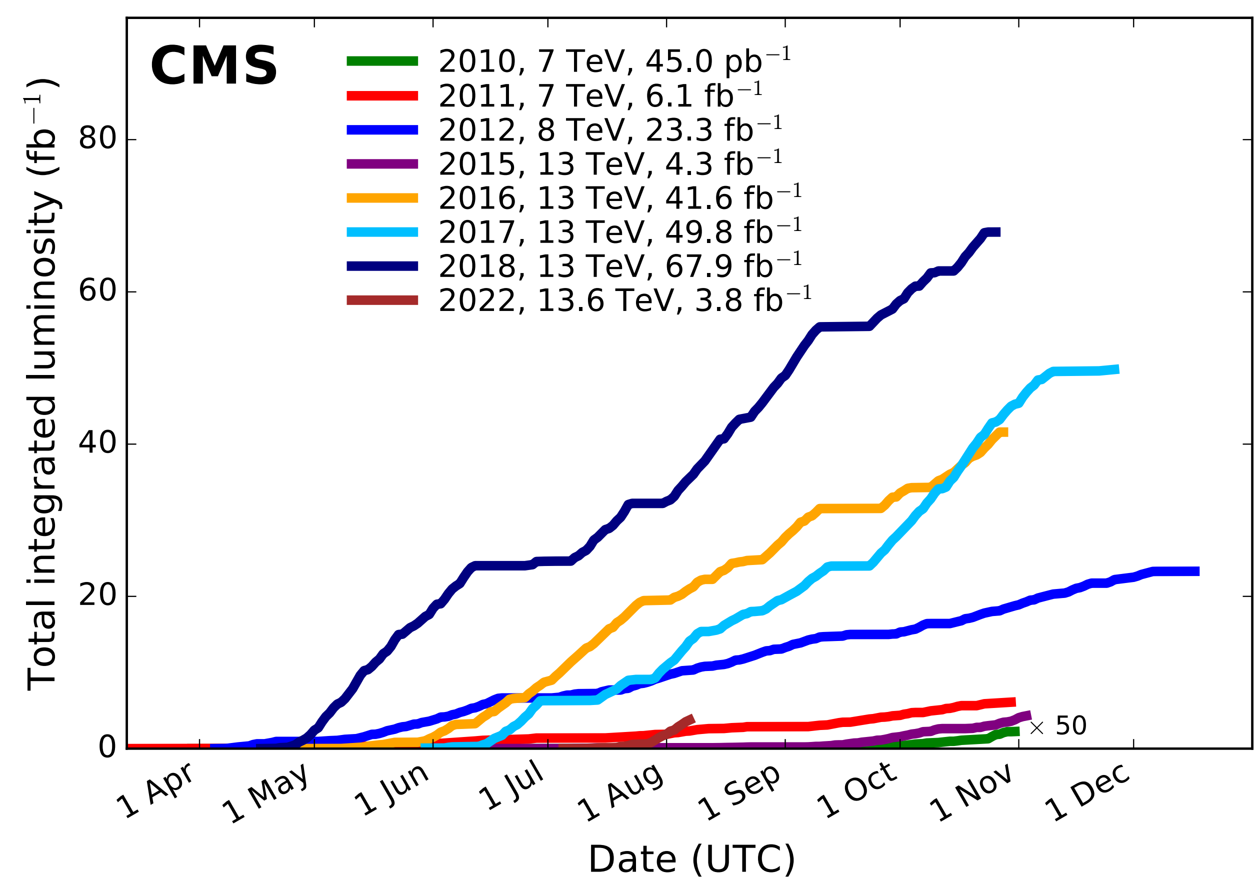
Precision Higgs and other Electroweak Measurements

Keti Kaadze on behalf of
the ATLAS, CMS,
and LHCb Collaborations

CIPANP, Aug 30, 2022

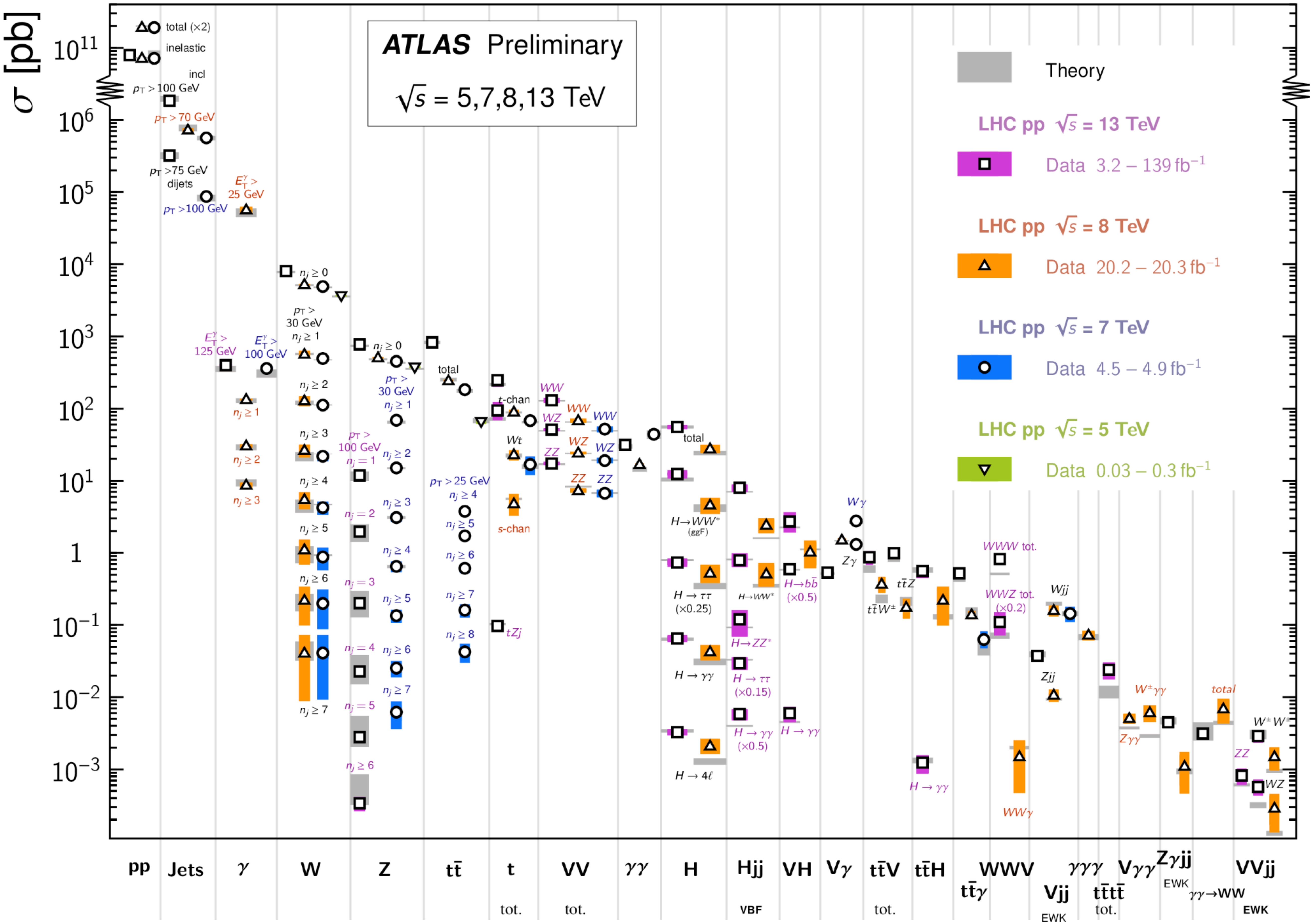
Introduction

- Very successful Run 1 and 2 at the LHC: $\sqrt{s}$ = 8,13 TeV, Lumi = ~20, ~140/fb
  - Remarkable performance of LHC and the experiments
- Particle physics research at the energy frontier has entered an exciting era
  - Improve precision of measurements; Have an access to rare processes; Discover some for first time observed in pp collisions



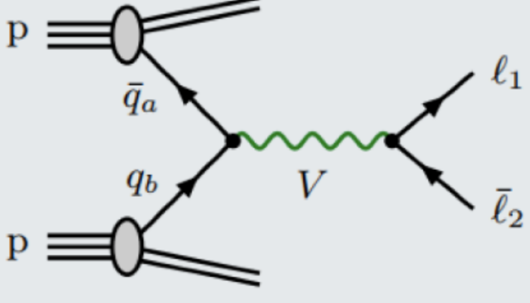
Standard Model Production Cross Section Measurements

Status: February 2022



Objectives

- Study of EW processes enables to
  - Validate our knowledge of the SM (detector performance, backgrounds)
  - Provide input to PDF fits; Test higher order QCD/EW corrections
  - First time observe rare EWK processes
- Study of Higgs boson
  - Significantly advances our knowledge on this unique particle and confirms the SM theory
  - Yet, the SM remains a low energy approximation of a more fundamental theory; Higgs could be the key to physics beyond the SM
- Precise measurements in EWK/Higgs sectors are another important handle to probe for presence of new particles
- Here are presented my personal picks of some of the latest results from the ATLAS, CMS, and LHCb experiments.

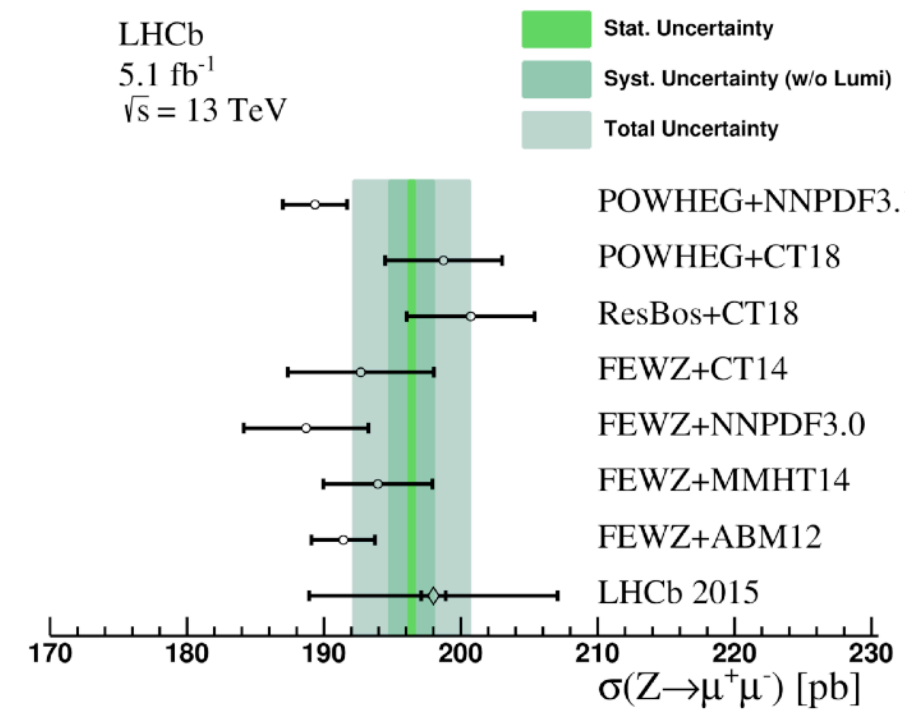


Forward Z production

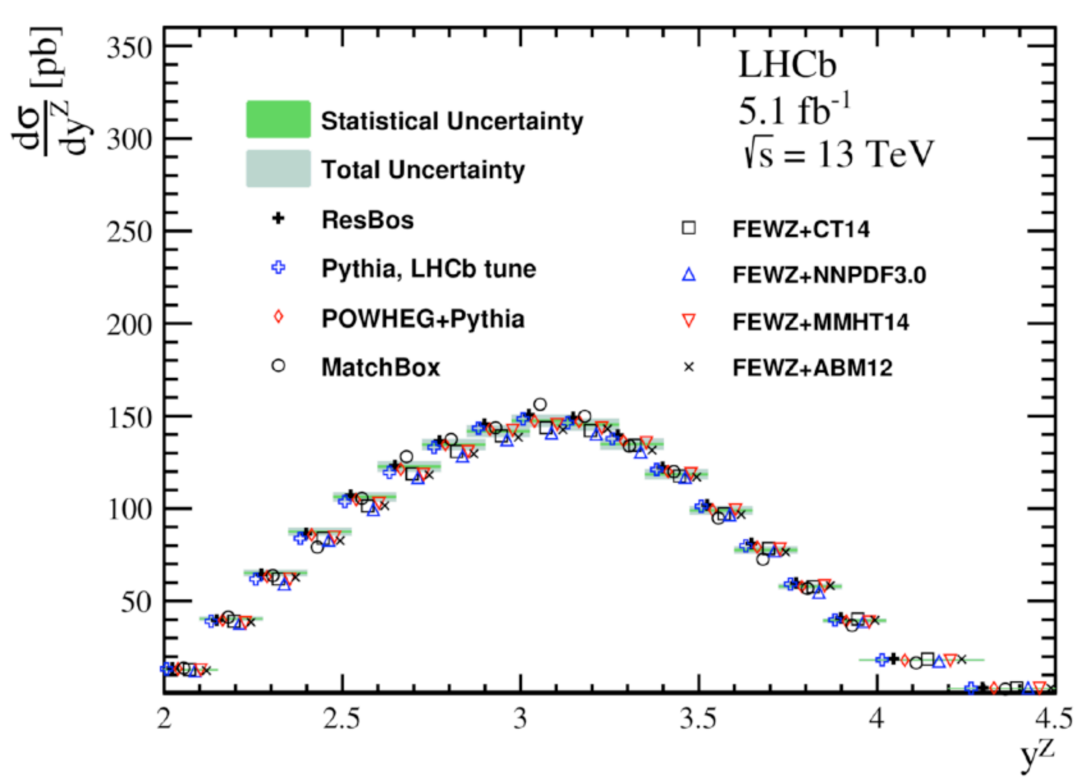
arXiv:2112.07458

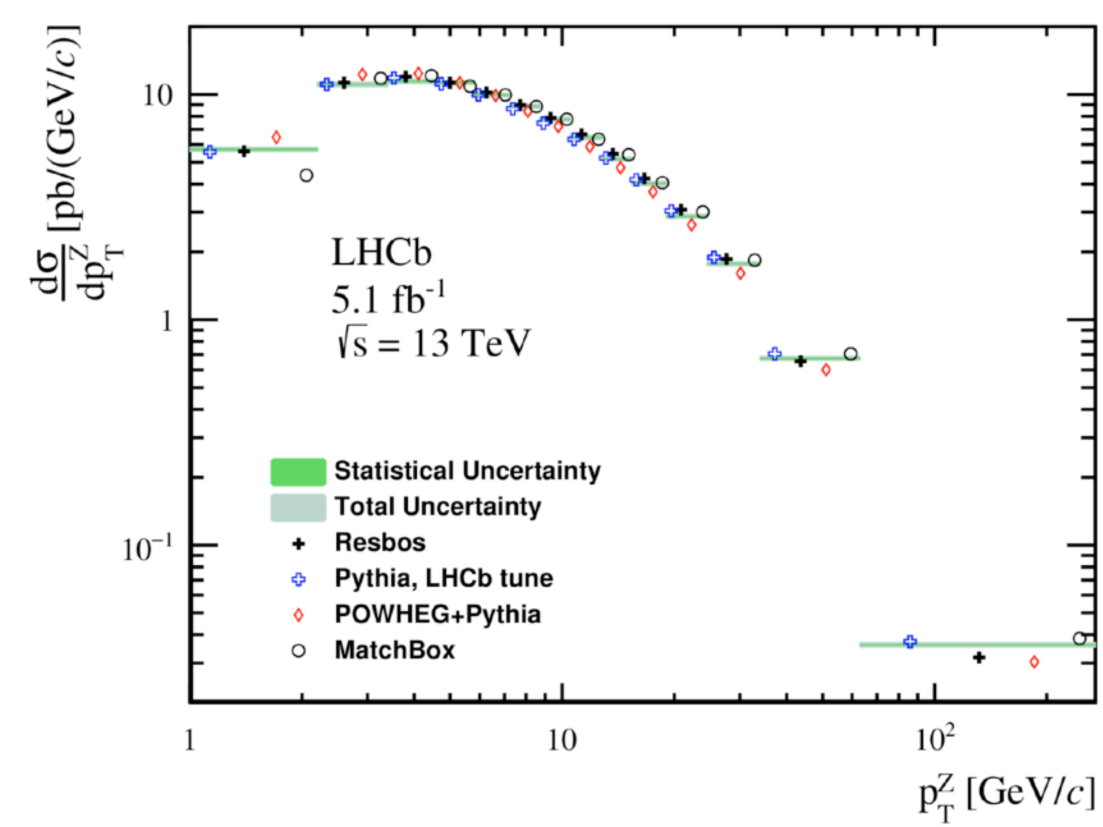
The most precise measurement at 13 TeV

$$\sigma(Z \to \mu^+\mu^-) = 196.4 \pm 0.2 \pm 1.6 \pm 3.9pb$$



- Vector boson production is an important tool for testing perturbative QCD at high energy, probing α_S, constraining PDFs
- Z bosons at the LHCb are highly boosted. Hence, measurements are particularly important for constraining PDFs for very high-x and high momentum transfer
  - Will help future W mass and θ_W measurements
- Run 2 dataset 5.1± 0.1 \fb; $\mu^\pm$ events, p_T>20 GeV, $2<\eta<4.5$, $60<M_{\mu\mu}<120$ GeV; Double-diff. σ also measured.

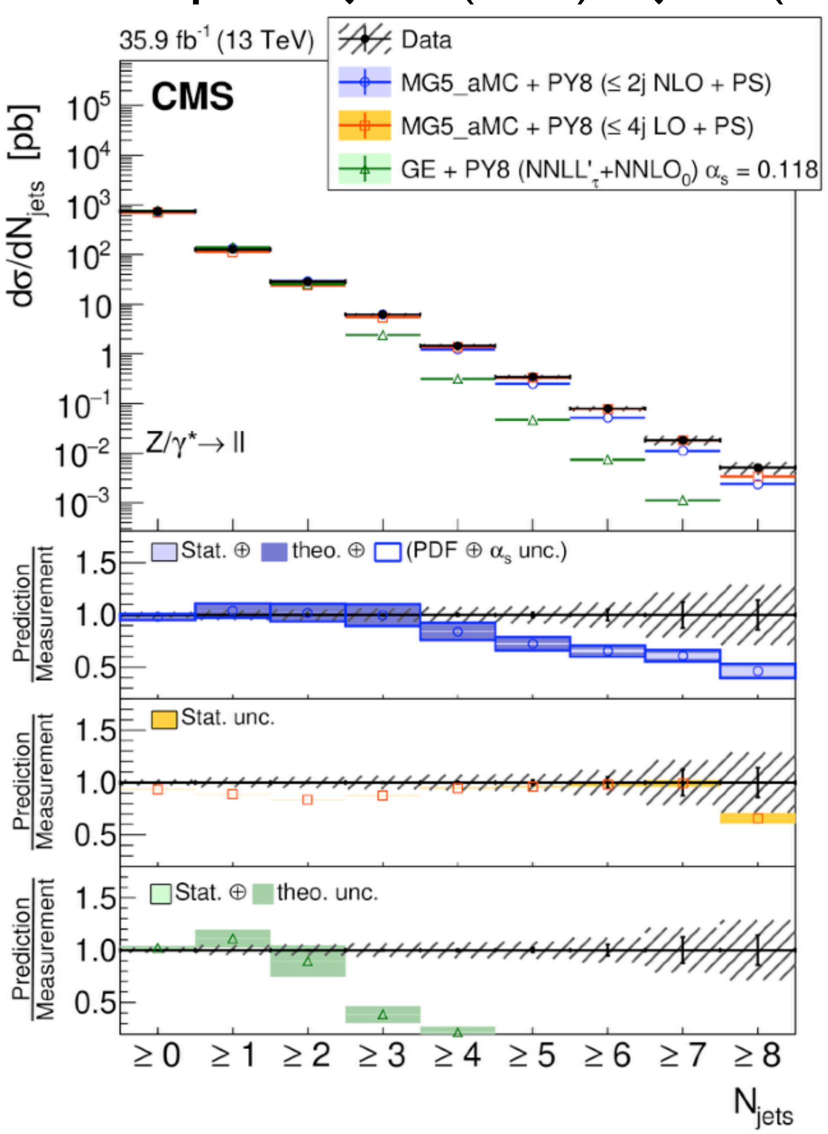


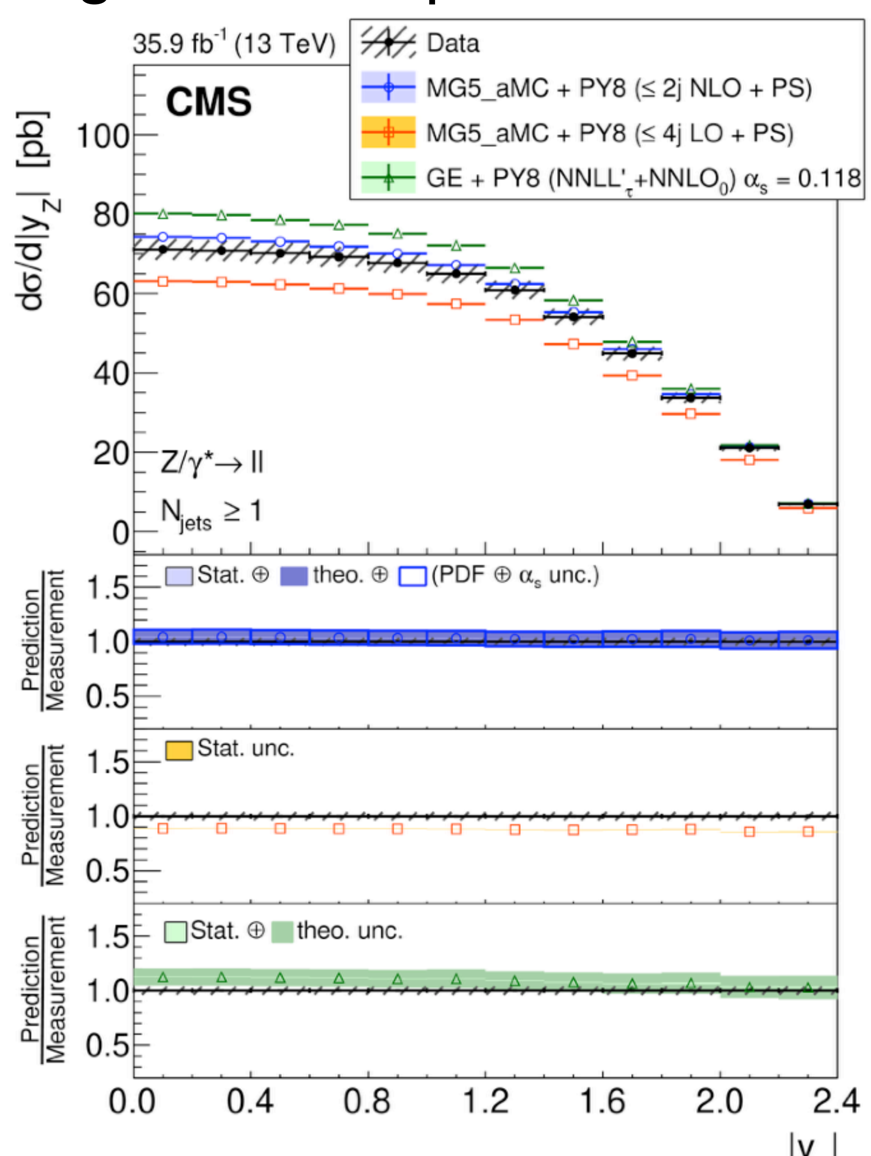


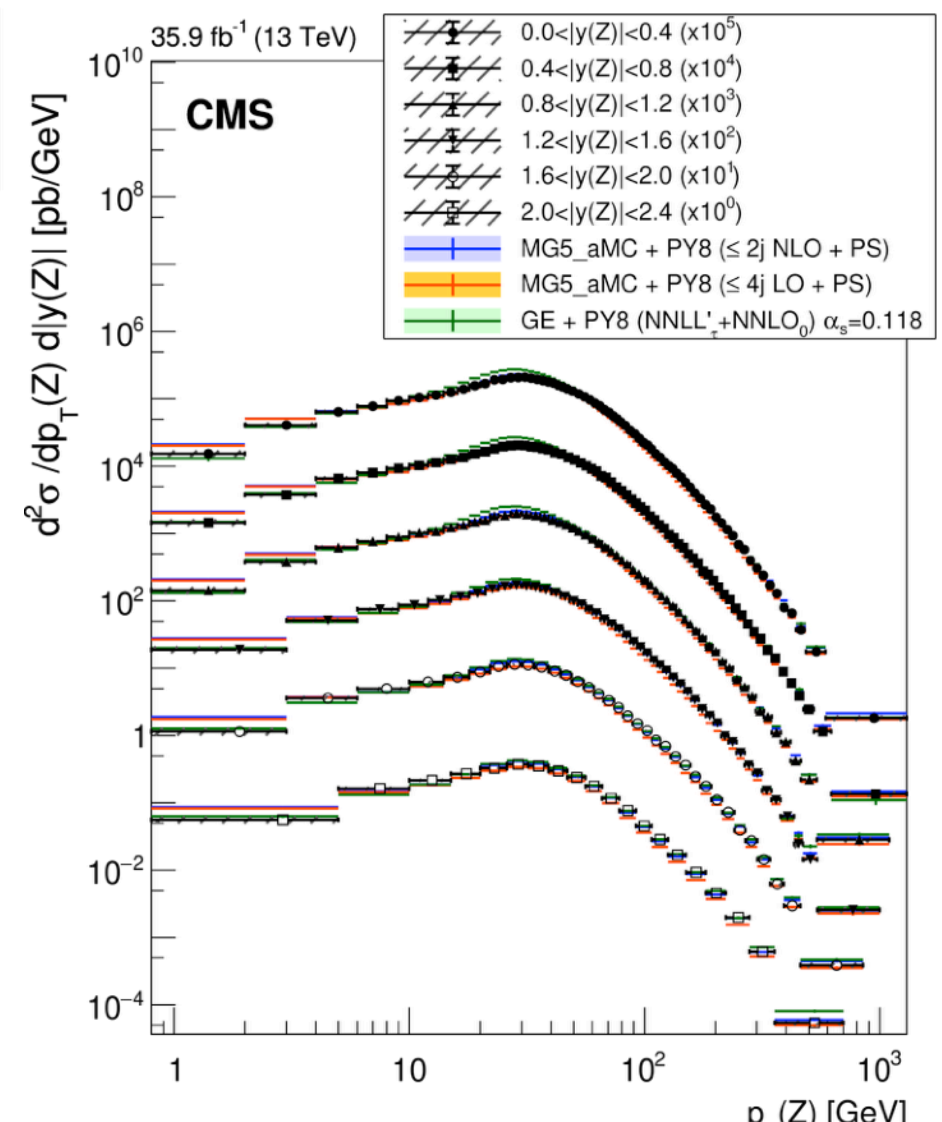
arXiv:2205.02872

Z+Jets Cross Section Measurements

- Key tool for calibrating detector, different object reconstruction and identification, validate background to Higgs measurements and new physics searches
- New measurement from CMS with 35/fb data (previous measurement with 2.19/fb)
  - di-electron/muon channels, $71 < m_{\ell\ell} < 111$ GeV
  - up to 8jets (incl.), 5jets (diff), larger values of p_T, double differential measurements

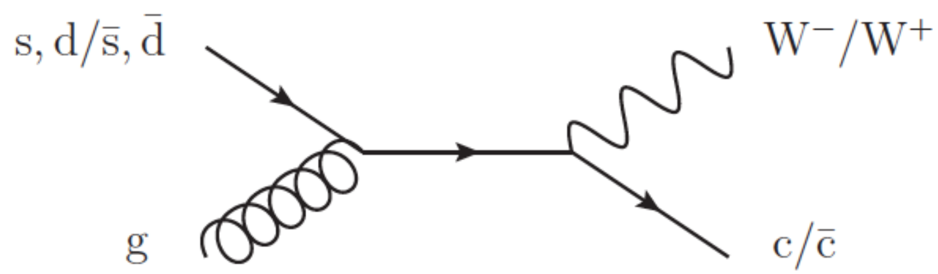




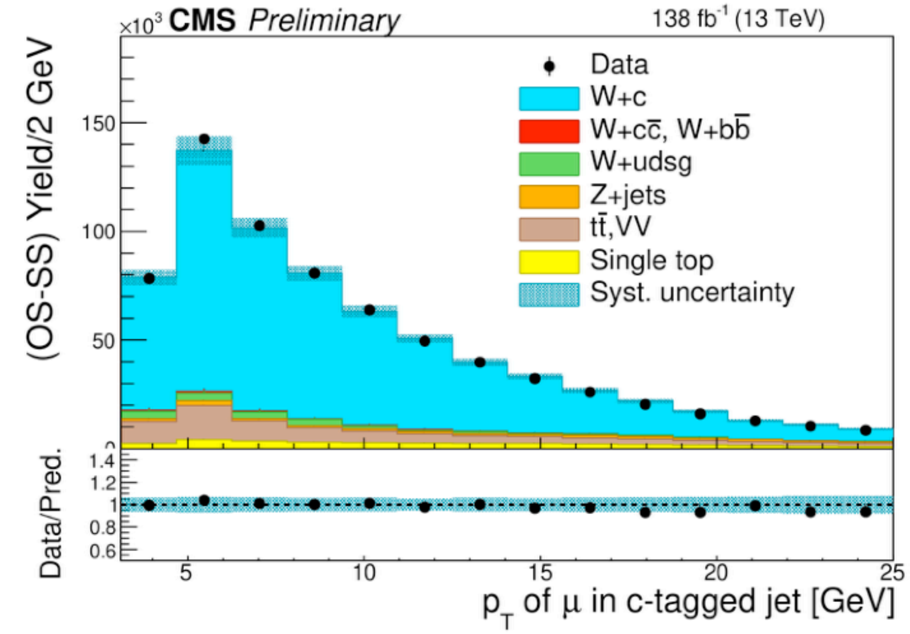


W+c Measurement

CMS-SMP-21-005

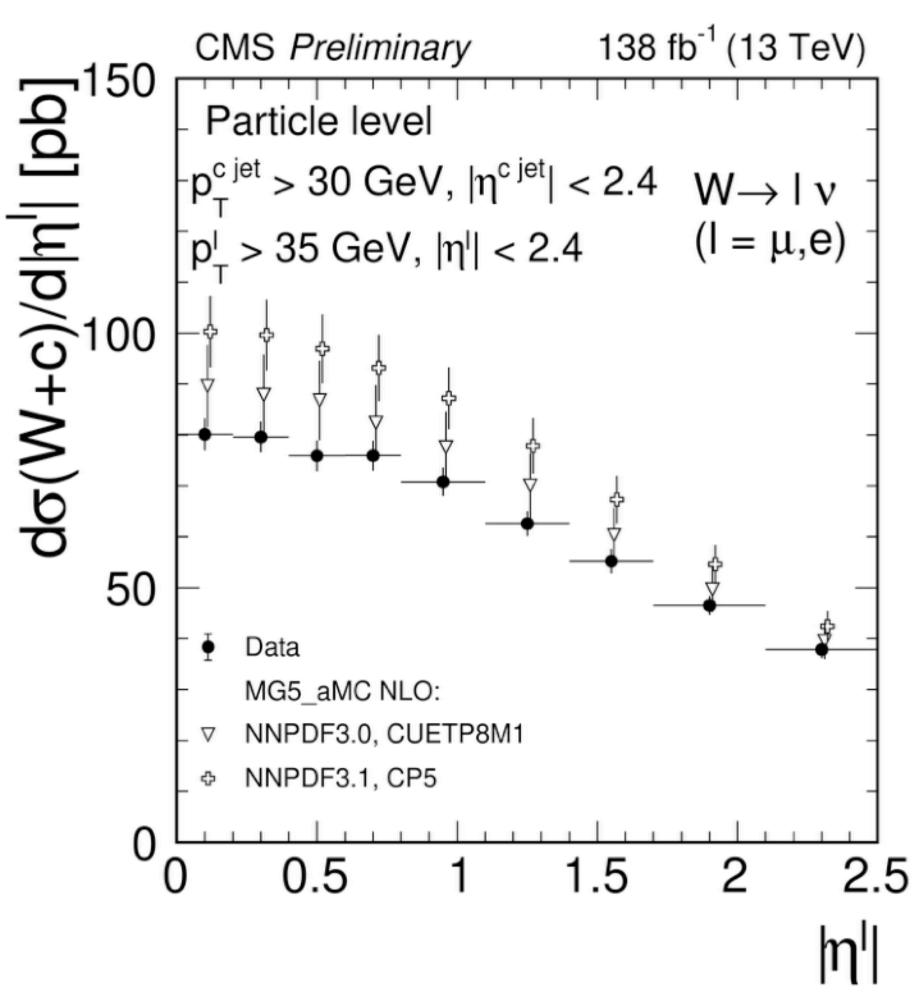


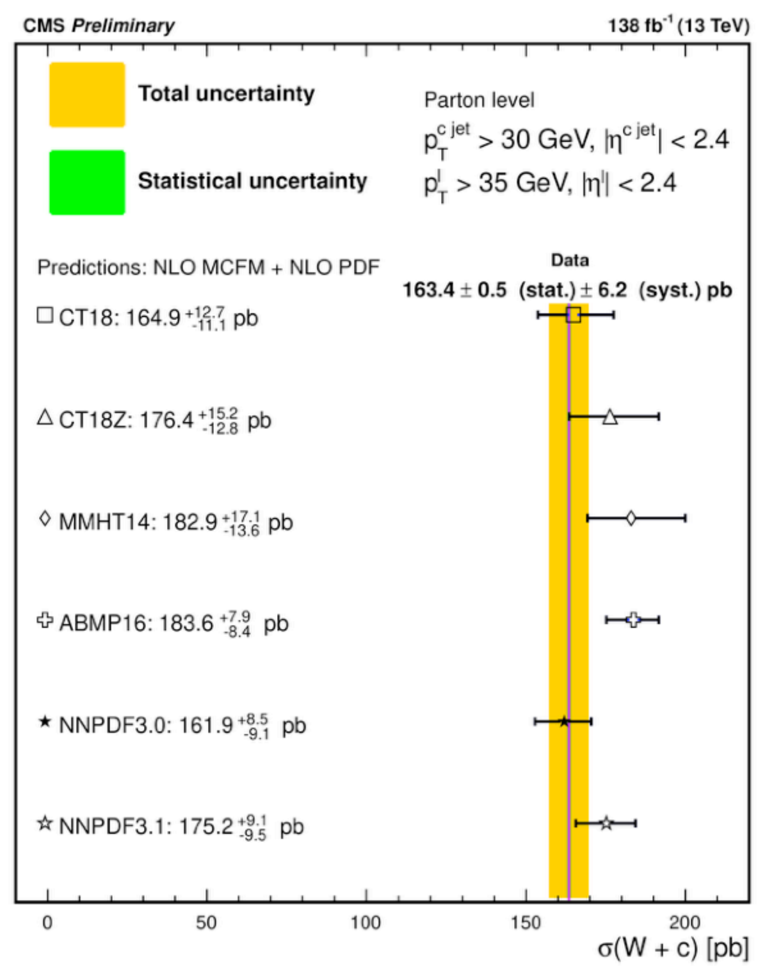
- The production depends on strange quark content in colliding protons at the energy scale of the W mass
- Provides information to strange quark PDFs; $R^{\pm}_C$ measurement constrains ratio of strange and non-strange sea-quarks PDFs; Understand background to WH, H→cc
- Whole Run 2 data; electron/muon channels with a secondary vertex or a muon in a jet; W and charm with opposite signs helps to reduce background.

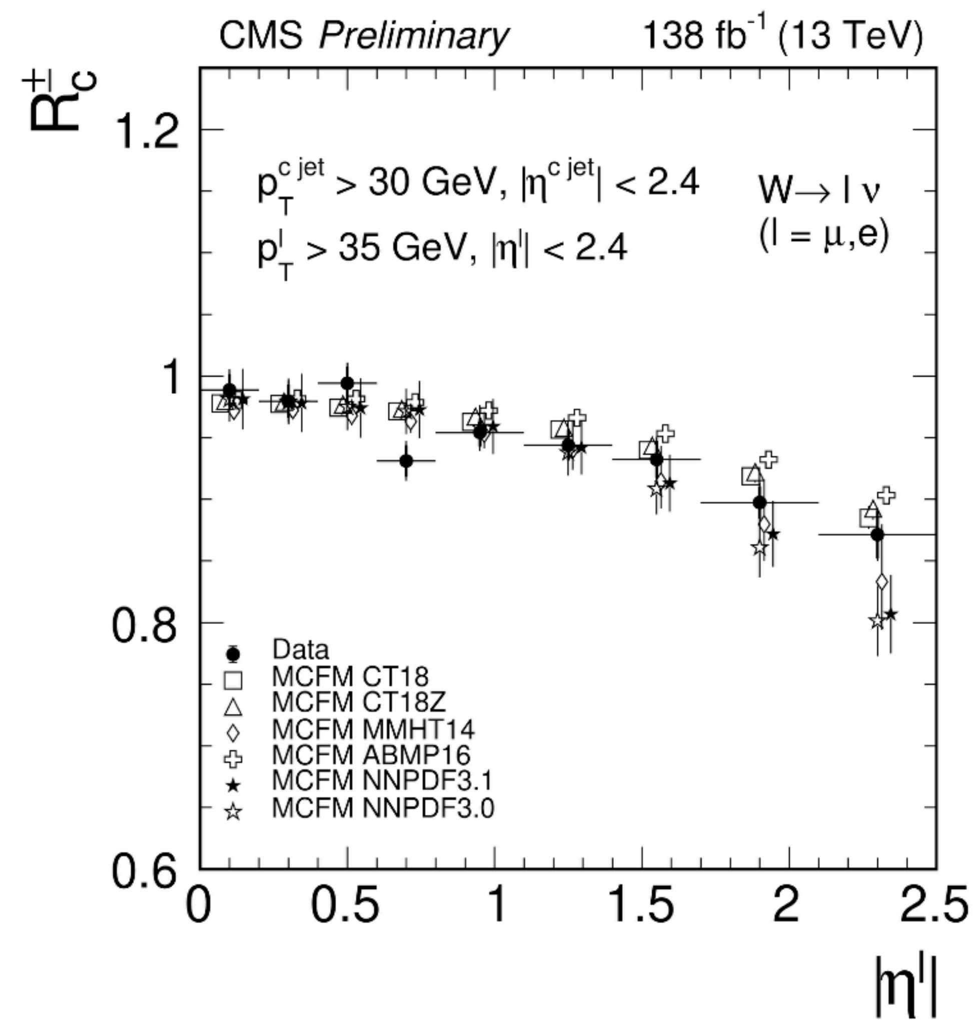


$$R^{\pm}_c = \sigma(W^+ + \bar{c})/\sigma(W^- + c)$$

$$0.950 \pm 0.005\,(\text{stat}) \pm 0.010\,(\text{syst})$$





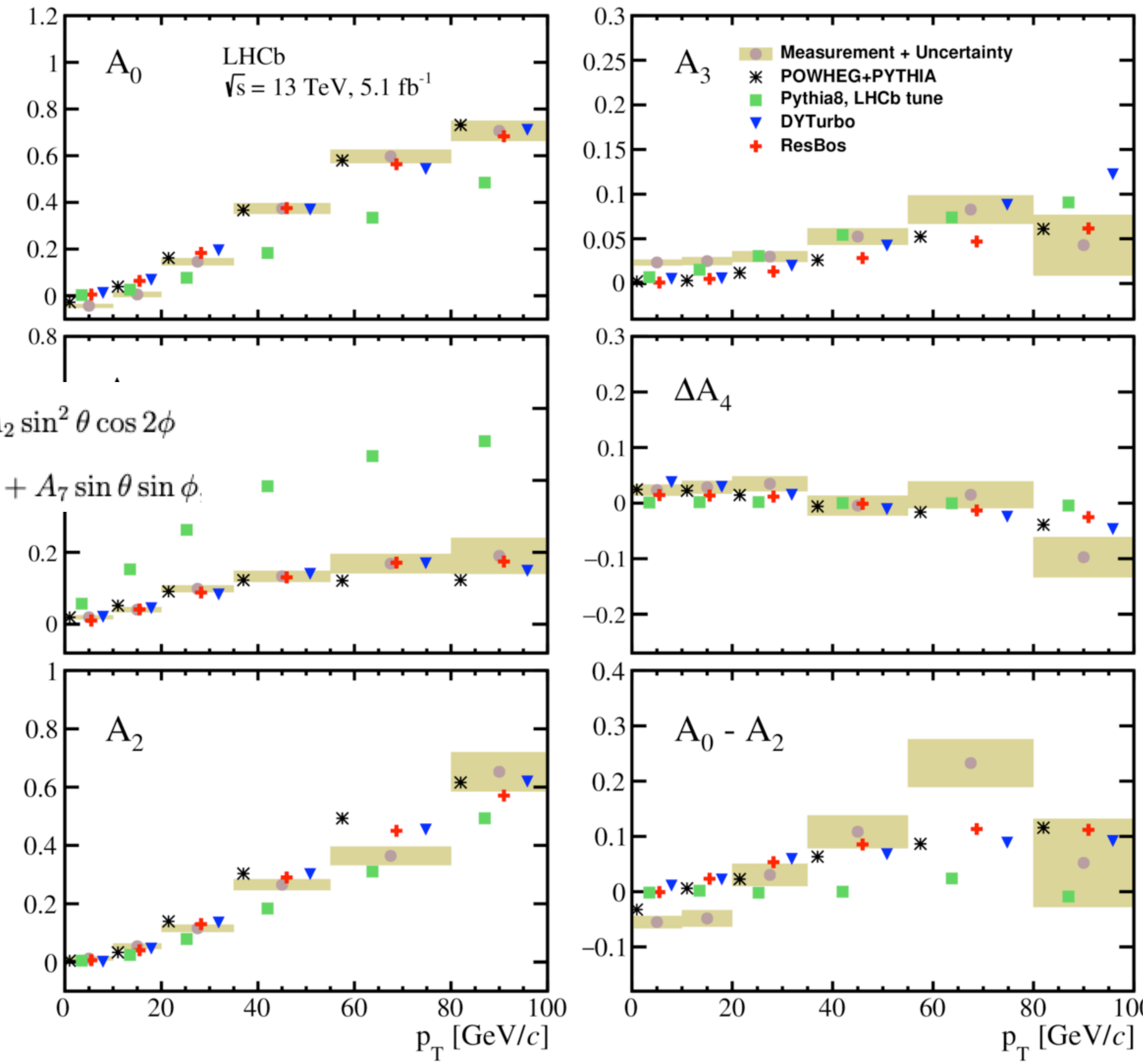


[arXiv:2203.01602](https://arxiv.org/abs/2203.01602)

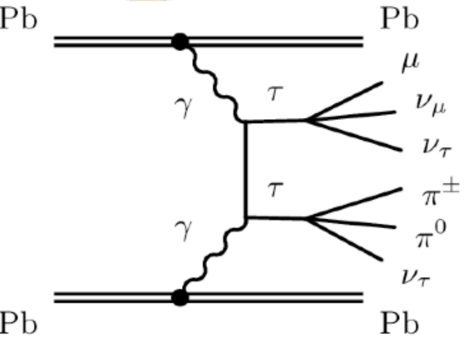
Z angular coefficients

- Kinematics of final state leptons can probe the polarization of a boson, which is sensitive to perturbative QCD
- At Born level angular distribution of leptons in the boson rest frame is given

$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi$$
$$+ A_3 \sin\theta\cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$



  - At LO all coefficients vanish except A4
  - At NLO A0 and A3 are non-zero
  - At NNLO A5, A6, A7 have small non-zero values
- The first measurement in forward region at 13 TeV
  - Coefficients determined in region $75 < m_{\mu\mu} < 105$ GeV
  - Yet, statistically dominated..



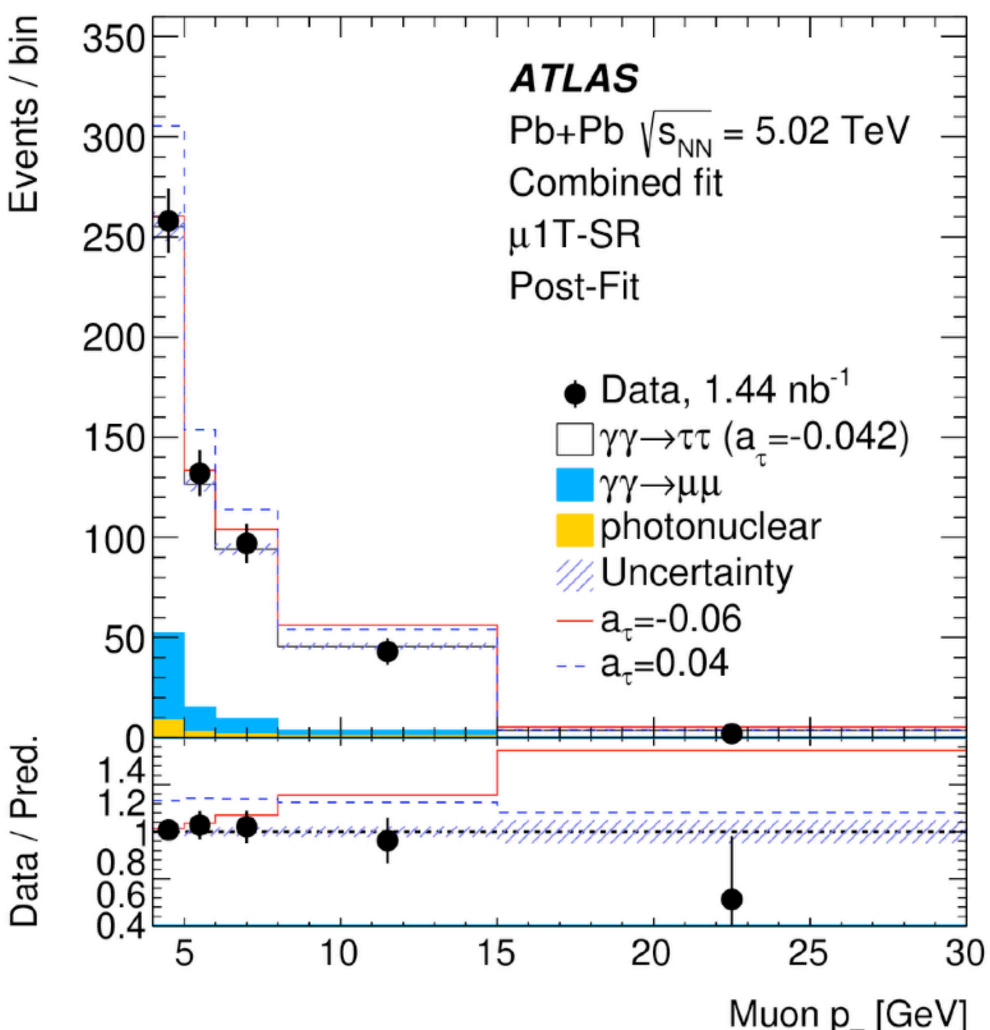
arXiv:2204.13478

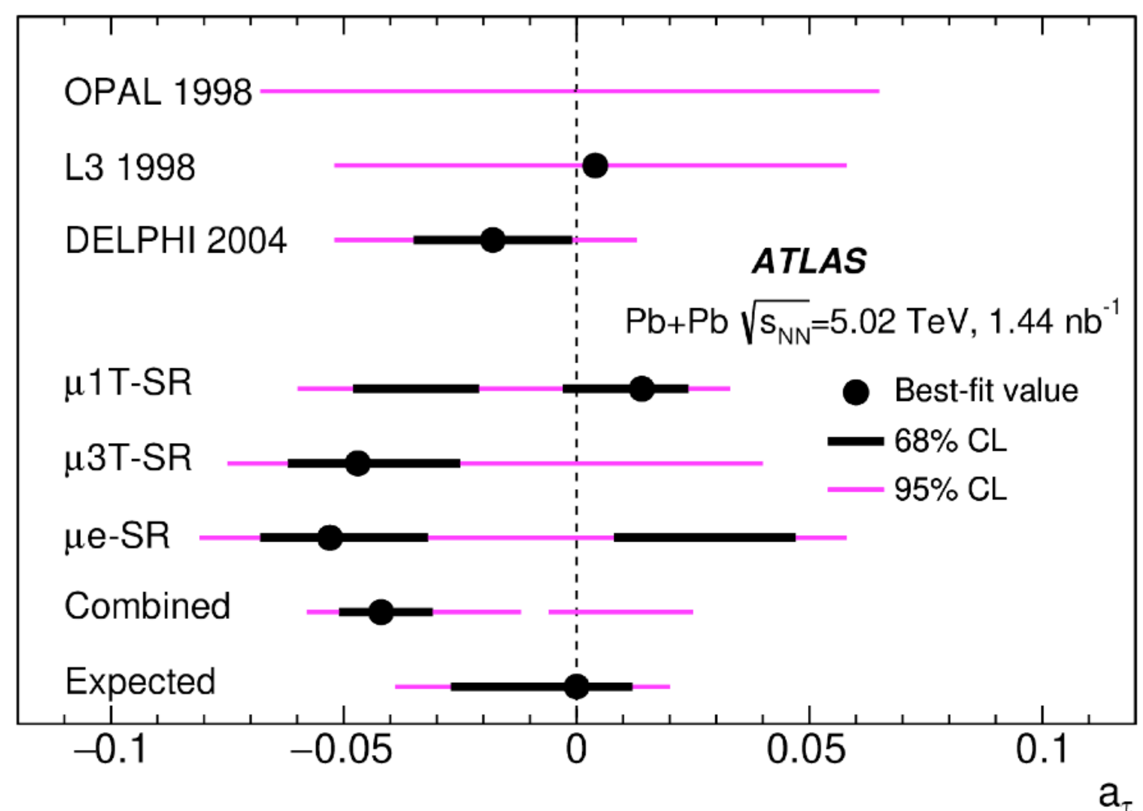
$\gamma\gamma\to\tau\tau$ in PbPb Collisions

- Anomalous magnetic moments are sensitive to BSM physics $a_l = \frac{(g-2)_l}{2}$ where $\vec{\mu} = g\frac{q}{2m}\vec{S}$
- a_e and a_μ are precisely measured, while a_τ is much less constrained due to its short lifetime
- Heavy Ion collisions offer clean environment to study photon-induced processes. It is significantly enhanced over the production in pp collisions
- 2018 dataset, signatures with μ+e/1track/3tracks in low-multiplicity events

$\gamma\gamma\to\tau\tau$ observation @ 5σ

- Expected 95% CL limits from combined fit:
  $$a_\tau \in (-0.039, -0.020)$$
- Observed 95% CL limits:
  $$a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$$





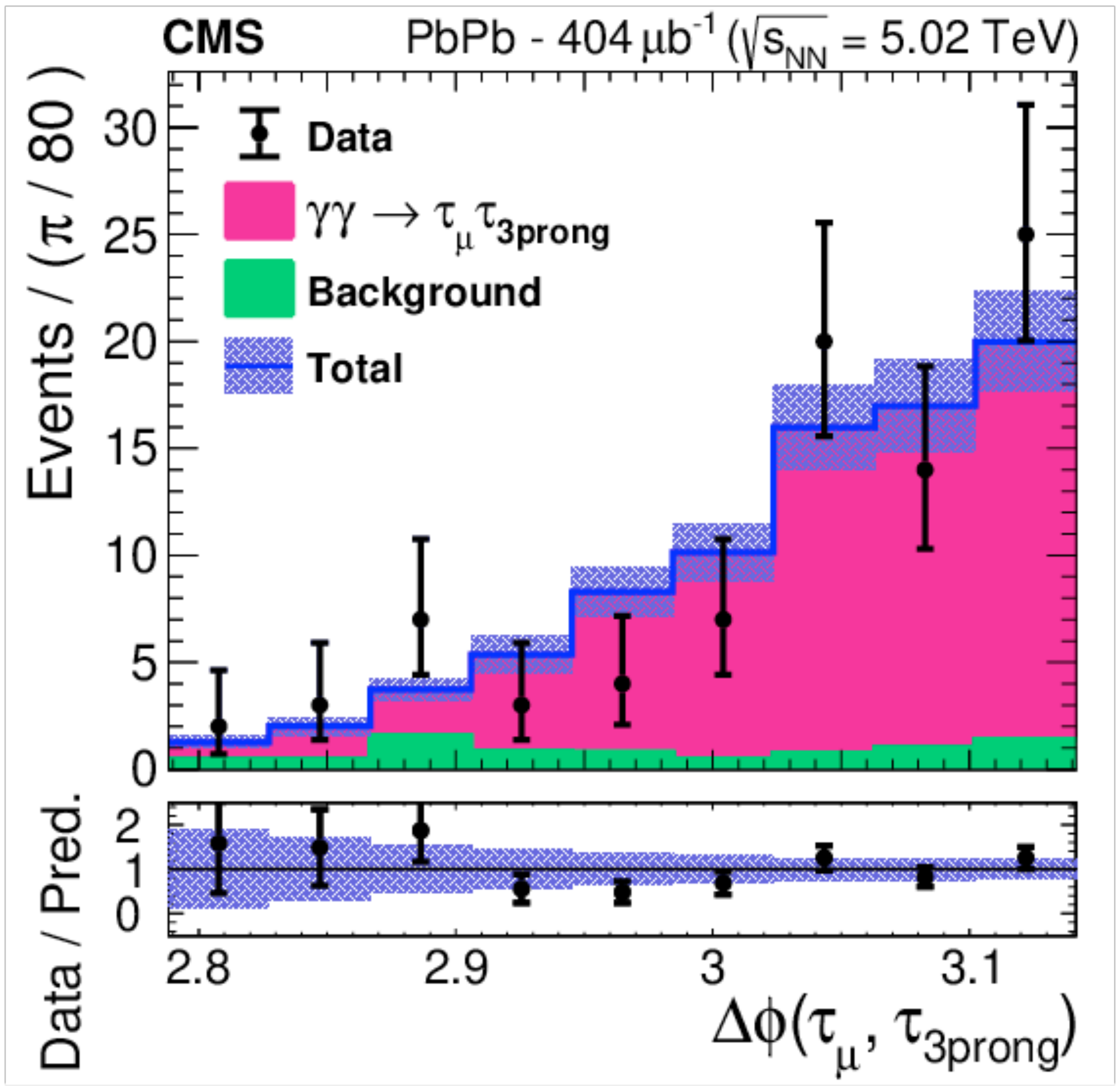
arXiv:2206.05192

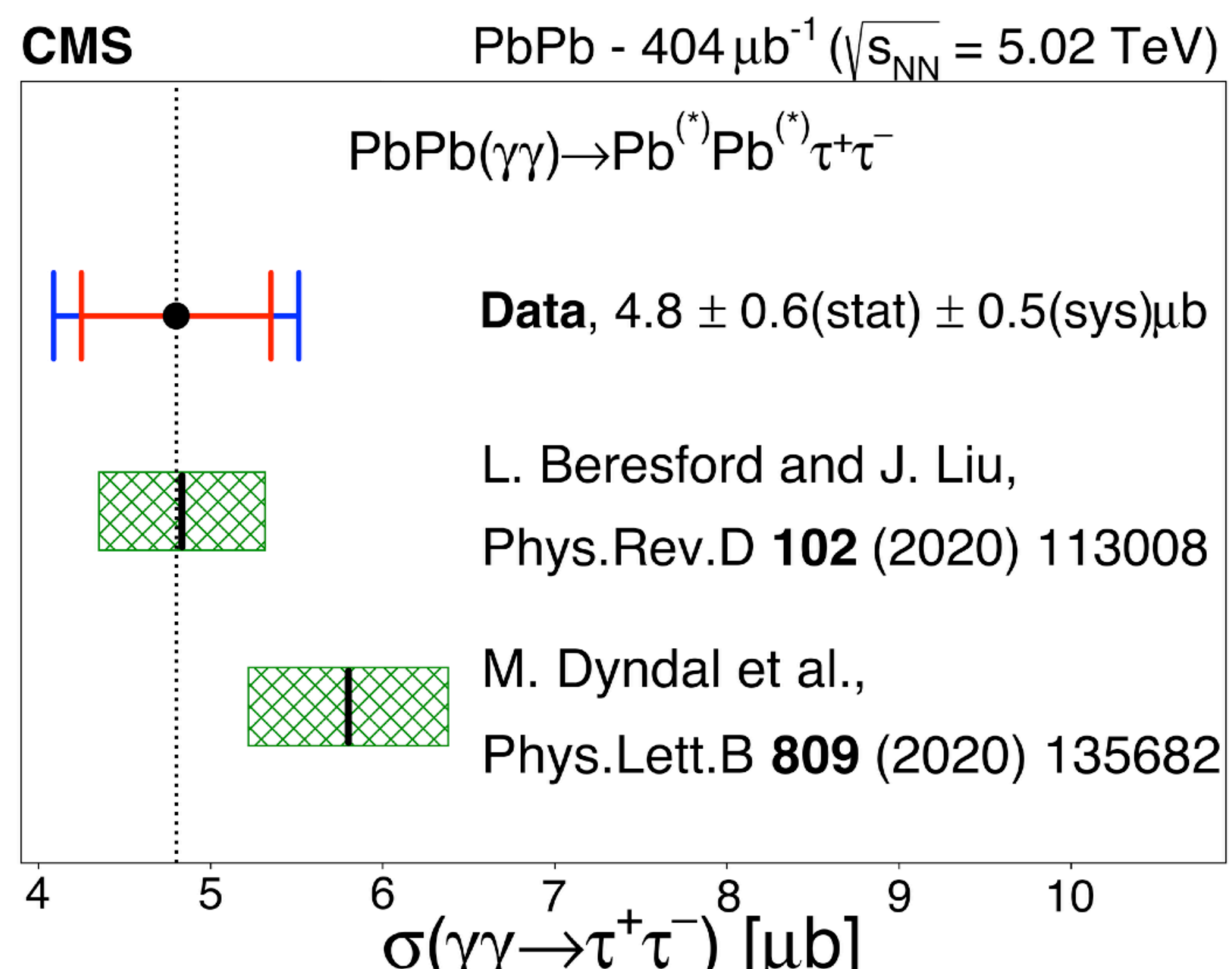
Observation of $\gamma\gamma\rightarrow\tau\tau$ at CMS

- Similarly, the first observation with 5σ significance at CMS
- Using 2015 dataset, using signature with **μ**+3prong **τ**$_h$

$$\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6\,(\text{stat}) \pm 0.5\,(\text{syst})\,\mu\text{b}$$

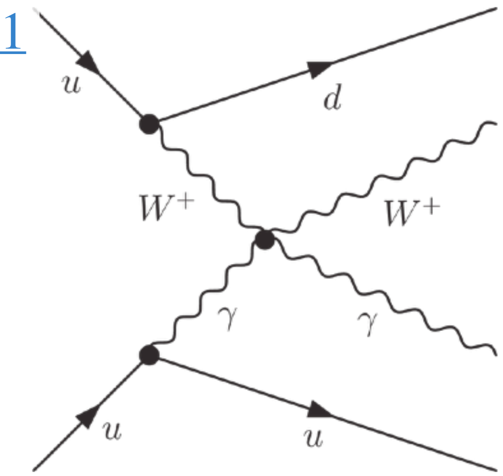
$$a_\tau = 0.001^{+0.055}_{-0.089} \text{ at a 68\% confidence level}$$



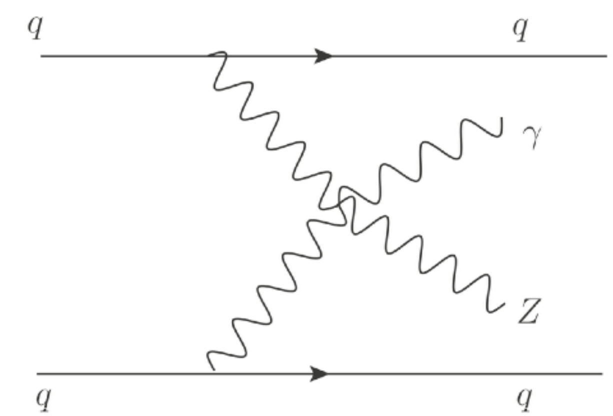


ATLAS-CONF-2021-038 CMS-PAS-SMP-21-011

EWK Vγjj production



- VBS processes play important role for understanding EWSB; Offer unique features to probe BSM physics.
  - Many VBS processes are observed and studied by ATLAS and CMS
  - Important to distinguish between EW and QCD Vγjj productions
  - Handle to probe anomalous QGC: high m_{jj}, high p_T^{γ}

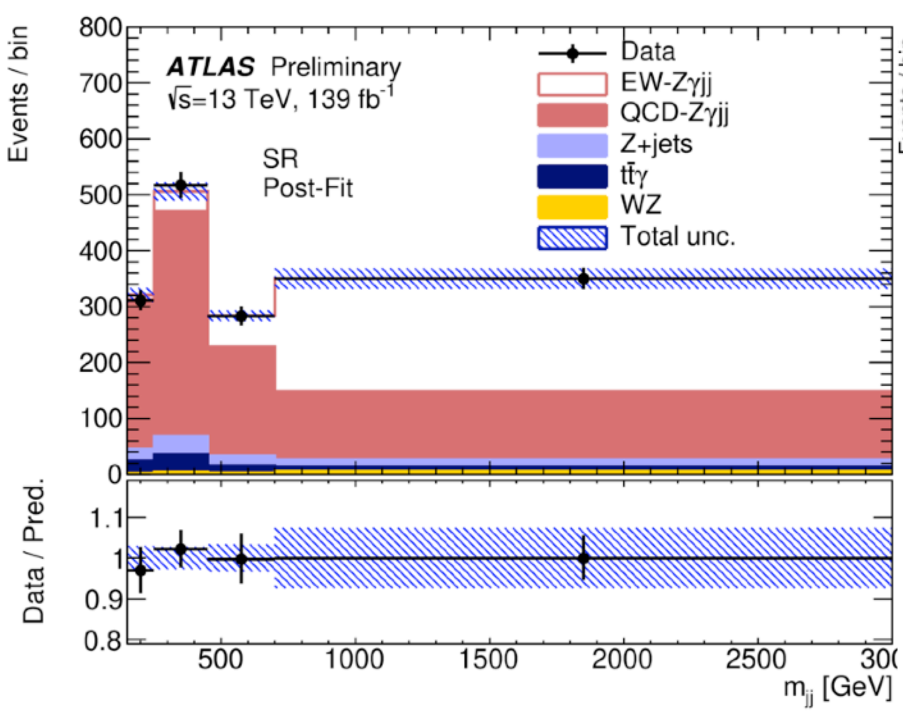


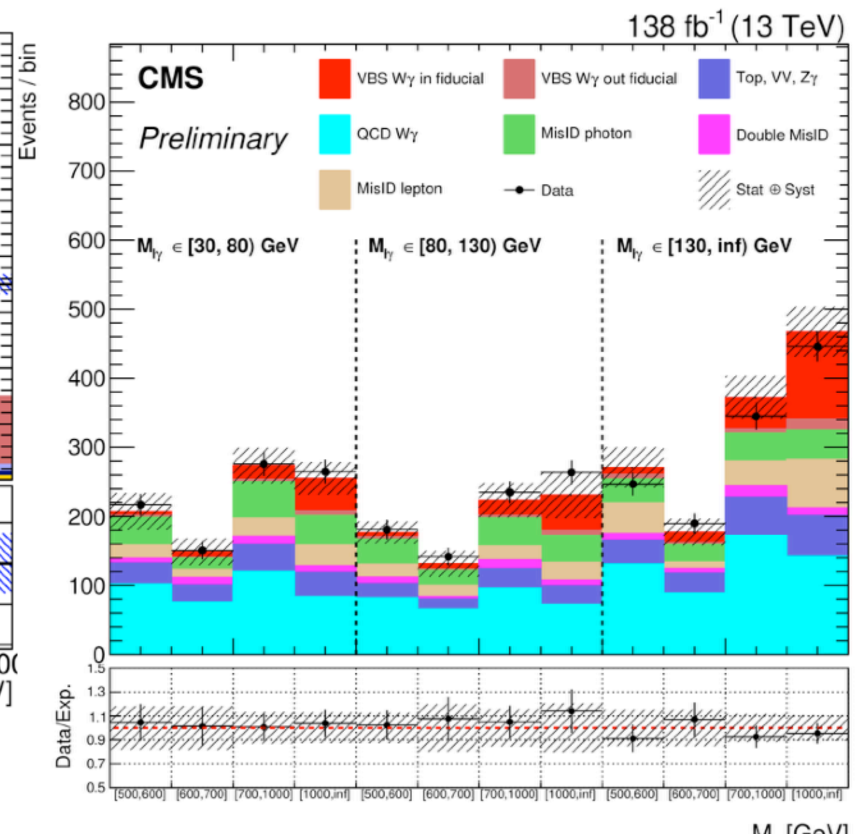
ATLAS: Zγ+jj with Z→ee/$\mu\mu$

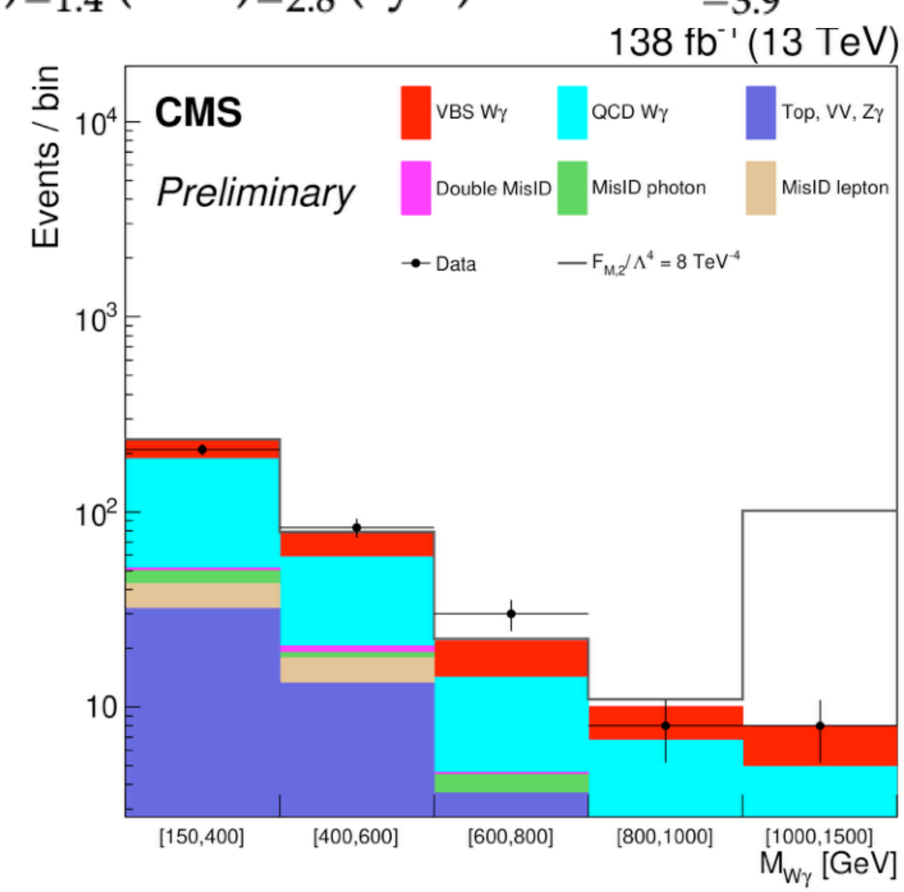
$$\sigma_{EW} = 4.49 \pm 0.40\,(\text{stat.}) \pm 0.42\,(\text{syst.})\ \text{fb}$$

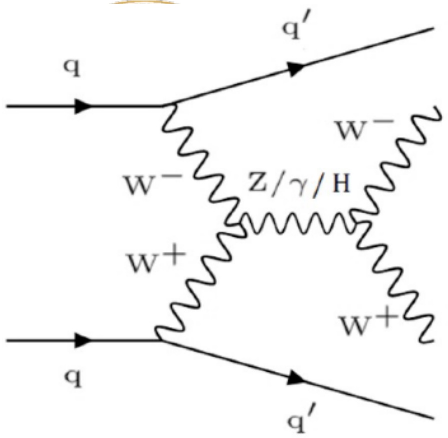
CMS: Wγ+jj with W→eν/$\mu\nu$

$$\sigma_{\text{EW}}^{\text{fid}} = 19.2^{+2.3}_{-2.3}\,(\text{stat})^{+1.6}_{-1.4}\,(\text{theo})^{+2.9}_{-2.8}\,(\text{syst})\ \text{fb} = 19.2^{+4.0}_{-3.9}\ \text{fb}$$





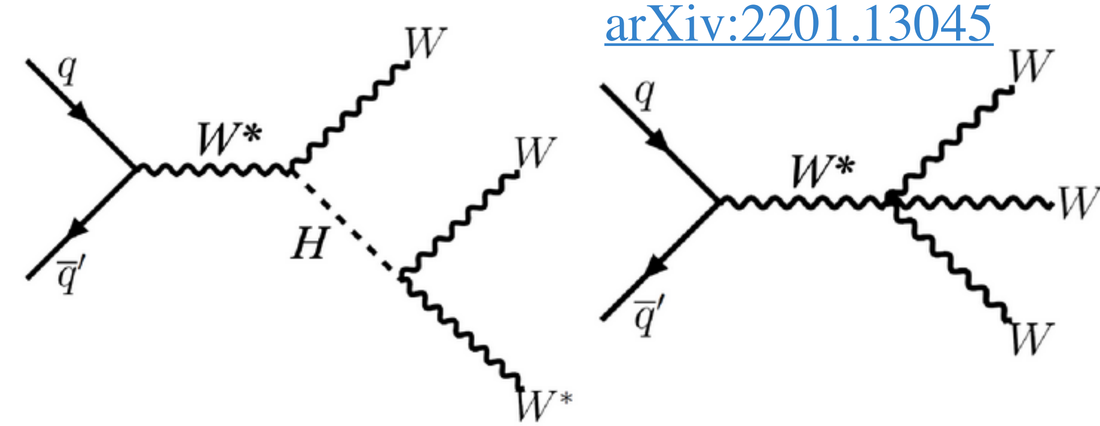




arXiv:2205.05711

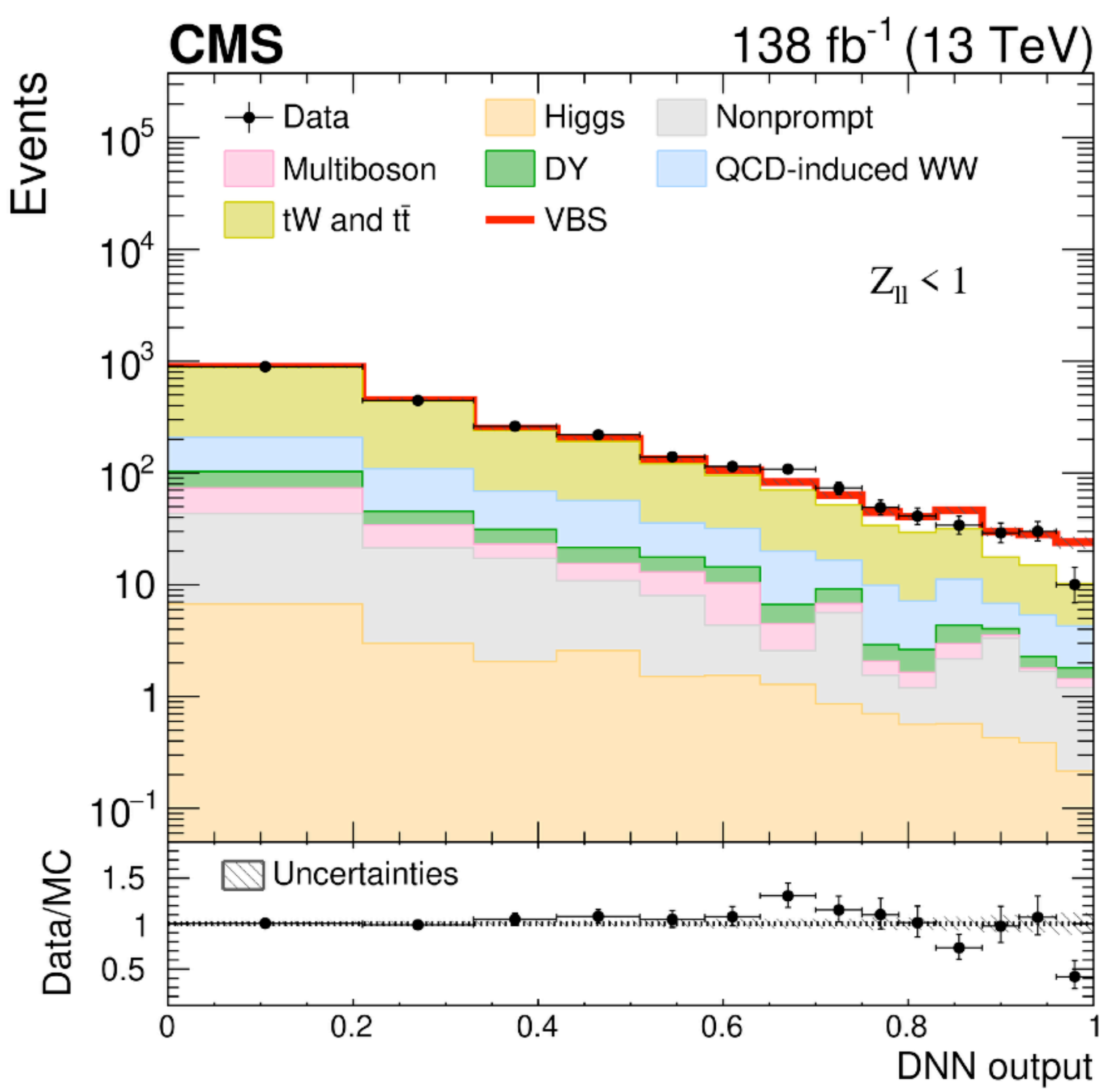
After Multiple Ws

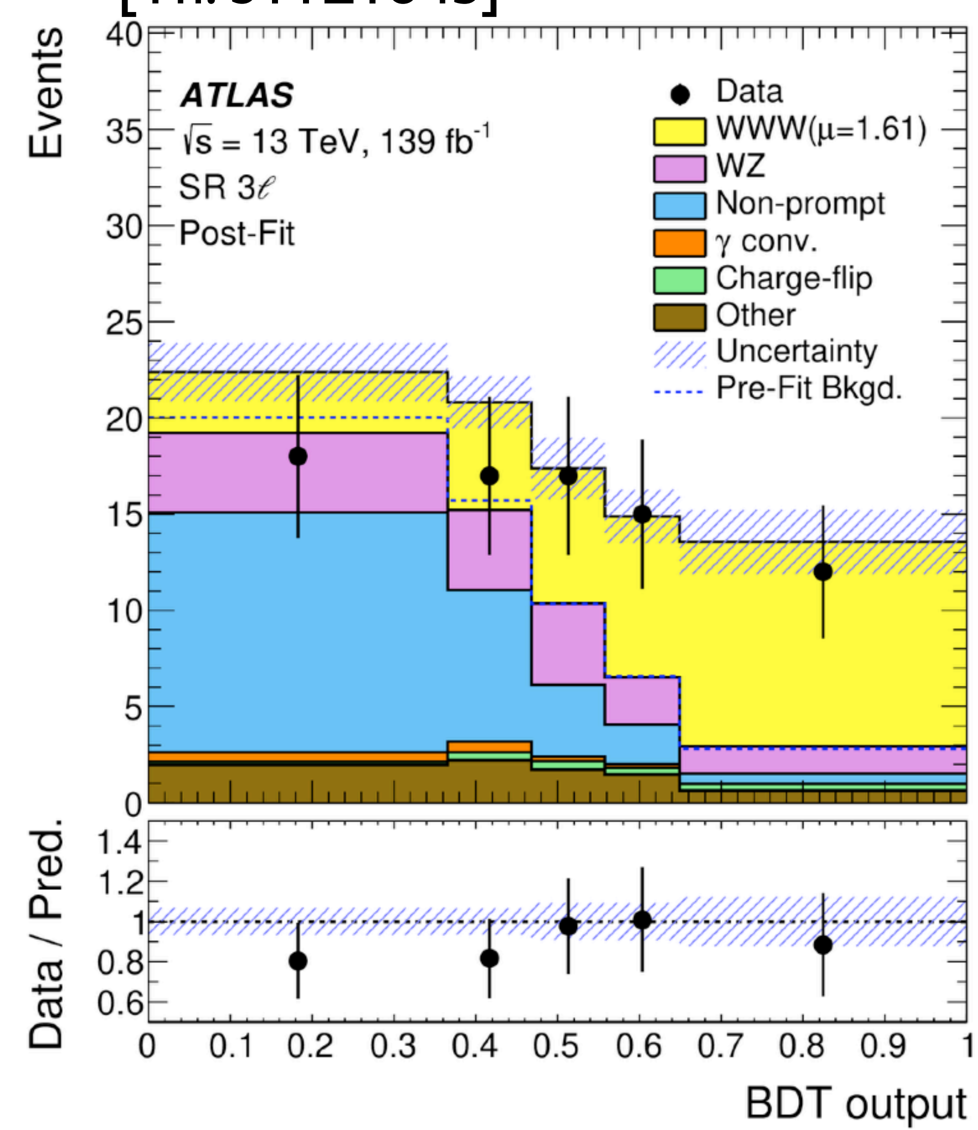
arXiv:2201.13045



- The first observation of EWK WWjj production at CMS at 5.6 S.D:
  OS ee,eμ,μμ final states
- Measured cross section
  σ=10.2±2.0 fb [Th: 9.1±0.6 fb]

- The first observation of three W bosons at ATLAS at 5.4 S.D:
  2ℓ+2jets, 3ℓ final states
- Measured cross section
  σ=820±100(stat.)±80(syst.)fb
  [Th: 511±18 fb]





years HIGGS boson discovery

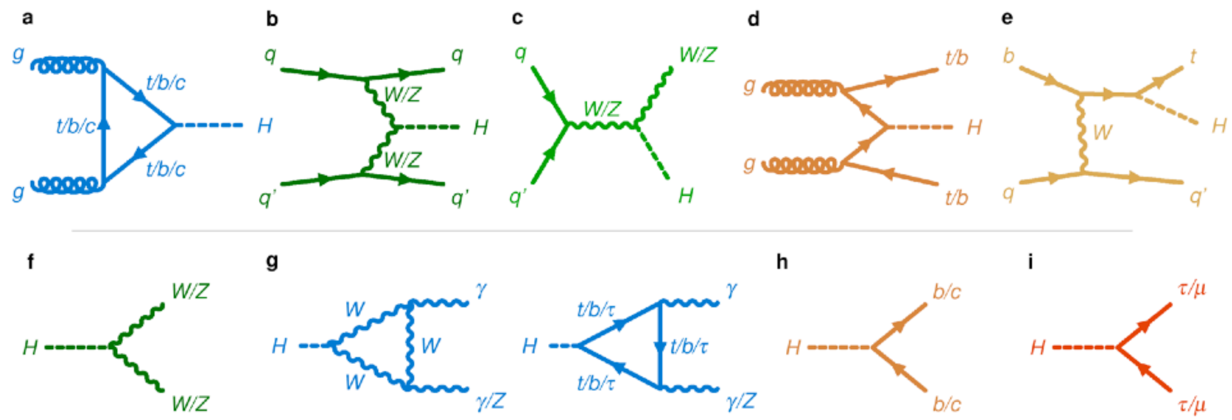
[Nature: ATLAS]

[Nature: CMS]

[Phys. Lett. B 805 (2020) 135425]

[arXiv:2207.00320]

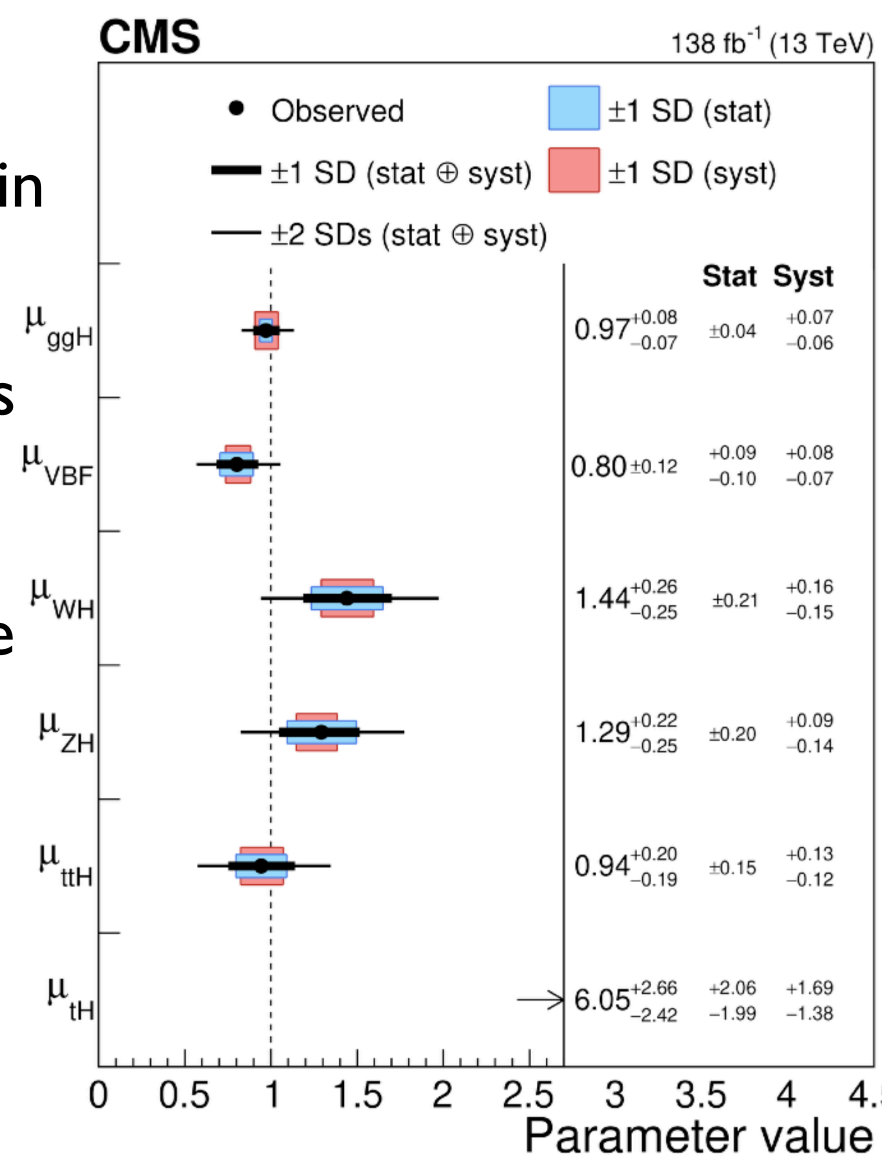
Higgs Status

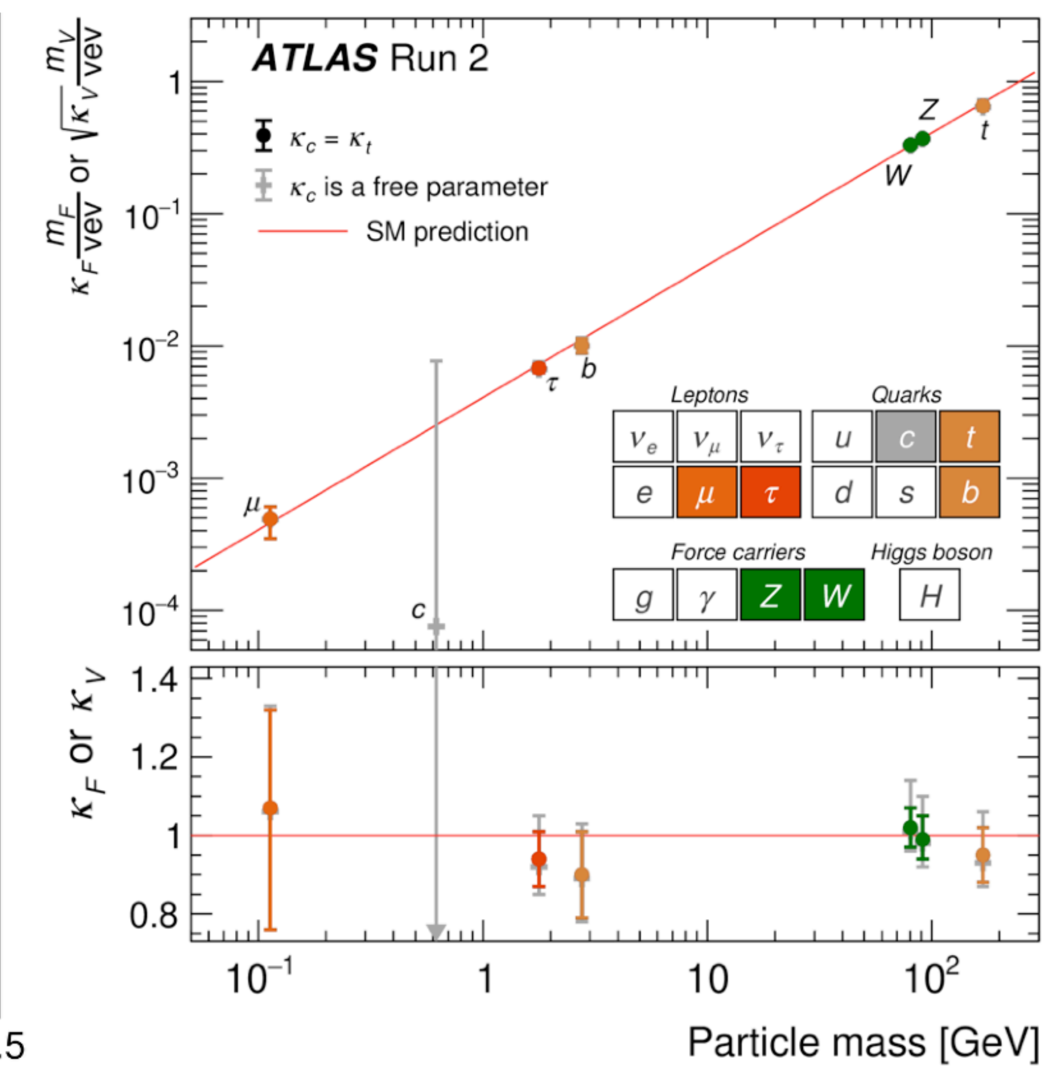


Mass measurement with 1 per mille precision

ATLAS+CMS Run1	125.09 ± 0.24	(± 0.21 stat ± 0.11 syst) GeV
CMS Run1 + 2016	125.38 ± 0.14	(± 0.11 stat ± 0.08 syst) GeV
ATLAS Run1 + *4l* Run2	124.94 ± 0.17	(± 0.17 stat ± 0.03 syst) GeV

- Observation of all main production processes
- Observation of decays to bosons and third-generation fermions and evidence of decay to **μμ**





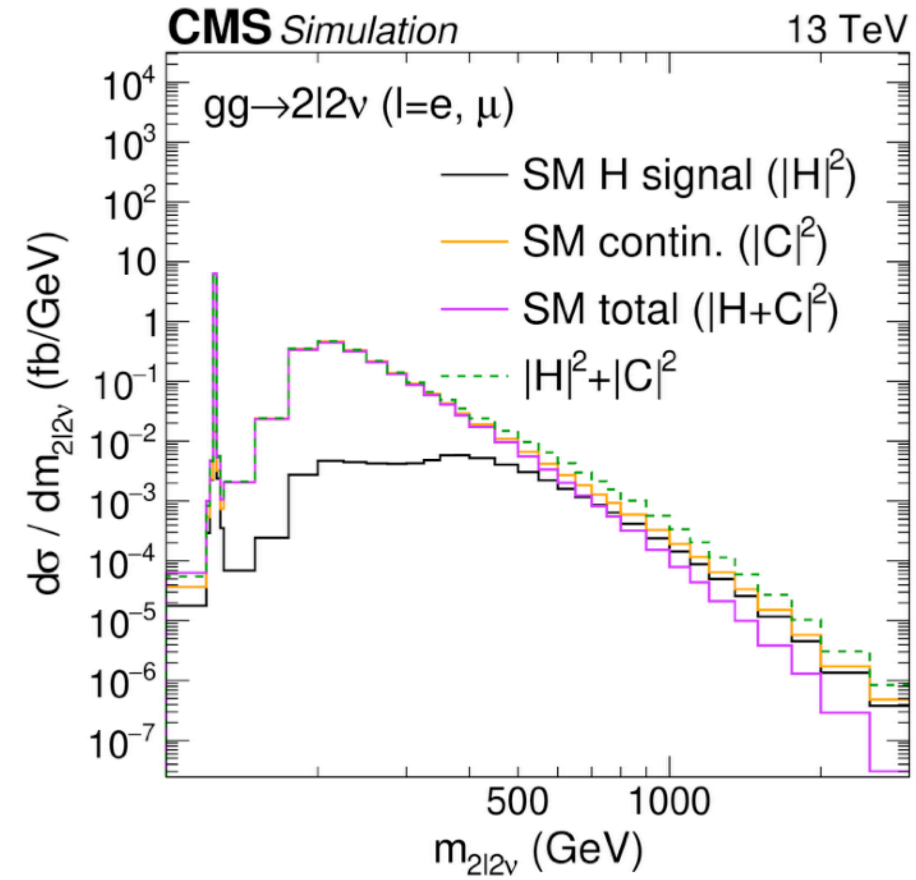
Keti Kaadze, Kansas State University

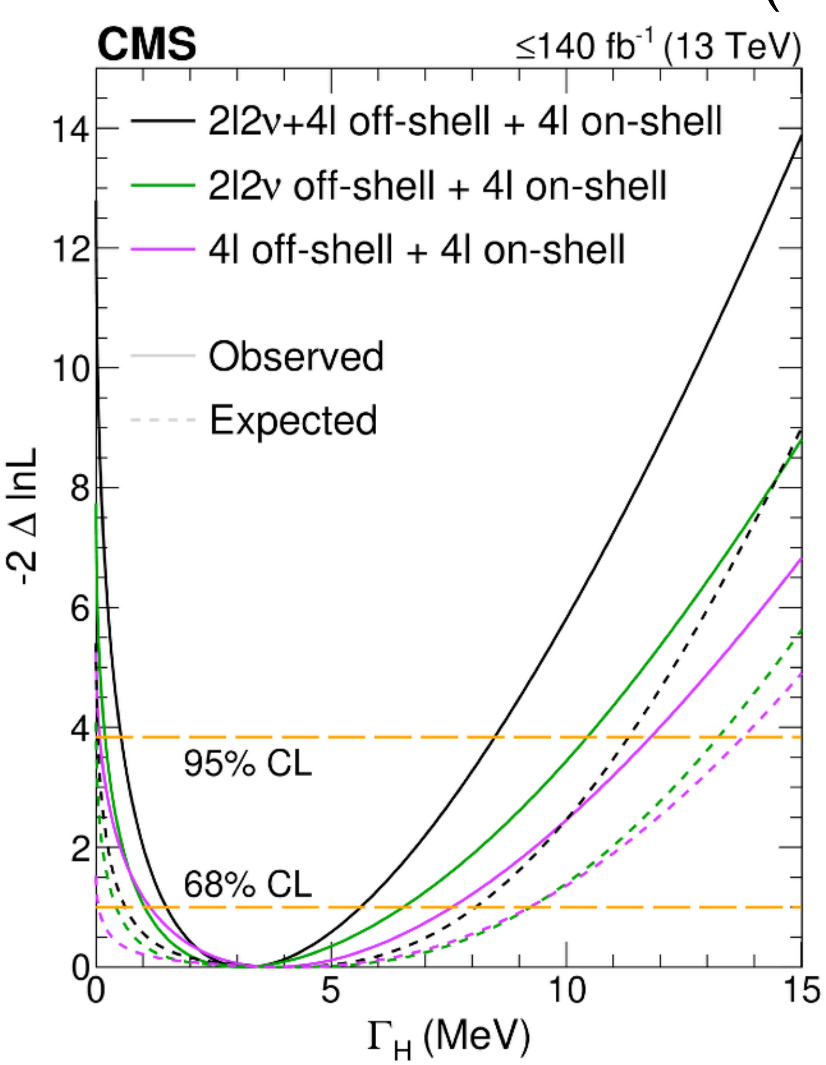
NP arXiv:2202.06923

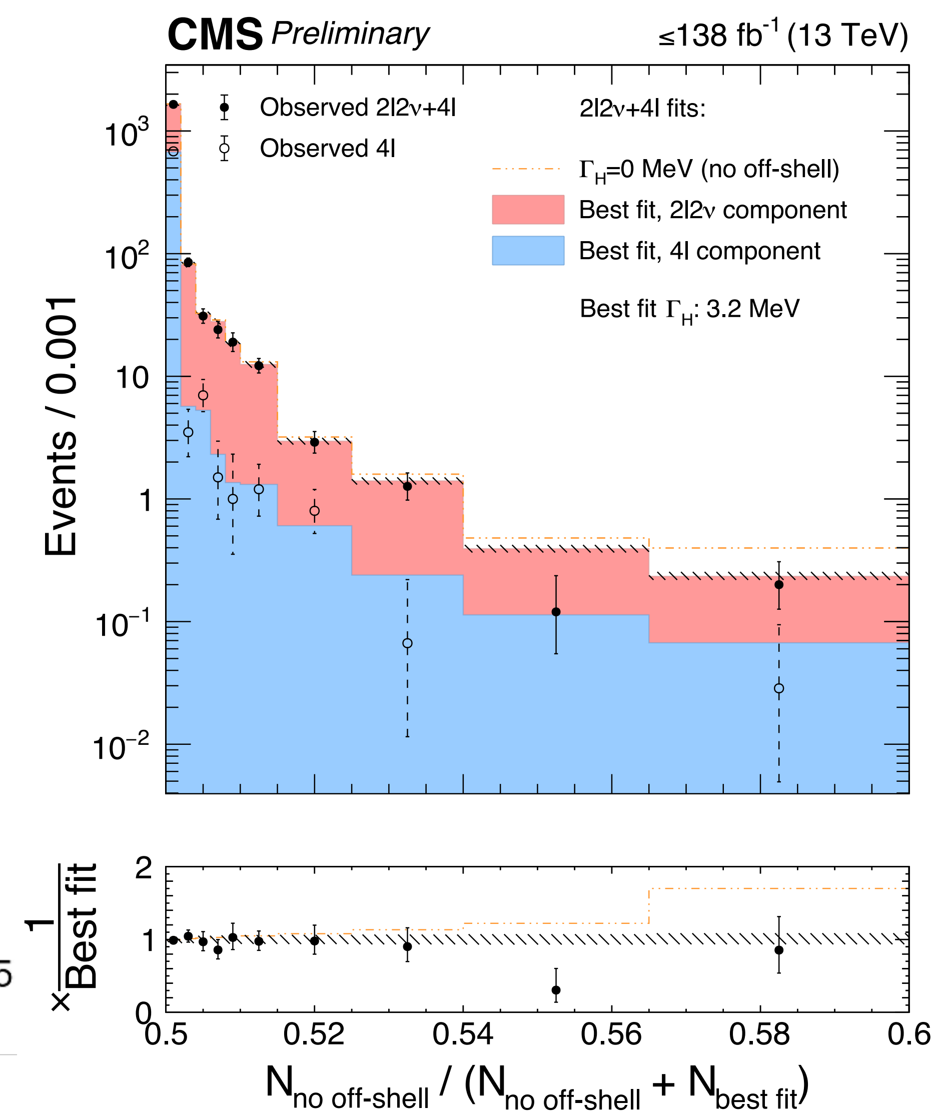
Off-shell Higgs production

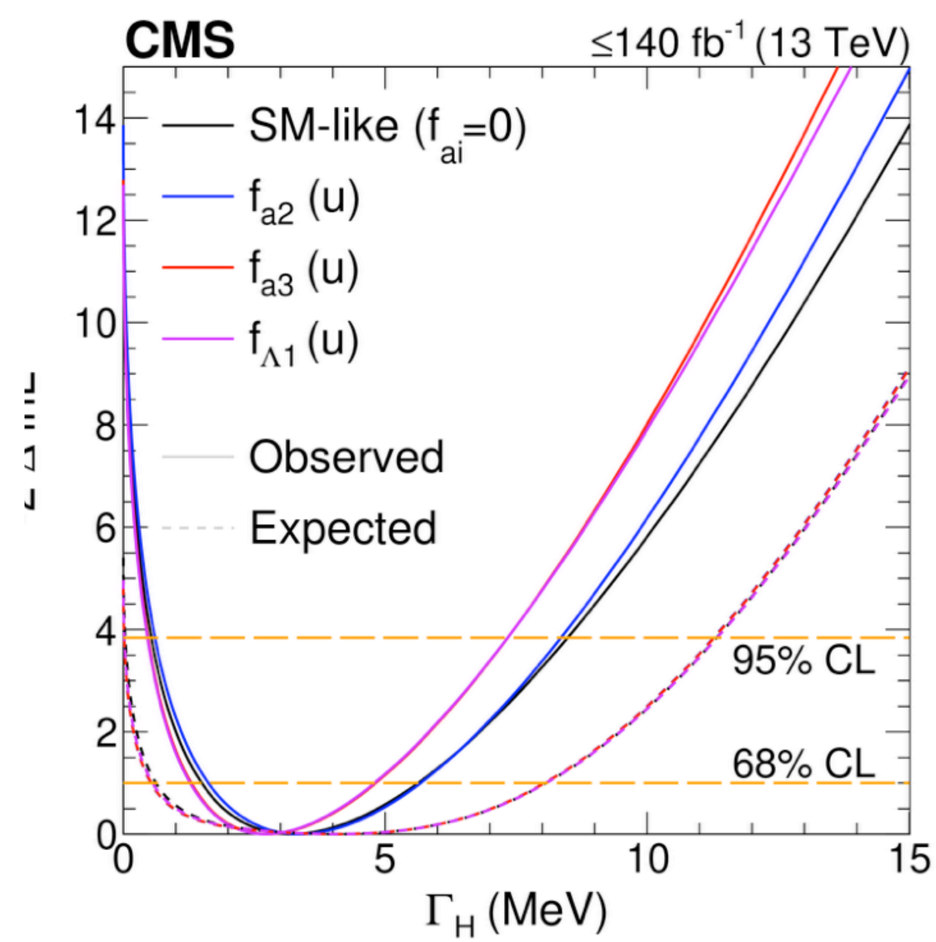
- The SM prediction Γ_H = 4.1MeV; Direct meas. Γ_H < 1.1 GeV at 95% CL
- Off-shell H production above $2M_Z$ is enhanced; Combination of $H\rightarrow ZZ\rightarrow 4\ell$ and $H\rightarrow ZZ\rightarrow 2\ell 2\nu$ channels for best results
  - Comparison of on-shell and off-shell rates constrains the Higgs width

$\Gamma_H = 3.2^{+2.4}_{-1.7}$MeV
No off-shell scenario excluded at
99.97% CL (3.6 s.d.)



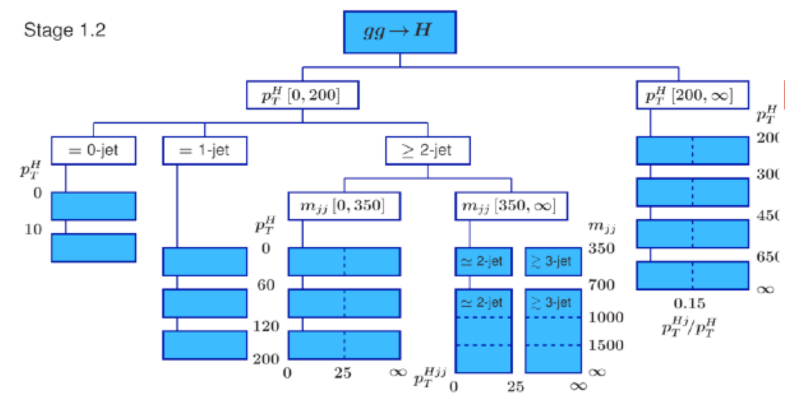


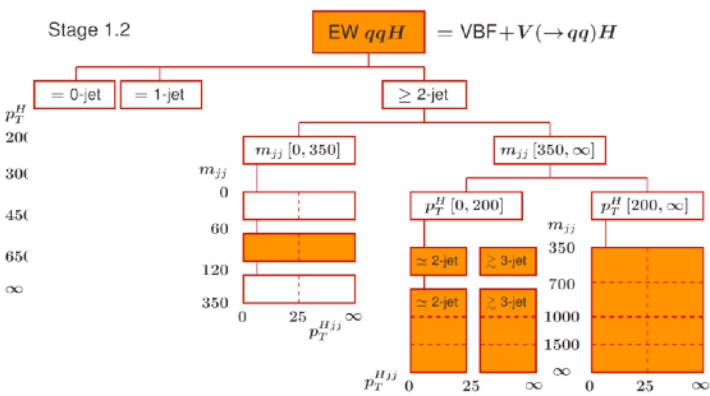


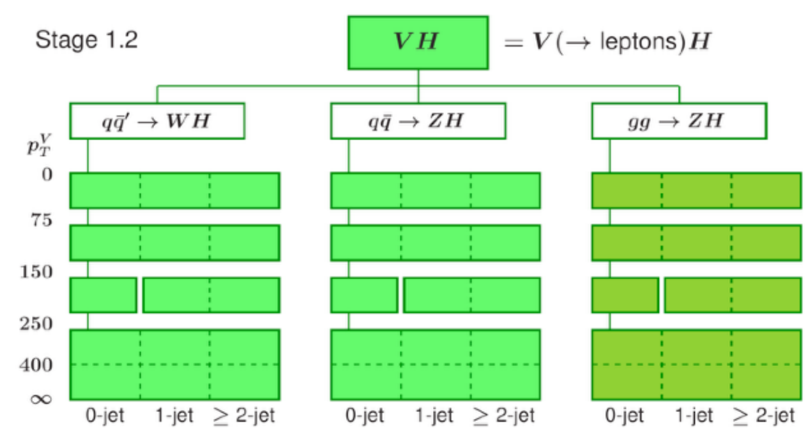


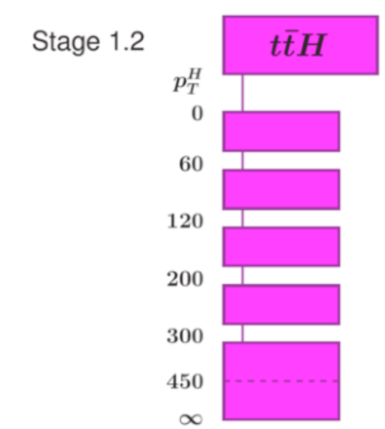
Cross Sections

- From total cross sections to Simplified Template Cross Sections (STXS)
  - Measure production modes separately in mutually exclusive kinematic regions defined by pT(H), Njets, Mjj, pT(V), but inclusively over the Higgs decay
  - Less model-dependent measurements
  - Best sensitivity to signal/BSM and reducing theory uncertainty







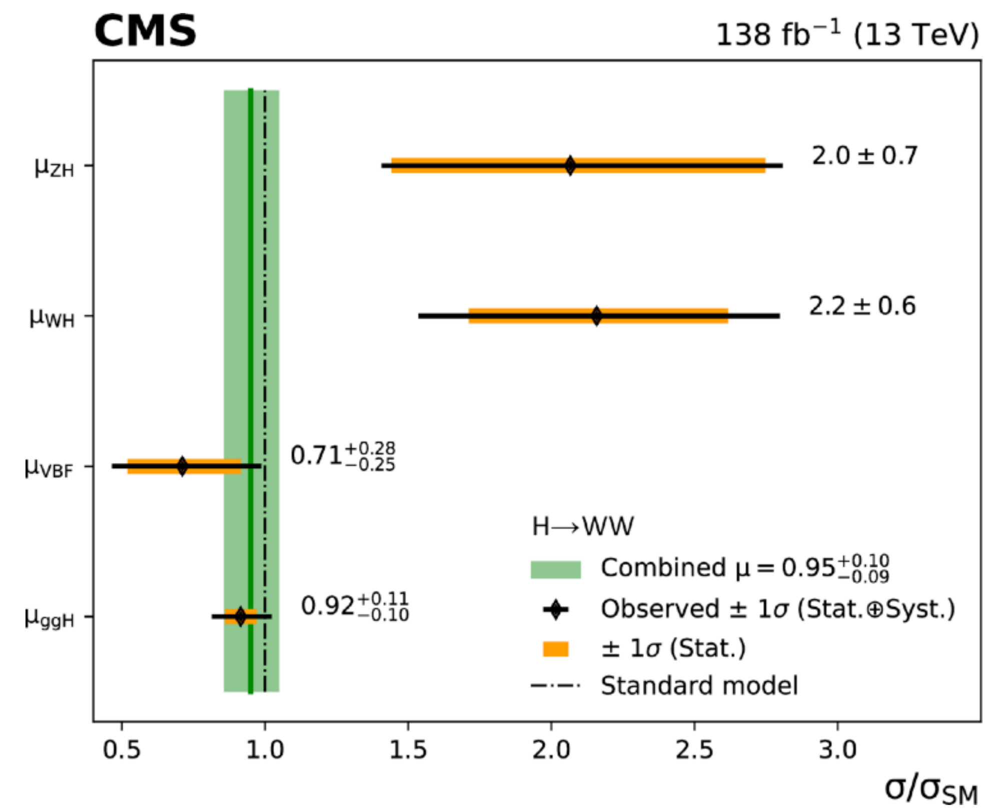


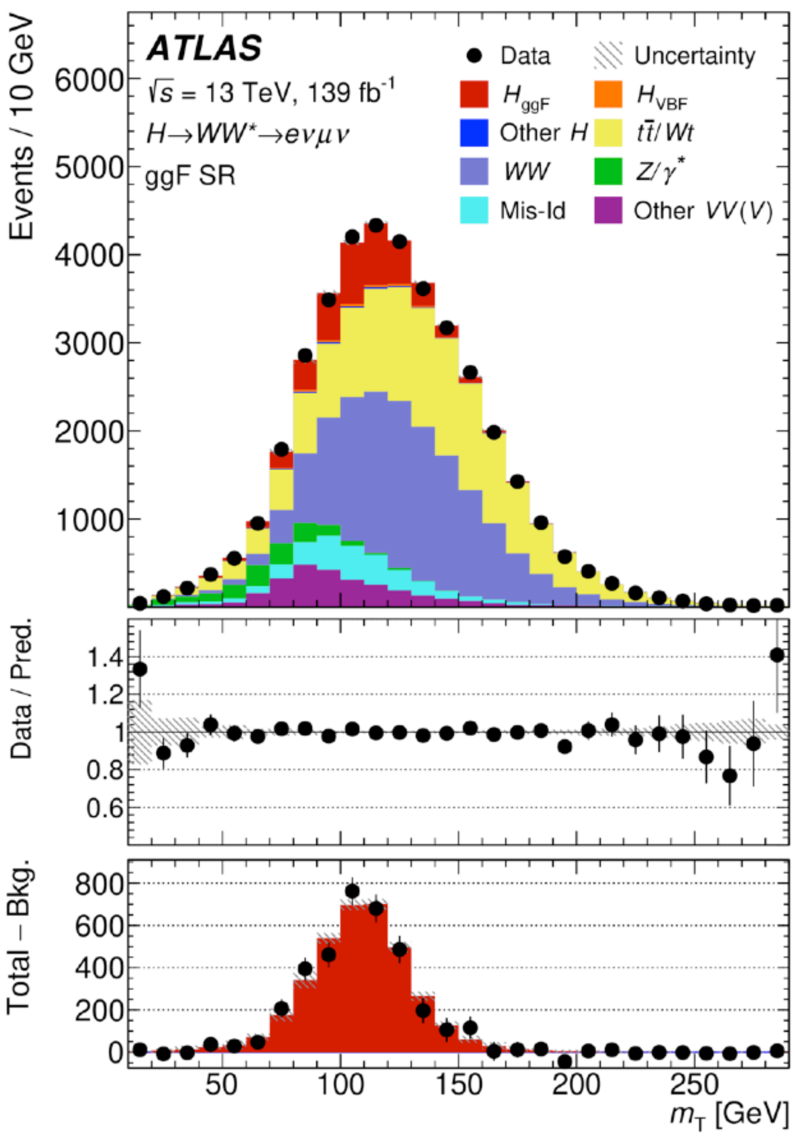
- Fiducial Cross Section
  - More model independent than STXS
  - Fiducial phase space defined based on the Higgs decay product
  - Differential distributions in kinematic variables sensitive to BSM effects

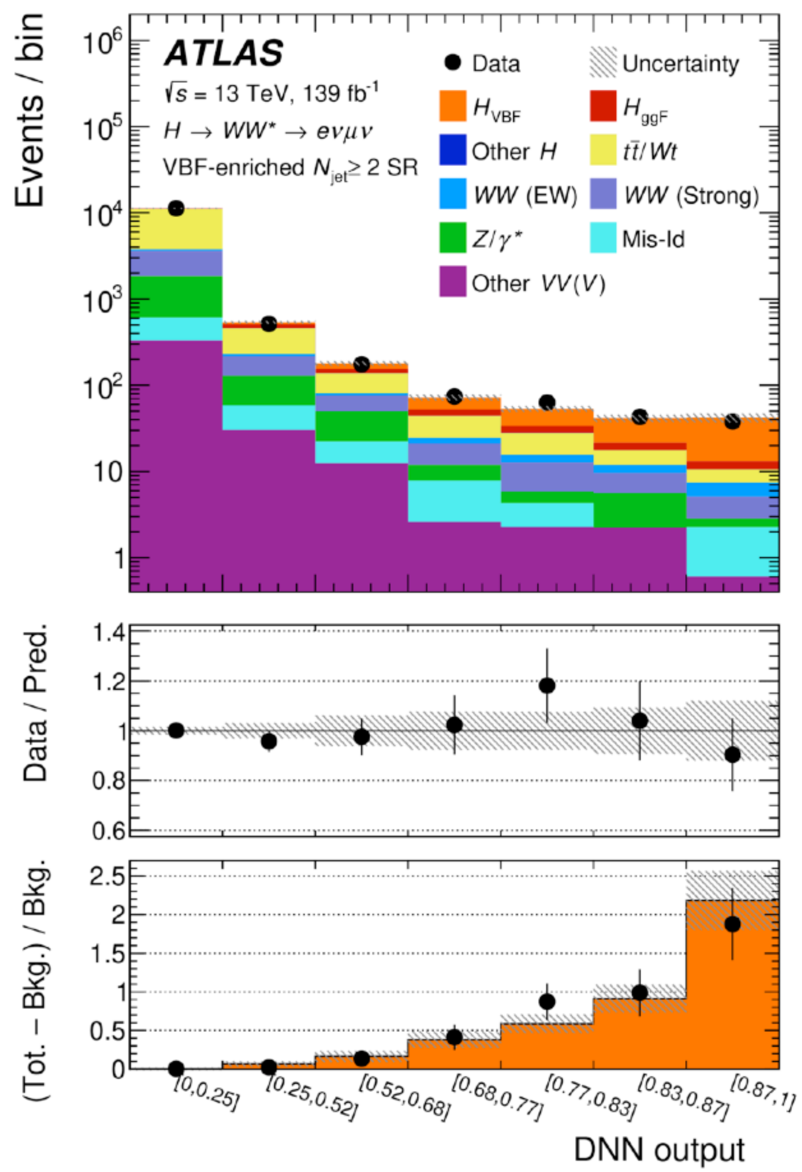
arXiv:2207.00338
arXiv:2206.09466

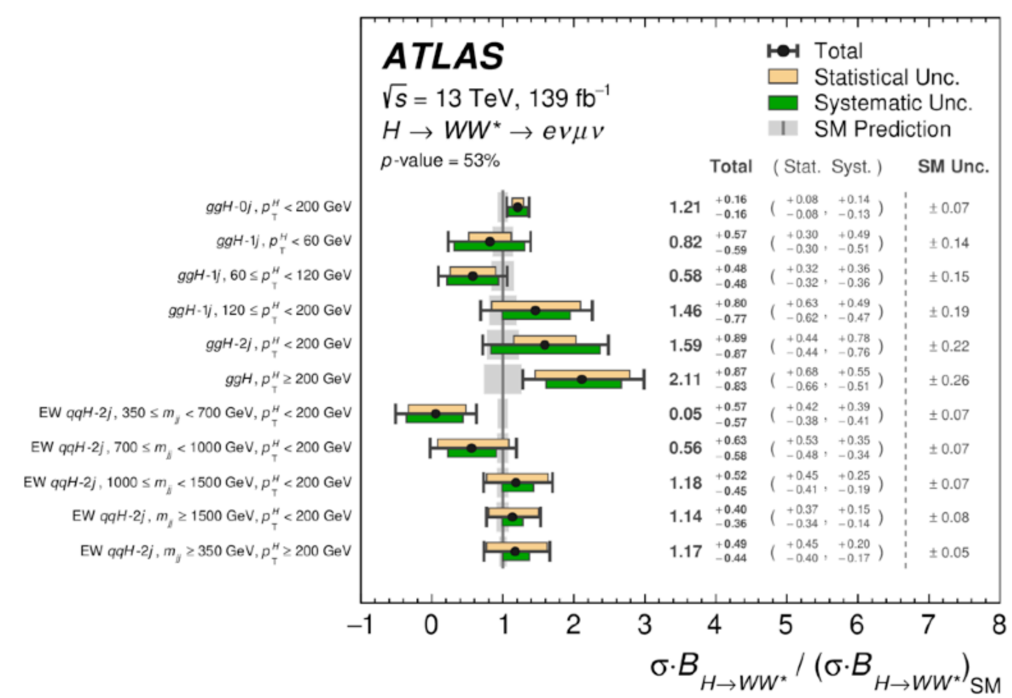
STXS Measurement: H→WW

- Recent measurements of ggH, VBF, (also VH in case of CMS) productions from both ATLAS and CMS using the whole Run 2 data
- σ_{ggH}=12.0±1.4 pb, $\sigma_{VBF}=0.75^{+0.19}_{-0.16}$ pb from ATLAS







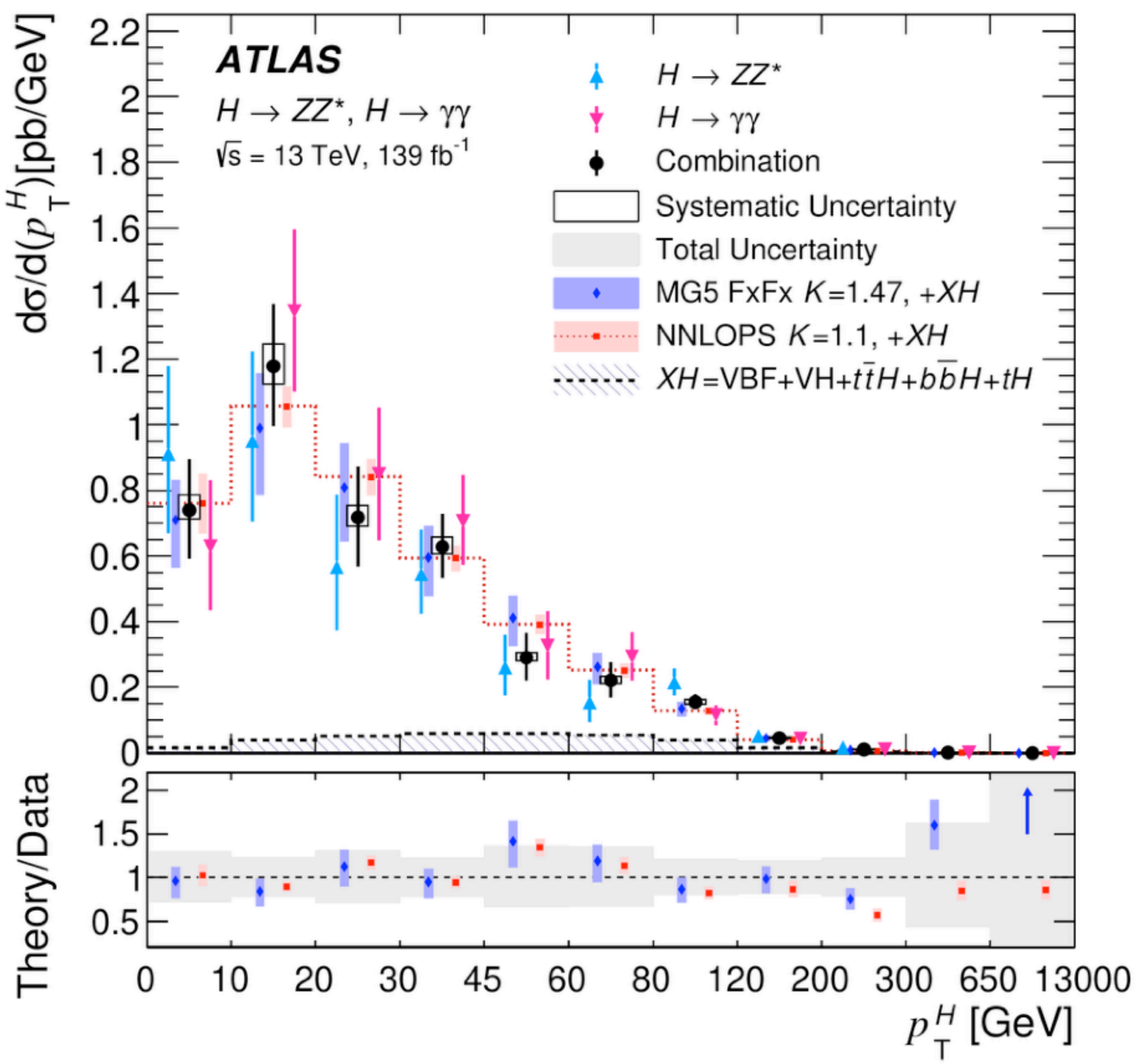


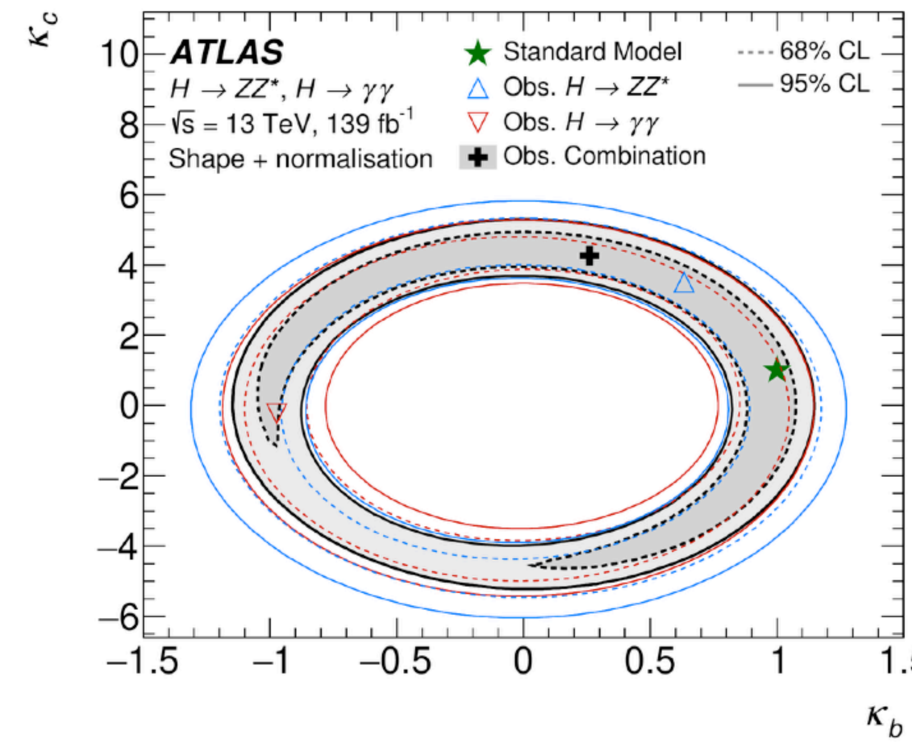
arXiv:2207.08615

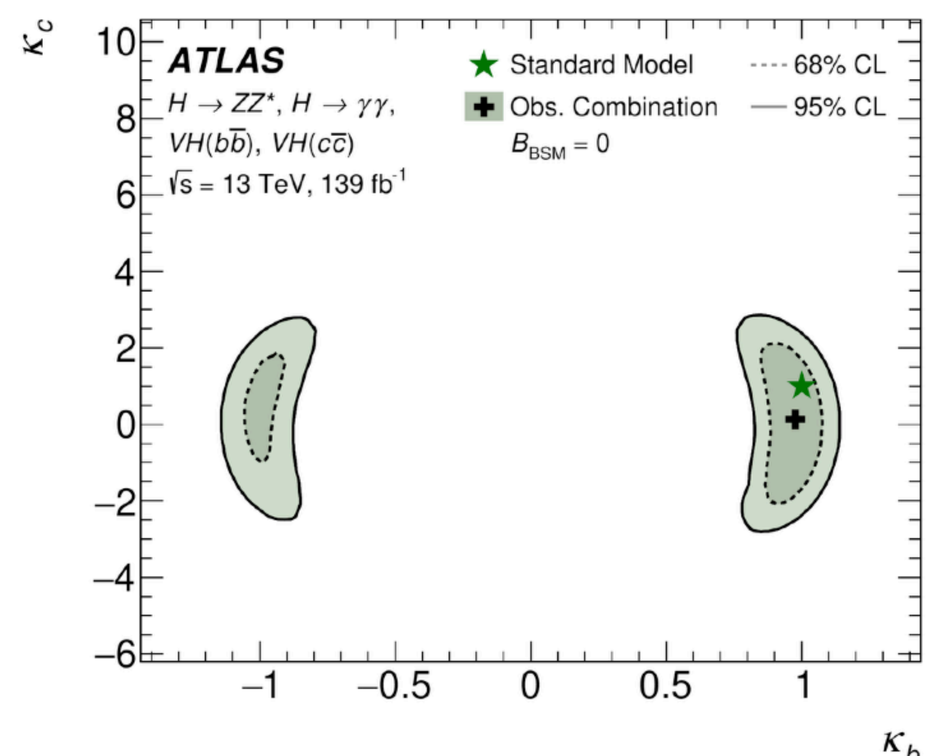
Differential Measurements: H→ZZ,$\gamma\gamma$

- Combination of differential measurements in high resolution channels H→$\gamma\gamma$ and H→ZZ→4ℓ

- Higgs pT measurement can constrain coupling to b and c quarks due to loop-induced ggH production.
  - Including κ_b and κ_c from VH, H→bb/cc analyses further improve constraints

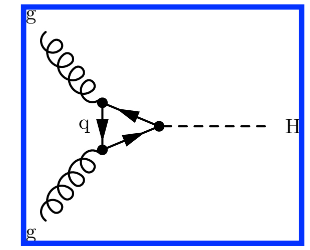


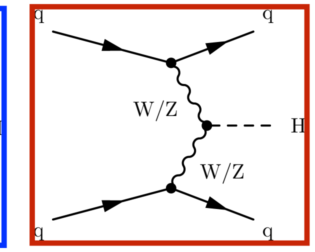




arXiv:2107.11486

Differential Measurements: H→ττ

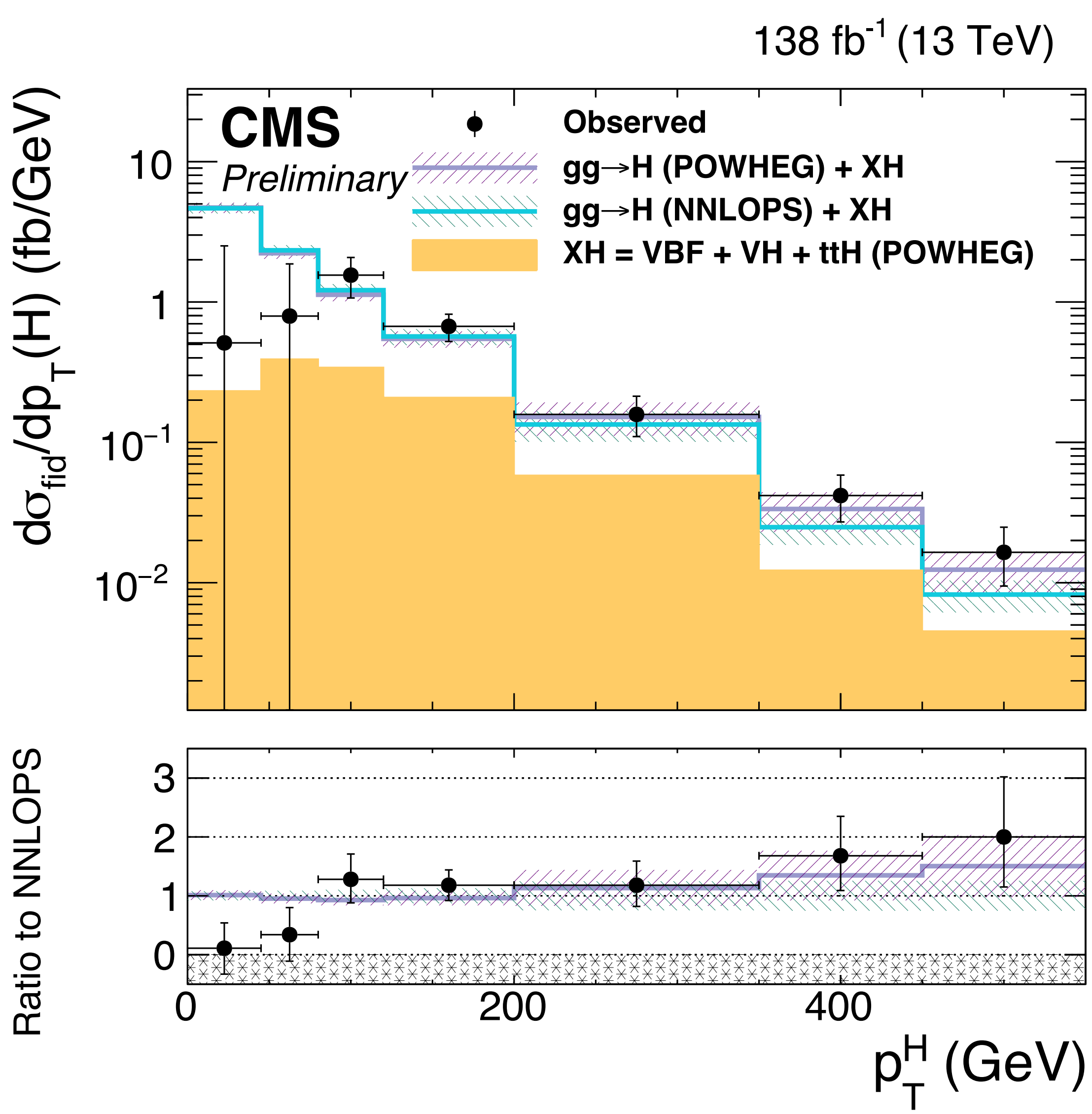


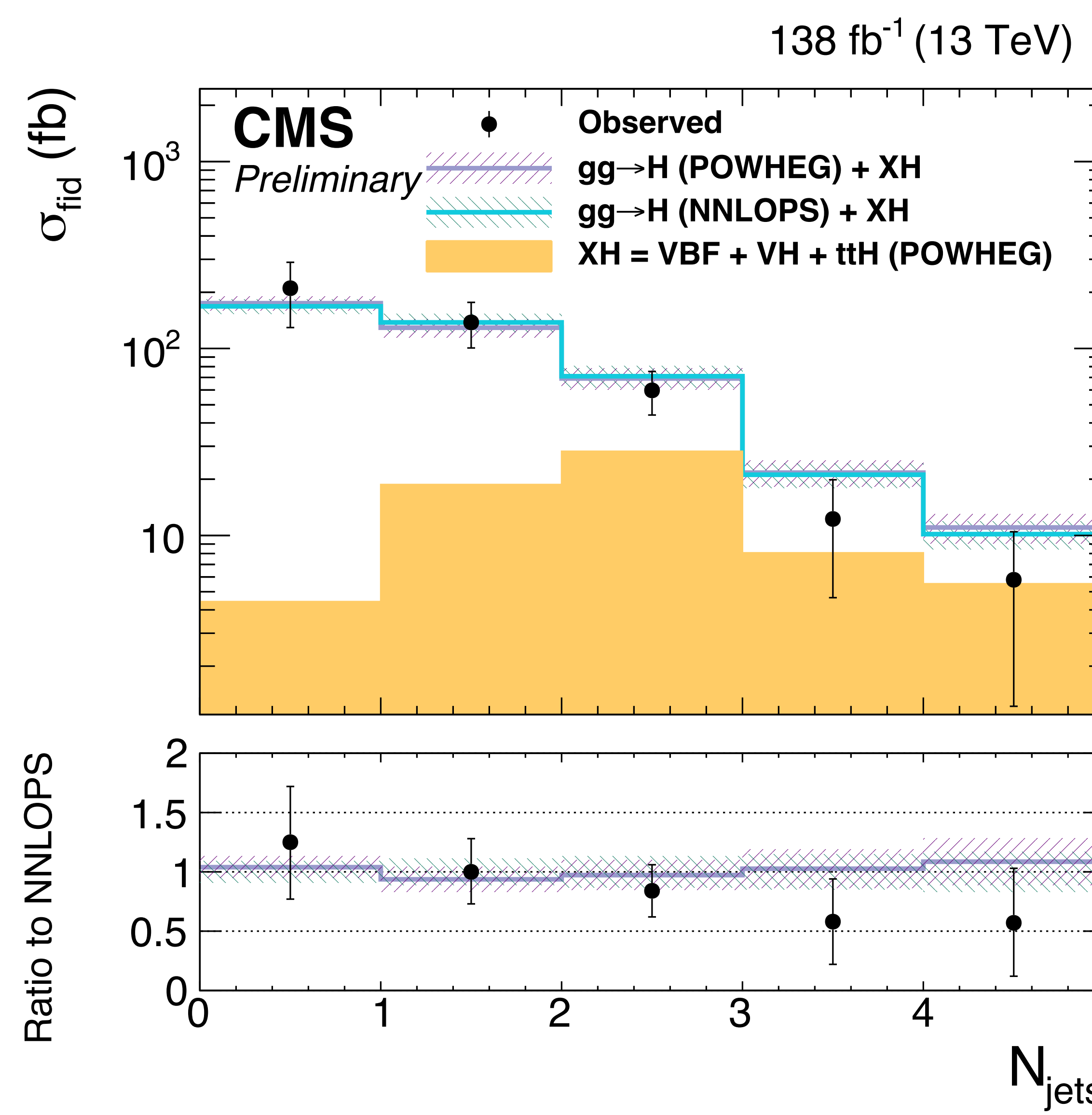


- First measurement of fiducial and differential cross-sections with H→ττ decay
- Measurement is performed over three variables (pT(H), Njets, pT(j)) integrating different Higgs production modes
  - Four distinct final states: $\tau_h\tau_h$, $\tau_h\mu$, $\tau_h e$, $e\mu$

Measurement: σ^{fid} = 427 ± 102 fb

Theory: σ^{fid} = 408 ± 27 fb



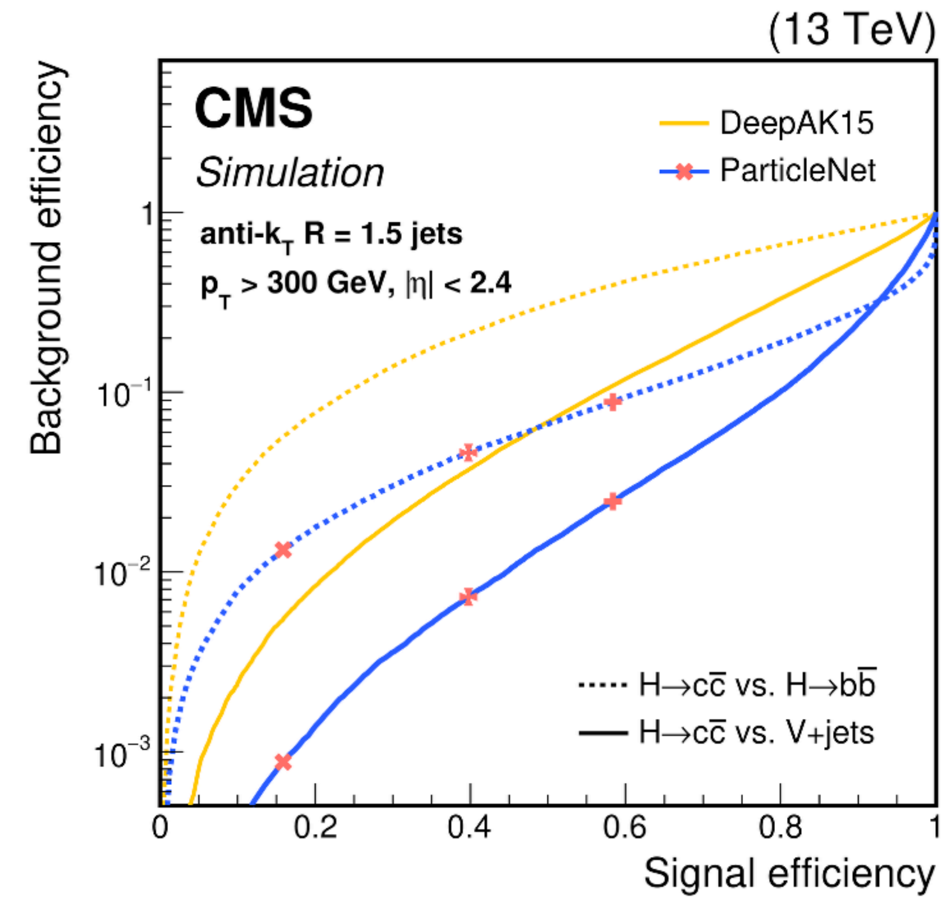


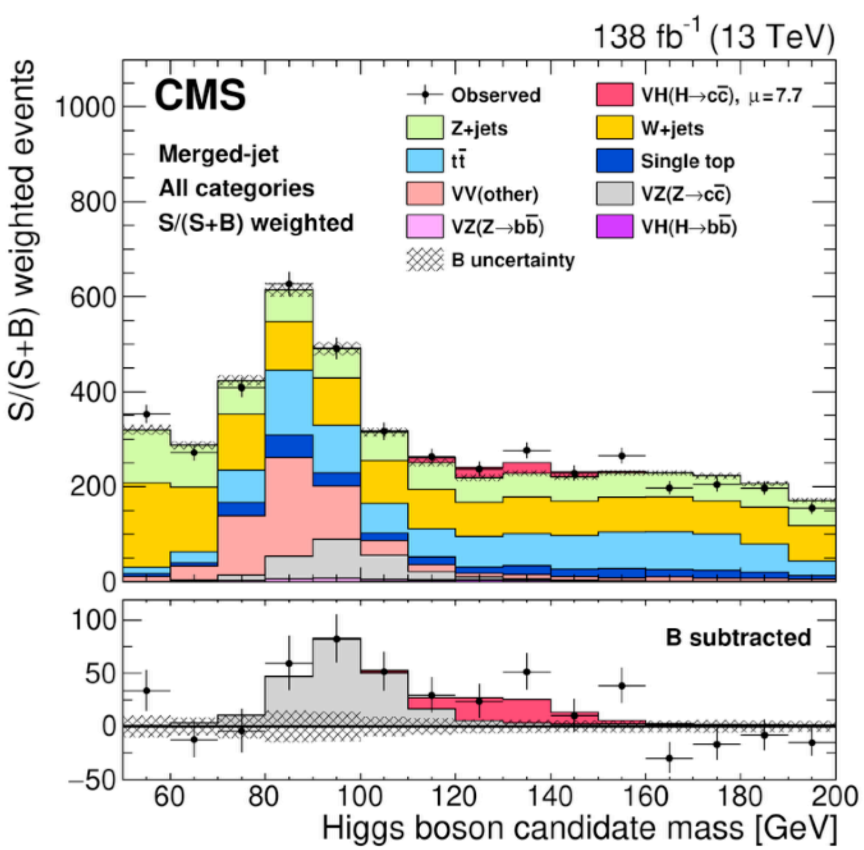
CMS-HIG-21-012
arXiv:2205.05550

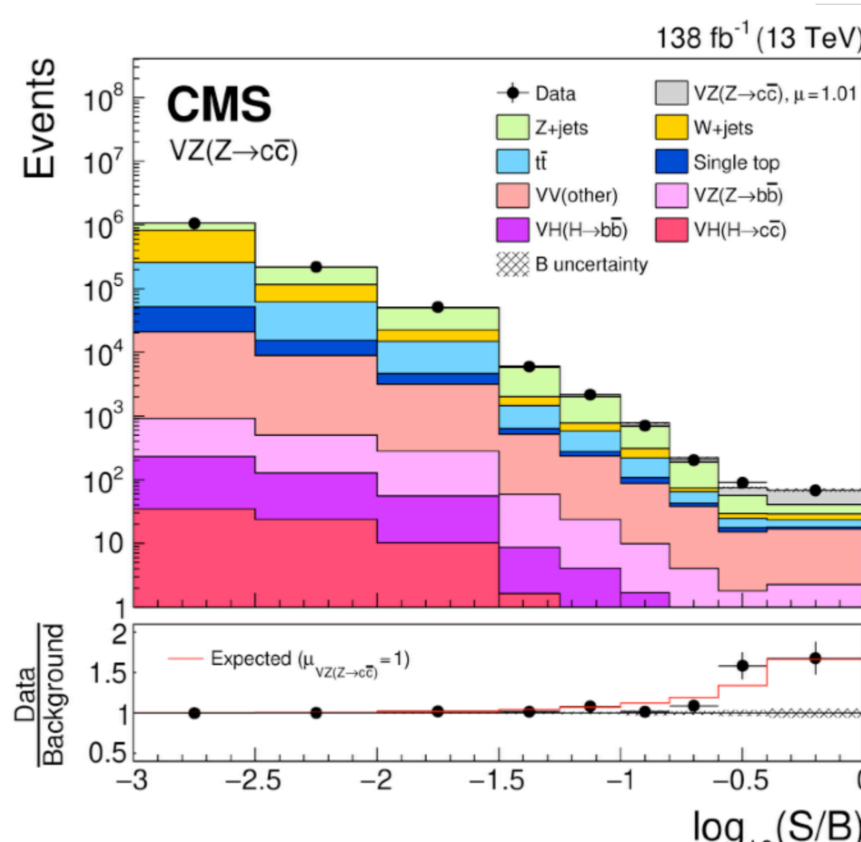
Higgs-charm coupling

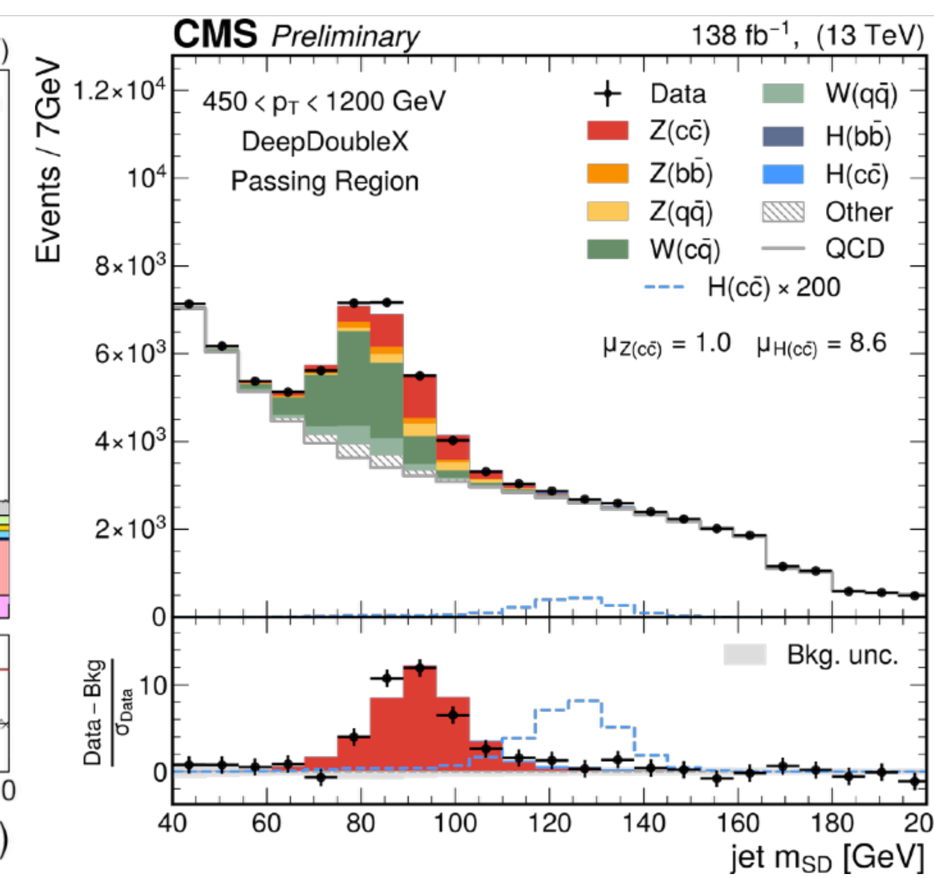
- Higgs-charm coupling measurement is very challenging
- CMS developed new charm-tagging technique
- Two different analyses targeting VH and ggH productions, respectively
- Z→cc serves as calibration candle

The first observation of VZ, Z→cc with 5.7s.d.
The first observation of Z+jets, Z→cc with over 5σ





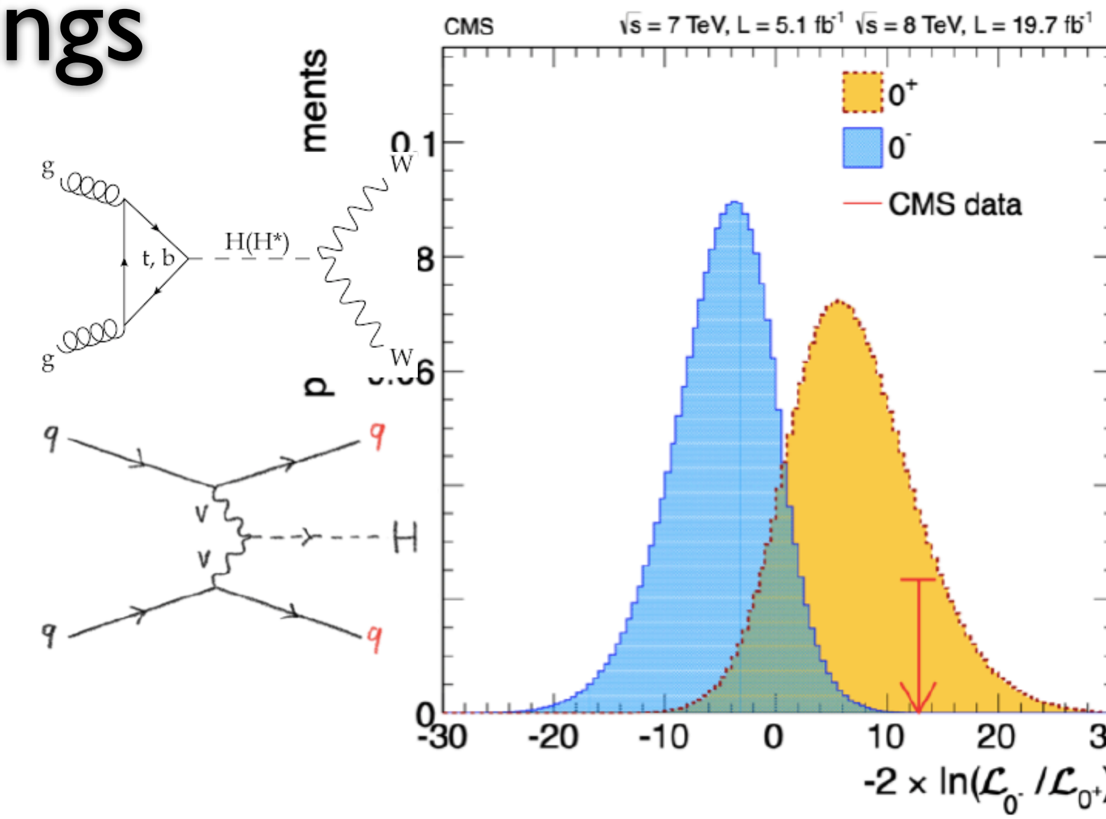


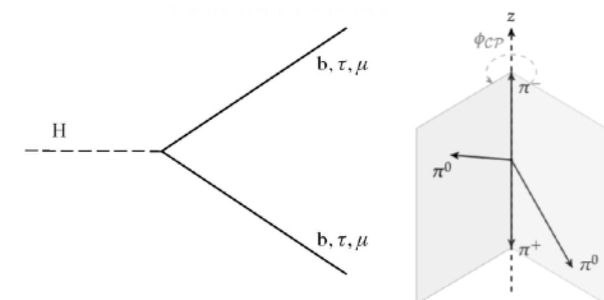


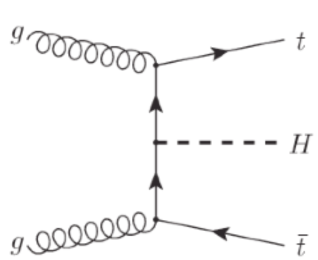
CMS-HIG-20-007

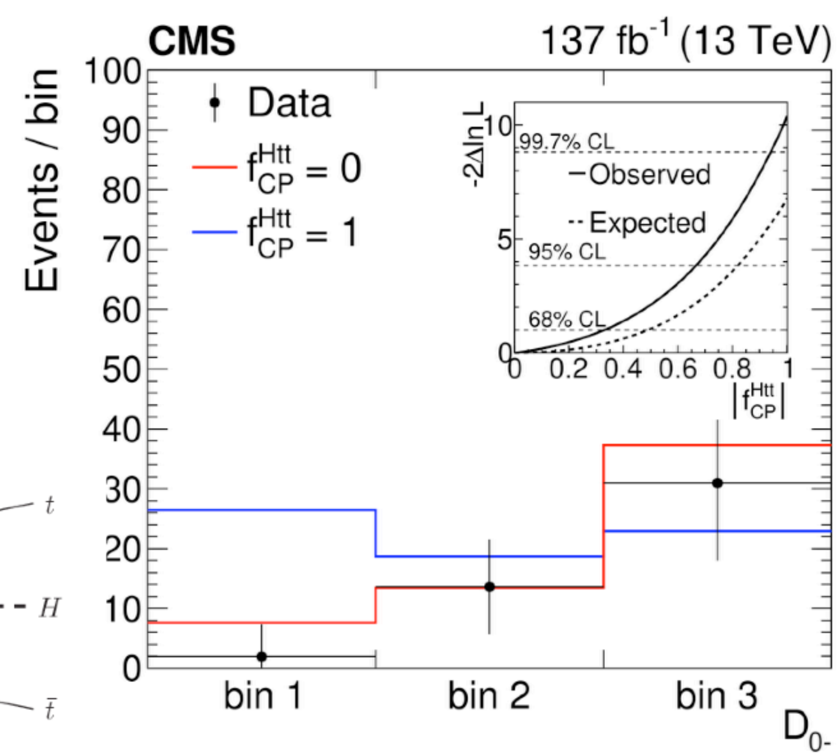
CP structure of Higgs couplings

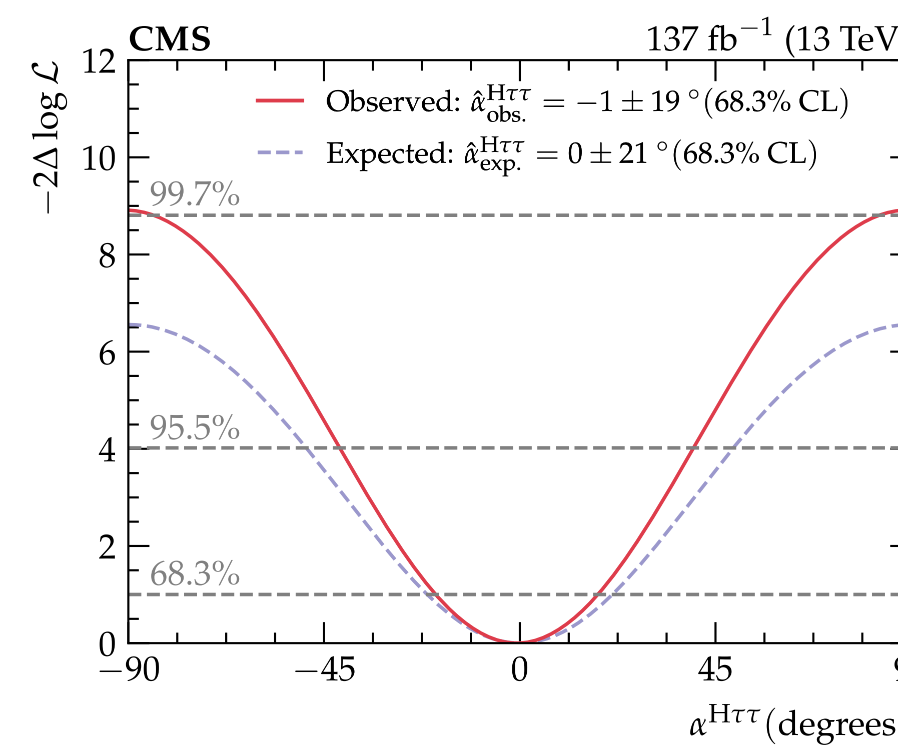
- The SM predicts a scalar Higgs boson $J^{CP} = 0^{++}$
  - CP structure of HVV coupling is more extensively studied; However, CP-odd contributions could be suppressed by NP scale
  - CP-violating Hff coupling may occur at tree level
  - Measuring CP-properties of interactions with the SM particles allow us to probe BSM scenarios
- Both ATLAS and CMS have extensive program to constrain CP structure of Higgs couplings









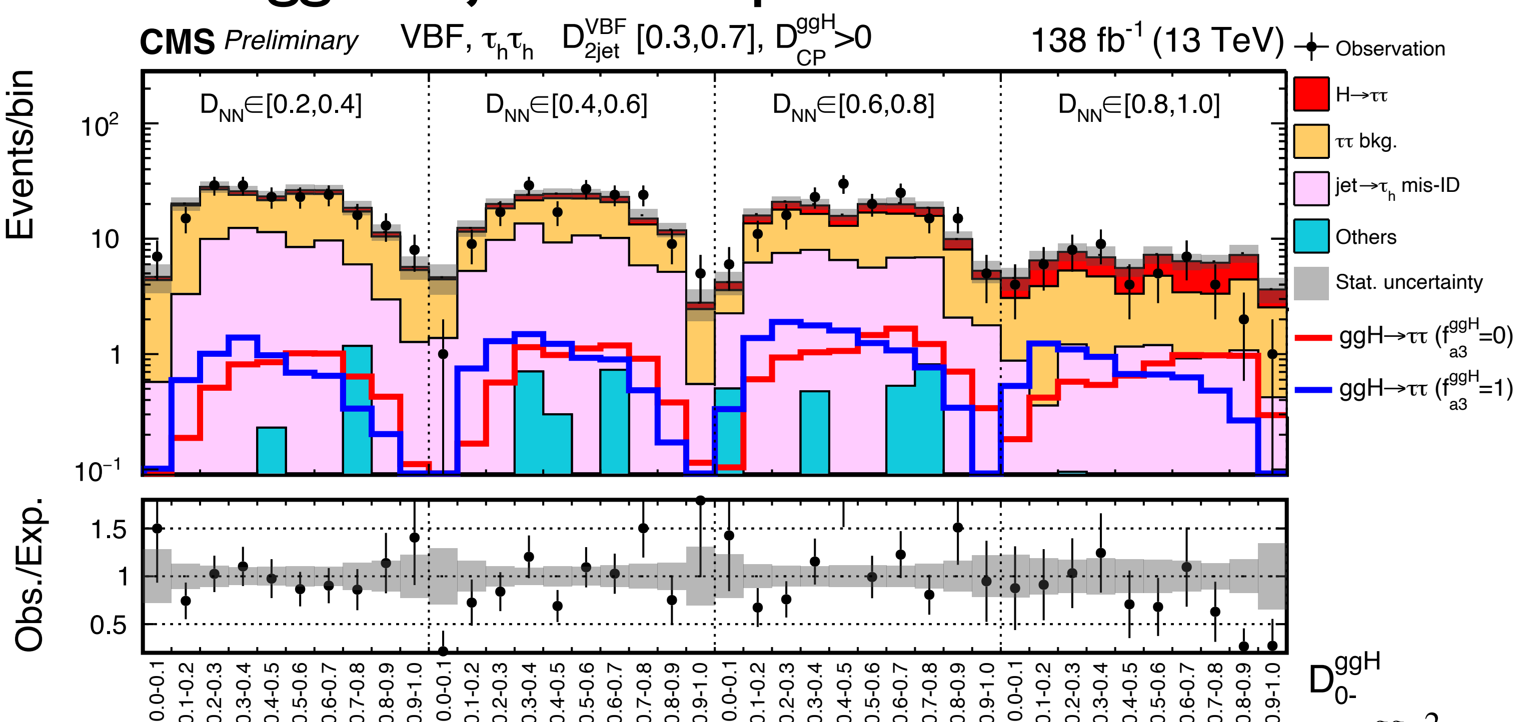


AC in VBF/ggH production, H→ττ

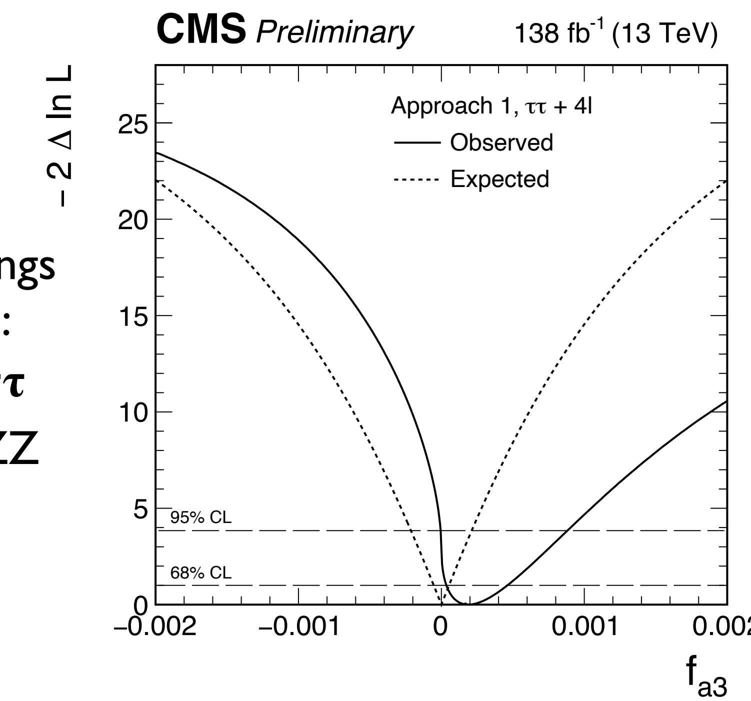
arXiv:2205.05120
Phys. Rev. D 104 (2021) 052004
Phys. Rev. Lett. 125 (2020) 06180

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_i}{a_1}\right)$$

- VBF, ggH+2j, and VH productions

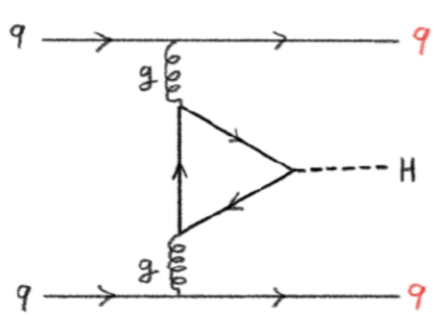


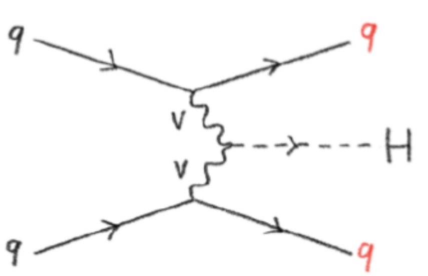
HVV AC couplings Combination:
VBF, VH, H→ττ
ggH, VBF, H→ZZ



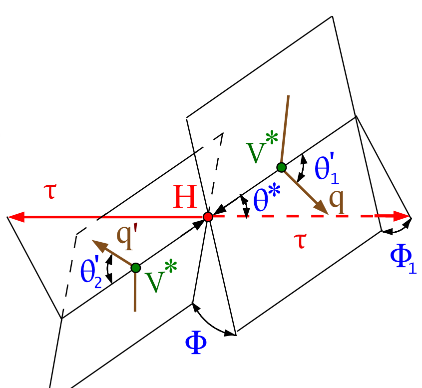
$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \operatorname{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

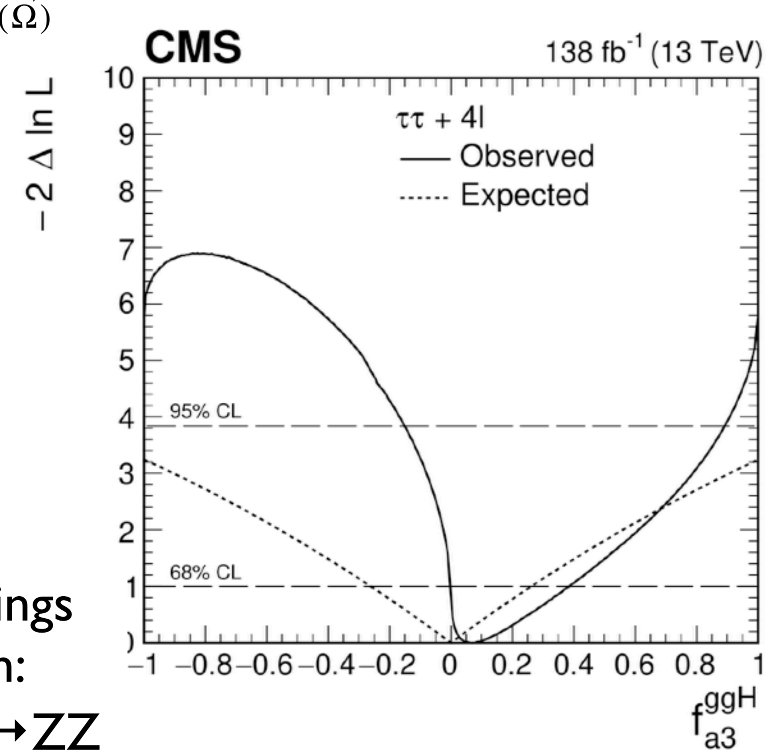
$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} \operatorname{sgn}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$



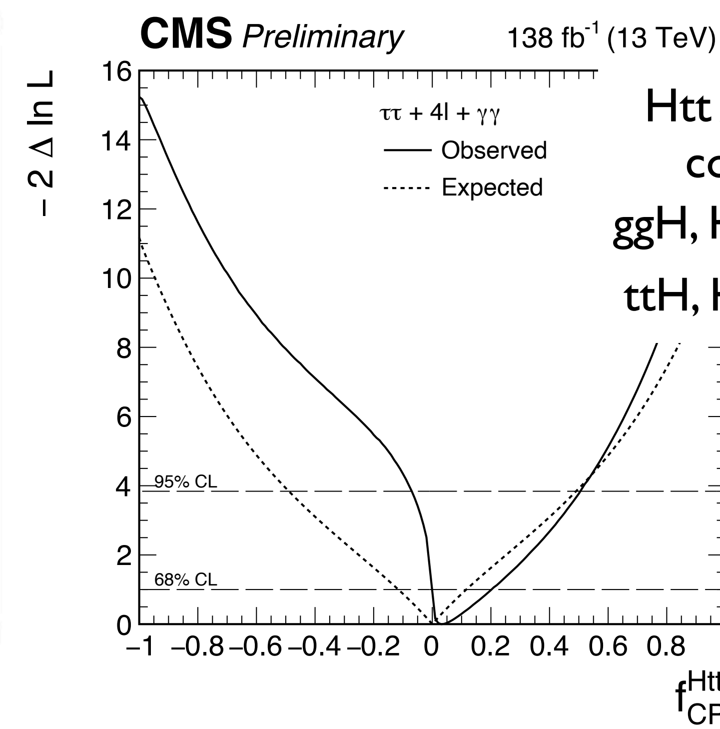


$$\mathscr{D}_{BSM} = \frac{\mathscr{P}_{SM}(\vec{\Omega})}{\mathscr{P}_{SM}(\vec{\Omega}) + \mathscr{P}_{BSM}(\vec{\Omega})}$$



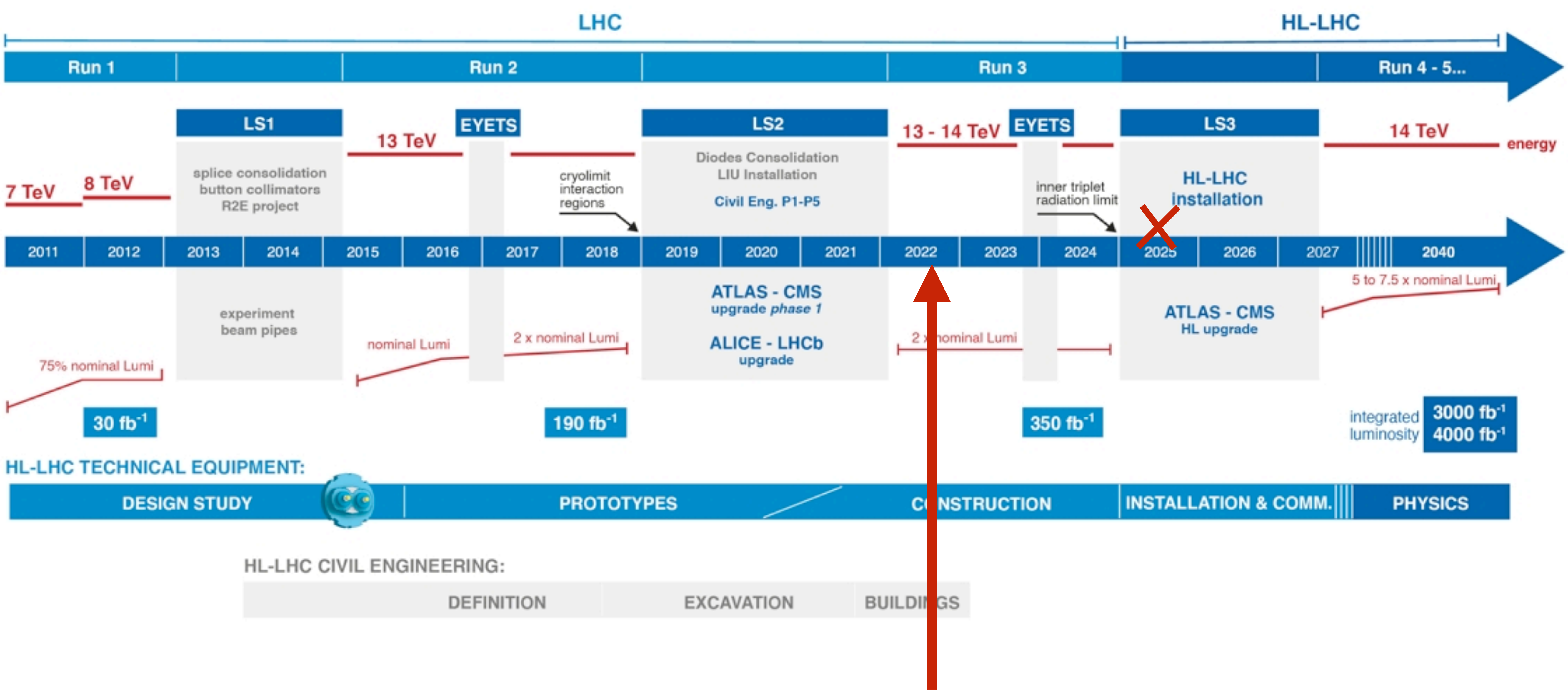


ggH AC couplings combination:
ggH, H→ττ, H→ZZ



Htt AC couplings combination:
ggH, H→ττ, H→ZZ,
ttH, H→ZZ, H→γγ

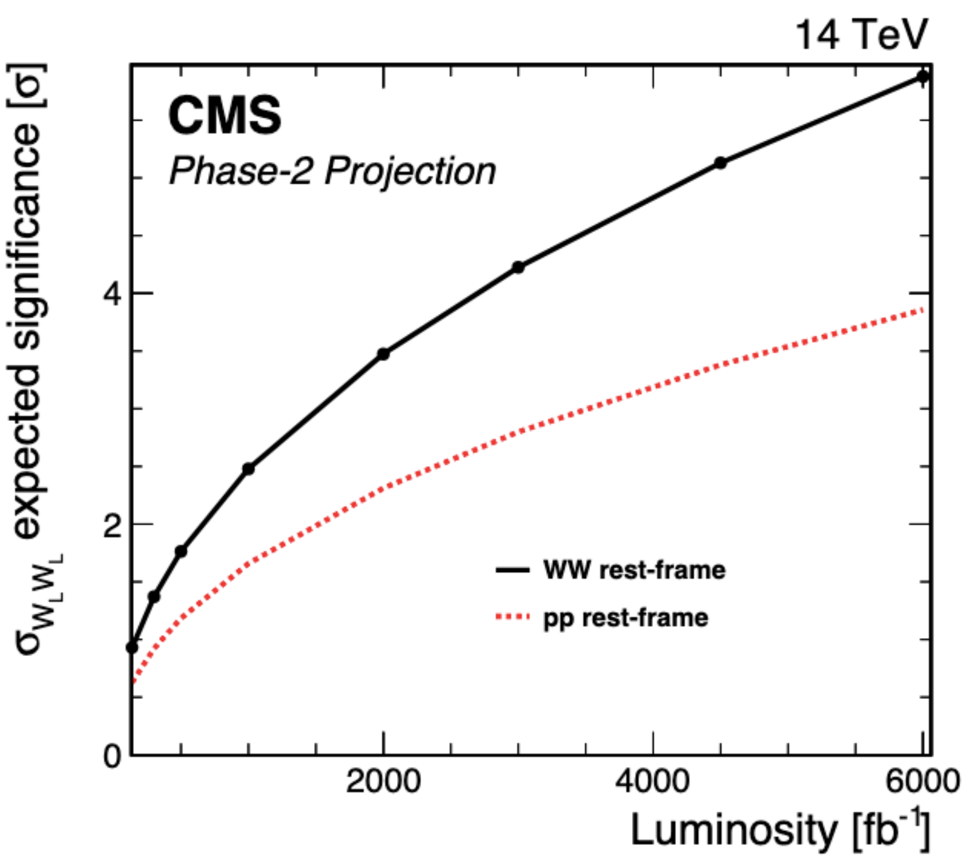
LHC / HL-LHC Plan

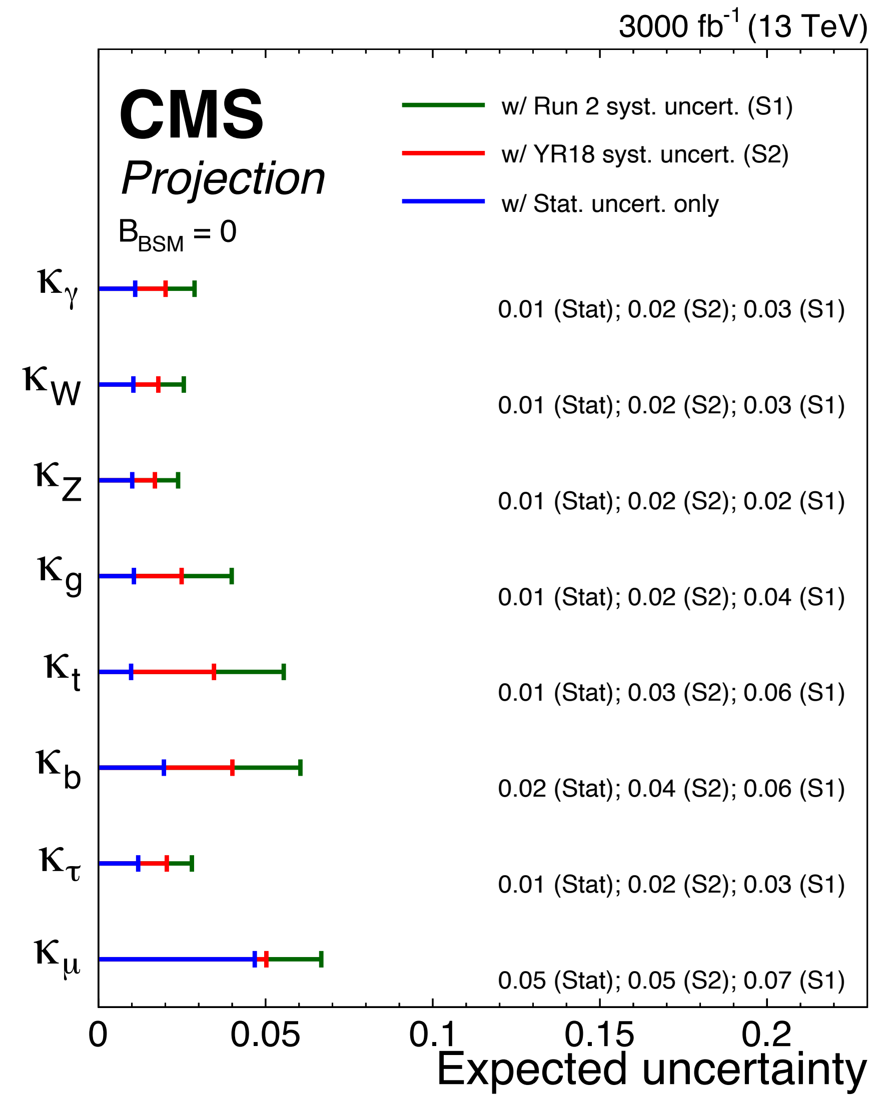


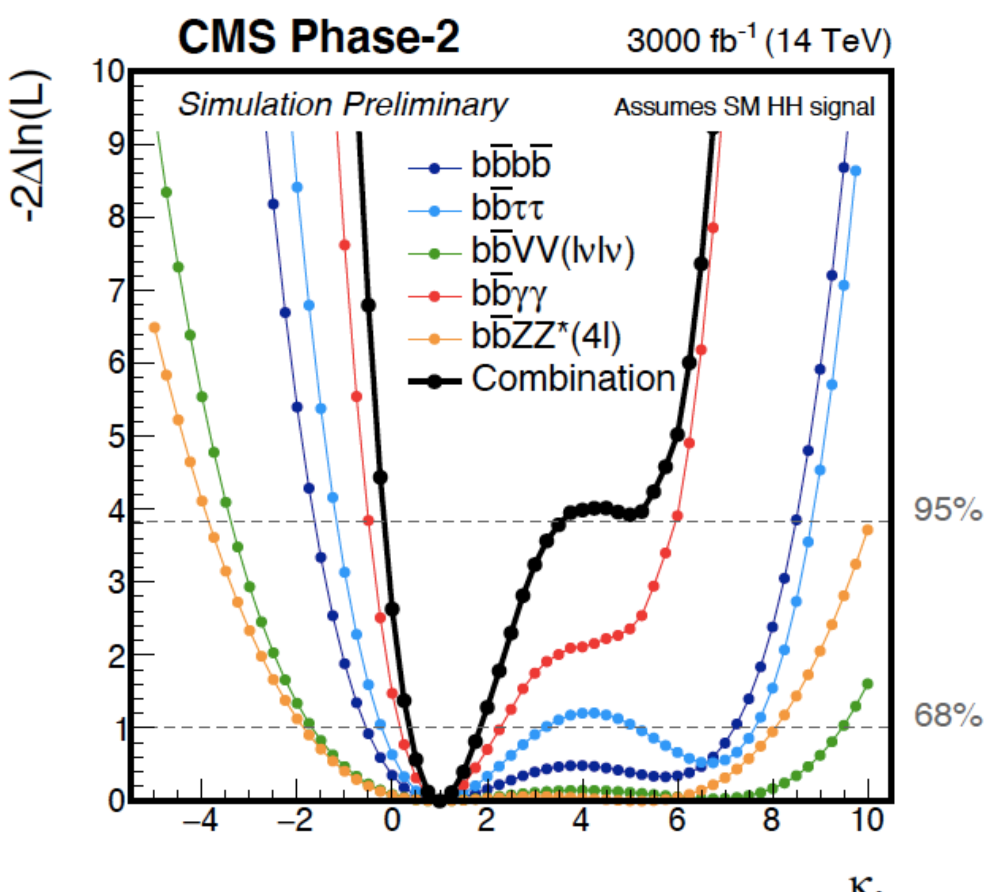
We are here!
Twice more time to go!
Twenty times more data to come!
And before all those, Run 3 has ‘just’ started!

Looking Into the Future

CMS-FTR-18-011
CMS-FTR-18-019
CMS-FTR-21-001







Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Conclusion

- Broad range of EWK physics at the LHC using full Run 2 data
  - Test and validate our knowledge of the Standard Model
  - Shed light of some of the unexplored parts
  - Significant input to our theory community
- Plenty of Higgs results from ATLAS and CMS using full Run 2 data
  - Decays to vector bosons or third generation fermions are established
  - STXS, fiducial inclusive and differential cross sections measurements
  - Rare and very challenging final states are studied
  - All results show agreement with the SM prediction albeit the many measurements are still dominated by the statistical uncertainties
- We have already ~7/fb data collected by the CMS/ATLAS.
- Significant improvement in precisions of EWK and Higgs sector will come with Run 3 and HL-LHC data!

BACKUP