Standard Model Precision Measurements

João Guimarães da Costa
(IHEP, Chinese Academy of Sciences)

On behalf of the ATLAS and CMS Collaborations

Lepton Photon 2023
Melbourne, Australia
17 July 2023

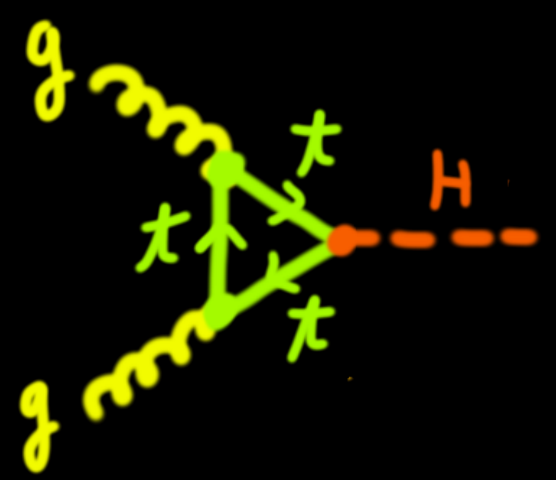
Why Standard Model Physics?

...in the era of the Higgs Boson

Search for deviations from SM:

- Many new physics models reveal deviations from SM similar to the ones from NLO or NNLO QCD

  Example: contact interactions as opposed to bump-hunting search

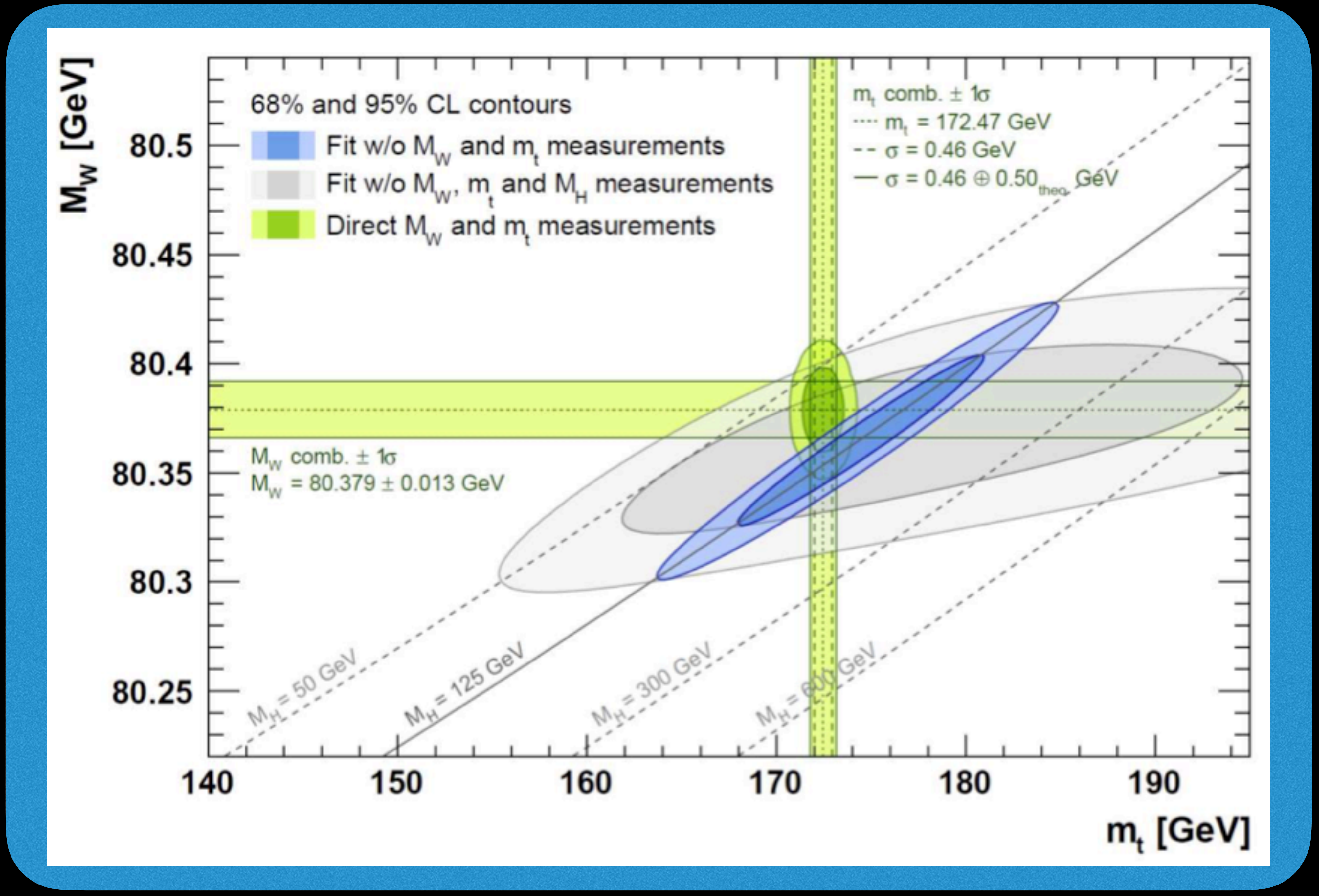


Establish:

- Understanding of backgrounds to new physics searches
- Improved proton PDFs

Explore the SM self consistency:

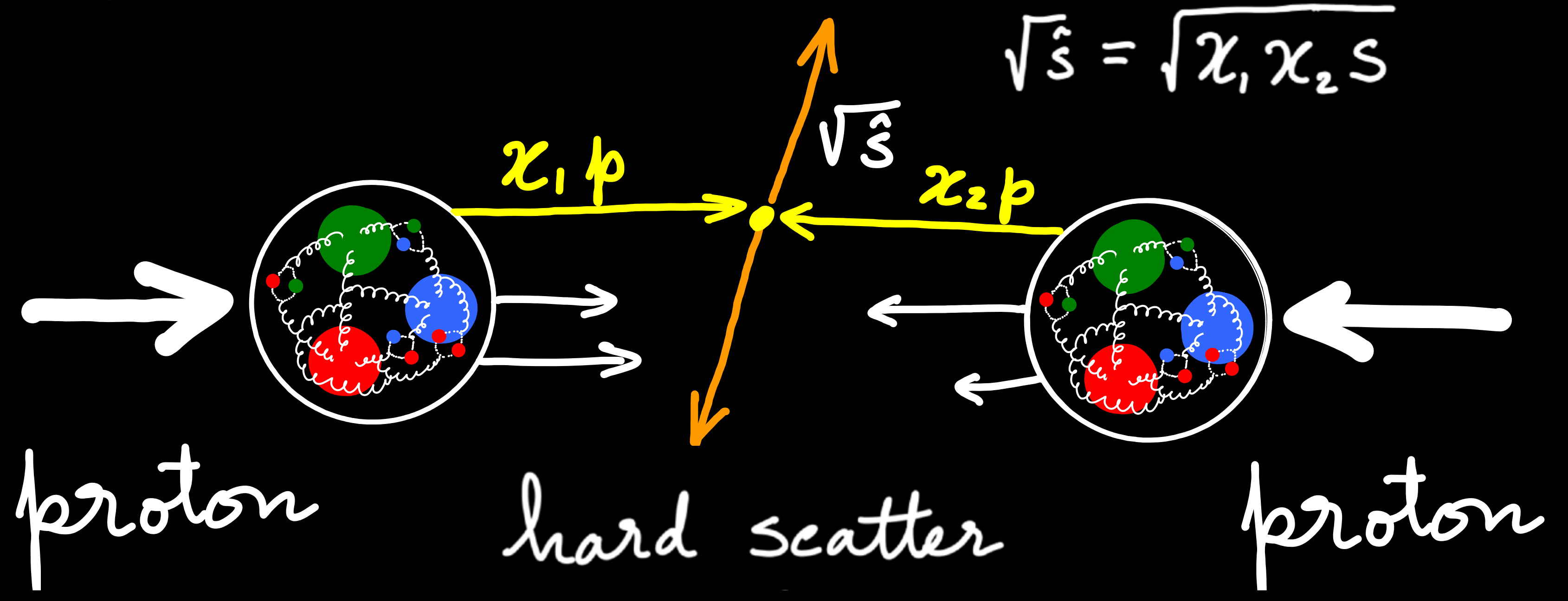
Measure its parameters with high-precision



After the Higgs discovery,
measuring the top and W mass precise
enough is an enduring challenge

How we do it?

LHC:



Number of collisions that can be produced in one detector **per cm² and per second**

$$\mathcal{L} = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y}$$

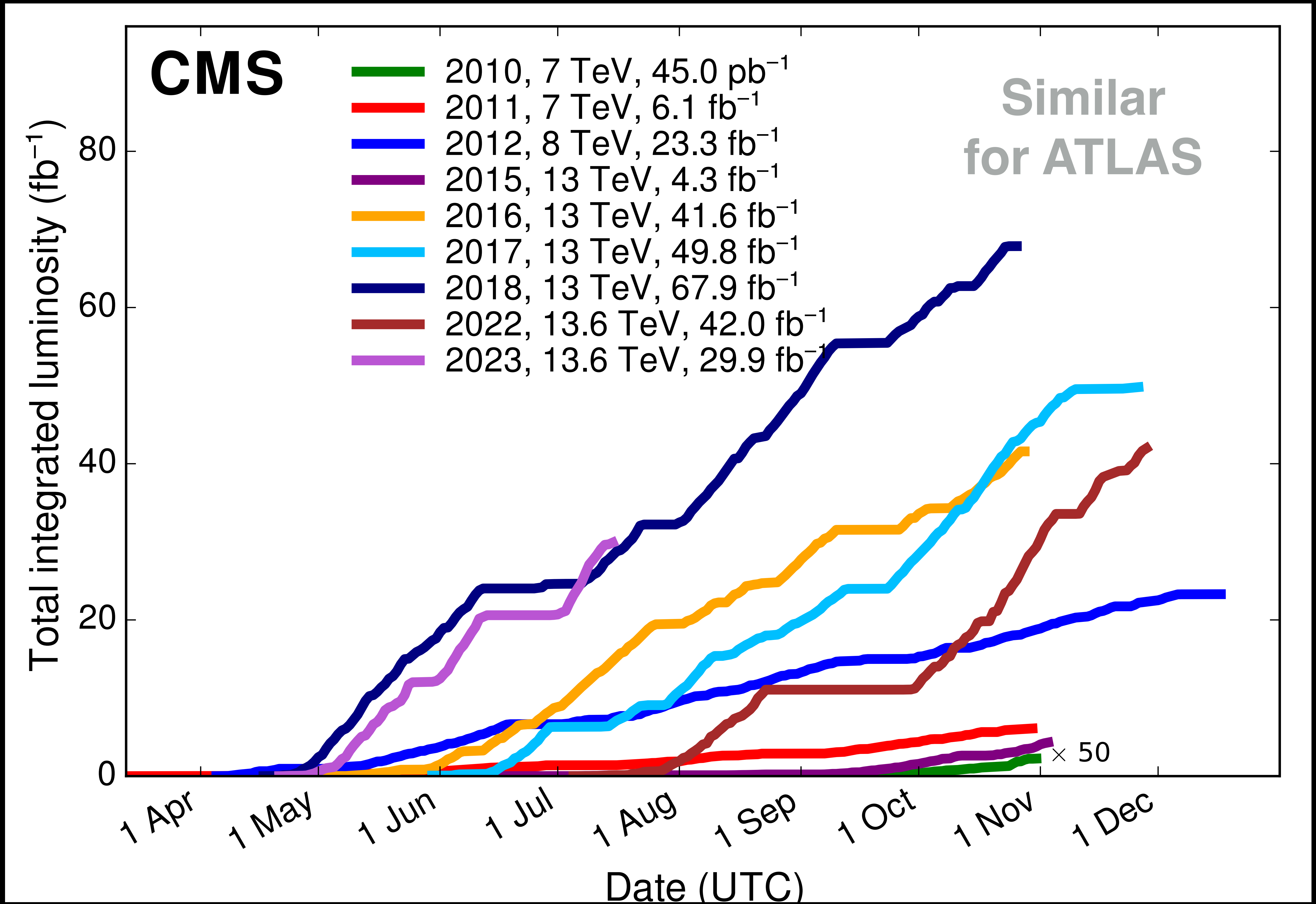
Number of protons per bunch (N)

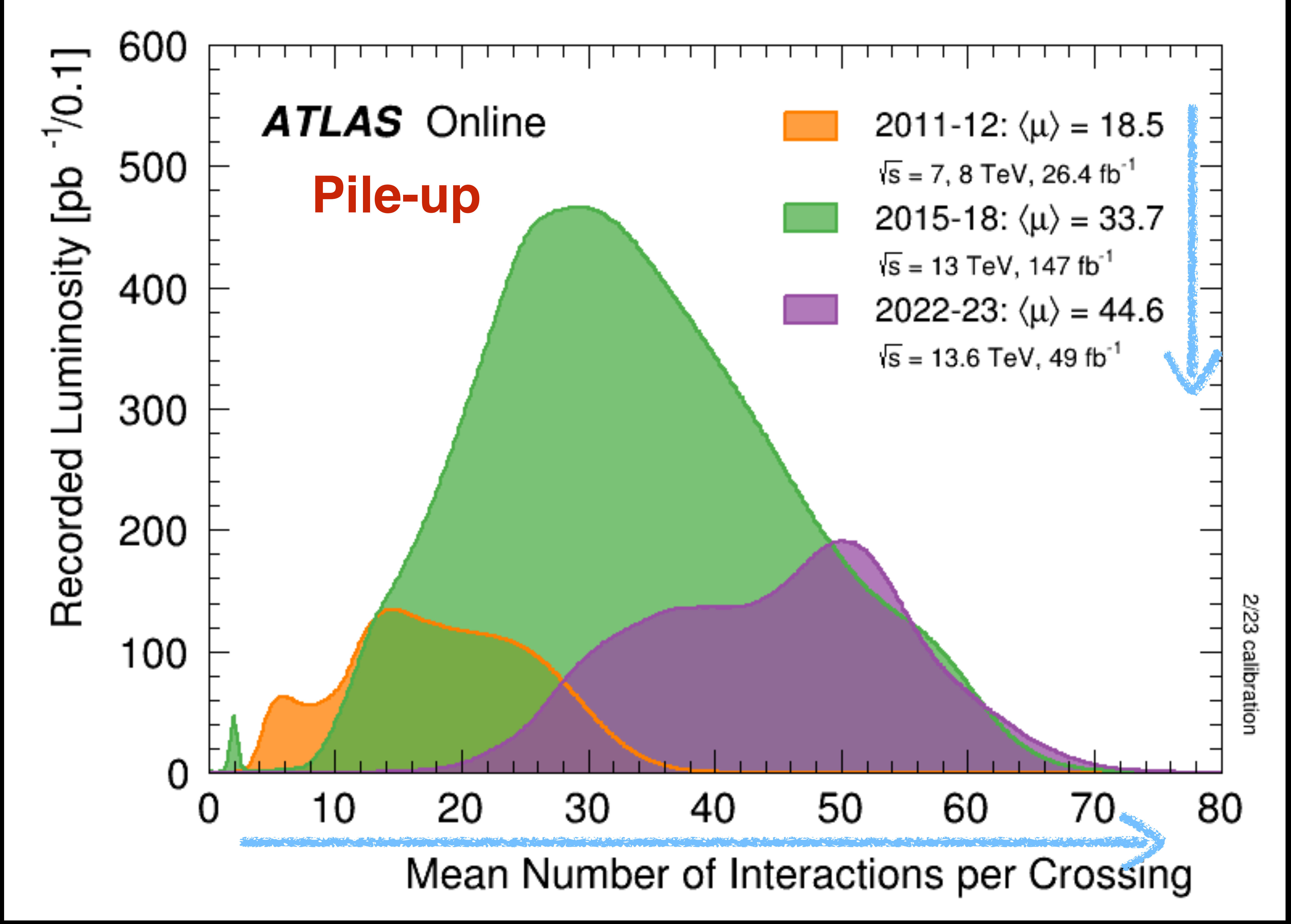
Number of bunches (k_b)

Beam size at interaction point (IP) ($\sigma_x \sigma_y$)

First papers (2010): $L_{total} \sim nb^{-1}$

Now (2023): $L_{total\ integrated} \sim 260\ fb^{-1}$





How we do it?

Probes

Jets
inclusive
dijets
multijets
jet sub-structure
HF production

Photons
inclusive
diphotons
γ + jets
γ + HF

Hadrons

Physics

Non-perturbative QCD

Perturbative QCD

Proton PDF
Valence, strange quarks
Gluons

EWK corrections

Electroweak parameters

Probes

W/Z Bosons
inclusive
V+jets
Ratio W/Z + jets
W and Z + HF

Top quark

Dibosons
WW, WZ, ZZ, Wγ, Zγ
VV+jets

Higgs

Combine analyses, *e.g.* to obtain the most information about PDFs

How we do it?

Probes

Jets
inclusive
dijets
multijets
jet sub-structure
HF production

Photons
inclusive
diphotons
γ + jets
γ + HF

Hadrons

Physics

Non-perturbative QCD

Perturbative QCD

Proton PDF
Valence, strange quarks
Gluons

EWK corrections

Electroweak parameters

Probes

W/Z Bosons
inclusive
V+jets
Ratio W/Z + jets
W and Z + HF

Top quark

Dibosons
WW, WZ, ZZ, Wγ, Zγ
VV+jets

Higgs

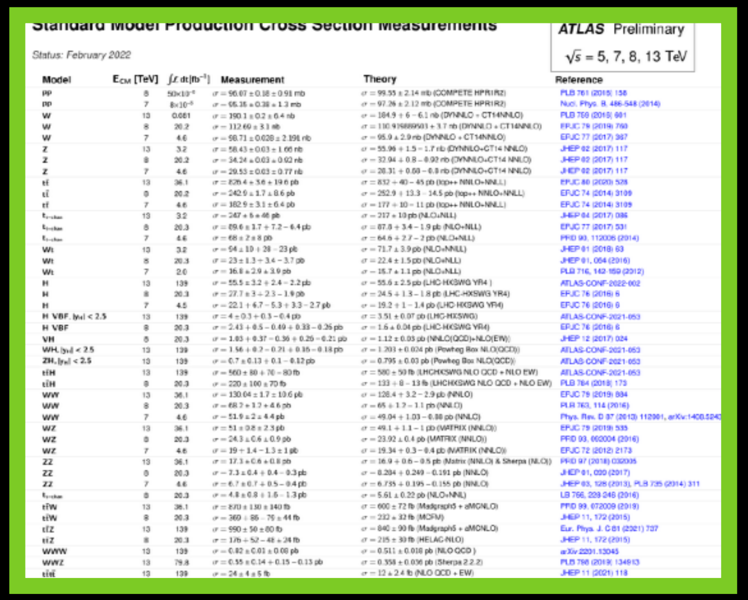
Combine analyses, *e.g.* to obtain the most information about PDFs

Many topics left out:
- SM Higgs production
- Heavy-flavour physics (B-physics)
- Heavy-ion physics (physics in dense media)

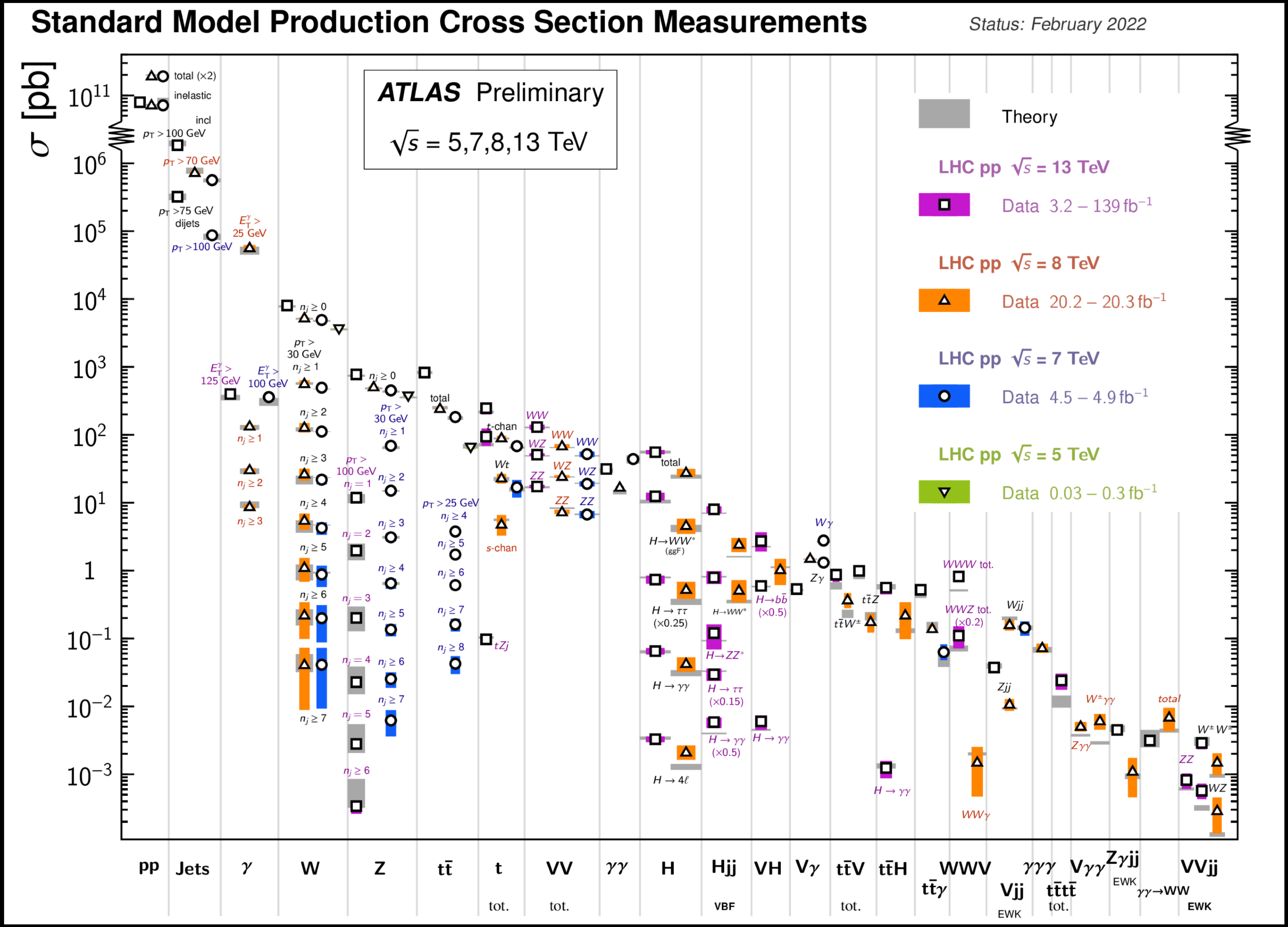
Will give emphasis to most recent results

Overview of Standard Model measurements at LHC

Publication list



15 orders of magnitude



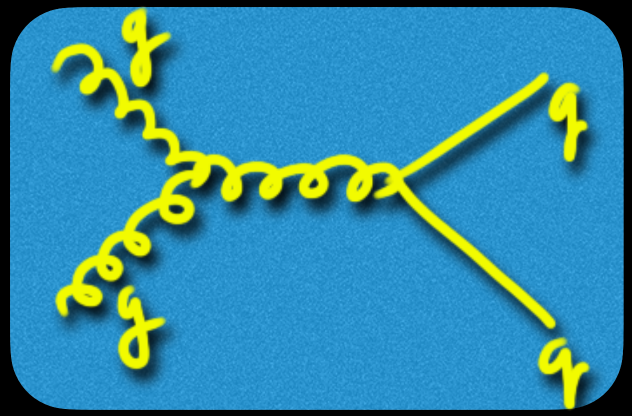
CMS has similar plots (see)
and explored similar phase space

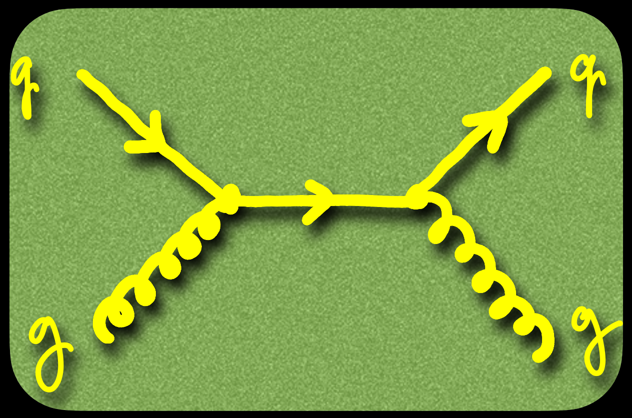
QCD with Jets and Photons

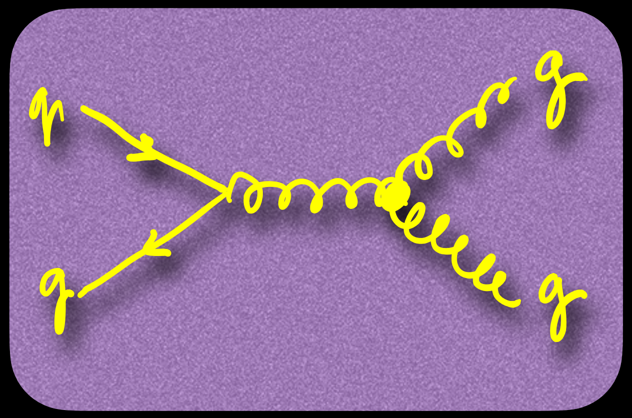
Multi-differential measurements of the dijet cross section

CMS-PAS-SMP-21-008

Double-differential (2D) measurements

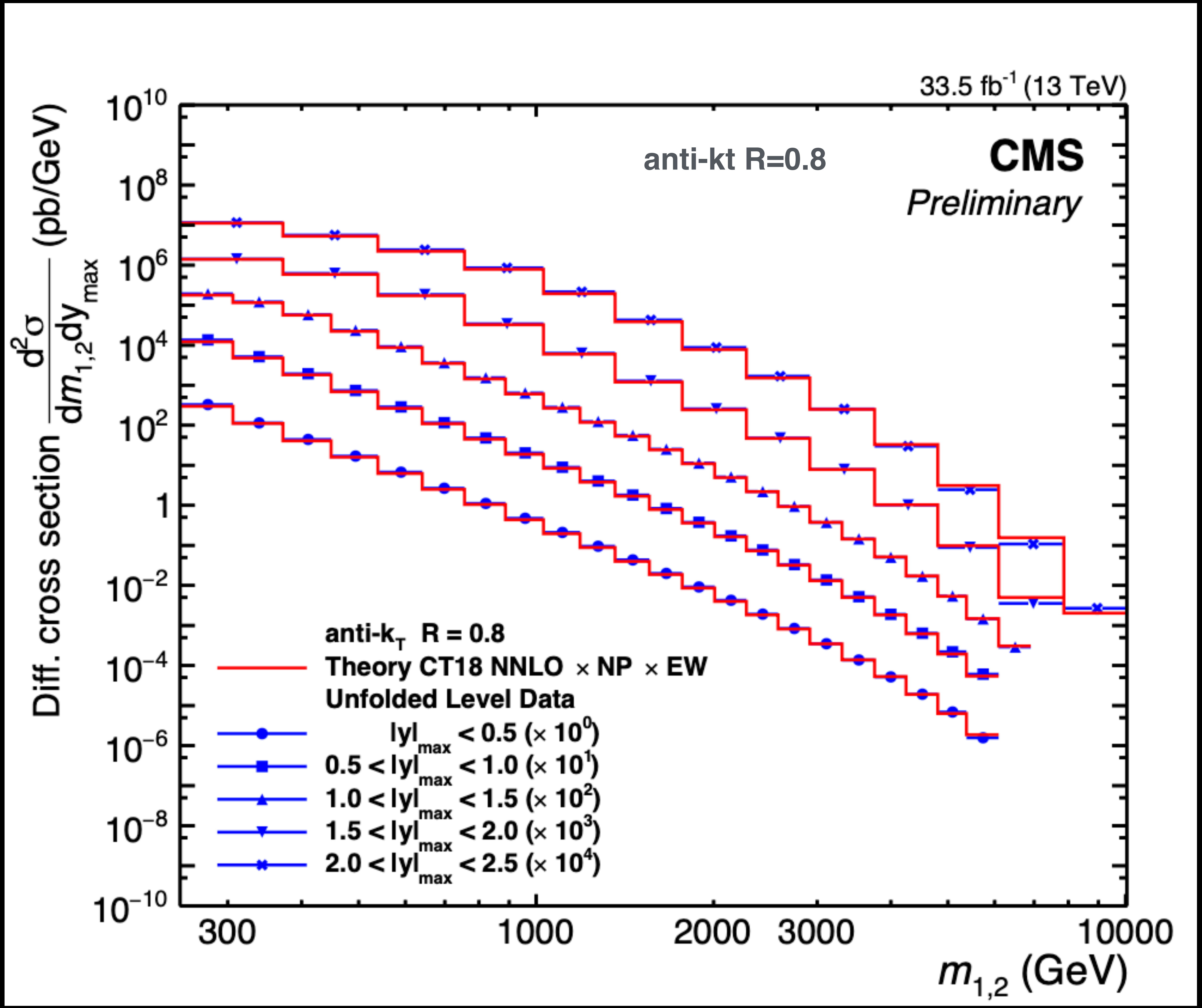






Measurement with jet algorithms:
anti-kt R=0.4
anti-kt R=0.8

Measured as a function of the kinematic properties of the two jets with largest transverse momenta

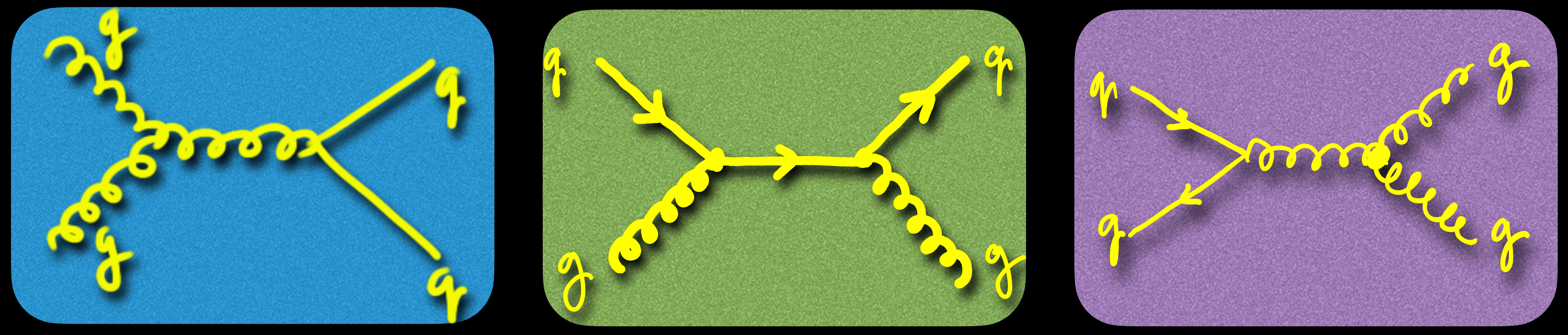


Dijet invariance mass

Multi-differential measurements of the dijet cross section

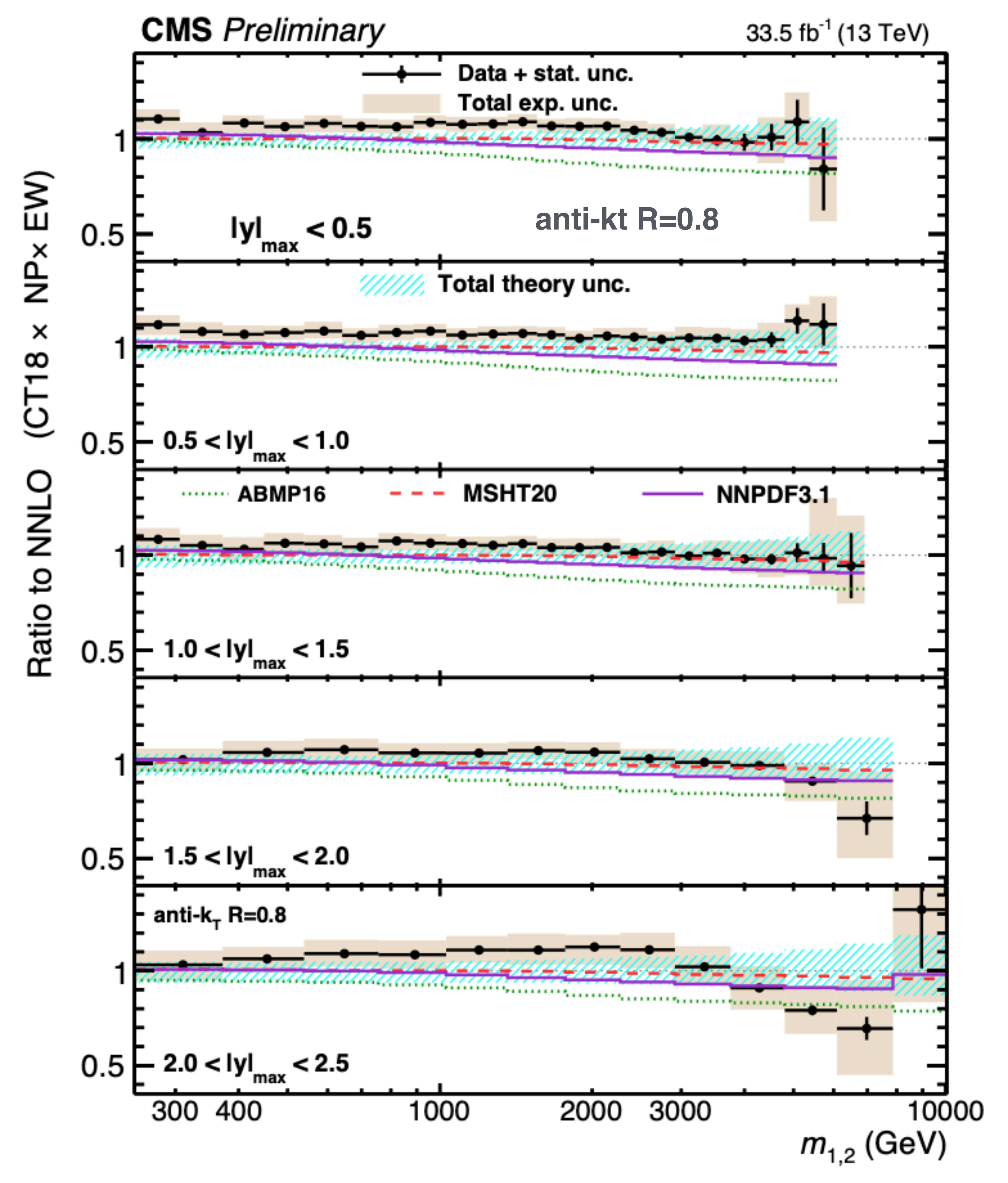
CMS-PAS-SMP-21-008

Double-differential (2D) measurements



Measurement with jet algorithms:
anti-kt R=0.4
anti-kt R=0.8

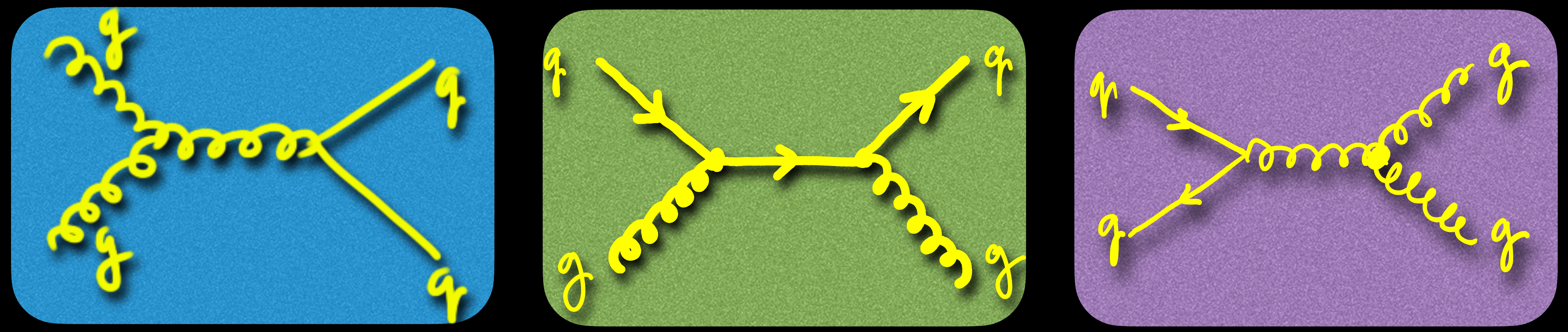
Comparison to fixed-order theory calculations at NNLO, for different PDF predictions:
CT18
ABMP16
MSHT20
NNPDF3.1



Multi-differential measurements of the dijet cross section

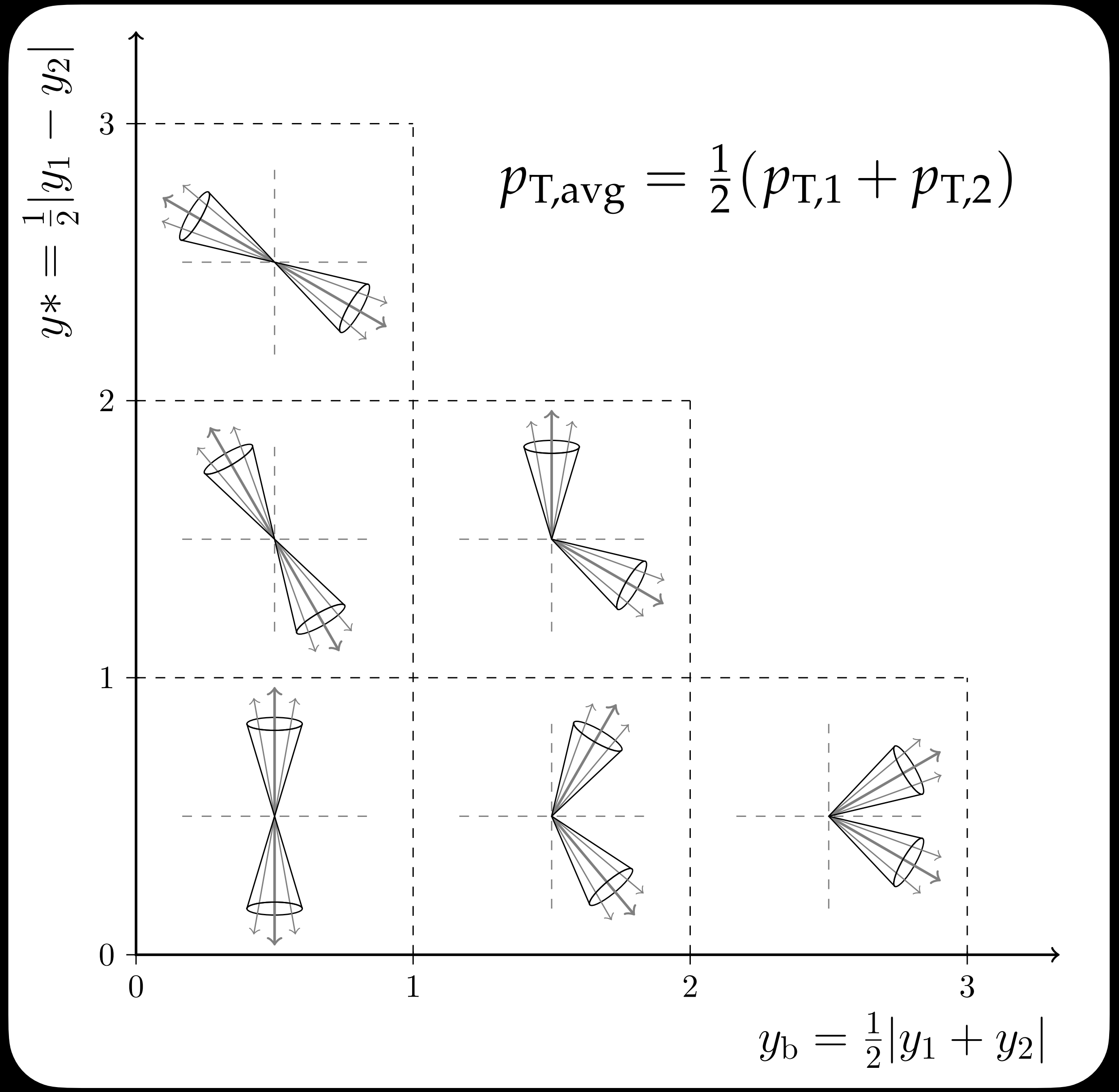
CMS-PAS-SMP-21-008

Triple-differential (3D) measurements

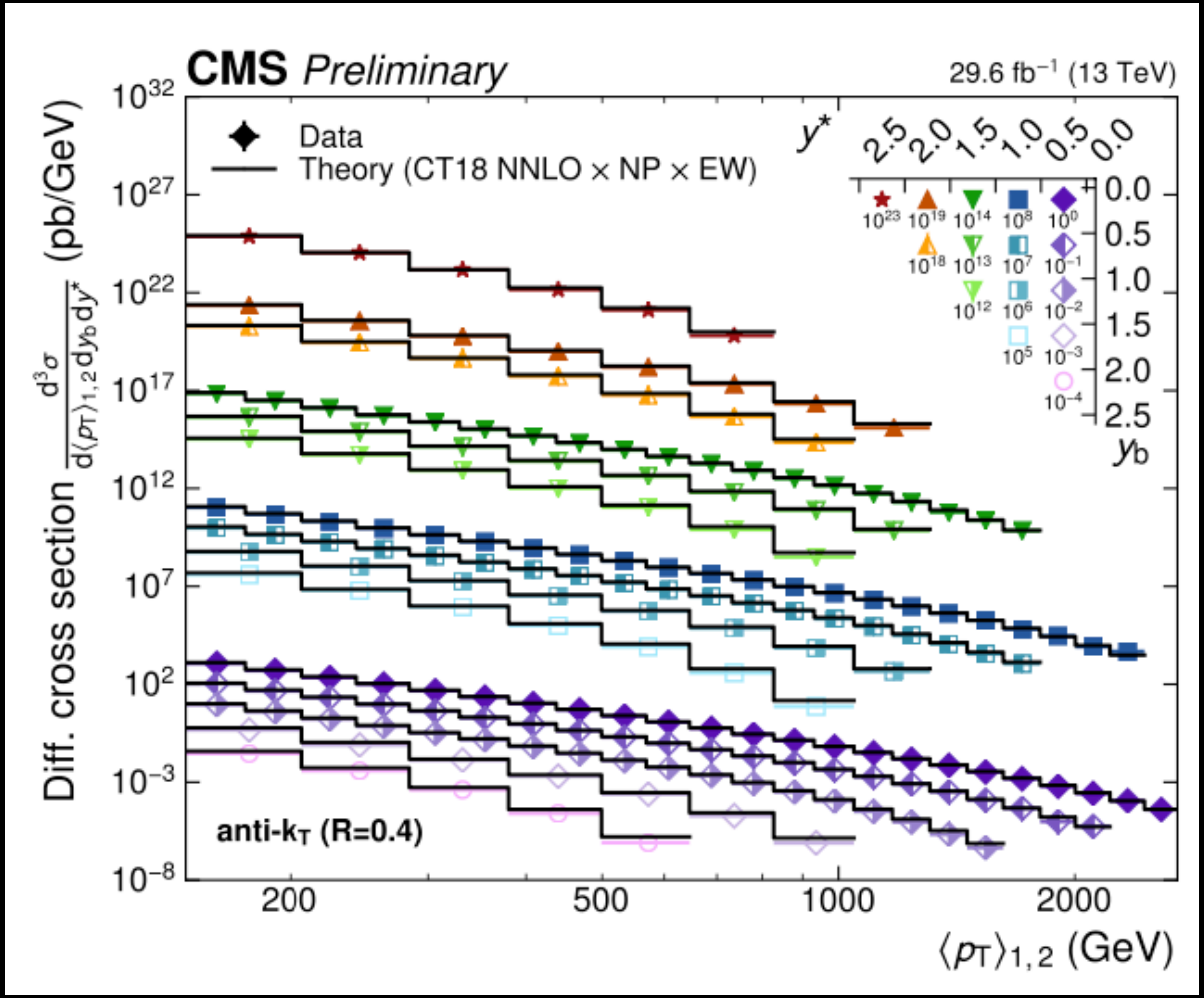


Measurement with jet algorithms:
anti-kt R=0.4
anti-kt R=0.8

y^*: dijet rapidity separation



y_b: total boost of dijet system

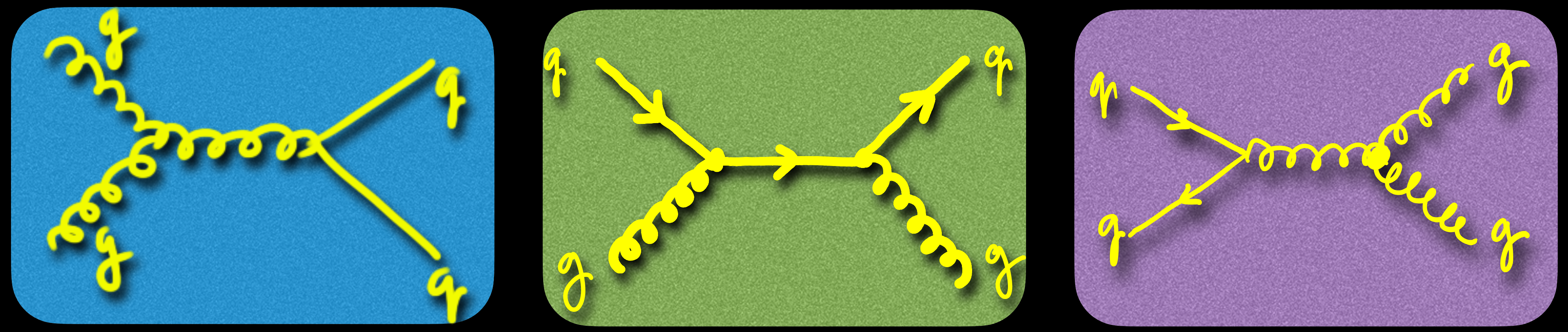


Average dijet transverse momentum

Multi-differential measurements of the dijet cross section

CMS-PAS-SMP-21-008

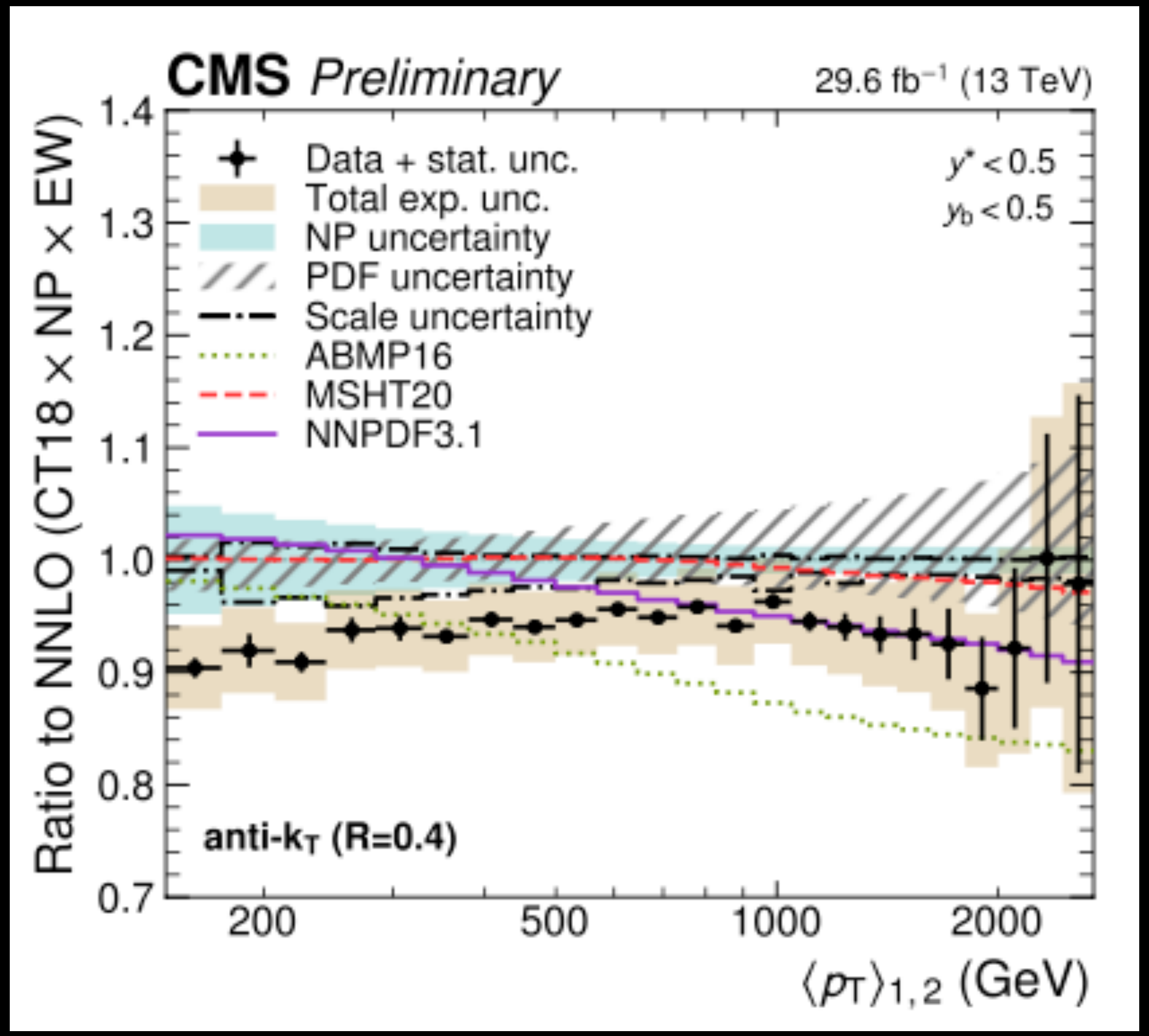
Triple-differential (3D) measurements

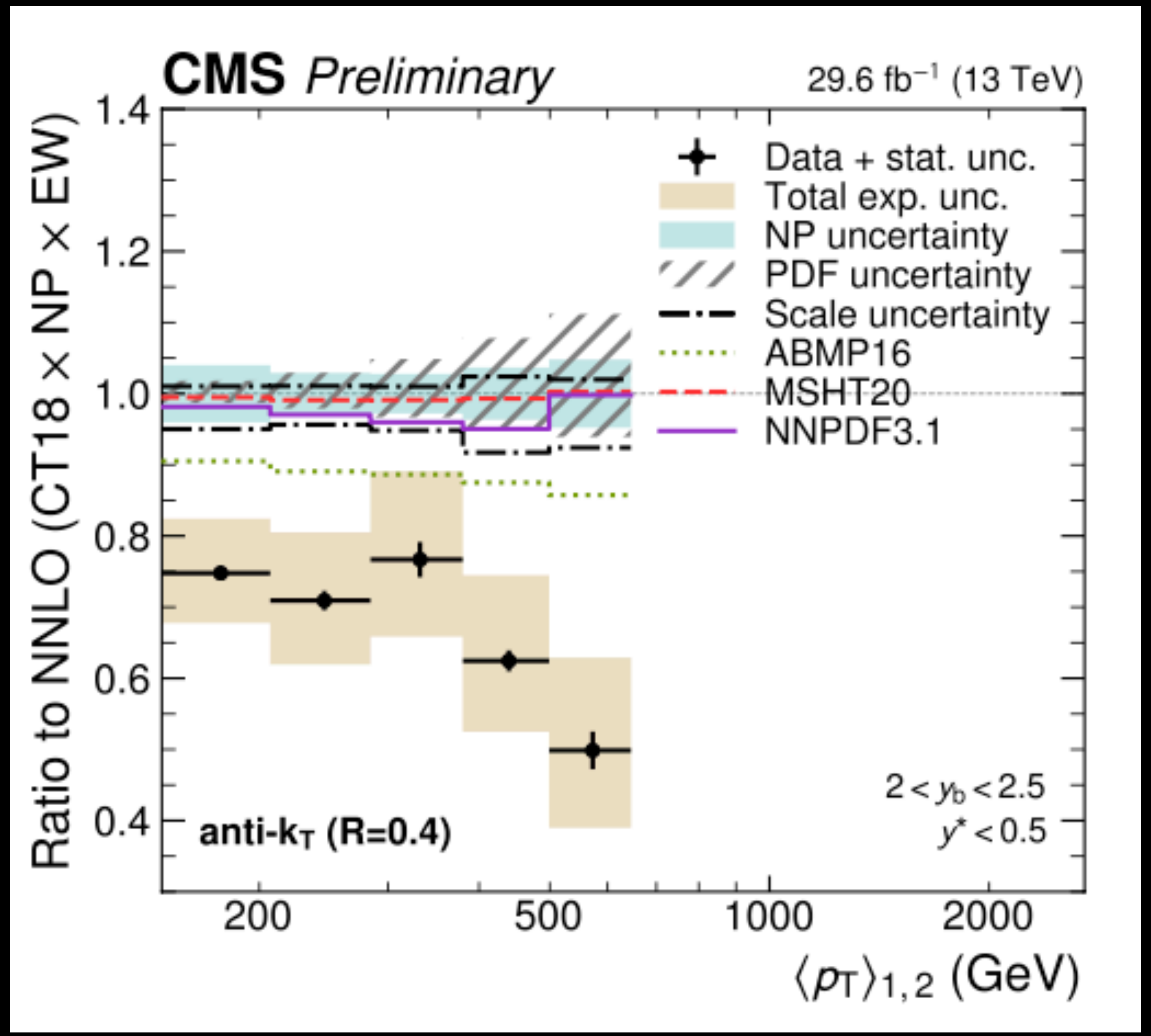


Measurement with jet algorithms:
anti-kt R=0.4
anti-kt R=0.8

Comparison to fixed-order theory calculations at NNLO, for different PDF predictions:
CT18
ABMP16
MSHT20
NNPDF3.1

Total of 15 rapidity regions

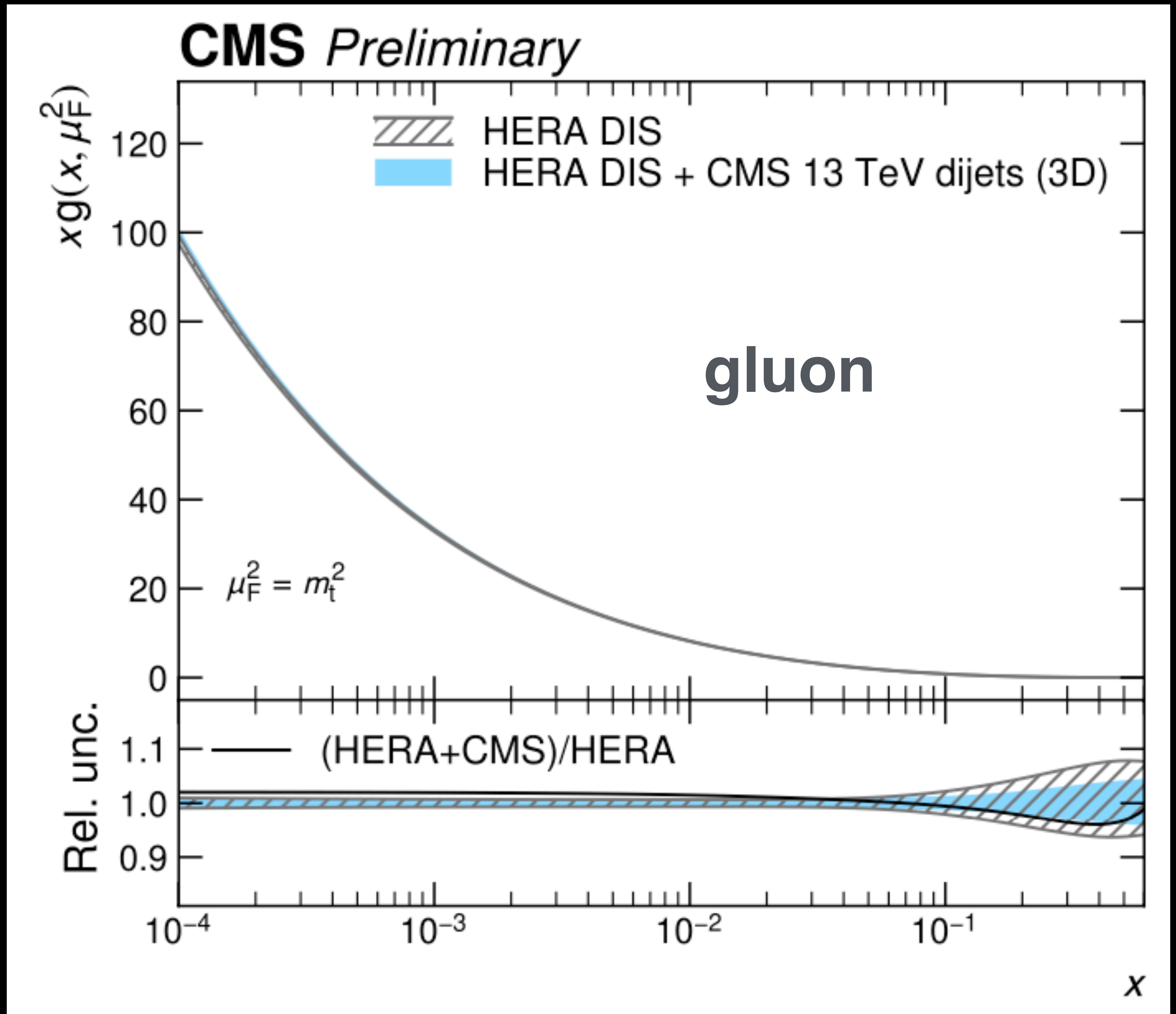


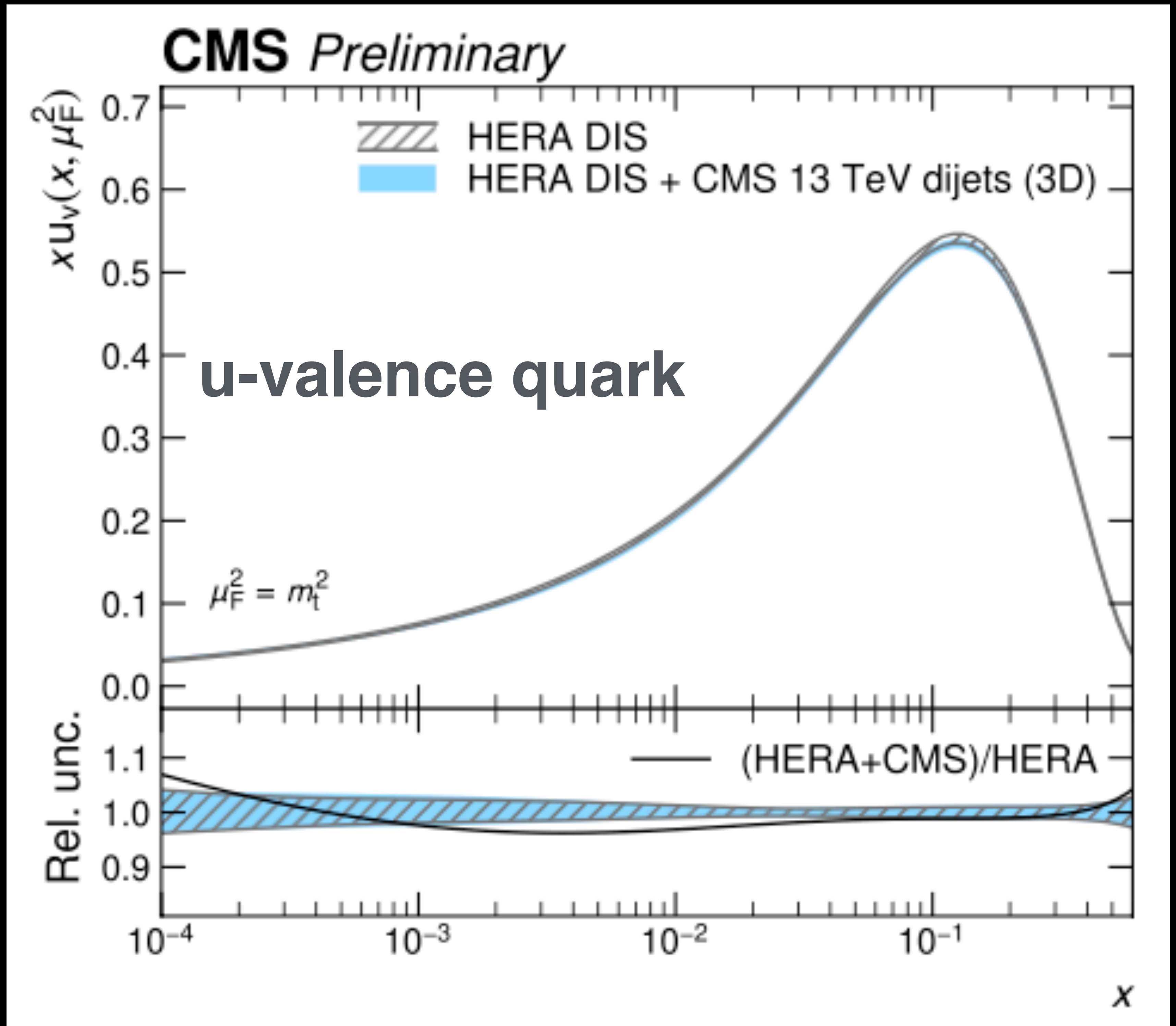


Multi-differential measurements of the dijet cross section

CMS-PAS-SMP-21-008

PDF fits from HERA DIS and CMS 3D dijet data





CMS+HERA: χ^2 / n_{dof} = ~1.17

Extraction of Strong Coupling Constant (α_S)

PDF fit repeated with α_S as a free parameter

2D: $\alpha_s(m_Z) = 0.1201 \pm 0.0010\,(\text{fit}) \pm 0.0005\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0006\,(\text{param.})$

3D: $\alpha_s(m_Z) = 0.1201 \pm 0.0012\,(\text{fit}) \pm 0.0008\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0005\,(\text{param.})$

About 1σ from world average

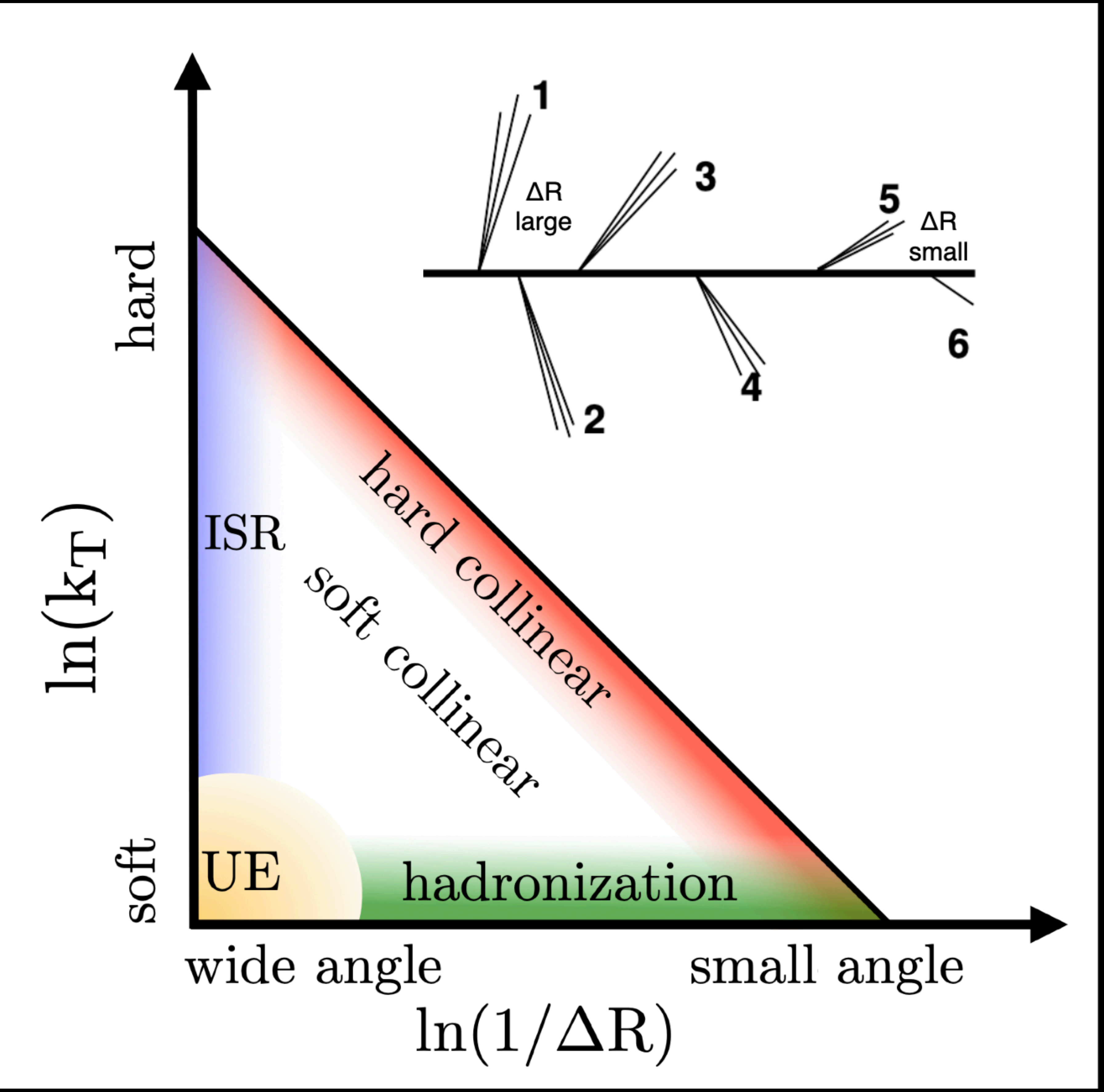
Measurement of primary Lund Jet Plane density

CMS PAS SMP-22-007

Lund Jet Plane: representing QCD radiation in parton shower/internal structure of jets

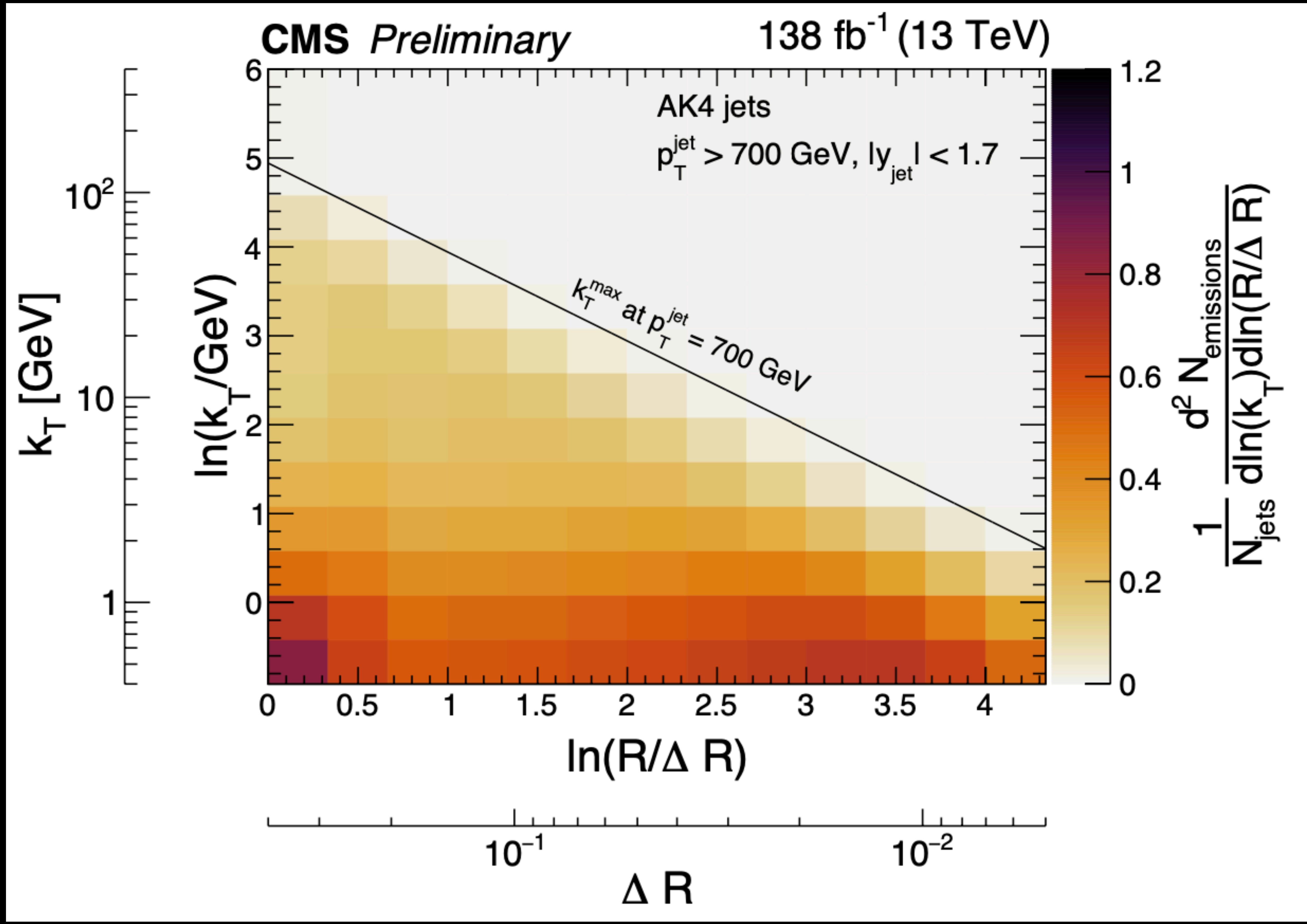
Representation of the phase space of 1 → 2 partonic splittings inside jets

Transverse momentum k_T of the emission relative to its emitter



Splitting angle of the branching ΔR

Anti-K_T 4 Jets



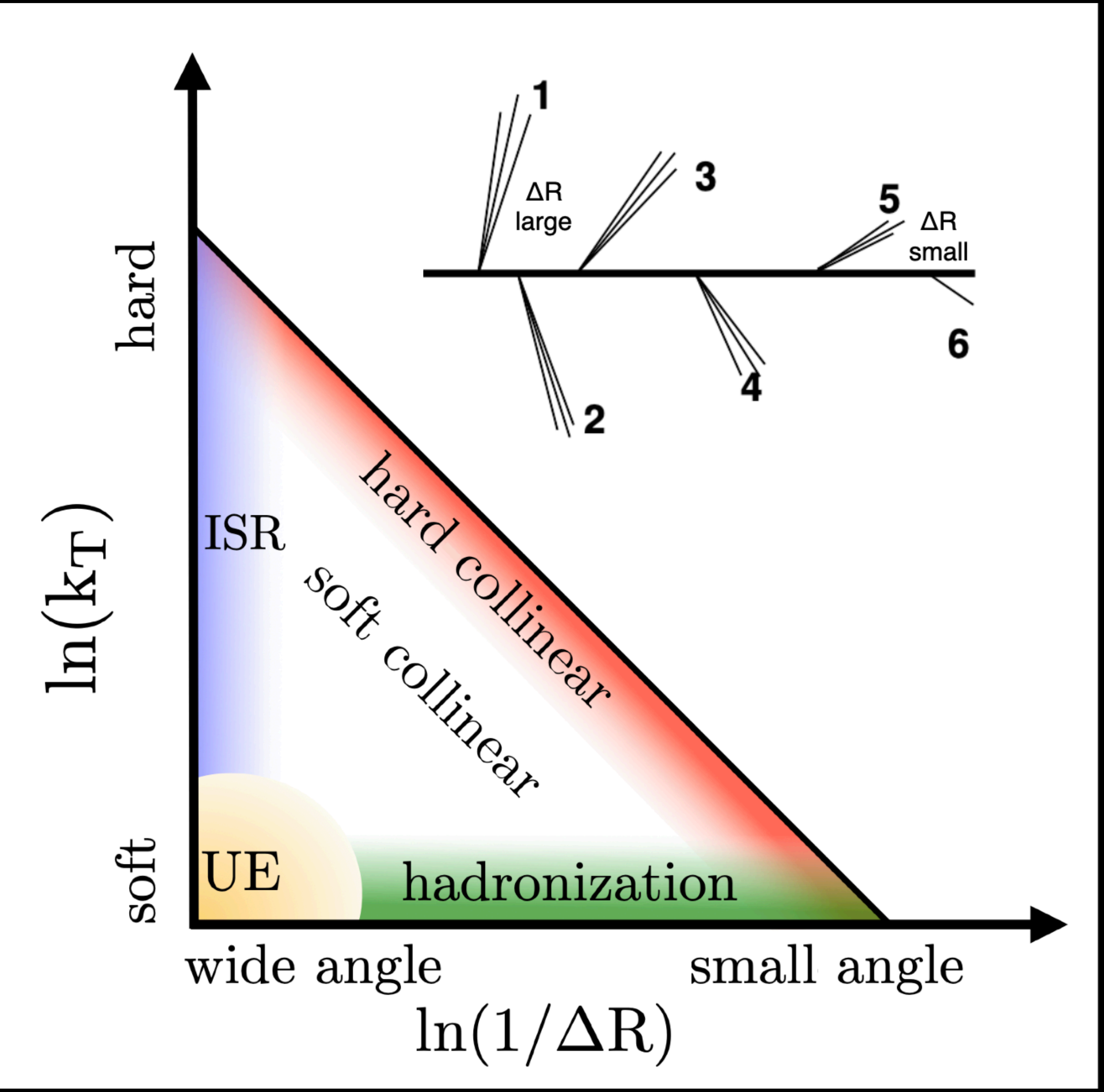
Measurement of primary Lund Jet Plane density

CMS PAS SMP-22-007

Lund Jet Plane: representing QCD radiation in parton shower/internal structure of jets

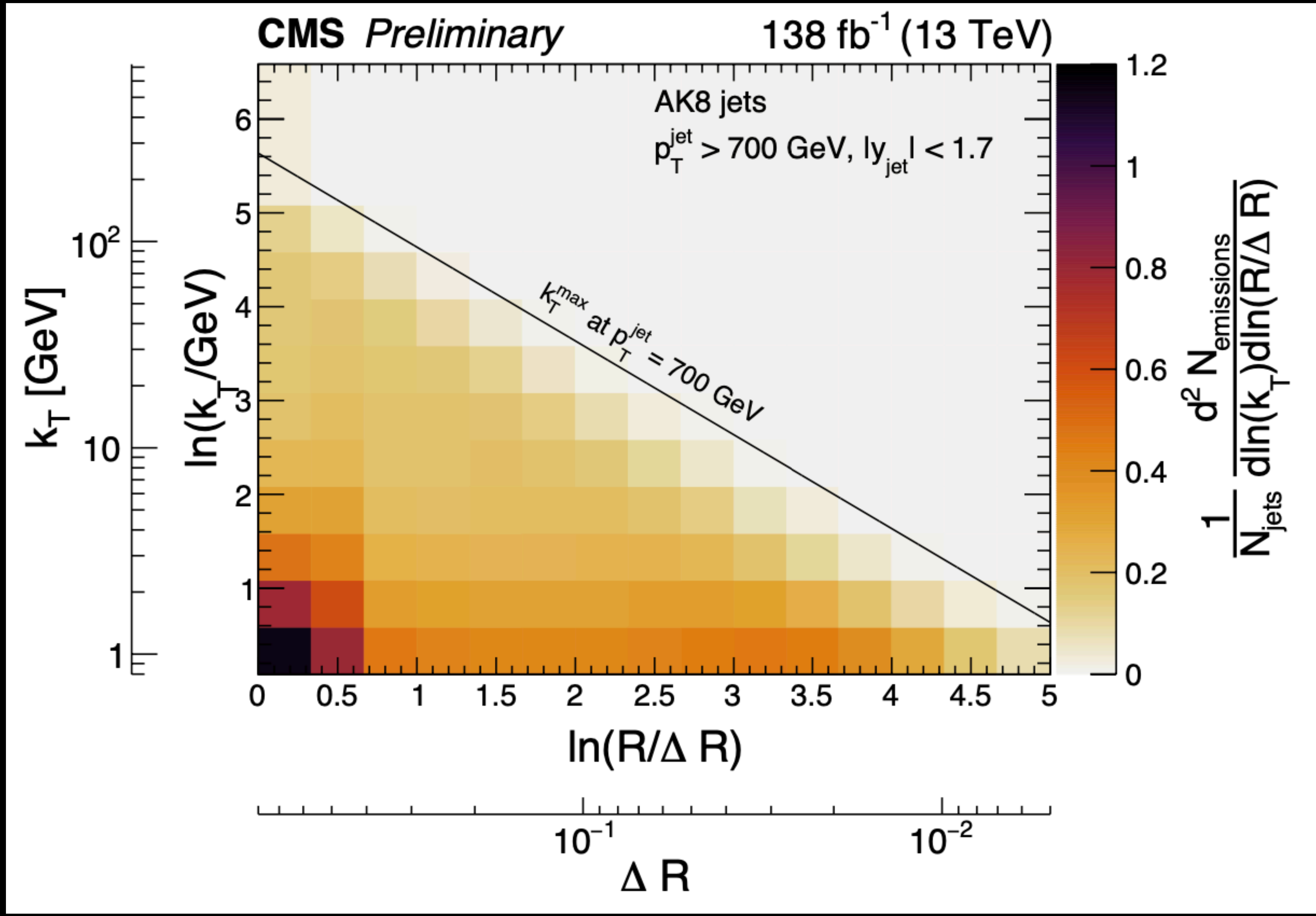
Representation of the phase space of 1 → 2 partonic splittings inside jets

Transverse momentum k_T of the emission relative to its emitter



Splitting angle of the branching ΔR

Anti-K_T 8 Jets

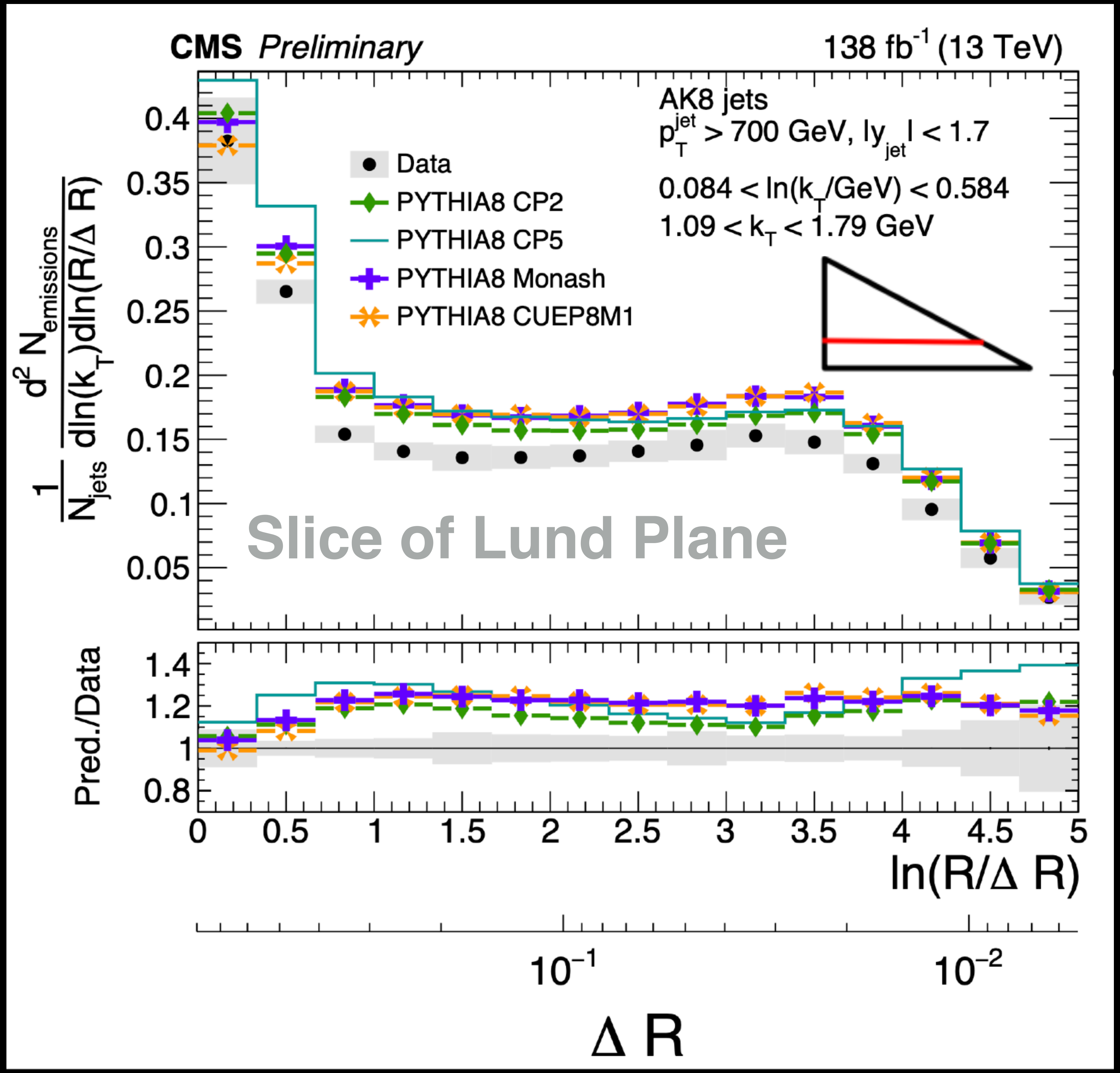


Measurement of primary Lund Jet Plane density

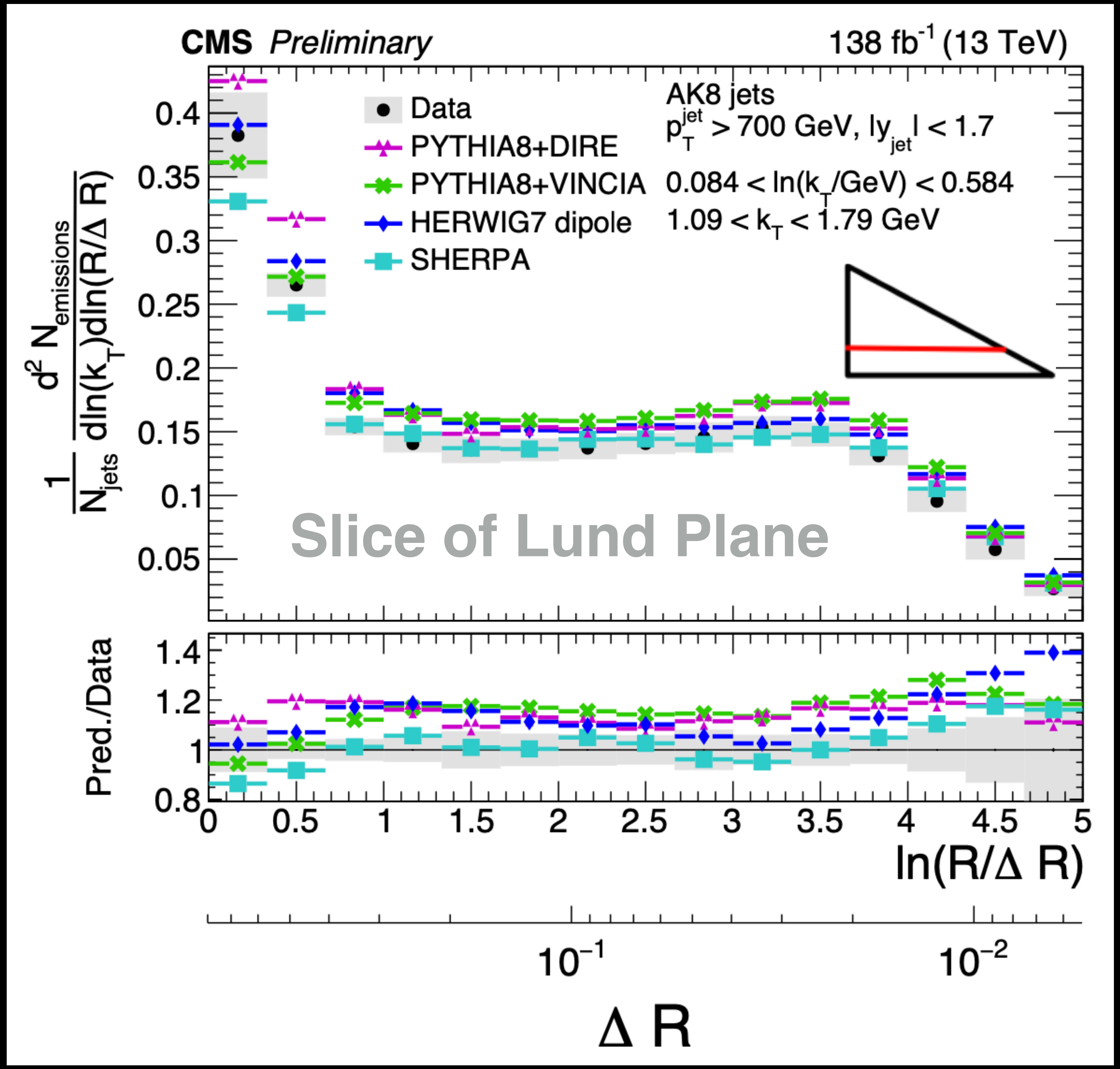
CMS PAS SMP-22-007

Measurement can be used as an input to improve the description from event generators and for future developments of parton showers with corrections beyond leading-logarithmic accuracy

Different Pythia tunes



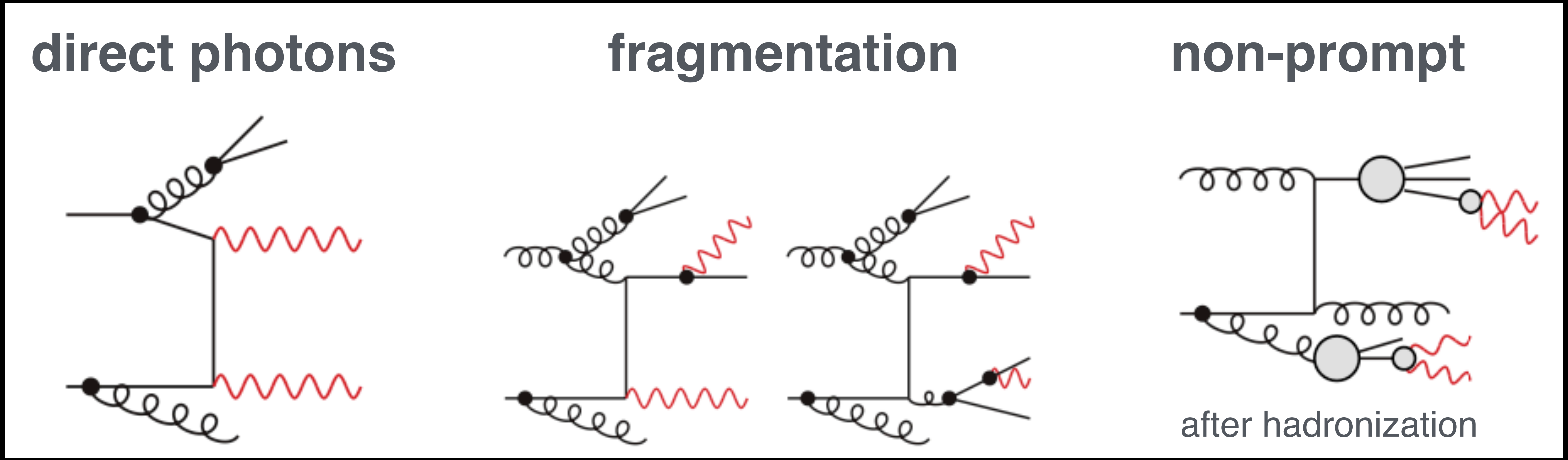
Different parton showers

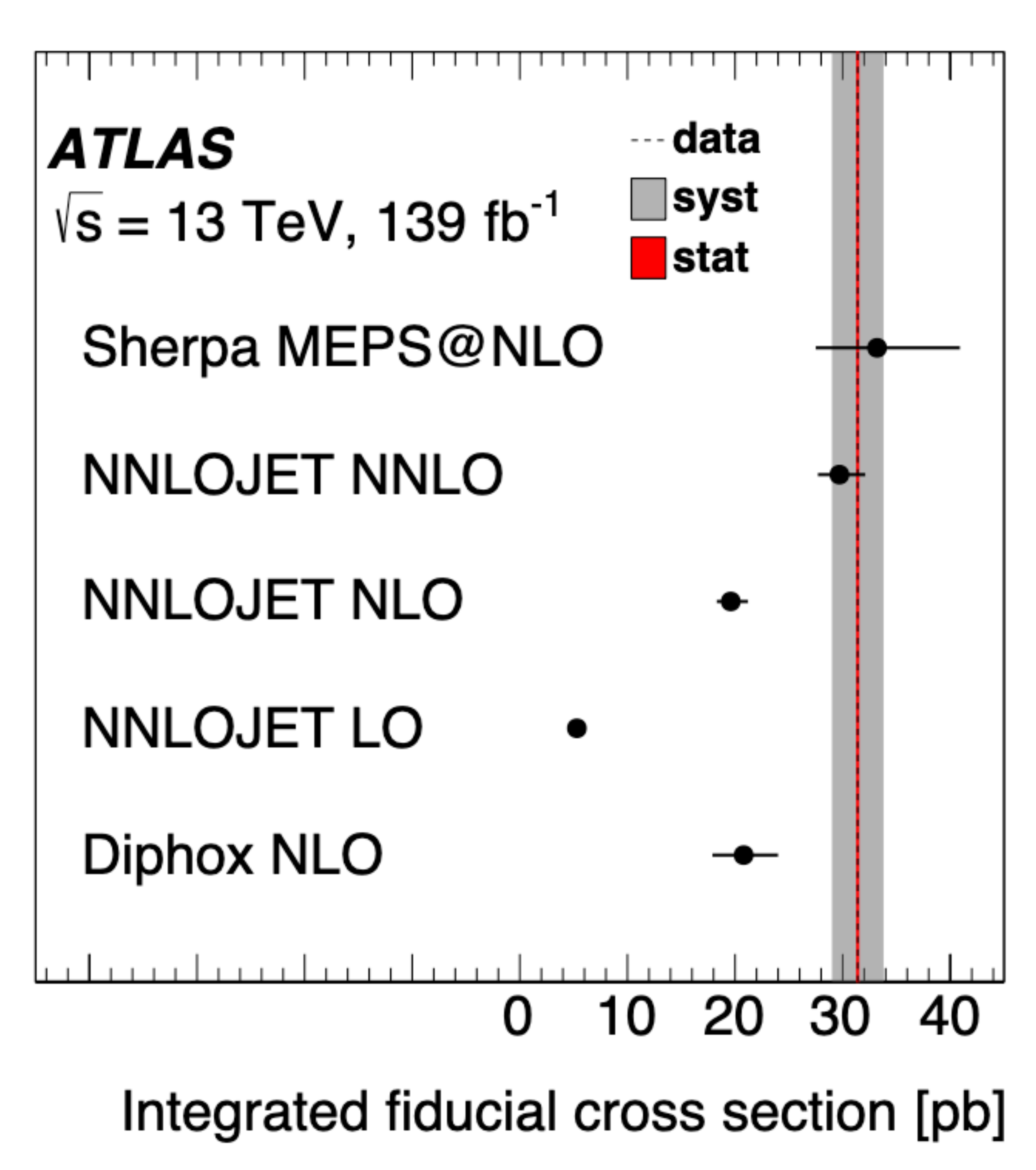


Similar studies from ATLAS published: Phys. Rev. Lett. 124, 222002

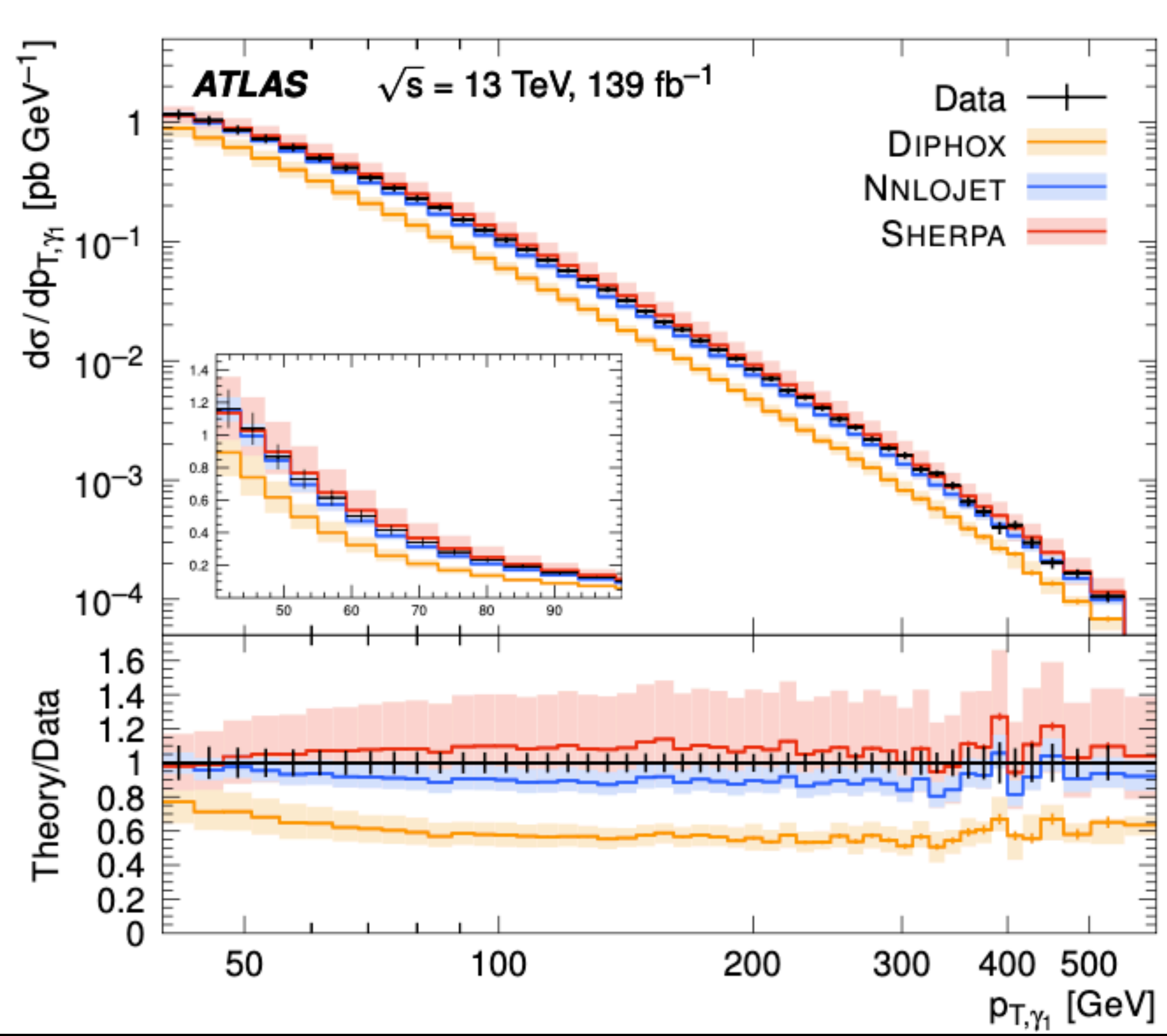
Production cross section of pairs of isolated photons

JHEP 11 (2021) 169





Higher order corrections at NNLO necessary to describe the data



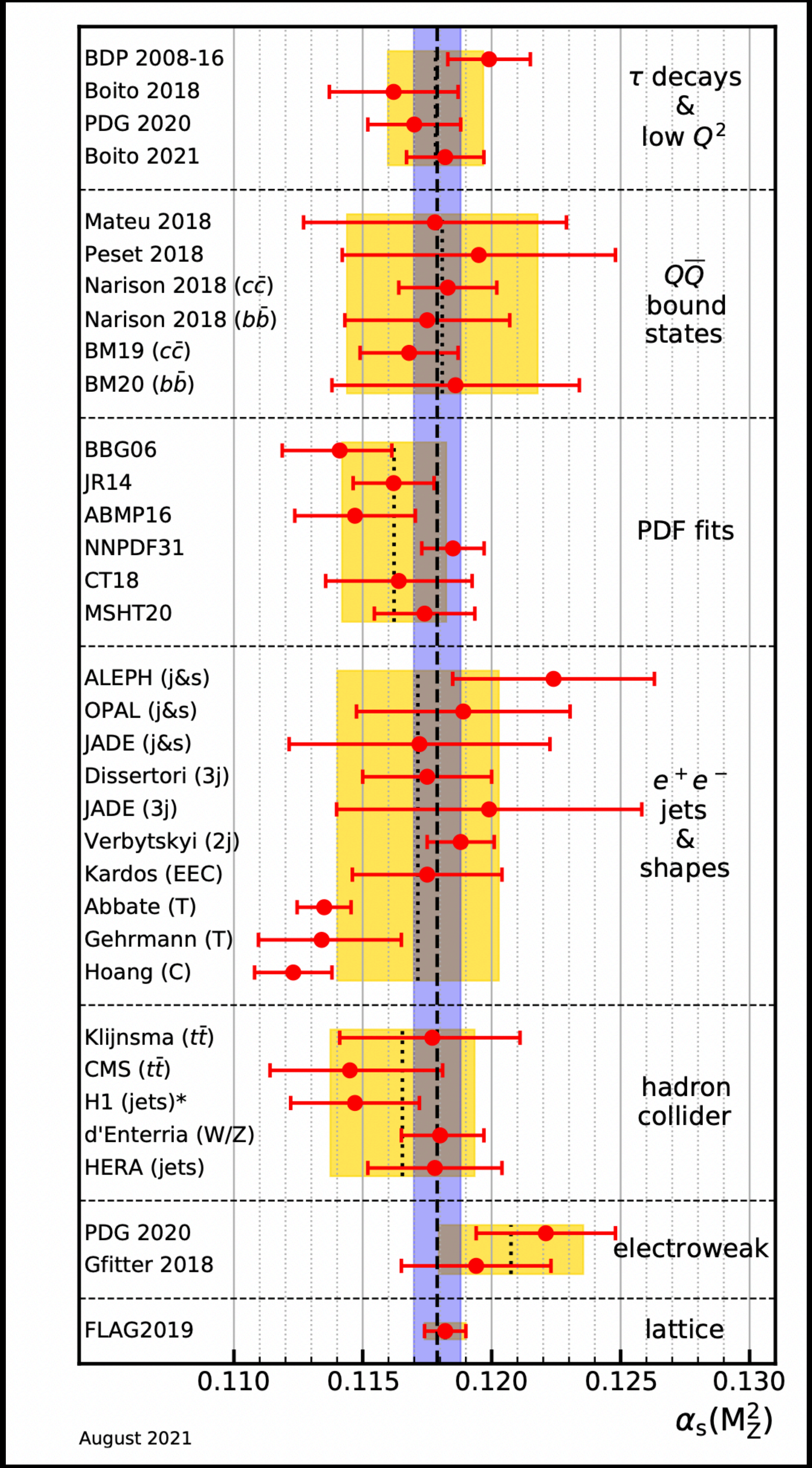
The strong coupling strength α_s

The strong force is still the least well known interaction of nature
α_s uncertainty ~ 1%

- Impacts physics at the Planck scale:
  - EW vacuum stability, Grand Unification
- Is among the dominant uncertainties of several precision measurements at colliders
  - Higgs couplings at the LHC
  - EW precision observables at e^+e^- colliders

World Average (PDG): α_s (m_Z) = 0.1179 ± 0.0009

Conventionally determined at the reference scale Q = m_Z
Decreases ("runs") as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$



PDG

Determination of the strong coupling constant from transverse energy correlations

arXiv:2301.09351

Energy–energy correlation (EEC): event-shape observable, infrared safe

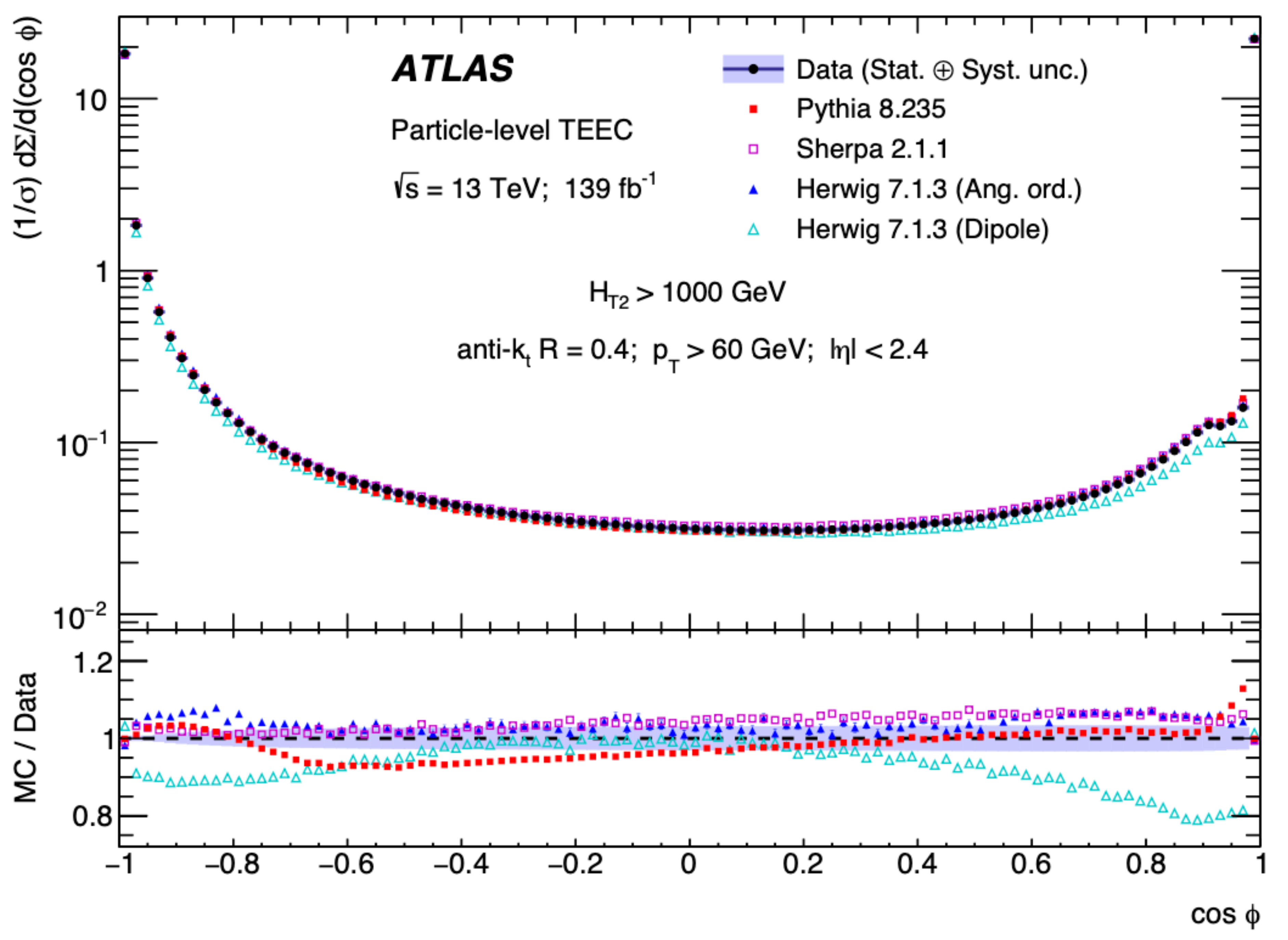
TEEC:

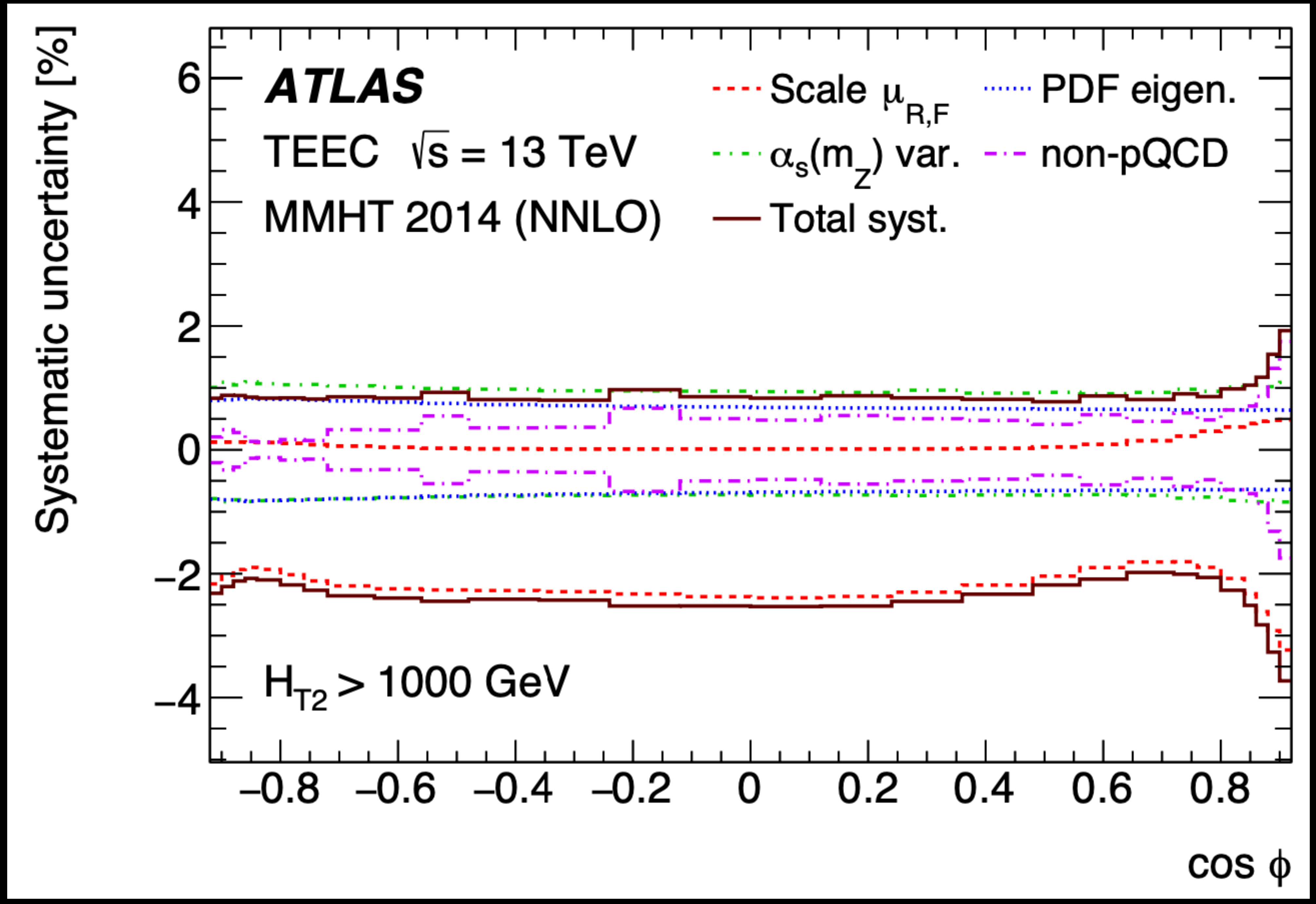
$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j}\mathrm{d}\cos\phi}x_{\mathrm{T}i}x_{\mathrm{T}j}\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^{A}_{\mathrm{T}i}E^{A}_{\mathrm{T}j}}{\left(\sum_k E^{A}_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

ATEEC:

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma^{\mathrm{asym}}}{\mathrm{d}\cos\phi} = \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\pi-\phi}$$

Generalization for hadronic collider



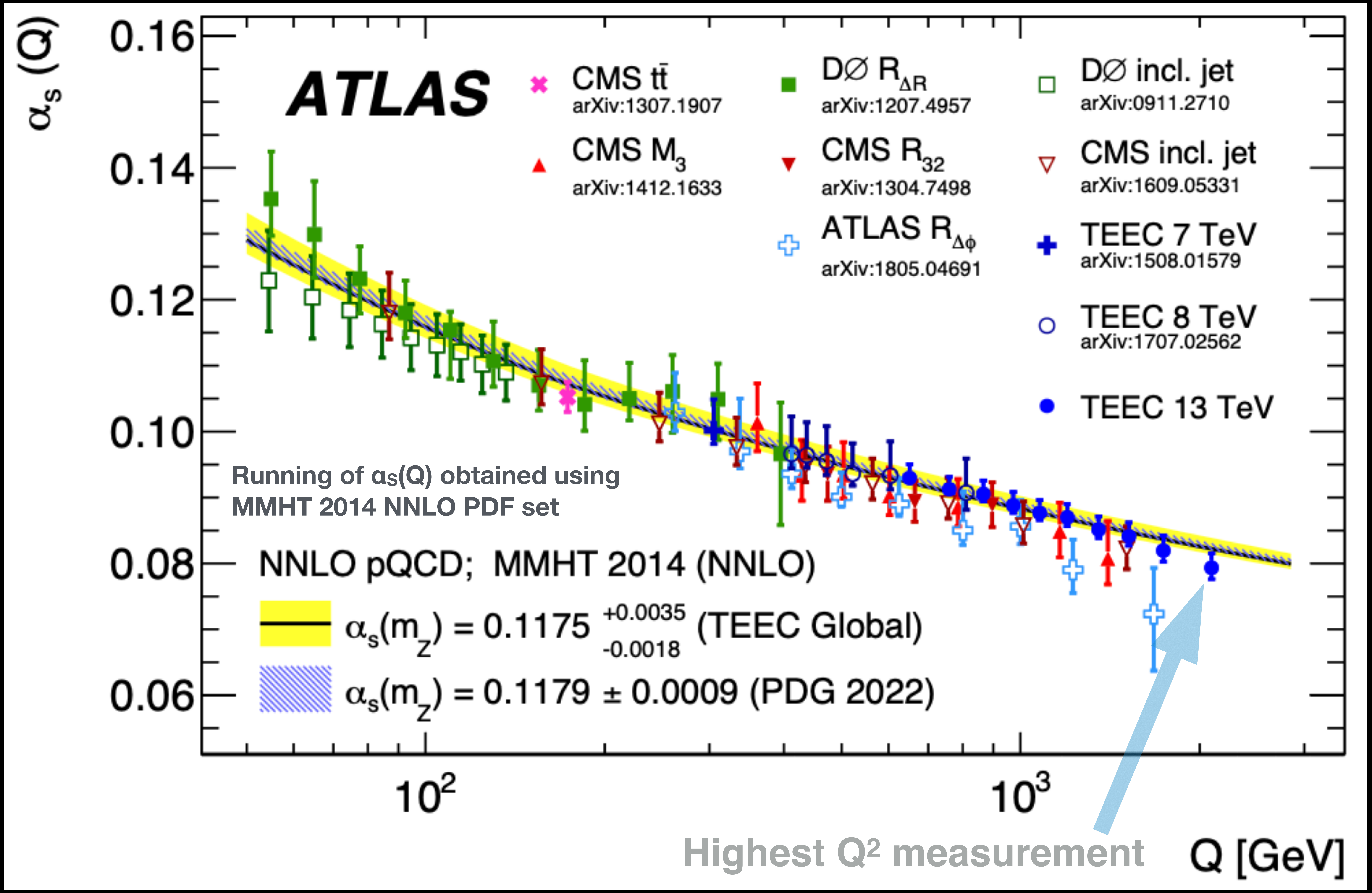


Dependence on α_s variation of ± 0.001

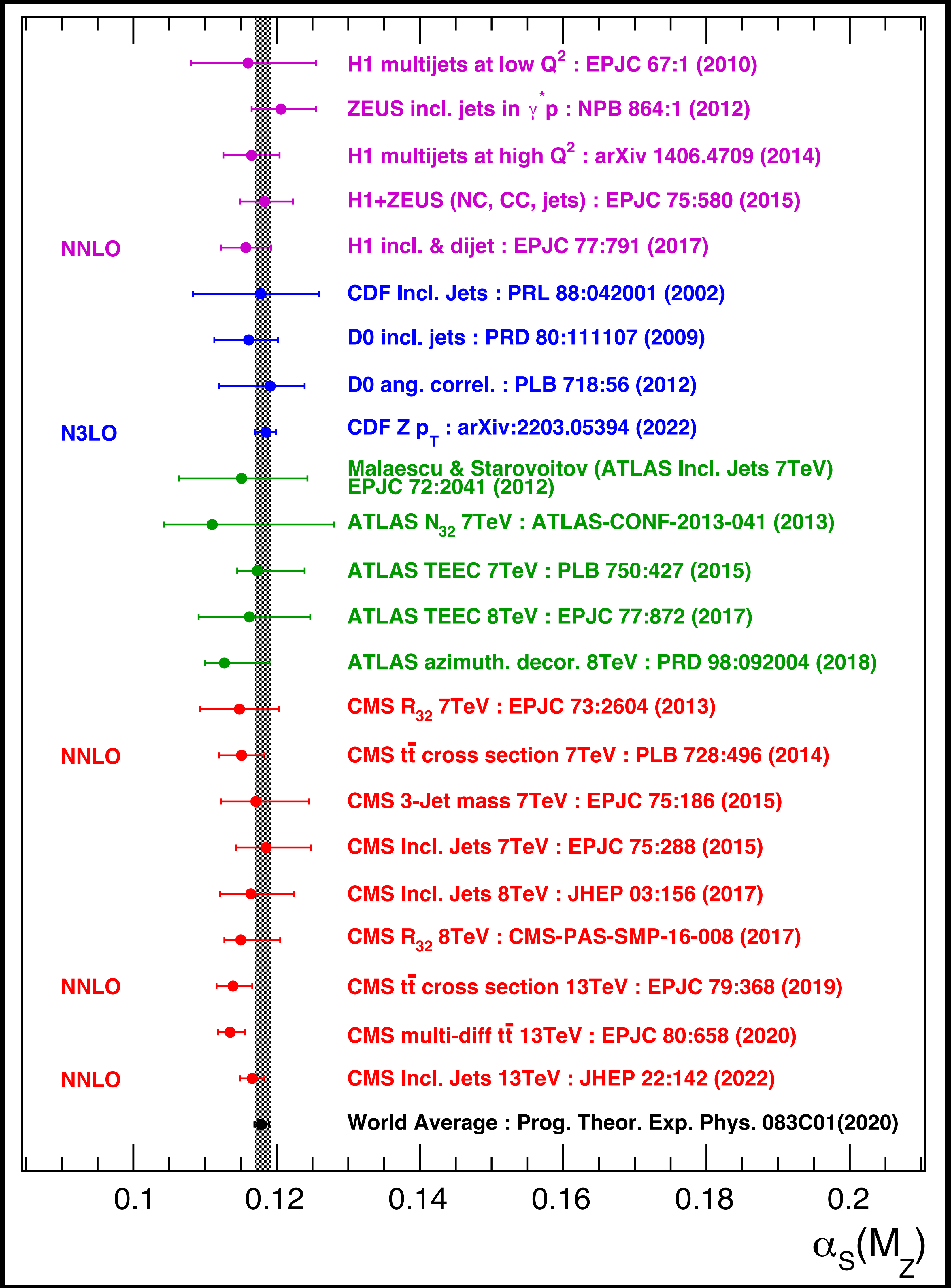
Determination of the strong coupling constant from transverse energy correlations

arXiv:2301.09351

TEEC (ATEEC) distributions are fitted to extract α_s



other $\alpha_s(M_Z)$ measurements

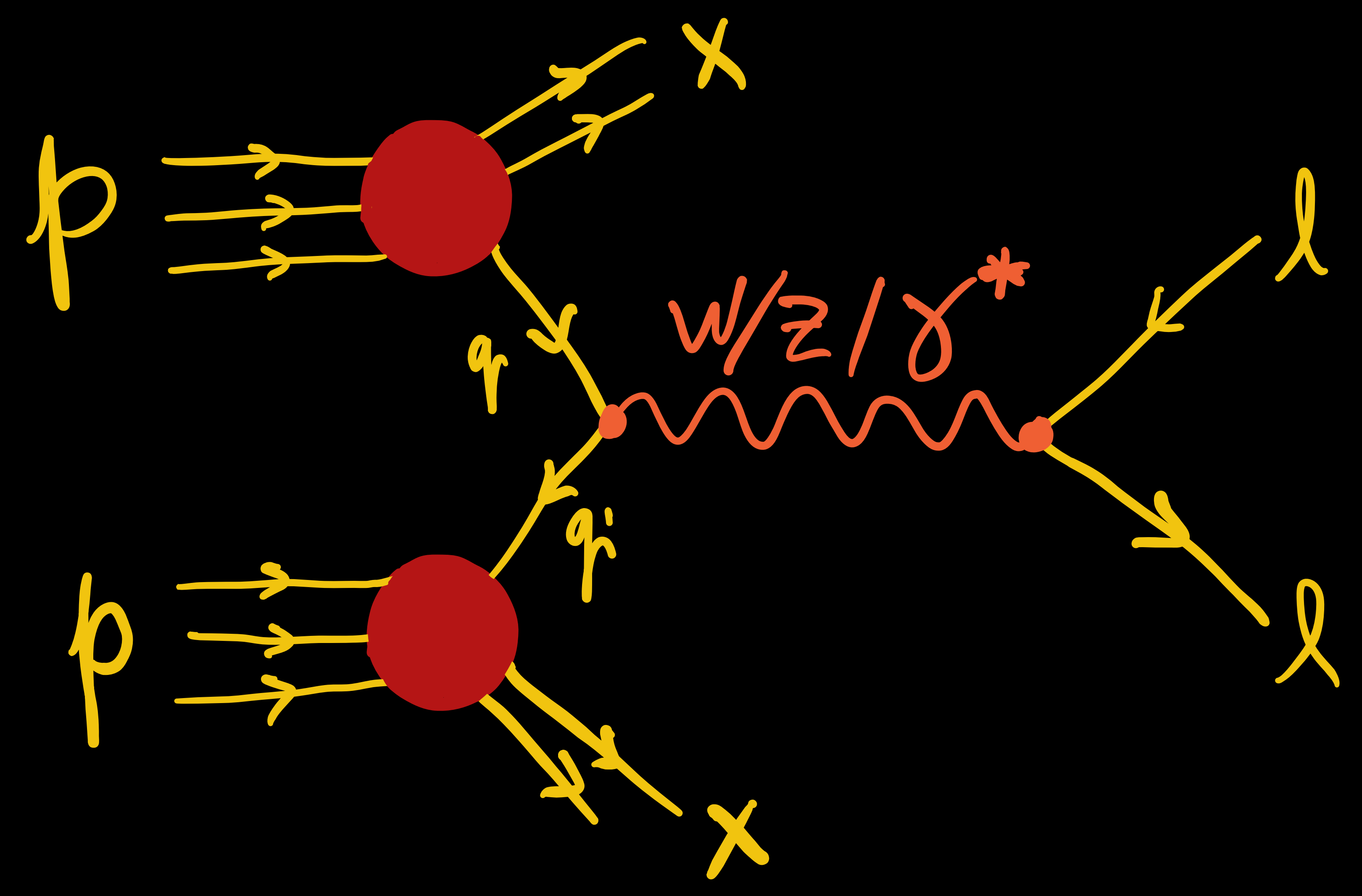


ATEEC: $\alpha(m_Z) = 0.1185 \pm 0.0009\ (\text{exp.})^{+0.0025}_{-0.0012}\ (\text{theo.})$

W and Z boson production physics

Drell-Yan process and measurement of SM parameters

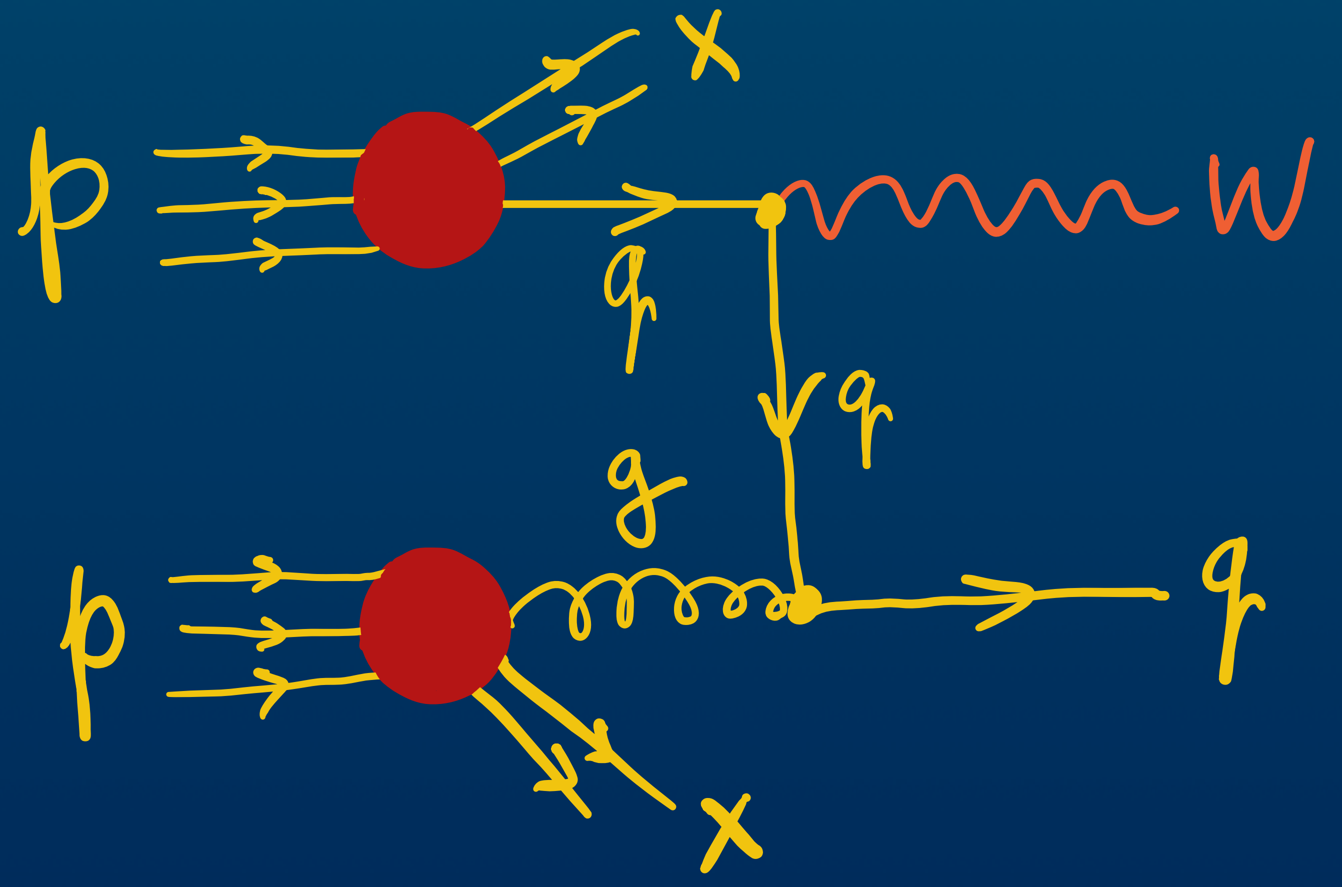
The Drell-Yan process is a standard candle for precision measurements at the LHC



Used to measure:
- W-boson mass
- $\sin^2(\theta_W)$
- PDFs
- $\alpha_s(m_Z)$

The p_T of the W, Z bosons comes from from higher order corrections to the leading order Drell–Yan processes…

….. and from non-perturbative effects such as the primordial k_T of the incoming partons.



Production properties of the Z-boson in the full phase space of the decay leptons

ATLAS-CONF-2023-013

Factorize the production dynamic and the decay kinematic properties of the dilepton system

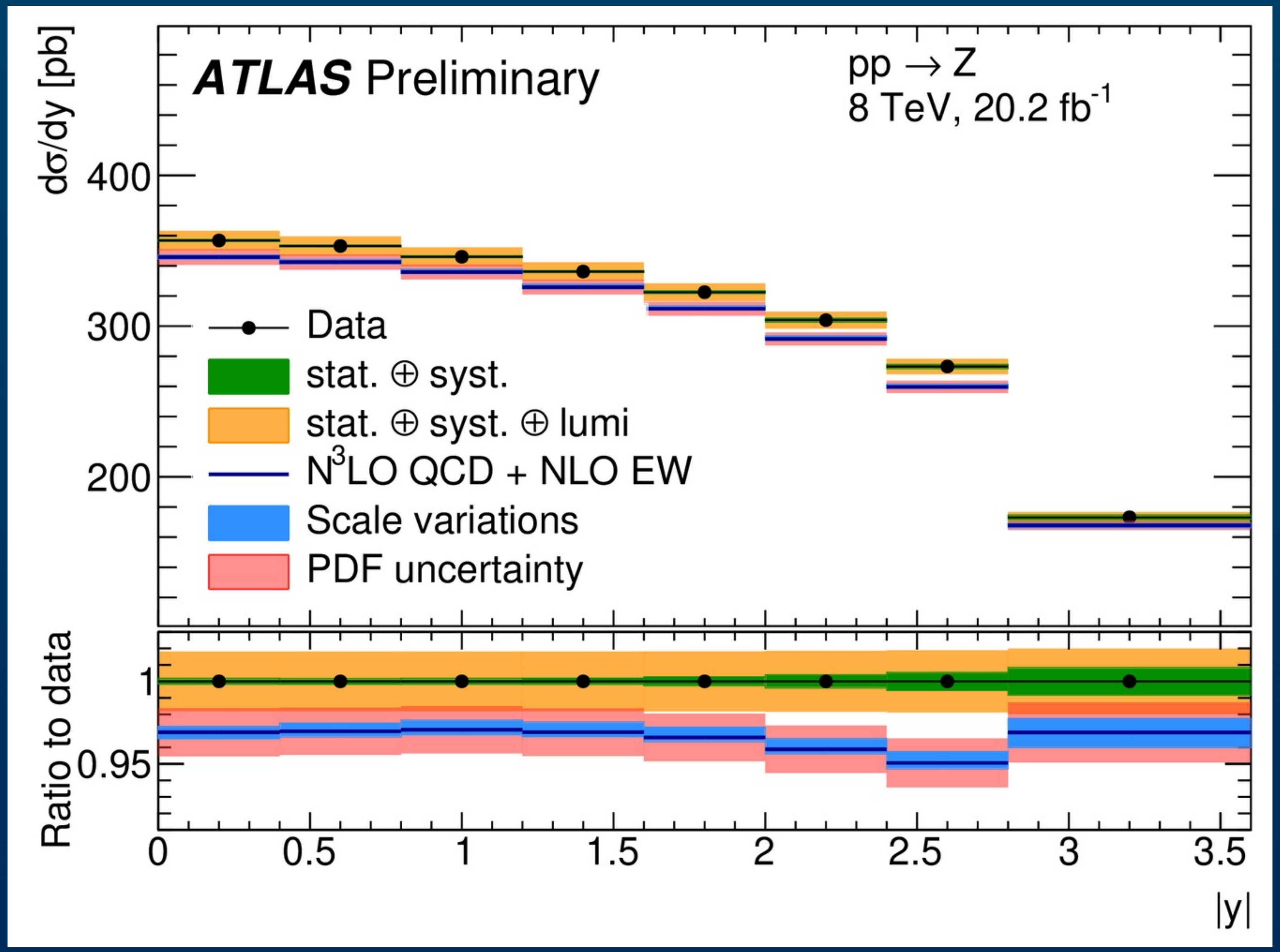
$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1 + \cos^2\theta + \sum_{i=0}^{7} A_i(y, p_T, m) P_i(\cos\theta, \phi)\right)$$

A_i angular coefficients: dynamics

lepton angular $\cos\theta$ and ϕ distributions in the Collins-Soper frame

Fiducial cuts removed by analytic integration of ($\cos\theta$, ϕ) in the full phase space of the decay leptons through the measured Ai coefficients

Rapidity

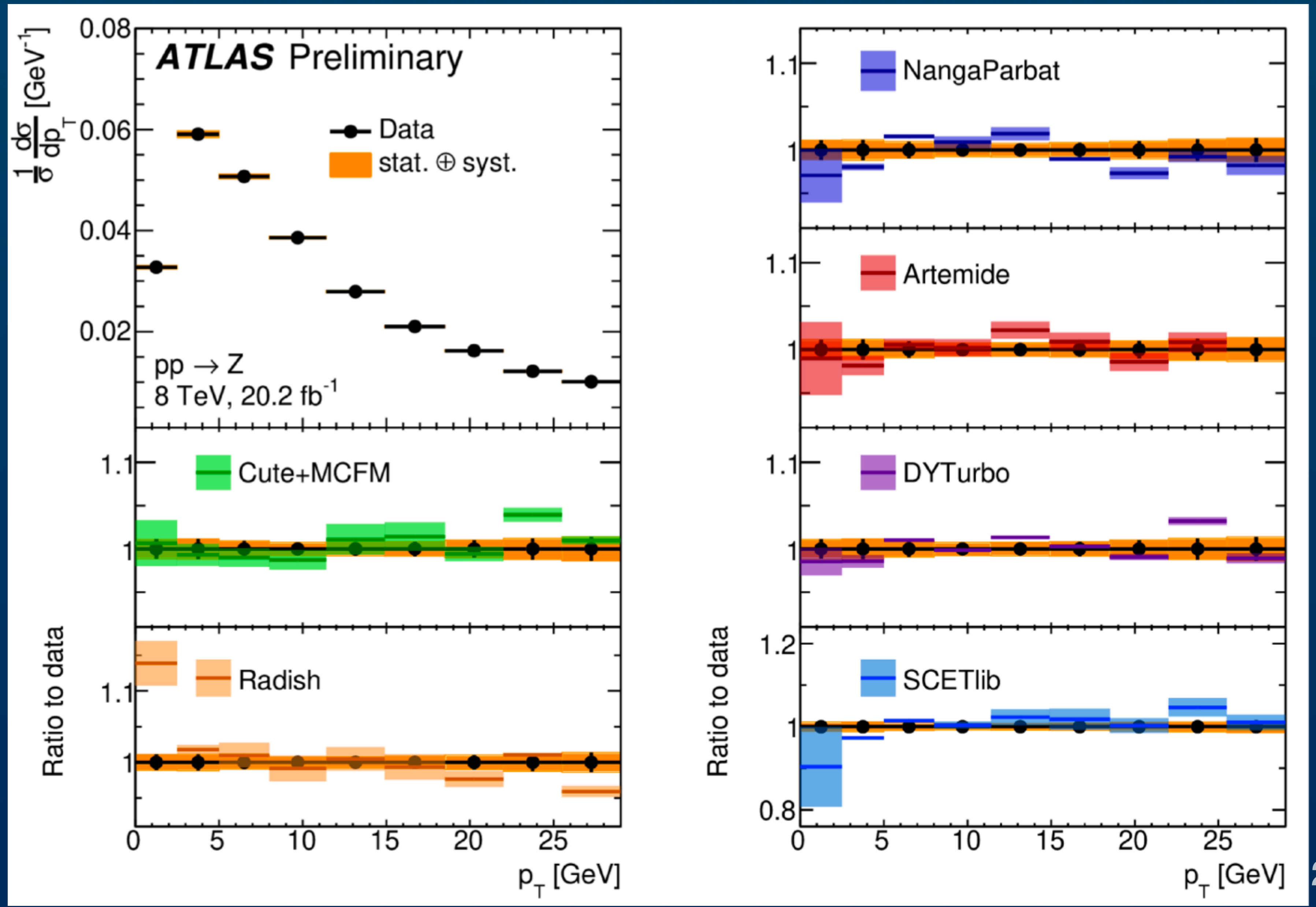


Run-1 8 TeV data only

negligible theoretical uncertainties for all measurements

First comparison to N3LO QCD predictions and N4LL resummation

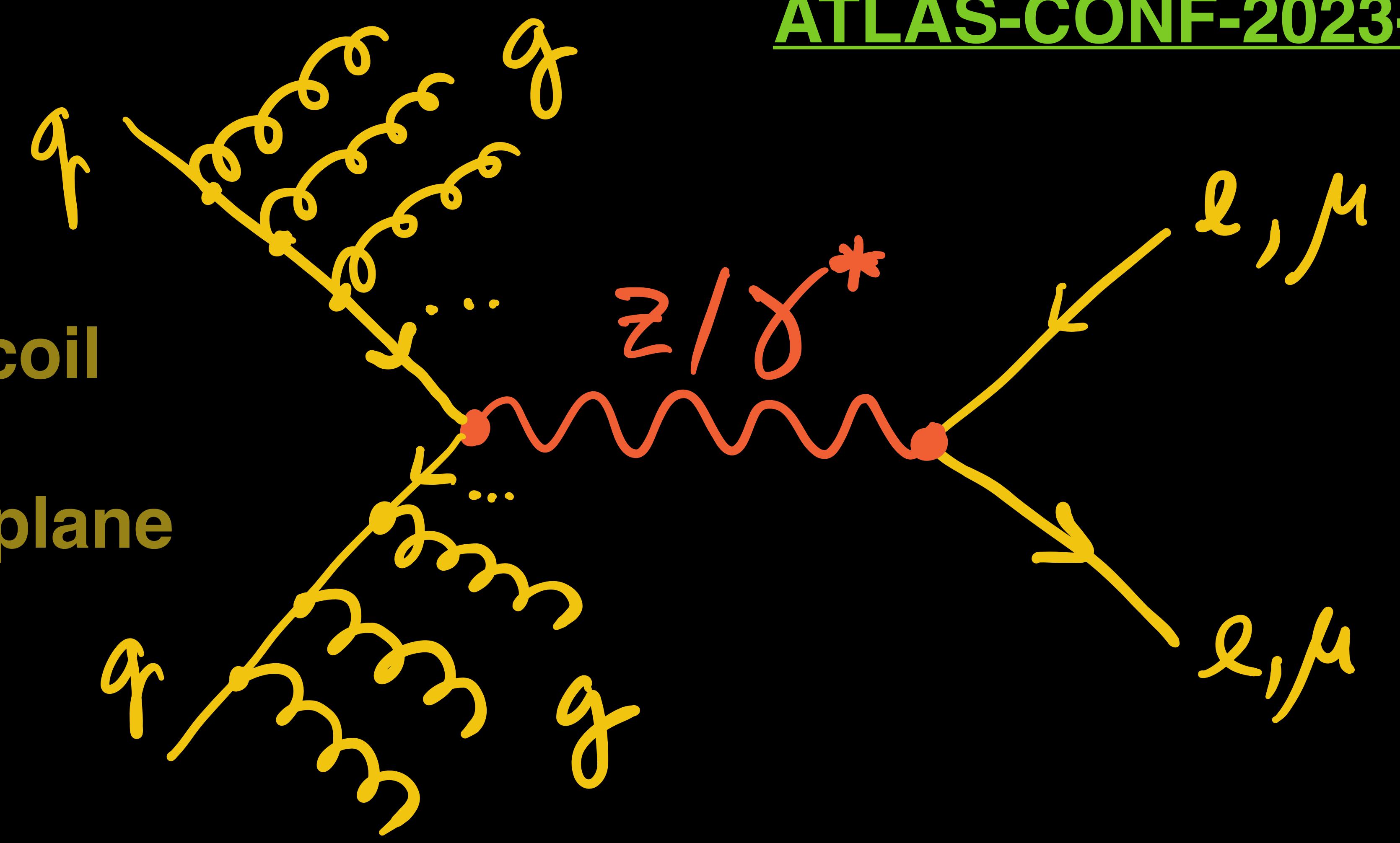
Transverse Momentum



Determination of $\alpha_s(m_Z)$ from Z p_T at 8 TeV

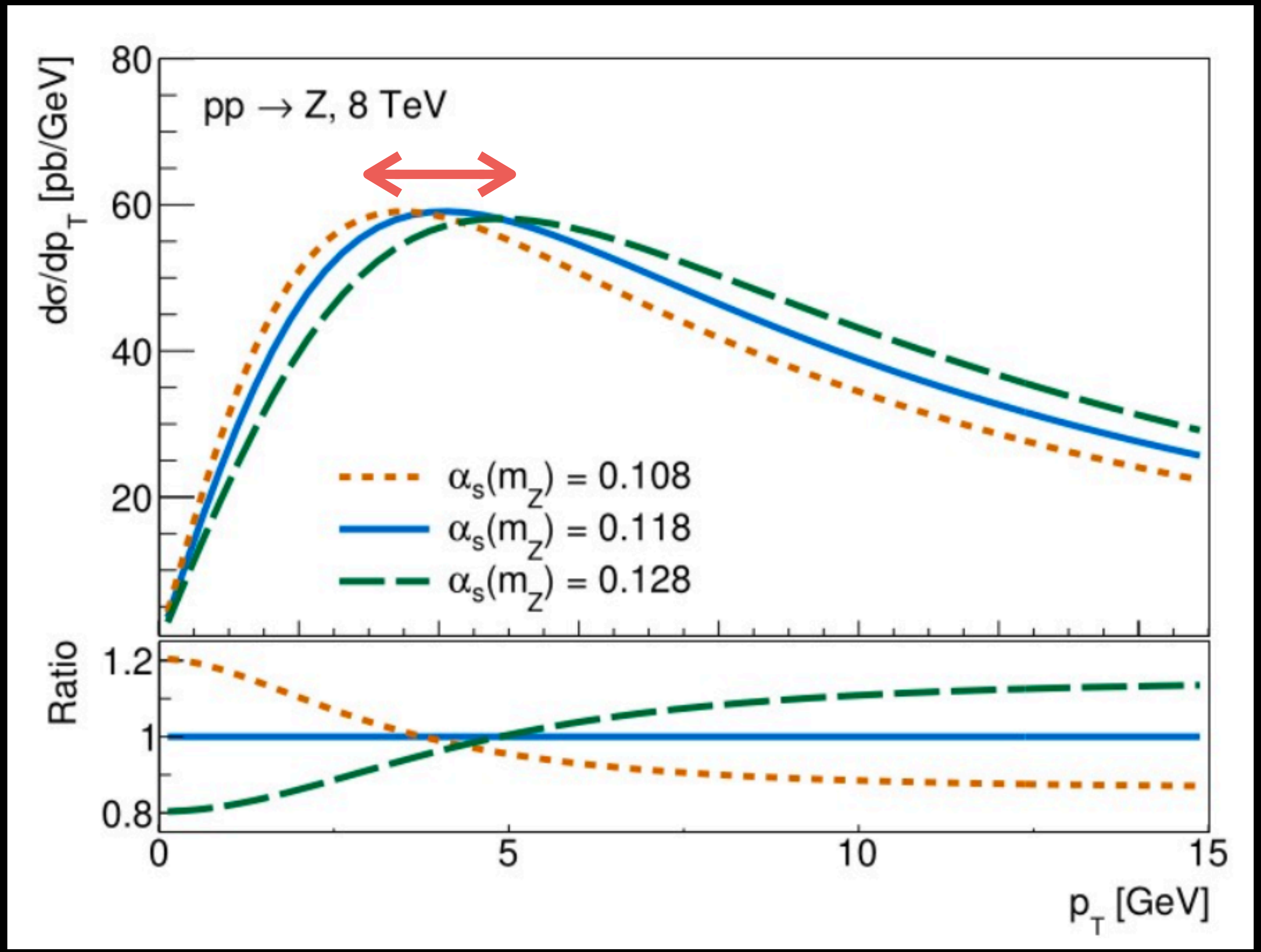
ATLAS-CONF-2023-015

Take advantage of this fantastic precision of Z p_T measurement to extract $\alpha_s(m_Z)$



Z bosons produced in hadron collisions recoil against QCD initial-state radiation:
ISR gluons will boost the Z in the transverse plane

The position of the Z p_T peak is sensitive to $\alpha_s(m_Z)$

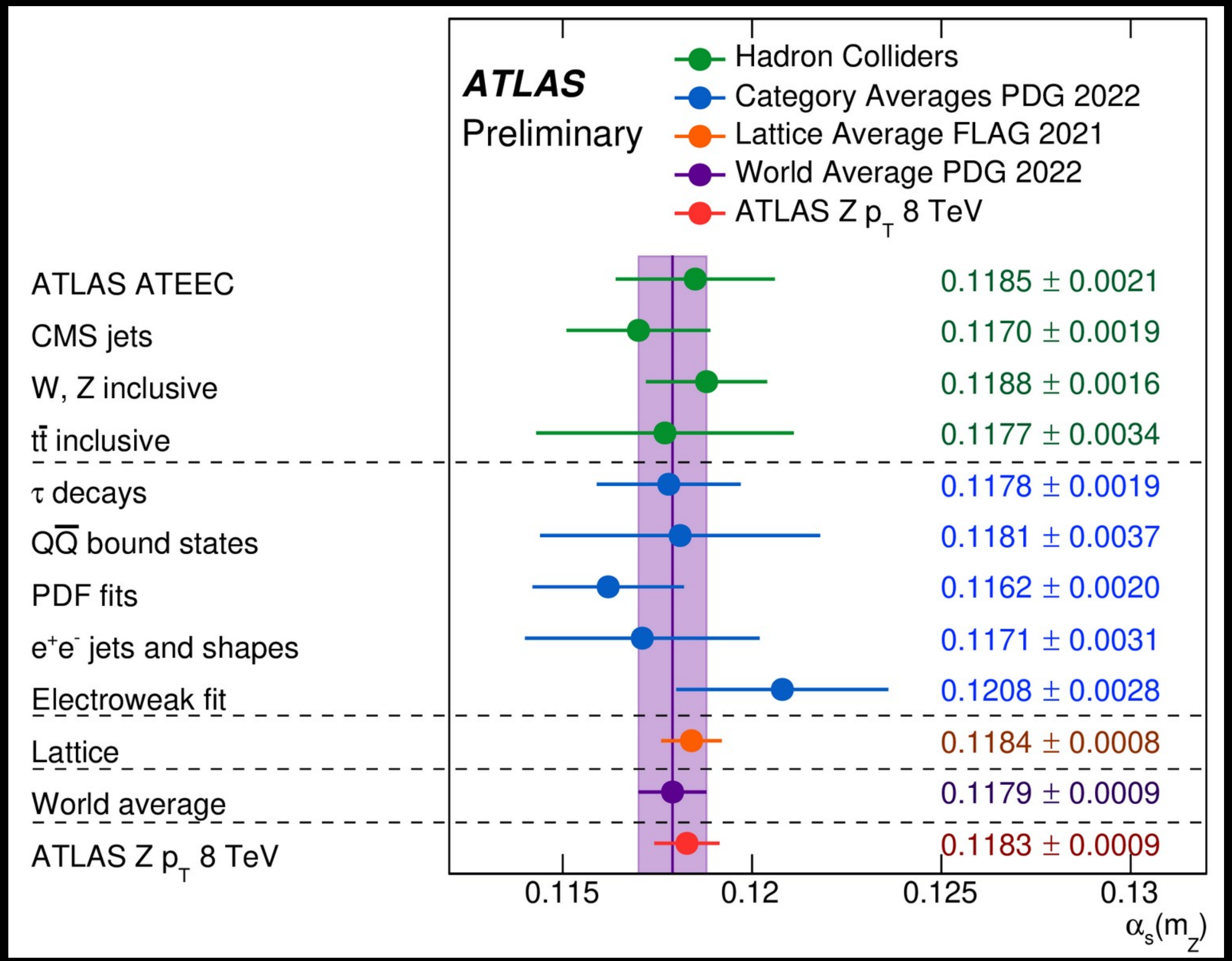


First $\alpha_s(m_Z)$ determination at N3LO+N4LL

$$\alpha_s = 0.11828^{+0.00084}_{-0.00088}$$

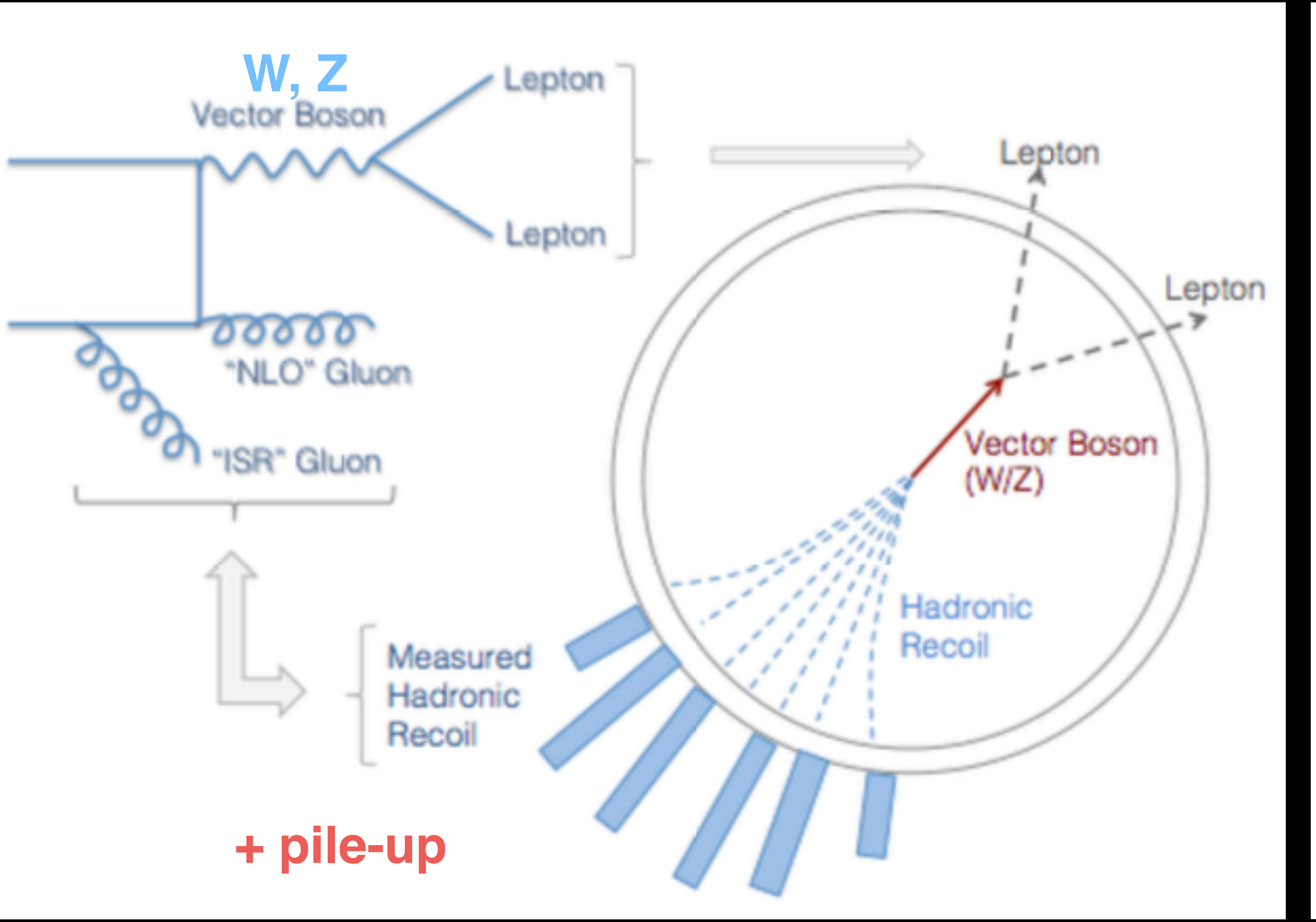
(uncertainty ~0.7%)

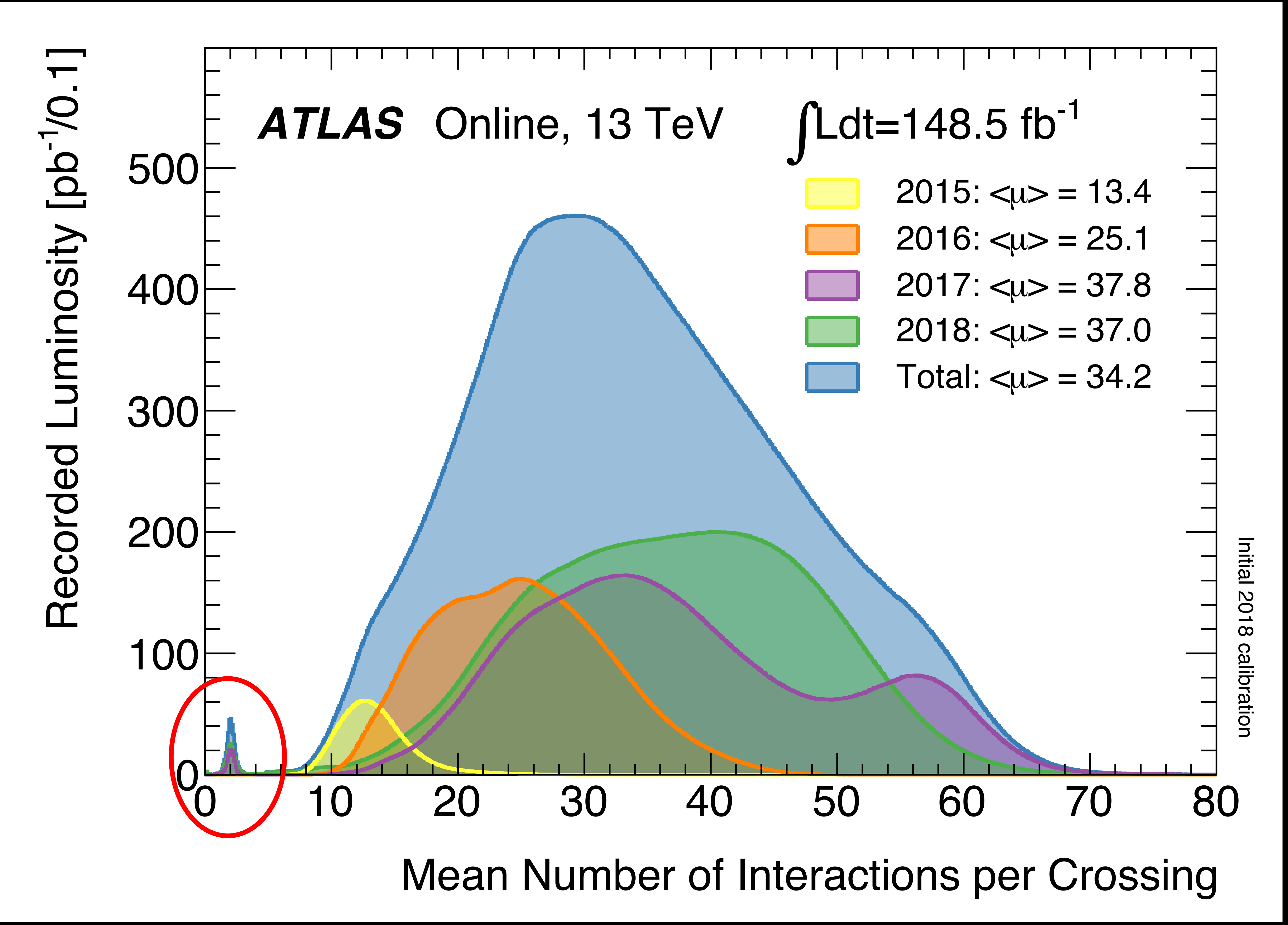
Most precise experimental determination of $\alpha_s(m_Z)$, as precise as the PDG and Lattice calculation and world averages



Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

ATLAS-CONF-2023-028





Pile-up events add energy to the recoil and hinder the experimental extraction of W pT

Take dataset with very low multiple hard interactions per bunch crossing
ATLAS collected such dataset at $\sqrt{s}$ = 5 and 13 TeV

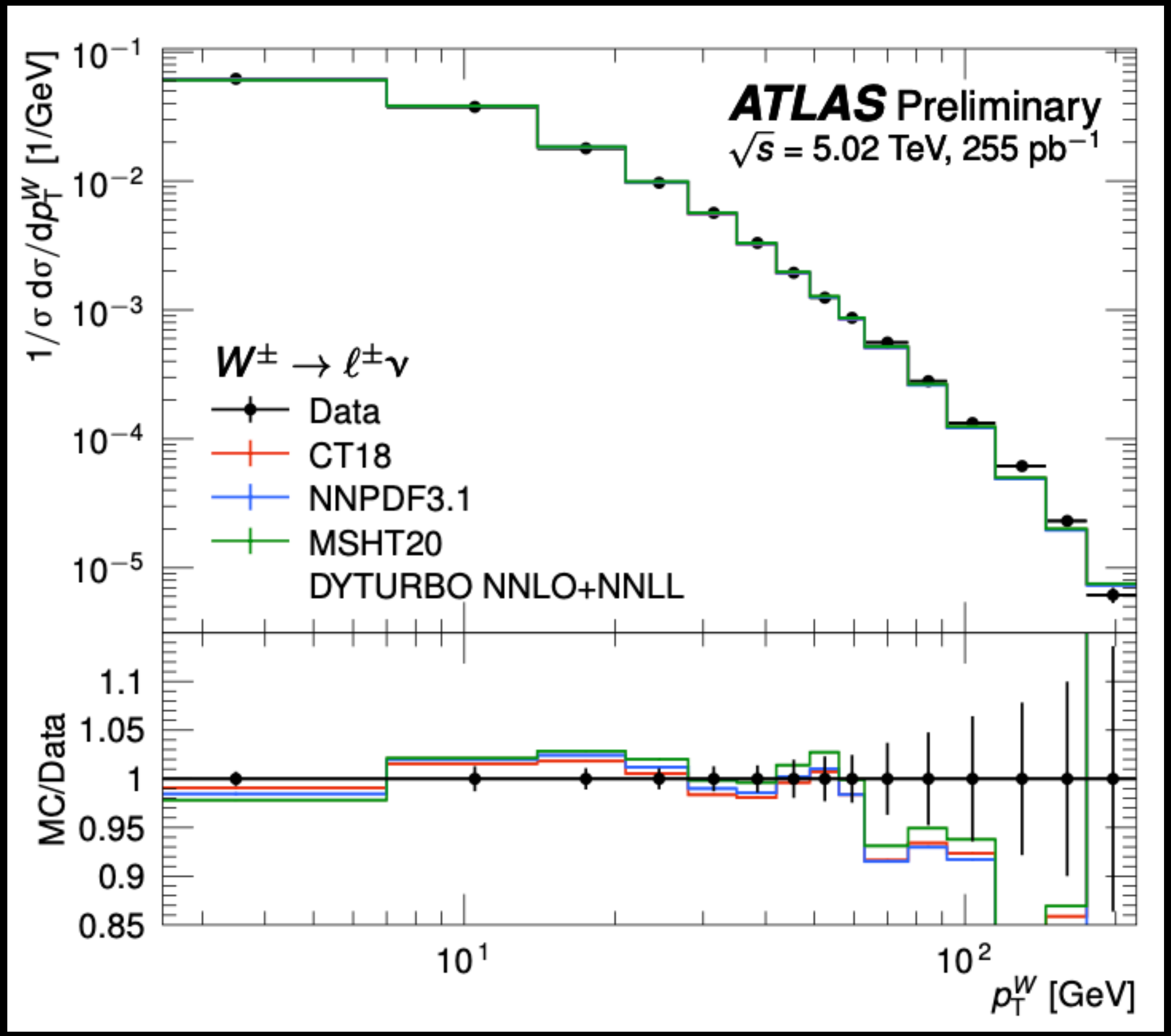
Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

ATLAS-CONF-2023-028

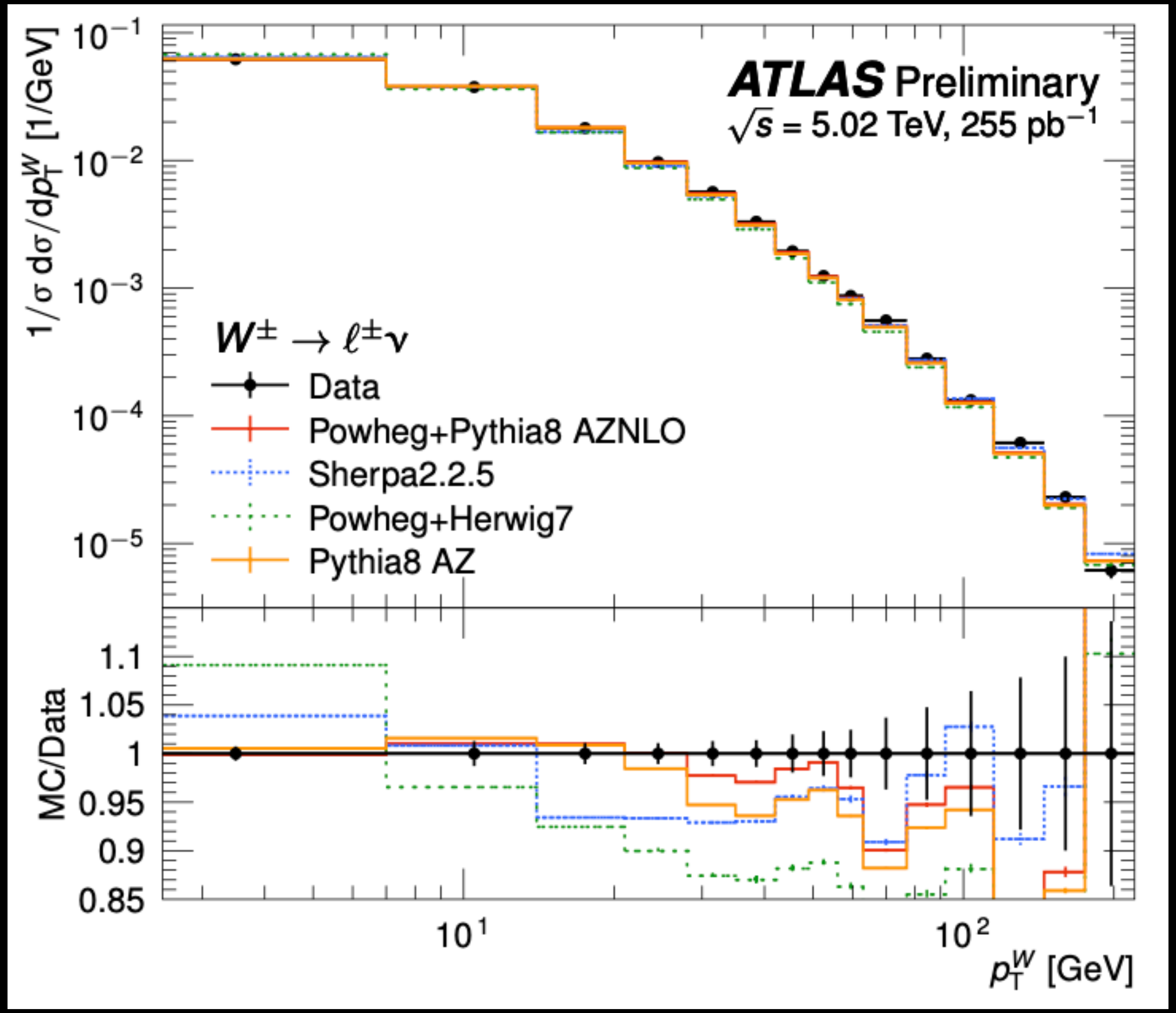
Precise measurements and predictions of the spectra for p_T < ~30 GeV are particularly interesting for future measurement of the W-boson mass at LHC

$\sqrt{s}$ = 5 TeV

Compared to DYTURBO predictions with different PDF sets



Compared with different MC predictions



DYTURBO resummed predictions show the best agreement and generally match the data at the percent level

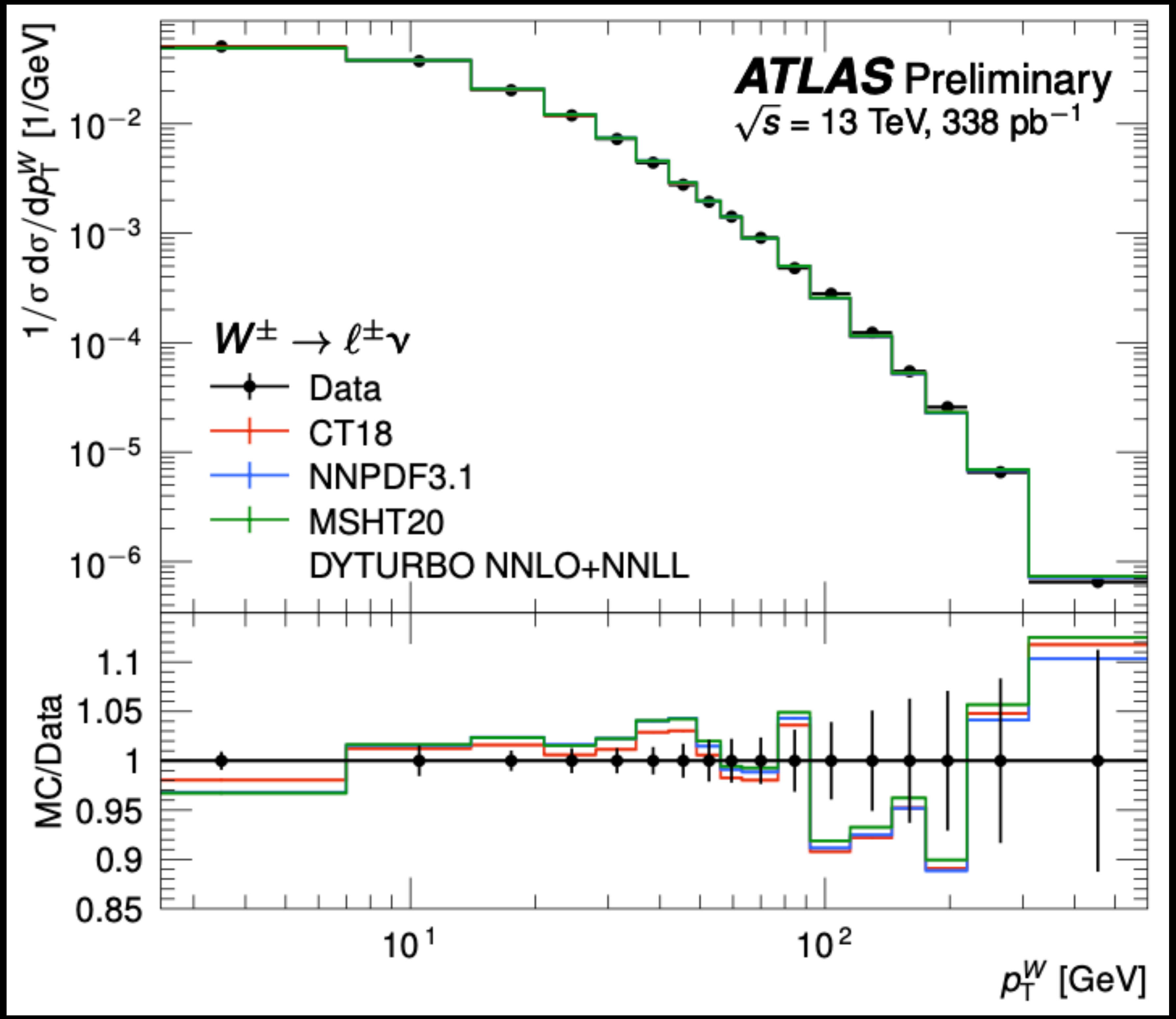
Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

ATLAS-CONF-2023-028

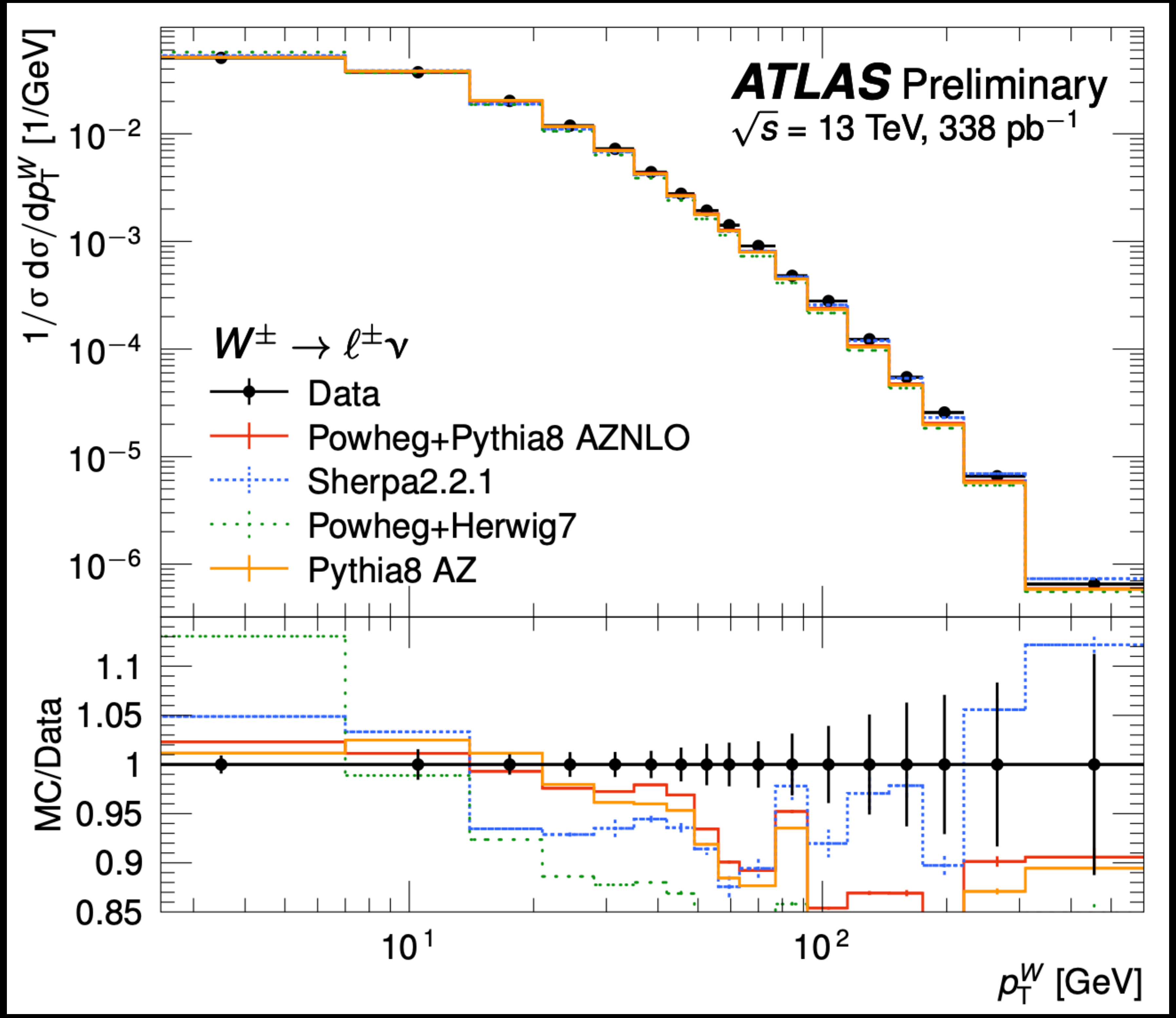
Precise measurements and predictions of the spectra for p_T < ~30 GeV are particularly interesting for future measurement of the W-boson mass at LHC

$\sqrt{s}$ = 13 TeV

Compared to DYTURBO predictions with different PDF sets



Compared with different MC predictions

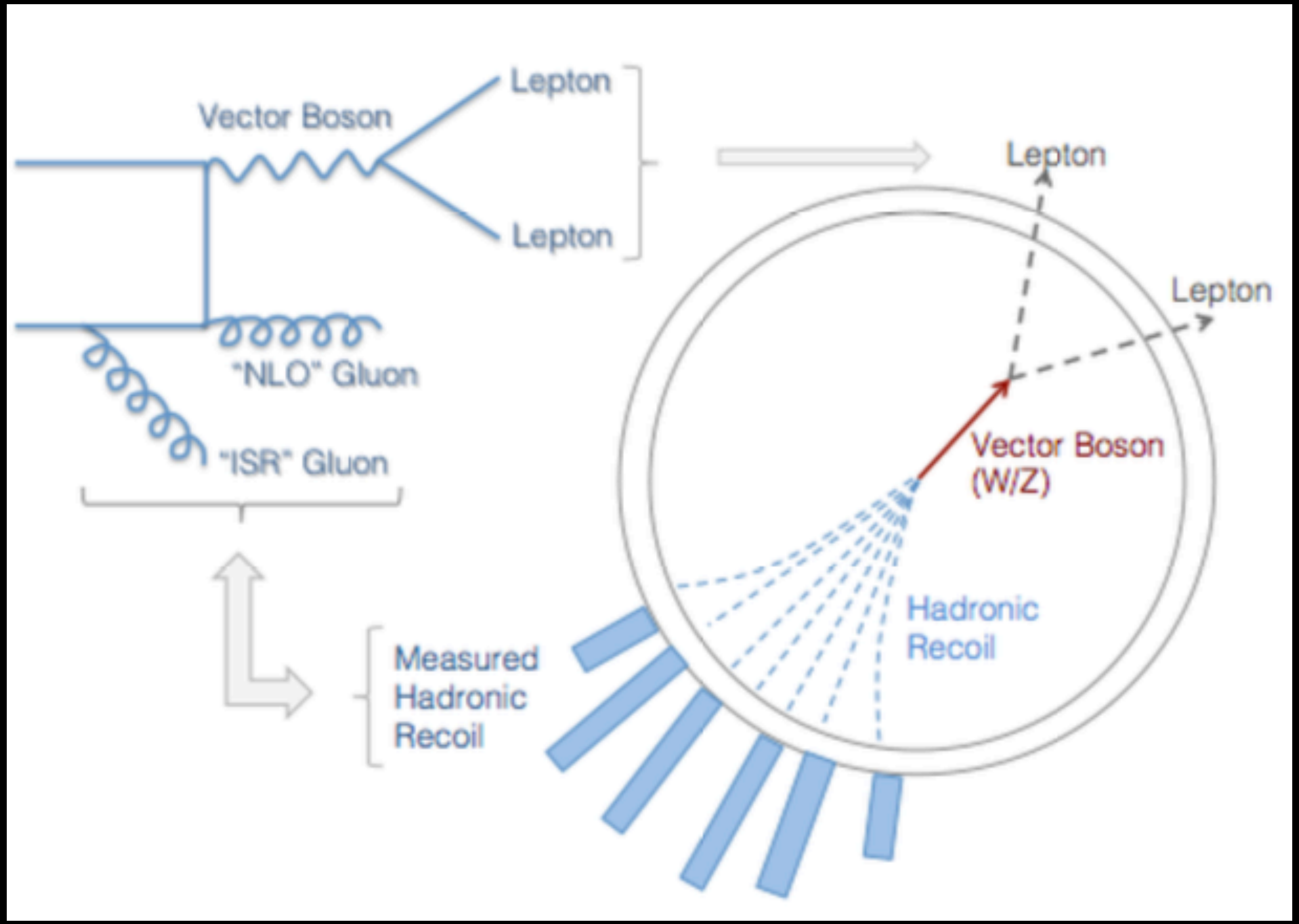


DYTURBO resummed predictions show the best agreement and generally match the data at the percent level

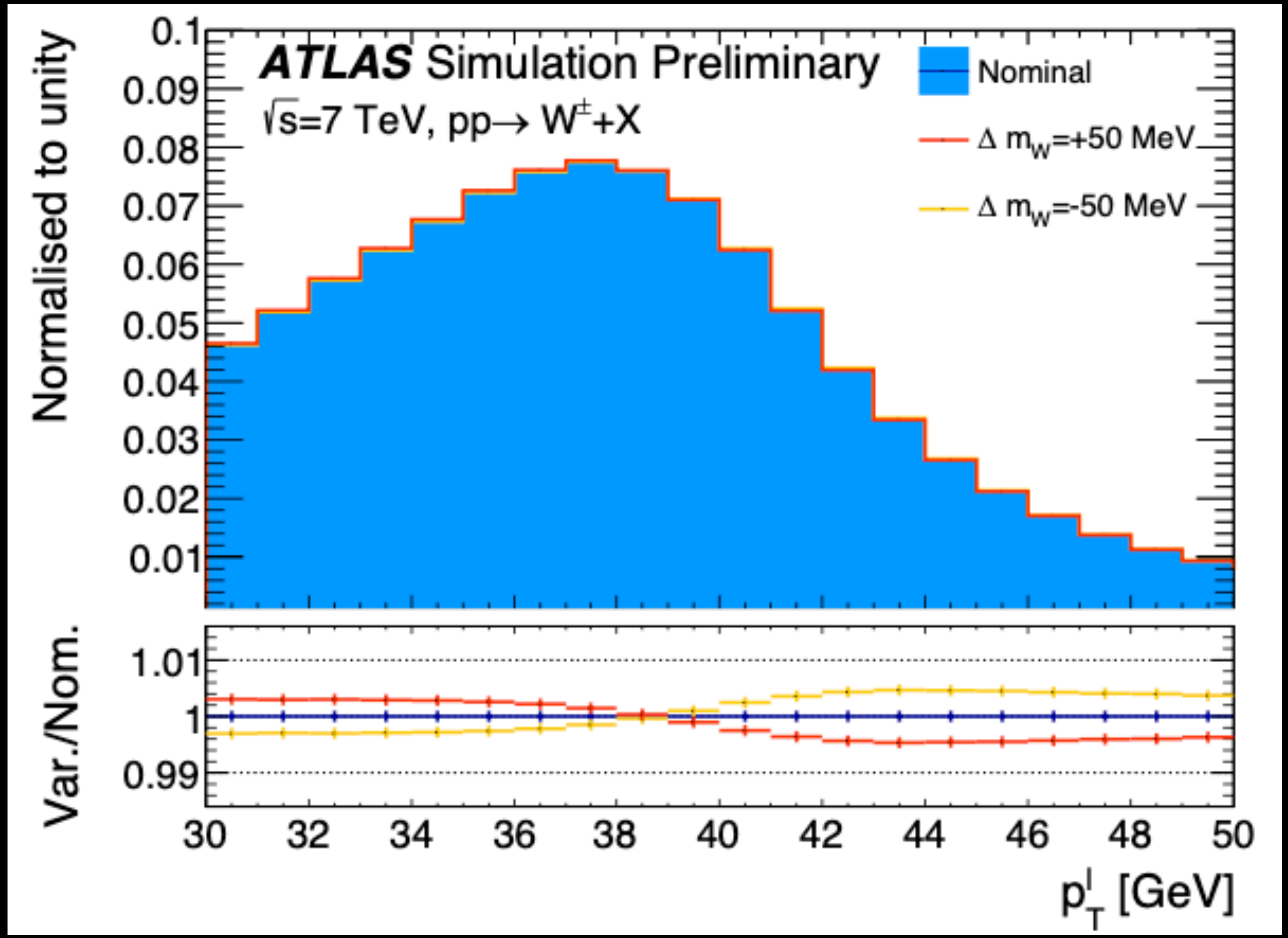
New W mass measurement from ATLAS

ATLAS-CONF-2023-004

Determine the W boson mass from the dependence of the leptonic transverse momentum (p_T) and the transverse mass (m_T)



M_W shift = ± 50 MeV



Revisited measurement from 2017, using the same data, but with more advanced physics model and profile likelihood fitting:

- Advantage: Reduce systematic uncertainties during the fit
- Disadvantage: Computational expensive, challenging to investigate systematics

W mass: physics modeling and analysis improvements

Physics modeling

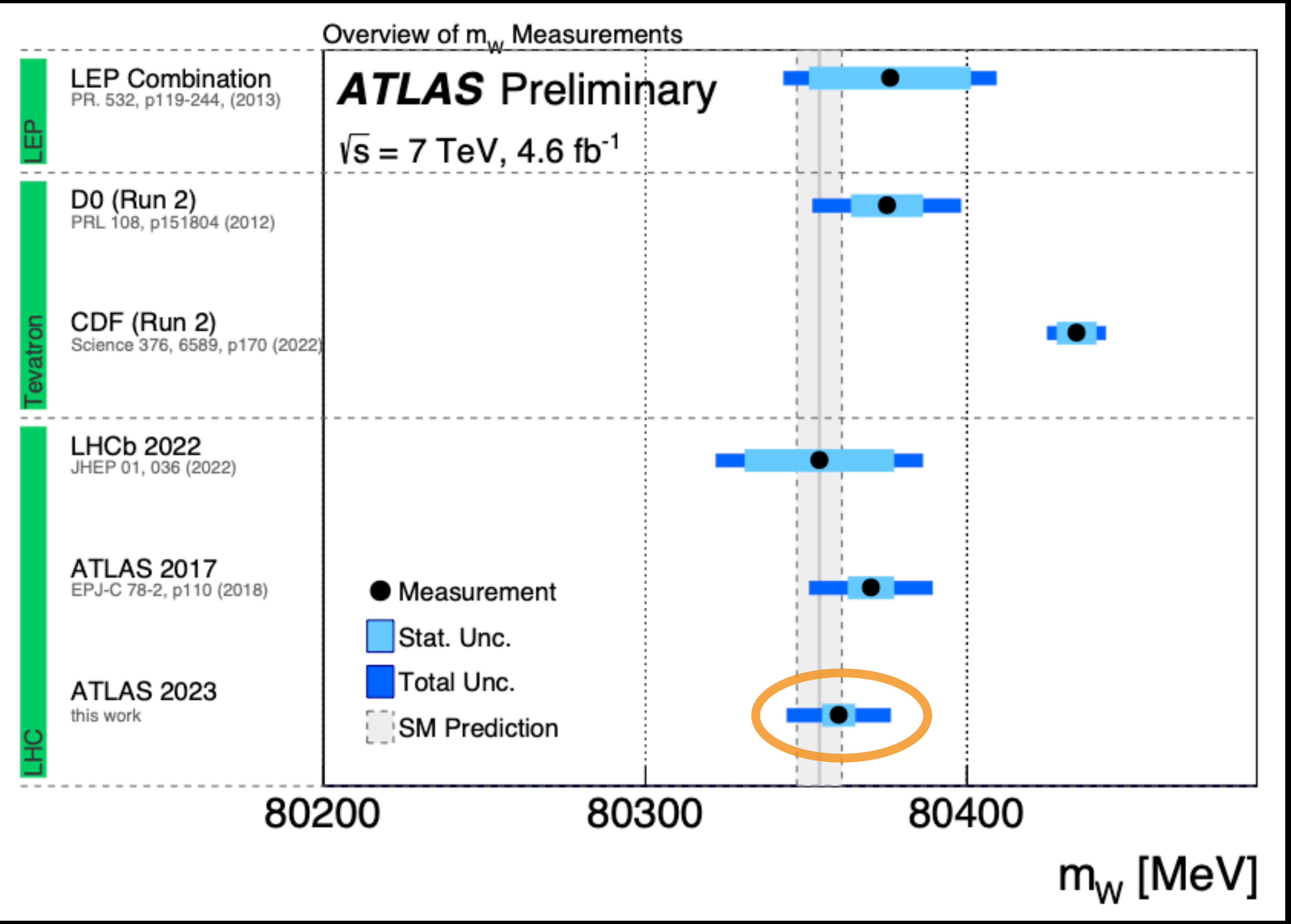
- **Baseline: Pythia AZ tune (based on Z boson)**
  - Z Boson Data, Parton Shower Variations
- **New Verifications:**
  - AZ tune describes hadronic recoil spectrum of W's in low-pileup data at 5 TeV within experimental uncertainties
  - DYTurbo (resumed calculation) also agrees with AZ Tune.
- **Treatment of angular coefficients unchanged**
- **Parton Distribution Functions:**
  - Studied full set of available PDF Sets at NNLO: CT10, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0
    - New Baseline CT18

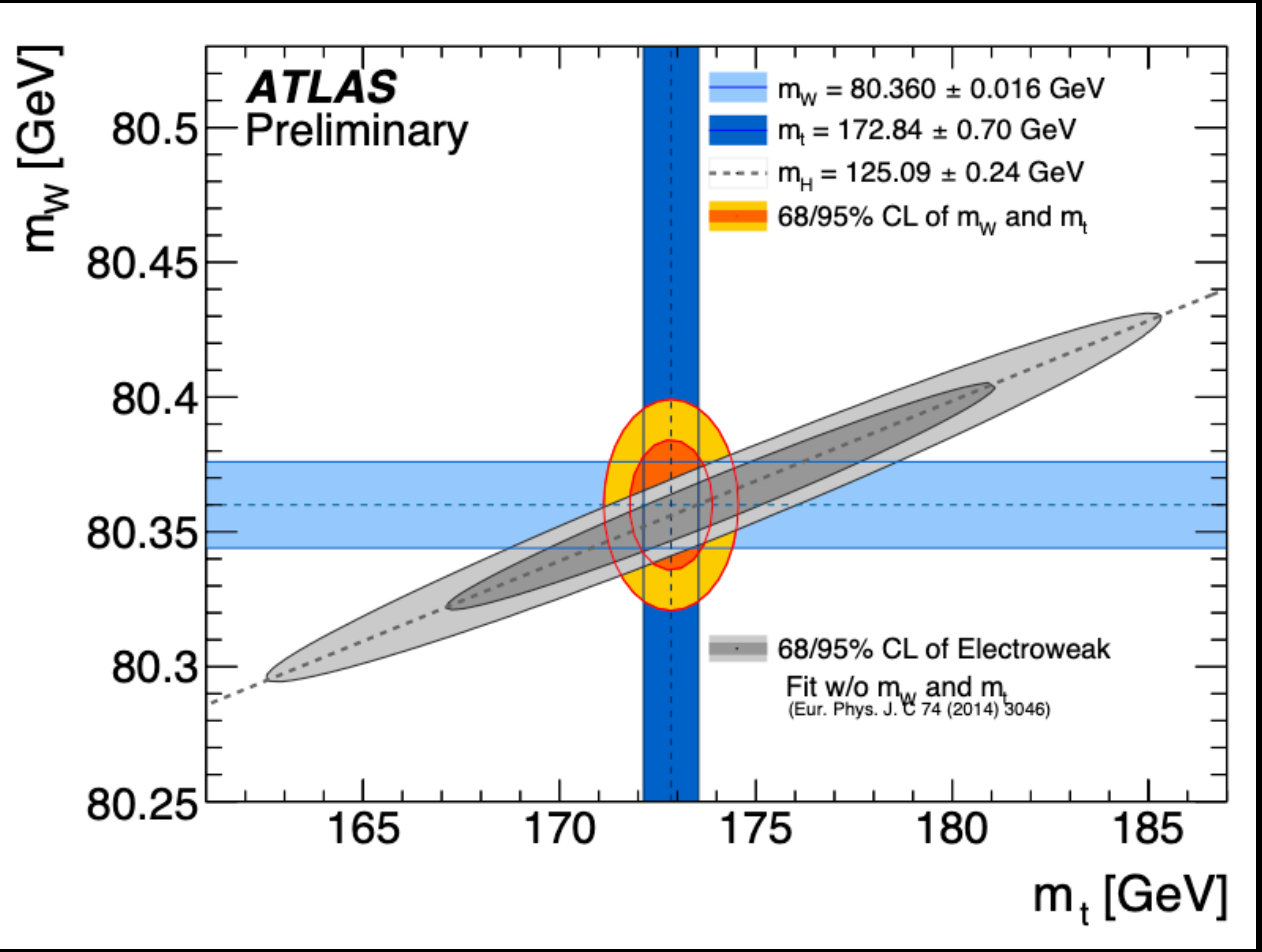
Analysis improvements

- **Multijet Background Estimation**
  - Systematic shape variations using PCA
  - New transfer function from CR to SR
  - Reduction of uncertainty by 2 MeV
- **EWK uncertainty evaluated at detector level**
  - increase uncertainty by 1-2 MeV
- **Recovering data in the electron channel**
  - Increased statistics by 1.5%
- **Add W width as NP parameter**
- **Improving random generator setup for the electron energy calibration**

New W mass measurement from ATLAS

ATLAS-CONF-2023-004



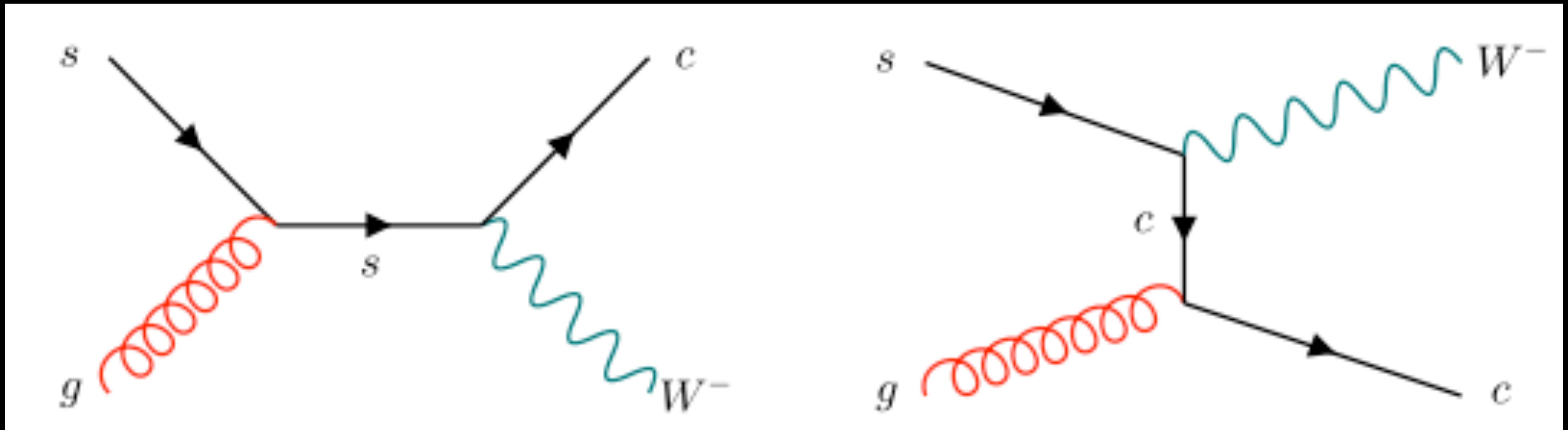


m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV (0.02% uncertainty)

Previous measurement from 2017: m_W = 80370 ± 19 MeV

Measurement of the production of a W boson in association with a charmed hadron

Measuring Wc production probes the strangeness in the proton (PDF)



→	W^-c	$W^+\bar{c}$
gs	~90%	
$g\bar{s}$		~95%
gd	10%	
$g\bar{d}$		5%

CKM suppressed

Constrain the ratio between strange and non-strange sea quark PDFs

Probe the level of asymmetry between s and s-bar

Two different measurement approaches

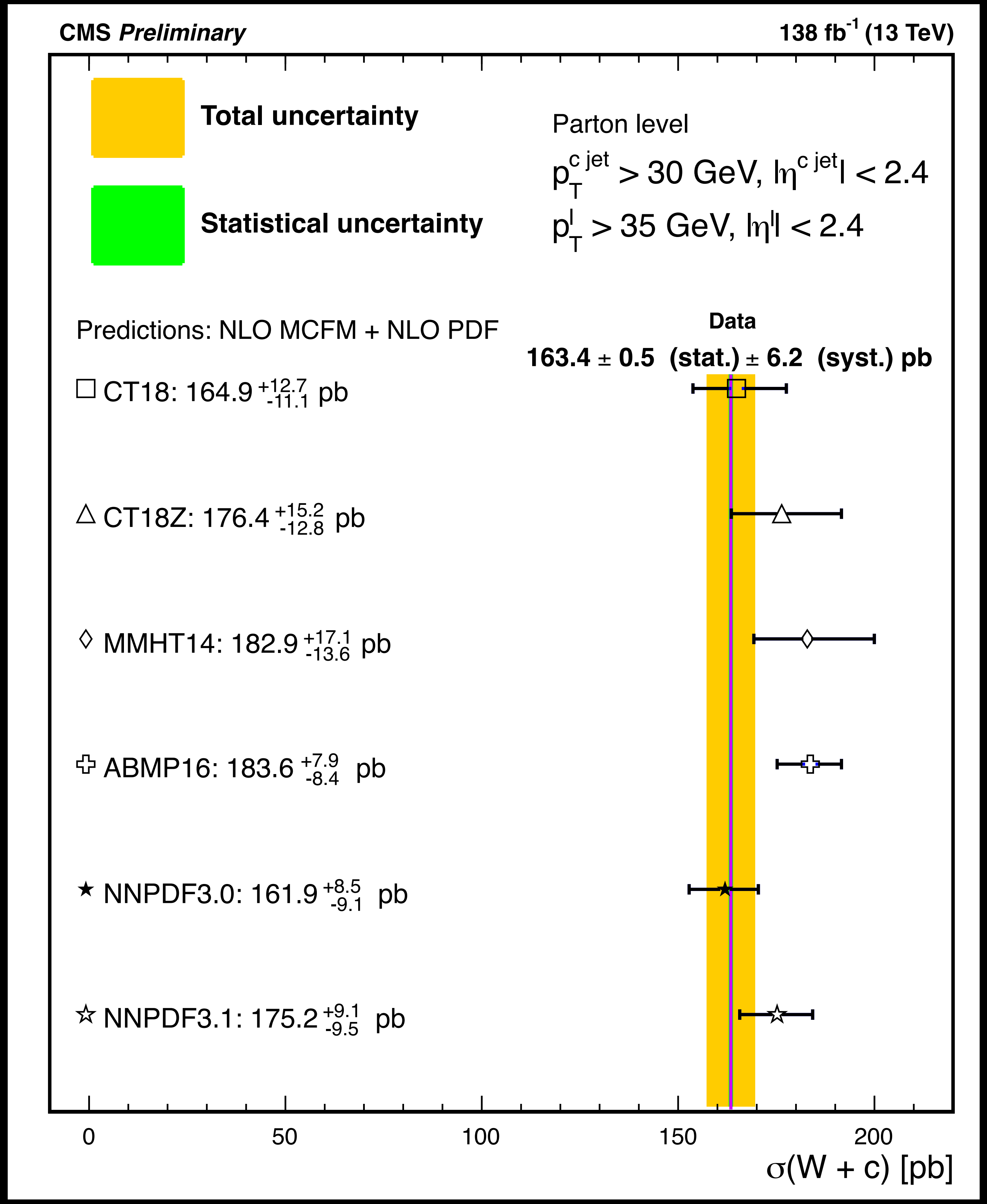
Measurement of the production of a W boson in association with a charmed hadron

Two different measurement approaches

Both measure inclusive and differential cross sections

CMS

Measure charm content by tagging charm jets



CMS-PAS-SMP-21-005

Wc cross section

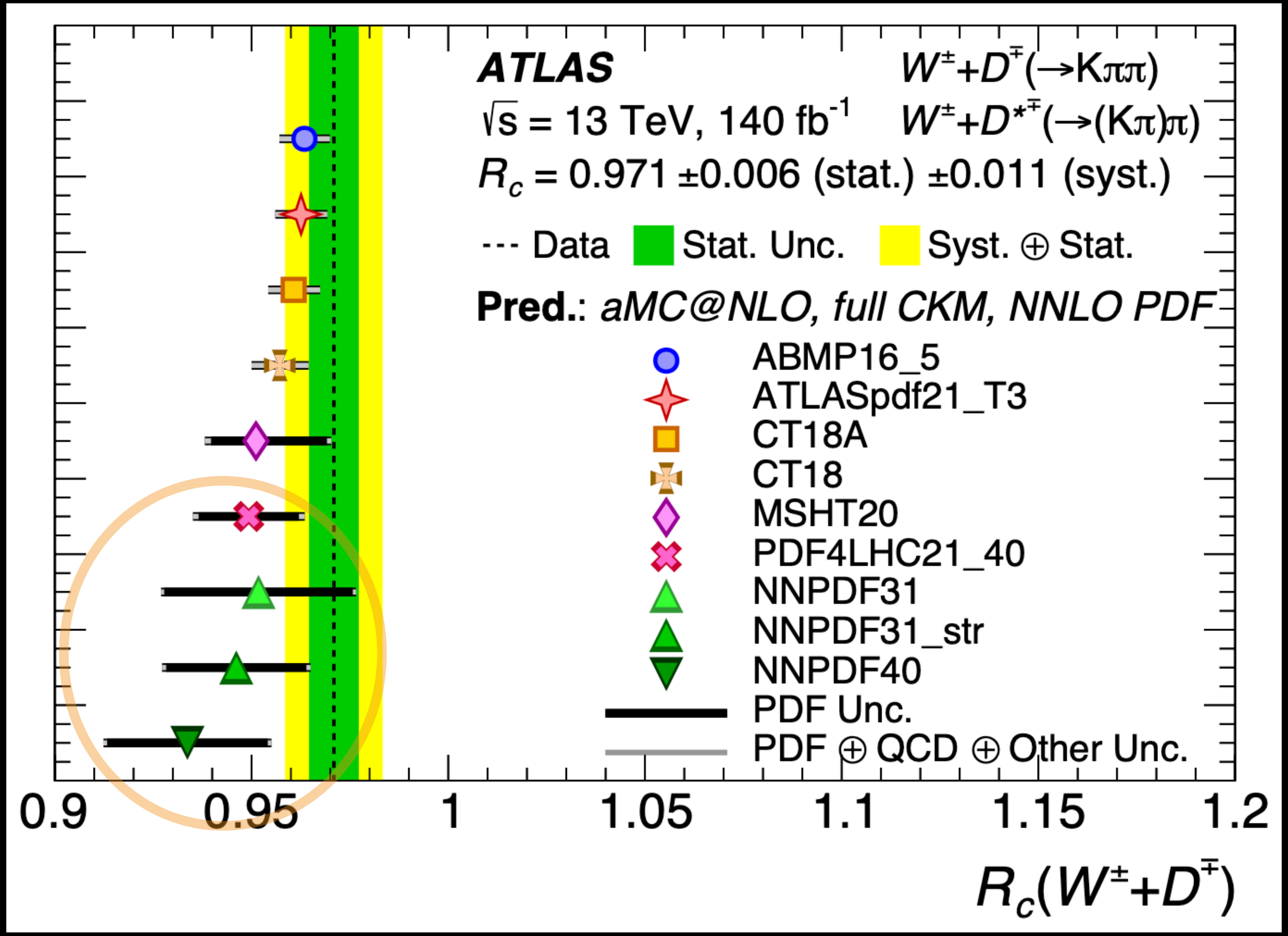
W+/W- + charm ratio

Comparable precision ~1.3%

Consistent with symmetric strange sea

ATLAS

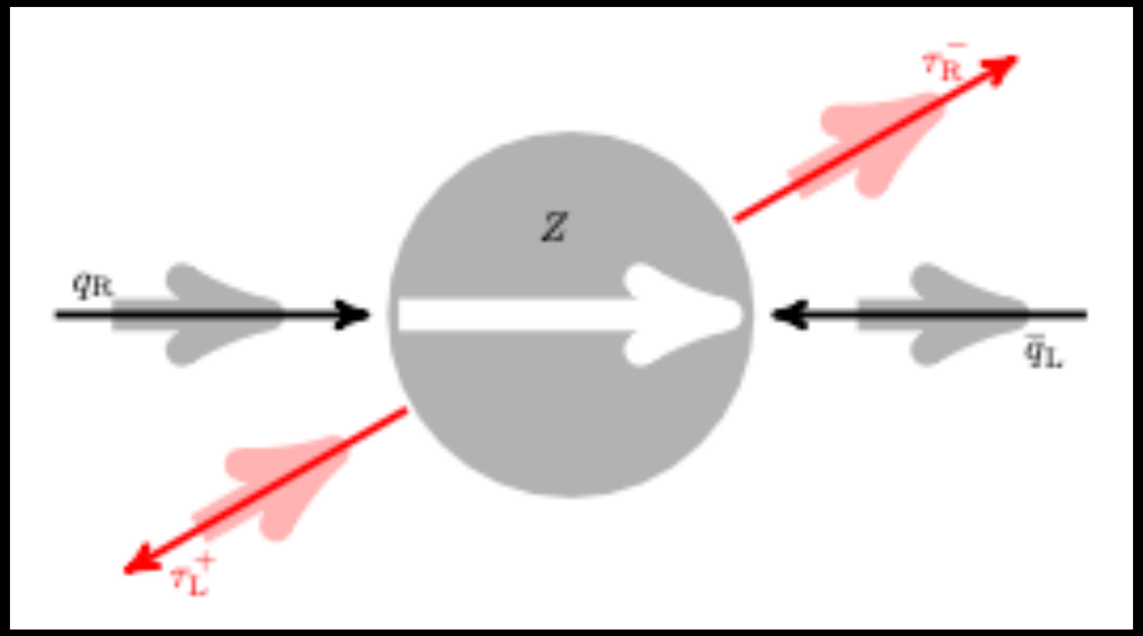
Measure charm content by identifying D(*) mesons



arXiv:2302.00336

Measurement of tau lepton polarization in Z boson decays

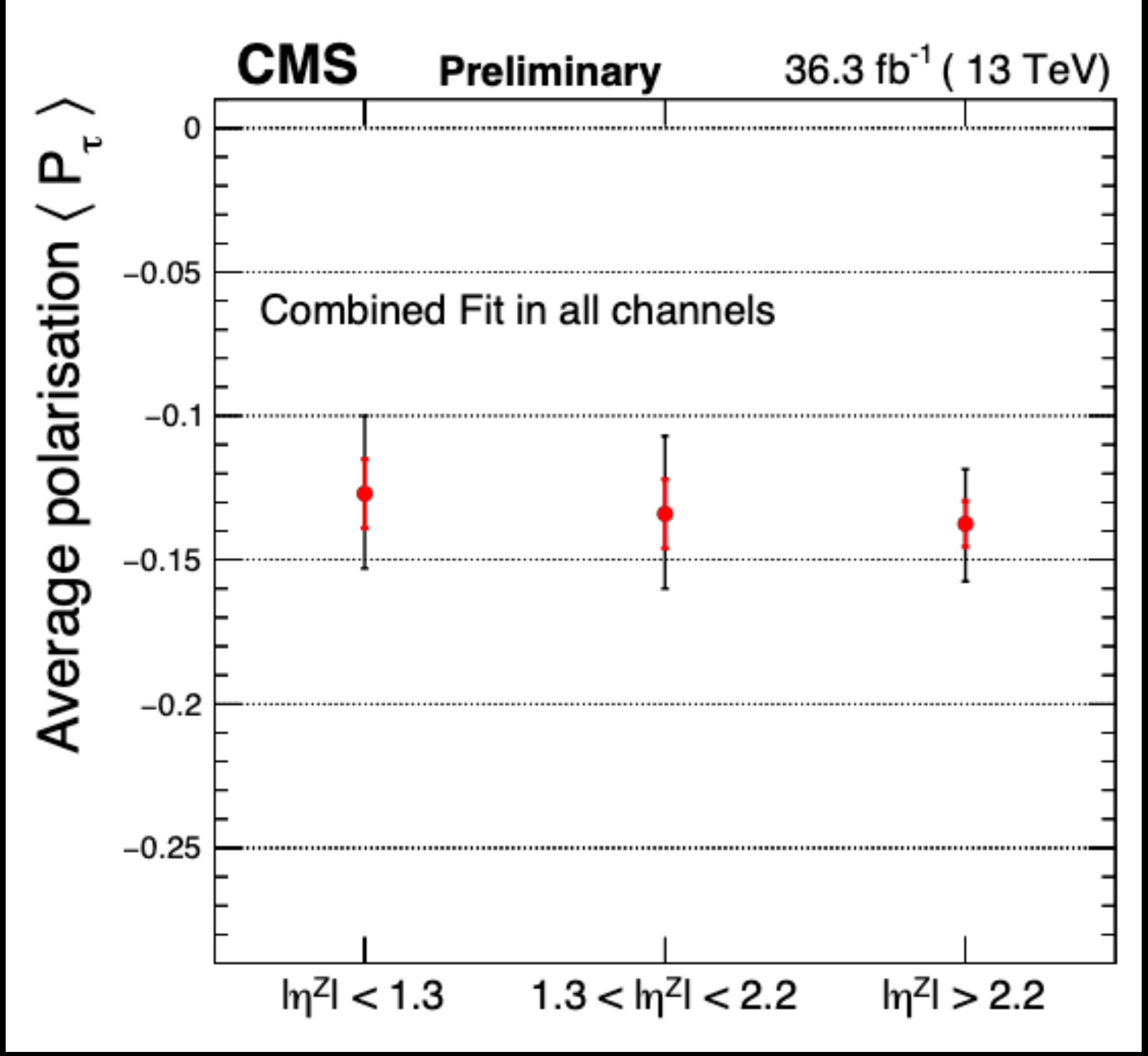
CMS-PAS-SMP-18-010

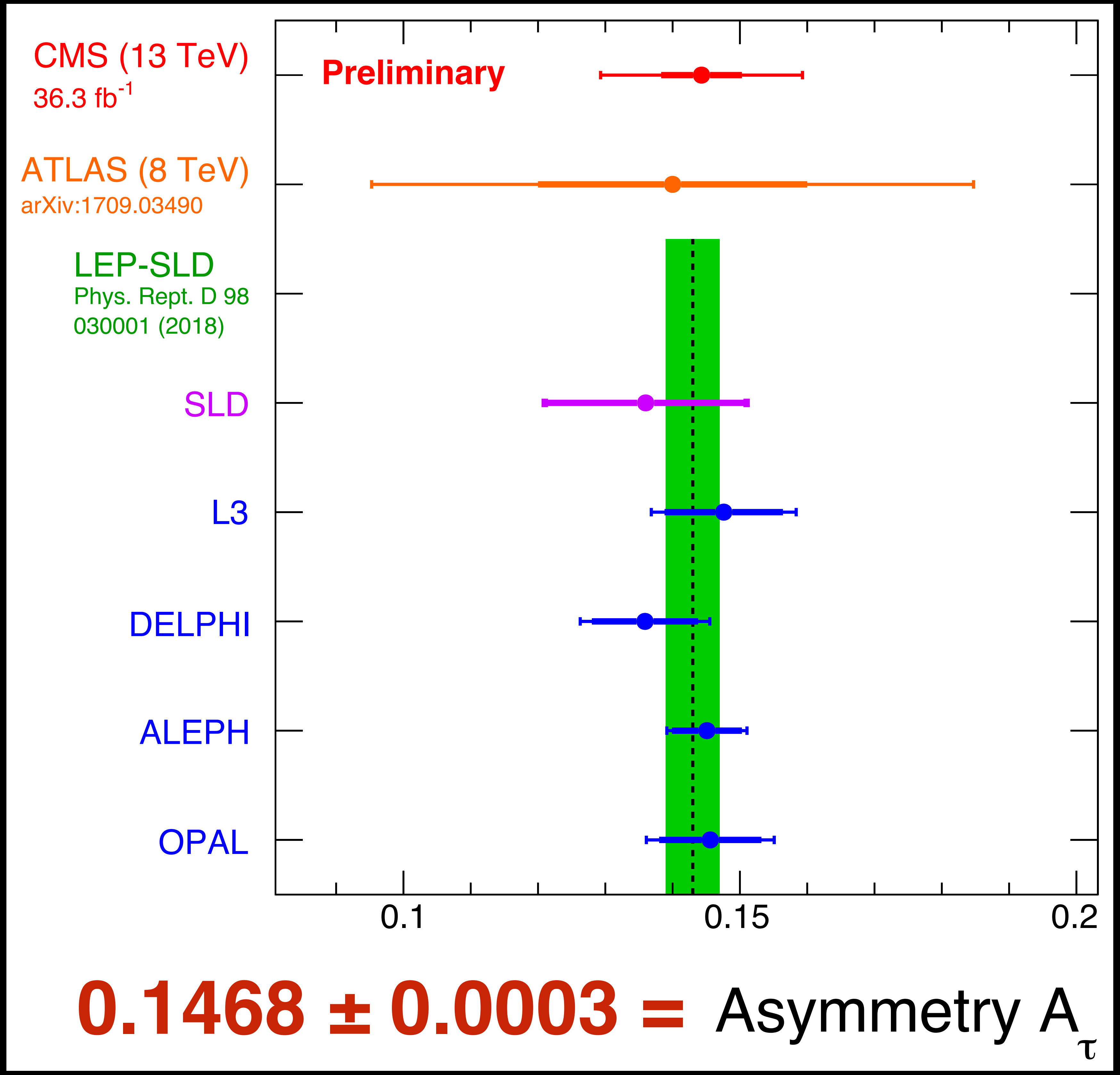


Measurement of τ polarization can probe underlying electroweak parameters: A_τ , $\sin^2(\theta_W)$

Result extracted from a simultaneous fit to 11 categories (leptonic/hadronic)

Agrees with SM expectations

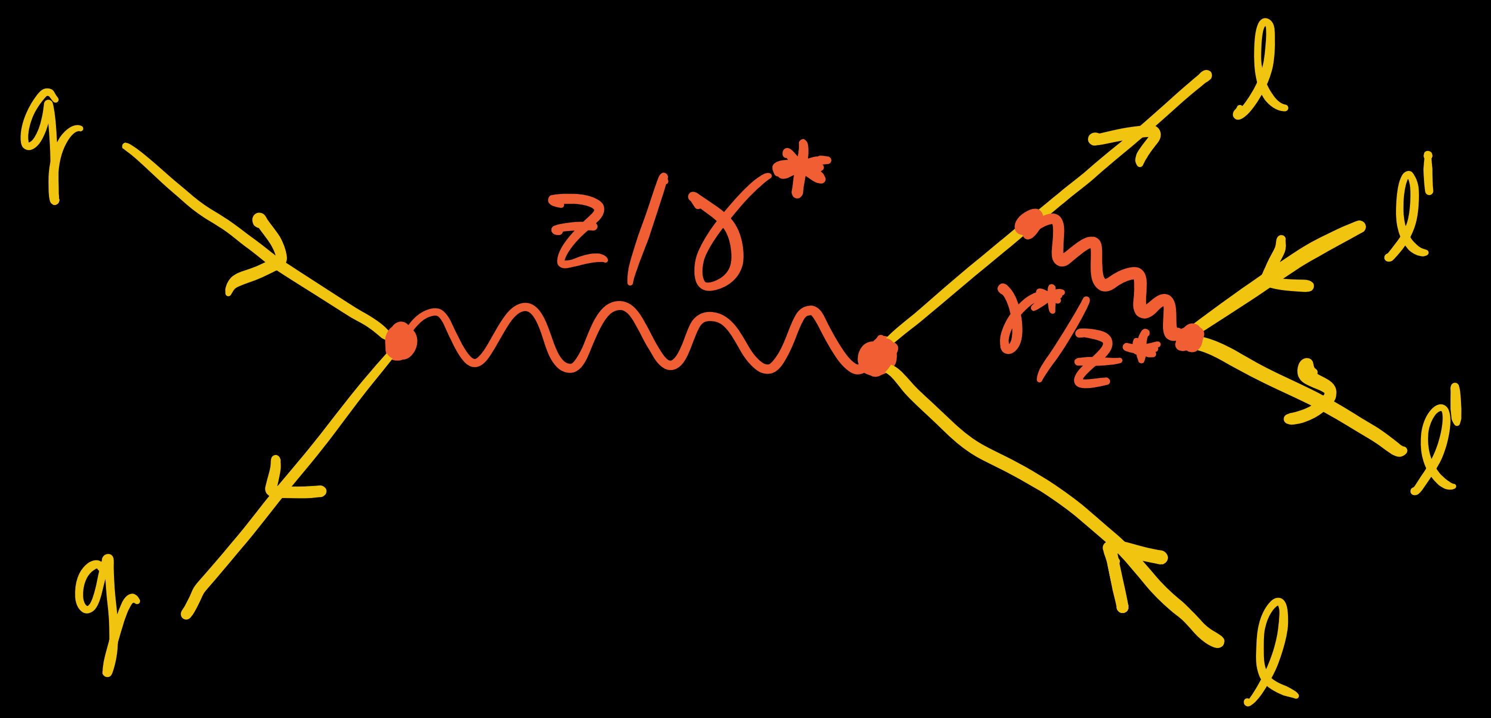




Precision not far from single LEP experiments

Search for rare decay of Z → ττμμ

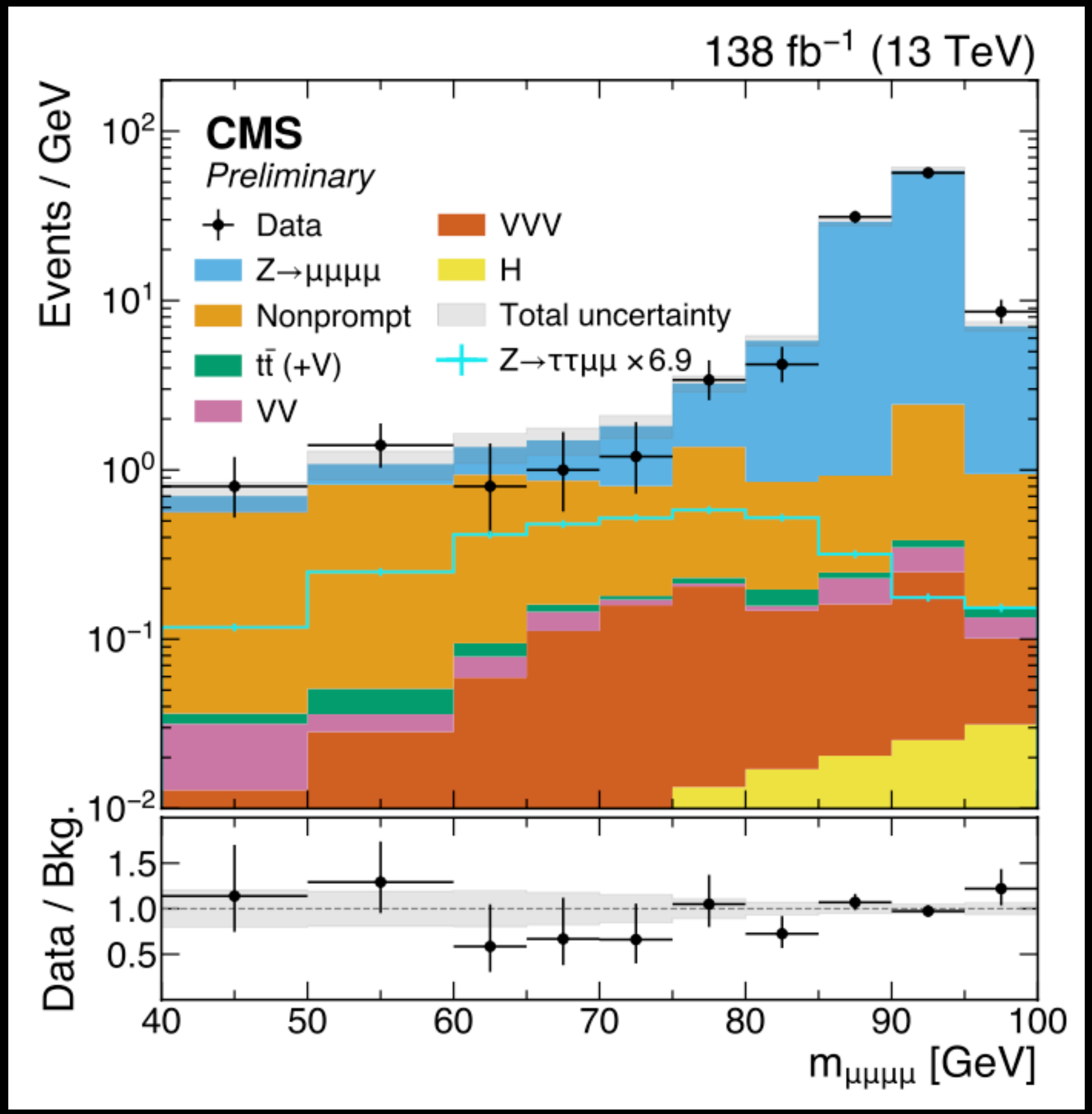
CMS-PAS-SMP-22-016

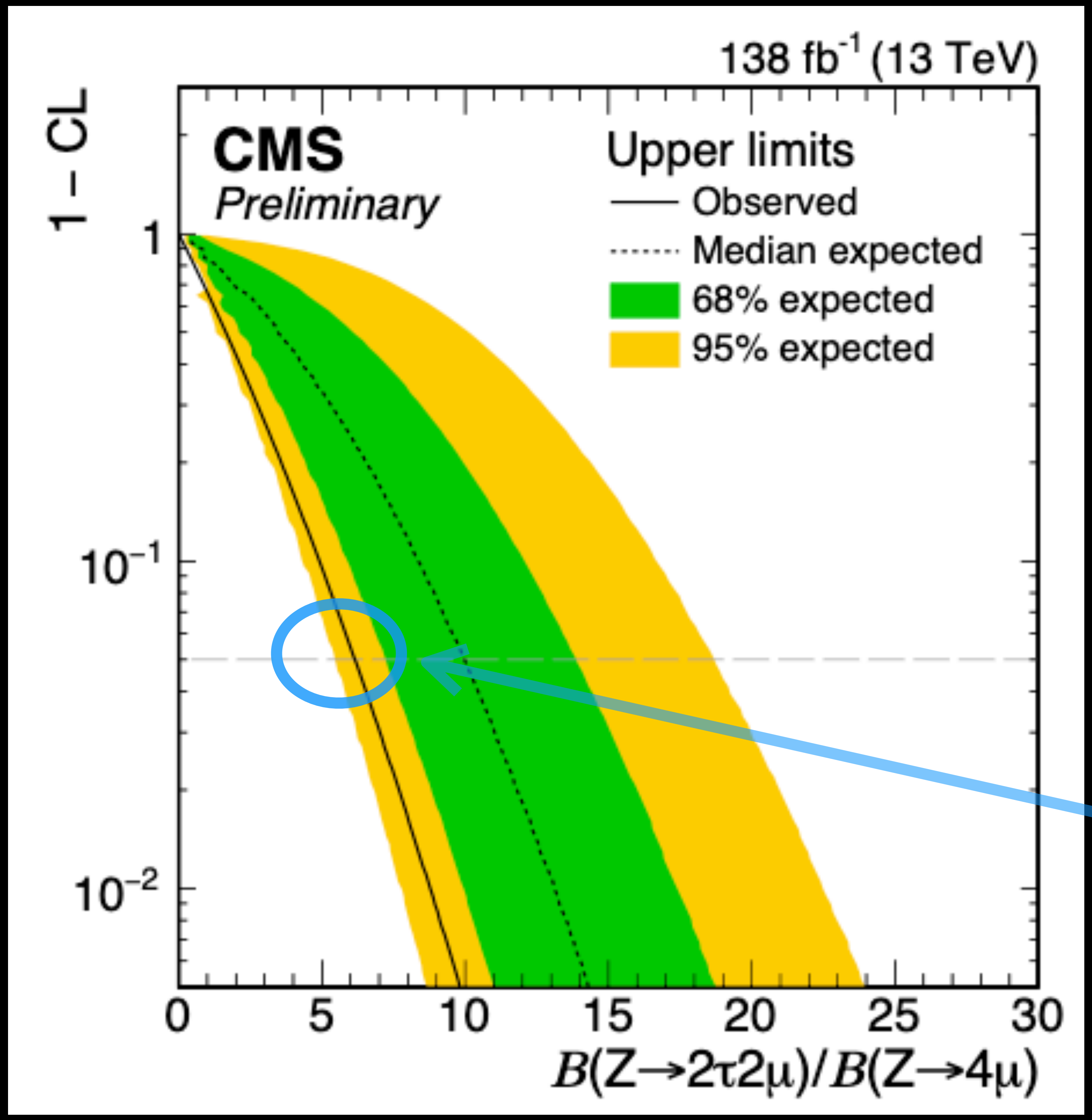


First ever search for this rare decay mode, SM BR ~ 10^{-6}

Possibly sensitive to new physics

e.g existence of a Z' could enhance cross section





Limit set on the ratio of BR Z → ττμμ relative to Z → μμμμ

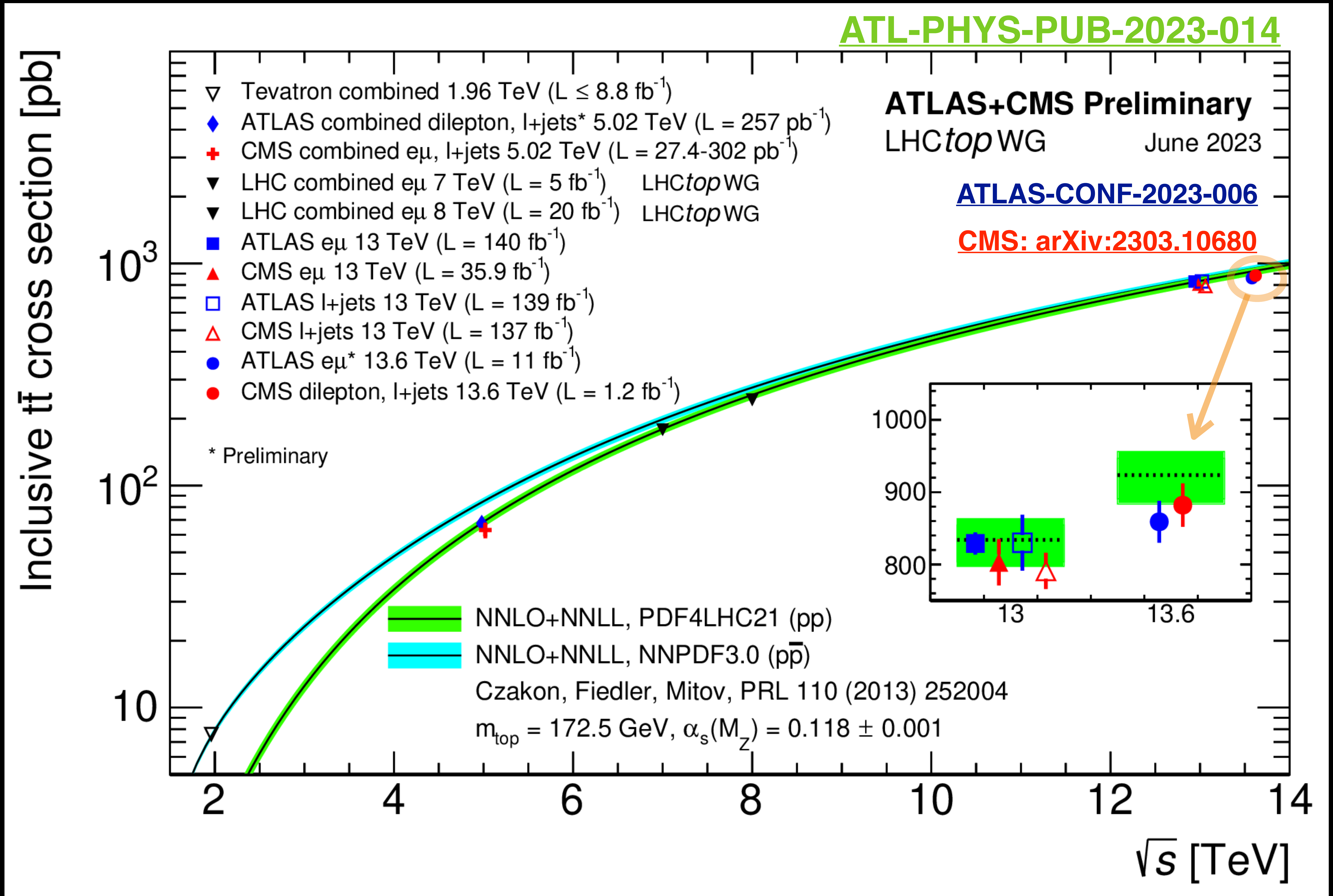
Ratio above 6.2 excluded at 95% CL

Corresponds to 6.9x SM expectation

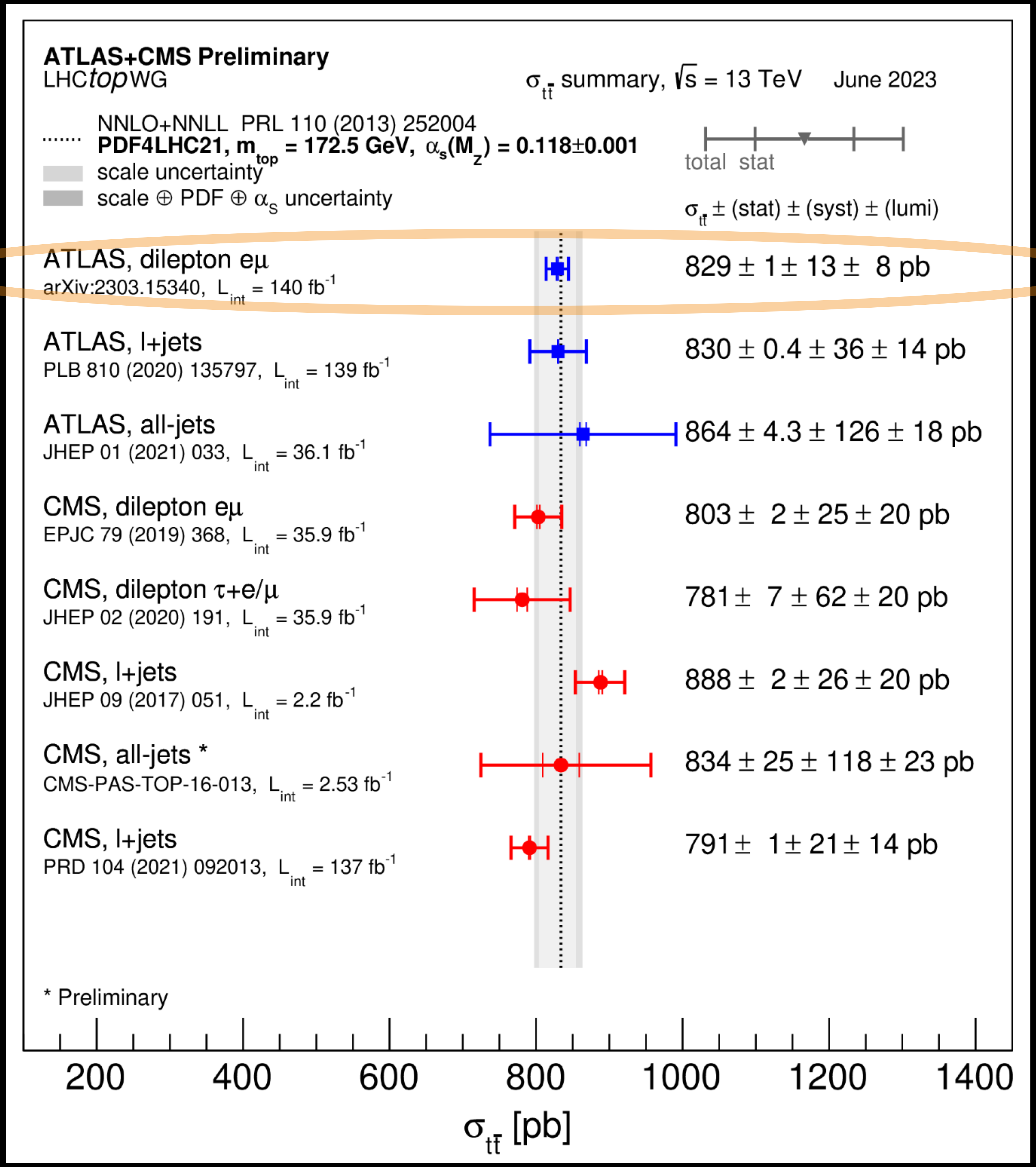
Top quark

Top quark pair production

New top cross section measurements from ATLAS and CMS at 13.6 TeV, consisted with NNLO+NNLL theoretical predictions
(ATLAS: eμ channel; CMS: dilepton, lepton+jets)



New measurement from ATLAS in eμ channel at 13 TeV
(Experimental uncertainty: ~1.8%)

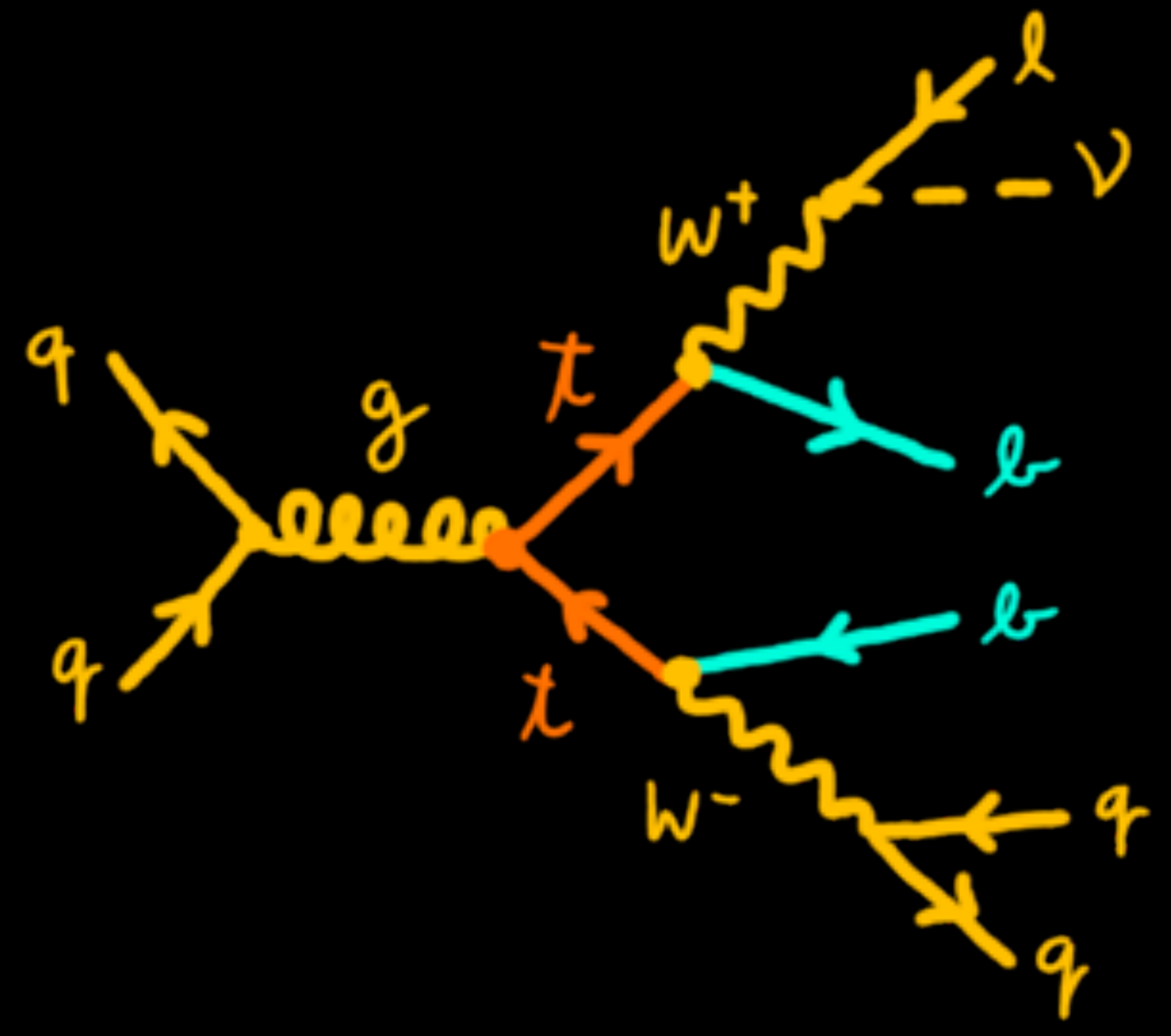


Start constraining gluon PDFs!

Top quark mass measurements

ATL-PHYS-PUB-2023-015

Measured in different channels with different techniques

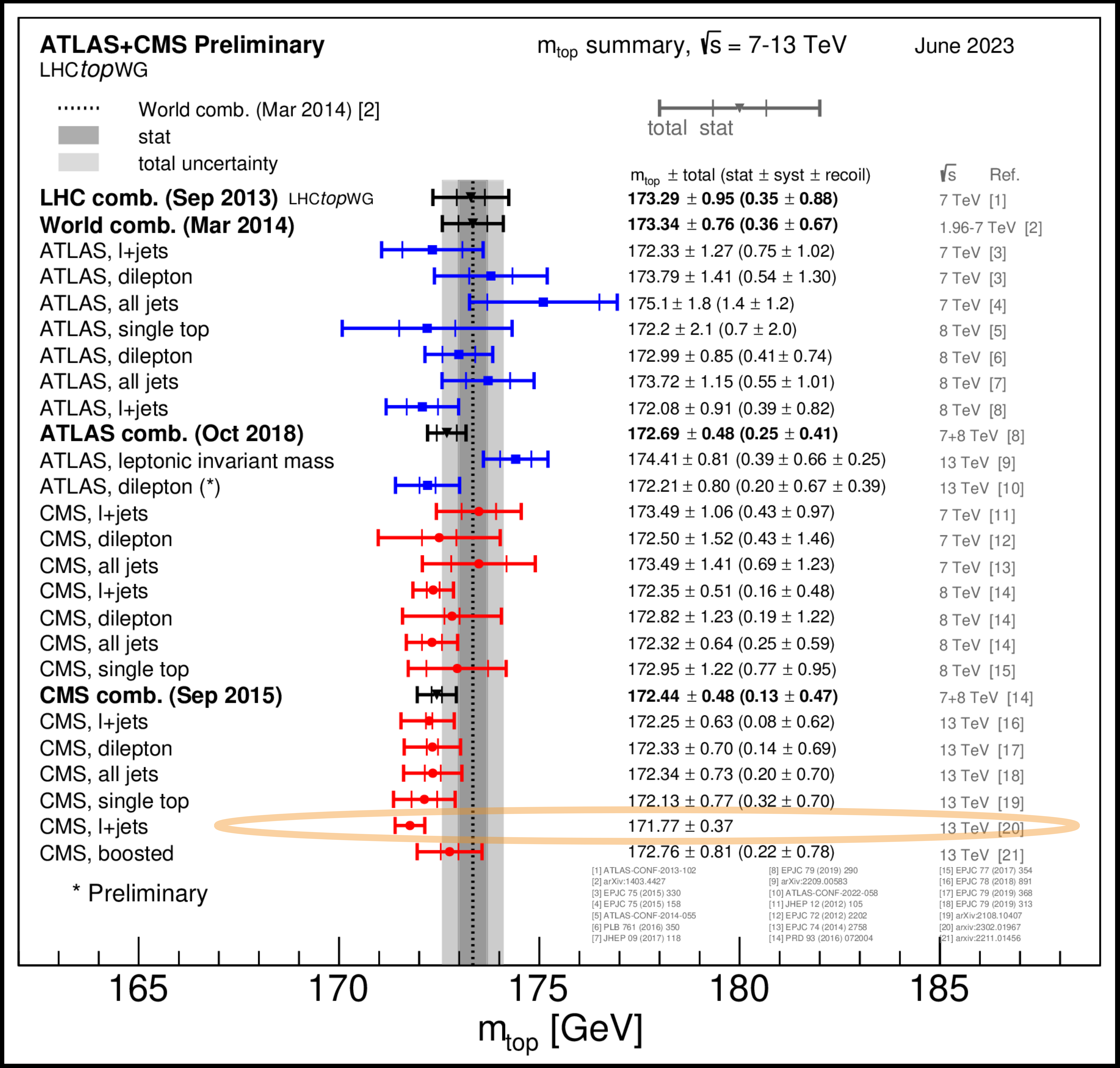


Best single measurement is from CMS, lepton+jets profile likelihood new result with 13 TeV data

m_{top} = 171.77 ± 0.37 GeV

Uncertainty reached ~ 0.2%

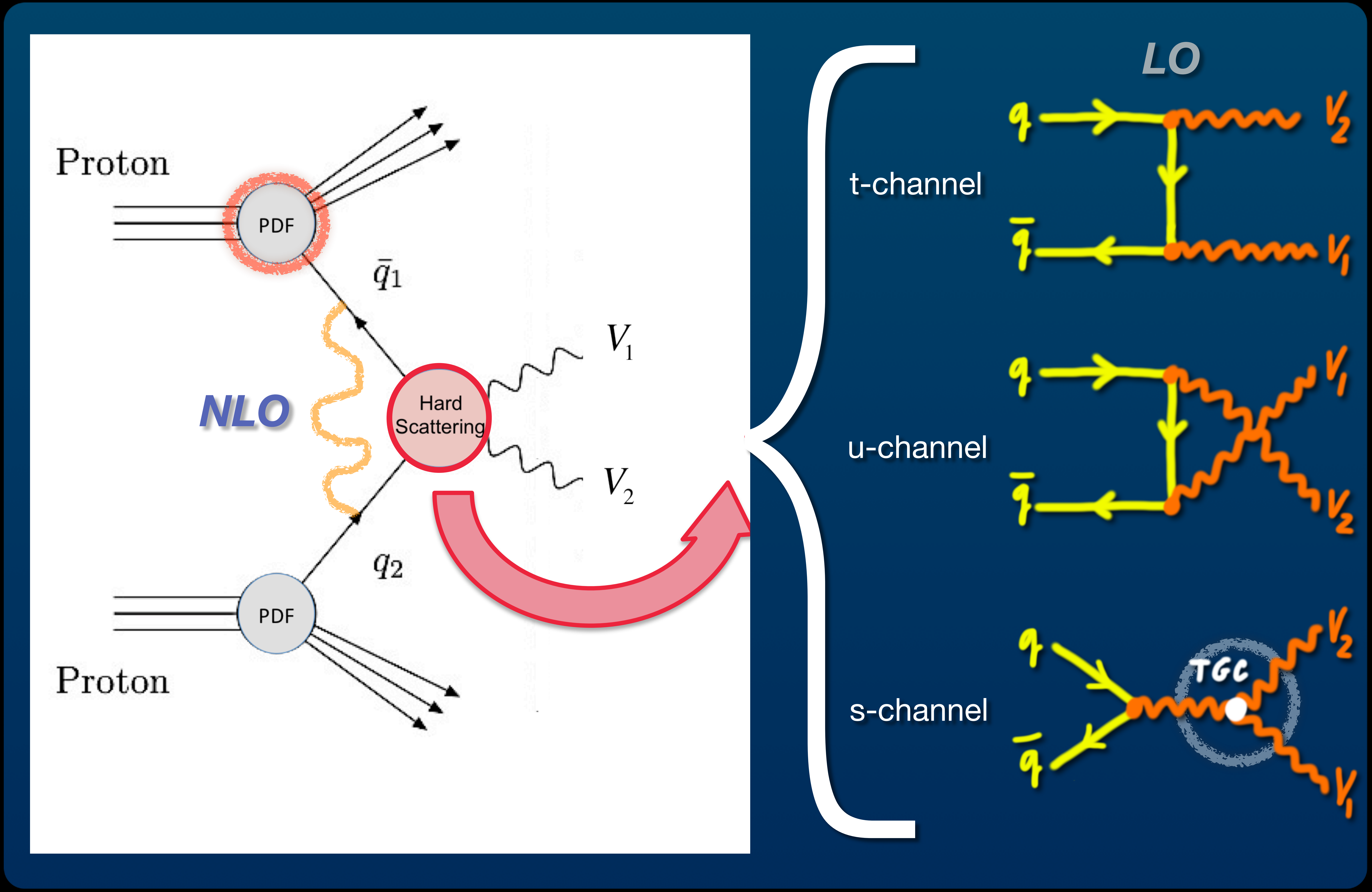
40% improvement relative to previous measurement



CMS-TOP-20-008

Dibosons and tribosons

Diboson production at the LHC



Diboson production cross-section measurements

CMS summaries

Extensive program both in ATLAS and CMS

γγ

Wγ

Zγ

See plenary talk from Marcel Vos on Friday

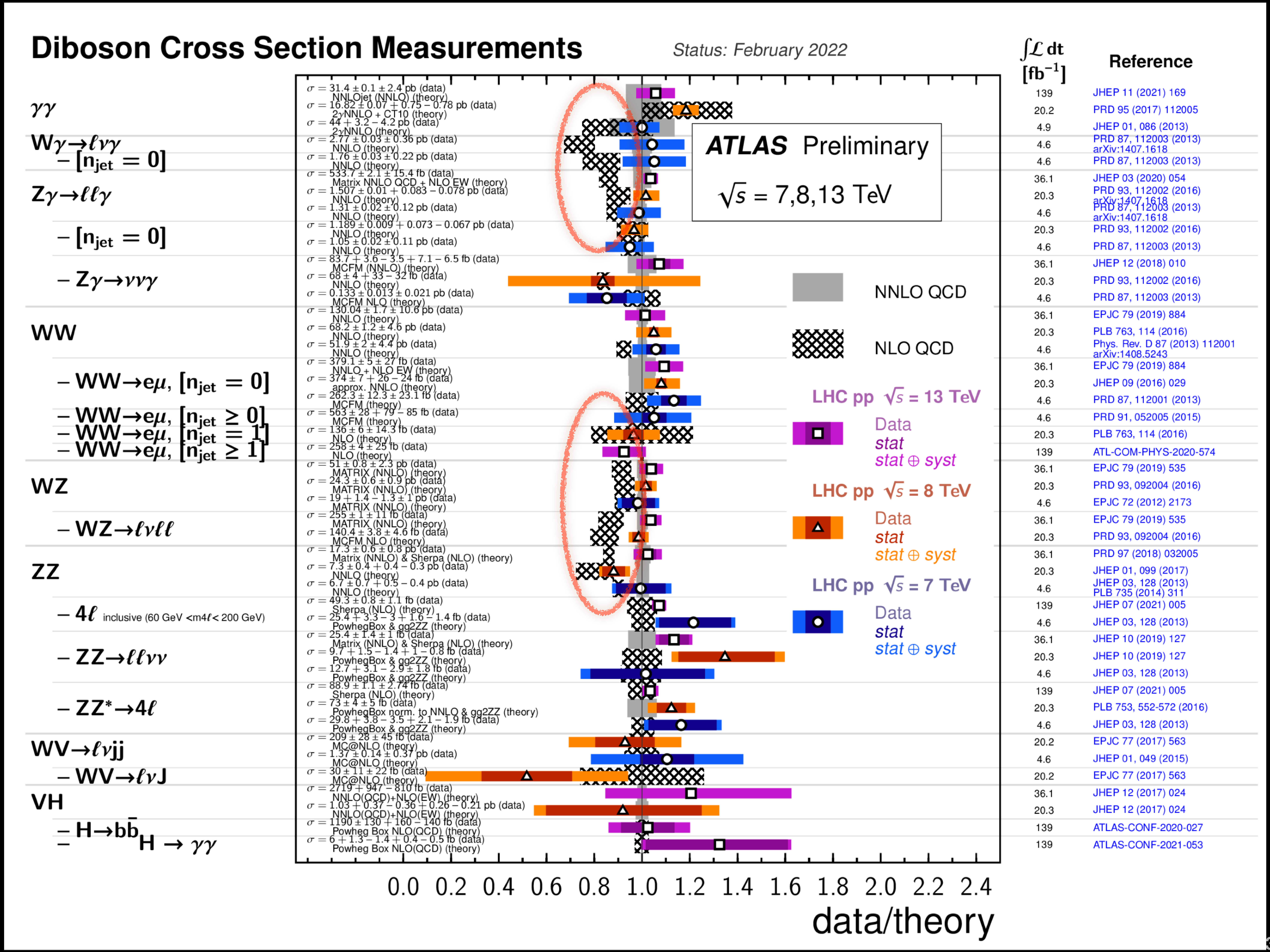
WW

WZ

ZZ

Experimental results demanded higher precision theoretical calculations

Excesses observed years ago disappeared once NNLO QCD calculations became available

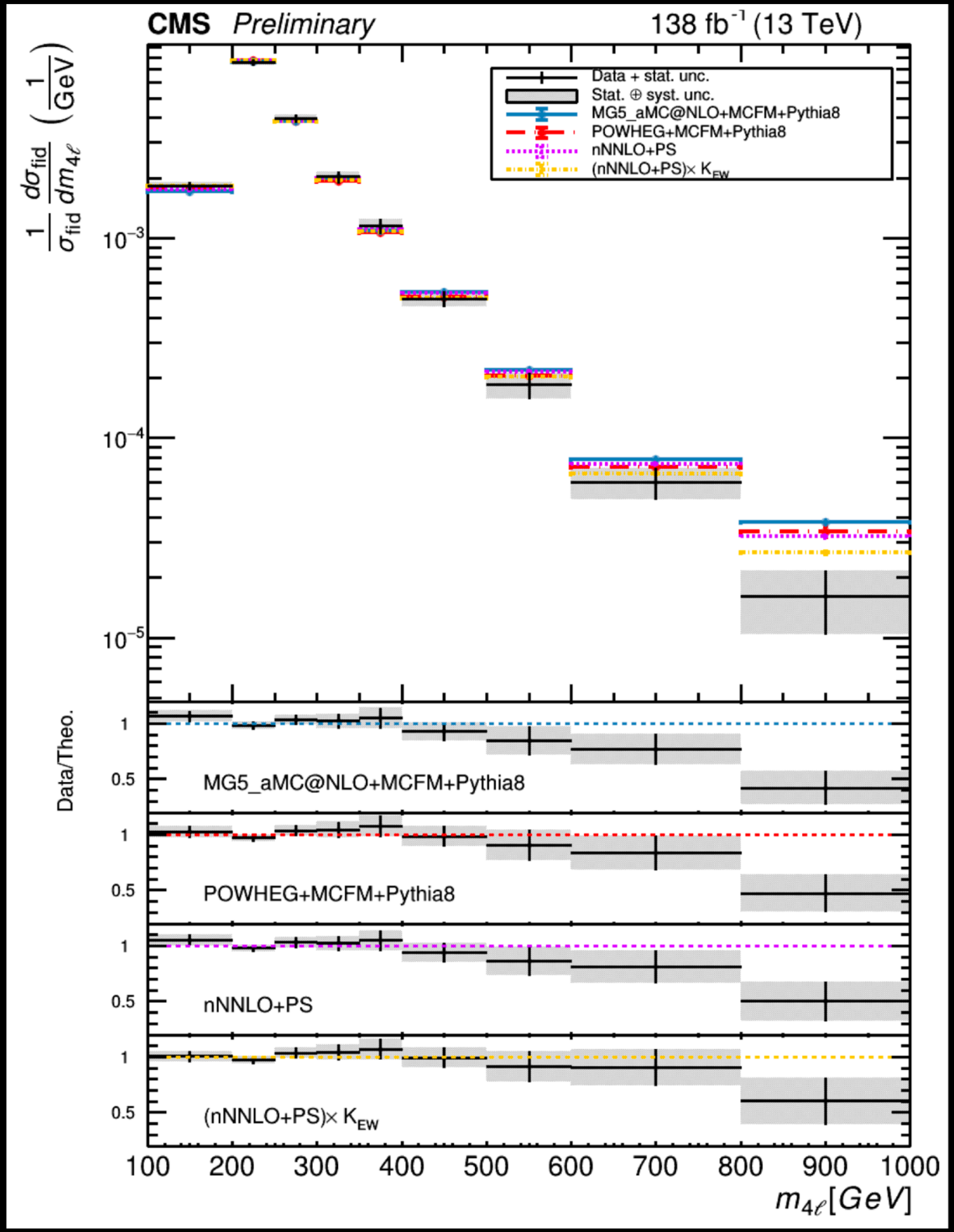


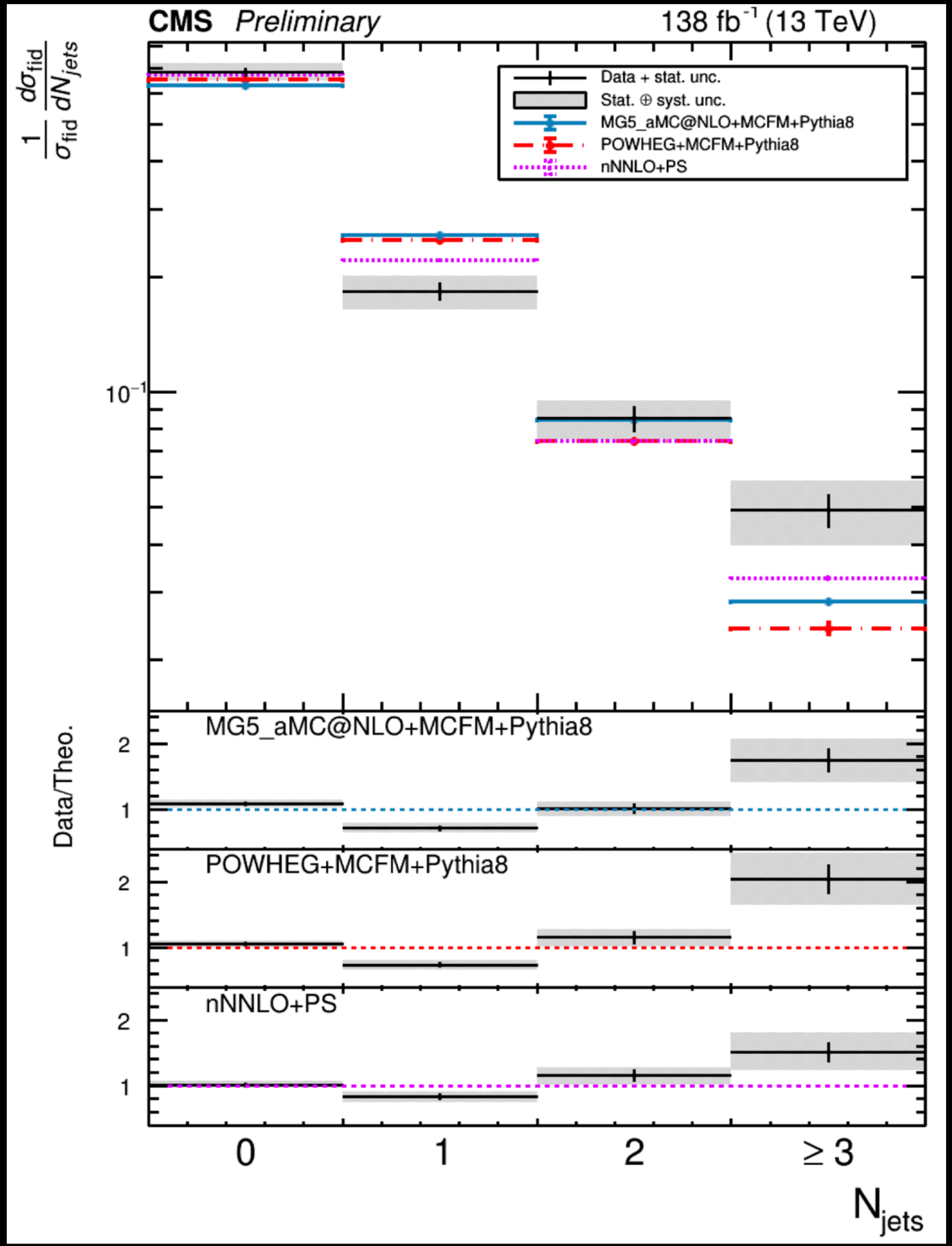
ZZ+ jets differential cross section

CMS PAS SMP-22-001

Four-lepton production in association with jets (non-resonant production of Z bosons)

Precision already enough to test predictions made recently available at next-to-next leading order (NNLO) in QCD





nNNLO+PS with MiNNLO$_{PS}$

Buonocore

Better than Madgraph or Powheg

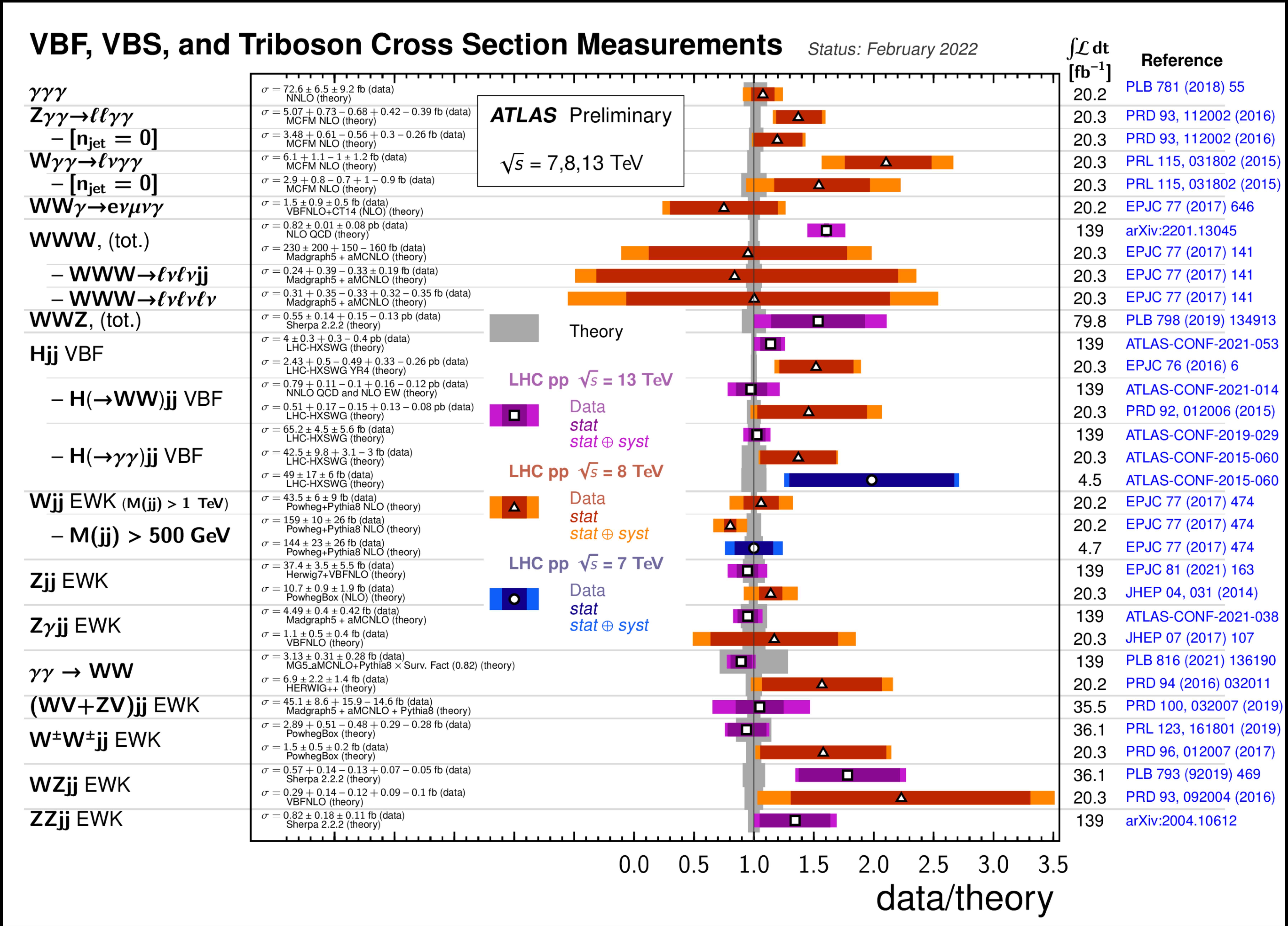
EWK corrections needed to improve agreement for m$_{4l}$

Vector boson fusion, vector boson scattering, and triboson production

Rare SM processes with cross sections down to < 1 fb^{-1}

See plenary talk from Marcel Vos on Friday

CMS summaries



Closing remarks

The LHC proton-proton runs have produced exceptionally precise Standard Model results at 5, 7, 8 and 13 TeV

Ratification of the Standard Model of Particle Physics

=> Discovery of the Higgs Boson

=> Many precision measurements of ever increasing complexity and exploring smaller and smaller cross sections, without finding significant deviations

The LHC Run 3 is at full speed → larger datasets → increased precision

=> Potential for significant discoveries and deeper precision measurements

Standard Model measurements and direct searches will continue playing complementary roles in the search for new physics at LHC and at future colliders (ILC, FCC-ee, CEPC)

Extra Slides

Overview of Standard Model measurements in ATLAS

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

Standard Model Production Cross Section Measurements

Status: February 2022

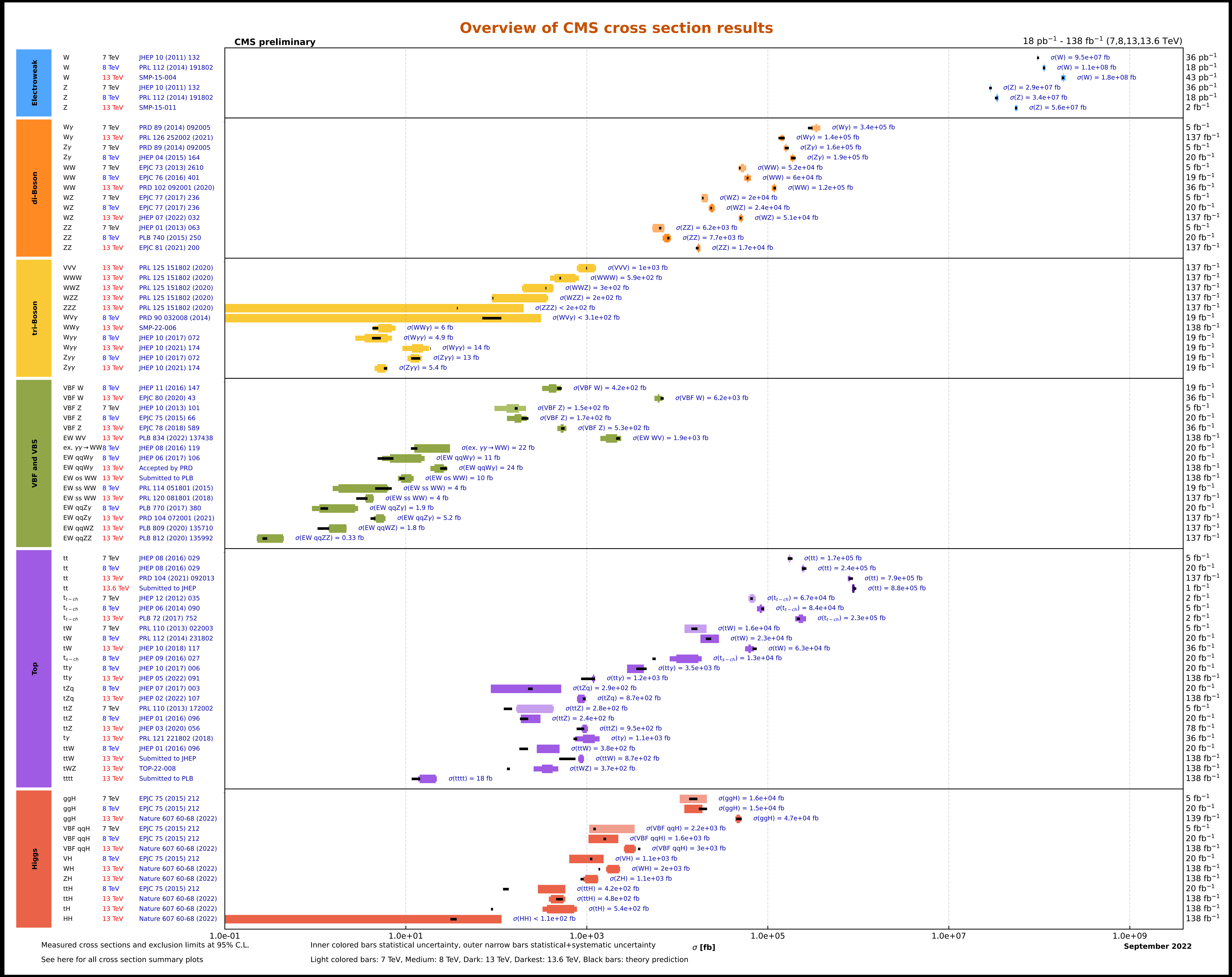
ATLAS Preliminary

$\sqrt{s}$ = 5, 7, 8, 13 TeV

Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt[fb^{-1}]$	Measurement	Theory	Reference
pp	8	50×10^{-8}	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb	$\sigma = 99.55 \pm 2.14$ mb (COMPETE HPR1R2)	PLB 761 (2016) 158
pp	7	8×10^{-8}	$\sigma = 95.35 \pm 0.38 \pm 1.3$ mb	$\sigma = 97.26 \pm 2.12$ mb (COMPETE HPR1R2)	Nucl. Phys. B, 486-548 (2014)
W	13	0.081	$\sigma = 190.1 \pm 0.2 \pm 6.4$ nb	$\sigma = 184.9 + 6 - 6.1$ nb (DYNNLO + CT14NNLO)	PLB 759 (2016) 601
W	8	20.2	$\sigma = 112.69 \pm 3.1$ nb	$\sigma = 110.919889503 \pm 3.7$ nb (DYNNLO + CT14NNLO)	EPJC 79 (2019) 760
W	7	4.6	$\sigma = 98.71 \pm 0.028 \pm 2.191$ nb	$\sigma = 95.9 \pm 2.9$ nb (DYNNLO + CT14NNLO)	EPJC 77 (2017) 367
Z	13	3.2	$\sigma = 58.43 \pm 0.03 \pm 1.66$ nb	$\sigma = 55.96 + 1.5 - 1.7$ nb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
Z	8	20.2	$\sigma = 34.24 \pm 0.03 \pm 0.92$ nb	$\sigma = 32.94 + 0.8 - 0.92$ nb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
Z	7	4.6	$\sigma = 29.53 \pm 0.03 \pm 0.77$ nb	$\sigma = 28.31 + 0.68 - 0.8$ nb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
$t\bar{t}$	13	36.1	$\sigma = 826.4 \pm 3.6 \pm 19.6$ pb	$\sigma = 832 + 40 - 45$ pb (top++ NNLO+NNLL)	EPJC 80 (2020) 528
$t\bar{t}$	8	20.2	$\sigma = 242.9 \pm 1.7 \pm 8.6$ pb	$\sigma = 252.9 + 13.3 - 14.5$ pb (top++ NNLO+NNLL)	EPJC 74 (2014) 3109
$t\bar{t}$	7	4.6	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb	$\sigma = 177 + 10 - 11$ pb (top++ NNLO+NNLL)	EPJC 74 (2014) 3109
t_{t-chan}	13	3.2	$\sigma = 247 \pm 6 \pm 46$ pb	$\sigma = 217 \pm 10$ pb (NLO+NLL)	JHEP 04 (2017) 086
t_{t-chan}	8	20.3	$\sigma = 89.6 \pm 1.7 + 7.2 - 6.4$ pb	$\sigma = 87.8 + 3.4 - 1.9$ pb (NLO+NLL)	EPJC 77 (2017) 531
t_{t-chan}	7	4.6	$\sigma = 68 \pm 2 \pm 8$ pb	$\sigma = 64.6 + 2.7 - 2$ pb (NLO+NLL)	PRD 90, 112006 (2014)
Wt	13	3.2	$\sigma = 94 \pm 10 + 28 - 23$ pb	$\sigma = 71.7 \pm 3.9$ pb (NLO+NNLL)	JHEP 01 (2018) 63
Wt	8	20.3	$\sigma = 23 \pm 1.3 + 3.4 - 3.7$ pb	$\sigma = 22.4 \pm 1.5$ pb (NLO+NLL)	JHEP 01, 064 (2016)
Wt	7	2.0	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb	$\sigma = 15.7 \pm 1.1$ pb (NLO+NLL)	PLB 716, 142-159 (2012)
H	13	139	$\sigma = 55.5 \pm 3.2 + 2.4 - 2.2$ pb	$\sigma = 55.6 \pm 2.5$ pb (LHC-HXSWG YR4)	ATLAS-CONF-2022-002
H	8	20.3	$\sigma = 27.7 \pm 3 + 2.3 - 1.9$ pb	$\sigma = 24.5 + 1.3 - 1.8$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
H	7	4.5	$\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7$ pb	$\sigma = 19.2 + 1 - 1.4$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
H VBF, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 4 \pm 0.3 + 0.3 - 0.4$ pb	$\sigma = 3.51 \pm 0.07$ pb (LHC-HXSWG)	ATLAS-CONF-2021-053
H VBF	8	20.3	$\sigma = 2.43 + 0.5 - 0.49 + 0.33 - 0.26$ pb	$\sigma = 1.6 \pm 0.04$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
VH	8	20.3	$\sigma = 1.03 + 0.37 - 0.36 + 0.26 - 0.21$ pb	$\sigma = 1.12 \pm 0.03$ pb (NNLO(QCD)+NLO(EW))	JHEP 12 (2017) 024
WH, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 1.56 + 0.2 - 0.21 + 0.16 - 0.18$ pb	$\sigma = 1.203 \pm 0.024$ pb (Powheg Box NLO(QCD))	ATLAS-CONF-2021-053
ZH, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 0.7 \pm 0.13 + 0.1 - 0.12$ pb	$\sigma = 0.795 \pm 0.03$ pb (Powheg Box NLO(QCD))	ATLAS-CONF-2021-053
$t\bar{t}H$	13	139	$\sigma = 560 \pm 80 + 70 - 80$ fb	$\sigma = 580 \pm 50$ fb (LHCHXSWG NLO QCD + NLO EW)	ATLAS-CONF-2021-053
$t\bar{t}H$	8	20.3	$\sigma = 220 \pm 100 \pm 70$ fb	$\sigma = 133 + 8 - 13$ fb (LHCHXSWG NLO QCD + NLO EW)	PLB 784 (2018) 173
WW	13	36.1	$\sigma = 130.04 \pm 1.7 \pm 10.6$ pb	$\sigma = 128.4 + 3.2 - 2.9$ pb (NNLO)	EPJC 79 (2019) 884
WW	8	20.3	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb	$\sigma = 65 + 1.2 - 1.1$ pb (NNLO)	PLB 763, 114 (2016)
WW	7	4.6	$\sigma = 51.9 \pm 2 \pm 4.4$ pb	$\sigma = 49.04 + 1.03 - 0.88$ pb (NNLO)	Phys. Rev. D 87 (2013) 112001, arXiv:1408.5243
WZ	13	36.1	$\sigma = 51 \pm 0.8 \pm 2.3$ pb	$\sigma = 49.1 + 1.1 - 1$ pb (MATRIX (NNLO))	EPJC 79 (2019) 535
WZ	8	20.3	$\sigma = 24.3 \pm 0.6 \pm 0.9$ pb	$\sigma = 23.92 \pm 0.4$ pb (MATRIX (NNLO))	PRD 93, 092004 (2016)
WZ	7	4.6	$\sigma = 19 + 1.4 - 1.3 \pm 1$ pb	$\sigma = 19.34 + 0.3 - 0.4$ pb (MATRIX (NNLO))	EPJC 72 (2012) 2173
ZZ	13	36.1	$\sigma = 17.3 \pm 0.6 \pm 0.8$ pb	$\sigma = 16.9 + 0.6 - 0.5$ pb (Matrix (NNLO) & Sherpa (NLO))	PRD 97 (2018) 032005
ZZ	8	20.3	$\sigma = 7.3 \pm 0.4 + 0.4 - 0.3$ pb	$\sigma = 8.284 + 0.249 - 0.191$ pb (NNLO)	JHEP 01, 099 (2017)
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb	$\sigma = 6.735 + 0.195 - 0.155$ pb (NNLO)	JHEP 03, 128 (2013), PLB 735 (2014) 311
t_{s-chan}	8	20.3	$\sigma = 4.8 \pm 0.8 + 1.6 - 1.3$ pb	$\sigma = 5.61 \pm 0.22$ pb (NLO+NNL)	LB 756, 228-246 (2016)
$t\bar{t}W$	13	36.1	$\sigma = 870 \pm 130 \pm 140$ fb	$\sigma = 600 \pm 72$ fb (Madgraph5 + aMCNLO)	PRD 99, 072009 (2019)
$t\bar{t}W$	8	20.3	$\sigma = 369 + 86 - 79 \pm 44$ fb	$\sigma = 232 \pm 32$ fb (MCFM)	JHEP 11, 172 (2015)
$t\bar{t}Z$	13	139	$\sigma = 990 \pm 50 \pm 80$ fb	$\sigma = 840 \pm 90$ fb (Madgraph5 + aMCNLO)	Eur. Phys. J. C 81 (2021) 737
$t\bar{t}Z$	8	20.3	$\sigma = 176 + 52 - 48 \pm 24$ fb	$\sigma = 215 \pm 30$ fb (HELAC-NLO)	JHEP 11, 172 (2015)
WWW	13	139	$\sigma = 0.82 \pm 0.01 \pm 0.08$ pb	$\sigma = 0.511 \pm 0.018$ pb (NLO QCD)	arXiv:2201.13045
WWZ	13	79.8	$\sigma = 0.55 \pm 0.14 + 0.15 - 0.13$ pb	$\sigma = 0.358 \pm 0.036$ pb (Sherpa 2.2.2)	PLB 798 (2019) 134913
$t\bar{t}t\bar{t}$	13	139	$\sigma = 24 \pm 4 \pm 5$ fb	$\sigma = 12 \pm 2.4$ fb (NLO QCD + EW)	JHEP 11 (2021) 118

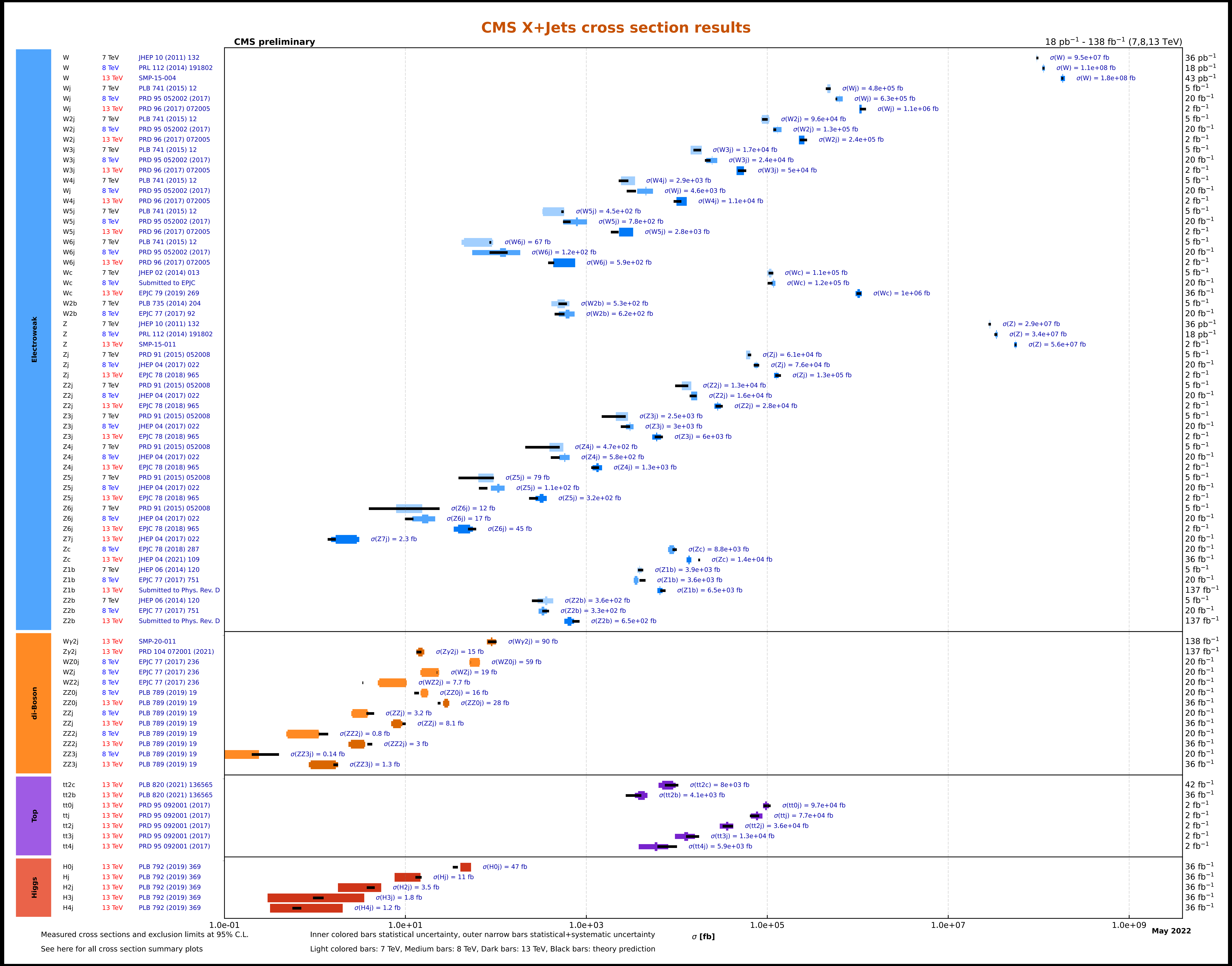
Overview of CMS cross section results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

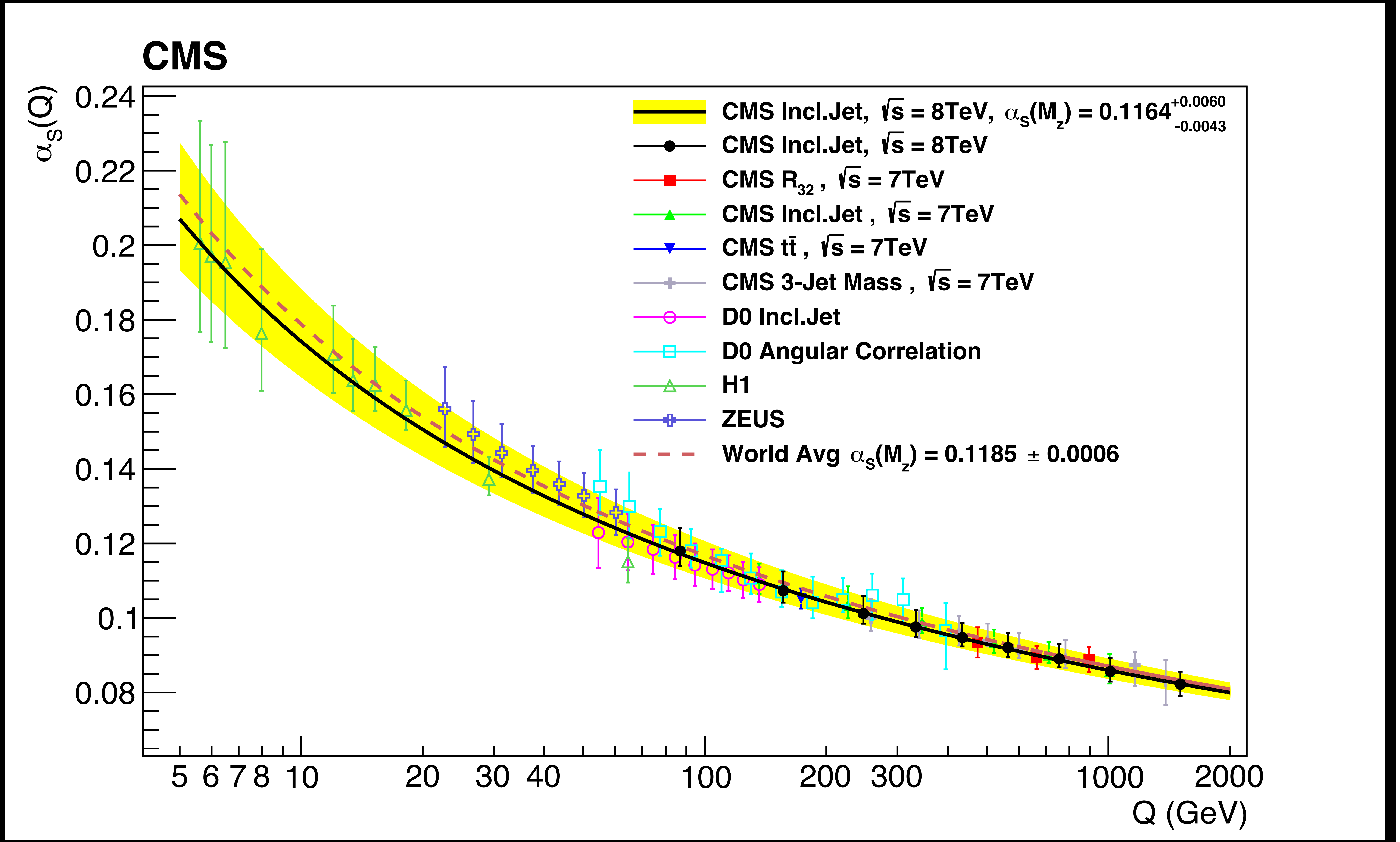


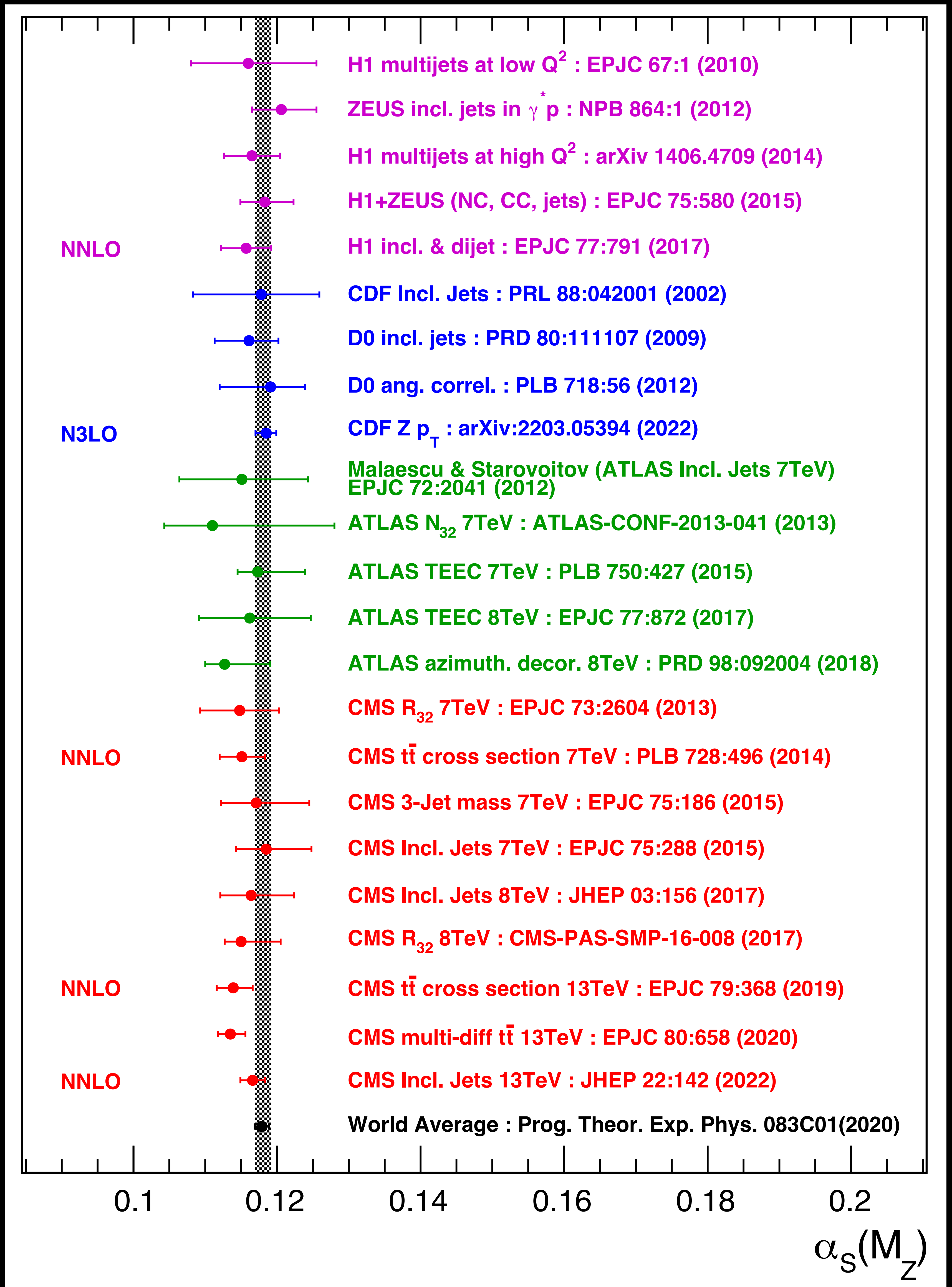
Overview of CMS X+jets cross section results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



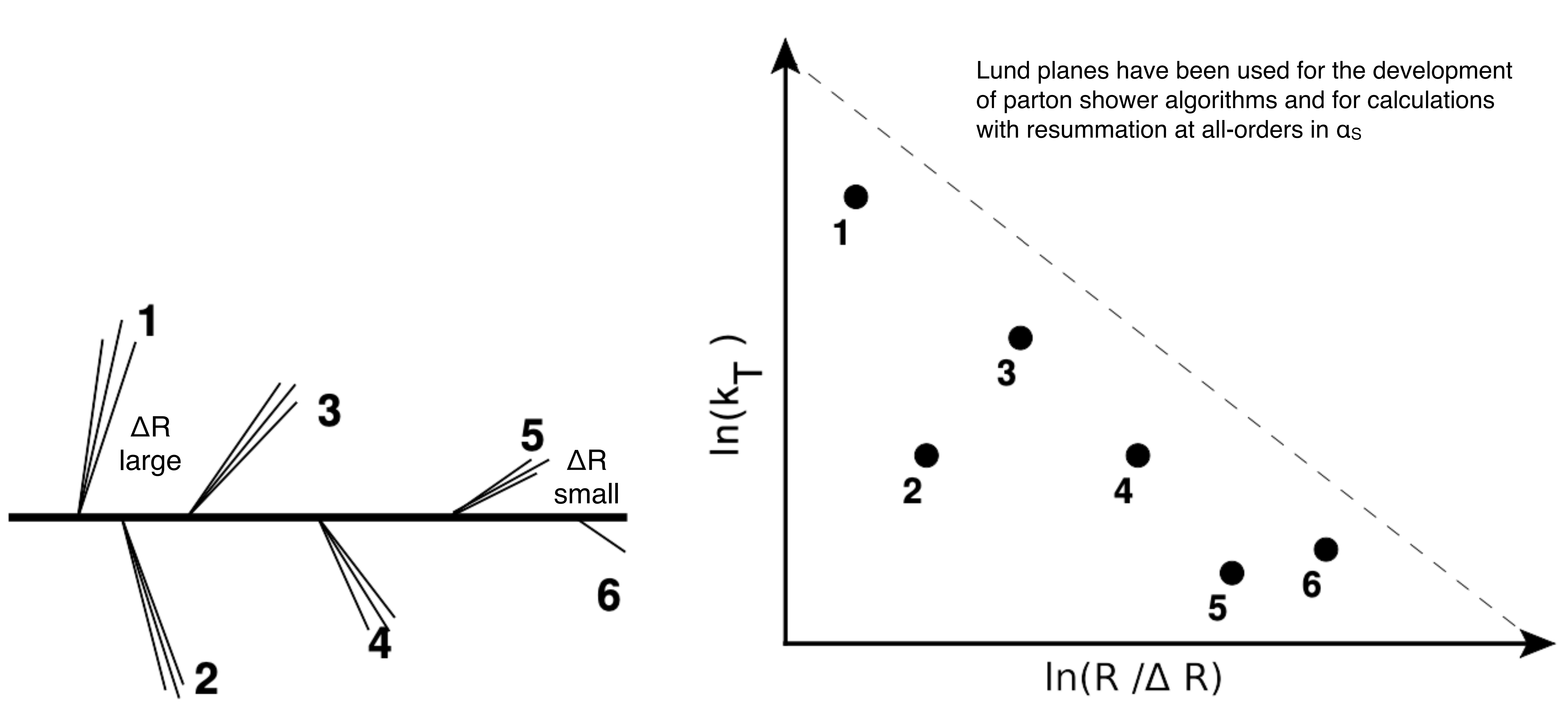
Determination of the strong coupling constant from CMS





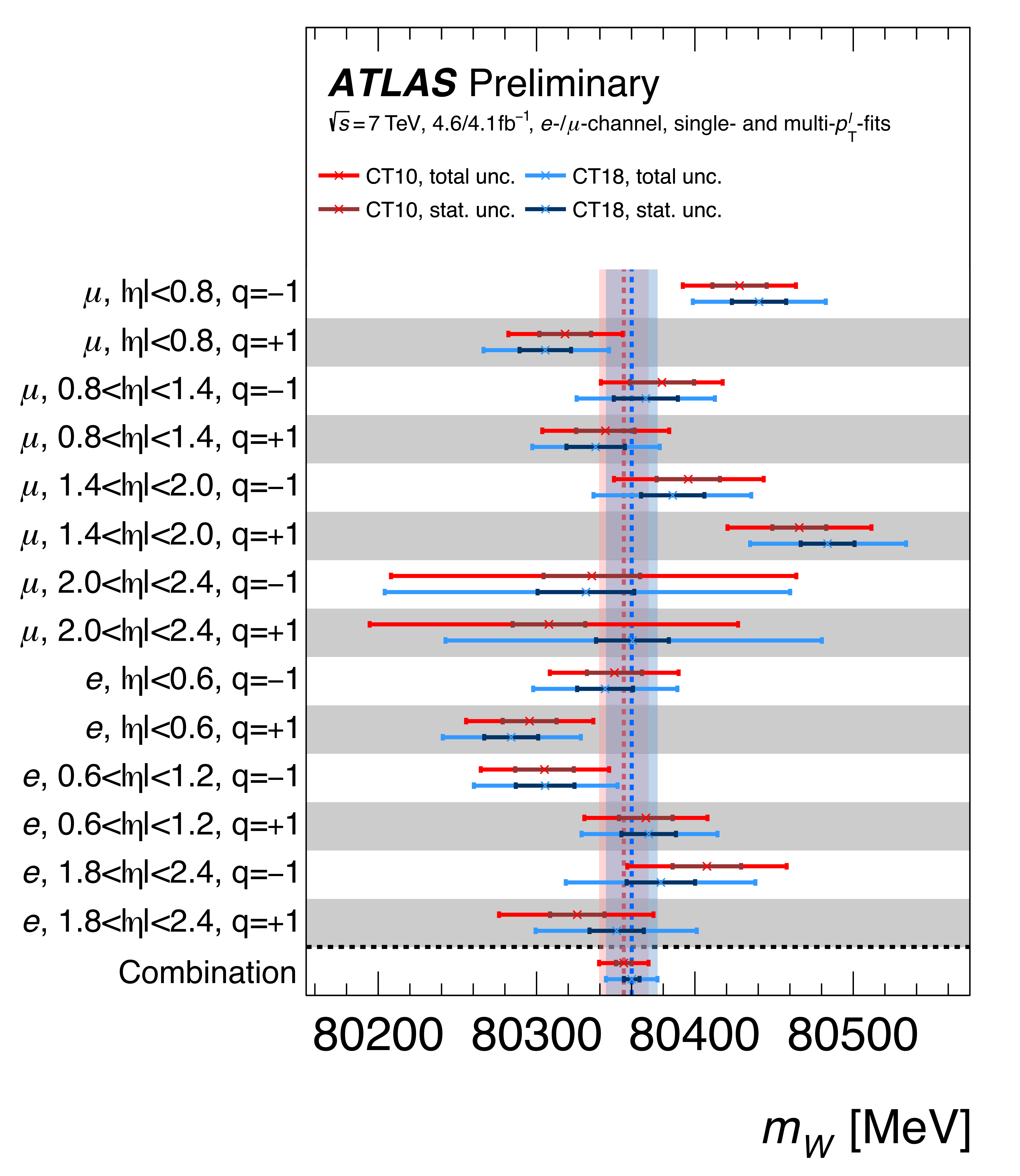
Cambridge/Aachen algorithm and Lund plane

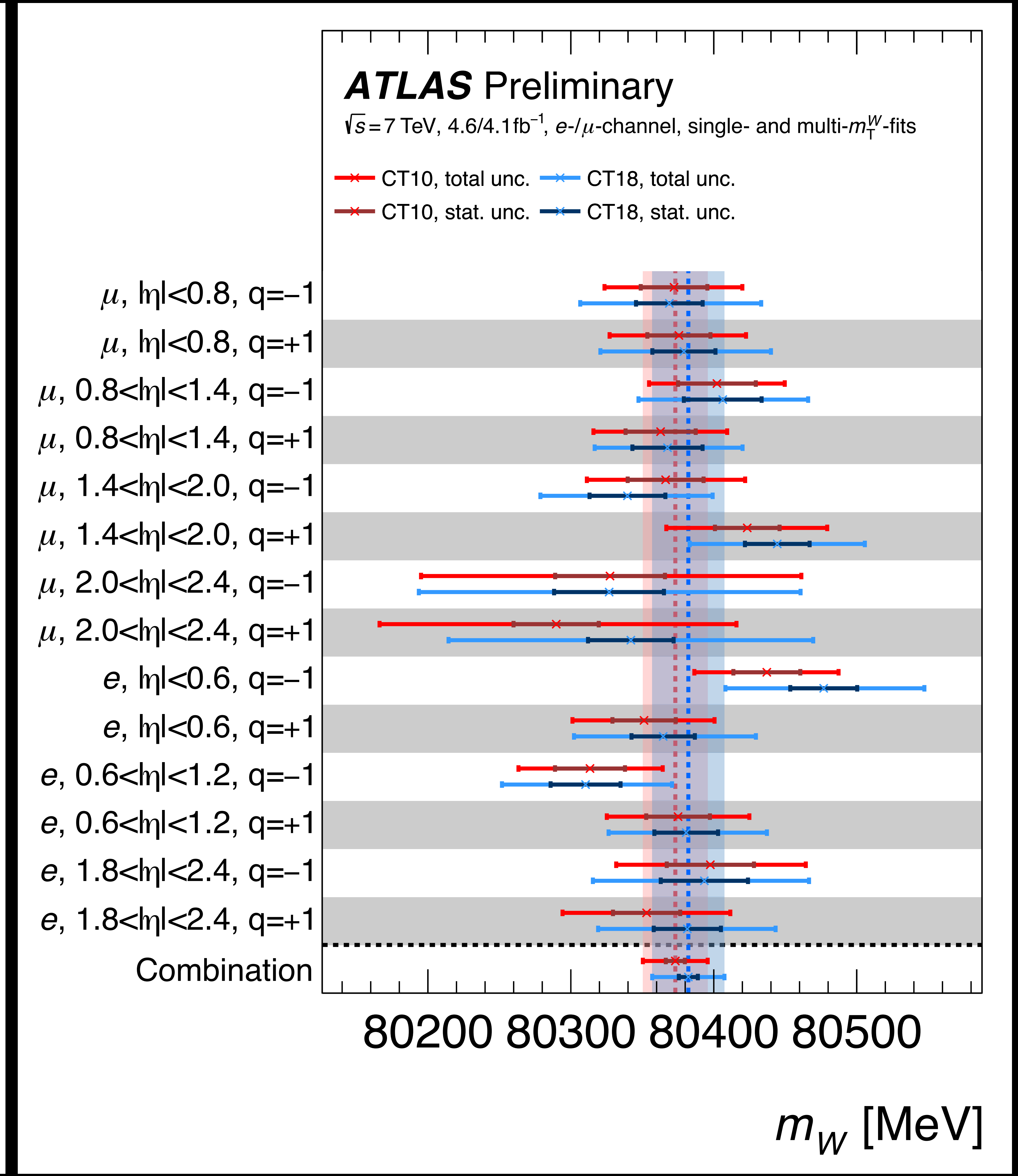
Cambridge/Aachen primary declustering tree of a jet → the emissions are angular ordered



Cross checks of W mass measurement

Comparison of the PLH fit results of the individual measurement categories as well as the combination of all between the PDF set CT10 and CT18





Cross checks of W mass measurement

Results are determined using a PLH approach and in comparison with a χ2-minimization approach using statistical uncertainties only