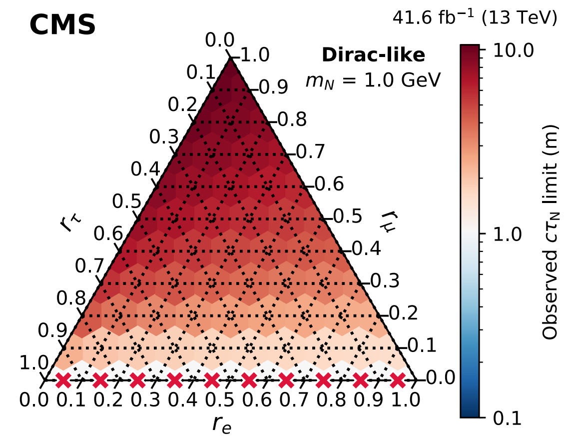


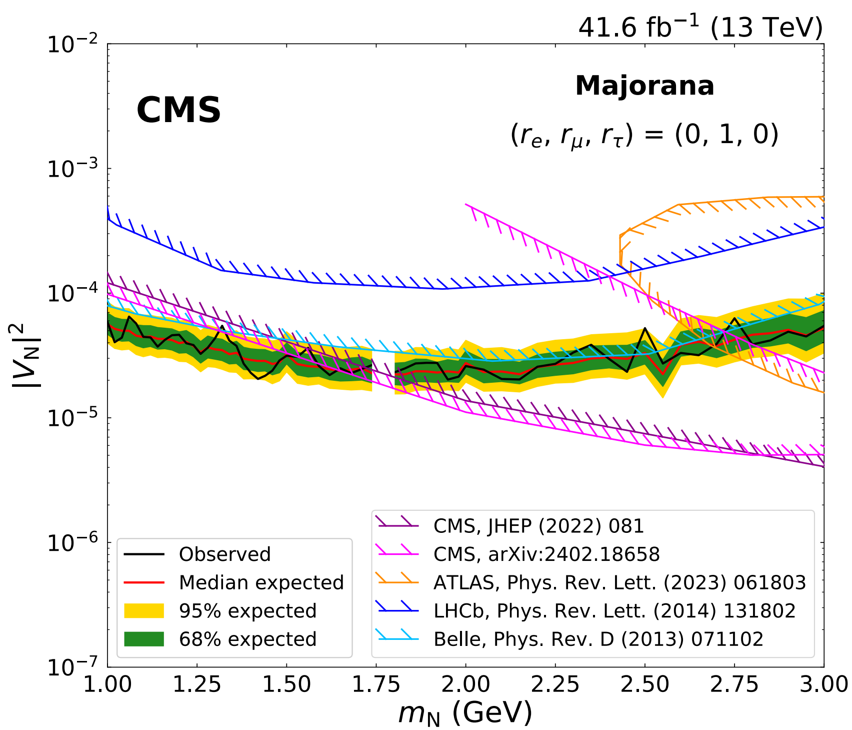


CMS JHEP 06 (2024) 183

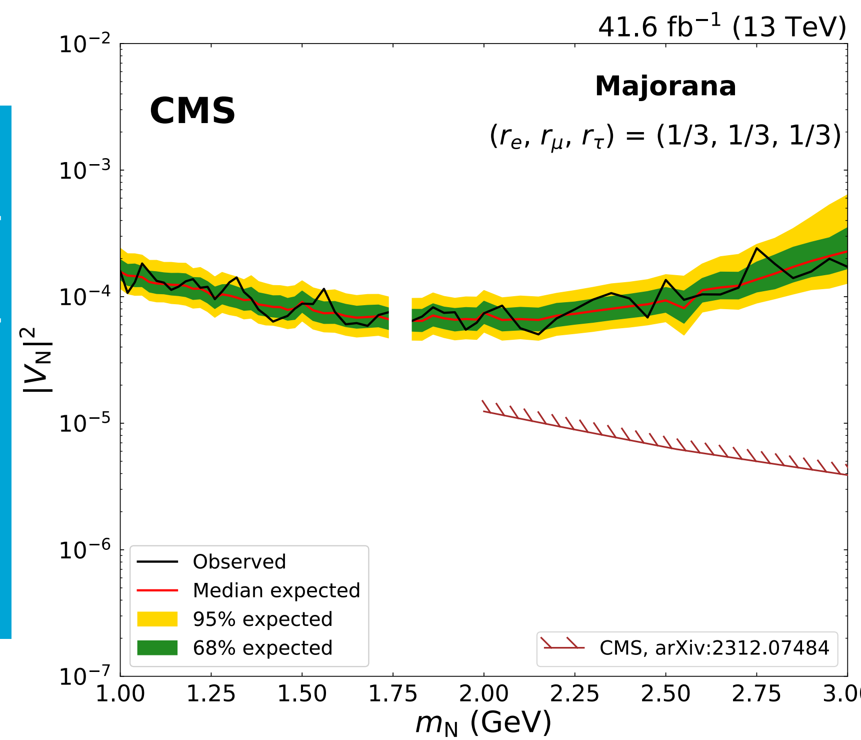
HNL Limits

- Set limits on |VN|2 as a function of the HNL mass (which fixes the lifetime), as well as limits on the lifetime for selected masses as a function of r_ℓ's
- Most stringent limits below ~2 GeV





CMS JHEP 06 (2024) 183

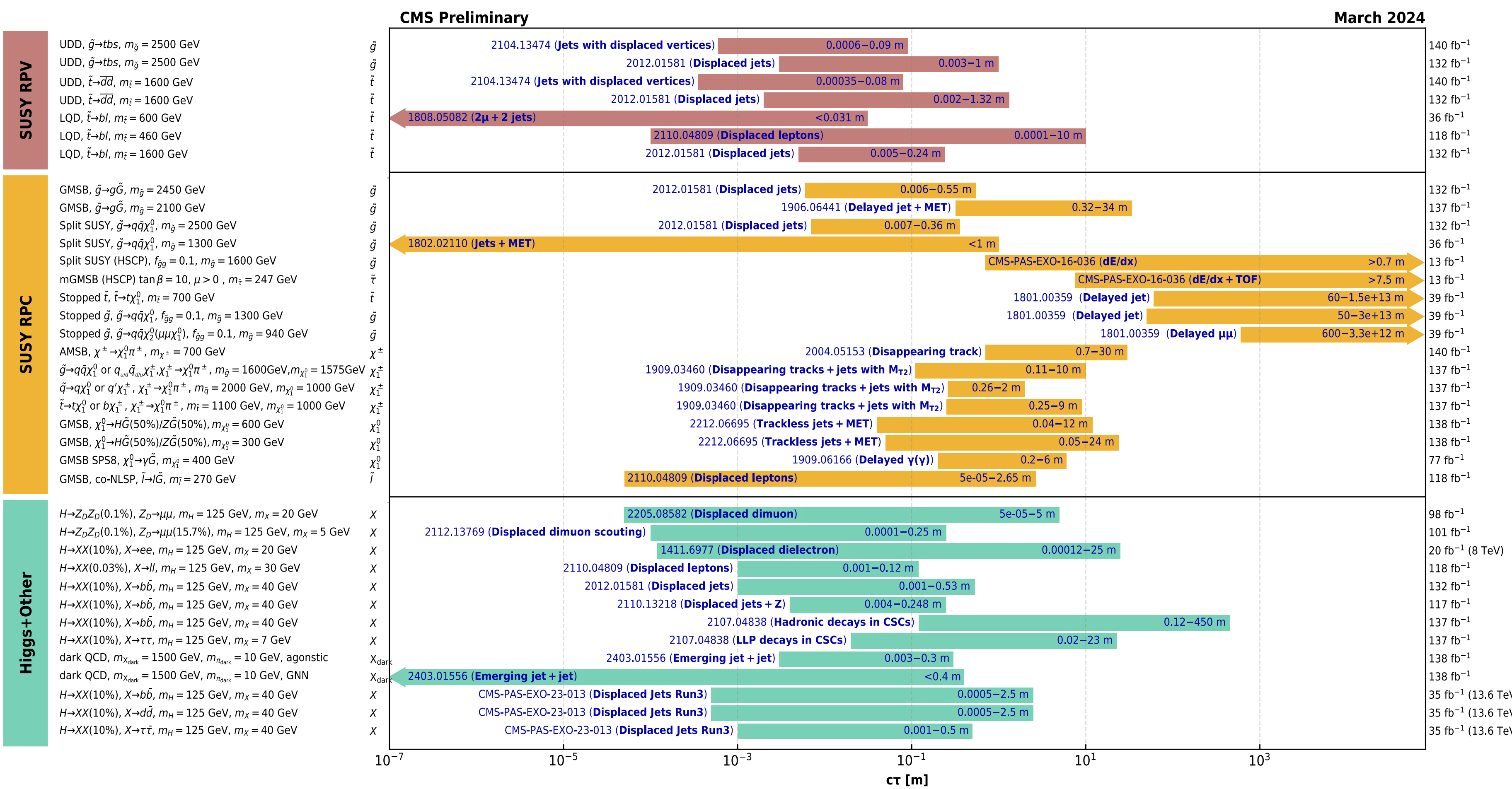


BROWN

Toward Long Lifetimes

✦ Plethora of models and experimental results

Overview of CMS long-lived particle searches

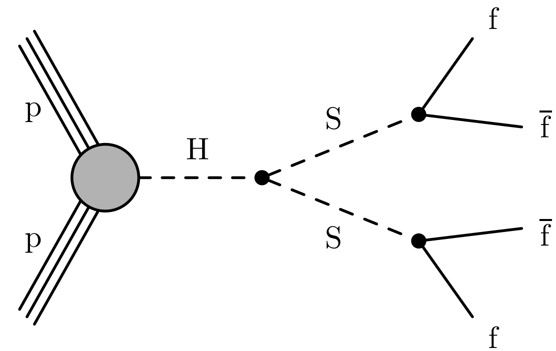


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

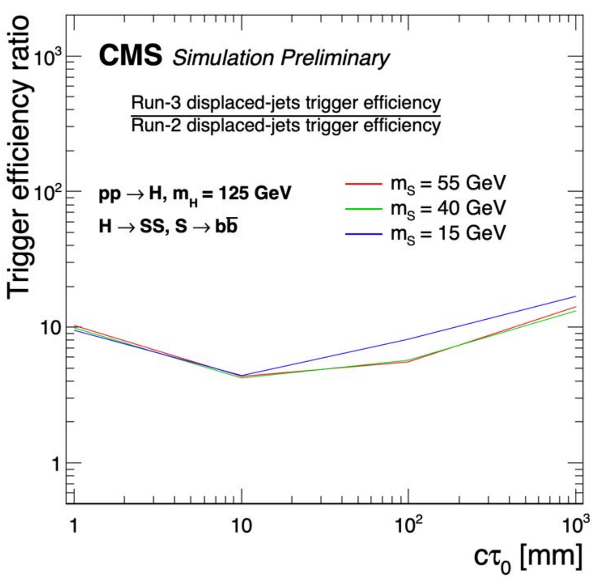
More in A. De Roeck's talk Wed

Run 3 Search for Displaced Jets

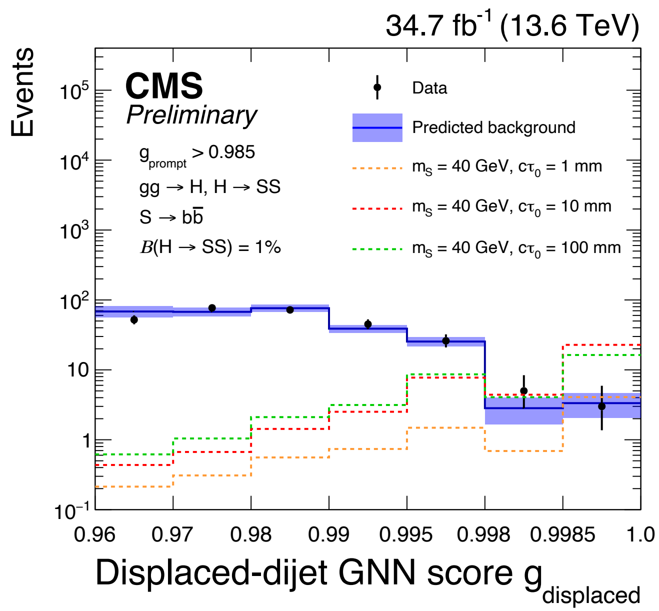
- Installed much more performant (x4-11) displaced-jet trigger in Run 3, based on lower H_T threshold (430 vs. 1050 GeV) and better track veto
- Advanced graph NN for better background suppression
- New limits exceed the Run 2 ones by up to an order of magnitude for low-mass long-lived particles decaying into a pair of jets

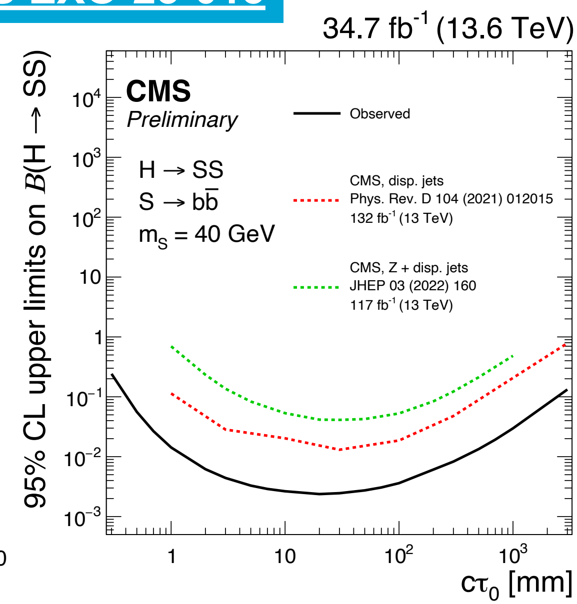


CMS DPS 2023/043



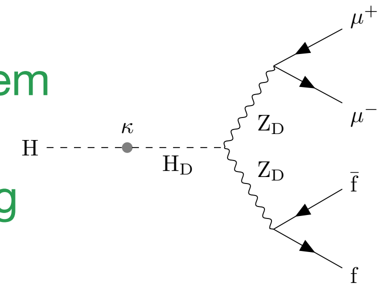
CMS PAS EXO-23-013

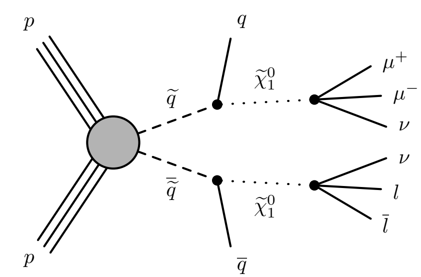




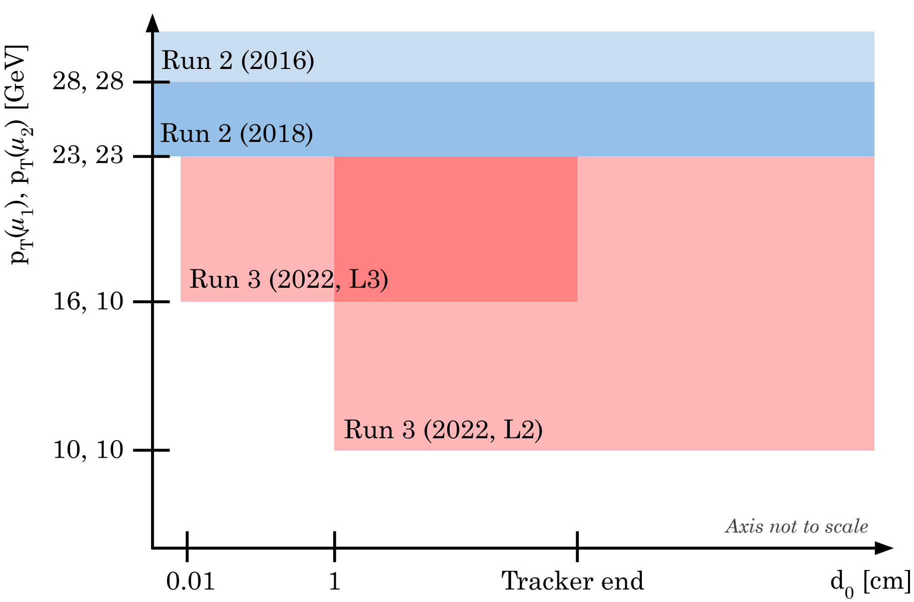
Run 3 Search for Displaced Muons

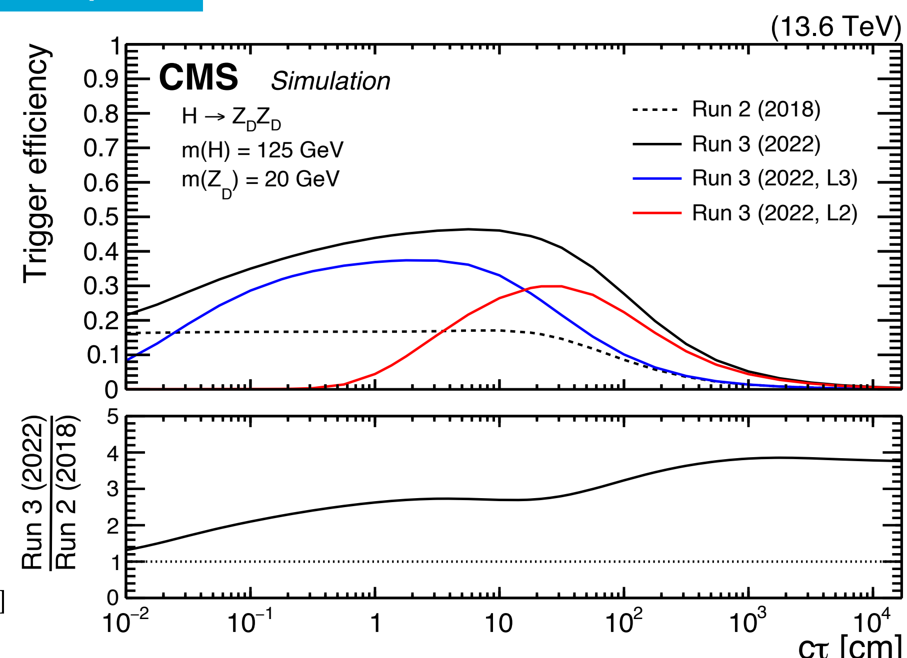
- Displaced muons appear in a variety of BSM scenarios; CMS with its excellent muon system offers unique capabilities in this channel
- Triggers in Run 3 were optimized by removing the beam-spot constraint at L1 and lowering the p_T thresholds
- HLT triggers were also optimized
- As a result, the trigger efficiency increased by up to a factor of four w.r.t. to the 2018 running





CMS JHEP 05 (2024) 047

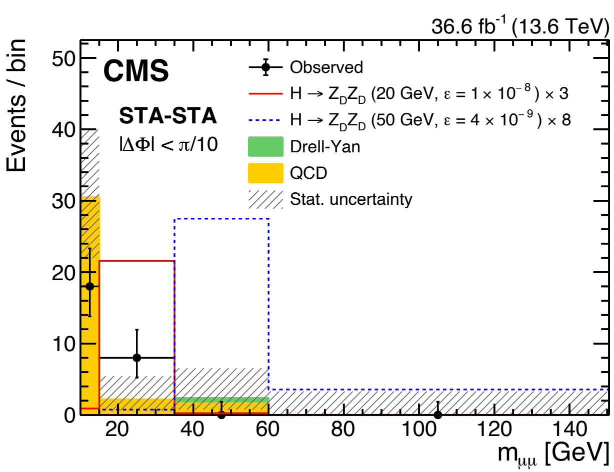


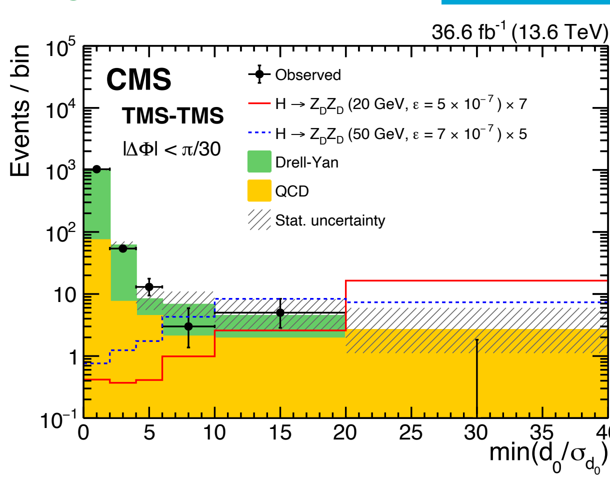


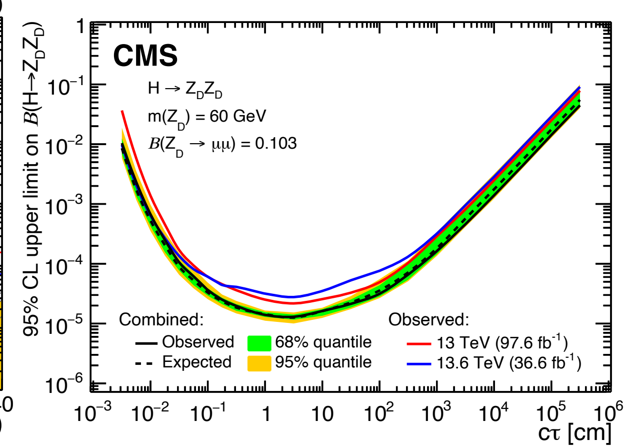
Displaced Muon Search

- The analysis is based on 2022 data
- Uses two combinations of muons: STA-STA (muon detector only) and TMS-TMS (tracker + muon detector)
- The analysis uses dimuon mass and the impact parameter significance as the discriminating variables
- Limits set (ZD model is shown as an example) are comparable or better than the Run 2 limits, despite 1/3 of integrated luminosity

CMS JHEP 05 (2024) 047





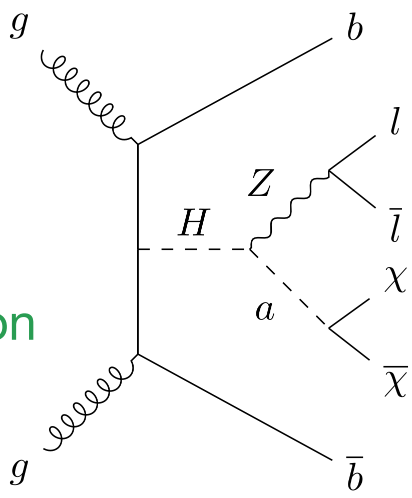


See also Xinhui Huang's talk on Saturday

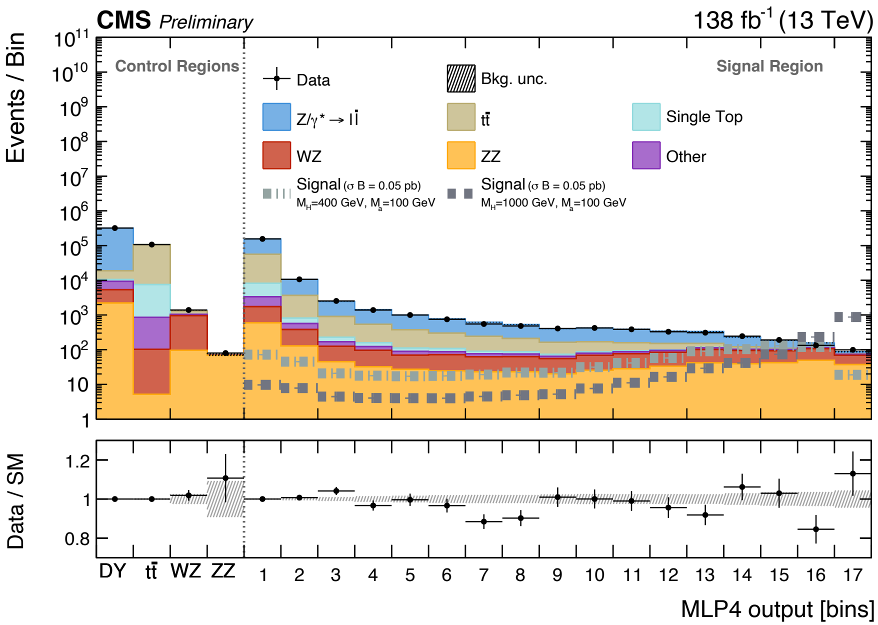
Dark Matter Searches

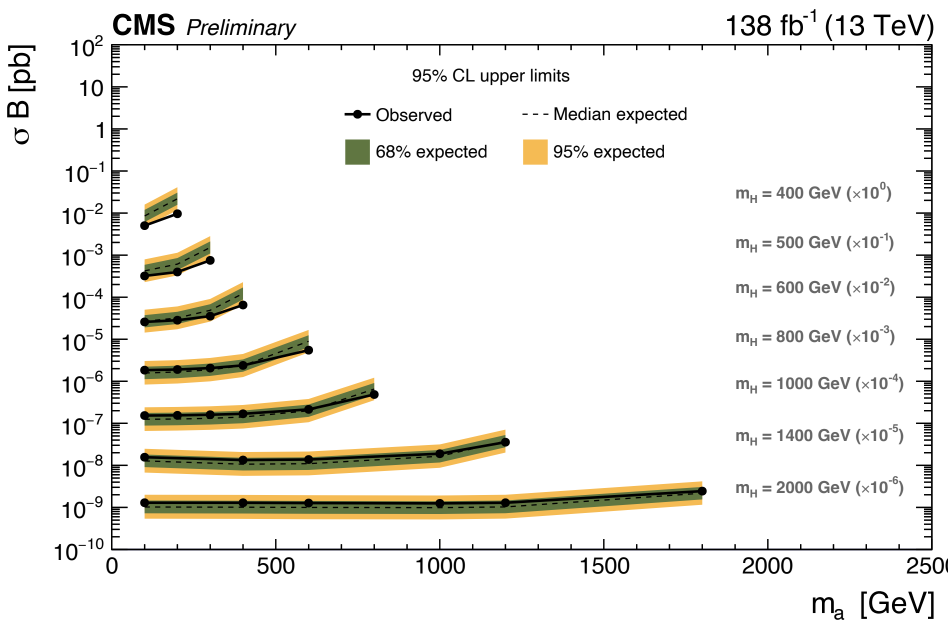
DM+bbll Search

- A variation on a mono-Z theme with a new channel: bbH → Z($\ell\bar{\ell}$)a($\chi\chi$), which is expected in a variety of models, including the ones explaining the galactic center ɣ ray excess
  - First dedicated search in this channel
- Relatively simple search based on a multivariate discrimination built of kinematic properties of the final-state particles
- Set model-independent limits on the cross section as a function of m_a



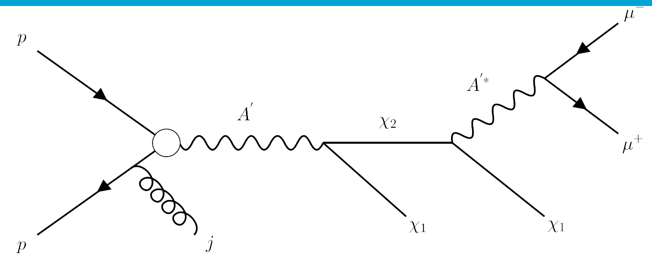
CMS PAS SUS-23-018



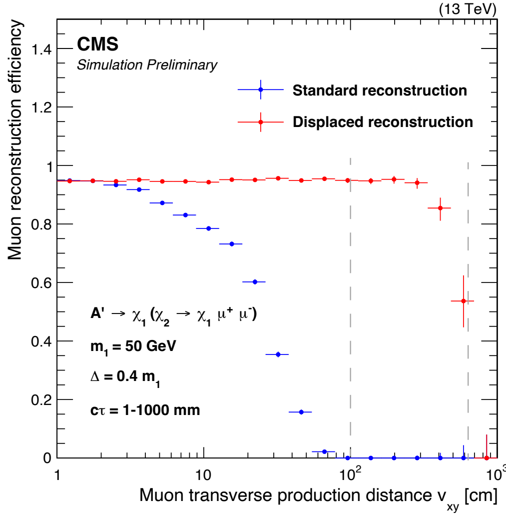


Search for Inelastic DM

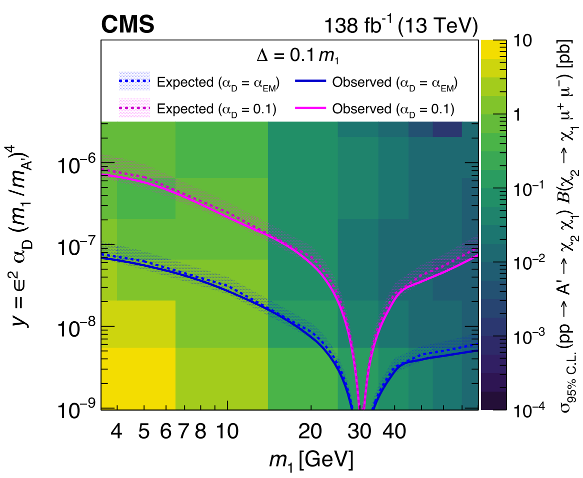
- Originally models of inelastic DM (IDM) were proposed to explain the DAMA anomaly; nevertheless they are generally viable models involving dark sectors - first IDM search at the LHC

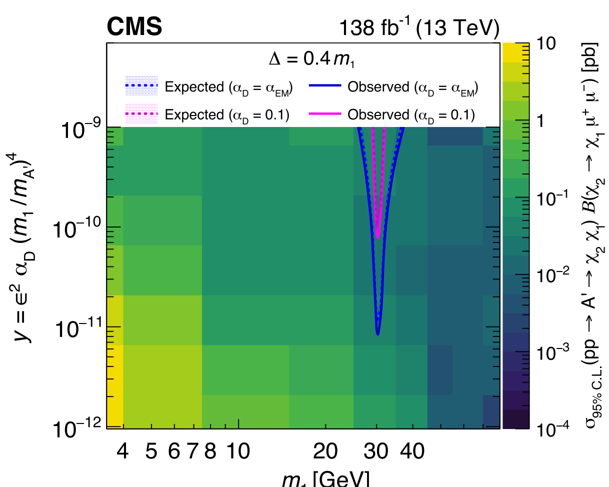


- Probe a model w/ 2 nearly mass-degenerate DM states, χ_1 and χ_2 ($m_2 - m_1 = \Delta = (0.1\text{-}0.4)m_1$), as well as a dark photon mediator A' ($m_{A'} = 3m_1$), which is long-lived
- The signature is two collimated displaced muons aligned with p_T^{miss} (also used for triggering)
- Special displaced muon reconstruction capable of extending sensitivity to large cτ
- A' is mixed both with photon and Z, hence peak in sensitivity around m(A') = m(Z)



CMS PRL 132 (2024) 041802

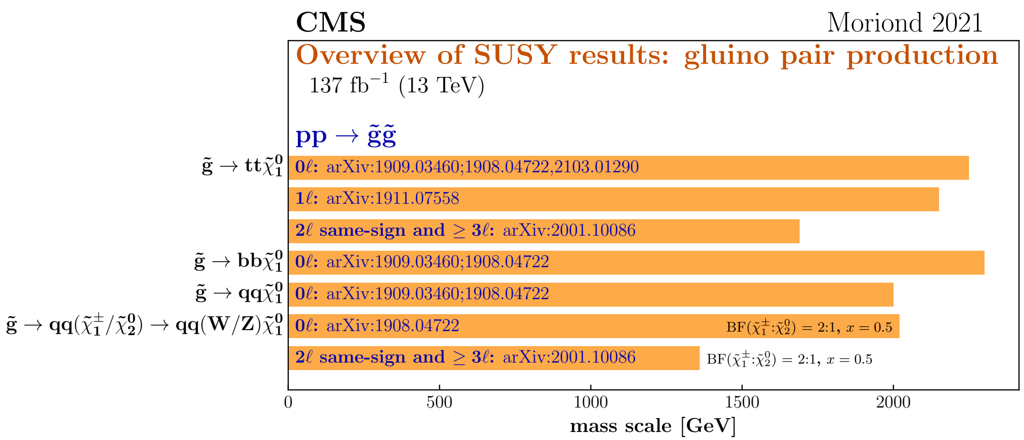




See also Yuya Mino's talk on Wednesday

SUSY Searches

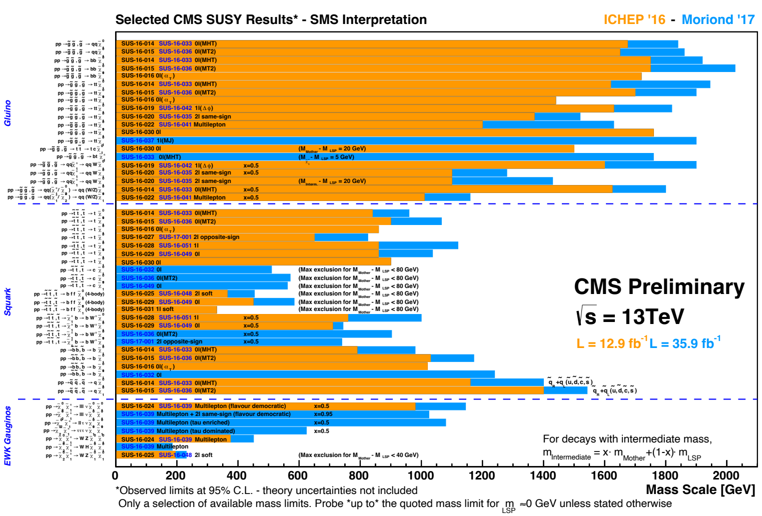
Supersymmetry of Supercemetery?

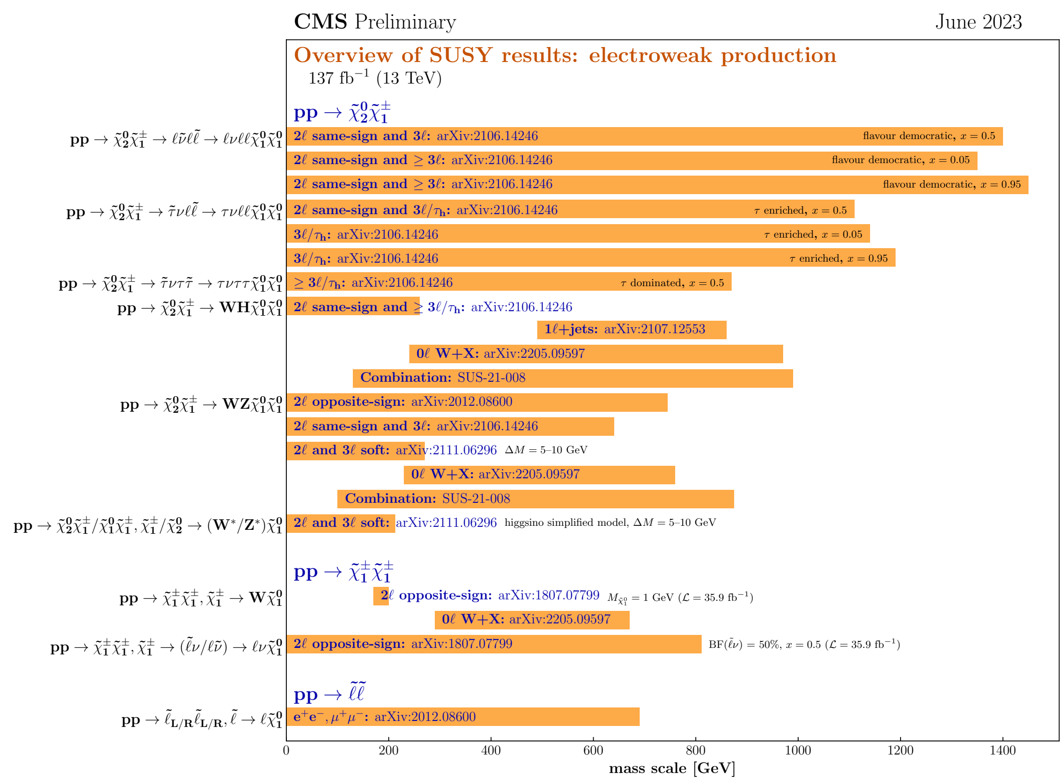


Limits, limits, limits…

But: read the fine print!

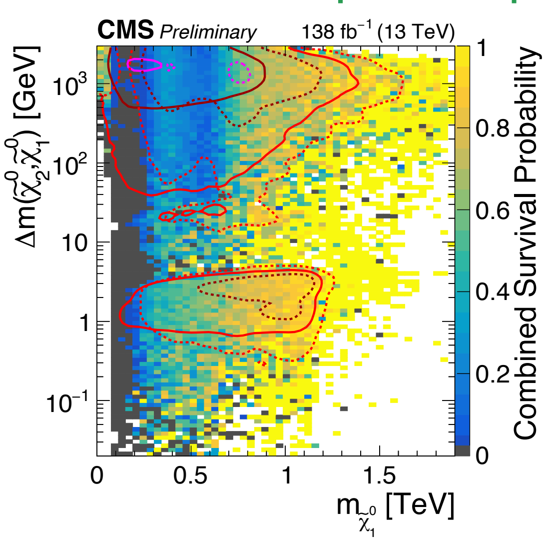
Simplified SUSY models are very simplistic and are unlikely to describe the actual SUSY realization!

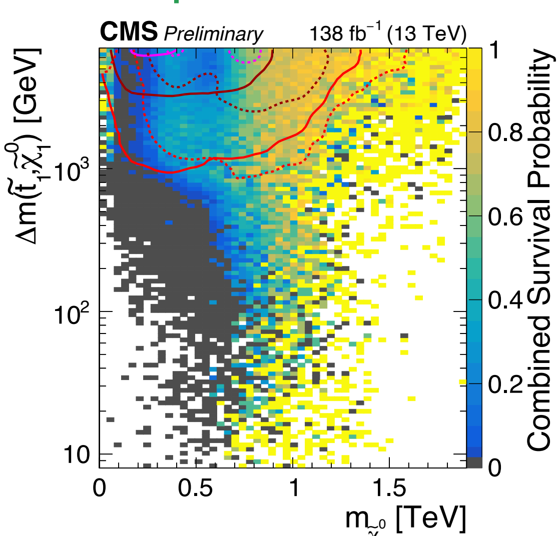


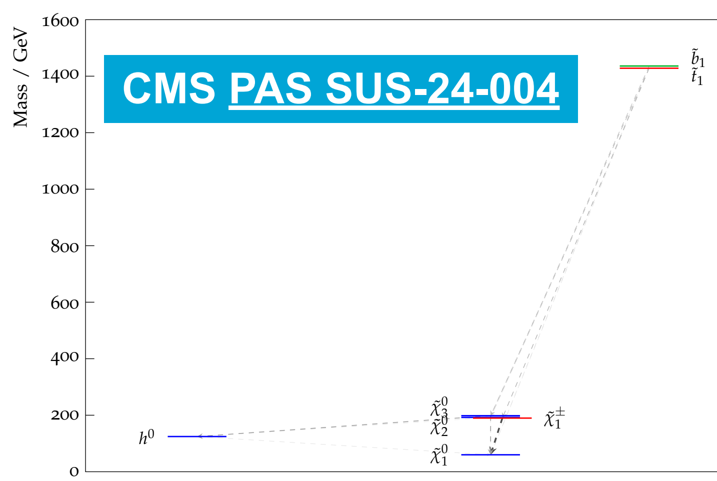


pMSSM Run 2 Interpretation

- Will highlight just one new analysis: the pMSSM interpretation of a plethora of Run 2 SUSY searches, which goes beyond the SMS interpretation
  - 19-parameter scan [3 gaugino parameters $M_{1,2,3}$; 6 squark masses; 4 slepton masses; 3 fermion-Higgs couplings, and 3 Higgs sector parameters ($\tan\beta$, μ, m_A)]
  - 5 CMS SUSY searches [soft OS lepton, jets+ME_T, SFOS, disappearing tracks, single lepton]
- Quantifies the impact of the Run 2 searches on the exclusion in various 2D planes
- Gives examples of pMSSM points with 2-3σ observed significance

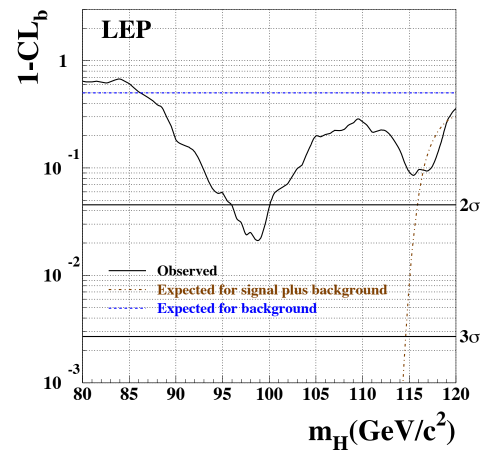






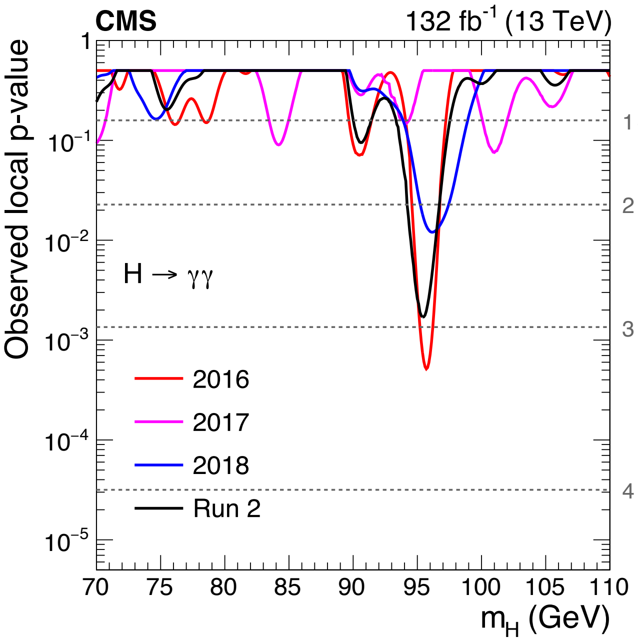
The 95 GeV Puzzle

- The long-standing puzzle with a ~2σ hint seen since LEP era
- A 2.8σ hint seen in CMS in H(ɣɣ) analysis with 20 fb^{-1} of 8 TeV + 36 fb^{-1} of 13 TeV data
- Recent CMS analysis of full Run 2 data sees a similar excess (albeit with much smaller cross section)
- New ATLAS result neither confirms nor kills this excess

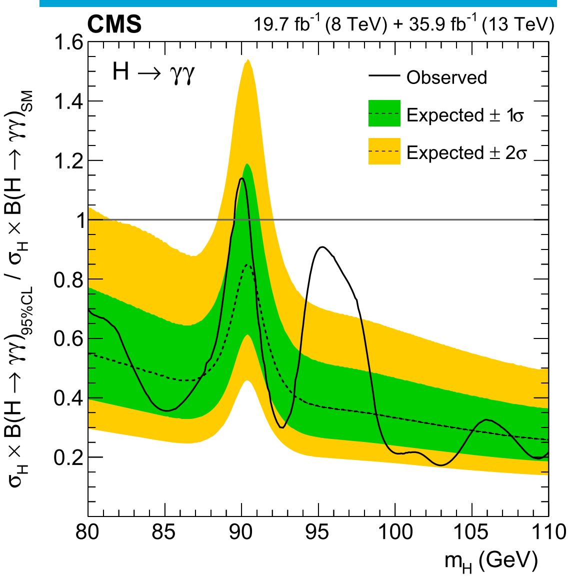


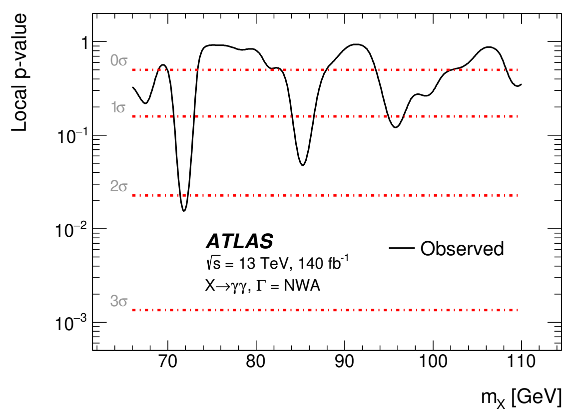
ADLO hep-ex/0306033

CMS arXiv:2405.18149



CMS PLB 793 (2019) 320



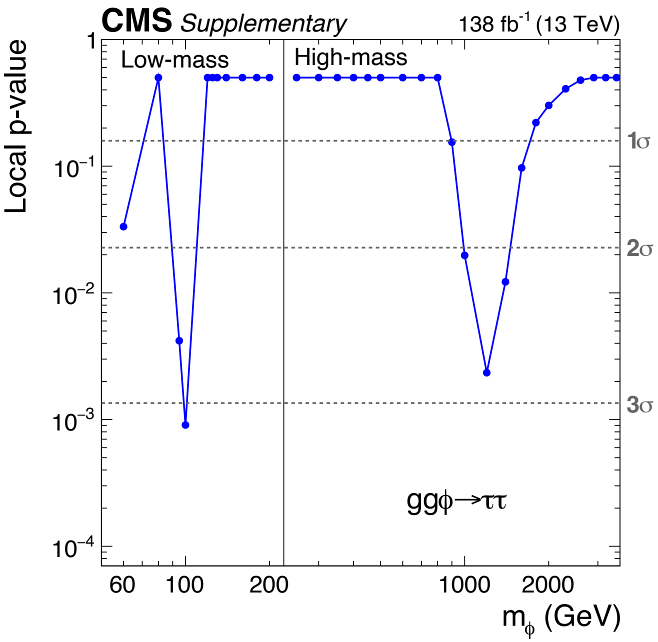


ATLAS arXiv:2407.07546

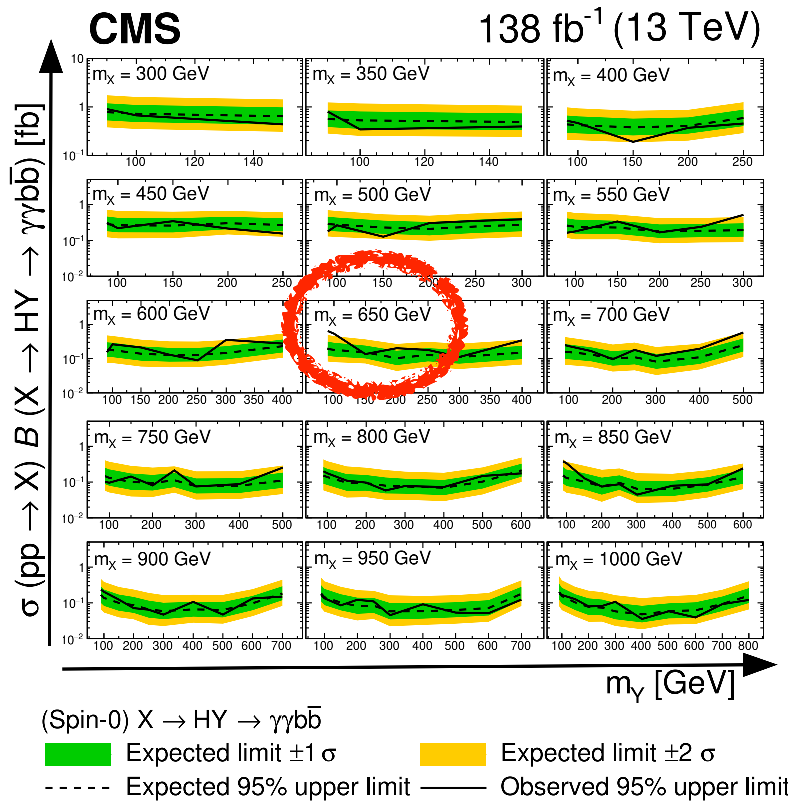
Wait, there is More!

- Two more CMS results seems to suggest some excess in the same 95 GeV region
  - MSSM H(ττ) search with an excess at m(ττ) ≈ 100 GeV
  - X → H(γγ)Y(bb) search with M_X ≈ 650 GeV and M_Y ≈ 100 GeV

CMS JHEP 07 (2023) 073



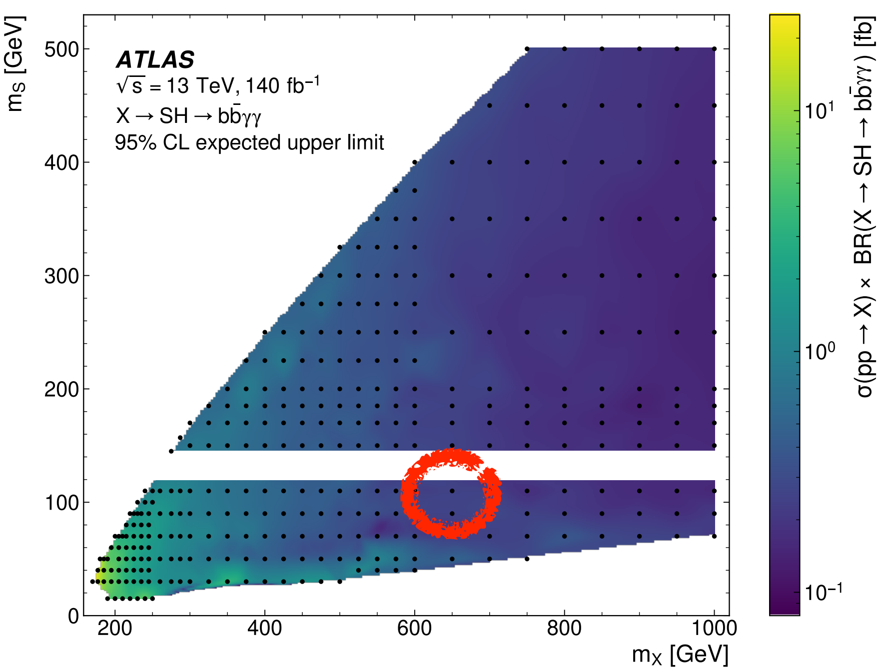
CMS JHEP 05 (2024) 316

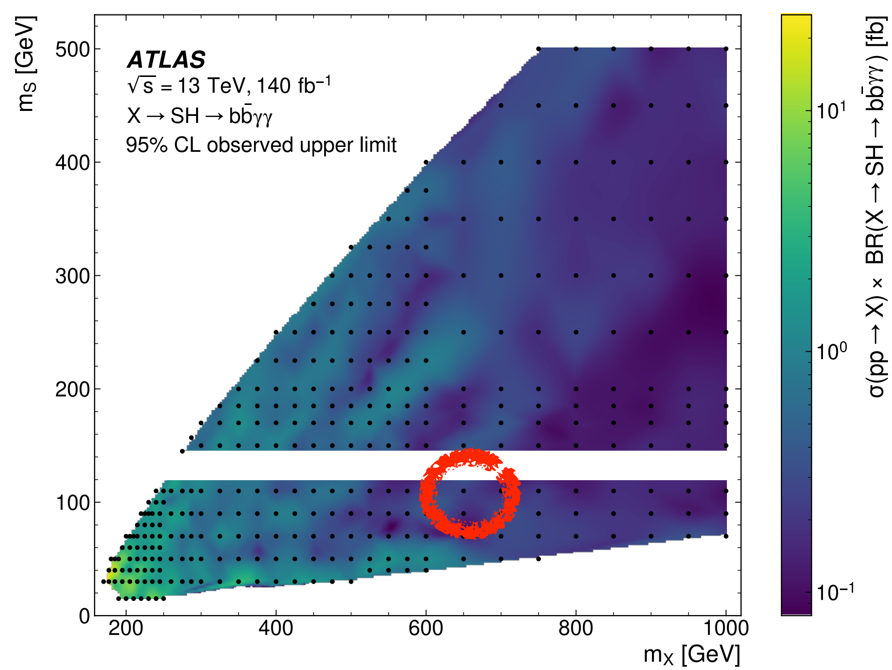


But…

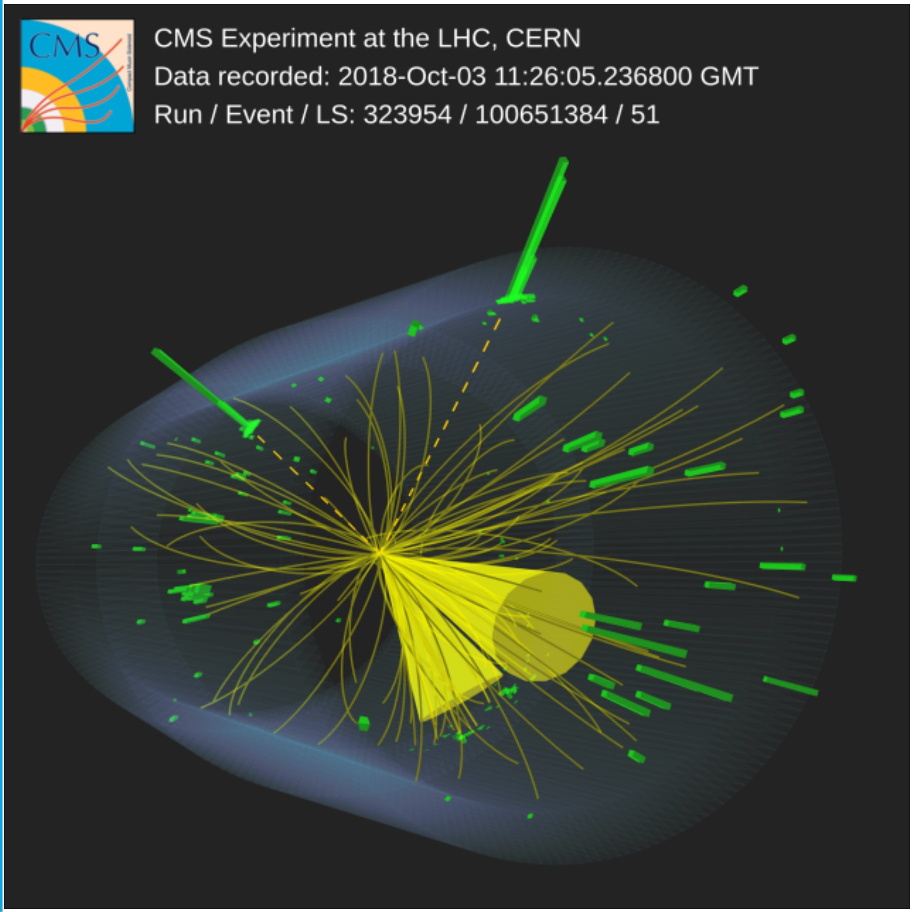
- Recent ATLAS result in the same X → H(γγ)Y(bb) channel sees no excess at the (650,100) GeV point and sets an upper limit on the cross section of 0.2 fb
- The jury is still out

ATLAS arXiv:2404.12915



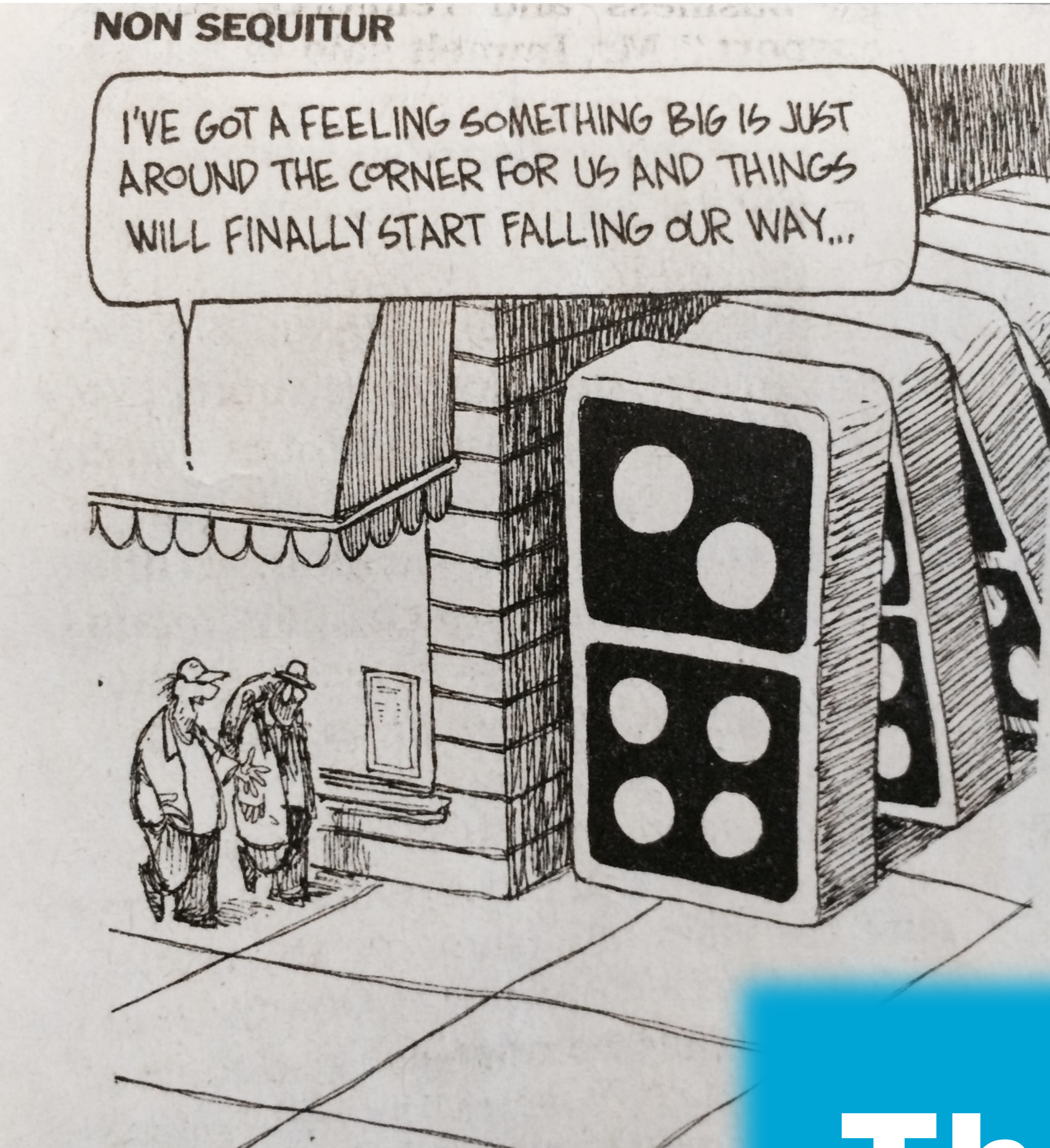


New Physics or Another 750?



Conclusions: Quo Vadis?

- LHC is an amazing machine, with a spectacular performance by far exceeding the expectations
- Discovery of the Higgs boson in 2012 has completed the standard model of particle physics and paved an avenue to decades of exploration
  - Cf. the richness of top quark physics now, nearly 30 years after the discovery!
- Precision standard model measurements, supported by the latest theory developments, continue to be very exciting and important
- Direct searches for new physics have unexpectedly failed so far, but not for the lack of trying!
  - Redirect searches away from theoretical lampposts, and toward challenging signatures and most sophisticated analysis techniques
  - If no observation: LHC will do for dim-6 operators what LEP did for the dim-4 ones (SMEFT approach)
- It's too early to throw a towel in: there are still hints for possible BSM physics and we will follow up on them diligently
- Stay tuned for many more new results from Run 3 data to come soon!


NON SEQUITUR
I'VE GOT A FEELING SOMETHING BIG IS JUST AROUND THE CORNER FOR US AND THINGS WILL FINALLY START FALLING OUR WAY...

Thank You!