LHC highlights and prospects

Jelena Jovićević, *IPB - Serbia*, on behalf of the **ATLAS**, **CMS** and **ALiCE** collaboration

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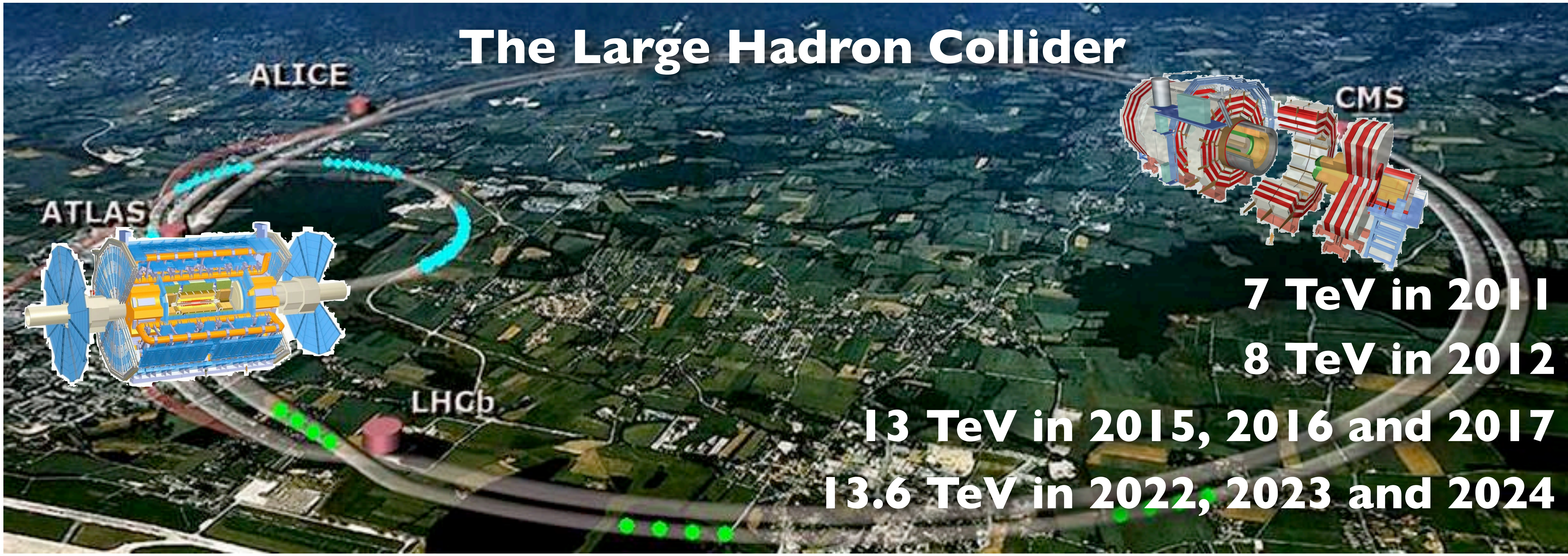
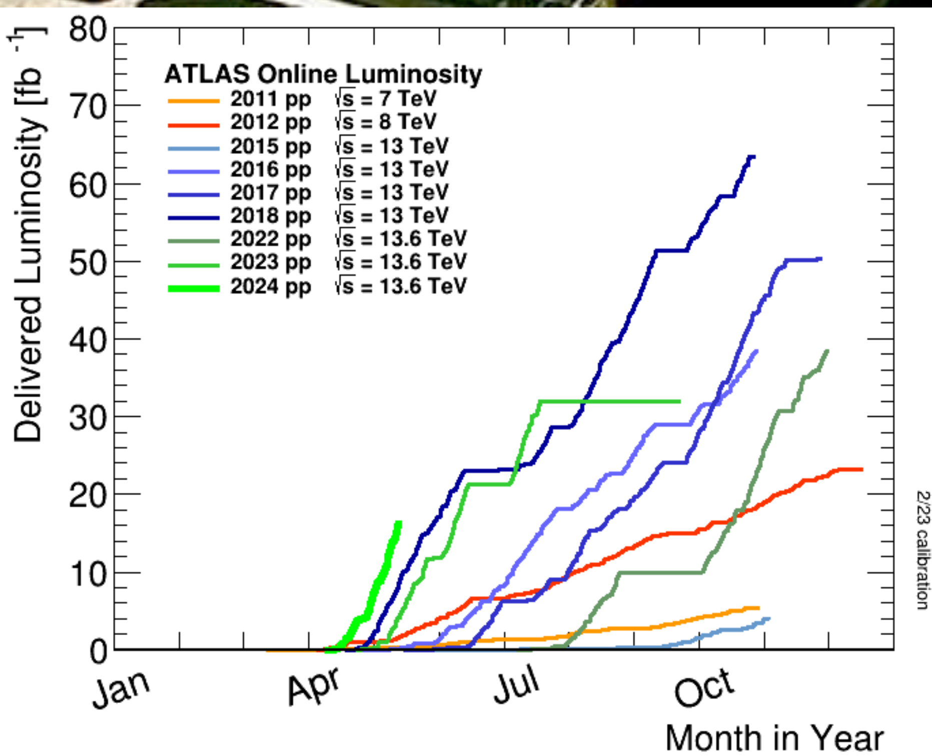
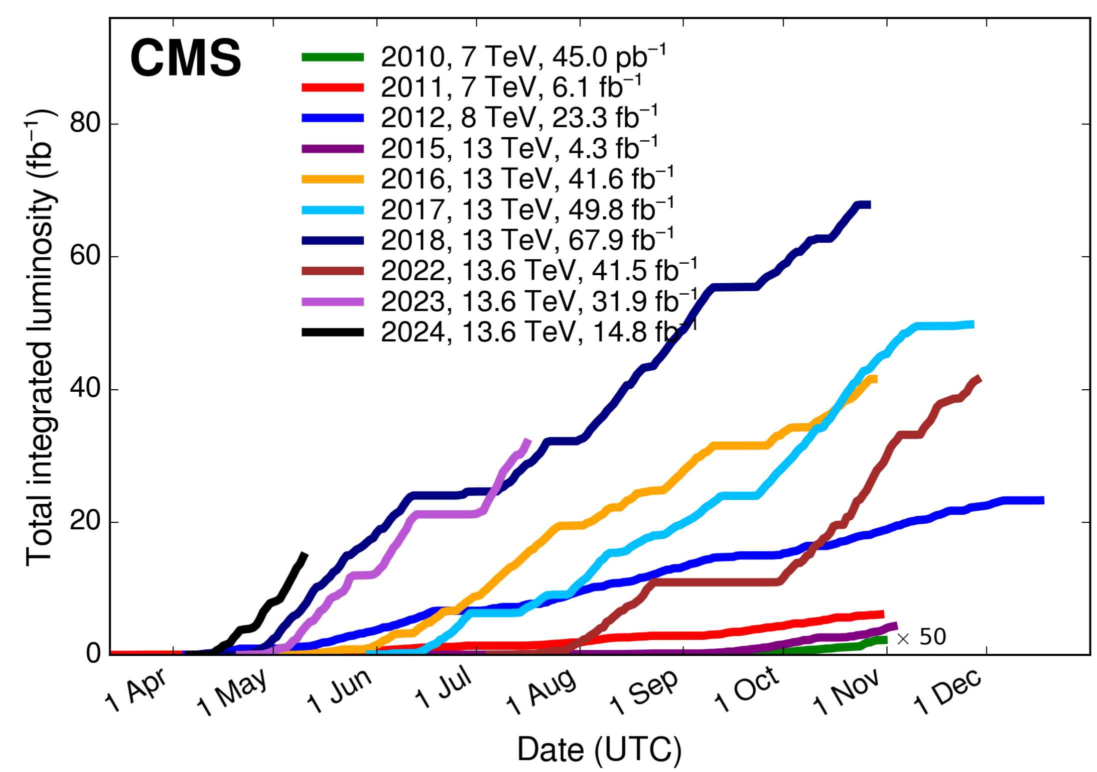
Content

- The summary and highlights of the recent and most interesting measurements are shown in following categories:
  - Higgs boson physics;
  - Top quark physics;
  - Precise SM measurements;
  - BSM searches;
  - Heavy Ion physics.
- Prospects for the HL-LHC physics reach;

LHC operation & data recorded







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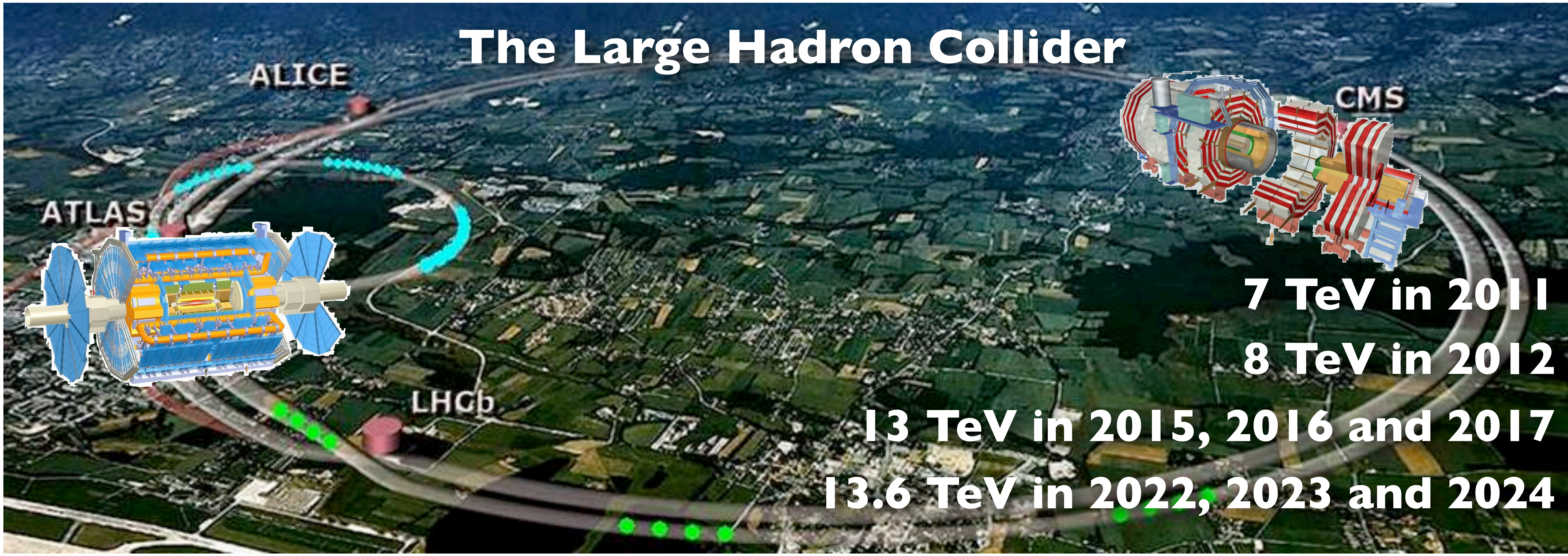

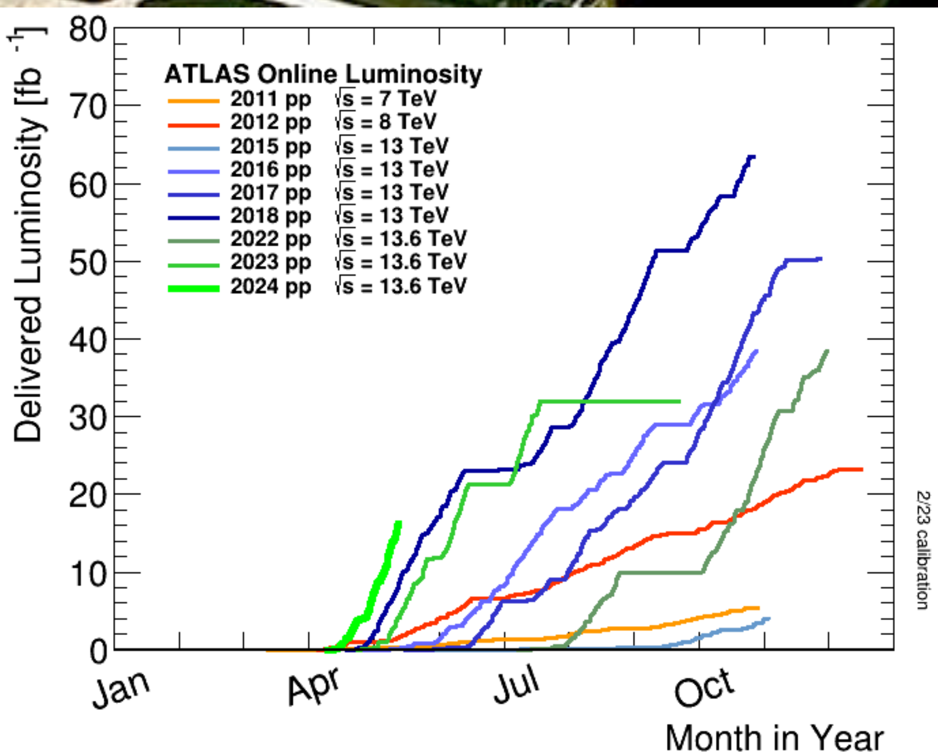

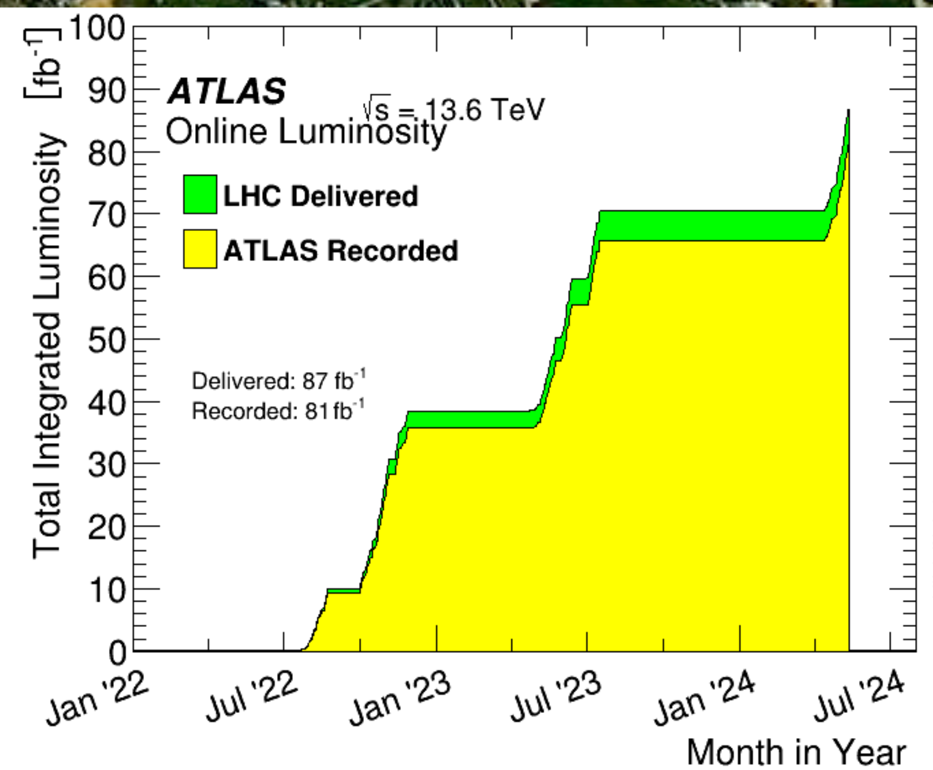

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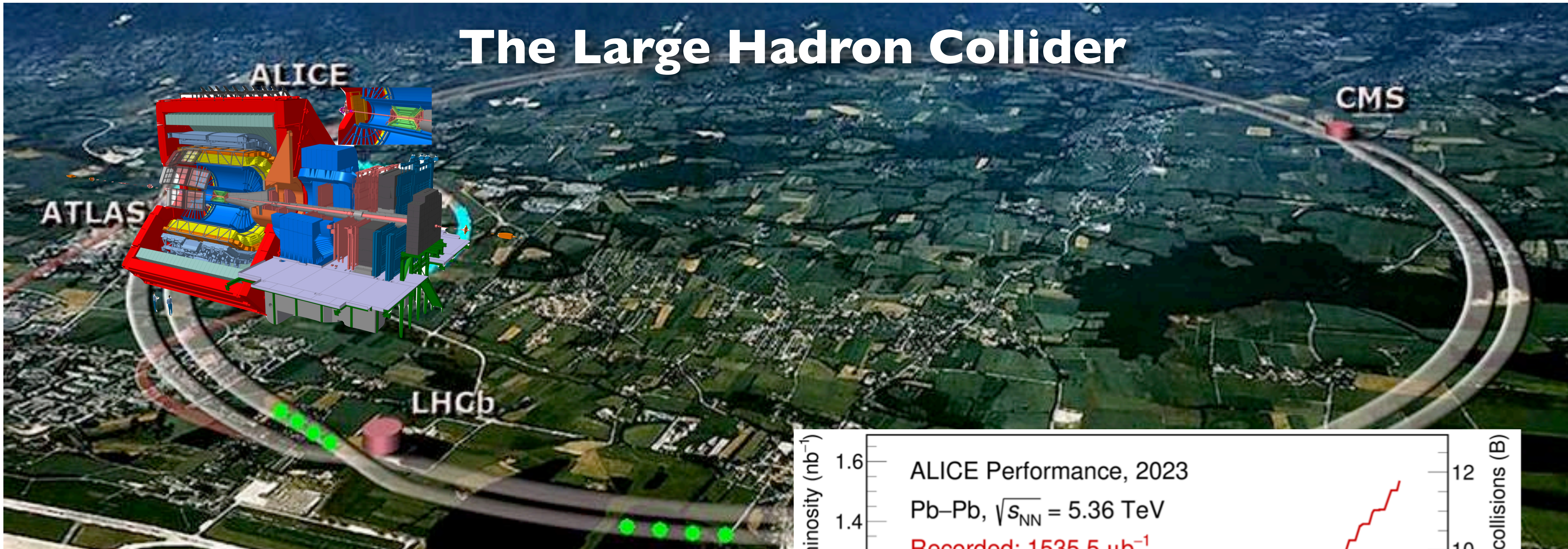
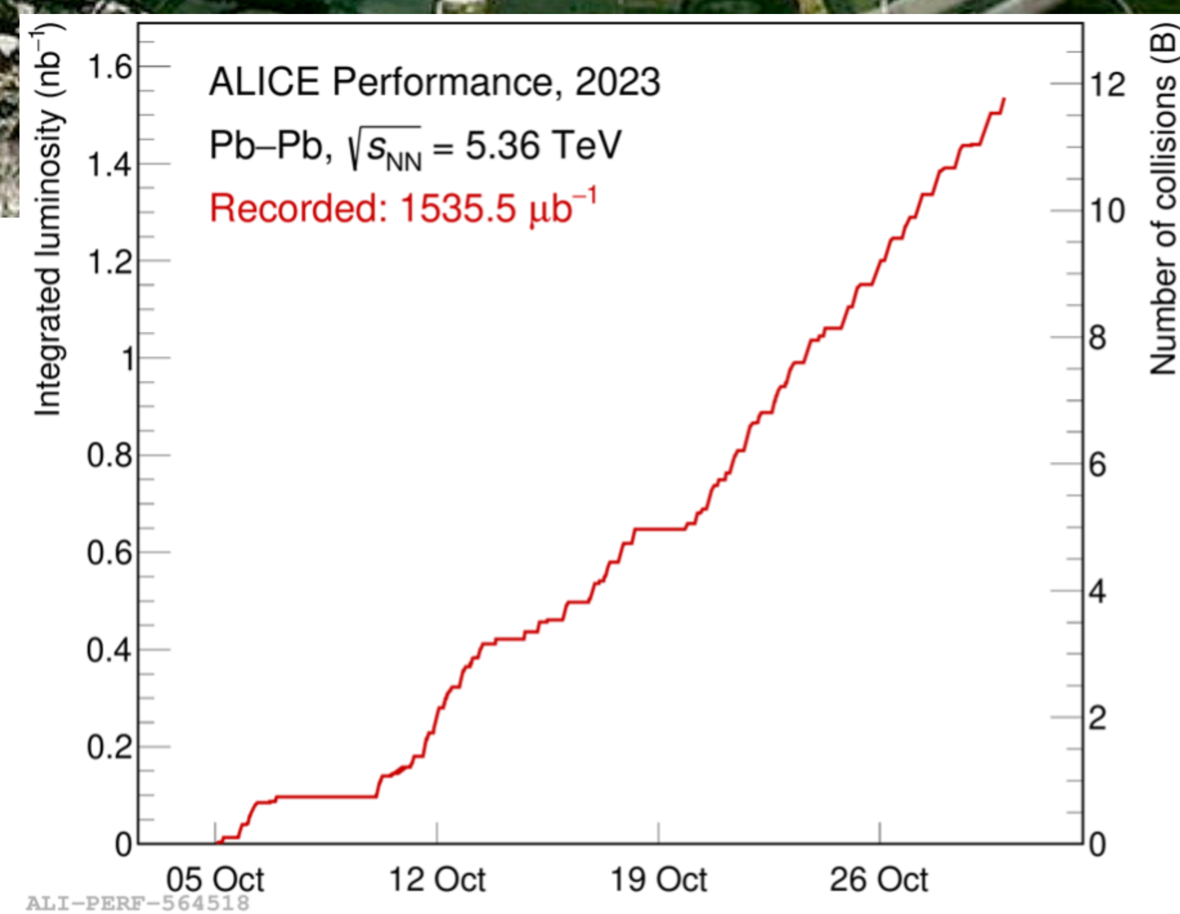


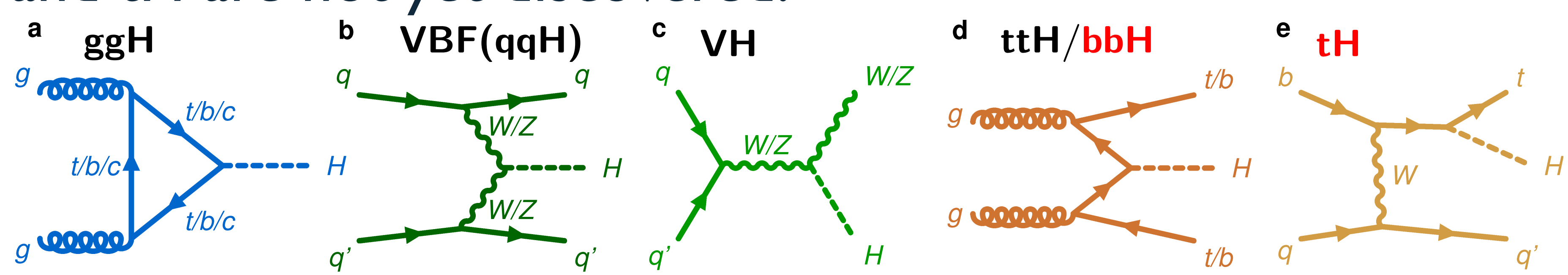


- 40 times more collisions recorded than previously (2010-2018);

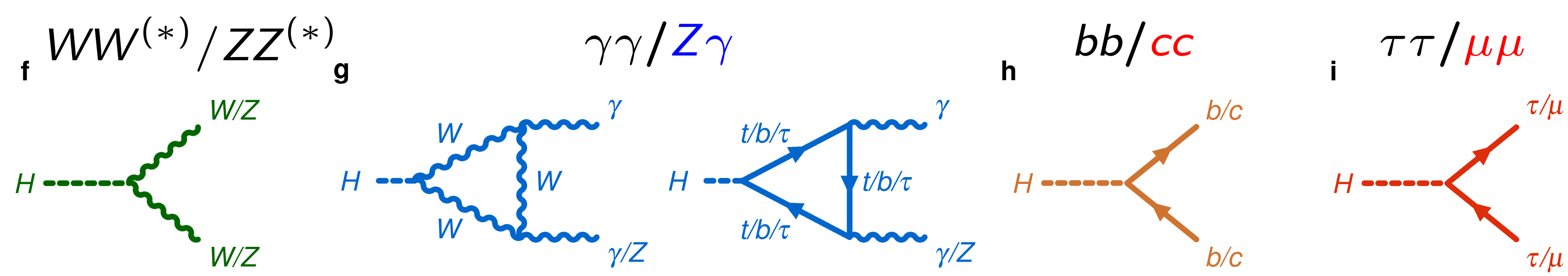
Higgs boson measurements

Higgs boson measurements

- Over a decade after the discovery of the Higgs boson, ATLAS and CMS have been performing extensive set of measurements to characterise its nature;
    - Indirect probe of the BSM physics;
- We explore all accessible Higgs boson production and decay modes;
    - bbH and tH are not yet discovered.



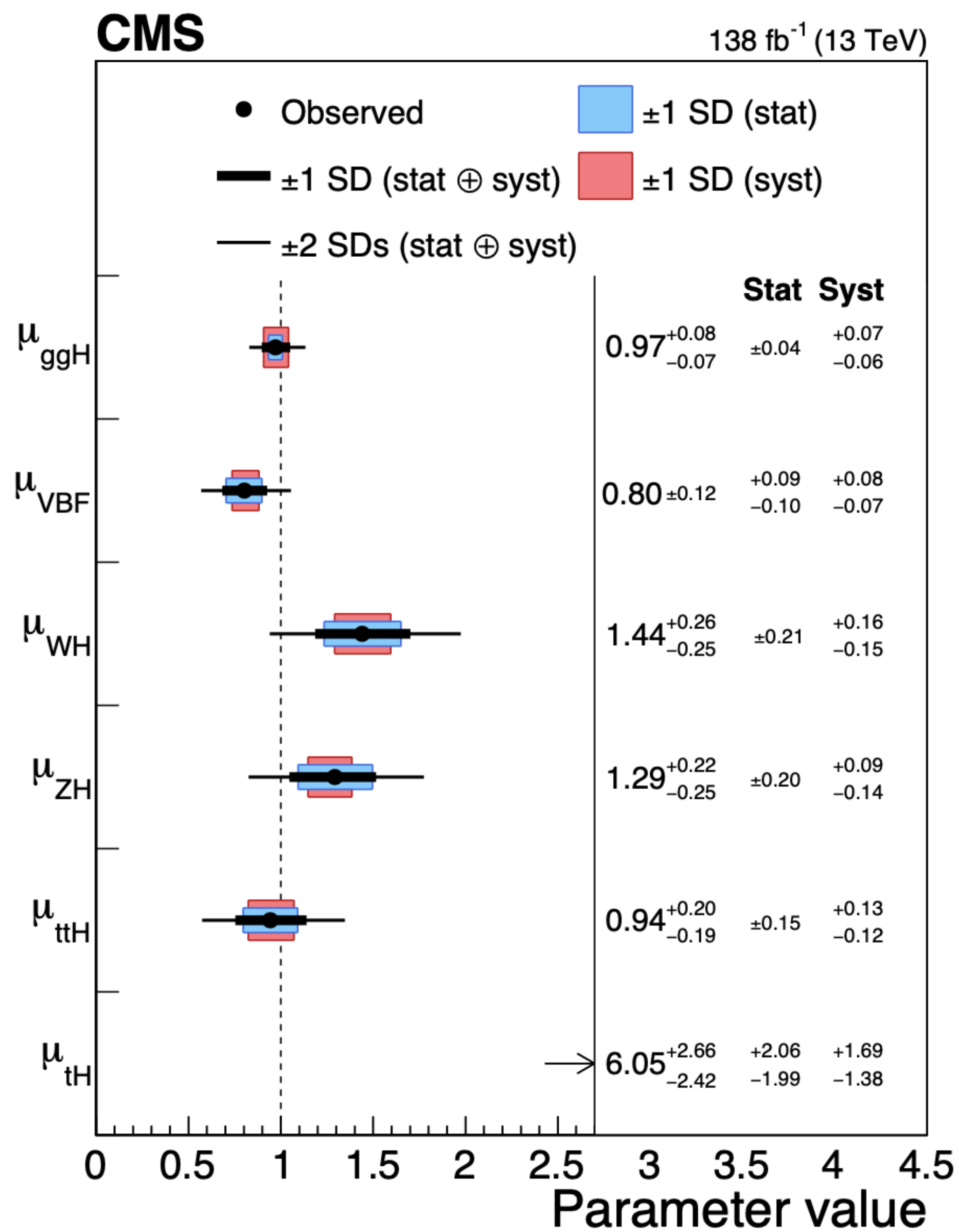
- cc and μμ are still under searching.

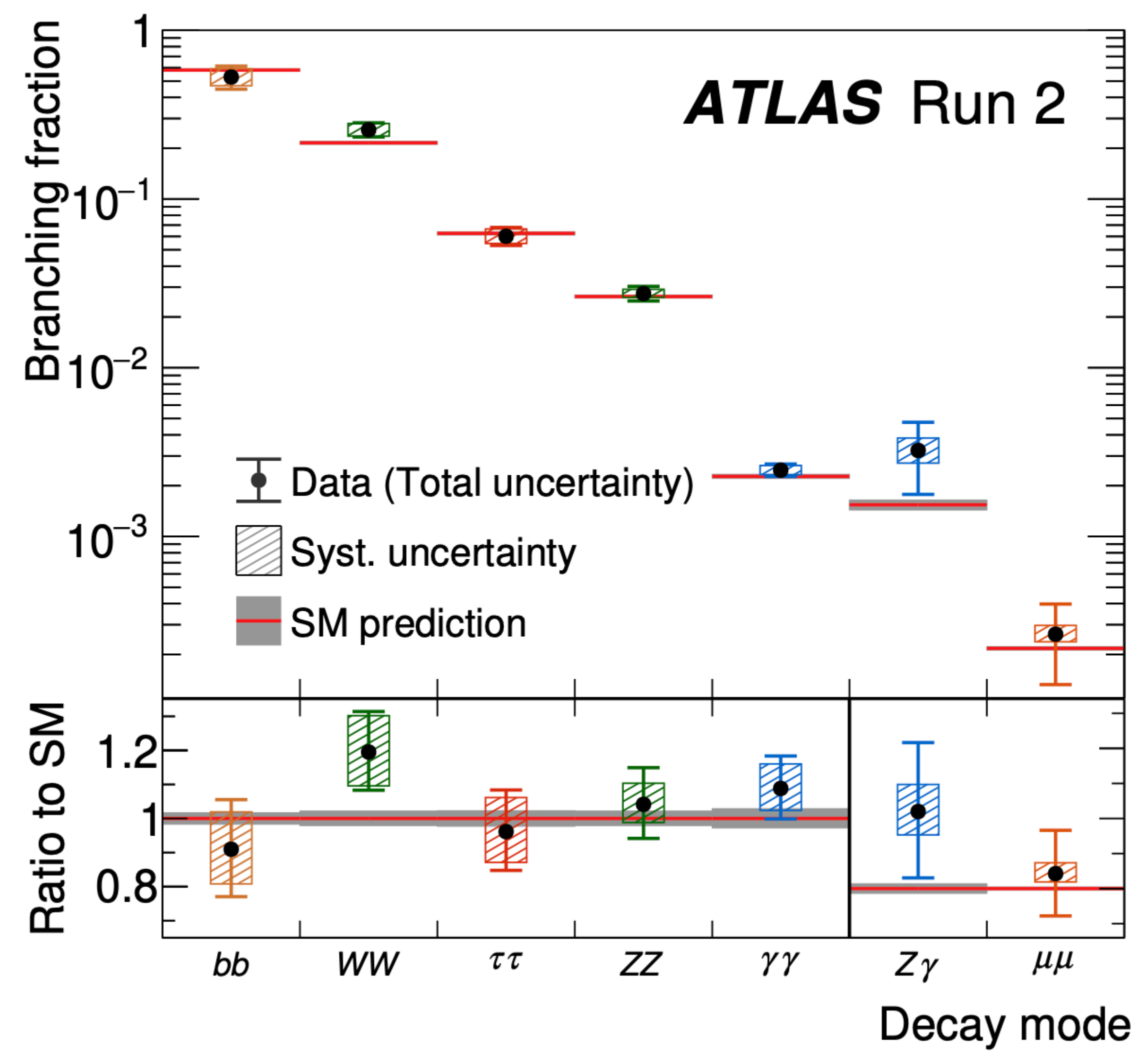


- Nature papers from ATLAS (Nature 607, 52 (2022)) and CMS (Nature 607 (2022) 60-68) give an overview of the Higgs boson ten years after discovery.. ATLAS Higgs Run 2 report contains updated summary.

Higgs boson production and decays

- Combination of measurements in all production and decay modes @13 TeV:
  - Consider signal strengths per-production and per-decay mode.

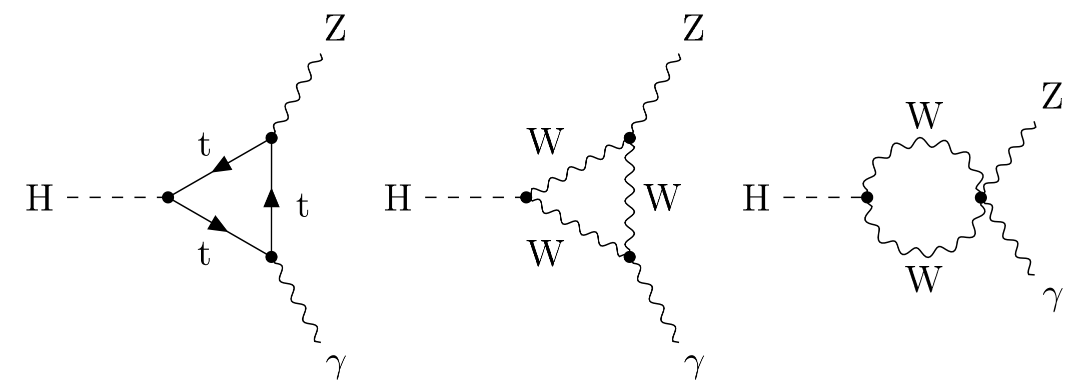




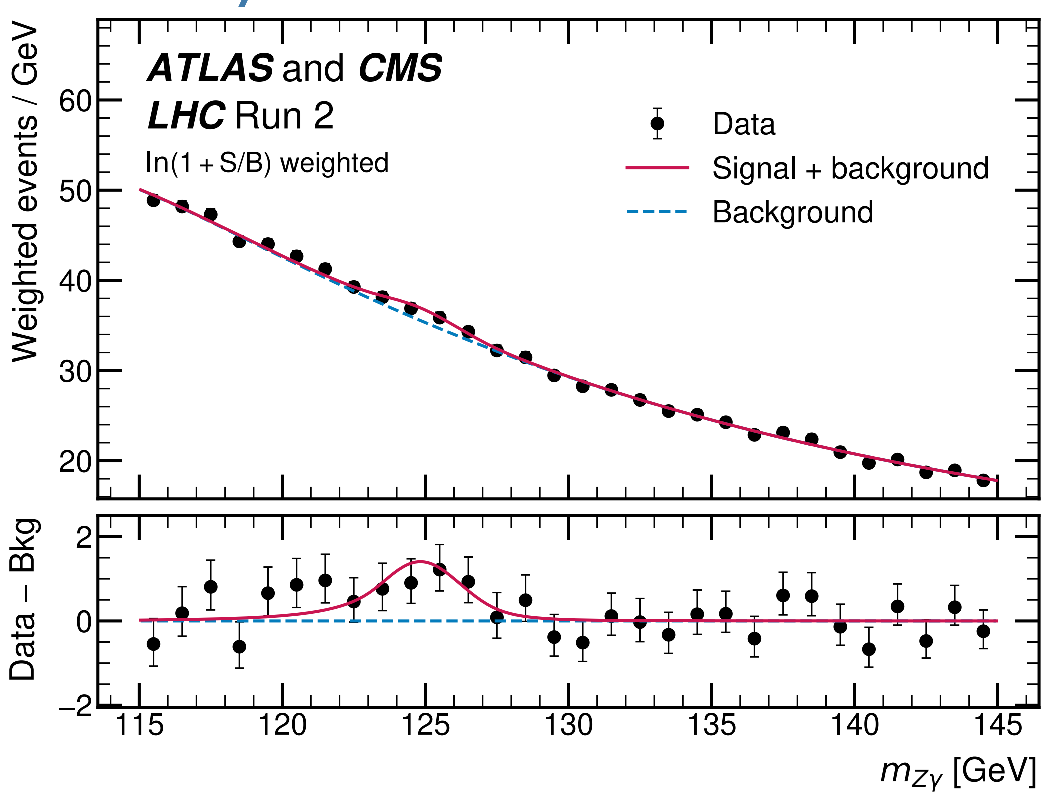
Compatible with SM expectation within the uncertainties

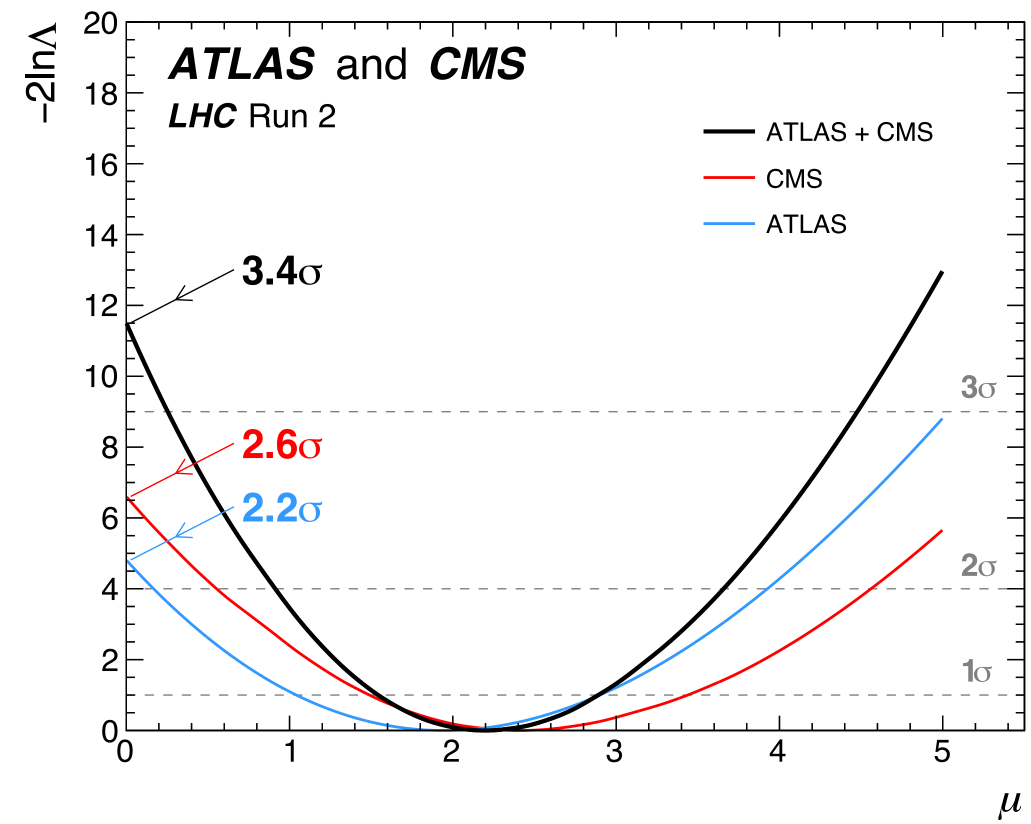
H → Zγ evidence

- The first evidence with a statistical significance of **3.4σ** is presented by the combination of ATLAS and CMS results.



[Phys. Rev. Lett. 132, 021803]

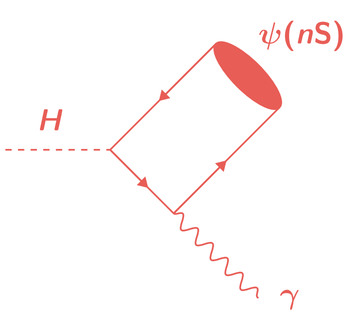


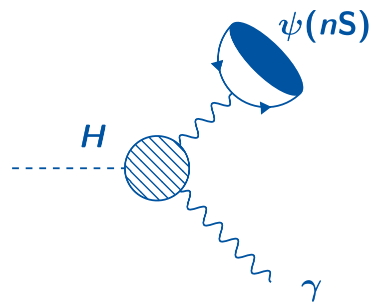


The observed signal strength is **2.2 ± 0.7** within 1.9σ of the deviations from the SM prediction.

Search for very rare decays

H→ψ(nS)γ



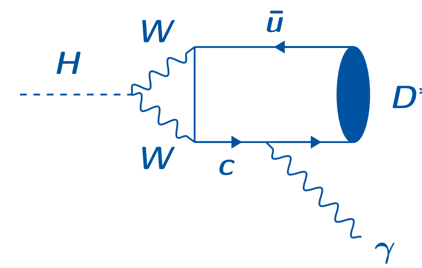


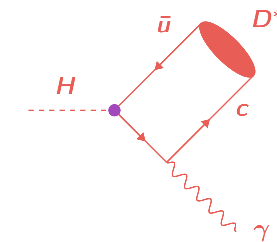
CMS-PAS-SMP-22-012

95% CL upper limit (obs.) on branching fraction	
$H \to J/\psi\,\gamma$	2.6×10^{-4}
$H \to \psi(2S)\,\gamma$	9.9×10^{-4}
$Z \to J/\psi\,\gamma$	0.6×10^{-6}
$Z \to \psi(2S)\,\gamma$	1.3×10^{-6}

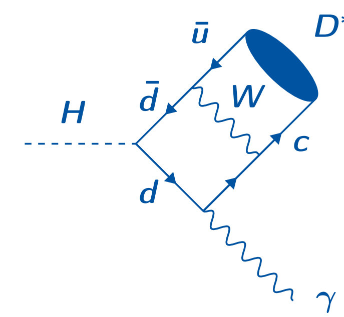
~2x improvement w.r.t. previous result. Hcc interpretation in combination with H→γγ: −157 < κc /κγ < 199 GeV comparable with ATLAS result.

H→D*γ & Z→D0/K0γ





Non SM diagram FCNC Hcu interaction



- Observation at LHC would indicate new physics;

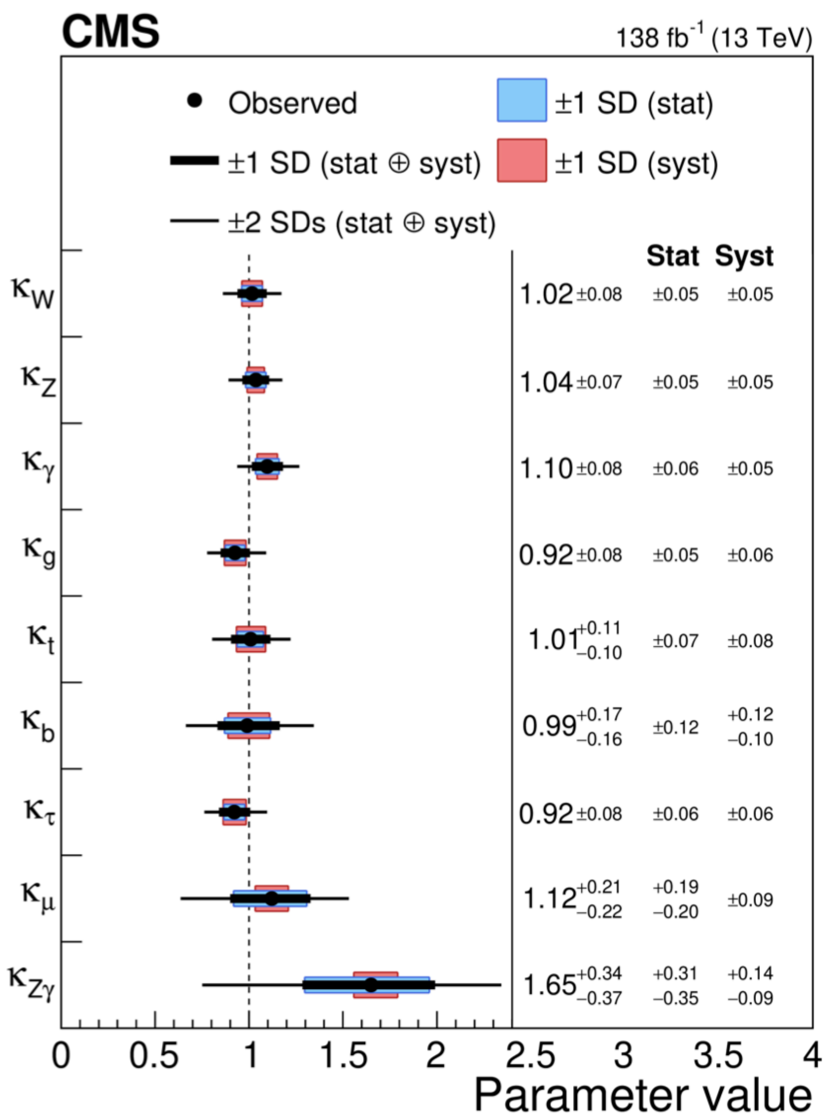
arXiv:2402.18731

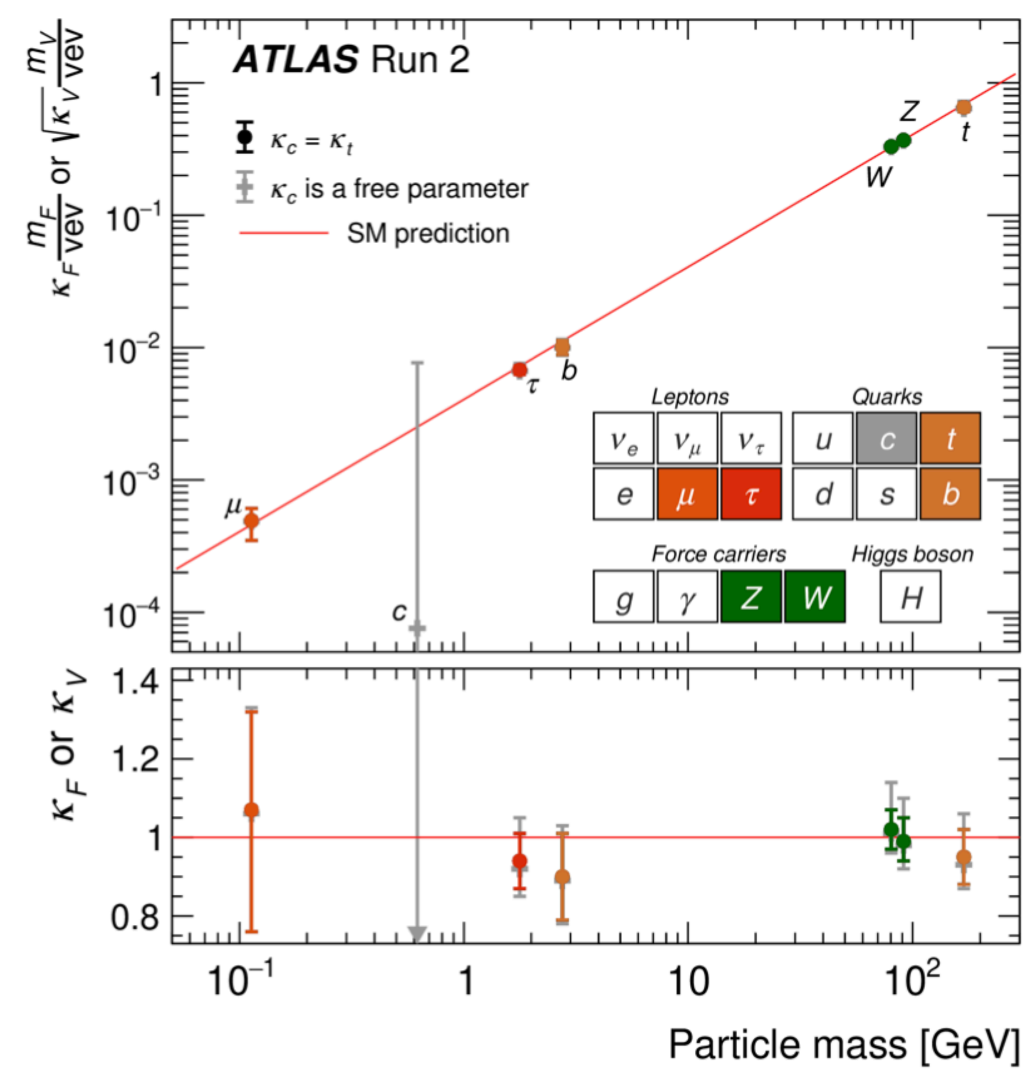
	95% CL upper limits			
	Branching Fraction		$\sigma \times \mathcal{B}$ [fb]	
Channel	Observed	Expected	Observed	Expected
$H \to D^*\gamma$	1.0×10^{-3}	$1.2^{+0.5}_{-0.3} \times 10^{-3}$	58	68^{+28}_{-19}
$Z \to D^0\gamma$	4.0×10^{-6}	$3.4^{+1.4}_{-1.0} \times 10^{-6}$	235	200^{+82}_{-56}
$Z \to K^0_s\gamma$	3.1×10^{-6}	$3.0^{+1.3}_{-0.8} \times 10^{-6}$	185	176^{+77}_{-49}

First limits on $H \to D^*\gamma$ and $Z \to K_S^0\,\gamma$!
~500x on existing $Z \to D^0\,\gamma$ limit from LHCb.

Higgs boson couplings

- Sensitivity estimated using combined coupling "modifiers" @13 TeV:
  - Consider model(s) with the most important physics message: κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z, (+ κ_g, κ_γ)'
  - Present results assuming SM dependance between particle mass and its coupling to Higgs boson

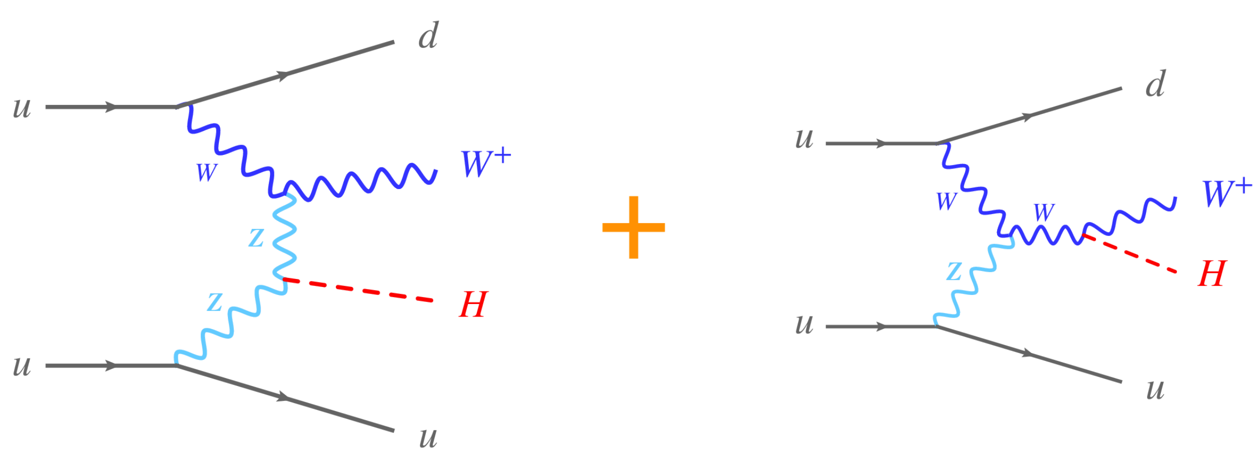




Compatible with SM expectation within the uncertainties

Relative sign of coupling to W and Z

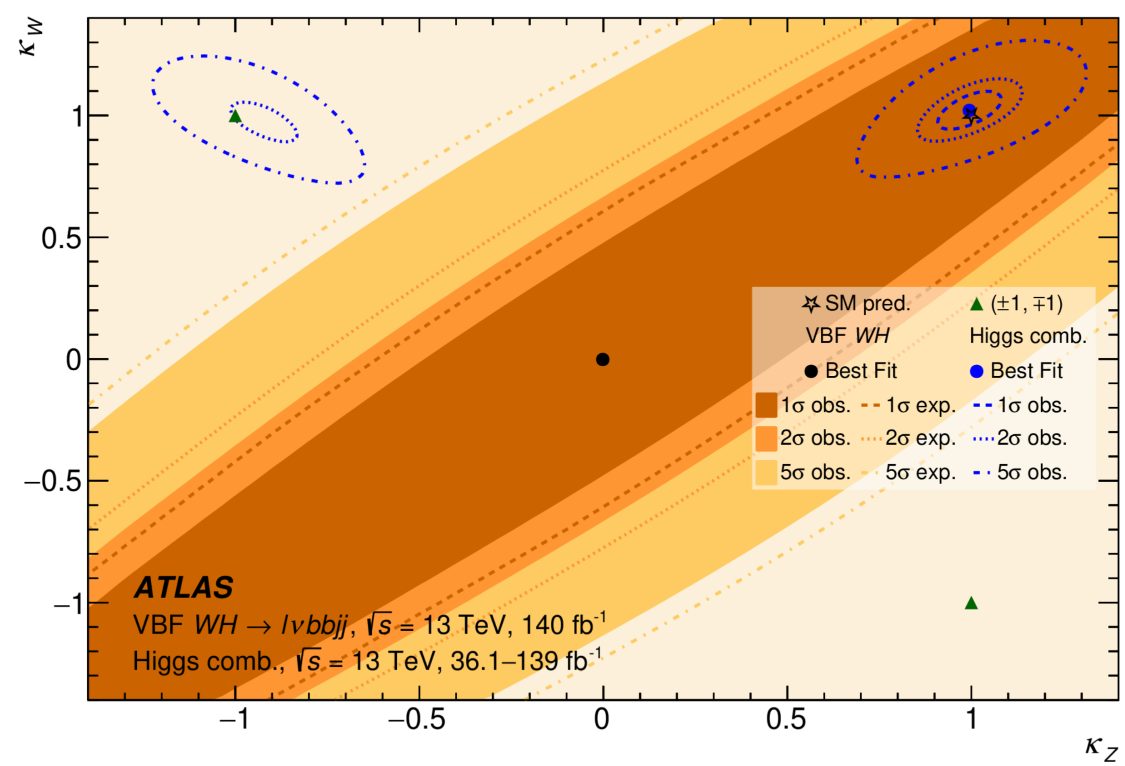
- Previously λ_{WZ} measured consistent with 1 (6% precision) using VBF +VH with $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ assuming κ_W and κ_Z positive;
- New measurement: VBF WH, $W \rightarrow l\nu$, $H \rightarrow bb$;



$\sim \kappa_Z^2$ Interference $\sim \kappa_W \kappa_Z$ $\sim \kappa_W^2$

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z \kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

arXiv:2402.00426



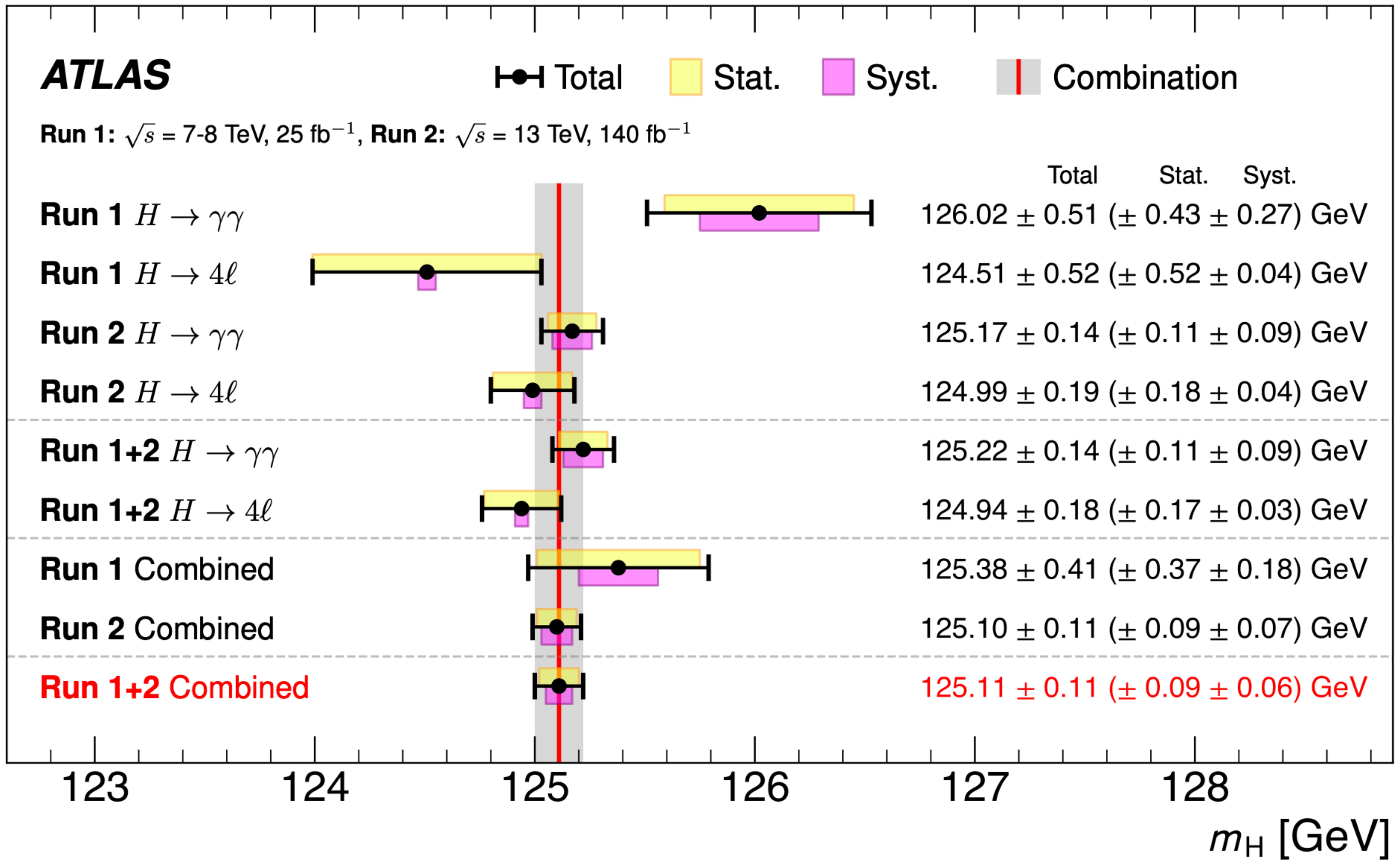
$\lambda_{WZ} < 0$ is excluded with significance much **greater than 5σ**.

$\lambda_{WZ} > 0$: μ = 0.9+2.3(stat.)**+3.3**(syst.)

Dominant unc; stat, tt and W+jets modelling.

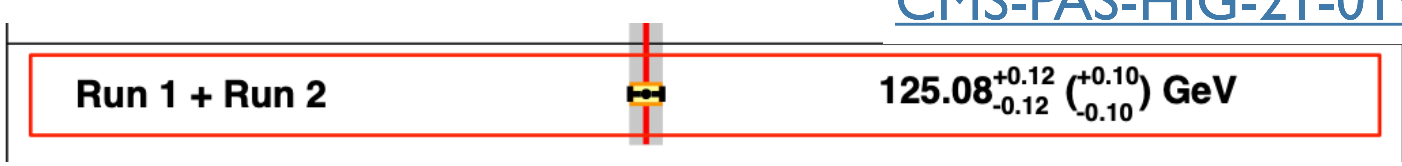
Higgs boson mass and width

Higgs boson mass ATLAS-CONF-2023-037



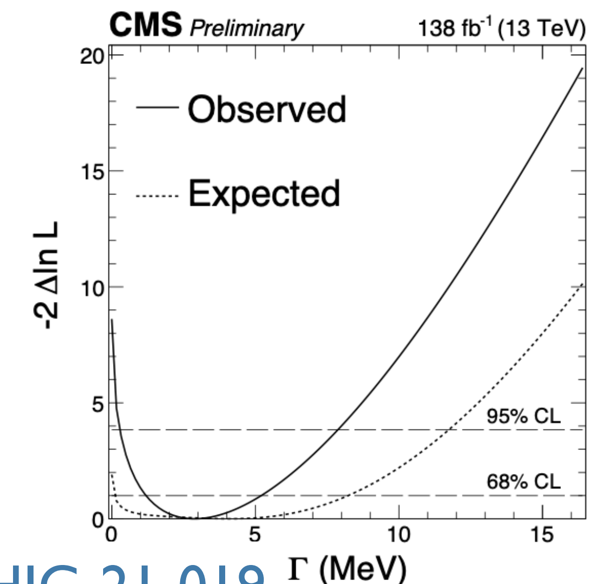
ATLAS combination : Most precise measurement of **m_H (0.09%)** up to date!

CMS-PAS-HIG-21-019



H→ZZ*→4l channel (CMS) : Most precise single-channel measurement !

Higgs boson width



CMS-PAS-HIG-21-019

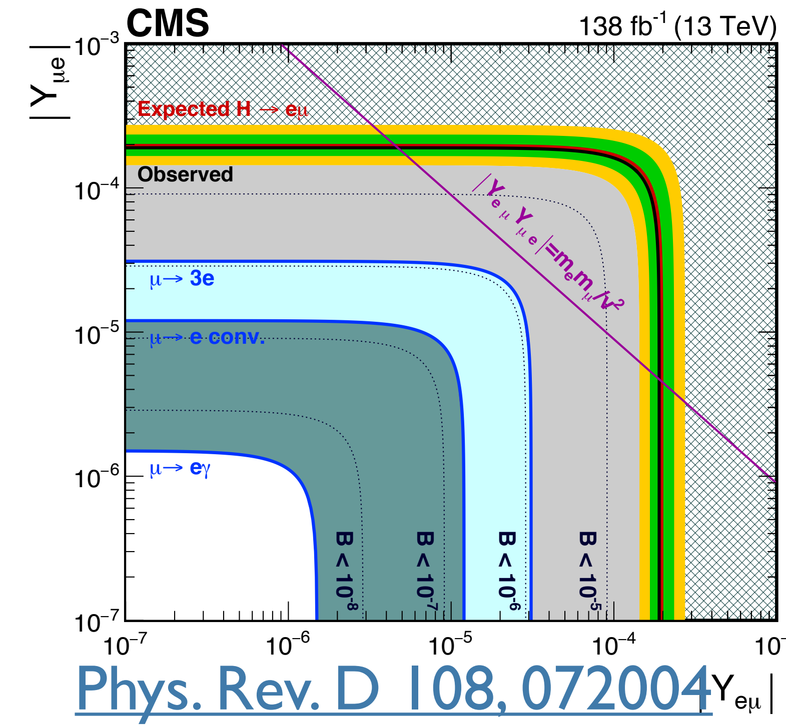
Width Γ(H) extracted assuming identical coupling in on-shell and off-shell productions.

$$\Gamma(H) = (\mu_{off\text{-}shell}/\mu_{on\text{-}shell})\Gamma_{SM}(H)$$

Measurement	Γ(H) [MeV]
ATLAS 4l+llvv (PLB 846 (2023) 138223)	$4.6^{+2.6}_{-2.5}$
CMS 4l+llvv (Nat. Phys. 18 (2022) 1329)	$3.2^{+2.4}_{-1.7}$
Updated CMS 4l (CMS-PAS-HIG-21-019)	$2.9^{+2.3}_{-1.7}$

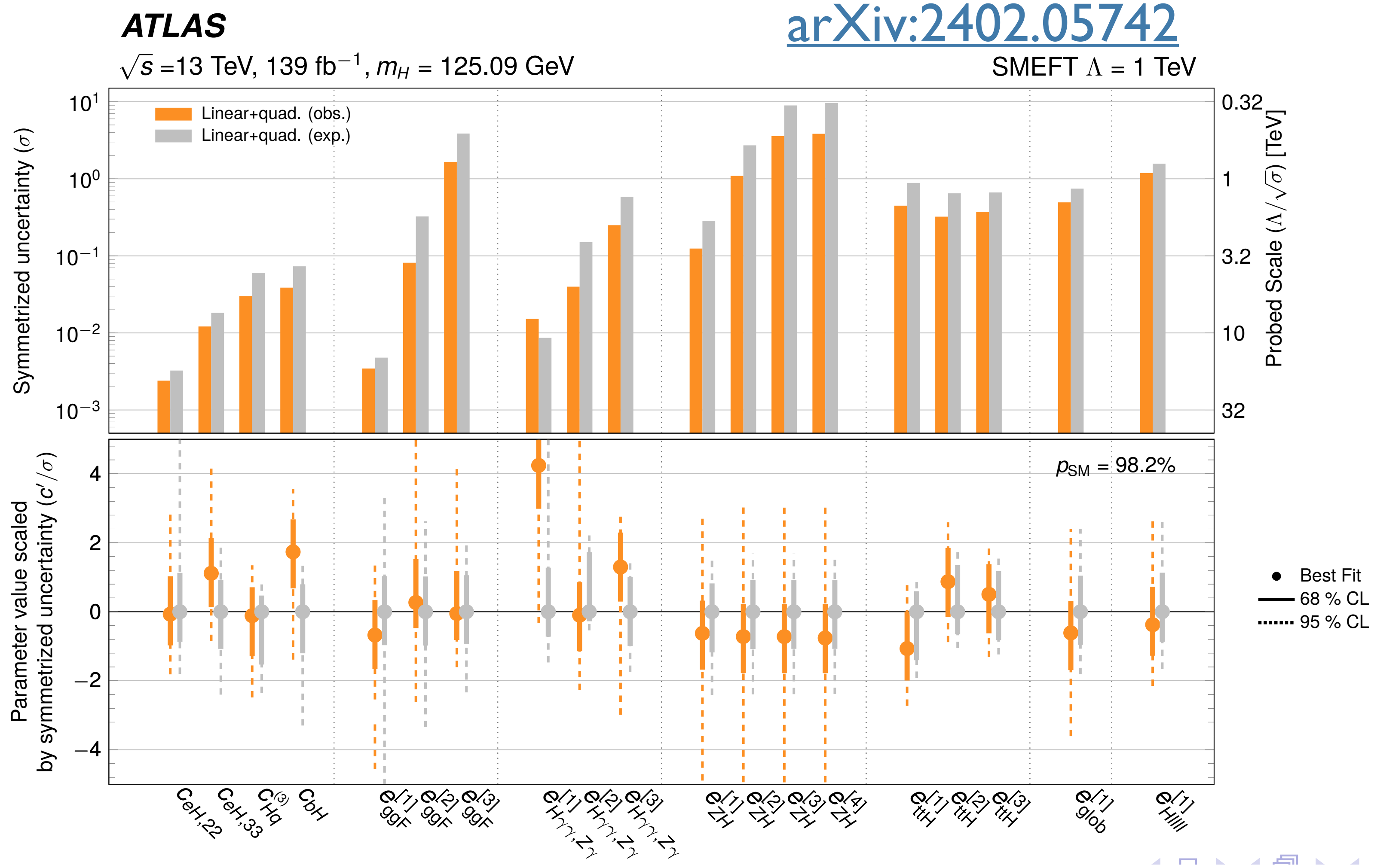
And many more results...

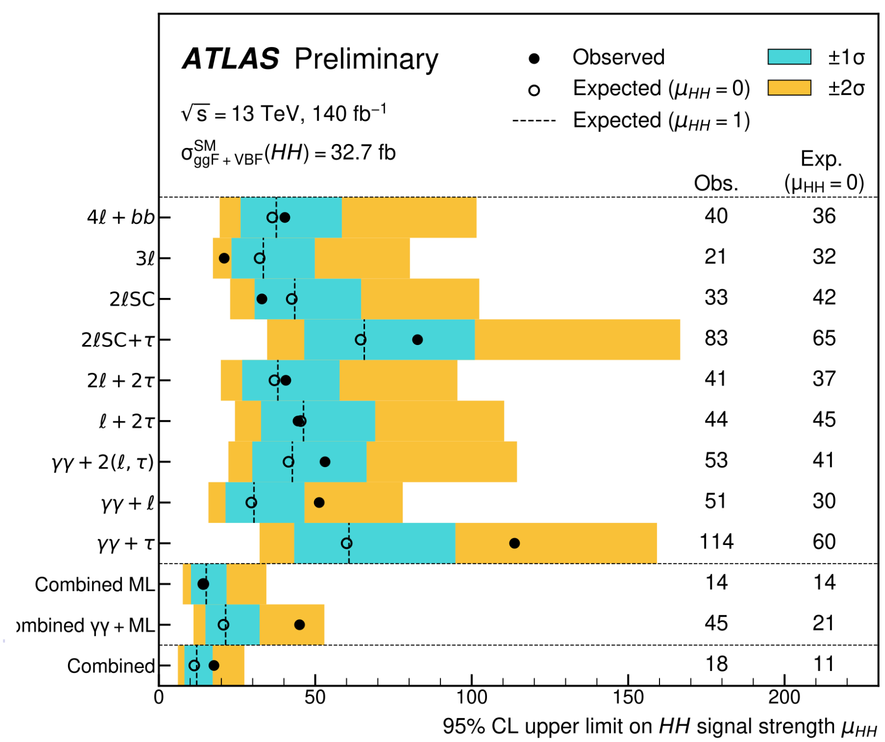
- Differential measurements - no deviation from the SM within uncertainties.
- STXS with EFT interpretation;
- Exotic Higgs decays, LFV;
- Di-Higgs resonant and non-resonant searches;



Phys. Rev. D 108, 072004

arXiv:2402.05742





ATLAS-CONF-2024-005

And many more results…

- Differential measurements - no deviation from the SM within uncertainties.
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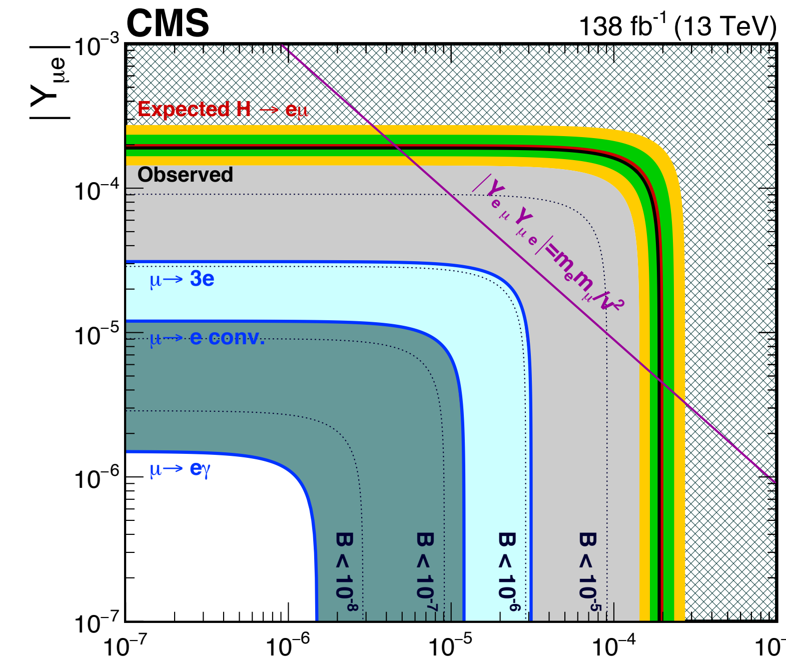
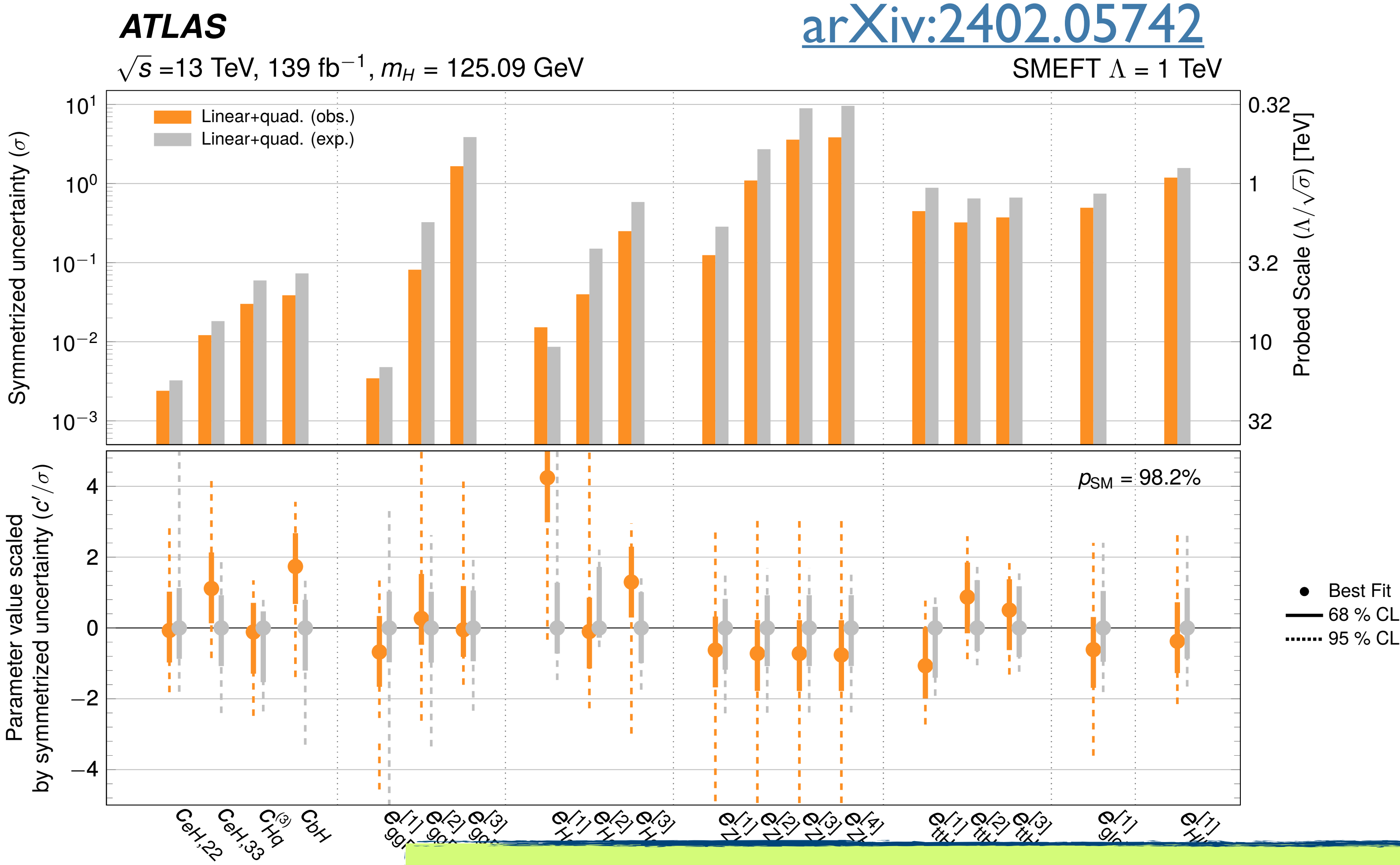
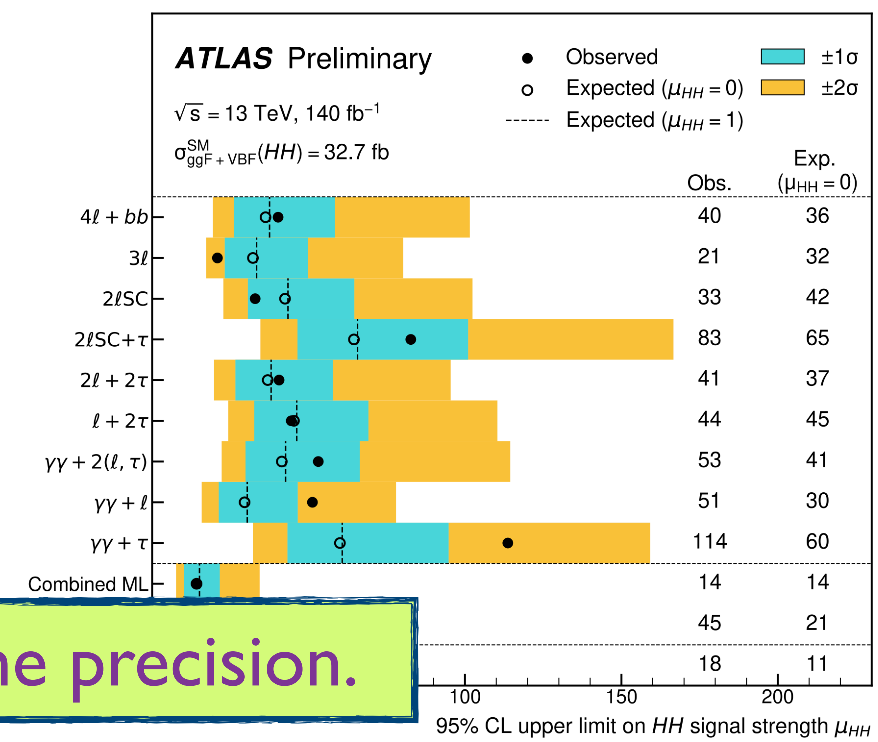


Phys. Rev. D 108, 072004

arXiv:2402.05742





No hint yet of new physics within the precision.

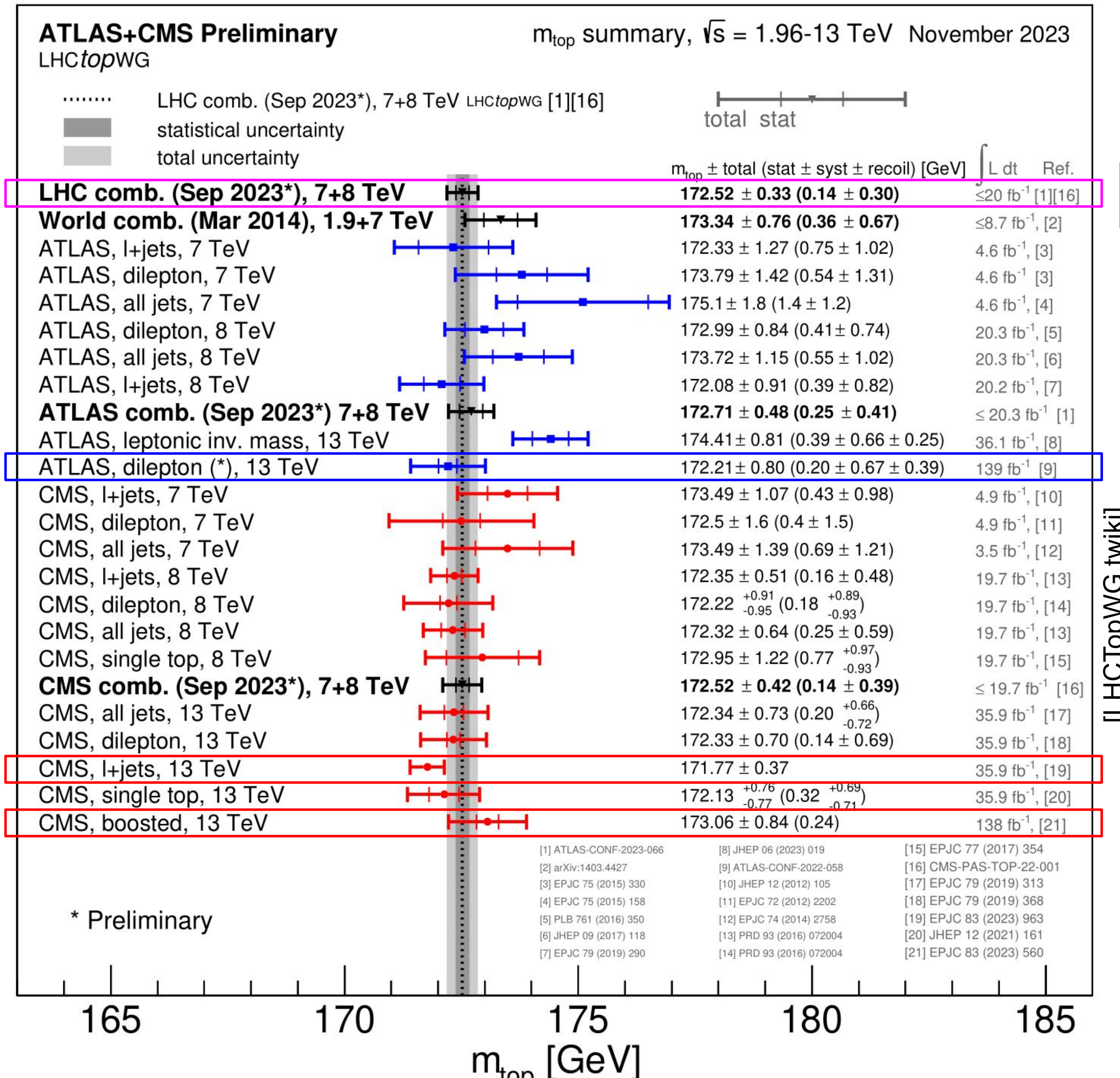
ATLAS-CONF-2024-005

Top quark measurements

- Showing a selection of recent results
- Vast number of measurements from ATLAS and CMS could be found on the ATLAS and CMS public results.

Top quark mass

- Important SM parameter (loop corrections, Yukawa coupling, EWSM,...);



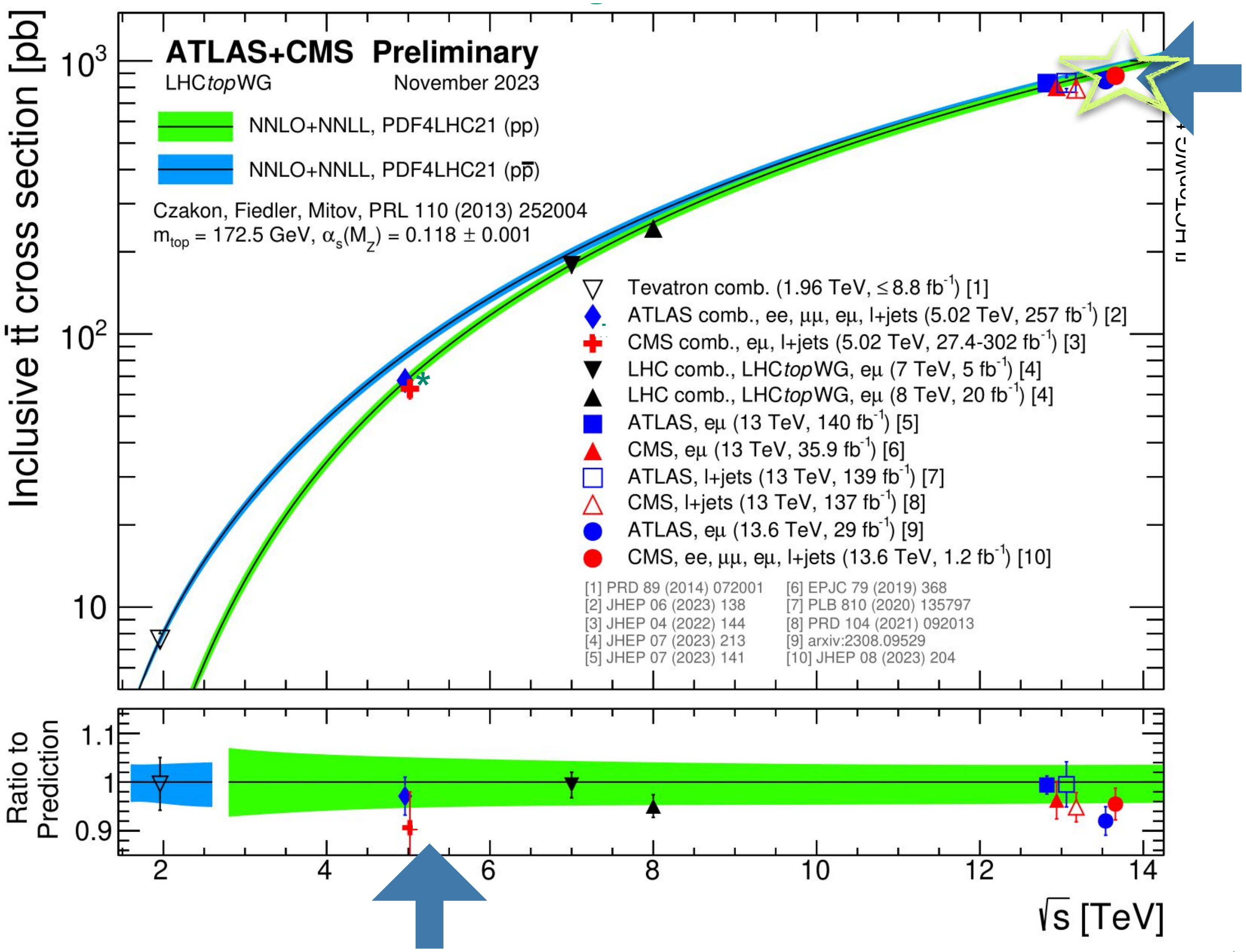
m_t = 172.52 ± 0.33 GeV

Precision below 2 permil!
LHC top program milestone!

m_t = 172.21 ± 0.80 TeV
precise Run 2 single experiment results with new analysis methods.
m_t = 172.77 ± 0.37 TeV

arXiv:2402.08713

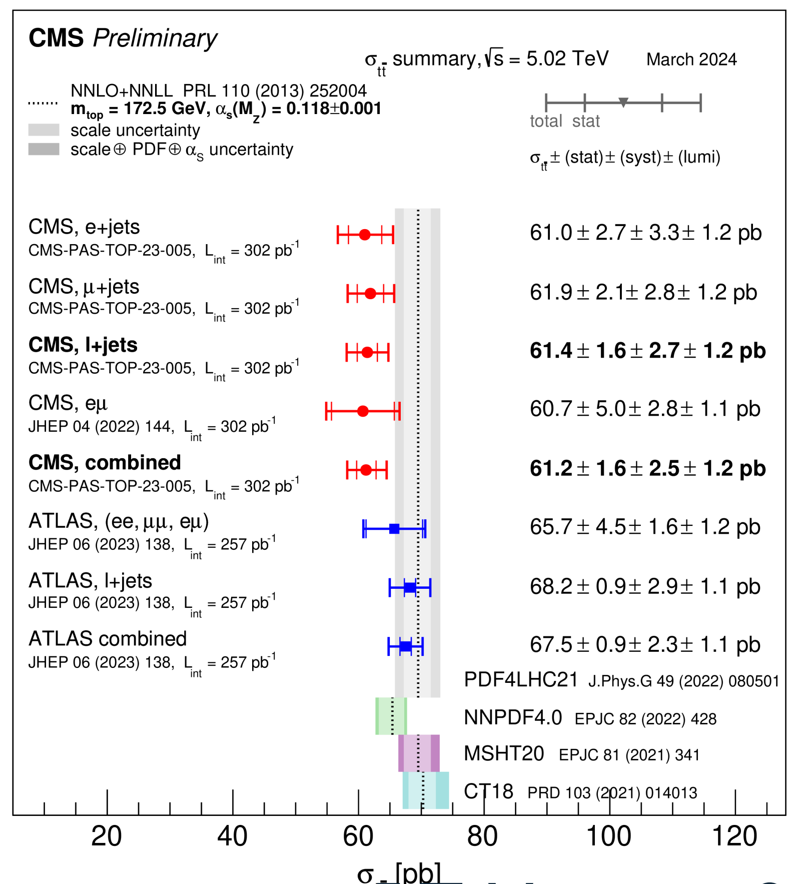
tt cross-section



13.6 TeV results @
3.2% using 29 fb^{-1} (ATLAS)
3.5% using 1.21 fb^{-1}(CMS)

13 TeV ATLAS 1.8% unc. !

To be updated with new CMS result

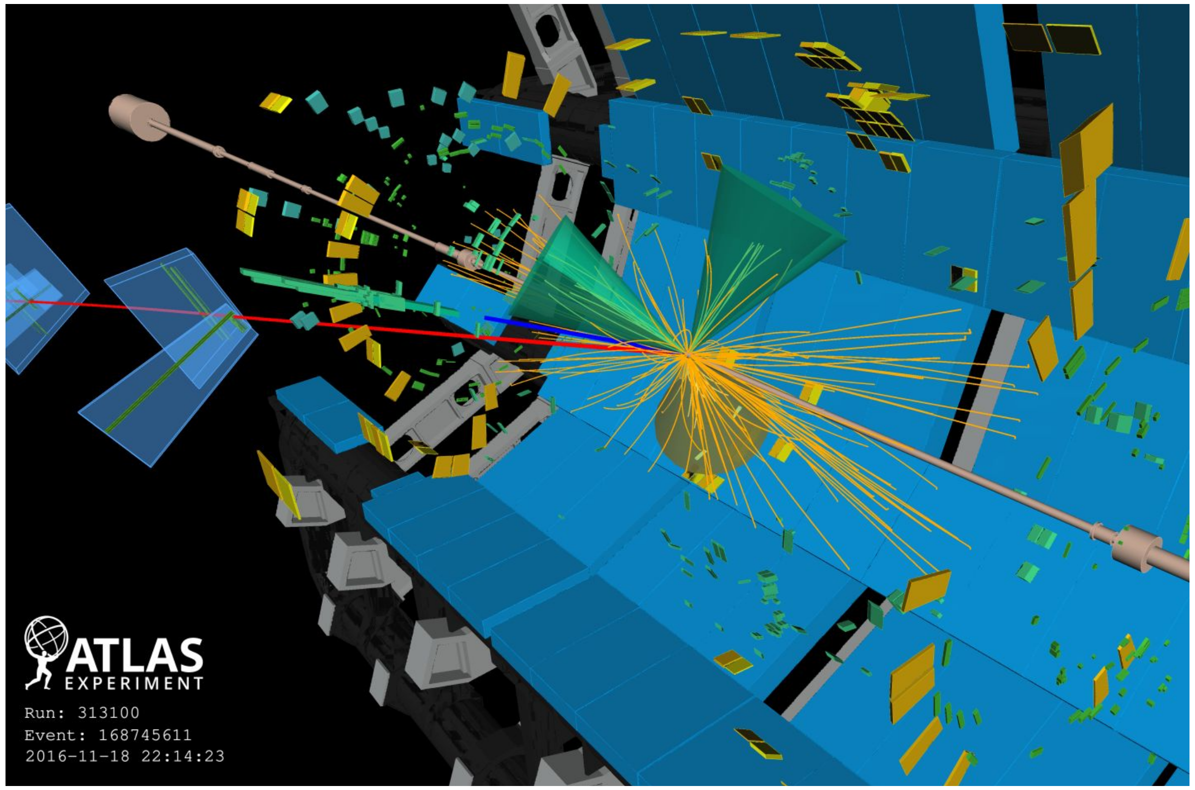


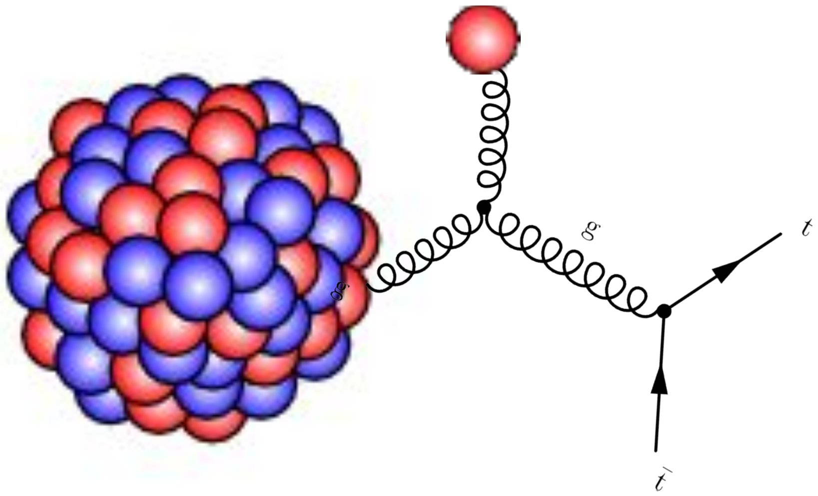
Low intensity 5 TeV run in 2017 (<μ> = 2) using l+jets events;

CMS-PAS-TOP-23-005

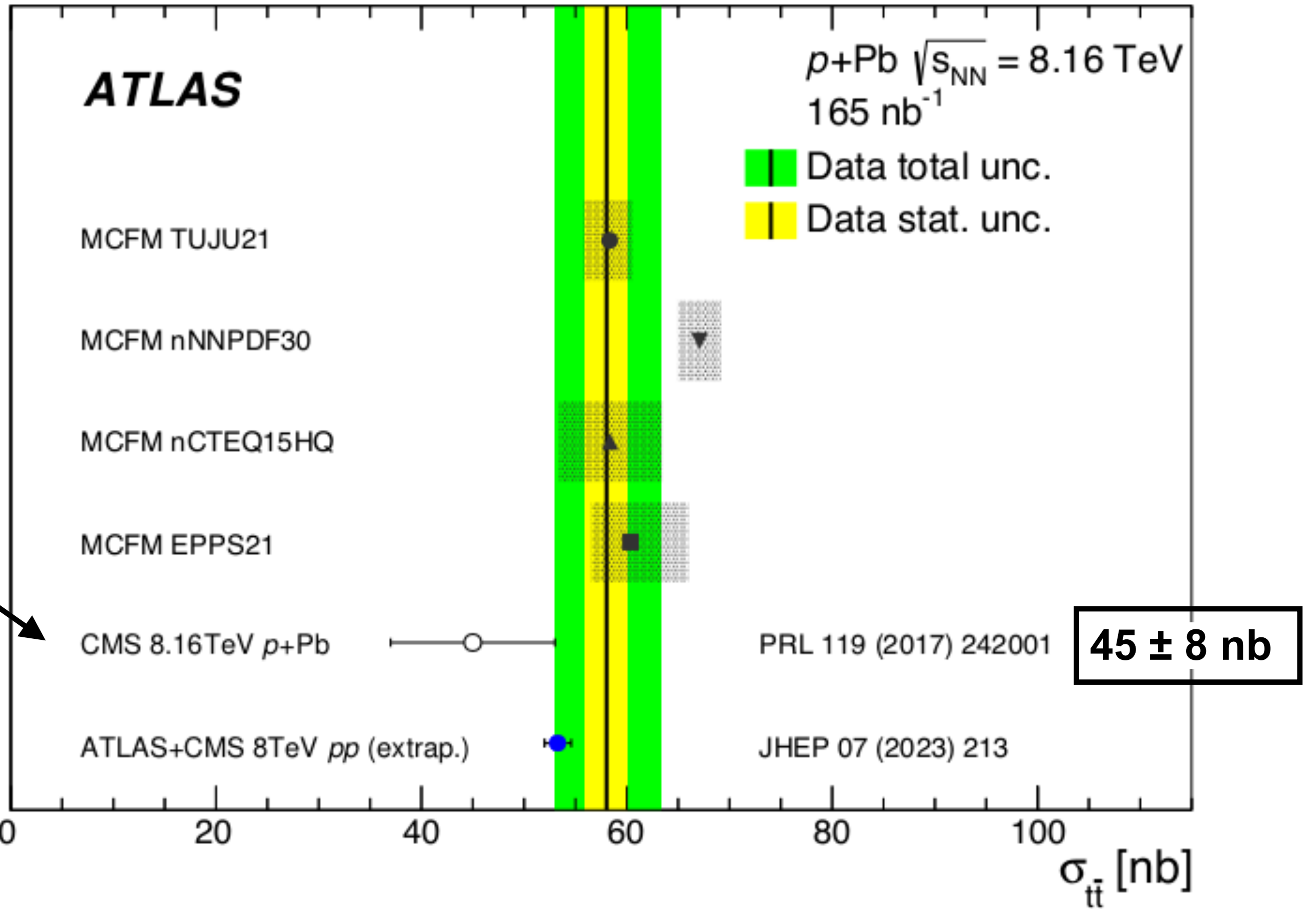
No significant deviation from the SM prediction at all measured CME.

tt cross-section in heavy Ion collisions





arXiv:2405.05078



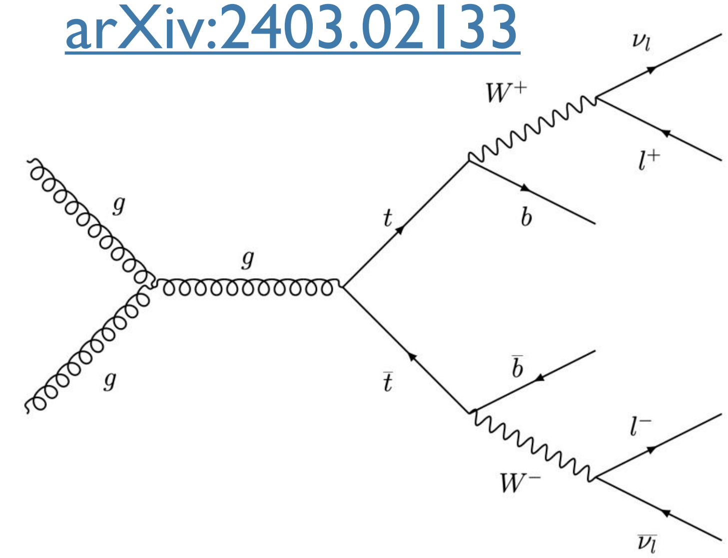
- First observed by CMS;
- Used both l+jets and dilepton;
- Observation: with **9%** precision: 58.1 ± 2.0 (stat.)$^{+4.8}_{-4.4}$(syst.) nb;
  - Dominant uncertainties from JES, tt modelling and misidentified leptons.
- Constraint nPDFs in the high-x region
- Evidence for top quark production in Pb-Pb collisions (CMS) - PRL. 125, 222001

Lepton flavour universality in W decays

- Exploiting leptons from W decays in tt dilepton events;
- SM predicts R =1;

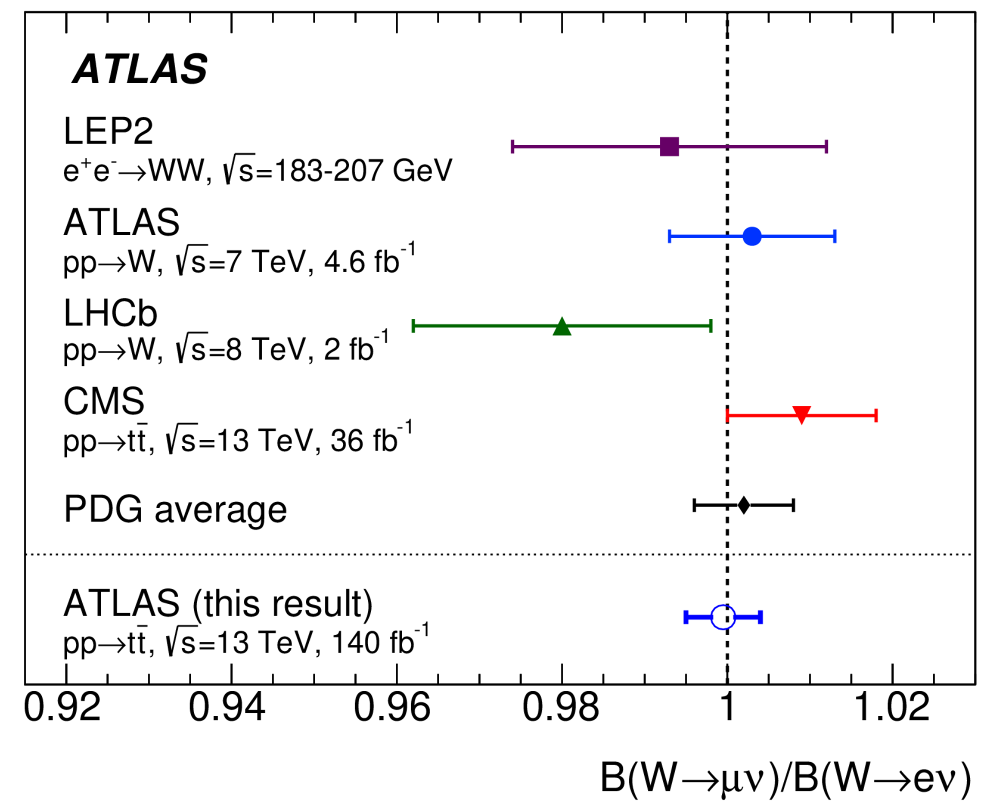
arXiv:2403.02133

$$R = \frac{BR(W\to\mu\nu)}{BR(W\to e\nu)} \approx 1$$



$R^{\mu/e}_W$= 0.9995 ± 0.0022 stat. ± 0.0036 syst. ± 0.0014 extern. = 0.9995 ± 0.0046

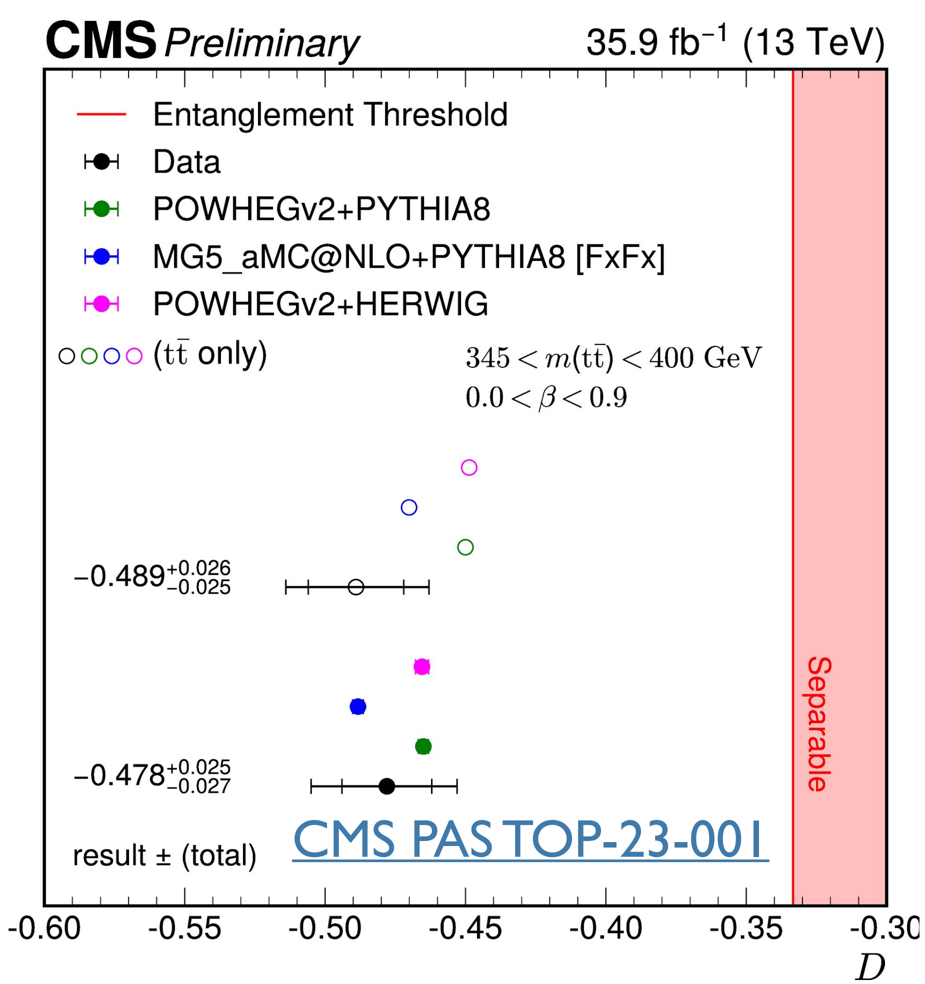
- No evidence of LFU violation;
- Measurement dominated by systematic uncertainties (PDFs. tt * Z modelling, lepton ID and resolution)



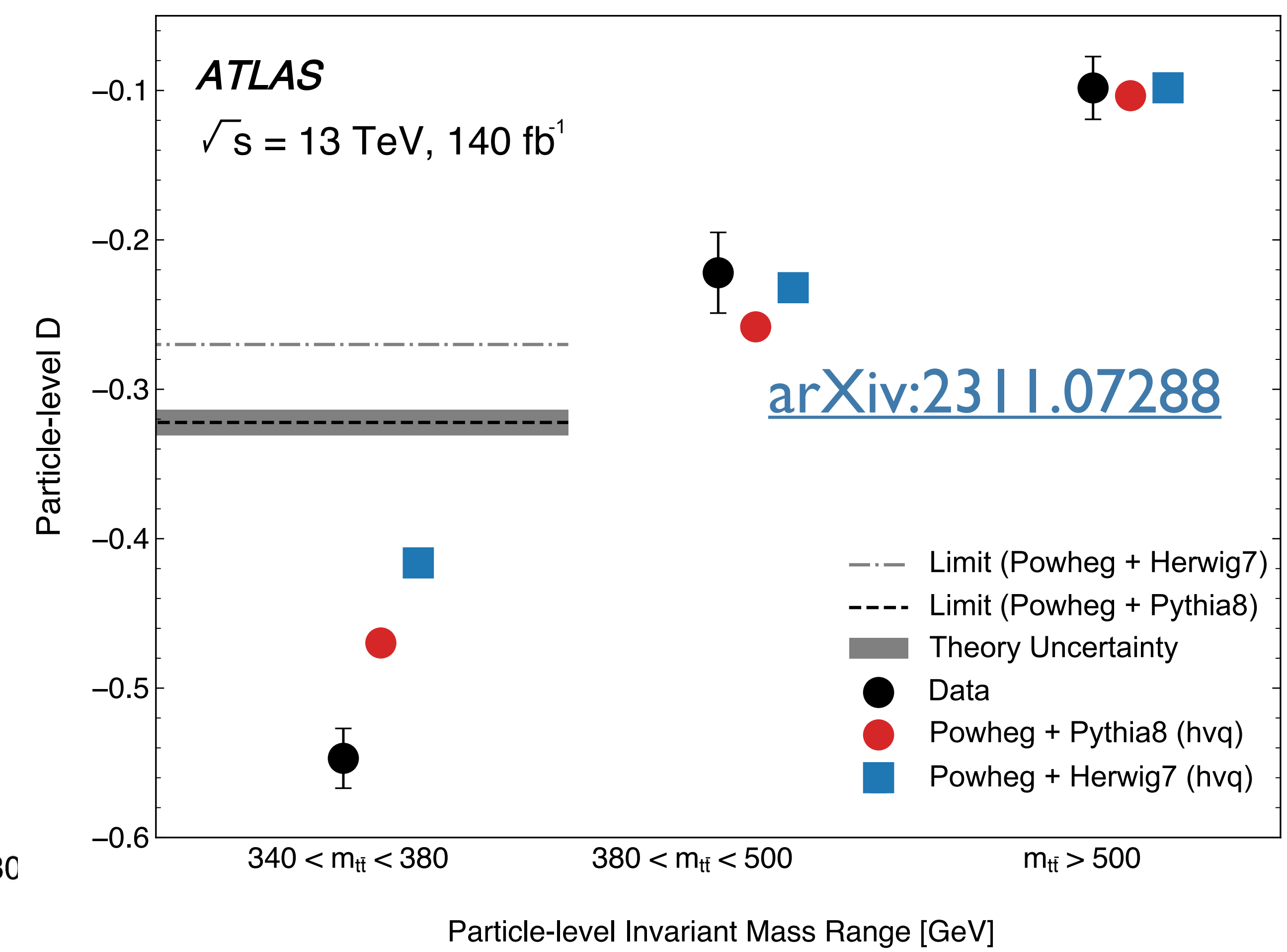
Most precise e/μ universality test, improving on the previous PDG average

Observation of quantum entanglement

- Entanglement explored the first time between a pair of quarks at relativistic energies. In tt spin information is correlated and transferred to decay products.
- Spin correlations at low m(tt) used as a proxy to estimate the entanglement.
- Study two-qubit states at tt production threshold (system is spin-singlet, rotationally invariant), with well-specified fiducial phase-space. (ATLAS: particle level, CMS: parton level)
  - Observable dependent on the angle between the leptons in rest frame of their parents.



CMS PAS TOP-23-001



arXiv:2311.07288

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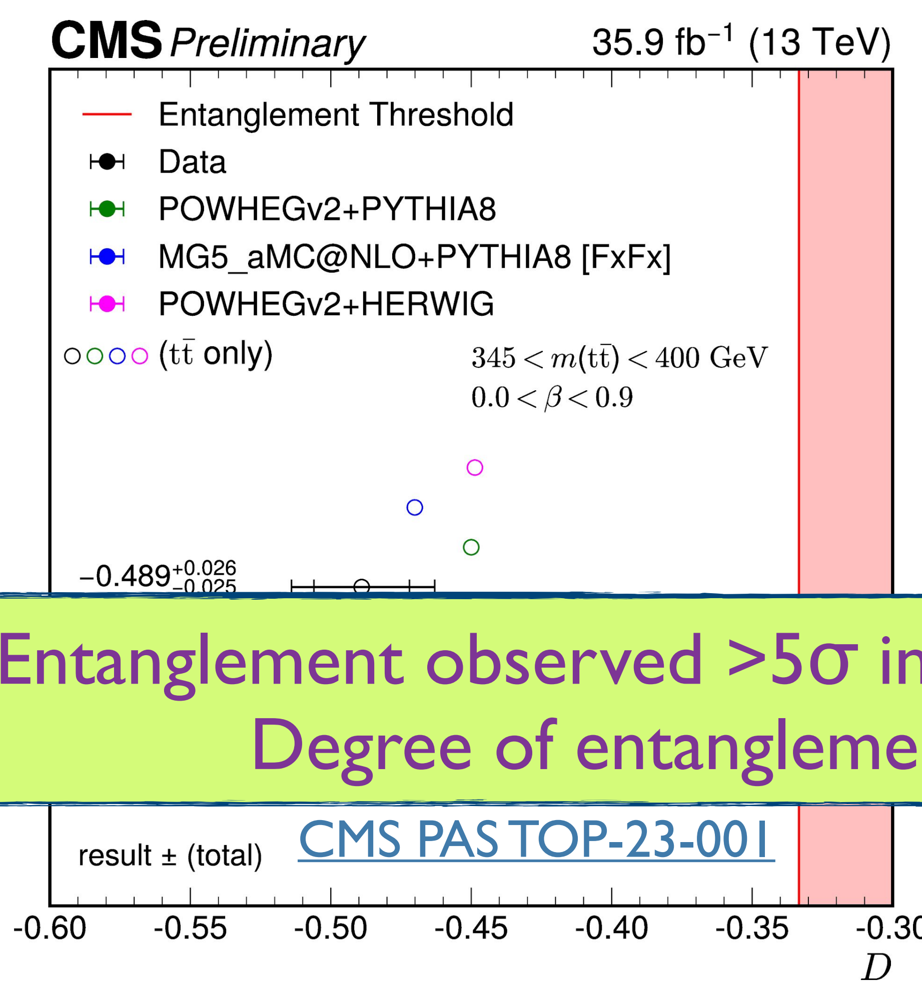
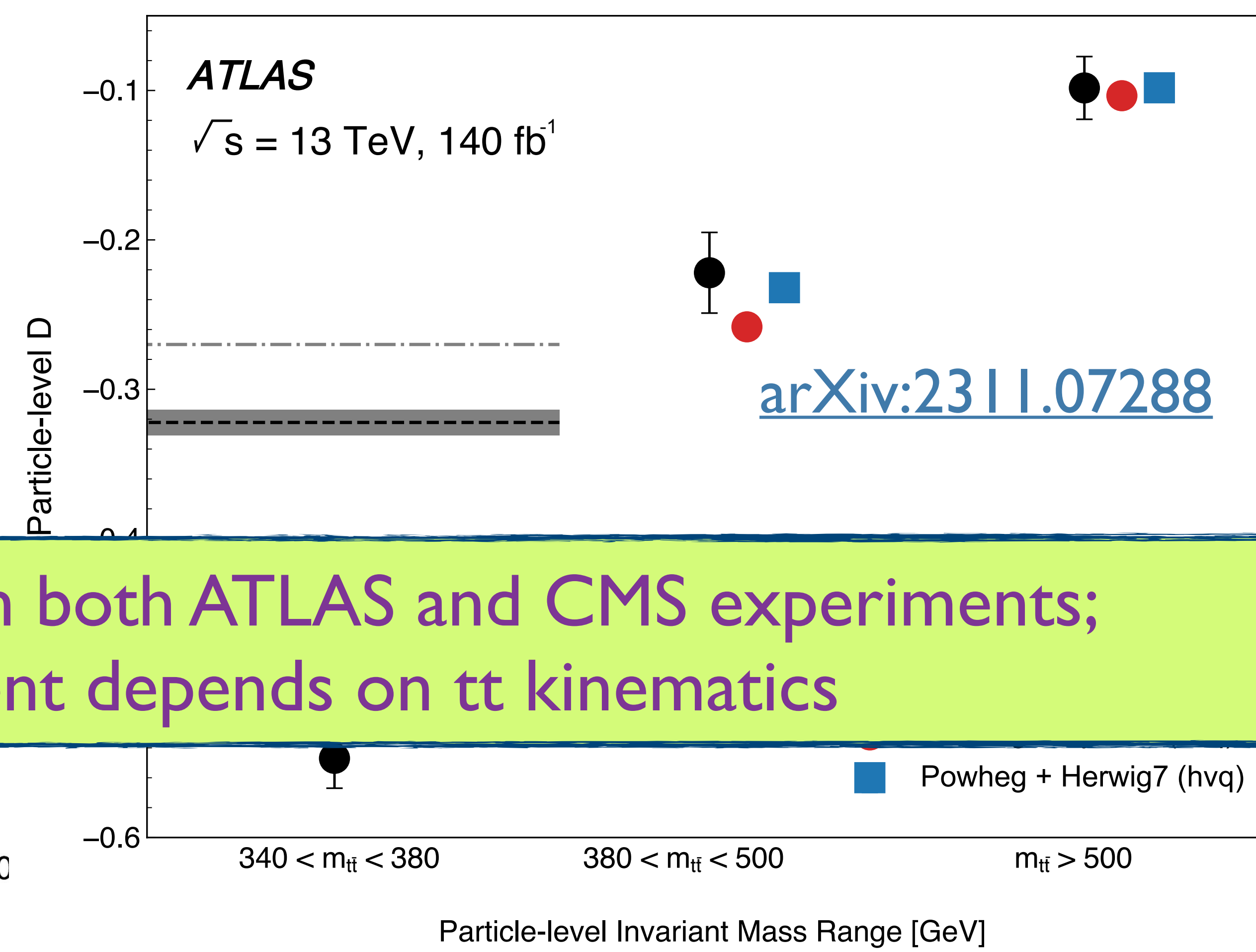


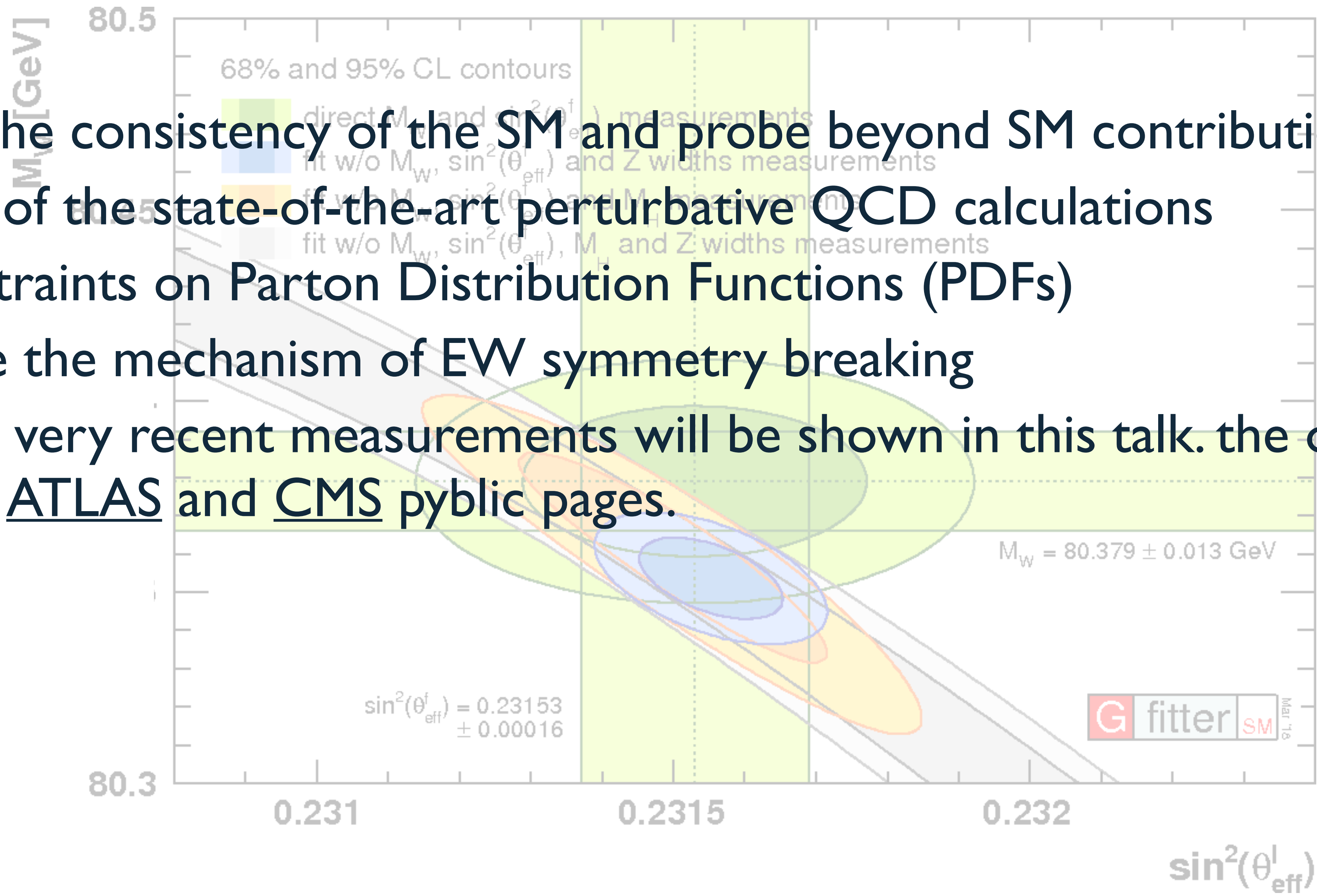


Entanglement observed >5σ in both ATLAS and CMS experiments;
Degree of entanglement depends on tt kinematics

SM precision measurements (EW and QCD)

- Test the consistency of the SM and probe beyond SM contributions
- Tests of the state-of-the-art perturbative QCD calculations
- Constraints on Parton Distribution Functions (PDFs)
- Probe the mechanism of EW symmetry breaking

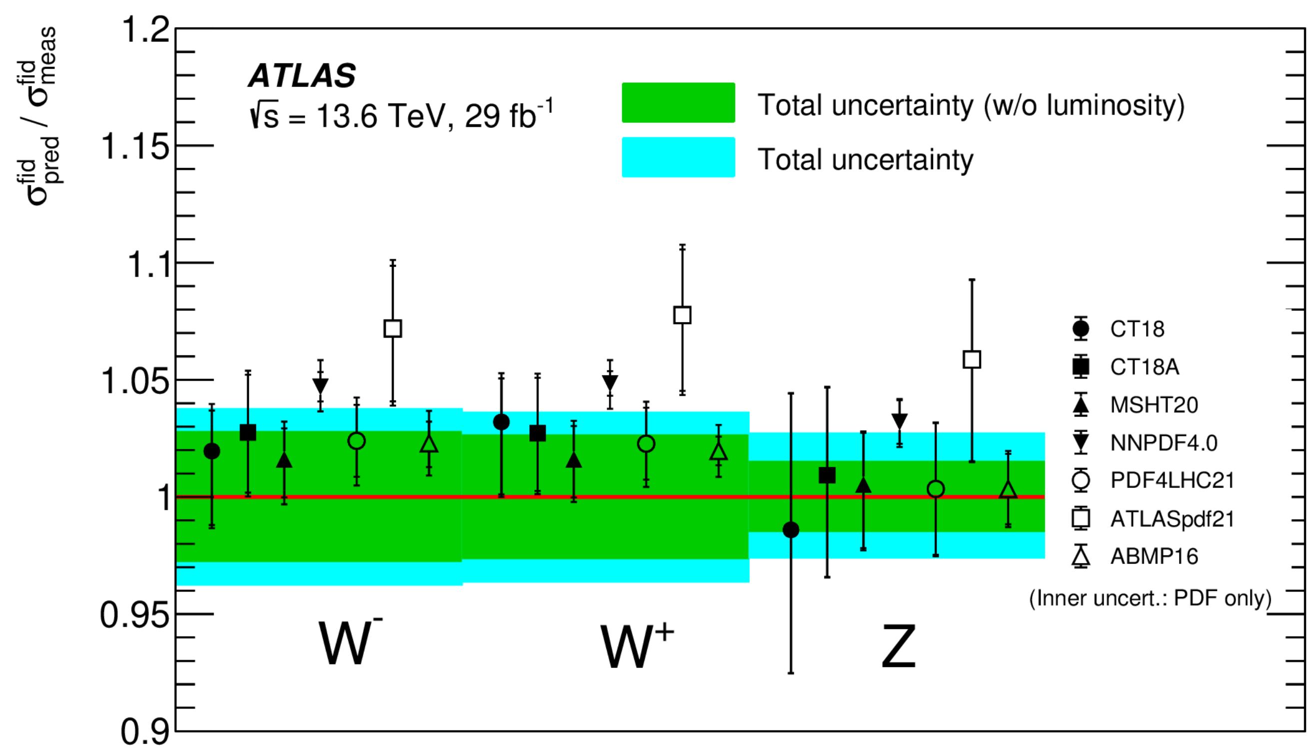
Only few very recent measurements will be shown in this talk. the others can be found on ATLAS and CMS pyblic pages.

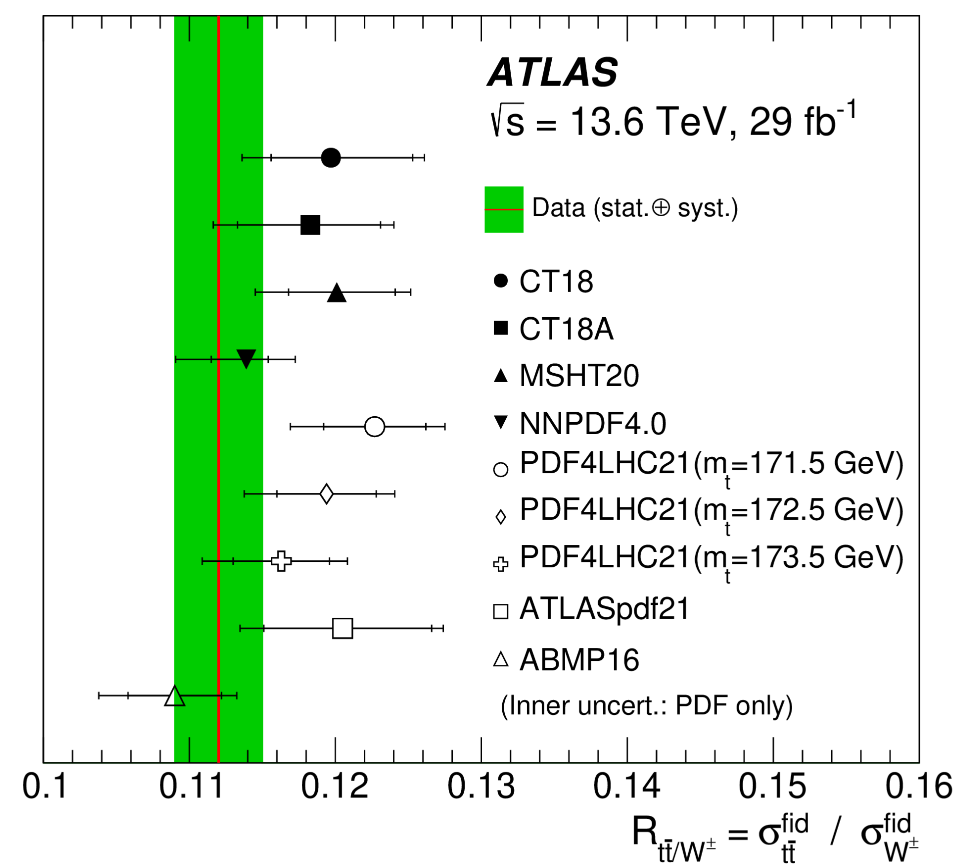


W and Z cross-sections at 13.6 TeV

- Data collected in 2022 with an integrated luminosity of 29 fb^{-1};
- Integrated luminosity uncertainty of 2.2%
- Ratios of tt to W boson cross sections are measured as well;
- Compared to various PDF predictions

arXiv:2403.12902





In agreement with Standard-Model predictions calculated at NNLO in αs, NNLL (q_t-resummation) accuracy and NLO electroweak accuracy.

Effective weak mixing angle

- New CMS Run 2 measurement of the leptonic effective weak mixing angle;
- Measurements of both the forward-backward asymmetry and unfolded A_4;
- The measurement includes central-central μμ and ee channels as central-forward ee using forward calorimeters (sensitivity to A_{FS});

$$\frac{16\pi}{3\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\phi} = 1+\cos^2\theta+\sum_{i=0}^{7} A_i f_i(\theta,\phi),$$

$$f_0 = 0.5(1-3\cos^2\theta),\ f_1 = \sin 2\theta\cos\phi,$$

$$f_2 = 0.5\sin^2\theta\cos 2\phi,\ f_3 = \sin\theta\cos\phi,\ f_4 = \cos\theta,$$

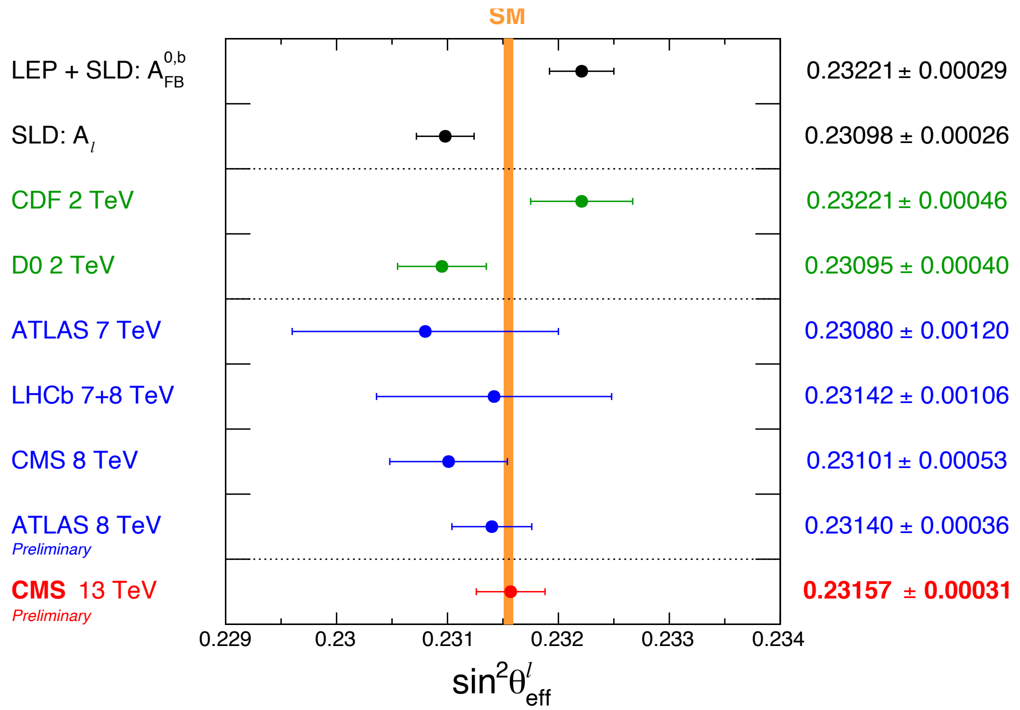
$$f_5 = \sin^2\theta\sin 2\phi,\ f_6 = \sin 2\theta\sin\phi,$$

$$f_7 = \sin\theta\sin\phi.$$

$$A_{\mathrm{FB}} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$$

$$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23157 \pm 0.00010(\mathrm{stat}) \pm 0.00015(\mathrm{syst}) \pm 0.00009(\mathrm{theo}) \pm 0.00027(\mathrm{PDF})$$

CMS PAS SMP-22-010



Most precise hadron collider measurement!

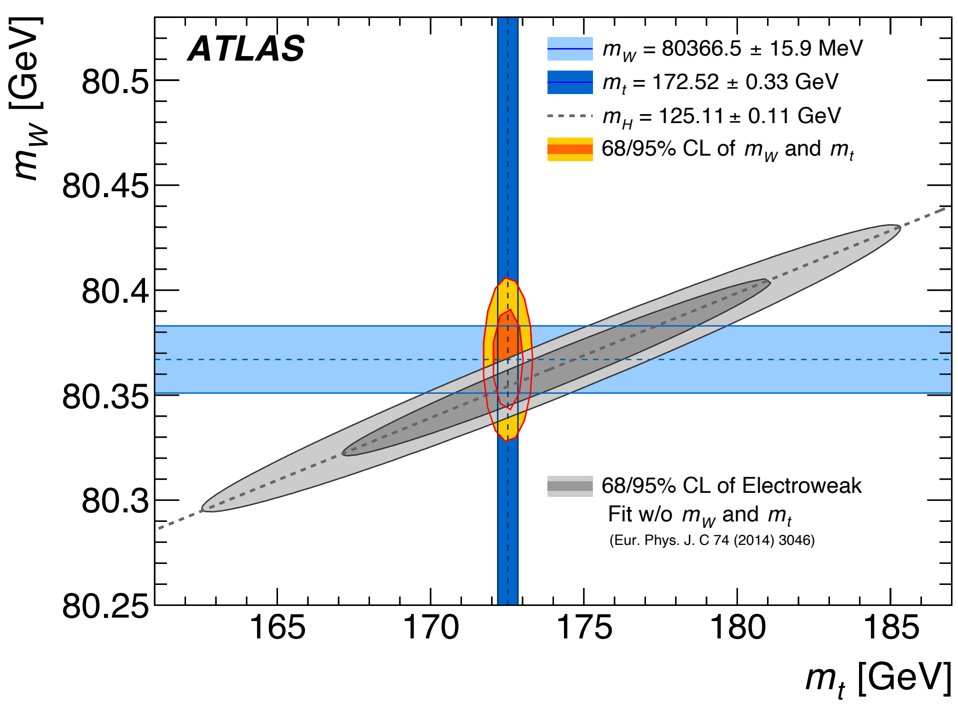
Precision comparable to LEP and SLD results. (PDF uncertainties dominate)

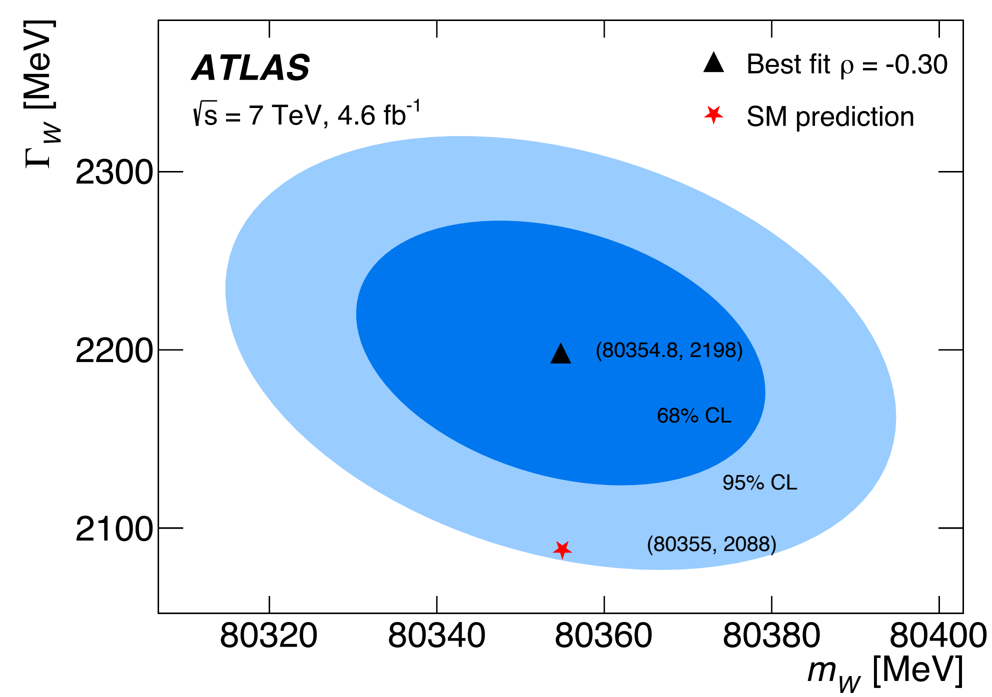
W boson width and mass

- Extremely challenging at hadron colliders - prone to biases due to QCD effects;
- Use the lepton p_T and the transverse mass m_T to extract m_W;
- **15% reduction in the uncertainty** on m_W w.r.t. 7 TeV data sample
- First measurement of Γ_W at the LHC and most precise from the single exp.

$$m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV} = 80366.5 \pm 15.9\ \text{MeV}.$$

$$\Gamma_W = 2202 \pm 32\ (\text{stat.}) \pm 34\ (\text{syst.})\ \text{MeV} = 2202 \pm 47\ \text{MeV},$$





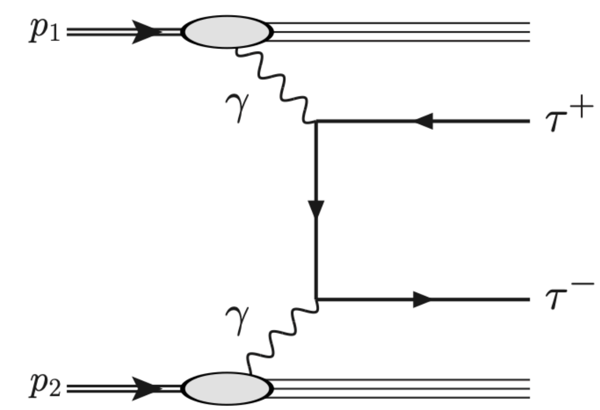
arXiv:2403.15085

- Central value of m_W shifts down by 12 MeV;
- ~30% correlation between mW and Γ_W.

Observation of γγ→ττ

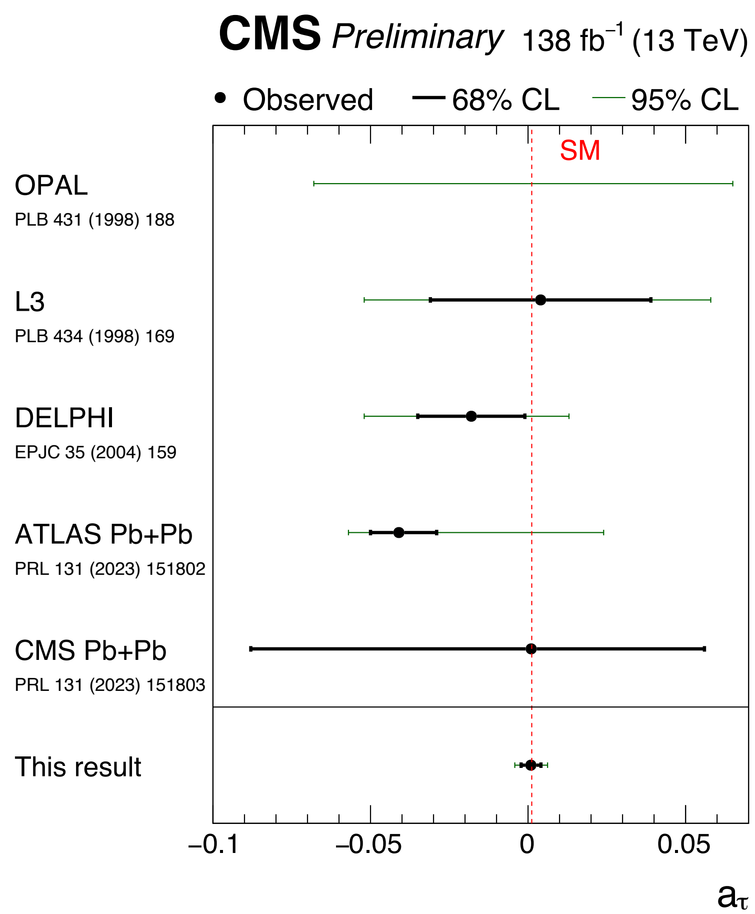
- Previously observed by ATLAS and CMS in PbPb collisions;
- CMS using 138 fb^{-1} data at 13 TeV;
- Events with small number of tracks are close to the di-tau vertex are selected to isolate photon induced processes;
  - Correct the number of tracks in simulation

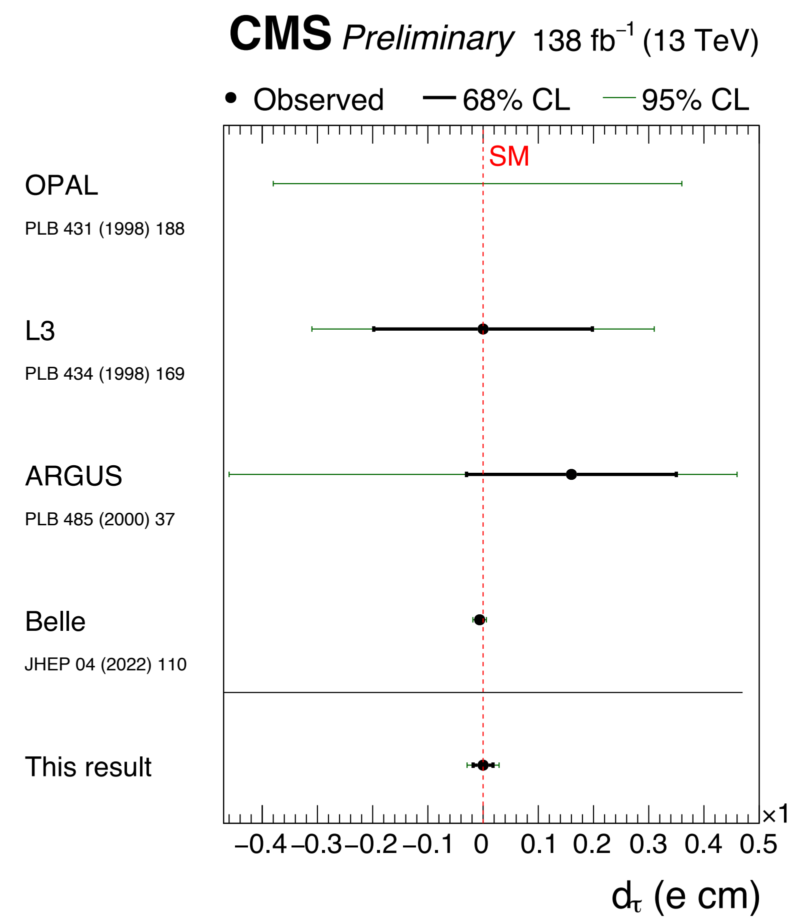
CMS PAS SMP-23-005



$$a_\tau = 0.0009^{+0.0016}_{-0.0015}\,(\text{syst})^{+0.0028}_{-0.0027}\,(\text{stat}).$$

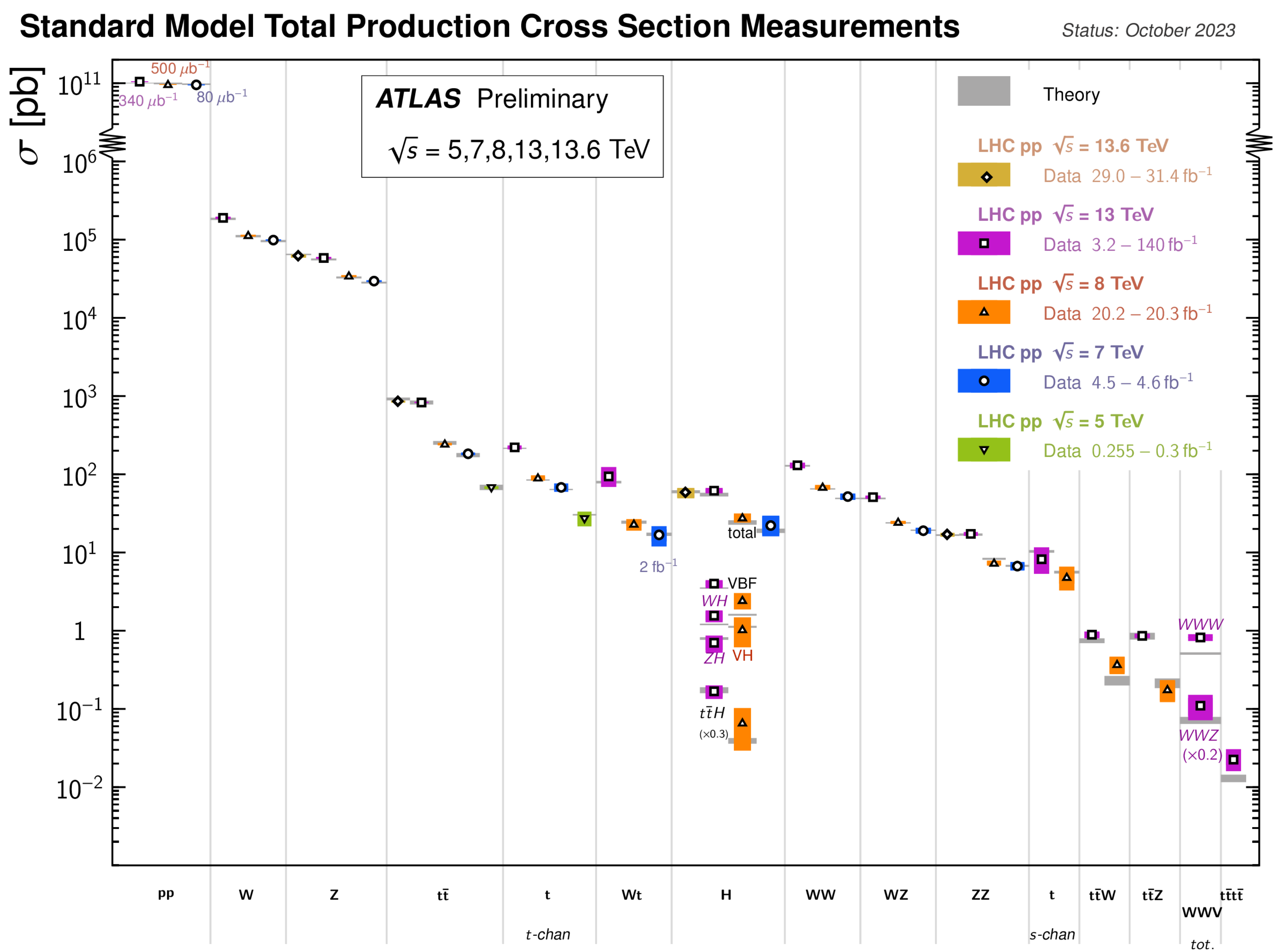
- Constrain the anomalous electromagnetic moments of τ lepton using the visible mass distribution





5.3 (6.5) observed (expected) significance

Summary of the measurements



resonances

heavy neutrinos

dark sector

Leptoquarks

Axions

Highly ionising particles

compositeness

BSM searches

Selected recent results with accent on searches that results in tension with SM predictions

WIMPS

Supersymmetry

vector like quarks

Extra dimensions

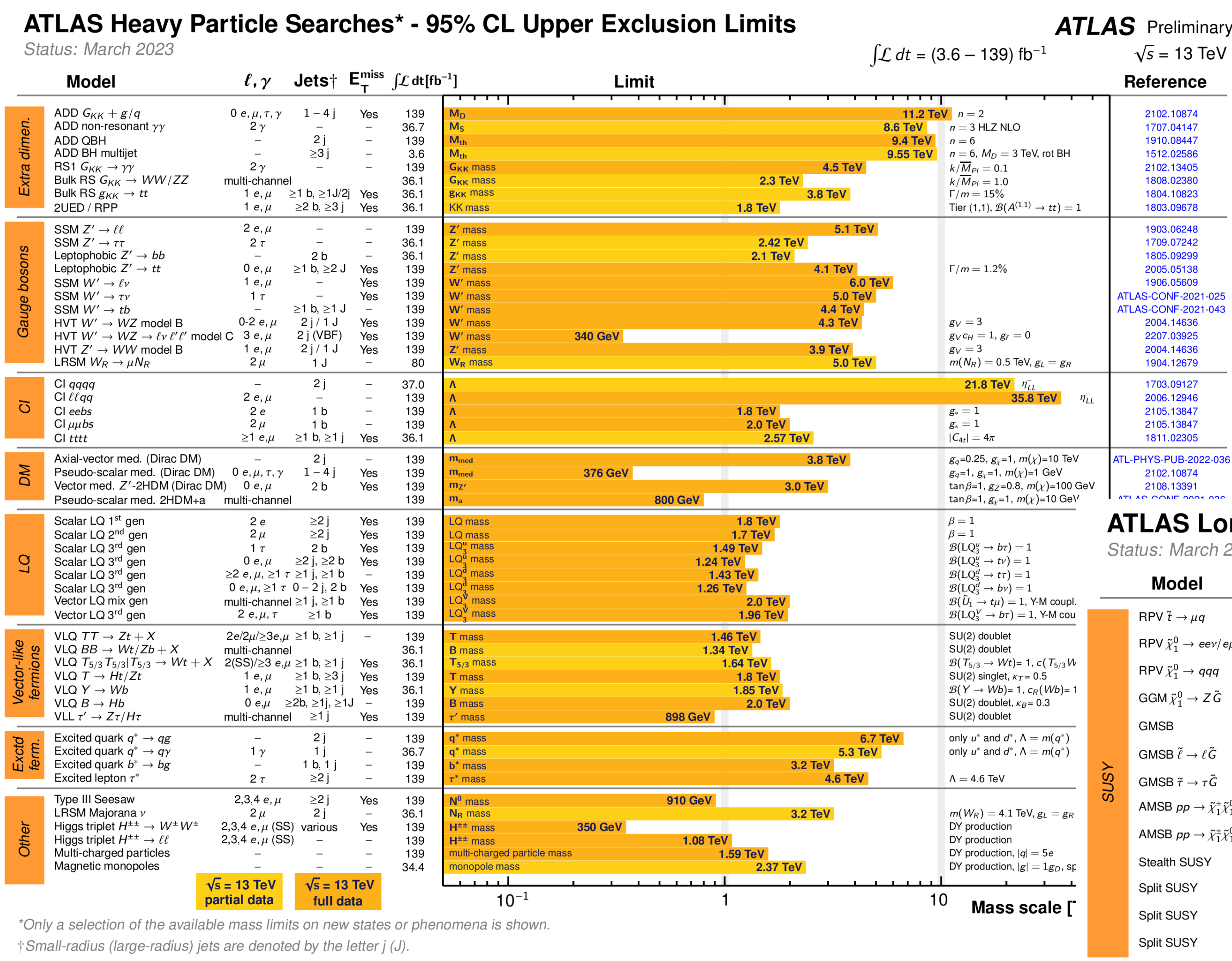
Dark Matter

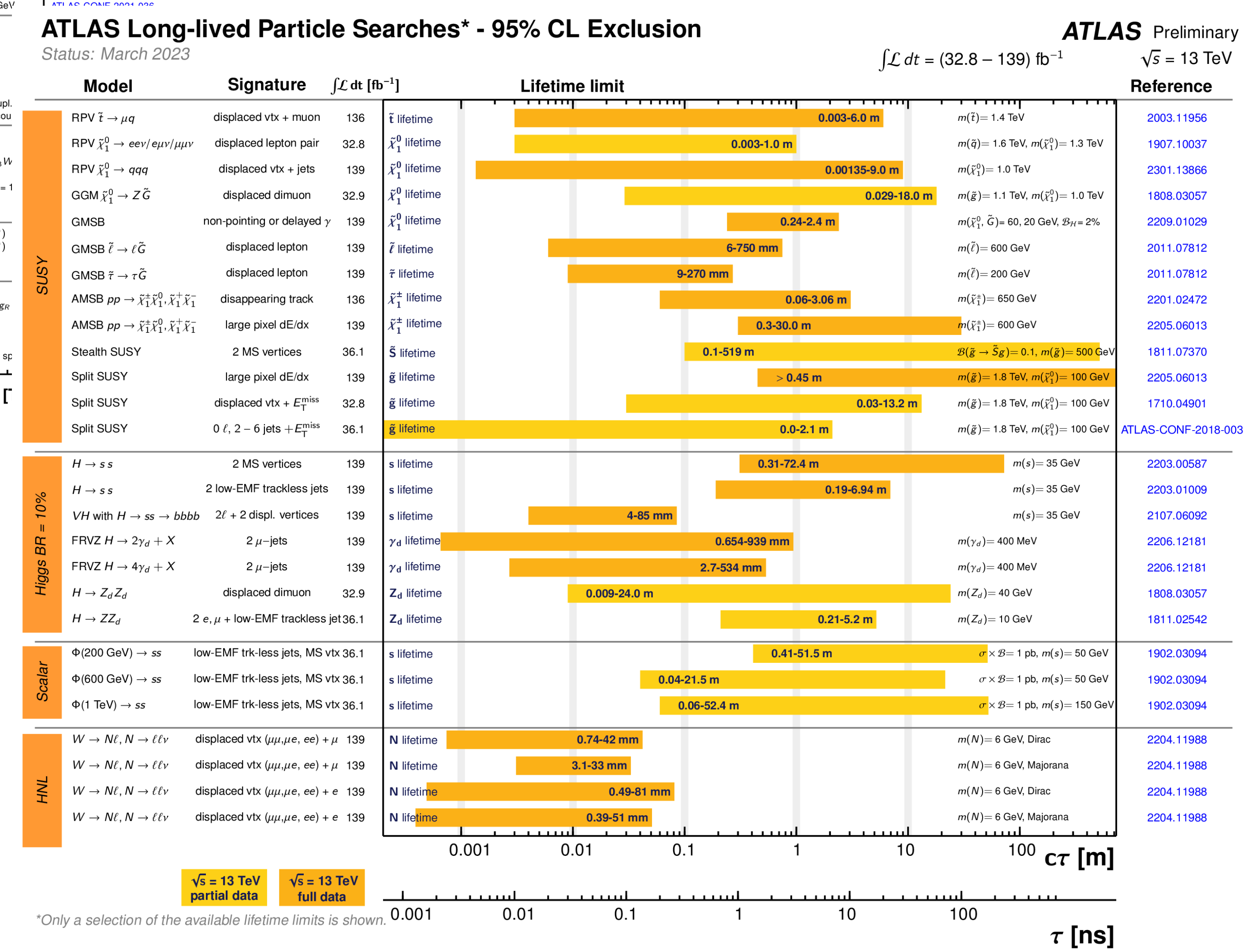
contact interactions

Invisible decays

Long Lived Particles

Exclusion limits so far....



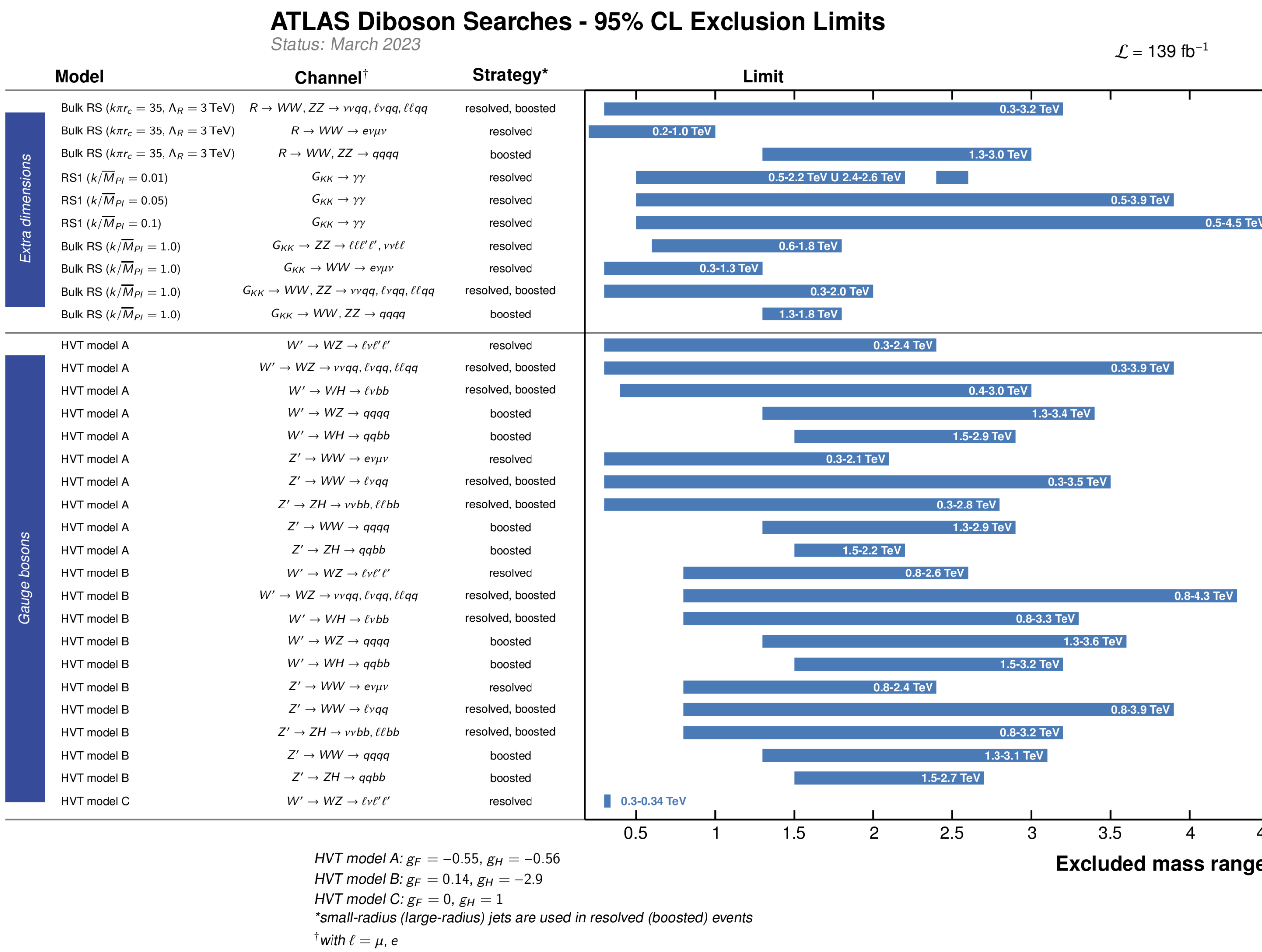


[Link to the summary plots]

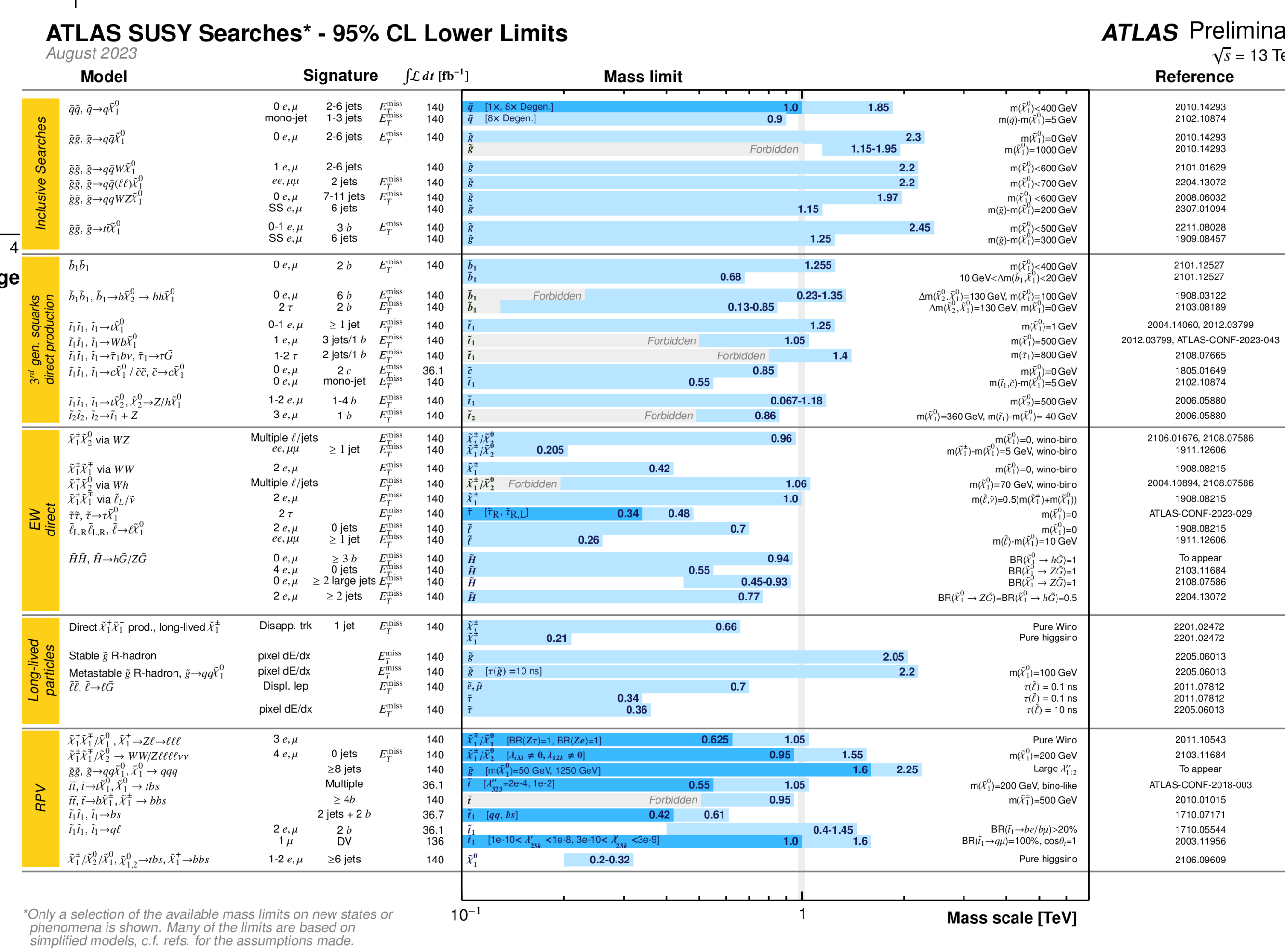
- No observation of BSM processes in direct searches yet.

Exclusion limits so far....

[Diboson search plots](#)



[Supersymmetry search summary plots](#)



- No observation of BSM processes in direct searches yet.

Low mass di-photon search

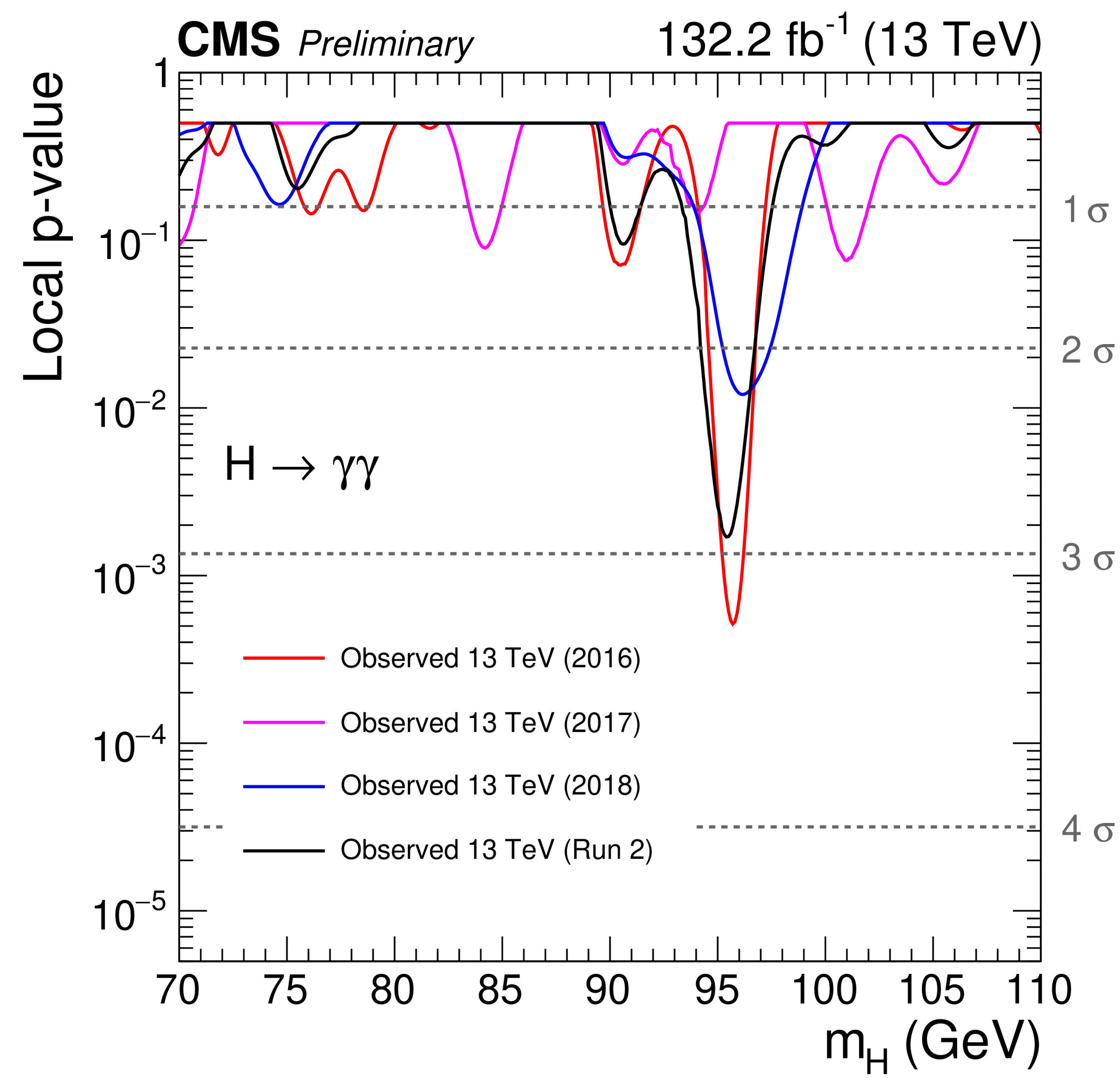
Motivation:

- Small excess of events (~2σ) at m_H = 98 GeV in H(bb) at LEP @ √s = 189 GeV;
- Previous CMS search @ √s = 8 and 13 TeV data from 2012+2016 that observed local (global) significance of 2.8 (1.3) σ (PLB 793 (2019) 320) at 95.3 GeV;

CMS search:

- Analysis strategy: kinematic di-photon BDT used to select the signal;
- Main background is continuum γγ production, with additional contribution from Drell-Yan → e+e- with electrons faking photons;
- Excess previously seen in 2016 data persists, **2.9 (1.3) σ local (global)** significance at **95.4 GeV**;

CMS-PAS-HIG-20-002



Low mass diphoton search

Motivation:

- Small excess of events (~2σ) at m_H = 98 GeV in H(bb) at LEP @ $\sqrt{s}$ = 189 GeV;
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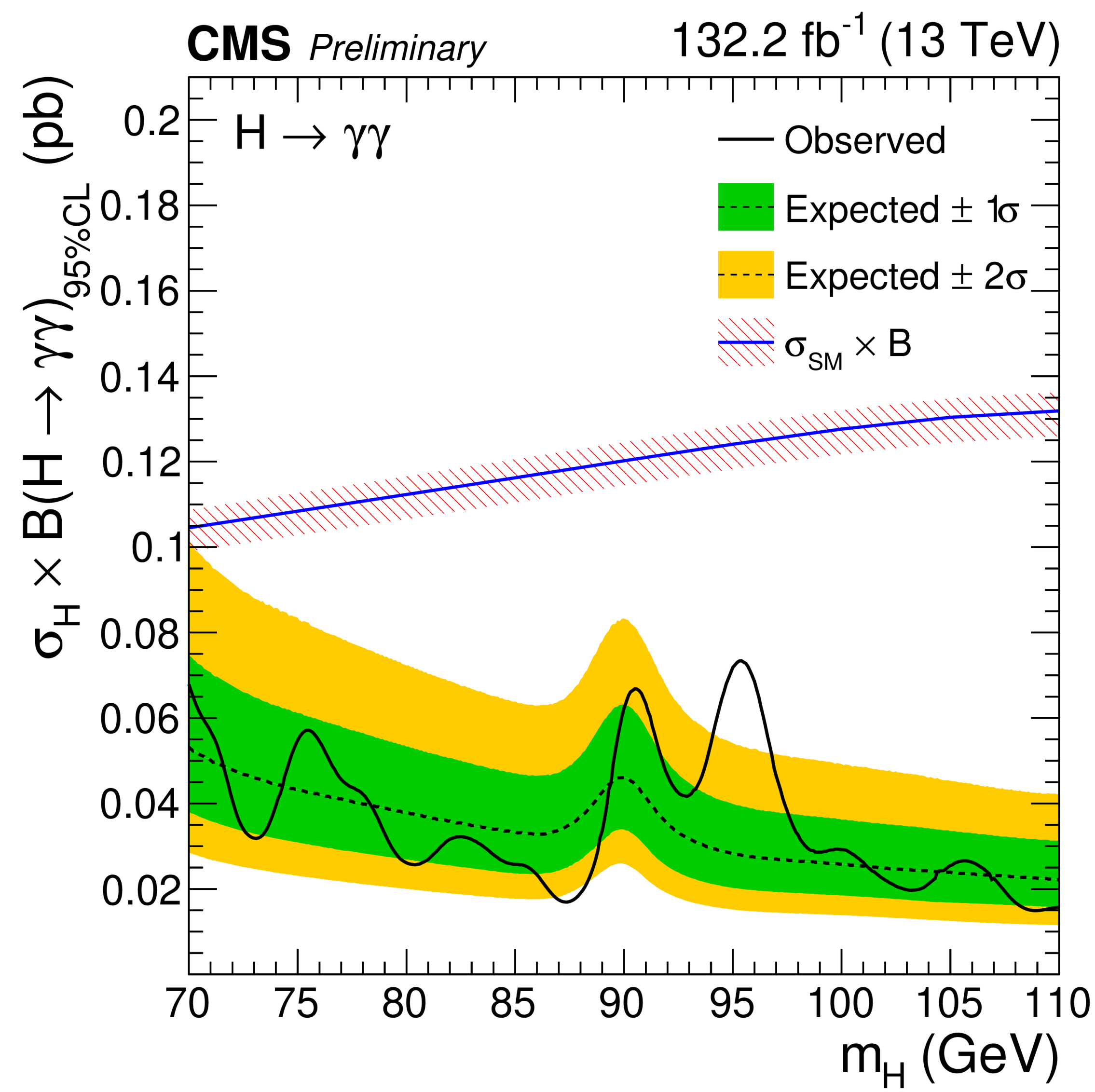
CMS search:

- Analysis strategy: kinematic diphoton BDT used to select the signal;
- Main background is continuum γγ production, with additional contribution from Drell-Yan → e+e- with electrons faking photons;
- Excess previously seen in 2016 data persists, **2.9 (1.3) σ local (global)** significance at **95.4 GeV**;
- Limits set on $\sigma_H \times B(H\rightarrow\gamma\gamma)$ for additional SM-like Higgs boson.

CMS-PAS-HIG-20-002

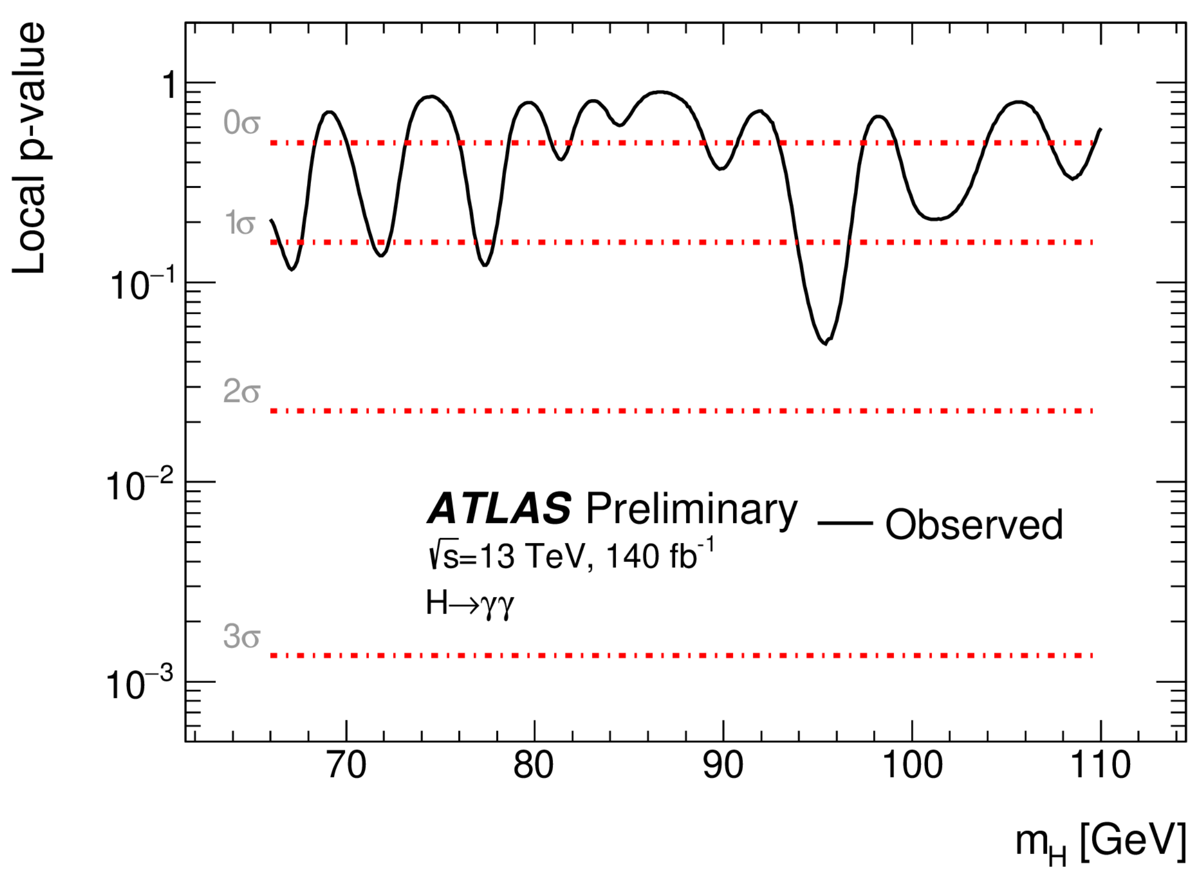


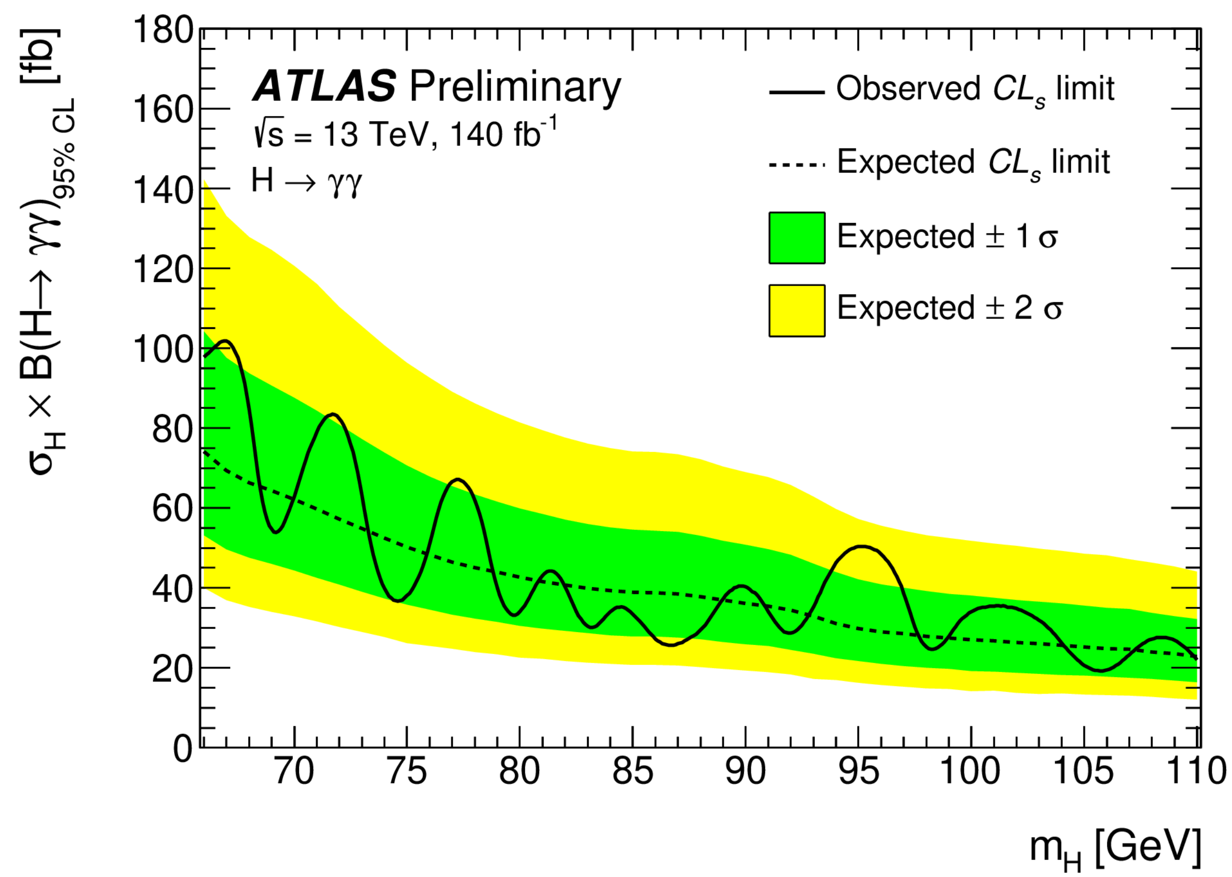
Low mass diphoton search

ATLAS search:

- Search performed in range 66 < $m_{\gamma\gamma}$ < 110 GeV
- Categorisation of events based on whether photon converts to electron pair;
- Model-dependent search uses BDT for additional event categorisation;
- At **95.4 GeV**, observe **1.7 σ (local)** deviation;

ATLAS-CONF-2023-035

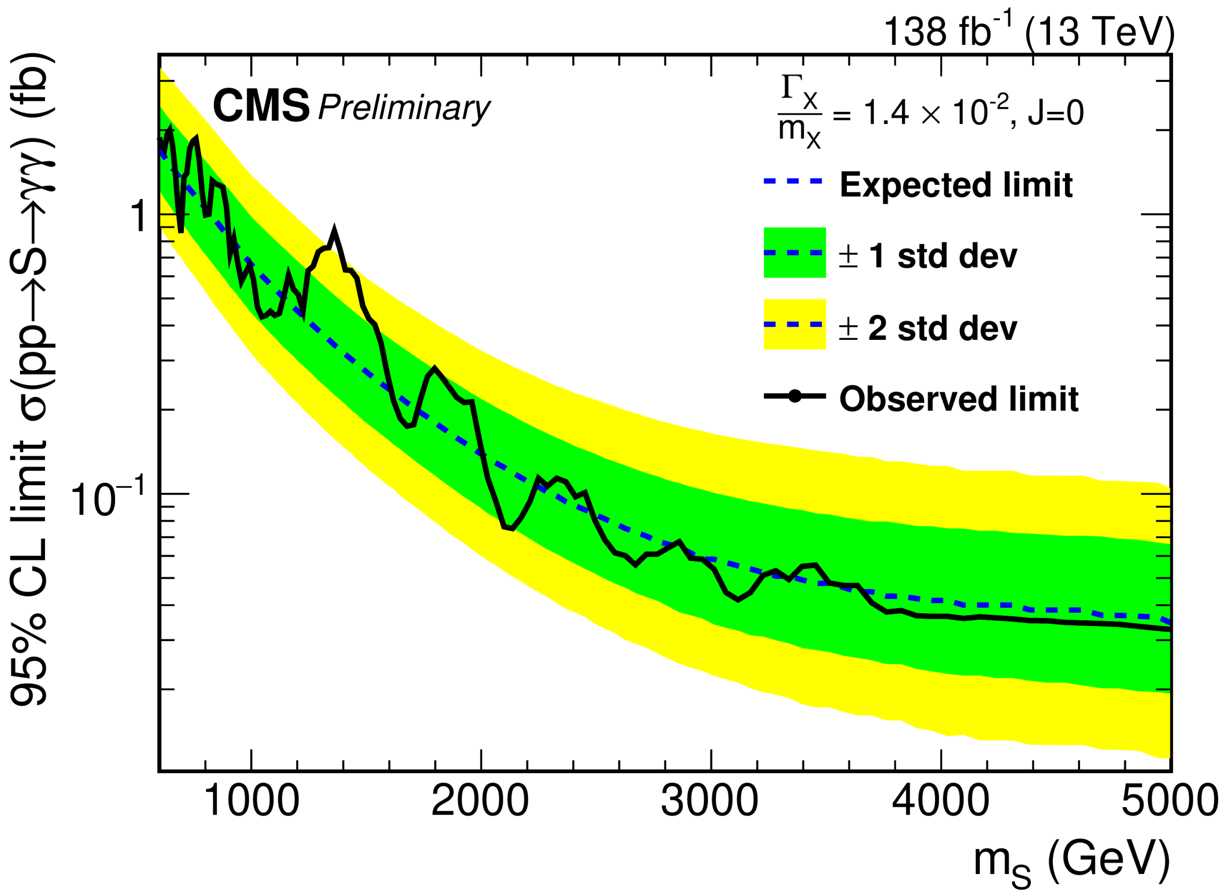




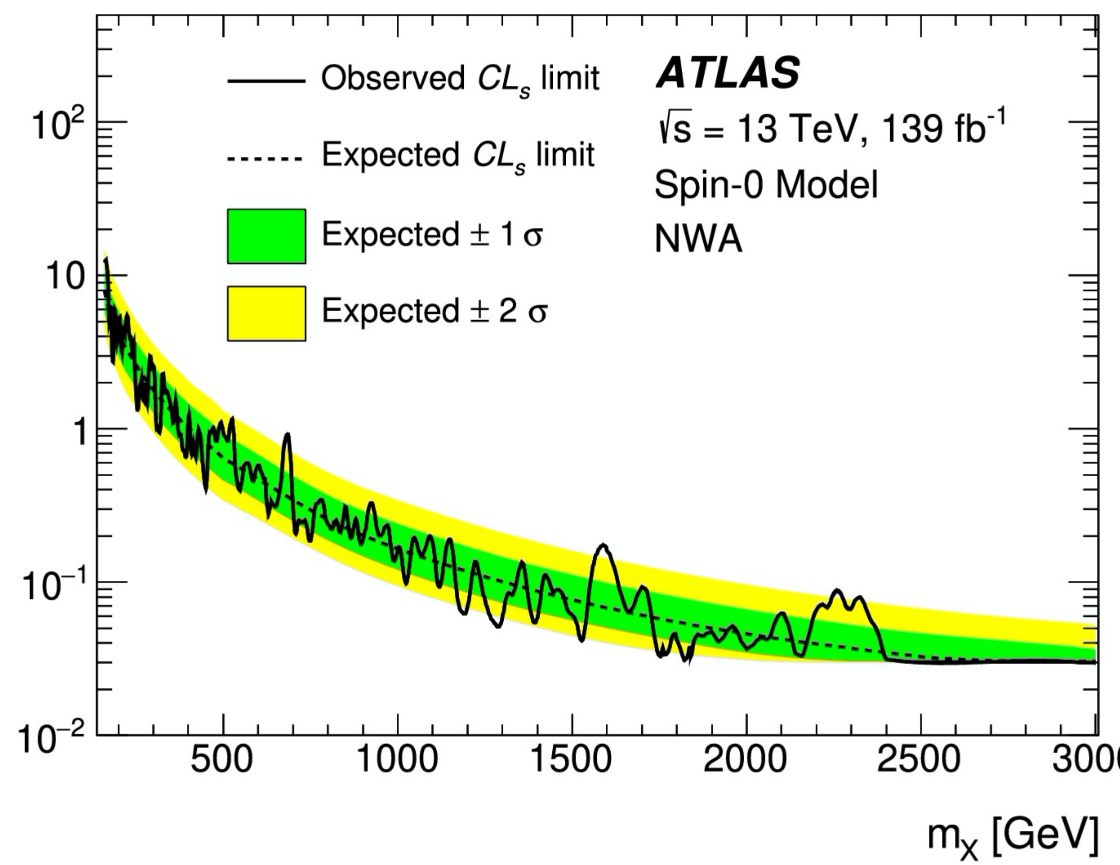
High mass di-photon search

- ATLAS and CMS search for high mass di-photon resonance considering spin-0 and spin-2 particles;
- The analysis strategy is based on fitting di-photon invariant mass spectrum;

CMS-PAS-EXO-22-024



PLB 882 (2021) 136551



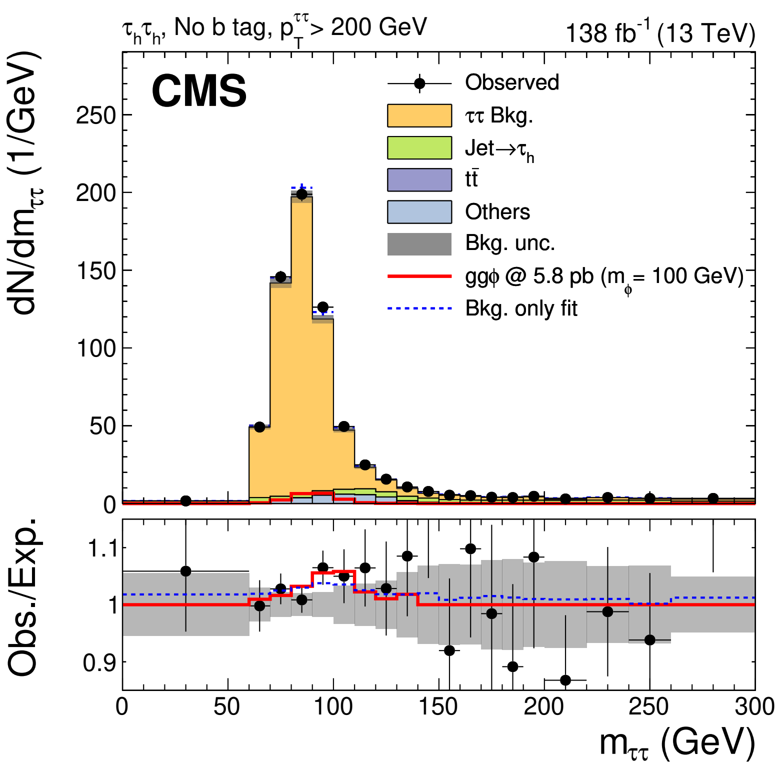
CMS: most significant excess at **1.3 TeV**: **2.6 (0.8) σ local (global)**.

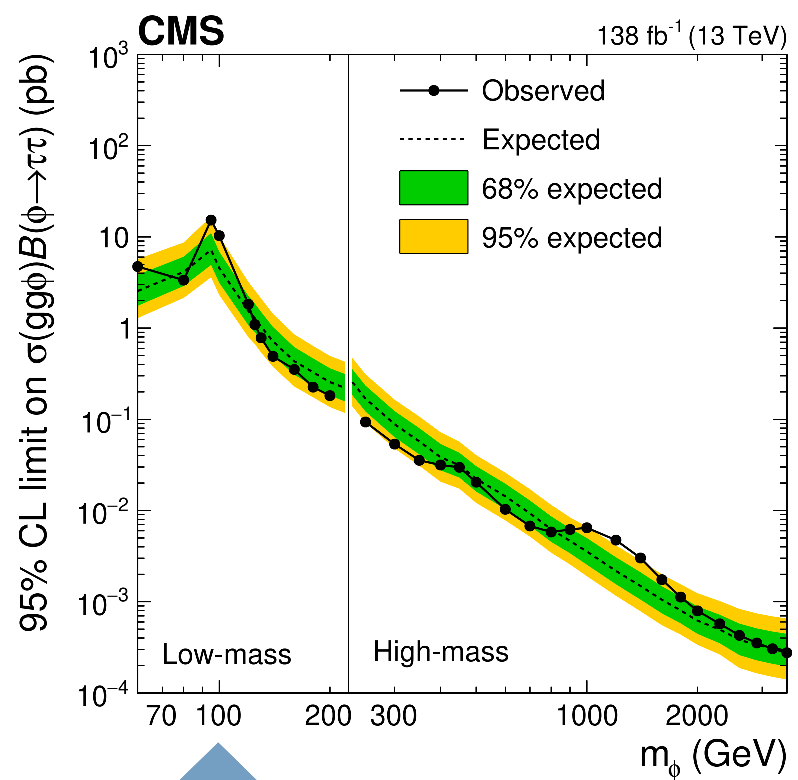
ATLAS: most significant excess at **684 GeV**: **3.3 (1.3) σ local (global).**

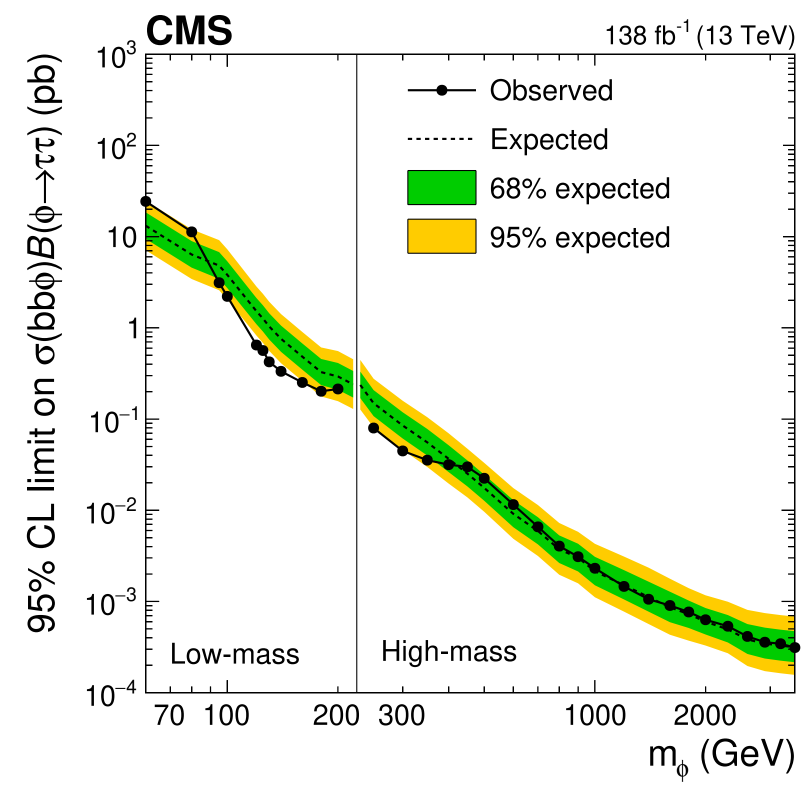
Low mass di-τ search

- CMS searched for additional Higgs bosons in ττ final state;
- Categorisation of events based on b-tagged jets and $p_T(\tau\tau)$.

[JHEP 07 (2023) 073]



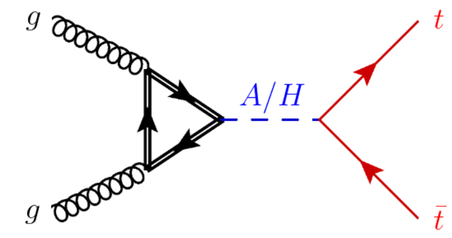




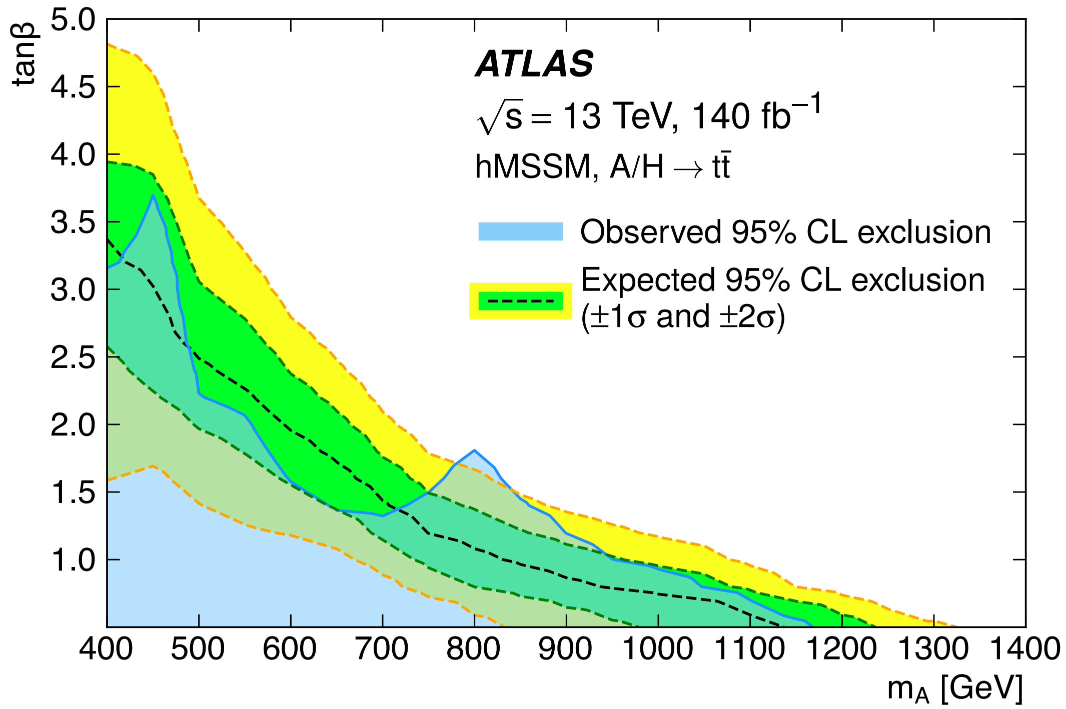
Largest deviation for ggΦ production at **m_ϕ = 100 GeV** with **local (global) significance of 3.1 (2.7) σ 2.6 (2.3) σ at 95 GeV.**

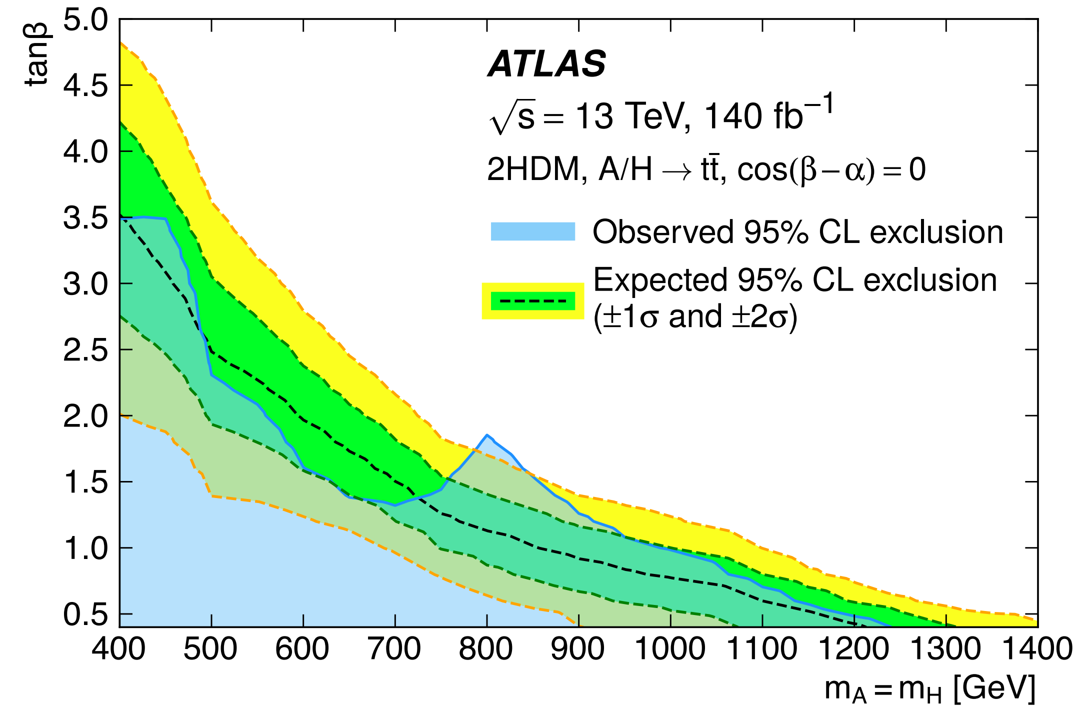
Heavy neutral Higgs bosons A/H→tt

- Extensions of the SM such as 2HDM, MSSM predicts additional Higgs bosons;
  - In the tt decay mode - dominant for small tanβ * values;
  - Looked into both boosted and resolved;
- Large interference with SM tt background;
- Reconstructed mass used as a final discriminant;



arXiv:2404.18986





No deviation from SM observed. Largest at 800 GeV at 2.3σ local significance.
2HDM (hMSSM) exclusion: tanβ < 3.49 (3.16) at 95% CL, for mA = mH = 400GeV,:
m_H < 1240 GeV for tanβ = 0.4 (m_H < 950 GeV for tanβ = 1.0);

* ratio of the vacuum expectation values of the two Higgs doublets,

Light LLP with displaced vertices (DV)

arXiv:2403.15332

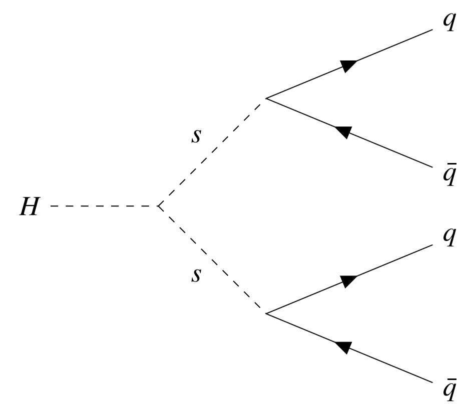
- Per-jet BDTs to select displaced jets, $BDT_{j0} \times BDT_{j1}$ as main discriminant;
- Displaced vertex reconstruction, search regions based on n_{DV};

No deviation from SM observed. 10 times improvement in B(H→ss→4q) w.r.t. previous result!

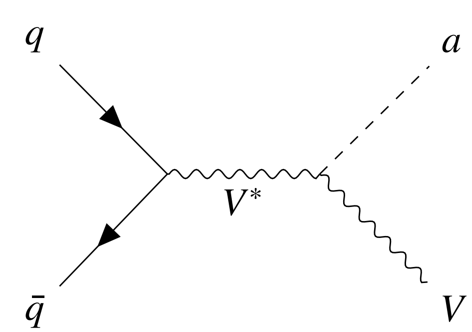
- Two more interpretations for ALPs (first of their kind):
  - ALP in association with W or Z;
  - Decay of top to ALP: t→aq.

B(H→ss→4q)

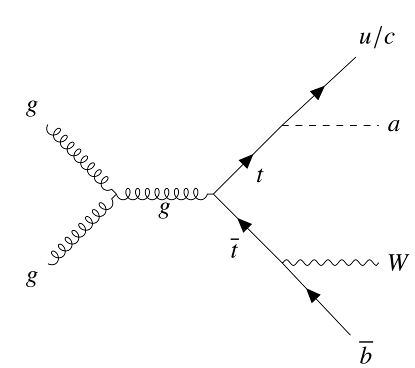
H→ss→4b for m_s = 16, 40, 55 GeV:
H→ss→4c for m_s = 5 GeV/

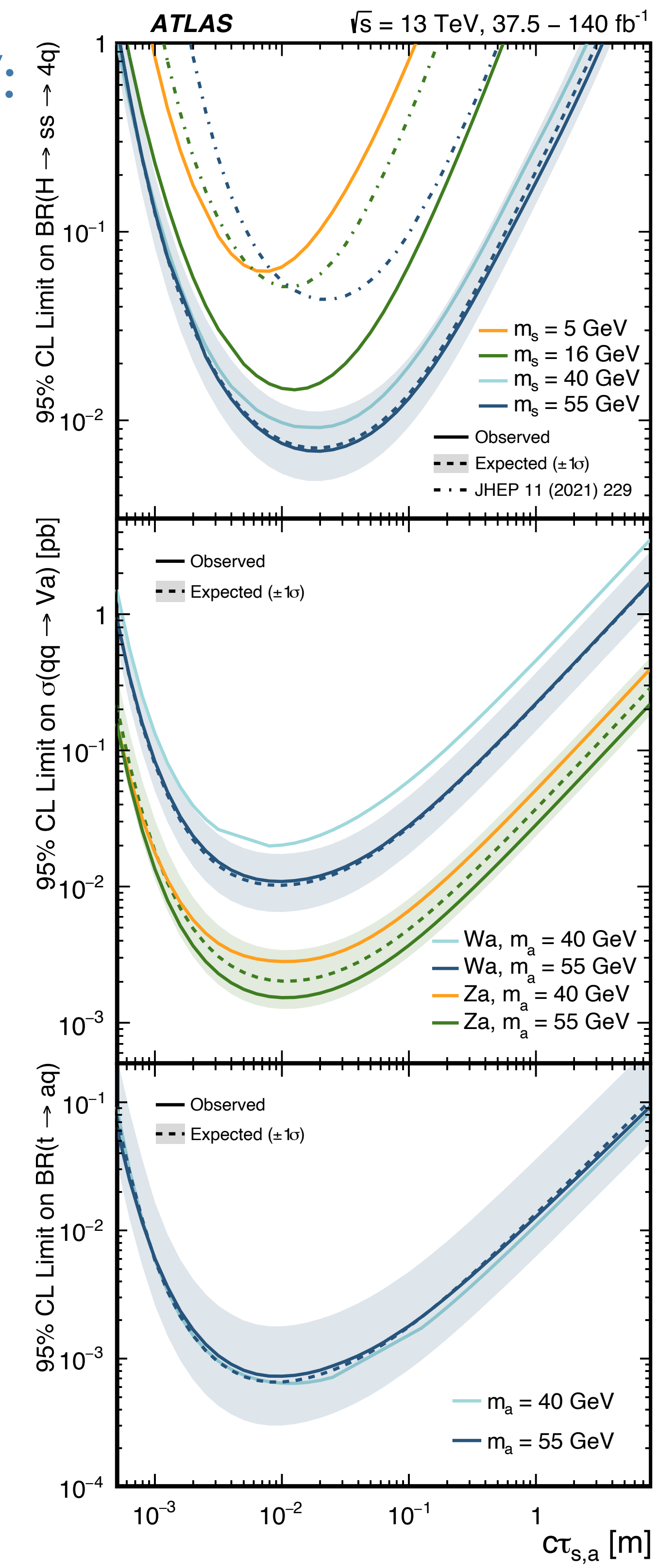


σ(qq→Va)



B(t→aq)



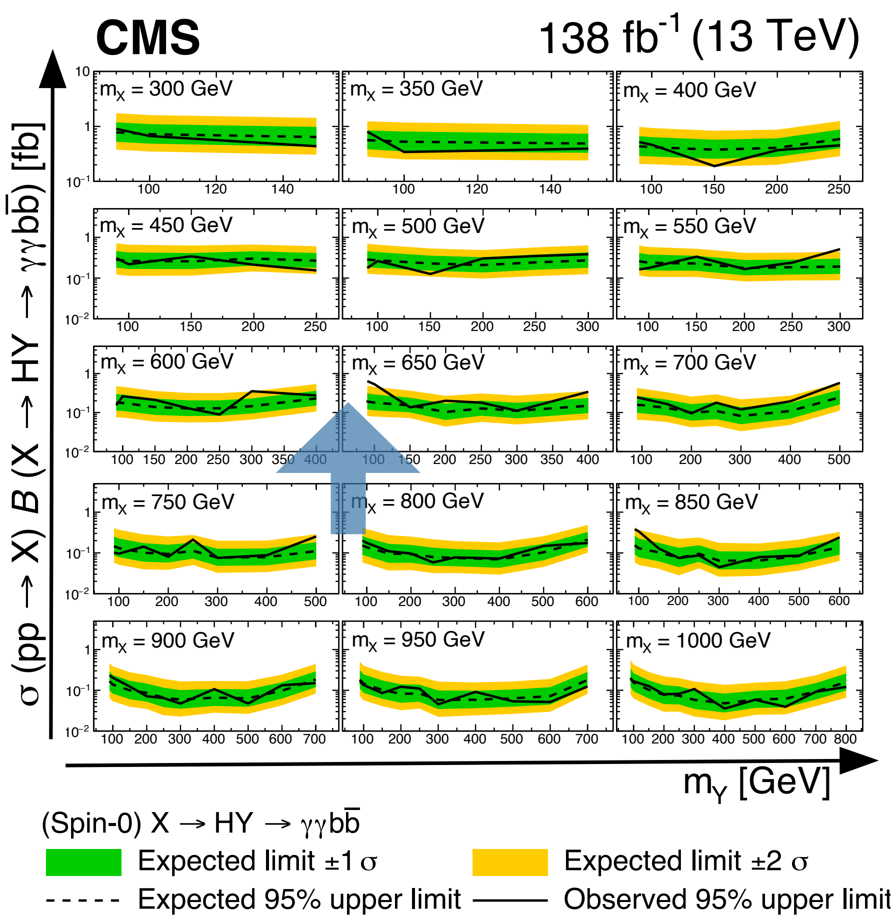


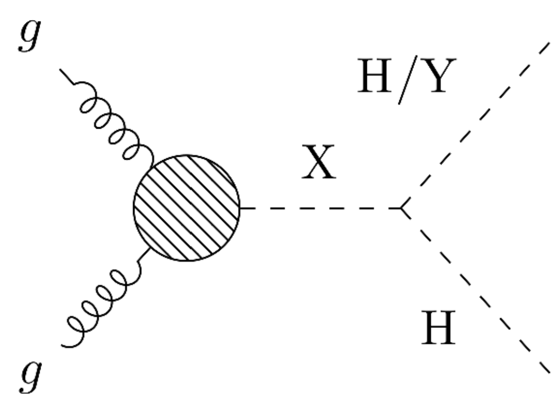
Search for heavy resonance X→YH

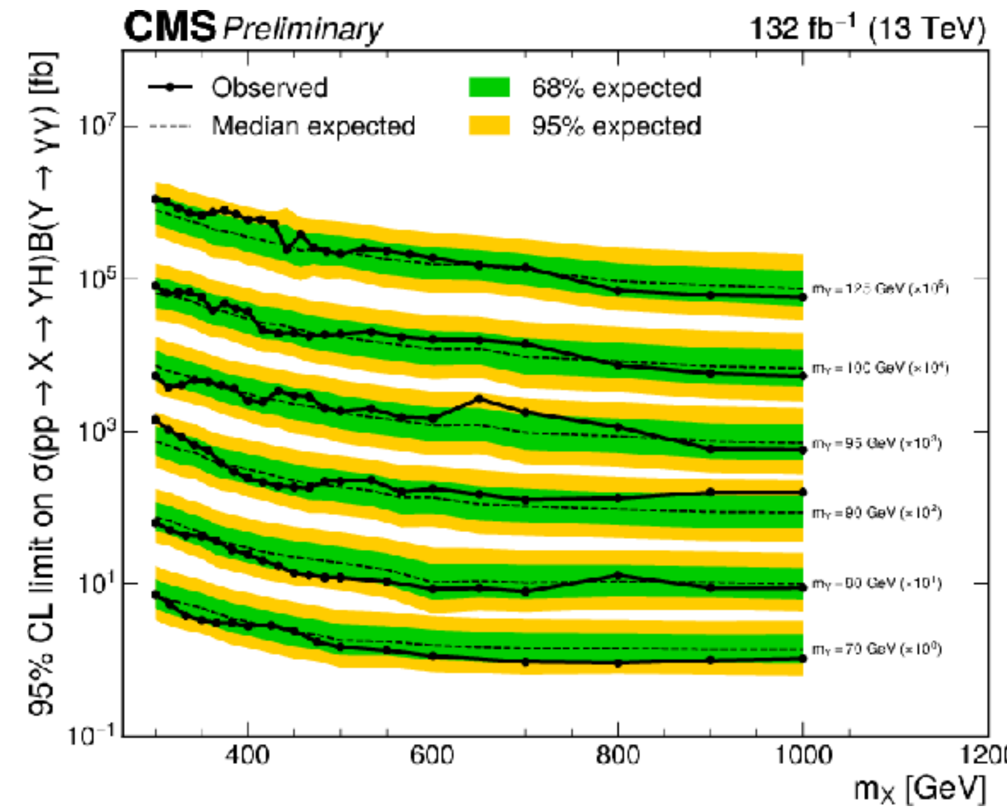
- Searches targeting resonance decaying to H and additional scalar Y;
  - Motivated by NMSSM, TRSM (SM extended by two real singlet fields) .

arXiv:2310.0164

CMS-PAS-HIG-22-012







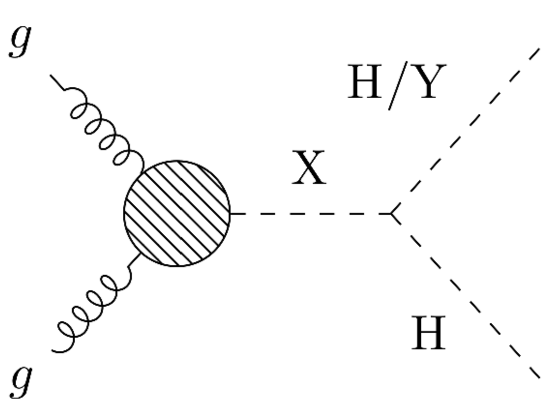
Most significant excess at
m_X = 650 GeV, m_Y = 90 GeV:
3.8 (2.8) σ local (global)
significance for Y(bb)H(γγ)

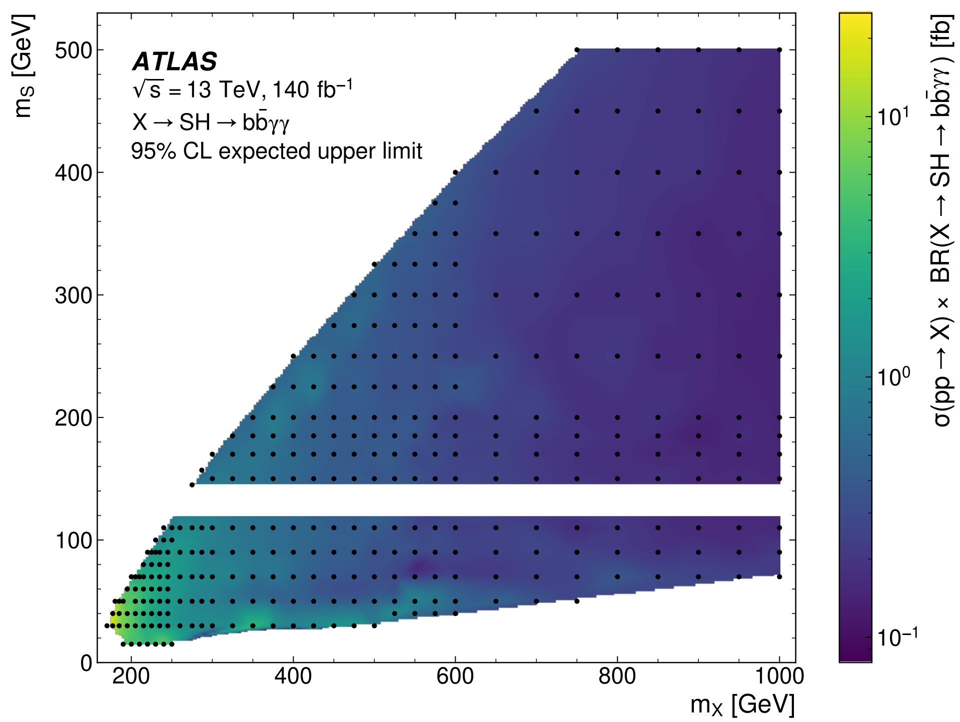
Mild excess seen in Y(γγ)H(ττ) at
m_X =650 GeV, m_Y = 95 GeV
with **2.3 σ local** significance
(but large LEE)

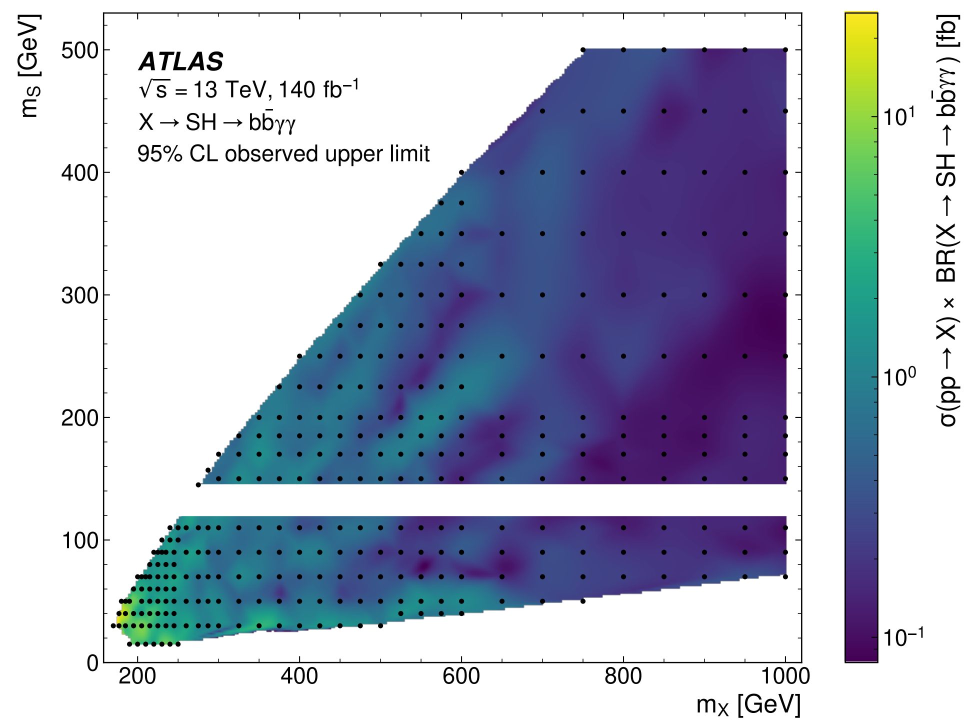
Search for heavy resonance X→YH

- Searches targeting resonance decaying to H and additional scalar Y;
    - Motivated by NMSSM, TRSM (SM extended by two real singlet fields) .

arXiv:2404.12915



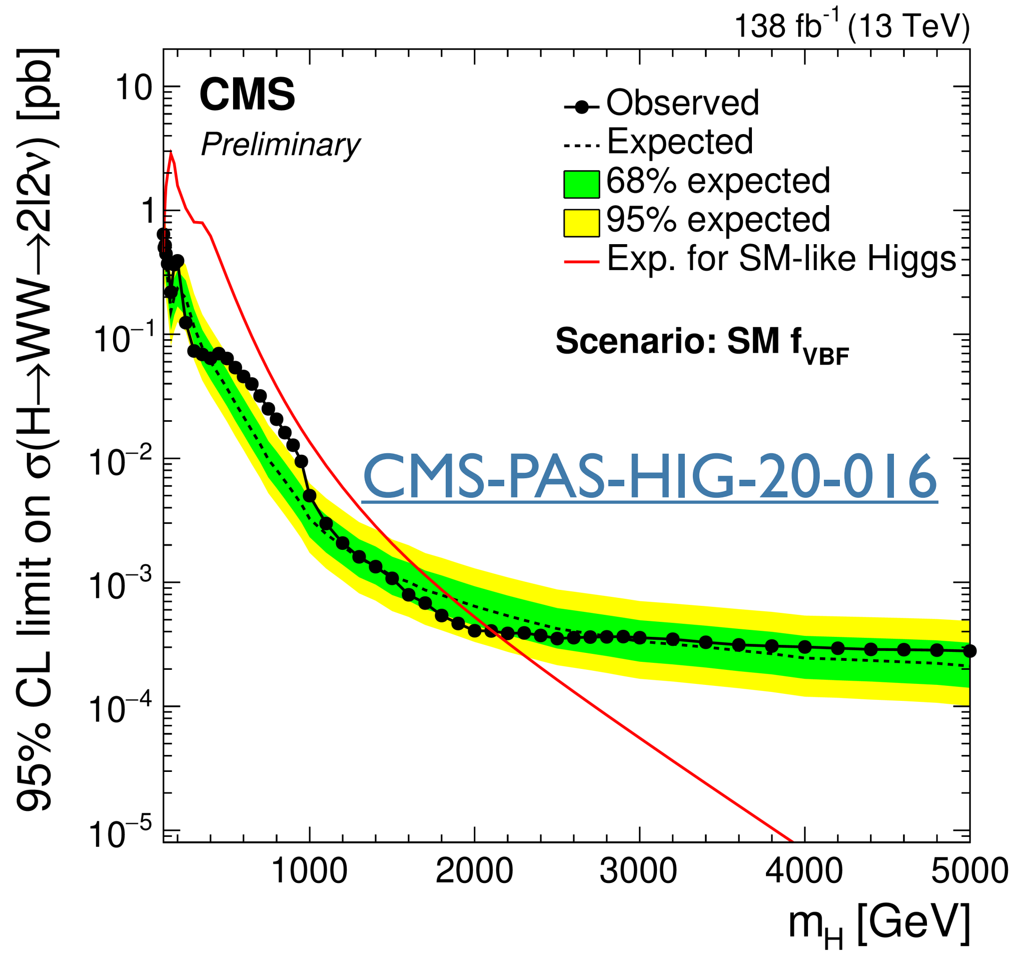




ATLAS X→Y(bb)H(γγ) search: largest deviation at $\mathbf{m_X}$ **= 575 GeV,** $\mathbf{m_Y}$**= 200 GeV** with **3.5 (2.0) σ local (global)** significance. No excess seen at same masses as CMS.

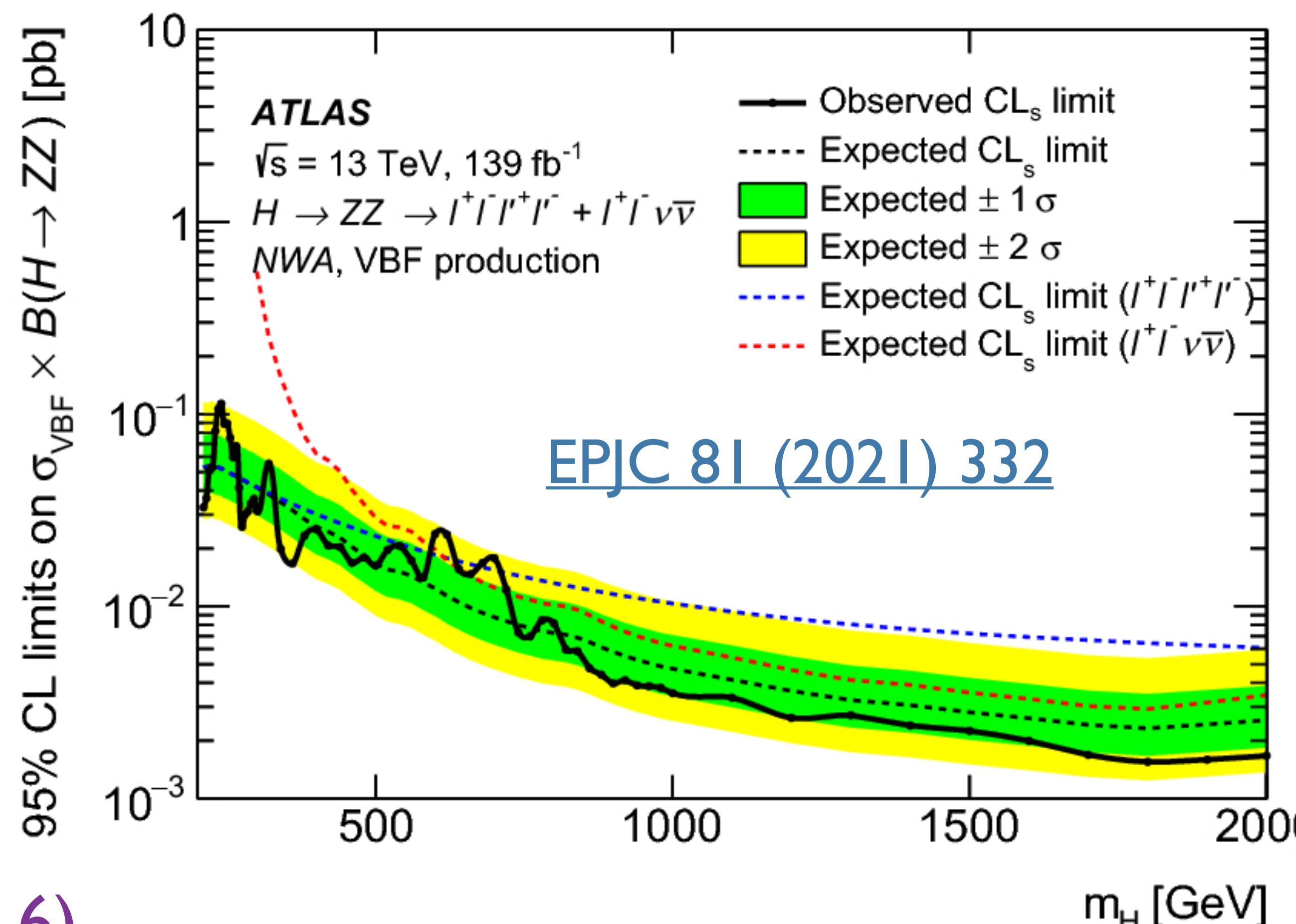
High mass WW and ZZ search

- Search for heavy resonance decaying to W^+W^- in $115 < m_{WW} < 5000$ GeV in 2l2ν final states from CMS.



Largest local (global) significance of 3.8 (2.6) σ found for $f_{VBF} = 1$ scenario at 650 GeV
No significant excess seen by ATLAS in its eμ2ν search (ATLAS-CONF-2022-066).

- Search for heavy resonance decaying to ZZ in $200 < m_{ZZ} < 2000$ GeV in 4l and 2l2ν final states from ATLAS. (in NWA, LWA and spin-2 resonance)



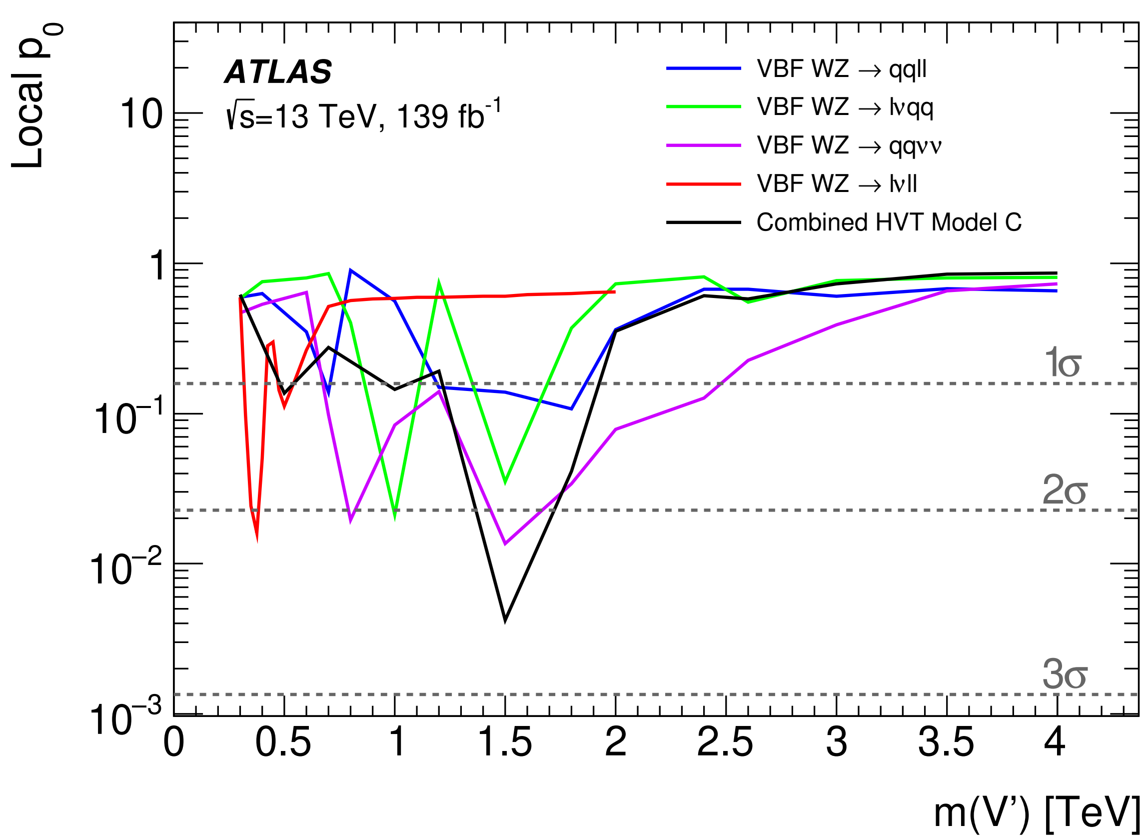
Largest local (global) significance of 2.4 (0.9) σ found for VBF mode scenario at 620 GeV

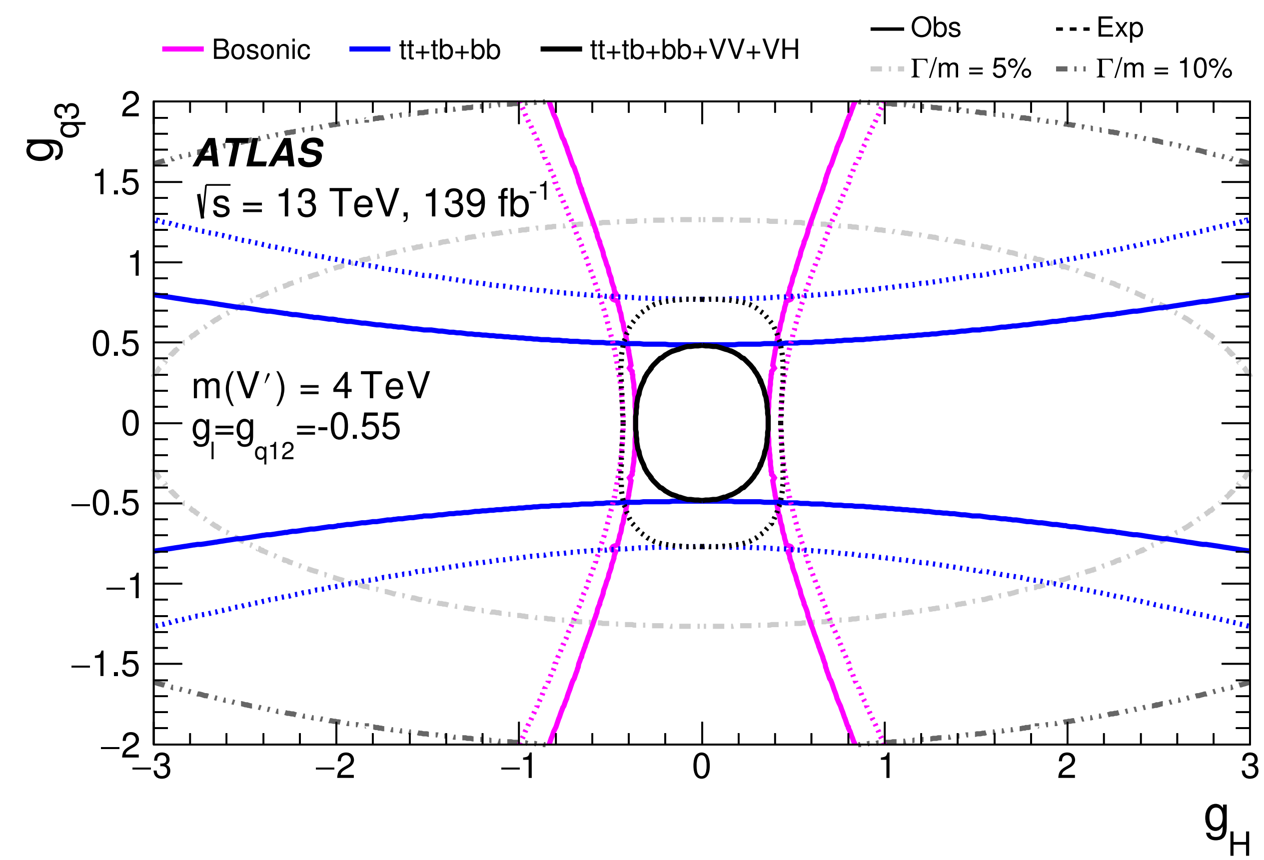
Heavy resonant combination

- Many combinations available: 2HDM+a, Heavy Resonance. 3rd Gen Leptoquark;

Heavy resonance combination:

- Combine searches for di-boson, di-quark, di-lepton resonances;
- Set limits on couplings of HVT model (gq, gl, gH...);
  - Consider benchmark coupling points, e.g. HVT model C (gH = 1, gf = 0), VBF production;





Full combination of all channels yields stringent limits, improving on previous result by up to 60% depending on resonance mass & spec. coupling parameters;

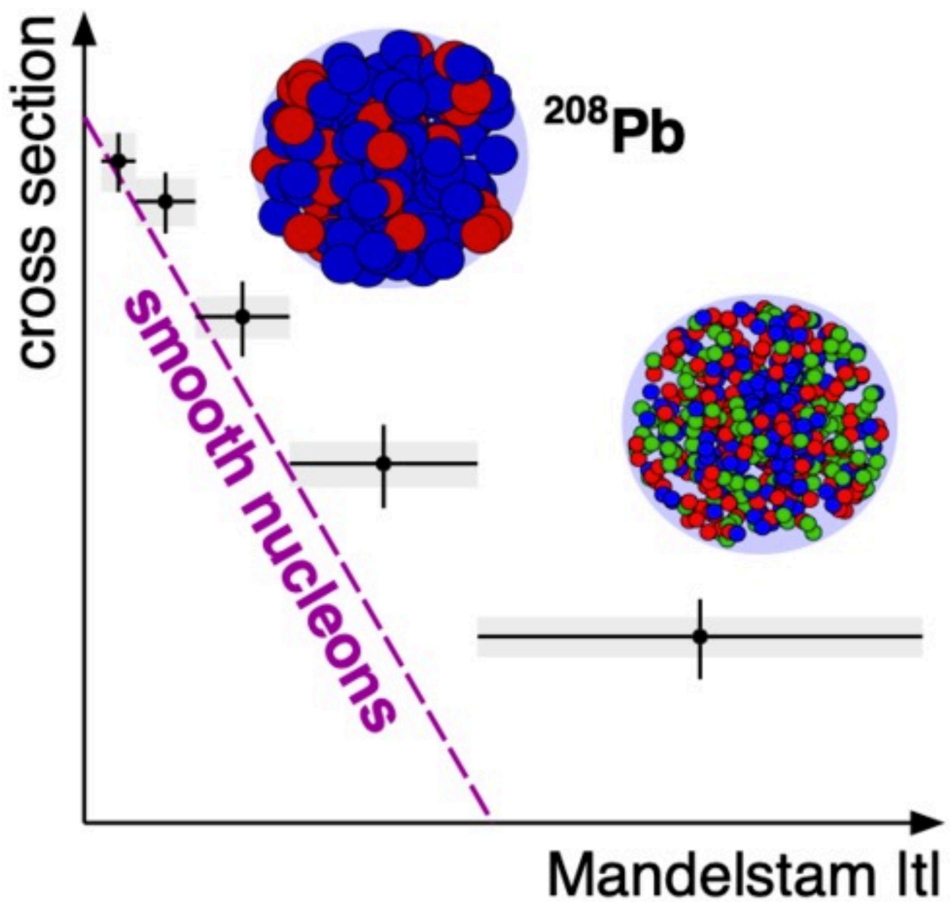
BSM searches summary

- Rich program of experimental searches for new physics at ATLAS and CMS;
  - No observation of BSM physics yet
- Some excesses seen at the 2-3 σ level worth following up:
- In extended Higgs sector: (low-mass $\gamma\gamma$, $\tau\tau$ (90-95 GeV), high-mass dibosons (~650 GeV);
- Some excesses exist in one, but not another experiment (see also backup);
- More results with Run 2 and Run 3 data soon.

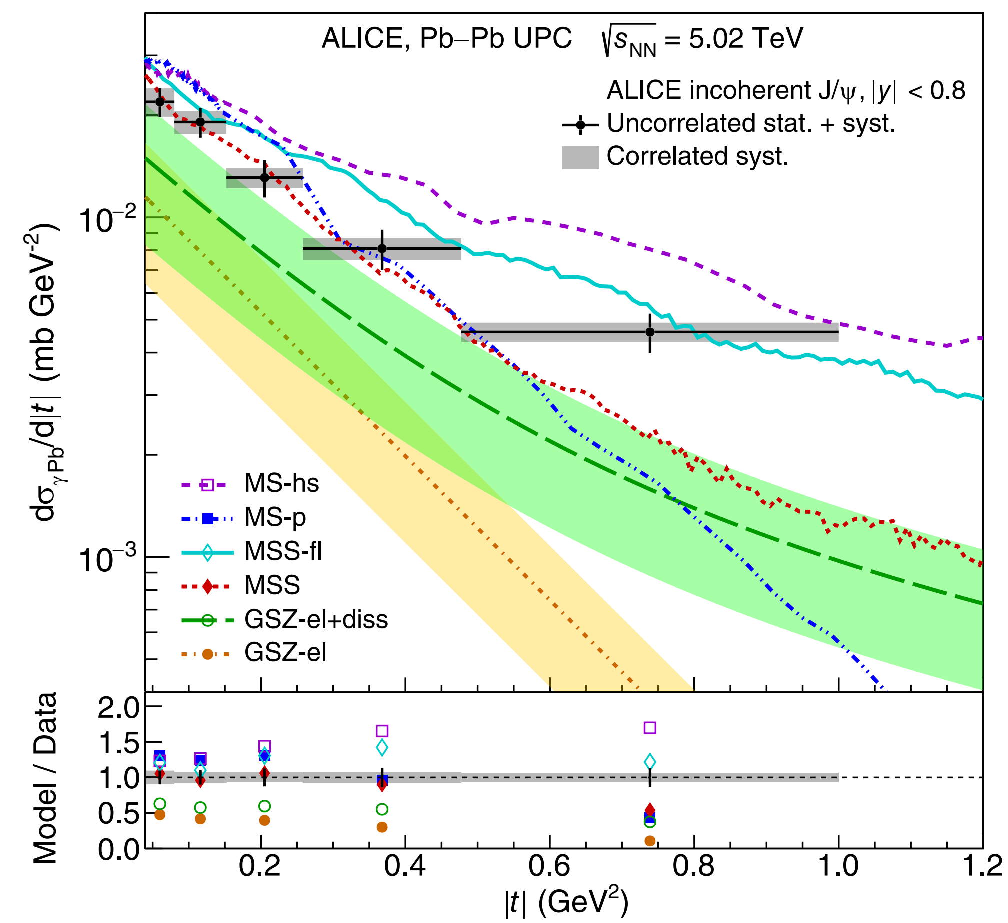
Heavy Ion physics

- Showing only most recent results;
- All results can be found on the ALICE public results page.

Incoherent J/ψ t-dependence



PRL 132, 162302 (2024)



- Gluonic subnucleon fluctuations needed to describe the data
- First measurement of this kind ever!
- Yet models fail to predict the normalisation

Antimatter/matter imbalance at the LHC

- New measurement of the antimatter/matter imbalance at the LHC;
- Statistical Hadronisation Model fits the measurements

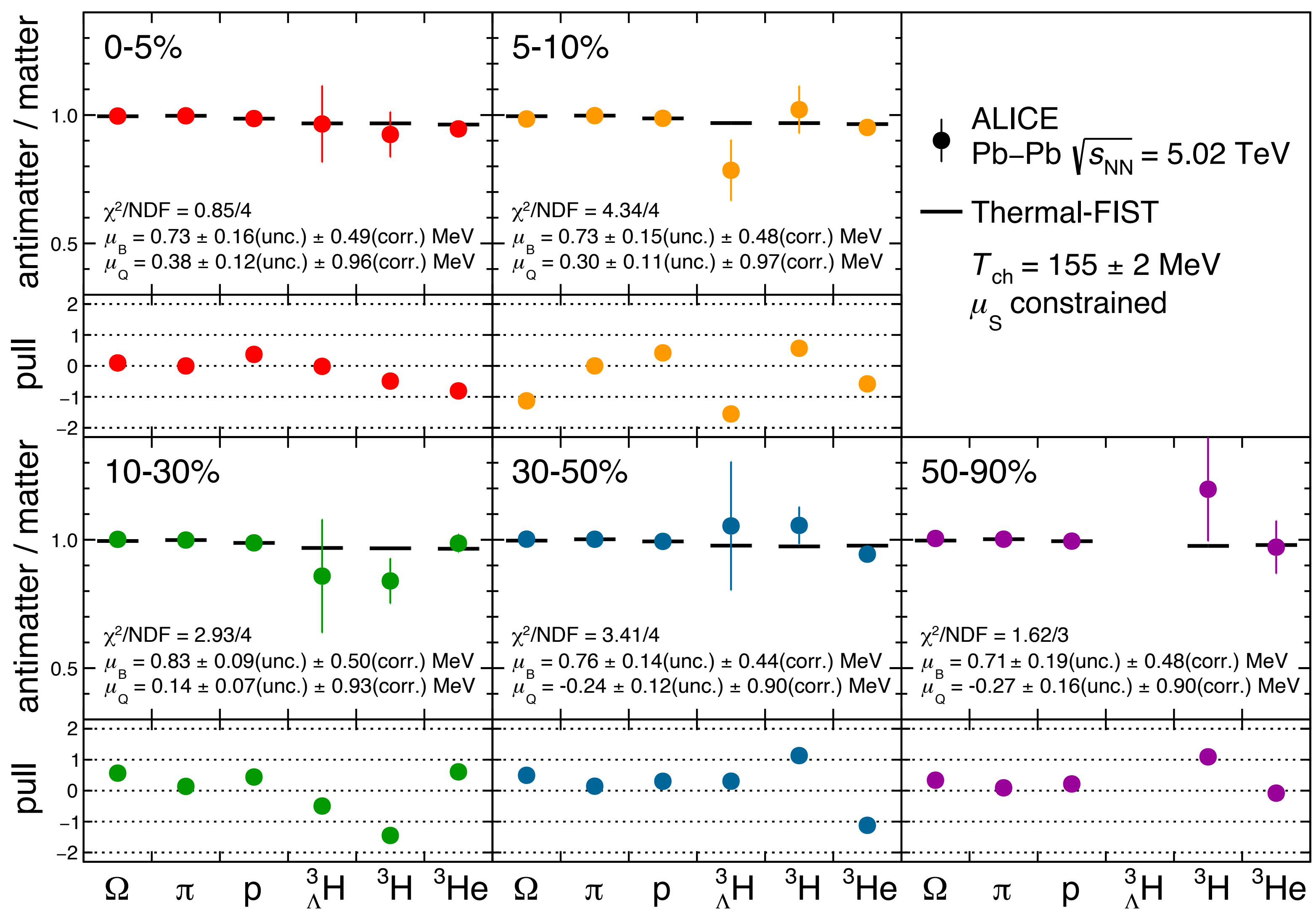
CERN-EP-2023-268

$$\frac{\bar{h}}{h} \propto e^{-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T}-2Q\frac{\mu_Q}{T}}$$

μ_B - baryon chemical potential, the net-baryon density of the system

μ_Q - electric charge potential, positive-negative charge imbalance of the gas

T = 155 ± 2 MeV from LQCD



Antimatter/matter imbalance at the LHC

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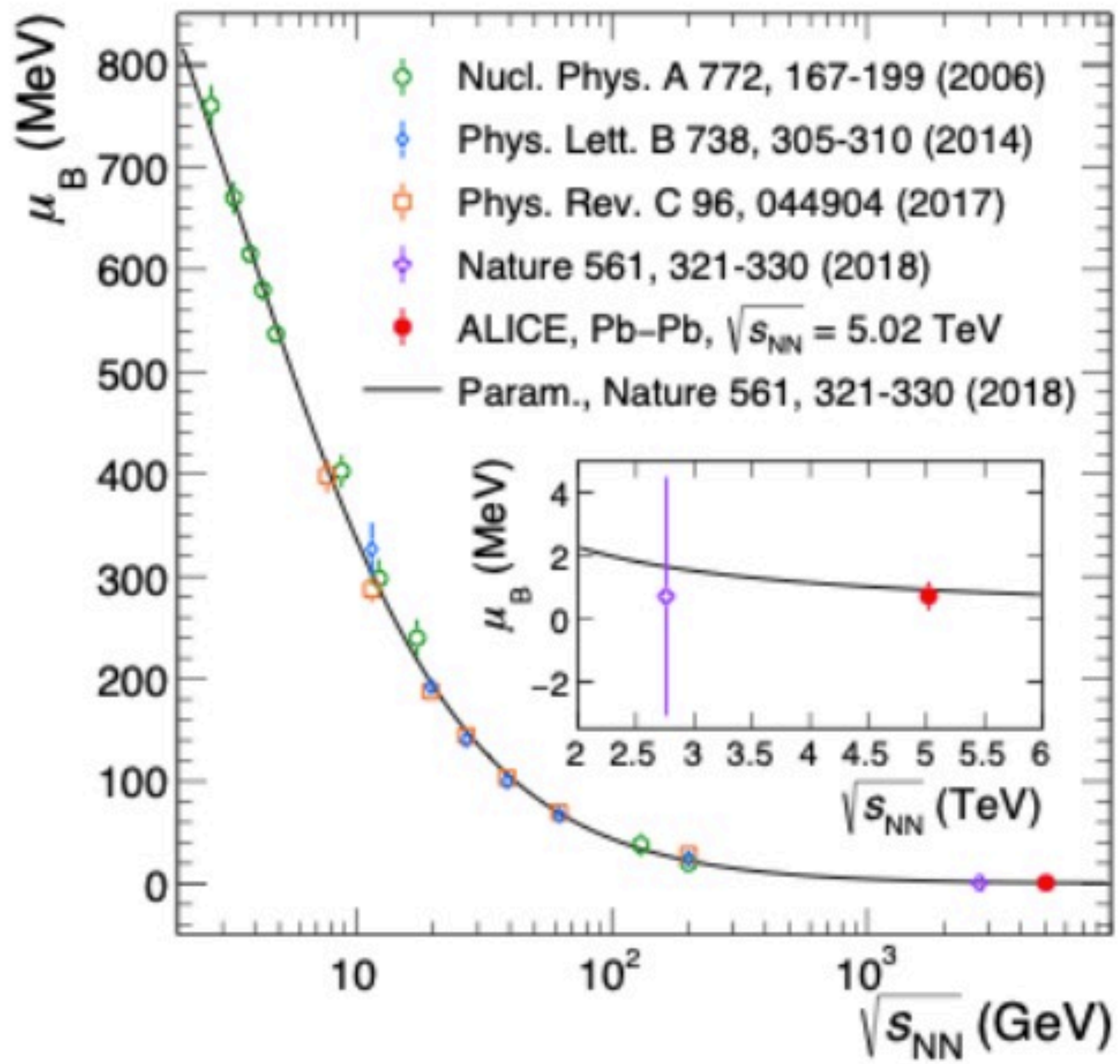
CERN-EP-2023-268

$$\frac{\bar{h}}{h} \propto e^{-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T}-2Q\frac{\mu_Q}{T}}$$

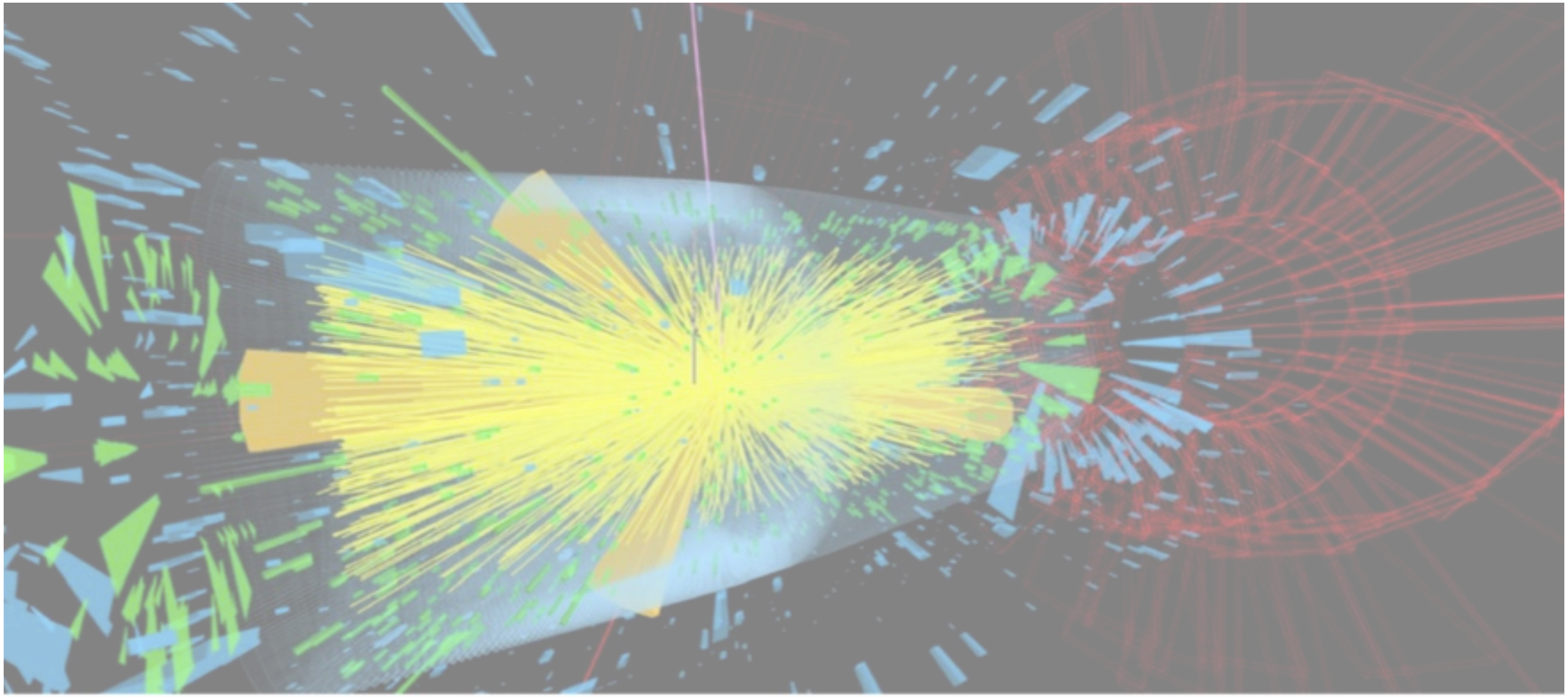


- From the fits : new determination of the baryochemical potential at hadronization with unprecedent precision:

$$\mu_B = 0.71 \pm 0.45 \text{MeV}$$

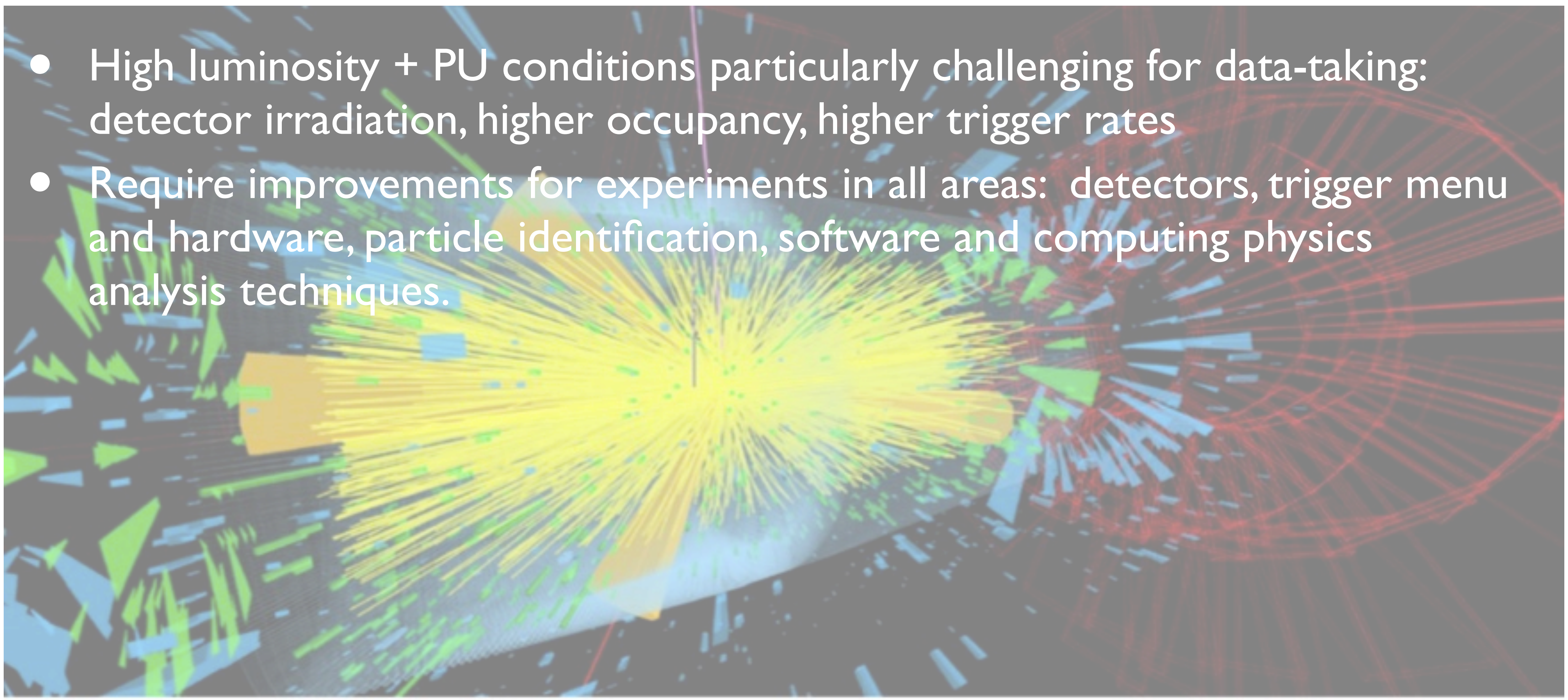
- Ø Net-baryon free system at the LHC for|y|< 0.5. μ_B close to 0 at LHC

HL-LHC prospects



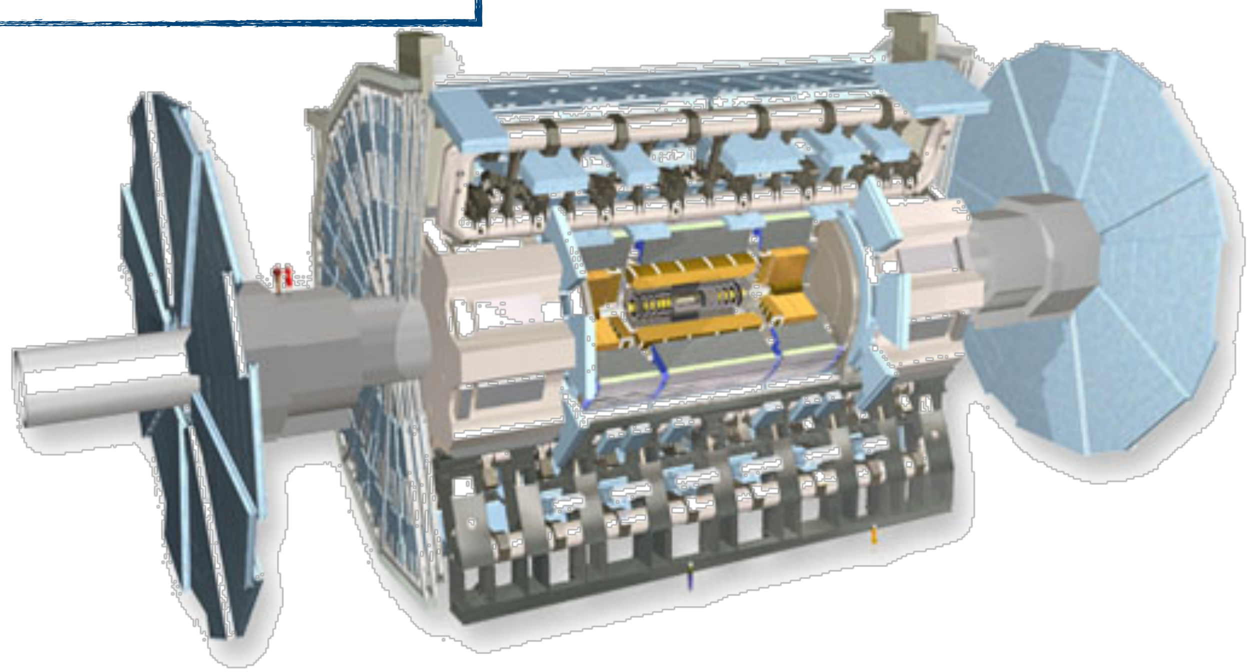
HL-LHC prospects

- High luminosity + PU conditions particularly challenging for data-taking: detector irradiation, higher occupancy, higher trigger rates
- Require improvements for experiments in all areas: detectors, trigger menu and hardware, particle identification, software and computing physics analysis techniques.

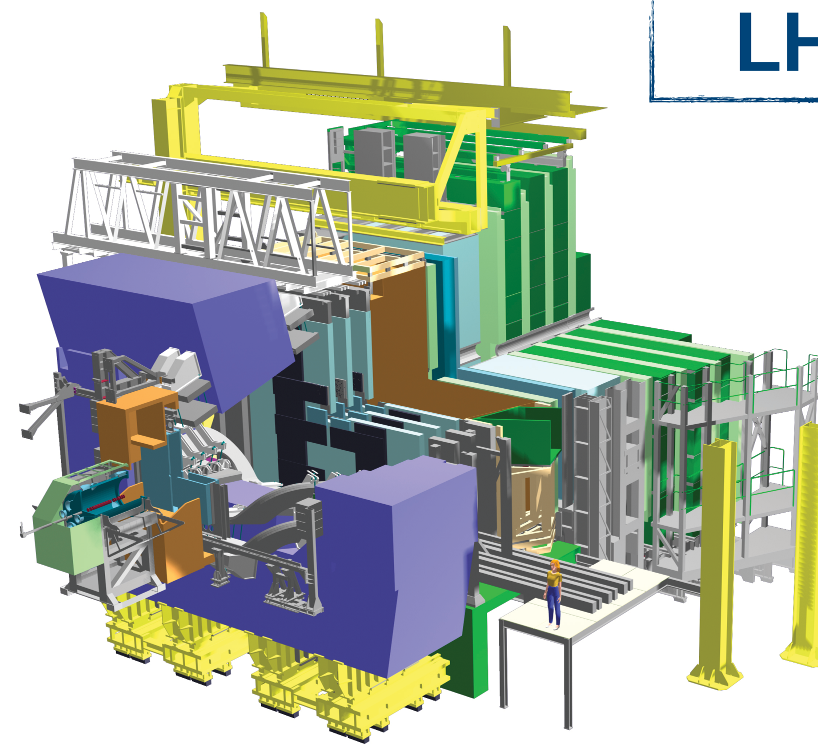


Upgraded detectors at HL-LHC

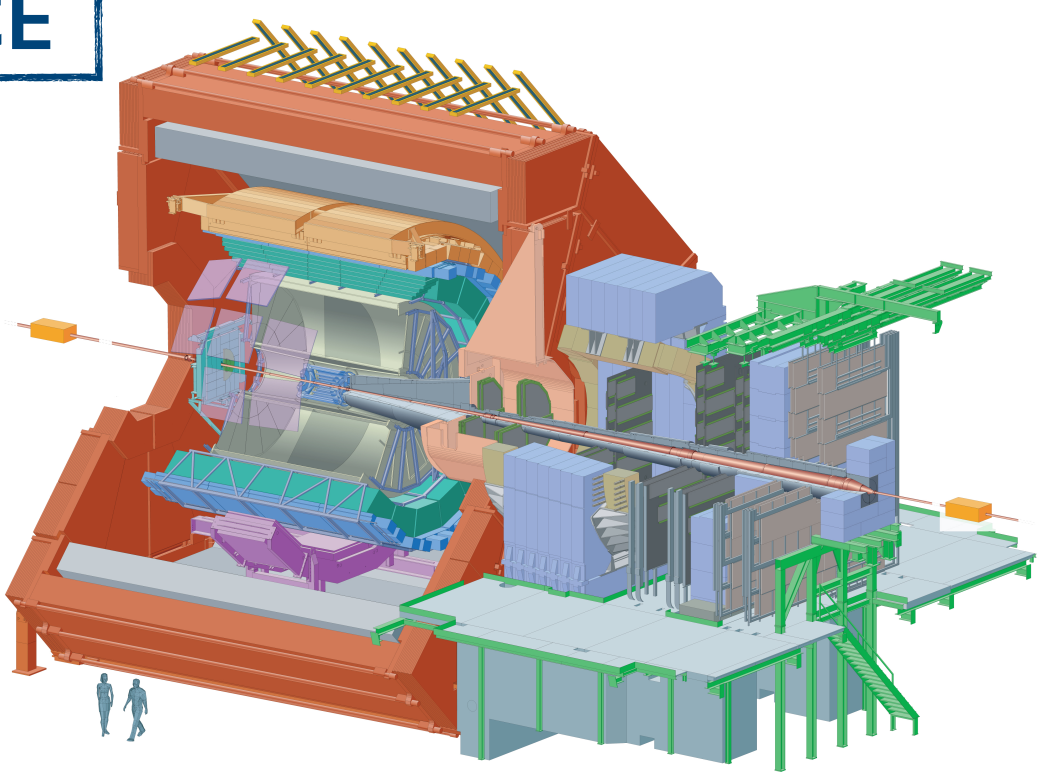
ATLAS



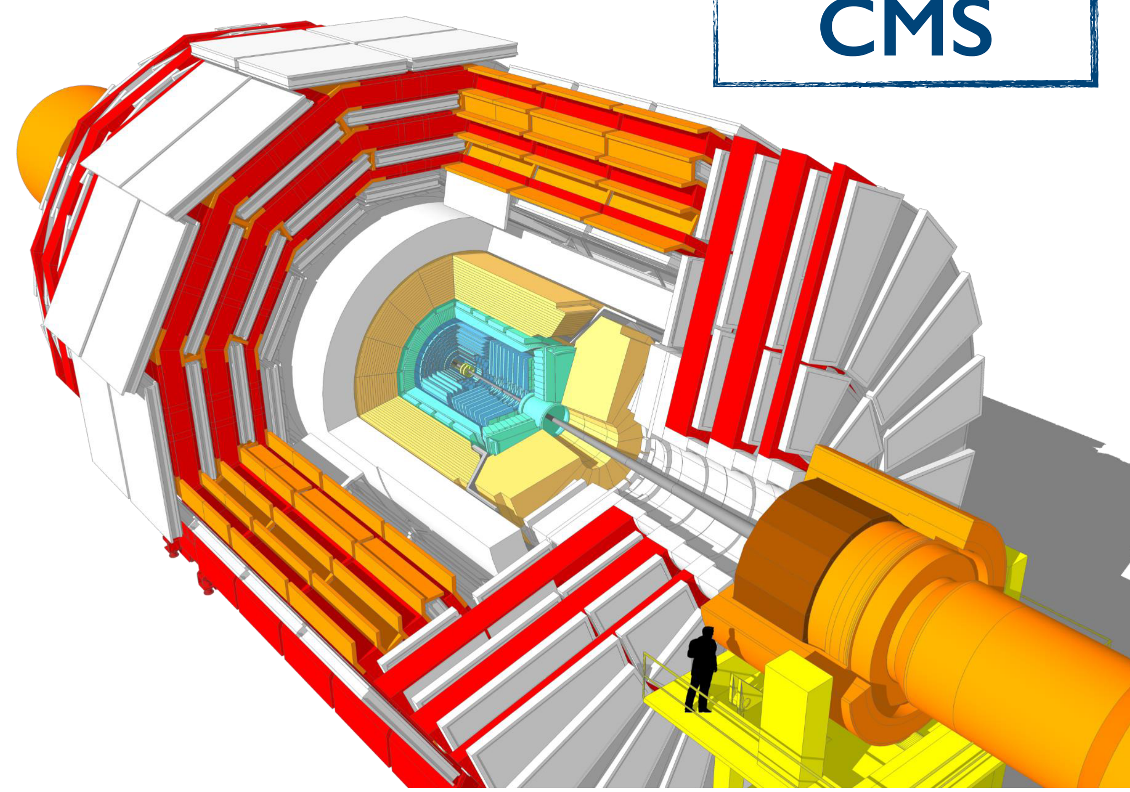
LHCb



ALICE

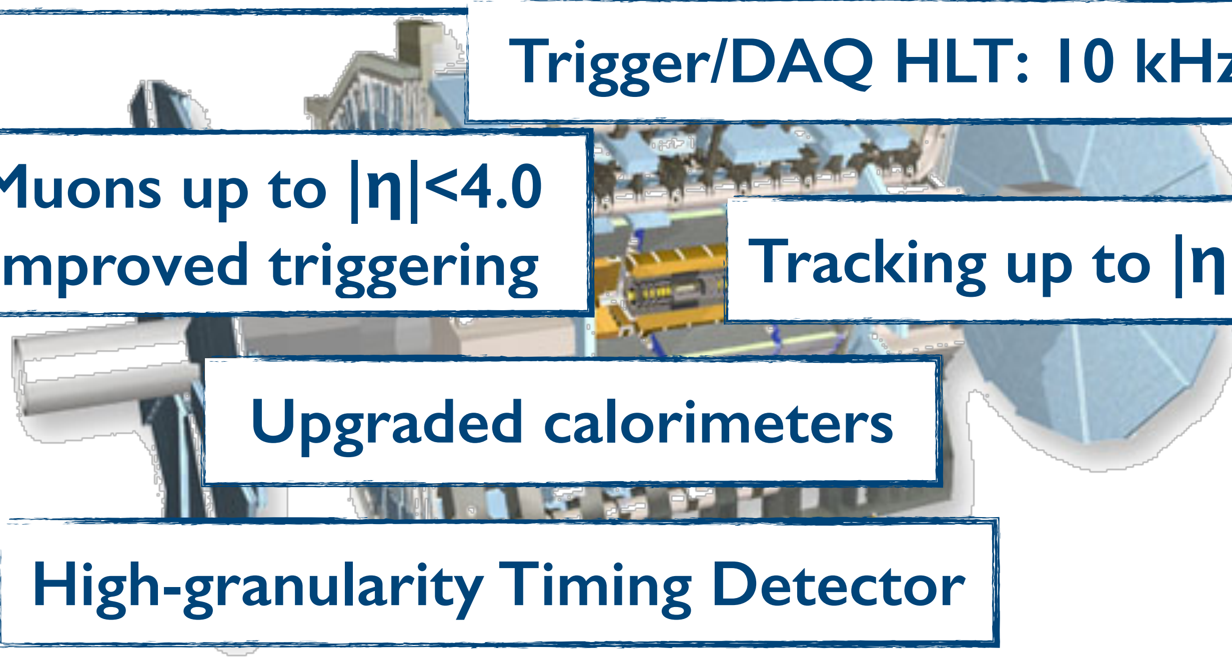


CMS



Upgraded detectors at HL-LHC

ATLAS



Trigger/DAQ HLT: 10 kHz

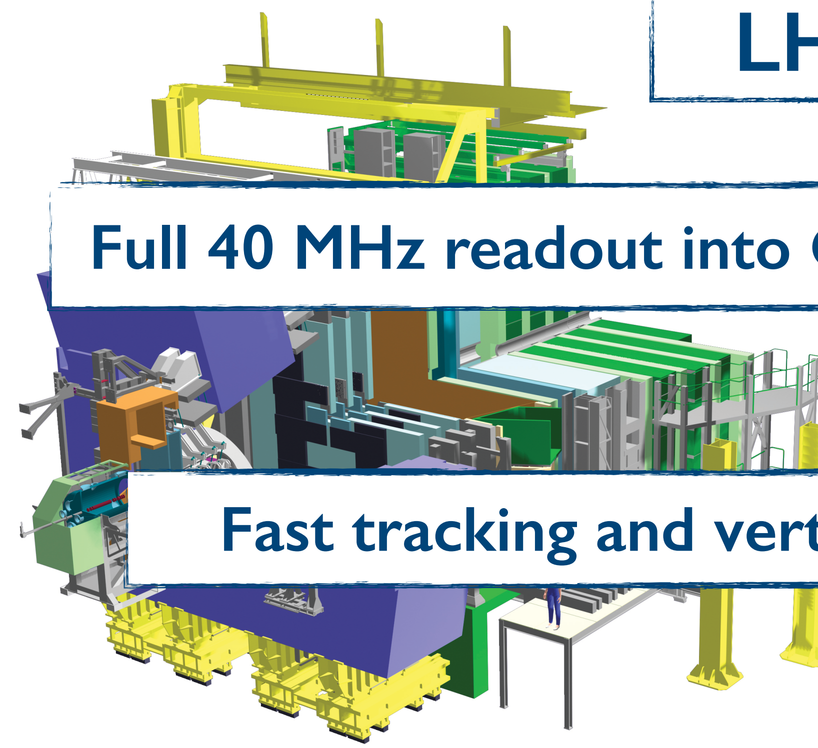
Muons up to |η|<4.0
Improved triggering

Tracking up to |η|<4.0

Upgraded calorimeters

High-granularity Timing Detector

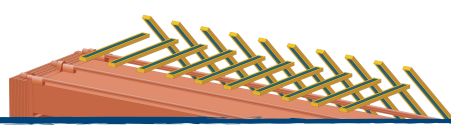
LHCb



Full 40 MHz readout into CPU farm

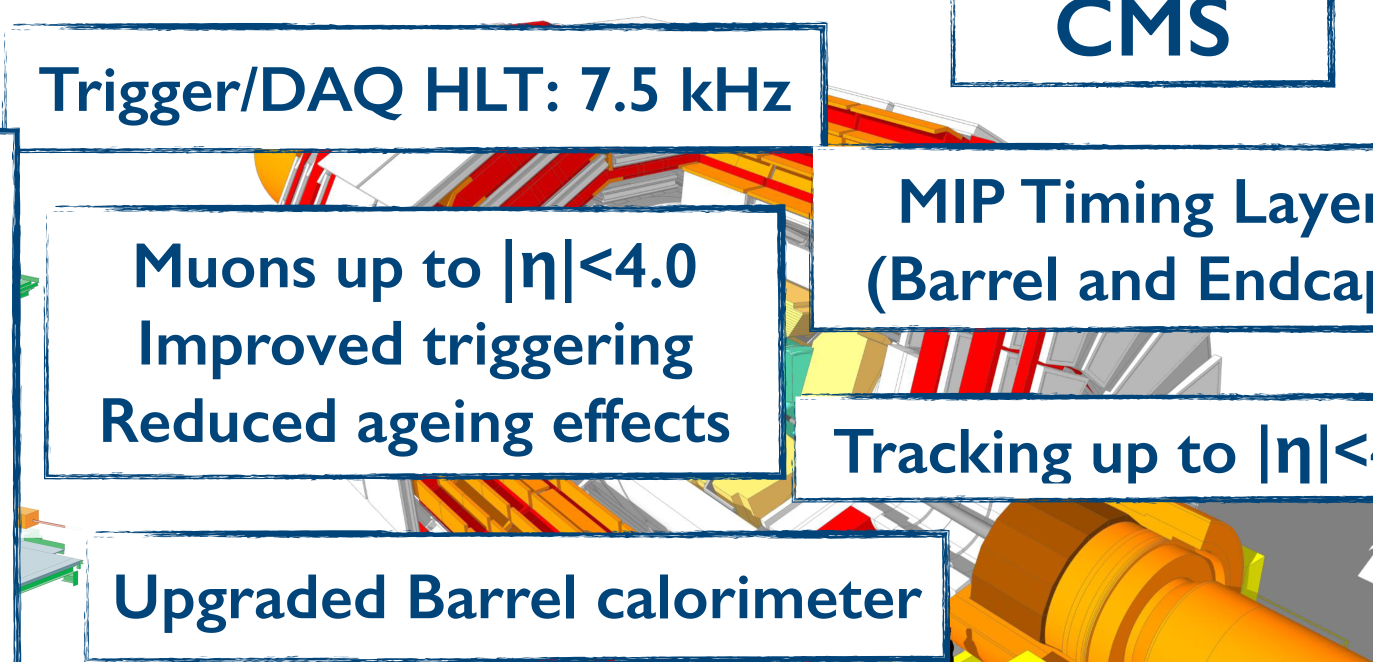
Fast tracking and vertexing

ALICE



LS3 plan: Forward caloremeters
Inner Tracking System 3.
LS4: New apparatus: compact and lightweight all-silicon tracker, retractable vertex detector, large acceptance, superconducting magnet system, continuous read-out and online processing.

CMS



Trigger/DAQ HLT: 7.5 kHz

MIP Timing Layer
(Barrel and Endcap)

Muons up to |η|<4.0
Improved triggering
Reduced ageing effects

Tracking up to |η|<4.0

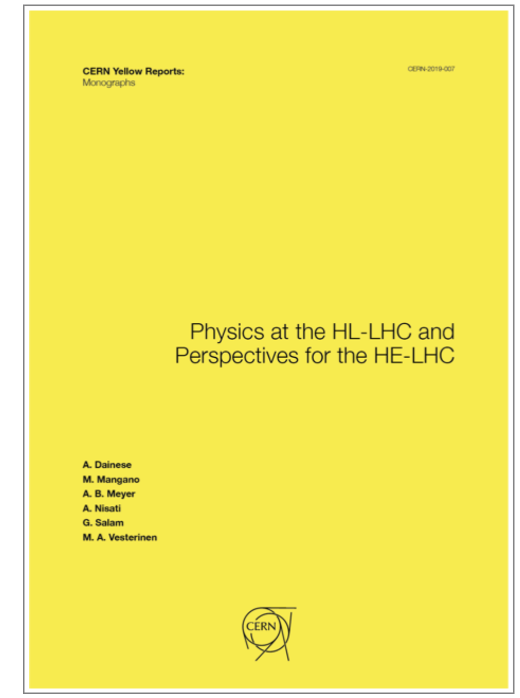
Upgraded Barrel calorimeter

High-granularity Endcap Calorimeter

Physics prospects for HL-LHC

HL-LHC projection results:

- Documented in 2018 Yellow Report [CERN-2019-007] with substantial update in the Snowmass2021 report [ATL-PHYS-PUB-2022-018];
- Based on extrapolations of (partial/full) Run-2 results to HL-LHC luminosity using parametric simulations of upgraded detectors;


CERN Yellow Reports: Monographs
CERN-2019-007

Physics at the HL-LHC and Perspectives for the HE-LHC

A. Dainese
M. Mangano
A. B. Meyer
A. Nisati
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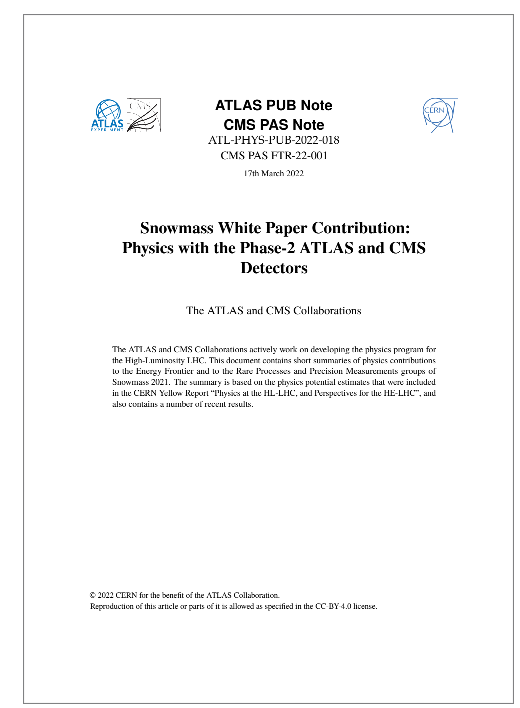
Extremely rich and exciting physics program ahead:

- **Higgs physics**: precise determination of Higgs properties, probing of small Higgs couplings;
- **Standard Model**: ultimate precision measurement of fundamental SM parameters, constraints on new physics through EFT interpretations;
- **Beyond Standard Model**: direct improvement in mass reach for many models, new analysis techniques can help close gaps in unexplored regions of phase space;
- **HI physics**: low-mass di-electrons ($\rightarrow$ QGP temperature), gluon nPDF at low Bjorken-x, exotic charm nuclei;


ATLAS PUB Note
CMS PAS Note
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
17th March 2022

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

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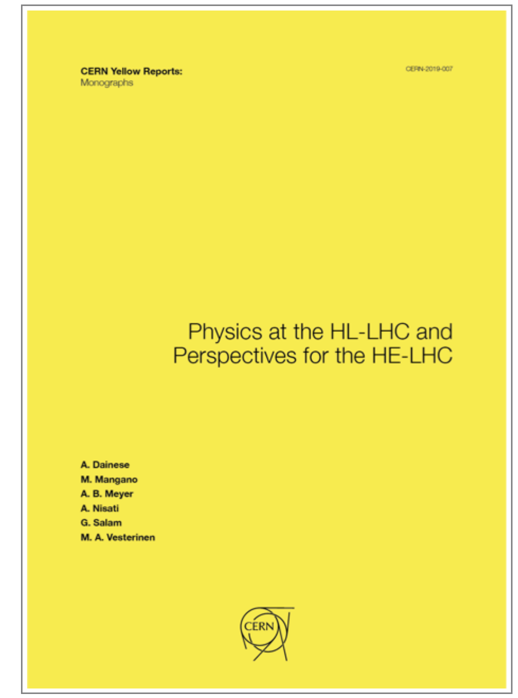

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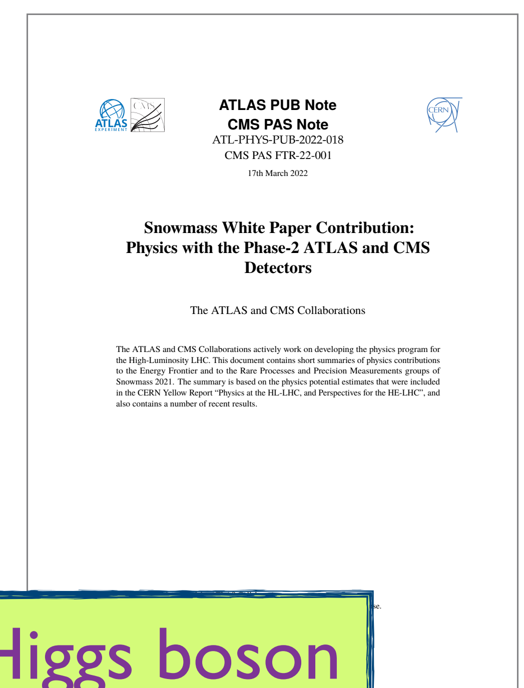
- HI p
gluo



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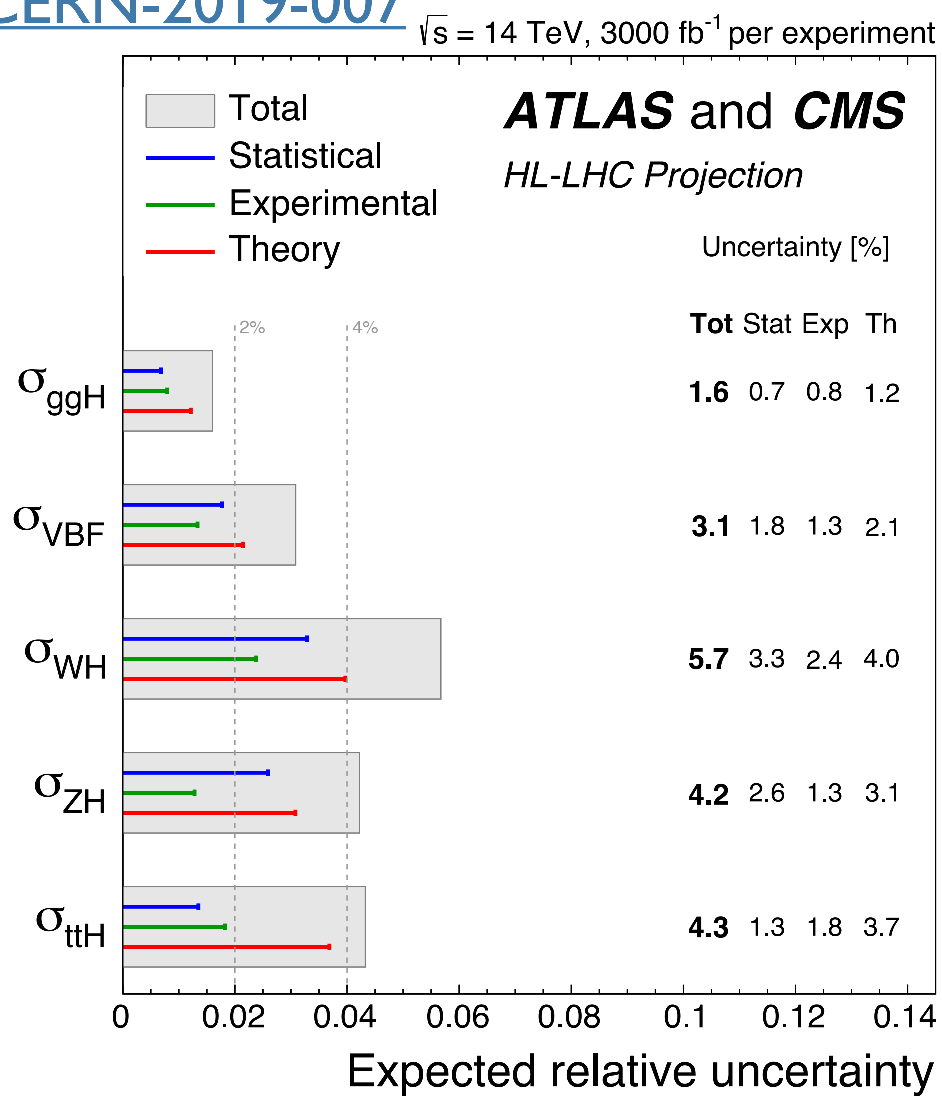
Only selected results will be shown, with main accent on Higgs boson production and properties.

Higgs boson cross-section and couplings

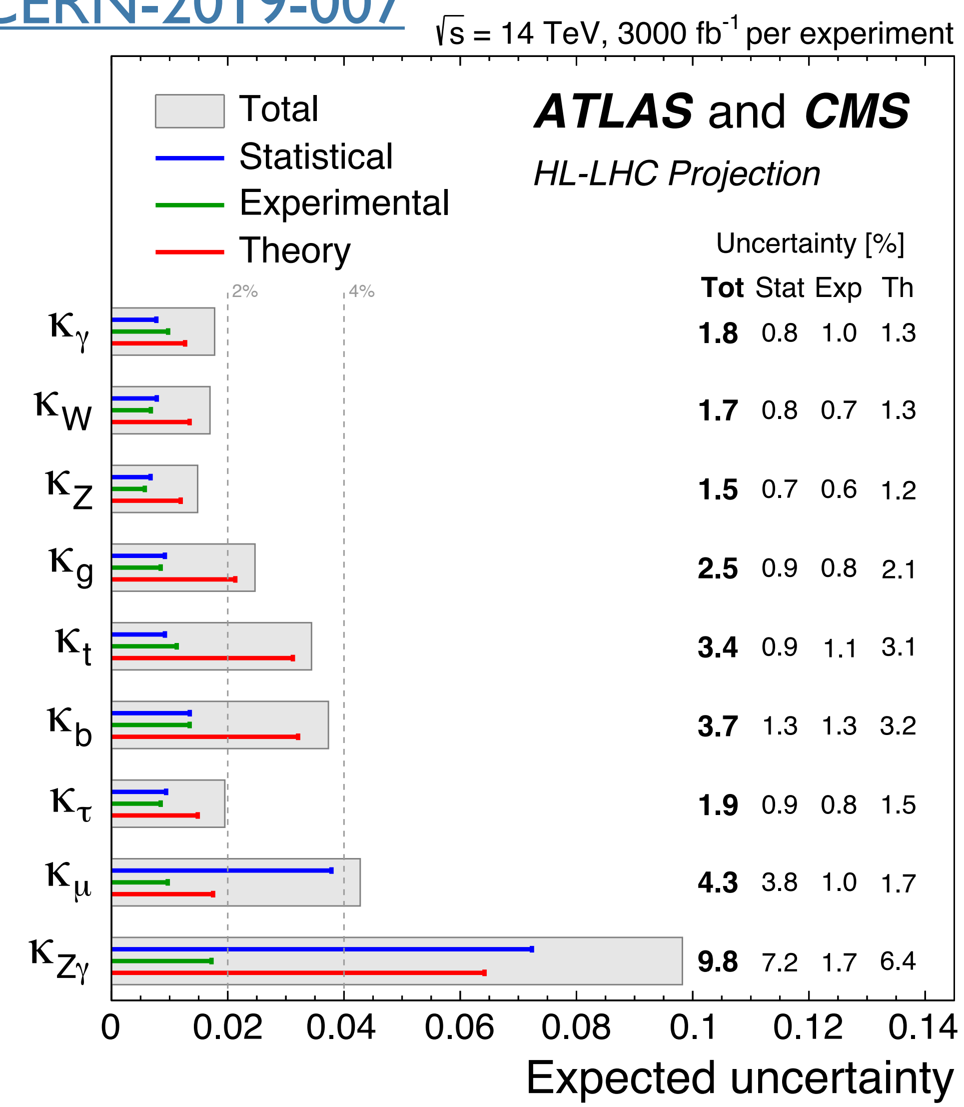
Production cross-sections

CERN-2019-007



Coupling modifiers

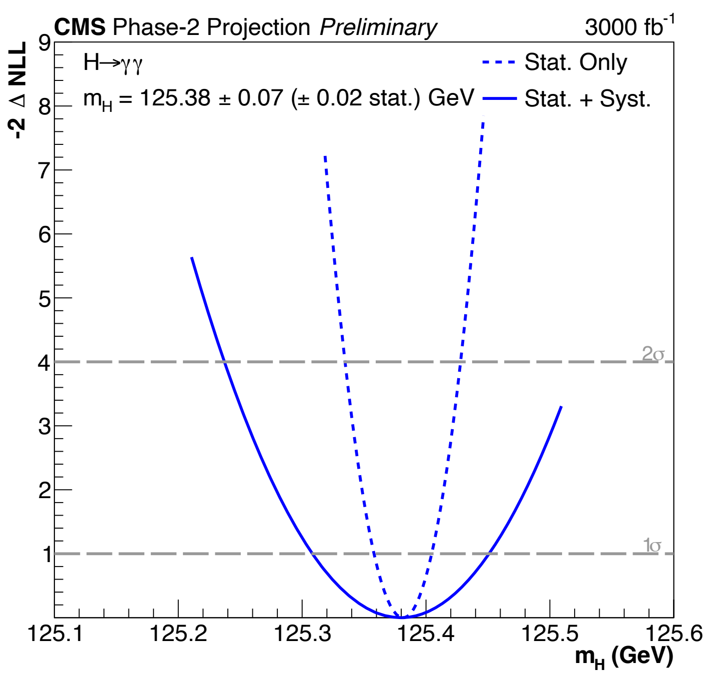
CERN-2019-007



- Expected precision reaching 2 - 5% at the end of HL-LHC (CMS+ATLAS)
- Large impact of theory uncertainty in many cases (despite being halved).

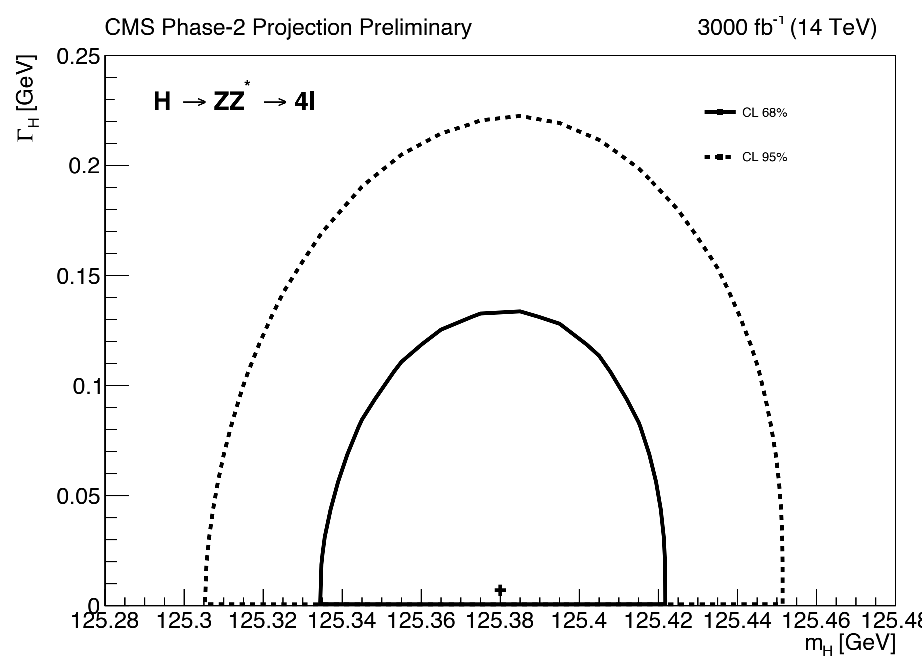
Higgs mass, width, differential & STXS

Mass in H→γγ



[CMS-PAS-FTR-21-008]

Mass vs width in H→ZZ→4l

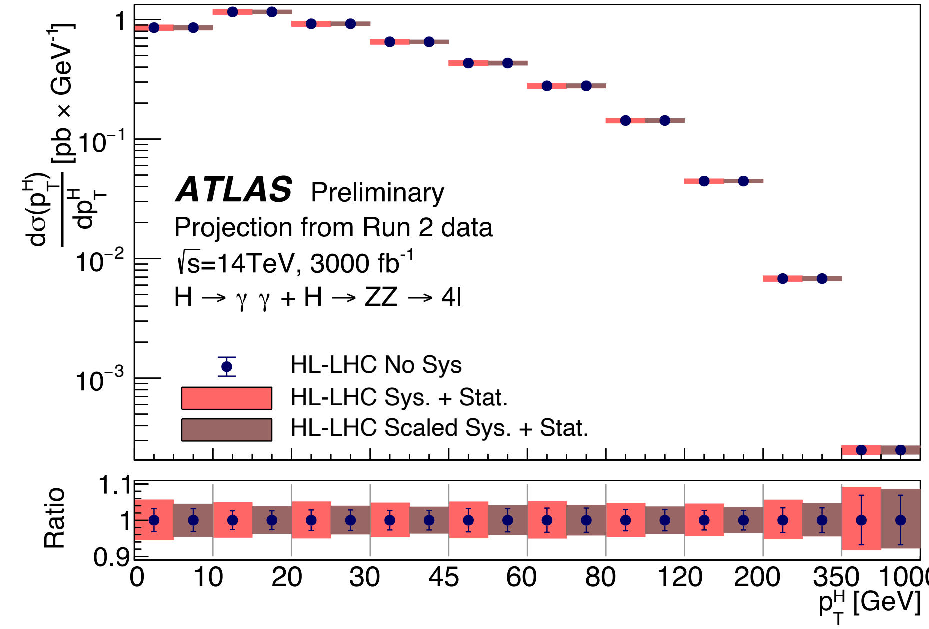


[CMS-PAS-FTR-21-00]

- $H\rightarrow\gamma\gamma$: Total uncertainty on m_H: 70 MeV Limited by photon energy scale (~0.05%)
- $H\rightarrow ZZ$: Total uncertainty on m_H: ~30 MeV comparable stat. and syst. uncertainties
- Direct constraint on width: Γ_H < 177 MeV

Differential and STXS

[CERN-2019-007]



- Expected to reach ~5% except in the highest $p_T(H)$ bin. Powerful to constraint light quark Yukawa couplings

STXS

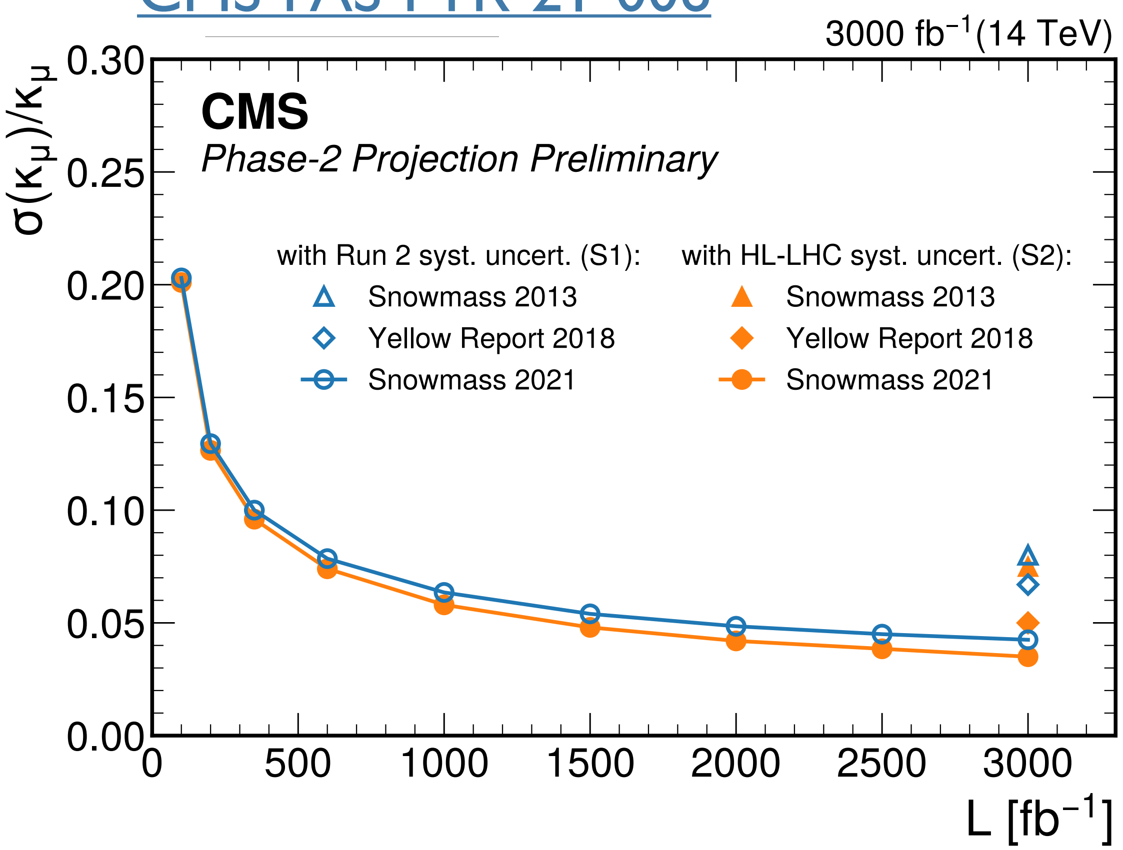
- Expected precision reaching 5 - 20% in most current STXS bins

Couplings to second generation

$H \to \mu\mu$

- Evidence already at Run 2;

CMS-PAS-FTR-21-006

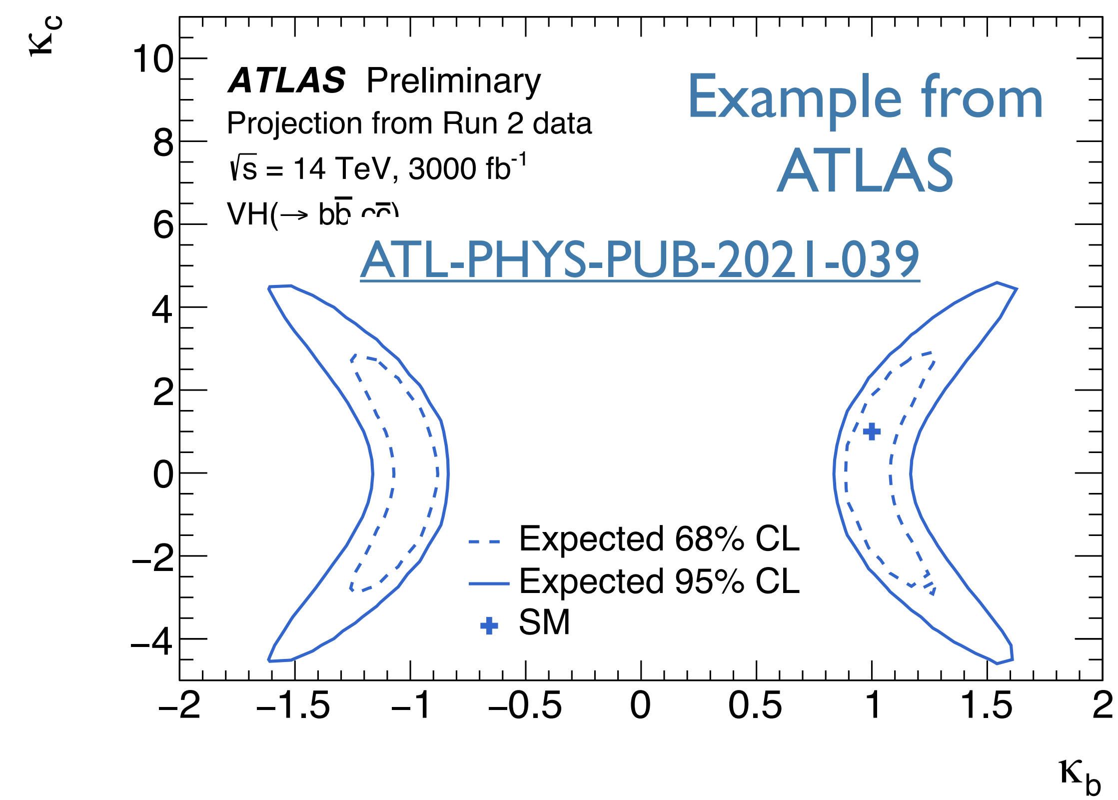


- 3 - 4% uncertainty on κ_μ at HL-LHC

$H \to cc$

Example from ATLAS

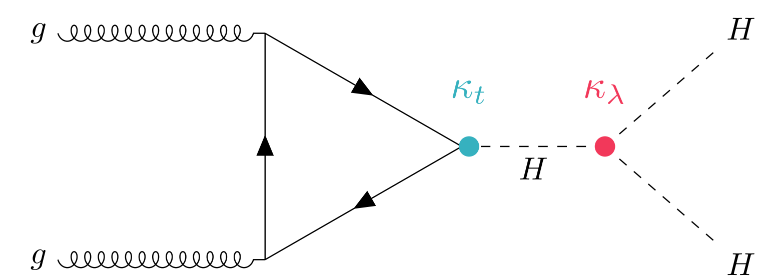
ATL-PHYS-PUB-2021-039

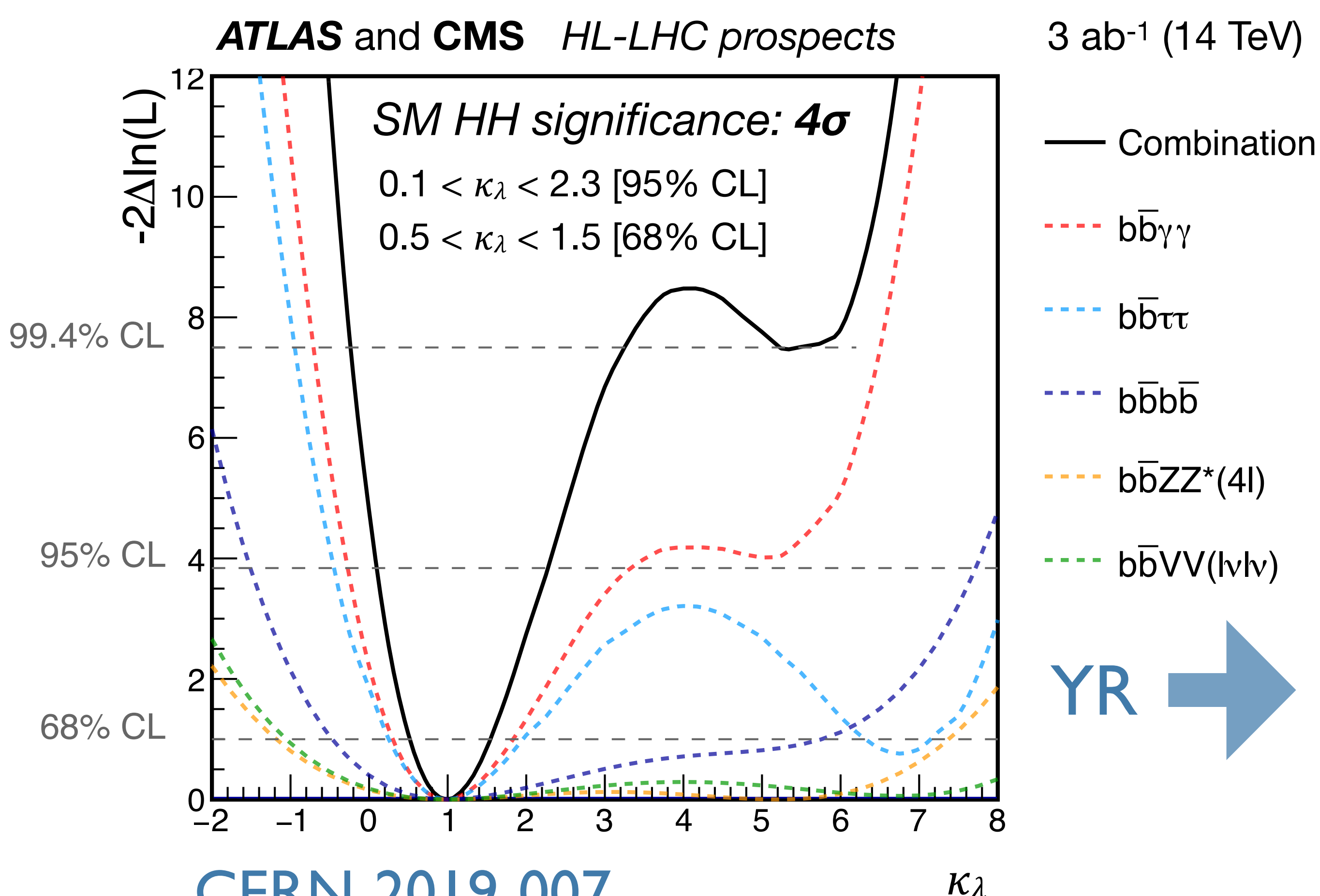


- small branching fraction (~3%) vs enormous hadronic backgrounds — charm tagging is the key;
- Simultaneous constraint of H → bb and H → cc;
- Expected sensitivity approaches the SM value for the Higgs-charm coupling.

HH production and Higgs self coupling

- one of the top priorities at the HL-LHC - crucial to probe the Higgs potential;

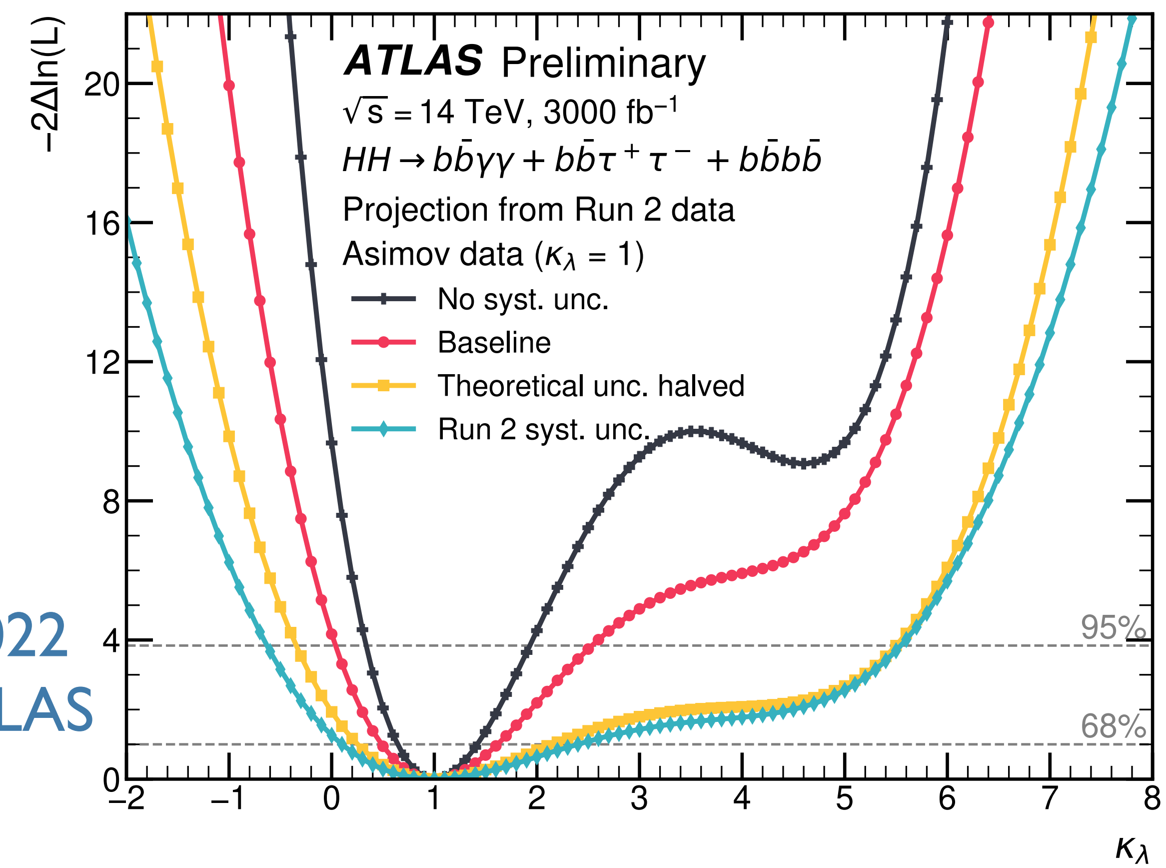




[CERN-2019-007]

YR → 2022 ATLAS

[ATL-PHYS-PUB-2022-053]



- 4.0σ w/ baseline systematics (4.5σ w/o syst.);
- $0.5 < \kappa_\lambda < 1.5$ [68% CL].

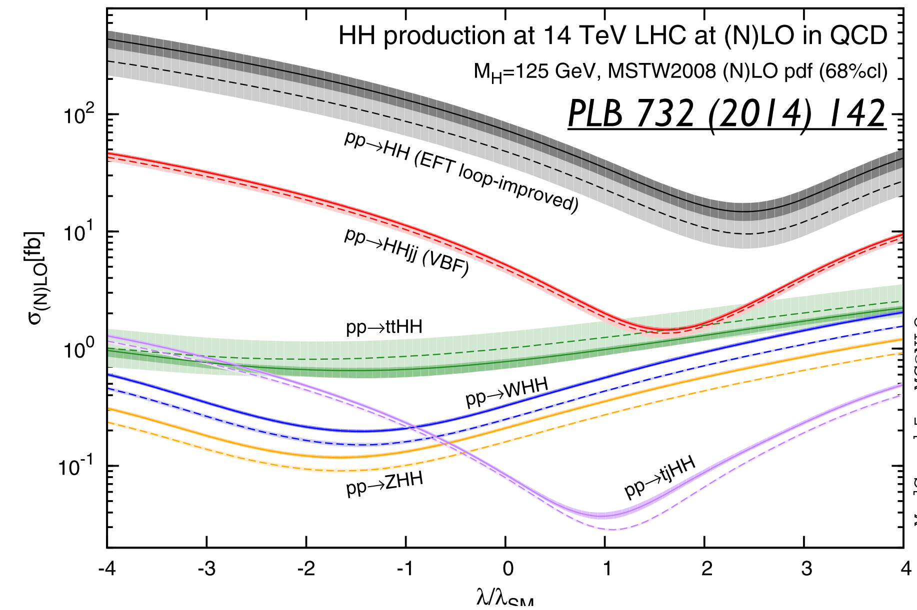
- 3.4σ with baseline systematics (4.9σ w/o syst.)
- $0.5 < \kappa_\lambda < 1.6$ [68% CL];
- CMS updated bbγγ result - similar improvement.

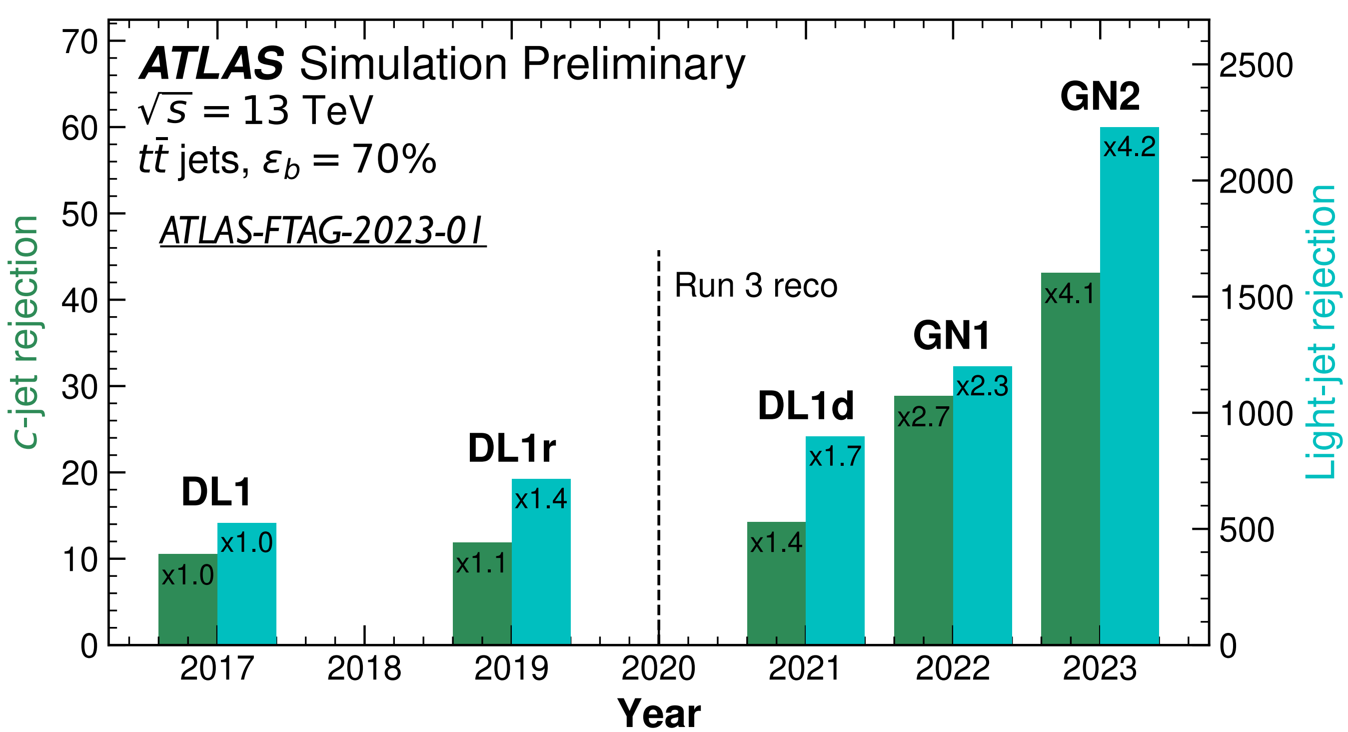
HH production and Higgs self coupling

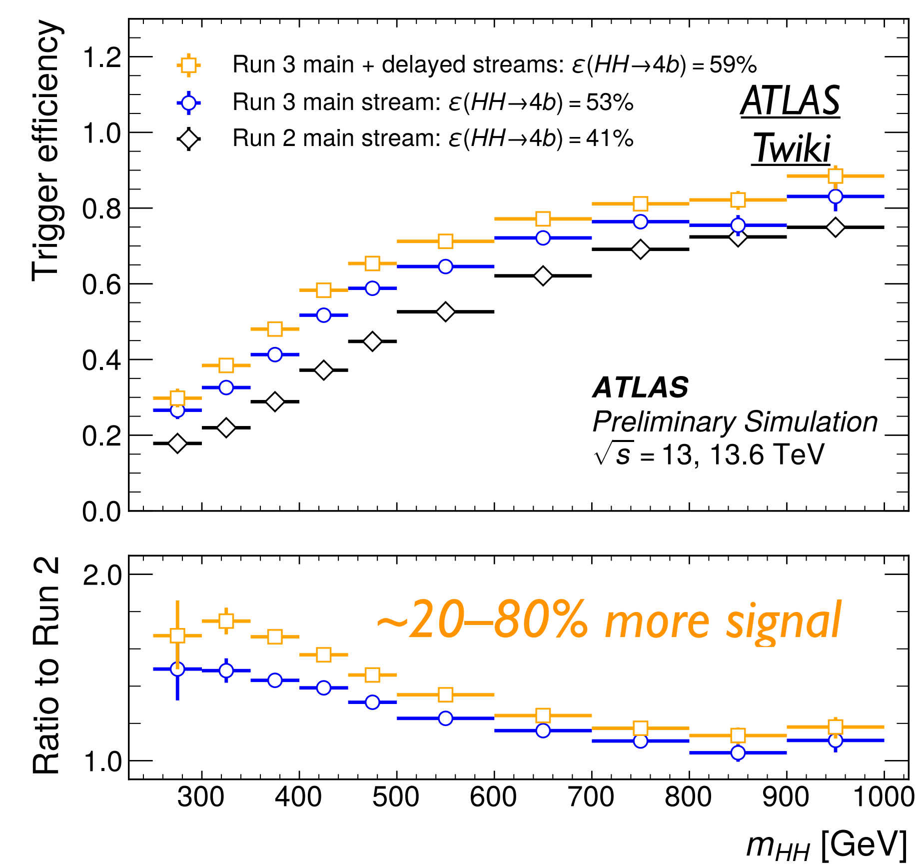
Further improvements:

- **More channels**: HH →WWγγ + ττγγ, ttHH
- **Tools**: significant performance improvement in H→bb/cc tagging (GNN/Transformers standard in ATLAS & CMS), mass regression, state-of-the-art taggers deployed at HLT for online event selection;

→ HH observation may arrive sooner than expected!







W and top mass measurements

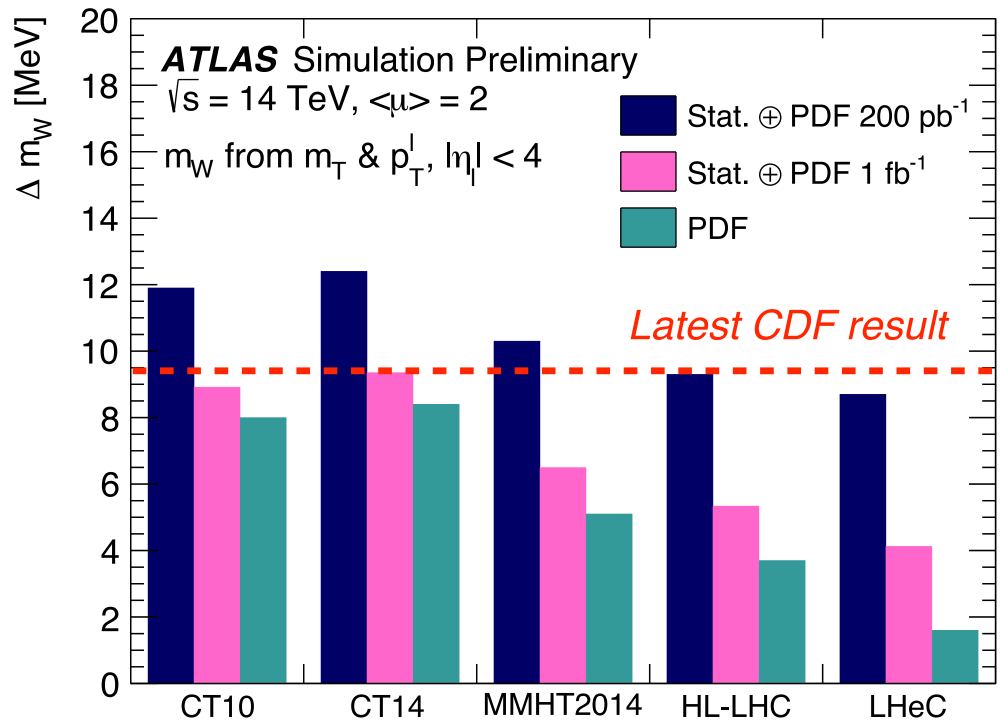
- Top, W and Higgs masses connected through loop corrections: accurate measurements one of the most important tests of the SM;

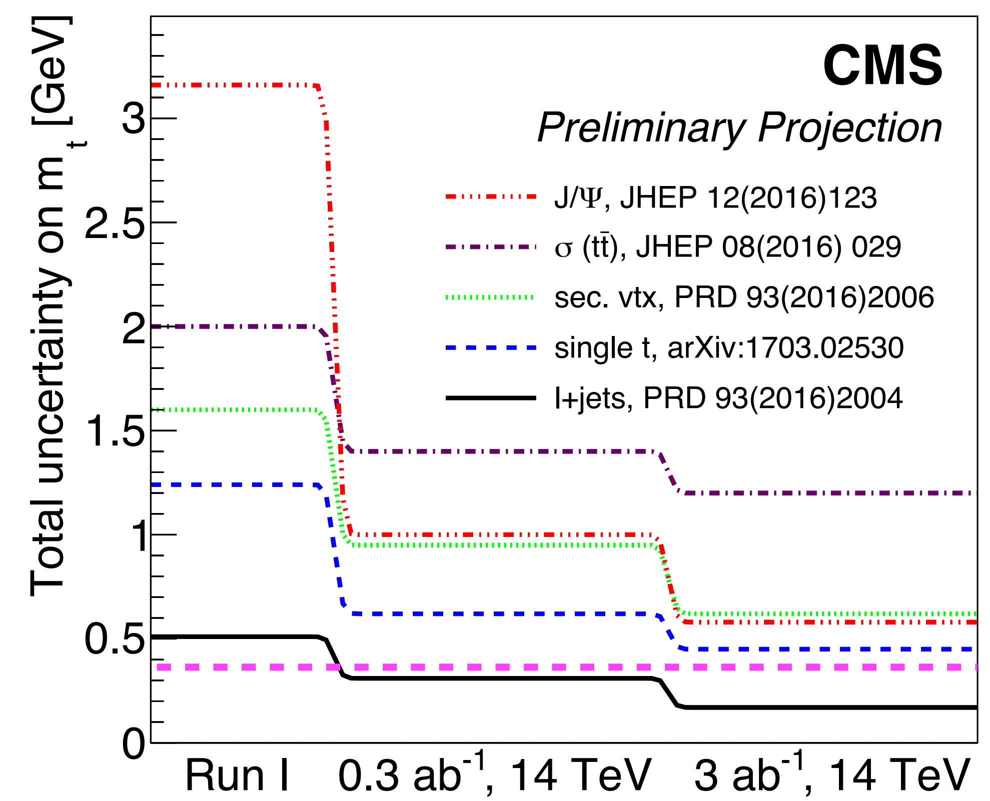
W mass:

- Measured at low μ and will benefit from: extended tracking coverage: -25% uncertainty, improved PDF precision: -50% on PDF systematic, arger dataset: 200 pb-1 per week at <μ>=2.
- With 200 pb^{-1}, precision of 8.6 (stat) + 3.7 (PDF syst) = 9.3 MeV / 5 MeV with 1 fb^{-1}

Top mass:

- Most precise from tt l+jets production - 0.17 GeV uncertainty;
- σ(tt) less precise but gives access to mt in a well-defined renormalisation scheme;
- additional methods expected to improve further precision in a combination.





BSM searches

- HL-LHC will increase reach of searches to weaker couplings and higher masses;
- SUSY: EWK production: larger benefit from HL dataset due to smaller cross-sections;
- LLP will benefit from improved trigger capabilities;
- Heavy resonances - up to 8 TeV (table with projections):

Model	*Run-2 exclusion*	*HL-LHC exclusion*
Excited lepton $\ell\ell\gamma$ *[1]*	*3.8-3.9 TeV*	*5.8 TeV*
Heavy Majorana neutrino $\ell\ell qq$ *[2]*	*4.6-4.7 TeV*	*8 TeV*
RS gluon tt [3]	*4.5 TeV*	*6.6 TeV*
W'_R *tb [4]*	*3.15 TeV*	*4.9 TeV*
SSM W' τ*+MET [5]*	*4.6 TeV*	*6.0 TeV*
SSM W' ℓ*+MET [4]*	*5.6 TeV*	*7.9 TeV*
SSM Z' $\ell\ell$ *[4-7]*	*5.1 TeV*	*6.8 TeV*

[1] CMS-PAS-FTR-18-029

[2] CMS-PAS-FTR-18-006

[3] CMS-PAS-FTR-18-009

[4] ATL-PHYS-PUB-2018-044

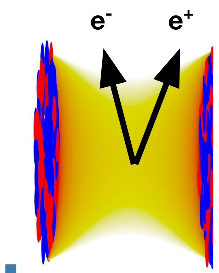
[5] CMS-PAS-FTR-18-030

[6] CMS-PAS-FTR-18-006

[7] CMS-PAS-FTR-21-005

ALICE programme beyond Run 3 and 4

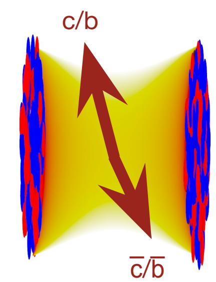
Precision measurements of dileptons:



- evolution of the quark gluon plasma temperature;
- mechanisms of chiral symmetry restoration in the quark-gluon plasma

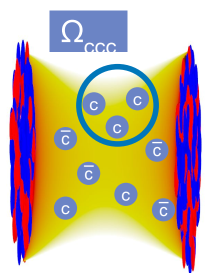
Systematic measurementsof (multi-)heavy-flavoured hadrons:

- transport properties in QGP;
- mechanisms of hadronisation from the QGP;



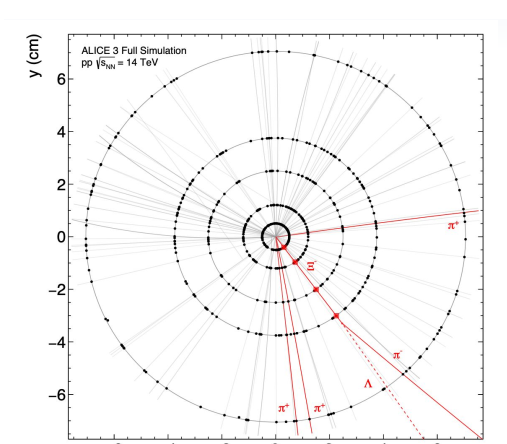
Hadron correlations:

- hadron-hadron interaction potentials, net-baryon and net-charm fluctuations,..

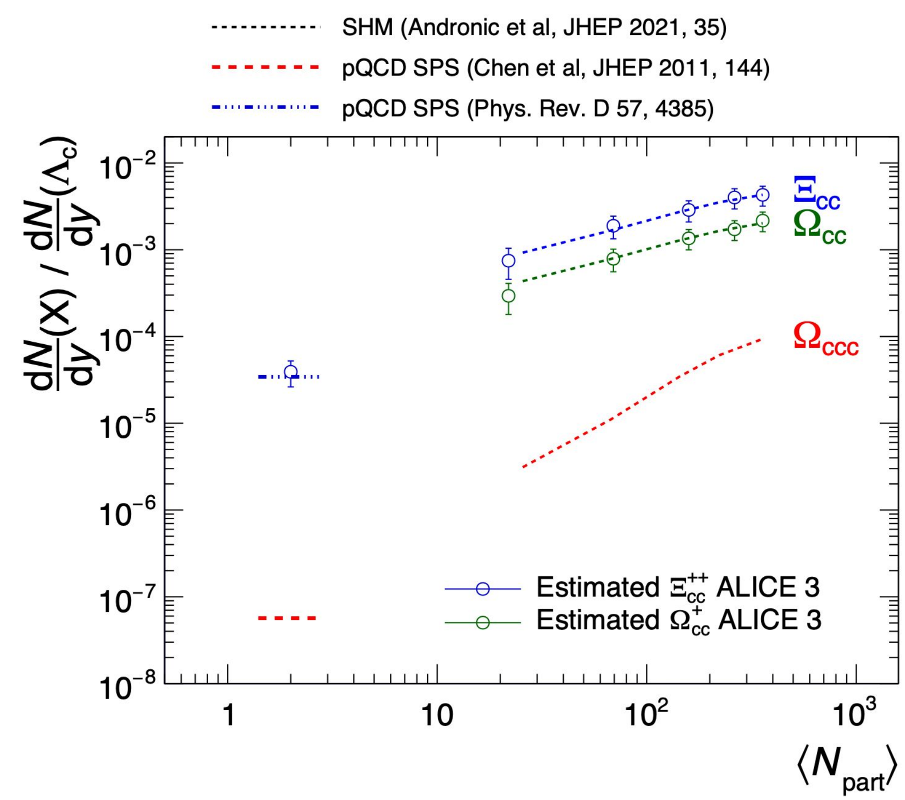


Multi-charm baryons:

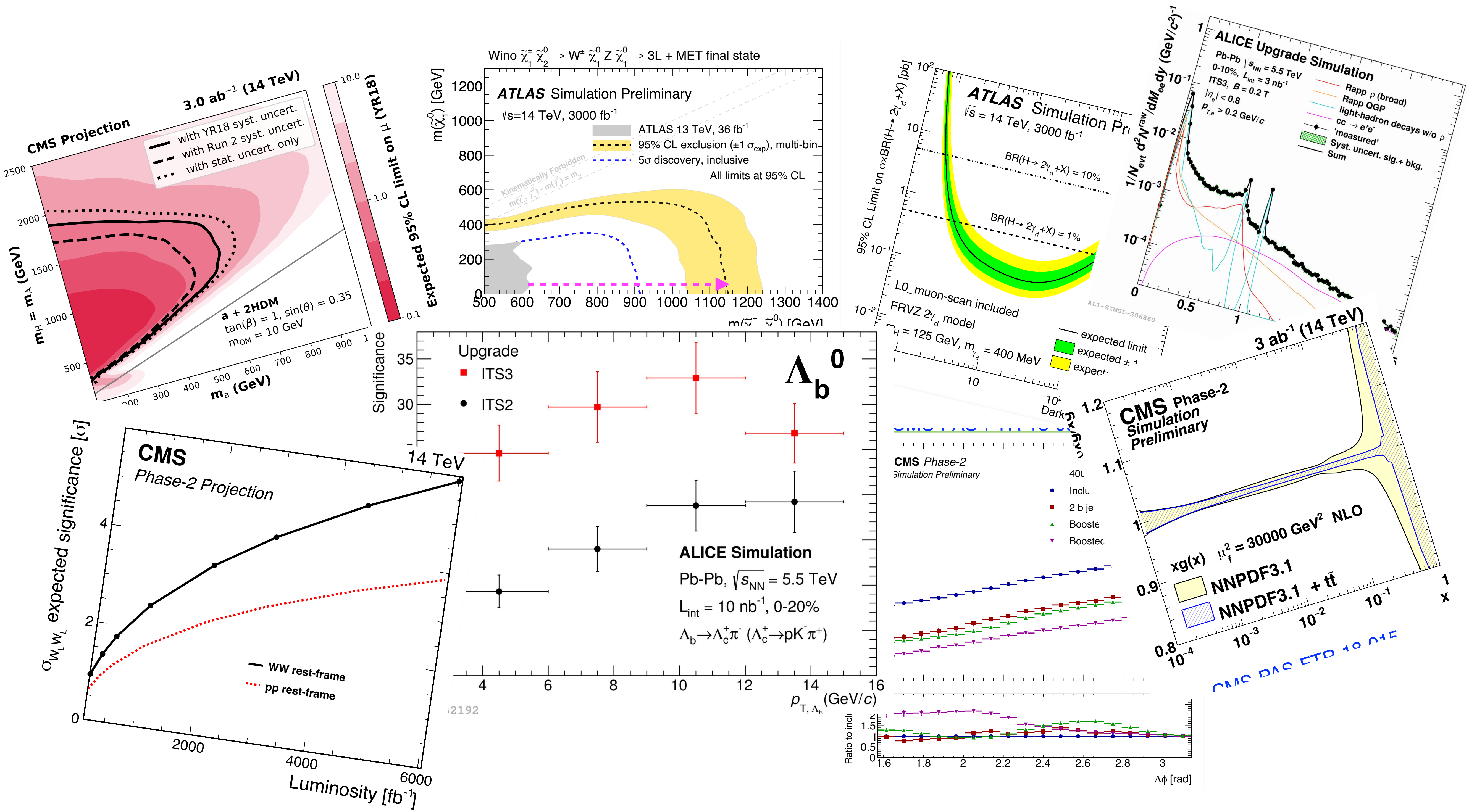
- New technique: strangeness tracking with Ξ baryon → high selectivity;



Multi-charm baryons vs system size
→ new insights in thermalisation and hadronisation dynamics



And many more....



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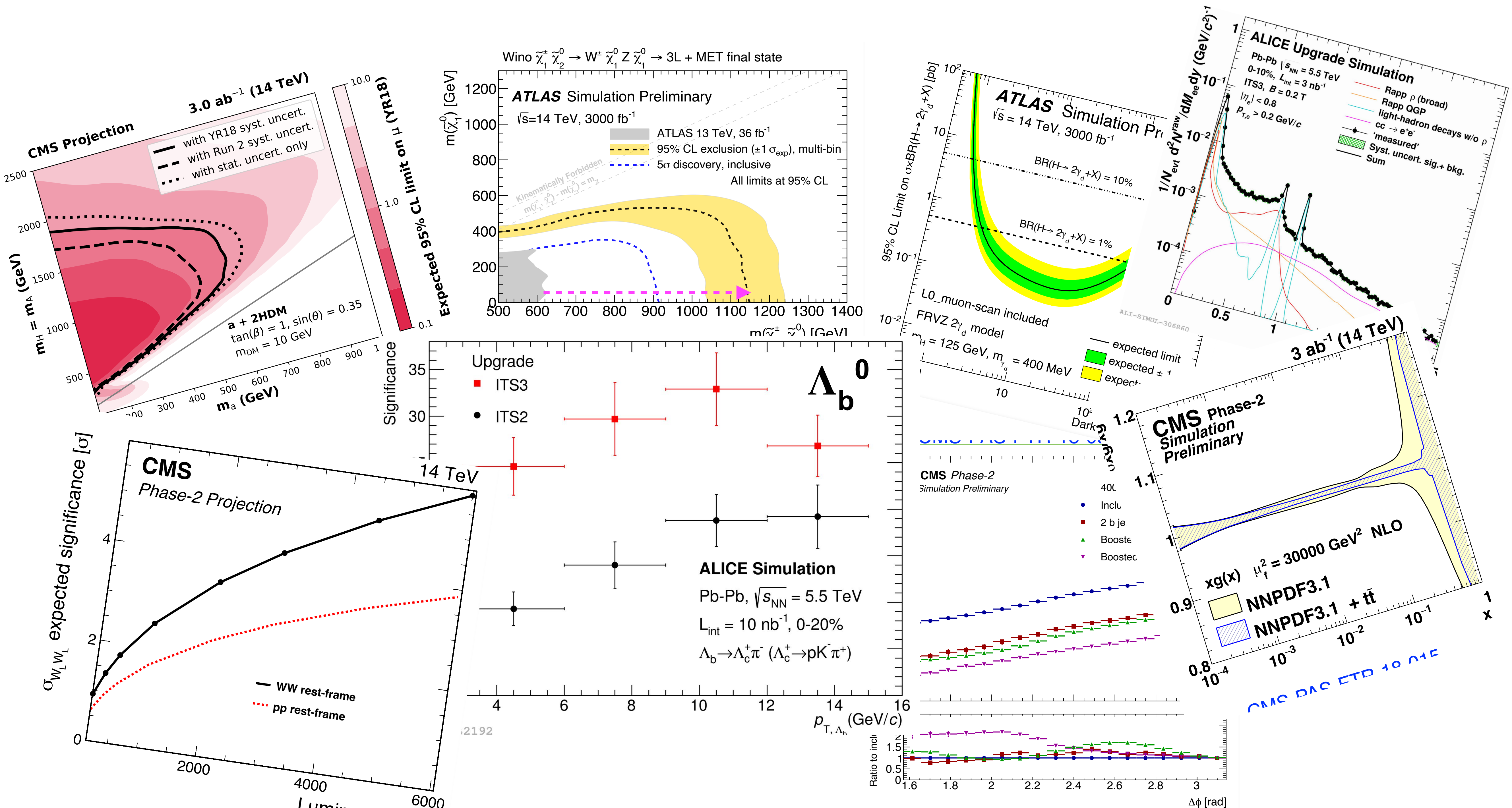

History thought us that we can always do better than expected.
Requires combined effort from theory, instrumentation, analysis techniques…

Conclusions

- Measurements @ 7, 8, and 13 TeV confirmed the immense potential of LHC
  - Measurements compatible with the SM predictions within uncertainties;
  - Many open questions remain;
- Near-term future measurements @ 13.6 TeV might provides us with some hints…
- HL-LHC: a unique opportunity to explore many of the open questions
  - Vast amount of data: ~20x more than what we have analysed;
- Next-generation accelerators & experiments are key to our understanding of the Nature!

Backup

Heavy neutral Higgs bosons A→Z(ll)H(tt)

- Search for CP-odd Higgs decaying to heavy CP-even Higgs and Z
  - Motivated by 2HDM, $m_A > m_H$ favoured by EW baryogenesis models. A→ZH dominates if mA - mH > 250 GeV.
  - H→tt becomes dominant when $m_H > 2\ m_t$.
- ATLAS search targets semi-leptonic tt decays, while CMS uses fullhad tt decay;
- Mass difference $\Delta m = m_{Acandidate} - m_{Hcandidate}$ as signal discriminant

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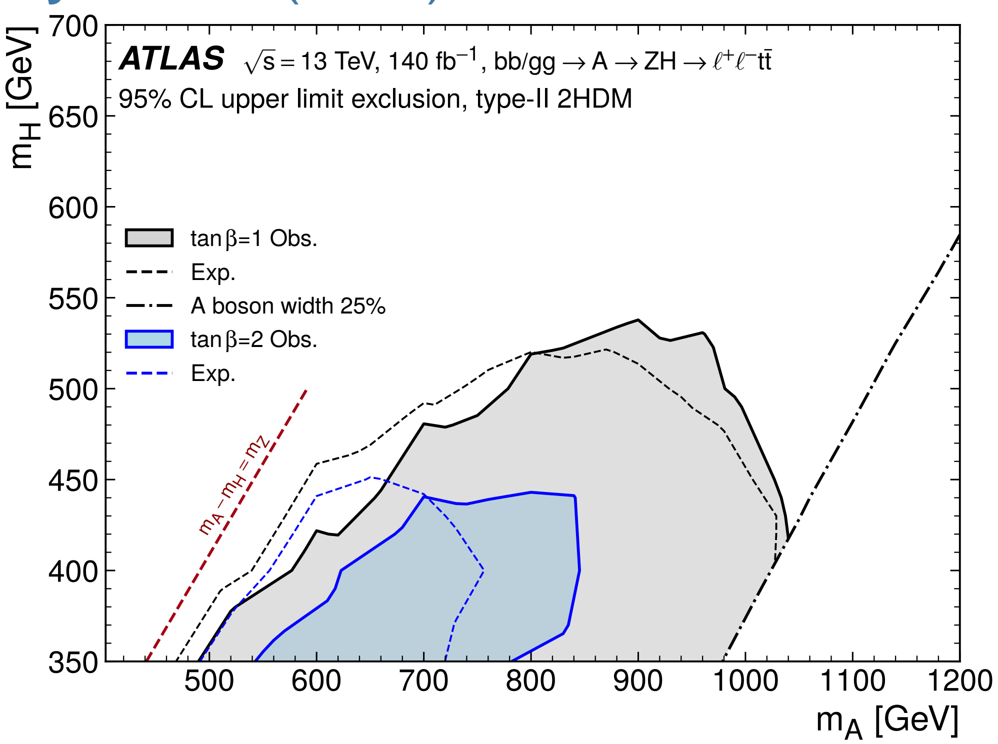

ATLAS most significant excess at m_A = 650 GeV, m_H = 450 GeV: 2.9 (2.4) σ local (global) significance - not confirmed with recent CMS result.

CMS-PAS-B2G-23-006