QCD at High Energies

ICFA2023, Hamburg, 28. 11. 2023

Oldrich Kepka
Institute of Physics, Prague

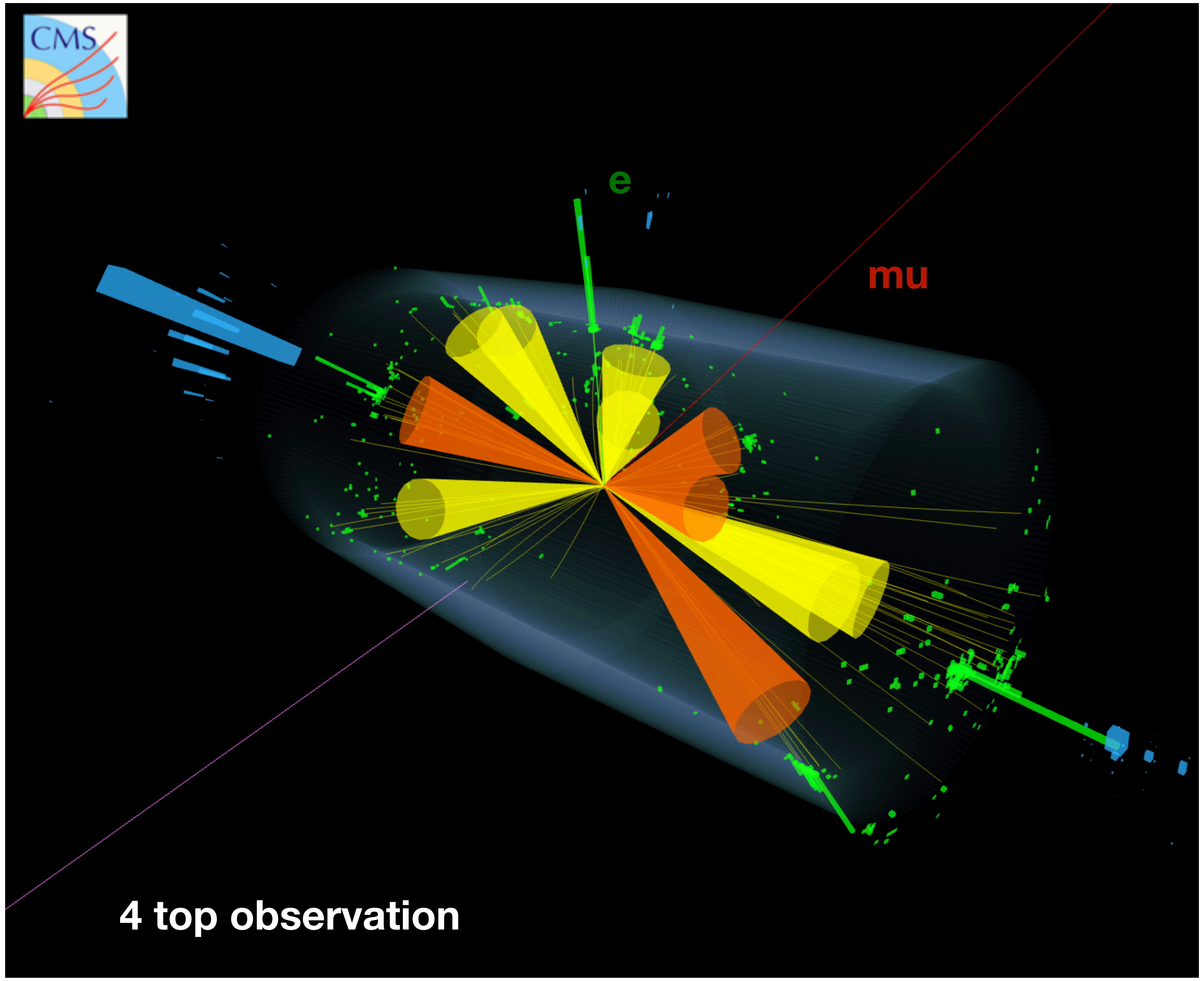
On behalf of ATLAS and CMS Collaborations

Quantum Chromodynamics at LHC

- All LHC observations rely on the modeling of QCD production, jets are ubiquitous at LHC

Objectives of QCD exploration

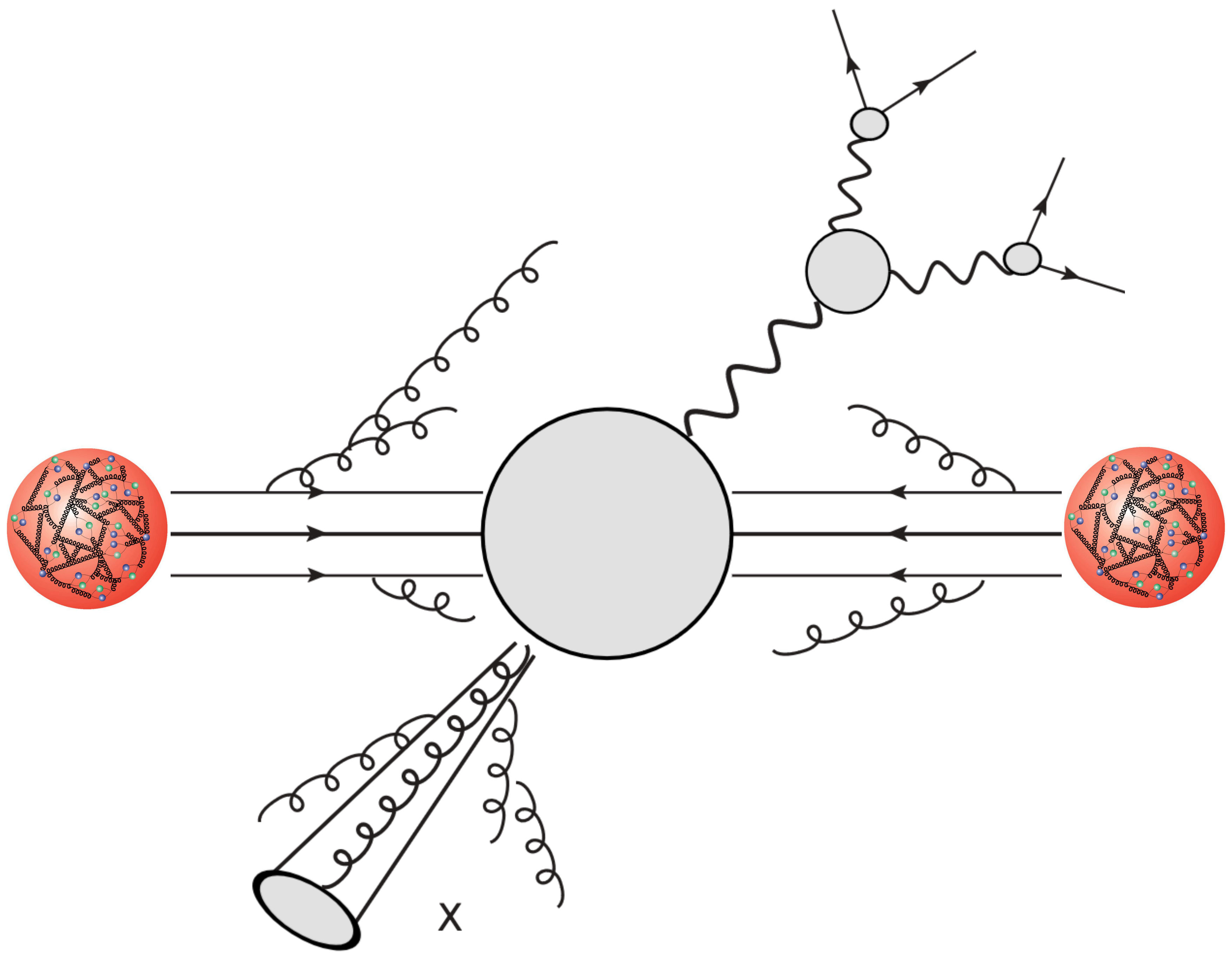
- More precise understanding of fundamental parameters of QCD
- Valuable inputs for theory development to describe the complexity of hadronic final state
- Improve future physics searches - isolate and measure SM processes which are backgrounds



ATLAS and CMS briefings

QCD in proton-proton collision

- **At short distances:** QCD is a theory of free partons scattering off each other
  - High-order perturbative calculation in α_s
  - Parton showers
  - Resummation of logarithmic corrections due to soft/collinear emissions
  - QCD dynamics of heavy quarks



- **At large distances:** strongly bound hadronic resonances, QCD confinement
  - PDF, Fragmentation functions (evolution still perturbative)
  - non-perturbative effects (color-reconnection, underlying event, multiparton interactions)

Collider experiments continue to produce extraordinary results with innovative techniques

Interpretations of LHC data need precise theory with higher-order QCD and EW calculations

Outline

High-order pQCD

α_s strong coupling

PDF

Jet substructure

- **At short distances:** QCD is a theory of free partons scattering off each other
  - High-order perturbative calculations in α_s
  - Parton showers
  - Resummation of logarithmic corrections due to soft/collinear emissions
  - QCD dynamics of heavy quarks
- **At large distances:** strongly bound hadronic resonances, QCD confinement
  - PDF, Fragmentation functions (evolution still perturbative)
  - non-perturbative effects (color-reconnection, underlying event, multiparton interactions)

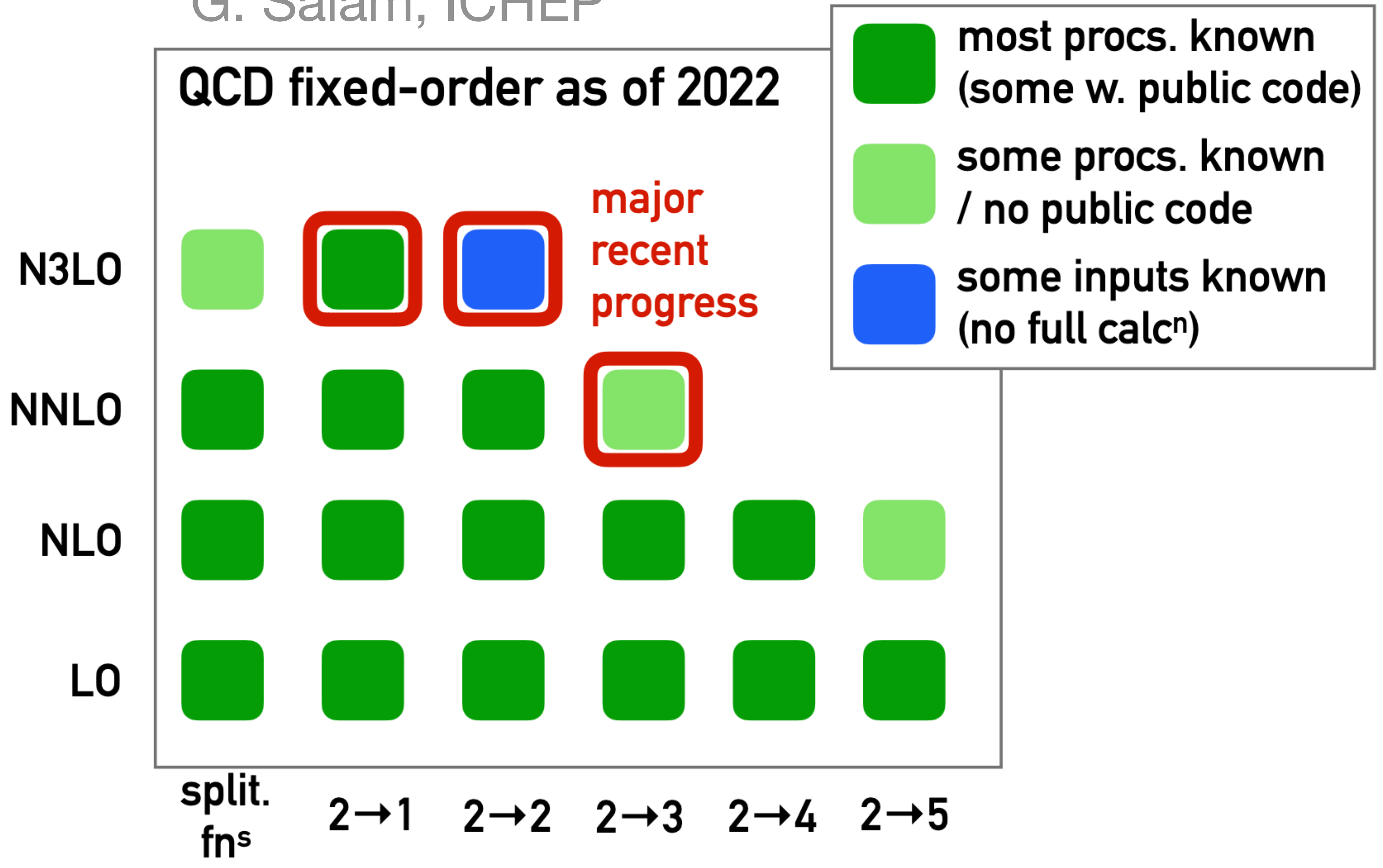
Collider experiments continue to produce extraordinary results with innovative techniques
Interpretations of LHC data need precise theory with higher-order QCD and EW calculations

High-order pQCD

Accuracy of QCD calculations

- **Fixed order calculations**
  - NNLO has become standard
  - Reduction of scale uncertainties from 10-20% (NLO) to *O*(%) at NNLO
  - Computational costs often limiting factor

G. Salam, ICHEP



- **MC with Parton Shower Simulations** (Pythia, Herwig, Sherpa)
  - **Matching** NLO ME to PS automated, matching to NNLO to PS is state-of-the art
  - **Merging** of exclusive 2 → n-jet productions at NLO or LO improves modeling of events with large number of jets

- Active development of **more accurate parton showers** (NLL)
  - The first shower algorithm introduced in ~1980
  - At the threshold of major breakthrough

- Parton shower uncertainties are dominant in many LHC measurements involving jets, in particular with the top

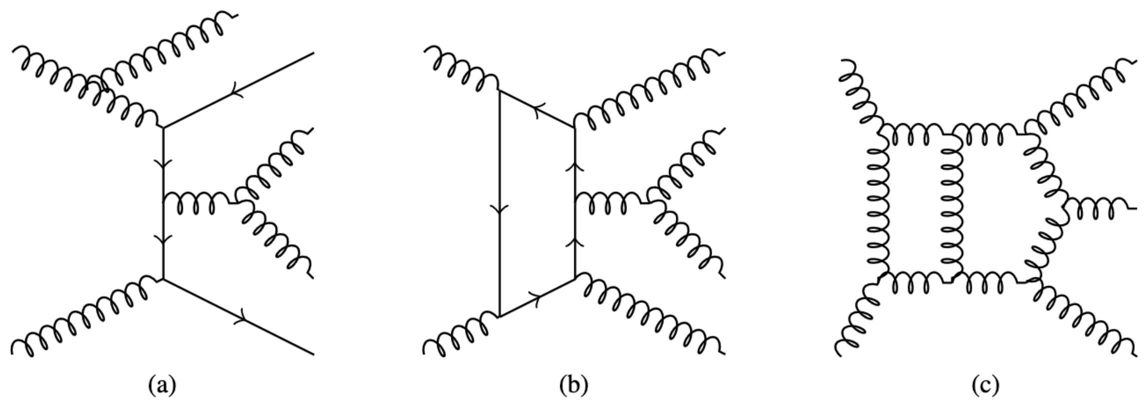
Correlation in multijet events

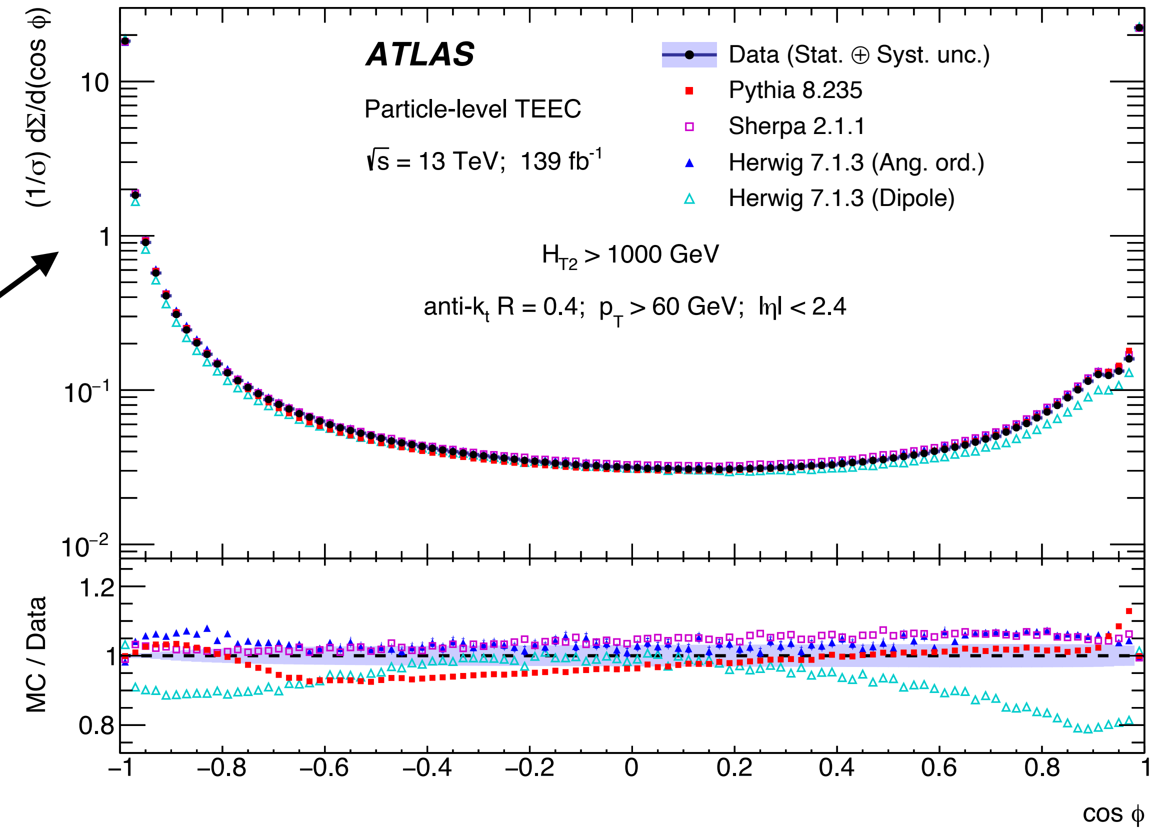
JHEP 07 (2023) 85 (ATLAS)

- Multi-jet event shape observables, large sensitivity to QCD radiation and α_s (see later)
- **TEEC** - energy-weighted distribution of azimuthal difference between jet pairs

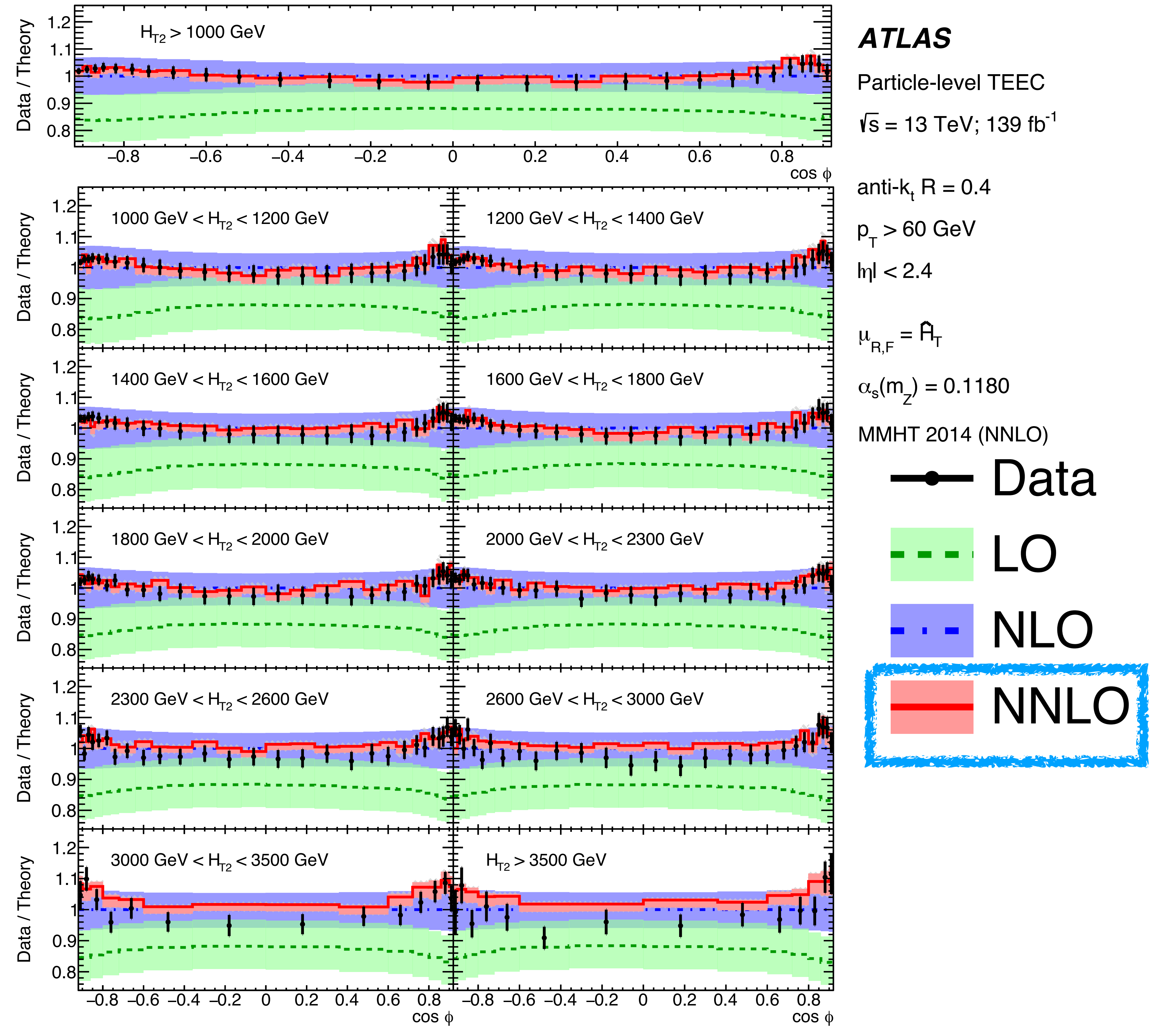
$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j}\mathrm{d}\cos\phi} x_{\mathrm{T}i}x_{\mathrm{T}j}\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k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

- Definition reduces exp. and theo. uncertainties
- **Requires 2 → 3 jet at NNLO** state-of-the art calculation





back-to-back

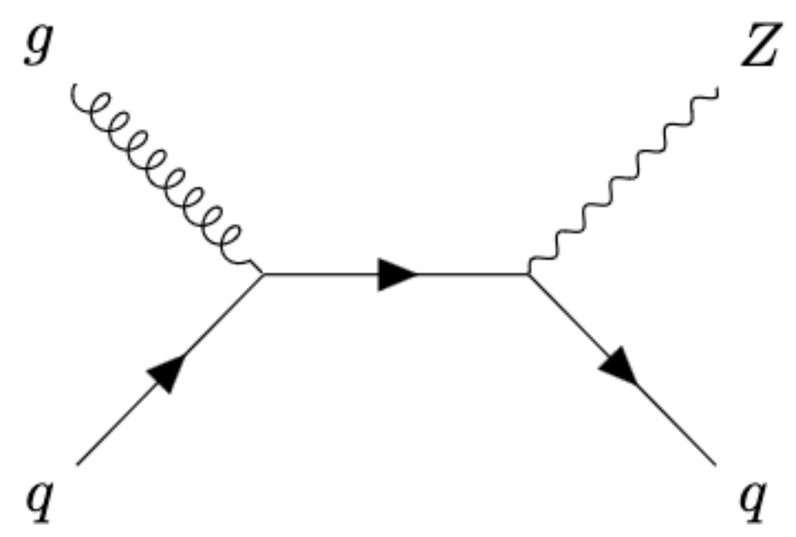


Excellent description with higher order QCD, substantial reduction of scale theory uncertainties with NNLO

$Z(\ell\ell)$+jets

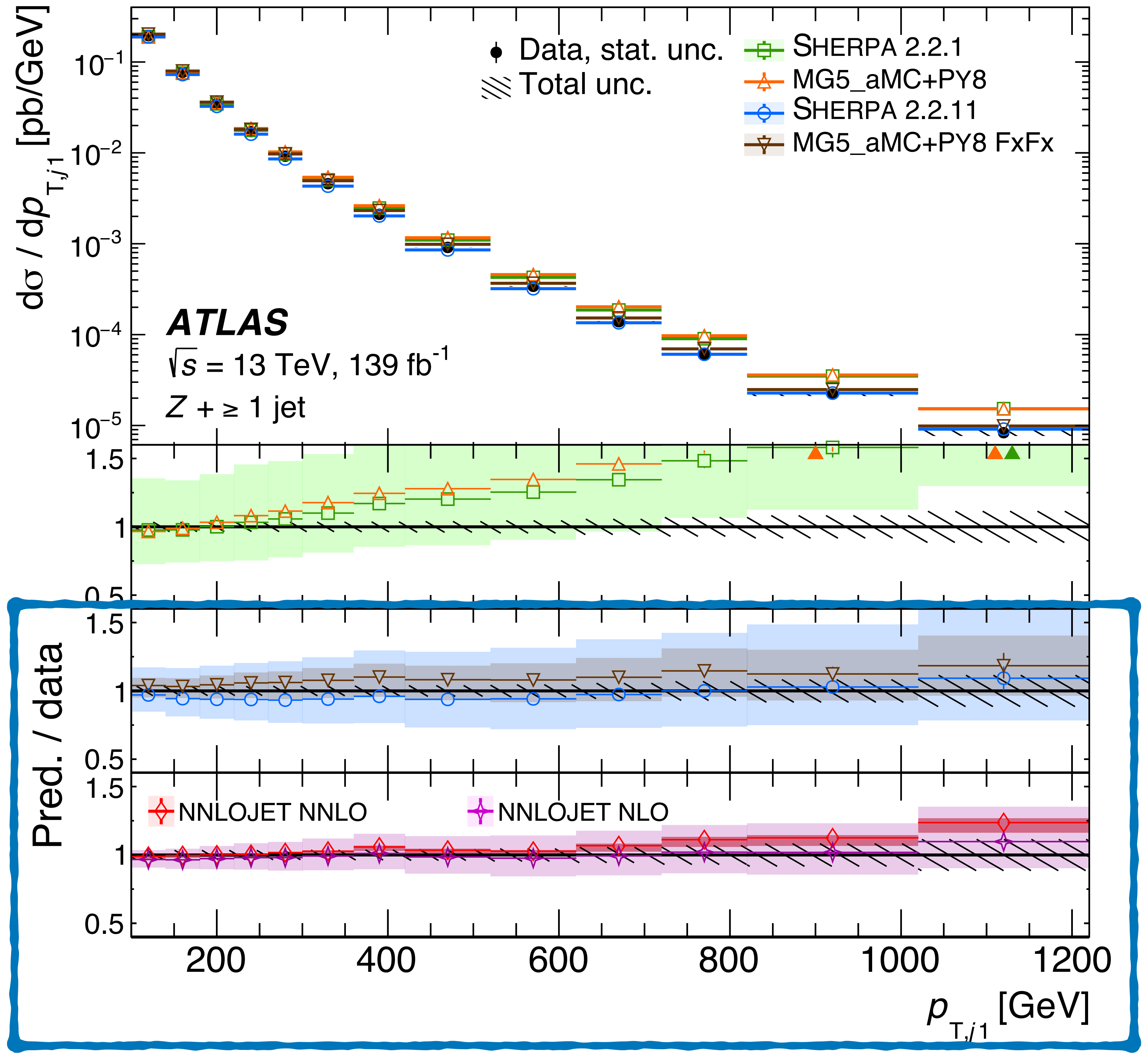
EPJC 83 (2023) 722 (CMS)
JHEP 06 (2023) 080 (ATLAS) PRD 108 (2023) 052004 (CMS)

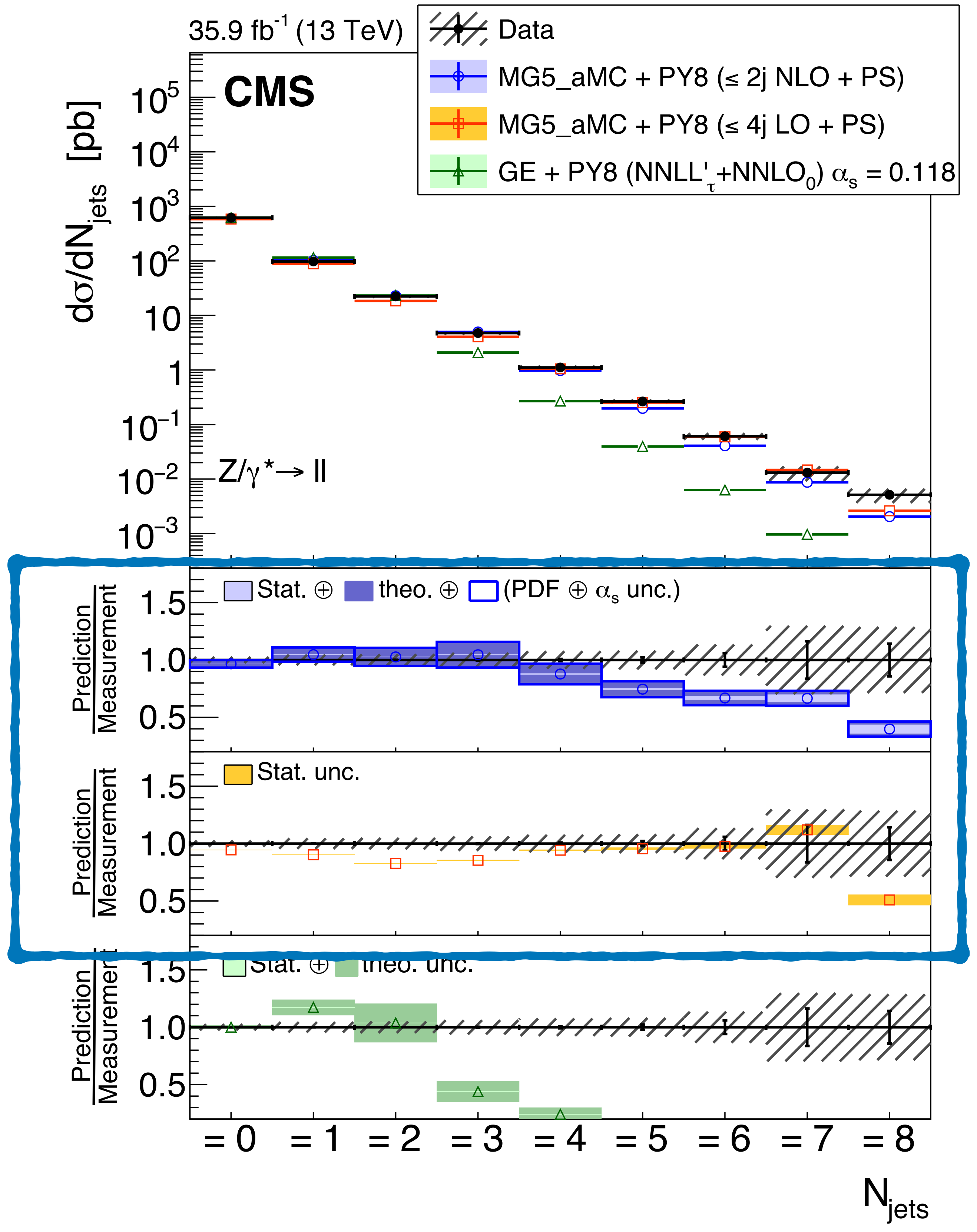
- High-precision measurements over wide range: up to 8 jets and jets beyond 1 TeV
- Testing ground for higher-order QCD predictions
  - Advanced multi-jet merged calculations (Madgraph FxFx and Sherpa) describe data well
  - Best description by fixed order NNLO calculations



Multi-jet merging+PS

NNLO





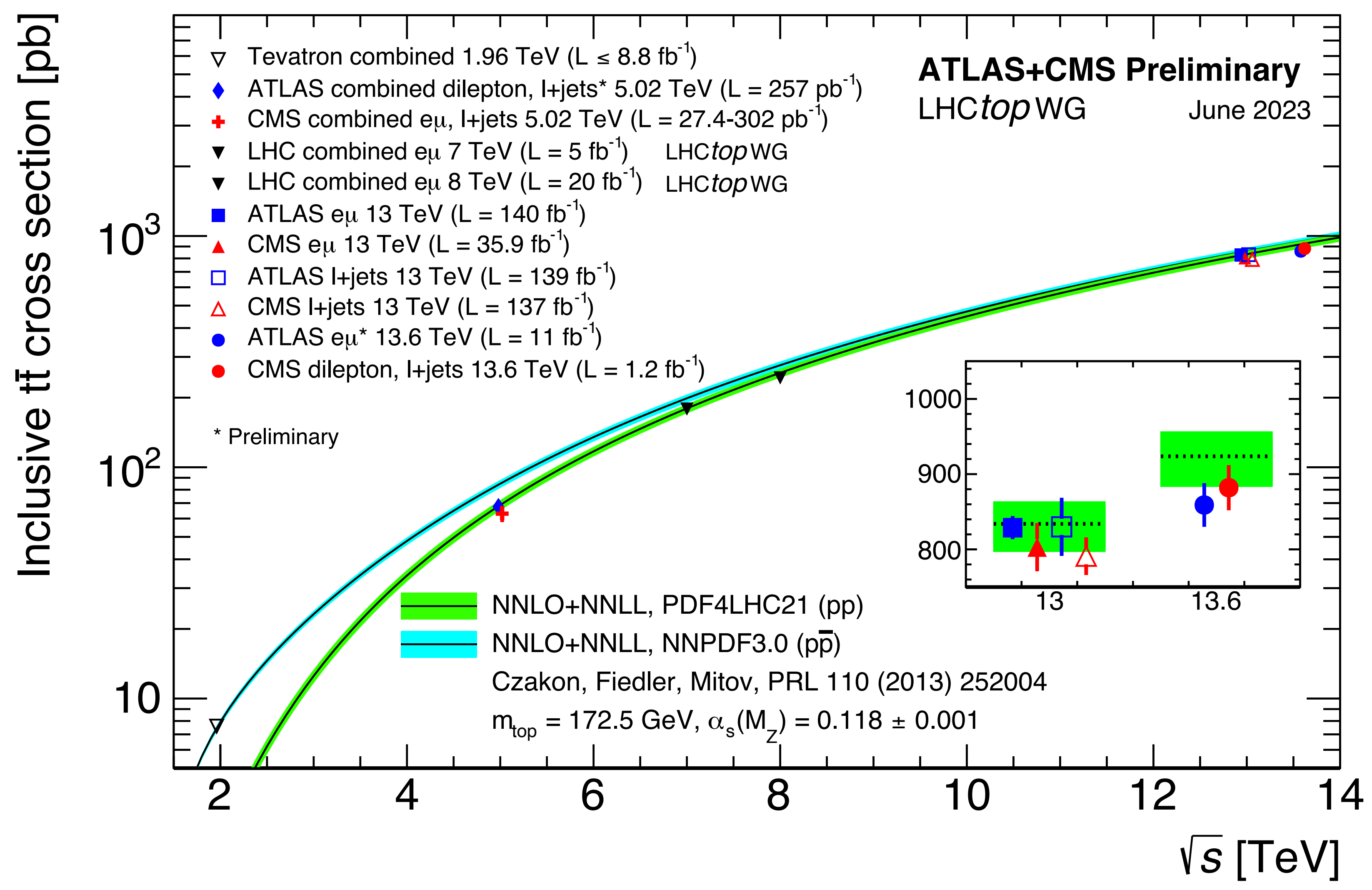
Multi-jet merging+PS

Top production

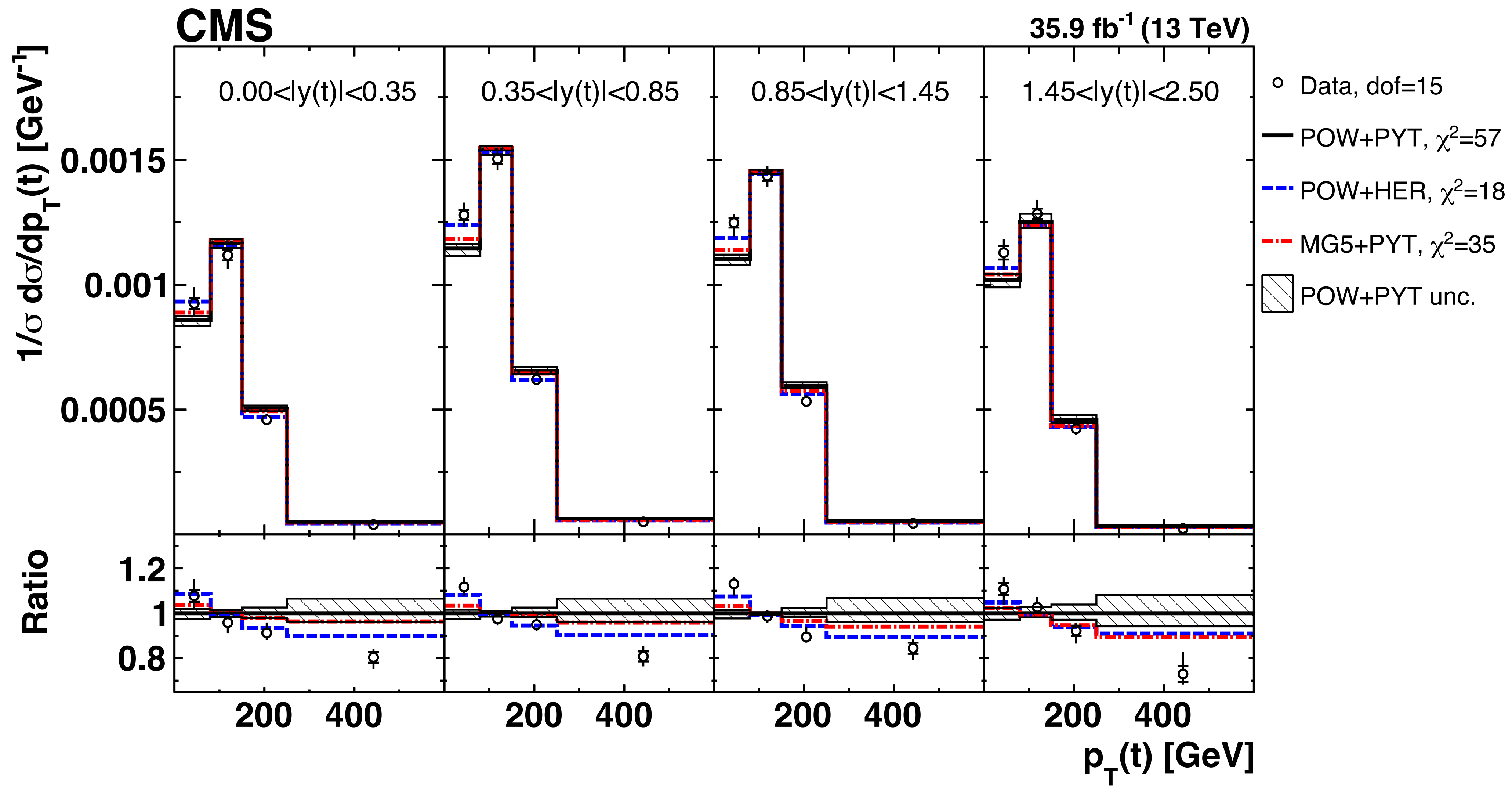
LHCTopWG

EPJC 80 (2020) 658 (CMS)

- Inclusive top-pair production
  - Impressive agreement over 2 orders of magnitude
  - At 13 TeV, exp. unc. of 1.8% (ATLAS $e\mu$+b-jets), compare with ~4% with PDF4LHC21



- Differential measurements
  - Issues with modelling of t and $t\bar{t}$ p_T distributions
  - Ad-hoc 2-point systematic comparisons



- **Full exploitation of present and future top samples needs improved MC**
  - Yields (ll, l+jet): O(10M) in Run2 → O(100M) at HL-LHC

Future: move to NNLO+PS simulation and improve shower uncertainty prescriptions

α_s strong coupling

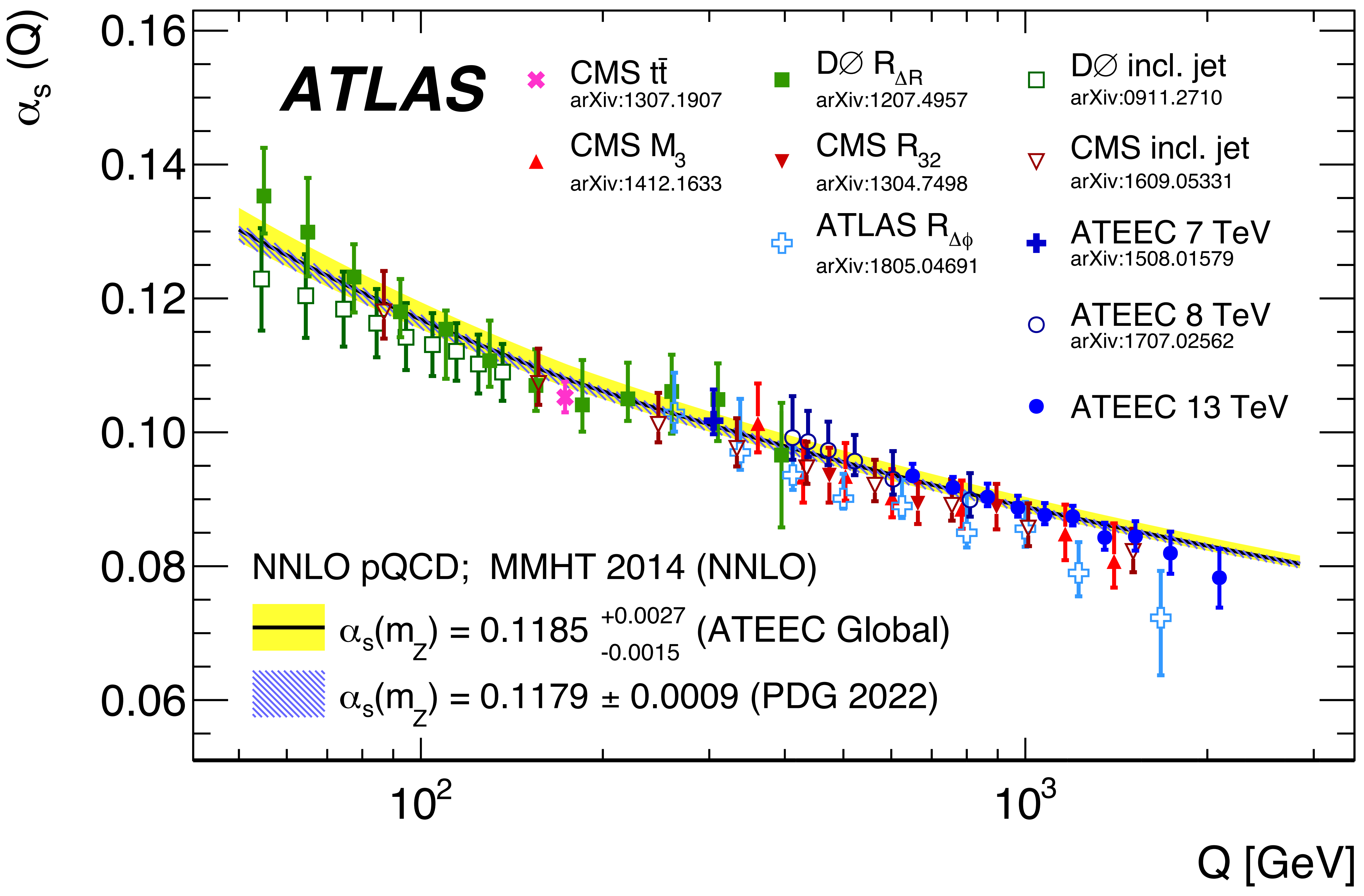
The strong-coupling strength

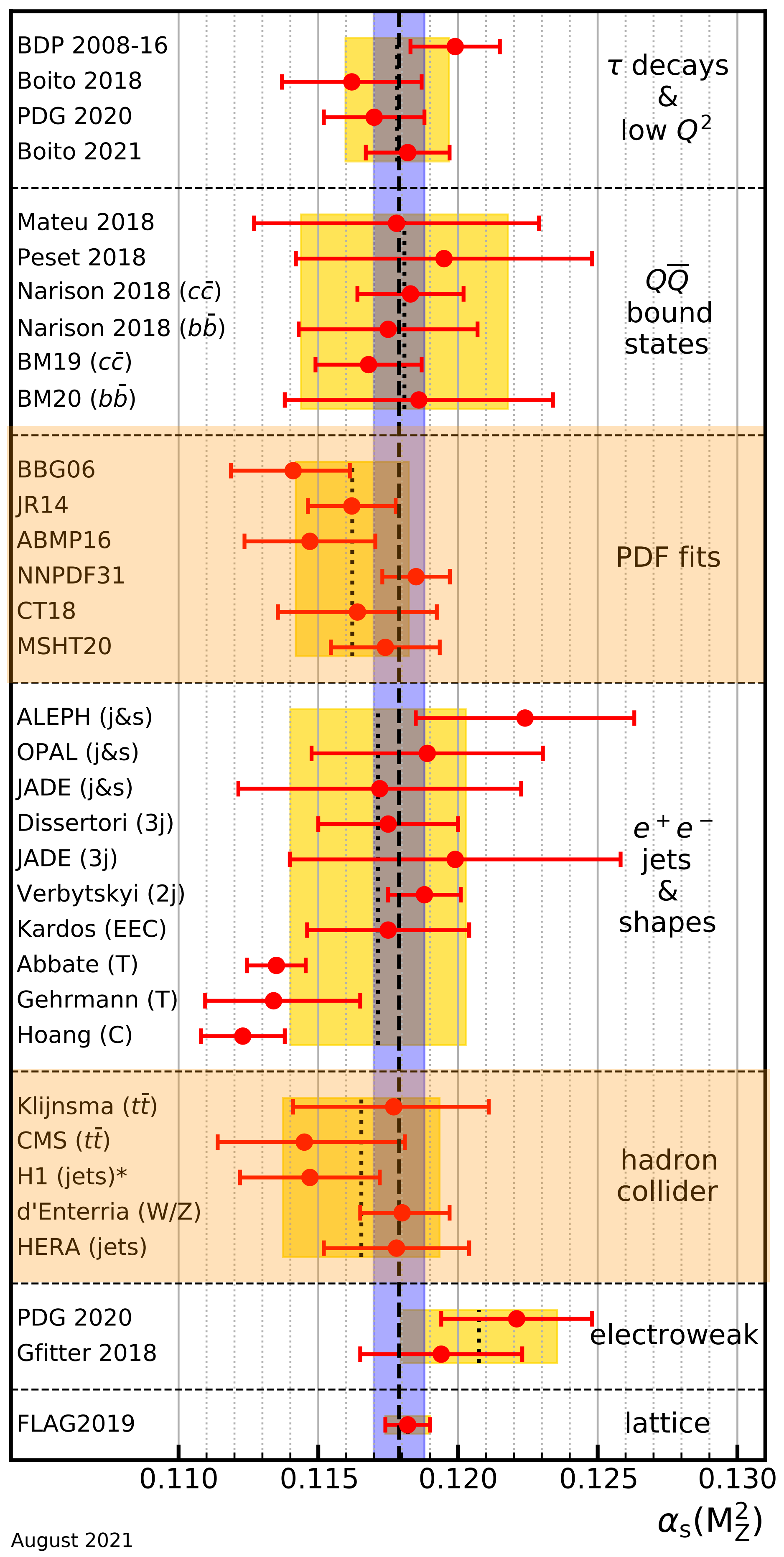
- **Least known** fundamental forces of nature
  - Large uncertainty in many LHC measurements, e.g. Higgs couplings
- Single free parameter in massless QCD limit
- **Asymptotic freedom** - decreasing with scale of the process $\sim \ln Q^2/\Lambda^2$, tested up to multi-TeV scale

$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-2}$

World PDG average over 7 categories

$$\alpha_s(Q^2 = m_Z^2) = 0.1179 \pm 0.0009$$





State-of-the-art for the strong coupling

CMS-PAS-SMP-21-008
JHEP 12 (2022) 035 (CMS)

- Most precise results from tau decays and Lattice

S. Camarda, QCD@LHC23

Category	$\alpha_s(m_Z)$	$\delta\alpha_s(m_Z)$	Rel. Unc.	Results
Tau decays and low Q^2	0.1178	0.0019	1.6%	4
$Q\bar{Q}$ bound states	0.1181	0.0037	3.1%	4
DIS and PDF fits	0.1162	0.0020	1.7%	6
e+e- jets and shapes	0.1171	0.0031	2.6%	10
Hadron colliders	0.1165	0.0028	2.4%	5
Electroweak boson decays	0.1208	0.0028	2.4%	2
Lattice QCD (FLAG 21)	0.1184	0.0008	0.7%	11
PDG 22 World Average	0.1179	0.0009	0.8%	39

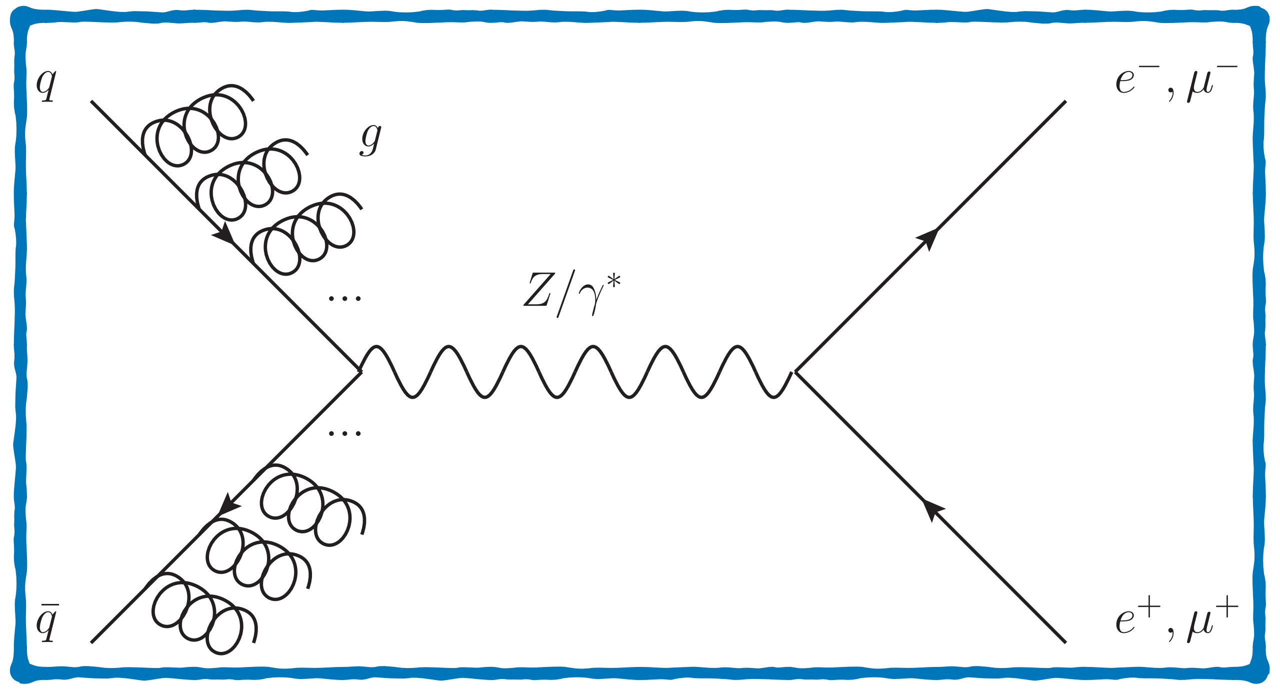
	$\alpha_s(m_Z)$	$\delta\alpha_s(m_Z)$	Rel. Unc.
ATLAS ATEEC	0.1185	0.0021	1.7%
CMS inclusive jets	0.1166	0.0016	1.4%
CMS dijets	0.1201	0.0020	1.7%
ATLAS Z pT	0.1183	0.0009	0.7%

- Several recent determinations from LHC at 13 and 8 TeV using NNLO reached percent level accuracy and **will have impact on the PDG world average**
- NNLO Theory scale uncertainty is the dominant source for jet based measurements, N^3LO for jets not within reach

Strong coupling from Z p_T distribution

2309.12986 (ATLAS)

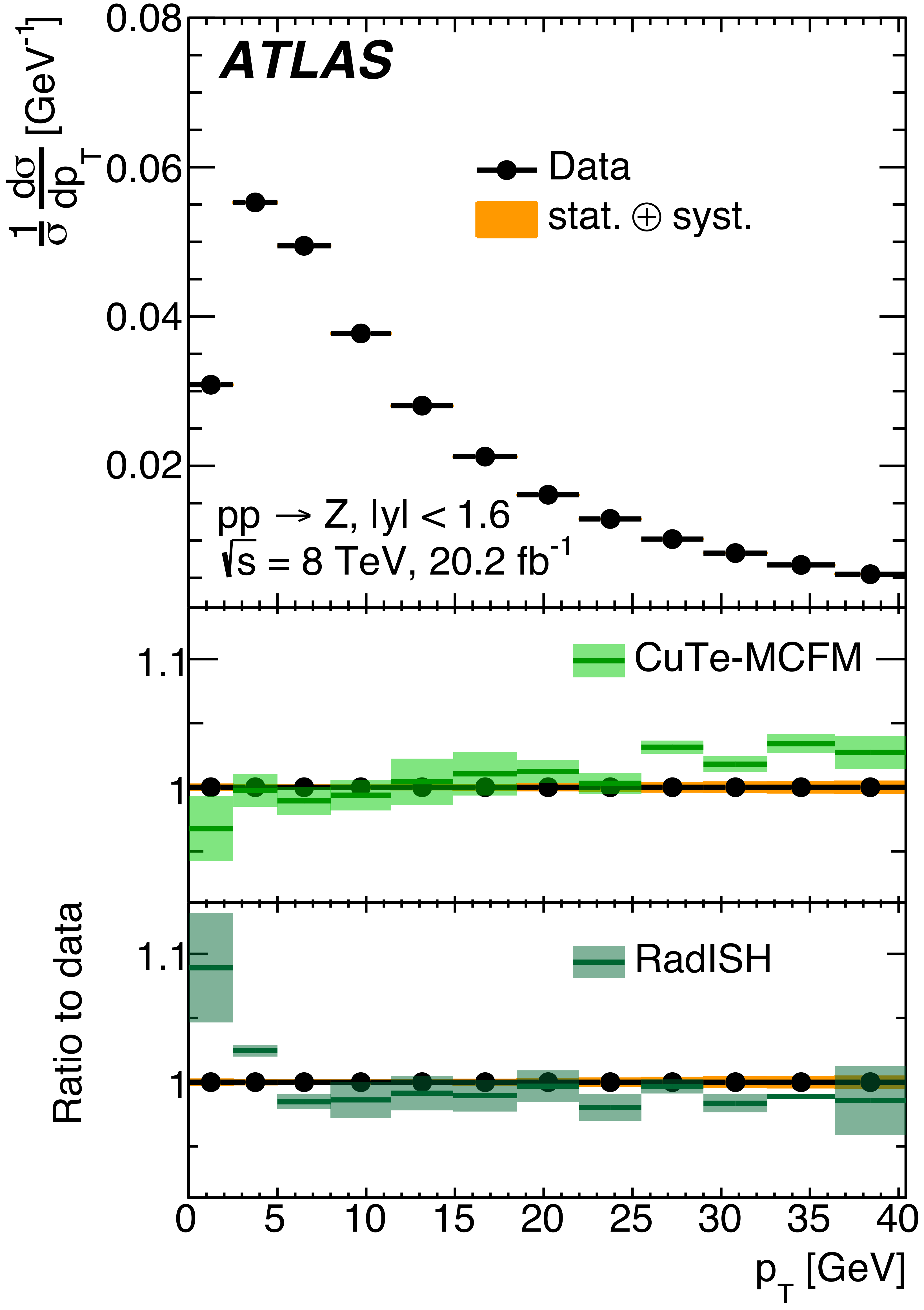
- A novel approach - extraction using low transverse momentum of Z, Z boson recoiling against QCD initial-state radiation



- Radiation inhibited observable requires resummation
  - Excellent agreement between data and predictions
  - Impressive progress in understanding of boson p_T modelling from theory and experiment => **also impact on m_W determination**
- Coupling extracted using state-of-the-art theory
  (aN⁴LL resummation matched to N³LO fixed order calculation, approximate N³LO MSHT20 PDF)

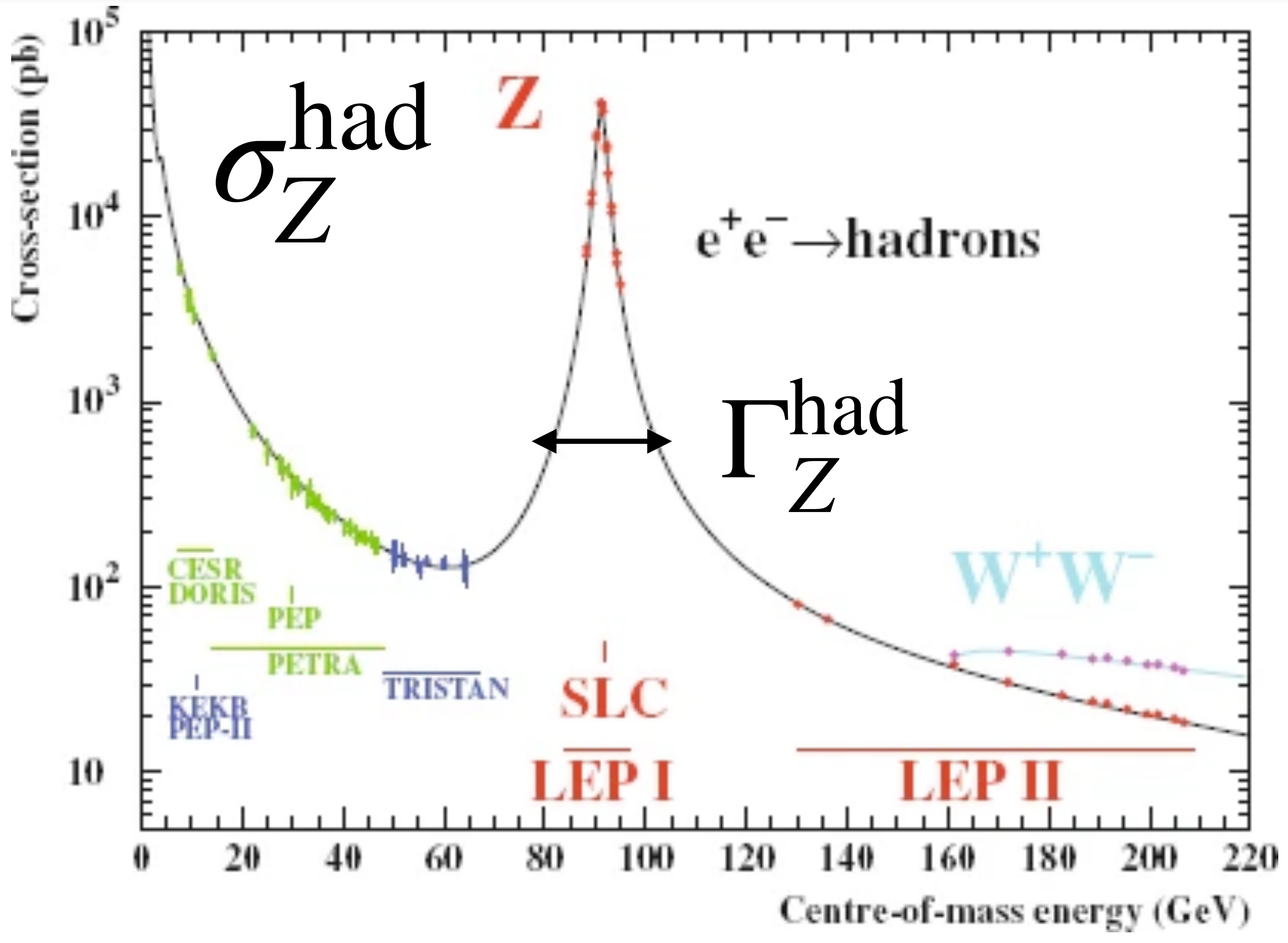
$$\alpha_s(m_Z) = \mathbf{0.1183 \pm 0.0009\ (0.74\%)}$$

Most precise experimental measurement of the strong coupling



α_s measurements at FCC-ee / CEPC

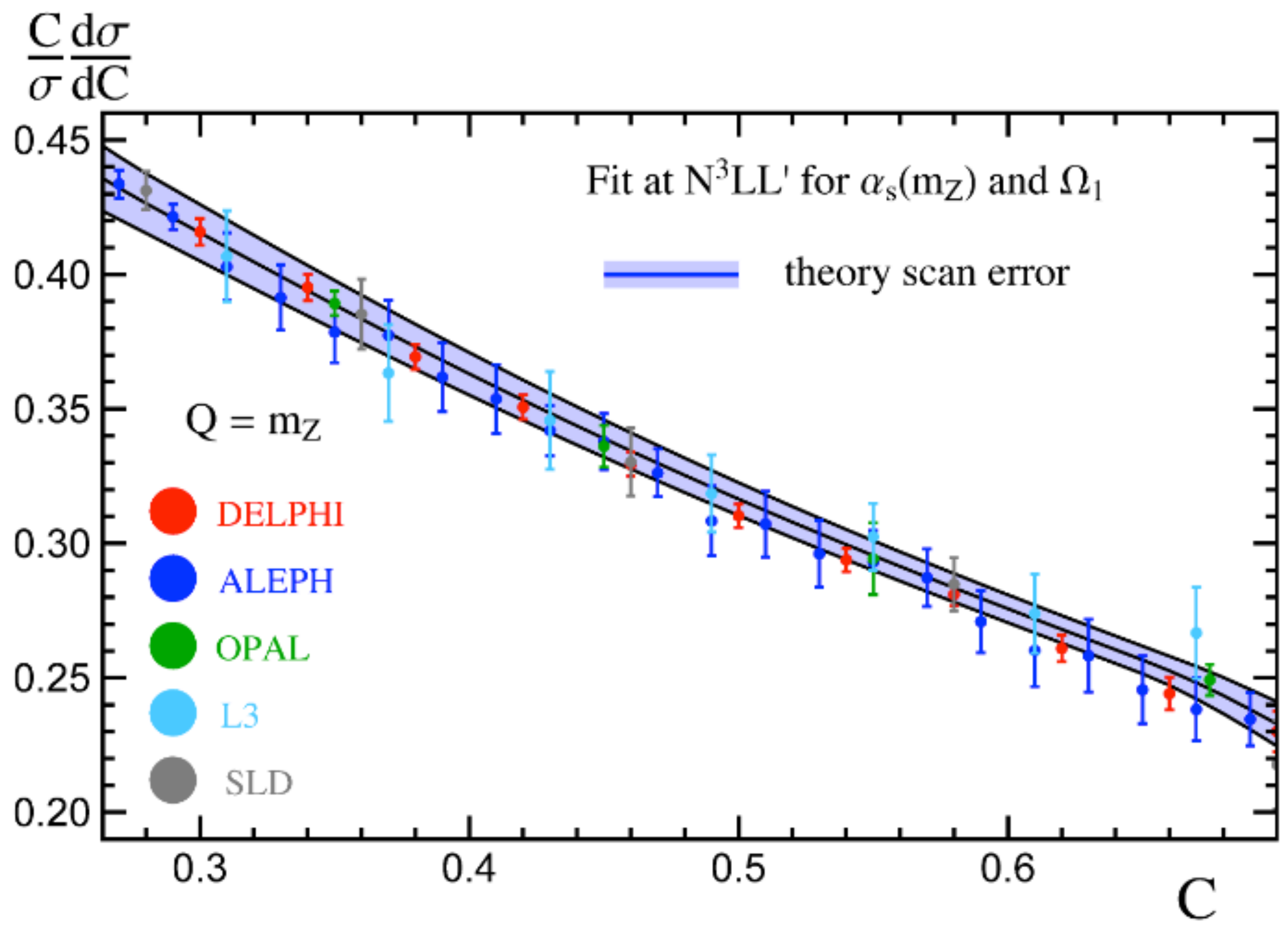
- **Hadronic W and Z decays** $\Delta\alpha_s/\alpha_s = 0.1 - 0.2\,\%$
  - Combined fit of Z pseudo observables ($R_Z = \Gamma_Z^{\text{had}}/\Gamma_Z^{\text{lep}}, \Gamma_Z^{\text{tot}}, \sigma_Z^{\text{had}}$) precisely measured using energy scan, Tera-Z FCC-ee(90)
  - Similar for WW, increase over LEP ($10^4 \rightarrow 10^8$), can be competitive
    (Improved α_{QED} (m_Z), $|V_{cs}|$, $|V_{cd}|$, m_W, assume N^{4}LO QCD)



- **τ-leptonic decays** $\rightarrow$ $\Delta\alpha_s/\alpha_s \ll 1\,\%$
  - $O(10^{11})$ from $Z \rightarrow \tau\tau$ at FCC-ee (90 GeV)
    (With expected improvements: N^{4}LO, improved τ spectral functions, estimate of higher pQCD (FOPT vs CIPT))

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C \Big(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)\Big) + \delta_{\text{np}}\Big)$$

- **Thrust, C-parameter, event shapes 3-jet cross sections**
  - Recent progress in understanding non-perturbative effects in C-parameter measured at LEP resolved tensions with the world average α_s, grooming techniques to suppress non-pert.



PDF

PDF motivation

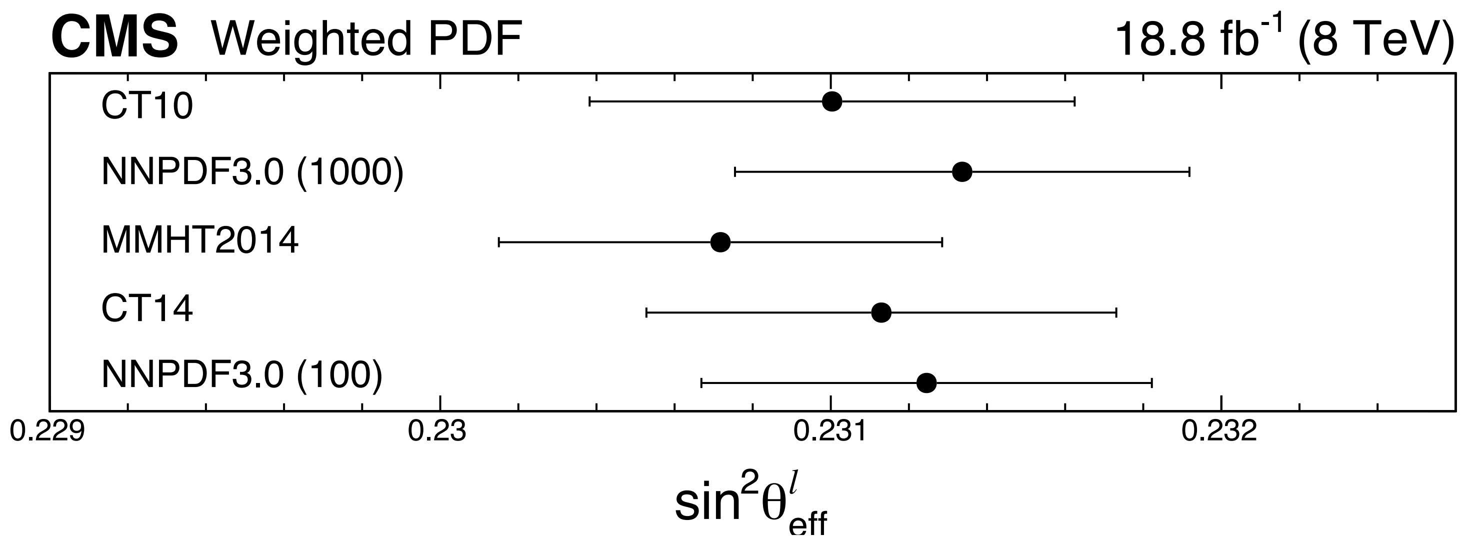
ATLAS-CONF-2023-004
EPJC 78 (2018) 701 (CMS)

- PDF uncertainties are a limiting factor in precision measurements at LHC
- **Uncertainty variations within 1 PDF set not covering difference with other PDF**
  - ATLAS m_W mass
  - ATLAS and CMS $\sin^2\theta_W$
  - CMS α_s extraction from ttbar production
  - …

Do we understand our PDF and uncertainties sufficiently well?

PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

NNPDF4.0 and CT10 differ by 18 MeV
Estimated PDF uncertainties 3 → 9 MeV



$$\sin^2\theta^\ell_{\mathrm{eff}} = 0.23101 \pm 0.00036\,(\mathrm{stat}) \pm 0.00018\,(\mathrm{syst}) \pm 0.00016\,(\mathrm{theo}) \pm 0.00031\,(\mathrm{PDF}),$$

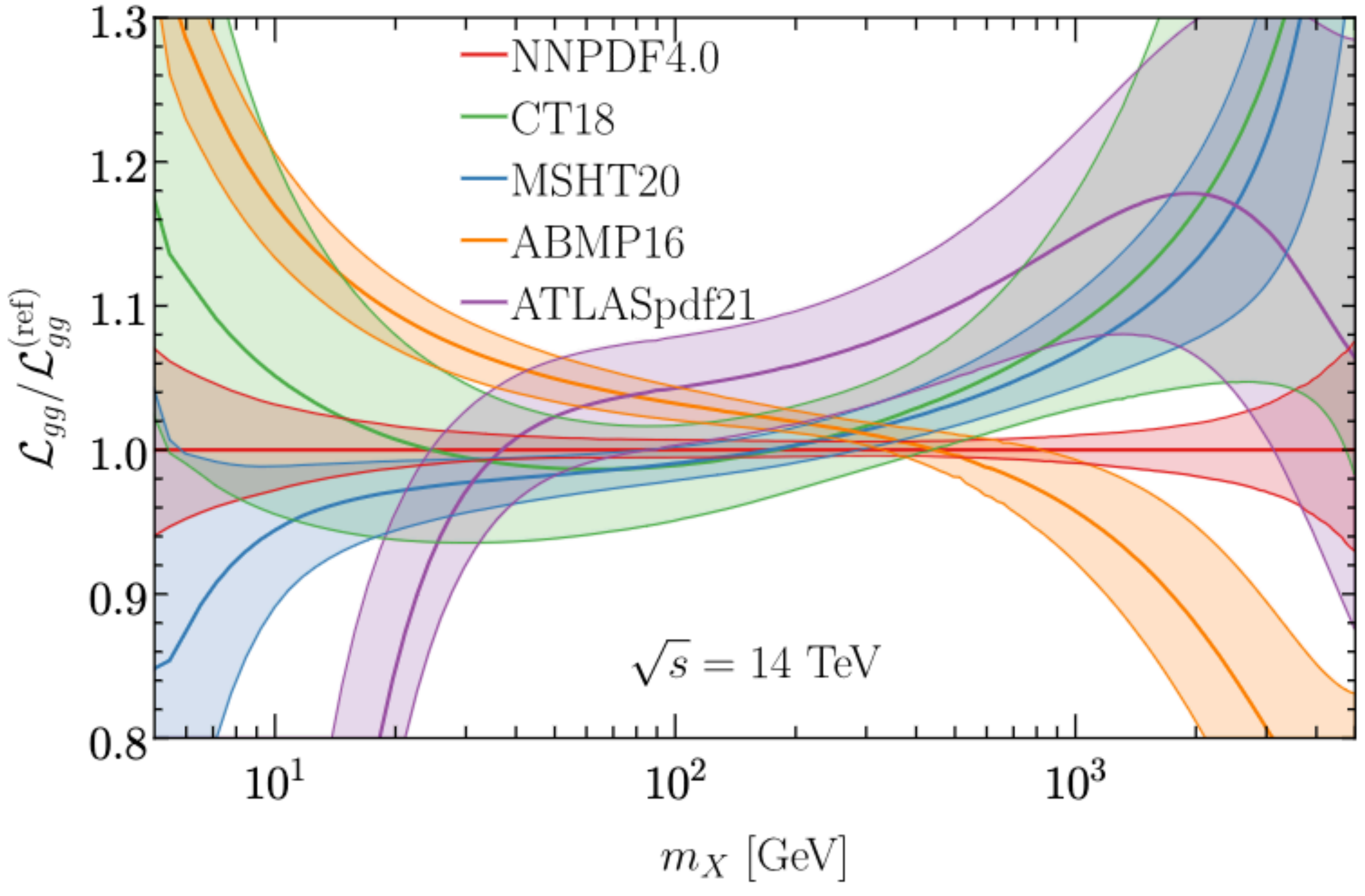
PDF envelope 0.0006 (MMHT2014 - NNPDF3.0)

Parton distribution functions

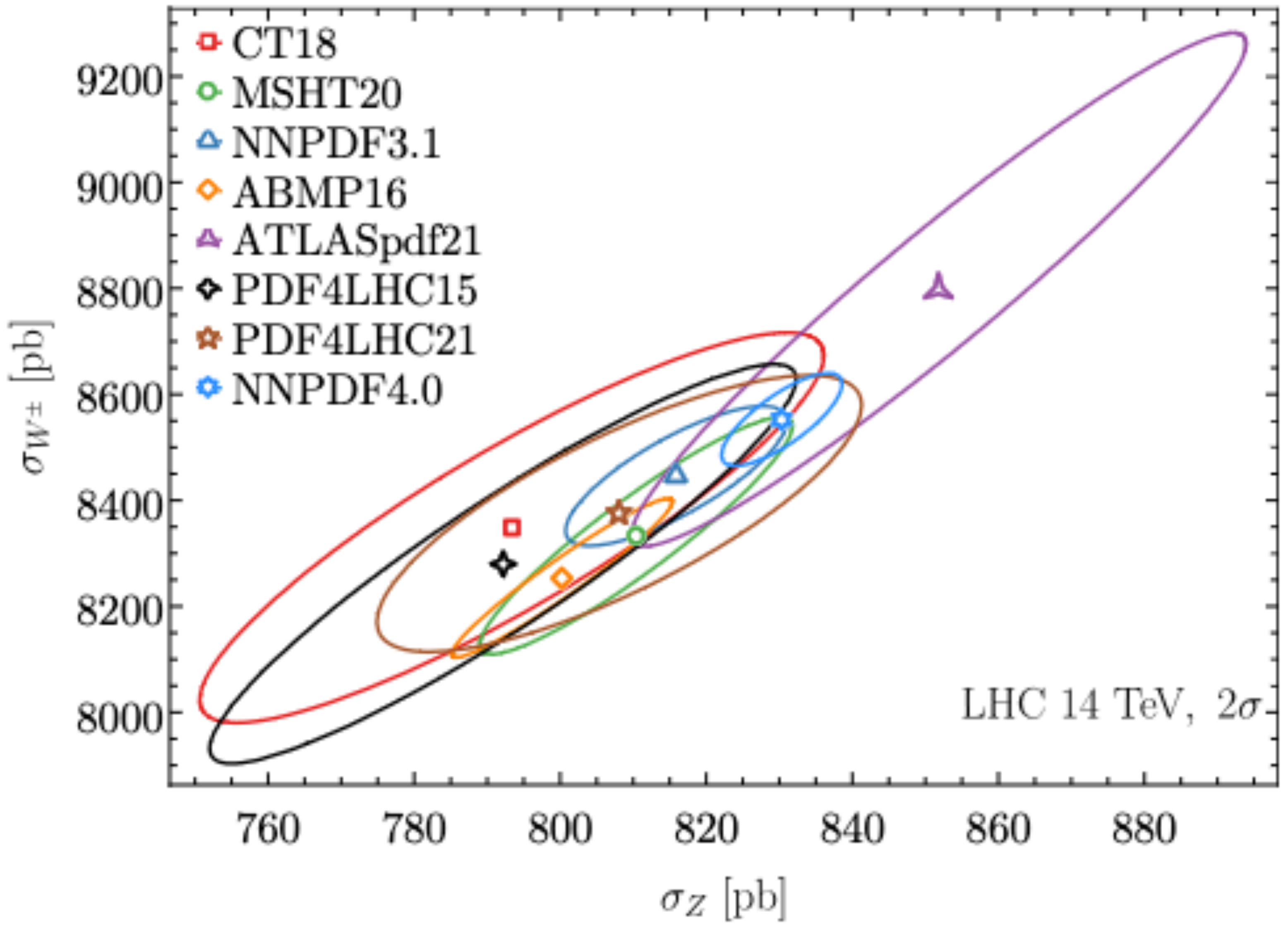
2203.13923

- PDF determined in global fits to fixed target, DIS and collider data
- More data are included as NNLO predictions become available, towards N3LO PDFs is in progress
- Precisions of 1% is being achieved for medium Bjorken-x
- **PDF Benchmarking**
    - Important effort to understand correlations between PDF set
    - gg luminosity shows spread of more than 20% in the multi-TeV region, $q\bar{q}$ agrees better, except around 300 GeV

Impact on searches



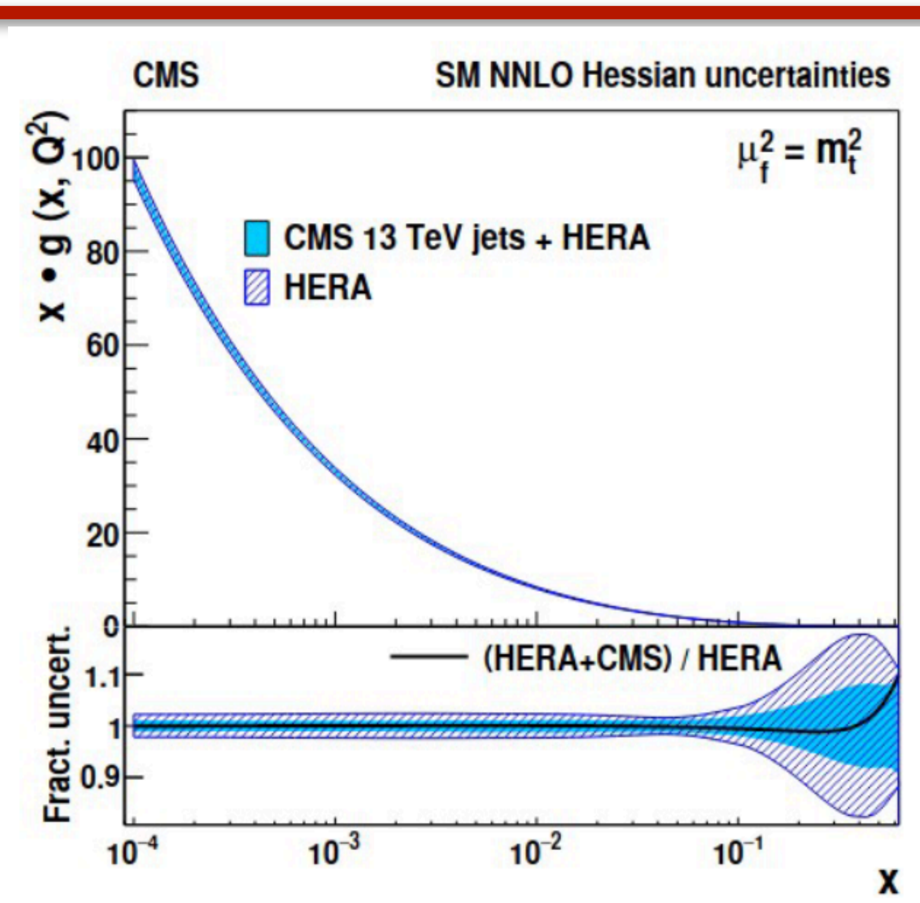
Impact on precision measurements

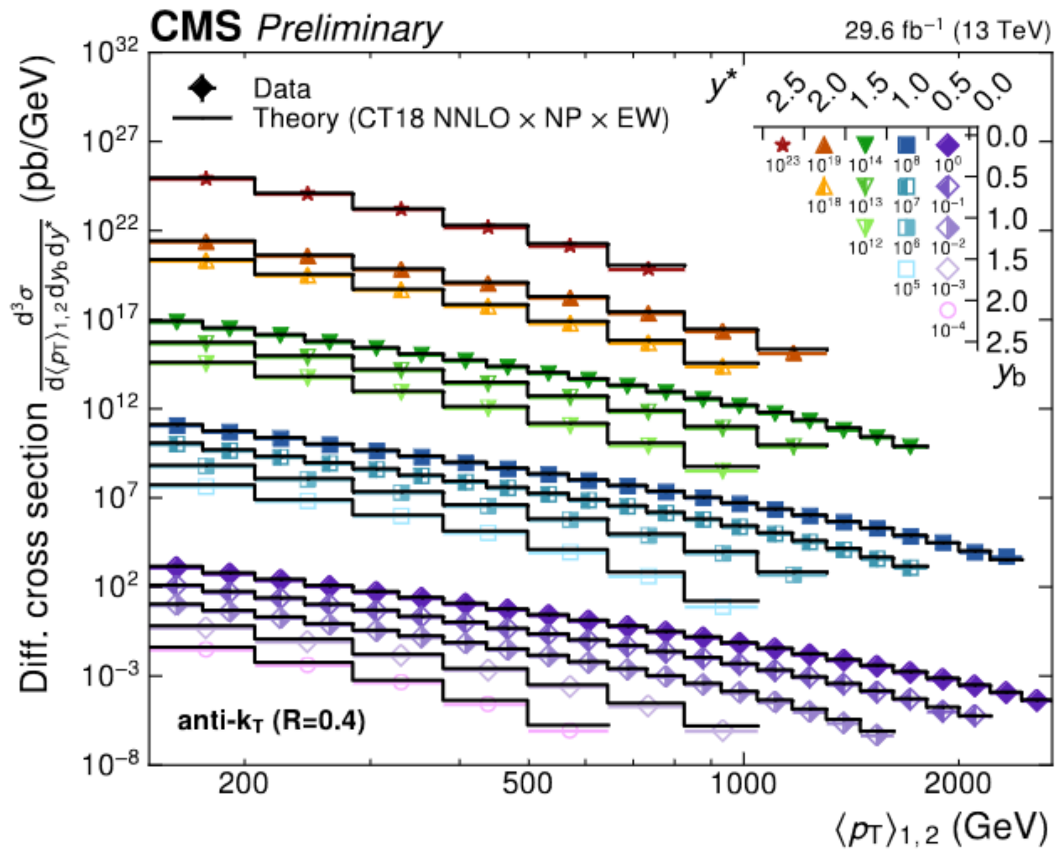


PDF constraining measurements

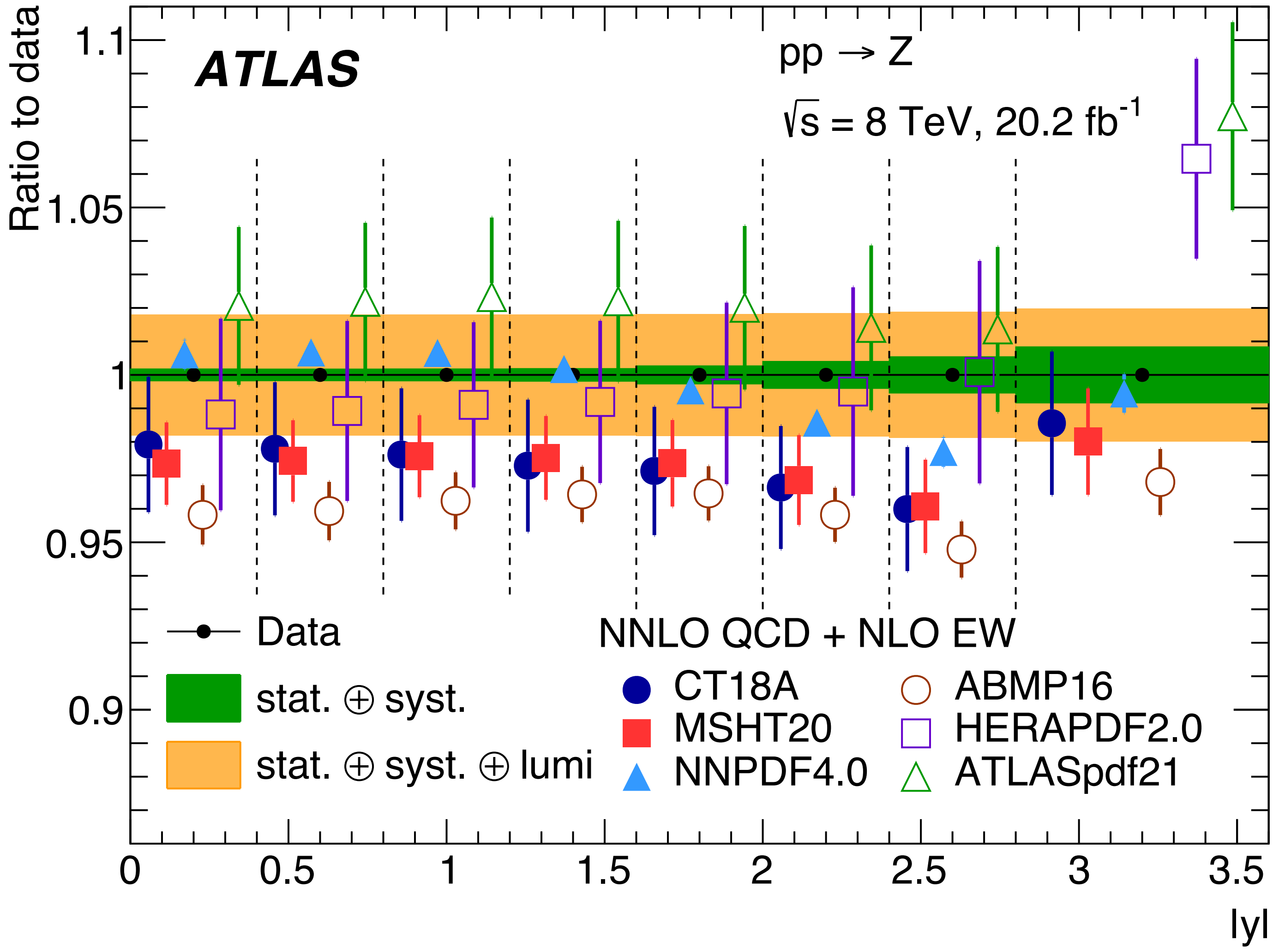
- **High-x gluon**
  - Jet and multijet production (multi-differential), precise jet energy scale at the level of 1-2%
  - Inclusive γ
  - ttbar and ttbar+j
- **Medium-x parton densities**
  - Most precise measurement of Z boson - new methodology
  - Per-mile uncertainty in the central and less than % in the forward regions
  - Full-lepton phase-space offers **unambiguous interpretation of PDFs**
- **Strange and charm parton densities**
  - **P**robed with W+D, W+b jet measurements

… also, LHCb brings in valuable coverage of forward region





CMS-PAS-SMP-21-008
JHEP 12 (2022) 035 (CMS)



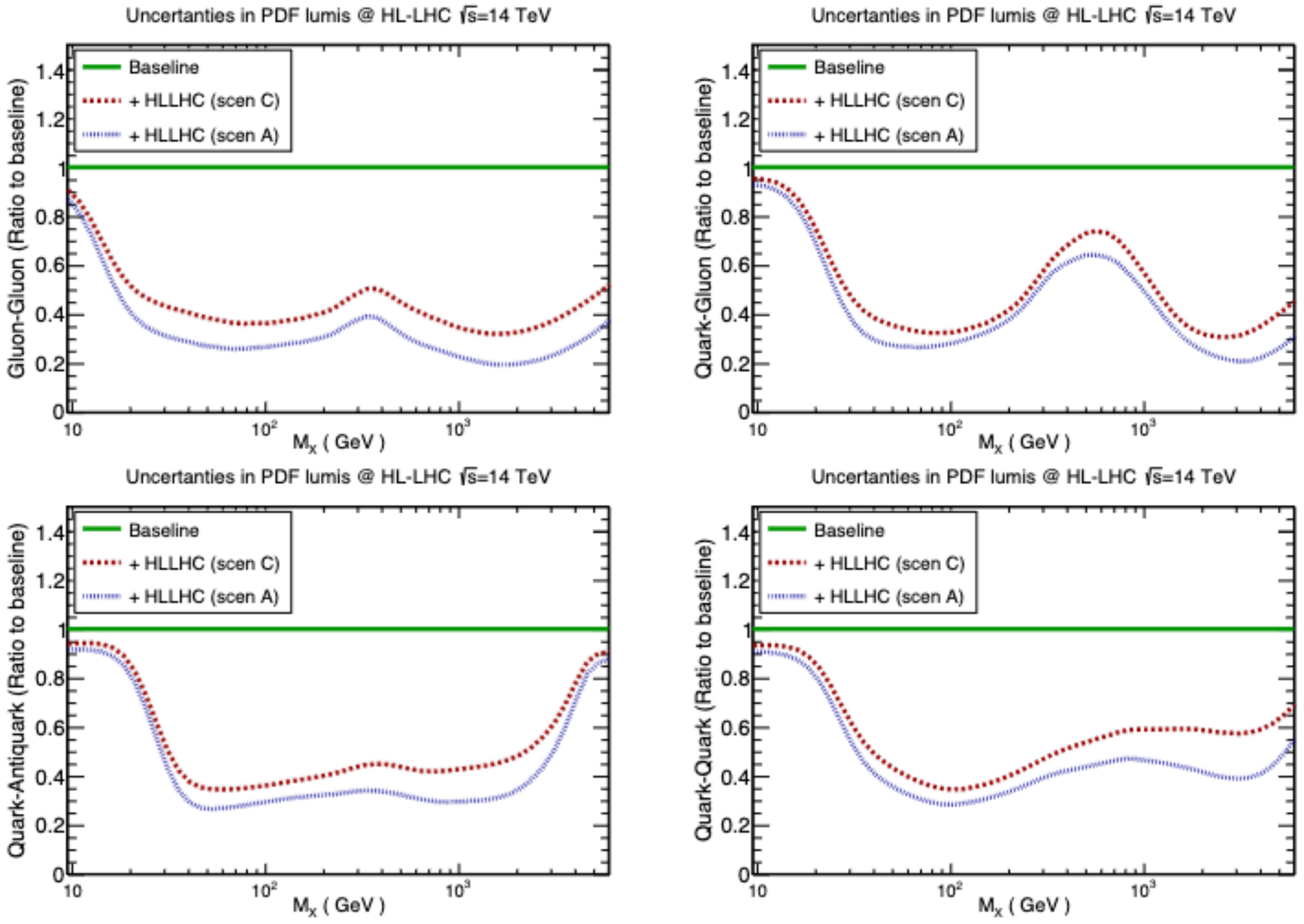
2309.09318 (ATLAS)

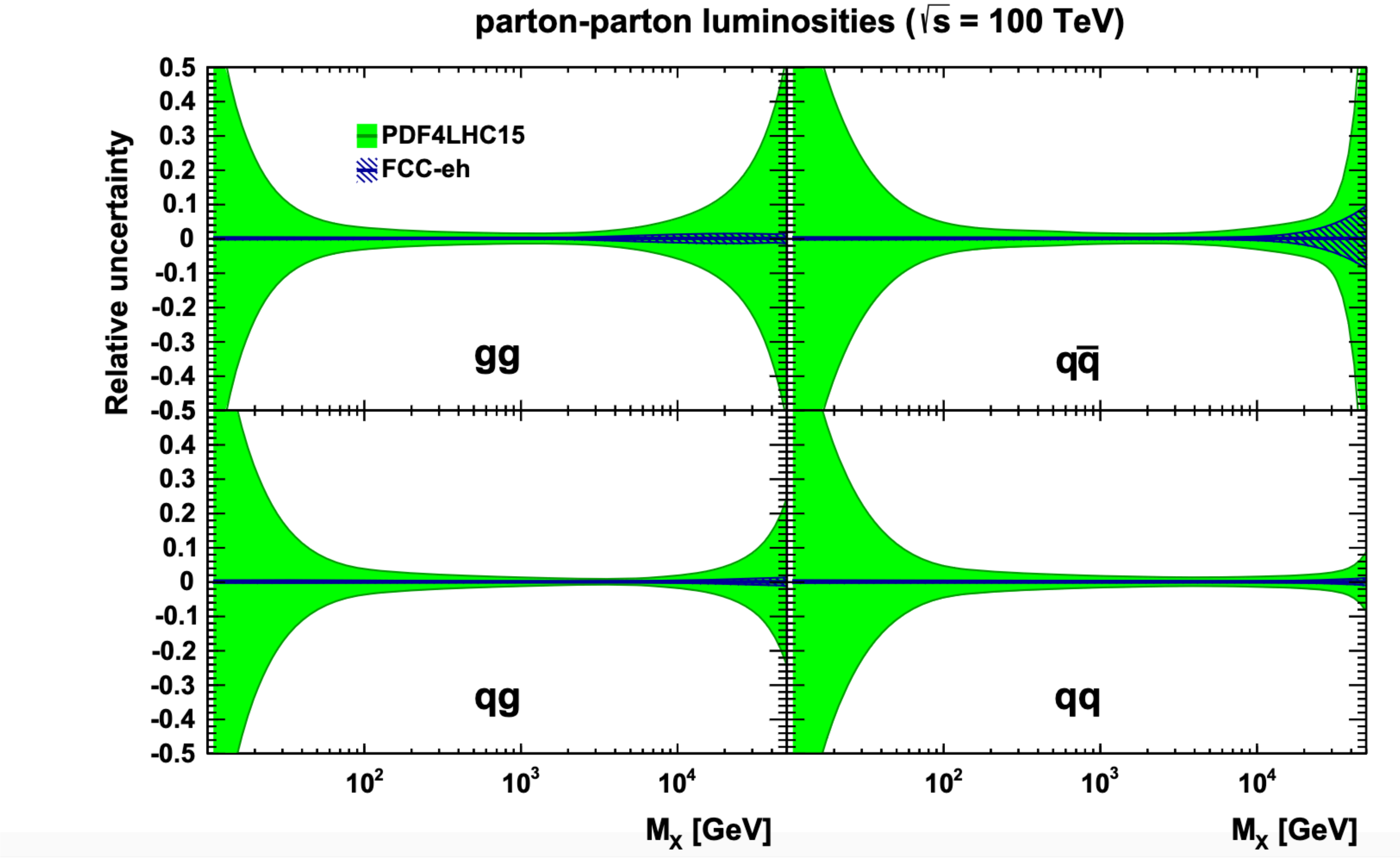
Achievable precision depends on syst. uncertainties of the data - correlations insufficiently known → results in tensions between dataset

PDF at HL-LHC and FCC-eh

1902.04070

- Factor 2 reduction of PDF uncertainties at the end of HL-LHC
- At FCC-eh - PDF uncertainties are strongly reduced, EIC in the next talk
- Precise PDF determination demanded by the precision physics program at hadron-hadron FCC-hh machine



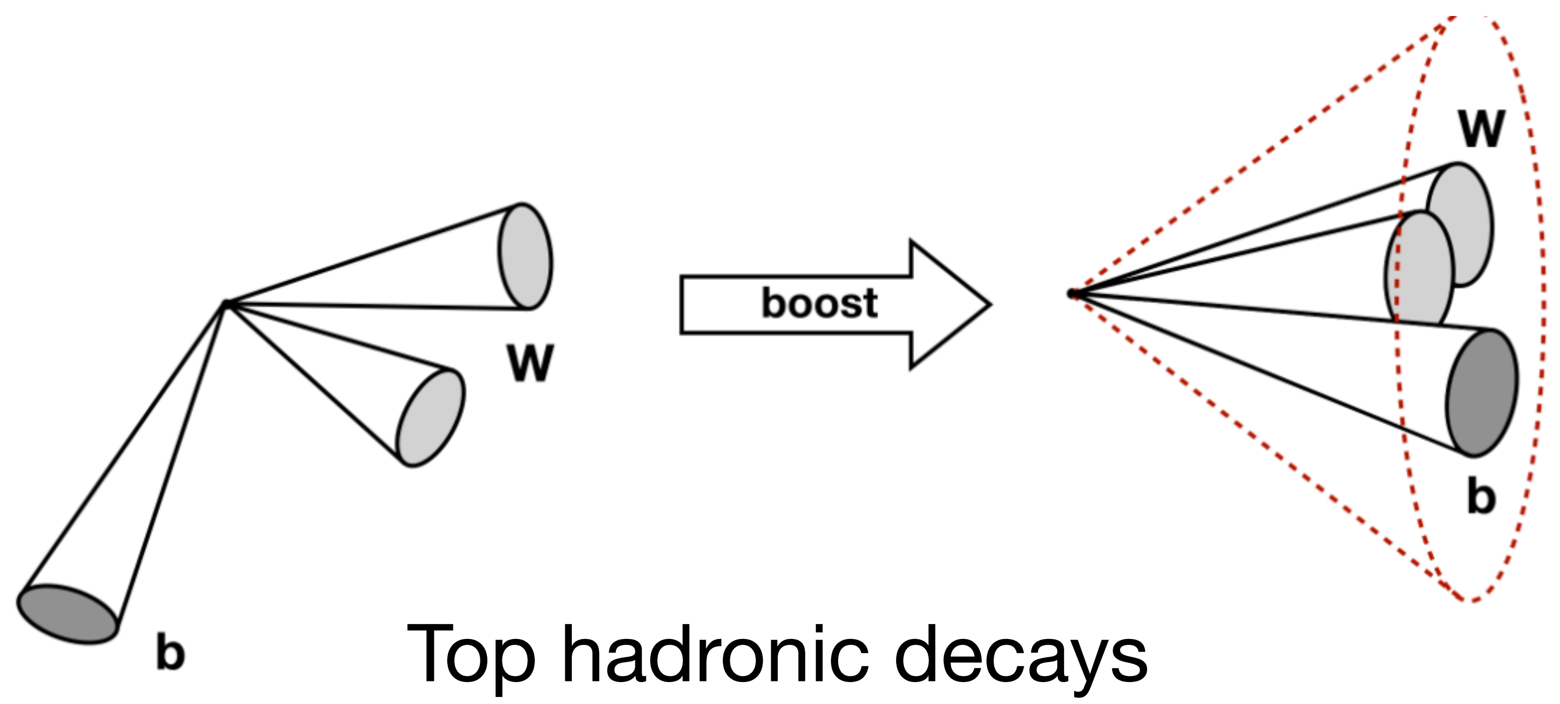


Jet substructure

Jet substructure

- Jet constituents four-momenta are mapped onto physically meaningful observable: $\{p_i\} \to \lambda$
(m$_J$, LJP, generalised angularities - LHA, width, thrust, multiplicity, …)

- Jet substructure reveal information about
  - Parton shower modelling
  - Flavour tagging (quark/heavy quark/gluon)
  - Large-R jets - particle content in boosted jet topologies
  - Fragmentation and non-perturbative effects
  - …



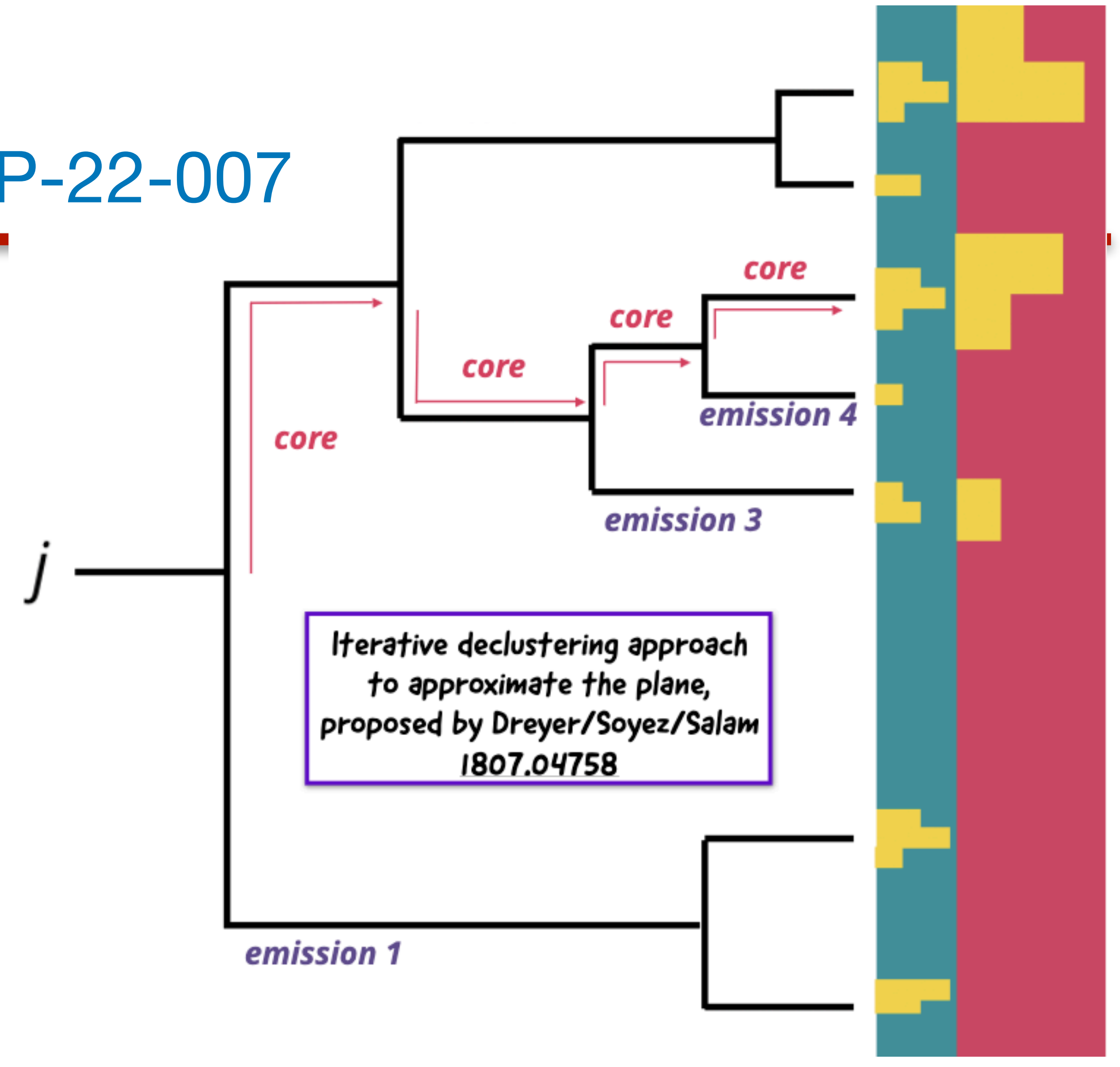
Top hadronic decays

Lund jet plane at 13 TeV

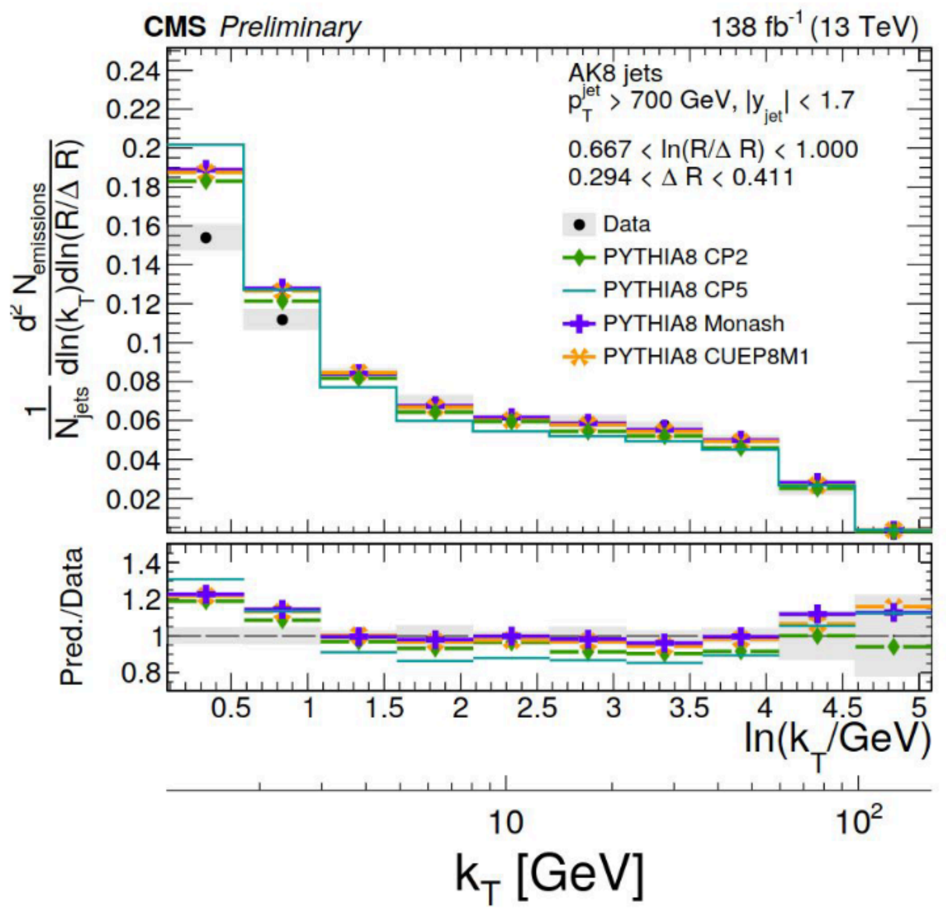
CMS-PAS-SMP-22-007

- A jet is approximated as soft emissions around a hard core which represents the original quark or gluon
  - Recluster jets with C/A algorithm and unwind widest angles first

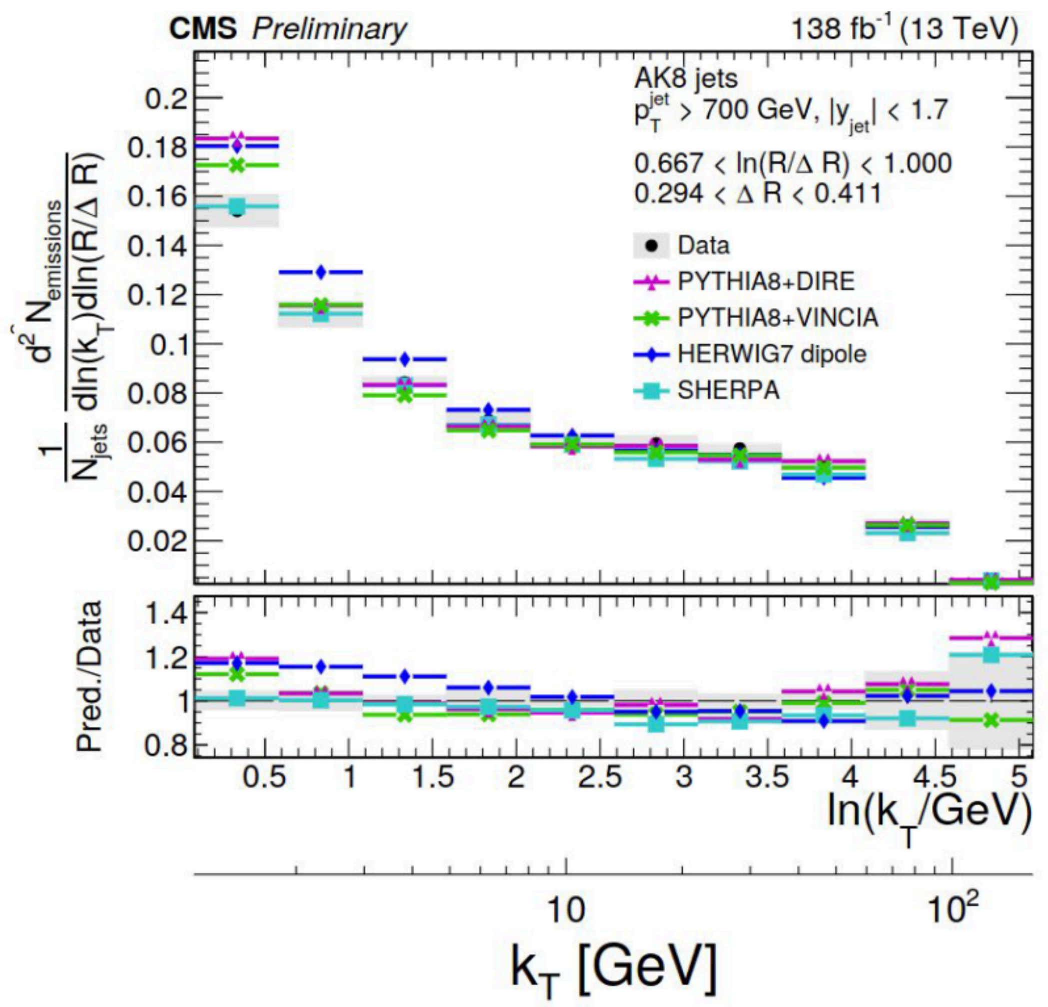
- 'Radiography' of jets - 10-20% mismodelling of the data
  - Crucial input for new NLL parton shower developments and MC tuning



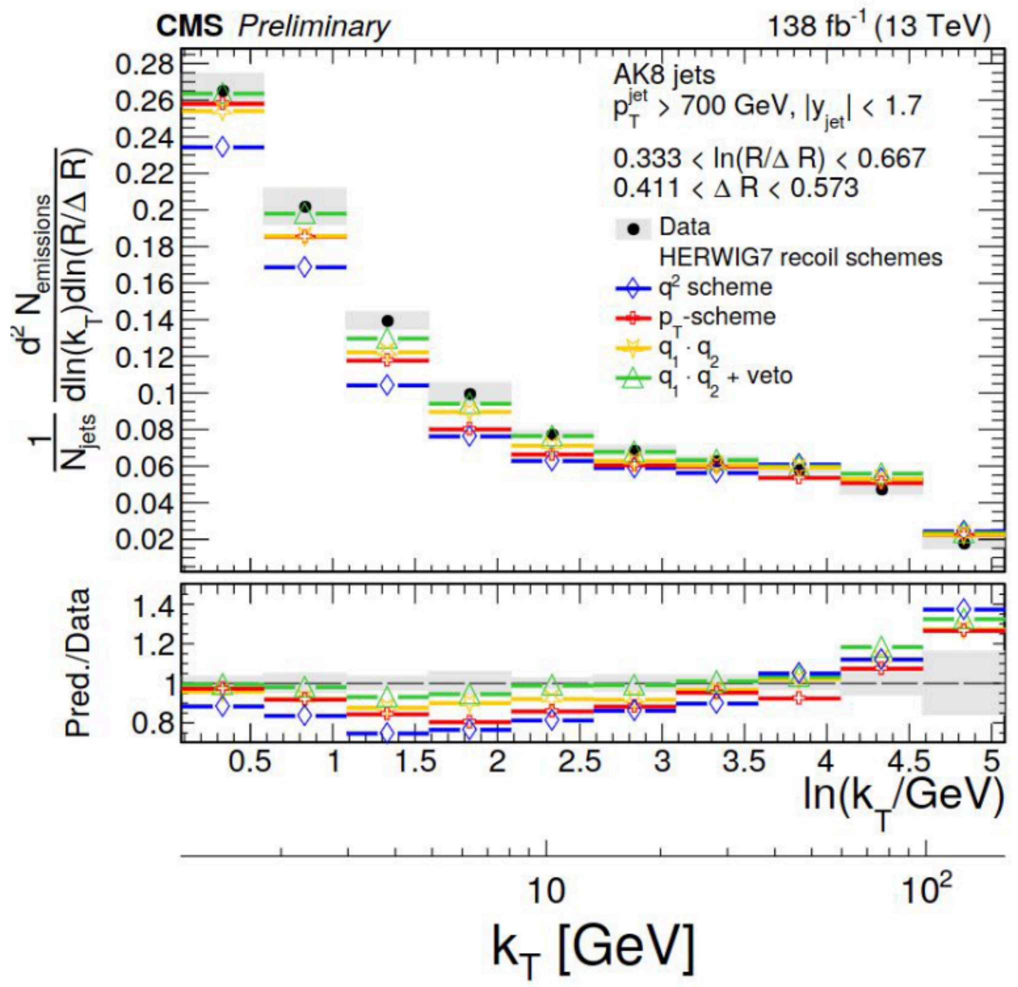
M. LeBlanc, adapted



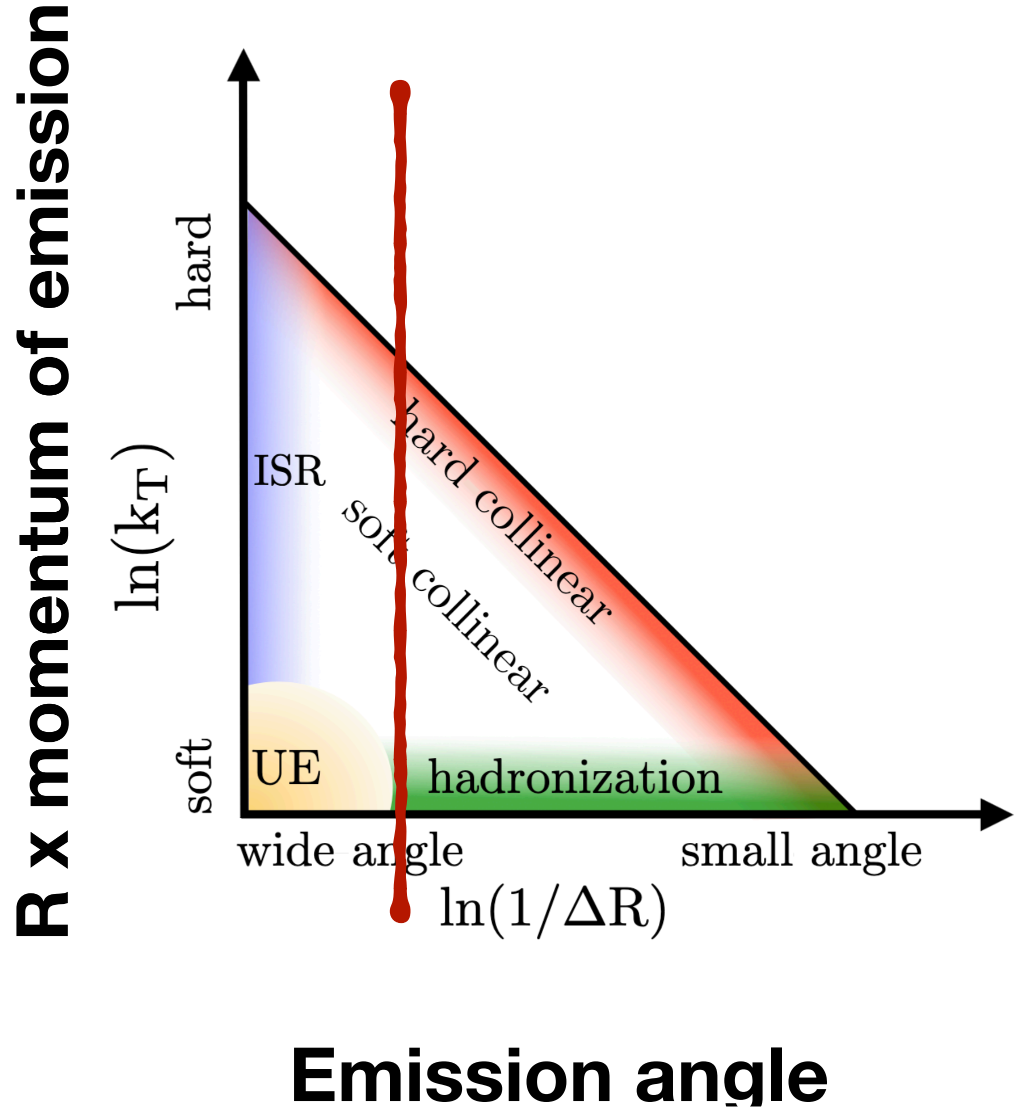
PYTHIA8 tunes (CP2, CP5, Monash, CUEP8m1)



Dipole showers (Vincia, Dire, Herwig7 dipole, Sherpa)



Herwig7 recoil schemes (angle-ordered)

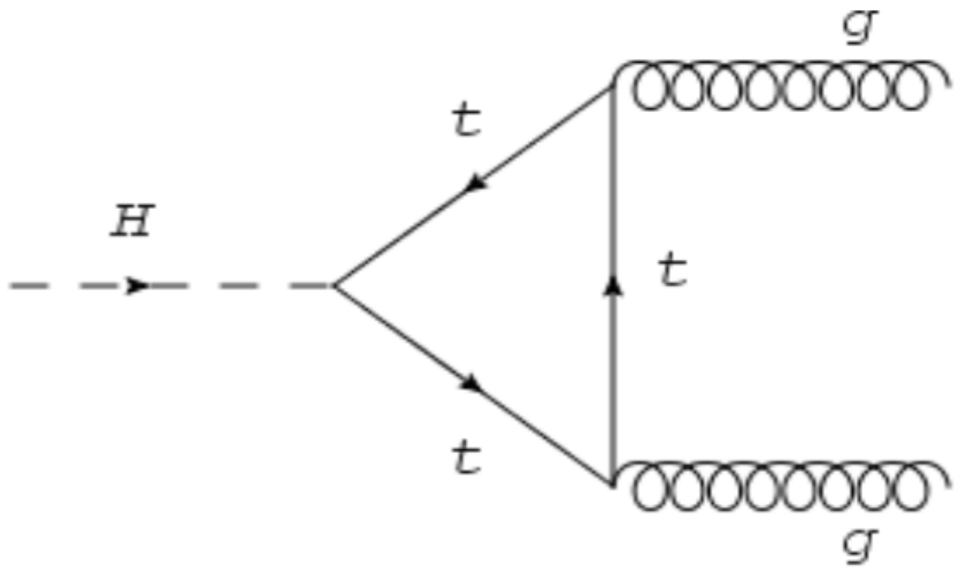


Other QCD program at future lepton facility

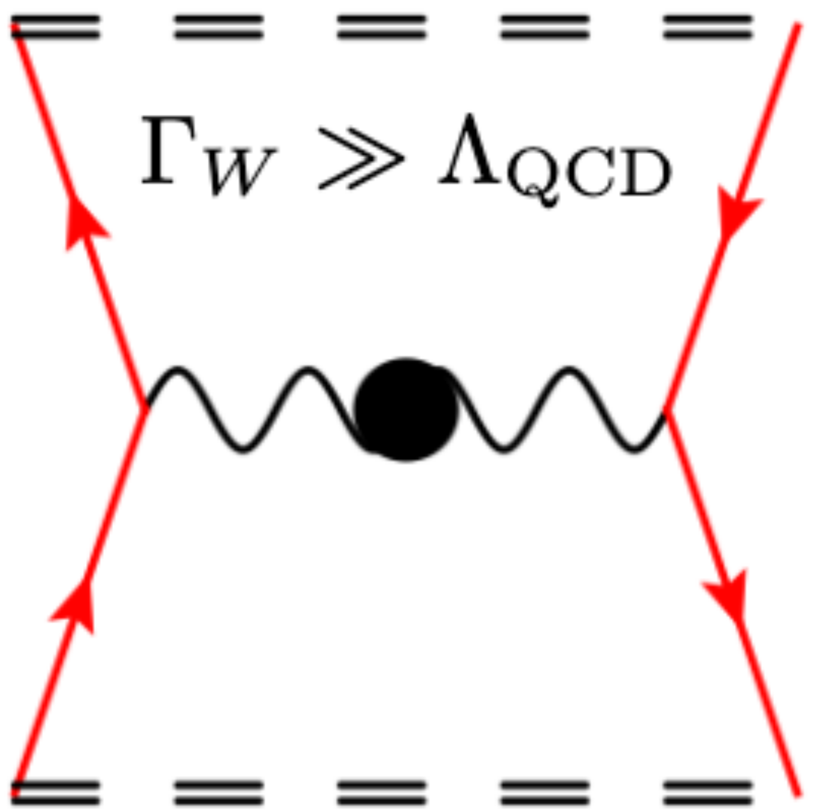
EPCJ 79 (2019) 474

- **Expect new generation of highly accurate MC models in the next decade**
  - NNLO calculations matched and merged with next-generation showers
  - ILC/FCC-ee/CEPC clean events to test PS/hadronization developments
  - Disentangling perturbative from non-perturbative corrections

- **High-precision quark and gluon substructure and fragmentation studies**
  - Current PS models differ on the gluon radiation pattern (less for quark)
  - Clean gluon $H \to gg$ factory, compare with $Z \to qq(g)$
  - q/s/c/b/gluon tagging



- **Colour reconnection studies -** CR is an uncertainty on m_{top}
  - String drag effect on W mass, No-CR excluded at 99.5% CL at LEP
  - Use threshold scan + huge sample of semi-leptonic WW to measure mW
    - input as constraint to make sensitive measurements of CR in hadronic WW



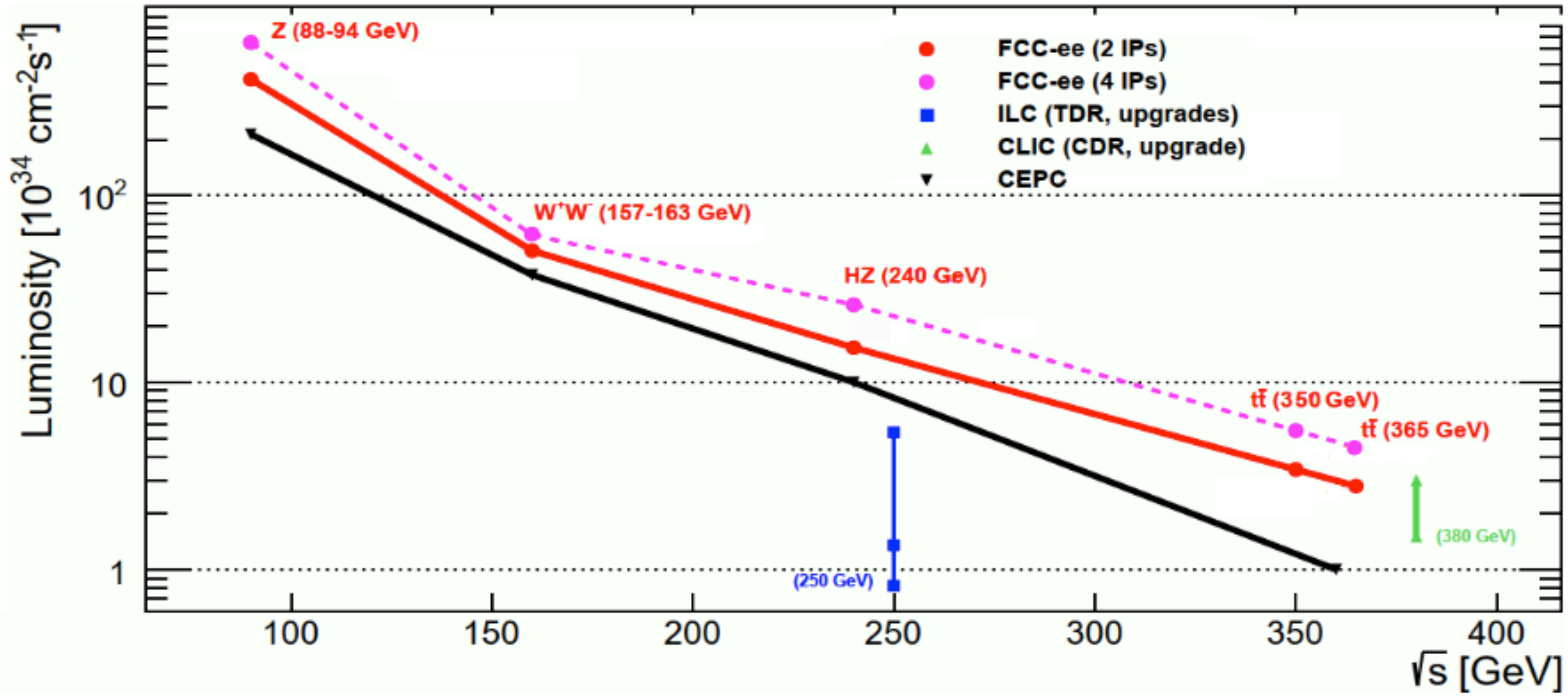
Summary

- **QCD physics at the LHC has entered % precision era both in terms of theory and experimental measurements**
- Accurate pQCD predictions are indispensable (NNLO computations are available for many processes)
- Parton showers is a fast developing field - showers uncertainties are often the dominant uncertainties in EWK measurements

Future lepton colliders will play an instrumental role to scrutinise ongoing theory developments on the way to the future hadron-hadron collider

Backup

QCD opportunities at future lepton colliders



- FCC-ee

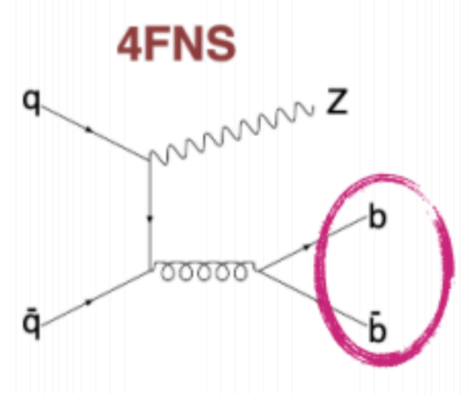
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s}$ ~ 350 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s} = 125$ GeV	? Years	~5000	$e^+e^- \to H$]	Never done	< 100 keV

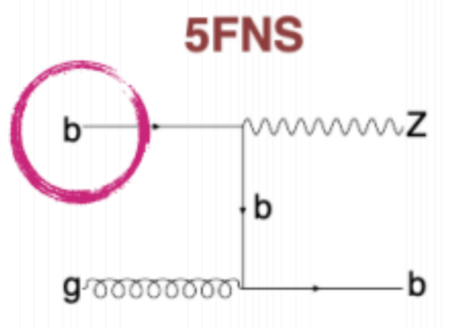
W/Z associated with charm and beauty

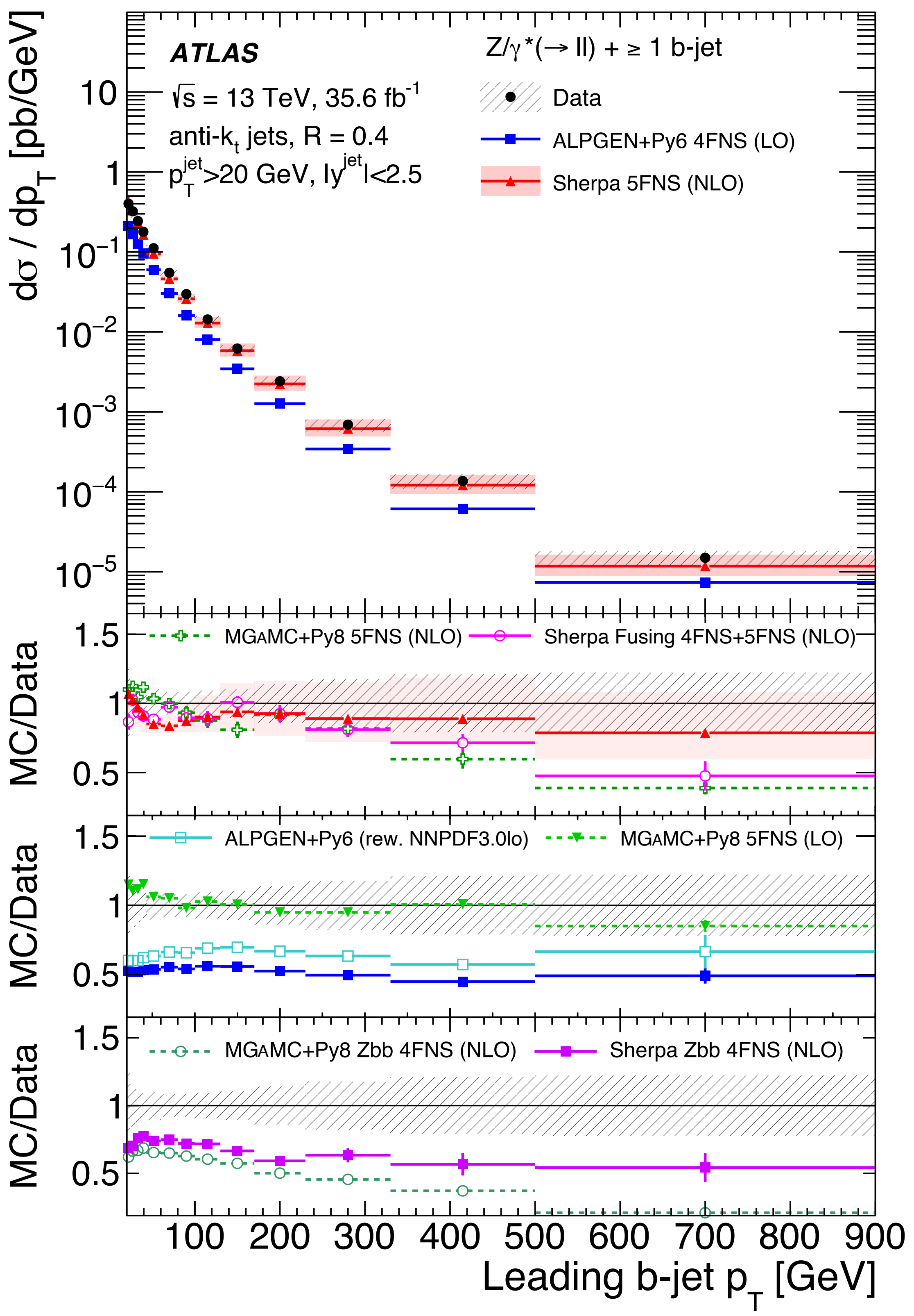
JHEP 07 (2020) 44 (ATLAS)
PRD 108 (2023) 032012 (ATLAS)

- **Z+b measurements** discriminate the effect of b quark PDF, important for VH-> bbll and BSM searches
  - test of pQCD: gluon splitting, HF mass effects, NLO effects

- **W+D measurements** reveal details of the strange parton density
  - $s - \bar{s}$ asymmetry constrained via ration of $W^+ + \bar{c}/W^- + c$

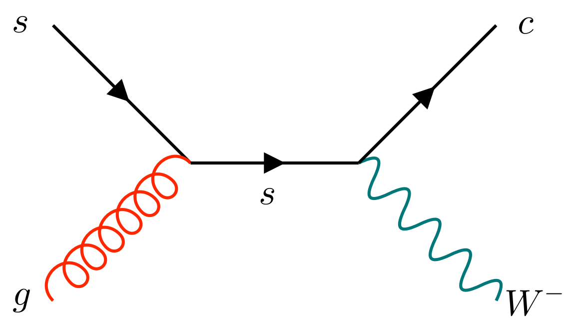




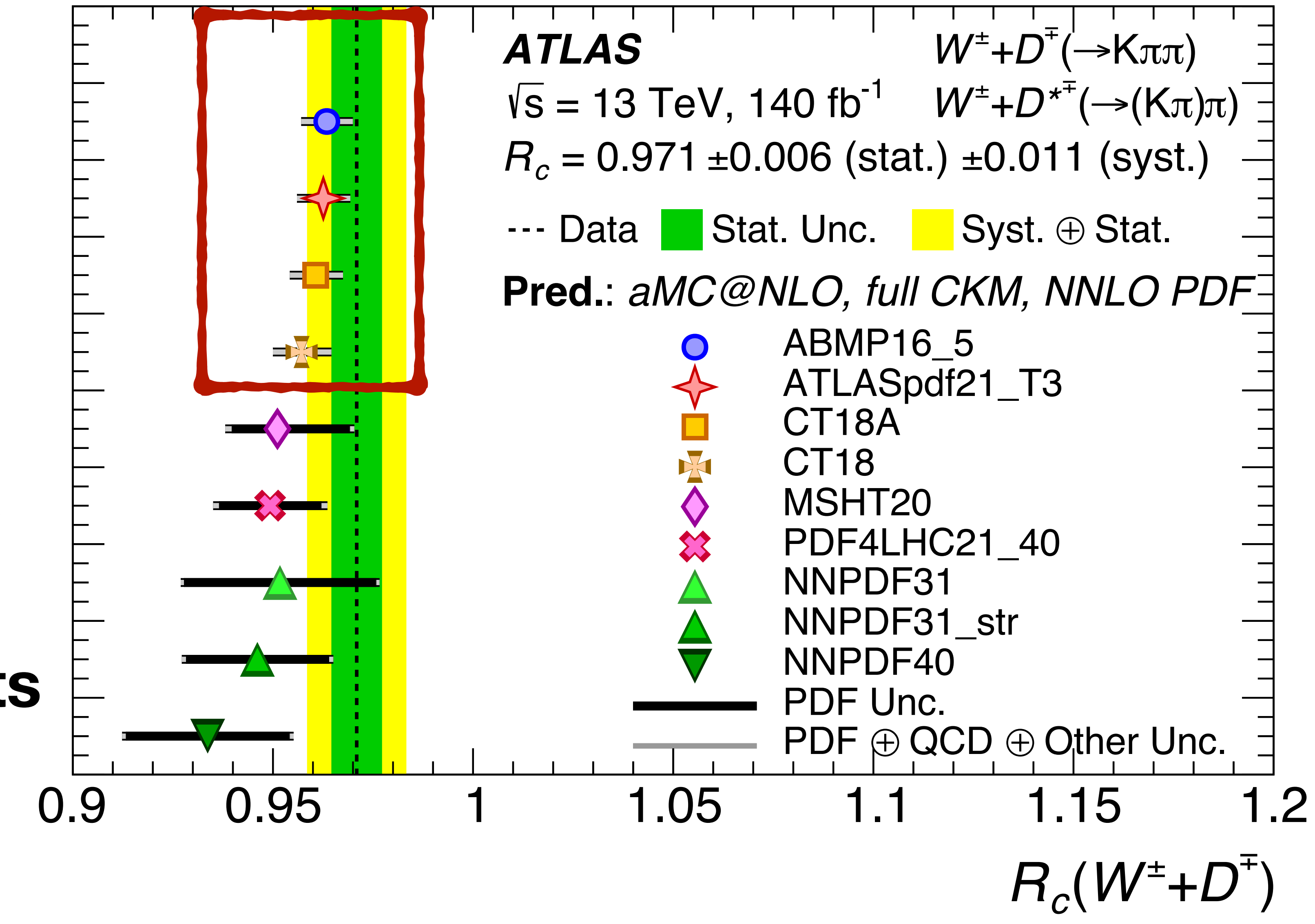


new Sherpa
4F+5F @ NLO
predictions

all 4F predictions
underestimate
the Z+1b xsection



symmetric s-sbar PDF



Suggests small s-sbar asymmetry

Outstanding challenge for PDF fits
predictions at NNLO with charm
fragmentation included needed

Jet response

- Particle response depends on the parton shower and hadronization
  - driven by the energy fraction of kaons and baryons in a jet