RECENT HIGHLIGHTS FROM THE LHC

Greg Landsberg

Ischia, Italy, 31.05.24

Vulcano Workshop 2024

Outline

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

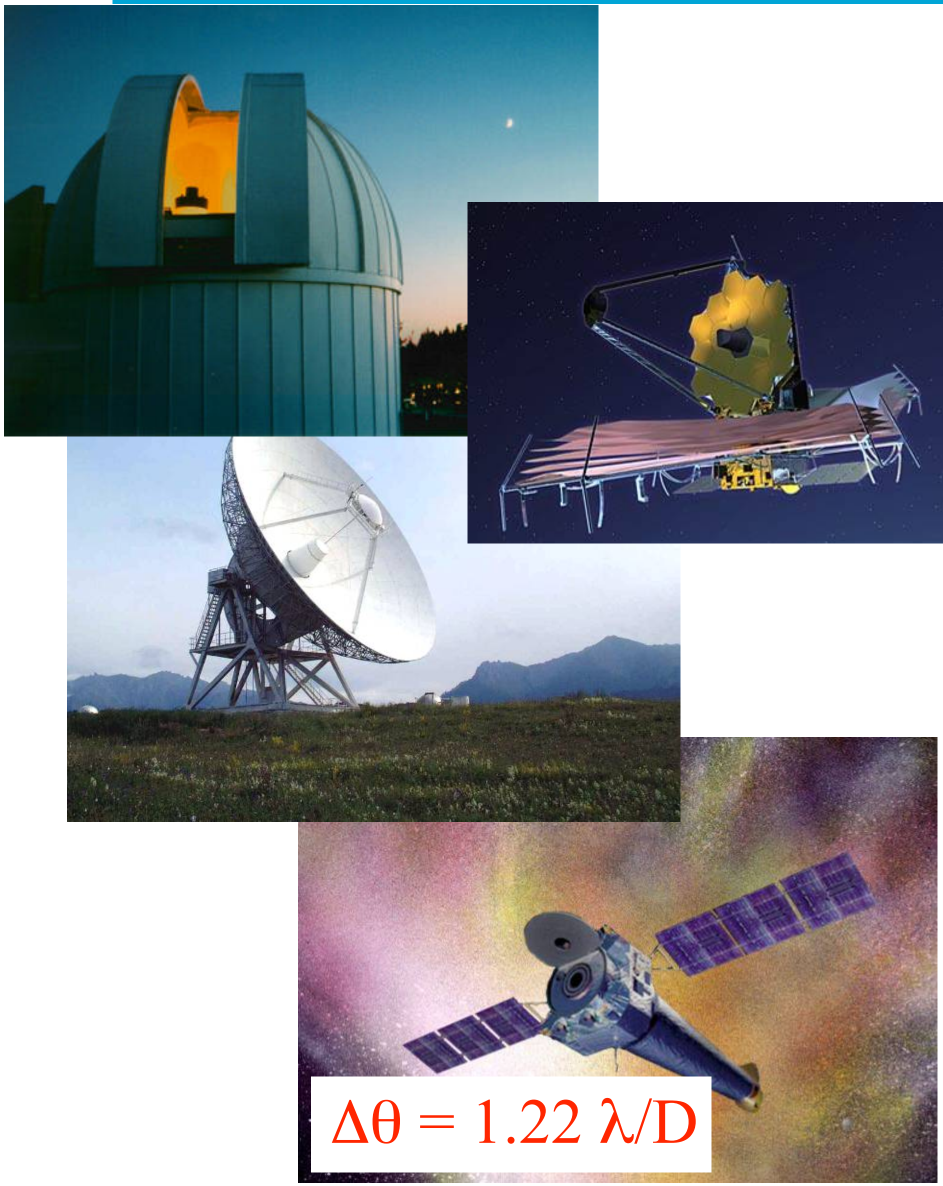
✦ Disclaimer: these are selected highlights of a large number of LHC results, with clear personal bias: they tell a story, rather than simply make up a shopping list... Priority is given to the results with direct connection to astrophysics and cosmology themes. All the links are clickable!

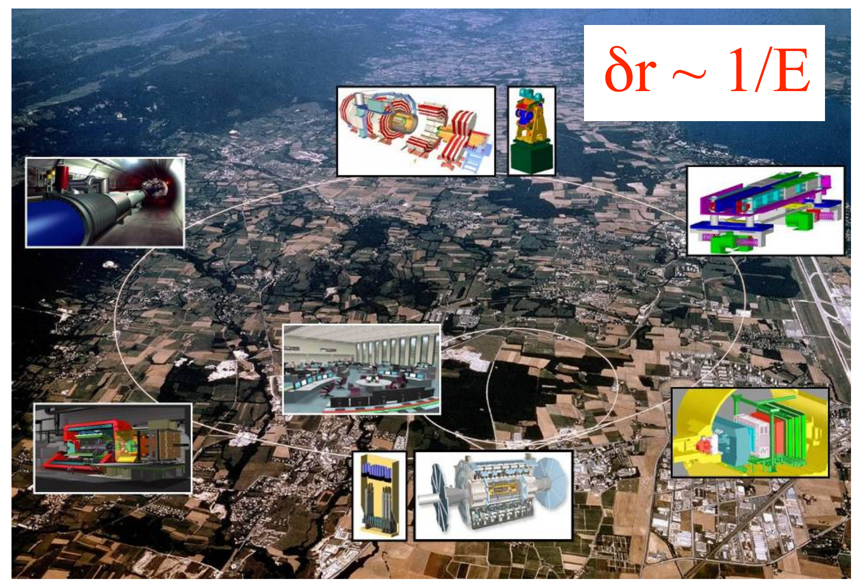
✦ For a full physics analysis landscape at the LHC, please refer to:
- https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- https://cms-results-search.web.cern.ch/
- https://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

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

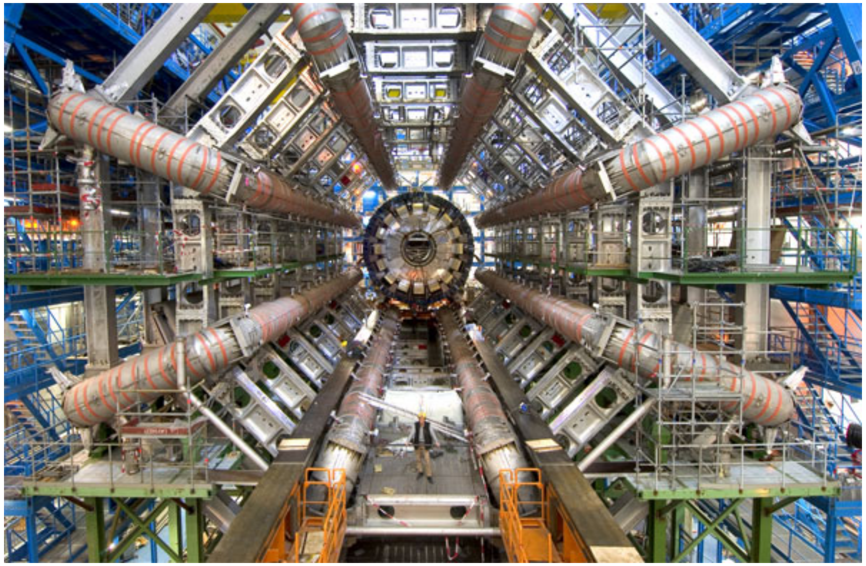
The LHC Legacy

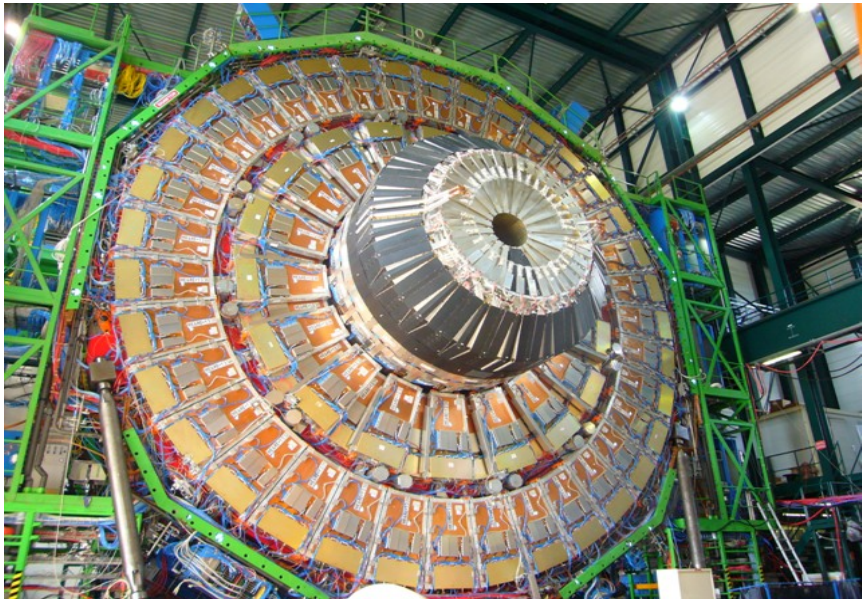
Telescopes vs. Microscopes



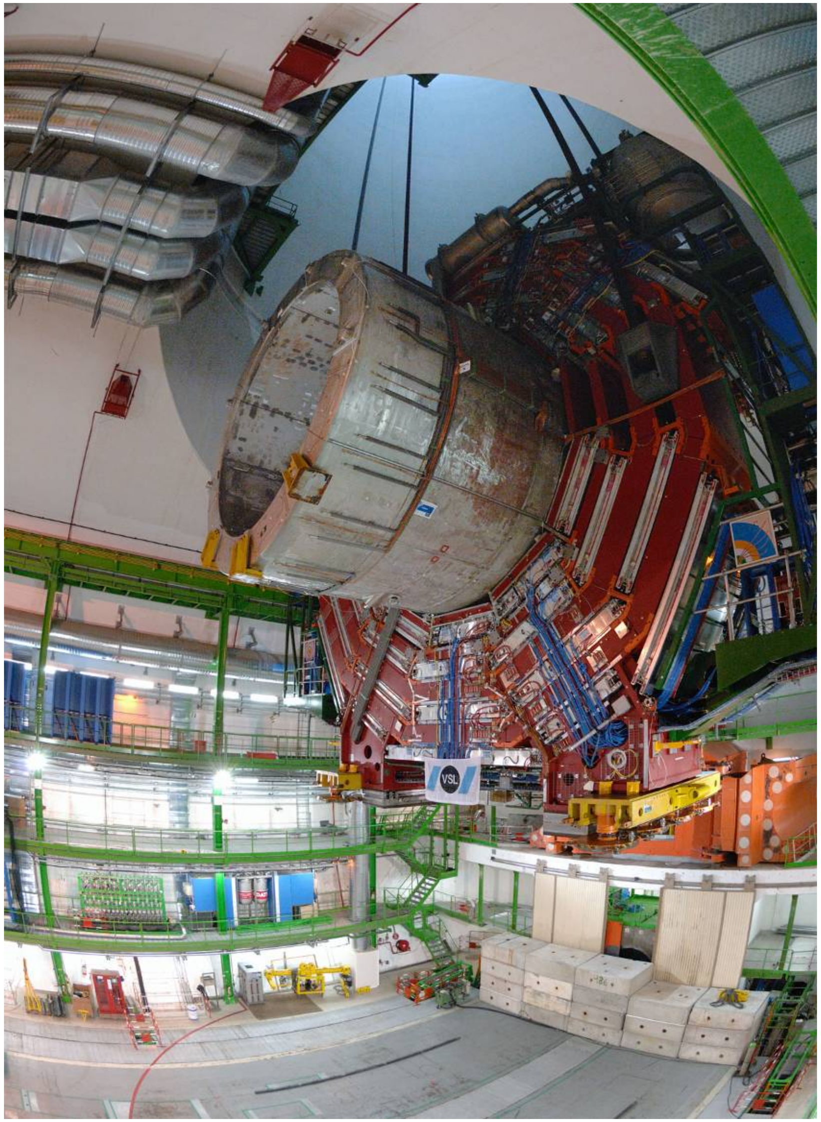


Beautiful Instruments

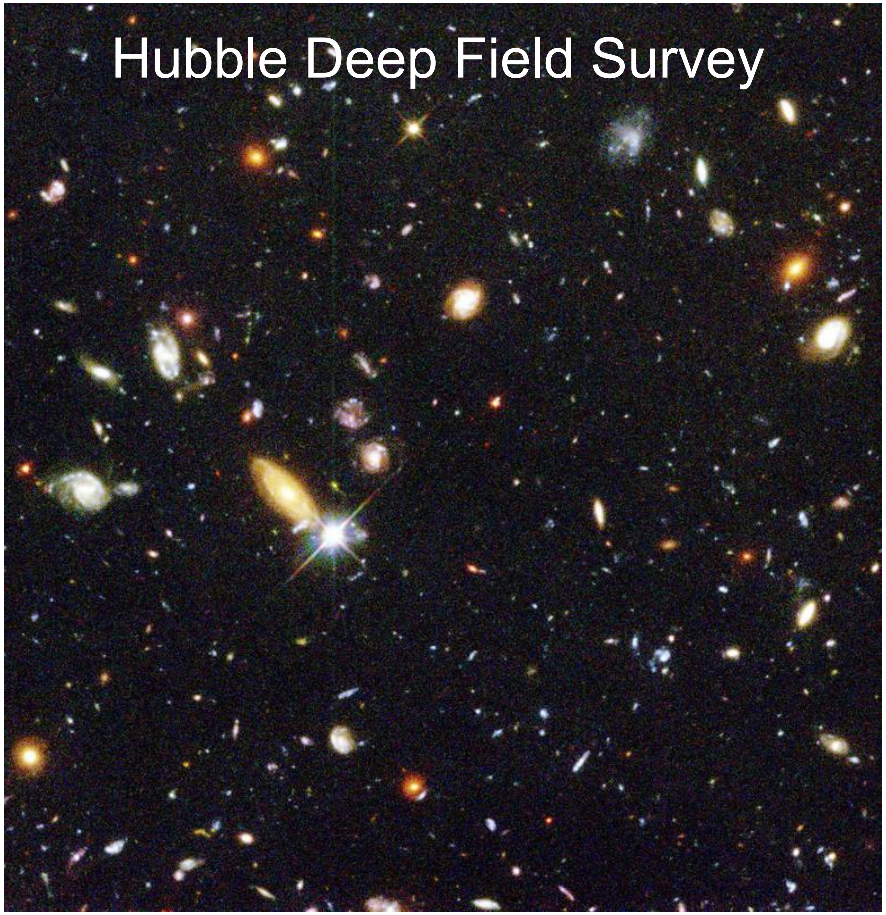


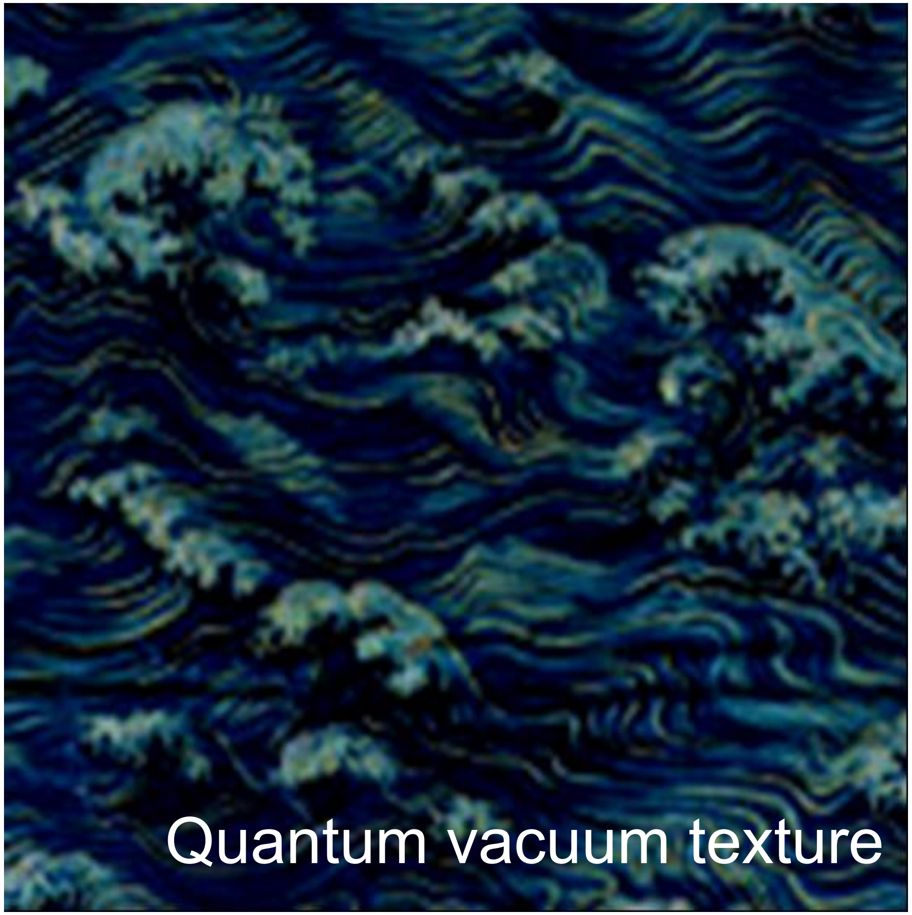


Spectacular Launches



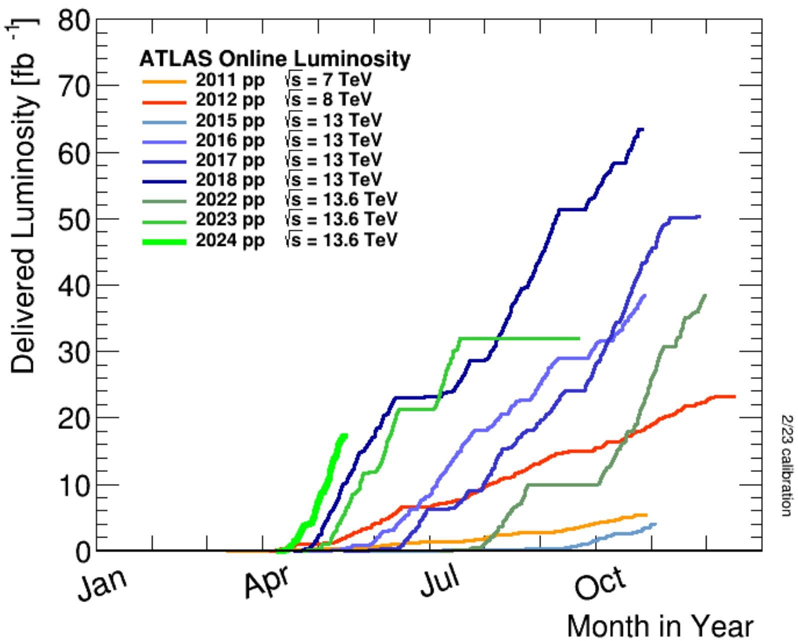
Deep Fields

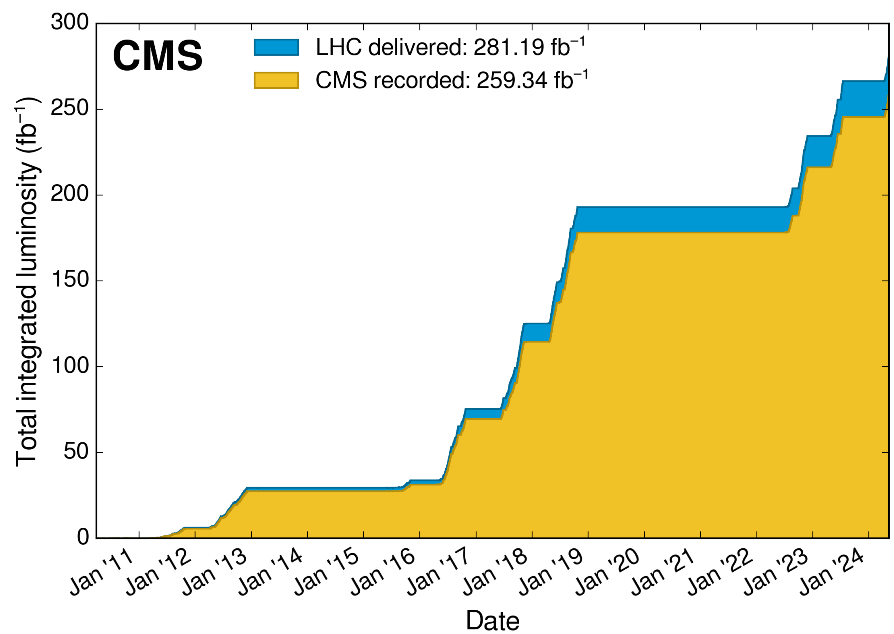




LHC - a Big Success!

- Nearly 300/fb of data have been delivered by the LHC in Runs 1-3 (2010-2023), at a c.o.m. of 7-13.6 TeV, exceeding the integrated luminosity projections
- Over 90% of the delivered data are 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 spectacular running!






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

The LHC Legacy

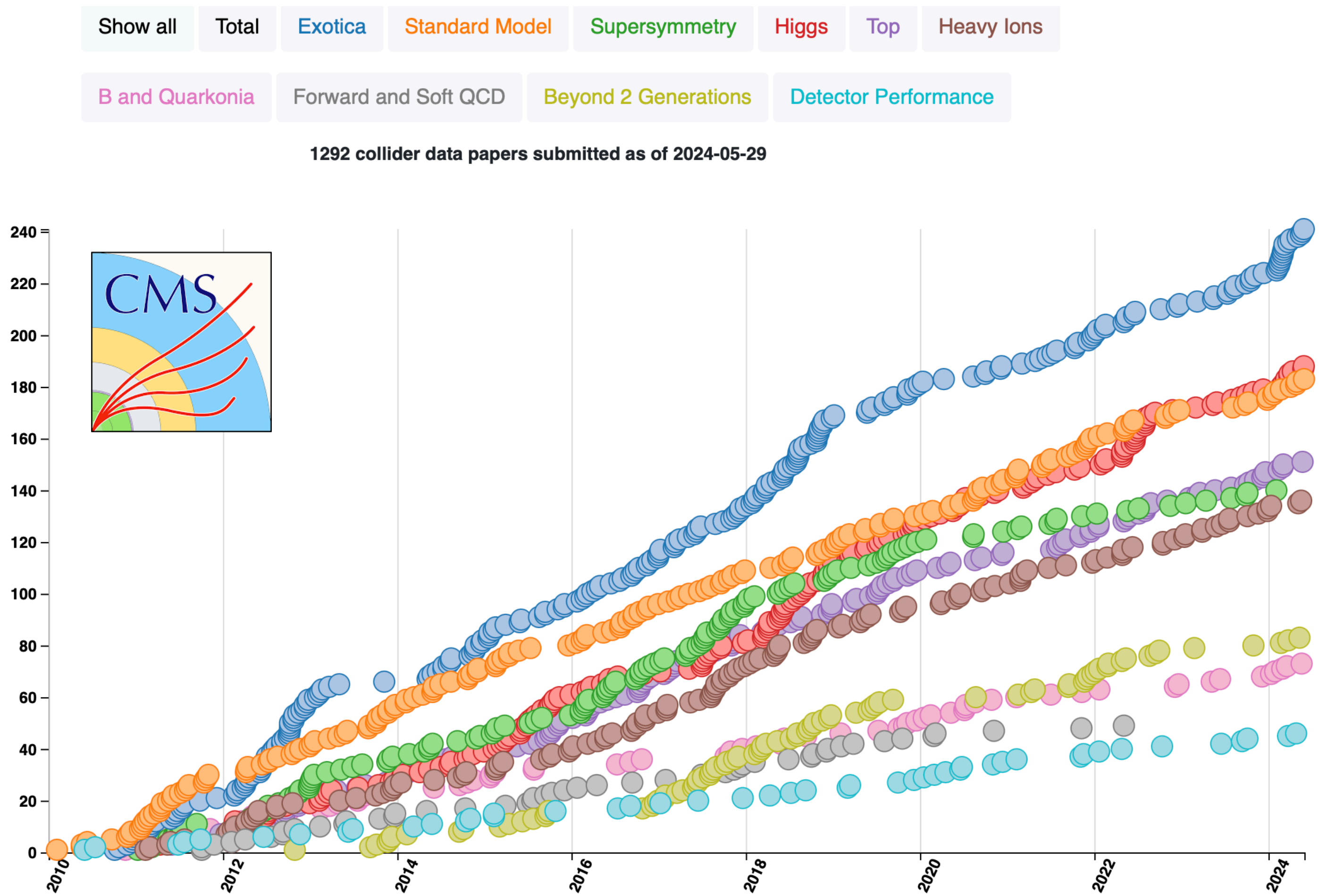
- The LHC has figuratively replaced three machines in one go:
  - Tevatron (Higgs, BSM searches, top physics, and precision EW measurements)
  - BaBar/Belle B factories (precision B physics)
  - RHIC (heavy-ion physics)
- It also added one more machine:
  - $\gamma\gamma$ collider (LbL scattering, Breit-Wheeler processes, searches for ALPs)
- The LHC experiments in general, and ATLAS & 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 LHC 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!
- Overall, a very fast turn-around compared to earlier generations of HEP experiments!

Publish or Perish!

✦ Nearly 1,300 papers submitted by each ATLAS and CMS; over 700 by LHCb, and nearly 500 by ALICE!

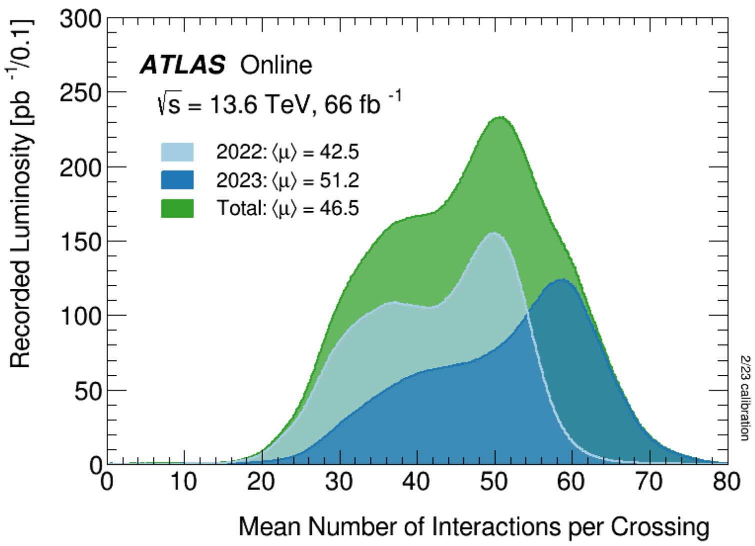


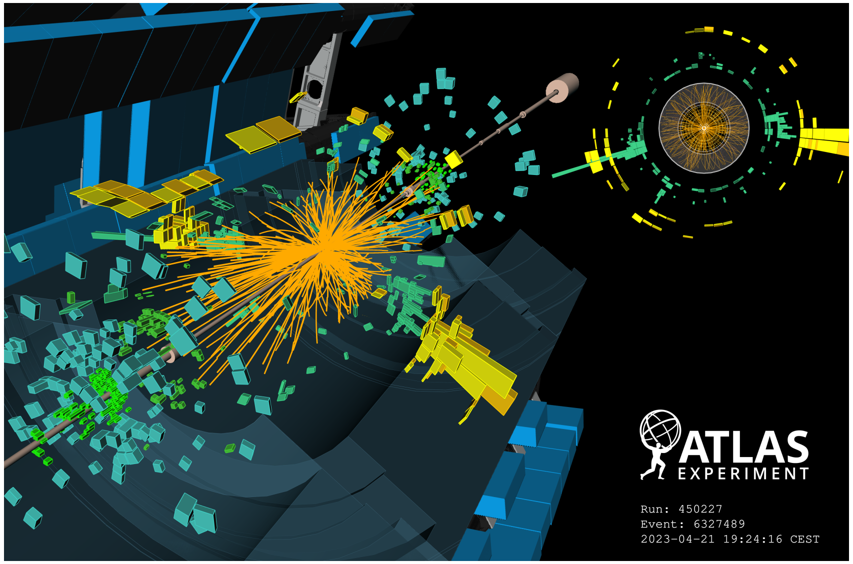
ATLAS+CMS Physics Reports

- ATLAS and CMS just submitted several Phys. Rept. articles on various aspects of the program
  - These are legacy Run 2 papers and a valuable resource on experimental techniques and results
- ATLAS:
  - arXiv:2403.02455, The quest to discover supersymmetry at the ATLAS experiment
  - arXiv:2403.09292, Exploration at the high-energy frontier: ATLAS Run 2 searches investigating the exotic jungle beyond the Standard Model
  - arXiv:2404.05498, Characterising the Higgs boson with ATLAS data from Run 2 of the LHC
  - arXiv:2404.06829, Electroweak, QCD and flavour physics studies with ATLAS data from Run 2 of the LHC
  - arXiv:2404.10674, Climbing to the Top of the ATLAS 13 TeV data
  - arXiv:2405.04914, ATLAS searches for additional scalars and exotic Higgs boson decays with the LHC Run 2 dataset
- 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 ATLAS and 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 the last two years
  - 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





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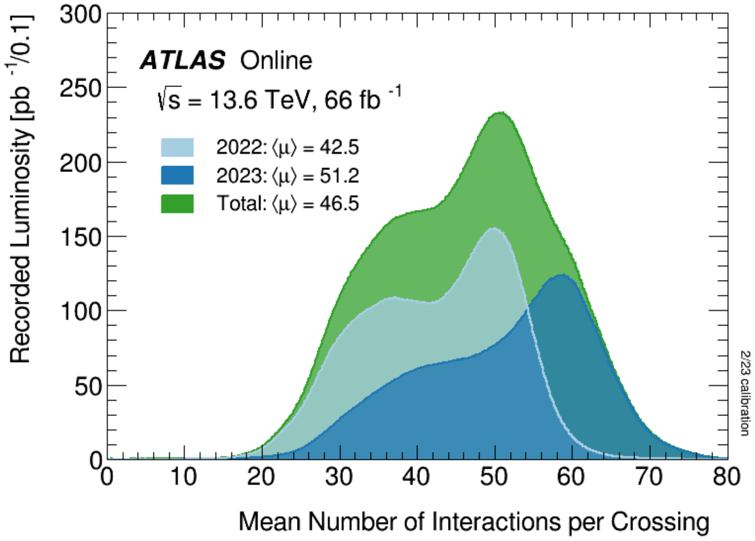
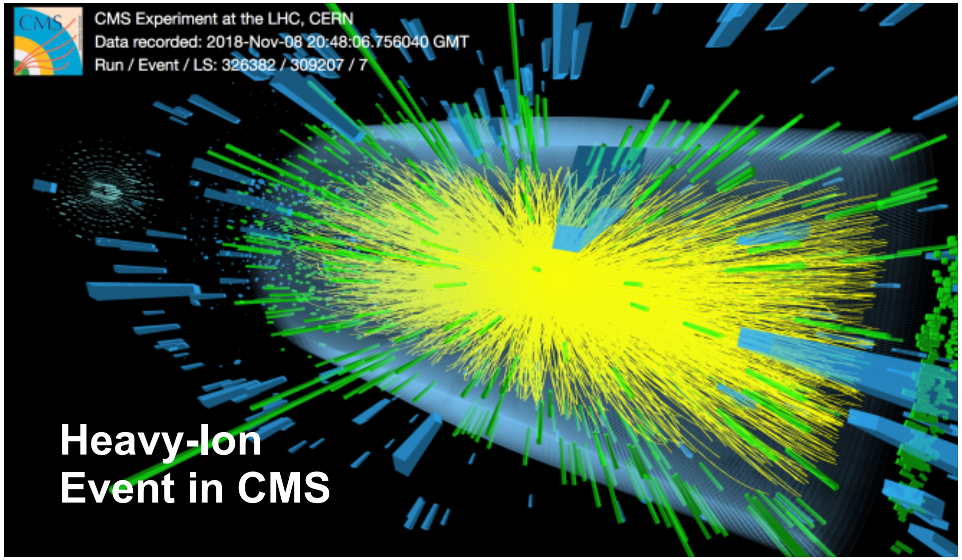
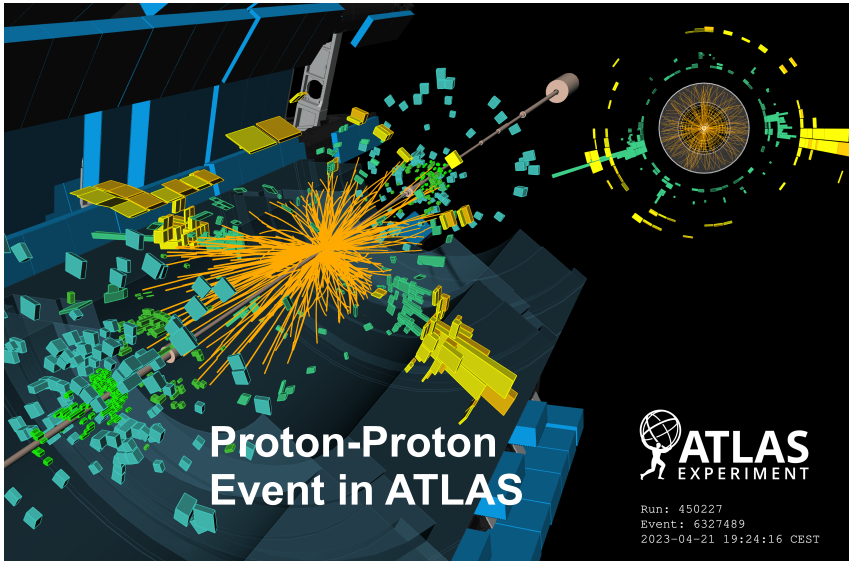
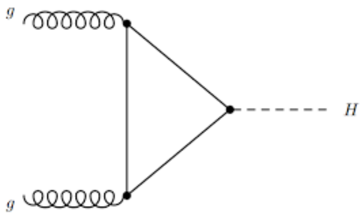






Higgs Physics Highlights

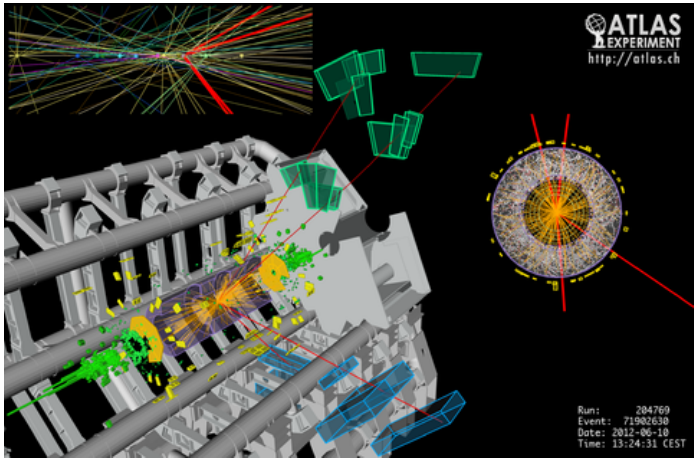
Higgs Factory

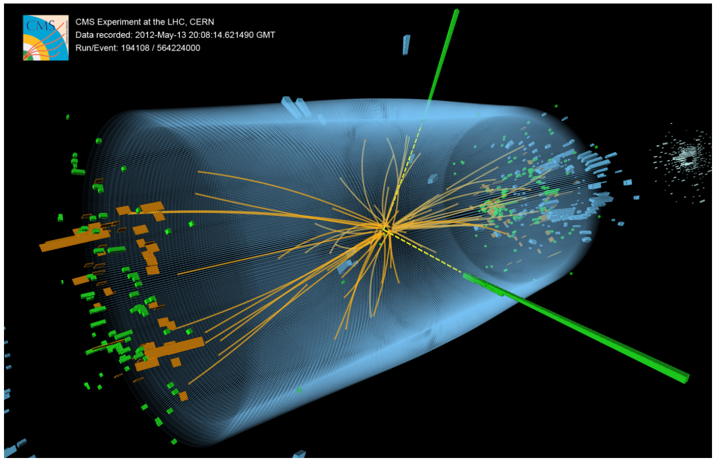


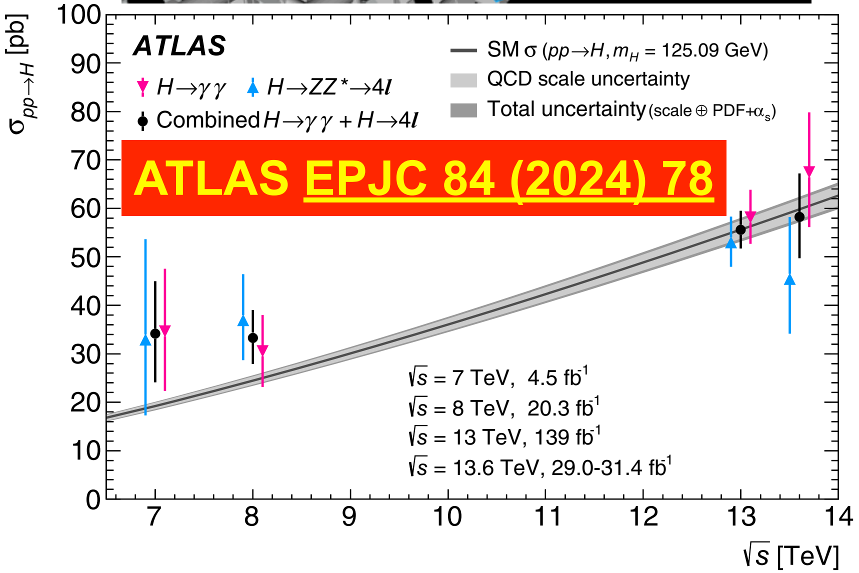
- LHC is the Higgs factory and the only place to study Higgs physics directly today
- At 13 TeV, the production cross section for the Higgs boson, dominated by gluon-gluon fusion, is ~50 pb
  - 14M Higgs bosons delivered by the LHC in Run 2!
  - By now ATLAS and CMS could have accumulated as many Higgs bosons as four LEP experiments accumulated Z bosons
  - With the cross section @13.6 TeV of ~60 pb another 11M 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

Higgs Boson Cross Sections

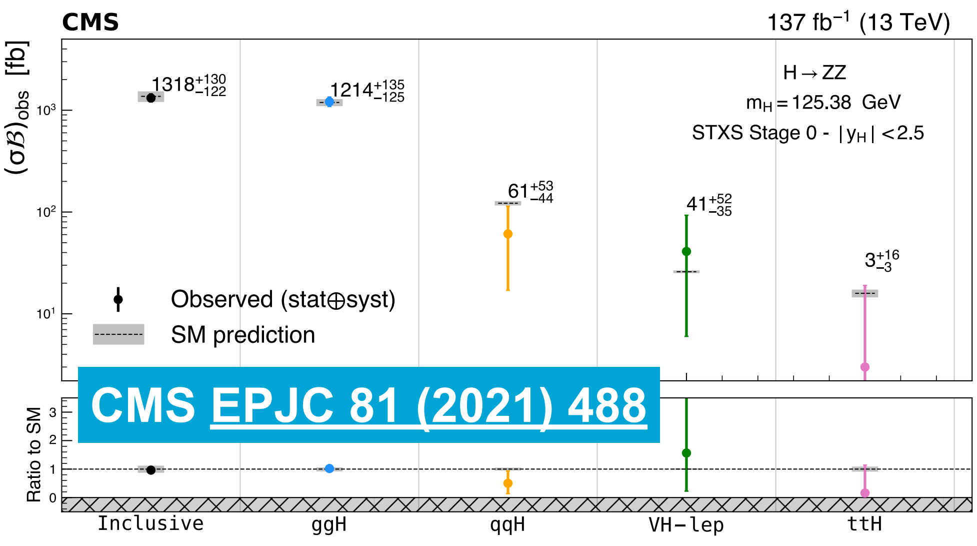
- Inclusive and fiducial cross section in multiple production modes have been measured and broadly agree with the SM predictions







ATLAS EPJC 84 (2024) 78



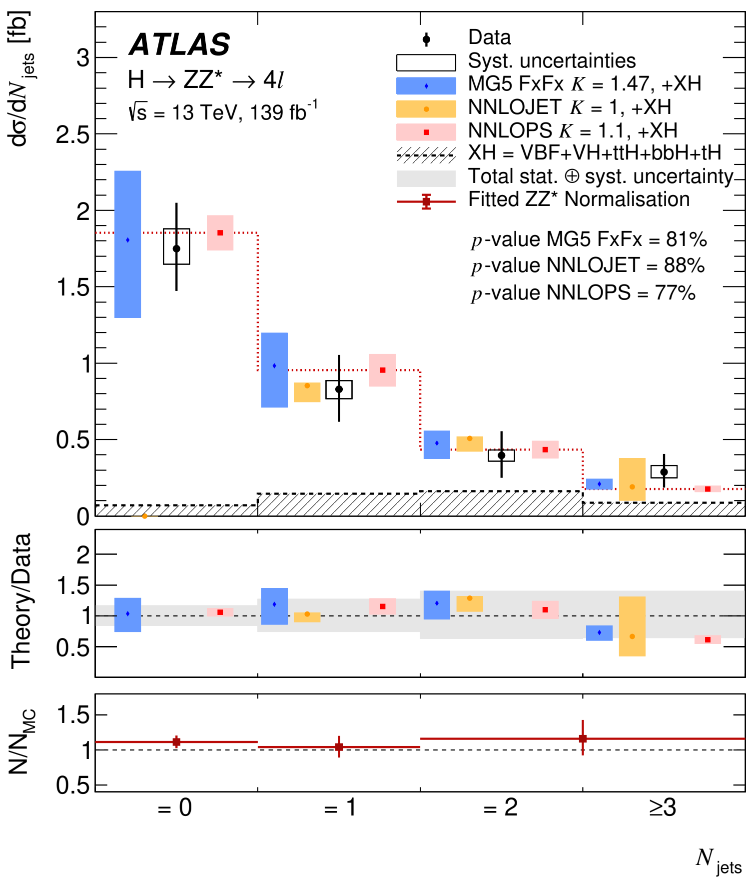
CMS EPJC 81 (2021) 488

BROWN

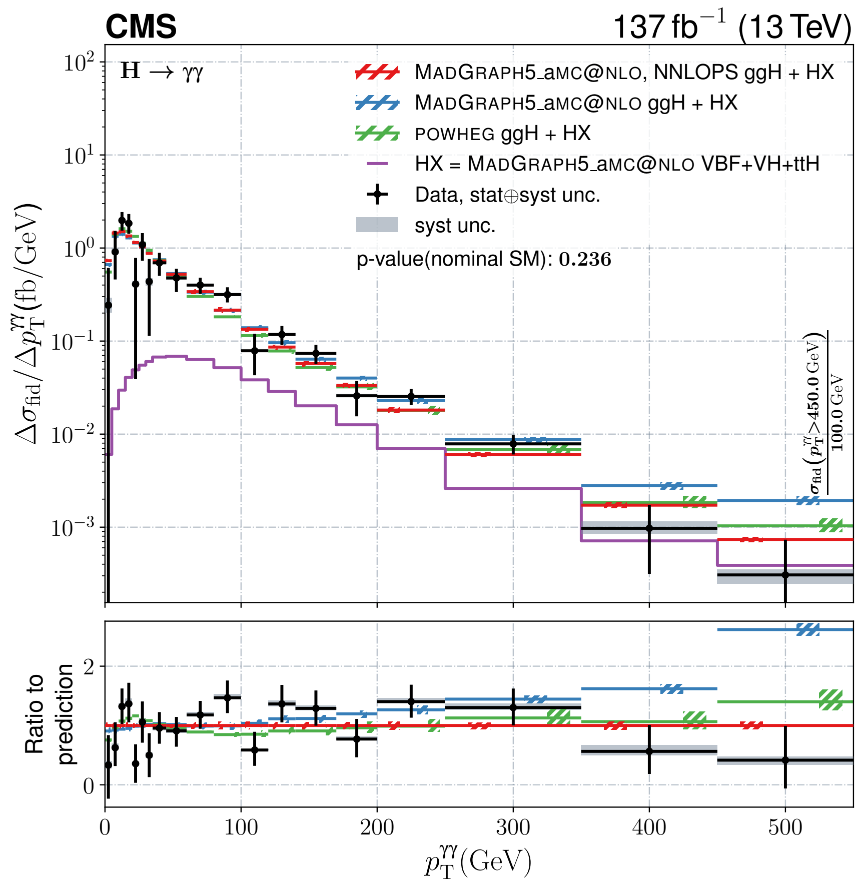
Going Differential

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

ATLAS EPJC 80 (2020) 941



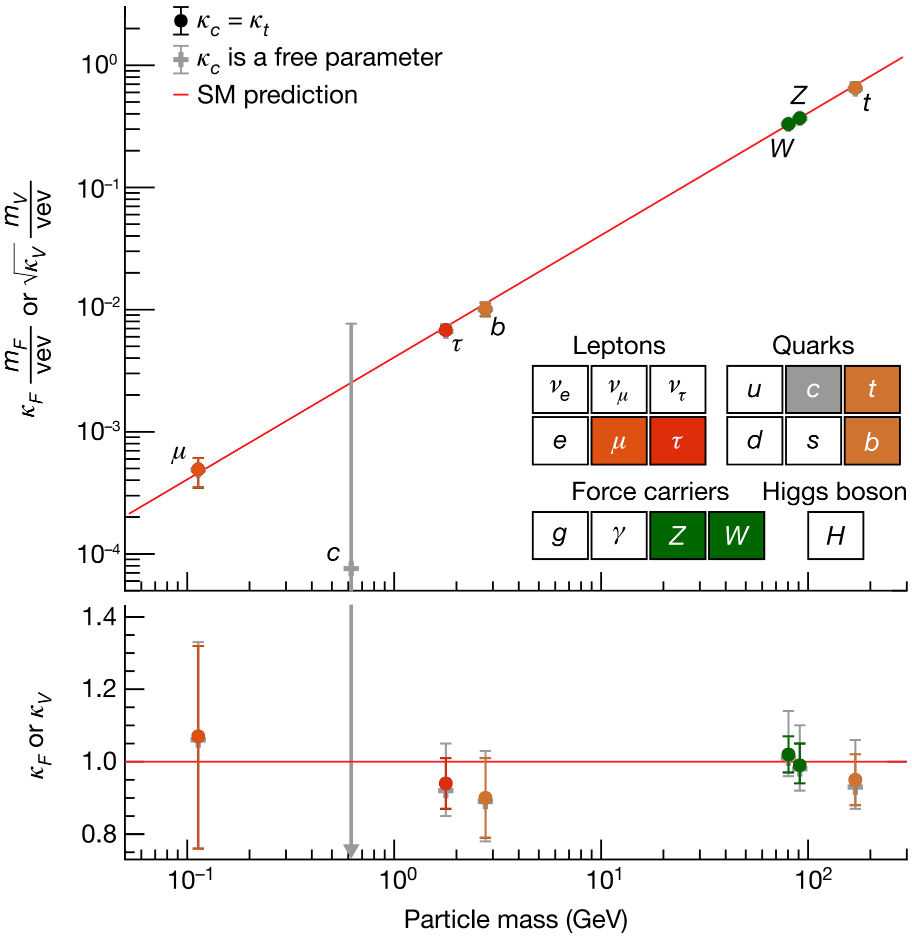
CMS JHEP 07 (2023) 091



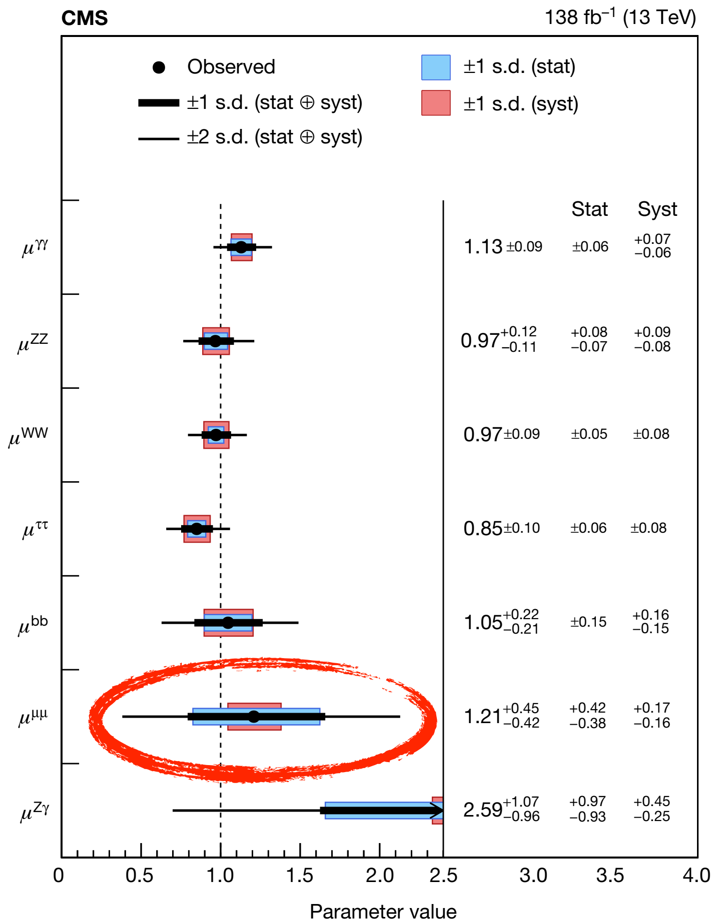
Higgs Boson Couplings

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

ATLAS Nature 607 (2022) 52

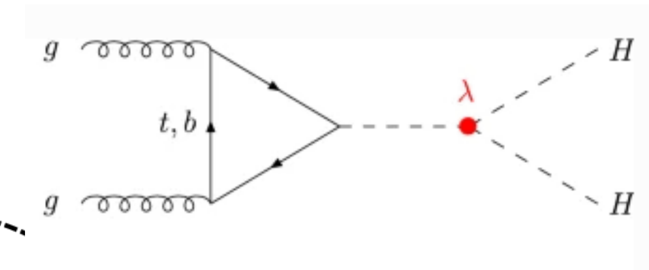


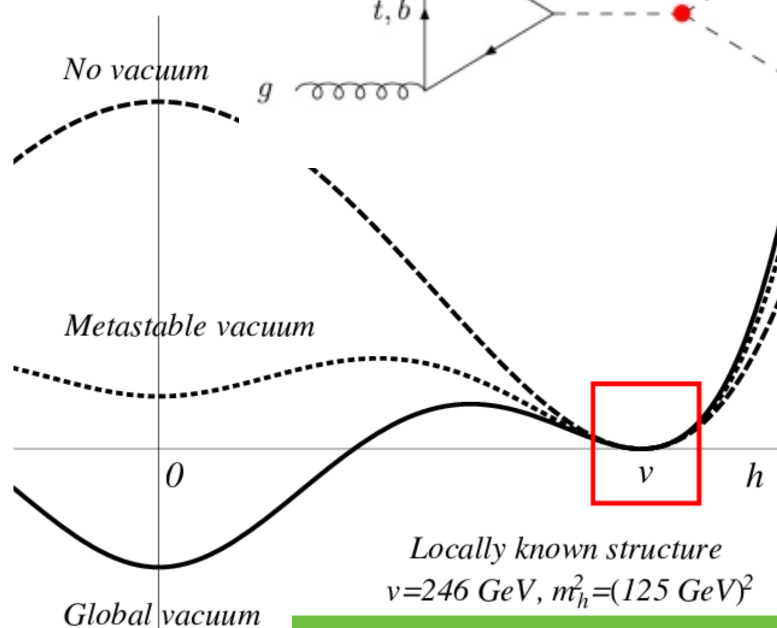
CMS Nature 607 (2022) 60



Exploring Higgs Potential

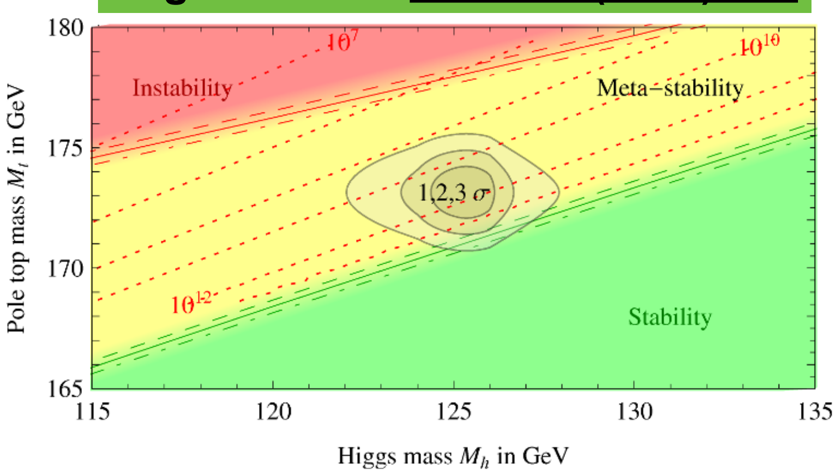
- One of the most important couplings is a Higgs boson self-coupling, λ
- Directly affects the shape of the Higgs potential, with implications for both early and late universe (e.g., EW vacuum stability)
- Depends on λ (or, in the SM, $m_H = \sqrt{2\lambda}v$), m_t, and α_s
- Important to precisely measure 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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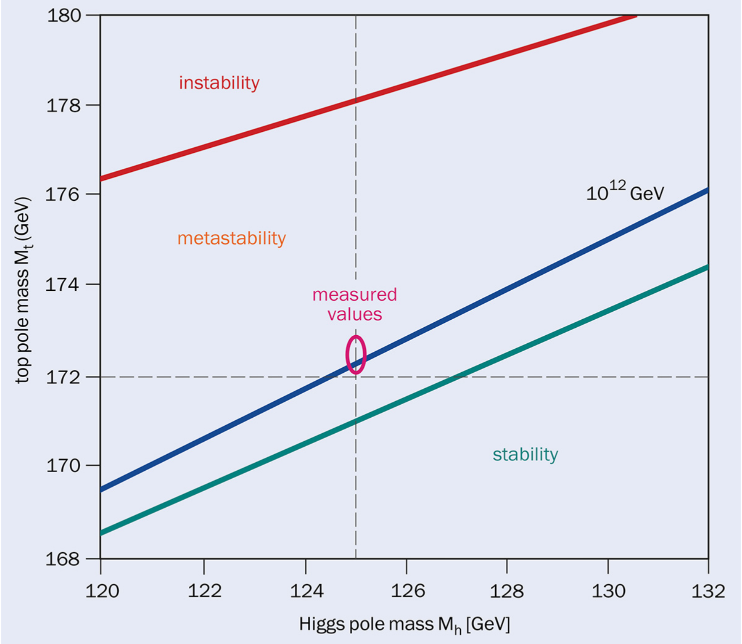
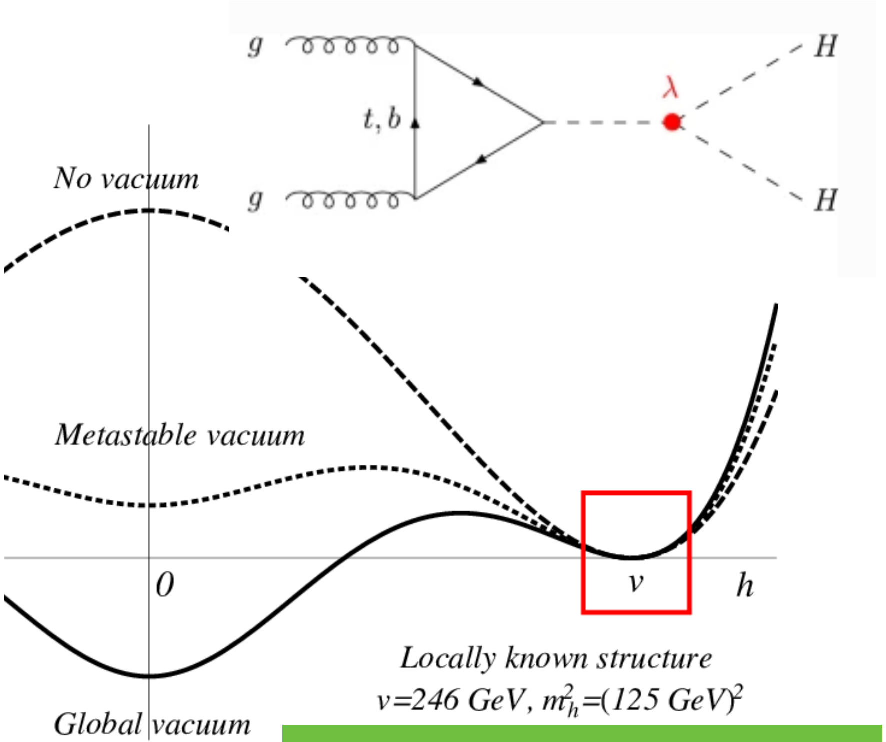
J. Ellis, CERN Courier 62 (2022) 59



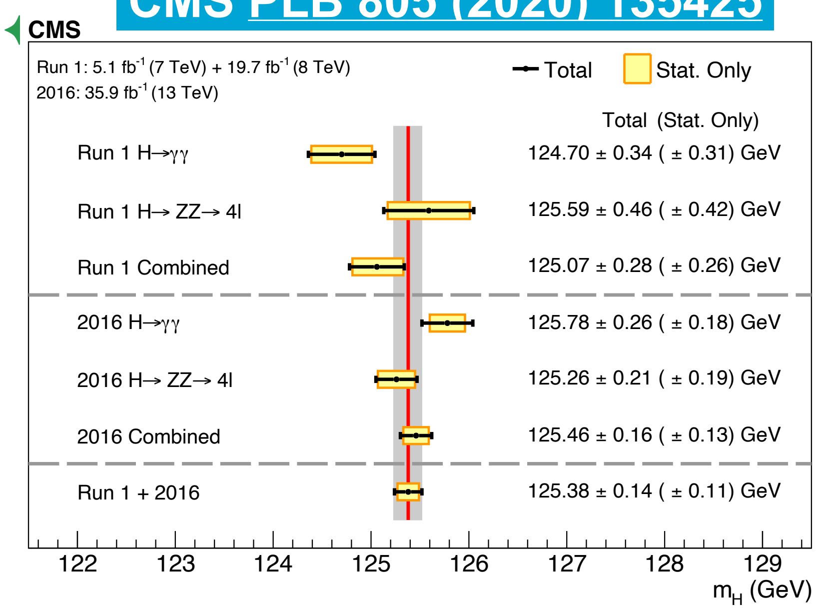


Bai et al. JHEP 07 (2021) 225

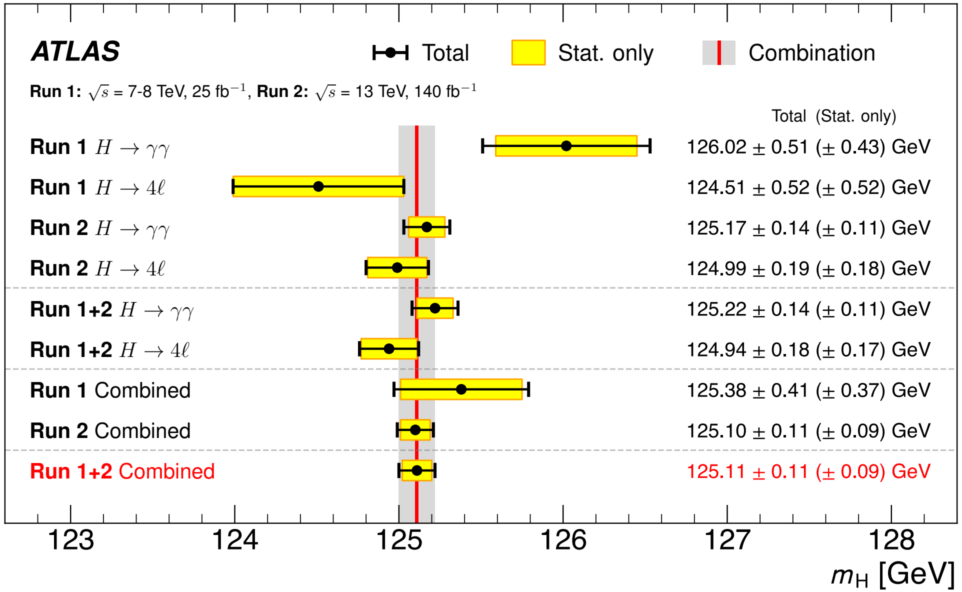
Higgs Boson Mass (and Width)

- New, more precise measurements of the Higgs boson mass by ATLAS and CMS, with sub-permille precision per experiment achieved!
- The two experiments 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]
  - $\Gamma_H = 4.5^{+3.3}_{-2.4}$ MeV [ATLAS, PLB **846** (2023) 138223]
- Measurements are in agreement with the SM prediction of Γ_H = 4.1 MeV

CMS PLB 805 (2020) 135425



ATLAS PRL 131 (2023) 251802



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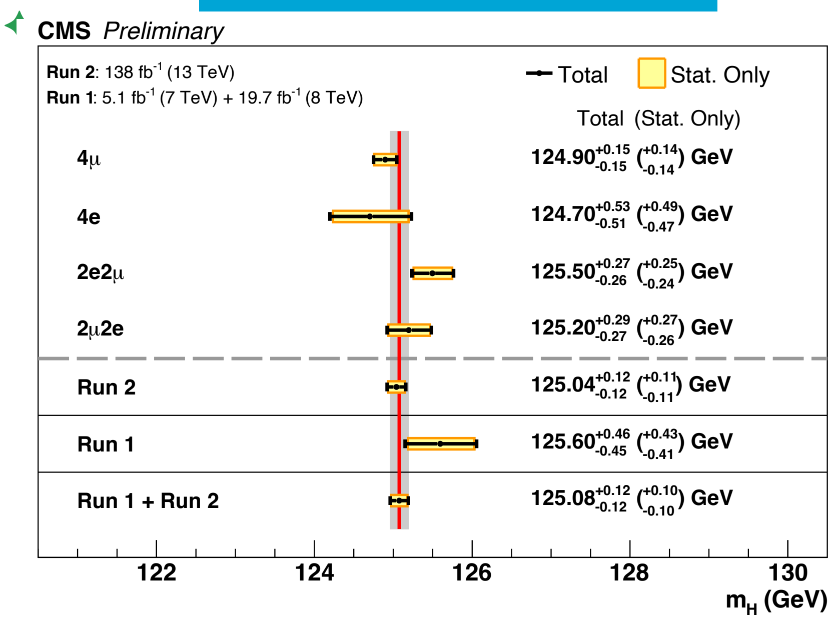
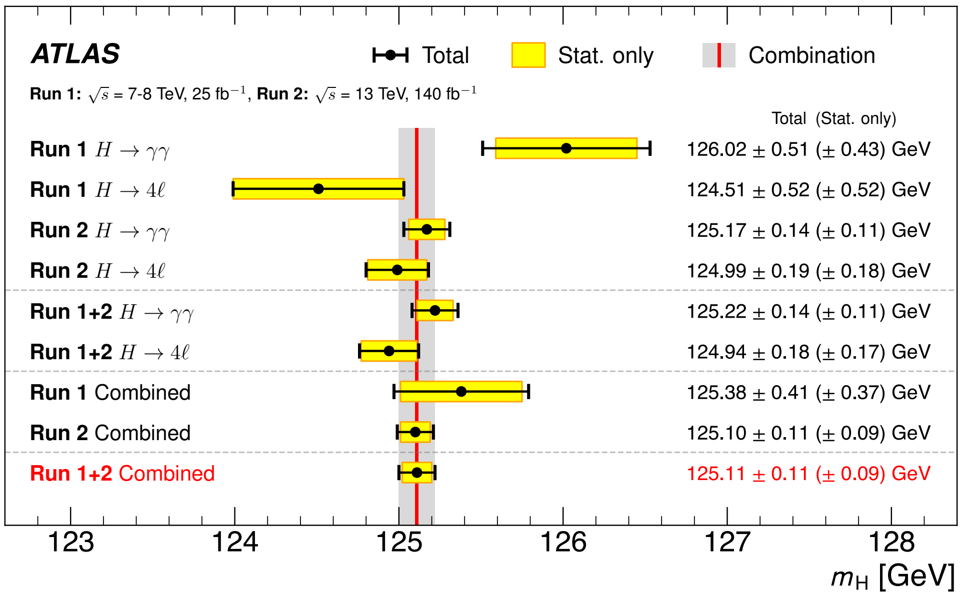
CMS PAS HIG-21-019



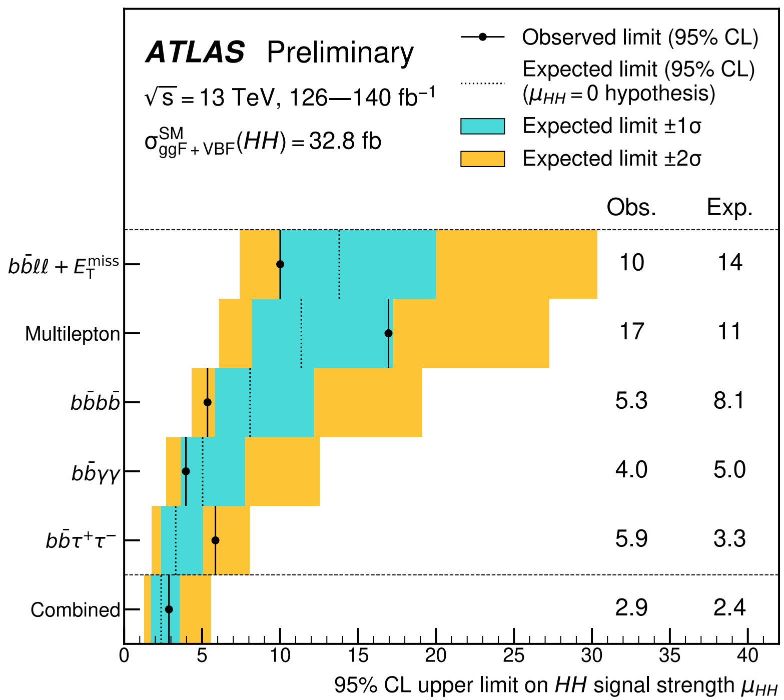
ATLAS PRL 131 (2023) 251802

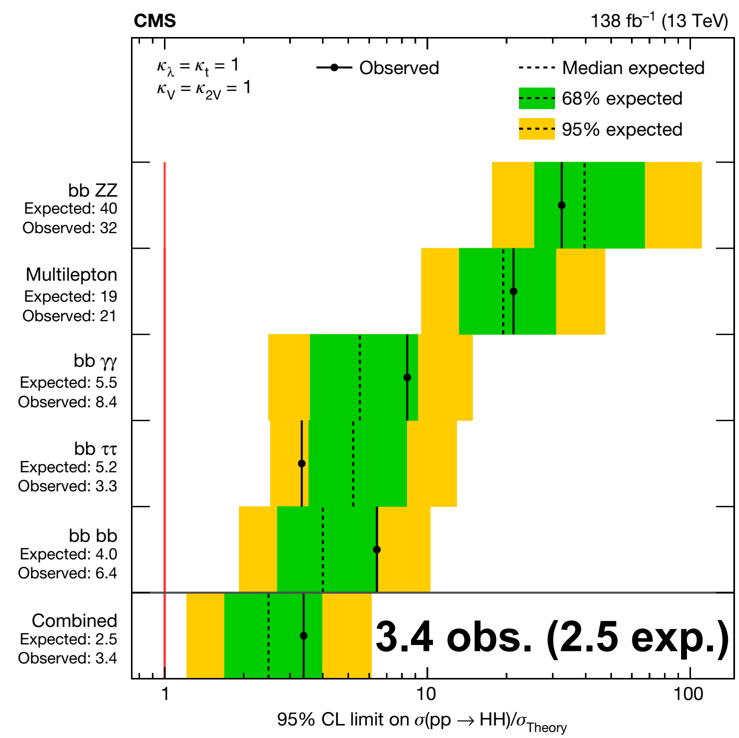


Probing Self-Coupling

- ✦ 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 and multivariate methods
- ✦ Current 95% CL limits on $\mu = \sigma/\sigma_{SM}$ for HH production are <2.9 (2.4) in ATLAS and <3.4 (2.5) in CMS [already exceeded early HL LHC projections![

ATLAS PLB 843 (2024) 137745

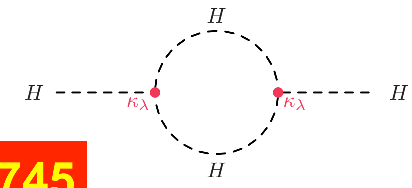




CMS Nature 607 (2022) 60

Sensitivity to λ

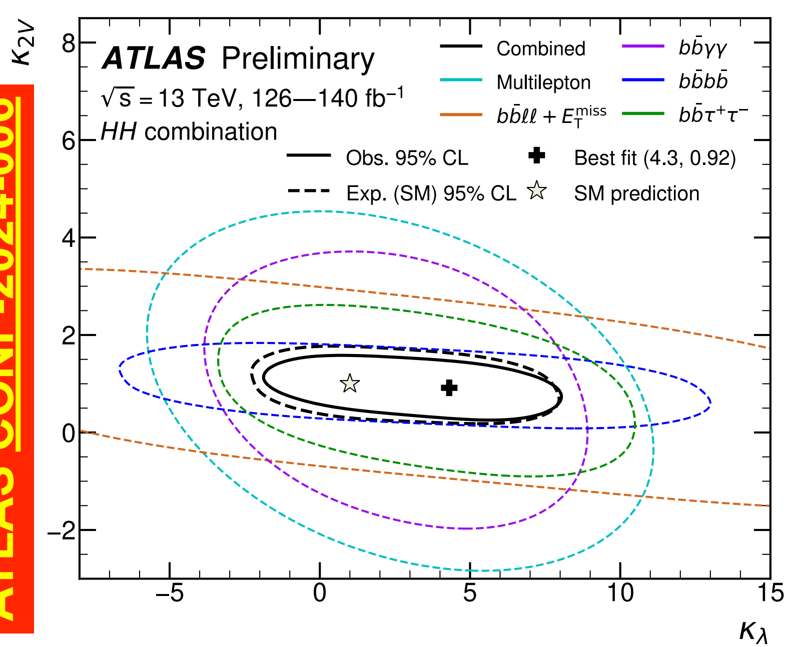
- ✦ Because of the negative interference, sensitivity to λ is non-trivial
  - ◉ Combination of single and double Higgs production helps to constrain the self-coupling in a more model-independent way: **ATLAS PLB 843 (2024) 137745** and **CMS PAS HIG-23-006**
  - ◉ Here we focus on just HH analyses:



$-1.2 < \kappa_\lambda < 7.2$ @ 95% CL

$0.57 < \kappa_{2V} < 1.48$ @ 95% CL

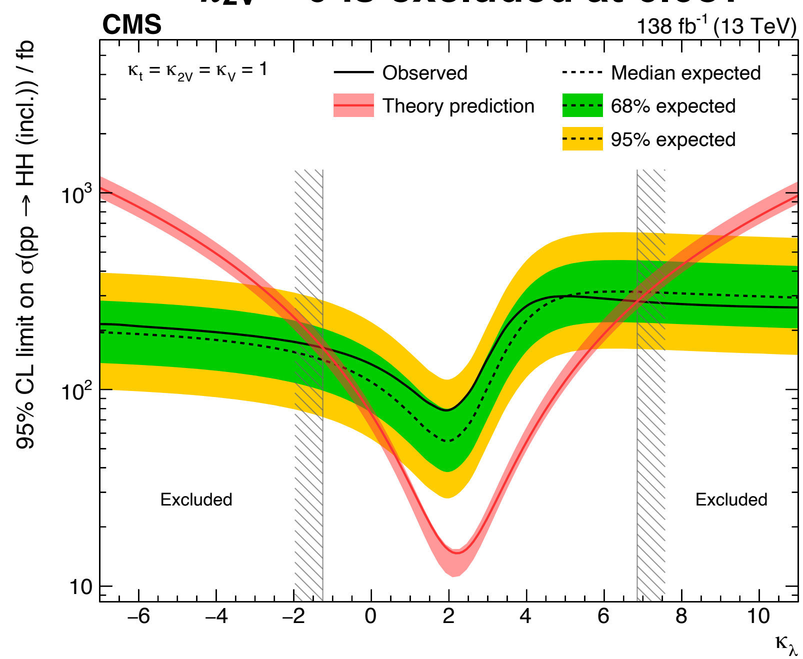
ATLAS CONF-2024-006



$-1.24 < \kappa_\lambda < 6.9$ @ 95% CL

$0.67 < \kappa_{2V} < 1.38$ @ 95% CL

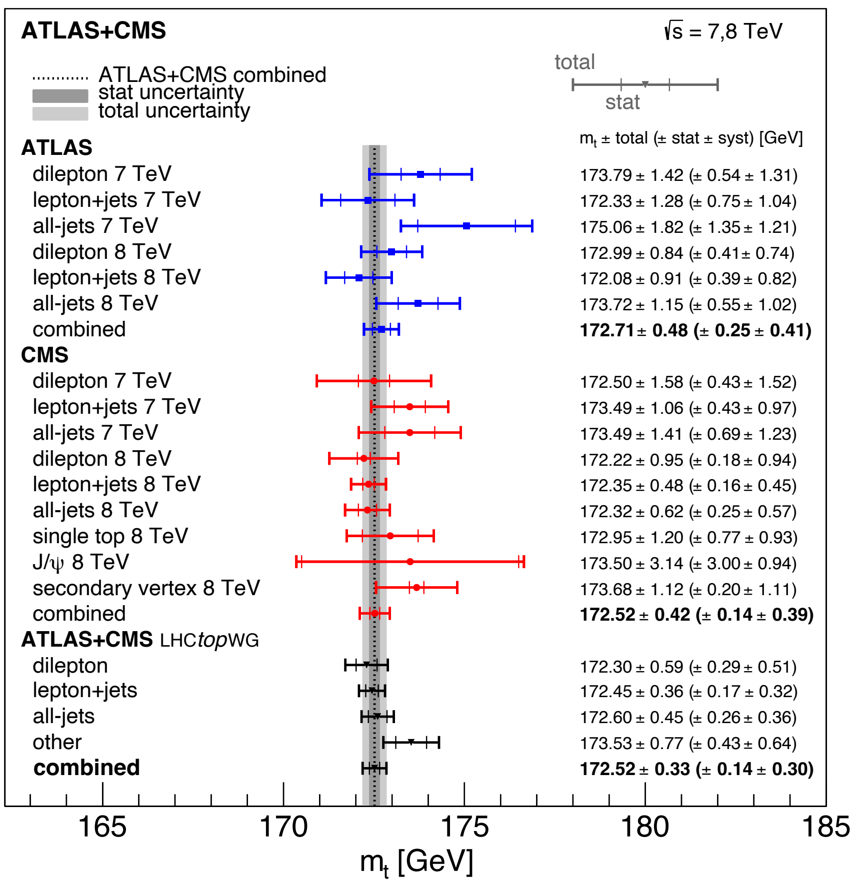
$\kappa_{2V} = 0$ is excluded at 6.6σ!

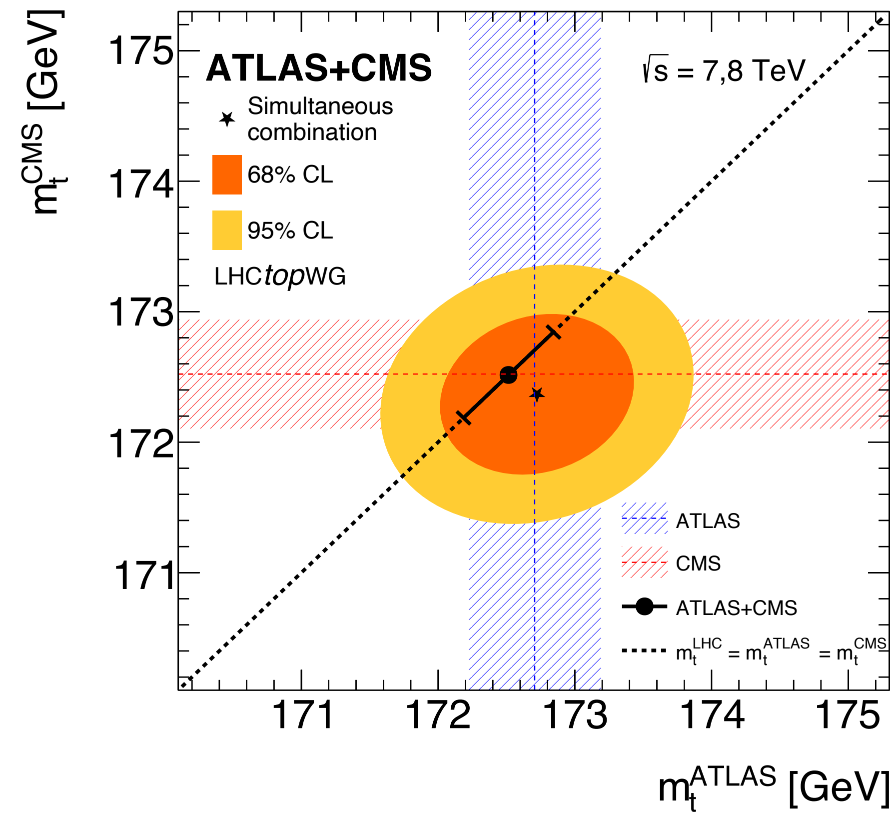


CMS Nature 607 (2022) 60

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 ± 0.33 GeV, with <2‰ precision
  - The most precisely measured quark mass!



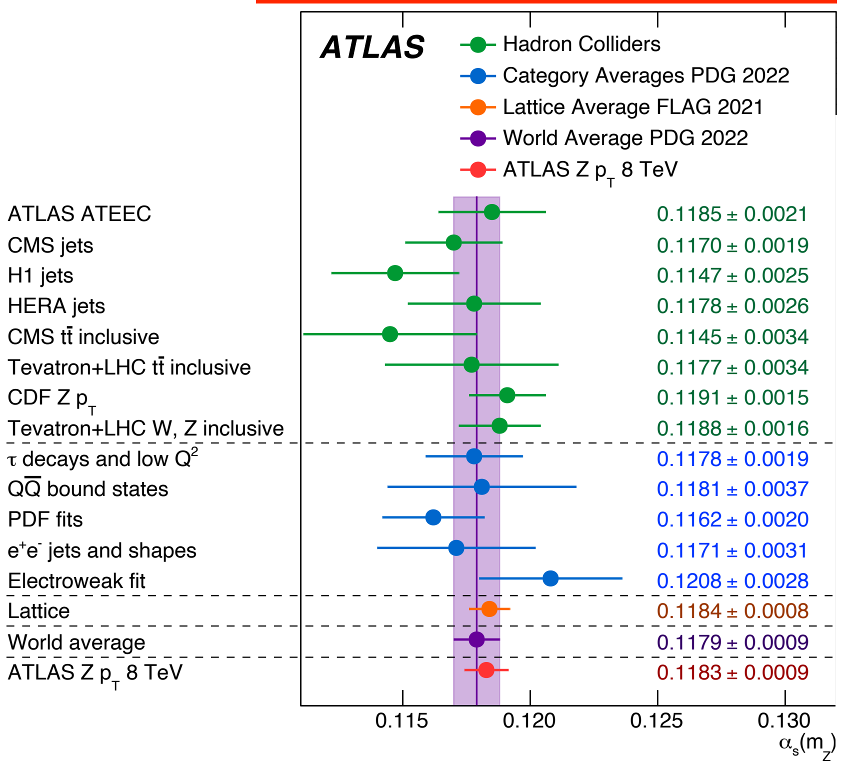


ATLAS & CMS arXiv:2402.08713

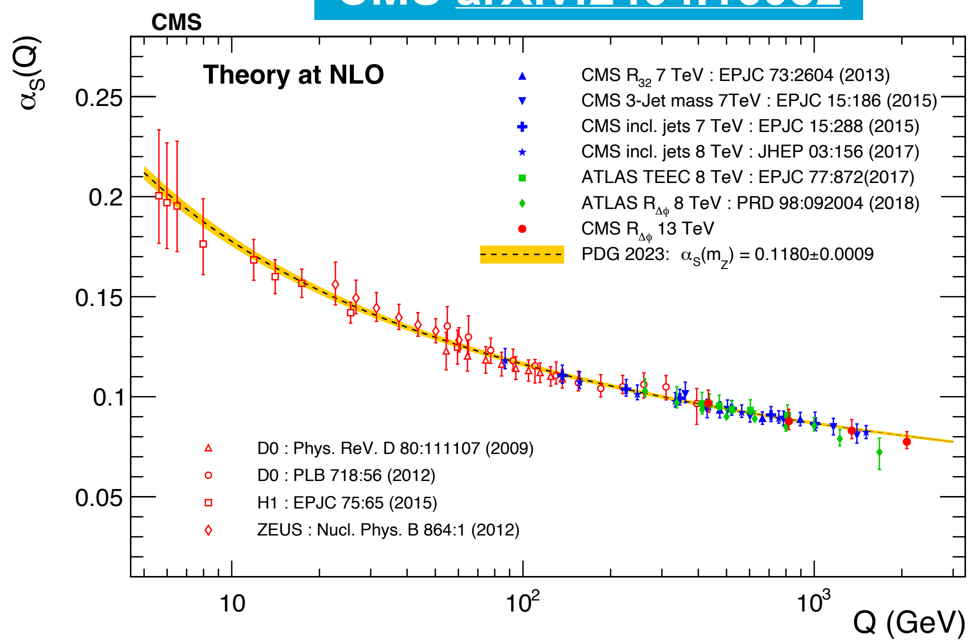
Strong Coupling Measurement

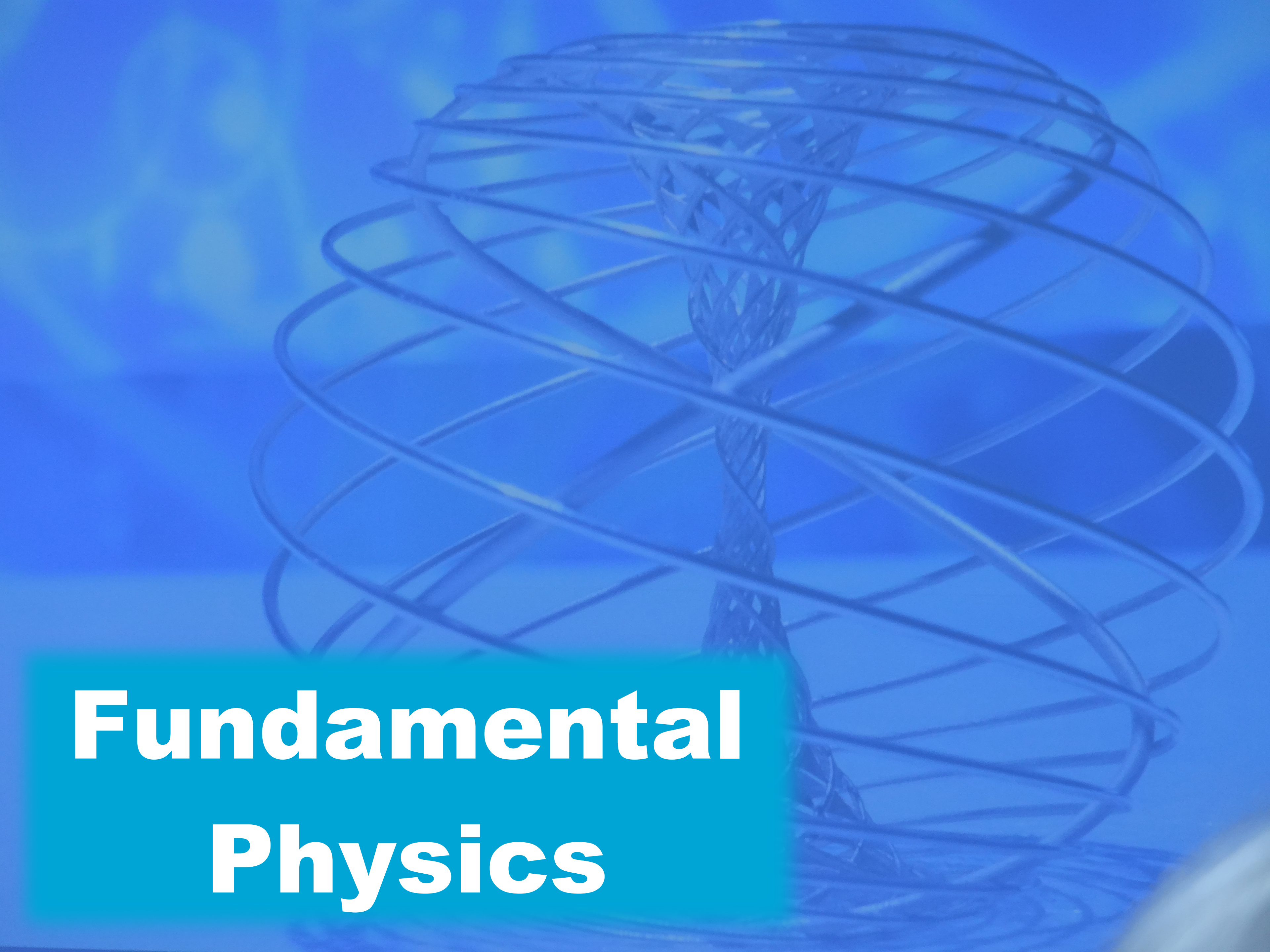
- Several new results from ATLAS and CMS, including ATLAS's novel N^{3}LO extraction based on Z boson p_T spectrum, which is as precise as 2022 world average! [Submitted to Nature Physics.]
- The running of $\alpha_S(Q)$ has been probed at the LHC over nearly 3 orders of magnitude in Q and agrees very well with the QCD NLO RGE evolution

ATLAS arXiv:2309.12986



CMS arXiv:2404.16082

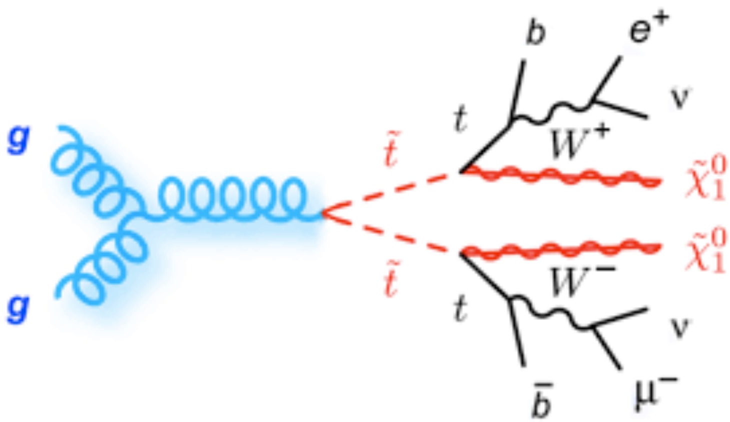




Fundamental Physics

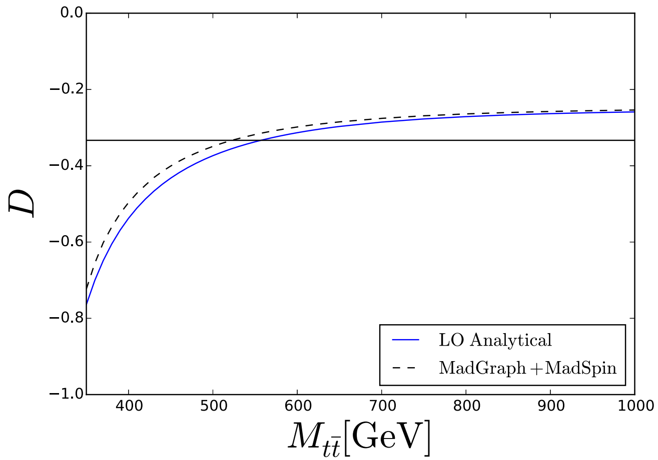
Top Quark Entanglement

- Top quark pair production is an excellen 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

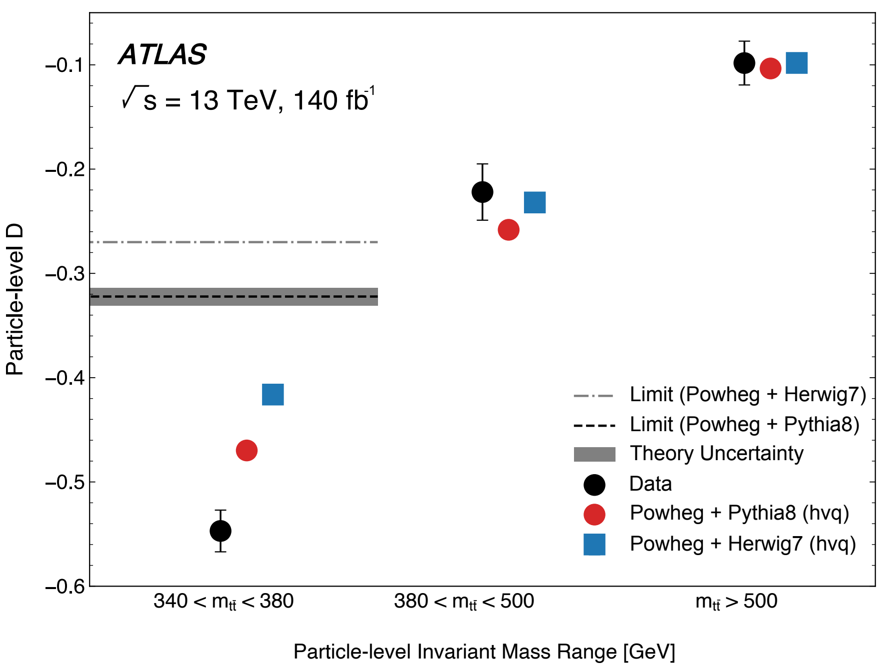
Afik, de Nova, EPJ+ 136 (2021) 907



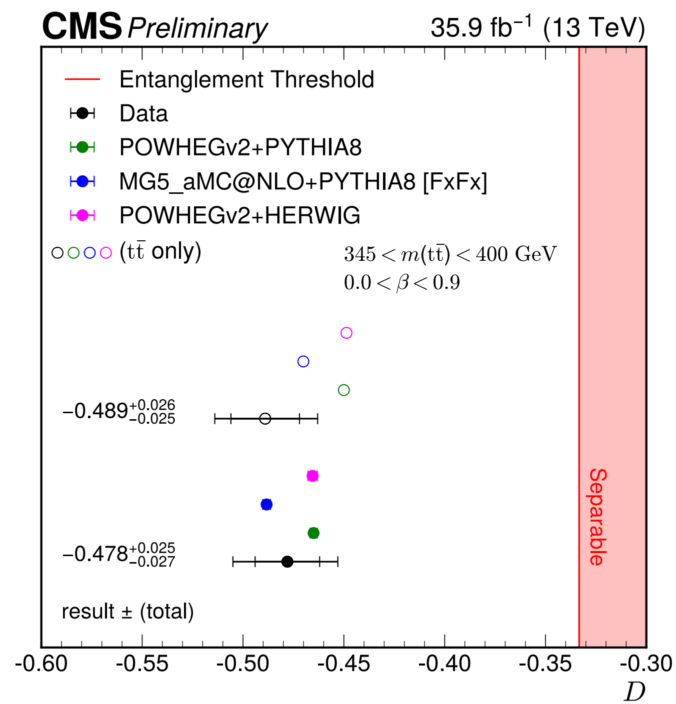
Observation of Entanglement

- New ATLAS result [submitted to Nature] is the first observation of quantum entanglement in the tt system: D = -0.547 ± 0.002 (stat) ± 0.021 (syst)
- Recently CMS confirmed this and showed that inclusion of the below-threshold toponium resonance improves the agreement between the observed and predicted entanglement

ATLAS arXiv:2311.07288

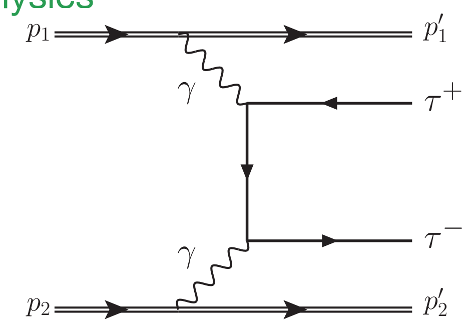


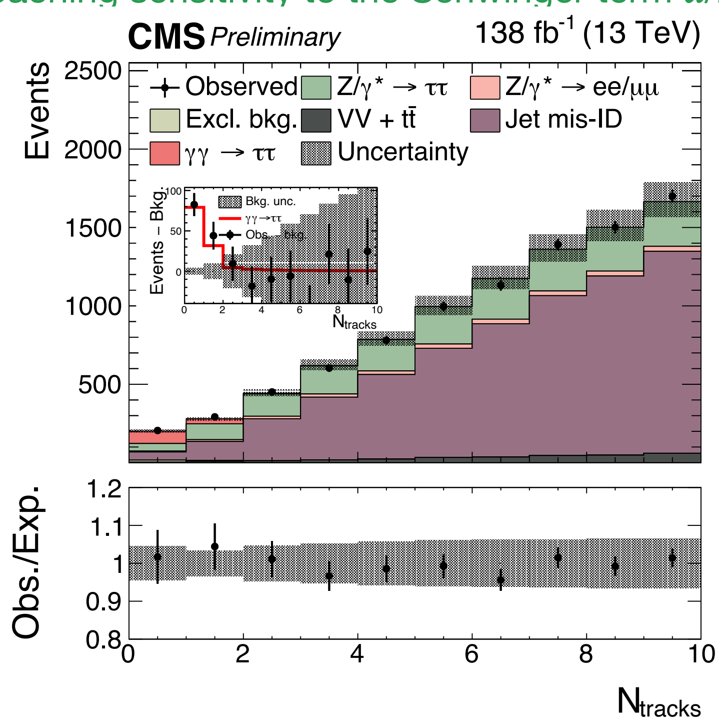
CMS PAS TOP-23-001



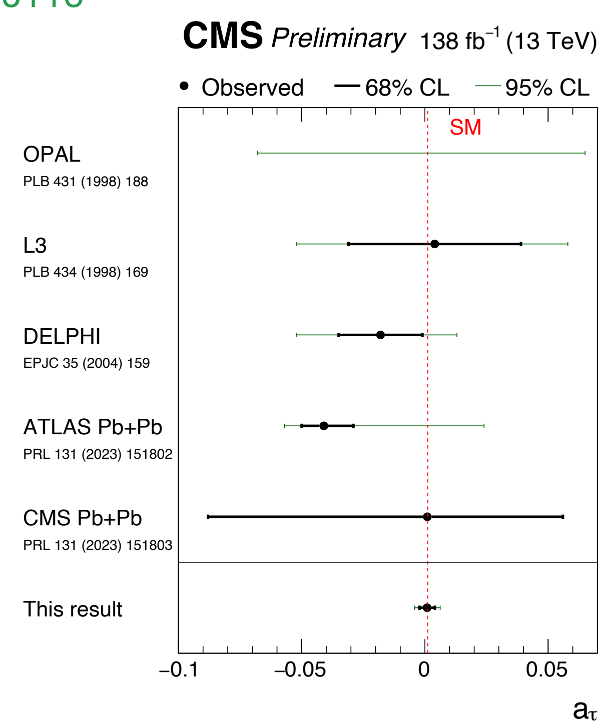
g-2 of the Tau Lepton

- Anomalous magnetic moments are fundamental parameters sensitive to new physics
  - Cf. Peter Winter's talk on the muon g-2 saga
- 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 PAS SMP-23-005



Lepton Flavor Universality

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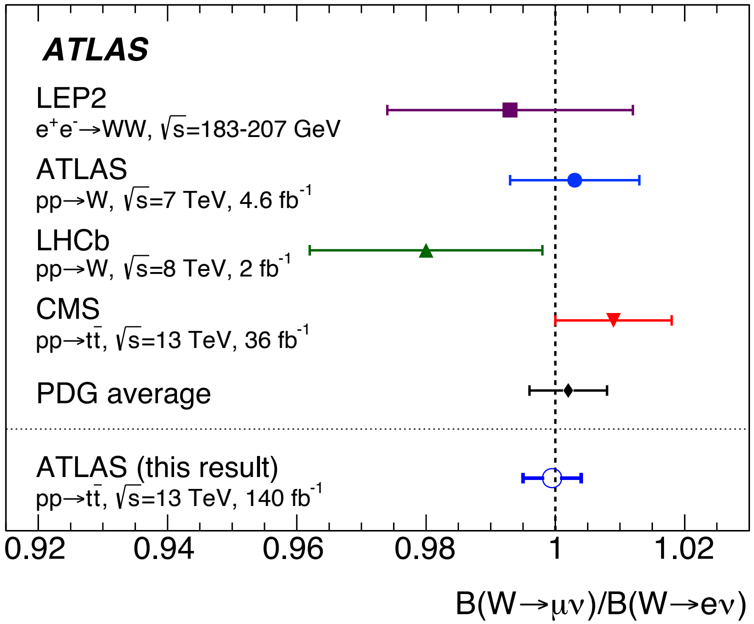
- In the SM, couplings of gauge bosons to fermions are universal, which is an accidental symmetry of the SM
- Recent interest in lepton flavor universality (LFU) violation sparkled by the LHCb claims of LFU violation in $b \to s l^+ l^-$ transitions [by now understood to be due to a missing background]
  - Higgs boson is the only known particle with non-flavor-universal couplings to leptons
- Recent precision test by ATLAS in $W \to e\nu$ vs. $\mu\nu$ decays
  - Uses tt production as a clean source of W events
  - Additionally uses the Z(ee)/Z(μμ) ratio, for which LFU has been firmly established by LEP and LHC, to reduce the uncertainty
- $R^{\mu/e}(W) = 0.9995 \pm 0.0022$ (stat) ± 0.0036 (syst) ± 0.0014 (ext)
- Most precise measurement to date

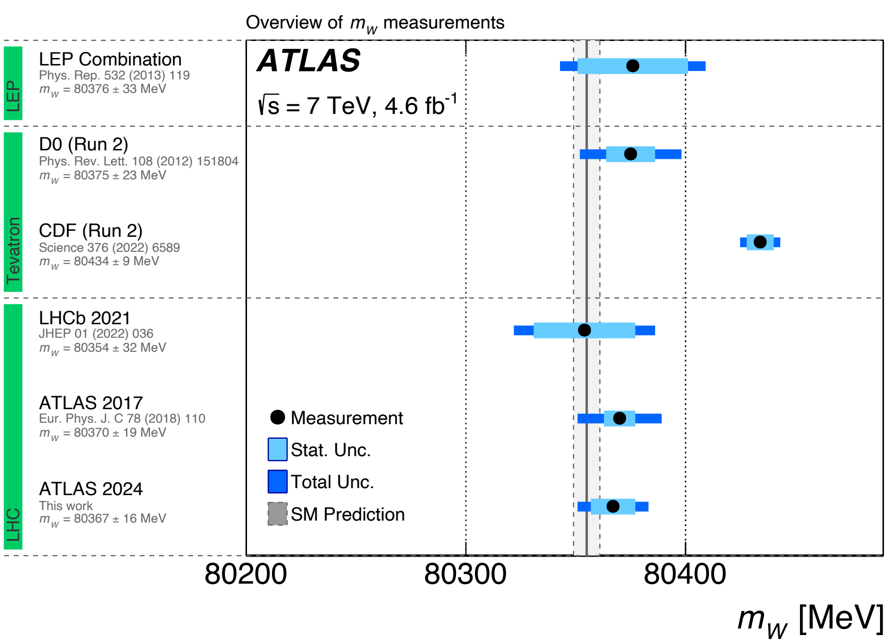
ATLAS arXiv:2403.02133

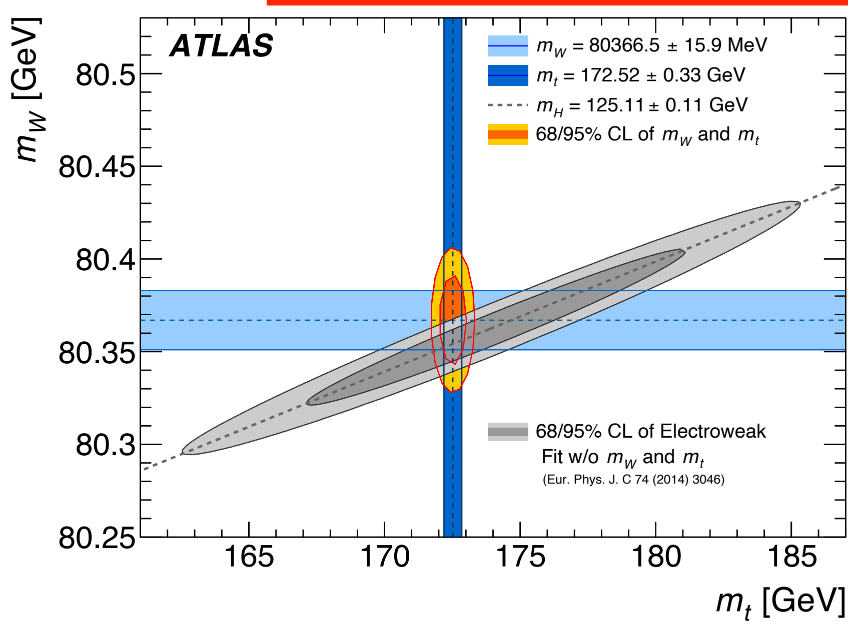


Measurement of the W Boson Mass

- ✦ The mass of the W boson is a fundamental parameter in the SM; also crucial for precision EW fits
- ✦ At the LHC the measurements have been so far down by ATLAS and LHCb
- ✦ Recent update of the earlier analysis by ATLAS to include the latest constraints on parton distribution functions
  - M_W = 80366.5 ± 15.9 MeV (reduction of the uncertainty by 2.6 MeV)
- ✦ Also measured the W width Γ_W = 2202 ± 47 MeV

ATLAS arXiv:2403.15085

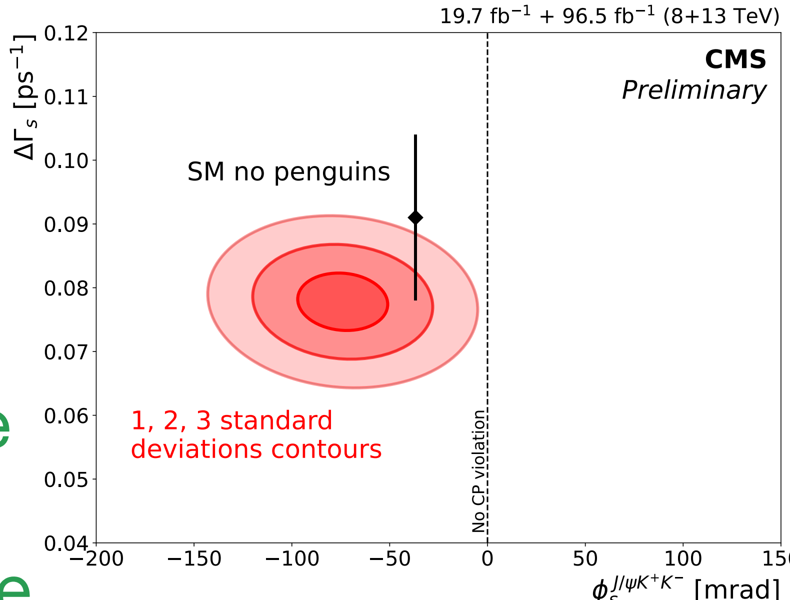




CP Violation in $B_s \to J/\psi\varphi$ Decays

- 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 $B_s \to J/\psi\phi$ 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



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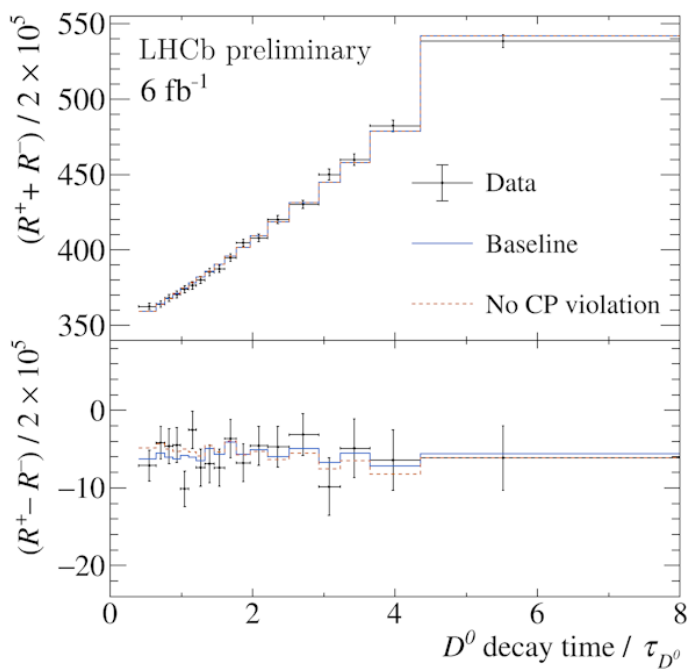
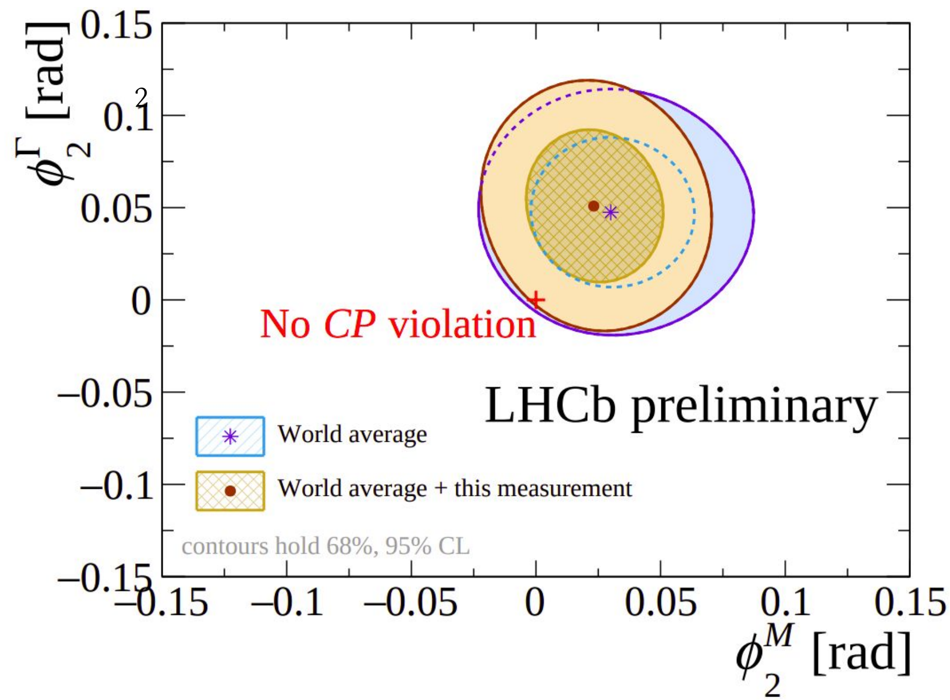
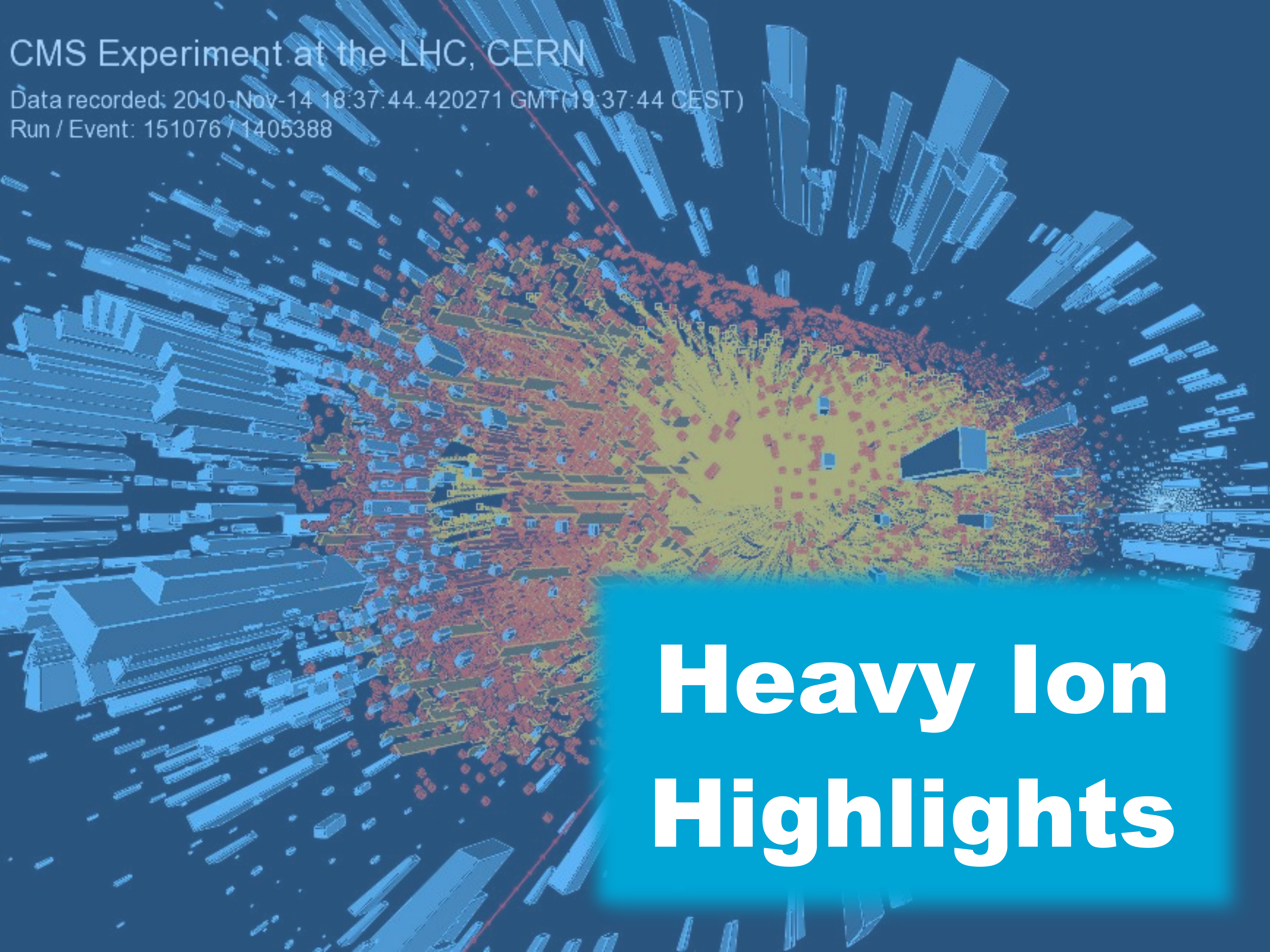
CP Violation in Charm

- CPV has been observed in strange, beauty, and recently charm sectors
  - In charm sector CPV can occur in $D^0 \leftrightarrow \overline{D}^0$ oscillations, directly in the decay, or in both
  - LHCb earlier observed CPV in the $D^0 \to K^+K^-$, $\pi^+\pi^-$ decays
- New LHCb result on a search for CPV in a charm decay: $D^0 \to K^+\pi^-$
  - Use D^* as a source of D^0, tagged via the $D^* \to D^0\pi$ decay; 410M D^0
  - No evidence for CPV in decay, mixing, or both



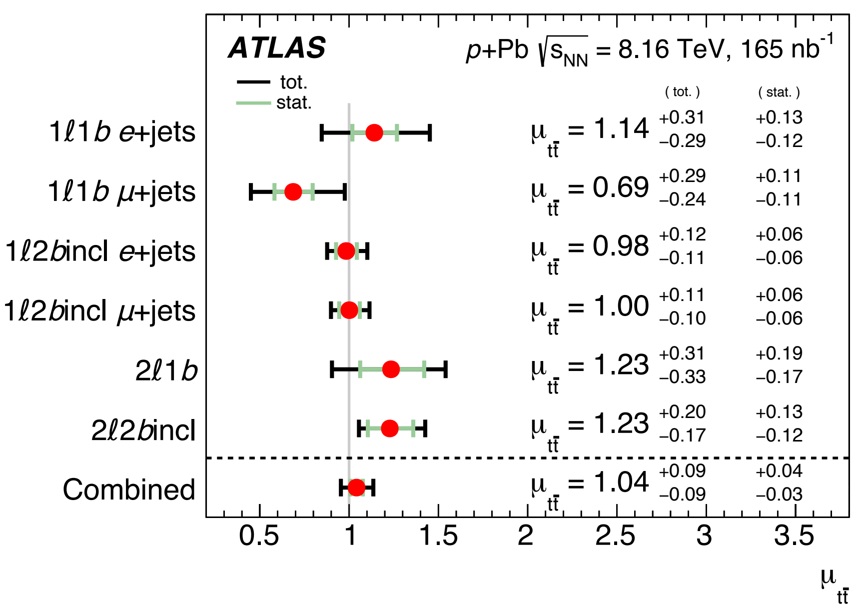




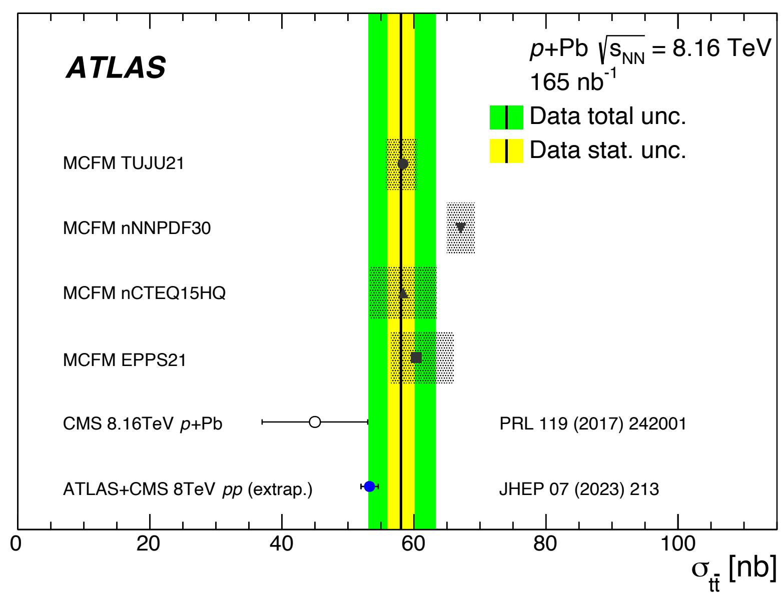
Heavy Ion Highlights

Observation of $t\bar{t}$ Production

- Top quark production in nucleus-nucleus collisions is an excellent probe of nuclear PDFs at low Bjorken x, particularly the gluon nPDF
- A new ATLAS analysis focuses on both l+jets and dilepton decay channels of the $t\bar{t}$ system in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV (165 nb^{-1})
- Signal observed w/ >5σ significance in each channel, with cross section $\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\text{stat})\ ^{+4.8}_{-4.4}\ (\text{syst})$ nb consistent with the scaled pp NNLO cross section calculations
  - Analysis approaches sensitivity necessary to probe nPDFs

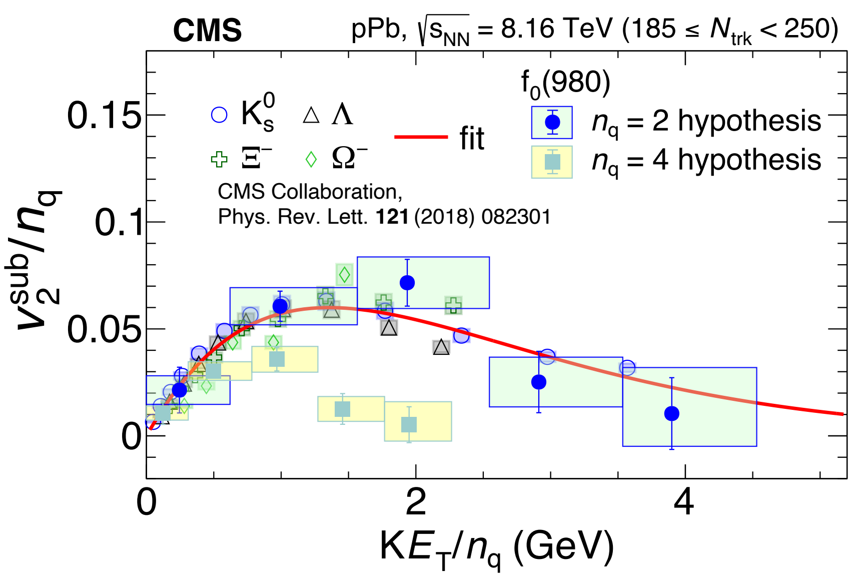


ATLAS arXiv:2405.05078

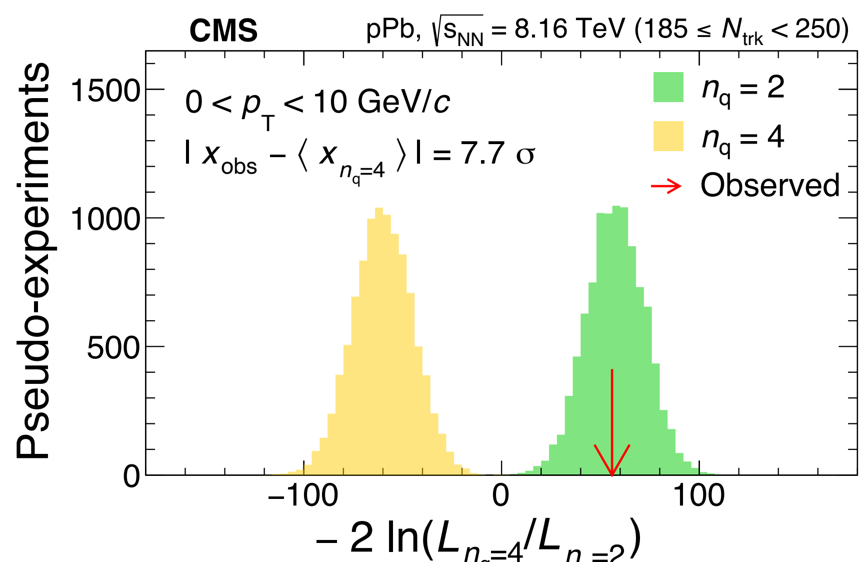


Resolving $f_0(980)$ Puzzle

- 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.]



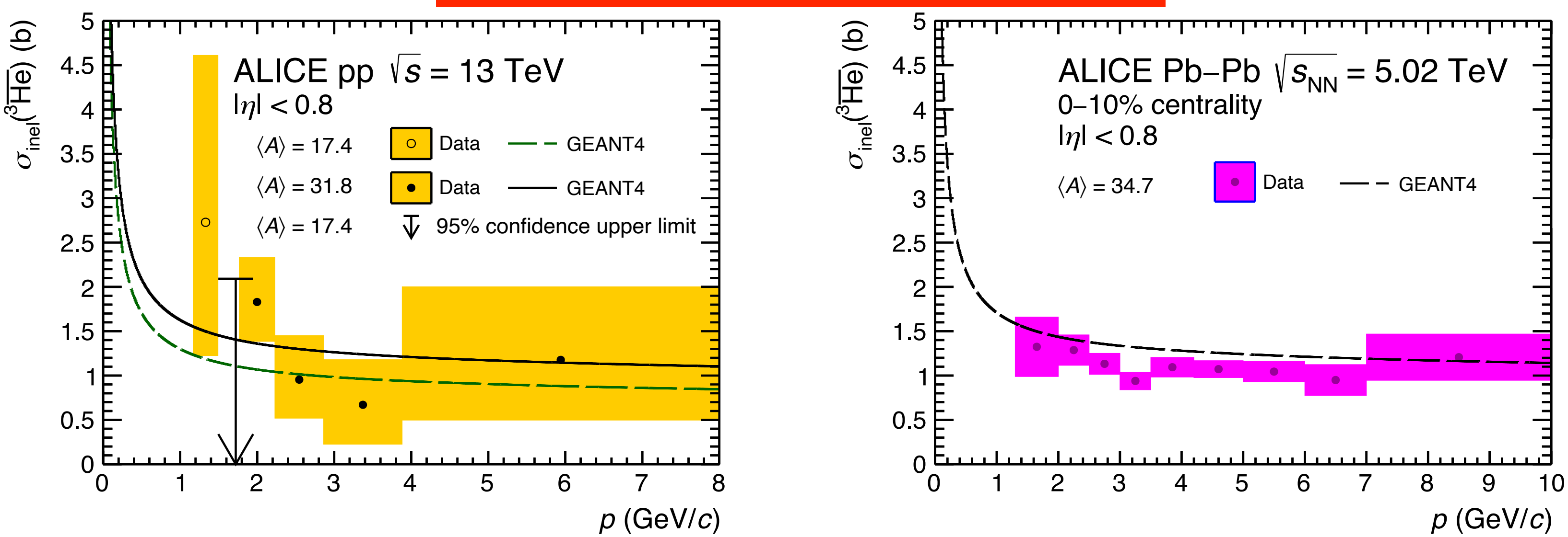
CMS arXiv:2312.17092



Anti-^{3}He Absorption in Matter

- Astrophysical observation of low-energy antinuclei, such as anti-^{3}He, is one of the most promising signatures of DM annihilation
  - Important question is the transparency of our galaxy to these antinuclei
- ALICE has measured for the first time the cross section of anti-^{3}He interactions as a function of momentum by measuring anti-^{3}He absorption in several sub-detectors
  - anti-^{3}He/^{3}He ratio method is used for pp collisions
  - anti-^{3}He disappearance in TRD is used for PbPb collisions

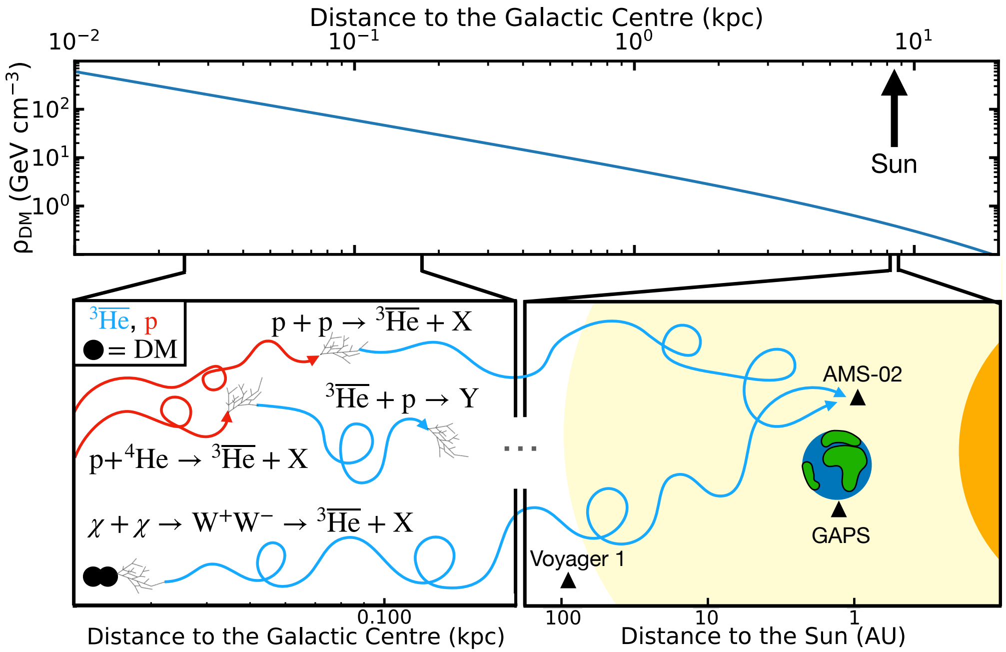
ALICE Nature Phys. 19 (2023) 61

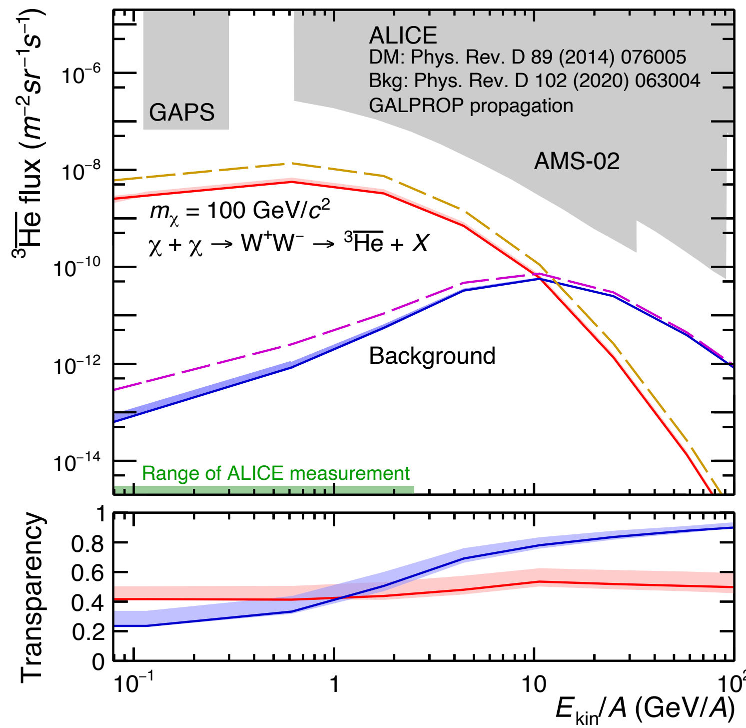


Astrophysical Impact

- These cross section measurements allowed to model our galaxy transparency to anti-^{3}He produced in DM annihilation in the center of Milky Way
- Various processes are considered, along with the effect of solar modulation
- Prediction for a 100 GeV WIMP are made and are about 1 order of magnitude below the current AMS-02 and GAPS sensitivity

ALICE Nature Phys. 19 (2023) 61

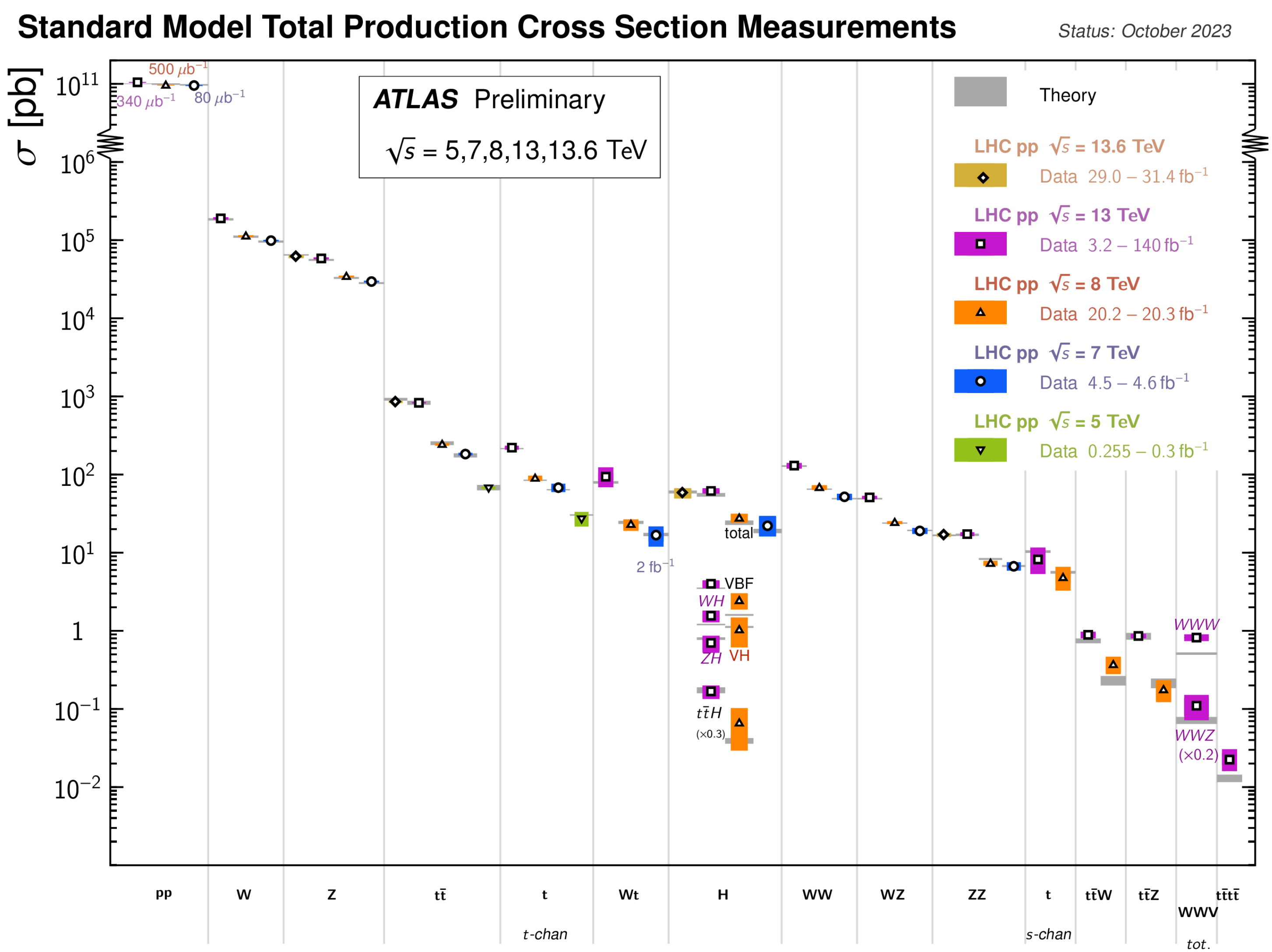




Standard Model Highlights

"Stairway to Heaven"

✦ Mind-boggling precision on so many SM processes!



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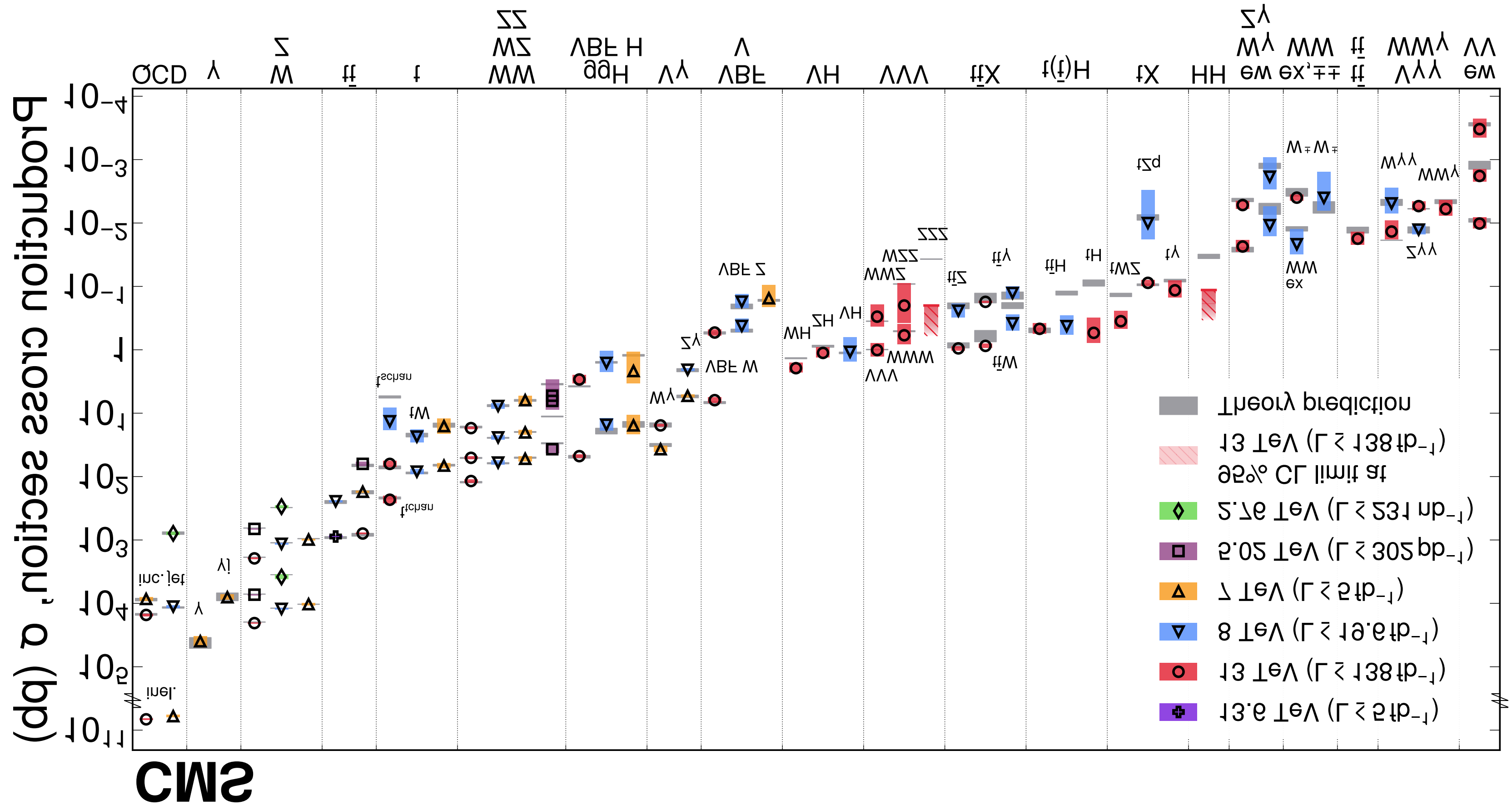

Searches for New Physics

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?

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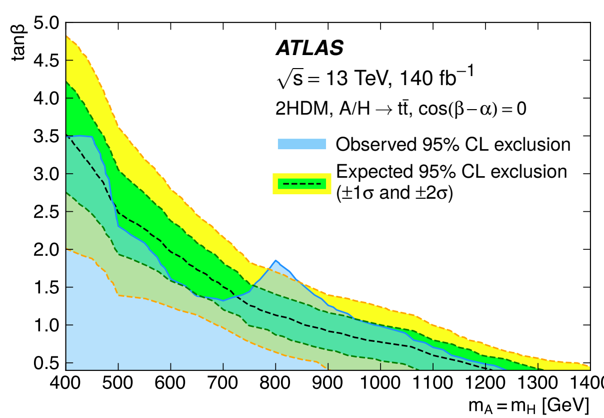

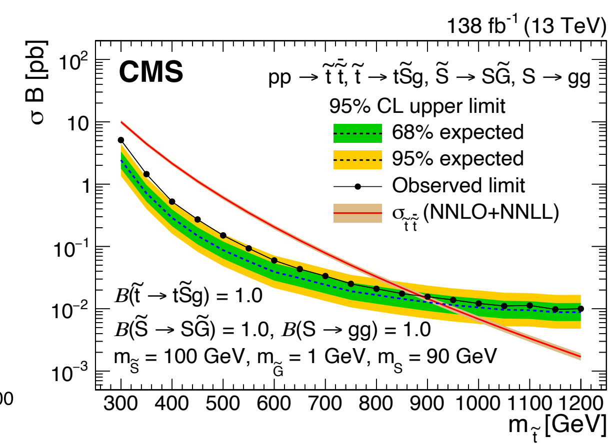

The Why

- 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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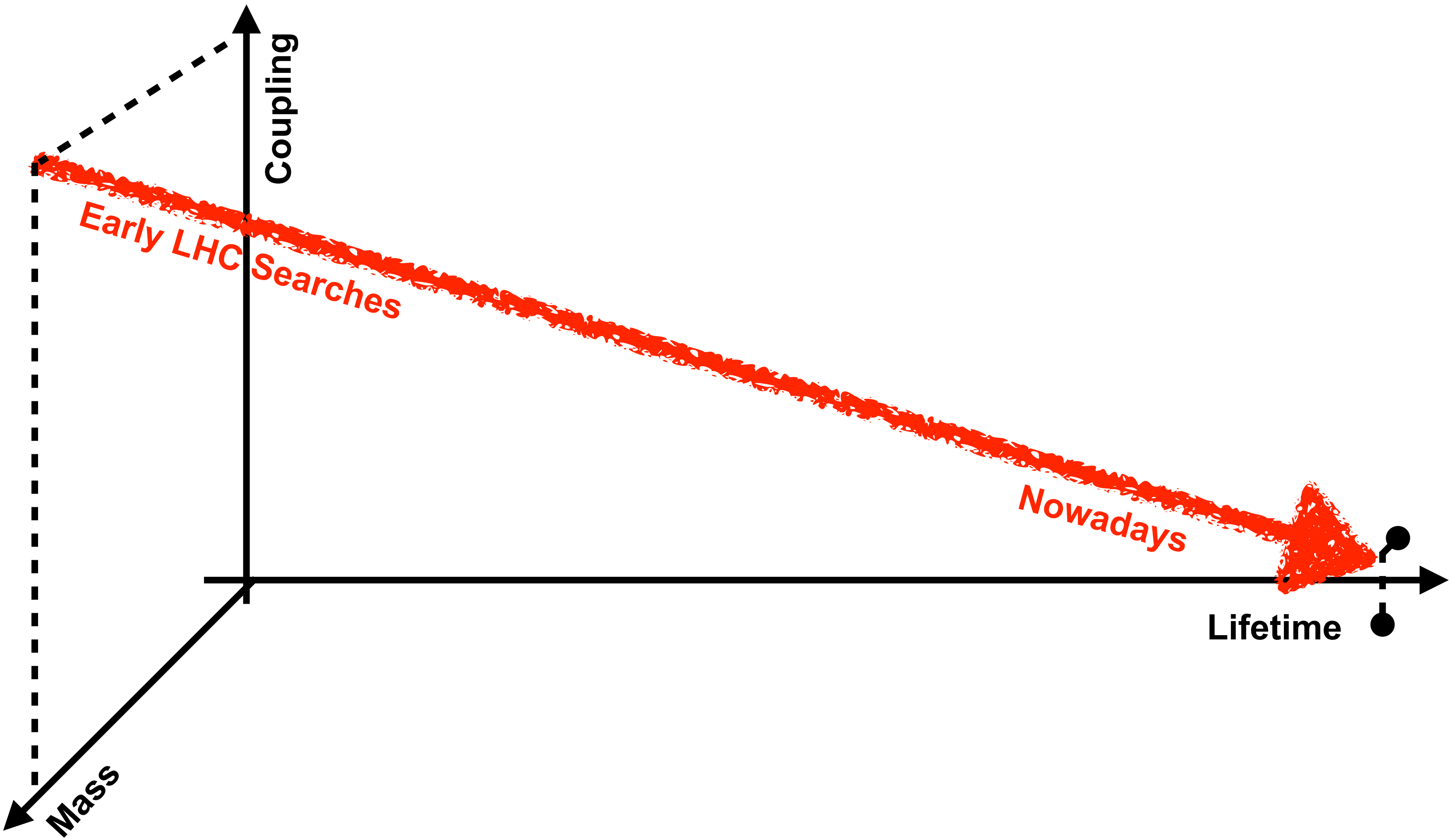
Stairway to Hell

✦ The paradigm shift

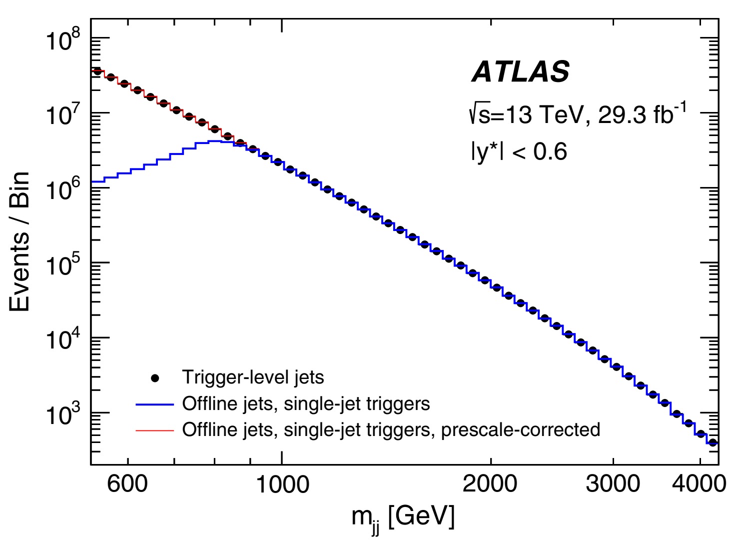


New Tools for the New Paradigm

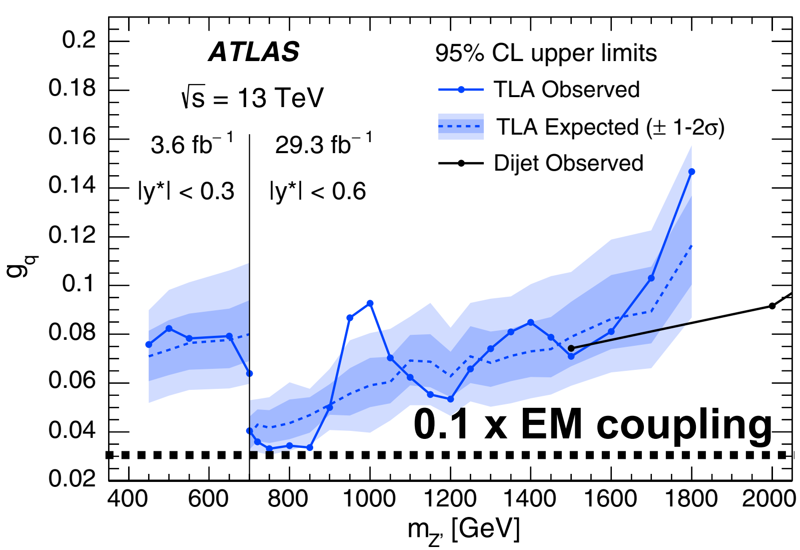
- Use of new triggers not available earlier in the LHC running
  - A variety of triggers optimized for long-lived particles
  - Trigger-level analysis (TLA), aka data scouting - ATLAS and CMS, and triggerless design with real-time alignment and calibration (LHCb)
    - Extensive use of GPU in the trigger
  - 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: TLA

- Trigger-level analysis (TLA) 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 TLA data stream
  - Avoids the use of (large) trigger prescales



ATLAS, PRL 121 (2018) 081801



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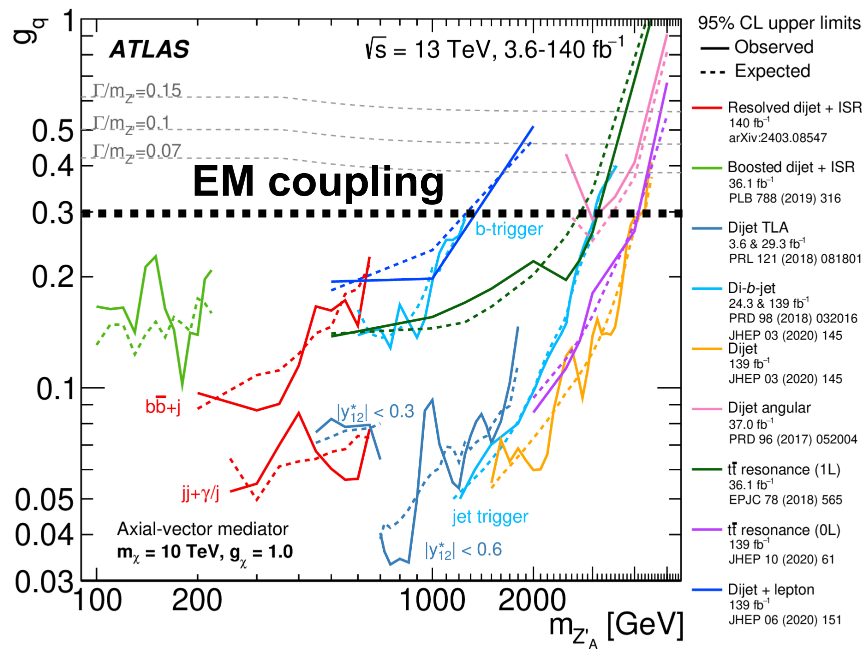
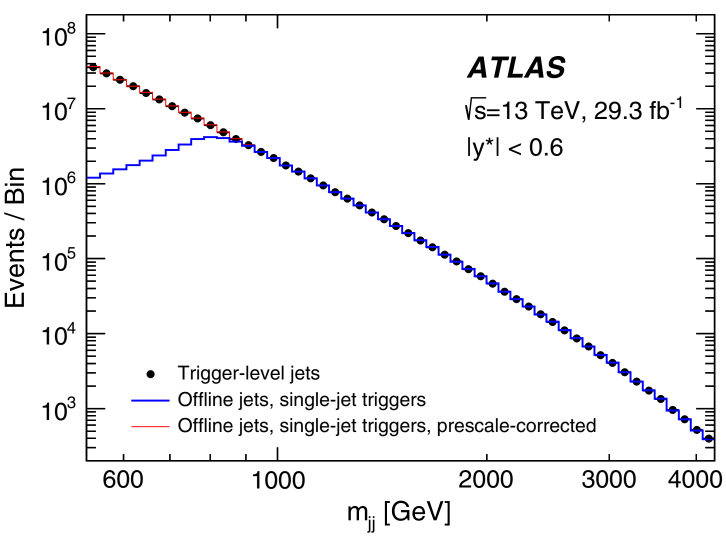
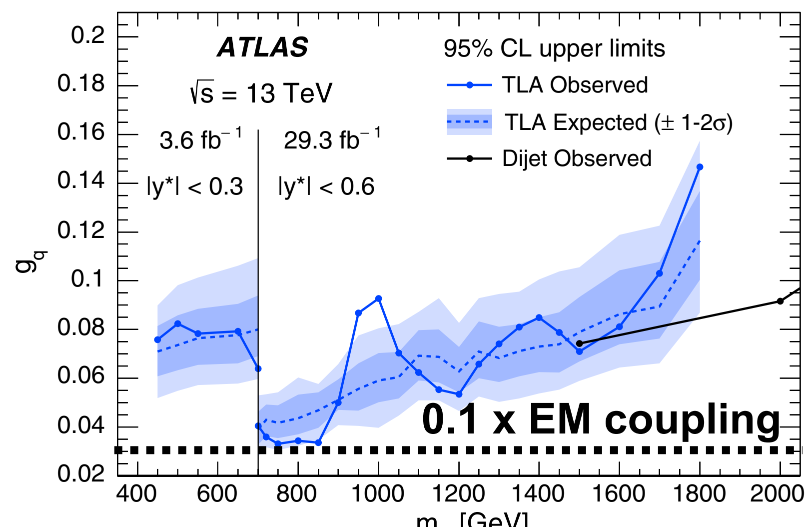


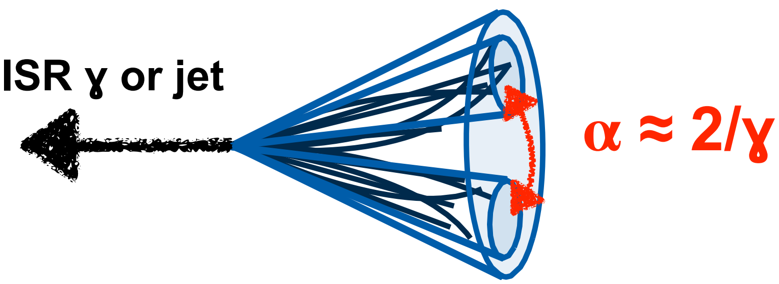


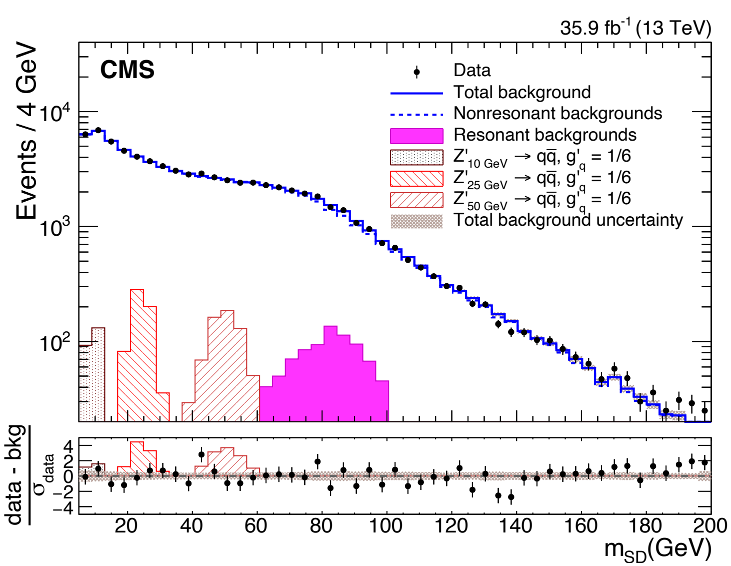
ATLAS, PRL 121 (2018) 081801



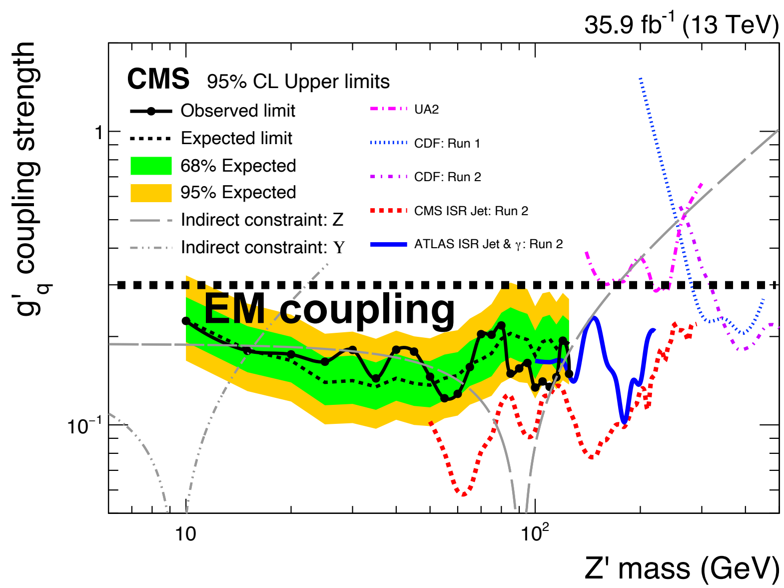
Toward Small Masses: ISR

- 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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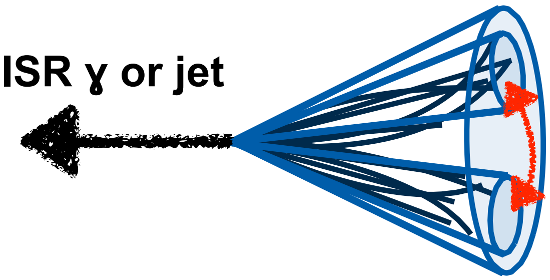
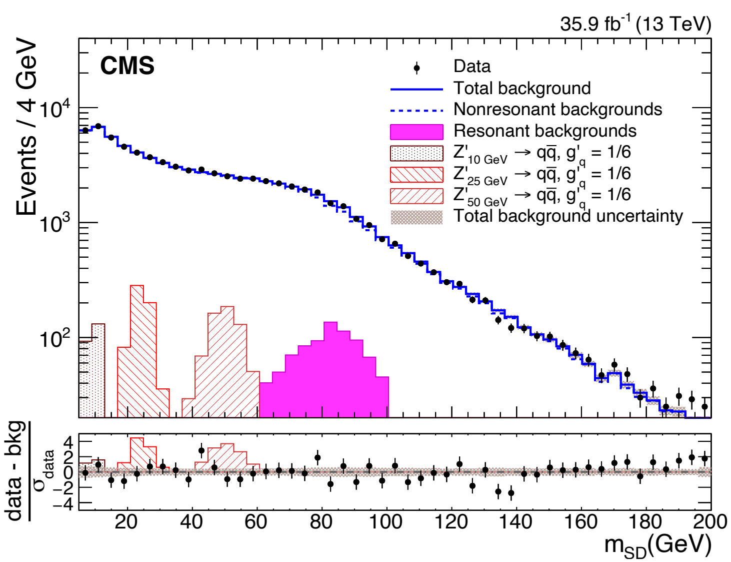
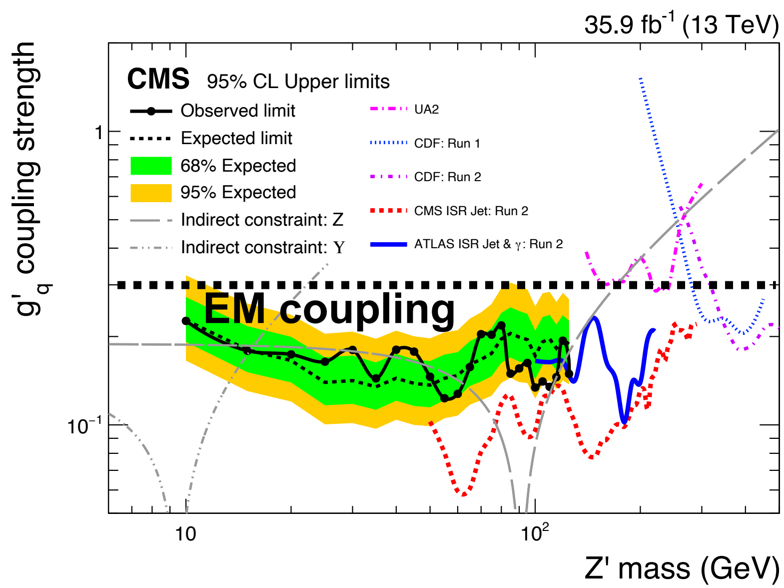


$\alpha \approx 2/\gamma$

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



CMS, PRL 123 (2019) 231803



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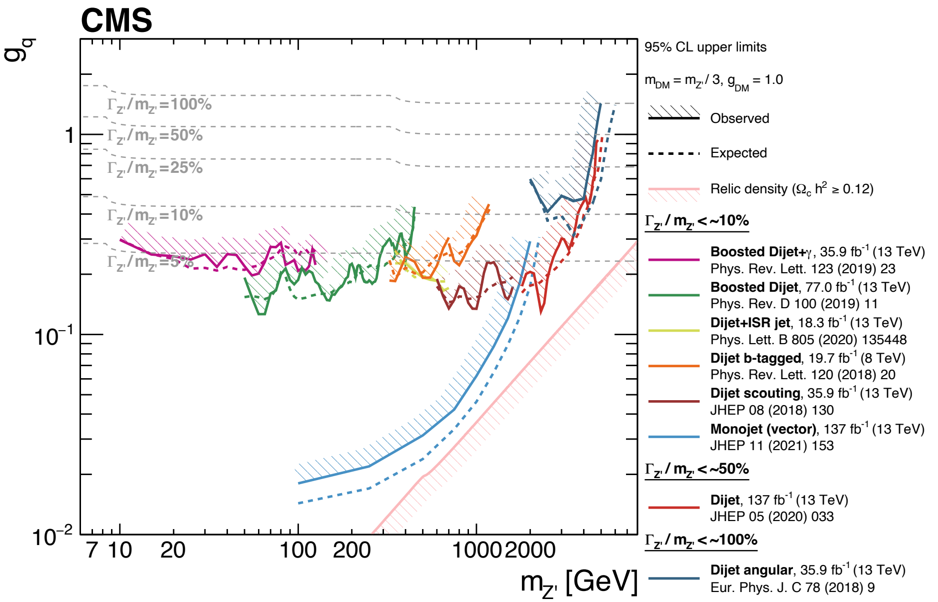
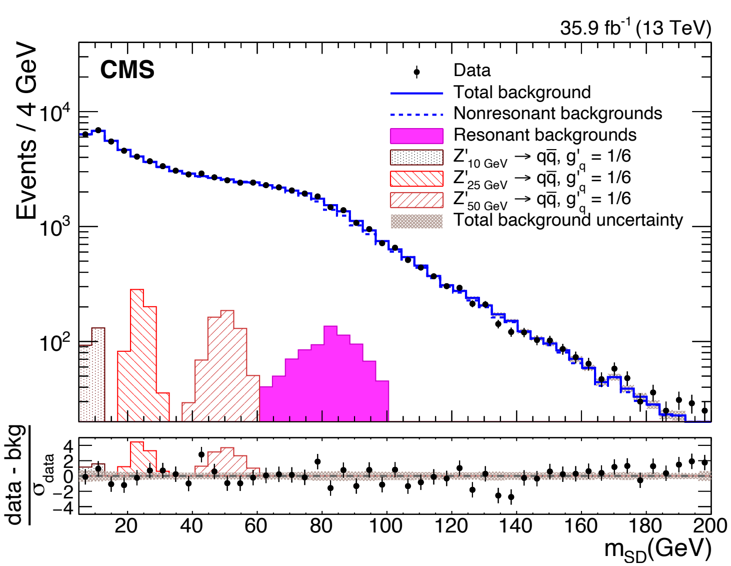
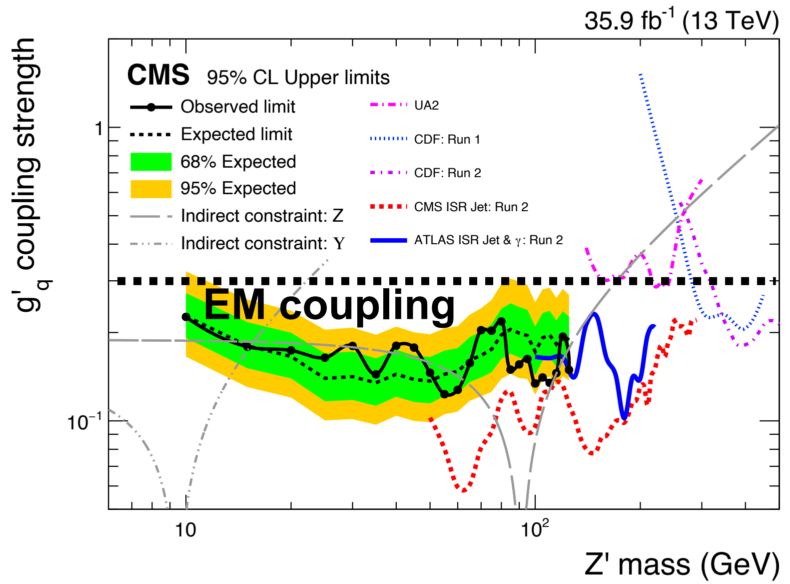
CMS, arXiv:2405.13778



CMS, PRL 123 (2019) 231803

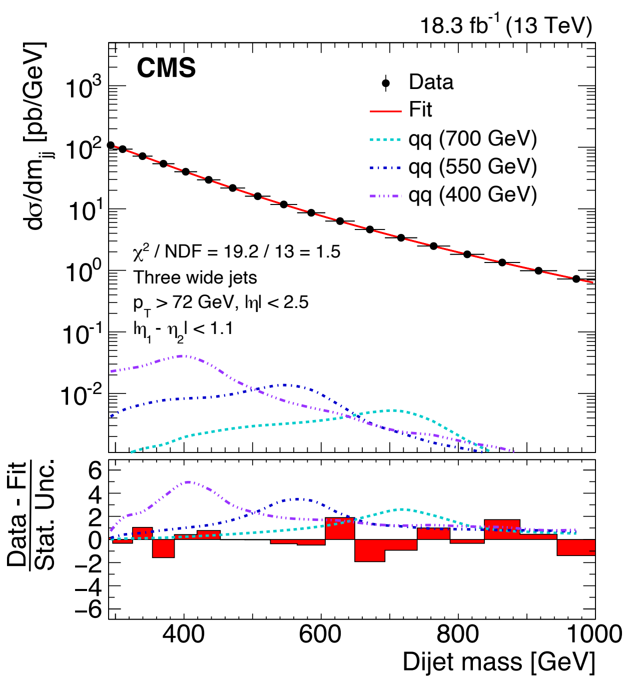


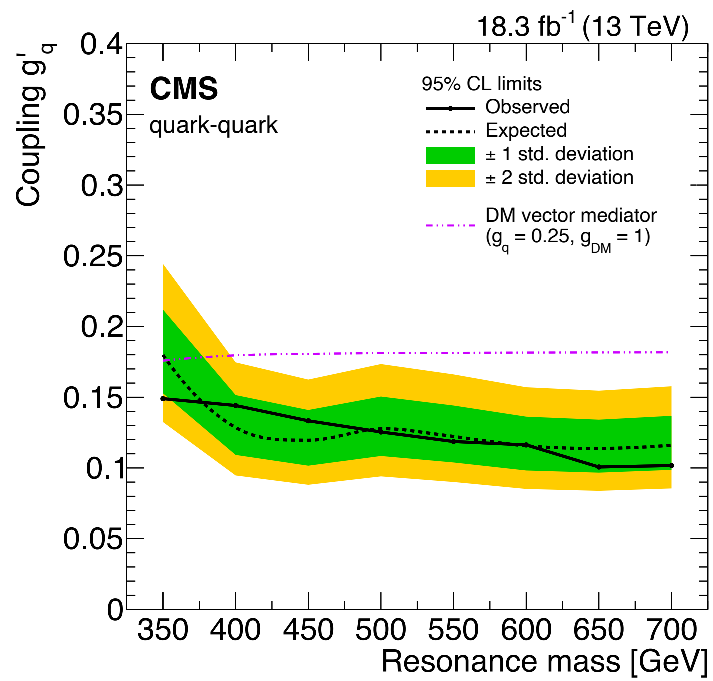


Toward Low Masses: ISR+Scouting

- 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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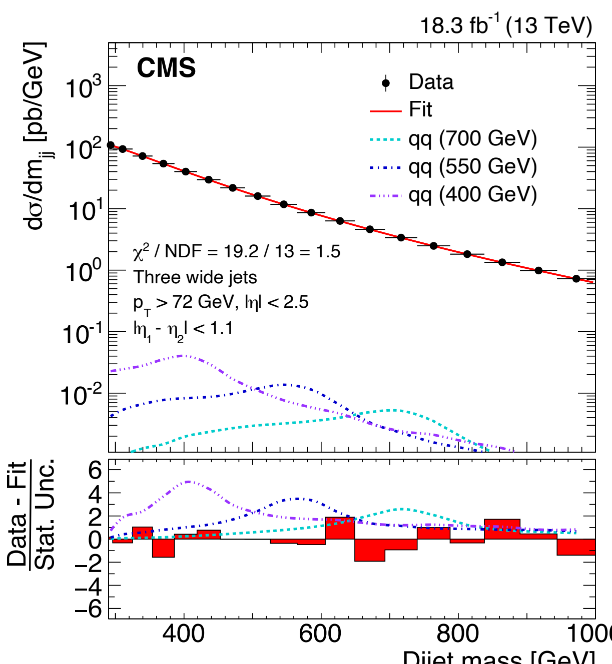
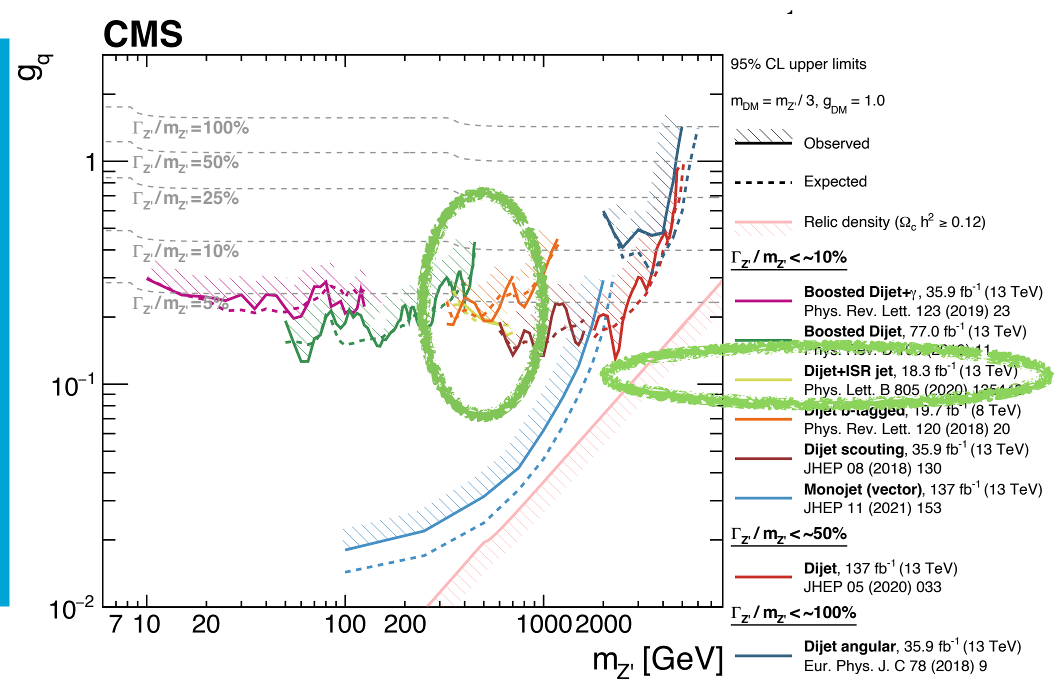
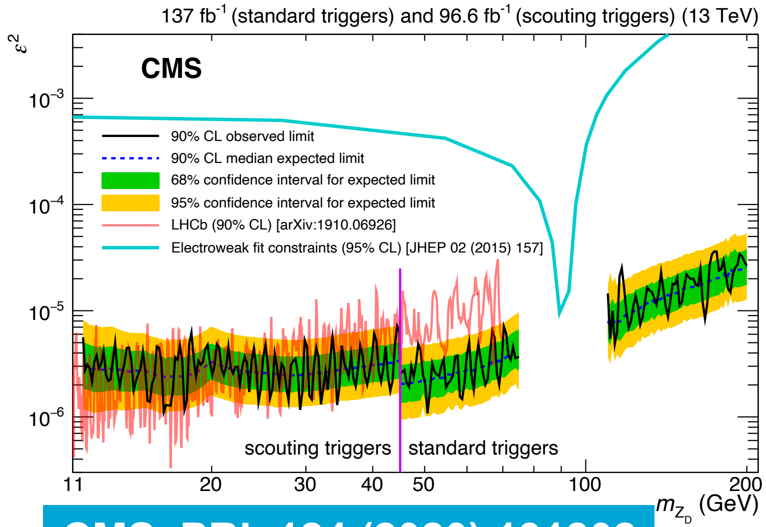


CMS, arXiv:2405.13778

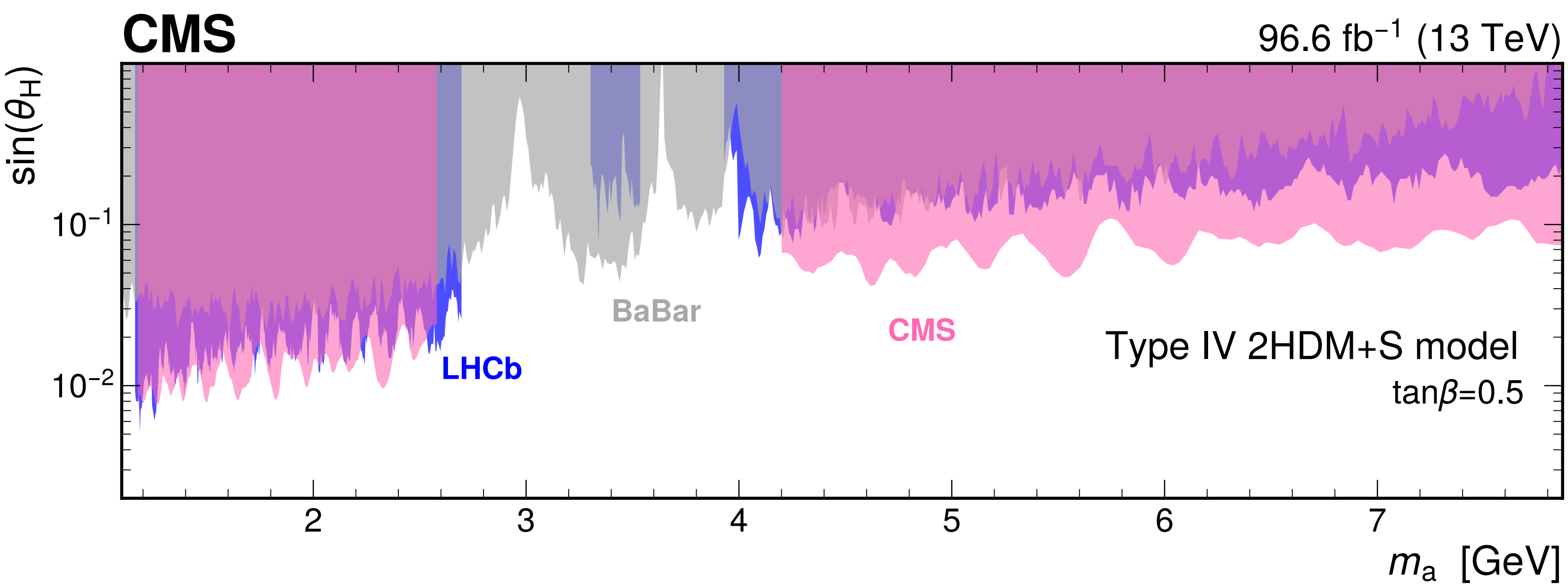


Low-Mass Dimuon Resonances

- 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

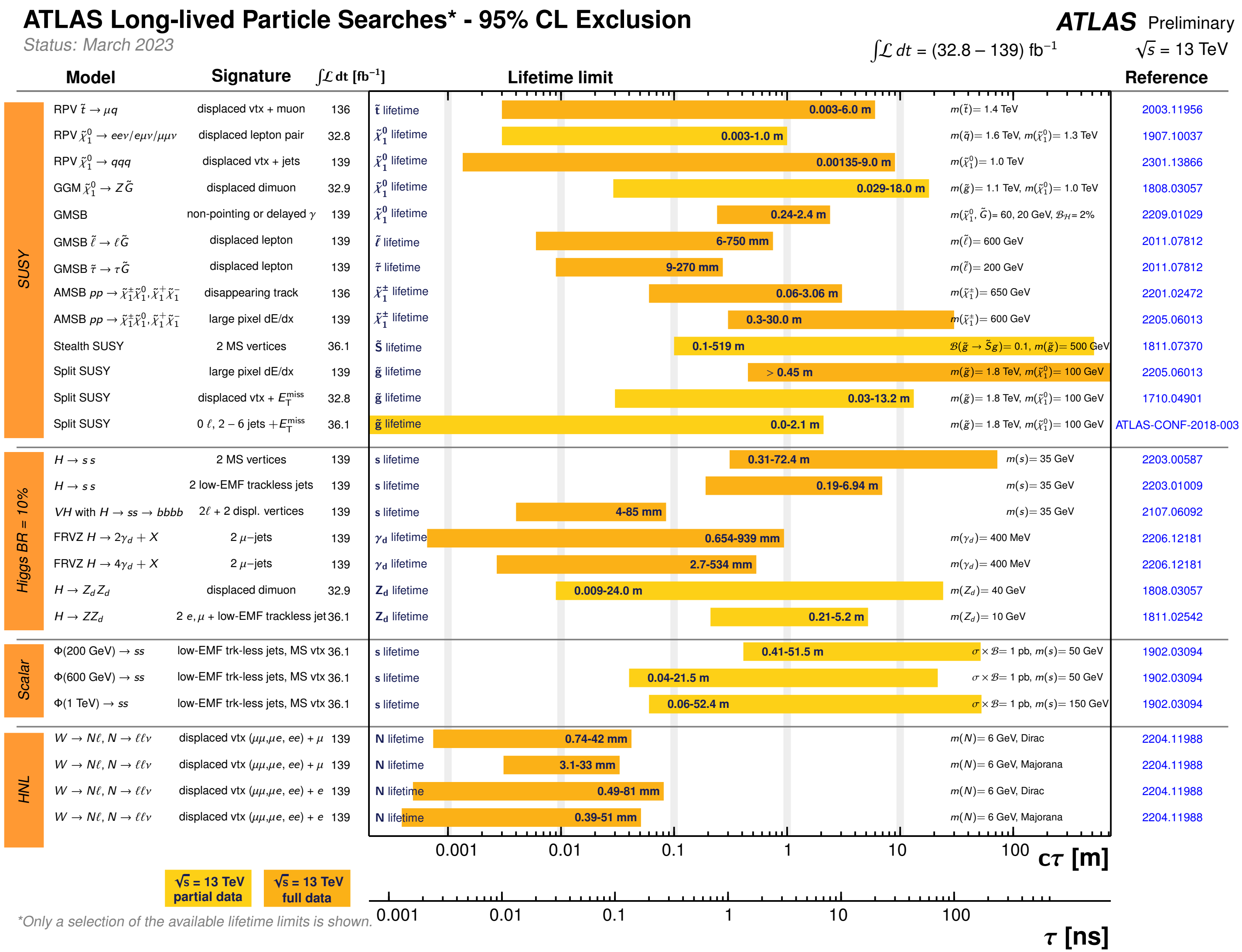


CMS JHEP 12 (2023) 070

BROWN

Toward Long Lifetimes

✦ Plethora of models and experimental results



SUSY (RPV and RPC)

H(125) → XY

H → SS

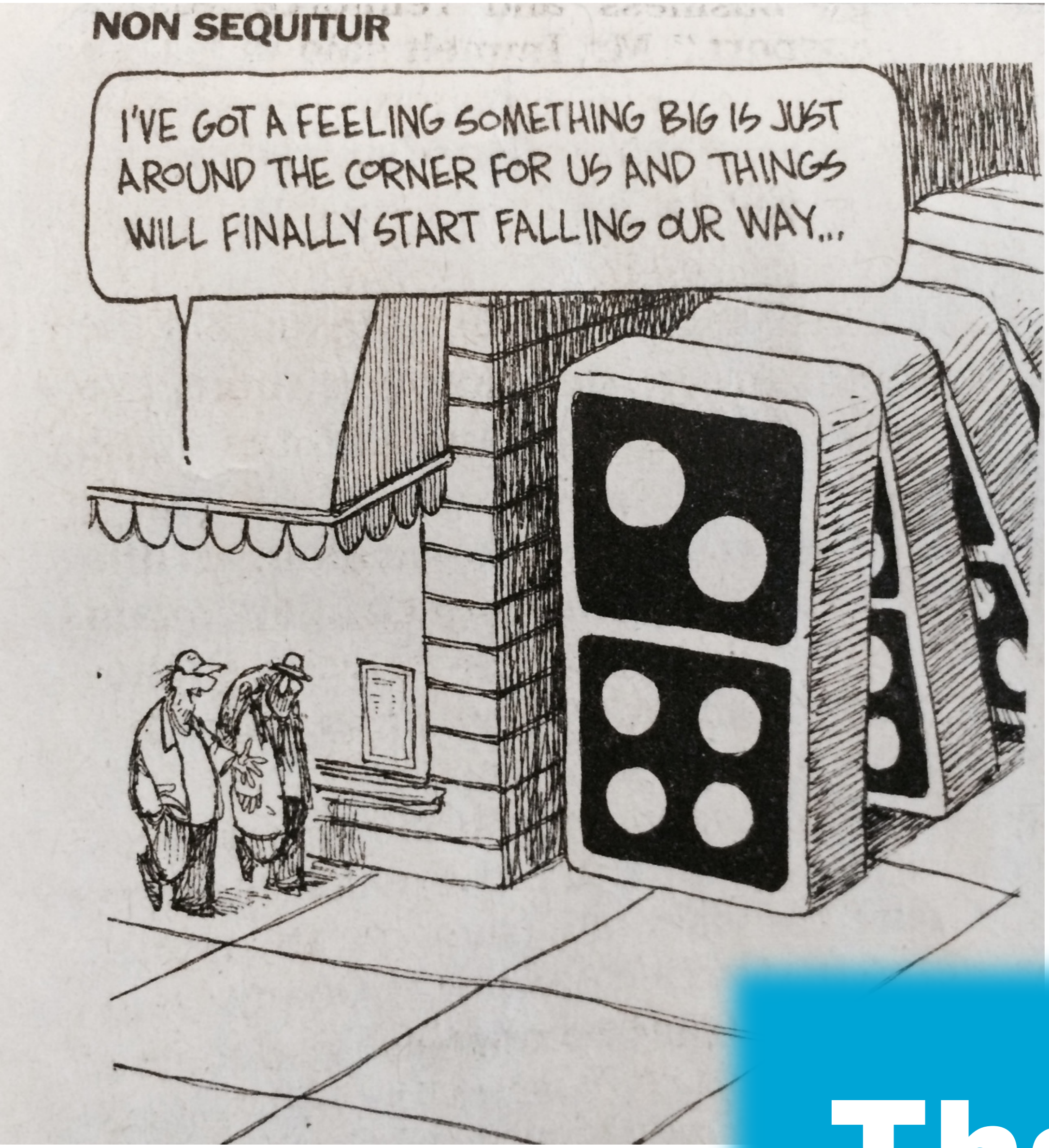
HNL

Cf. an excellent talk by Claudia Seltz

Dark Matter Searches

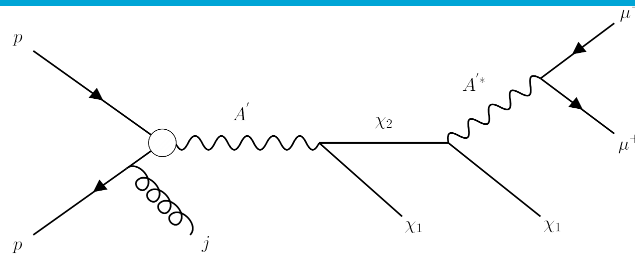
Conclusions: Quo Vadis?

- 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 new results from Run 3 data to come soon!

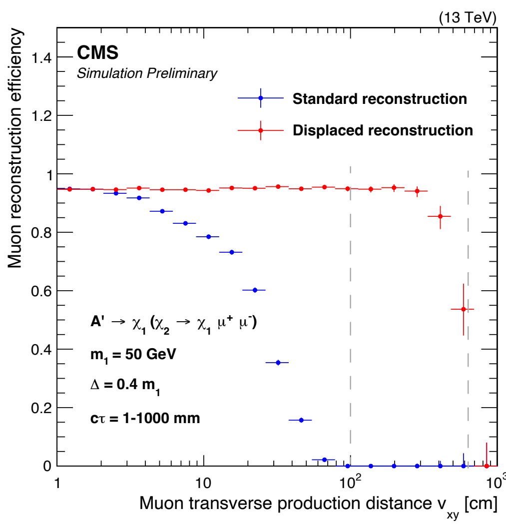

NON SEQUITUR
I'VE GOT A FEELING SOMETHING BIG IS JUST AROUND THE CORNER FOR US AND THINGS WILL FINALLY START FALLING OUR WAY...

Thank You!

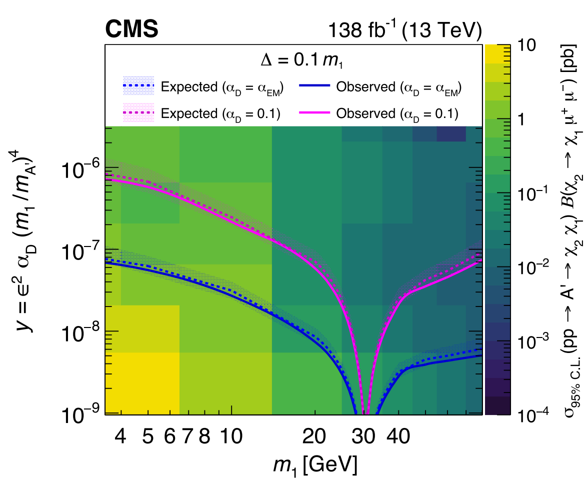
Search for Inelastic DM

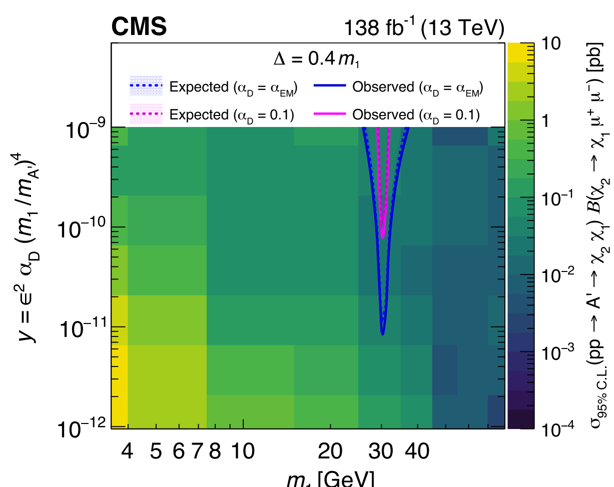


- Originally models of inelastic DM (IDM) were proposed to explain the DAMA anomaly; nevertheless they are generally viable models involving dark sectors - first IDM search at the LHC
- Probe a model w/ 2 nearly mass-degenerate DM states, χ_1 and χ_2 ($m_2 - m_1 = \Delta = (0.1\text{-}0.4)m_1$), as well 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





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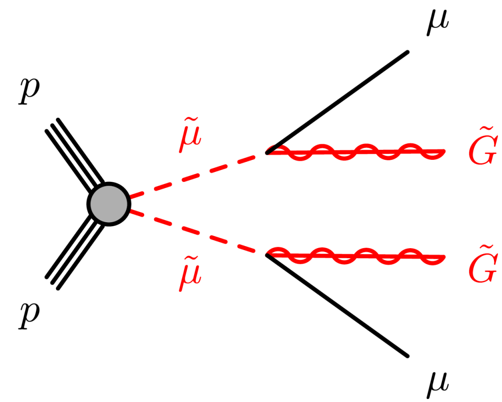
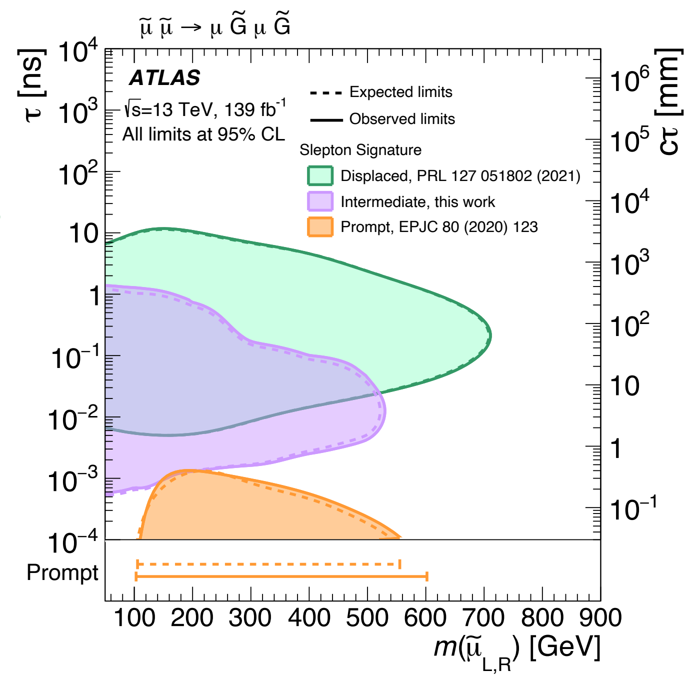
Search for Displaced Dimuons

- In many models (e.g., GMSB SUSY), leptons could be non-prompt, but characterized by a relatively small displacement (cτ ~ 0.3-3 mm)
- Dominant background is from b hadron decays and estimated by extrapolating from $0.1 < d_0^{\pm} < 0.3$ mm control regions
- Data agree well w/ expectations in 3 signal regions corresponding to different dimuon threshold masses
- The new result bridges the prompt searches ($d_0 < 0.3$ mm) and the dimuon LLP analysis (0.3 cm $< d_0 < 300$ cm)



ATLAS PLB 846 (2023) 138172



Set of Regions	Expected N_H^{bkg}	Observed N_H^{data}	Threshold $m_{\mu^+\mu^-}$	Additional cut
1	2.1 ± 0.8	1	200 GeV	-
2	12.5 ± 5.2	7	140 GeV	-
3	17.2 ± 7.4	14	125 GeV	$\Delta R_{\mu^+\mu^-} > 3$ rad.