Trends2024: New Trends in High-Energy and Low-x Physics

Standard Model Physics Results at the LHC

Sfântu Gheorghe, Romania

September 2nd, 2024

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on behalf of the CMS & ATLAS Collaborations

What are the *trends* of experimental Standard Model physics in 2024?

outline

- ☐ Where we are and where we go in SM physics
- ☐ Phenomenology of SM measurements at LHC
- ☐ Selected recent results from ATLAS and CMS
- ☐ Single boson, multiboson and boson+jets at $\sqrt{s} = 13(.6)$ TeV

Summary, directions and future *trends*

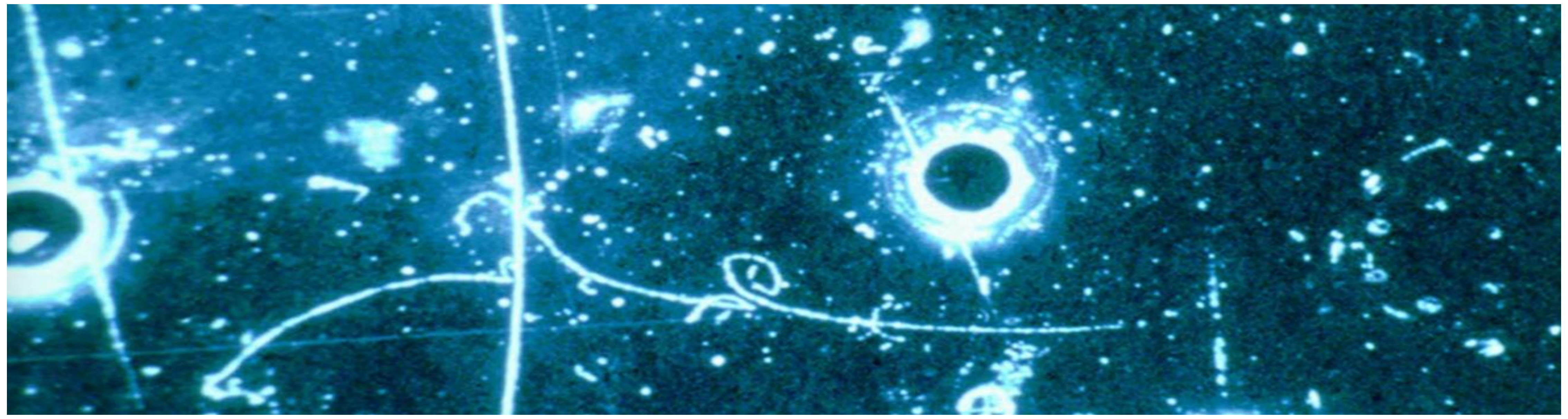
Introduction: a brief history of the Standard Model (up to 2024)

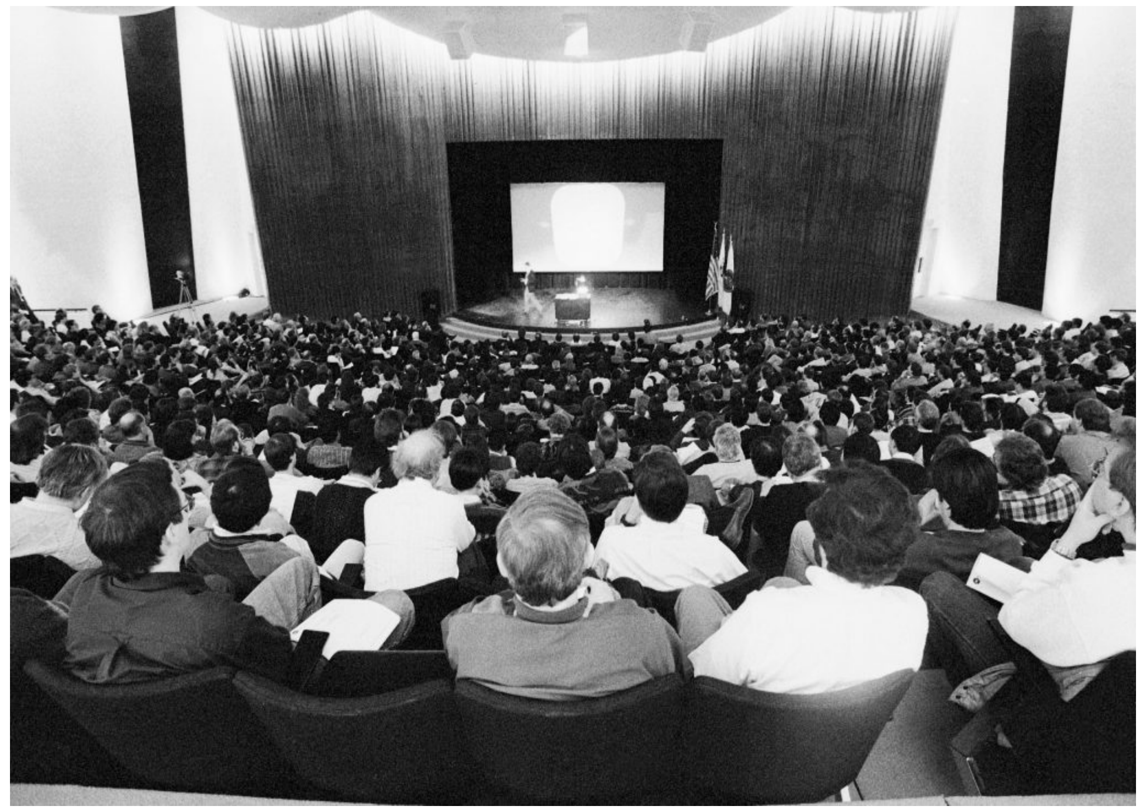
1954 Yang & Mills gauge theory of strong interactions.

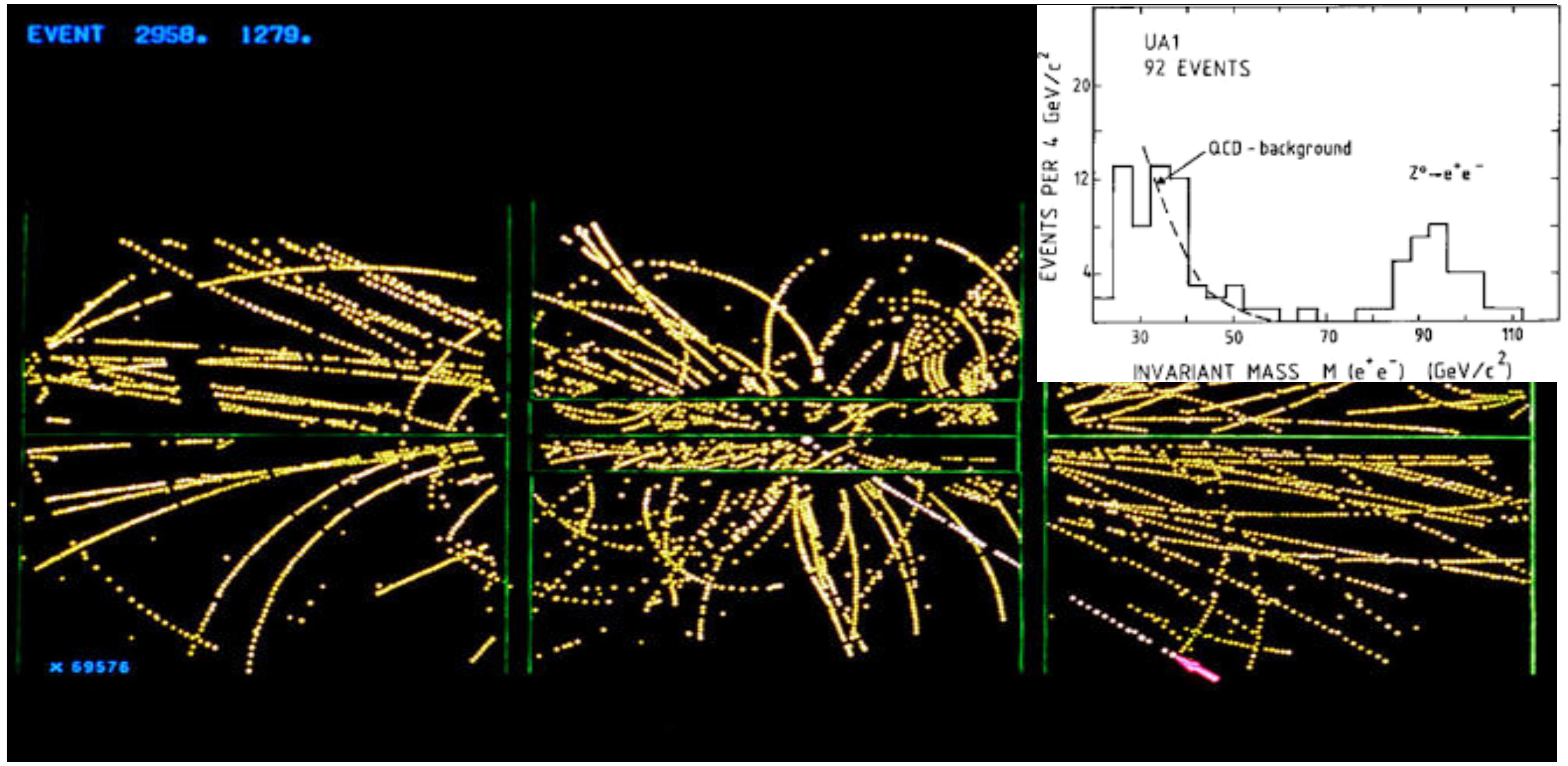
1956 M.me Wu parity violation in weak interaction.

1961 Glashow combined the electromagnetic and weak interactions

1967 Weinberg & Salam incorporated the Higgs mechanism into electroweak interaction giving it its modern form







1973 discovery of neutral currents from the Z at CERN

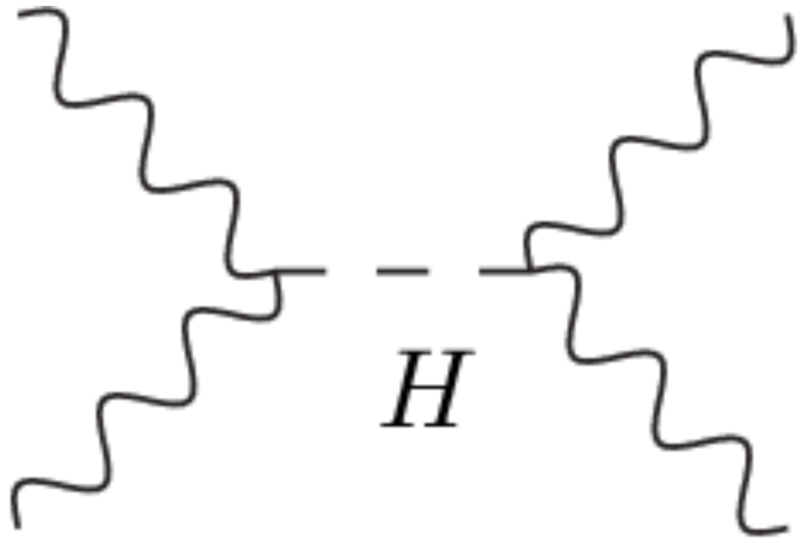
1983 discovery of the W and Z bosons at CERN

1989-2000, 11 years of electroweak precision tests at LEP

1995 top quark discovery @ Fermilab

2012 Higgs boson discovery @ CERN

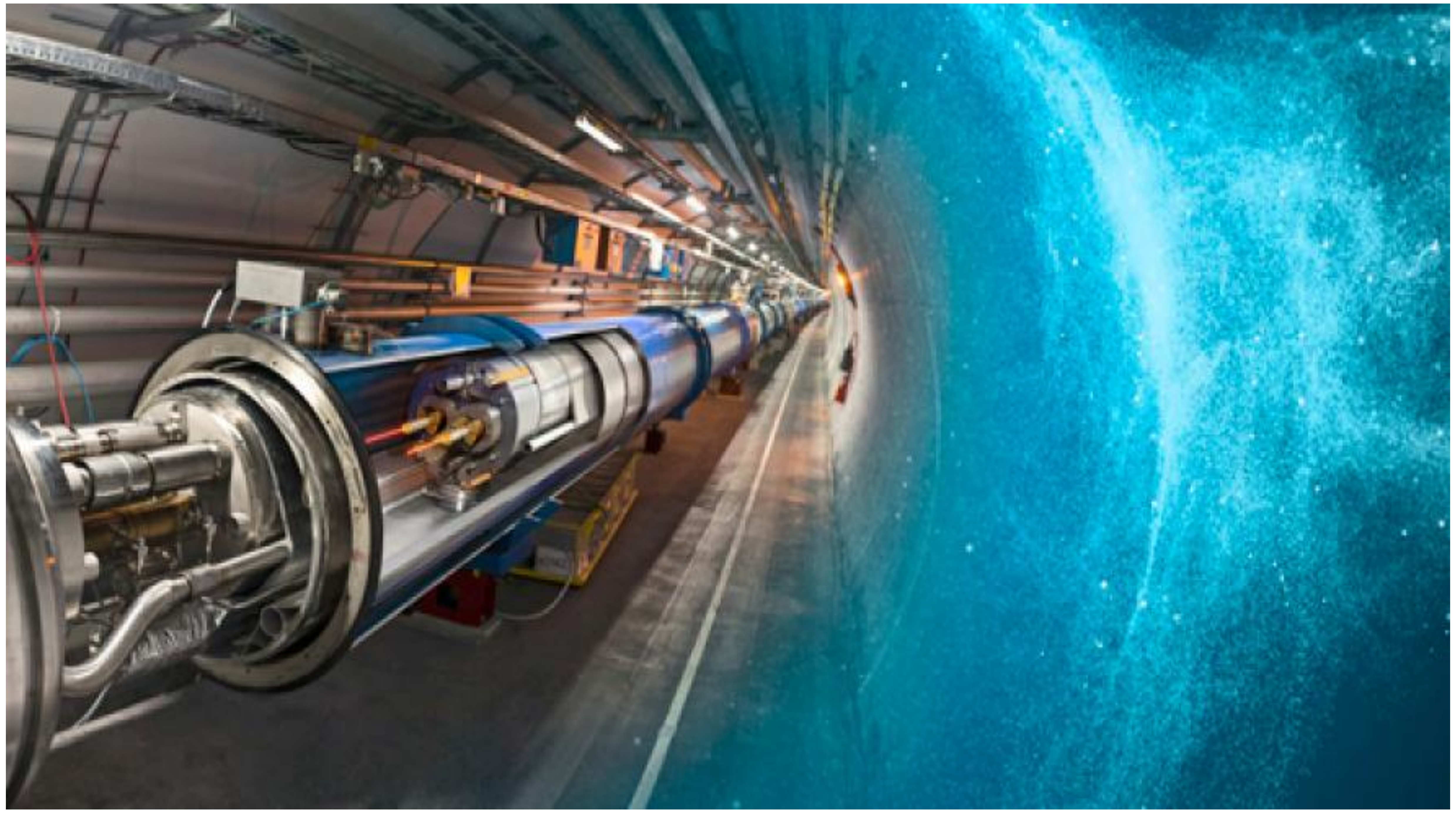
2024→ LHC era my presentation



Phenomenology of SM measurements at colliders: *the initial state*

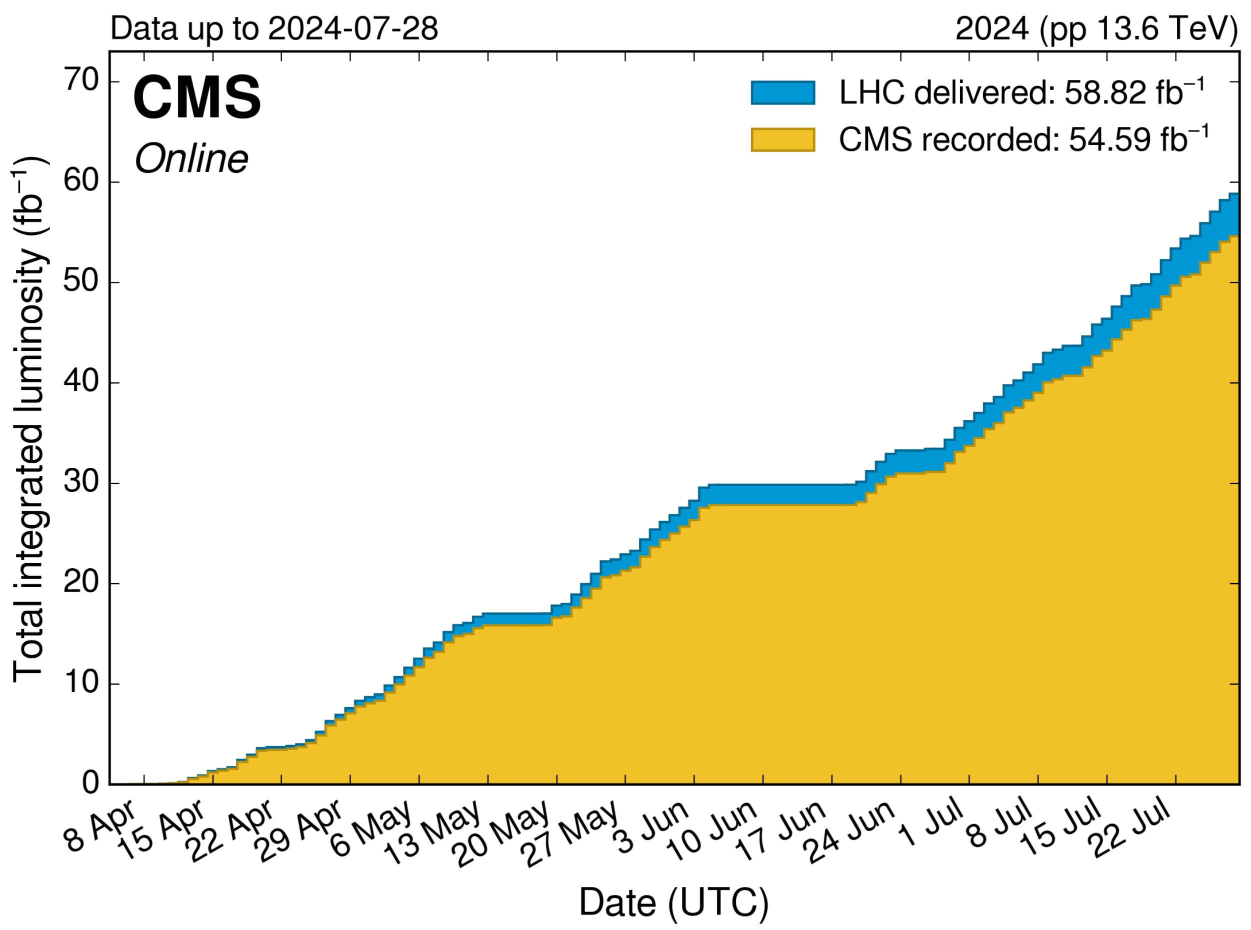
LHC p-p collisions $\sqrt{s}$ = 13 TeV (Run II) and 13.6 TeV (Run III)

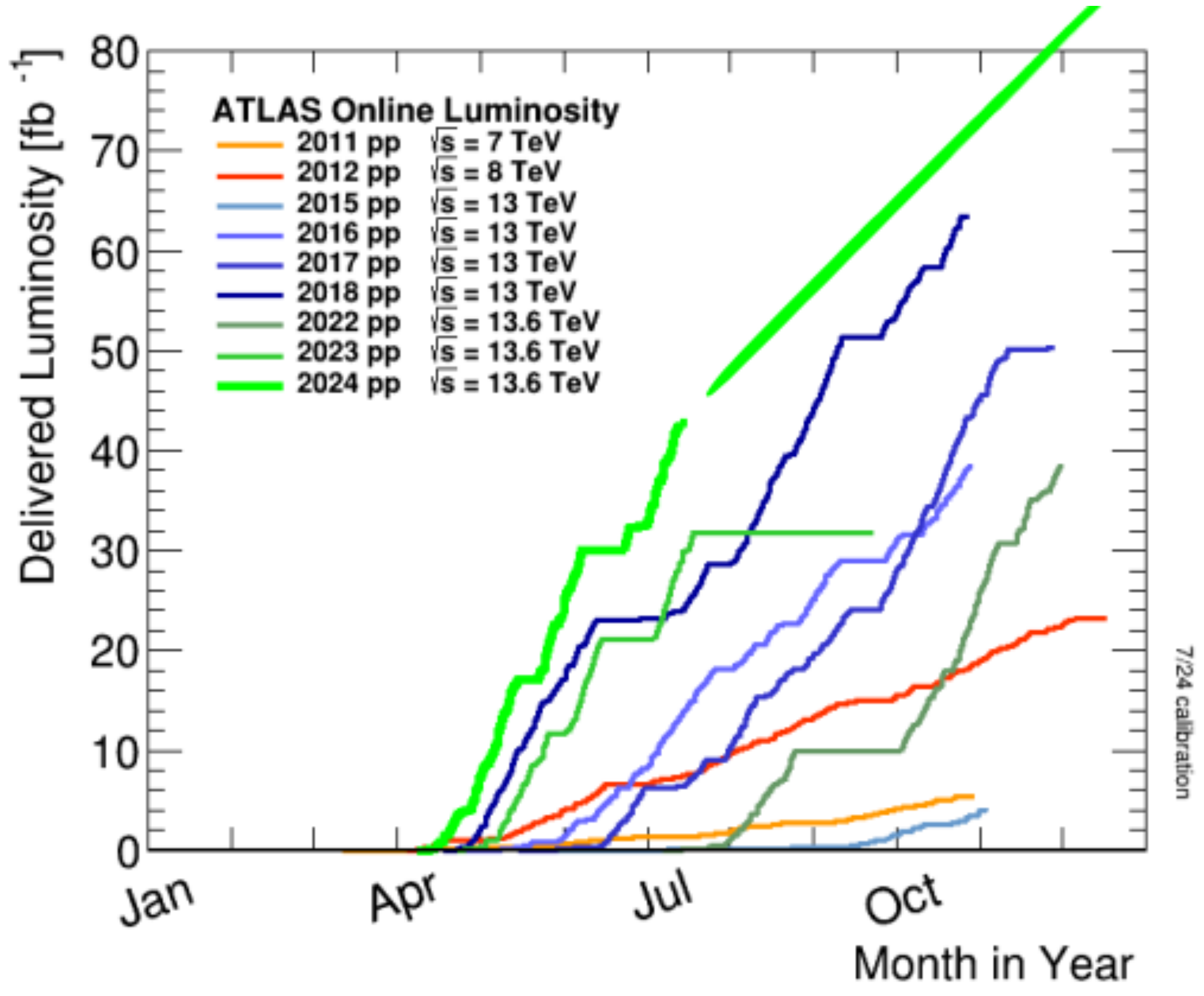
up to 63 simultaneous collisions/event



$$\int L dt = $$ = ~137 / fb (Run II) + ~100 /fb (Run III by 2024)

Aiming at >300 fb-1 (Run2+Run3) by the end of 2025



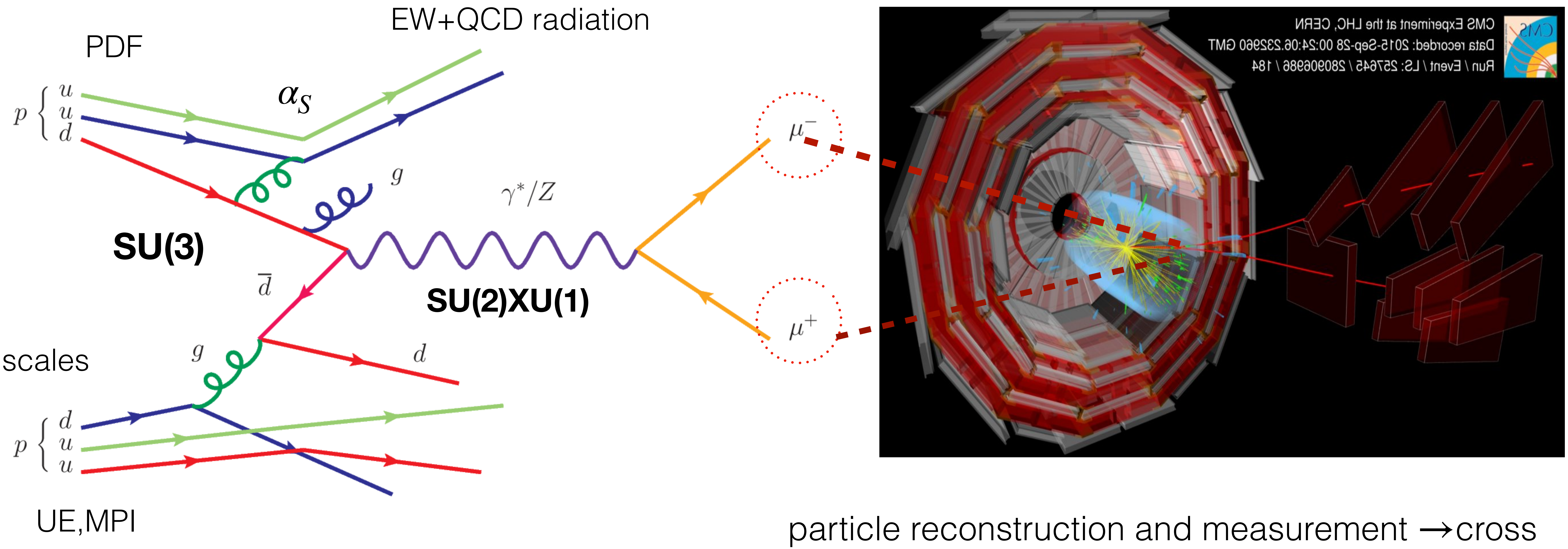


…how do we realize our SM process? →

Phenomenology of SM measurements at colliders: *the final state*

at the LHC the QCD dominates the initial + EW appears everywhere: modelling, tuning…

we need great experimental performances and accurate simulation to reach precision!

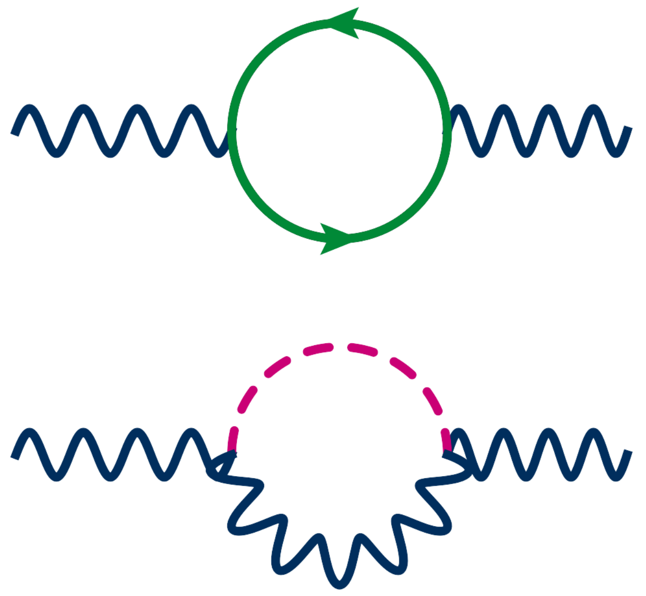


(a *Drell-Yan*+Jets process)

particle reconstruction and measurement →cross section →SM couplings, SM parameters….

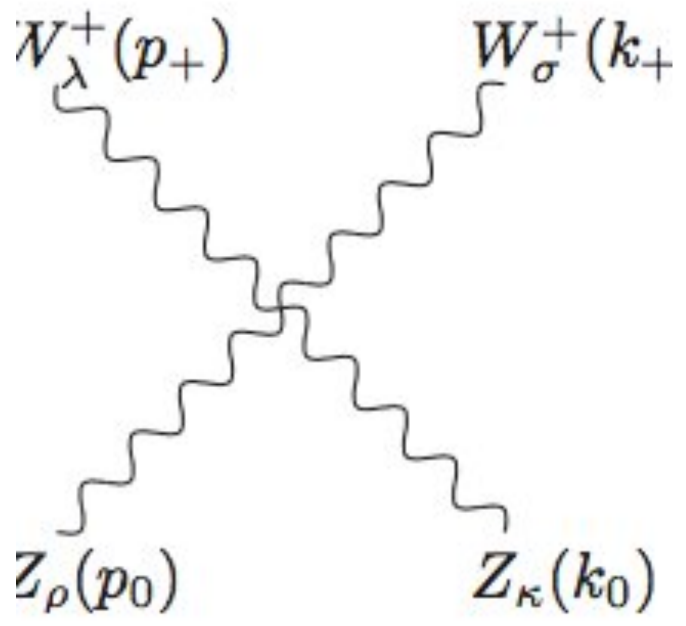
Phenomenology of SM measurements at colliders: *trends*

single boson



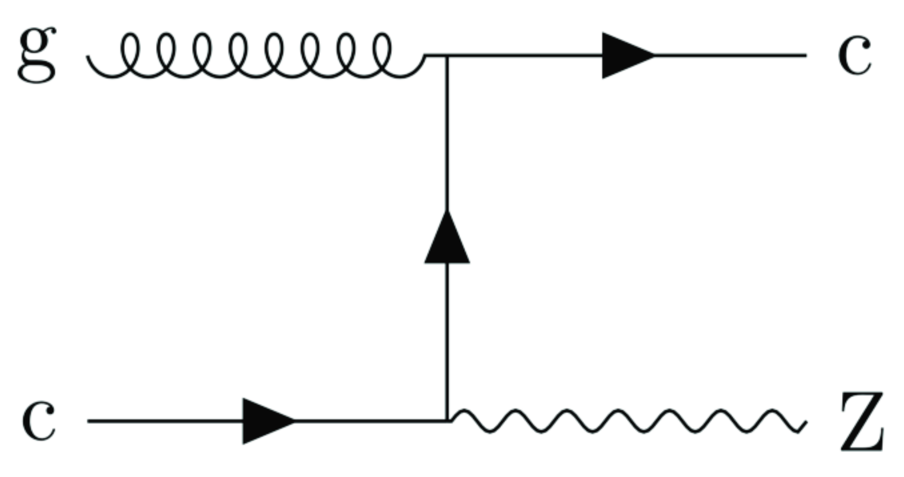
- test of the SM: measurement of key parameters
- at the heart of the EW theory: M_W, $\sin^2\theta_W$
- rare W/Z decay sensitive to new physics via loop

multiboson



- test of the non-abelian nature of the EW interaction
- anomalous gauge couplings experimental contrains
- rare SM processes like WZγ, WWZ
- critical for higgs physics and searches

boson + quarks



- powerful test of pQCD: PDF, scale, strong coupling
- heavy flavour content of the proton
- main background of several Higgs channels + heavy particle searches, heavy fermions, susy…

disclaimer!

Standard Model results at the LHC means a huge collection of extraordinary experimental results including VBS, Higgs, top… a lot of amazing scientific achievements are available!

what comes next is… my personal overview of the most recent W/Z results at 13 and 13.6 TeV from ATLAS and CMS

[enjoy!]

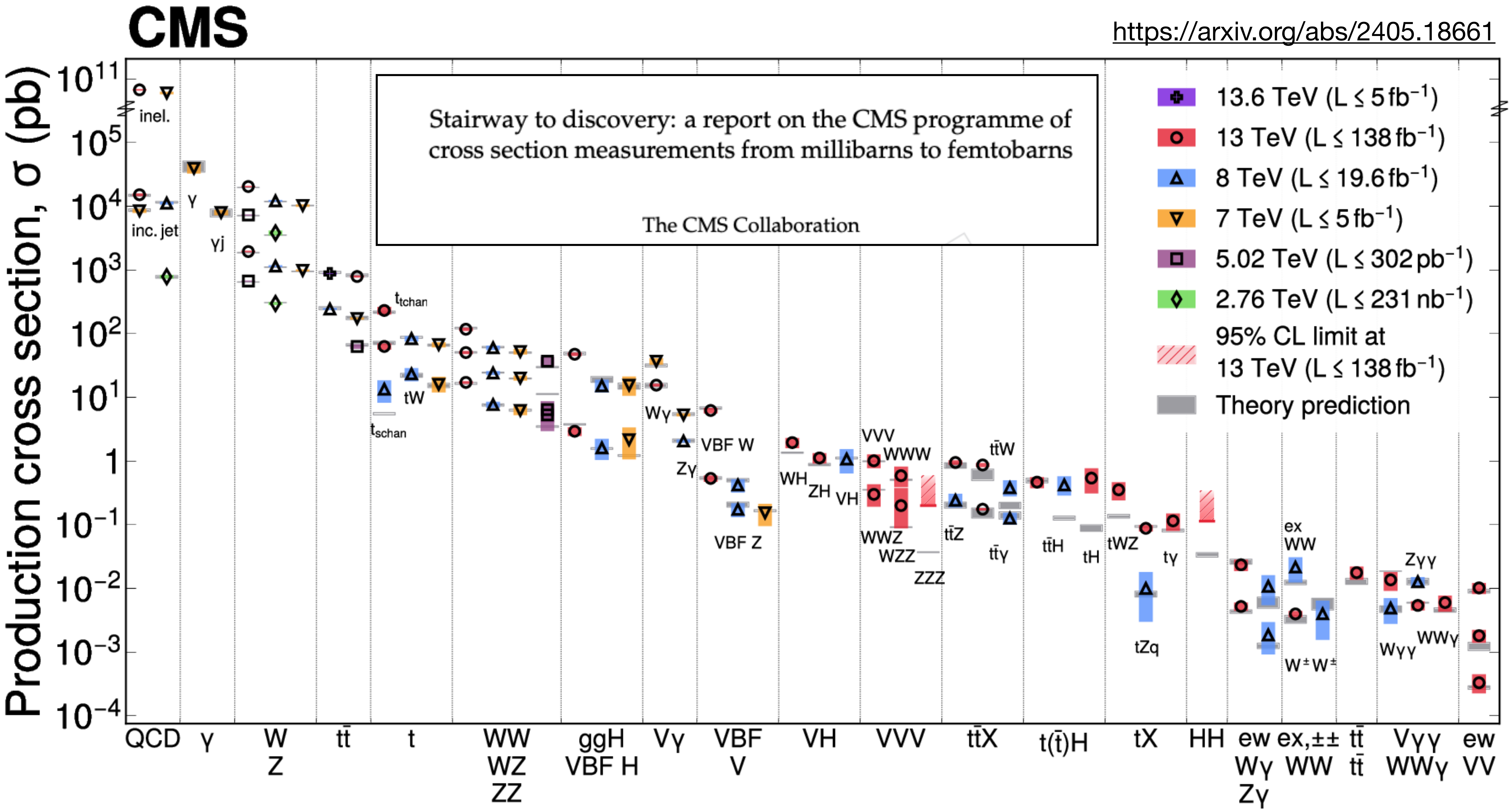
you can have a look at the full gallery of results from the two experiments here:

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Recent_Results

14 years plot of Standard Model Physics at CMS

https://arxiv.org/abs/2405.18661



Led Zeppelin IV (1971)

ATLAS version: https://arxiv.org/abs/2404.06829

Standard Model results with ATLAS and CMS

single boson properties precision measurements

multiboson, couplings & polarization

V + jets

Standard Model results with ATLAS and CMS

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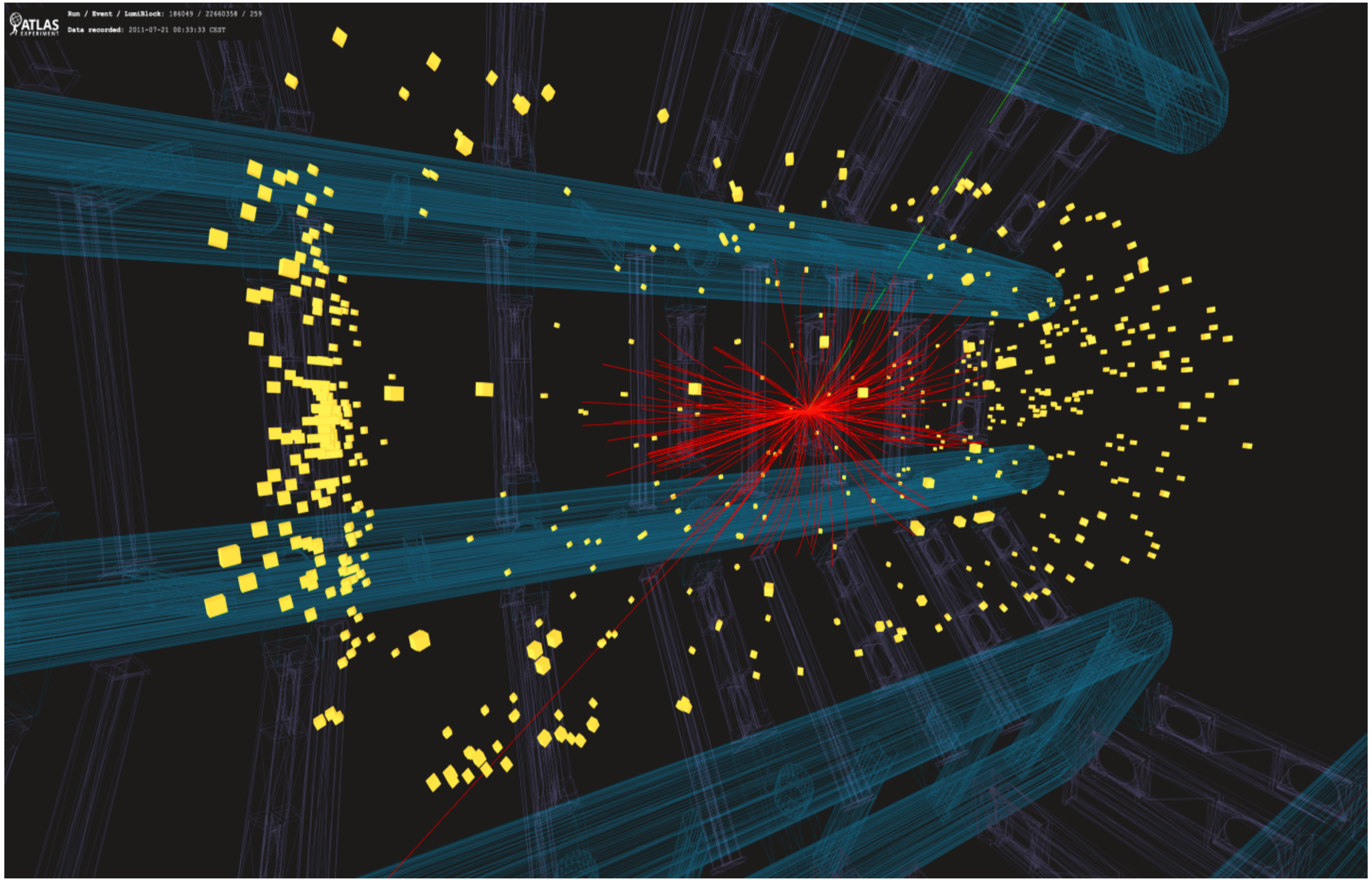
multiboson, couplings & polarization

V + jets

W boson mass, width and momentum with ATLAS

$W^{\pm} \rightarrow \ell^{\pm}\nu_{\ell}$

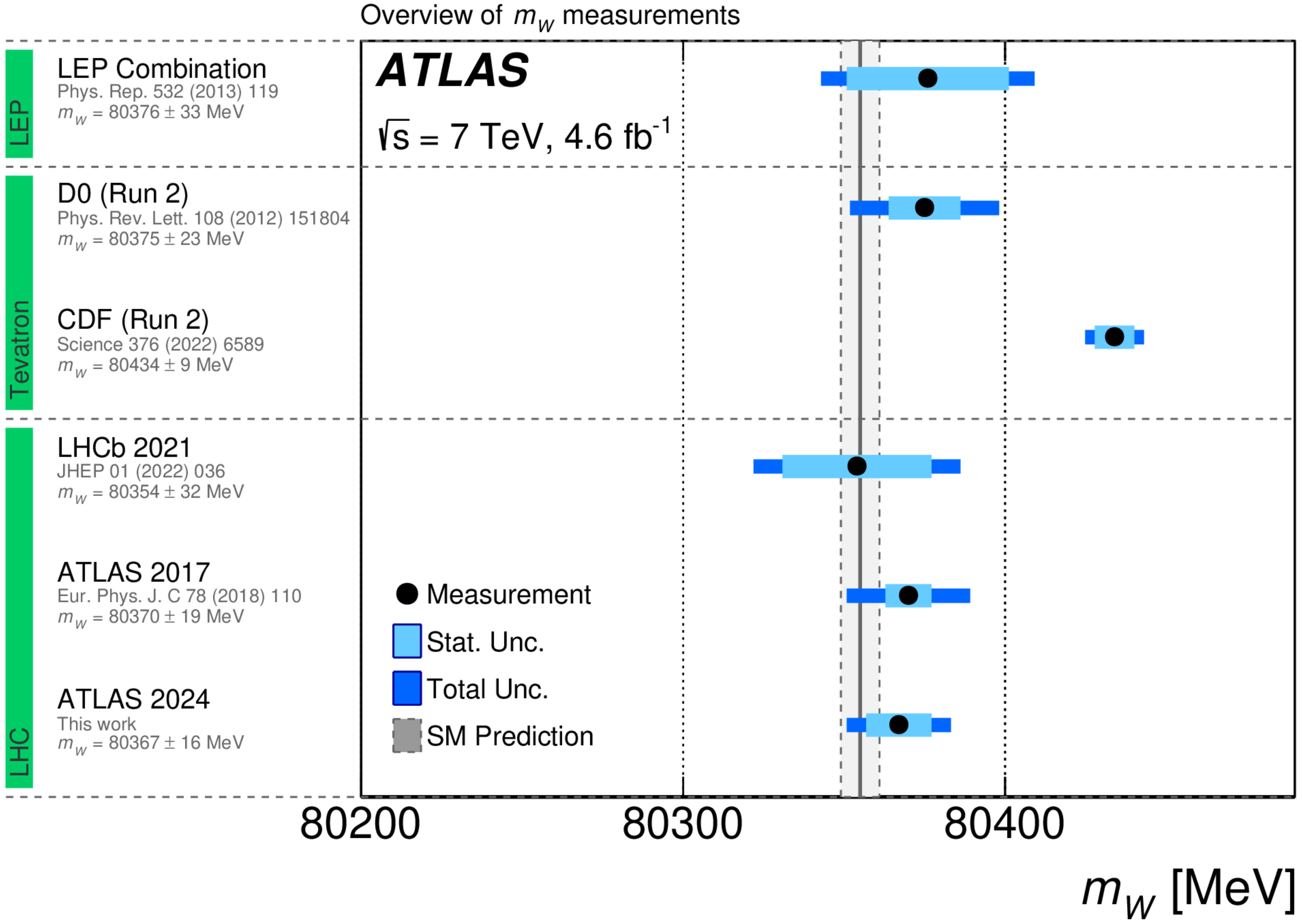


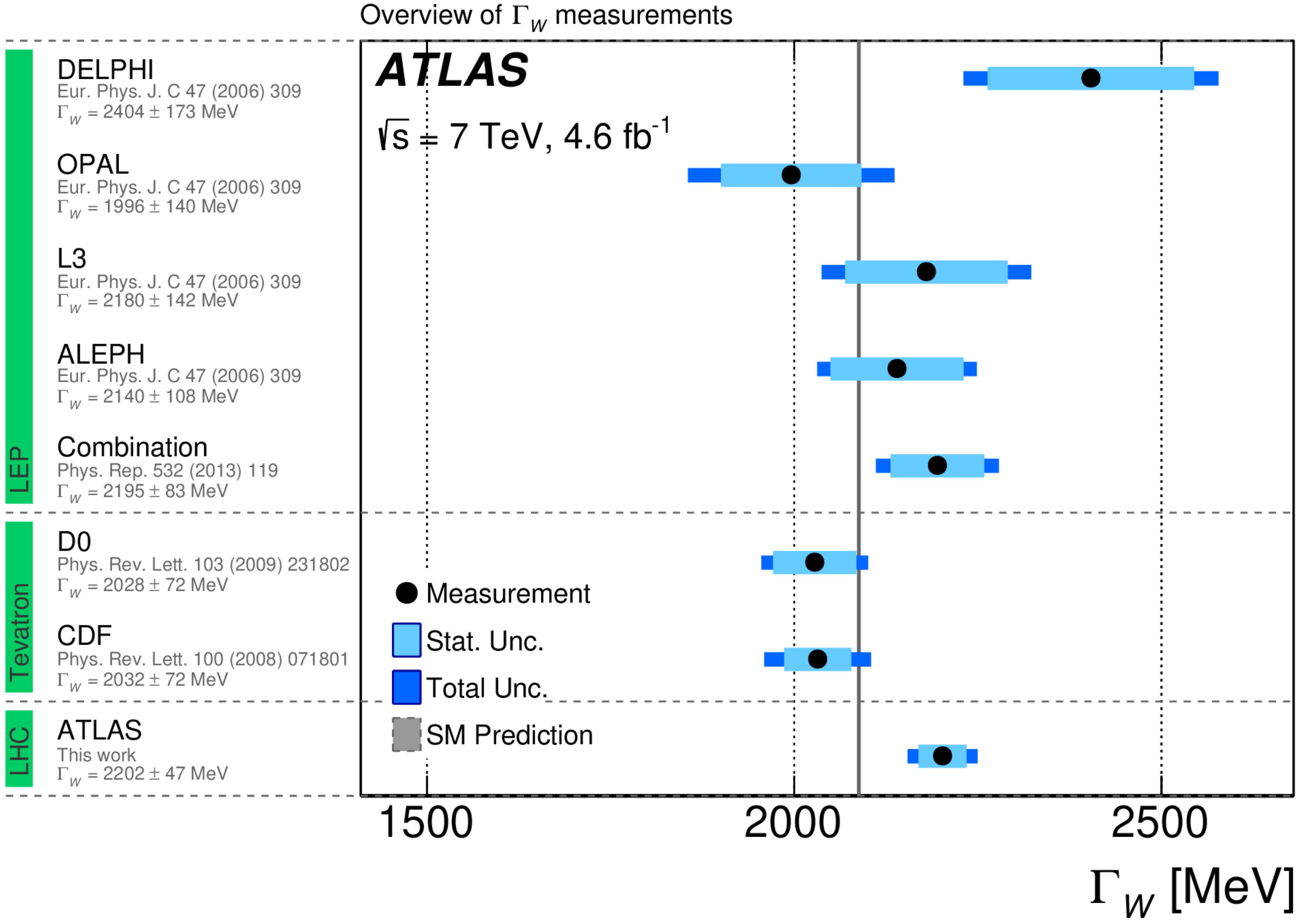
- After the CDF claim (7σ away from the SM), re-analysis of 7 TeV data motivated by large discrepancy in CDF measurement
- Separate measurement of the W mass and width (first measurement at the LHC)
- Precision transverse momentum measurement in a dedicated study
- Extended improvements on PDF, theory predictions, momentum calibration…

arXiv:2404.06204 , arXiv:0901.0512

W boson mass, width and momentum with ATLAS

arXiv:2404.06204
arXiv:0901.0512





m_W =80366.5 ± 15.9 MeV

Γ_W =80366.5 ± 15.9 MeV

W boson mass, width and momentum with ATLAS

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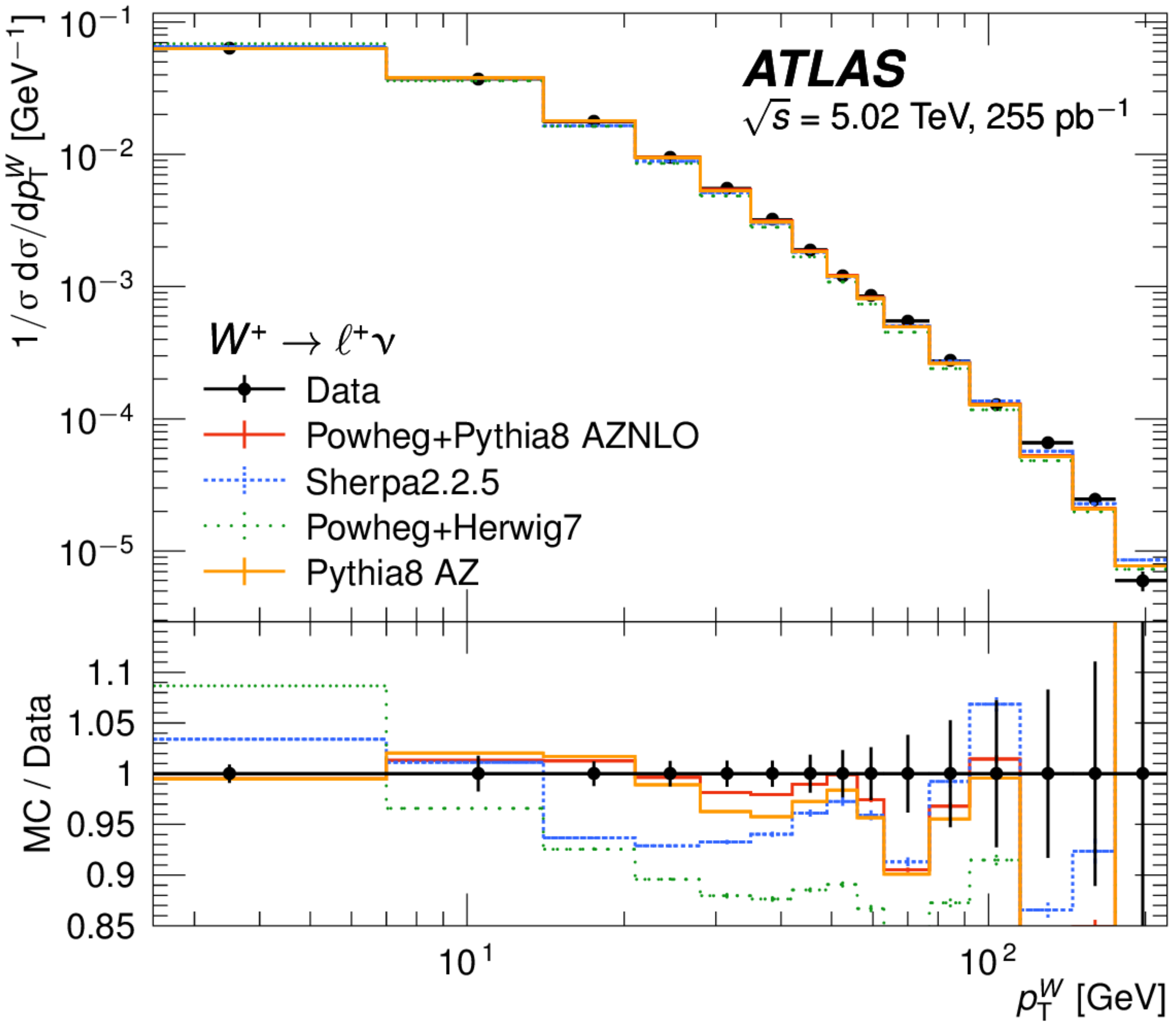
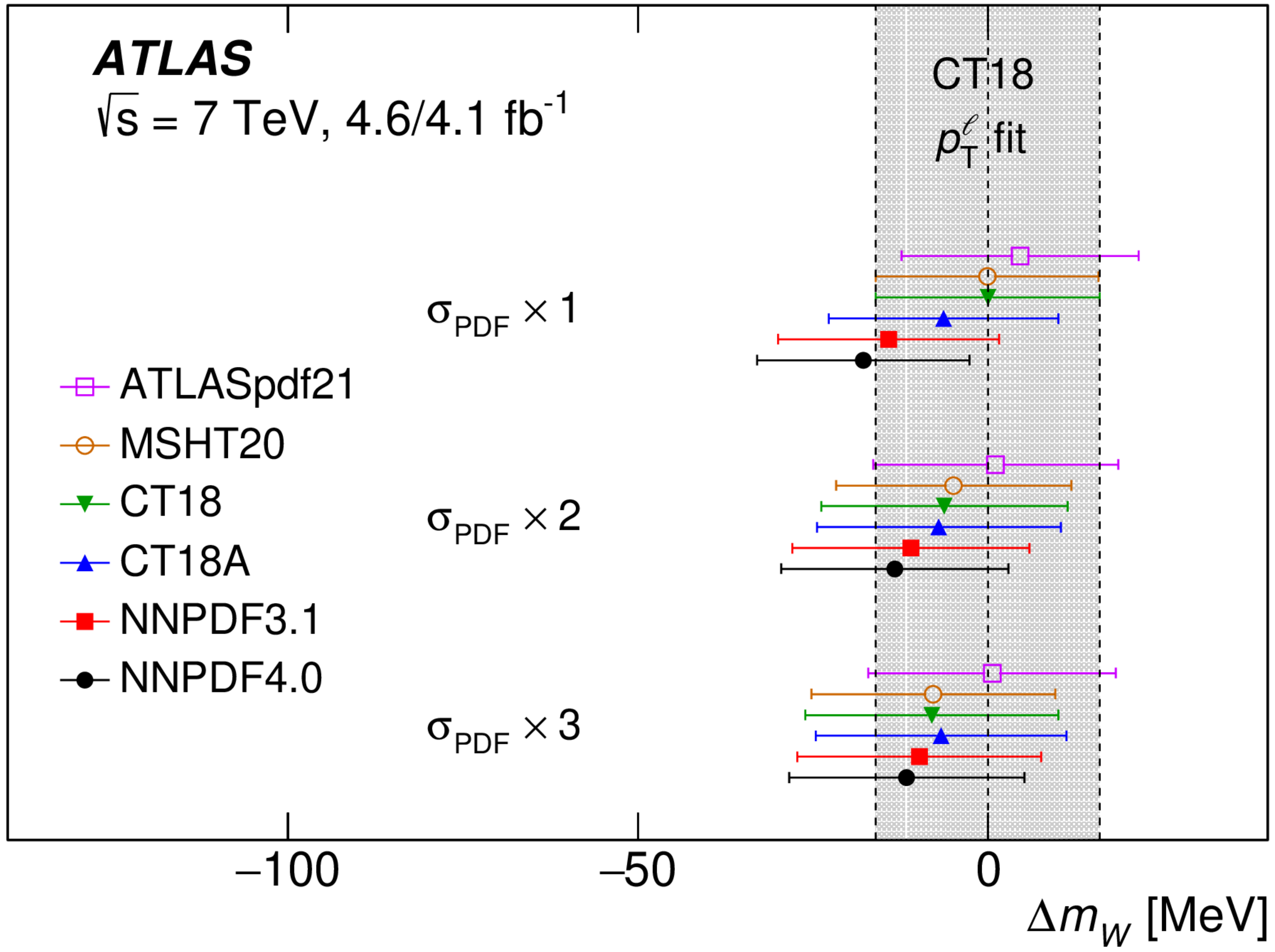


unfolded transverse momentum of the W



stability over PDF sets / uncertainty

W boson mass, width and momentum with ATLAS

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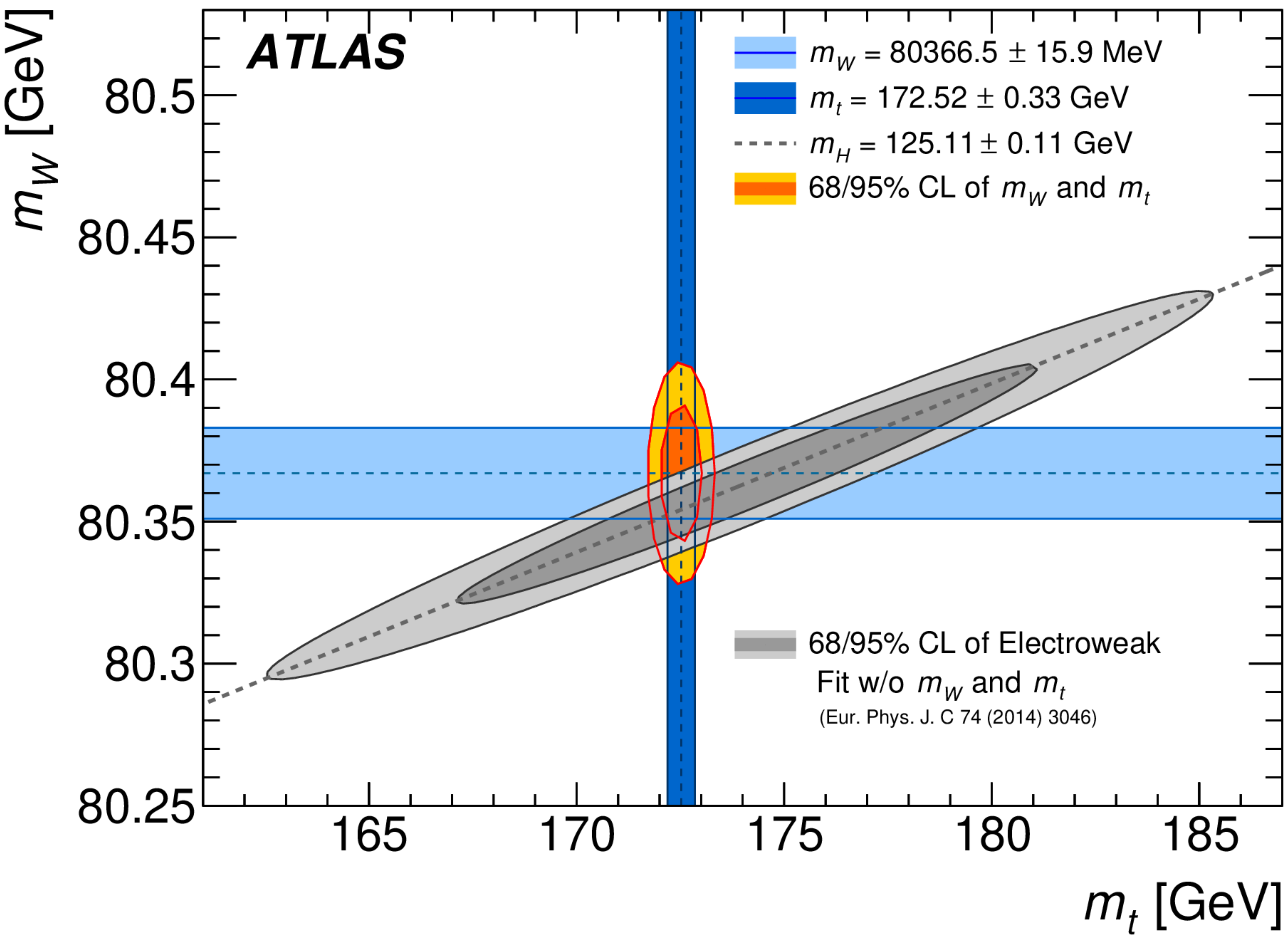


comparison of the W mass measurement to the global EW fit, TeVatron and LEP data

Electroweak mixing angle with CMS

arXiv:2408.07622

a puzzling past:

- Two most precise measurements from LEP & SLC differ by ~ 3σ.
- Latest CDF-II mW has significant tension
- models that describe CDF mW prefer lower (SLD) values

at the heart of the Standard Model $\sin^2\theta_W = (1 - m_W^2/m_Z^2)$

at the LHC the *effective* mixing angle (leptonic) is measured using DY events in the Collin-Soper frame

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_4\cos\theta$$

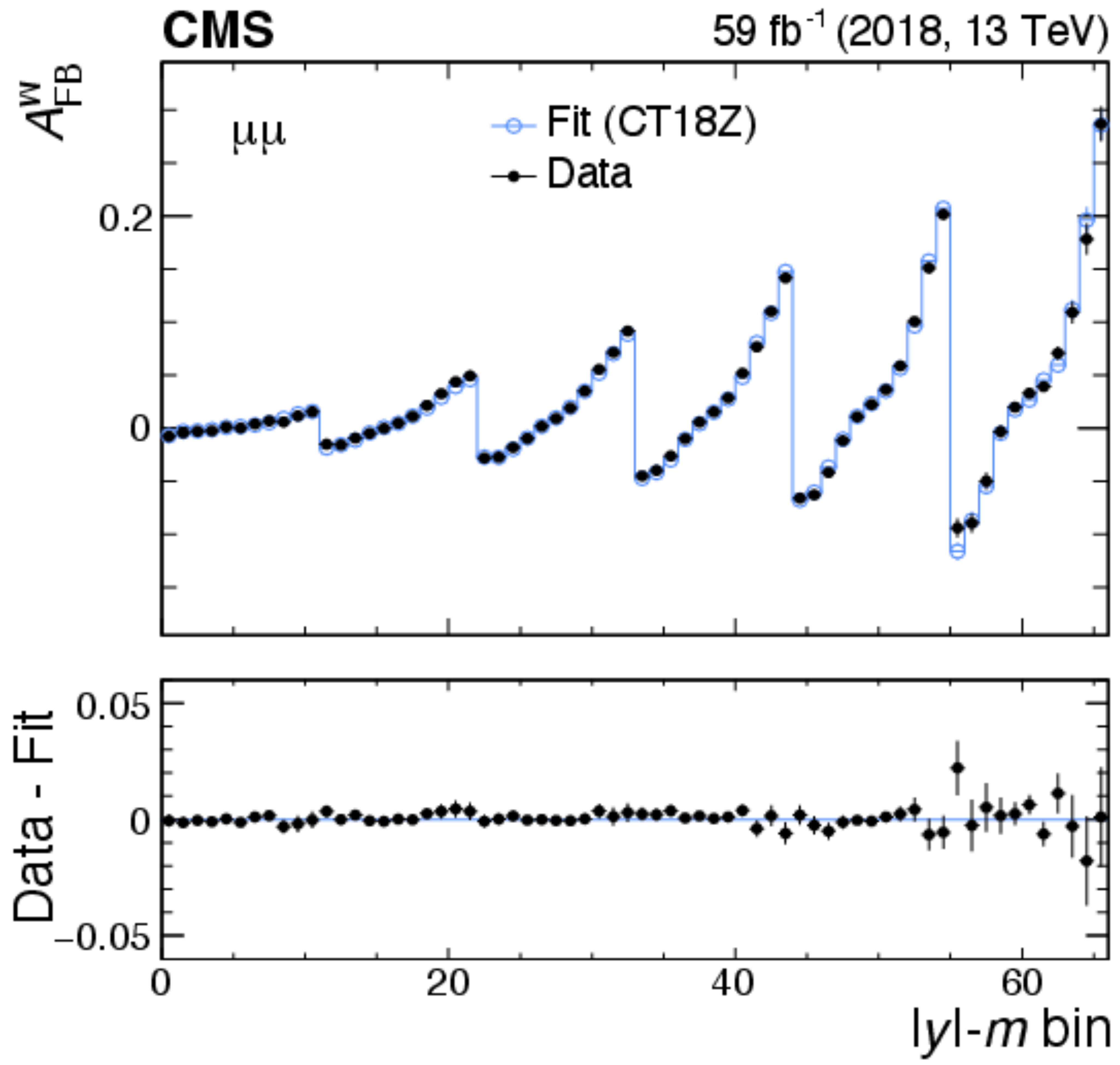
$$A_{FB} = 3A_4/8 \rightarrow \sin^2\theta^{\ell}_{eff}$$

improvements:

- electrons reco outside tracker acceptance $|\eta| < 4.36$
- rapidity-dependent: no ambiguity in quark direction
- unfolded A4 also measured

Signal generated with

POWHEG MiNNLO + Pythia8 + Photos; NLO weak + universal HO corrections



(also for e^+e^-)

Electroweak mixing angle with CMS

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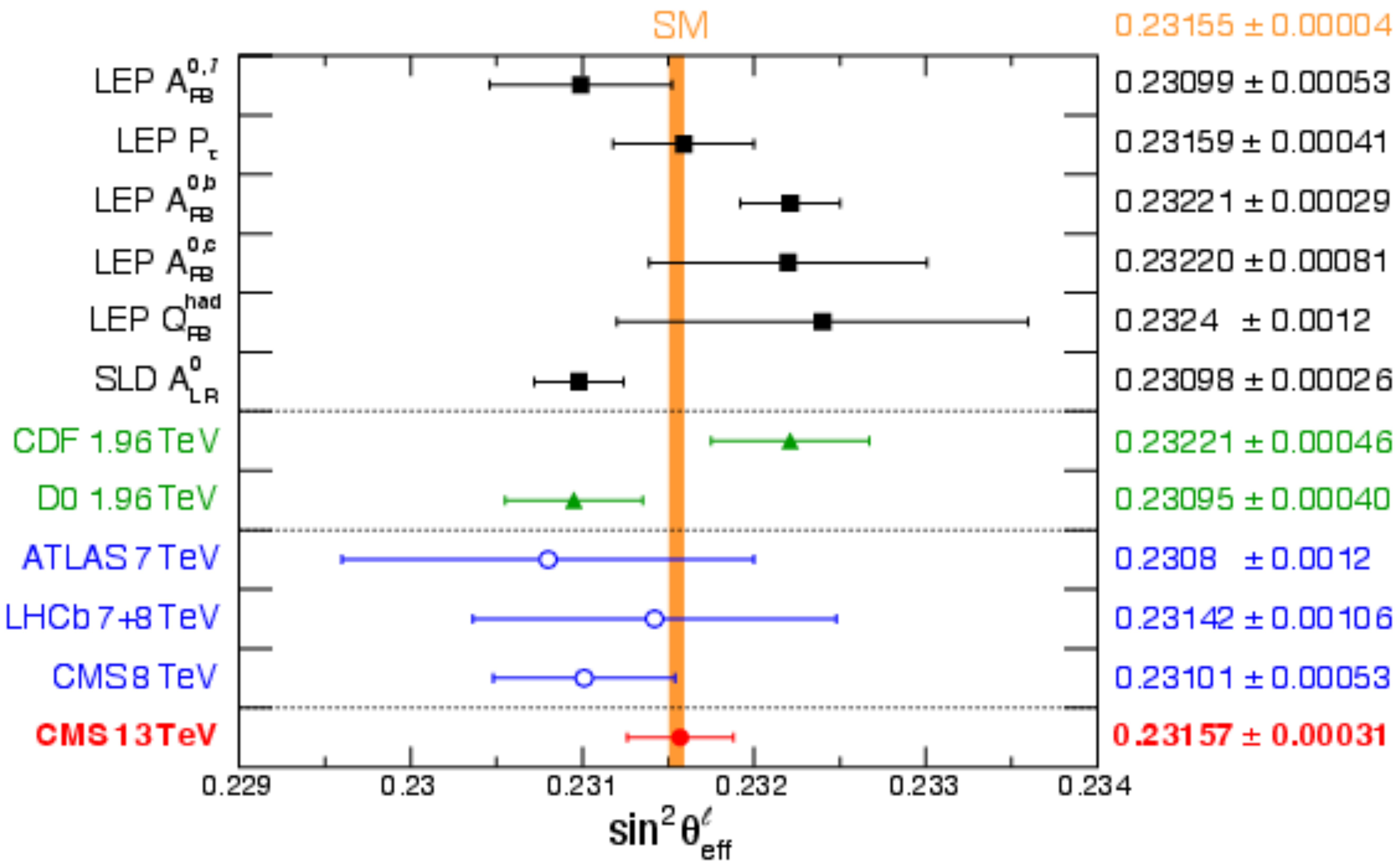
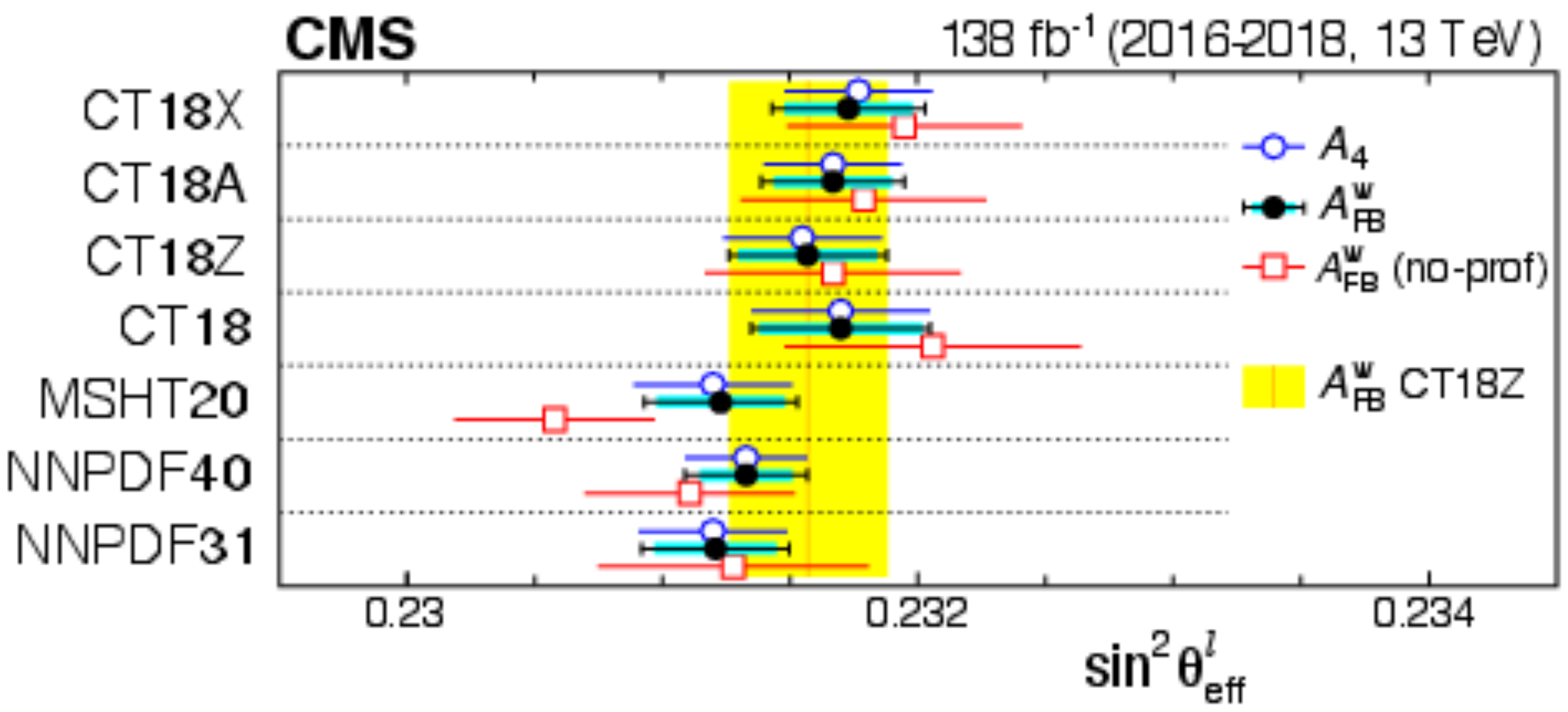




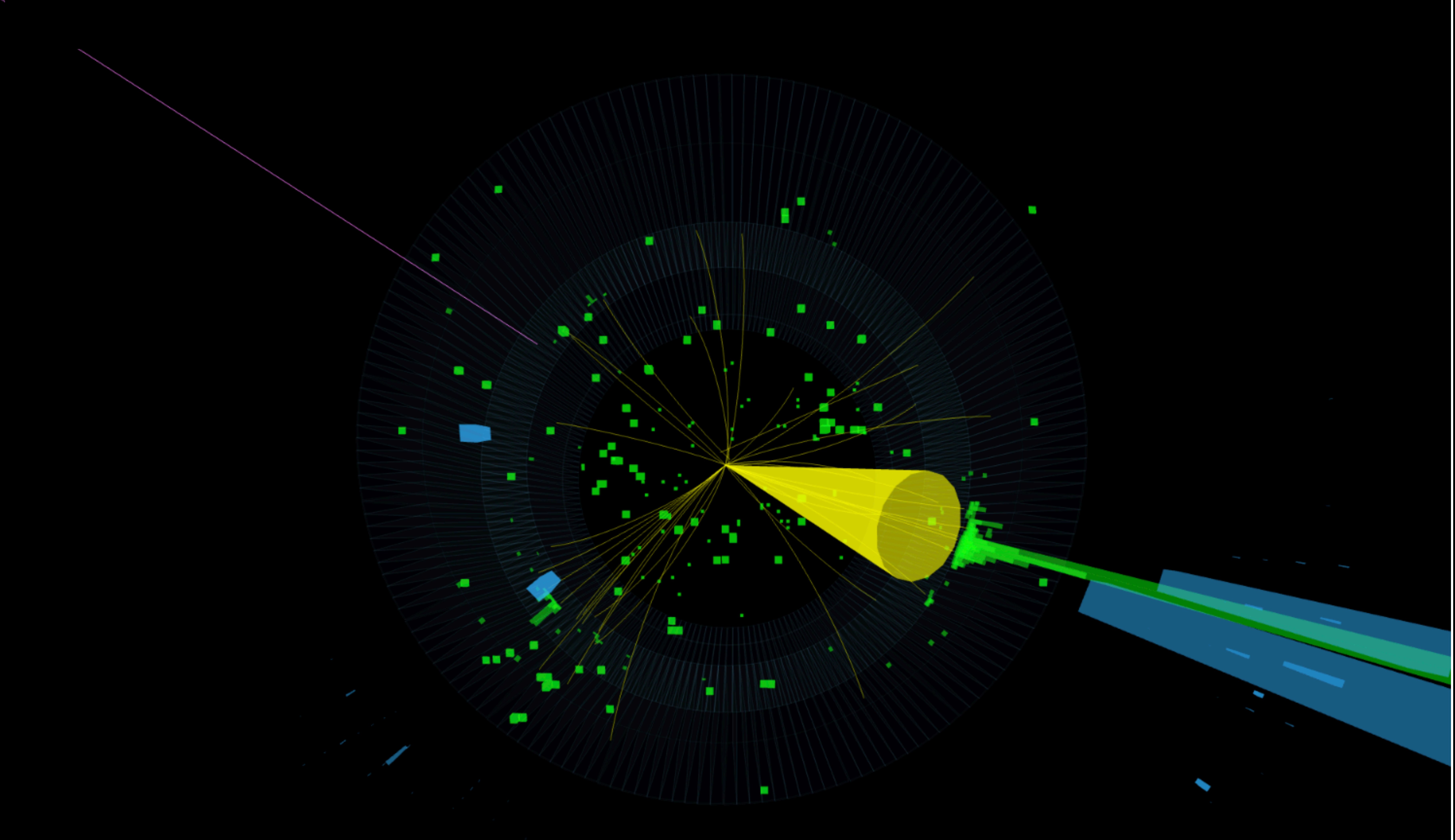
most precise at hadron colliders and comparable to LEP and SLD precision

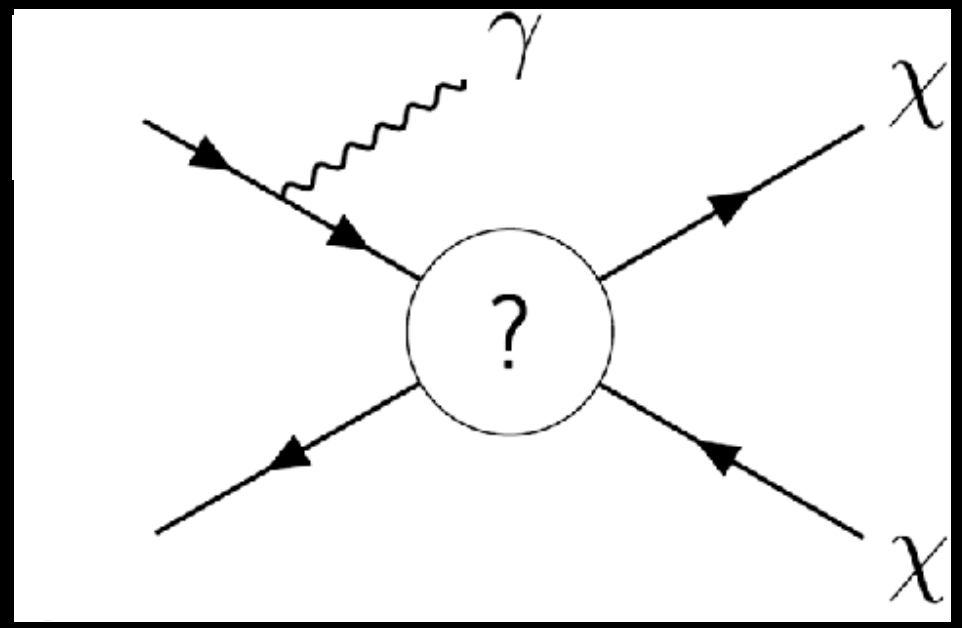
$$\sin^2\theta^\ell_{eff} = 0.23157 \pm 0.00010\ (\text{stat}) \pm 0.00015\ (\text{syst}) \pm 0.00009\ (\text{theo}) \pm 0.00027 (\text{PDF})$$

Measurement of the Z invisible width

CMS: PLB 842 (2023) 137563

ATLAS: Phys. Lett. B 854 (2024) 138705





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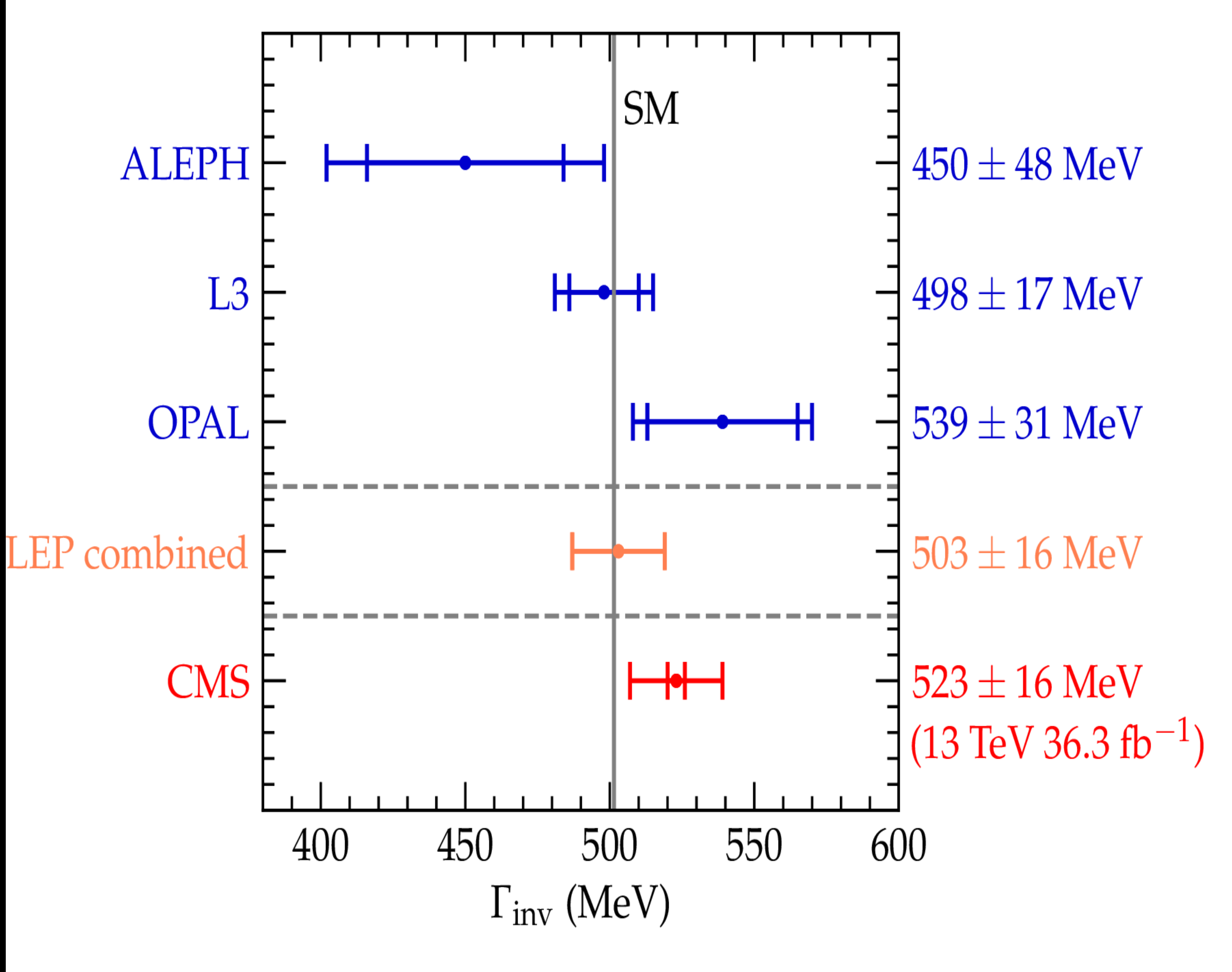
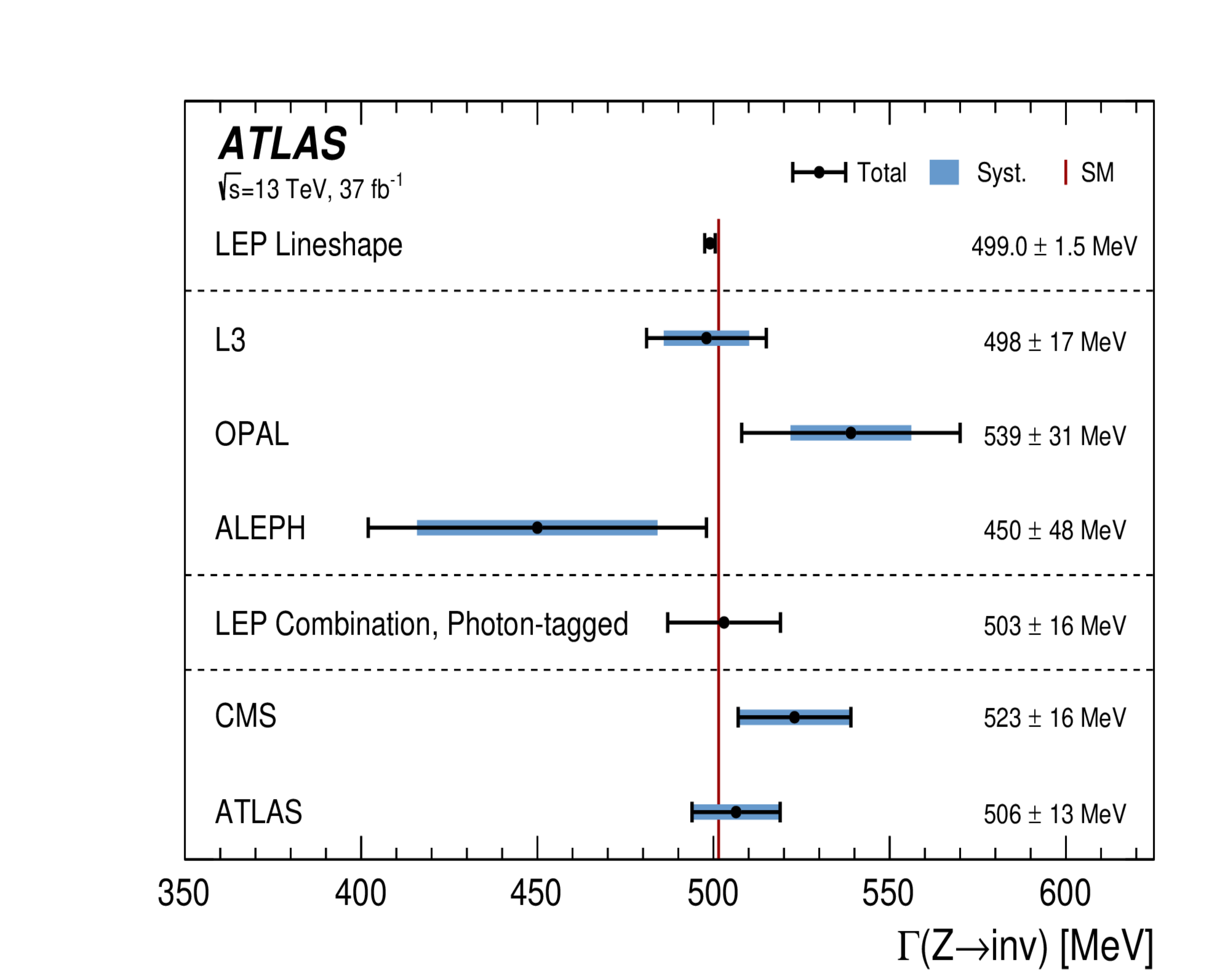
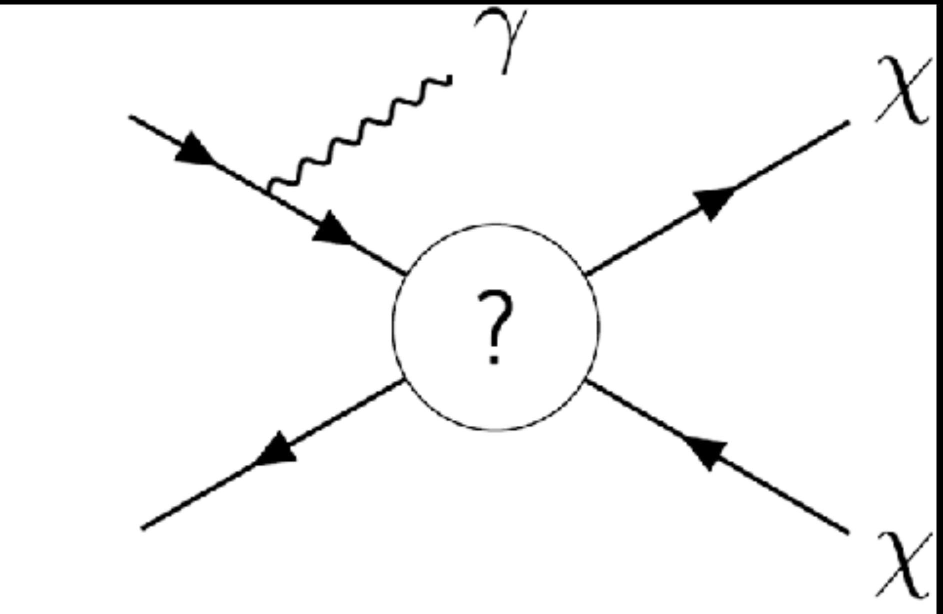






$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

use the *monojet* dark matter strategy as a way to make a precision SM measurement

first measurement of the Z invisible width at any hadronic collider

both ATLAS and CMS reach LEP’s level of precision

Measurement of the Z invisible width

CMS: PLB 842 (2023) 137563

ATLAS: Phys. Lett. B 854 (2024) 138705

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
p_T^{miss} trigger efficiency (jets plus p_T^{miss} region)	0.7
p_T^{miss} trigger efficiency ($Z/\gamma^* \to \mu\mu$ region)	0.6
Boson p_T dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
p_T^{miss} trigger efficiency (μ+jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_T dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2

CMS

Systematic Uncertainty	Impact on $\Gamma(Z \to \text{inv})$ in [MeV]	in [%]
Muon efficiency	7.4	1.5
Renormalisation & factorisation scales	5.9	1.2
Electron efficiency	4.9	1.0
Detector correction	4.4	0.9
QCD multijet	3.2	0.6
E_T^{miss}	2.4	0.5
$Z(\to \mu\mu)$+jets misid. lepton estimate	1.9	0.4
Jet energy resolution	1.6	0.3
$W(\to \ell\nu)$+jets normalisation	1.5	0.3
Pile-up reweighting	1.5	0.3
Non-collision background estimate	1.3	0.3
Jet energy scale	1.3	0.3
γ^*-correction	1.0	0.2
$Z(\to ee)$+jets misid. lepton estimate	1.0	0.2
Luminosity	1.0	0.2
Parton distribution functions + α_s	0.7	0.1
$\Gamma(Z \to \ell\ell)$	0.5	0.1
Tau energy scale	0.4	0.1
Muon momentum scale	0.3	0.1
$W(\to \ell\nu)$+jets misid. lepton estimate	0.3	0.1
(Forward) jet vertex tagging	0.2	< 0.1
Top subtraction scheme	0.2	< 0.1
Electron energy scale	0.1	< 0.1
Systematic	12	2.4
Statistical	2	0.4
Total	13	2.5

ATLAS

Standard Model results with ATLAS and CMS

single boson properties precision measurements

multiboson couplings & polarization

V + jets

ATLAS EXPERIMENT

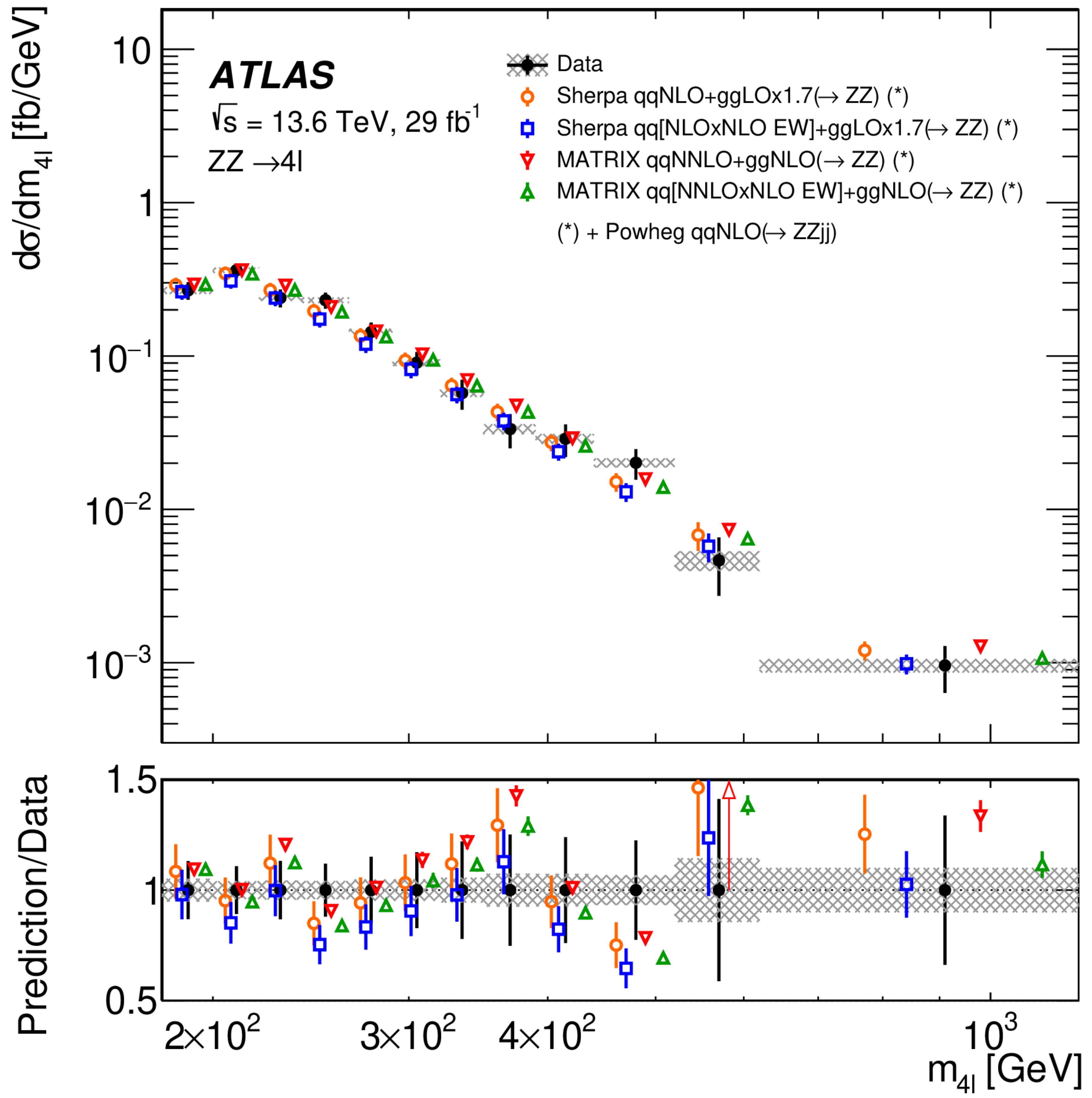
Phys. Lett. B 855 (2024) 138764

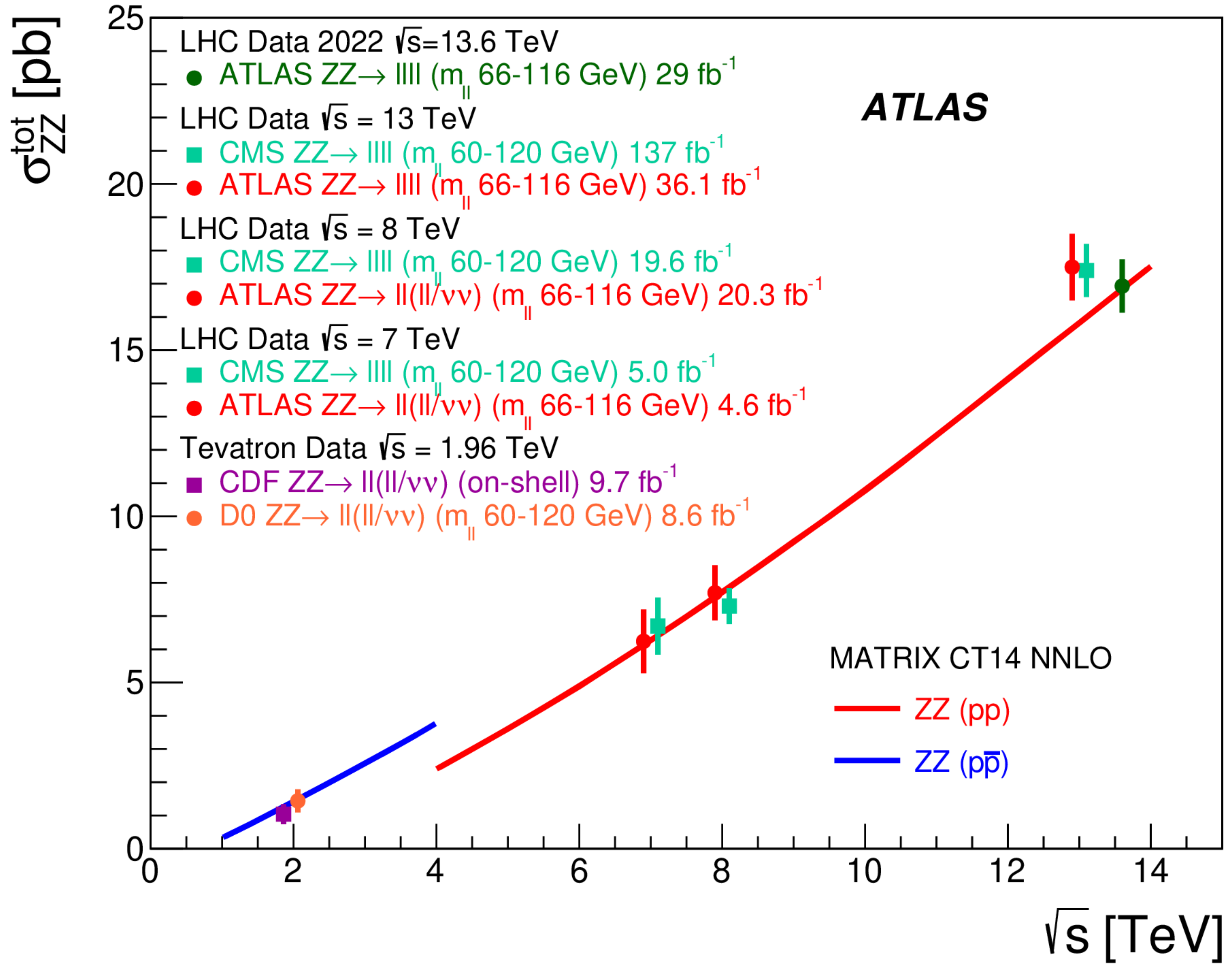
Diboson with ATLAS and CMS at $\sqrt{s} = 13.6$ TeV: ZZ

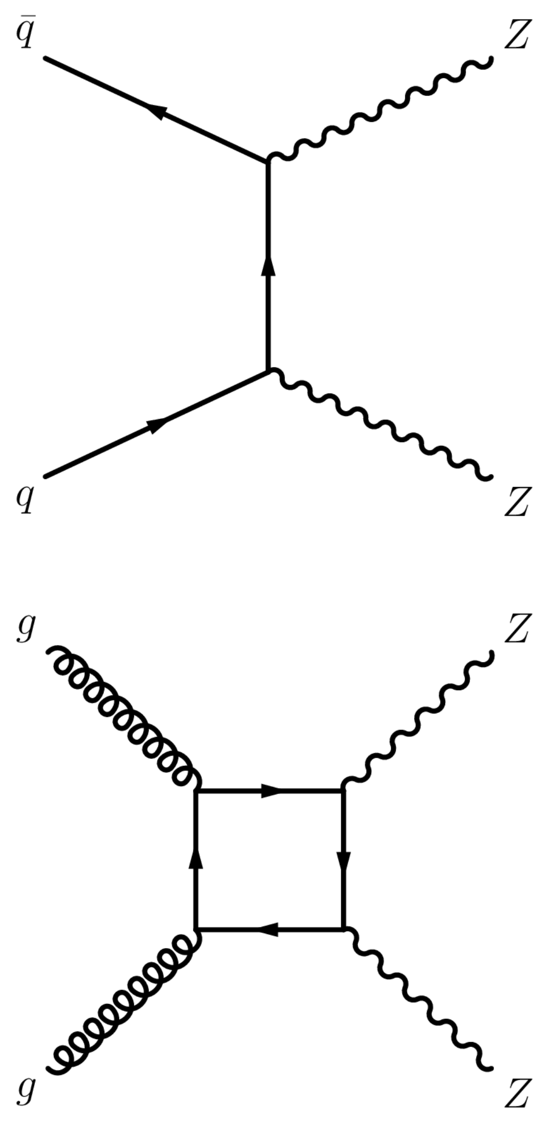
Diboson with ATLAS and CMS at $\sqrt{s}$=13.6 TeV: ZZ

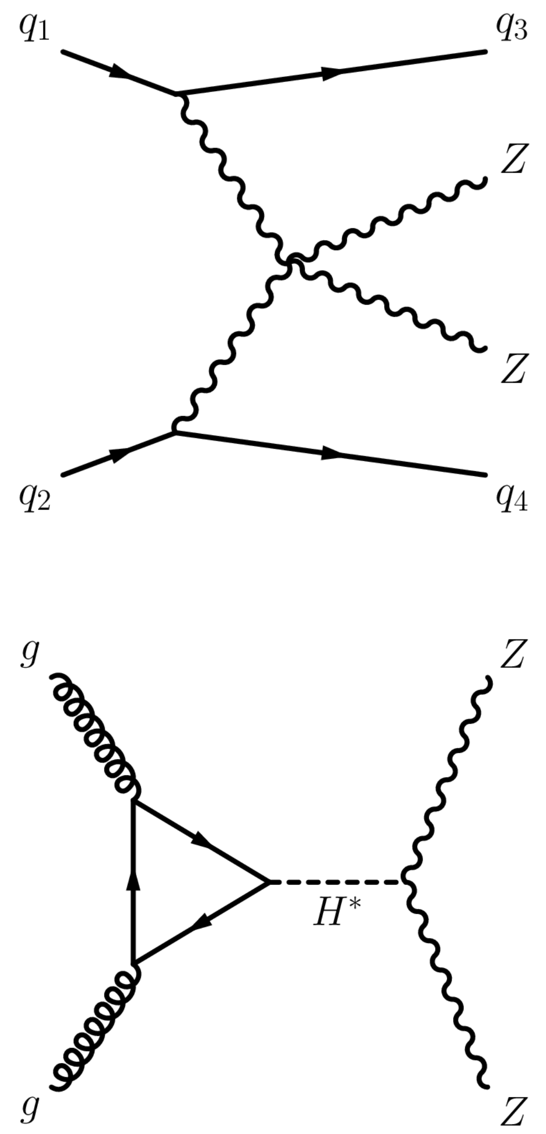
Phys. Lett. B 855 (2024) 138764

$$ZZ \to 4\ell(\ell = \mu, e)$$





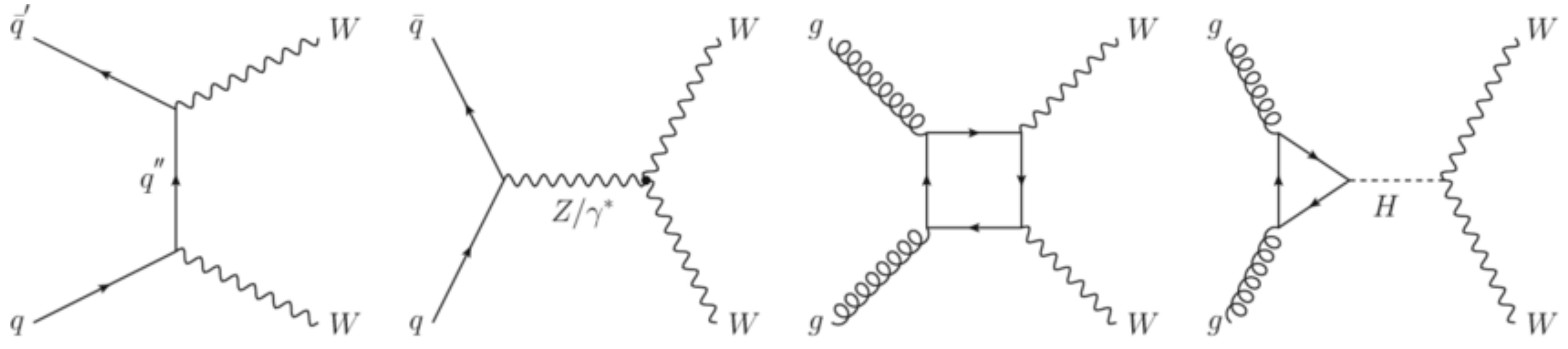




inclusive cross section extrapolated to the total phase space (66<mZ<116) GeV for both Z bosons, yielding (16.8±1.1) pb , accuracy up to NNLO QCD + NLO EW

Diboson with ATLAS and CMS at $\sqrt{s}$=13.6 TeV: WW

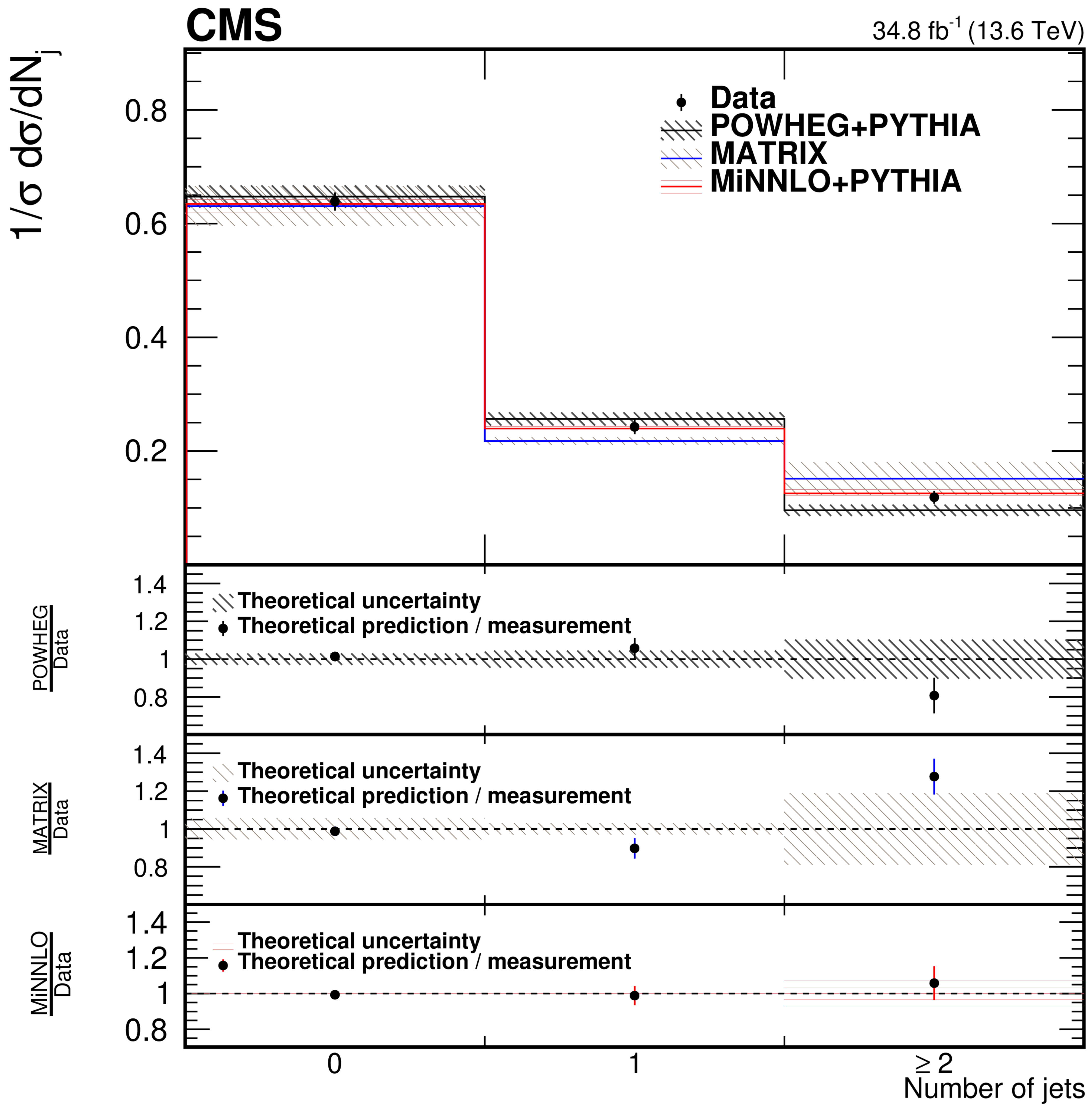
PLB 855 (2024) 138764



Observable	Requirement
Lepton origin	Direct decay of a W boson
Lepton definition	Dressed-leptons ($e^{\pm}\mu^{\mp}$)
Leading lepton p_T	$p_T^{\ell\,\max} > 25\,\mathrm{GeV}$
Trailing lepton p_T	$p_T^{\ell\,\min} > 20\,\mathrm{GeV}$
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m_{\ell\ell} > 85\,\mathrm{GeV}$
Jet p_T	$p_T^{j} > 30\,\mathrm{GeV}$
$\lvert\eta\rvert$ of jets	$\lvert\eta^{j}\rvert < 2.5$
Jet-lepton removal	$\Delta R(j,\ell) > 0.4$

fiducial phase space

Inclusive and normalized xsec measurement



σ^{obs} = 125.7 ± 2.3(*stat*) ± 4.8(*syst*) ± 1.8(*lumi*) pb

σ^{exp} = 125.8 ± 3.7 pb (QCD NNLO and EW NLO from MATRIX)

Diboson with ATLAS and CMS at $\sqrt{s}$=13.6 TeV: WZ

CMS-PAS-SMP-24-005

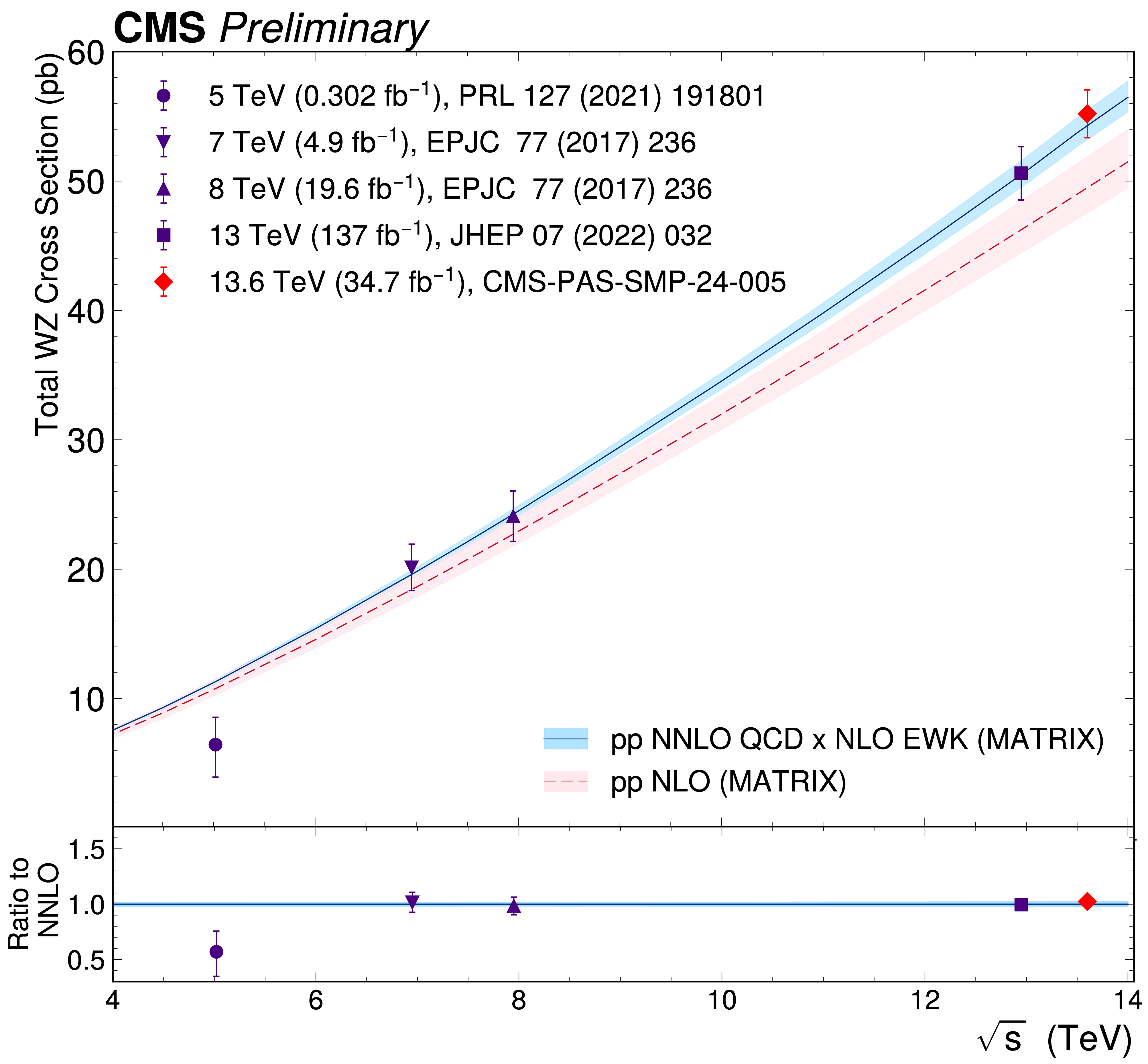
final states $eee, ee\mu, \mu\mu e, \mu\mu\mu$

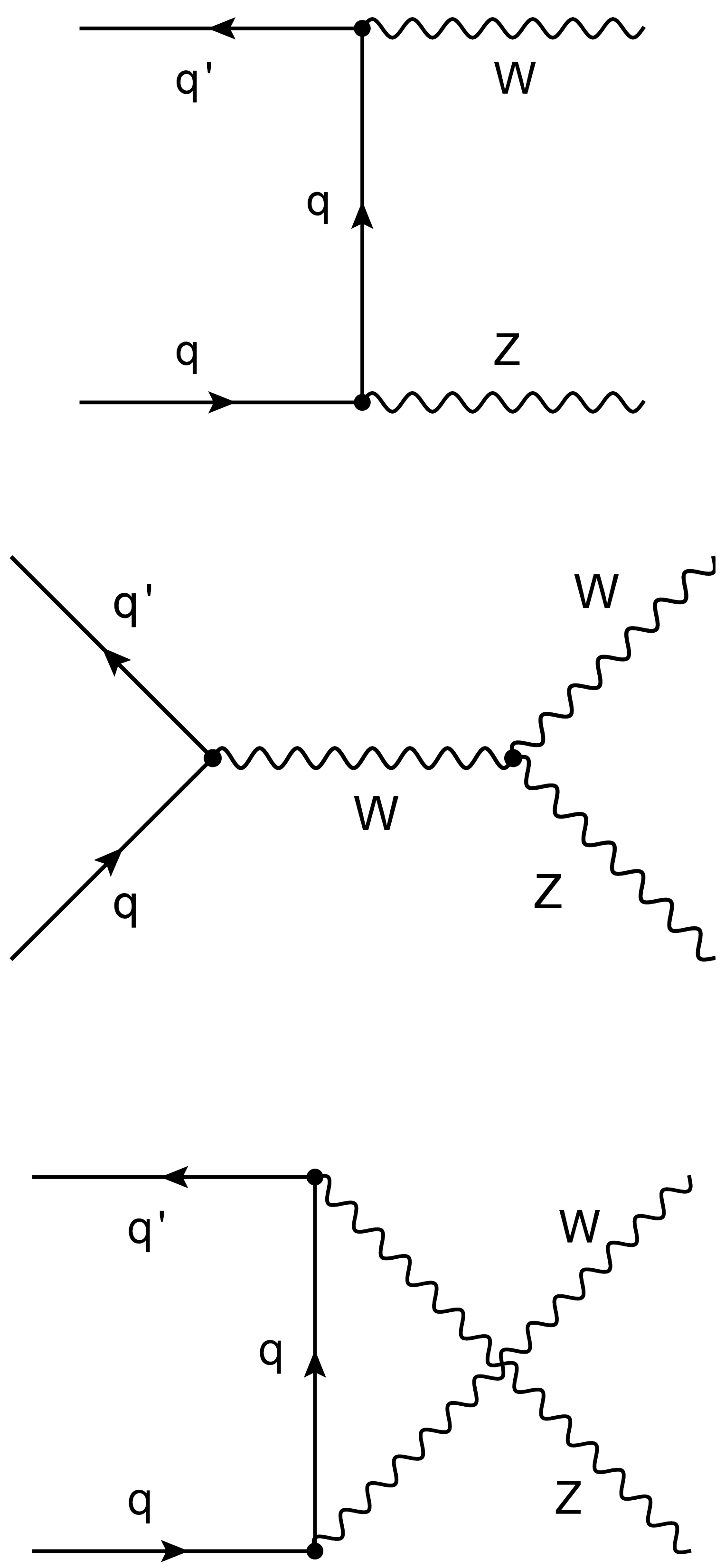
prompt lepton discrimination strategy

accuracy @ NNLO QCD X NLO EWK

Source	Inclusive	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Integrated luminosity	1.5	1.5	1.4	1.4	1.5
Trigger efficiencies	0.5	1.0	1.0	1.0	0.7
b tagging	0.1	0.1	0.1	0.1	0.1
Pileup	0.4	0.6	0.8	0.2	0.4
Jet energy scales	0.9	1.3	0.7	1.1	0.7
Electron ID efficiencies	0.7	3.6	2.4	1.1	-
Electron reconstruction	1.2	4.0	2.9	1.1	-
Electron energy scale	0.1	0.1	0.1	0.0	-
Muon efficiencies	0.7	-	0.3	0.8	1.2
Nonprompt normalization	0.7	1.6	0.5	0.7	0.7
VVV normalization	0.4	0.4	0.4	0.4	0.4
tZq normalization	0.1	0.1	0.1	0.1	0.1
ZZ normalization	0.3	0.8	0.7	0.5	0.5
$t\bar{t}$Z normalization	0.3	0.7	0.6	0.4	0.5
X + γ normalization	0.2	0.7	0.3	0.4	0.2
VH normalization	0.2	0.2	0.2	0.1	0.2
ISR/FSR	0.3	0.5	0.2	0.4	0.3
WZ theo (μ_R, μ_F, PDF)	0.2	0.2	0.2	0.2	0.2
MC statistical	0.5	1.9	0.9	1.0	0.9
Statistical	2.0	5.3	4.6	3.8	3.3
Total	3.3	8.4	6.4	5.0	4.2

precision compatible with previous measurements





WZ production cross section phase space mZ within 30 GeV:

$$\sigma_{total}(pp \rightarrow WZ) = 55.2 \pm 1.2(stat) \pm 1.2(syst) \pm 0.8(lumi) \pm 0.1(theo)pb$$

$Z\gamma$ invisible and triple gauge coupling

CMS-PAS-SMP-22-009

strategy

Exactly 1 high-p_T (>225 GeV) photon + MET

BDT algorithm to identify high-p_T photons (92% efficiency)

True photons bkg:

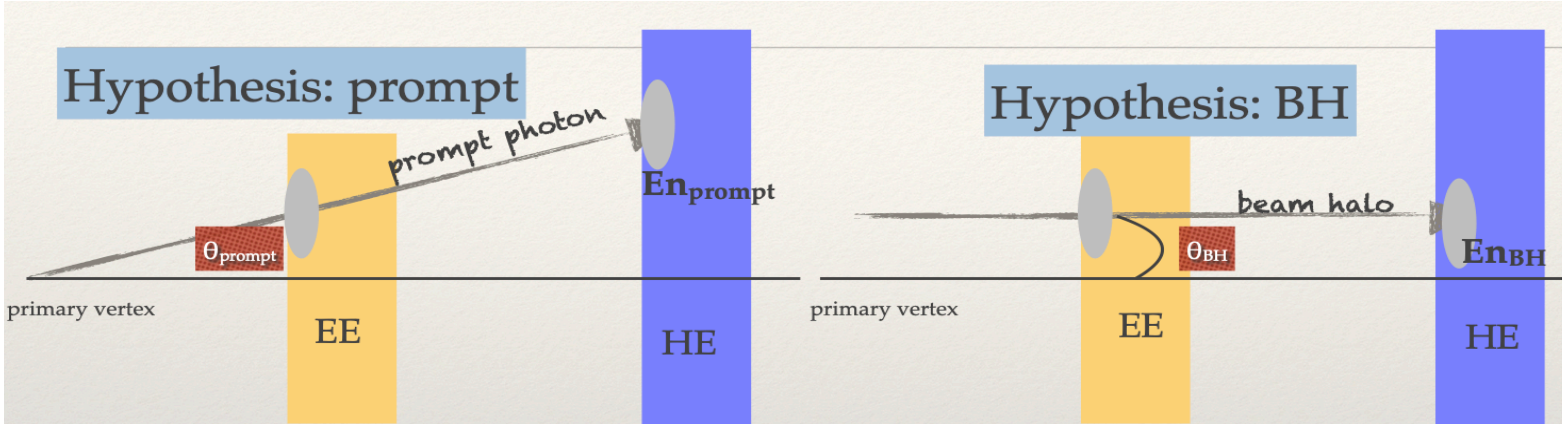
- γ+jets, VV (from MC), W(→lν)γ (from CR in data)

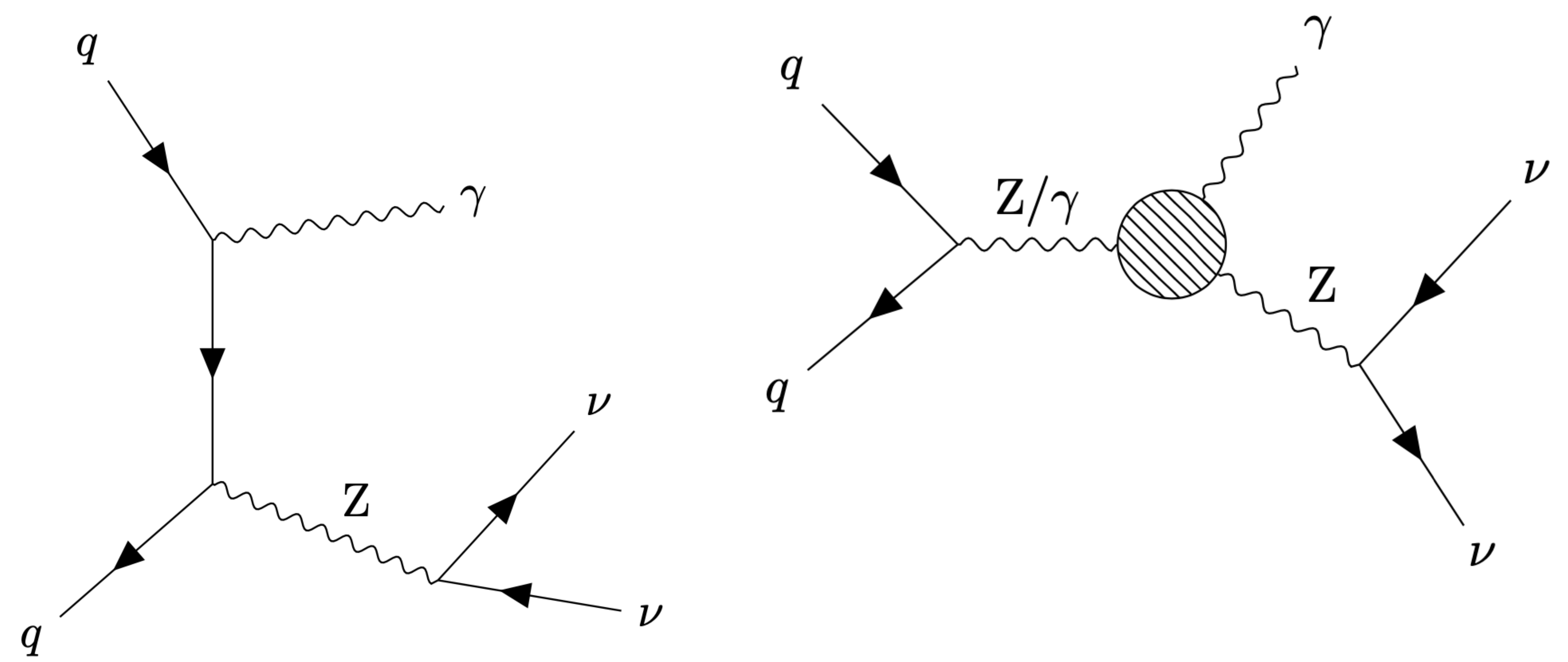
Fake photons bkg:

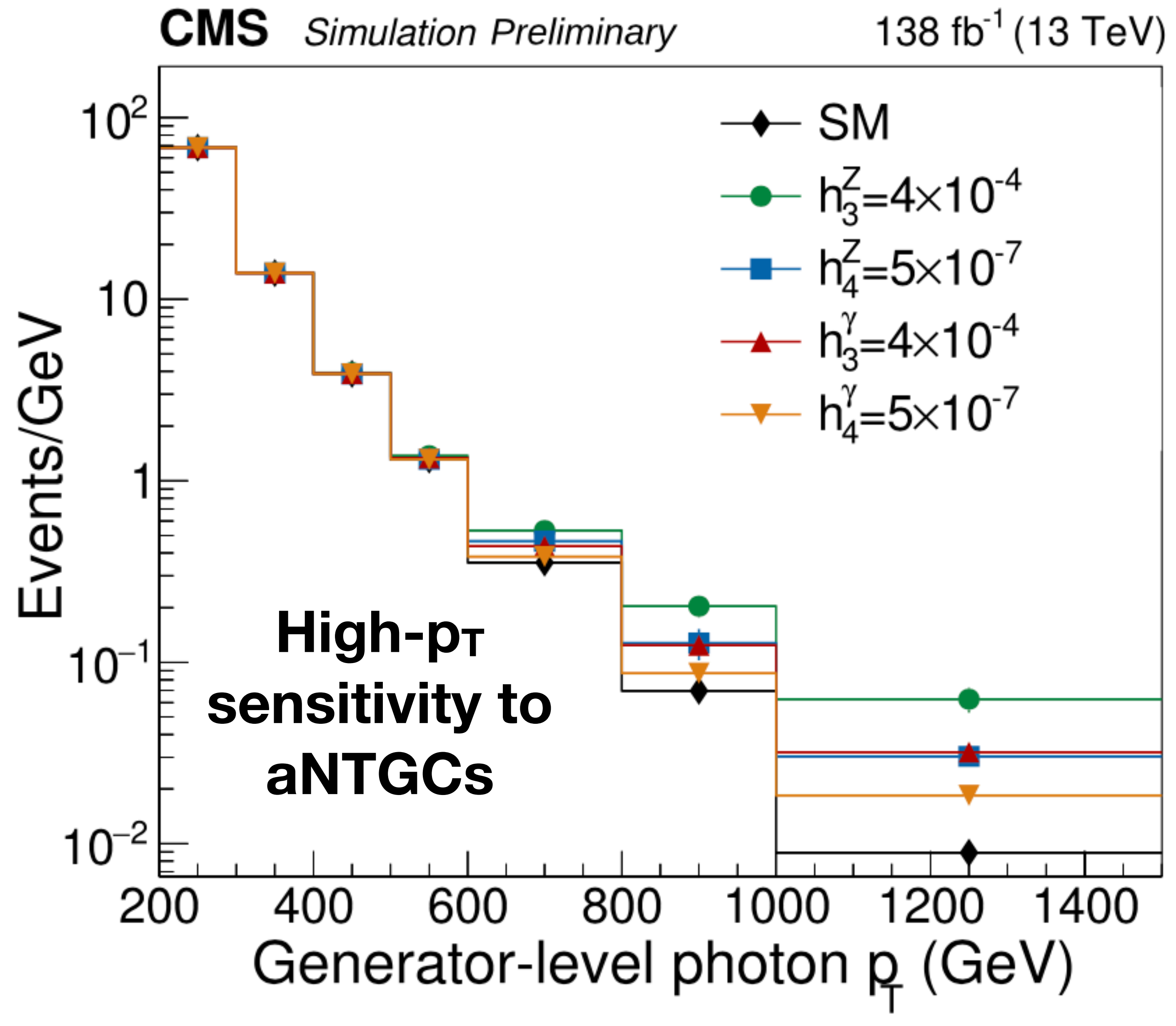
- e→γ, jet→γ (data-driven)
- Particles interacting with ECAL barrel's APDs (data-driven)
- Beam Halo in ECAL endcaps (data-driven)

New BH tagger built using energy deposits

Forward (1.6 < |η| < 2.5) photons included in the analysis for the first time

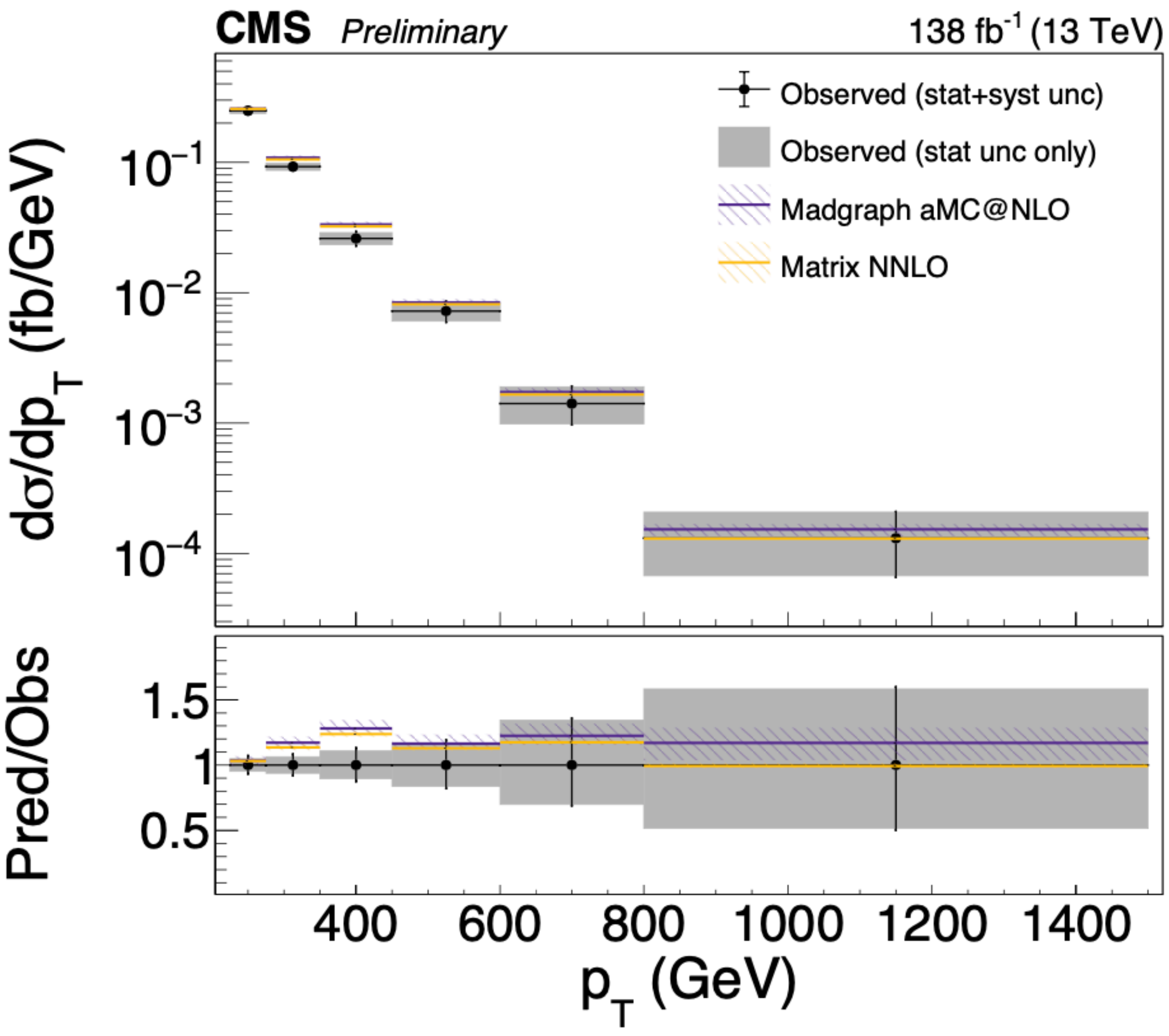




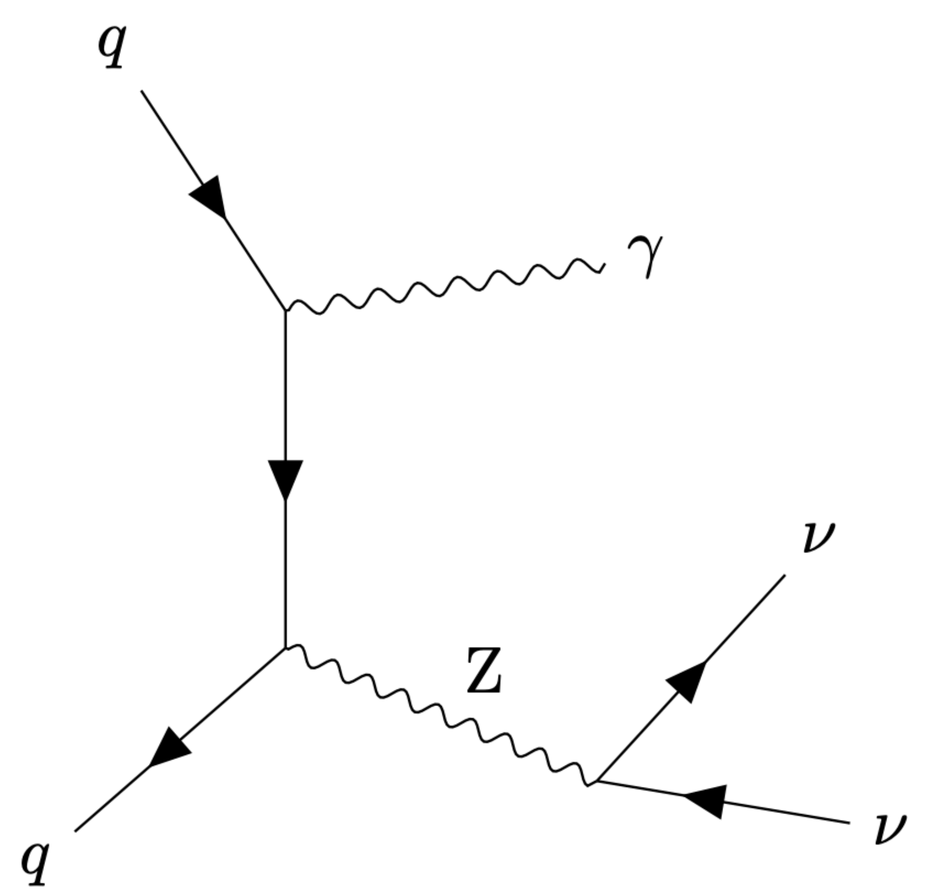


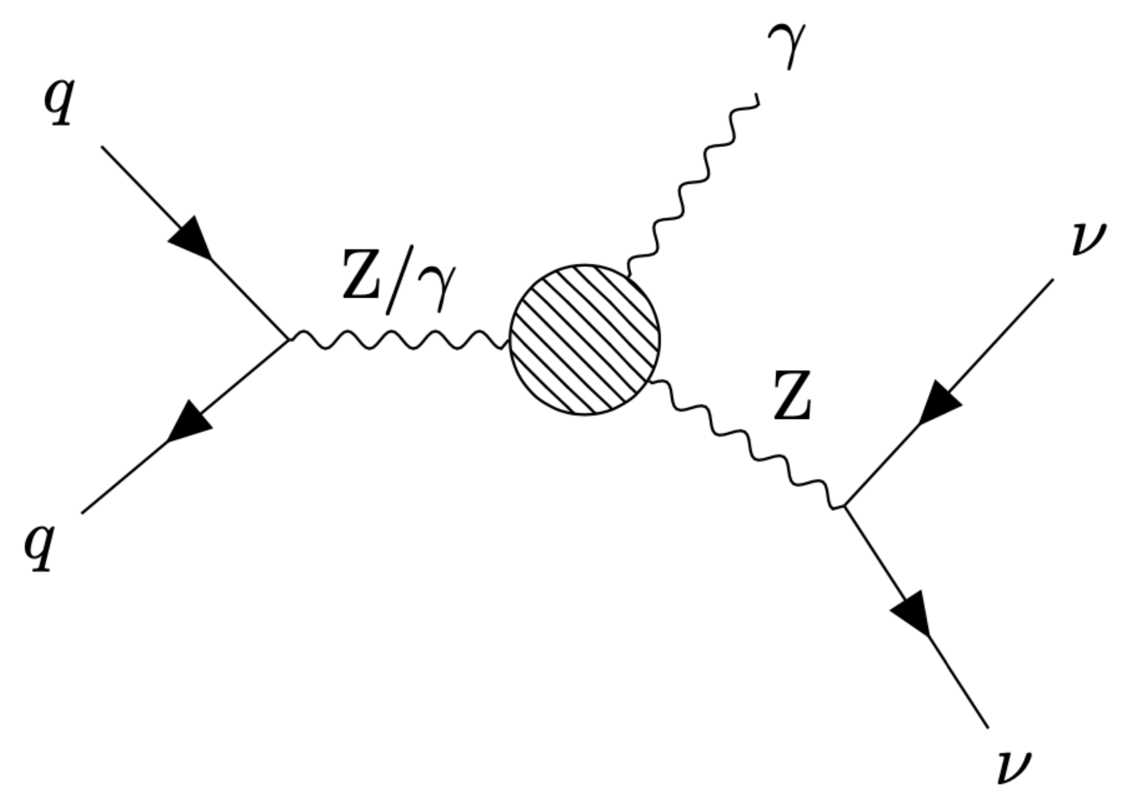
$Z\gamma$ invisible and triple gauge coupling

CMS-PAS-SMP-22-009



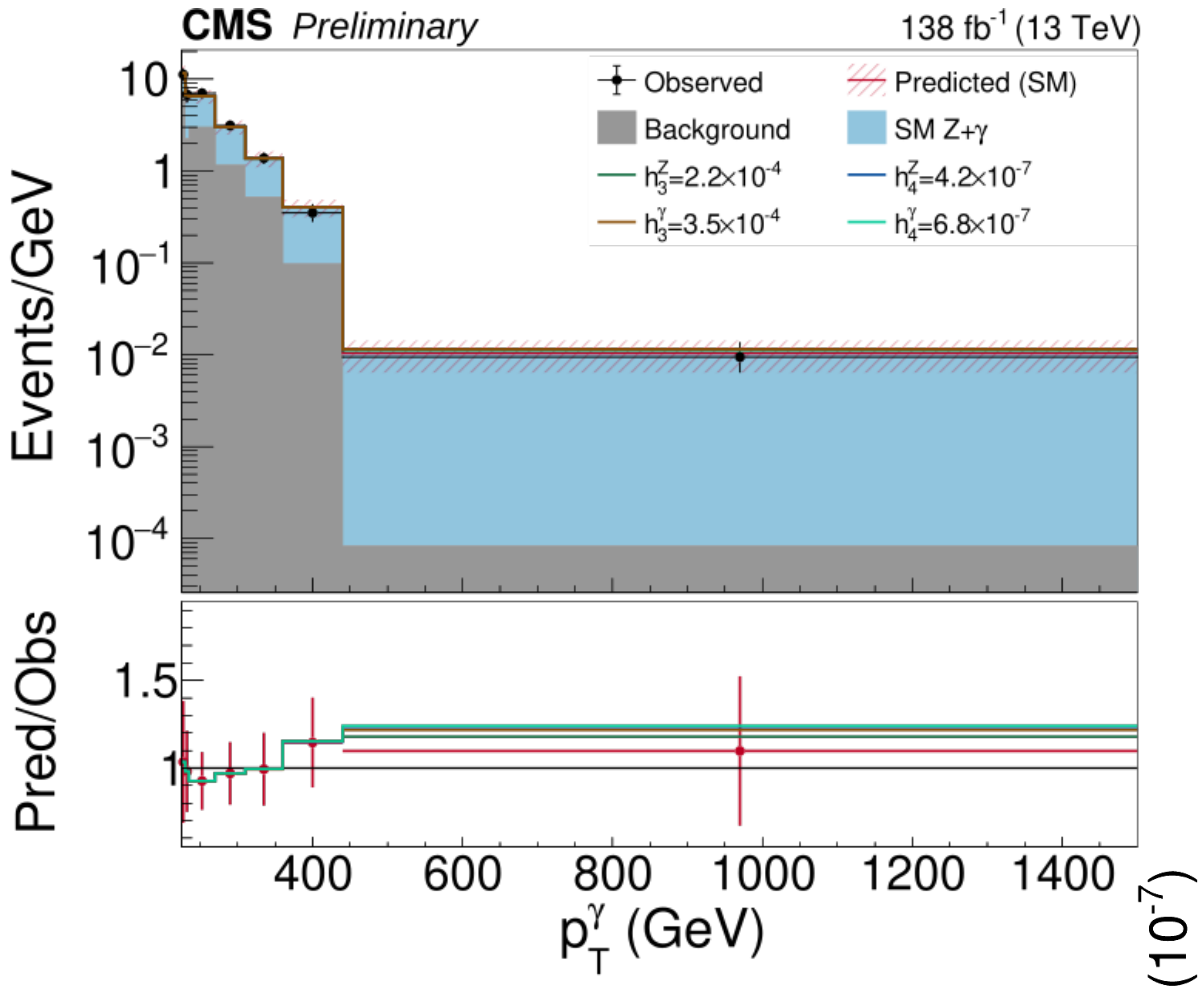
Region	Measured	NLO (Madgraph5)	NNLO (MATRIX)
Barrel $\lvert\eta\rvert < 1.4442$	$16.74^{+1.05}_{-0.99}$	$19.61^{+0.73}_{-0.69}$	$19.33^{+0.27}_{-0.33}$
Endcaps $1.4442 < \lvert\eta\rvert < 2.5$	$7.84^{+0.76}_{-0.70}$	$6.45^{+0.27}_{-0.31}$	$6.21^{+0.07}_{-0.09}$
Combination of barrel and endcaps	$23.32^{+1.40}_{-1.32}$	$26.07^{+0.96}_{-0.97}$	$25.45^{+0.41}_{-0.33}$





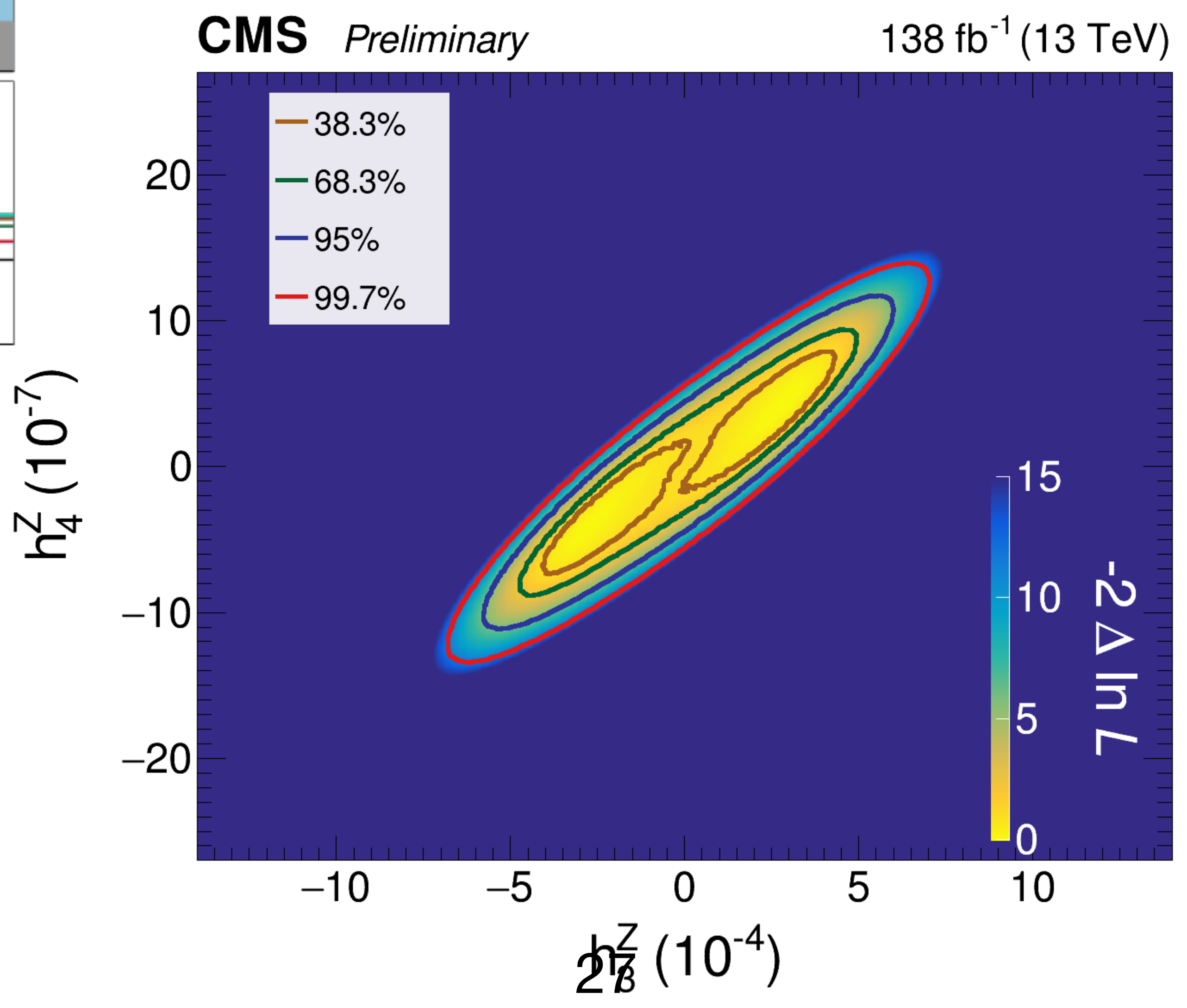
$Z\gamma$ invisible and triple gauge coupling

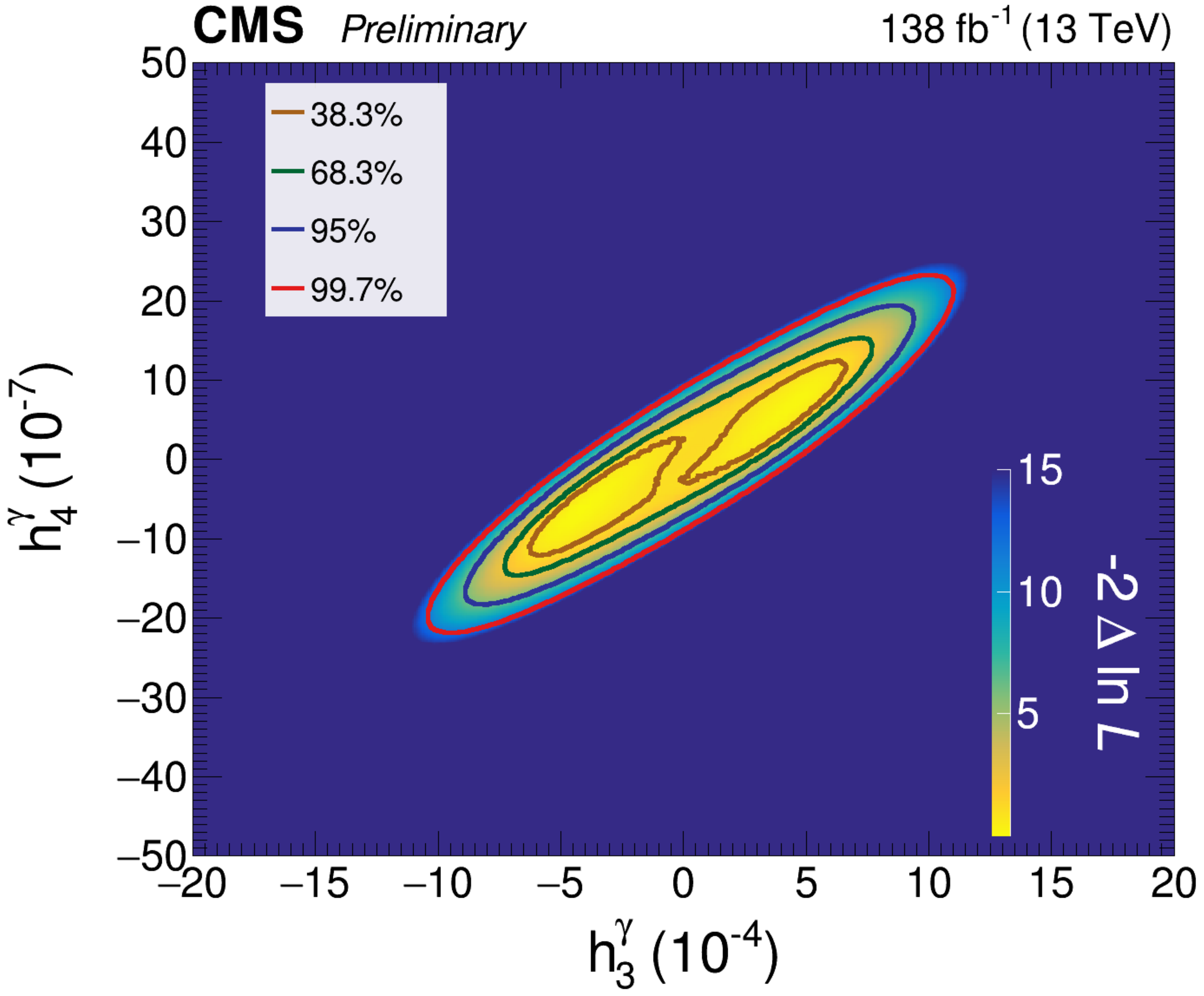
CMS-PAS-SMP-22-009



$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,\ q_2,\ p) = \frac{-e(p^2-m_V^2)}{m_Z^2}\left\{h_1^V\left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2}p^\alpha\left[(pq_2)g^{\mu\beta} - q_2^\mu p^\beta\right] + \right.$$
$$\left. - h_3^V \epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}p^\alpha\epsilon^{\mu\beta\rho\sigma}p_\rho q_{2\sigma}\right\},$$

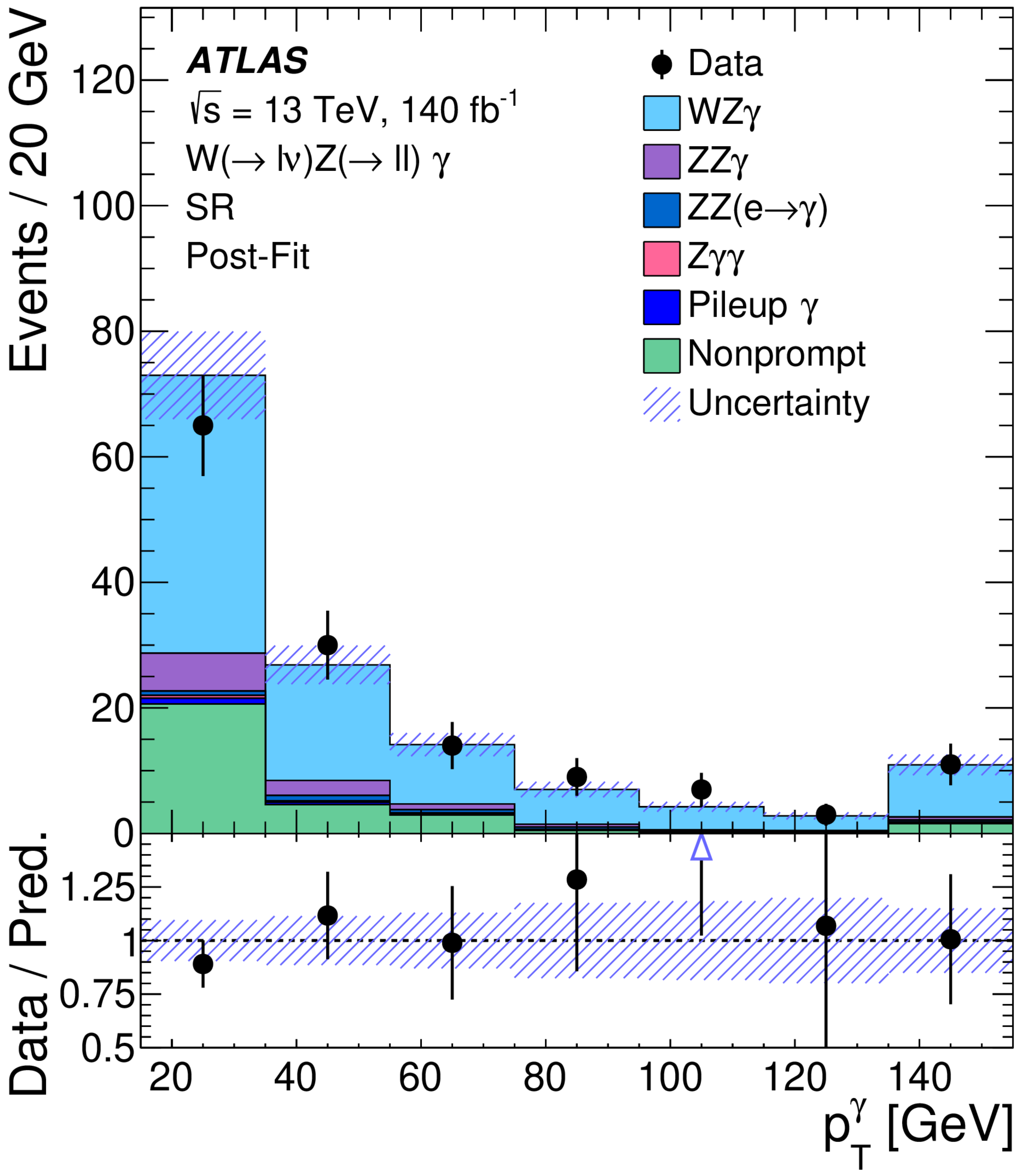
Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)



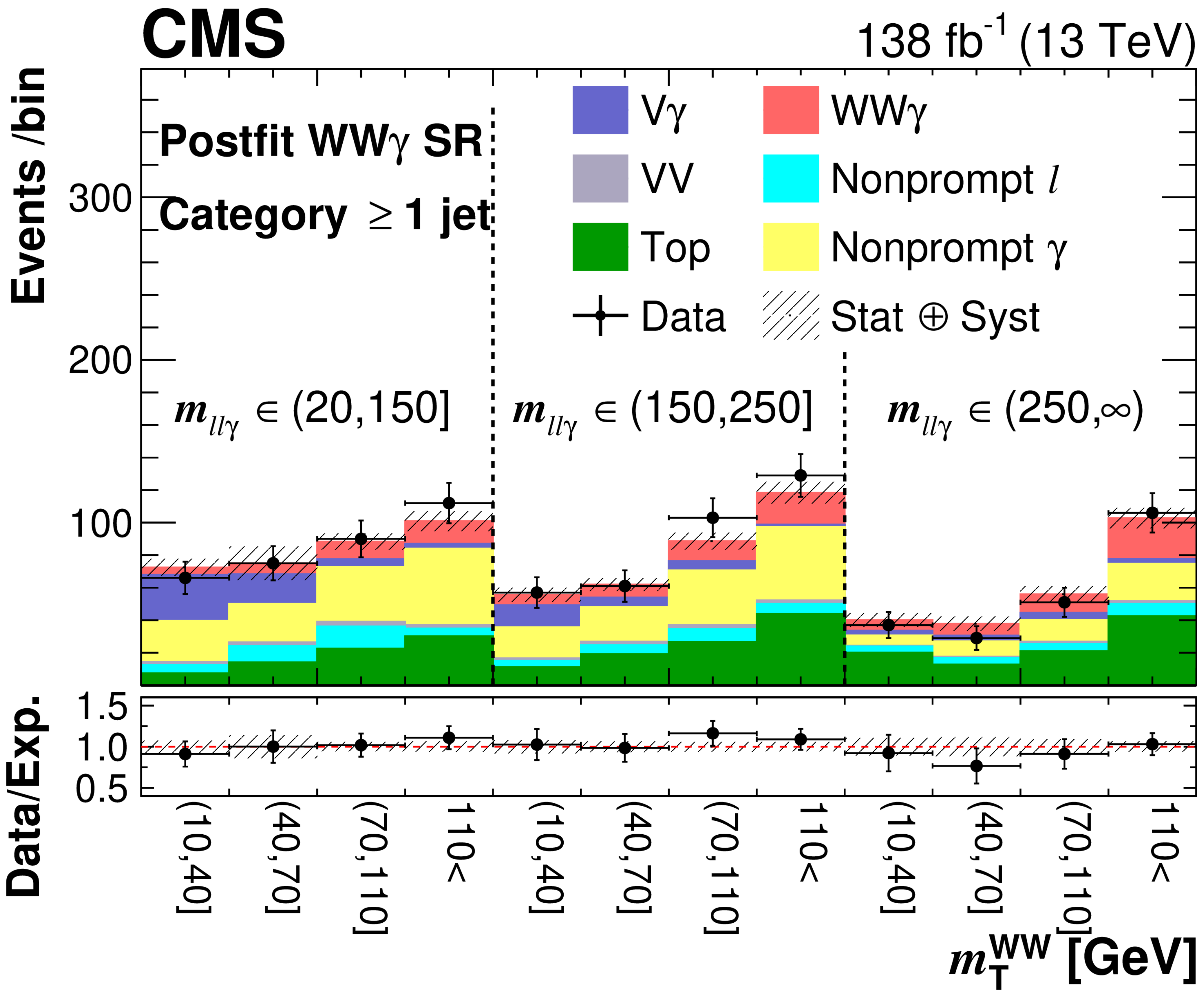


Observation of WZγ and WWγ

PRL132 (2024) 021802
PRL132 (2024) 121901



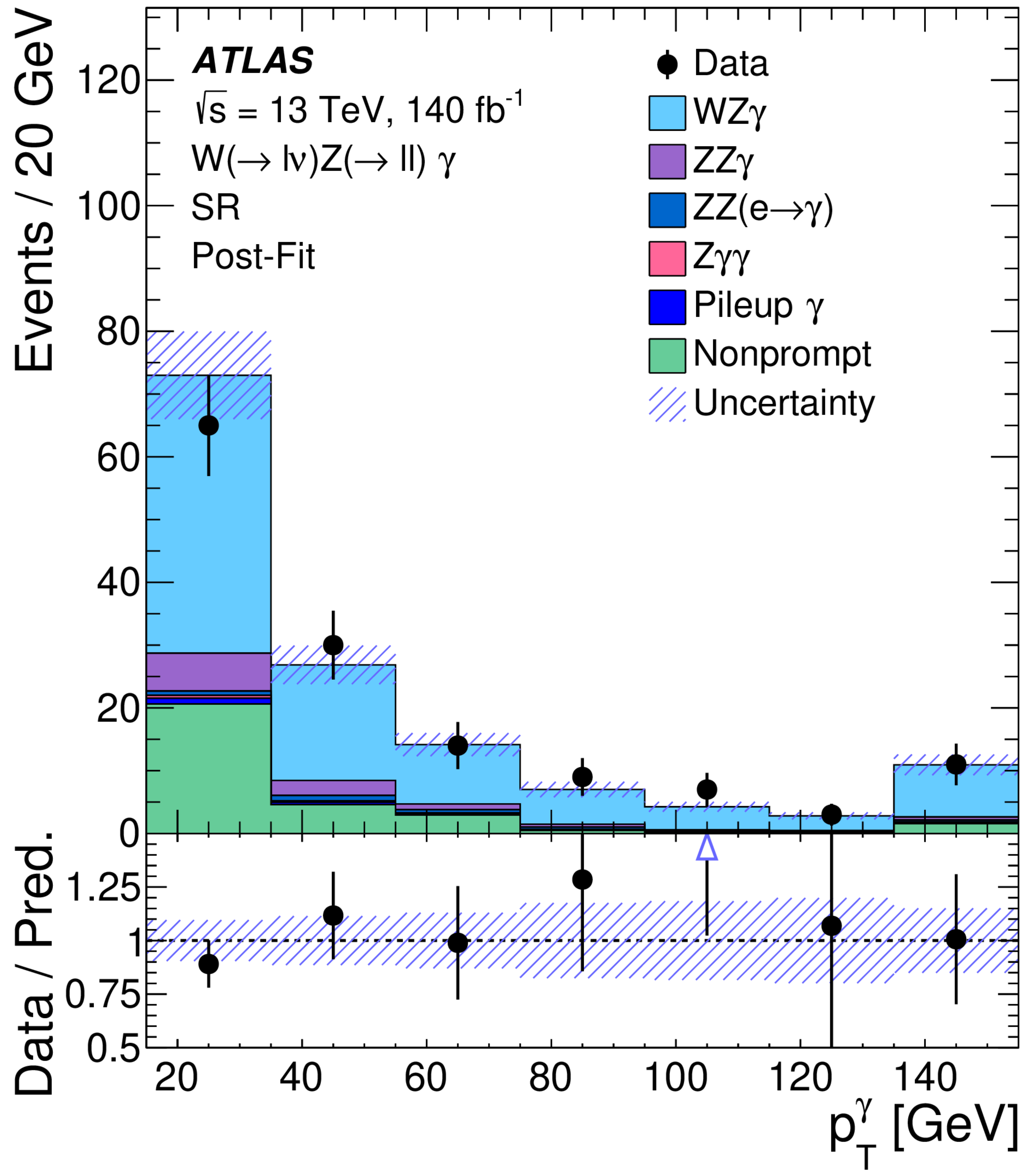
6.3 (5.0)σ obs.(exp.)

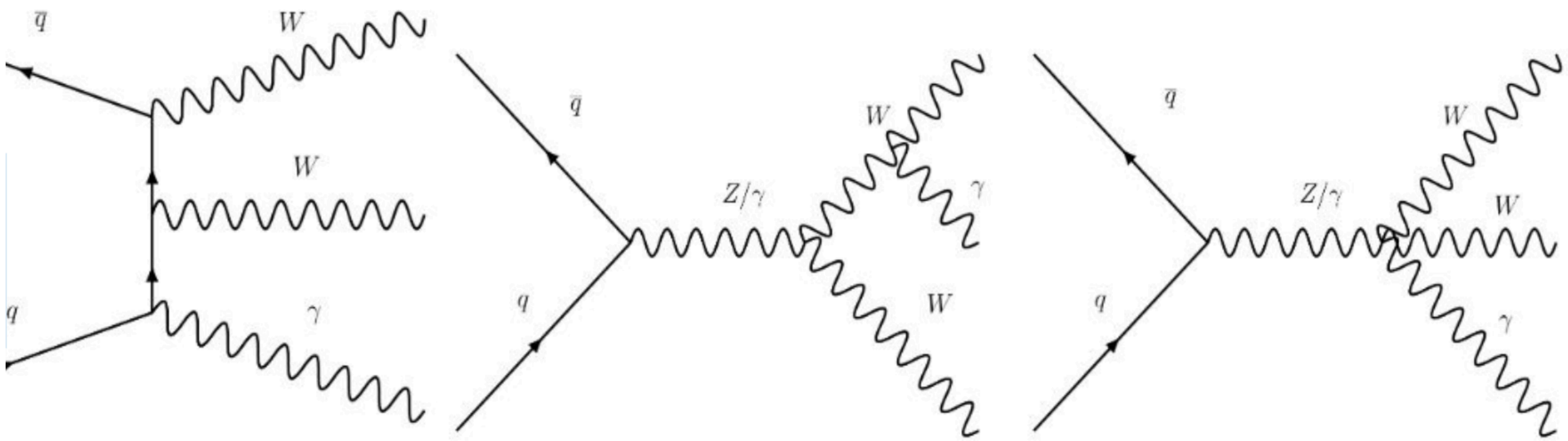


5.6 (4.7)σ obs.(exp.)

Observation of WZγ and WWγ

PRL132 (2024) 021802
PRL132 (2024) 121901





Process	SR	ZZγ CR	ZZ(e → γ) CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e\to\gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33

$$\sigma_{WZ\gamma} = 2.01 \pm 0.30\ (\text{stat.}) \pm 0.16\ (\text{syst.})\ \text{fb}.$$

Standard Model results with ATLAS and CMS

single boson properties precision measurements

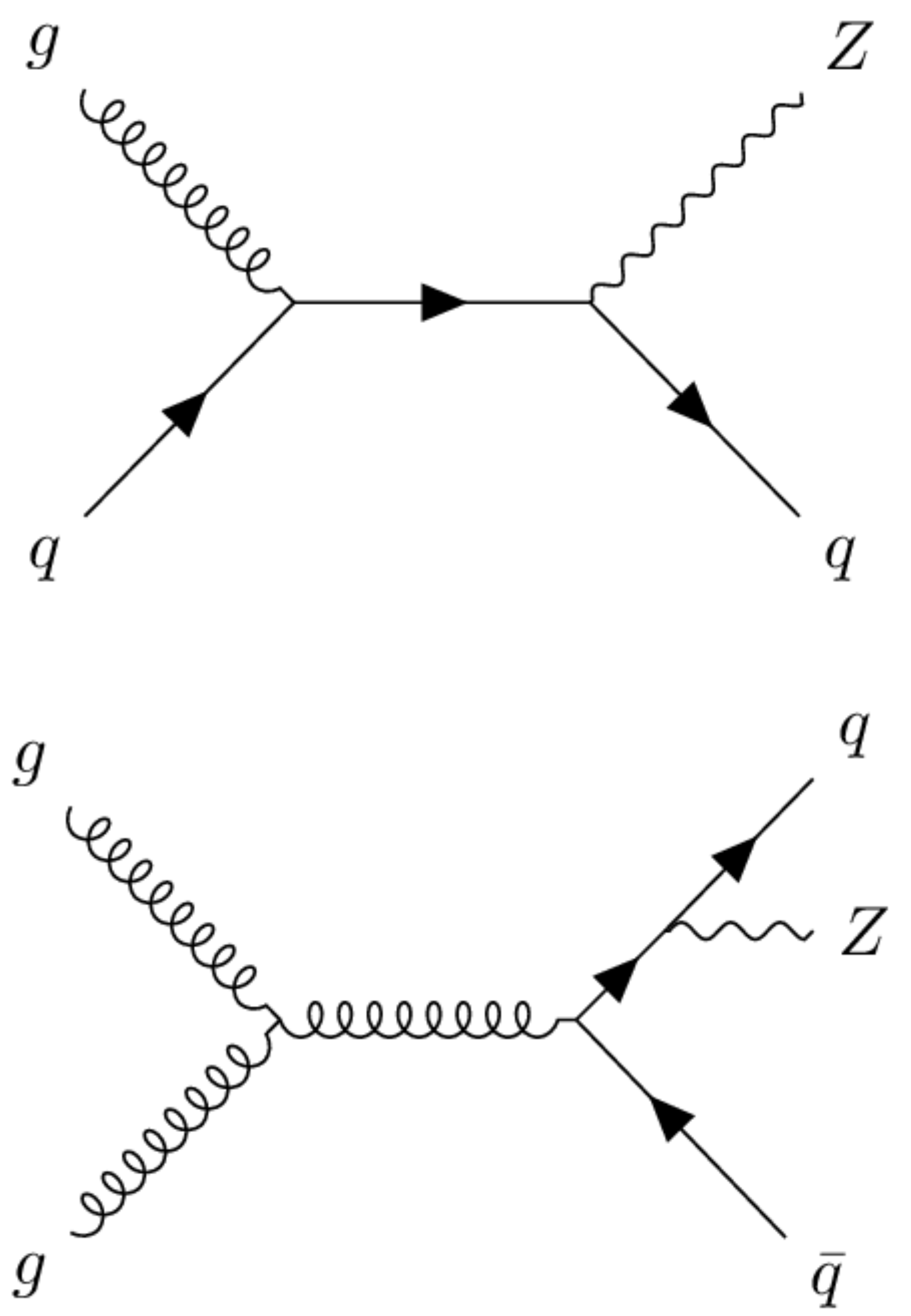
multiboson couplings & polarization

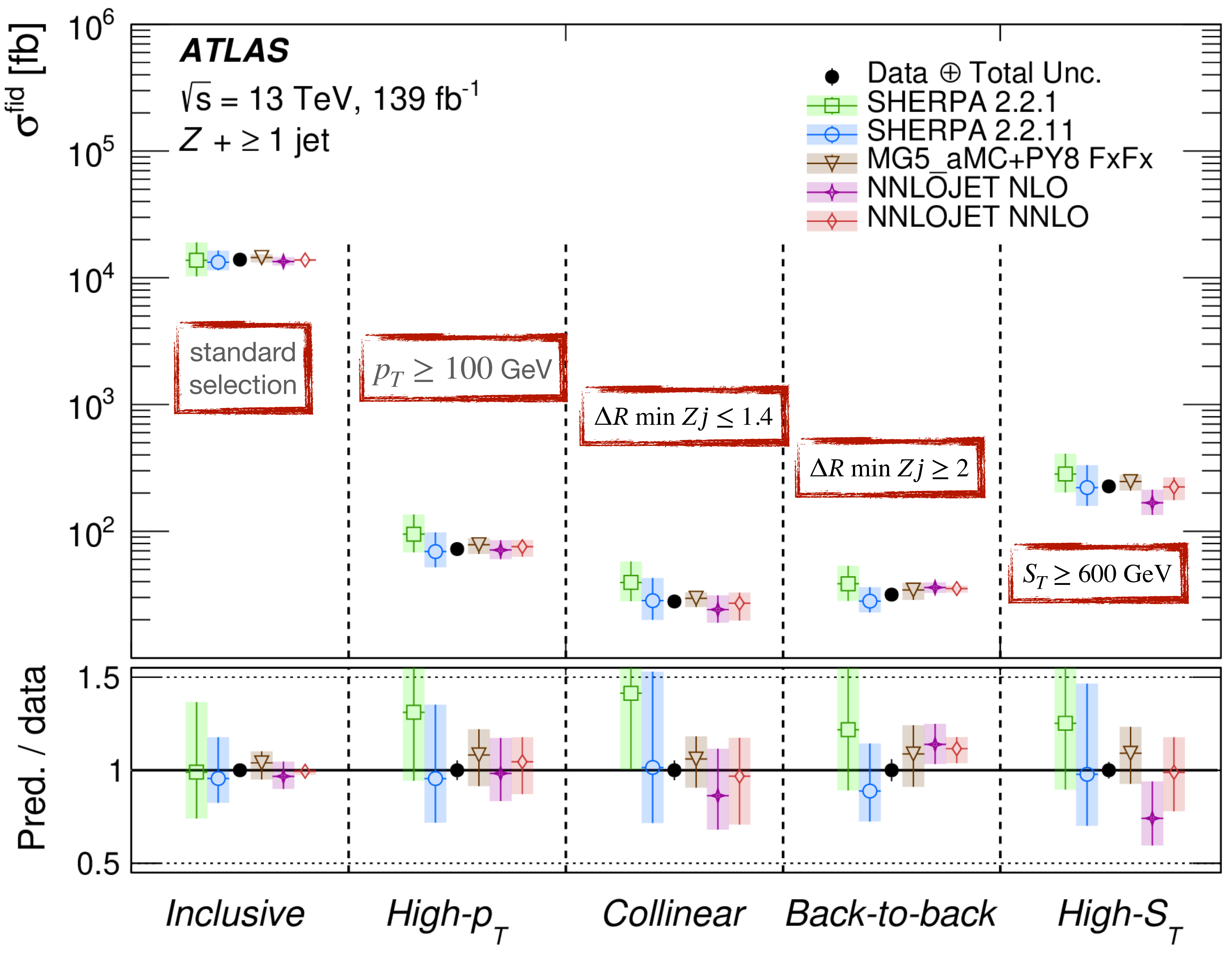
V + jets

Z+jets event topology with ATLAS

μμ/ee (25GeV) + jets: $Z + \geq 1$ antik_T04 jet $p_T \geq 100$ GeV |y|<2.5

Z boson is balanced against a single high-pT jet



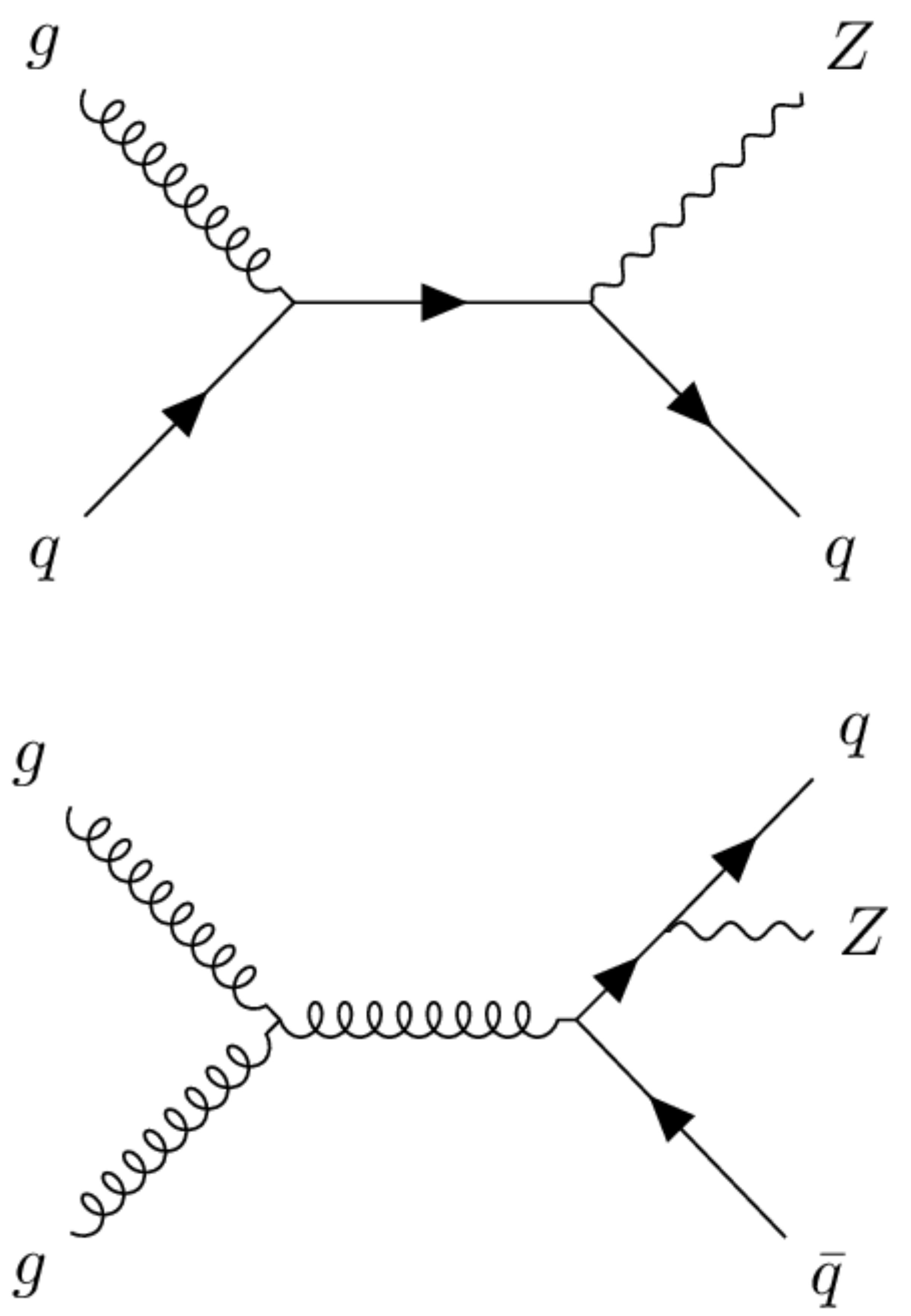


Z+1jets Z+2jets searches

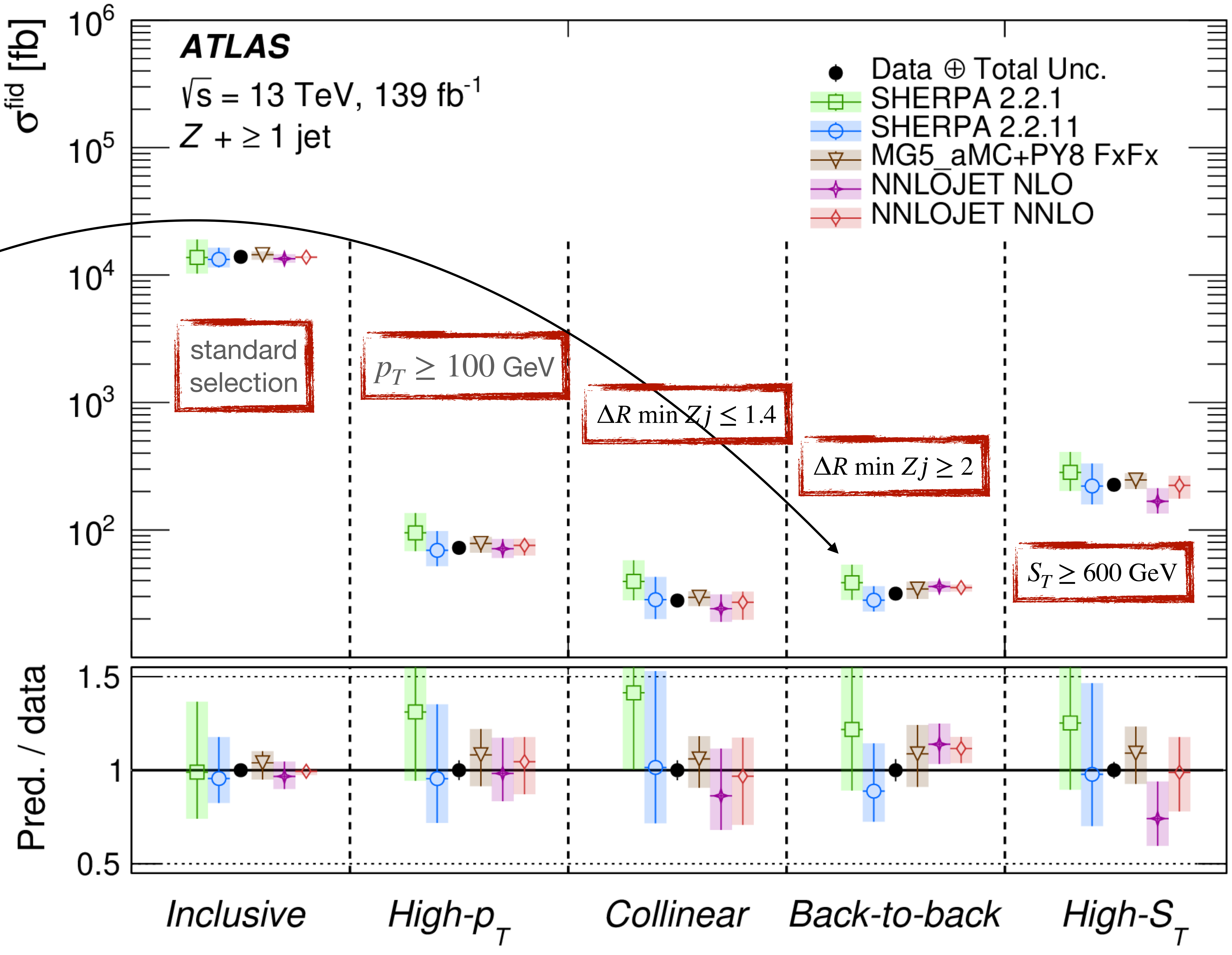
JHEP06(2023)080

Z+jets event topology with ATLAS

Z boson is balanced against a single high-pT jet



μμ/ee (25GeV) + jets: Z + ≥ 1 antik_T04 jet $p_T \geq 100$ GeV |y|<2.5



JHEP06(2023)080

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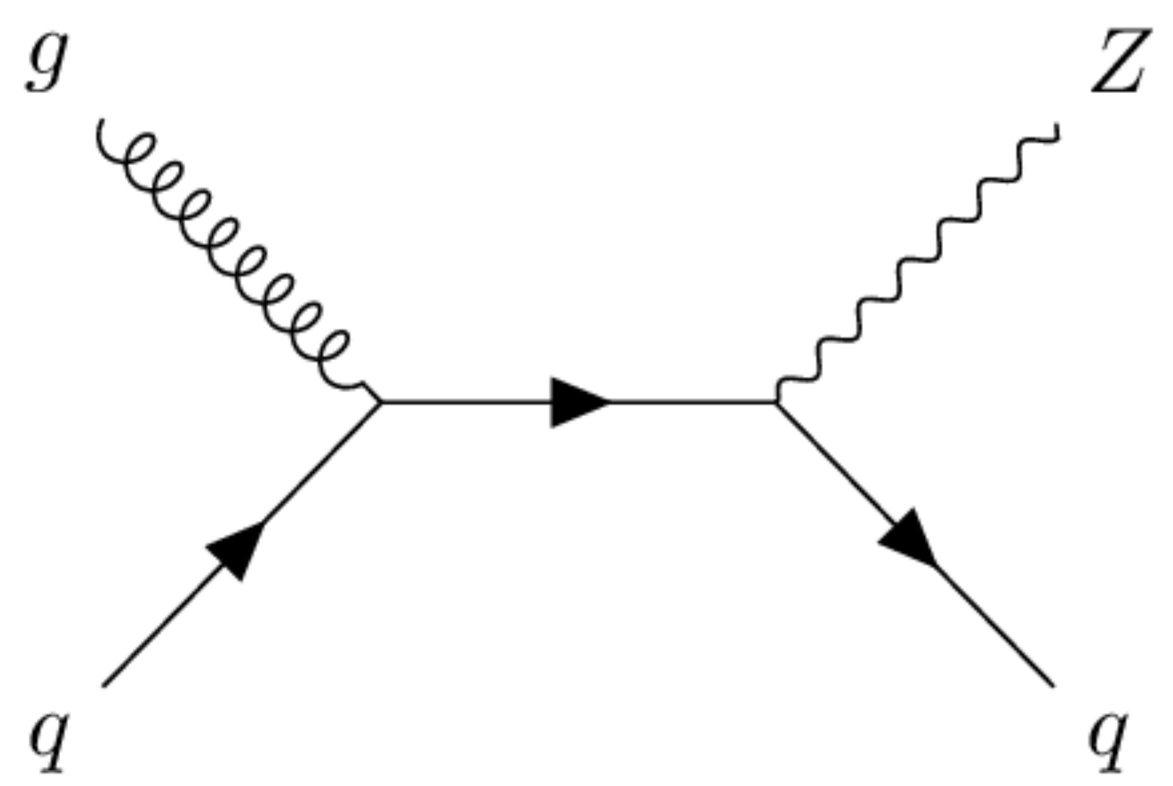
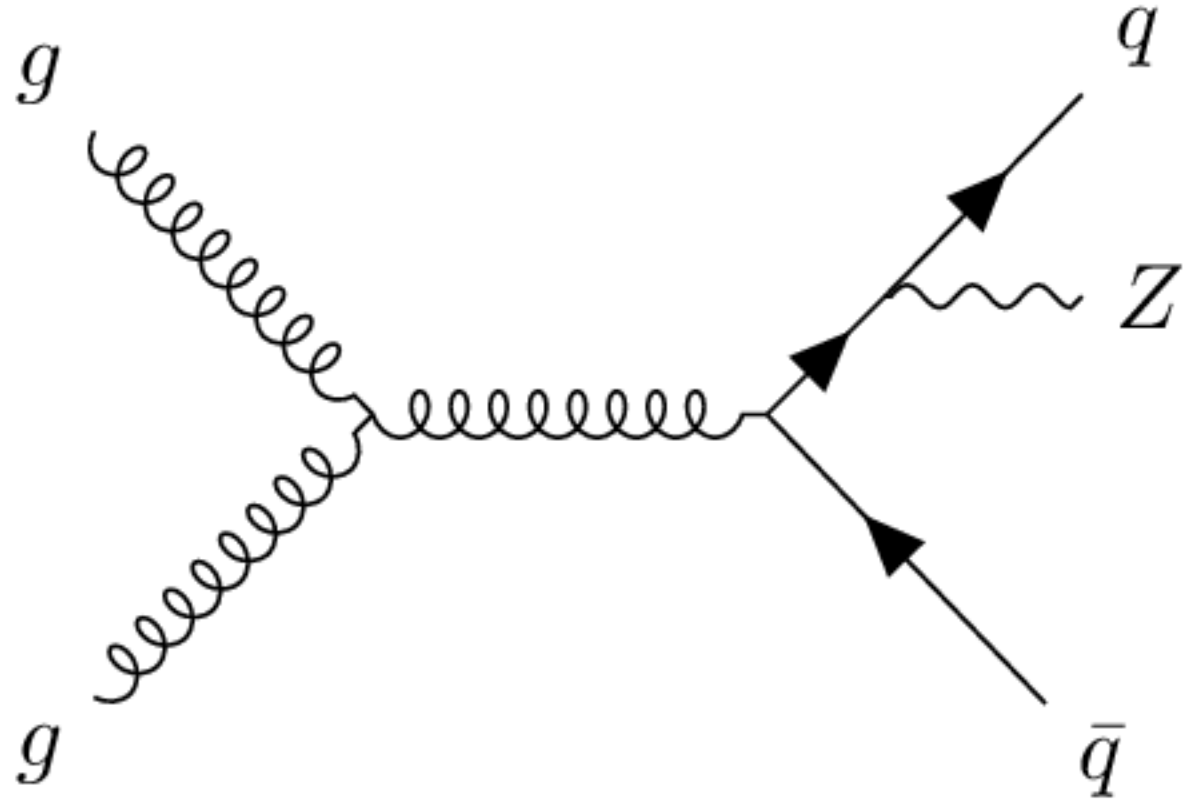
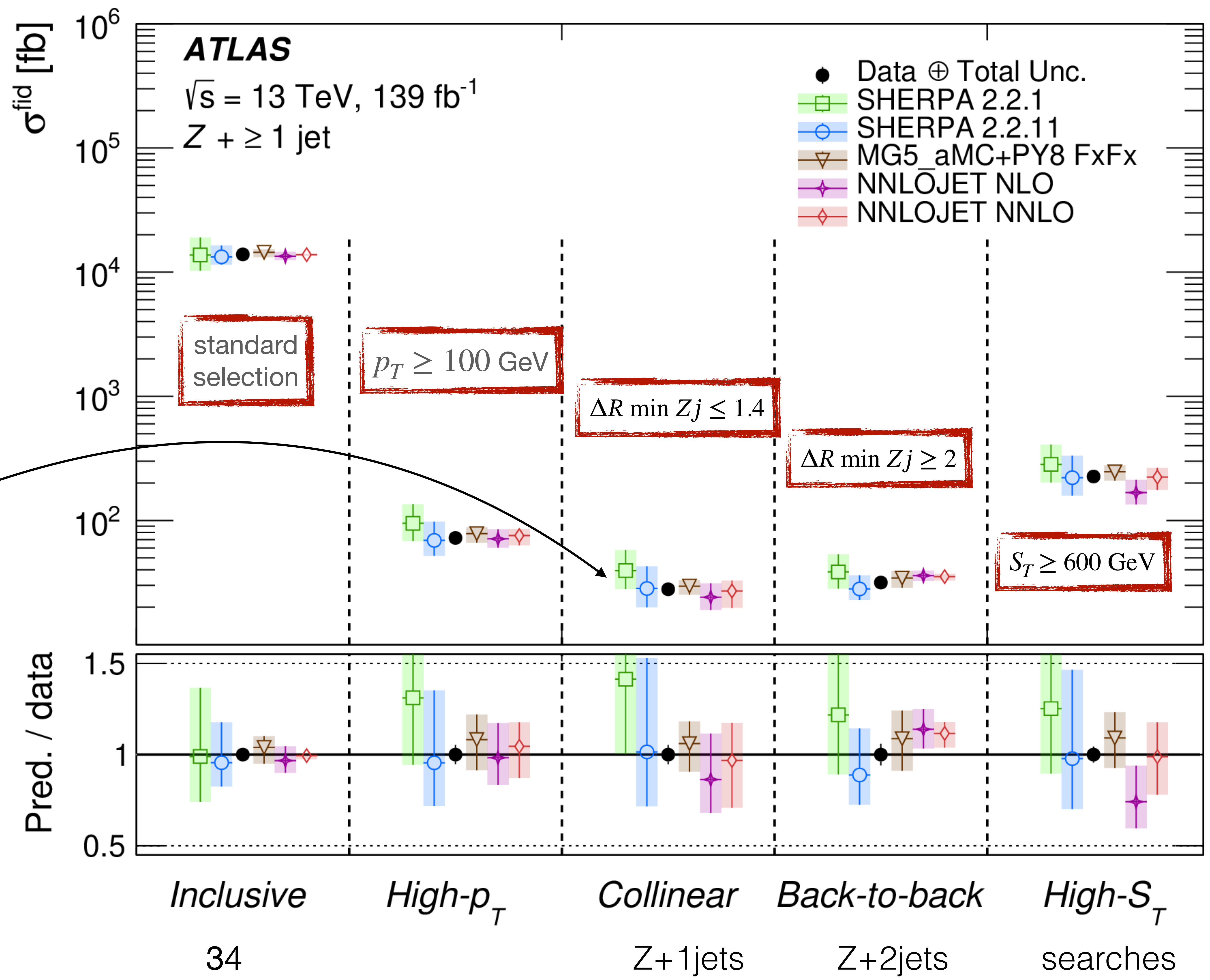
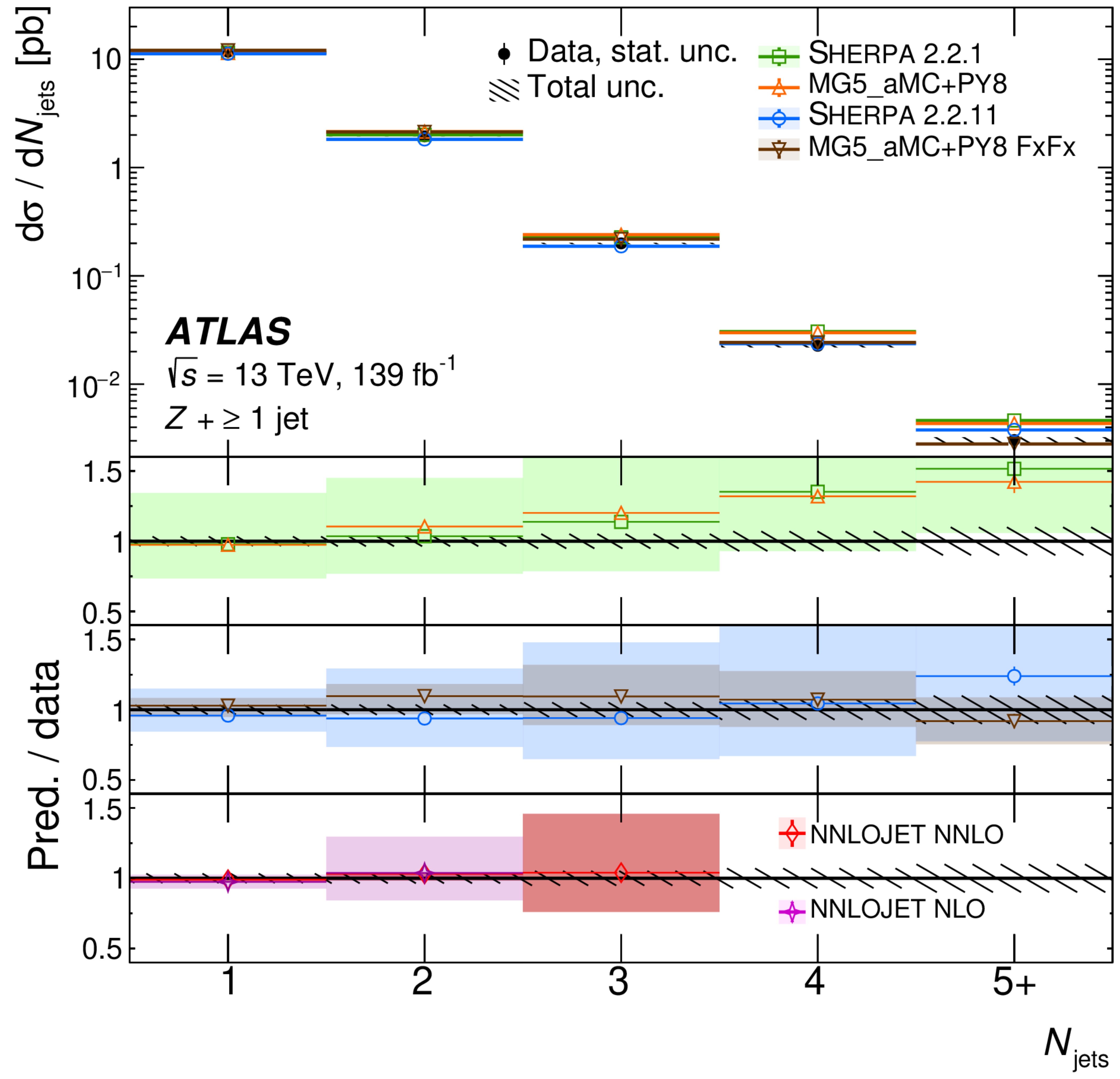




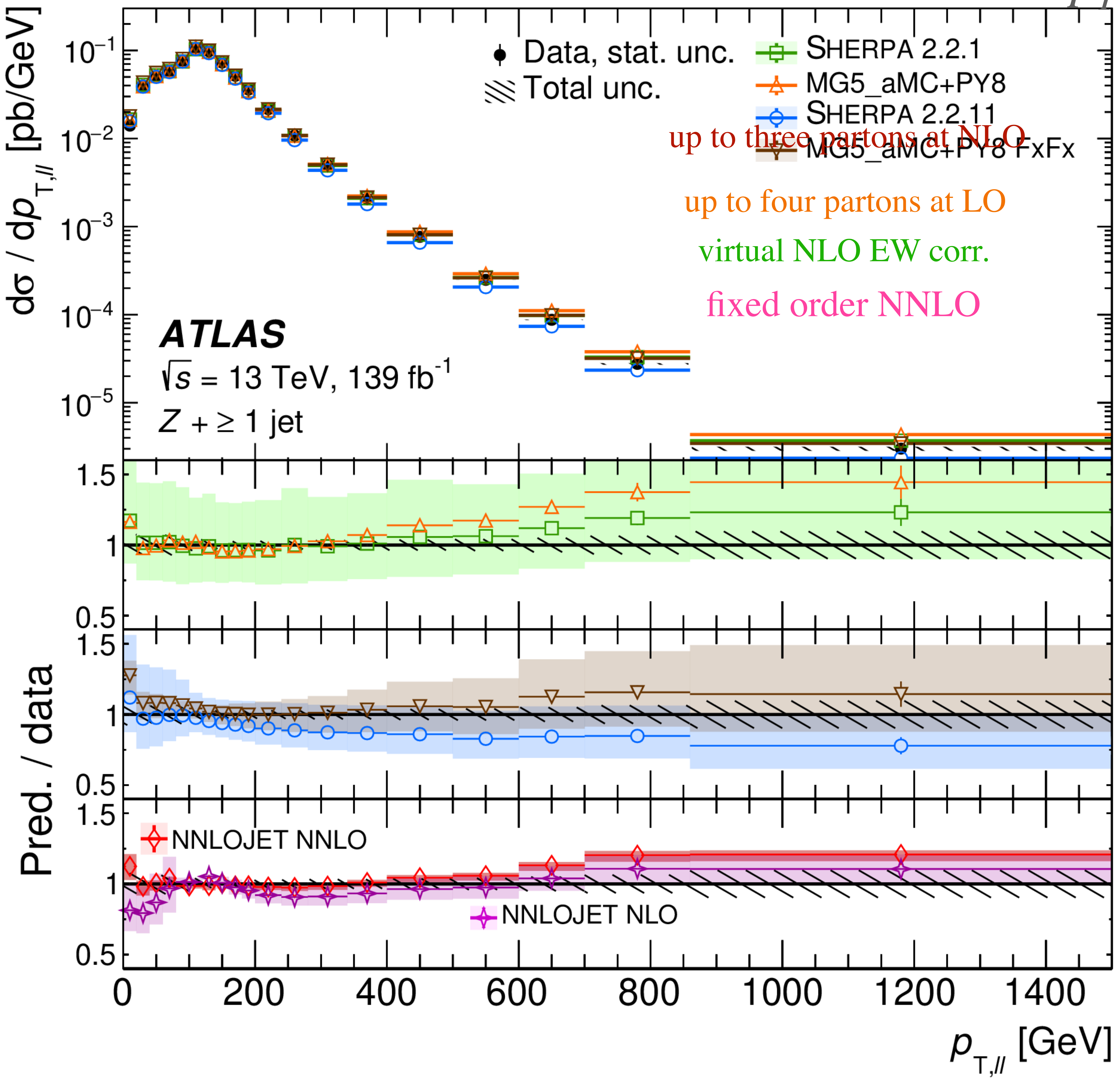


Z+jets event topology with ATLAS

unfolded jet multiplicity



unfolded Z boson p_T



Z+jets event topology with CMS

Eur. Phys. J. C 83 (2023) 722

unfolded differential cross sections

$p_T(Z) < 10$GeV

MADGRAPH5 aMC@NLO + pythia8

- NLO matrix element up to 2 partons
- FxFx jet merging
- NNPDF3.0 NLO PDF, CUETP8M1 Pythia8 tune

MCatNLO-CA3 (Z+1) NLO

- Fixed-order perturbative QCD calculation at NLO (2->Z+1)
- PB-NLO-set2 NLO PDF.

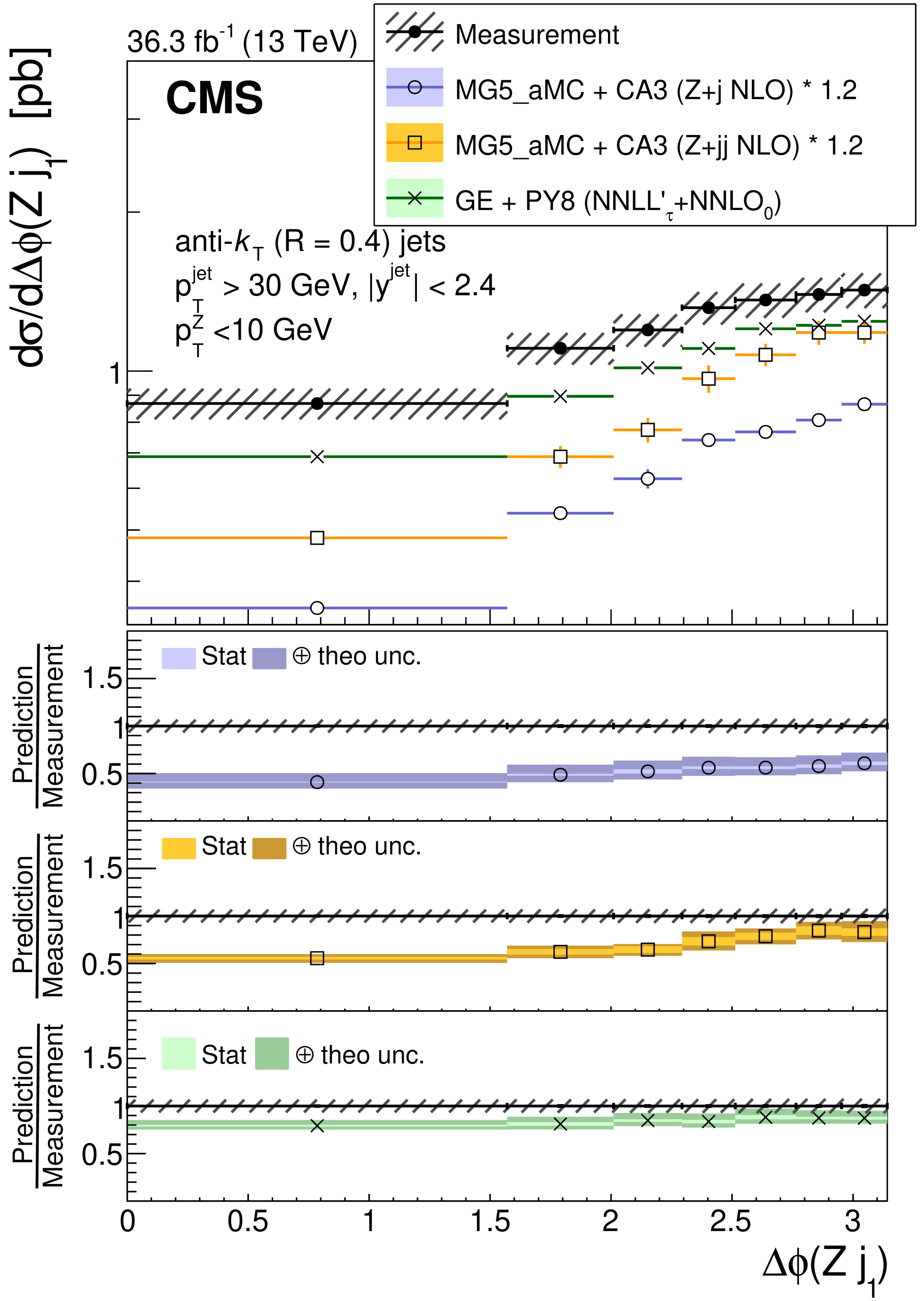
MCatNLO-CA3 (Z+2) NLO

- Fixed-order perturbative QCD calculation at NLO (2->Z+2)
- PB-NLO-set2 NLO PDF

GENEVA NNLO

- Resummed NNLO+NNLL' calculations for inclusive Z production at NNLO
- NNPDF 3.1, CUETP8M1 Pythia8 tune

Z boson is only weakly correlated with the leading jet



Eur. Phys. J. C 83 (2023) 722

Z+jets event topology with CMS

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- PB-NLO-set2 NLO PDF

GENEVA NNLO

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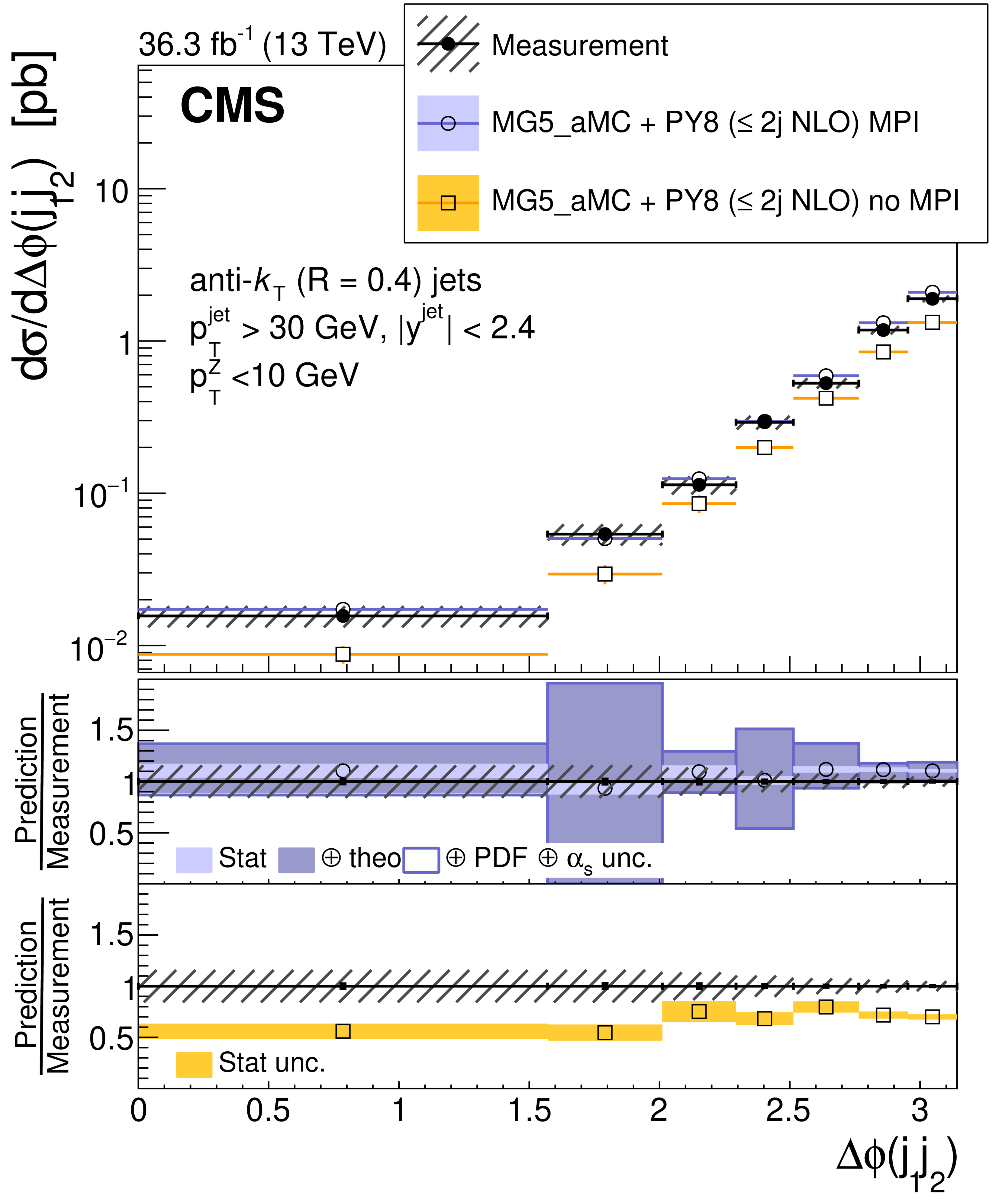
Multi-parton interaction contribution is about 40%

$p_T(Z) < 10$GeV



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GENEVA NNLO

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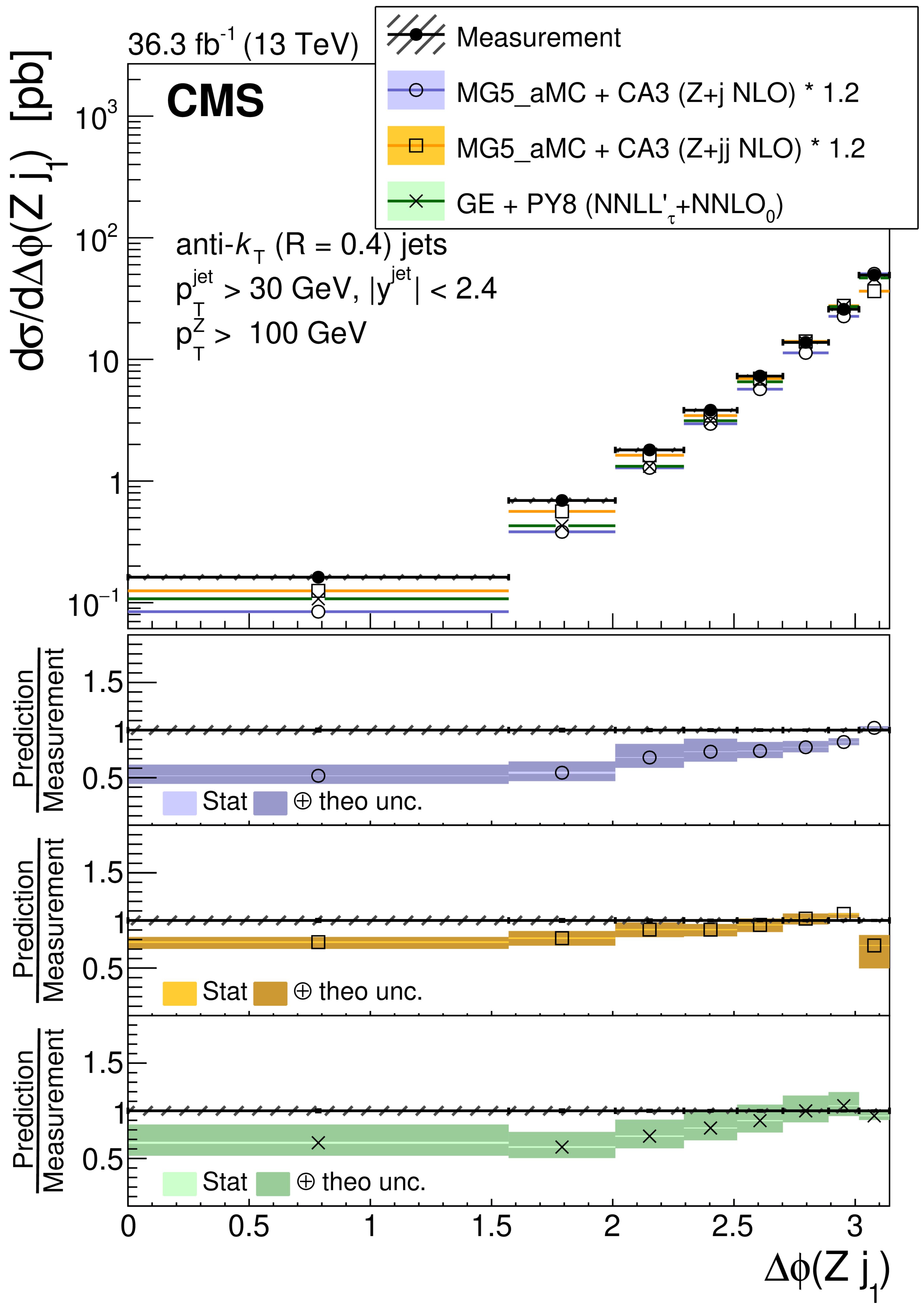
- NNPDF 3.1, CUETP8M1 Pythia8 tune

Z boson is highly correlated with the leading jet, and peaks in the back-to-back region.



Eur. Phys. J. C 83 (2023) 722

Z+jets event topology with CMS

unfolded differential cross sections

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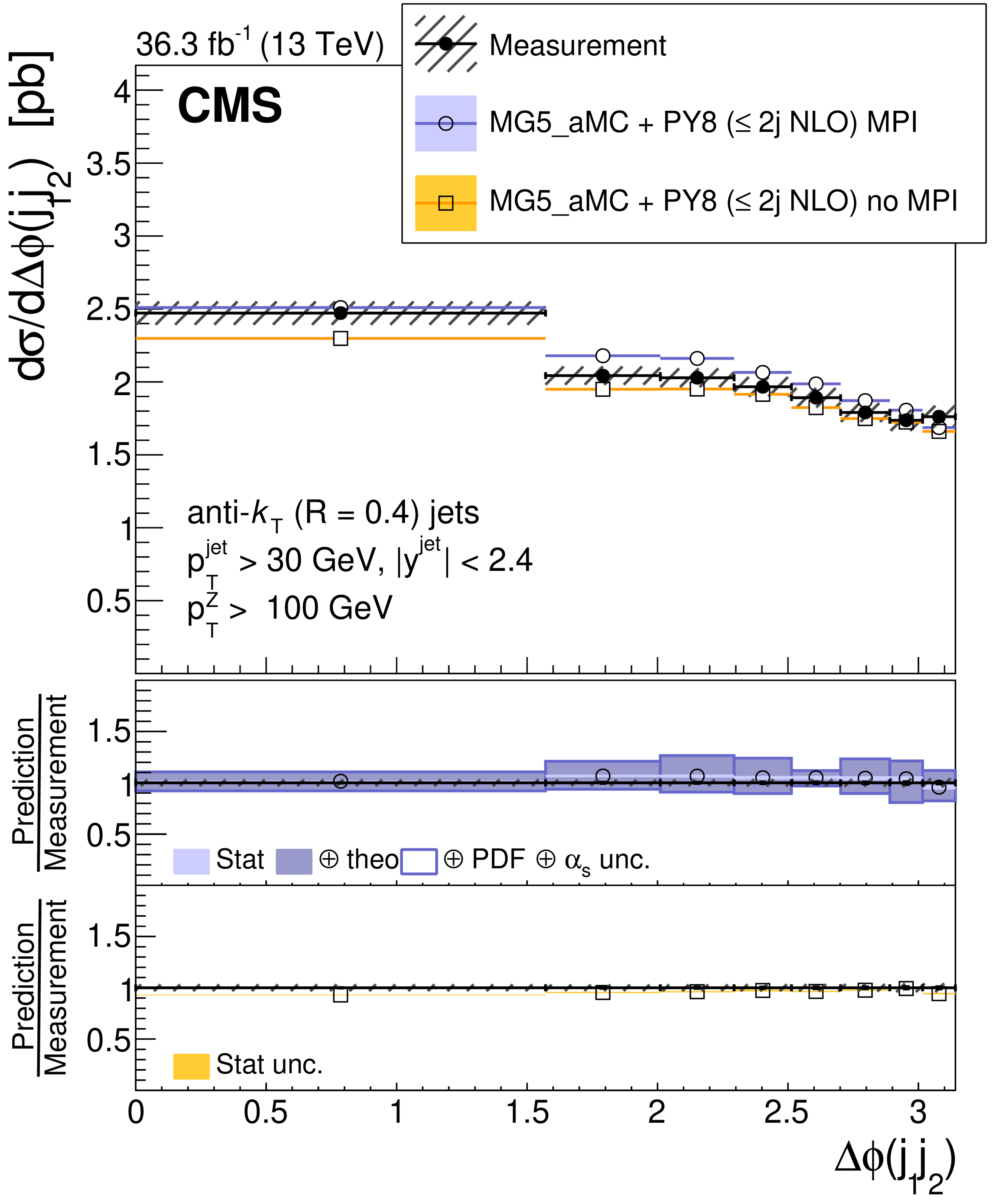
- NNPDF 3.1, CUETP8M1 Pythia8 tune

higher order matrix elements become important



Summary, directions and *new trends*

- A *discovery machine* like LHC turned out to be the most powerful *precision machine* for experimental SM in the world: huge set of unprecedented high-precision measurements

- We're improving our understanding of the Universe with to critical precision SM measurements (m_W, $\sin^2\theta_W$ but also Higgs, top, VBS)

  - *trends1* : achieving new precision with single boson measurements: PDFs, NNLO predictions, exp methods, statistics

  - *trends2* : multiboson at the tails of distributions: EFT approaches, polarization, VBF & search @ high p_T

  - *trends3* : V+jets, topology, new predictions, flavour (largely unexplored final states, stat. limited, long standing unsolved modeling issues)

see Evelin's talk!

backups

Status of theoretical calculations

- **MadGraph5_aMC@NLO** (ME) + **PYTHIA8** / **HERWIG** (PS)
  - LO: up to 4 partons, kT-MLM matching
  - NLO: up to 2 partons, FxFx merging
- **Powheg** (ME) + PYTHIA8 (PS) up to NLO
- **Sherpa** (ME + PS) up to NLO
- **Geneva** 1.0-RC2 (ME) + PYTHIA8 (PS):
  - NNLO DY production + NNLL higher order resummation
  - Only for Z+jets processes
- **MCFM (ME)**
  - Z/W+1 jet NNLO calculations

NNPDF PDFs available at LO and NLO

MMTH PDF set at NLO

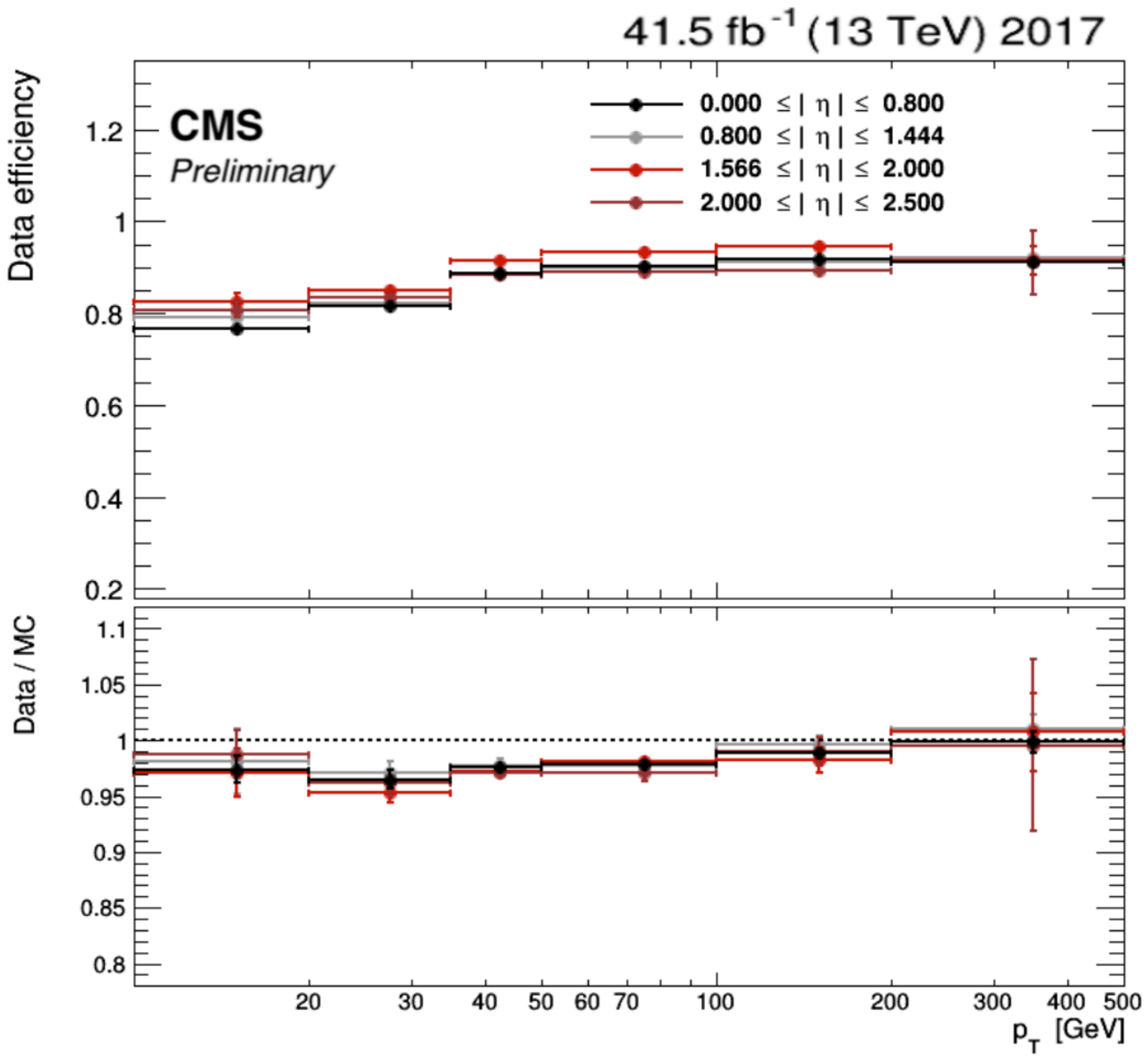
several (CP5) PYTHIA8 tunes

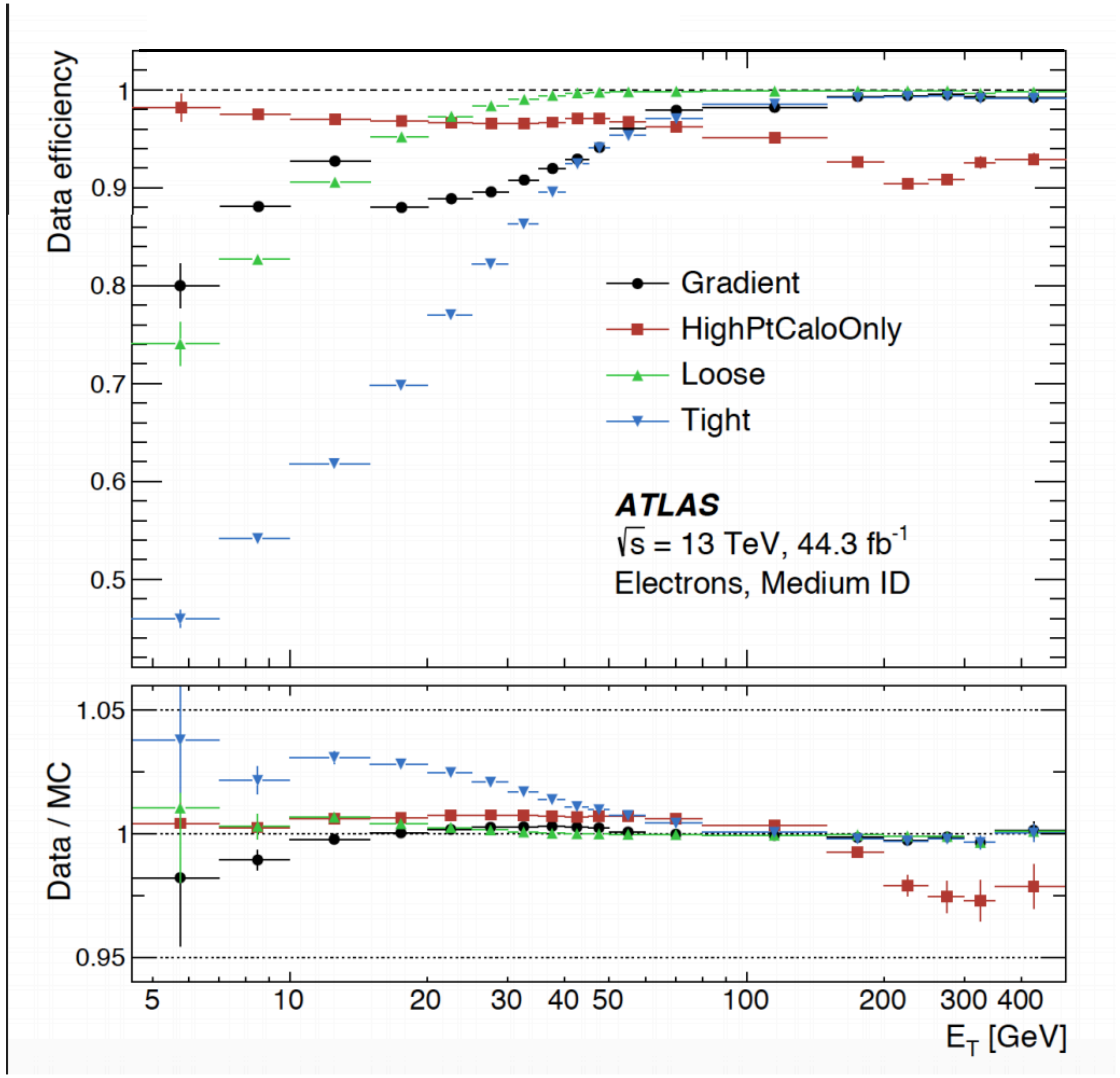
- **HF treatment**
  - 4FS, b mass and 4 PDFs
  - 5FS b mass=0 and 5 PDFs

Samples	0 j	1 j	2 j	3 j	4 j	> 4 j
LO MG5_aMC	LO	LO	LO	LO	LO	PS
NLO MG5_aMC/Powheg	NLO	NLO	NLO	LO	PS	PS
Geneva	NLO	NLO	LO	PS	PS	PS
Z/W+1 jet @ NNLO	-	NNLO	NLO	LO	-	-

How all of this is possible

precision SM tests, differential spectra and sensitivity to very rare processes are possible exploiting the ATLAS and CMS excellent detector performances

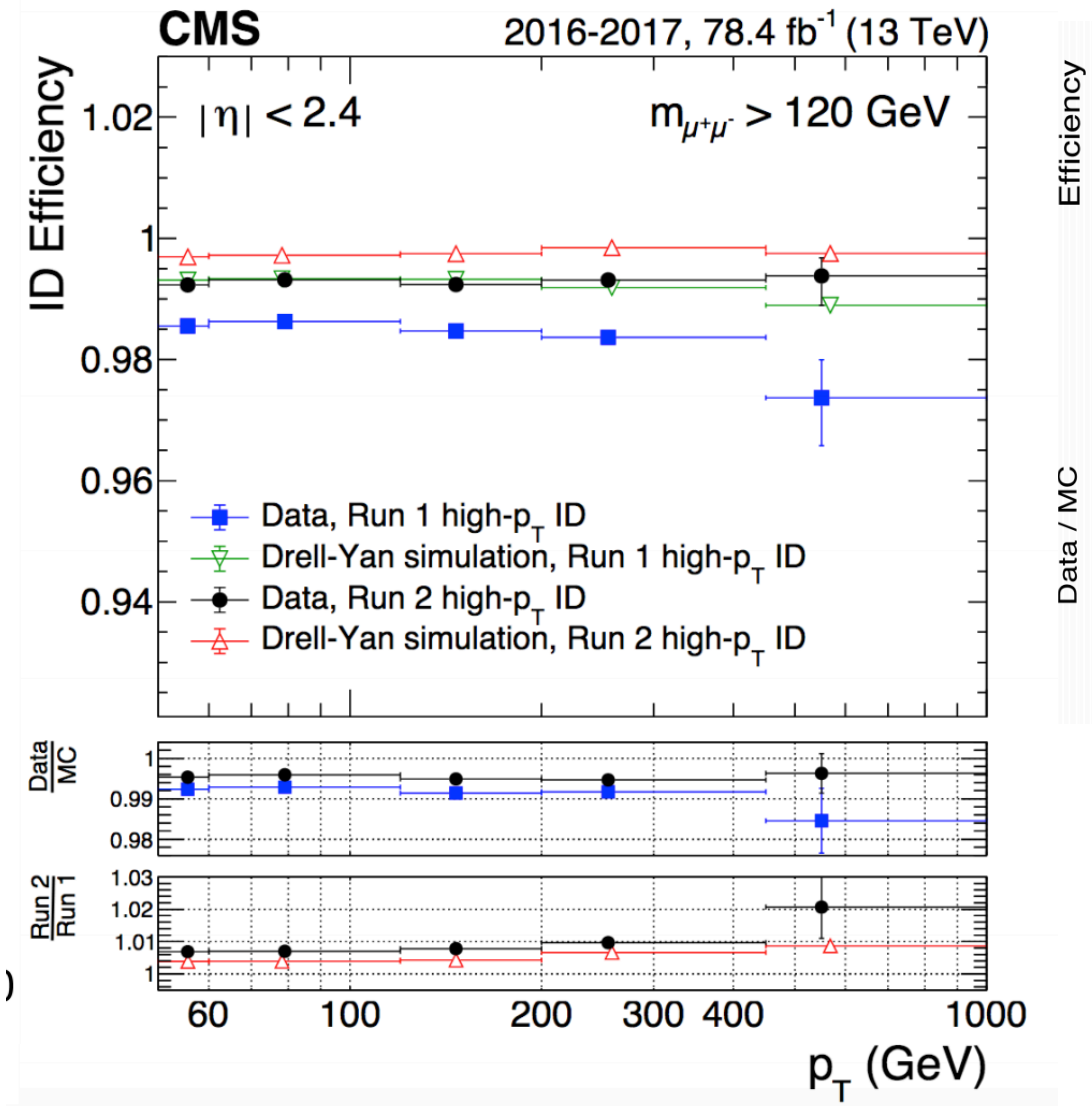




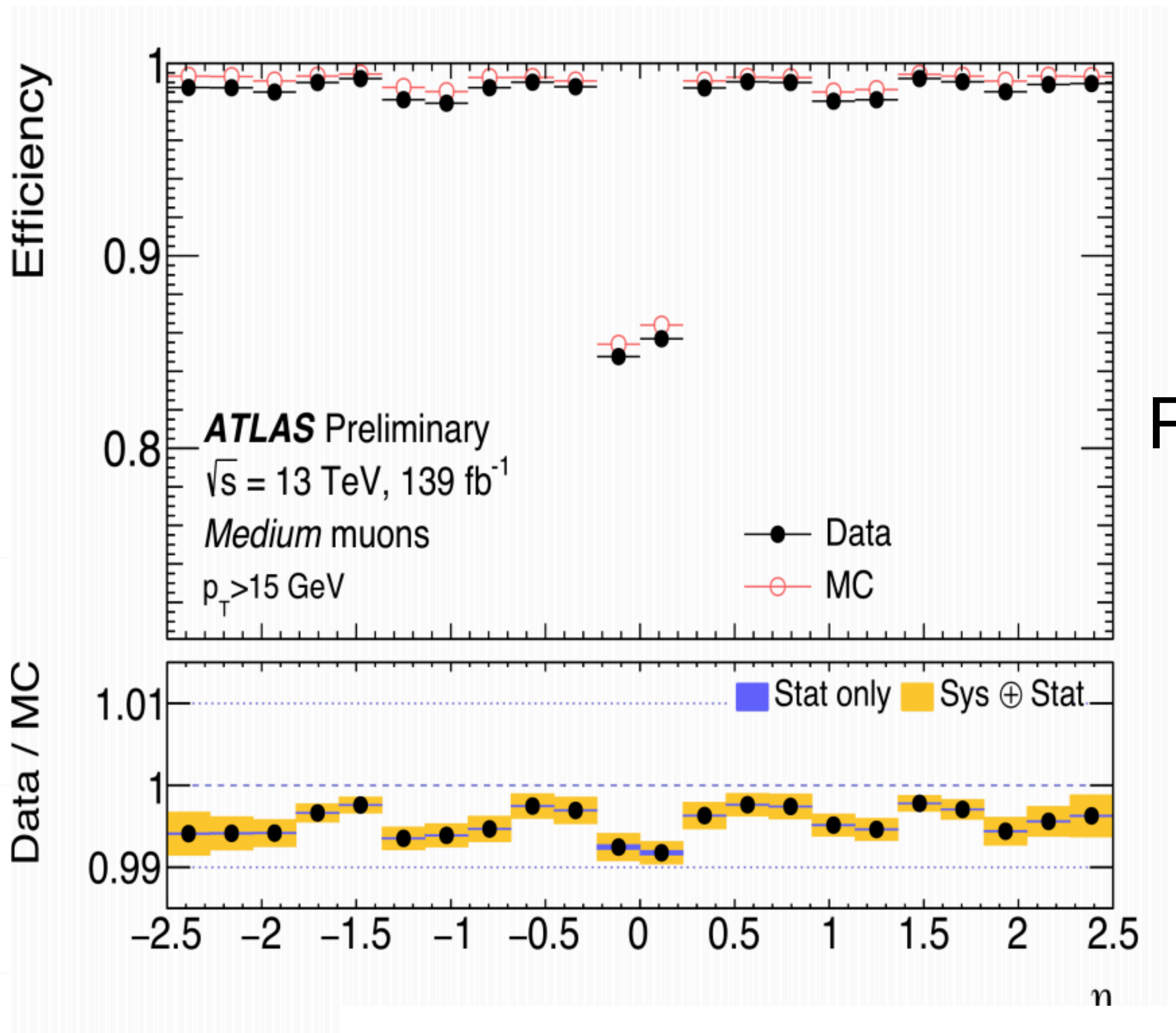
Electrons identification with $Z \to e^+e^-$ and $J/\psi \to e^+e^-$

both ATLAS and CMS achieve sub-% precision

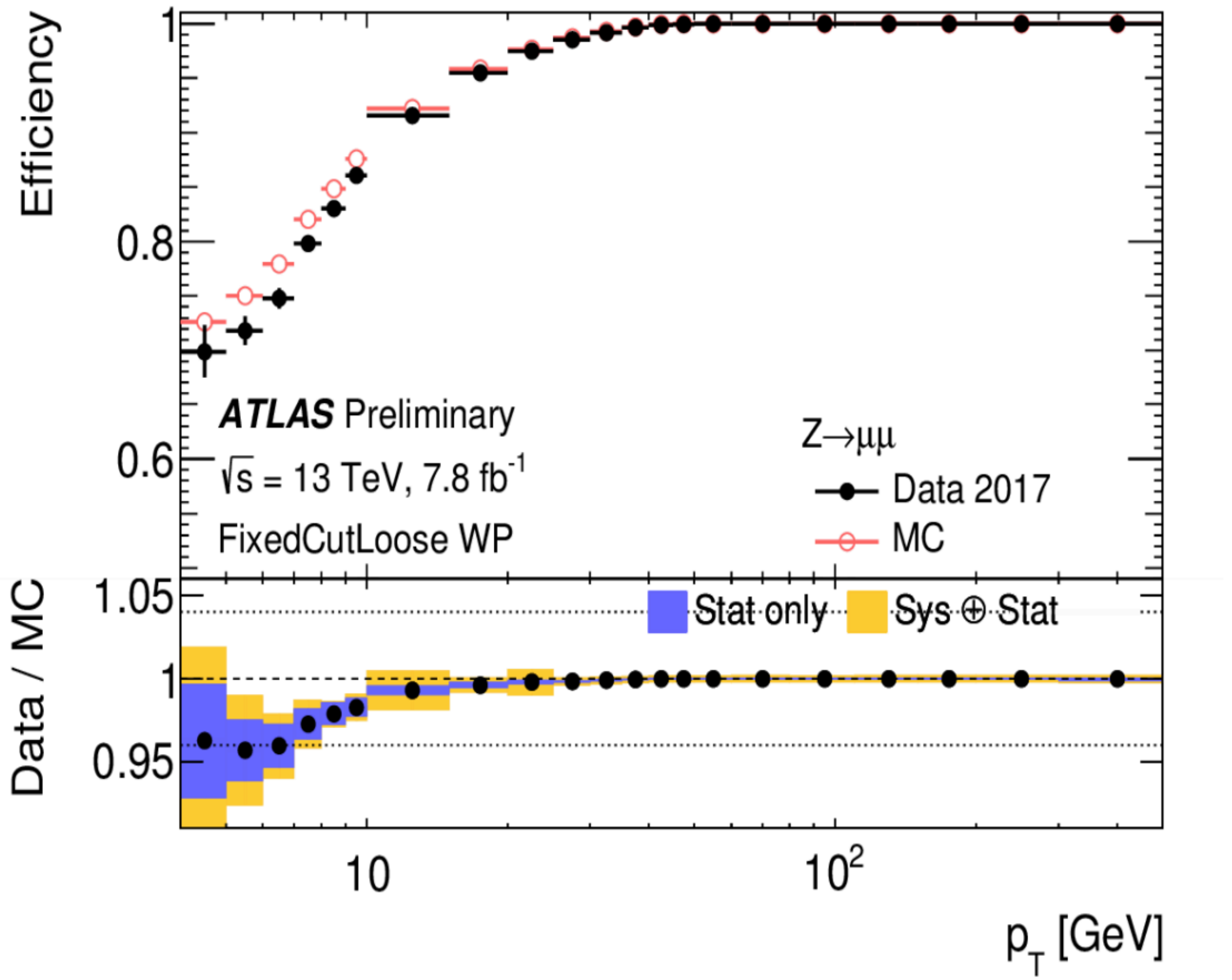
How all of this is possible



Muons identification with $Z \to e^+e^-$
up to 1 TeV



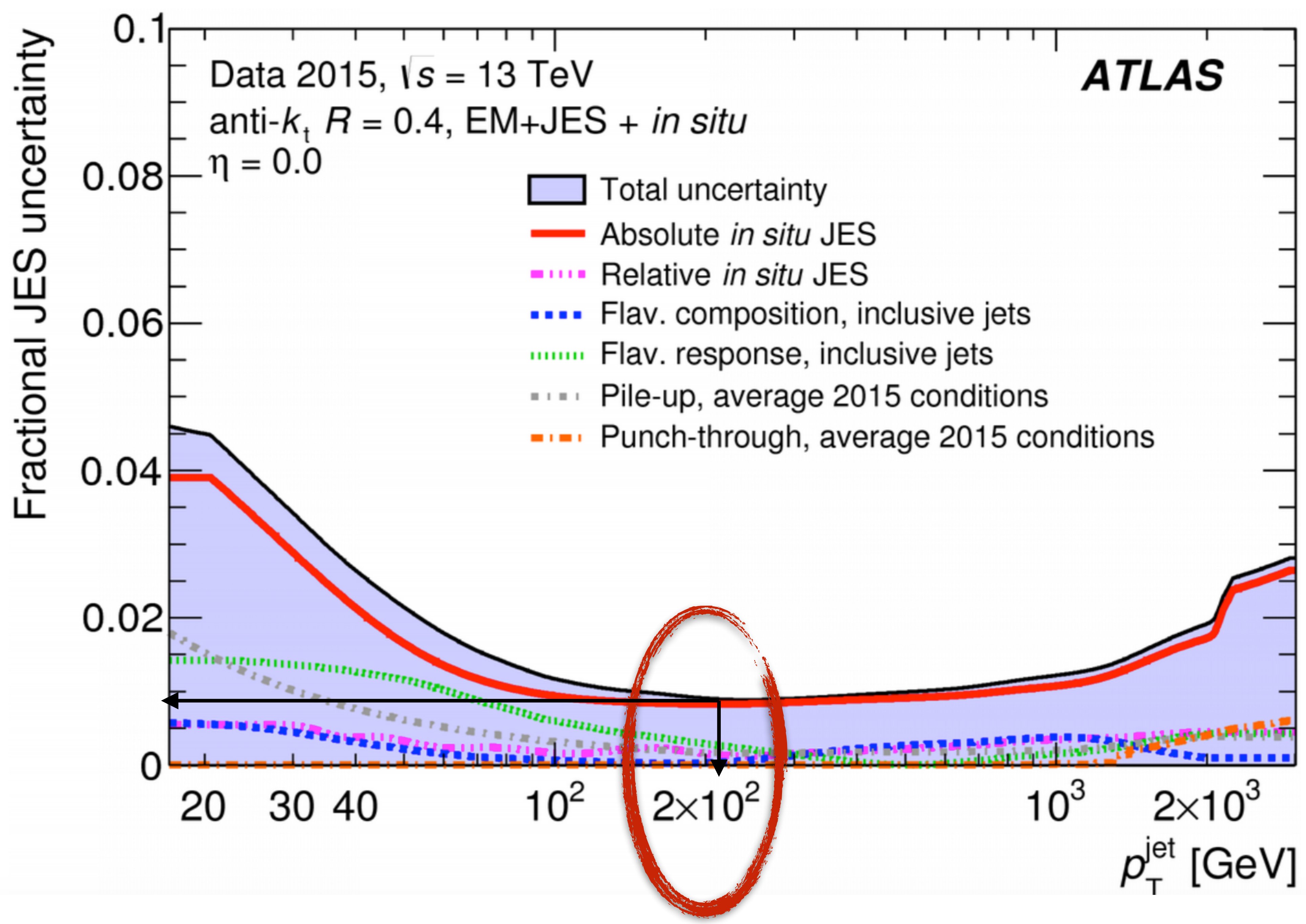
Muons Reconstruction and Isolation efficiency

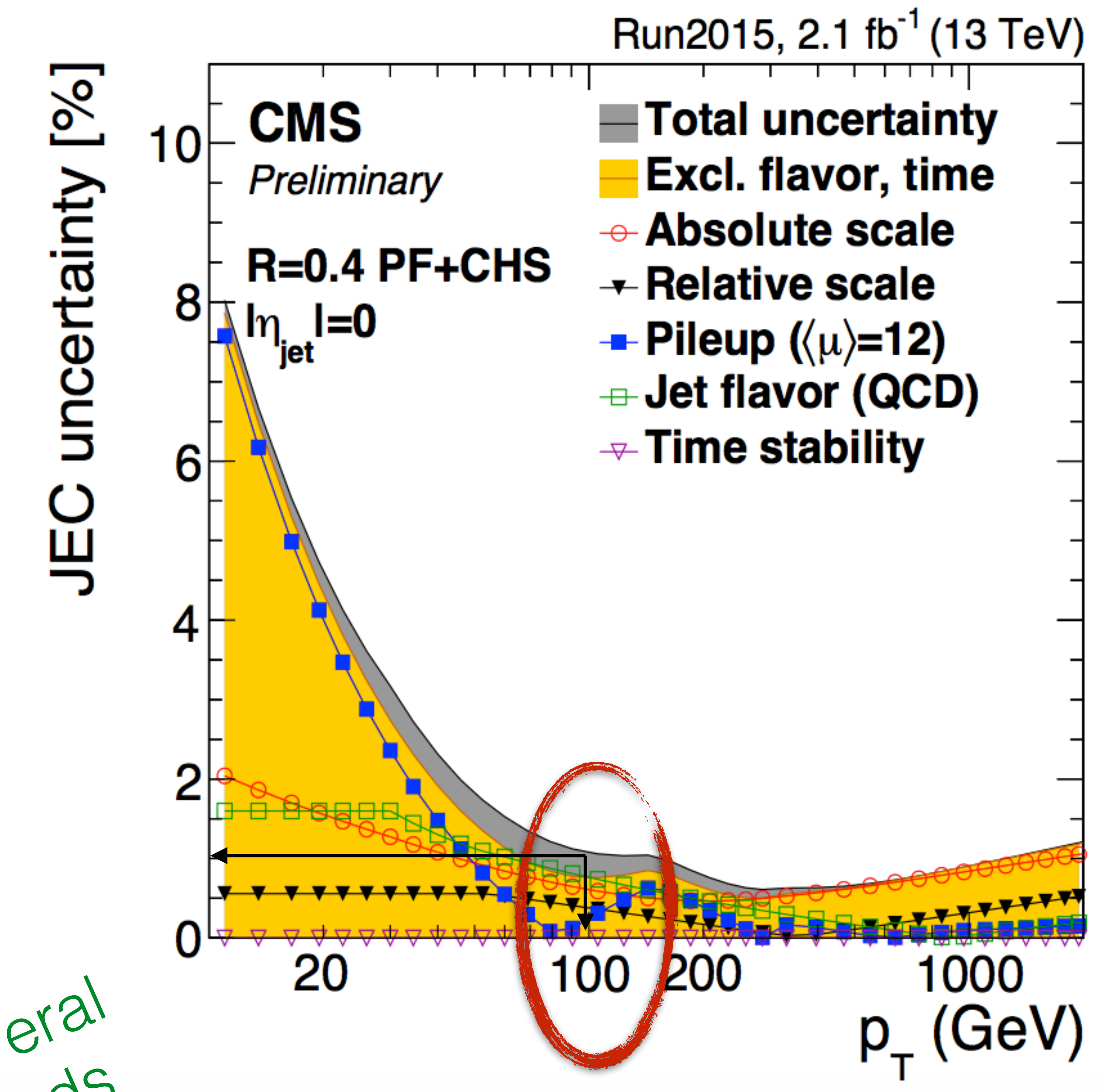


Outstanding precision

How all of this is possible

ATLAS ← both deliver jet energy corrections → **CMS**





Correct for

- Pile-Up
- Jet Flavor Composition
- Absolute/Relative Scale

thanks to several in-situ methods

Less than 2% in the region $p_T > 100$ GeV!

LHCb: ~10-15% for p_T of 10–100 GeV

Jet Reconstruction: Strategy

anti-k_T clustering algorithm
(infrared and collinear safe)

ATLAS/CMS: R=0.4 (Run II)

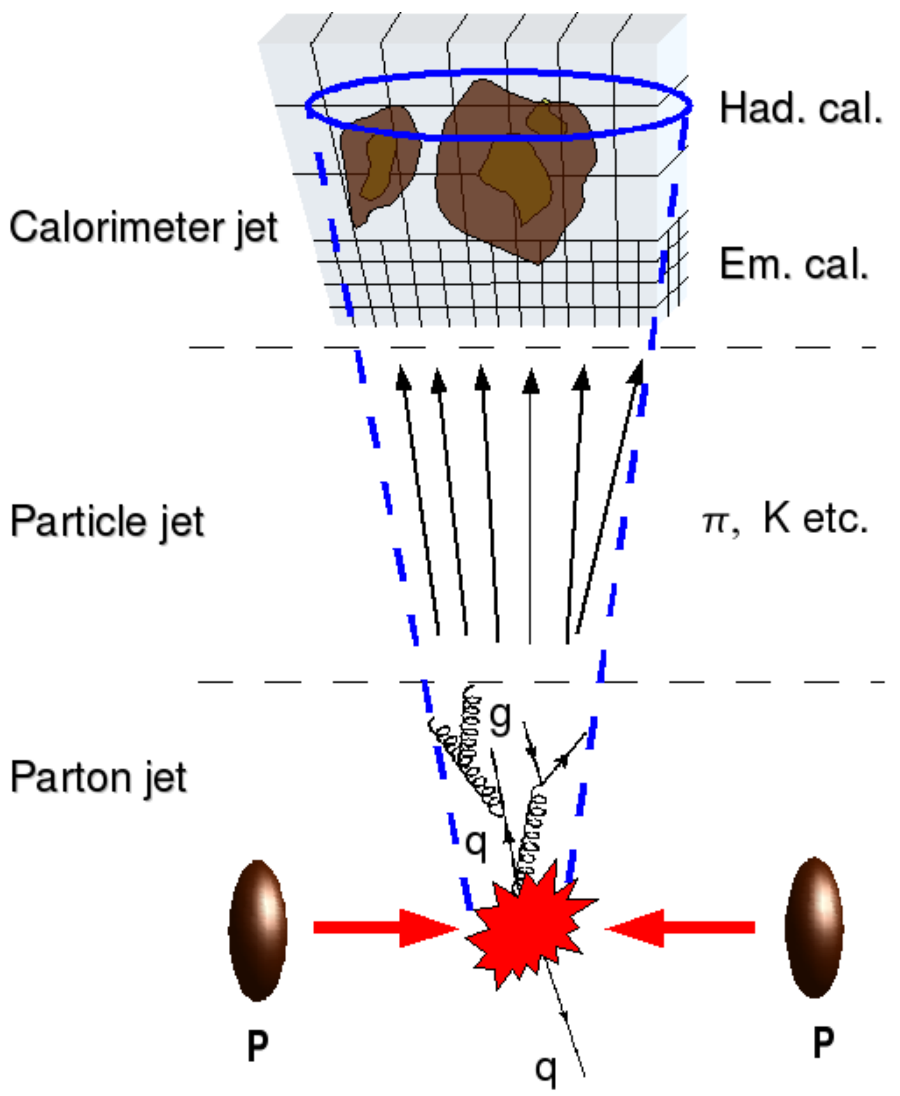
LHCb: R=0.5

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$
$$d_{iB} = k_{ti}^{2p},$$

← ↓ →

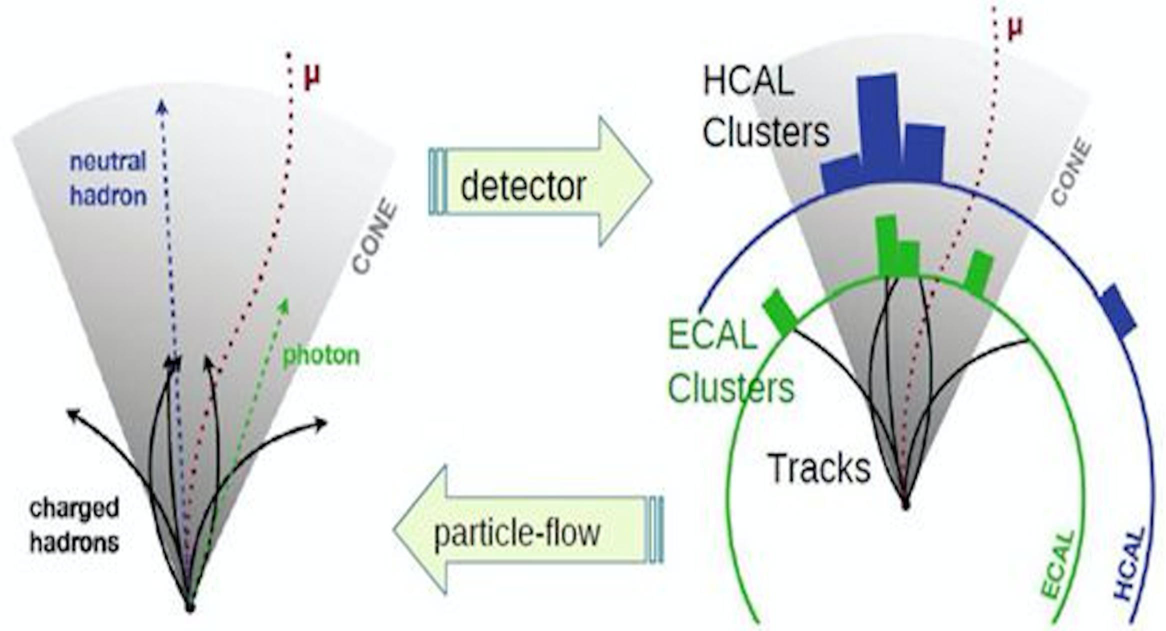
ATLAS

topological
calorimeter-cell
clusters



CMS

particle-flow



uses all the sub-detectors
information to reconstruct objects

LHCb

LHCb acceptance
forward direction

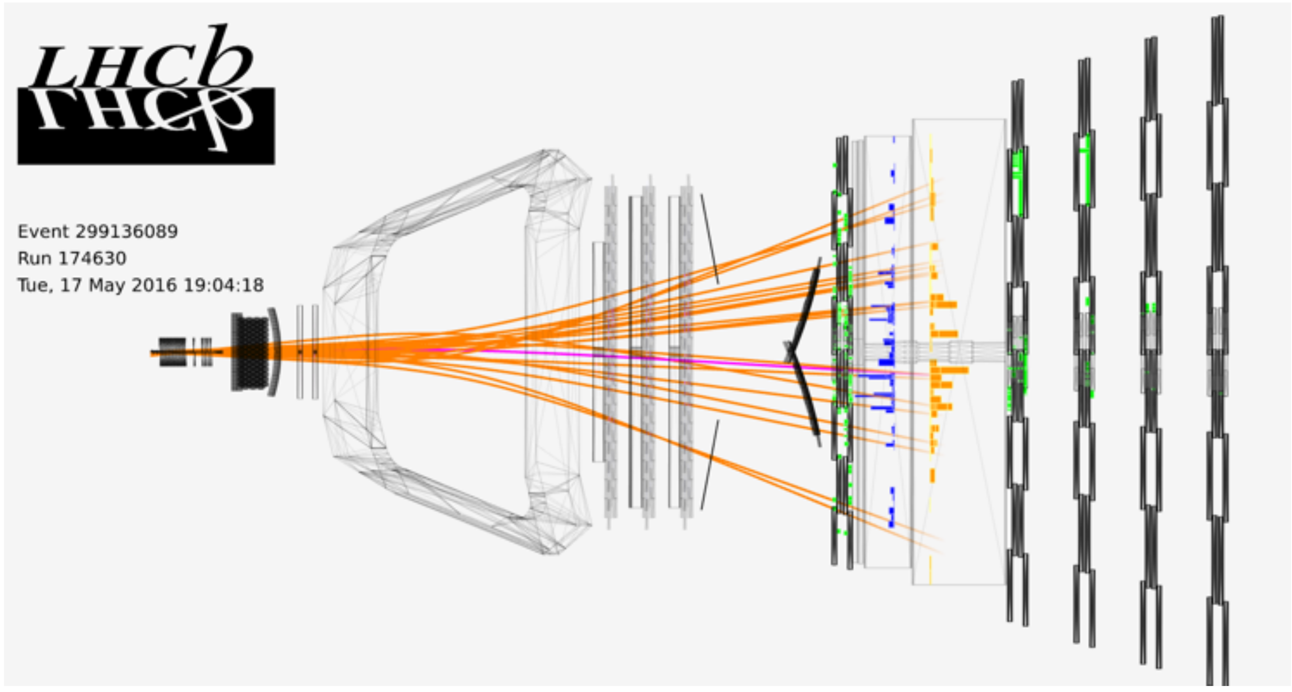
Particle Flow

calo cell E_T~10 GeV saturation

↓

use the precise
tracking information → use particles! (Λ,Ks,π,..)

($2 < \eta < 5$)

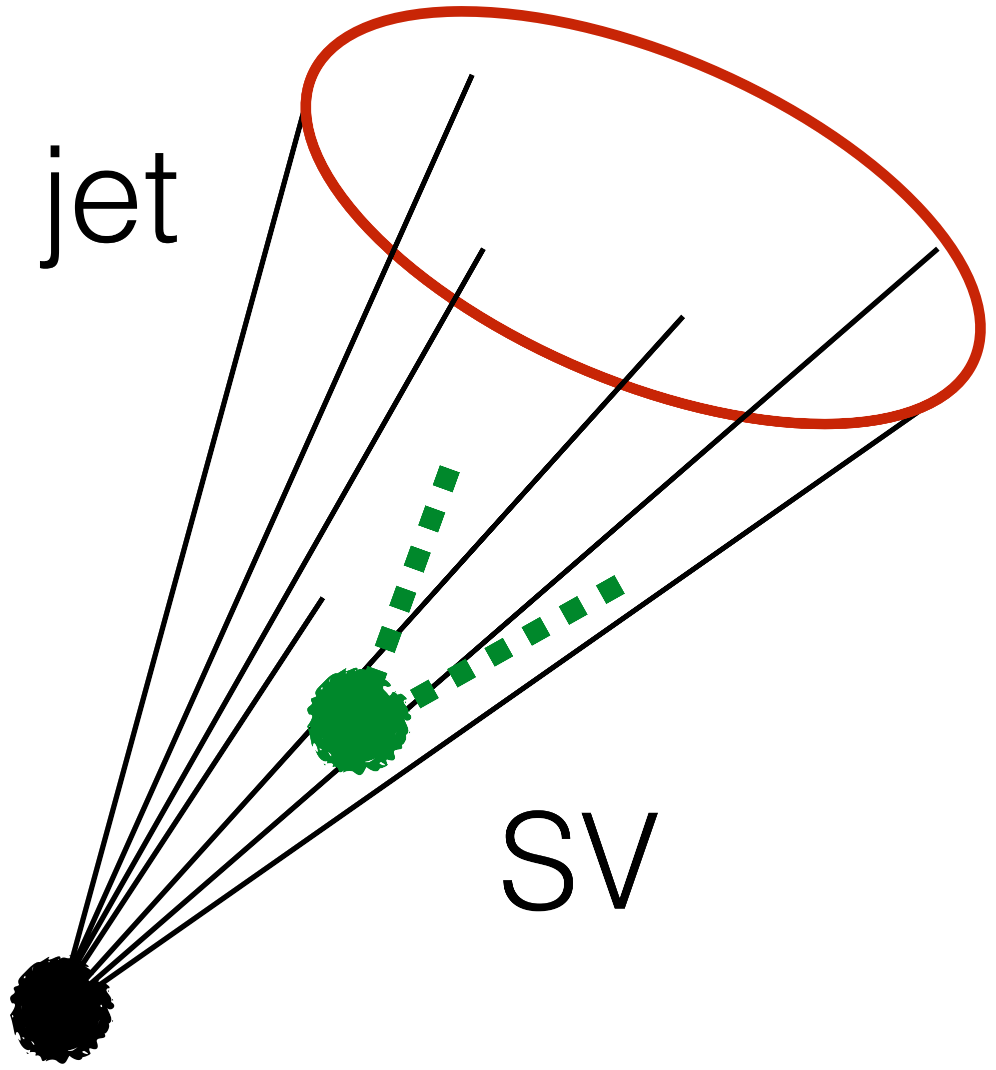


Heavy flavor tagging at collider

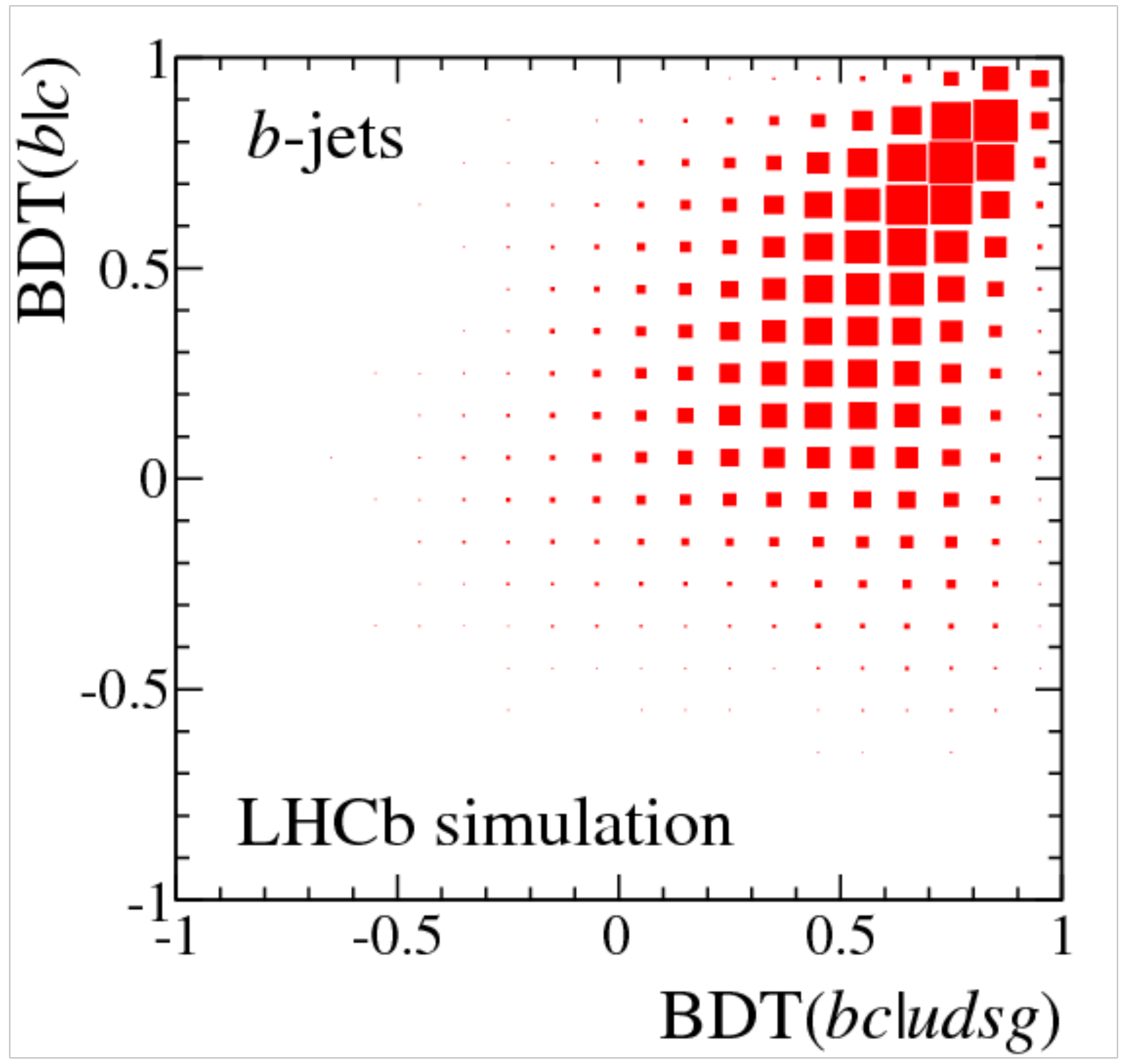
recipe

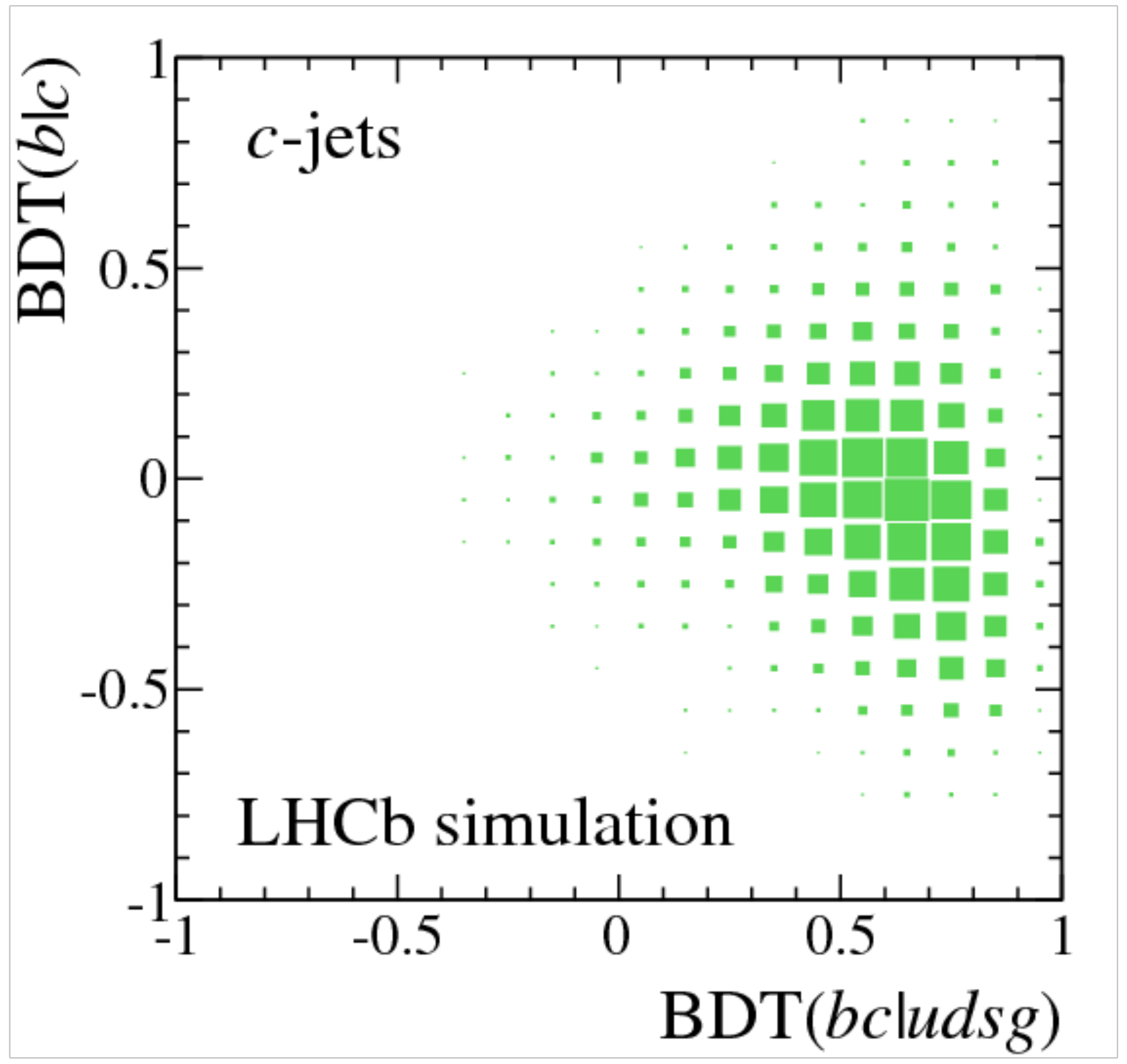
JINST 10 (2015) P06013

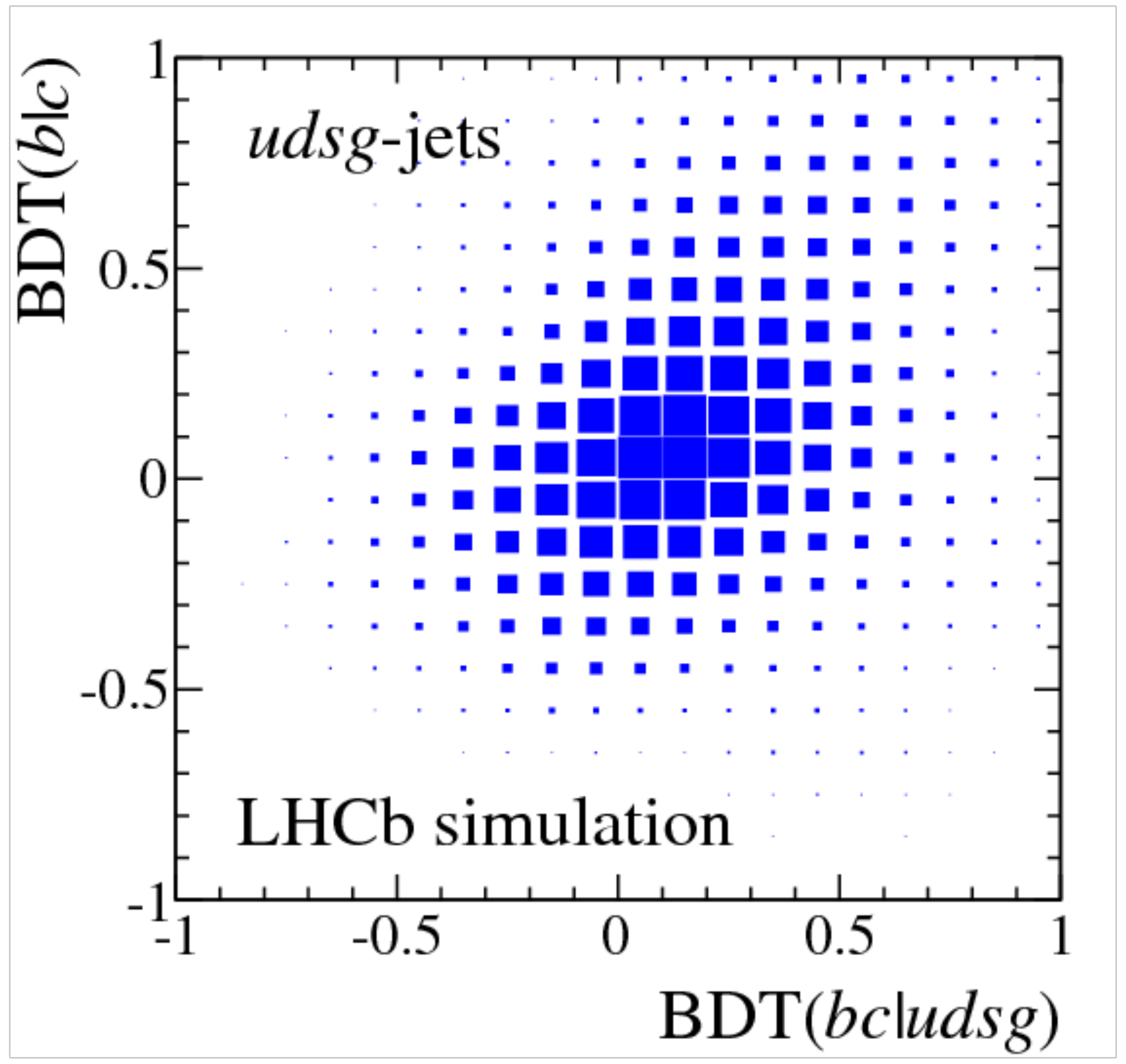
- reconstruct jets with the anti-kT05 algorithm
- tagging using b- and c- inclusive tagger
- reconstruct the two-body vertices in the event
- merge SV n-body by linking tracks and vertices associated
- associate vertices/jets requiring ΔR(SV, jet) < 0.5



BDT trained on SV/j properties to separate **heavy**/**light**







light-jet mistag rate < 1% for b-tag efficiency of 65% and c-tag efficiency of 25%

Heavy flavor tagging at collider

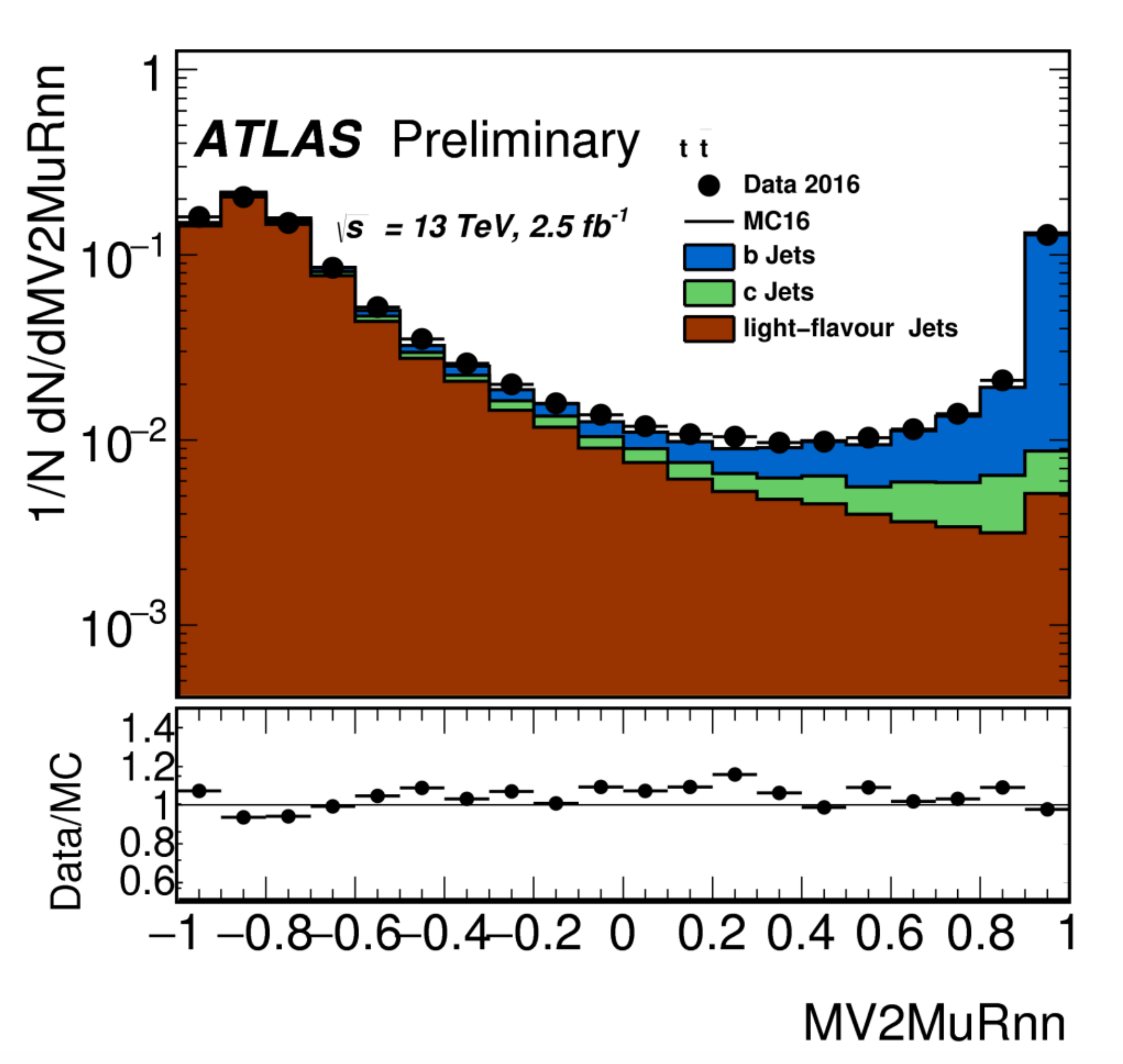
ATL-PHYS-PUB-2017-013
ATLAS-FTAG-2017-003

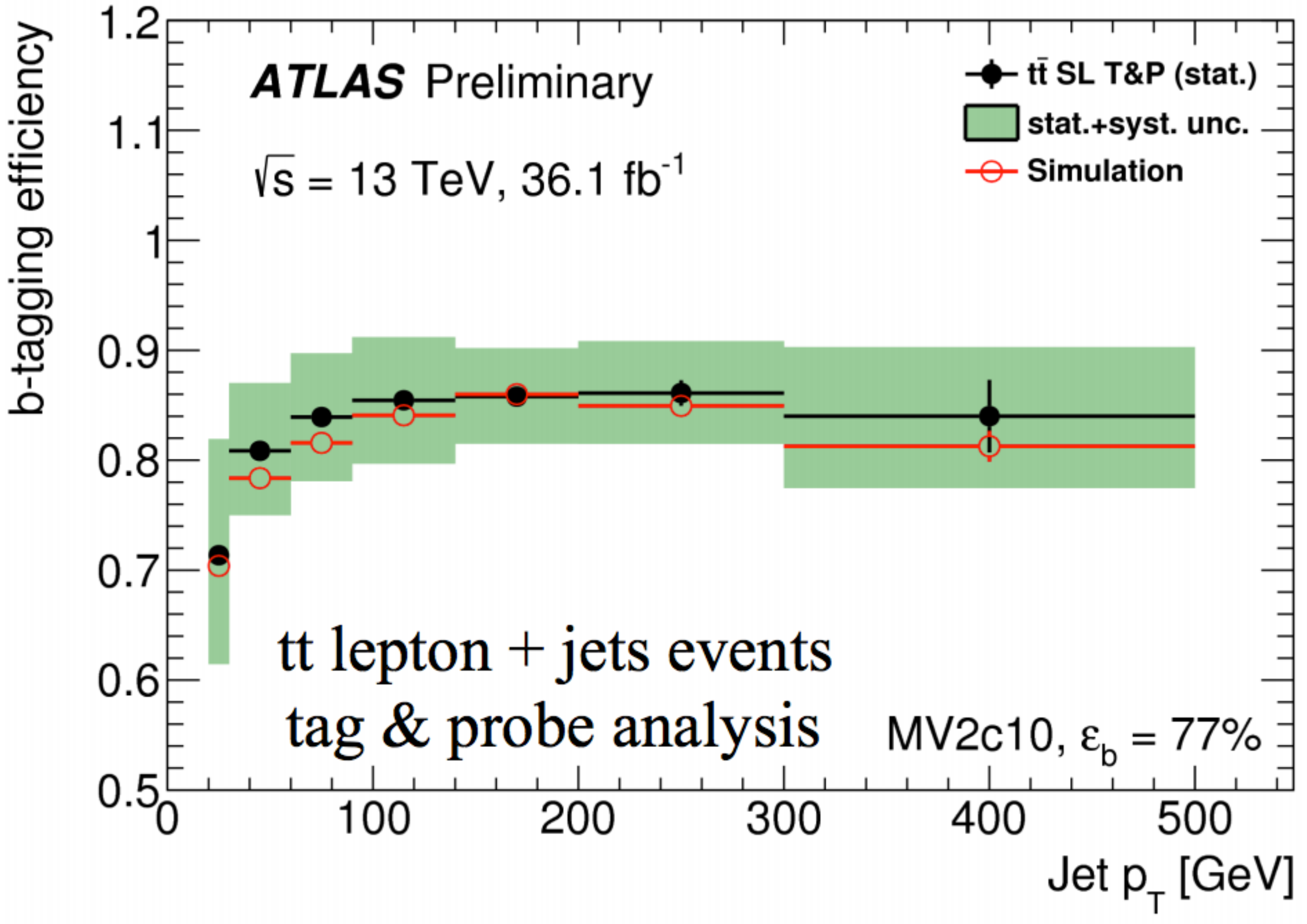
- several taggers:
  - track based (impact parameter tag)
  - soft muon (discriminate μ from b decays)
  - vertex based
- high-level taggers: MVA using all the information available to maximize the b-tag performance

→ BDT (trained on top + Z'bb events (*hybrid training*))

→ Deep Learning Neural Network

combine inputs from track, particle and vertex-based physics taggers using multivariate classifier





b-tag efficiency of 77% and c-tag efficiency of 25%

mistag rate of light flavored jets using dijet events with negative tag

< 2% under pT = 1 TeV

Heavy flavor tagging at collider

- several taggers:

CERN-CMS-DP-2017-005

CMS-PAS-BTV-15-001

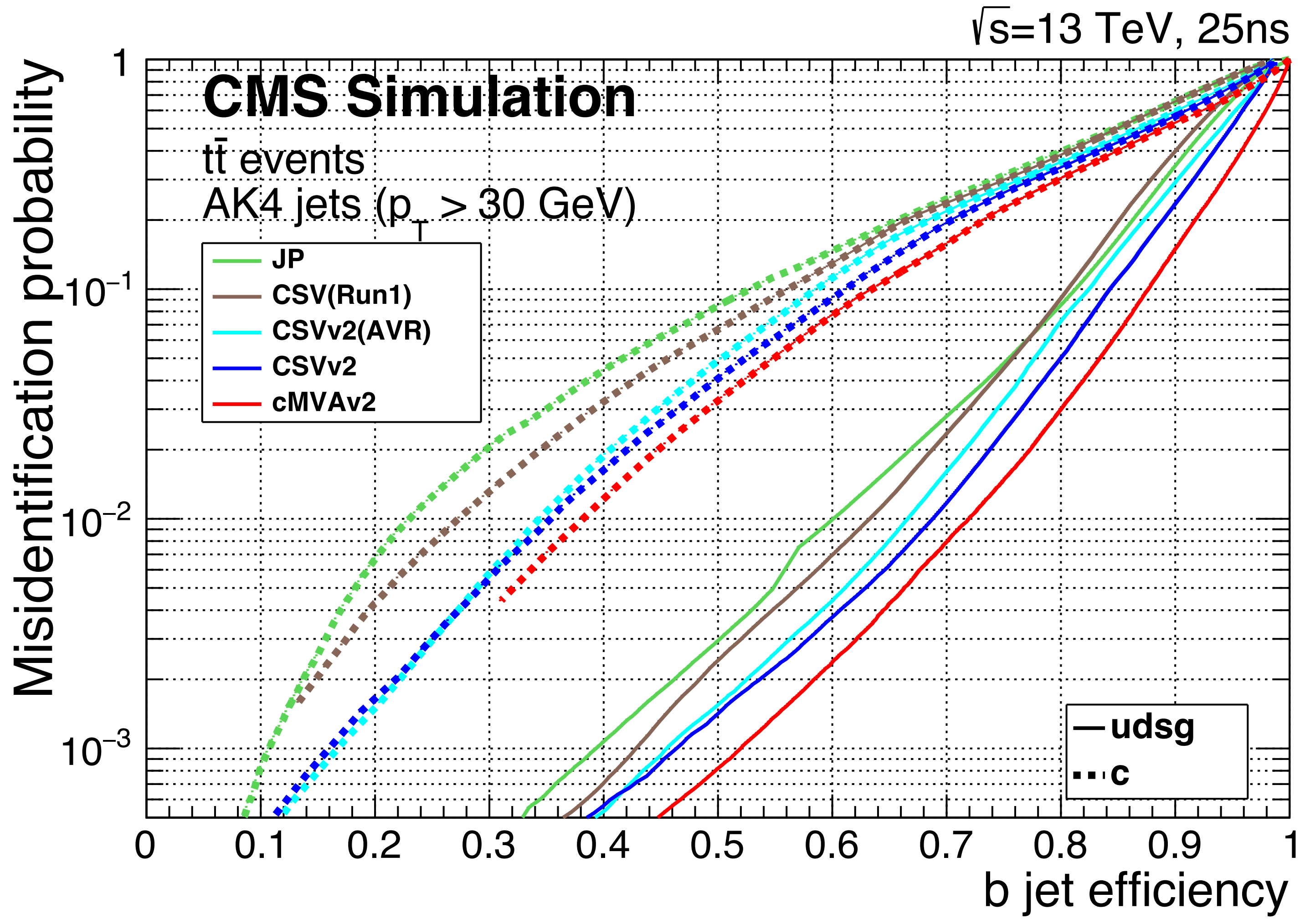
- Jet Probability: likelihood that jets is coming from primary vertex using tracks
- Combined (CSV): combination of displaced tracks with SV info associated to the jet using an MVA
- **CSVv2** evolution of CSV using neural networks

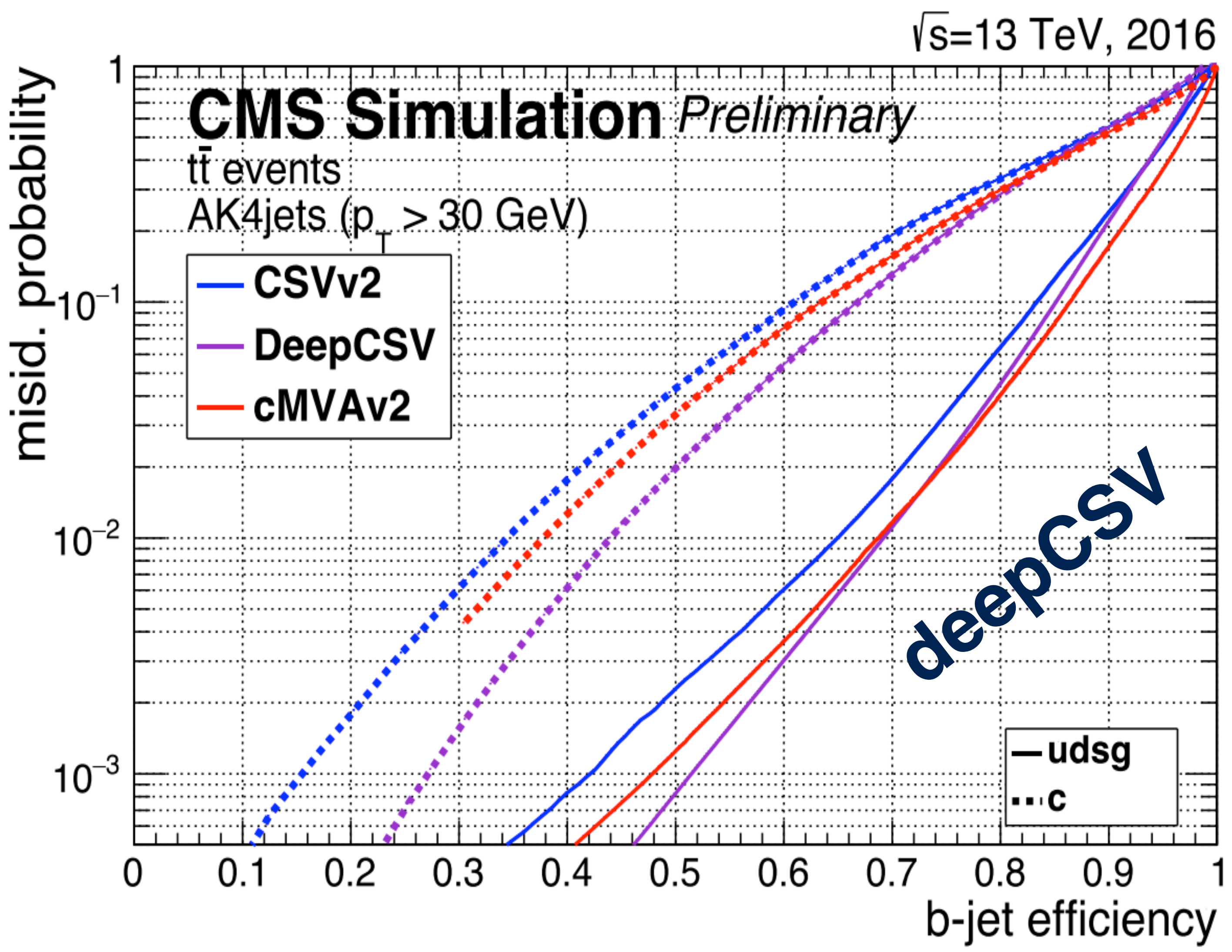
  cMVAv2 combines all the taggers

Tagger	operating point	discriminator value	ϵ_b (%)
JetProbability (JP)	JPL	0.245	≈ 82
	JPM	0.515	≈ 62
	JPT	0.760	≈ 42
Combined Secondary Vertex (CSVv2)	CSVv2L	0.460	≈ 83
	CSVv2M	0.800	≈ 69
	CSVv2T	0.935	≈ 49
Combined MVA (cMVAv2)	cMVAv2L	-0.715	≈ 88
	cMVAv2M	0.185	≈ 72
	cMVAv2T	0.875	≈ 53

deepCSV: based on CSVv2

+ more charged particles, based on deep NN

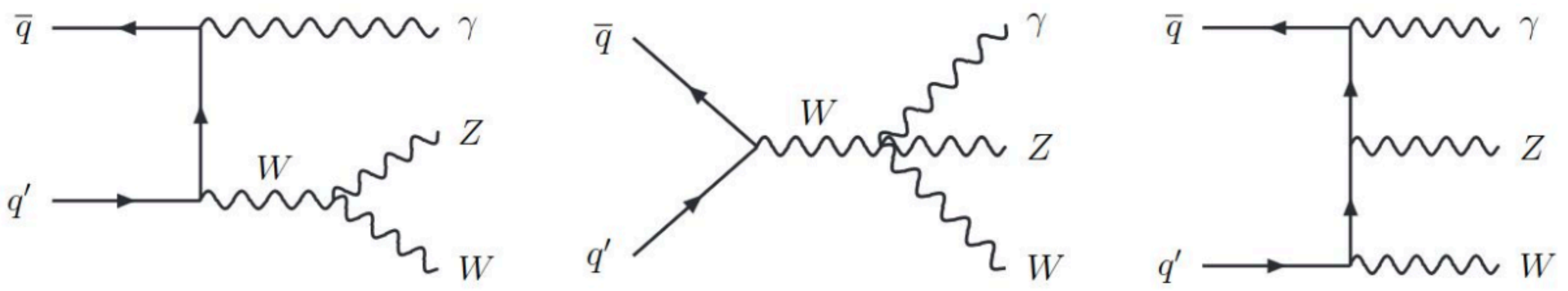




improves ~4% the b-tag efficiency with a mistag rate of 0.1%

Observation of WZγ and WWγ

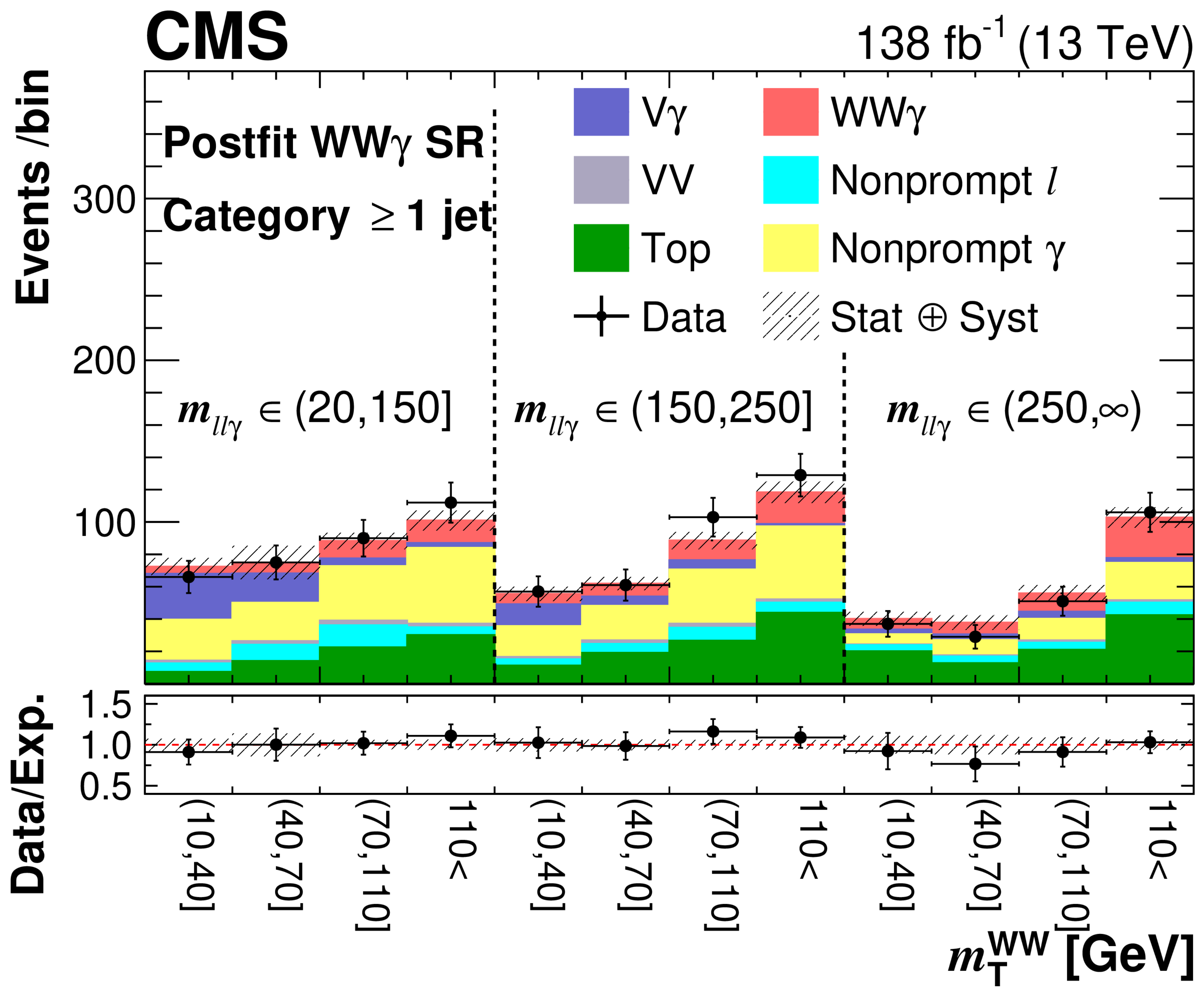
PRL132 (2024) 021802
PRL132 (2024) 121901



SR: 0 and >0 jet, eμ channel only

- SSWWγ and TOP+γ by control regions,
- data-driven non-prompt backgrounds
- maximum likelihood fit of 2D binned distributions.

$$\sigma_{WW\gamma} = 6.0 \pm 0.8(stat) \pm 0.7(syst) \pm 0.6(modeling) fb$$



Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)	$\lvert\bar{\kappa}_u\rvert \leq 7.5$ (6.1)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)	$\lvert\bar{\kappa}_d\rvert \leq 16.6$ (14.7)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)	$\lvert\bar{\kappa}_s\rvert \leq 32.8$ (25.2)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)	$\lvert\bar{\kappa}_c\rvert \leq 45.4$ (25.0)

Sensitive to Higgs couplings with light quarks (no gluon fusion contribution due to Furry's theorem)