SM and EFT measurements at the LHC

- recent results from ATLAS and CMS

李冰 (Bing Li)

山东大学 (Shandong University)

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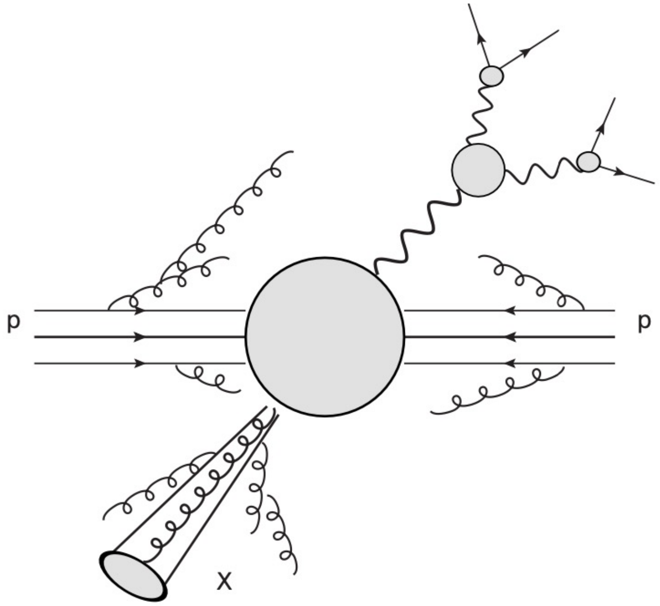
SM measurements at the LHC

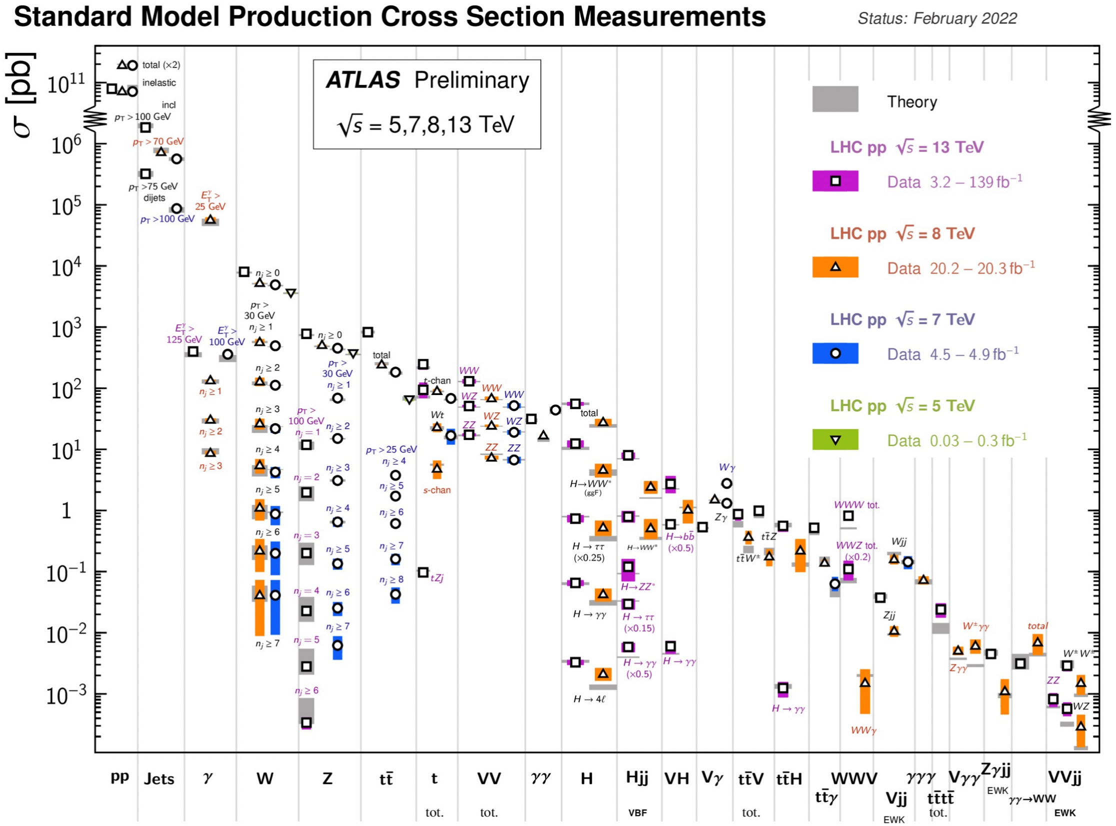
- Precision measurements of SM processes provide stringiest test of the SM at high energy
- Observation of rare SM processes not accessible before LHC
- Important background when searching for new physics

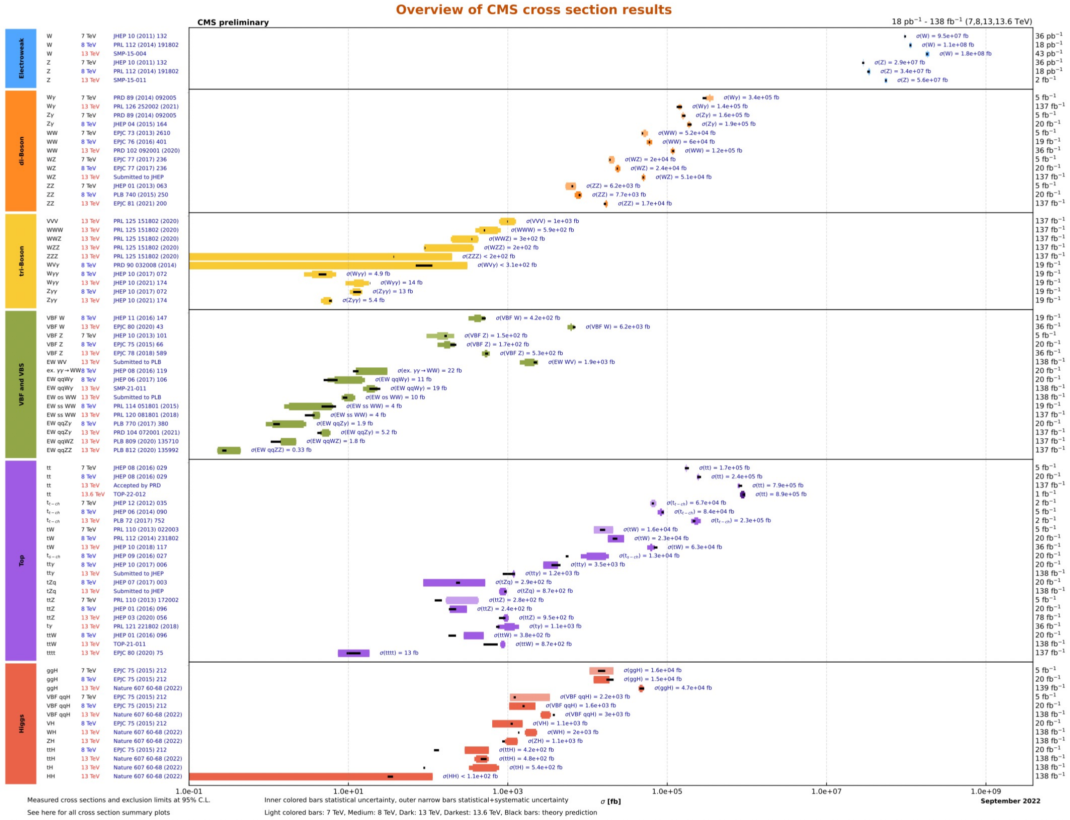


Coupling constants
Fermion, boson interactions
Higher order corrections
Parton density
…

All public results can be found here
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome
CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/

The current status





SM measurements at the LHC cover a lot of physics processes

Outline

- Jet measurements
- Single boson (+jets) measurements
- Multi-boson (+jets) measurements
- Exclusive production

- Could only focus on the most recent results
- See more detailed presentations in the TeV parallel sessions

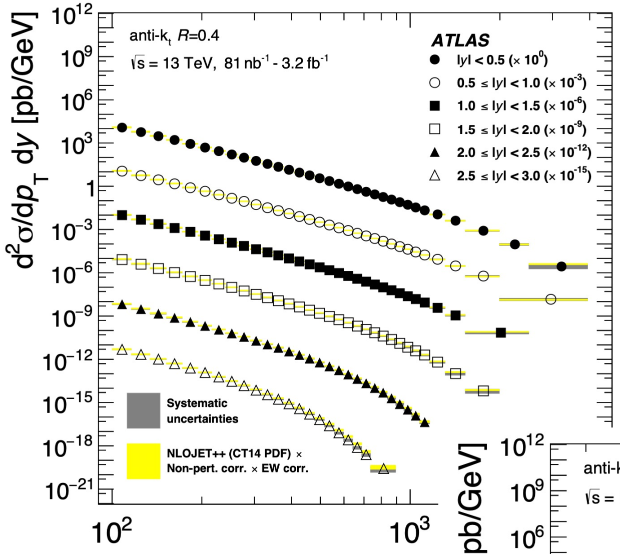
Jet measurements

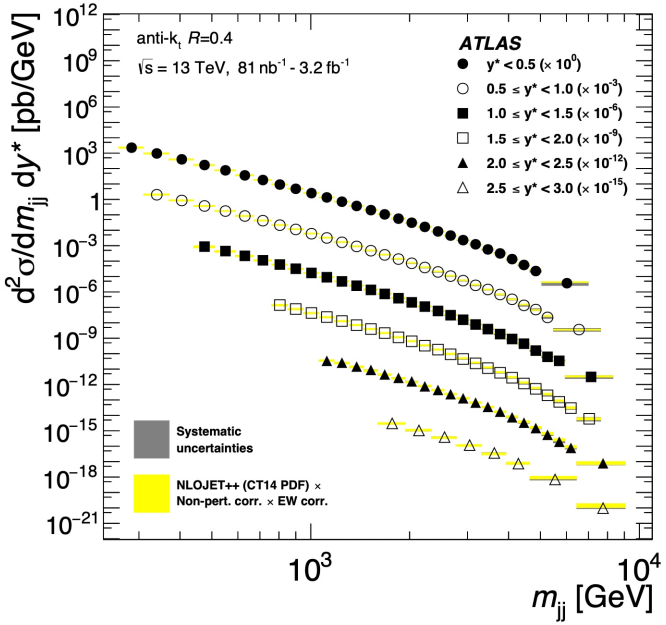
- Important inputs to PDF fit
  - Several 7 and 8 TeV results already included in PDF fits
  - Recent results are not yet included
- Precise measurements are needed for MC tuning
- Sensitive to the strong coupling constant

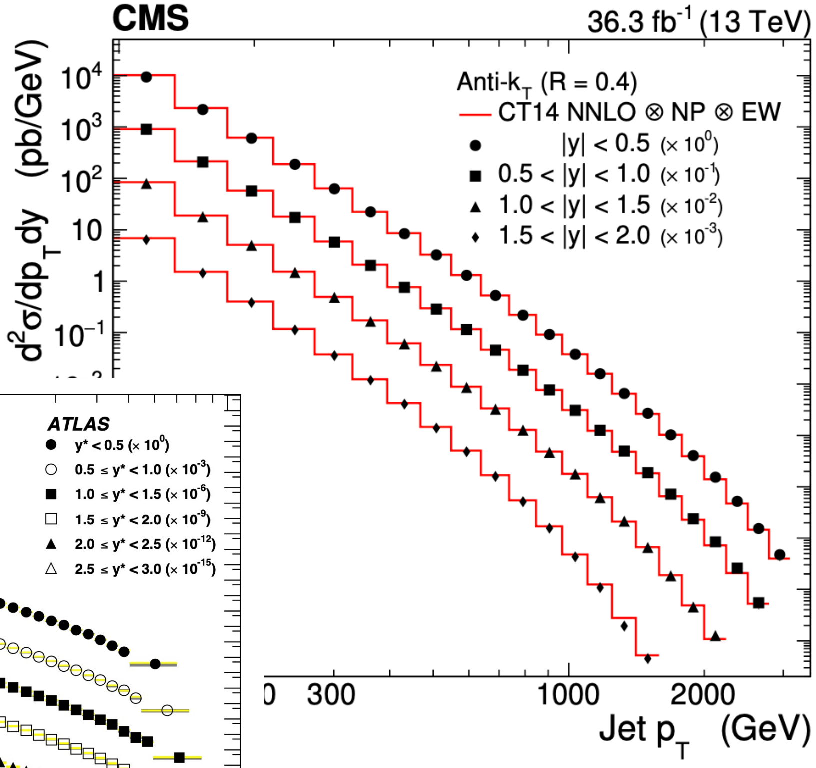
Inclusive jet measurements

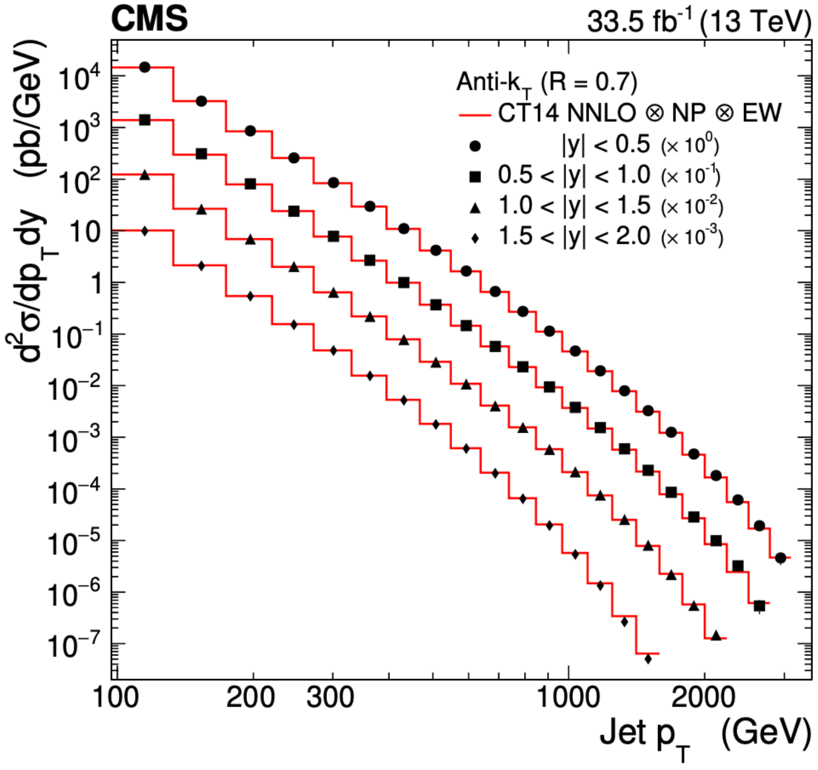
JHEP 02 (2022) 142
JHEP 05 (2018) 195

- Double-differential cross section measurement, as a function of jet pT and rapidity









ATLAS also measured m_{jj} using dijet events

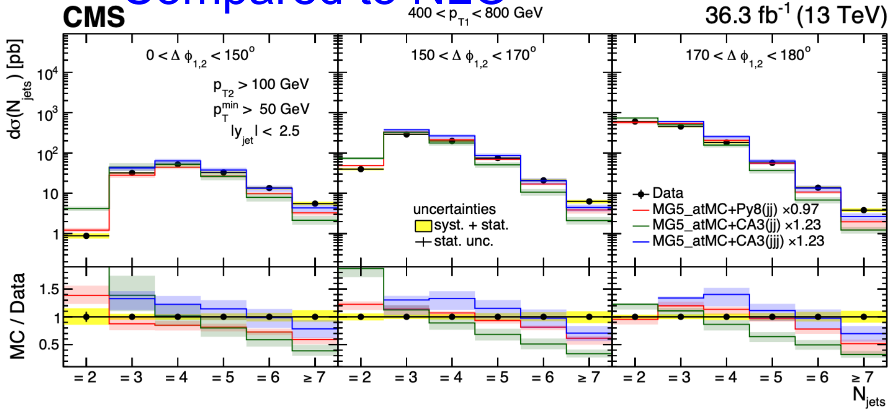
No significant differences between data and NNLO predictions
Recent results from CMS measured both anti-kT R = 0.4 and 0.7 jets

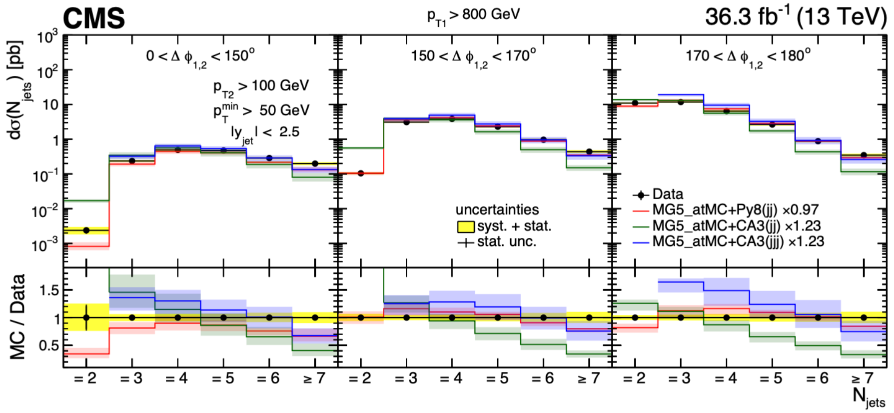
Multi-jet measurement

SMP-21-006

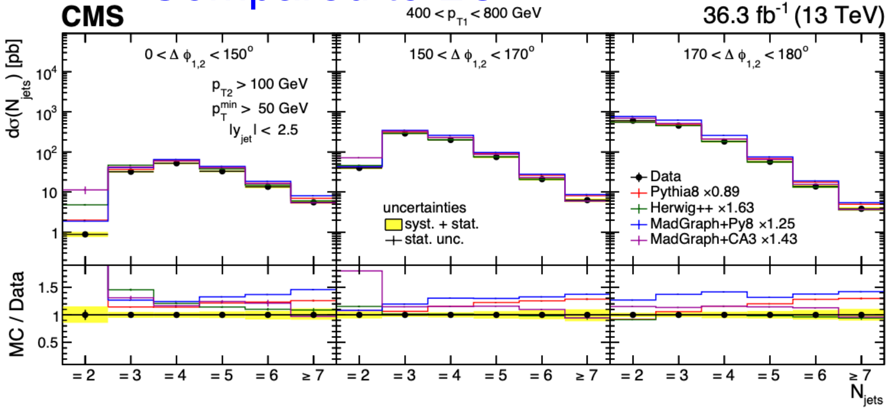
- Jet multiplicity and transverse momentum measurement, compared to LO and NLO predictions
- Jets with pT > 50 GeV and are produced in association with a high-pT dijet system

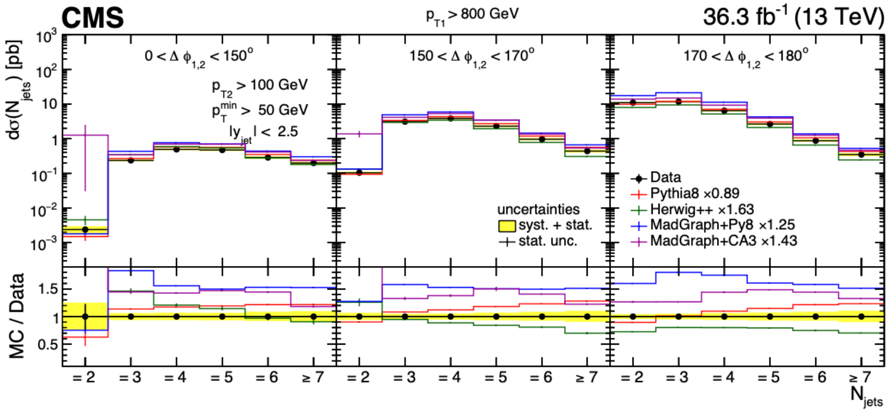
Compared to NLO





Compared to LO





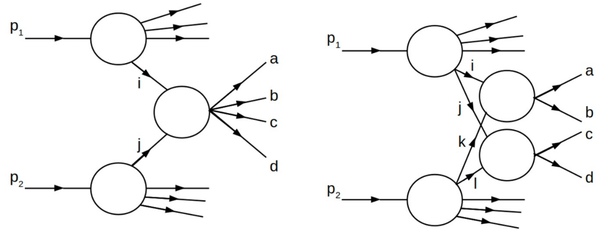
NLO modeling reasonable well in low Njets

LO modeling are not quite good

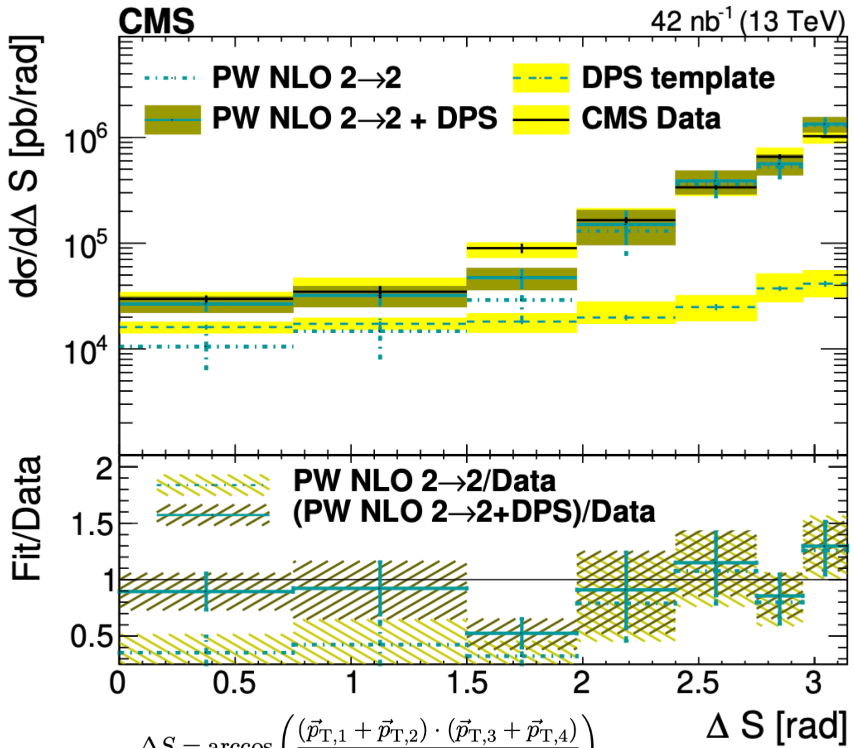
(Note normalization factors are applied in the plots)

Multi-jets from double-parton scattering

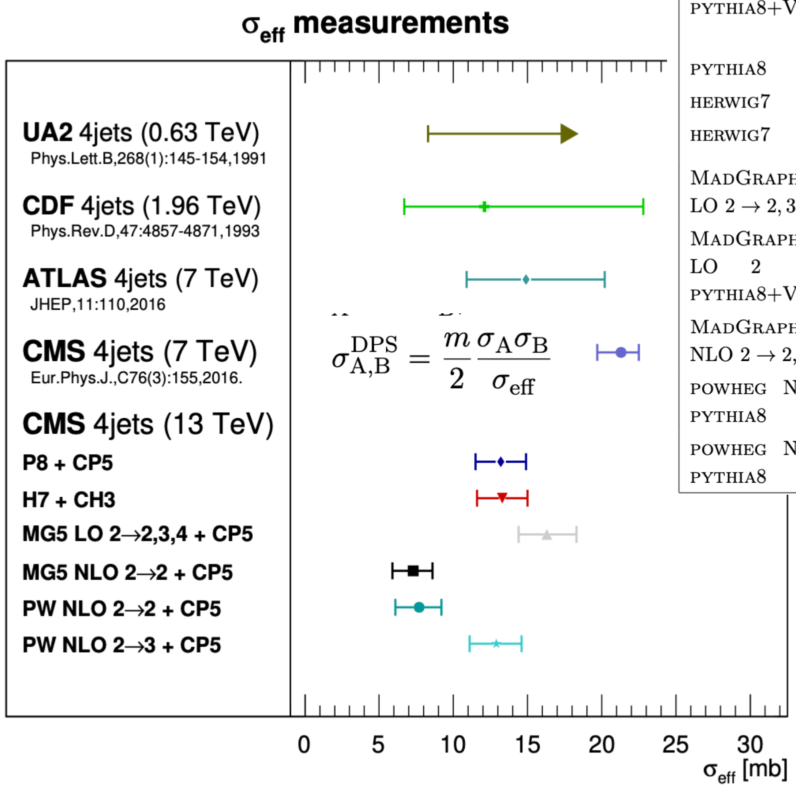
- Multi-jet final states are not very well modeled nor understood, indicating possible additional treatment needed
- Apart from single-parton scattering (SPS), the double-parton scattering (DPS) also could contribute to multi-jet final state
- A recent measurement of DPS using four-jet events



MC Model	Tune	$f_{DPS} \pm$ (stat) $\pm$ (syst) (%)		
—	—	Full tune	Hard MPI removed	Inherent DPS
PYTHIA8	CP5	$3.77 \pm 0.08\,^{+0.45}_{-0.68}$	$6.34 \pm 0.07\,^{+0.32}_{-0.57}$	$2.57 \pm 0.11\,^{+0.36}_{-0.62}$
PYTHIA8+VINCIA	Standard PYTHIA8.3	$2.40 \pm 0.07\,^{+0.41}_{-0.68}$	$3.84 \pm 0.07\,^{+0.34}_{-0.63}$	$1.44 \pm 0.10\,^{+0.37}_{-0.65}$
PYTHIA8	CDPSTP8S1-4j	$-1.30 \pm 0.08\,^{+0.39}_{-0.69}$	$3.06 \pm 0.07\,^{+0.28}_{-0.62}$	$4.36 \pm 0.11\,^{+0.34}_{-0.66}$
HERWIG7	CH3	$3.72 \pm 0.07\,^{+0.38}_{-0.68}$	$6.28 \pm 0.08\,^{+0.29}_{-0.58}$	$2.56 \pm 0.11\,^{+0.33}_{-0.63}$
HERWIG7	SoftTune	$2.67 \pm 0.07\,^{+0.42}_{-0.71}$	$4.85 \pm 0.08\,^{+0.31}_{-0.52}$	$2.18 \pm 0.11\,^{+0.36}_{-0.61}$
MADGRAPH5_aMC@NLO LO $2 \to 2, 3, 4$, PYTHIA8	CP5	$2.50 \pm 0.08\,^{+0.38}_{-0.69}$	$5.14 \pm 0.08\,^{+0.30}_{-0.56}$	$2.64 \pm 0.11\,^{+0.35}_{-0.62}$
MADGRAPH5_aMC@NLO LO $2 \to 2, 3, 4$, PYTHIA8+VINCIA	Standard PYTHIA8.3	$2.55 \pm 0.09\,^{+0.38}_{-0.66}$	$5.23 \pm 0.08\,^{+0.27}_{-0.53}$	$2.68 \pm 0.12\,^{+0.33}_{-0.60}$
MADGRAPH5_aMC@NLO NLO $2 \to 2$, PYTHIA8	CP5	$7.13 \pm 0.08\,^{+0.28}_{-0.42}$	$11.45 \pm 0.08\,^{+0.22}_{-0.27}$	$4.32 \pm 0.11\,^{+0.25}_{-0.36}$
POWHEG NLO $2 \to 2$, PYTHIA8	CP5	$4.77 \pm 0.08\,^{+0.32}_{-0.64}$	$10.89 \pm 0.08\,^{+0.24}_{-0.48}$	$6.12 \pm 0.11\,^{+0.28}_{-0.53}$
POWHEG NLO $2 \to 3$, PYTHIA8	CP5	$5.40 \pm 0.07\,^{+0.36}_{-0.67}$	$6.51 \pm 0.07\,^{+0.29}_{-0.51}$	$1.11 \pm 0.10\,^{+0.33}_{-0.59}$



$$\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}|\ |\vec{p}_{T,3} + \vec{p}_{T,4}|}\right).$$



$$\sigma^{\mathrm{DPS}}_{\mathrm{A,B}} = \frac{m}{2}\frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$$

DPS contributions can not be ignored in such phase space, and need better modeling

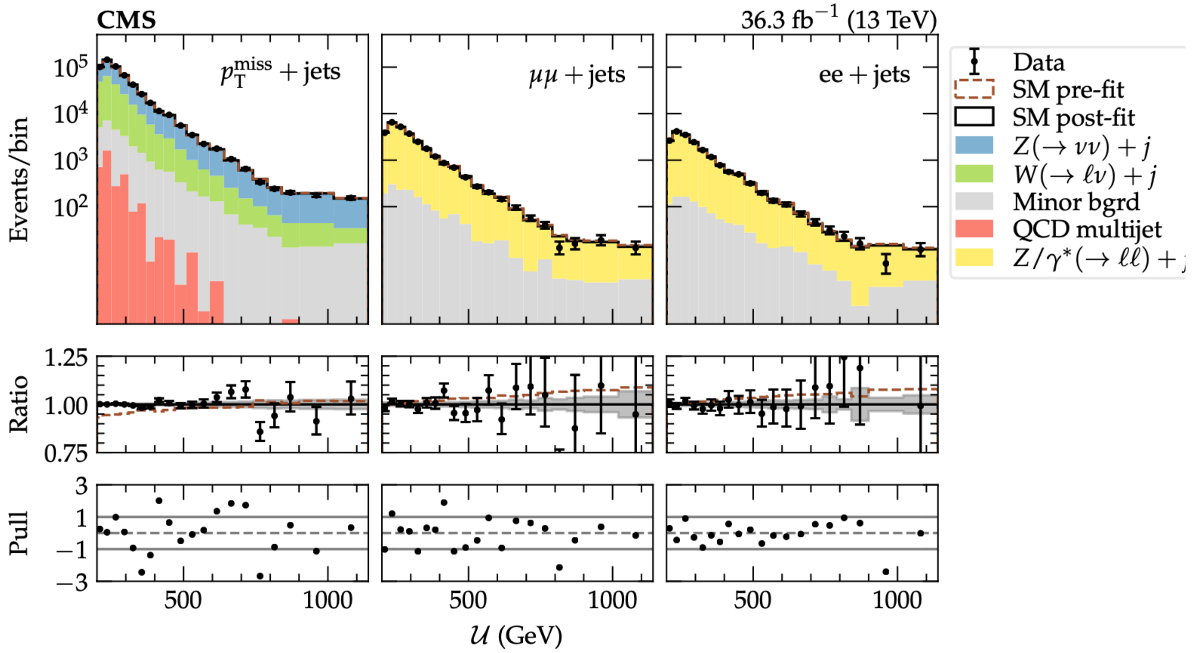
Single boson measurements

* Precision measurement of the W and Z boson, as well as the W/Z + jets processes
* Sensitive to QCD, PDF etc
* Often the large background when measuring other processes and searching for new physics

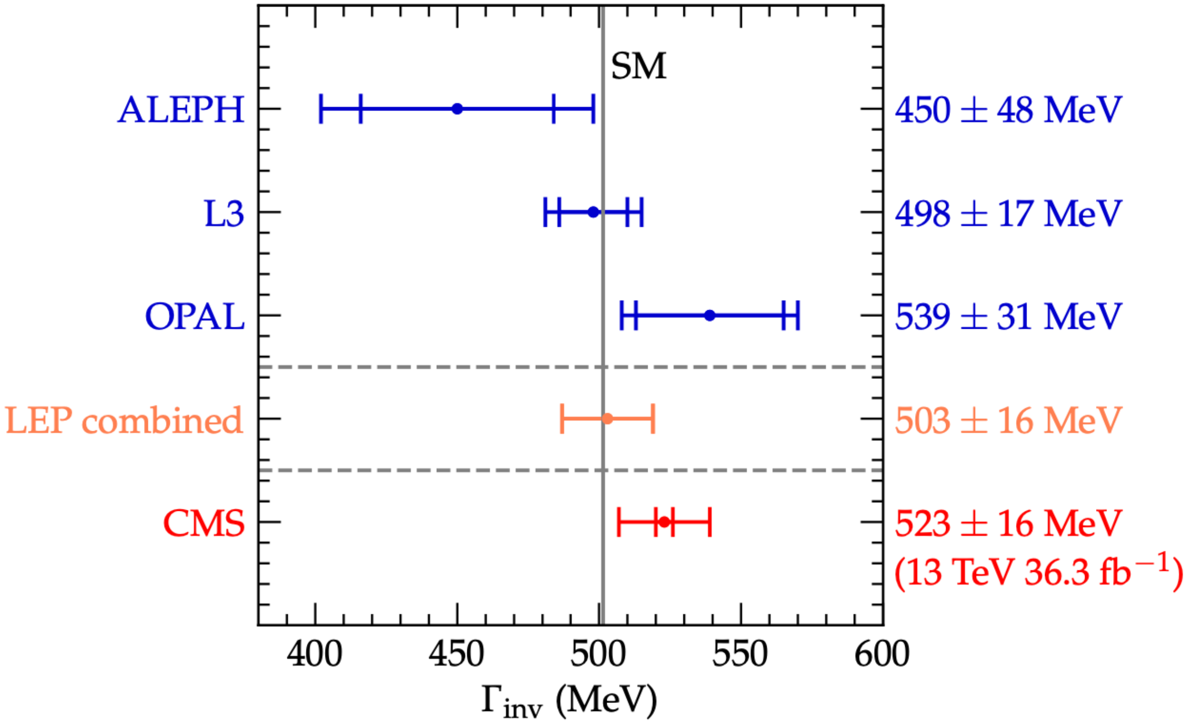
Z boson invisible width

SMP-18-014

- Indirect constraint of Z invisible width by LEP lineshape measurement to 1.5 MeV. Direct measurement using Z + ISR photon is at 16 MeV
- New CSM result extract the Z invisible width by measuring the pT(miss) + jets, Z + jets and e/m + jets.

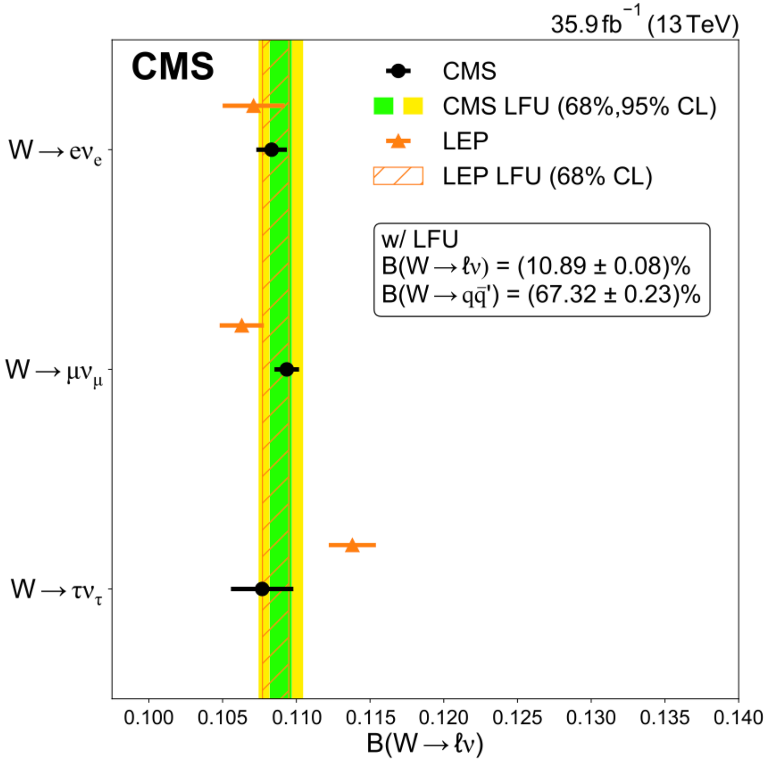


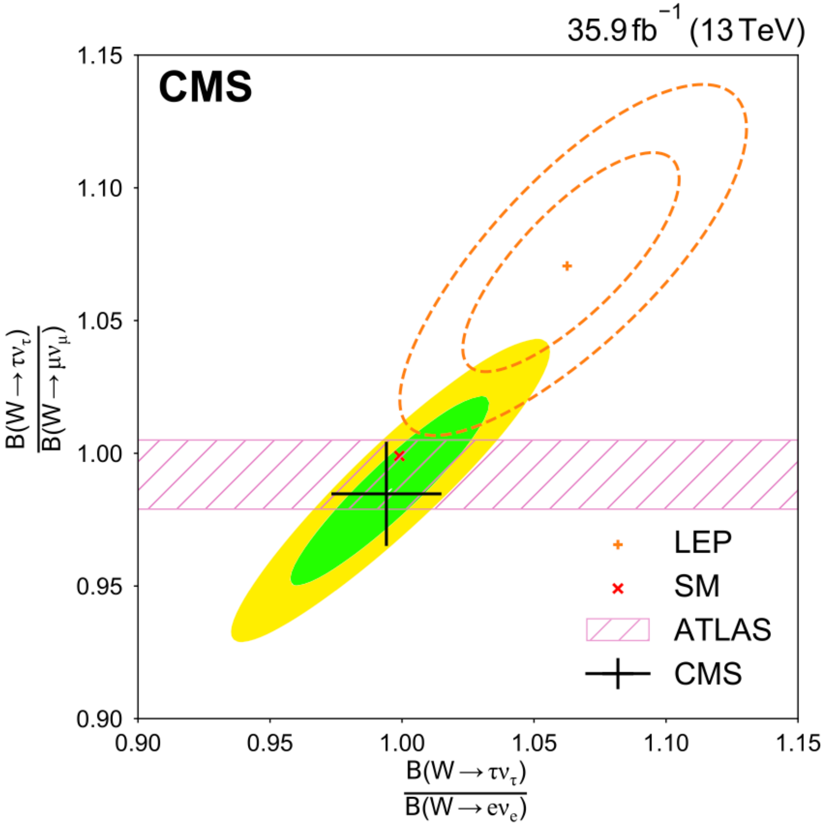
vector sum of $\vec{p}_T^{miss}$ and $\vec{p}_T$ of the charged leptons



W decay branching fractions [PRD 105 (2022) 072008]

- Test of the lepton flavor universality, where several hints of deviations from SM have been reported in the past years
- Events are categorized on lepton multiplicity and flavor, jet and bjet multiplicity



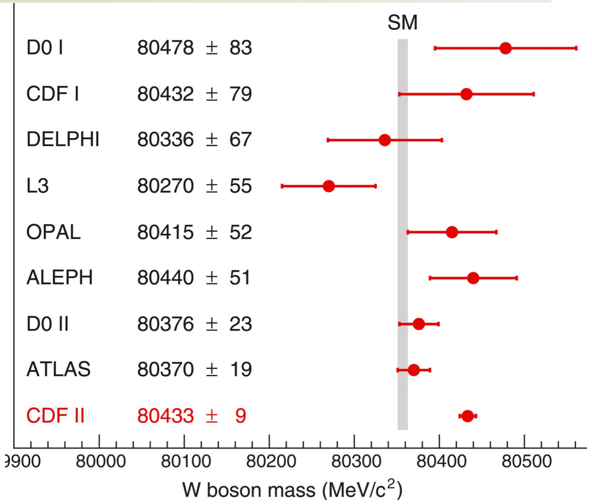


	CMS	LEP
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\%$
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\%$
$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\%$
$\mathcal{B}(W \to q\bar{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	$\cdots$
Assuming LFU		
$\mathcal{B}(W \to \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to q\bar{q}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

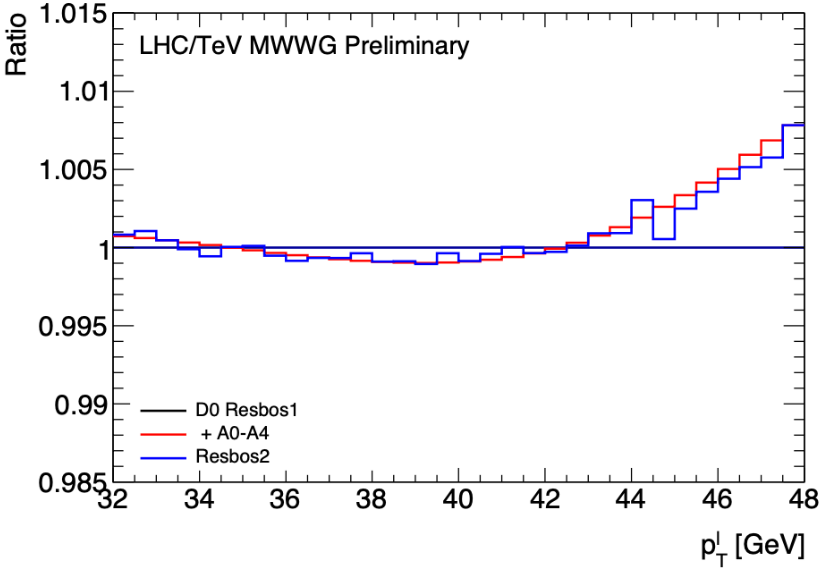
W boson mass

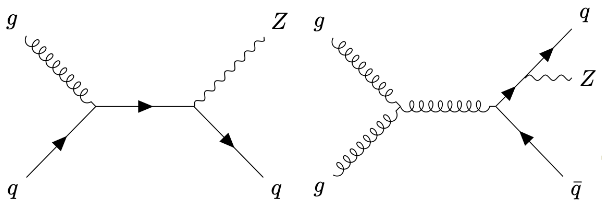
CERN-LPCC-2022-06/FERMILAB-TM-2779-V

- Key observable in the SM EW fit
- Need extremely good understanding of the detector and theory modeling
- There is ongoing effort from the LHC/TeVatron Electroweak WG towards combination
  - Understand the theoretical uncertainty correlations between different measurements
  - Angular coefficients of W and Z production in ResBos1 differ from more recent calculations



Science 376, 170-176 (2022)

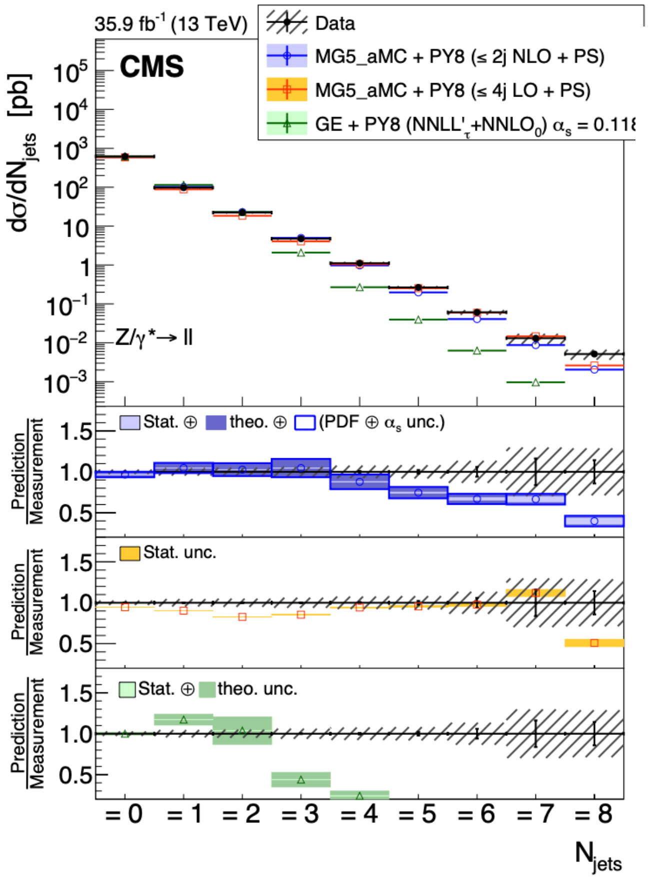


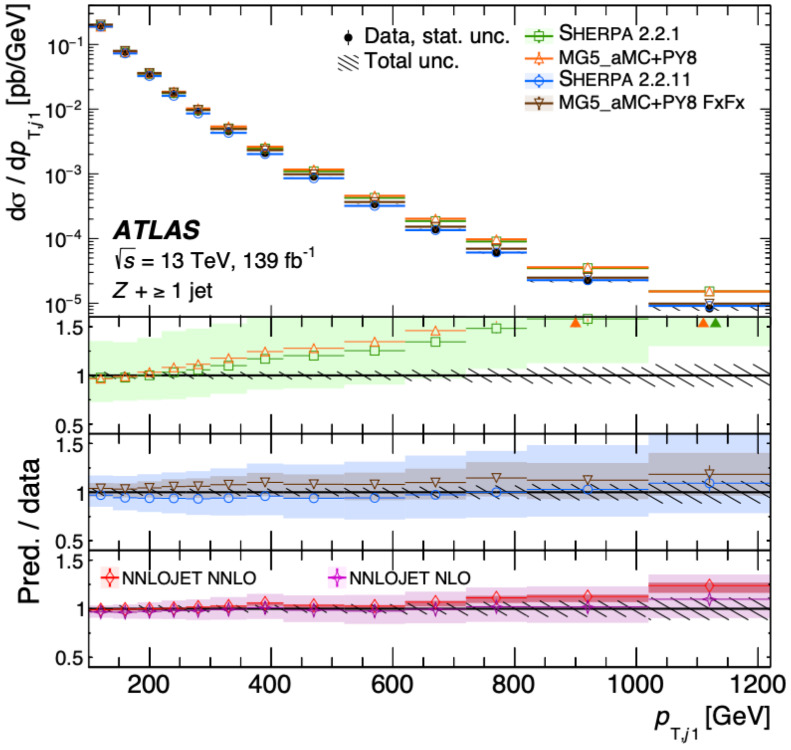


Z + jets measurements

[2205.02597](#)
[SMP-19-009](#)
[SMP-21-003](#)

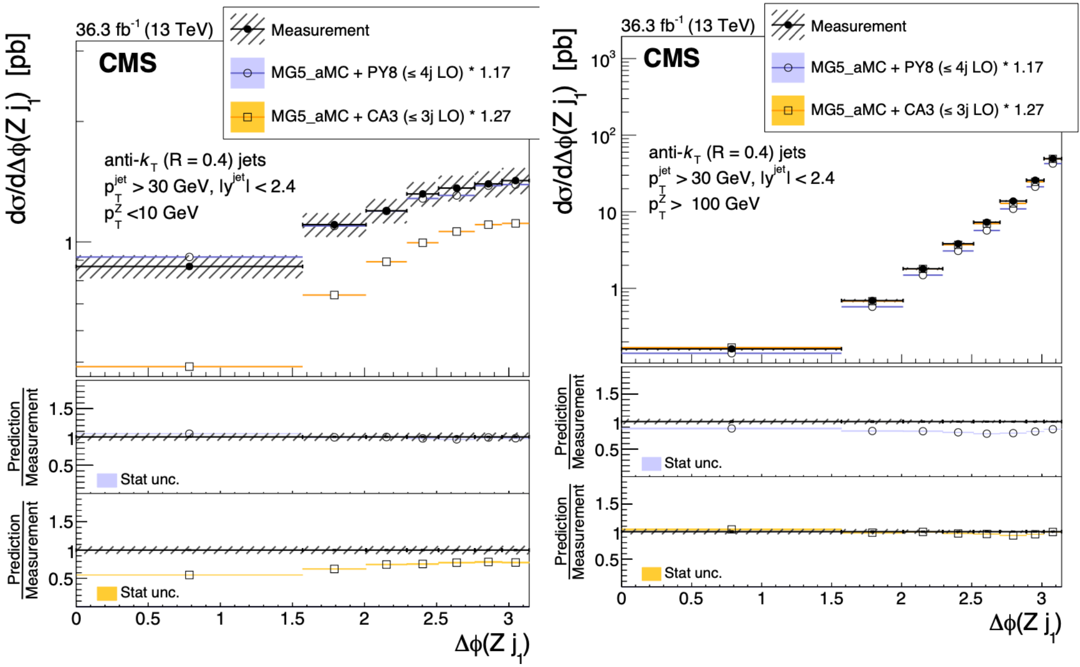
* High precision measurements covering a large range – up to >= 8 jets and probing jets beyond 1 TeV
* Provide critical test of QCD calculations





New multijet merged MC predictions agree generally well with data

Azimuthal correlation measured in different pT(Z) region



Small correlation in low pT(Z) region, and much larger correlation in high pT(Z) region

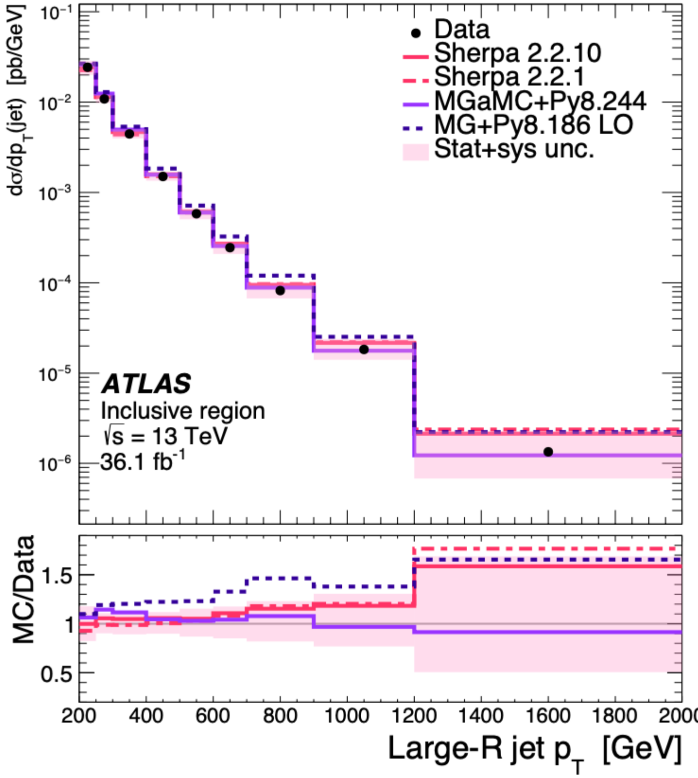
- ➢ Low pT region it's more like Z from electroweak correction to high-pT jet production
- ➢ High pT region dominant by Z+jet production

Z + heavy flavor jets

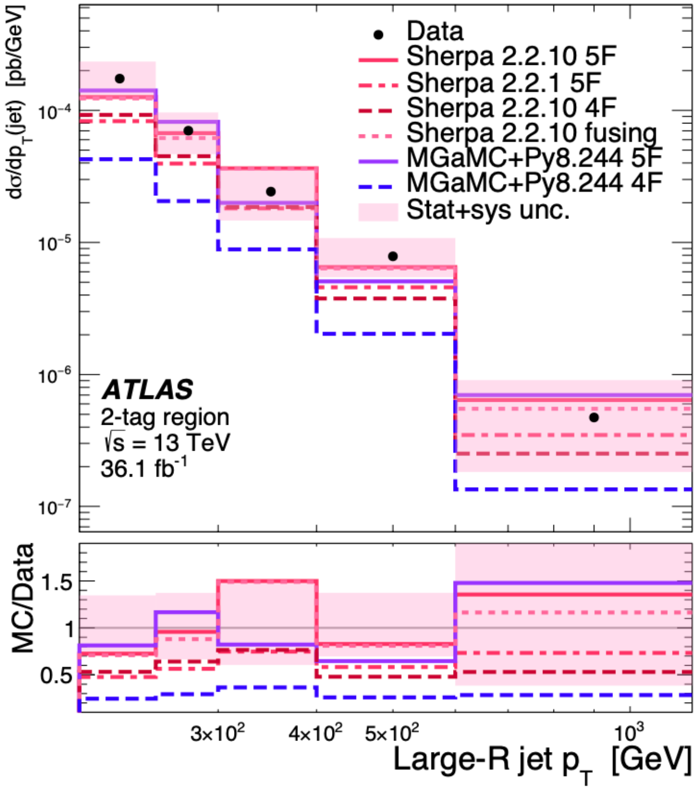
2204.12355

- Cross-section measurements in both flavor-inclusive and doubly b-tagged region (2 small-R jets within 1 large-R jet)
- Important test of QCD in kinematic and flavor configurations relevant to several Higgs and BSM searches

Inclusive region



2b-tagged region



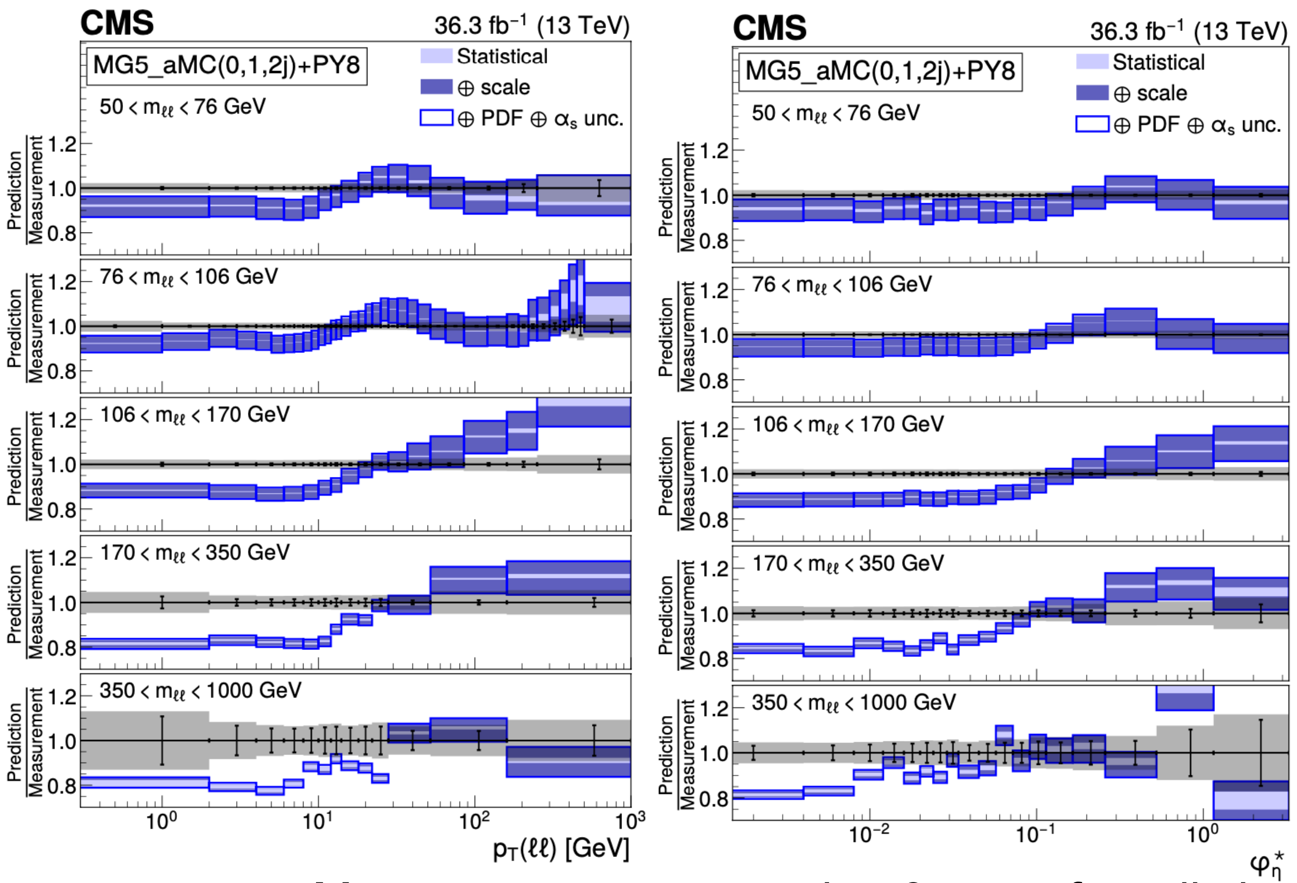
NLO MadGraph5_aMC@NLO + Pythia8 describes data well

2-tag region limited by data statistic

- Shape all look ok
- 4FNS (4-flavor number scheme) significantly underestimate the rate, and 5FNS is favored

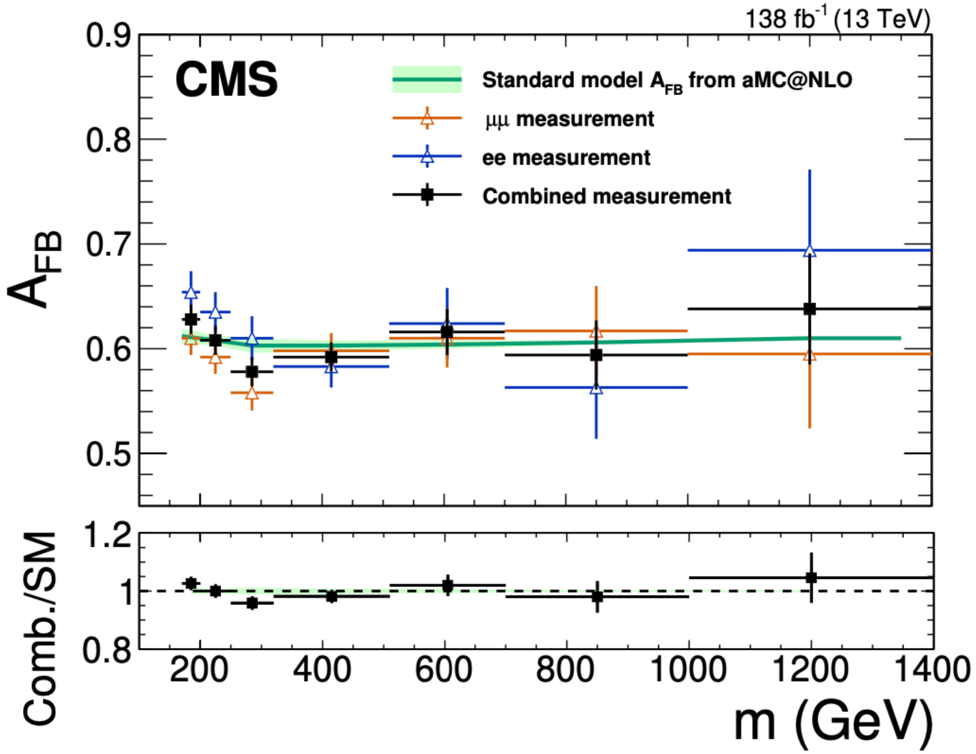
Z + jets double differential measurements

- Differential cross section in the pT(ll) and lepton angular variable φ_η^* are measured in different m_{ll} region



High mass events are also used to measure forward-backward asymmetry

Results are used to set limit on new physics with additional gauge bosons



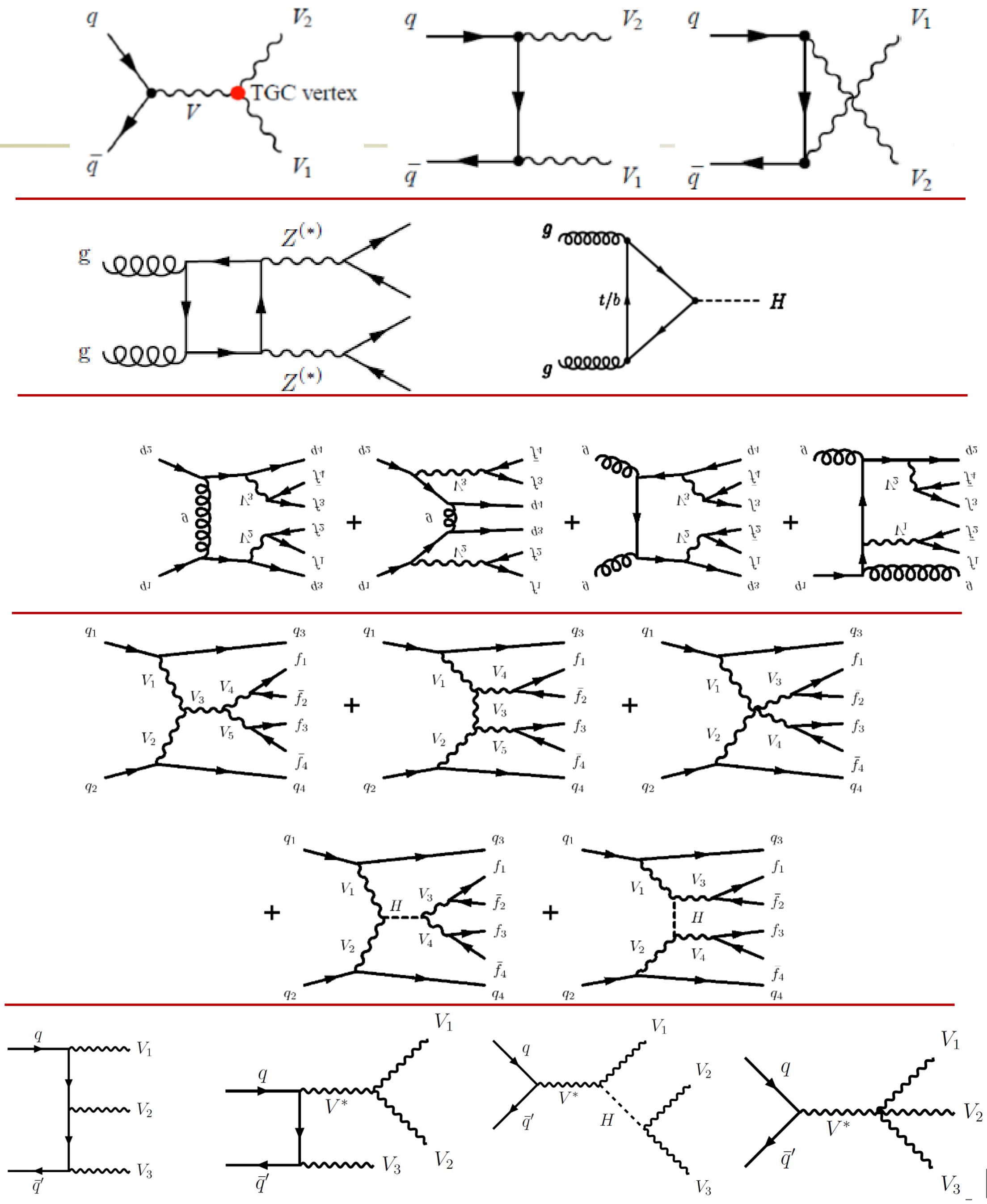
SMP-20-003

Measurement compared to 6 sets of prediction.
Find more in the paper.

JHEP 08 (2022) 063

Multi-boson production

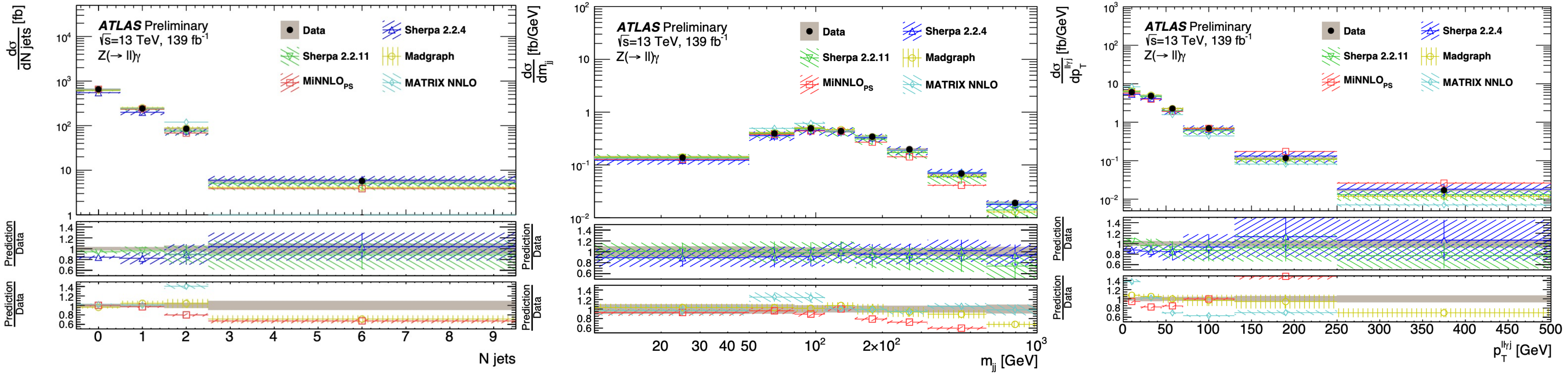
- Measurement of multi-boson productions at LHC is important to test the validity of the SM at TeV scale
  - Many precision differential measurements
  - VBF/S processes with relative lower cross-section, being key process to probe the mechanism of electroweak symmetry breaking (EWSB)
- Involve with Triple or Quartic Gauge Couplings (T/QGCs)
  - To look for vector boson self-couplings
  - Probe new physics through deviations from SM couplings
- EFT interpretation $\mathcal{L}_{\mathrm{SMEFT}} \approx \mathcal{L}_{\mathrm{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} O_j^{(8)}$
- A way to search for high mass resonance decaying to VV final state



Zγ + jets production

ATLAS-CONF-2022-047

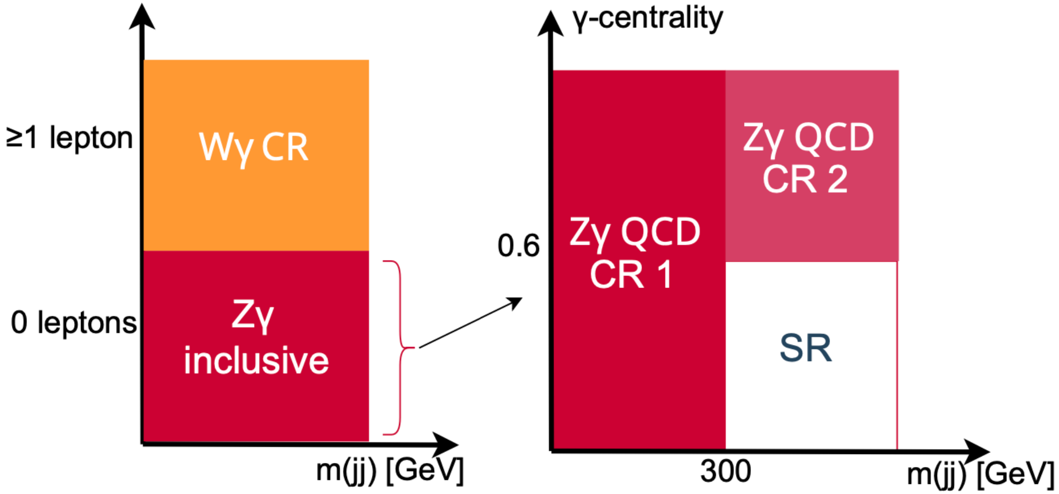
- Z decays leptonically, and enhanced in ISR region by requiring $m_{ll} + m_{ll\gamma} > 182$ GeV
- High statistical and high precision channel to study additional QCD radiation in the multiboson final states. Total uncertainty at 4% to 10% level
- Compared to several MC generators at different precisions, and in general good agreement

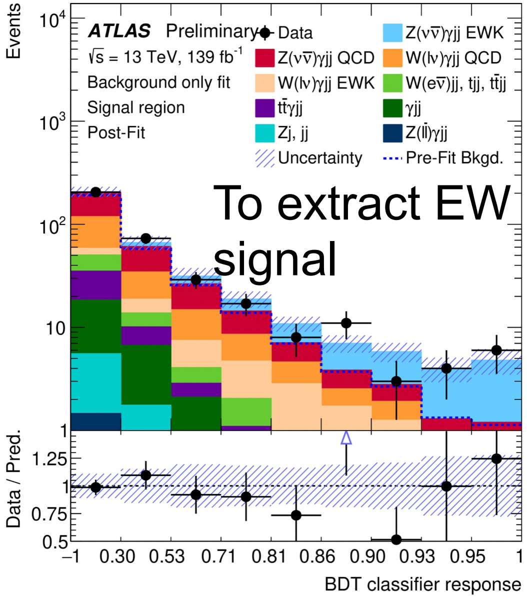


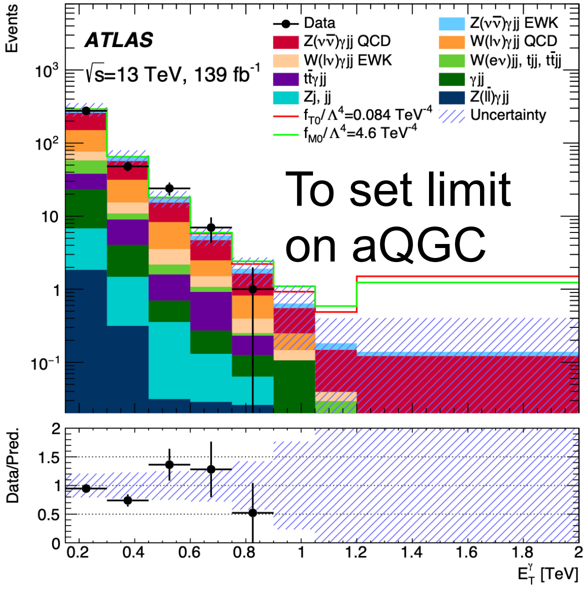
EW Z(νν)γjj production

2208.12741

- Recent ATLAS results focusing on high pT region, sensitive to aQGC
- Zγ QCD CR1: used to estimate QCD yield
- Zγ QCD CR2: used to check the m_{jj} modelling
- BDT used to extrapolate EW signal







Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

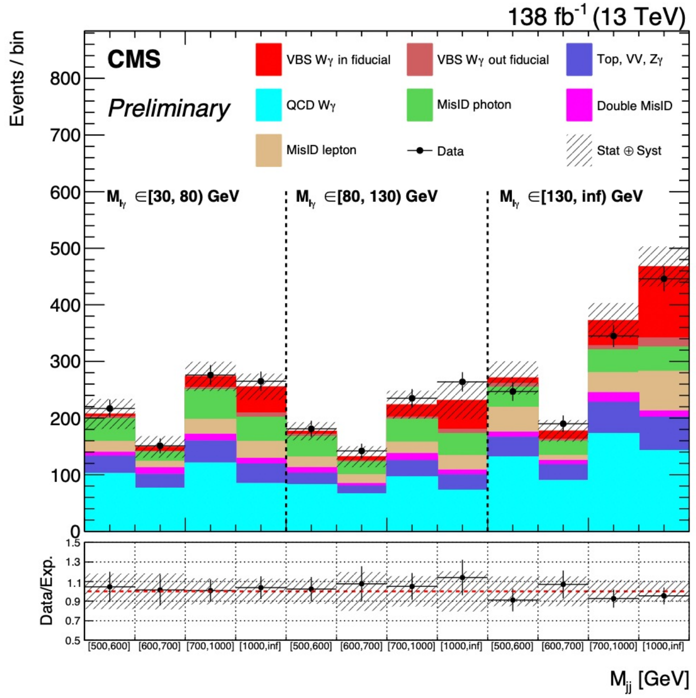
Comparison with previous ATLAS results focusing on low pT region

POI	Value		
	Current analysis	Ref. [7]	Combination
$\mu_{Z\gamma\mathrm{EWK}}$	0.78 ± 0.33	1.04 ± 0.23	0.96 ± 0.18
$\mu_{Z\gamma\mathrm{QCD}}$	1.21 ± 0.37	1.02 ± 0.41	1.17 ± 0.27
$\mu_{W\gamma}$	1.02 ± 0.22	1.01 ± 0.20	1.01 ± 0.13

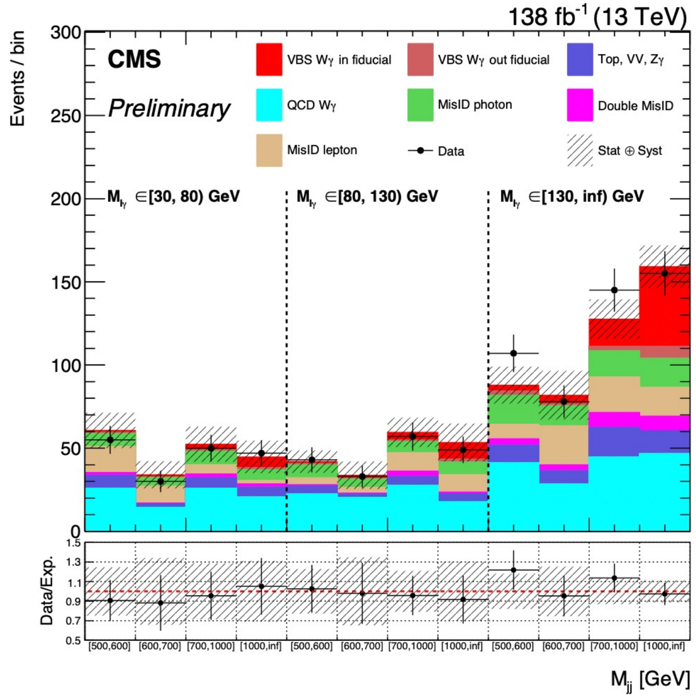
EW W(lν)γjj

SMP-21-011

- More observation of EW VVjj production
- New results from CMS with 6.0σ for Wγjj
- Cross sections agree well with SM predictions



(a) Barrel



(b) Endcap

Used in fit to extrapolate the EW Wγjj process

Several differential cross section measurements are also available

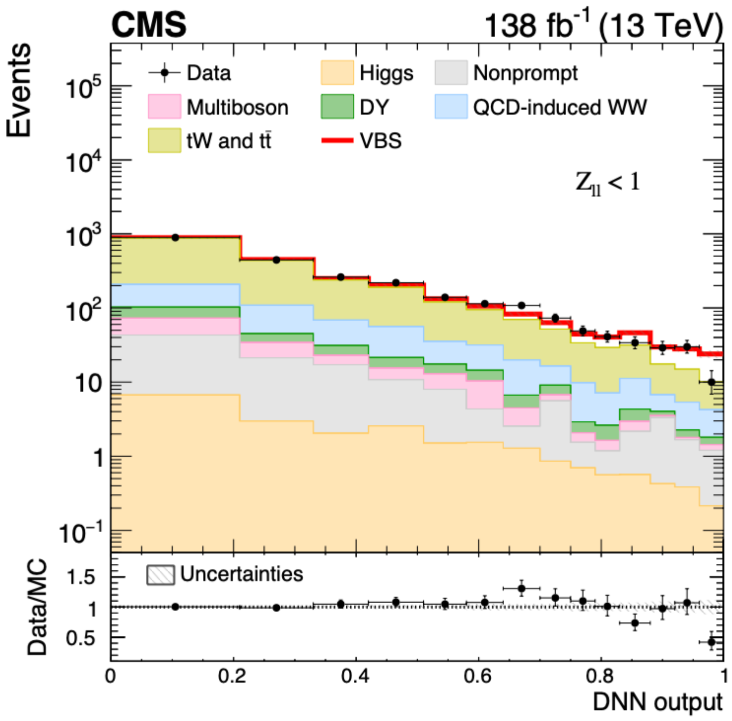
Expected. limit	Observed. limit	$\mathcal{U}_{\text{bound}}$
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

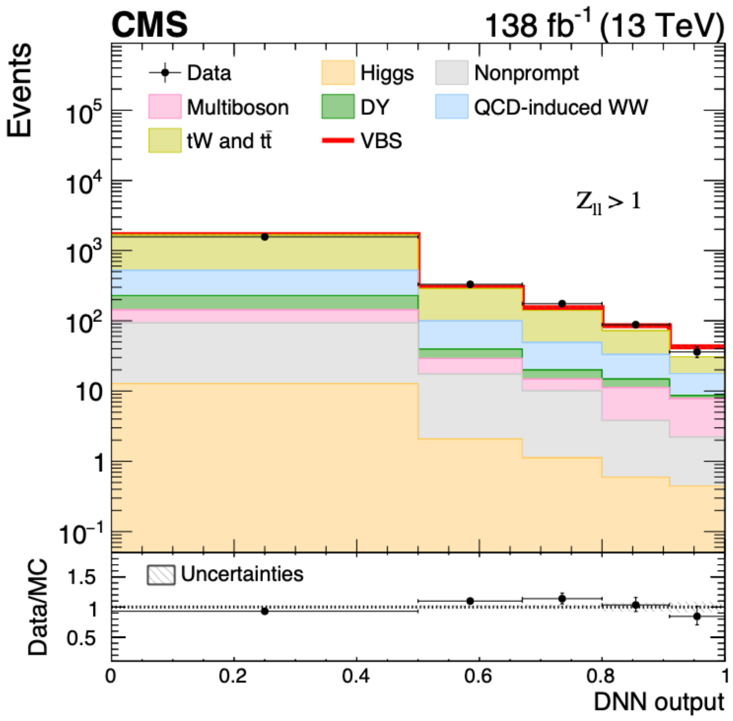
mWγ used to set limit

EW $W^+W^-(l\nu l\nu)jj$

SMP-21-001

- New results from CMS with 5.6σ for WWjj in the opposite-sign channel
- DNN is used to separate signal and background
- Measured cross section agrees well with SM predictions





DNN input variables

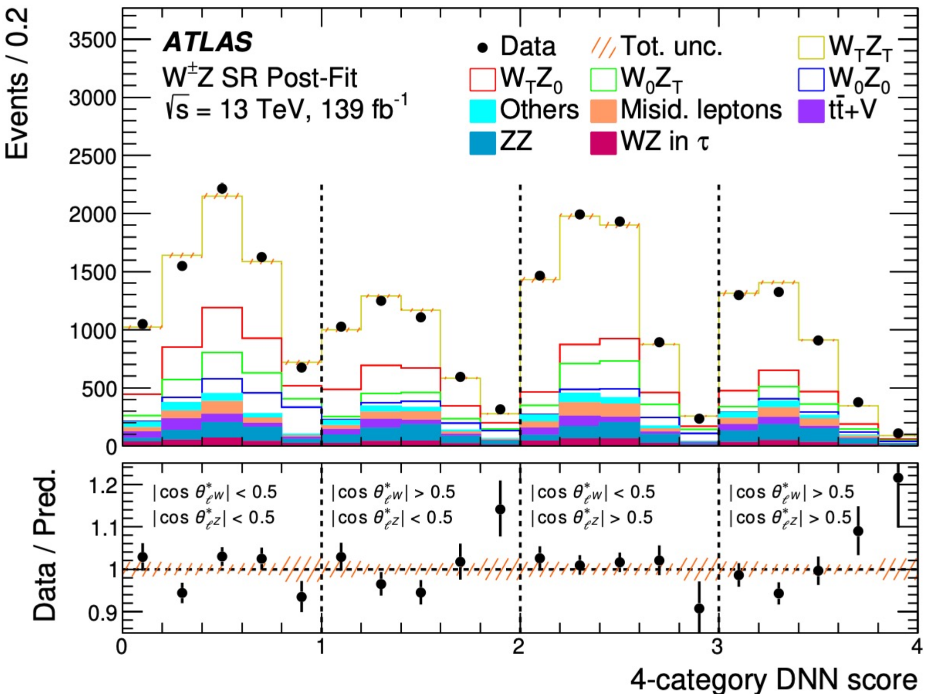
Variable	Description
m_{jj}	Invariant mass of the two tagging jets pair
$\Delta\eta_{jj}$	Pseudorapidity separation between the two tagging jets
$p_T^{j_1}$	p_T of the highest p_T jet
$p_T^{j_2}$	p_T of the second-highest p_T jet
$p_T^{\ell\ell}$	p_T of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
Z_{ℓ_1}	Zeppenfeld variable of the highest p_T lepton
Z_{ℓ_2}	Zeppenfeld variable of the second-highest p_T lepton
$m_T^{\ell_1}$	Transverse mass of the $(p_T^{\ell_1}, p_T^{miss})$ system

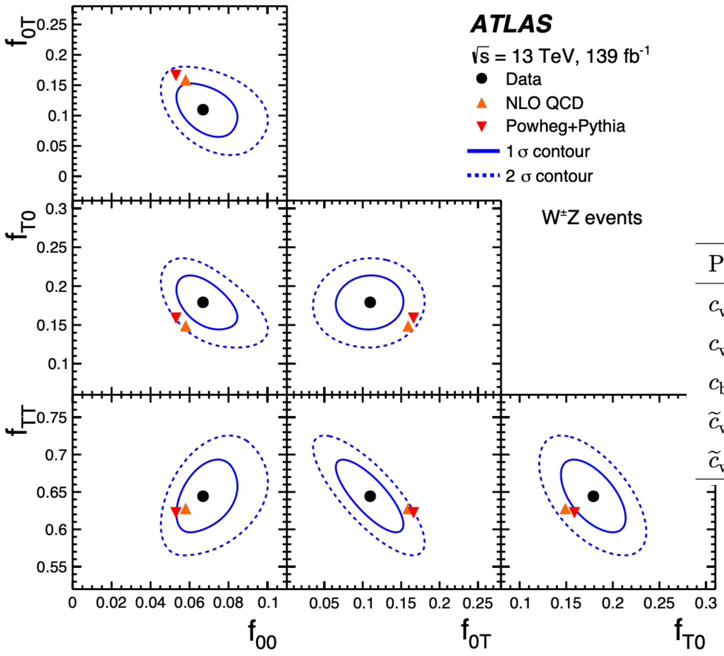
$$Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}|, \text{ where } Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$$

WZ polarization

2211.09435
JHEP 07 (2022) 032

- Longitudinal component is critical to understand the Higgs mechanism and probe VBS unitarization
- ATLAS reports the first measurement of joint polarization, with significance of the double-longitudinal component of 7.1σ





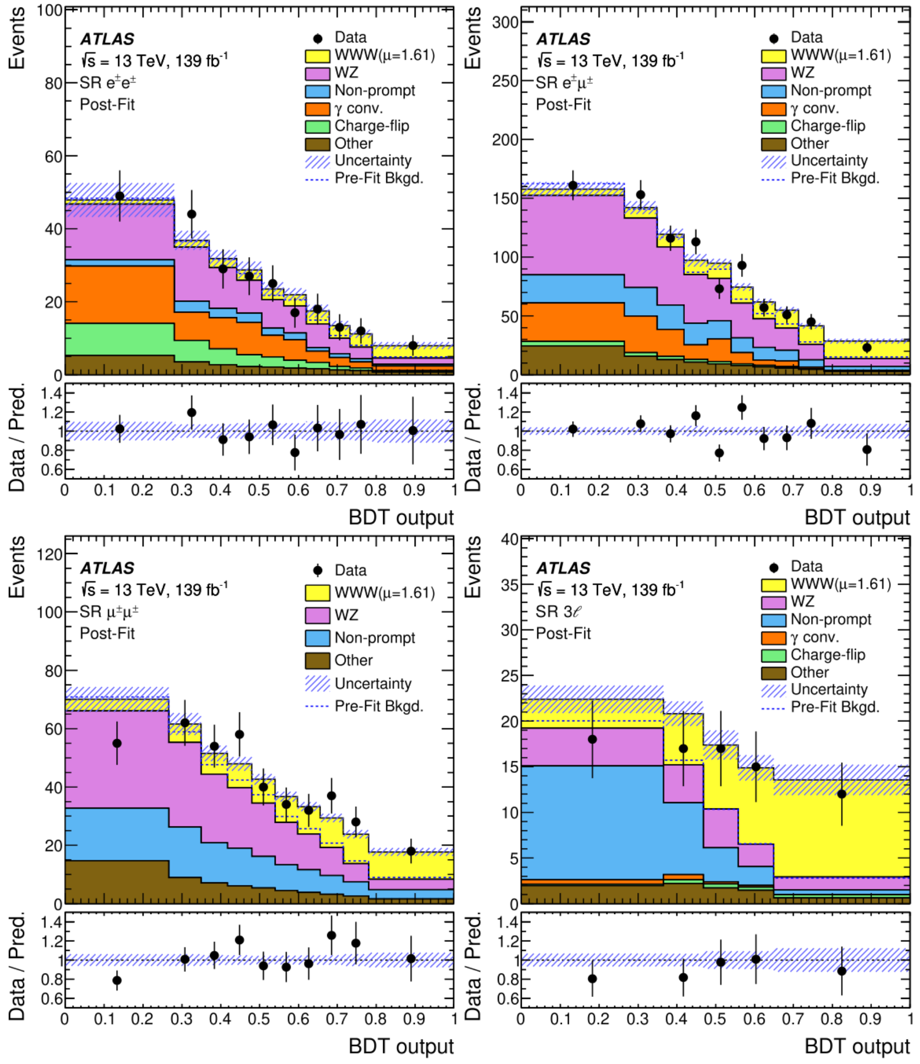
Both ATLAS and CMS provide several differential cross section measurements
CMS also reports the EFT limit

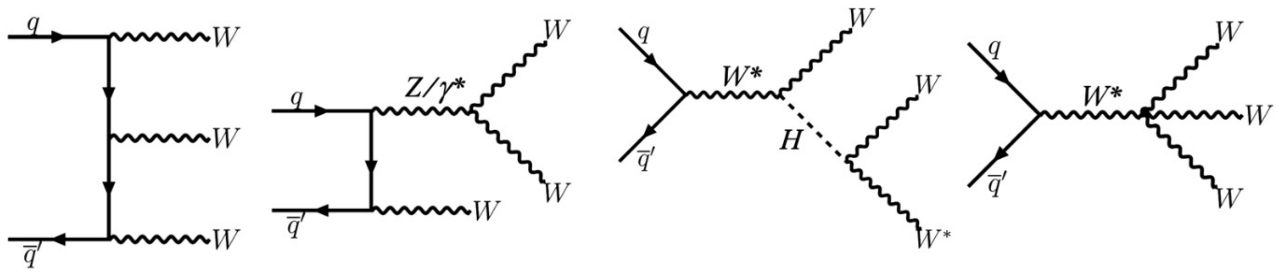
Parameter	95% CI, exp. (TeV^{-2})	95% CI, obs. (TeV^{-2})	Best fit, obs. (TeV^{-2})
c_w/Λ^2	$[-1.8, 2.1]$	$[-3.1, 0.3]$	-1.6
c_{www}/Λ^2	$[-8.5, 8.5]$	$[-4.2, 14.2]$	5.5
c_b/Λ^2	$[-200, 180]$	$[10, 380]$	200
$\tilde{c}_{www}/\Lambda^2$	$[-3.3, 4.1]$	$[-4.0, 3.6]$	-0.6
$\tilde{c}_w/\Lambda^2$	—	—	—

WWW production

Phys. Rev. Lett. 129 (2022) 061803

- Directly probe the gauge boson self-interactions
- Events with 2 same-sign leptons and two jets, or three charged leptons are considered
- BDT used to discriminate between signal and background
- Observation with 8.0σ





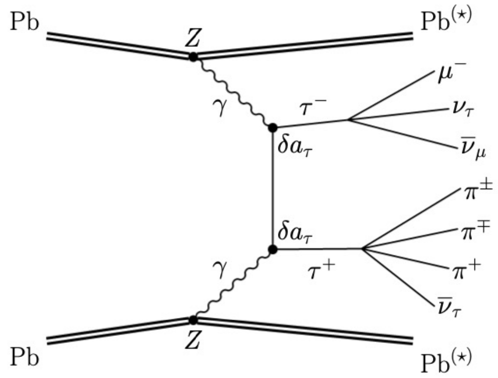
Measured cross section approximately 2.6σ higher than the SM prediction at NLO QCD and LO EW

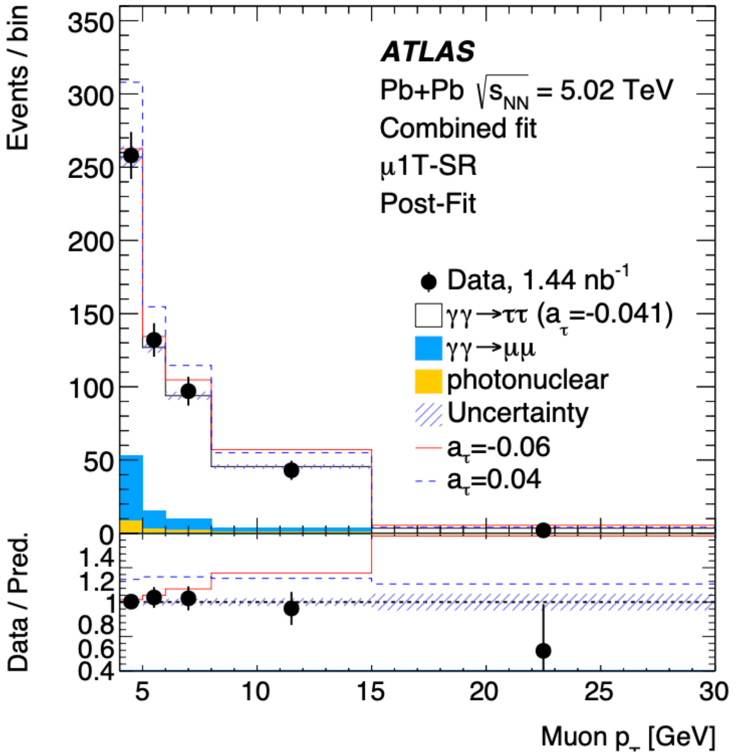
Exclusive production of $\gamma\gamma \rightarrow \tau\tau$ from Pb+Pb collision

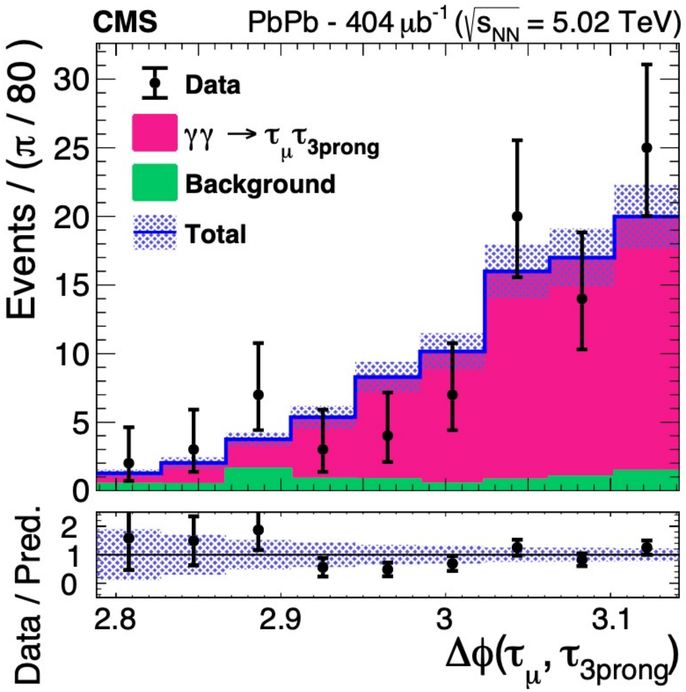
arXiv:2204.13478
arXiv:2206.05192

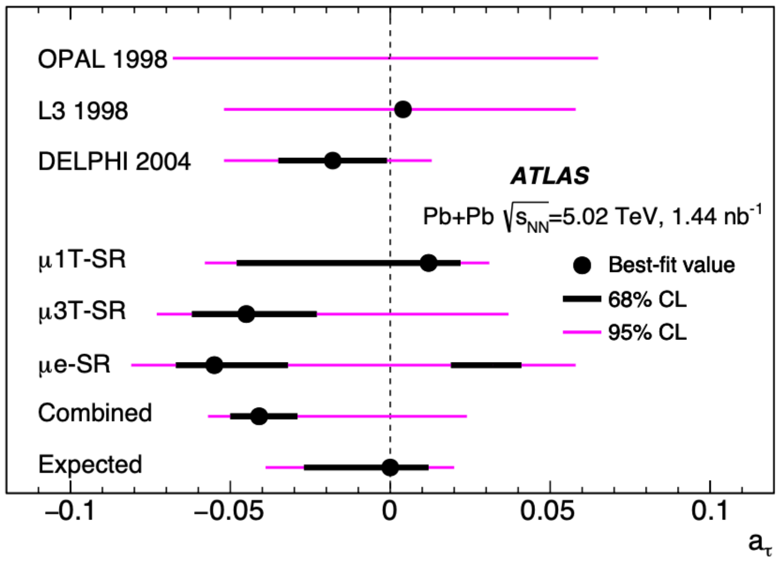
- Photon induced $\tau\tau$ production is sensitive to anomalous magnetic moment
- Both ATLAS and CMS have observed clear exclusive production of $\gamma\gamma \rightarrow \tau\tau$
- One muon is required in the final state

$$a_\ell = \frac{g_\ell - 2}{2} = \frac{\alpha}{2\pi} + \ldots \approx 0.0012$$





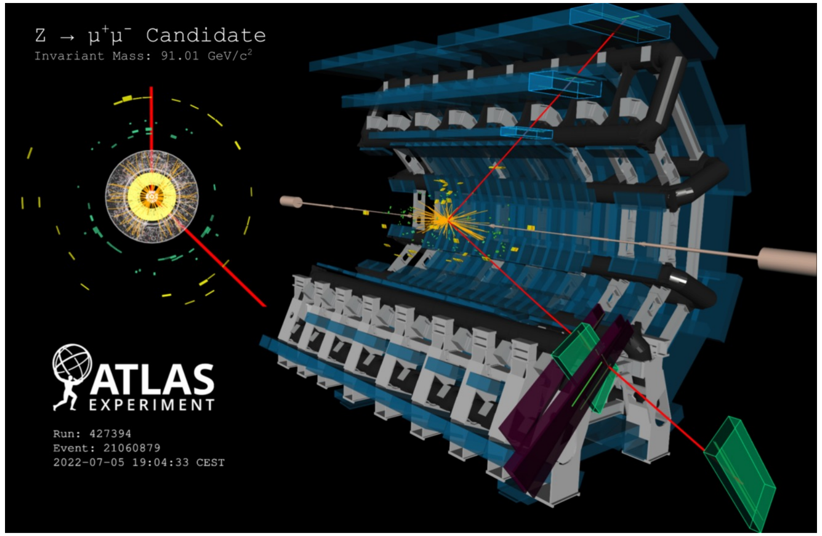


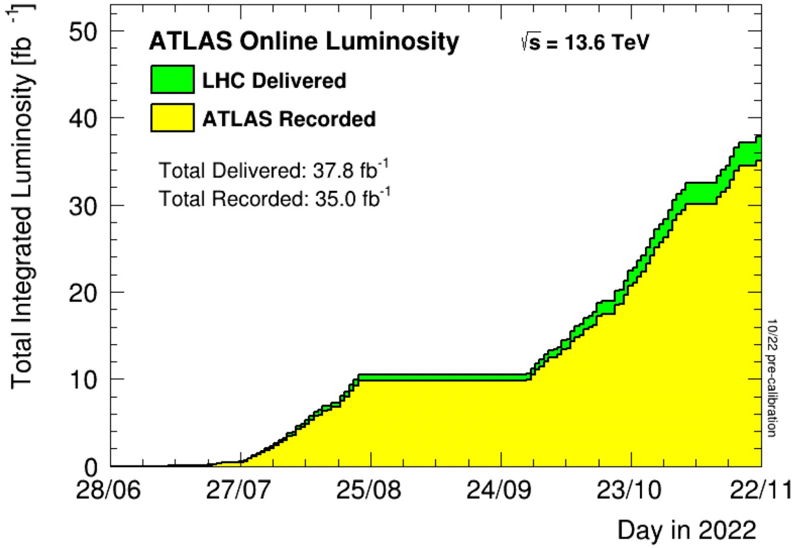


CMS $a_\tau = 0.001^{+0.055}_{-0.089}$ at a 68% confidence level.

Summary

- SM measurements at the LHC covers a large range of cross sections from many physics processes
  - Precision measurements over a wide kinematic ranges with many observables
  - First observation of several rare SM processes
  - Looking for possible deviations from SM
- LHC Run 3 already started and will give further opportunities





Backup

- Multi-jet production
  - ATLAS: ATLAS-CONF-2022-056
  - CMS: JHEP 01 (2022) 177, SMP-21-006, JHEP 02 (2022) 142, JHEP 01 (2022) 188
- Single boson (+jets) production
  - ATLAS: 2205.02597, 2204.12355, ATLAS-CONF-2022-065
  - CMS: SMP-18-014, SMP-20-003, SMP-19-009, JHEP 08 (2022) 063, PRD 105 (2022) 072008, SMP-21-003
  - LHC-TeVatron W mass combination: CERN-LPCC-2022-06/FERMILAB-TM-2779-V
- Multi boson (+jets) production
  - ATLAS: 2211.09435, 2208.12741, Phys. Rev. Lett. 129 (2022) 061803, ATLAS-CONF-2022-047,
  - CMS: SMP-21-001, JHEP 07 (2022) 032, PLB 834 (2022) 137438
- PDF constraint
  - ATLAS: Eur. Phys. J. C 82 (2022) 438
- Elastic cross section
  - ATLAS: 2207.12246
- Exclusive production
  - ATLAS: 2204.13478,
  - CMS: arXiv:2206.05192