High energy QCD experimental physics

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ATLAS/CMS/ALICE/LHCb collaborations

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GOBIERNO DE ESPAÑA
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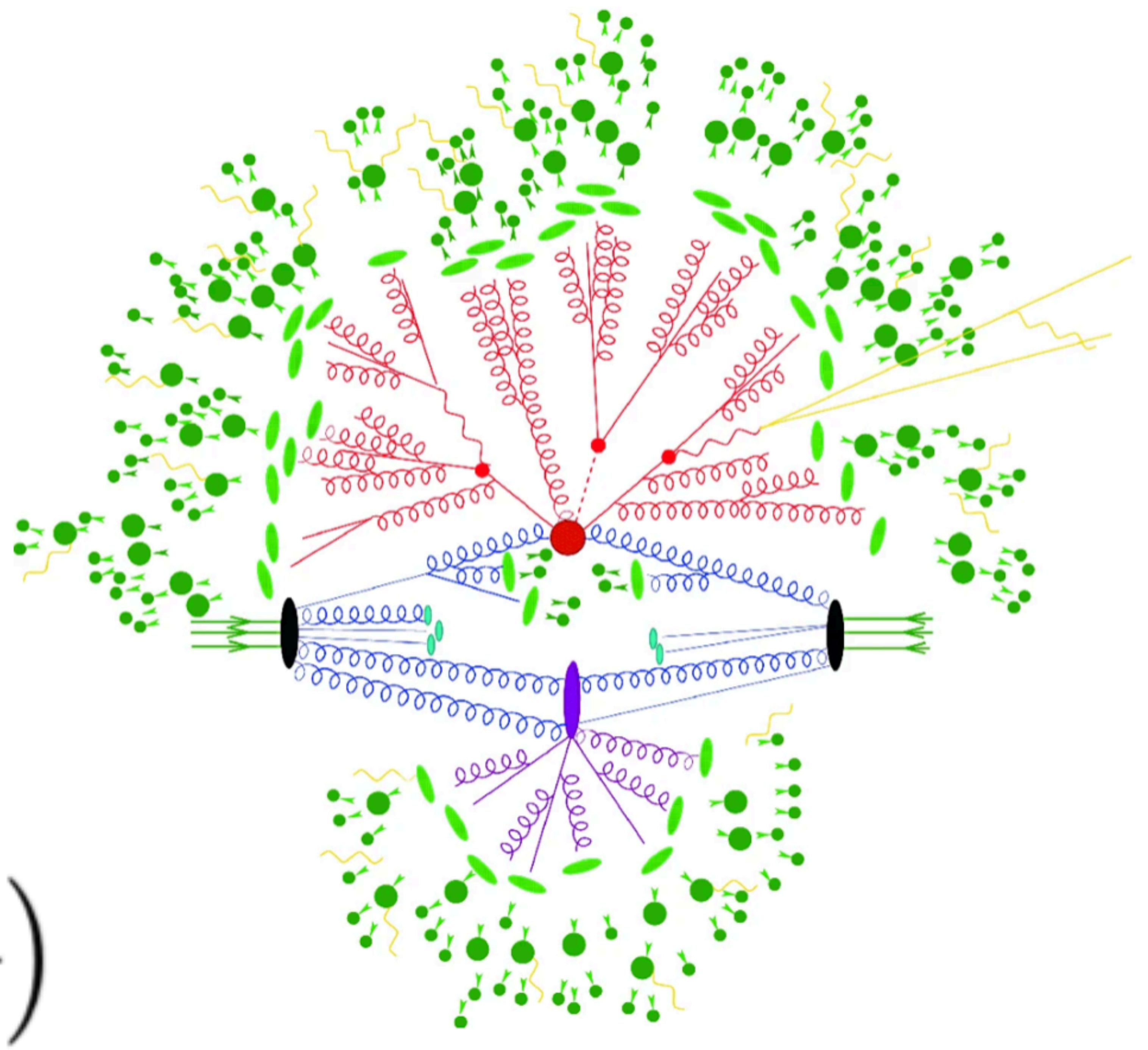
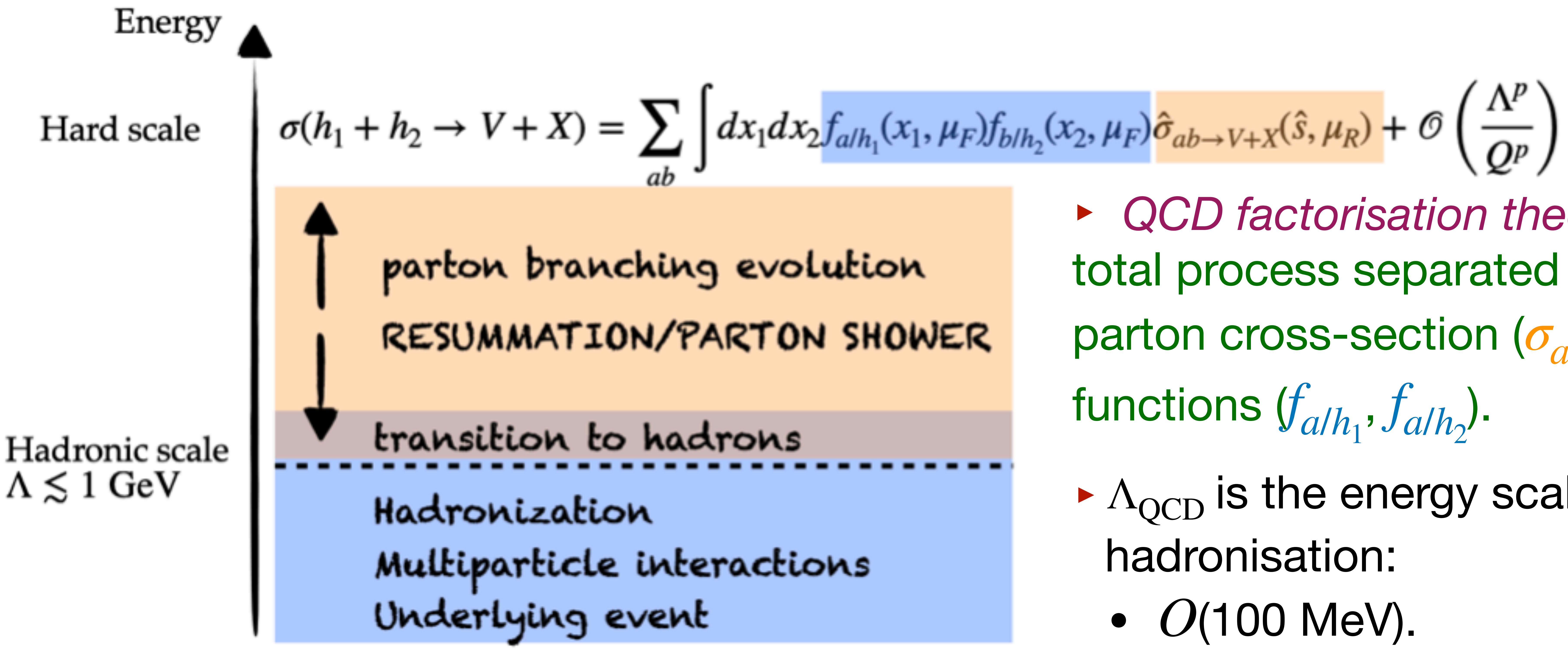
- Proton-proton collisions quite involved phenomena.
  - Different QCD phenomenology entering in the description of the event.
  - It can be separated in terms of the energy scale:
    - Hard interaction ($Q \sim \sqrt{\hat{s}}$).
    - Parton branching evolution ($\sqrt{\hat{s}} > Q > \Lambda_{QCD}$).
    - Hadronisation ($Q \sim \Lambda_{\text{QCD}}$), Parton Distribution Functions (PDFs).





- *QCD factorisation theorem*:
total process separated in two parts: short distance parton cross-section ($\sigma_{ab \to V+X}$) and long-distance functions ($f_{a/h_1}, f_{a/h_2}$).

- Λ_{QCD} is the energy scale associated to hadronisation:
  - O(100 MeV).

$$Q \sim \sqrt{\hat{s}}$$

Hard interaction:

- Quark and gluons within protons interact to produce high energetic objects.
- Interactions between quark and gluons within the protons can be ignored at this stage.
- It can be described by perturbative QCD:

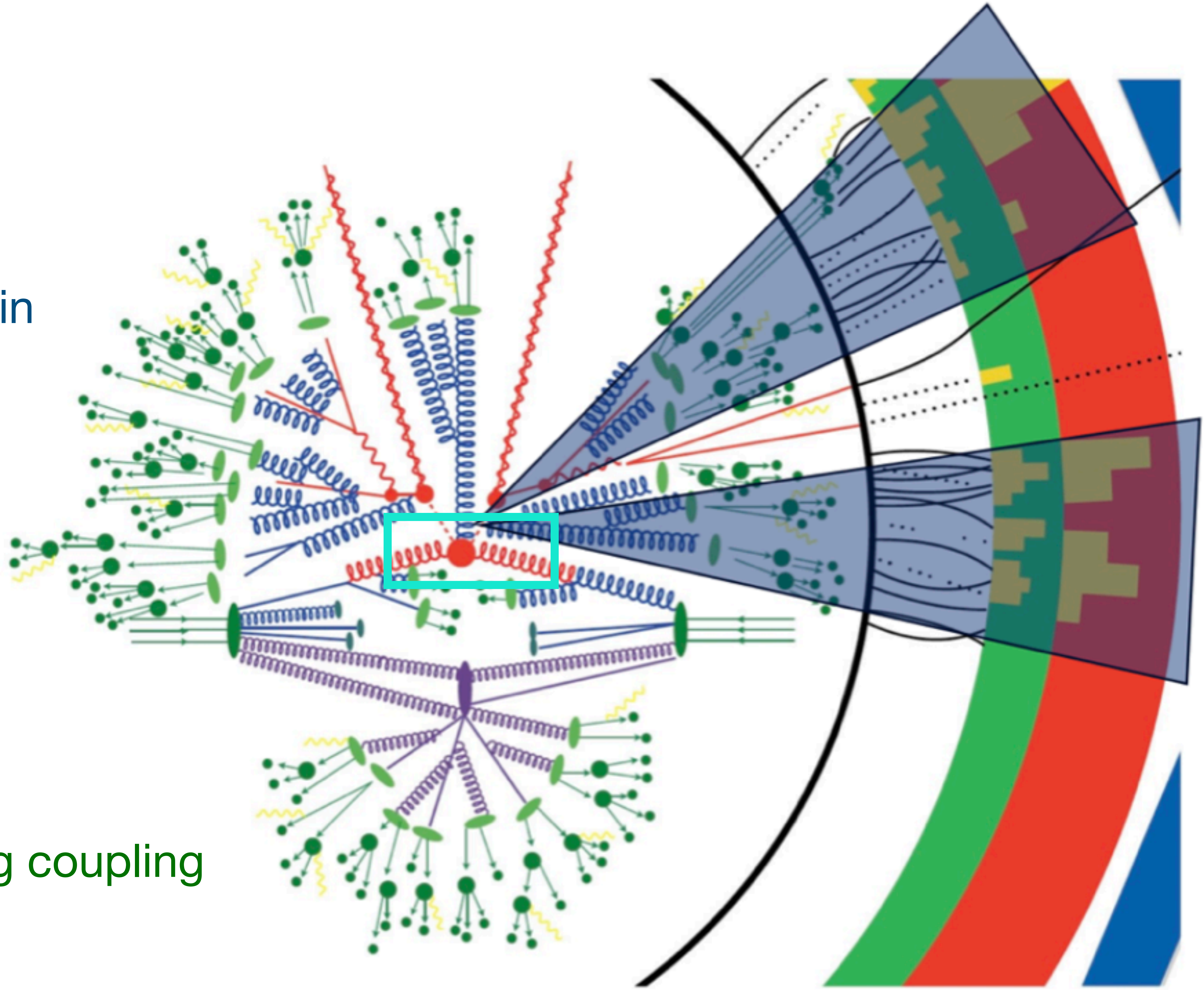
$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0)}_{ab} + \frac{\alpha_S}{2\pi}\hat{\sigma}^{(1)}_{ab} + \left(\frac{\alpha_S}{2\pi}\right)^2 \hat{\sigma}^{(2)}_{ab} + \ldots$$

$\mathcal{O}(100\%)$ $\mathcal{O}(20\%)$ $\mathcal{O}(5\%)$

LO NLO NNLO

▸ Perturbative expansion in terms of the strong coupling constant (α_S) since it is small at high energies.

- Running of $\alpha_S \equiv \alpha_S(Q)$.

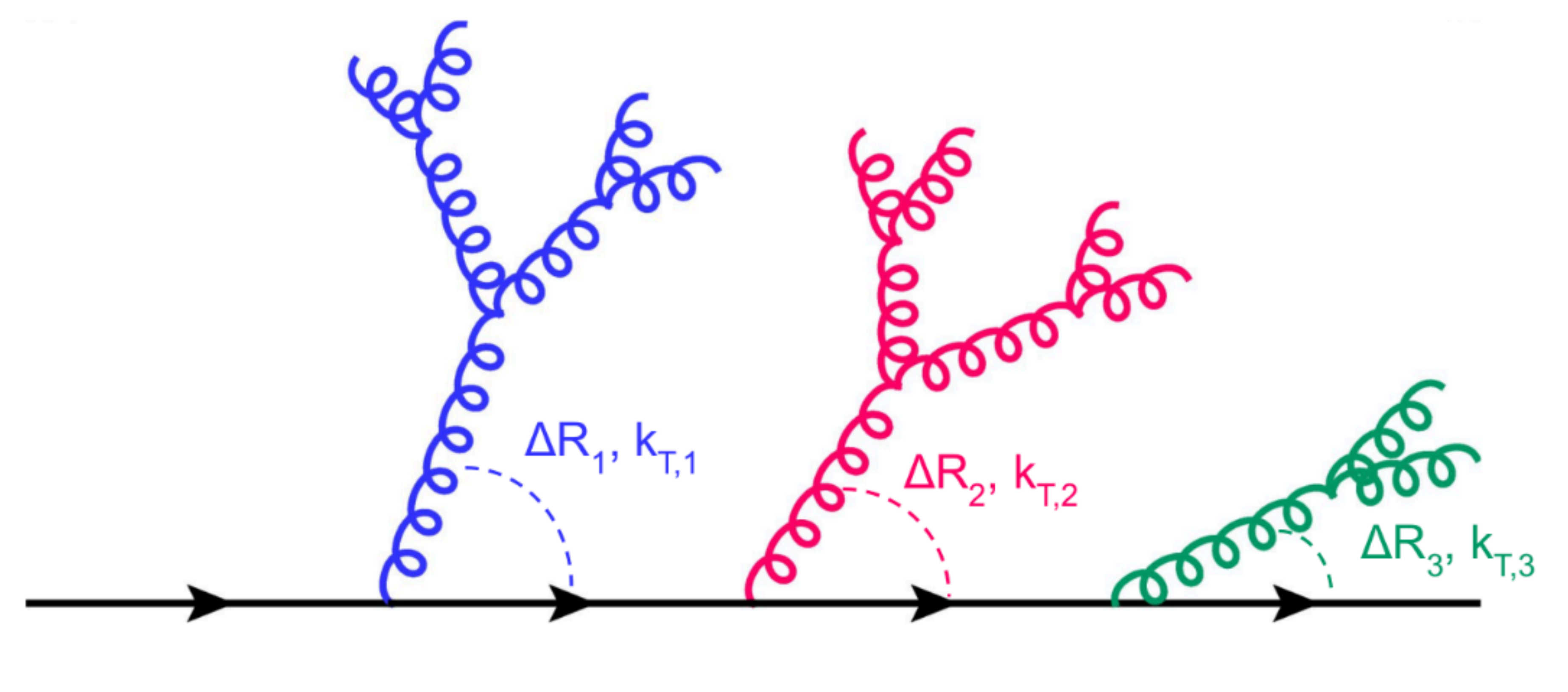


Original credit: Sherpa and Ben Nachman

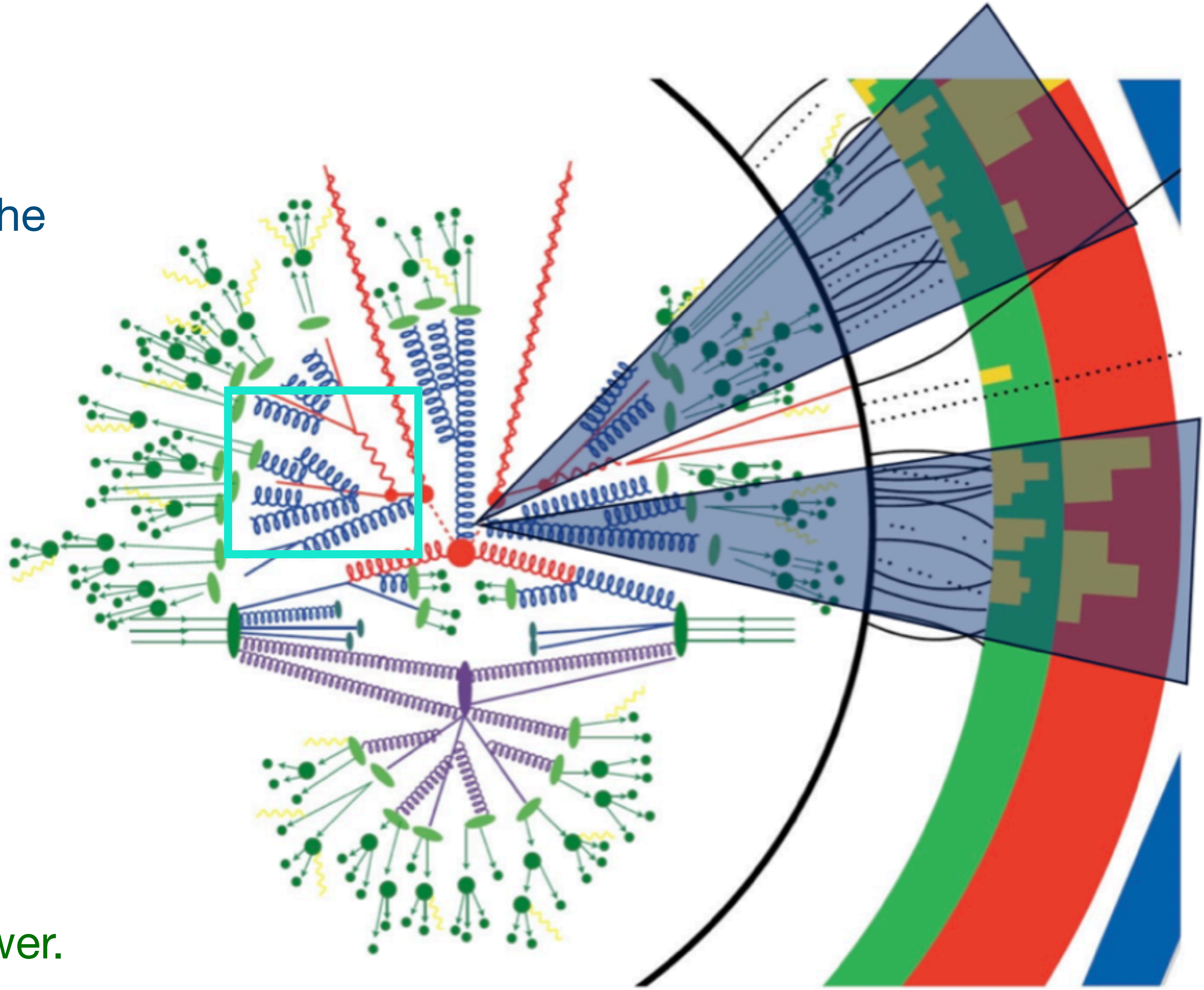
$$\sqrt{\hat{s}} > Q > \Lambda_{QCD}$$

Parton branching evolution:

- QCD shower of outgoing partons created in the hard interaction leading to jets of hadrons.
  - A multi scale process probing all-order structure of the perturbation theory.



Quark radiating gluons



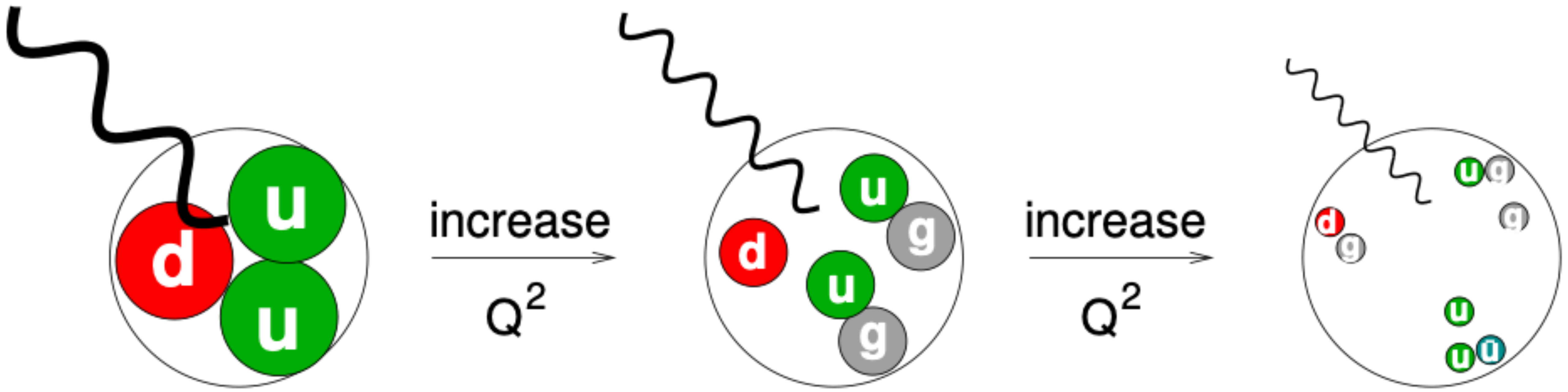
Original credit: Sherpa and Ben Nachman

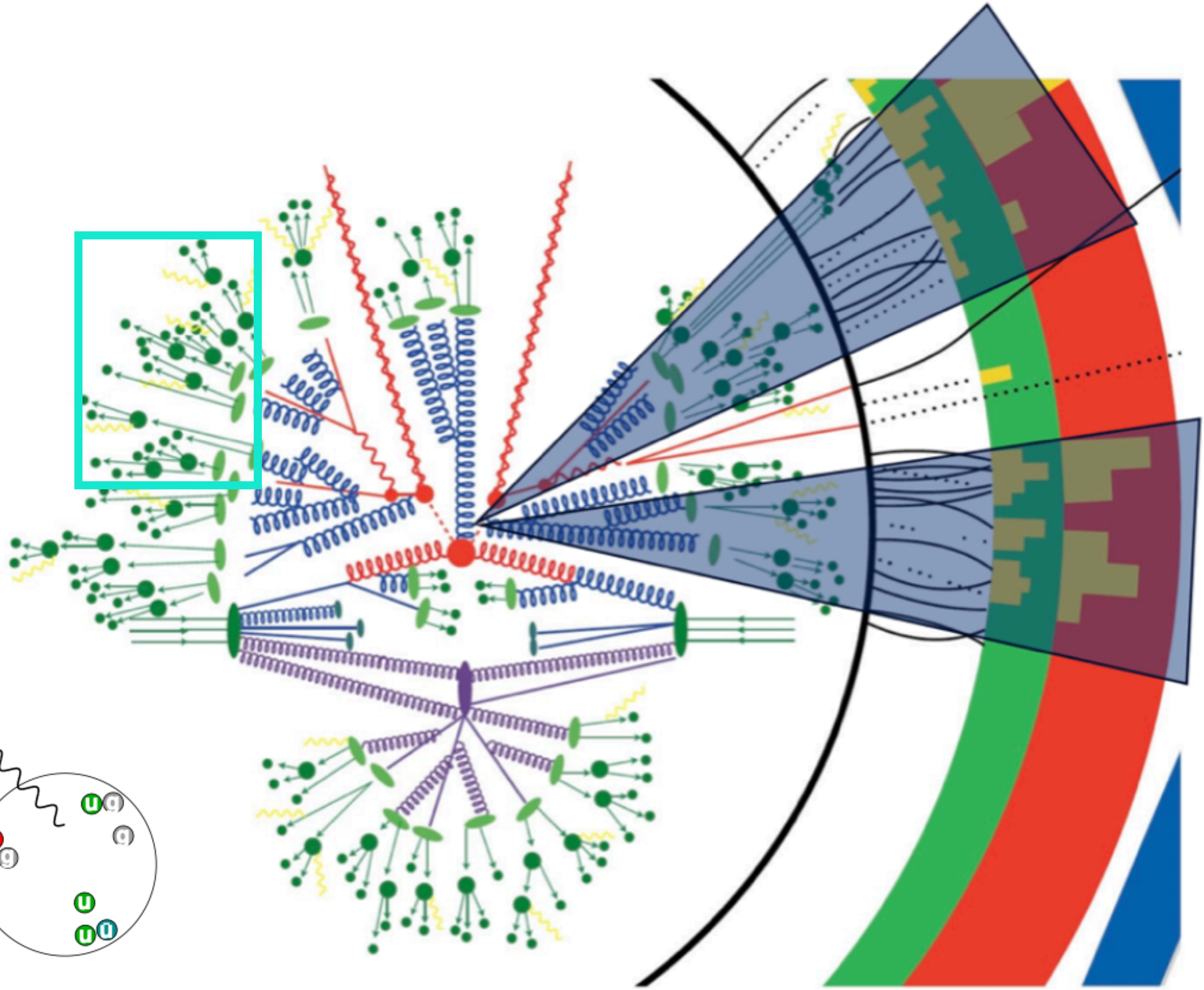
- Resummation of different orders in pQCD needed for a fair description of the QCD shower.
  - $\alpha_S^{\text{eff}}(Q) \sim \alpha_S \cdot \log(Q/\sqrt{\hat{s}}) \sim 1.$

$Q \sim \Lambda_{QCD}$

Non-perturbative effects:

- Recombination of quarks and gluons into hadrons (colorless particles).
- Parton Distribution Functions PDF(Q_{fact}, x).
  - x = fraction of proton p_z taken by partons.
    - It depends on energy scale Q_{fact}.
  - Estimated from fits to measurements.
  - Evolved using pQCD: DGLAP equations.

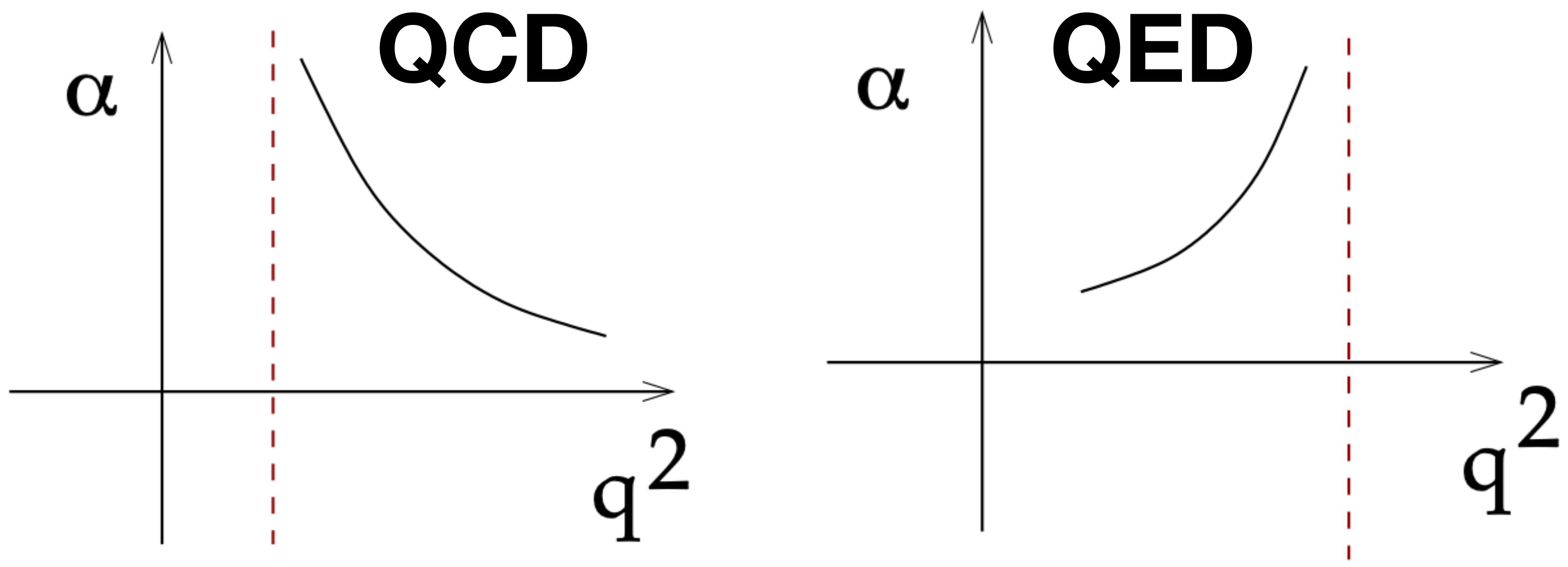




Original credit: Sherpa and Ben Nachman

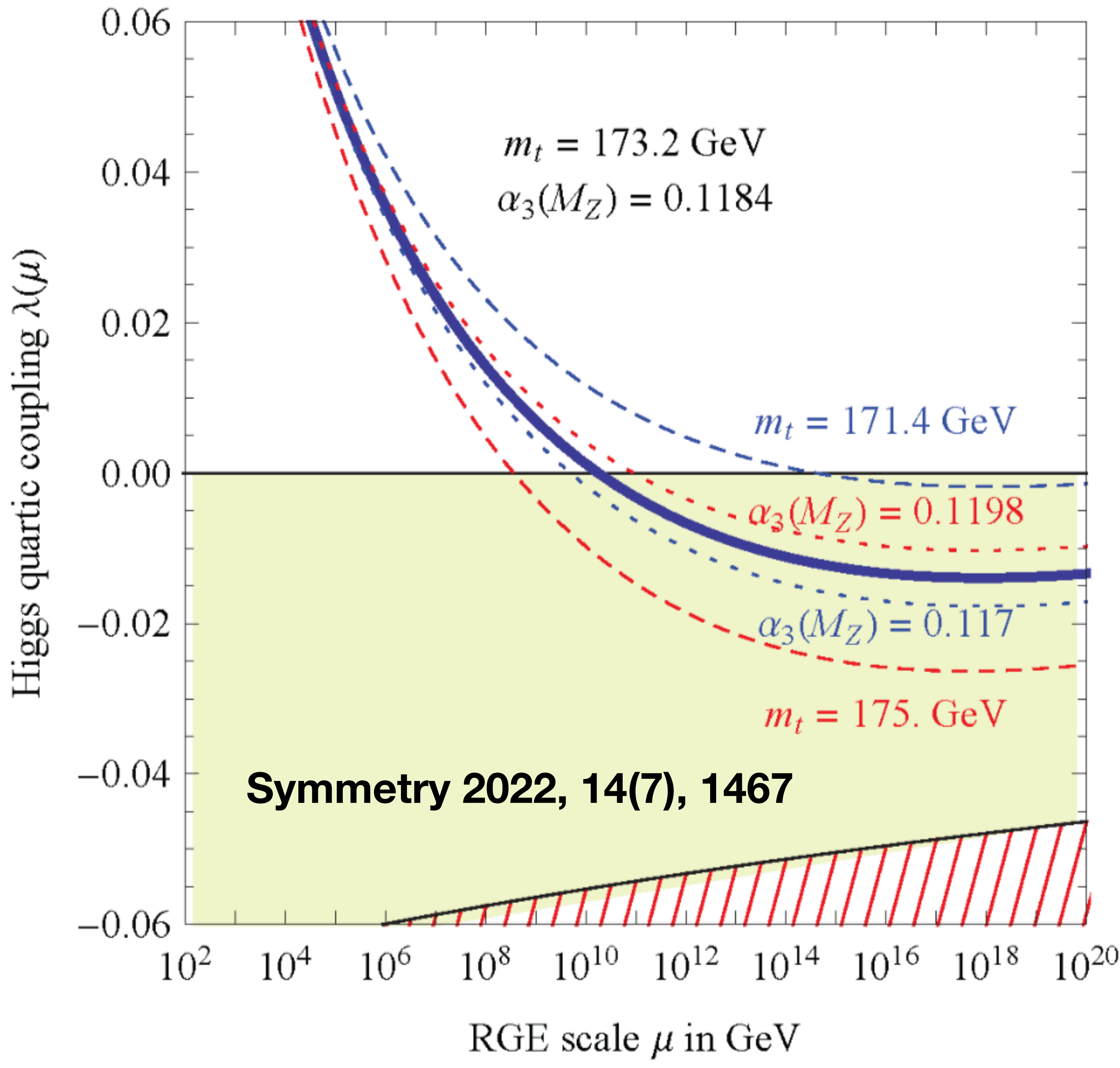
Introduction

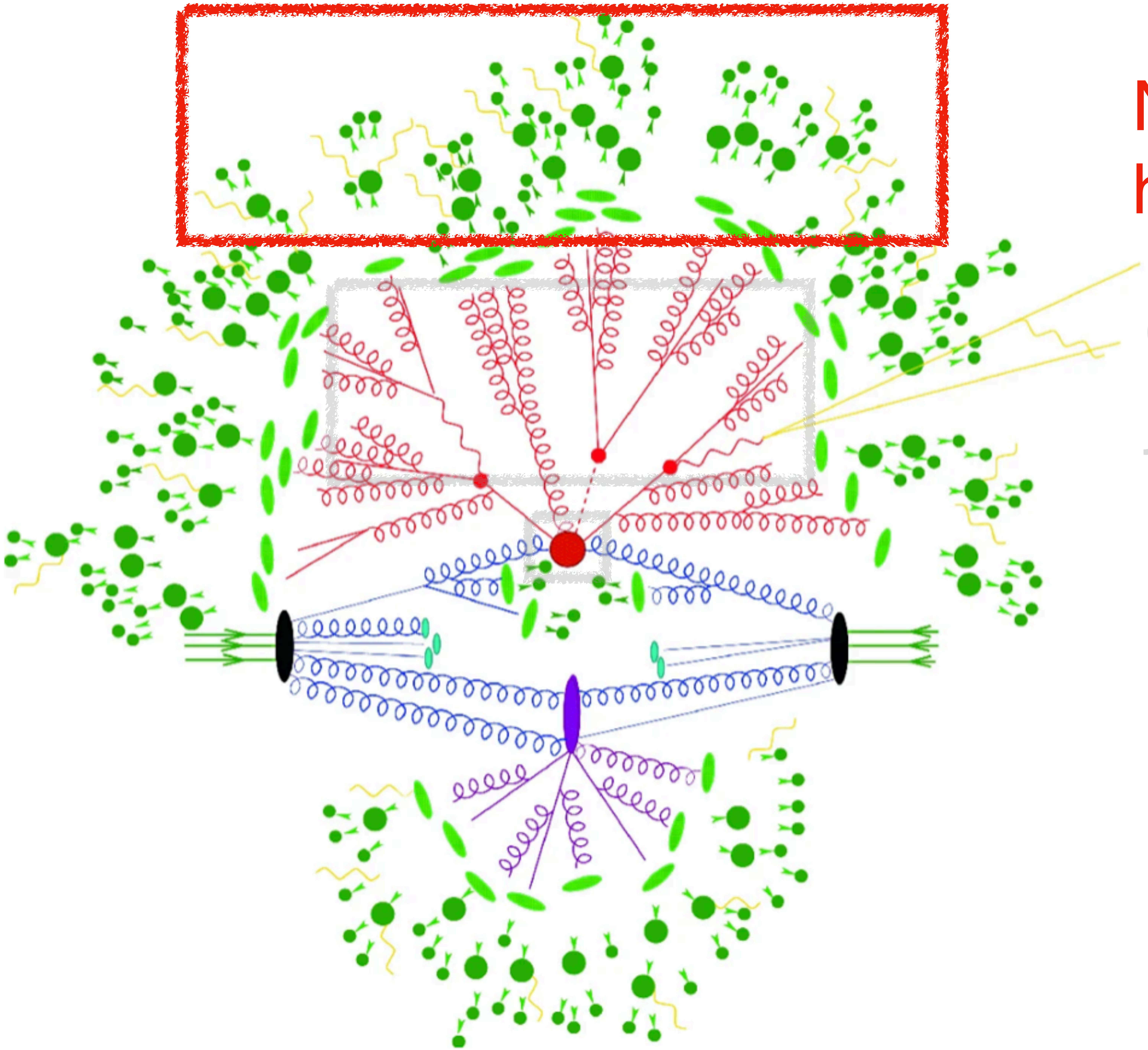
- QCD Lagrangian has 7 free parameters that need to be determined experimentally.
  - 6 quark masses which have EW origin: Higgs mechanism.
  - α_S which is the only fundamental parameter of QCD: quite predictive theory!.



- Asymptotic freedom property: QCD interaction becomes weaker as the energy scale increases.

- α_S is the SM coupling constant with the largest value.
  - QCD corrections are quite important for several processes.
  - It also affect vacuum stability due to the dependence of the Higgs quartic coupling (λ) on α_S through the Renormalisation Group Equations (RGE).
    - Very important to extract α_S with high accuracy.
  - Currently α_S is the less known SM coupling constant (w/o including Higgs sector).



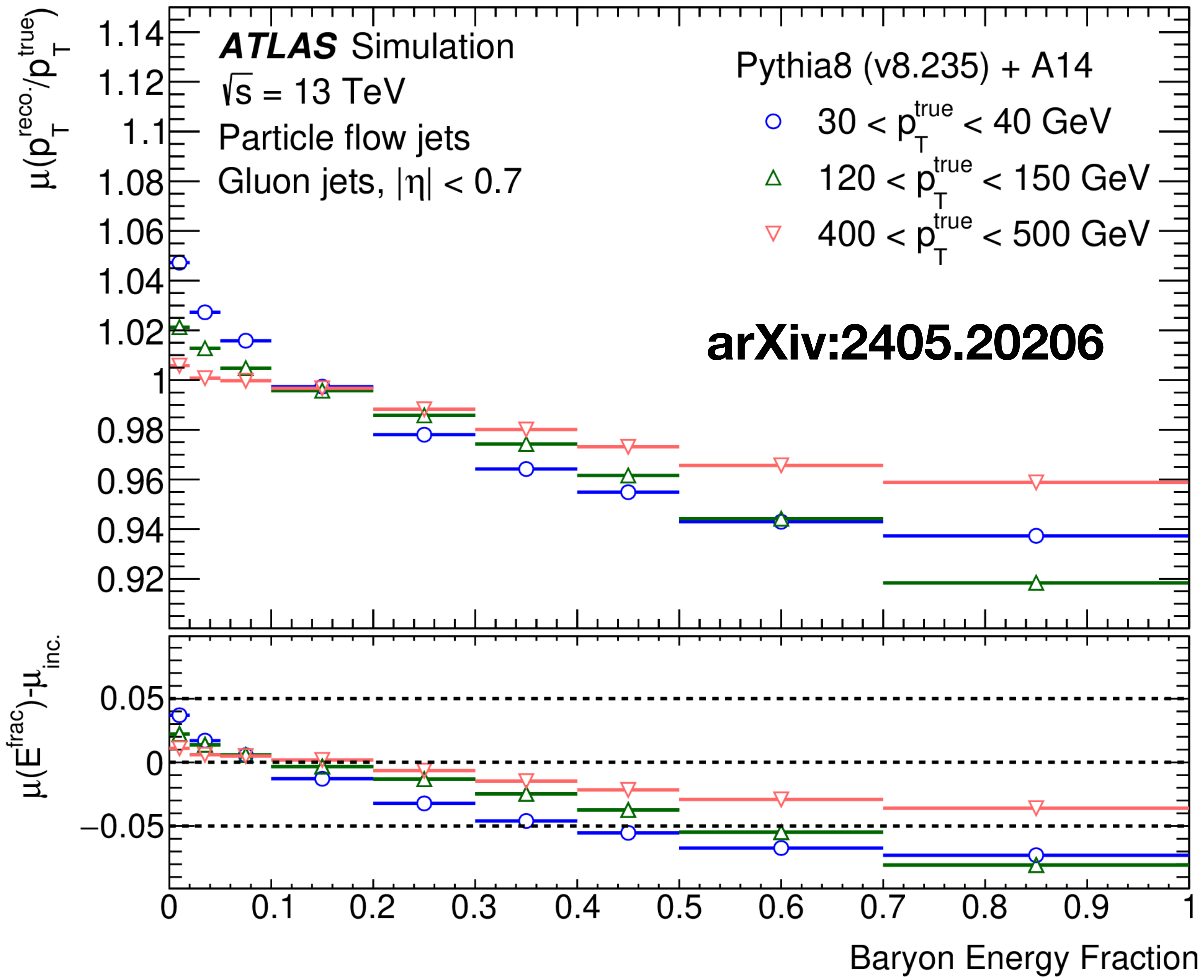


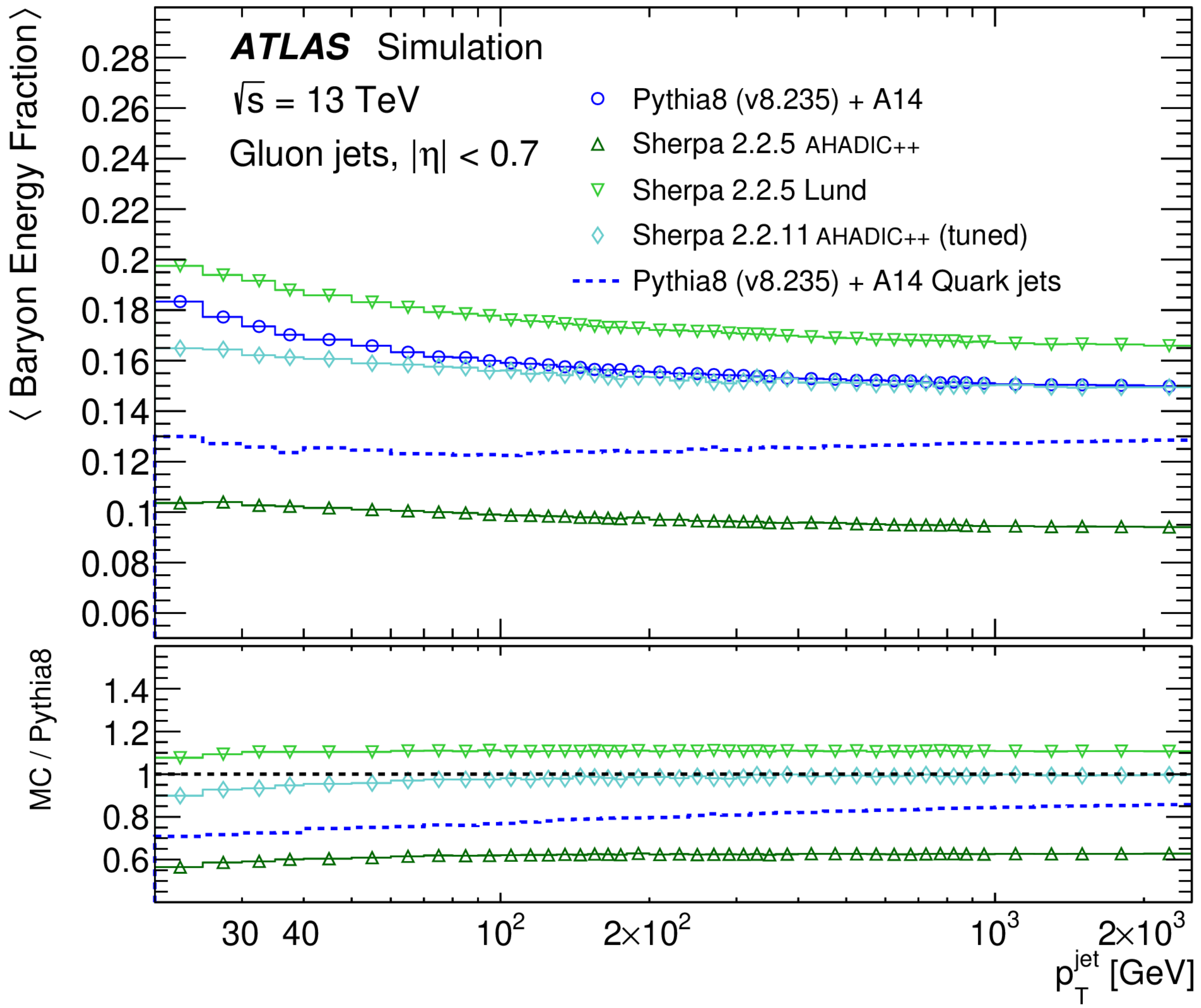
Non-perturbative QCD:
hadronisation

QCD resummation:
jet substructure

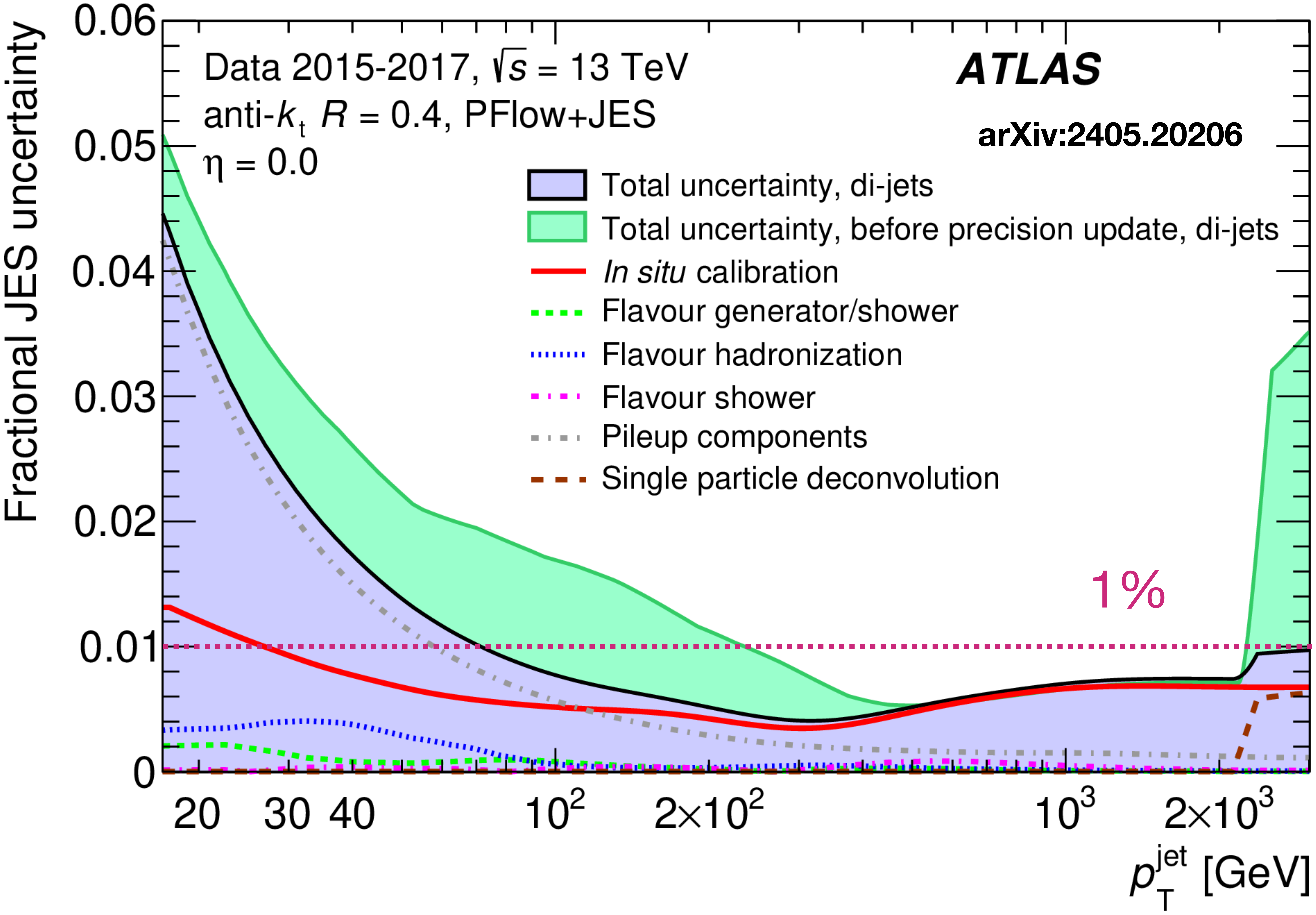
Hard QCD physics

- Hadronisation plays an important role in the description of a jet.
  - Particles interact differently with the detector which affects jet calibration i.e $\pi^0 \rightarrow \gamma\gamma$.
  - ATLAS calorimeter: energy response smaller for baryons than π^0, η.





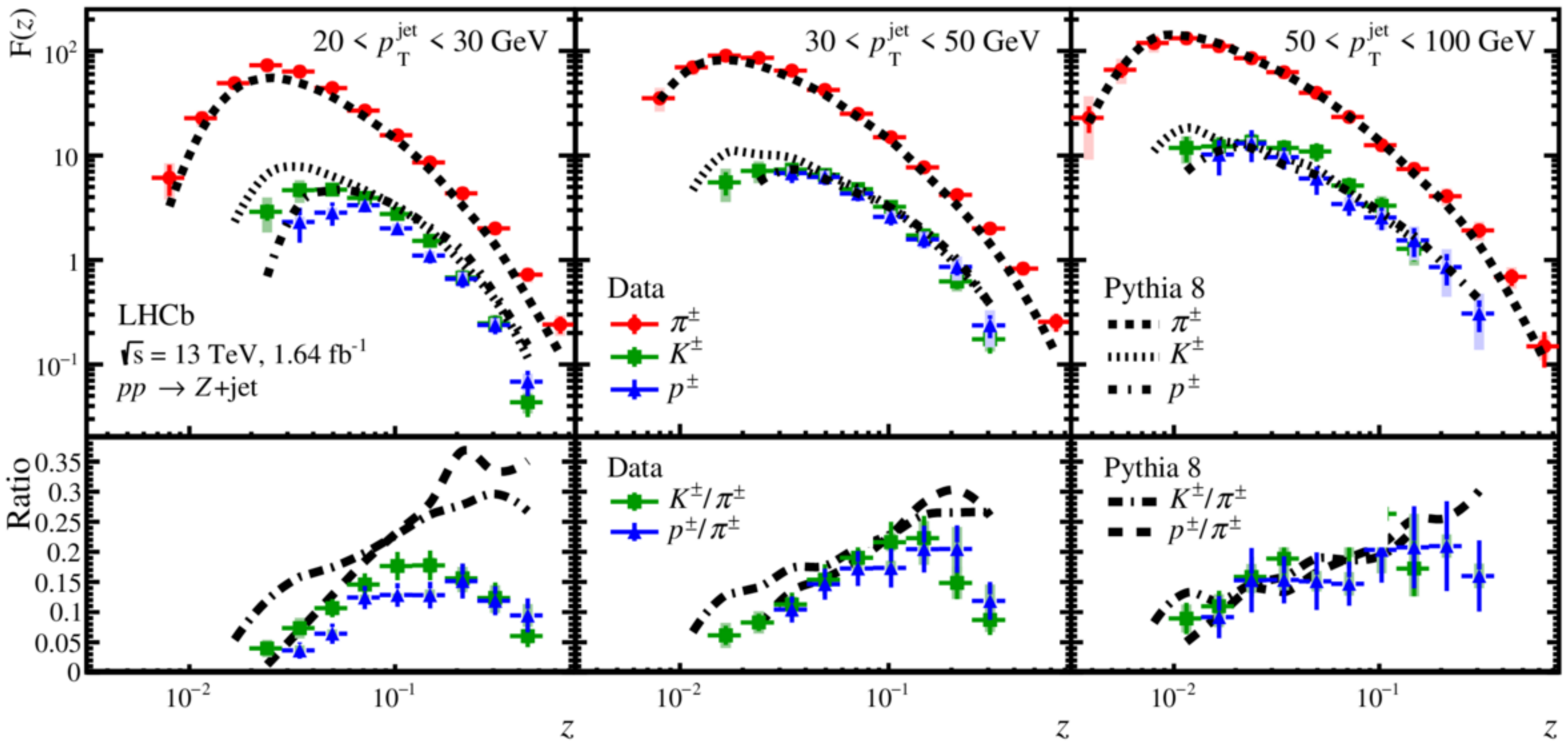
- Constraining hadronisation models helps to reduce JES uncertainties and reduce uncertainties of non-perturbative corrections to calculations.



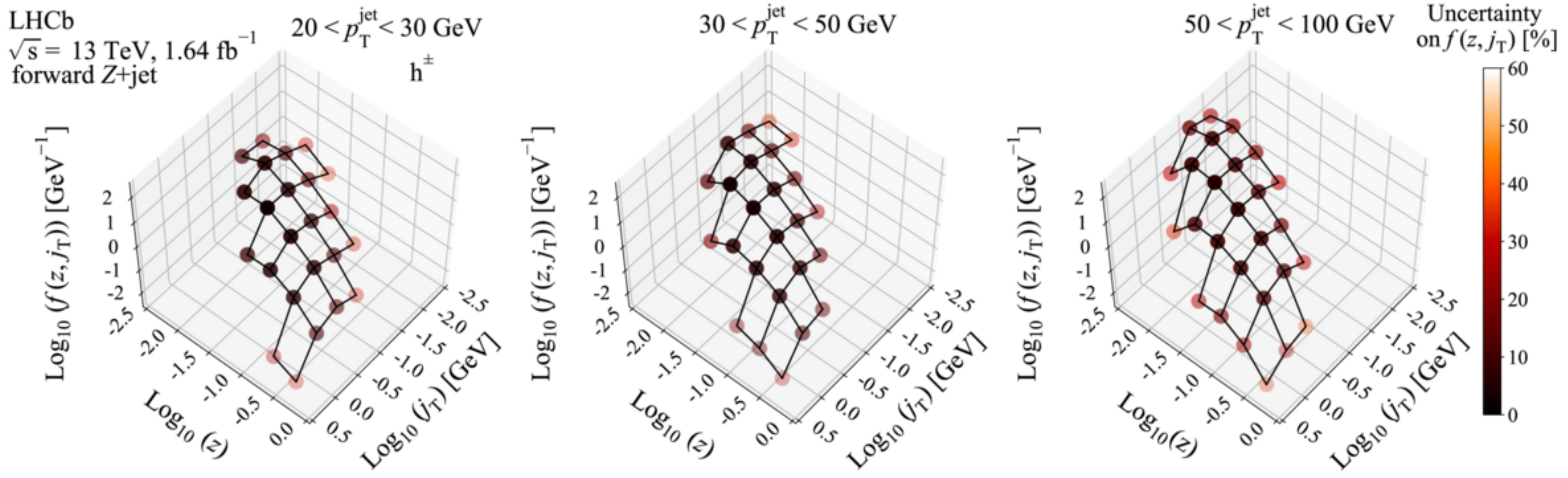
- Based on this observations, updated MC generator setups to define jet flavor response uncertainty.
  - Improvements on low/medium p_T^{jet} region.
- Updating single particle deconvolution uncertainty.
  - Improvements on high p_T^{jet} region.
- < 1% uncertainty on JES for $p_T^{jet} \gtrsim 70$ GeV.
- Uncertainty due to pile-up dominating at low p_T^{jet}.

Non-perturbative QCD: jet fragmentation functions

z distributions of identified pions, kaons and protons separately



Phys. Rev. D 108 (2023) L031103



Longitudinal profile

$$z = \frac{\mathbf{p}_{\text{had}} \cdot \mathbf{p}_{\text{jet}}}{|\mathbf{p}_{\text{jet}}|^2},$$

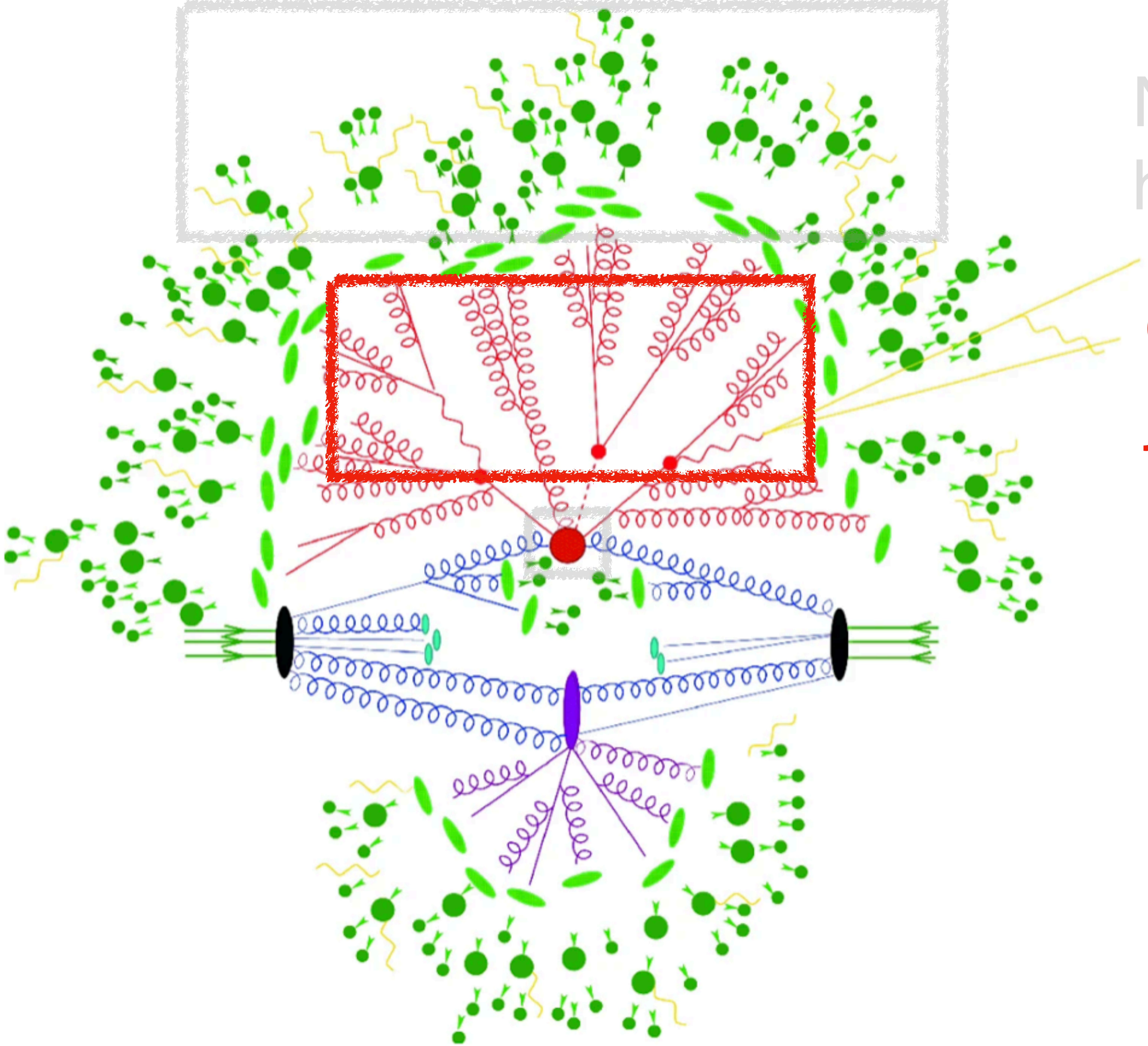
$$F(z) = \frac{1}{N_{Z+\text{jet}}} \frac{\mathrm{d}N_{\text{had}}(z)}{\mathrm{d}z},$$

Transverse profile

$$j_T = \frac{|\mathbf{p}_{\text{had}} \times \mathbf{p}_{\text{jet}}|}{|\mathbf{p}_{\text{jet}}|}$$

$$F(j_T) = \frac{1}{N_{Z+\text{jet}}} \frac{\mathrm{d}N_{\text{had}}(j_T)}{\mathrm{d}j_T}$$

- LHCb measurements of the double differential jet fragmentation functions for pions, kaons and protons.
- Discrepancies between Pythia MC including Lund hadronisation model and the measurements are observed:
  - Contribution from charged pions (kaons and protons) are largely underestimated (overestimated)
  - Further tuning on Lund model needed to improve the description.



Non-perturbative QCD: hadronisation

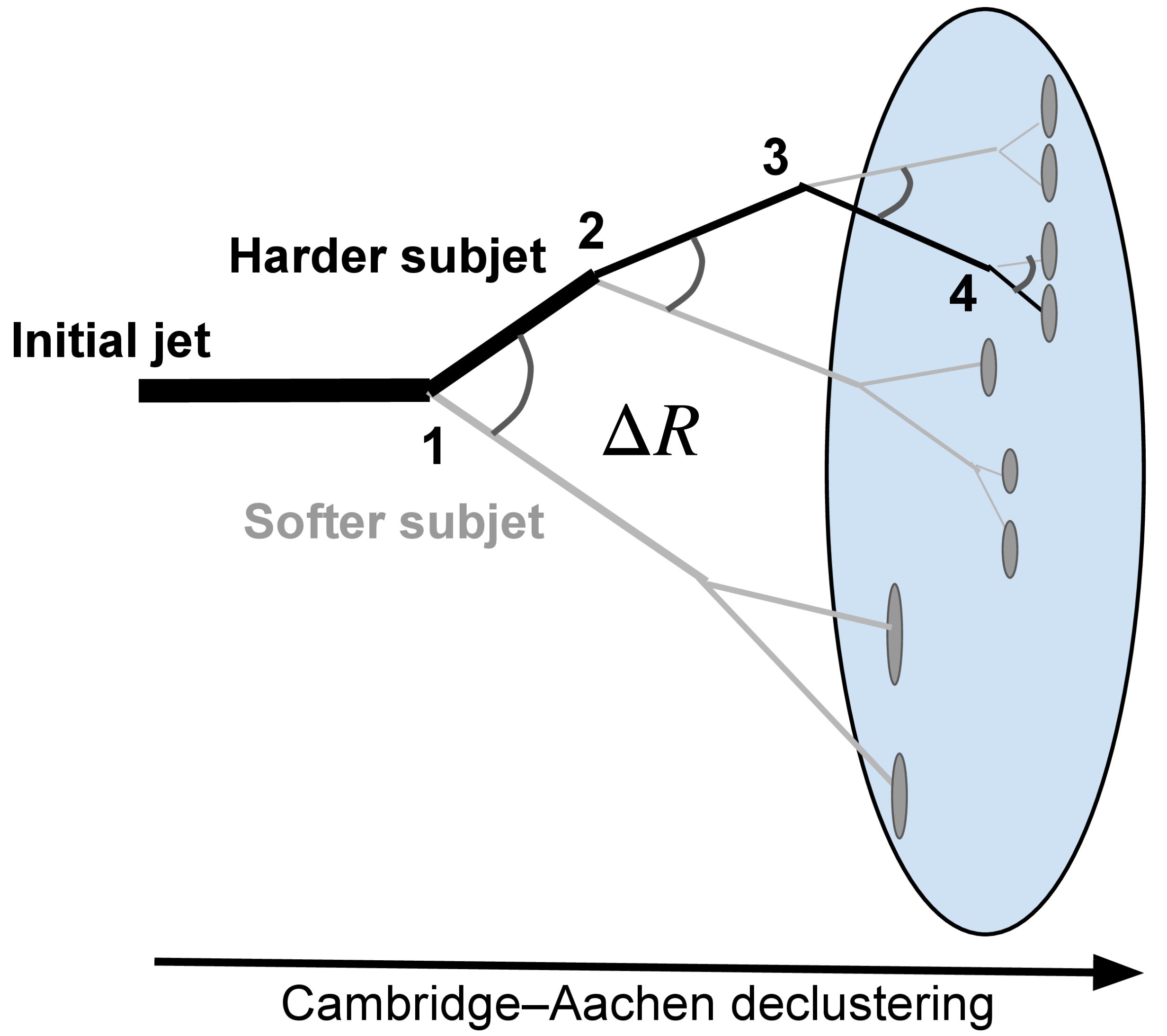
QCD resummation: jet substructure

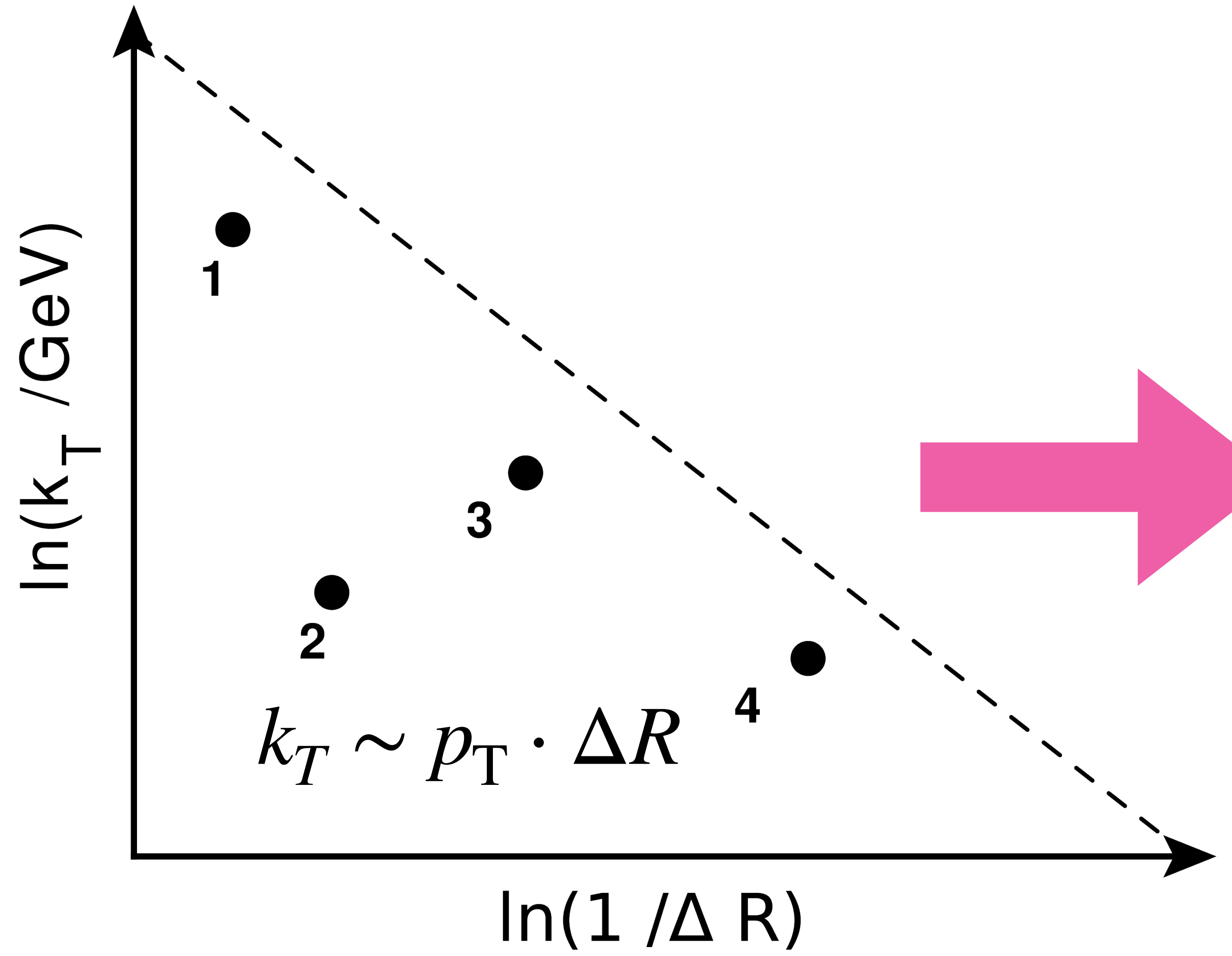
Hard QCD physics

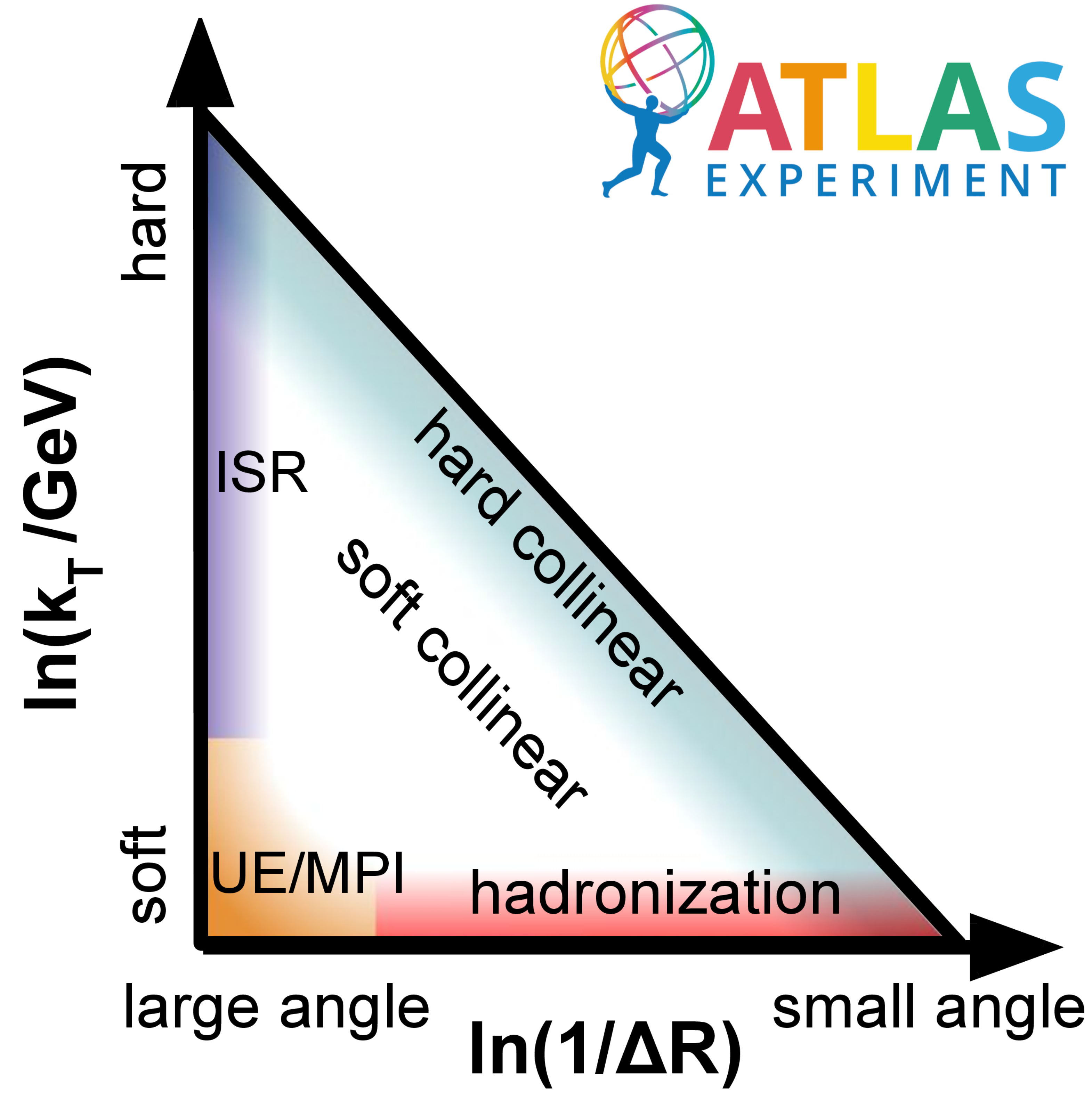
Jet substructure: Lund jet plane

- Lund jet plane (LJP) is a theoretical representation of the phase-space within jets, which includes information of the QCD radiation history.
- C/A declustering to get a proxy of partonic emissions within a jet!
  - LJP is filled with emissions ordered from large to small angles.

F. A. Dreyer et al., "The Lund Jet Plane", JHEP 12 (2018) 064

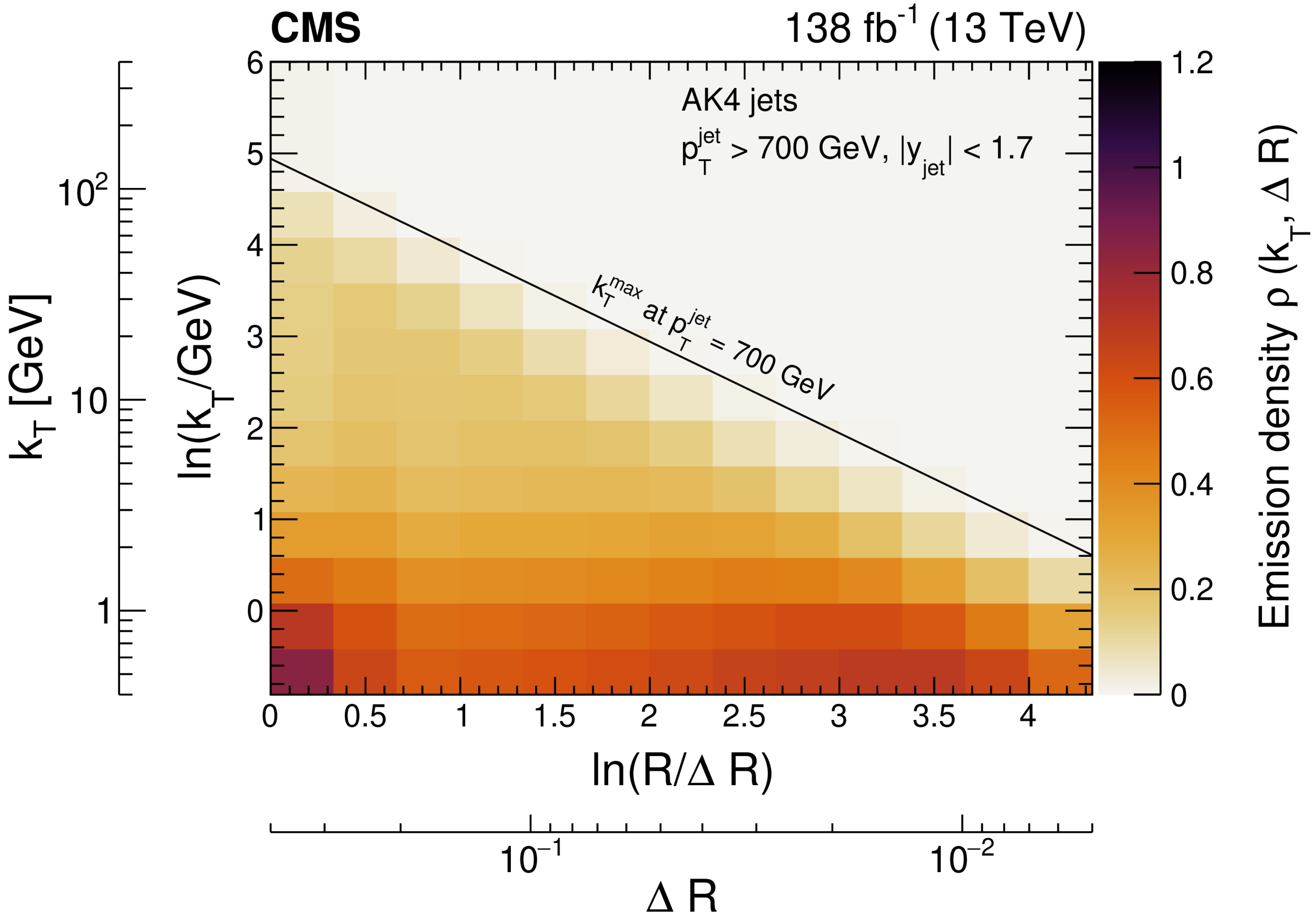


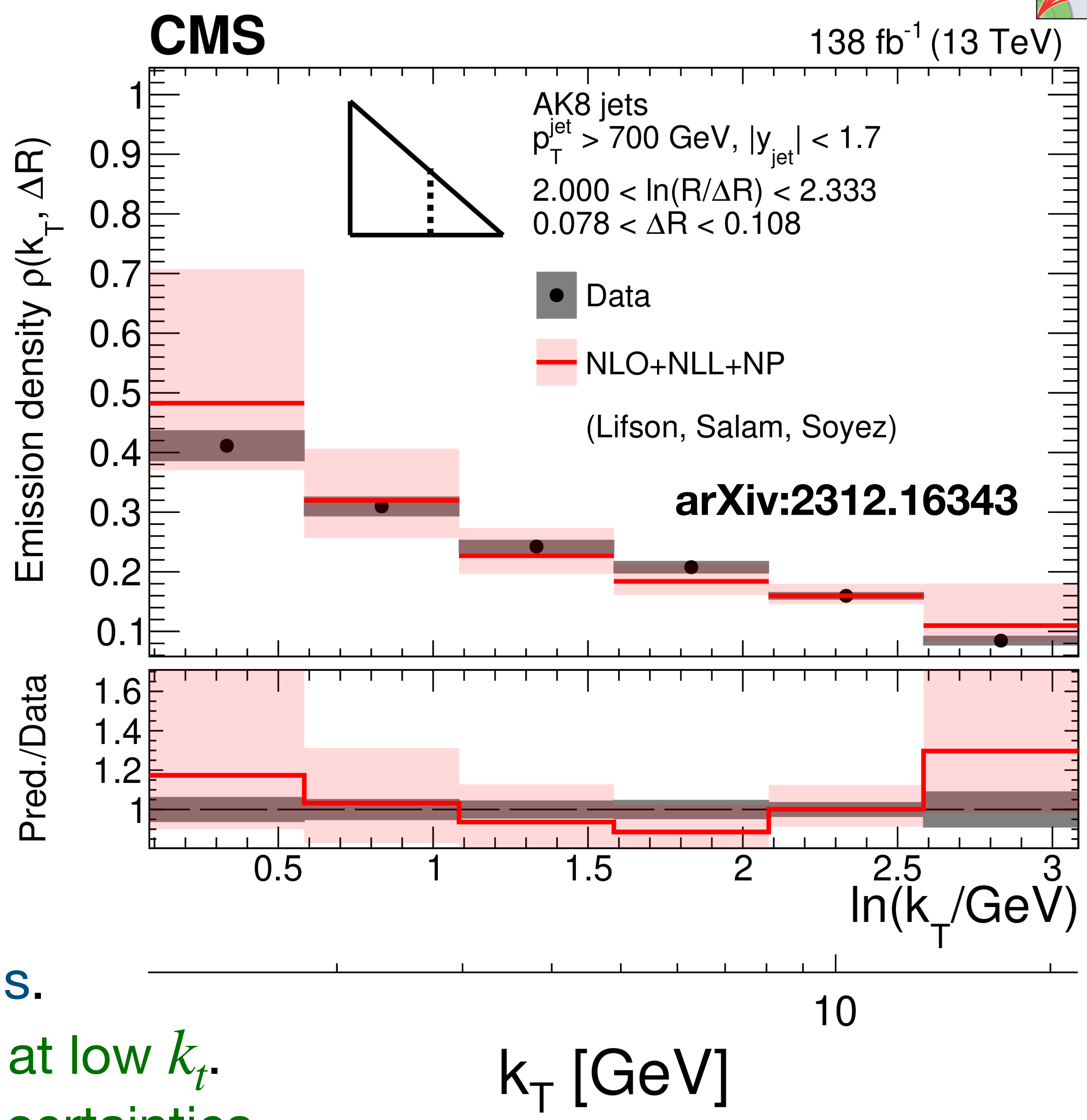




- The LJP contains a significant amount of information about the radiation pattern of the jet while allowing for a transparent physical interpretation.
  - Parton shower, hadronisation and UE activity approximately factoried in the LJP.
- Measurements of LJP by ALICE, ATLAS and CMS available:

ALICE: arXiv::2111.00020
CMS: arXiv:2312.16343
ATLAS: Phys. Rev. Lett 124 (2020) 02
ATLAS: arXiv:2407.10879 (W/top jets)



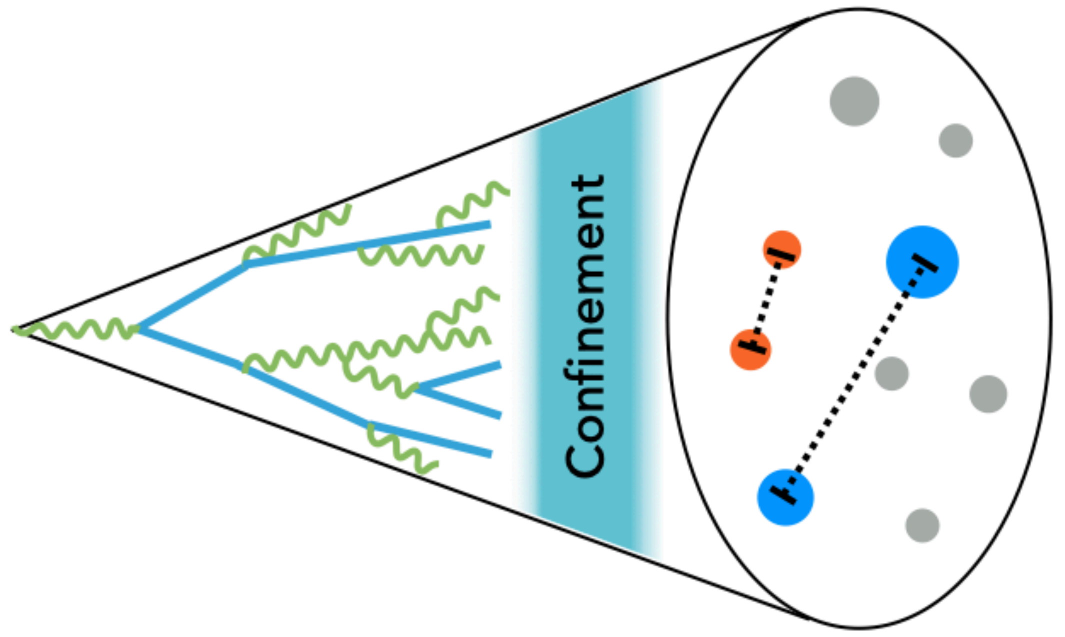


- Measurements compared to state-of-the-art calculations.
  - Non-perturbative corrections dominate uncertainties at low k_t.
  - Adequate description of the measurements within uncertainties.
- Increase of $\rho(k_T)$ towards low k_T due to α_S running.

Jet substructure: energy-energy correlations

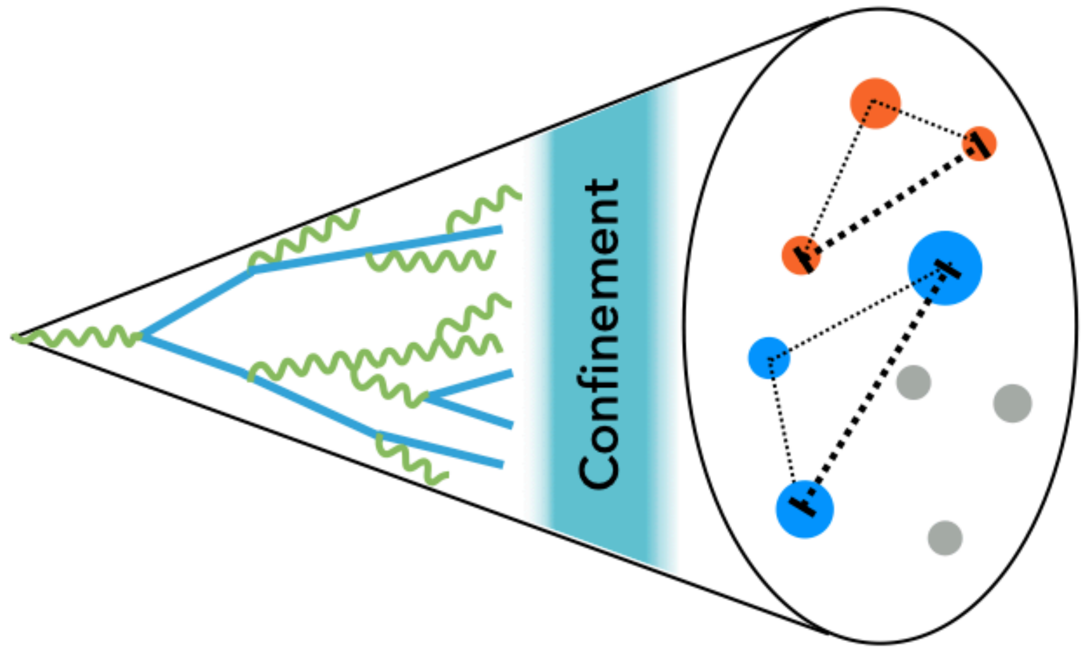
- Energy-energy correlators sensitive to energy flow within the jet.
  - Simple theoretical properties: symmetry and factorisation properties.
  - EEC ratios sensitive to α_S: $\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \mathcal{E}_3 \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[4]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta^{\gamma(4)-\gamma(3)}$

$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

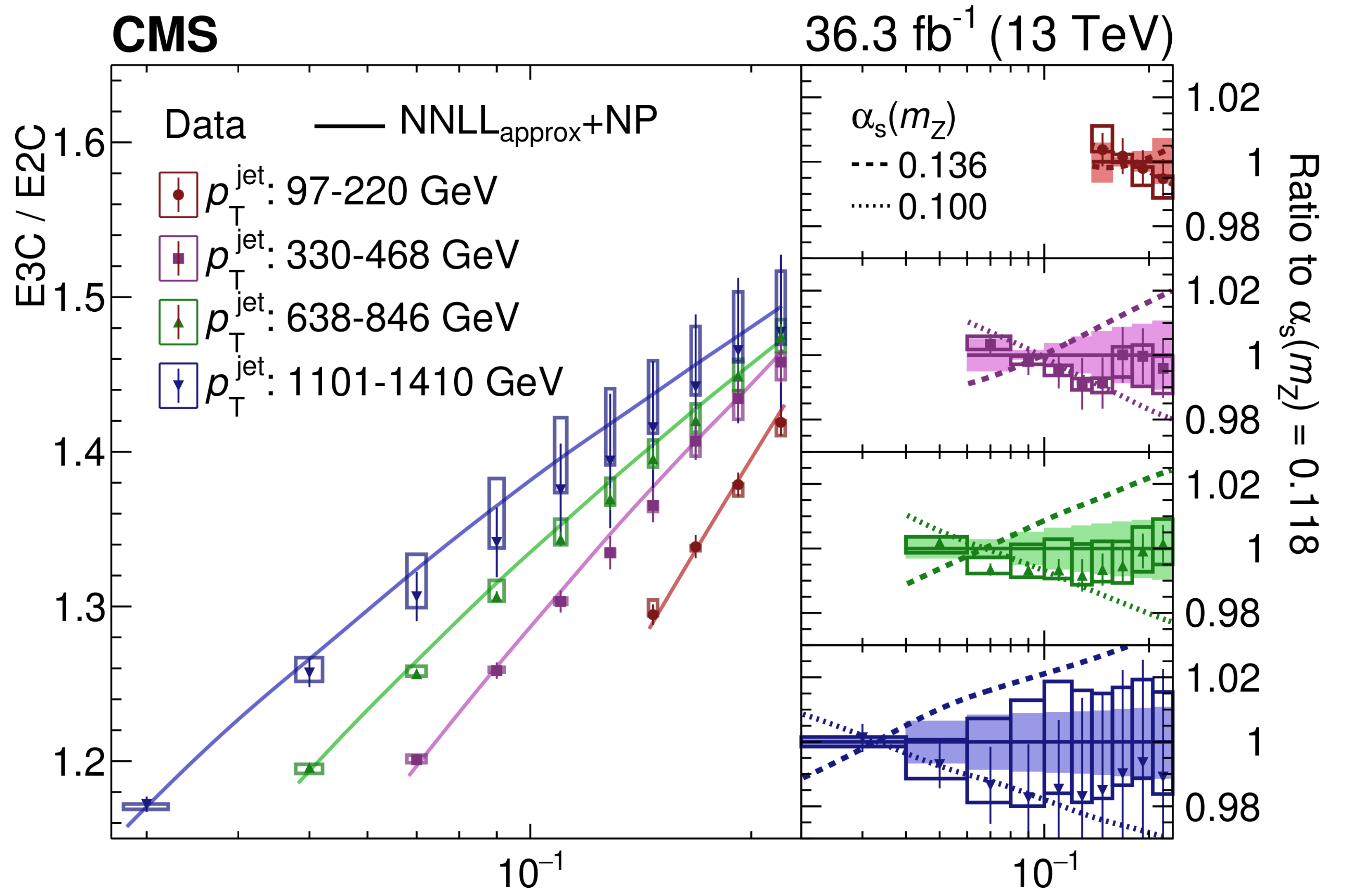


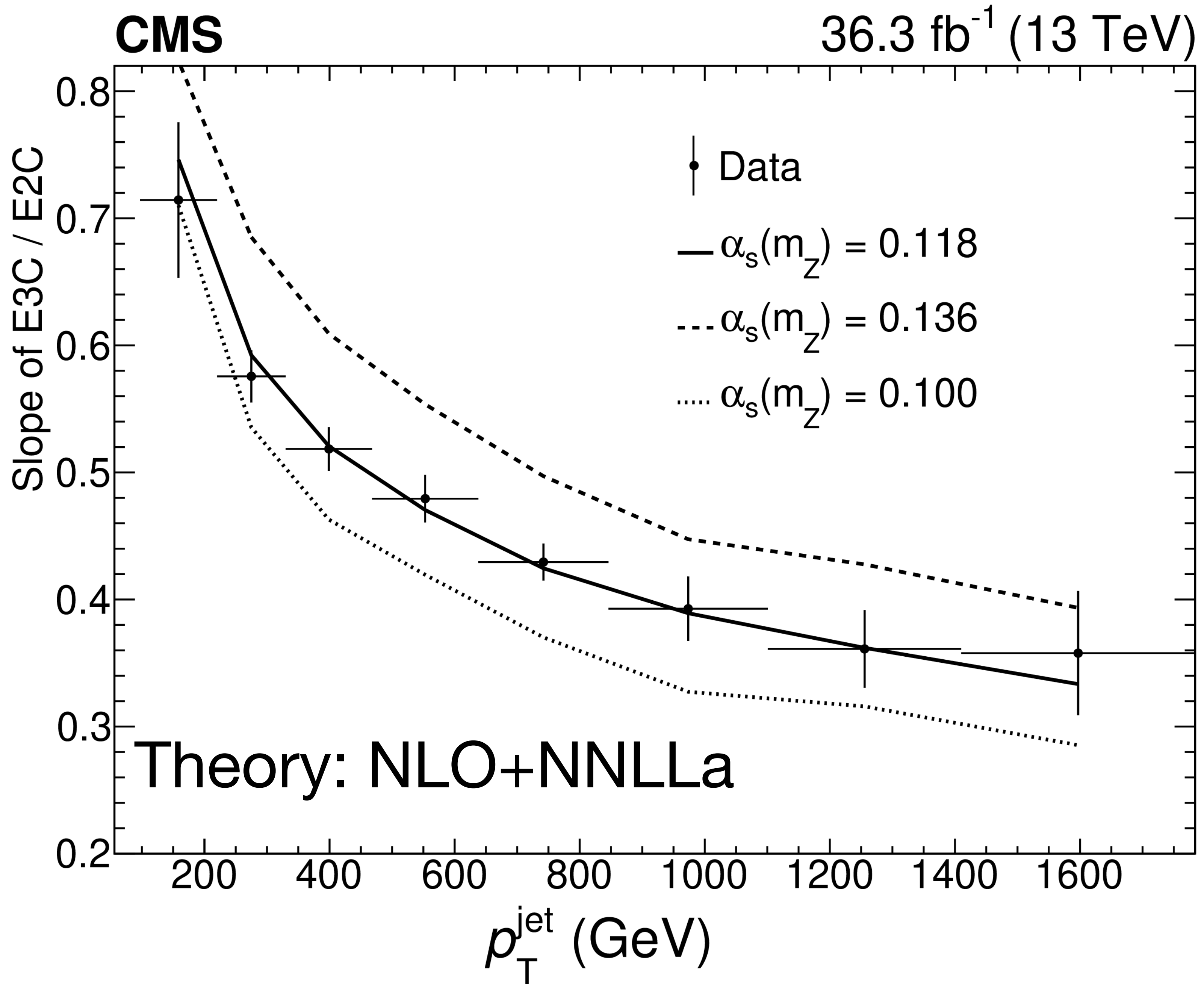
$$x_L = \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$$

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$



arXiv:2402.13864





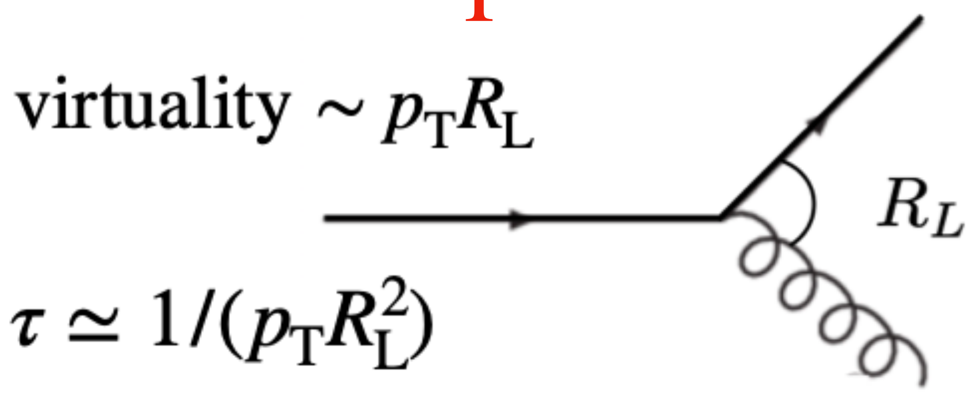
- Slope decreasing towards hight p_T consistent with α_S running.

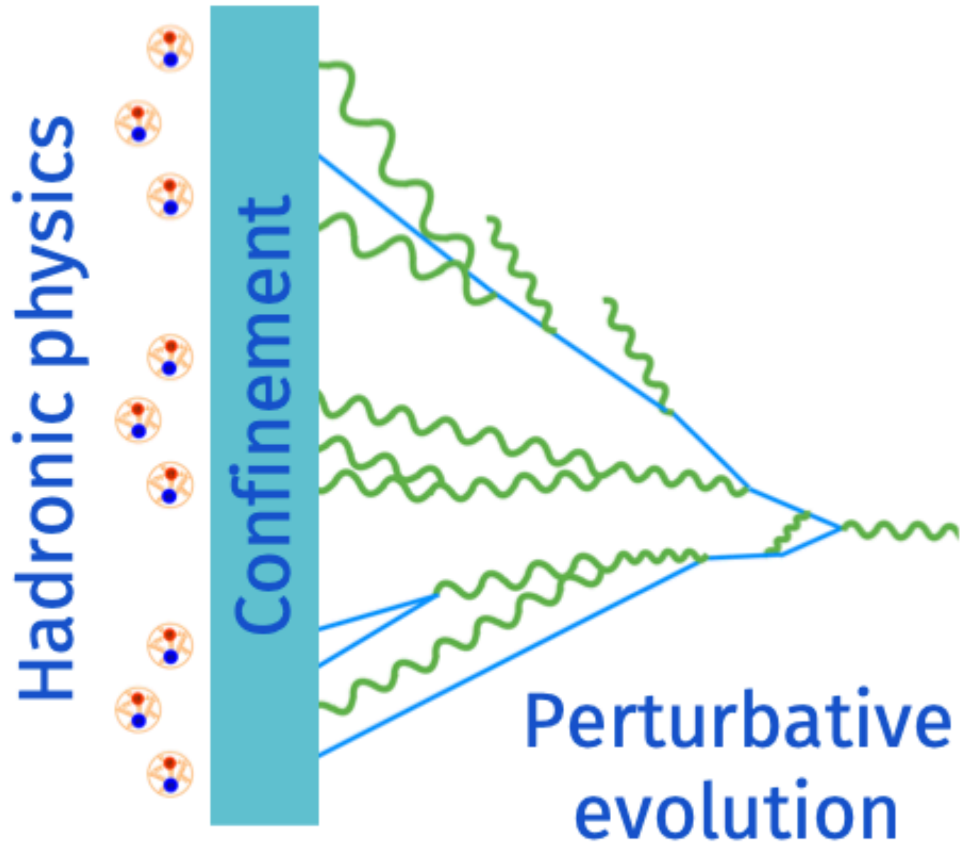
$$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\ (\text{stat})^{+0.0030}_{-0.0033}\ (\text{theo})^{+0.0023}_{-0.0036}\ (\text{exp})$$

- Uncertainty dominated by renormalisation scale (2.4%) and energy scale of jet constituents (2.3%).

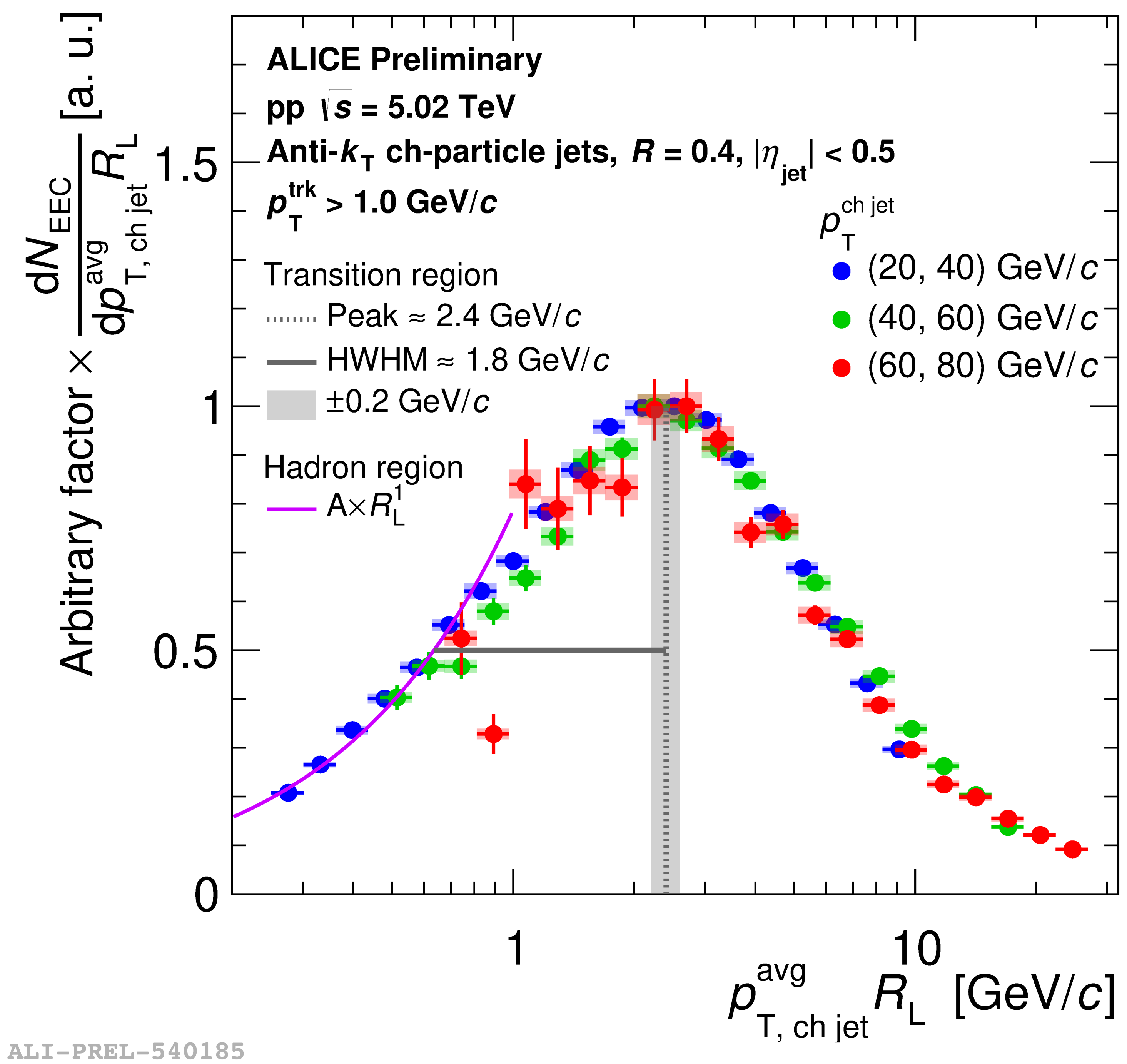
Jet substructure: energy-energy correlations

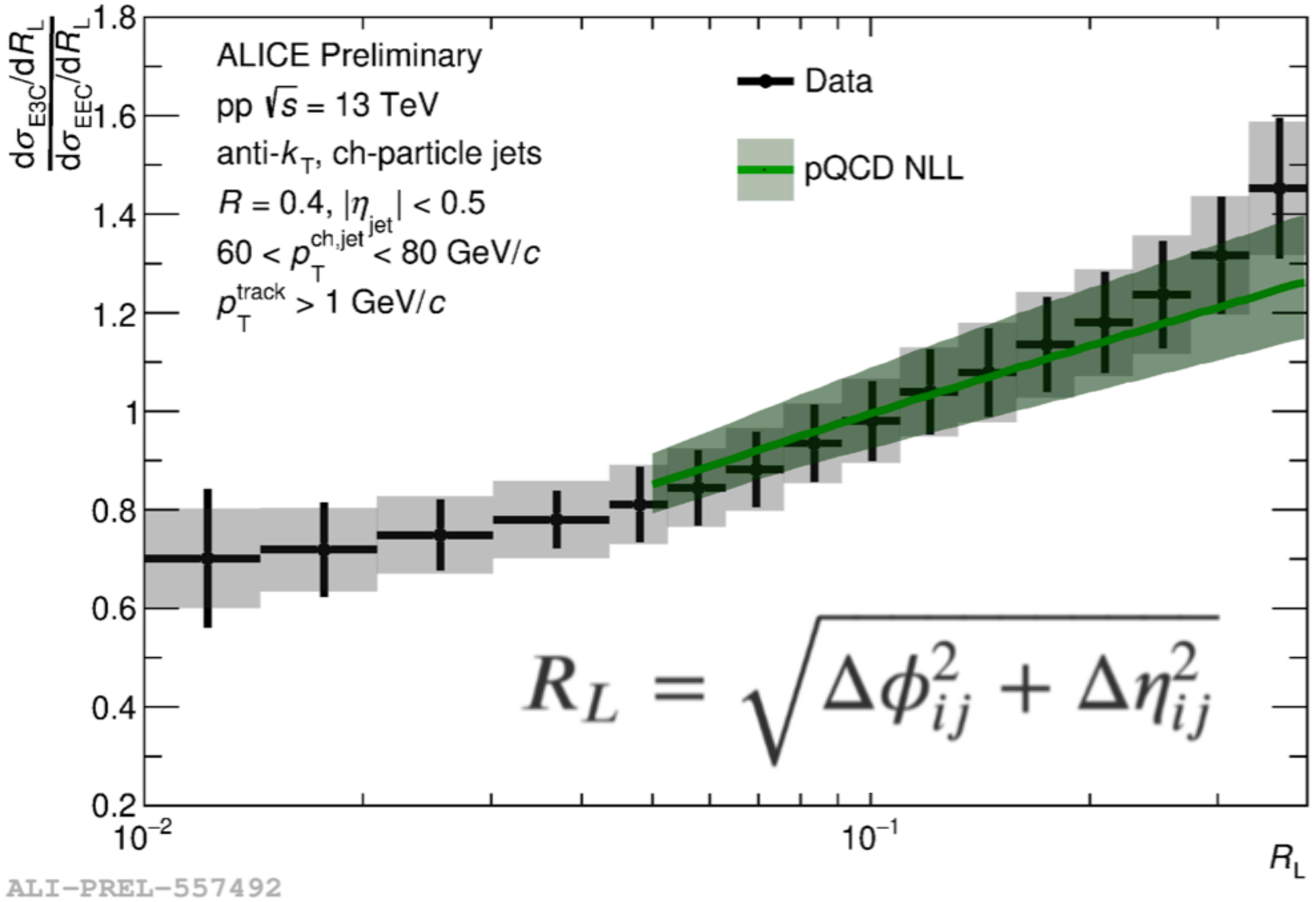
- EEC shows a clear distinction between pQCD and NP regions.
- Similar shape as a function of parton virtuality, for different $p_{\mathrm{T}}^{\mathrm{jet}}$ regions.

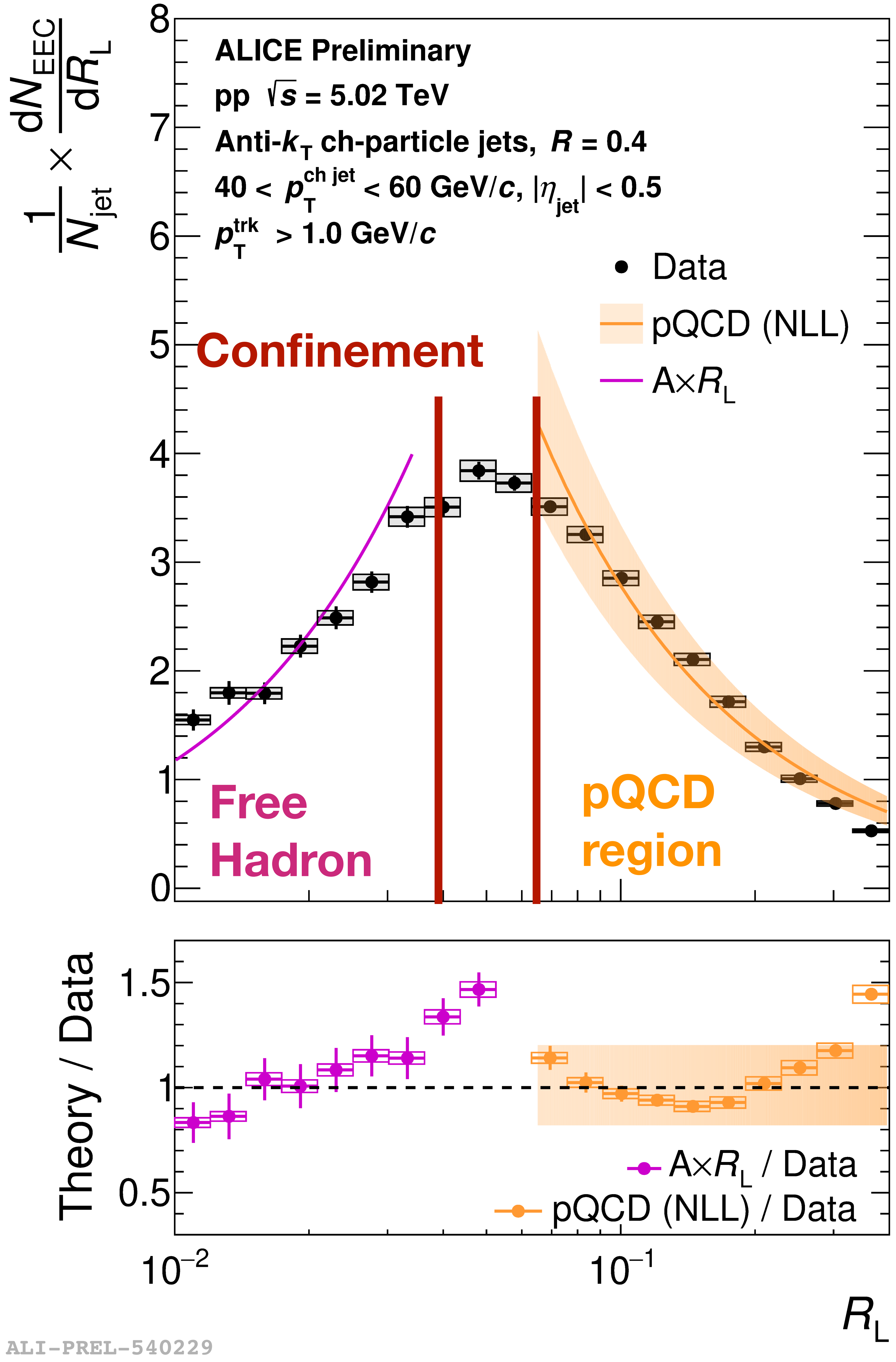


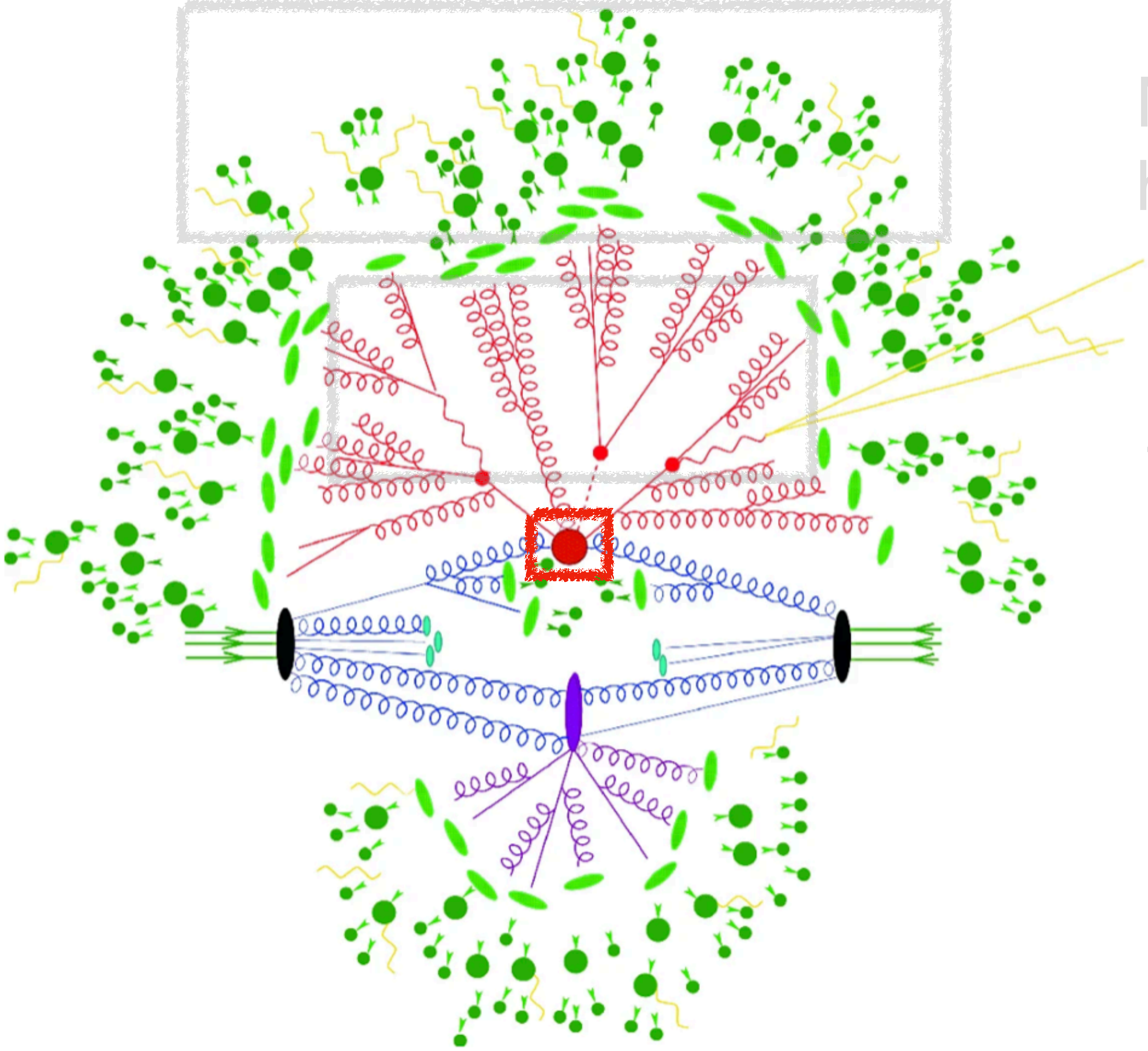


- Agreement with theoretical calculations.









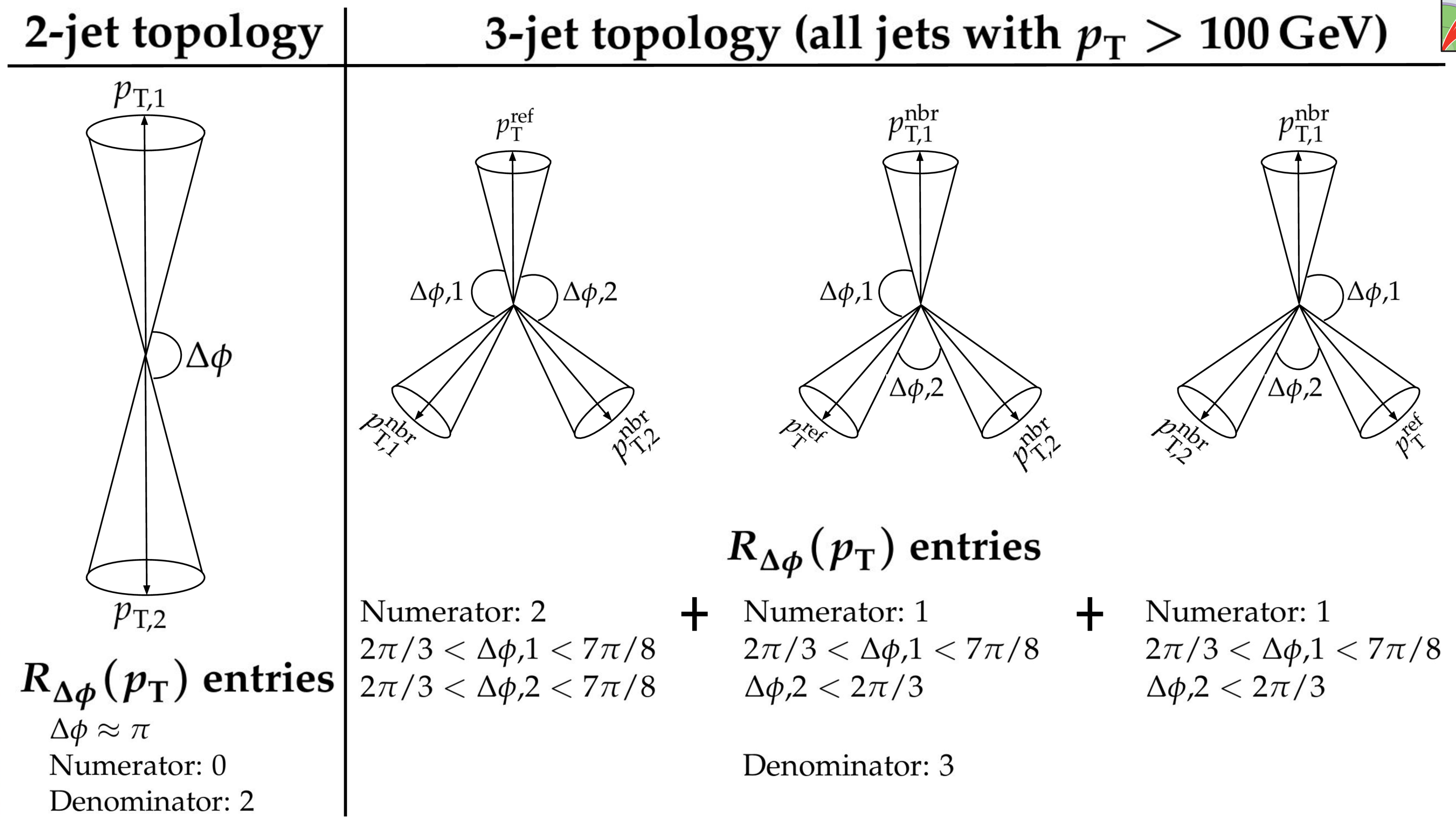
Non-perturbative QCD:
hadronisation

QCD resummation:
jet substructure

Hard QCD physics

Hard QCD physics: 3-jet/2-jet ratios

- Measurements with hight-p_T jets allow to test pQCD and extract α_S and its running.
  - Typically lower uncertainties compared to low-p_T jets.
  - Useful for PDF(Q, x) fits; specially for high-x region.



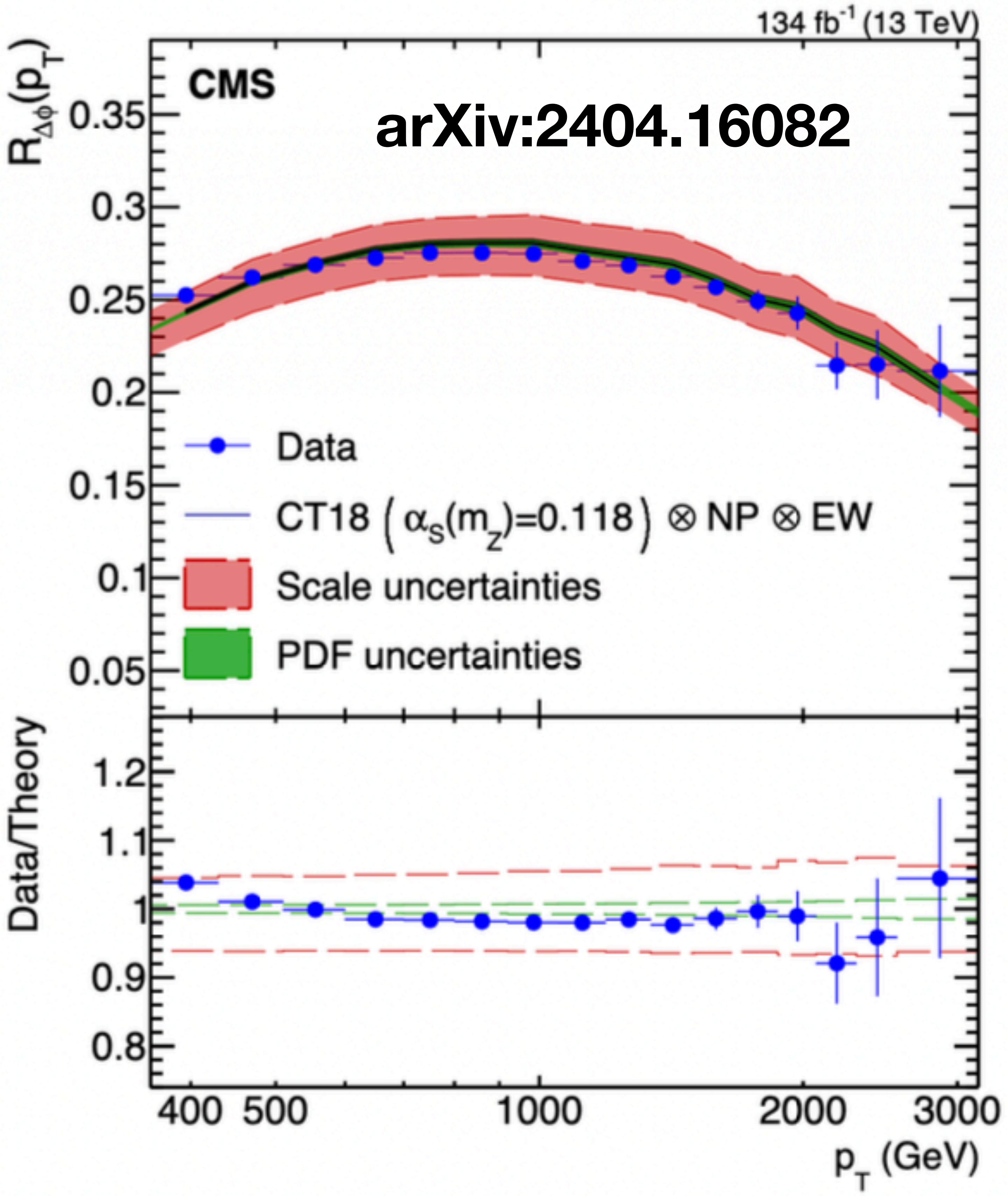
3-jet/2-jet ratios: $R_{\Delta\phi}$

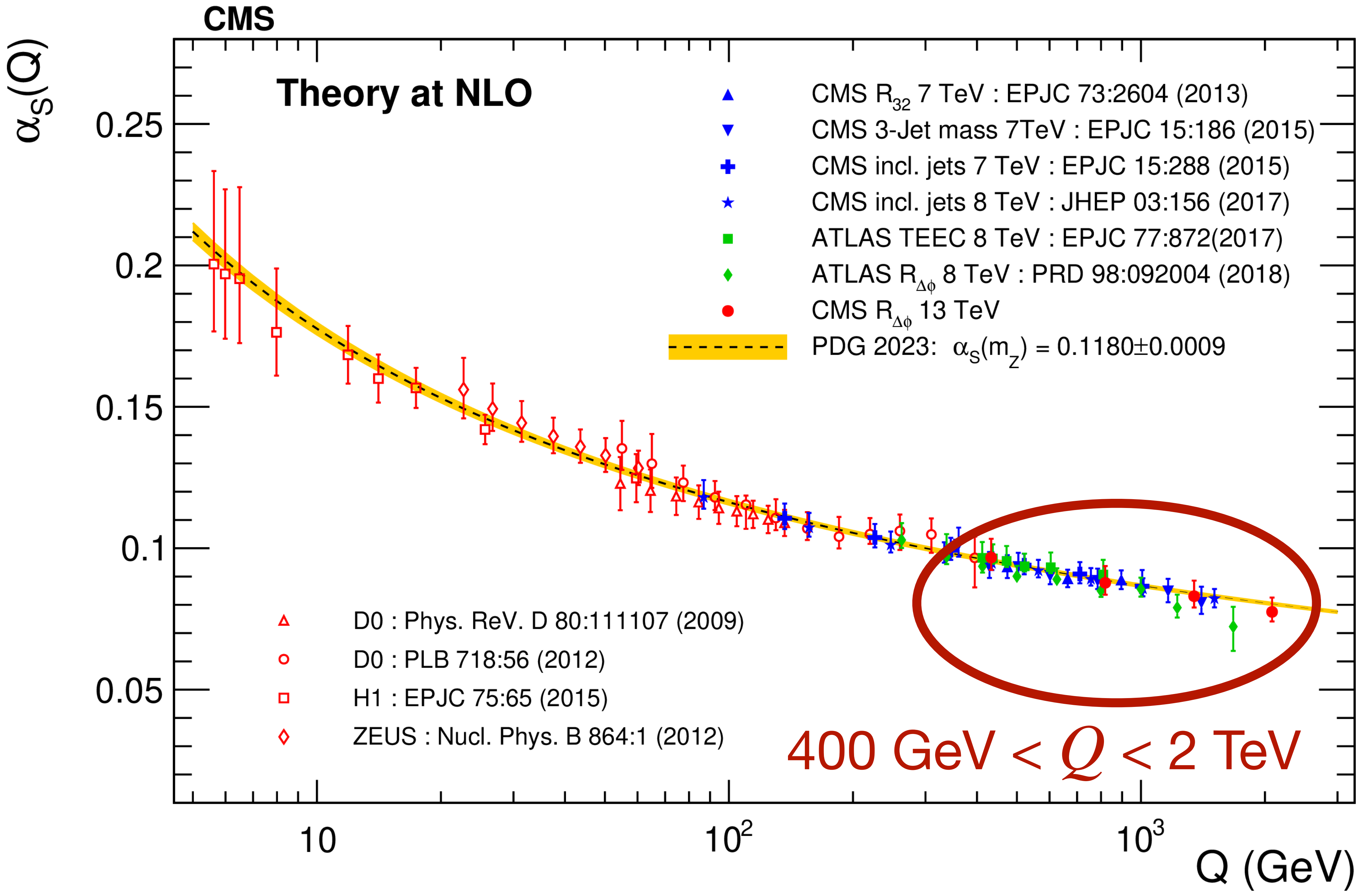
$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{\text{Tmin}}^{\text{nbr}})}{N_{\text{jet}}(p_T)}$$

$p_T^{\text{jet}} > 100$ GeV, $|y^{\text{jet}}| < 2.5$

- $\alpha_S(m_Z)$ extraction at NLO:

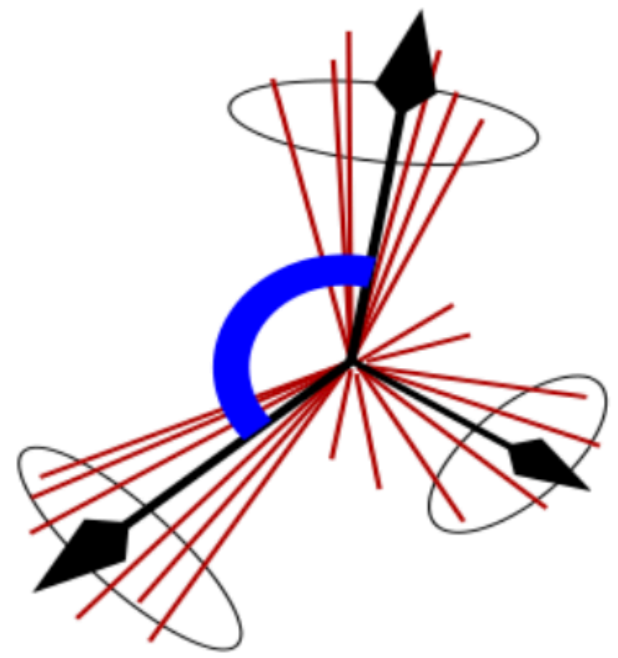
$$\alpha_S(m_Z) = 0.1177^{+0.0117}_{-0.0074}$$

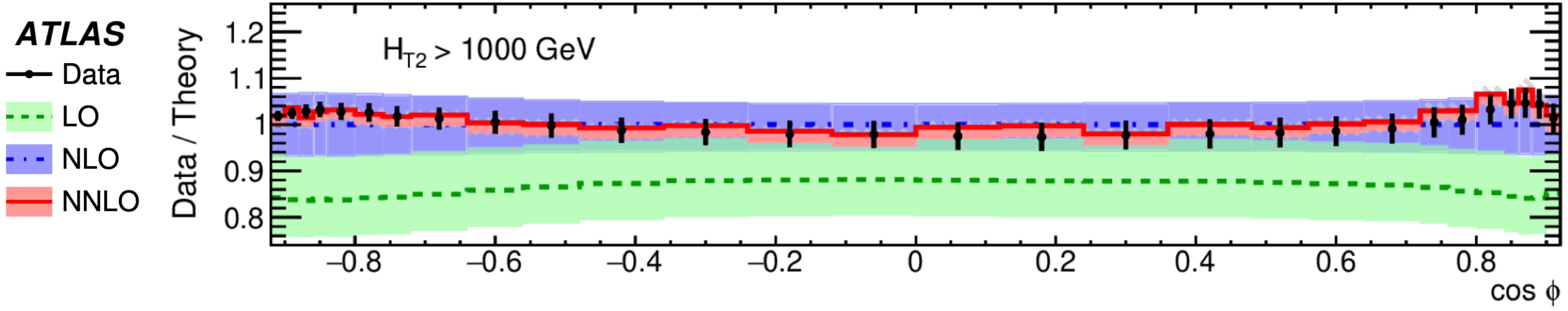




- Total uncertainty dominated by uncertainty on NLO calculations ≈ 10%.

3-jet/2-jet ratios (TEEC):





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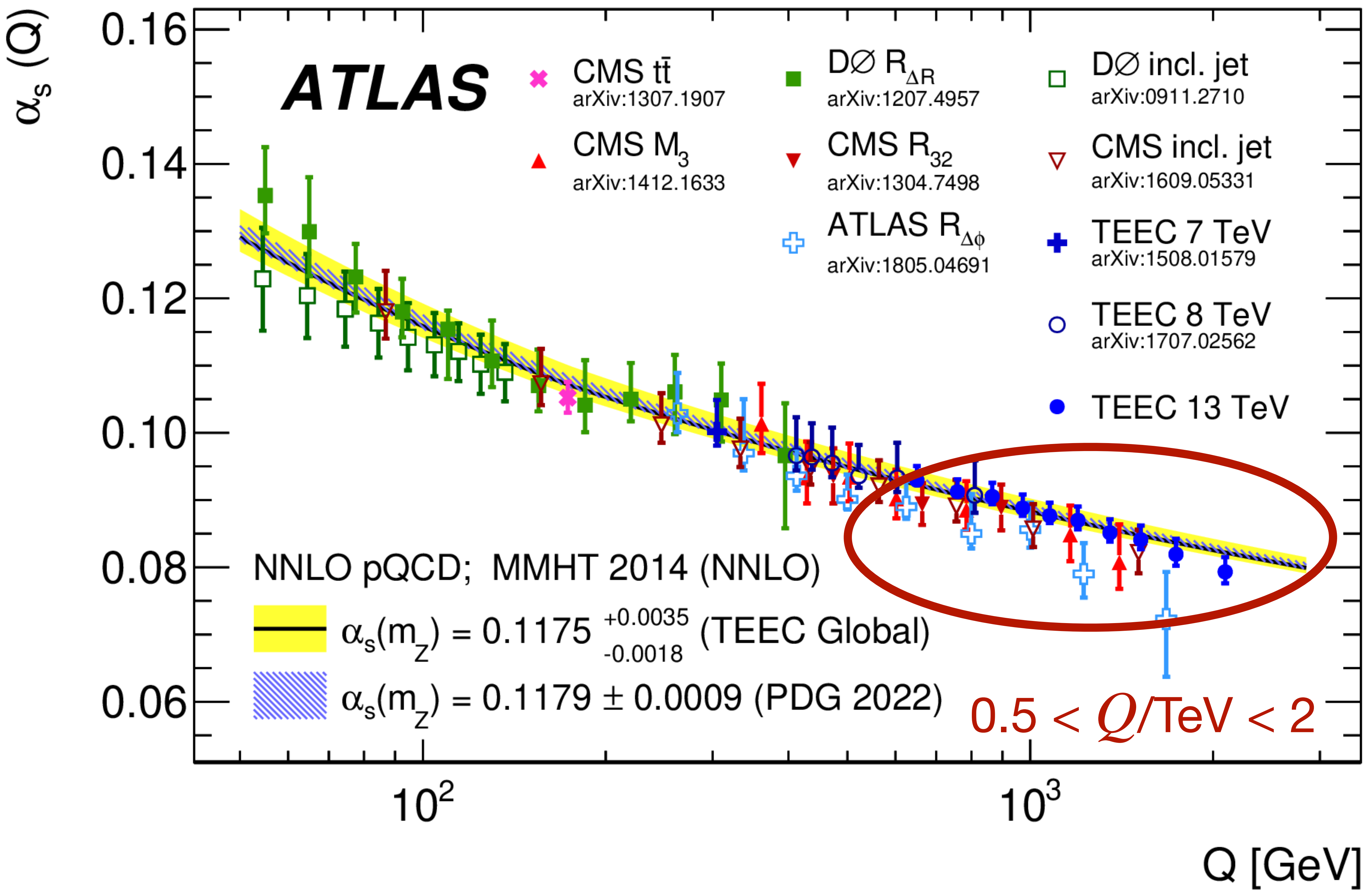


- Transverse energy-energy correlations ($E2C$) based on jets: $p_T^{\text{jet}} > 60$ GeV, $|y^{\text{jet}}| < 2.5$.
- Excellent agreement by NNLO: large reduction of theory uncertainty from NLO to NNLO on TEEC distribution.
- $\alpha_S(m_Z)$ extraction at NNLO:

$$\alpha_S(m_Z) = 0.1175^{+0.0035}_{-0.0018}$$

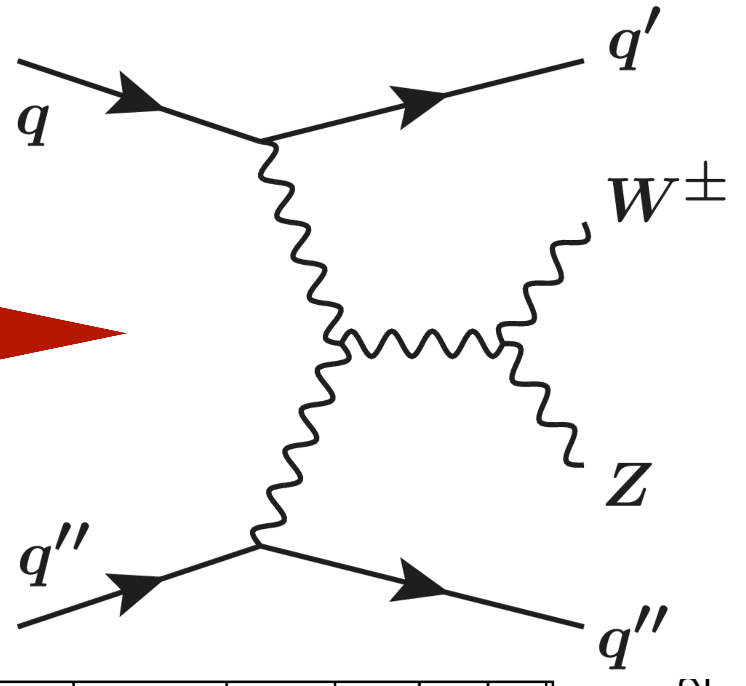
- At NNLO theory uncertainty on $\alpha_S(m_Z)$ amounts 2%!!!.

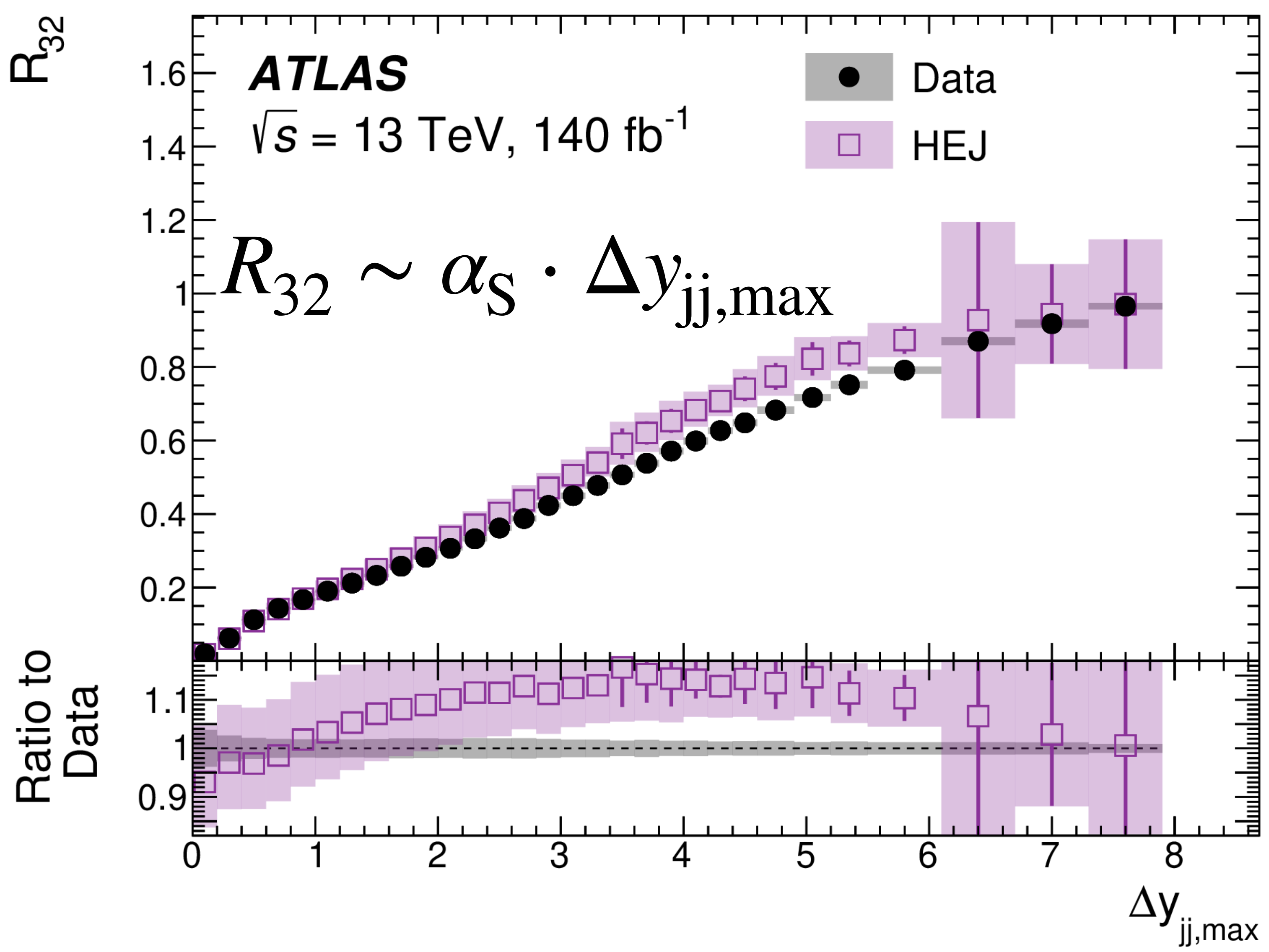
Hard QCD physics: 3-jet/2-jet ratios

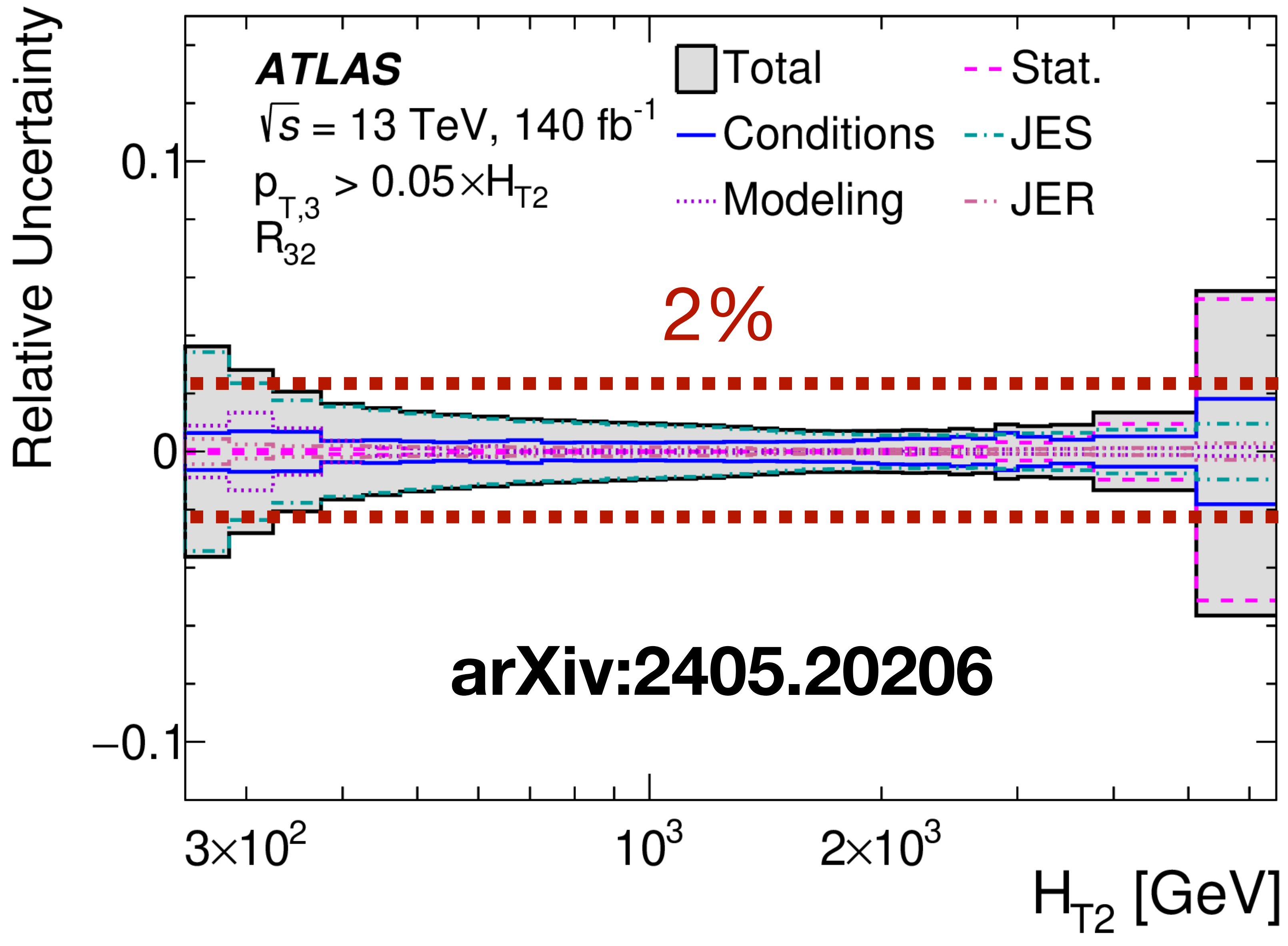
3-jet/2-jet ratios ($R_{3/2}$): $\frac{d\sigma_{3j}/dx}{d\sigma_{2j}/dx}$, where $x = H_{T2},\ m_{jj,max},\ |\Delta y_{jj,max}|,\ m_{jj},\ |\Delta y_{jj}|$

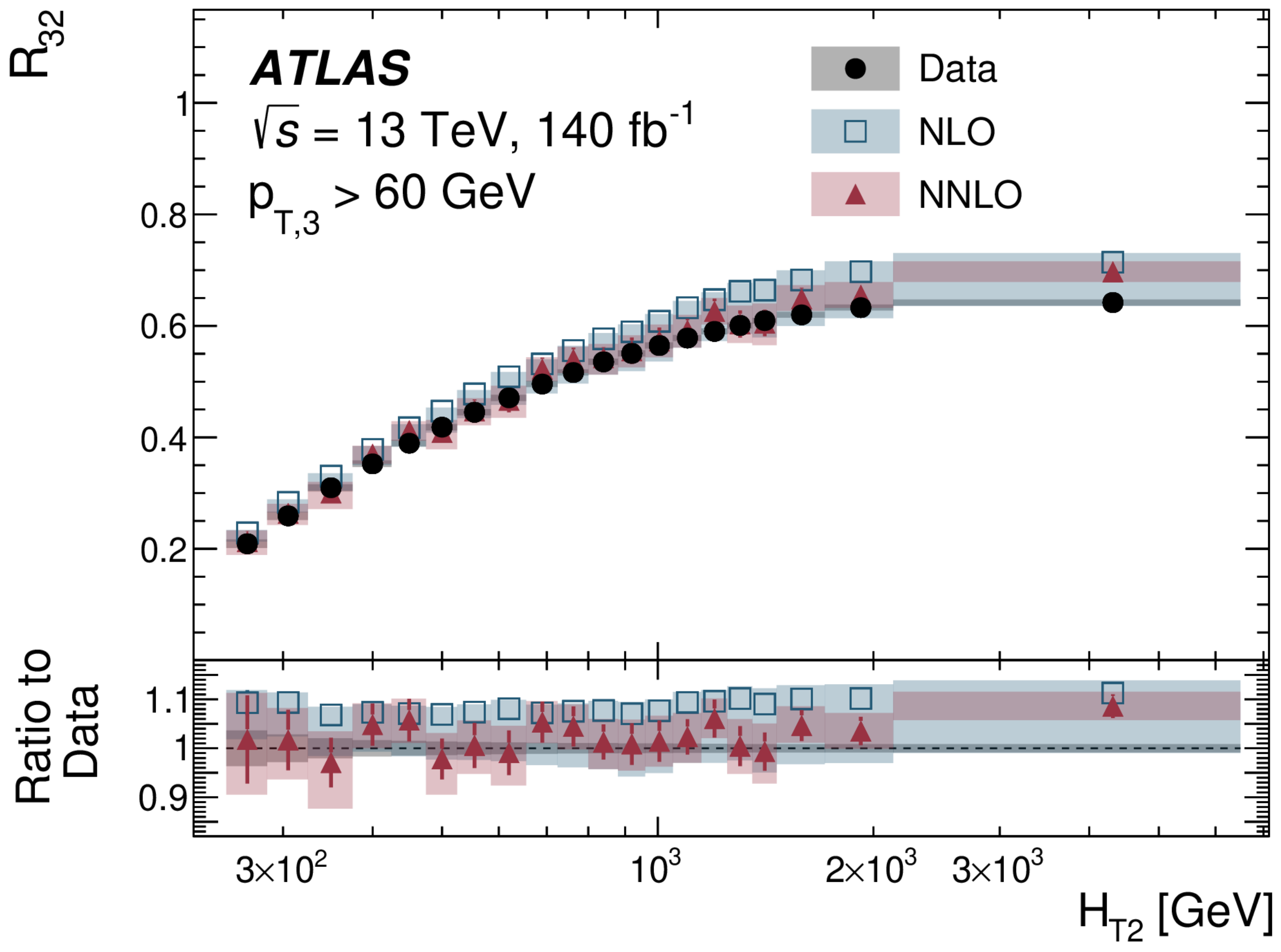
$p_T^{jet} > 60$ GeV, $|y^{jet}| < 4.5$

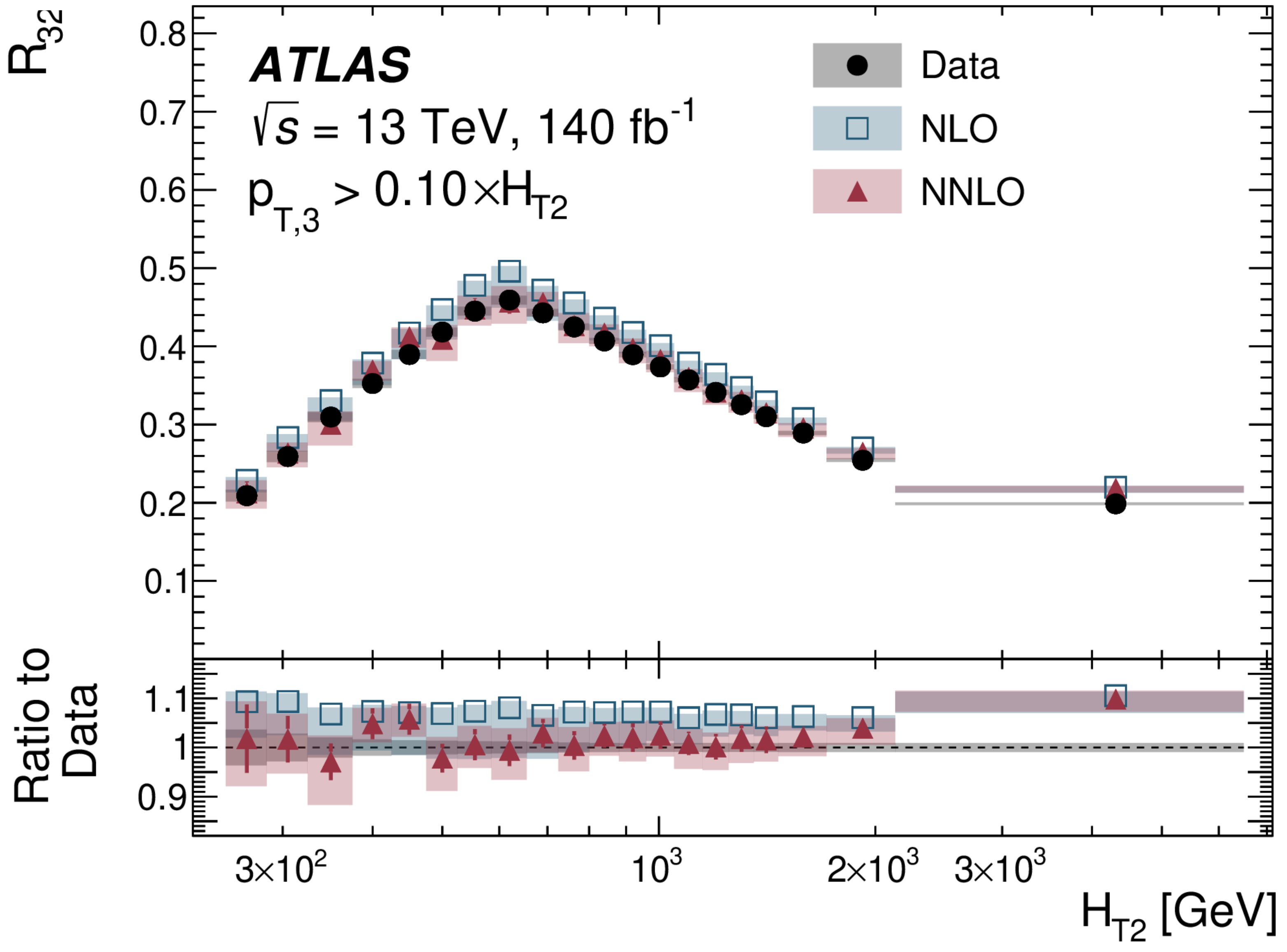
- Measurements performed for different p_{T3} regions.
  - Identify regions with $p_{T3}/H_{T2} << 1$ and test NNLO behaviour.
  - Comparisons with HEJ (including resummation of $\log(p_T^{jet}/E_{CM})$).
    - Important for VBF/VBS topologies.
- Good description by NNLO.
  - Beyond NLO terms reduce $R_{3/2}$ prediction by 5-10%.



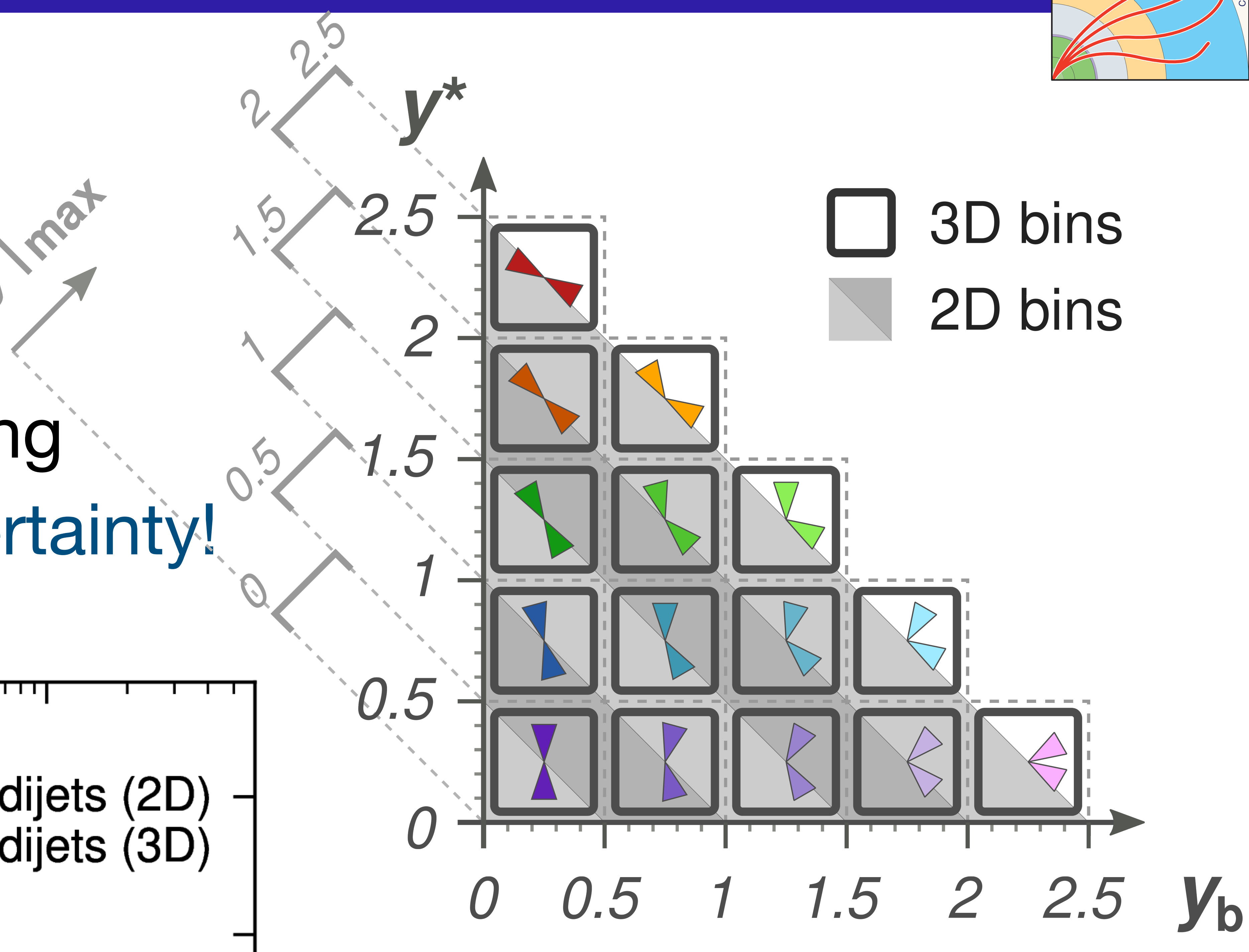






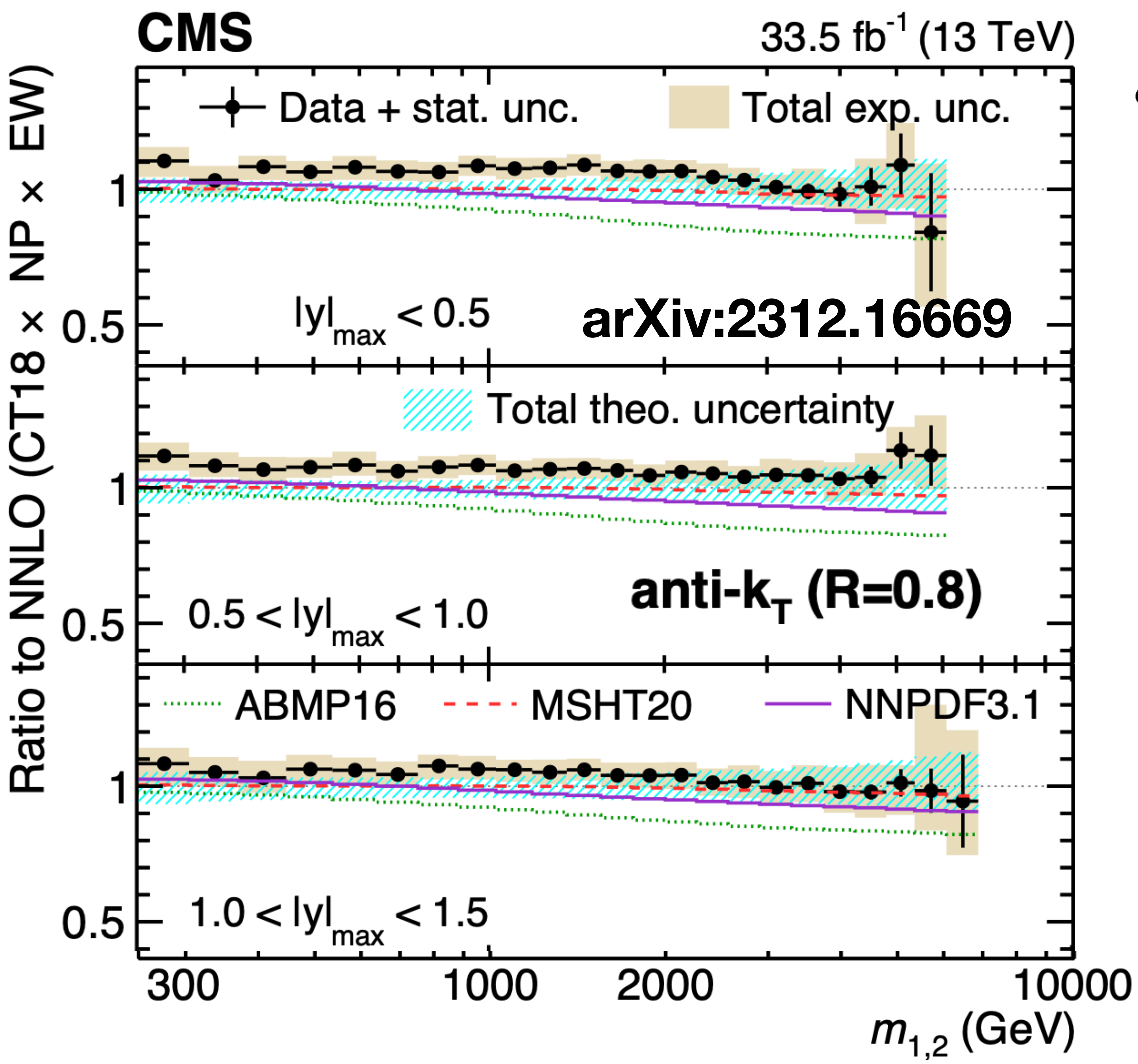


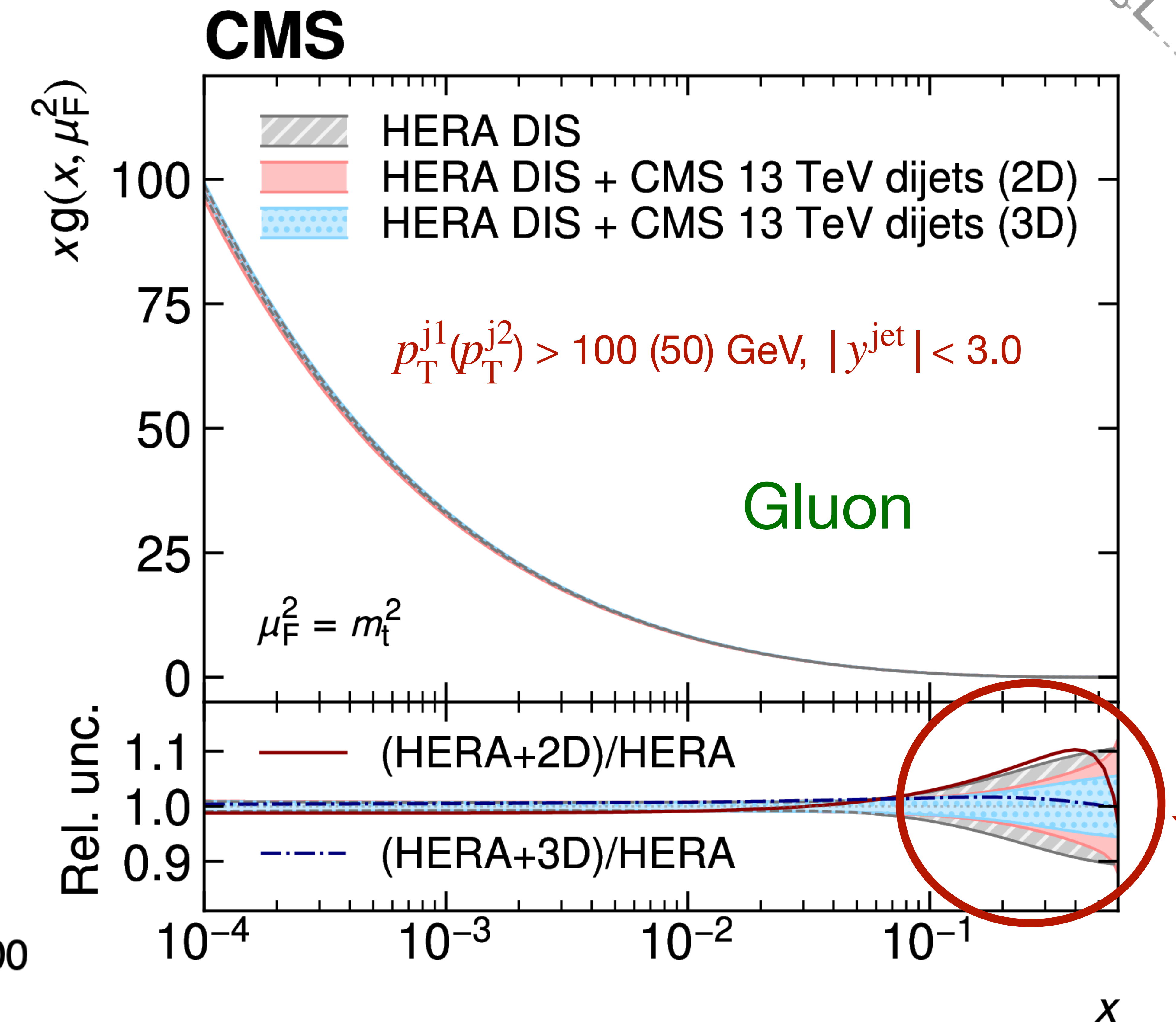
- Dijet cross-section measurements:
  - Test QCD dynamics: double or triple differential cross-section measurement
    - NNLO underestimating the measurements.
  - Sensitive to gluon PDF and α_S: combine PDF + α_S fits including HERA DIS data. $\alpha_S(m_Z) = 0.1179 \pm 0.0019$ 1% NNLO uncertainty!



3D 2D

3D	2D
$y^* = \frac{1}{2}\lvert y_1 - y_2\rvert$	y_{max}
$y_b = \frac{1}{2}\lvert y_1 + y_2\rvert$	$m_{1,2}$
$\langle p_T\rangle_{1,2} = \frac{1}{2}(p_{T,1} + p_{T,2})$	



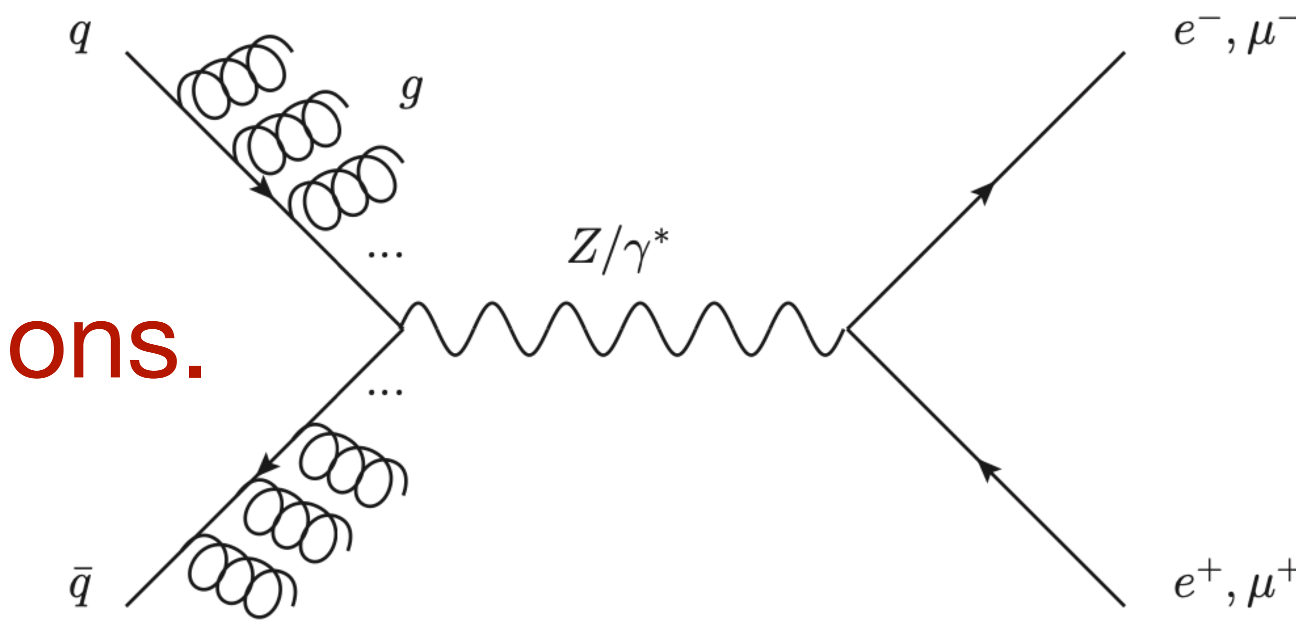


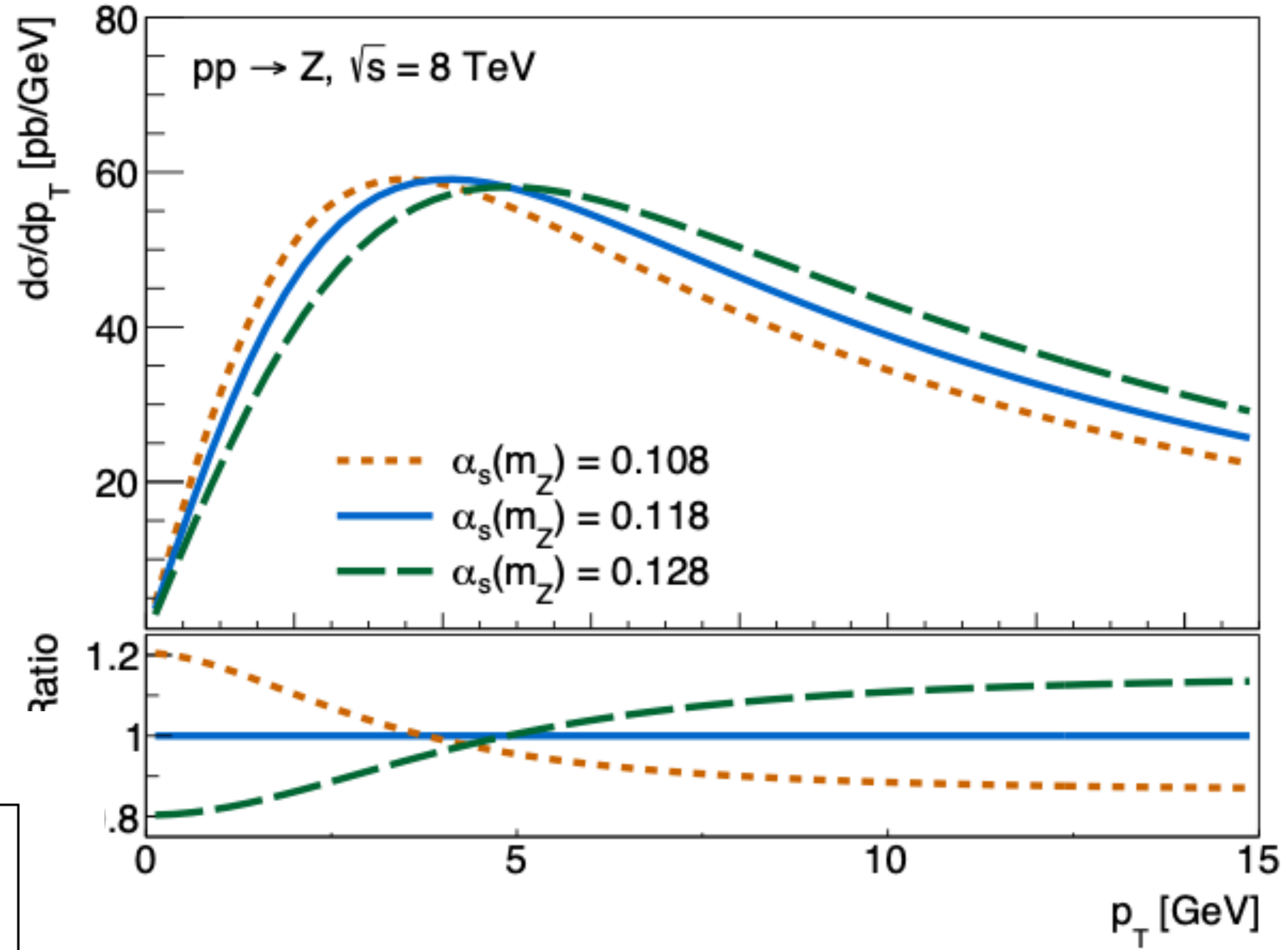
Improving high-x gluon PDF uncertainty!

Hard QCD physics: Z production

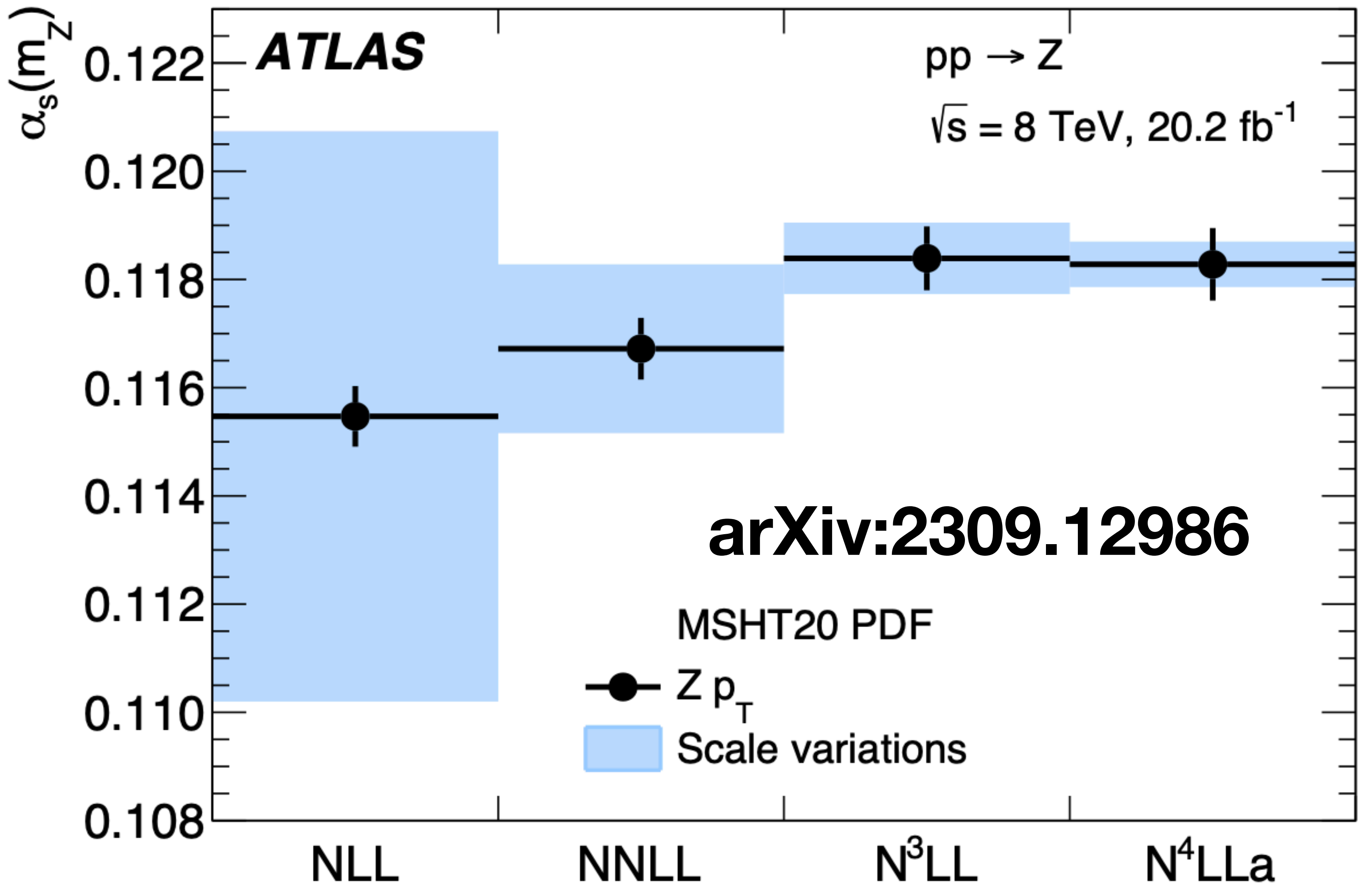
- p_T^Z in inclusive Z production events sensitive to α_S.
  - Strong forces responsible for the ISR radiation and the subsequent recoil of the Z boson.
  - Low-momentum Sudakov region.
  - $N^3LO + N^4LLa$ accuracy for predictions.

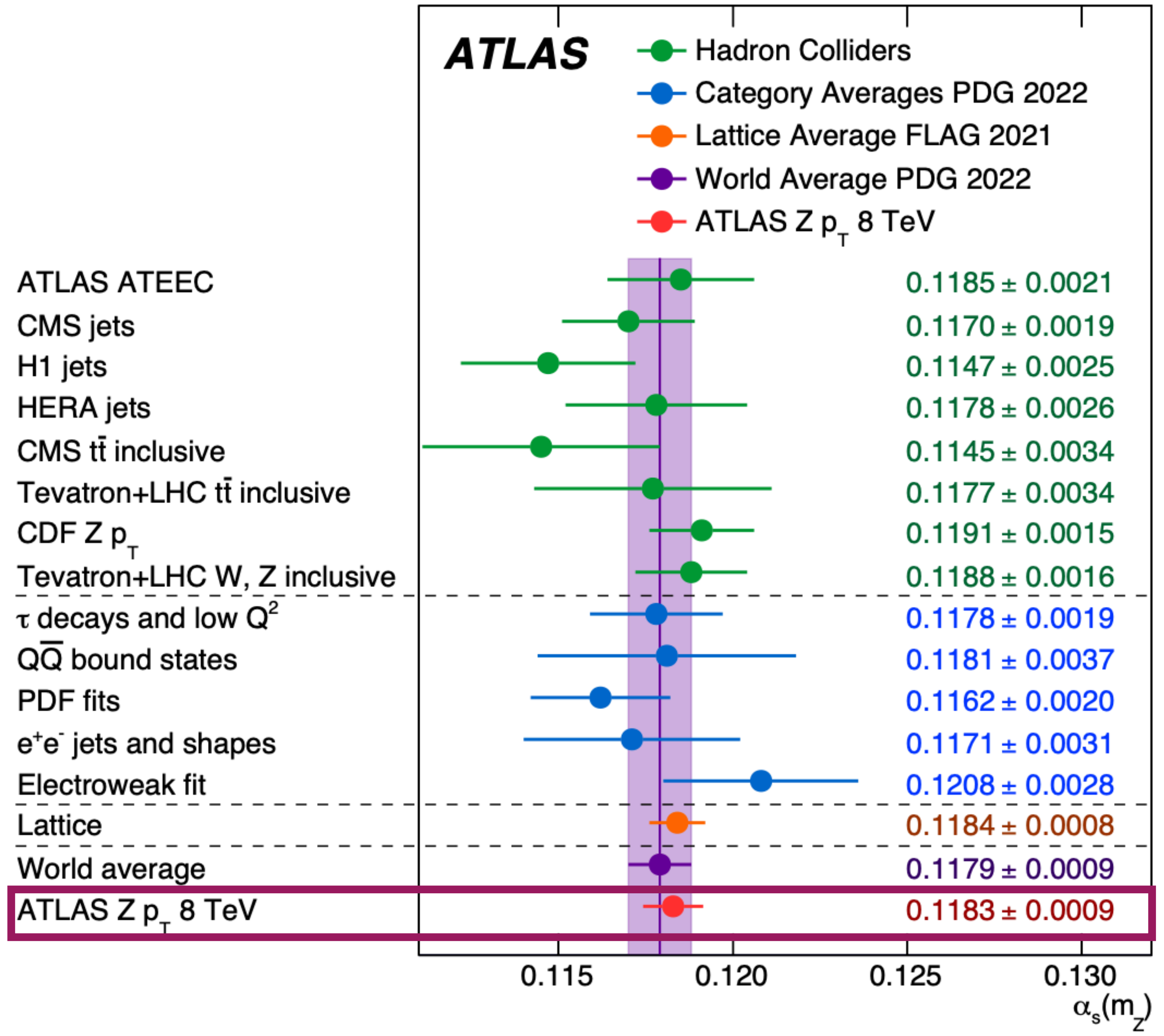
$$\chi^2(\beta_{\rm exp}, \beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 .$$





$\alpha_S(m_Z) = 0.1183 \pm 0.0009$





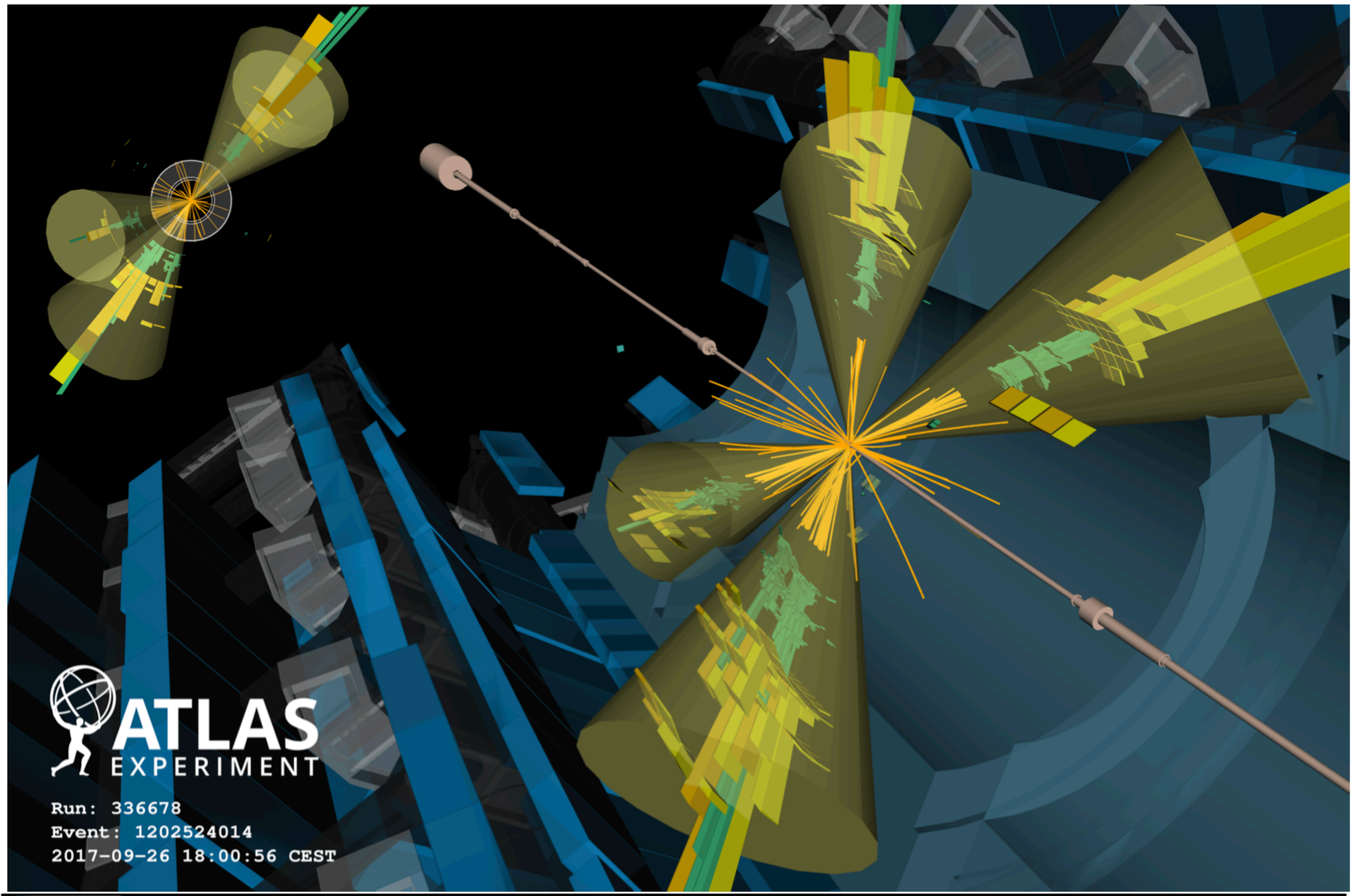
in units of 10^{-3}

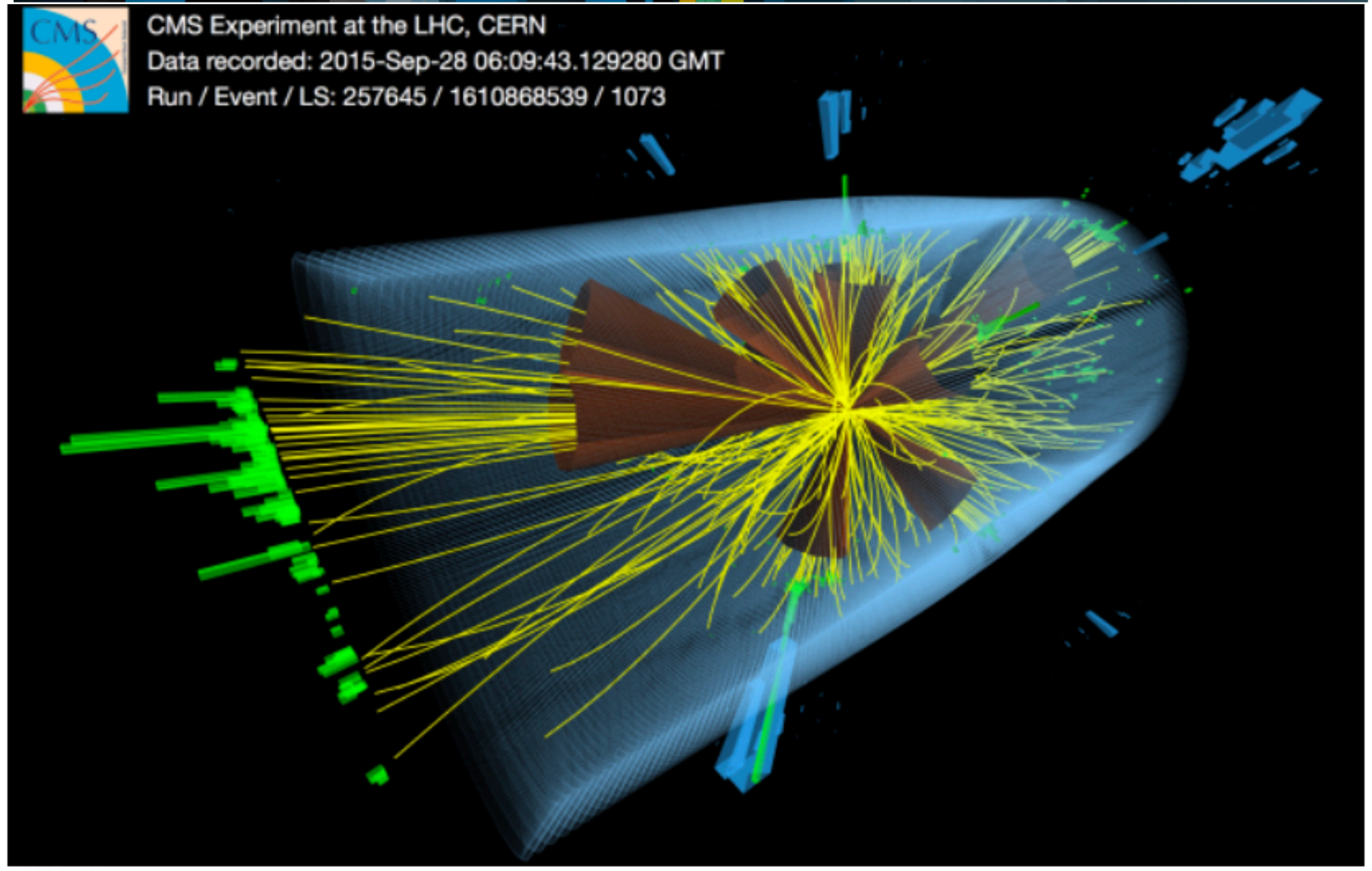
Experimental uncertainty	±0.44	
PDF uncertainty	±0.51	
Scale variation uncertainties	±0.42	
Matching to fixed order	0	−0.08
Non-perturbative model	+0.12	−0.20
Flavour model	+0.40	−0.29
QED ISR	±0.14	
N^4LL approximation	±0.04	
Total	+0.91	−0.88

Conclusions

- QCD has a quite rich phenomenology.
- Huge work on reducing systematics uncertainties and improving theory calculations.
  - They allow to perform thorough tests of QCD in a wide range of energy scales.
- Other interesting results not covered in this talk:
  - Z + HF jets (ATLAS): arXiv:2403.15093
  - Lund multiplicites (ATLAS): arXiv:2402.13052
  - Inclusive jets at (CMS): arXiv:2401.11355
  - Jet fragmentation functions (ALICE): arXiv:2311.13322
  - W + c (CMS): arXiv:2308.02285
  - Z + jets (CMS): arXiv:2205.02872
  - Dead-cone effect (ALICE): Nature 605 (2022) 440
  - Inclusive jets and NNLO α_S (ZEUS): arXiv:2309.02889
  - Groomed event-shapes (H1): arXiv:2403.10134

ATLAS and CMS multijet production event displays!



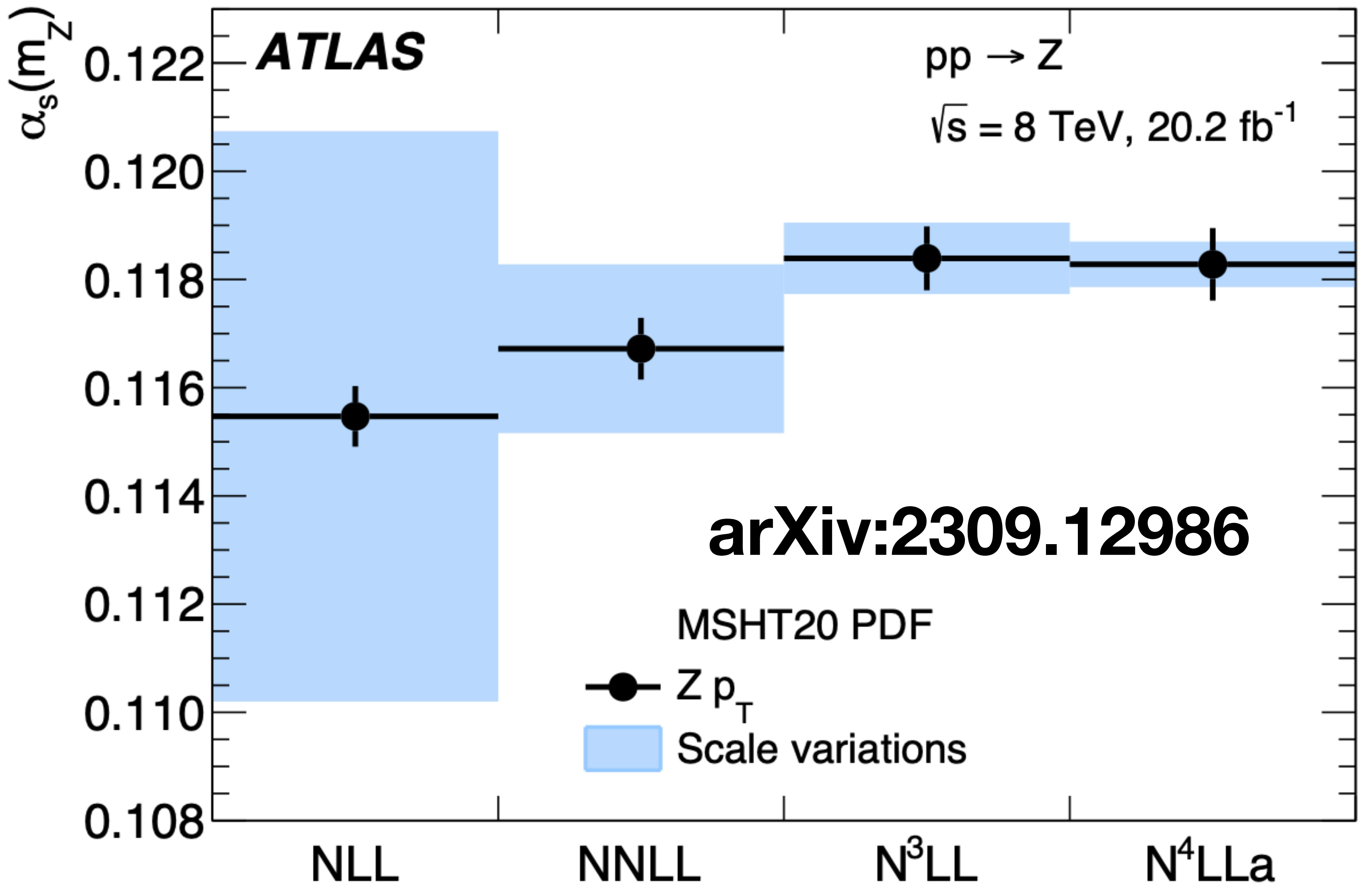


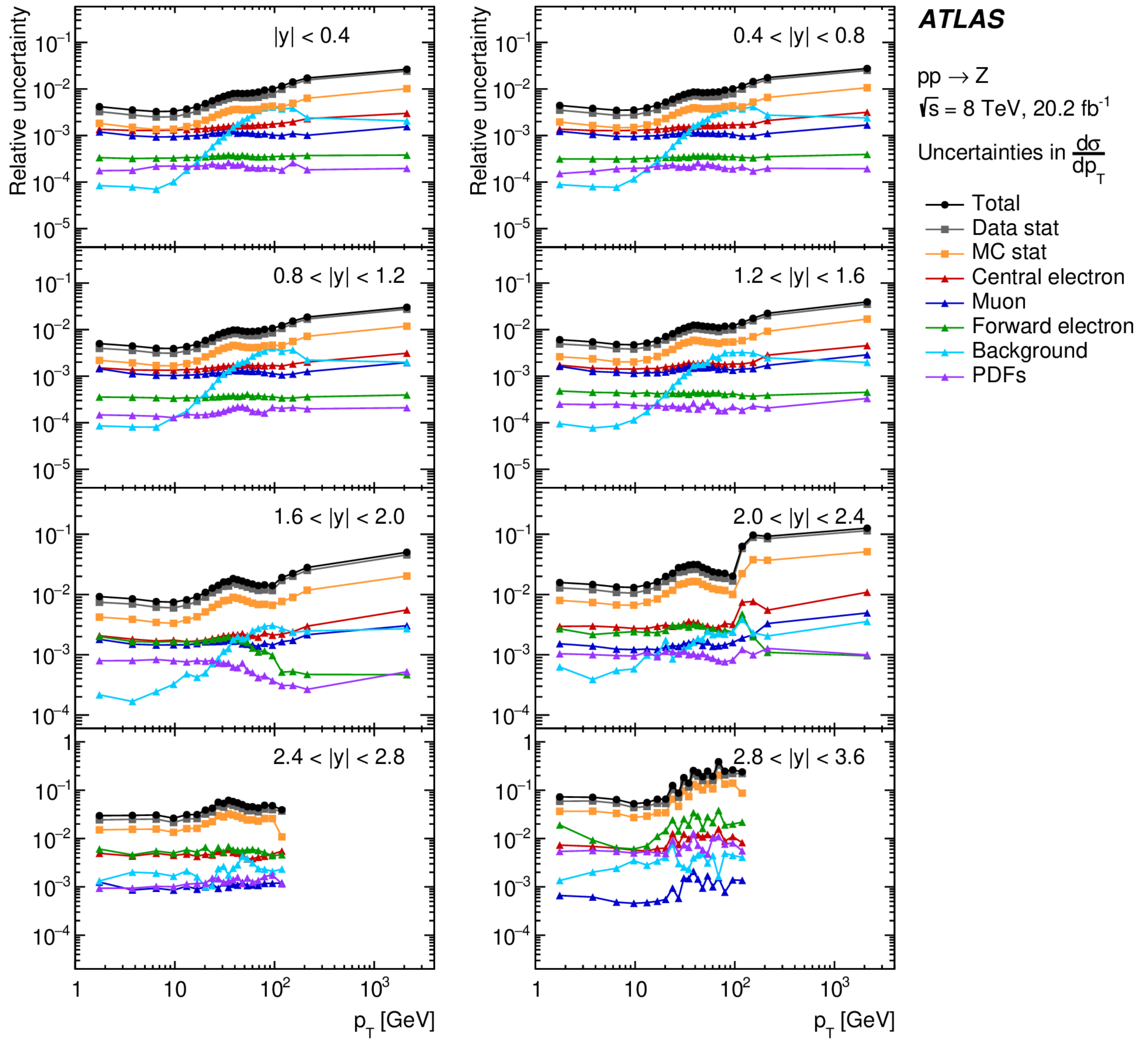
Backup

Hard QCD physics: Z production

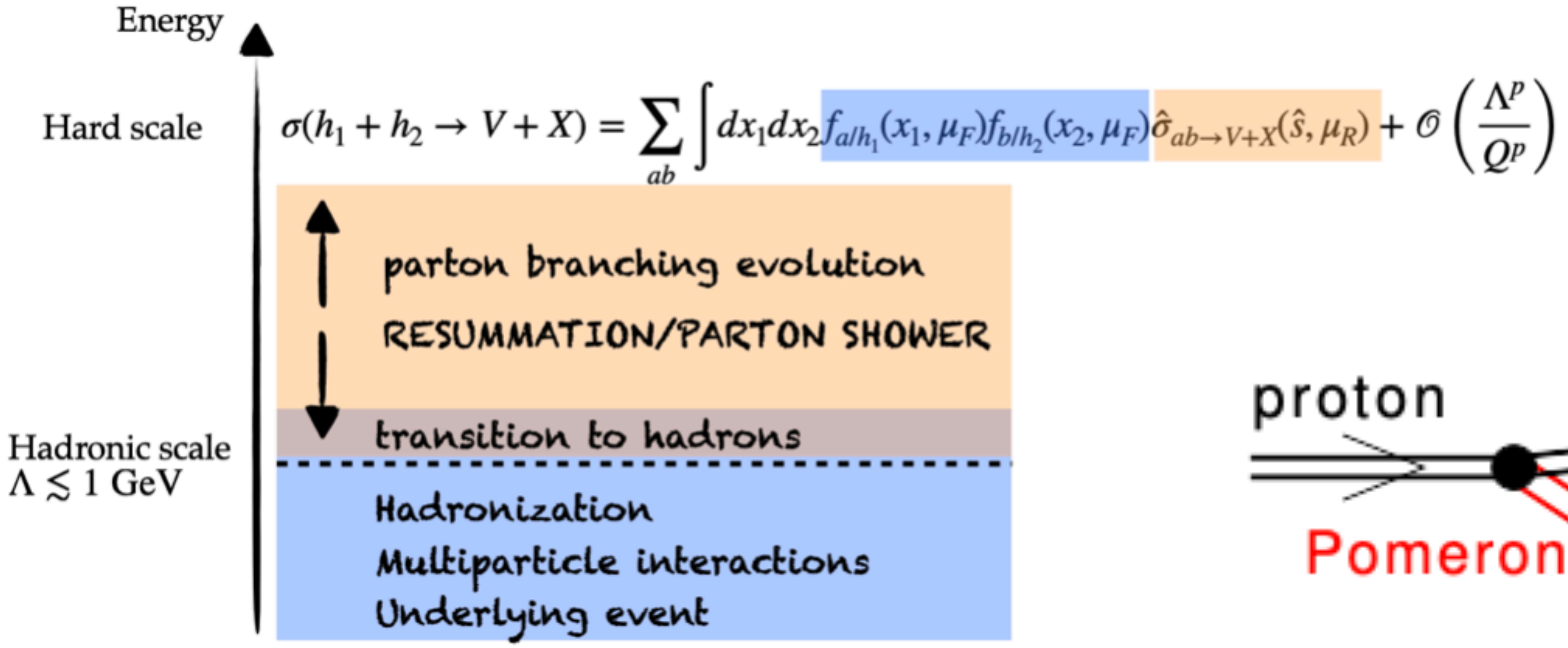
- p_T^Z in inclusive Z production events sensitive to α_S.
  - Strong forces responsible for the ISR radiation and the subsequent recoil of the Z boson.
  - Low-momentum Sudakov region.
  - $N^3LO + N^4LLa$ accuracy for predictions.

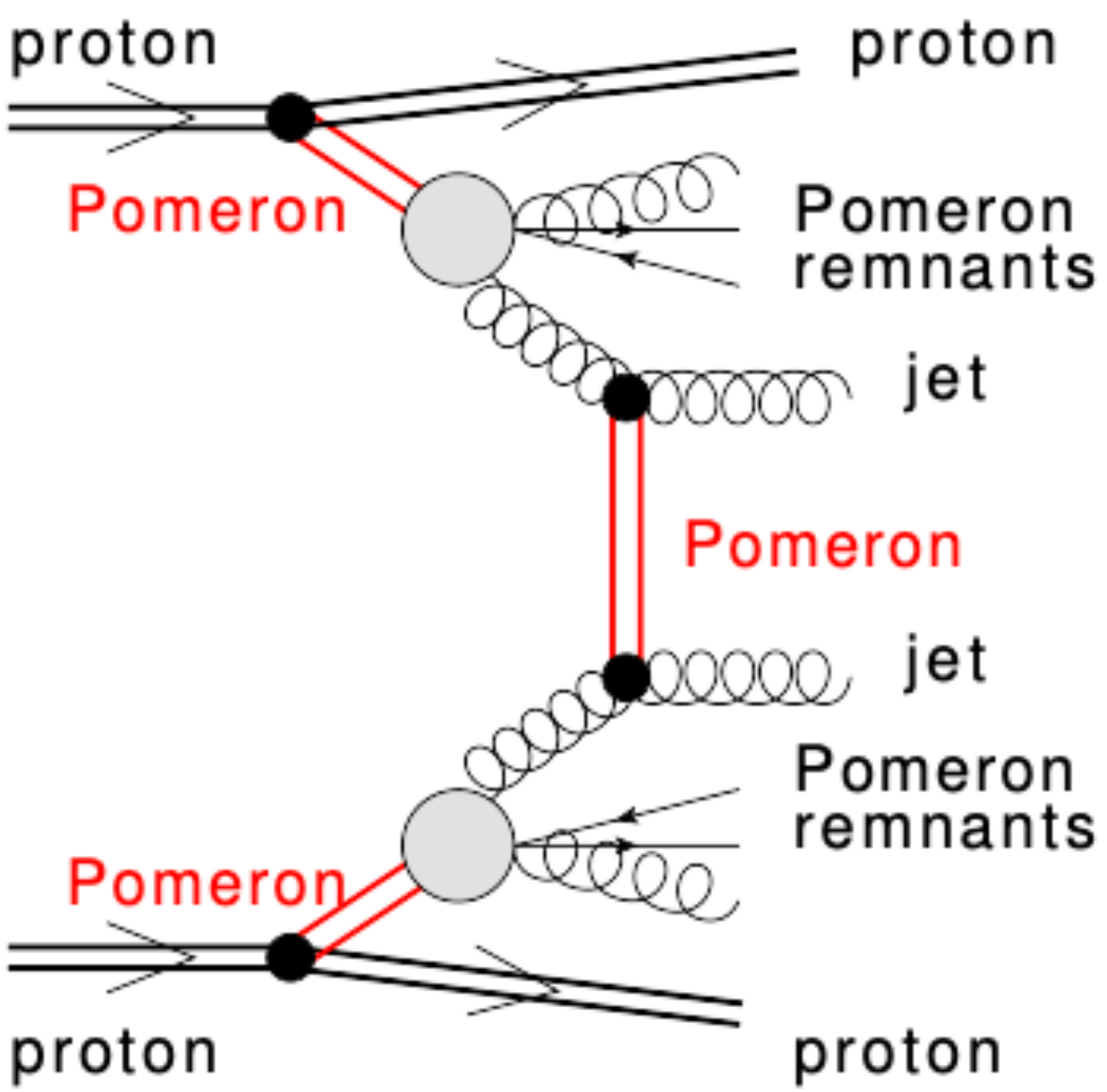
$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 .$$

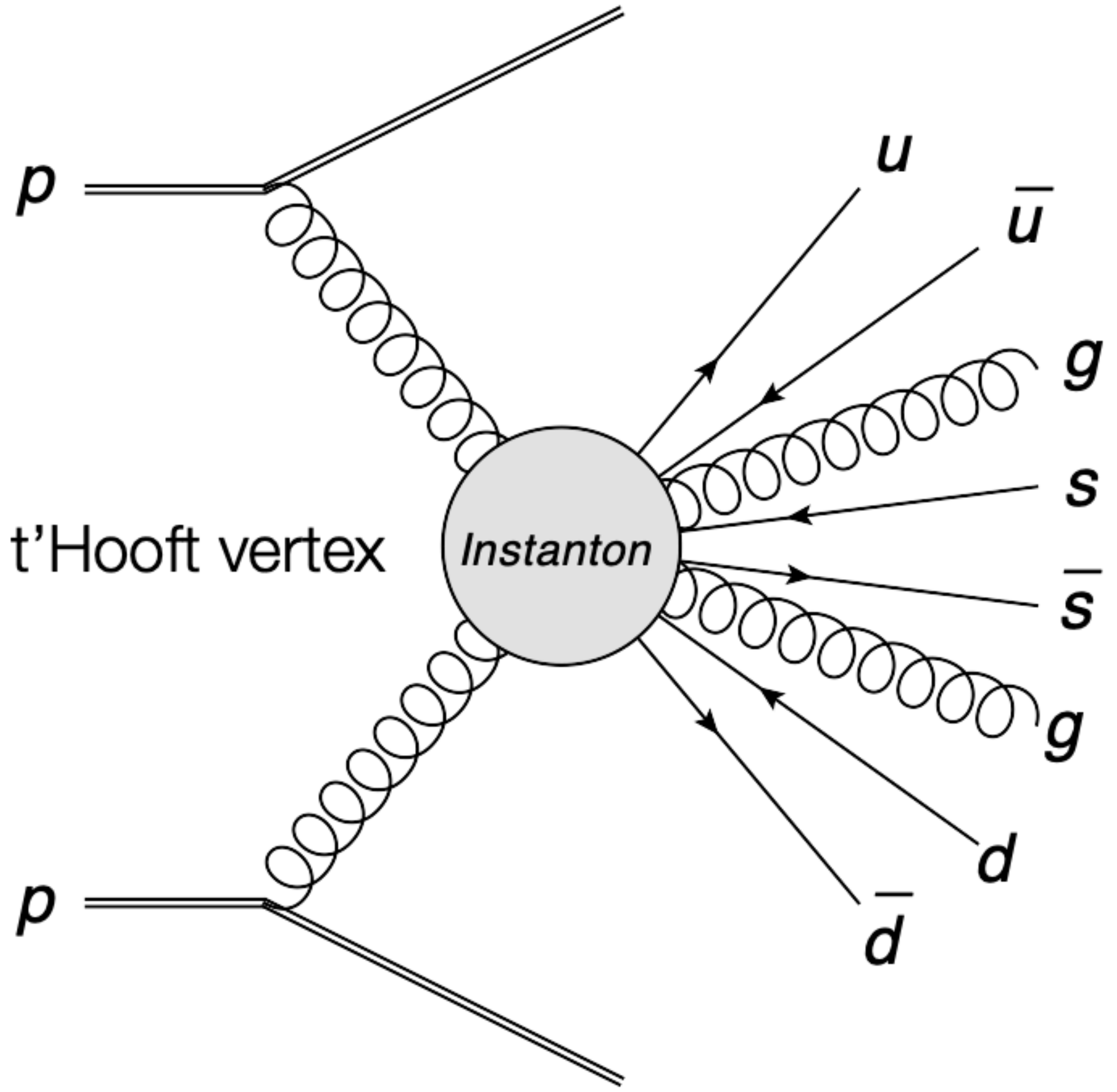




- Proton-proton collisions quite involved phenomena.
  - Different aspect of QCD entering in the description of the event.
  - Different QCD effects can be factorized in terms of the energy scale:







Not covered in this talk:

- Soft-QCD: SDP, DDP …
- Double parton scattering.
- QCD instantons.
- High density QCD …

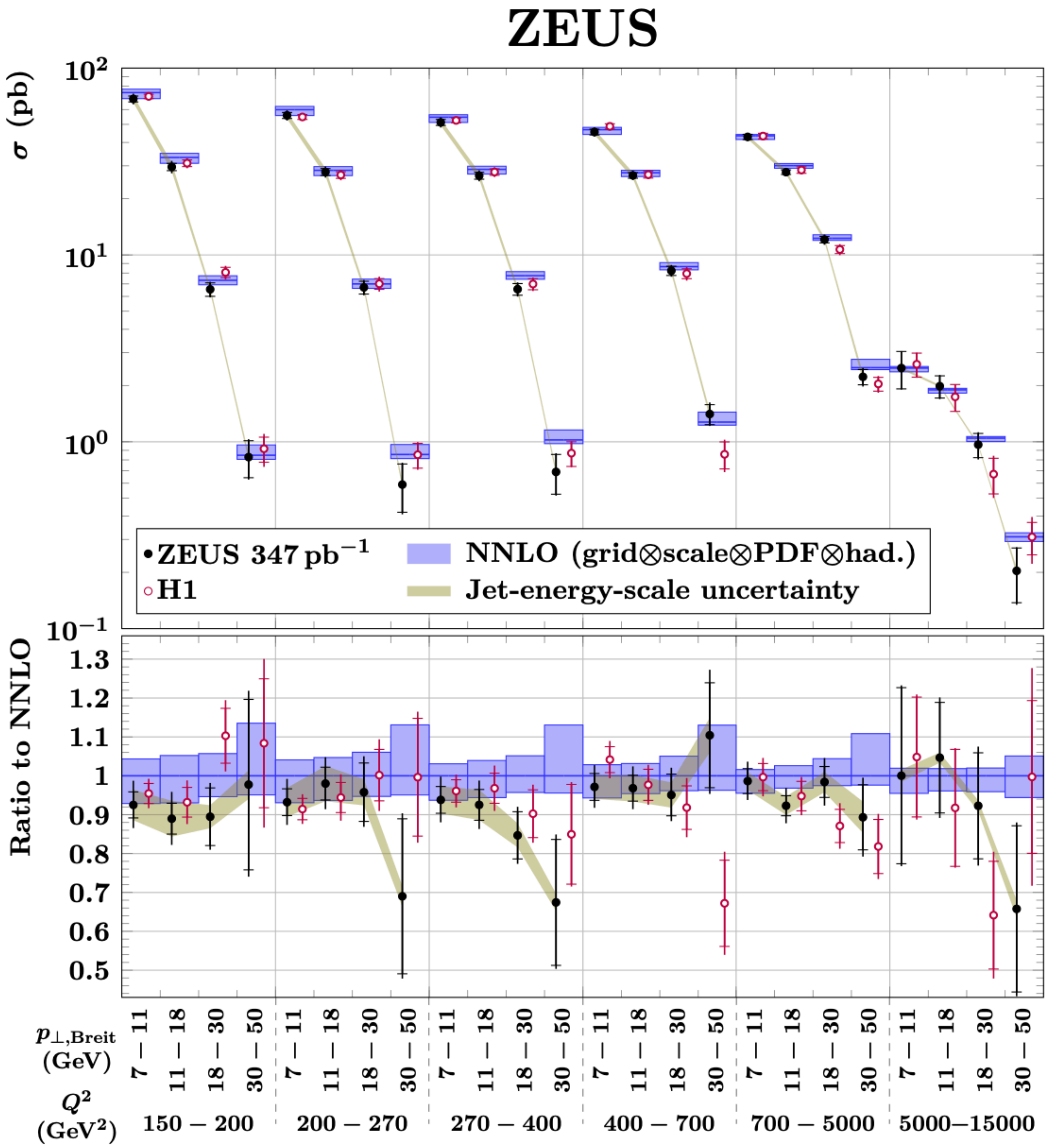
Hard QCD physics: inclusive jets an di-jets

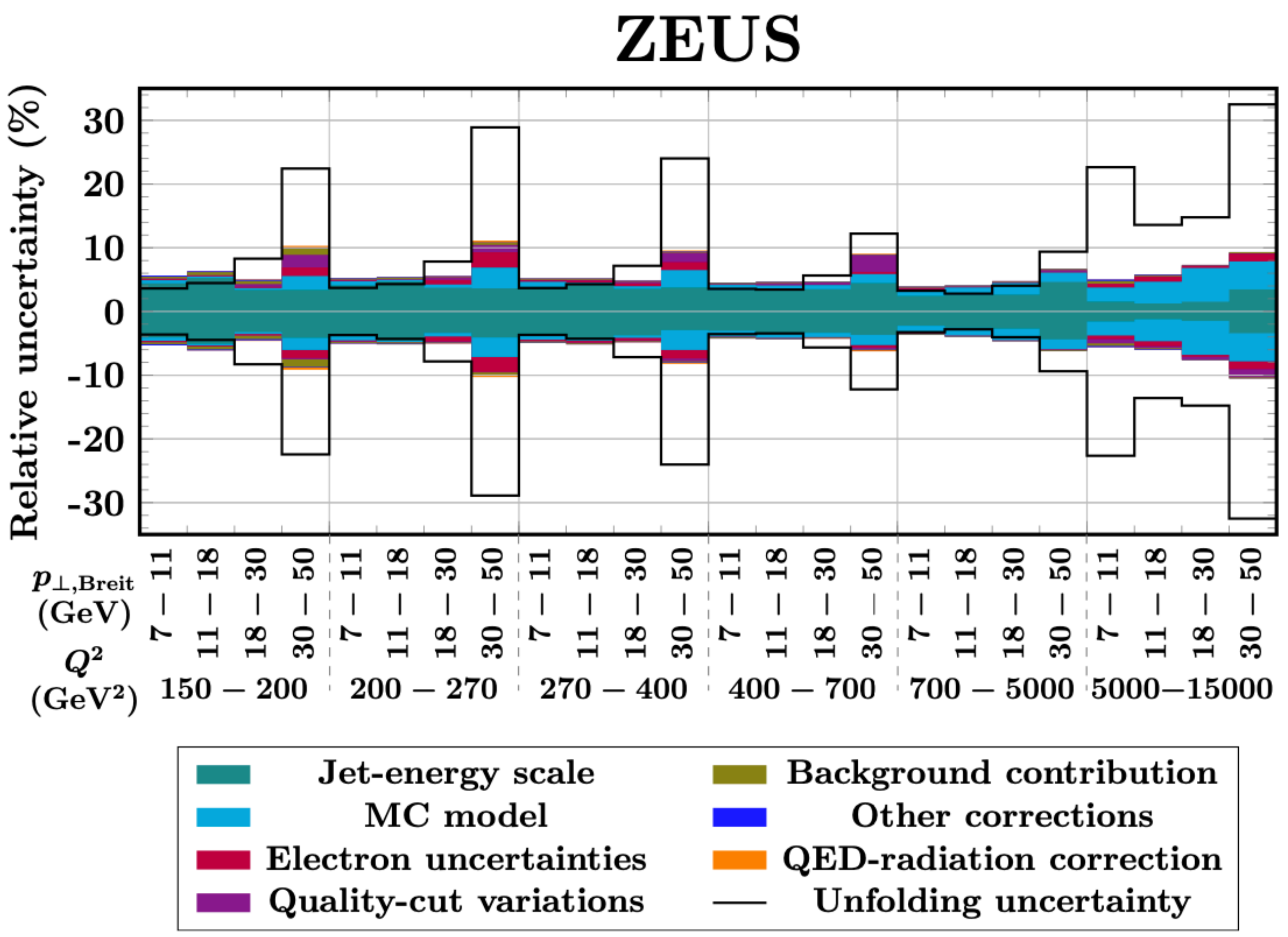
- New inclusive jet and dijet cross-sections by ZEUS to extract α_S in a PDF+α_S fit at NNLO.

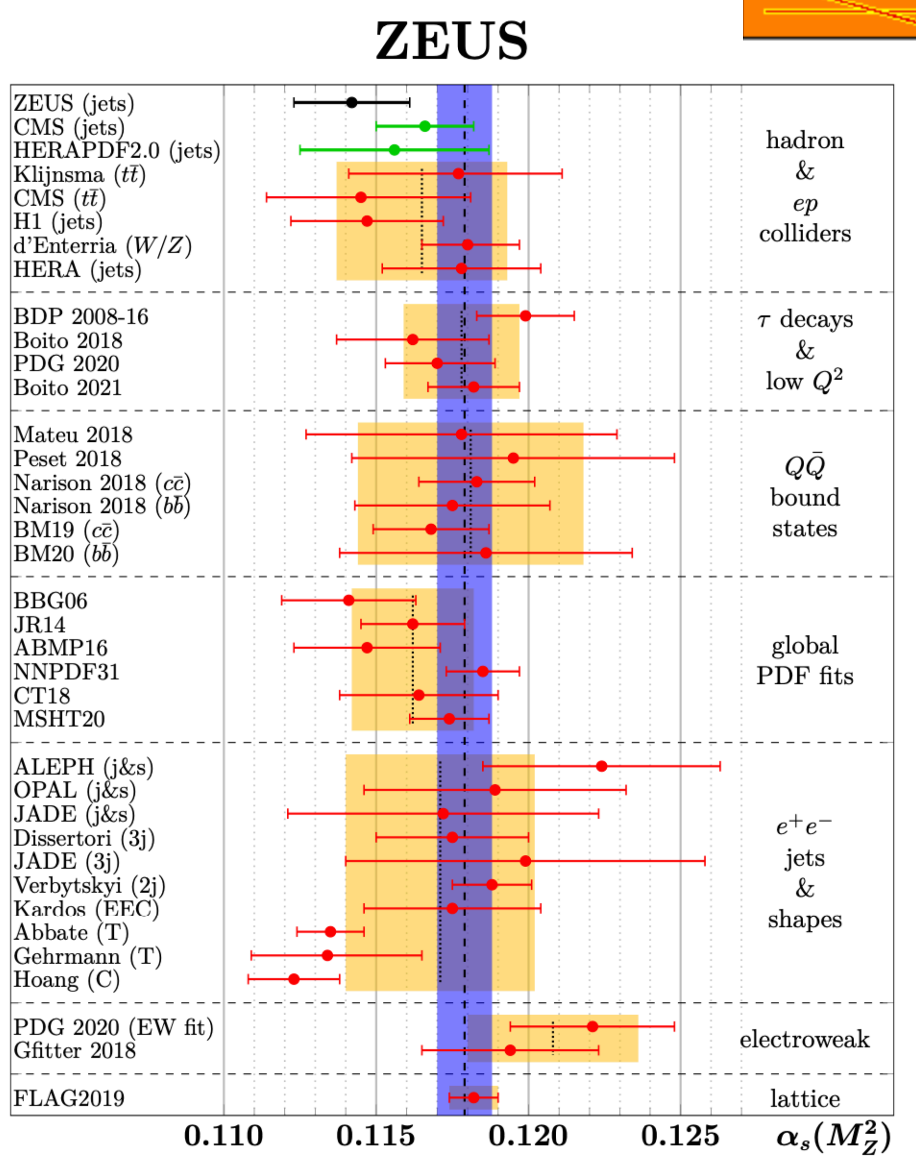
$$\text{NNLO: } \alpha_s(M_Z^2) = 0.1142 \pm 0.0017\ (\text{exp./fit})\ ^{+0.0006}_{-0.0007}\ (\text{model/param.})\ ^{+0.0006}_{-0.0004}\ (\text{scale}),$$

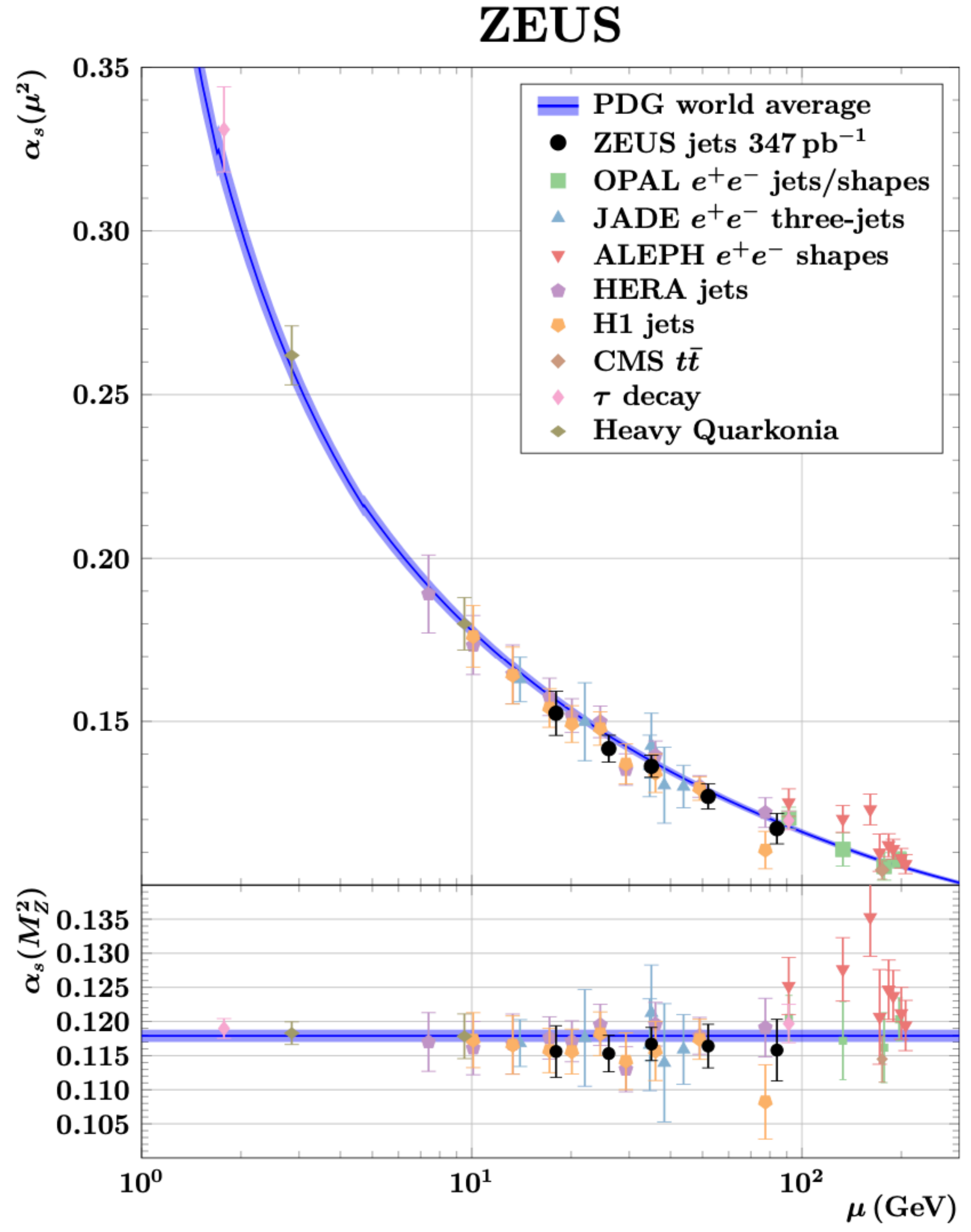
$$\text{NLO: } \alpha_s(M_Z^2) = 0.1159 \pm 0.0017\ (\text{exp./fit})\ ^{+0.0007}_{-0.0009}\ (\text{model/param.})\ ^{+0.0012}_{-0.0009}\ (\text{scale}).$$

arXiv:2309.02889



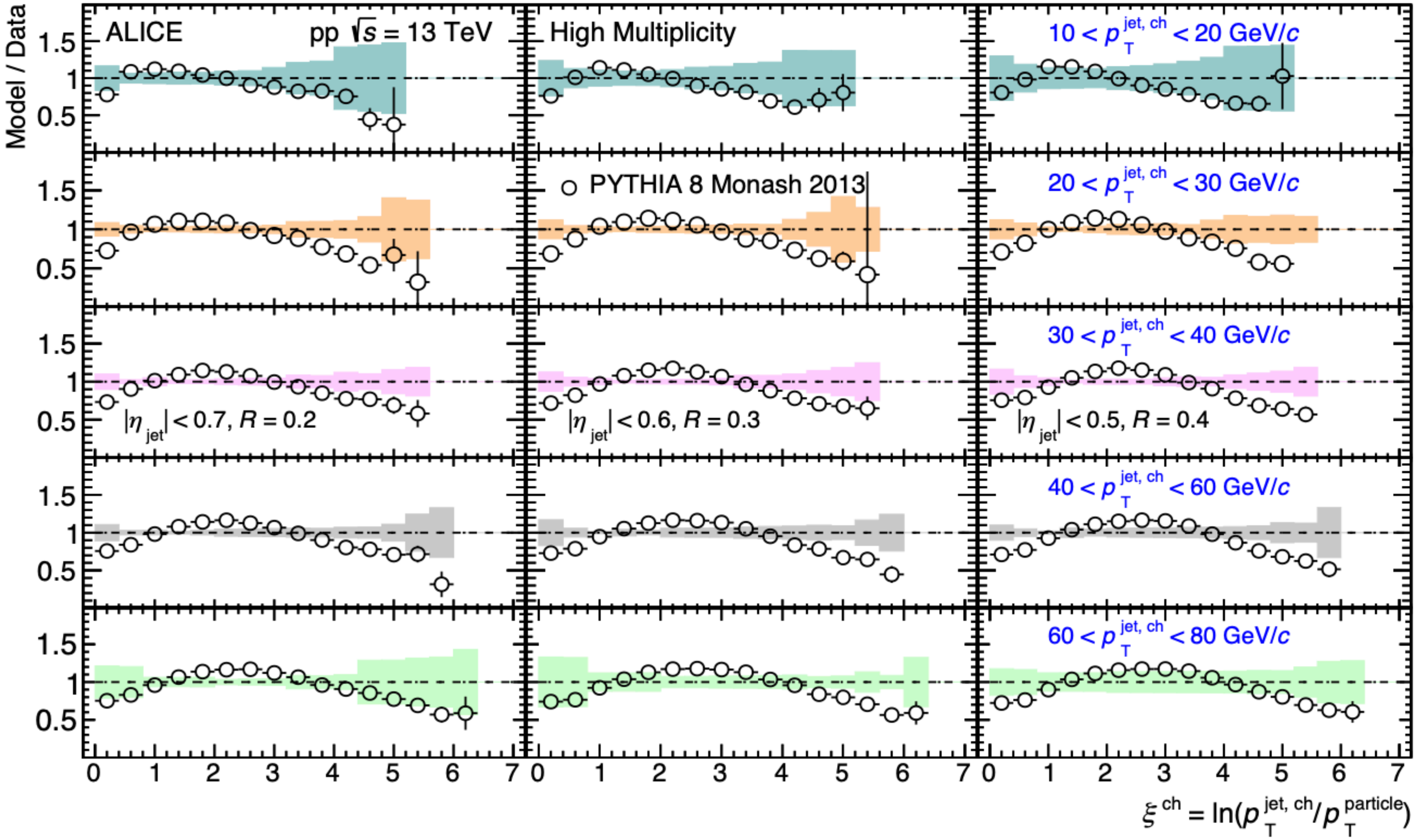






- Factor 2 reduction on theory uncertainty from NLO to NNLO (1% to 0.5%).
- α_S running tested for $18 < Q/\text{GeV} < 84$

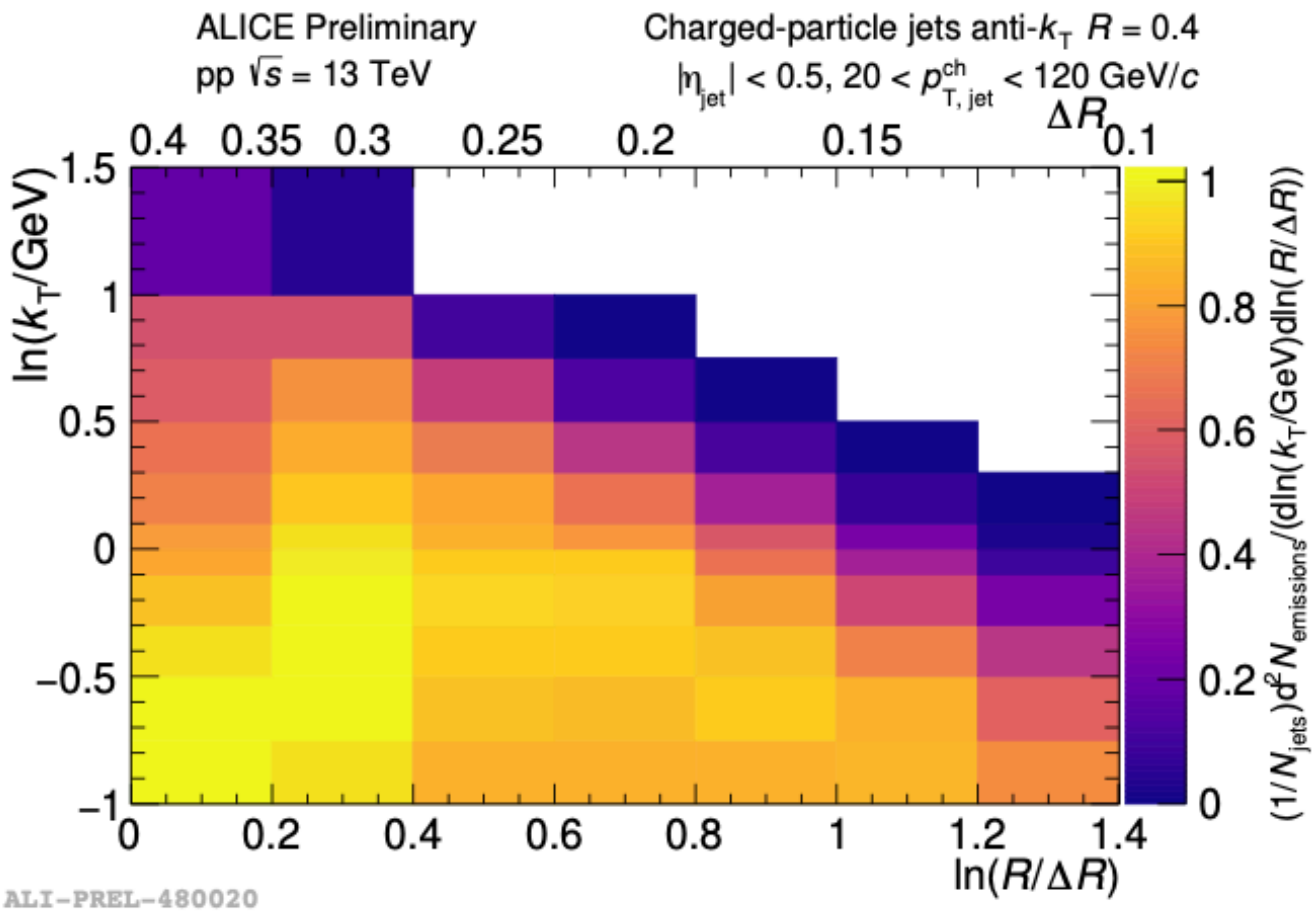
arXiv:2311.13322

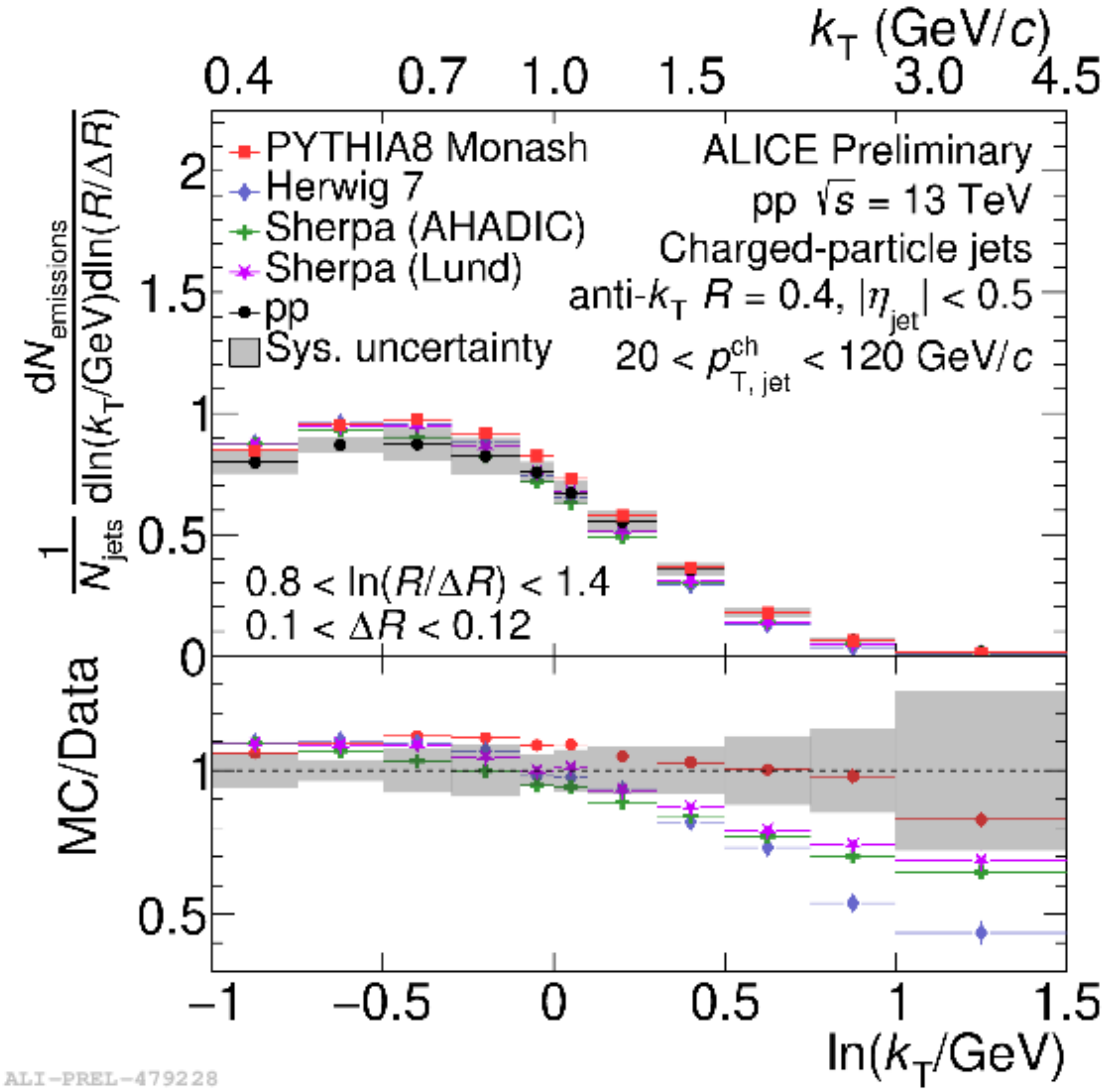


$$z^{\mathrm{ch}} = \frac{p_{\mathrm{T}}^{\mathrm{particle}}}{p_{\mathrm{T}}^{\mathrm{jet,ch}}}, \qquad \xi^{\mathrm{ch}} = \ln\left(\frac{1}{z^{\mathrm{ch}}}\right)$$

- Charged particle information important for GPF algorithms.
  - Match energy cluster with tracks.

arXiv::2111.00020





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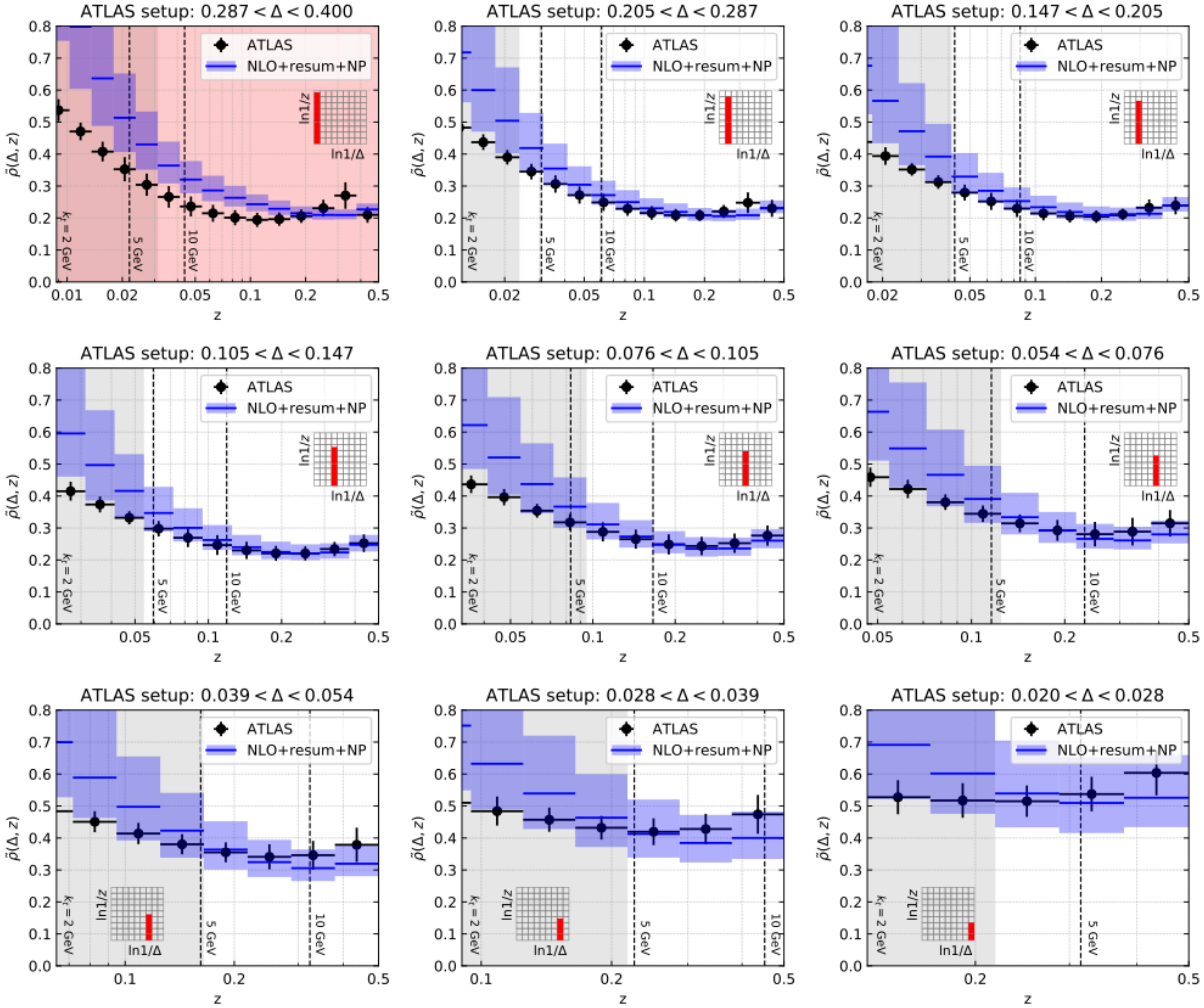
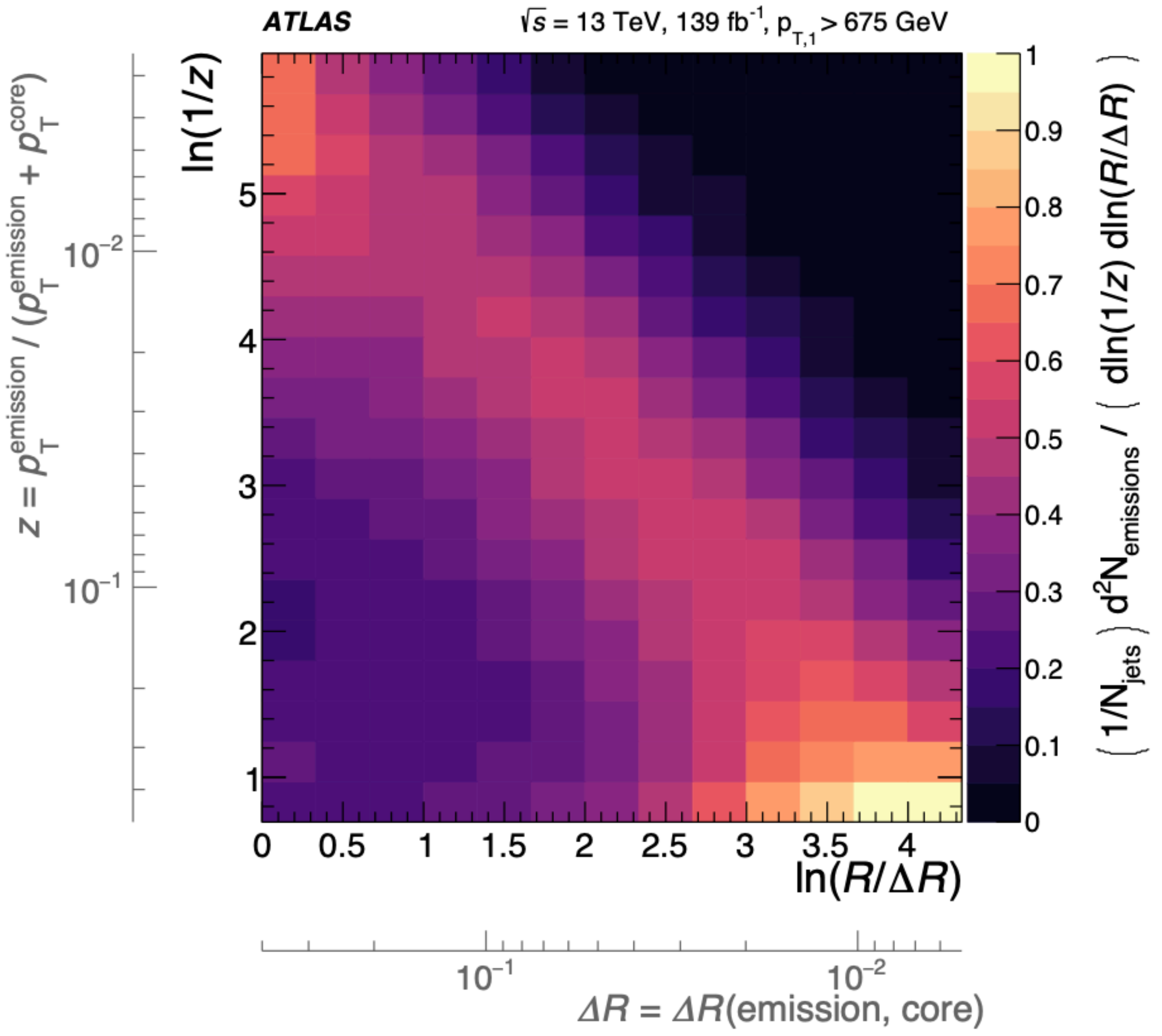


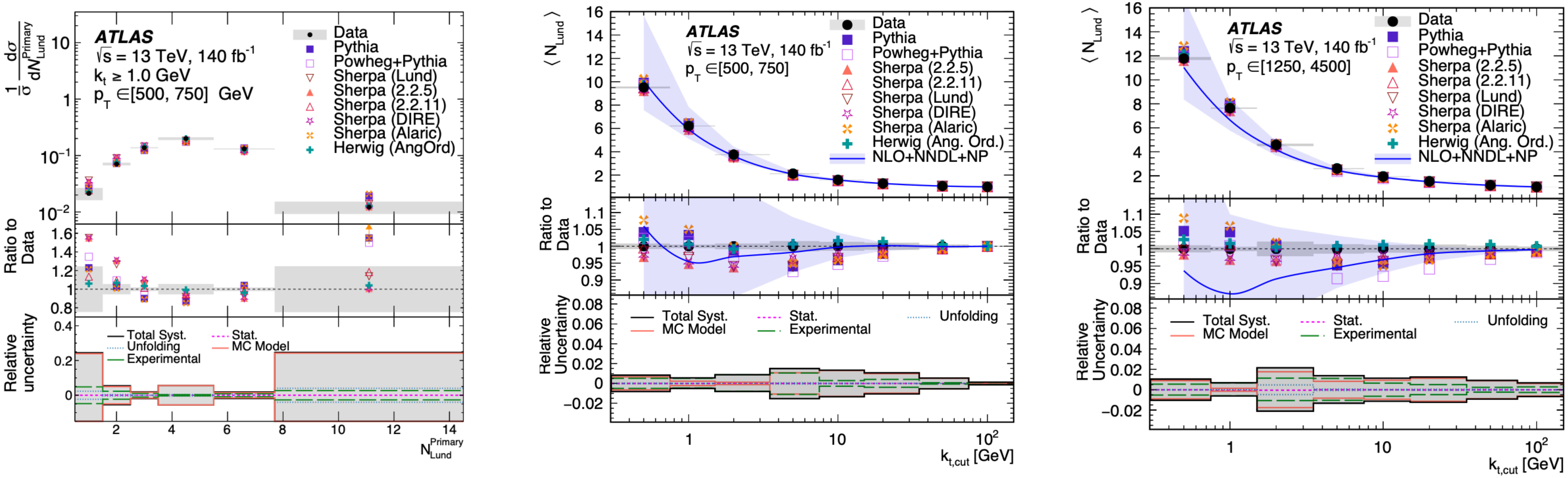
Phys. Rev. Lett 124 (2020) 02



Jet substructure: Lund multiplicities

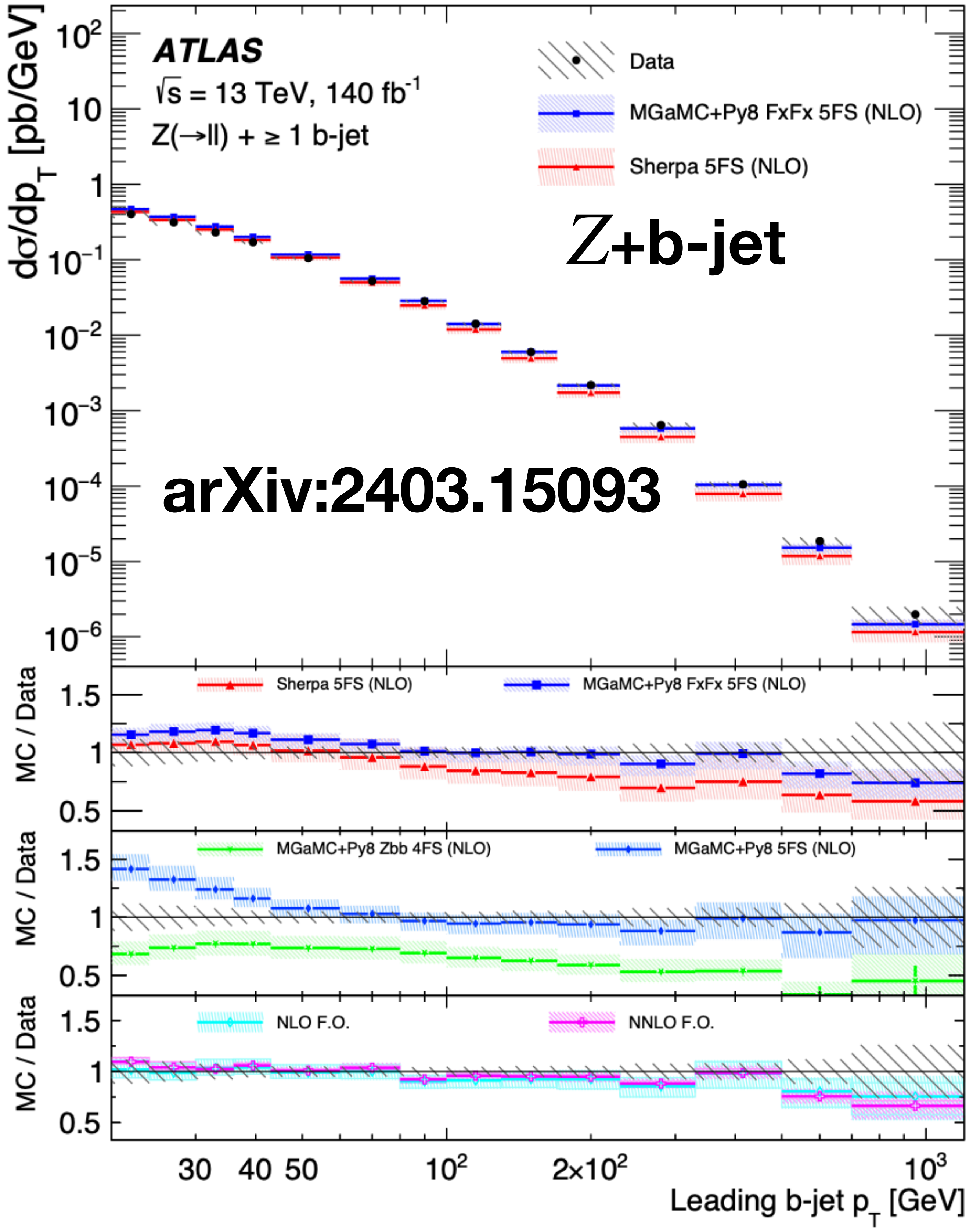
- Lund multiplicities built from the LJP.
  - Counts the number of emissions above a specified transverse momentum requirement.

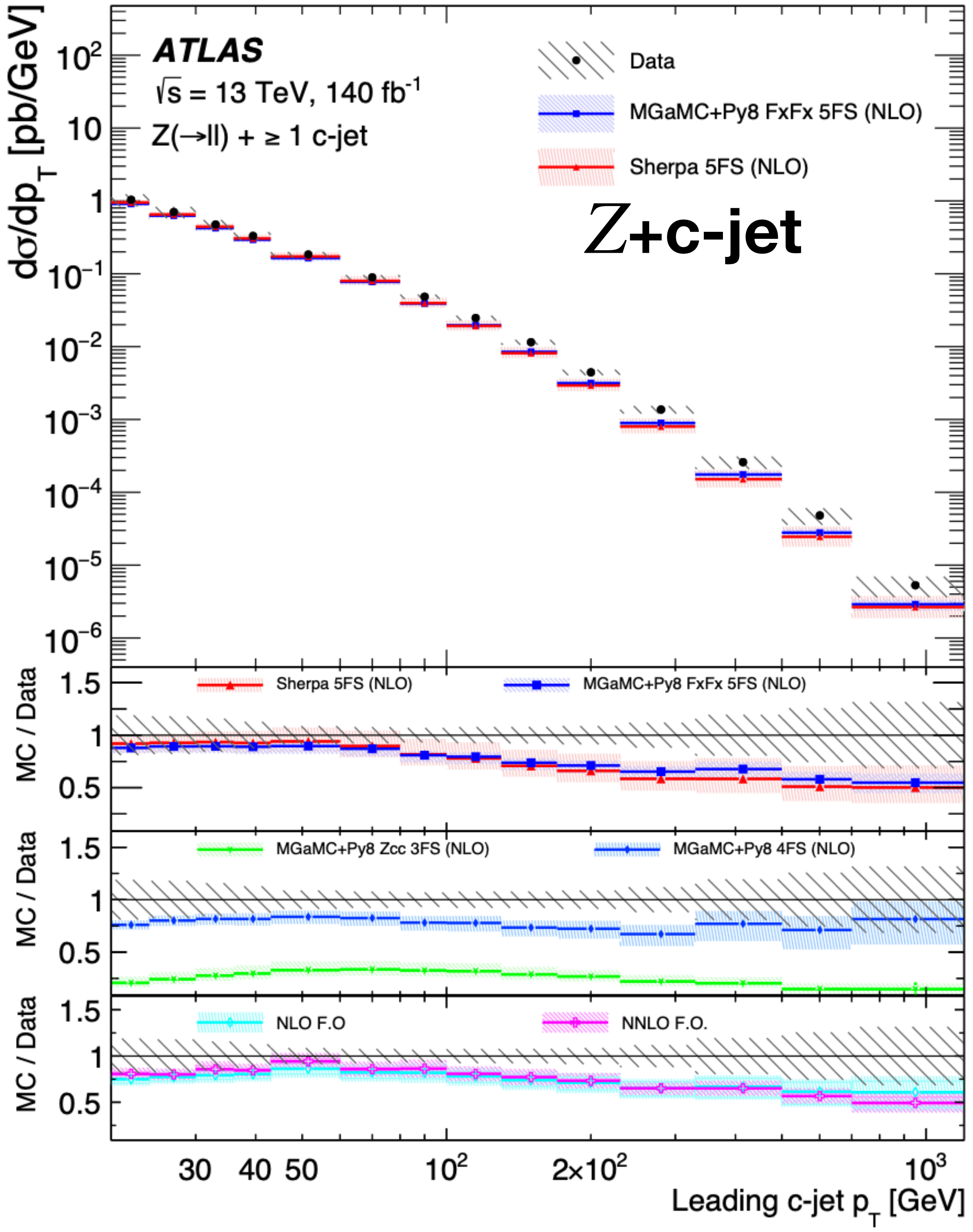
arXiv:2402.13052

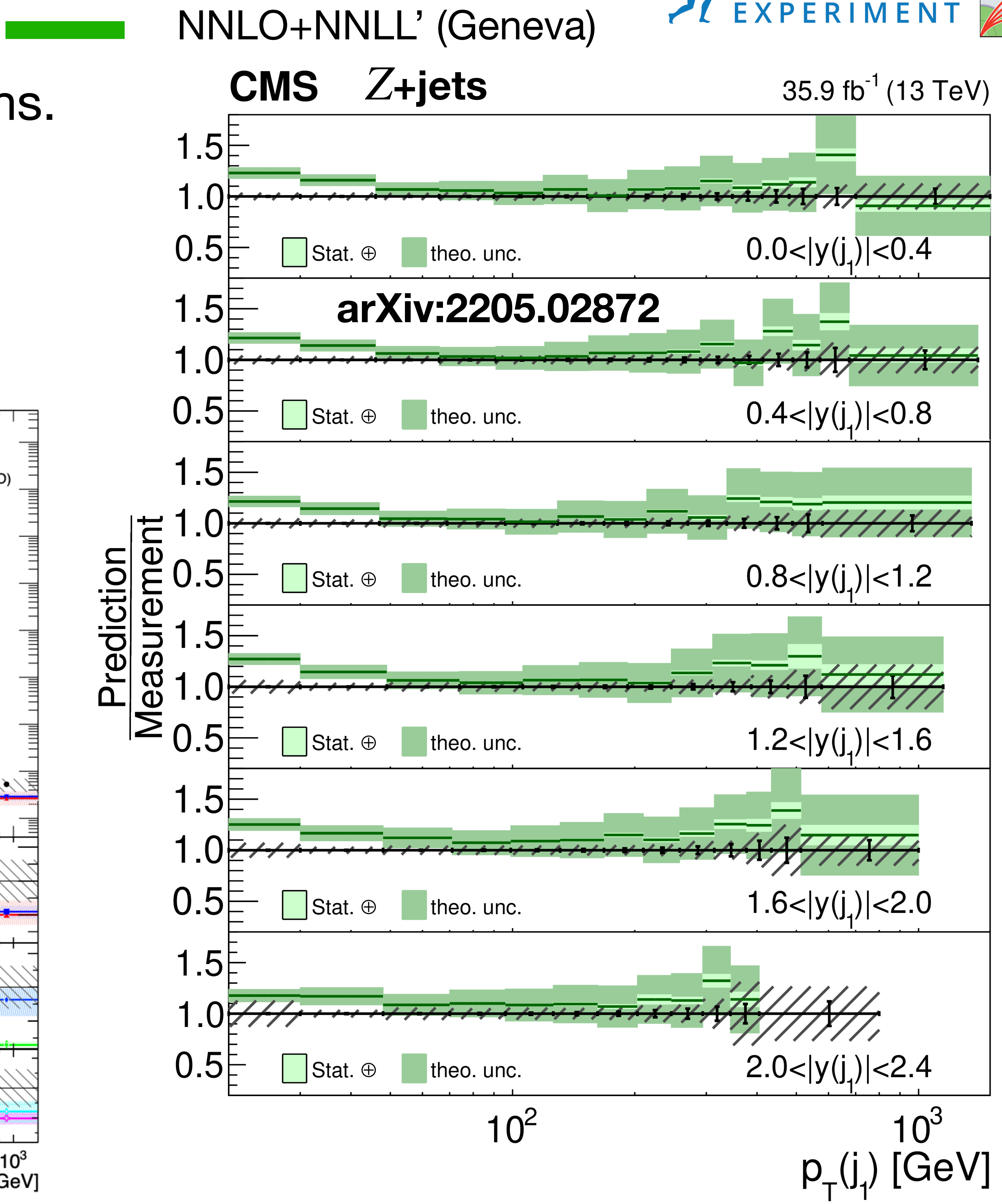


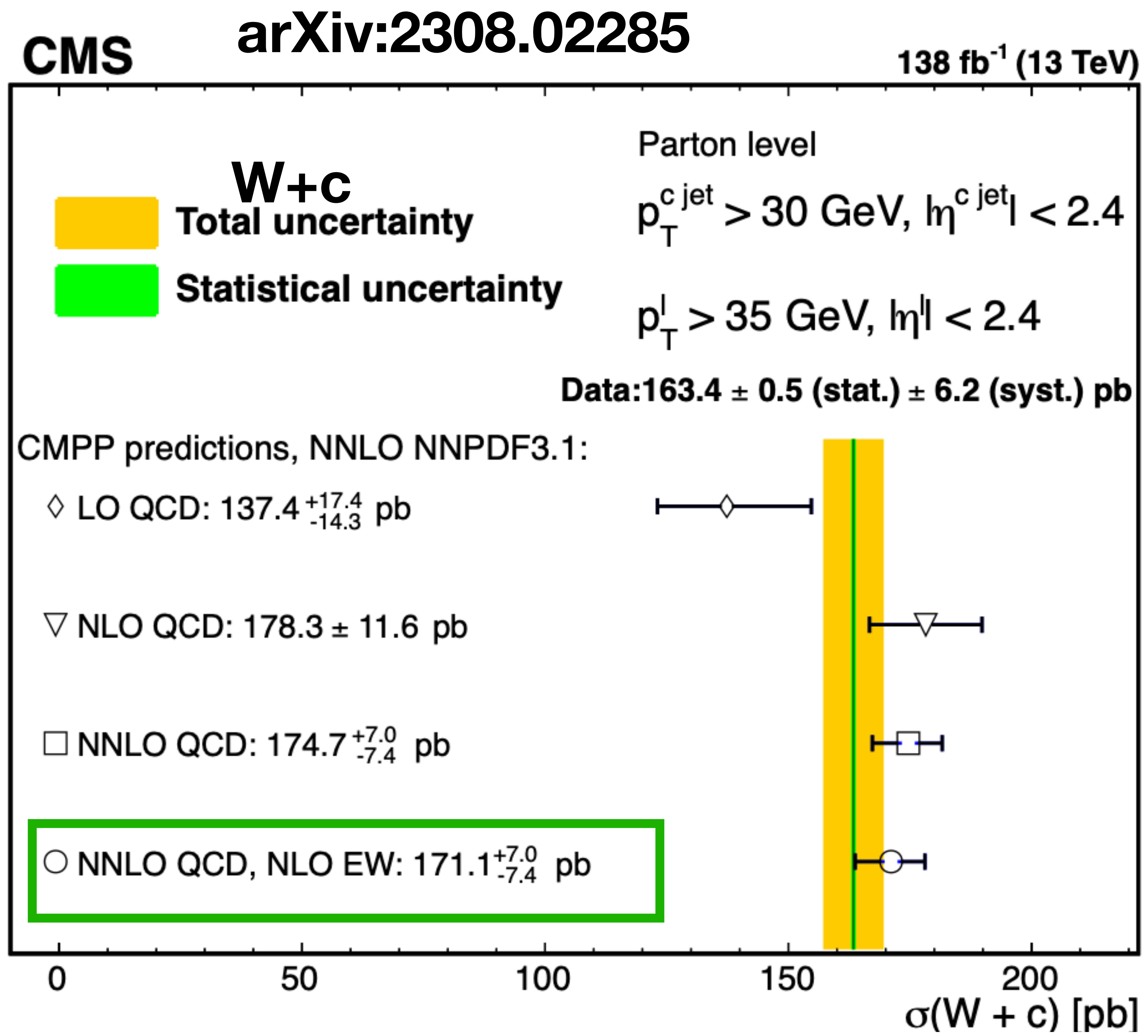
- Measurements compared with MC models including different hadronisation tunes, PS algorithms, ME accuracies.
  - Angular ordered Herwig showers give overall best description of the measurements.
- Measurements also compared to NLO+NNDL+NP.
  - Large uncertainty still due to NP corrections: estimated by comparing different models.
  - Observable also sensitive to α_S QCD-running.

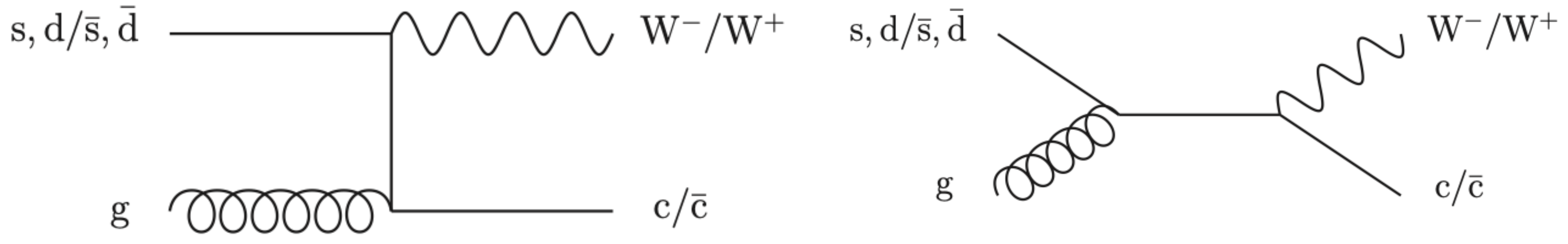
- V+jets production good properties to test pQCD:
  - Lower p_T threshold un-prescaled triggers for leptons.
  - Smaller experimental uncertainties.
  - Less involved final states compared to multi-jet.
    - Typically higher theory accuracy.
  - Allows to probe heavy-flavour quark PDFs.









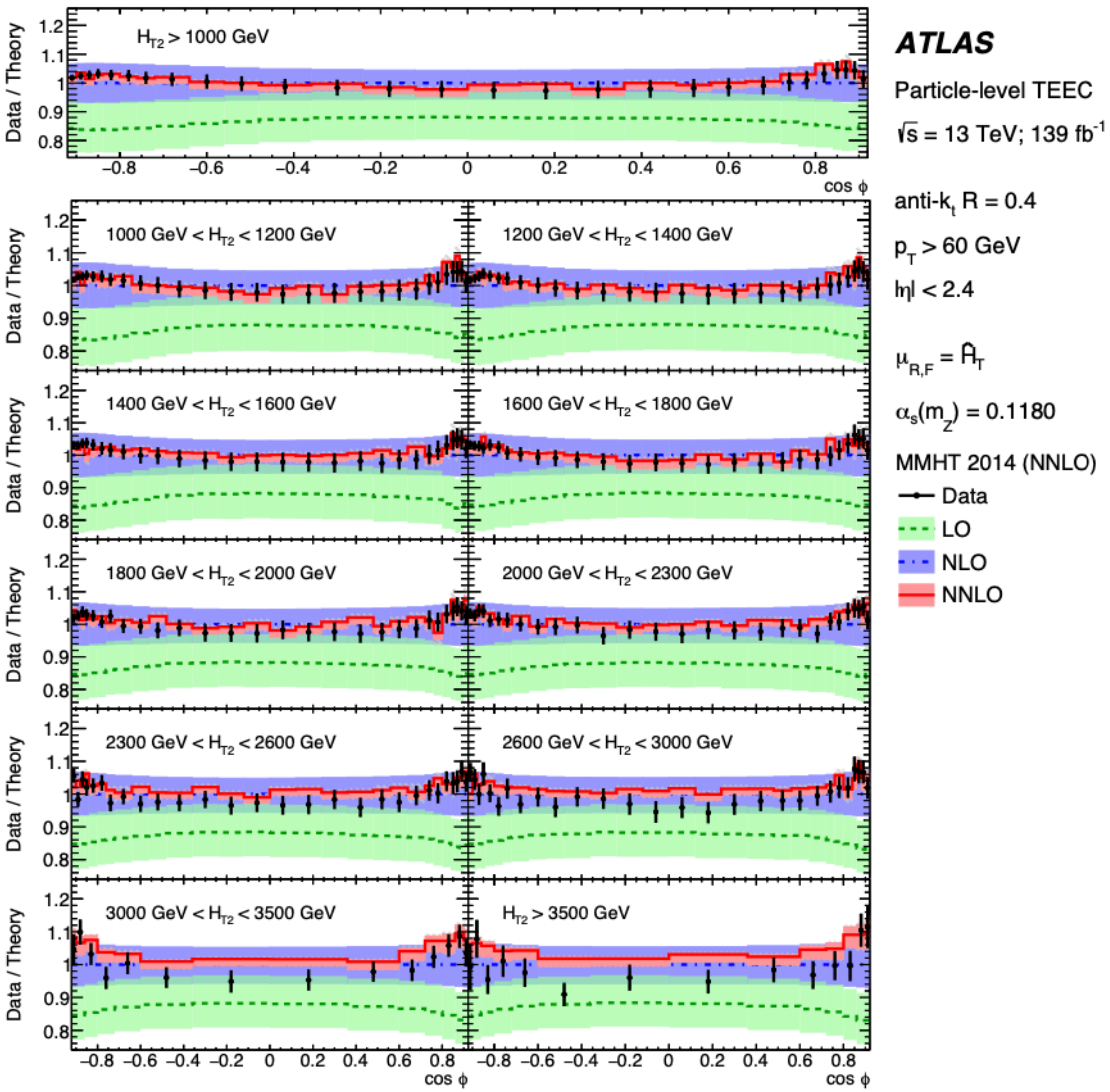


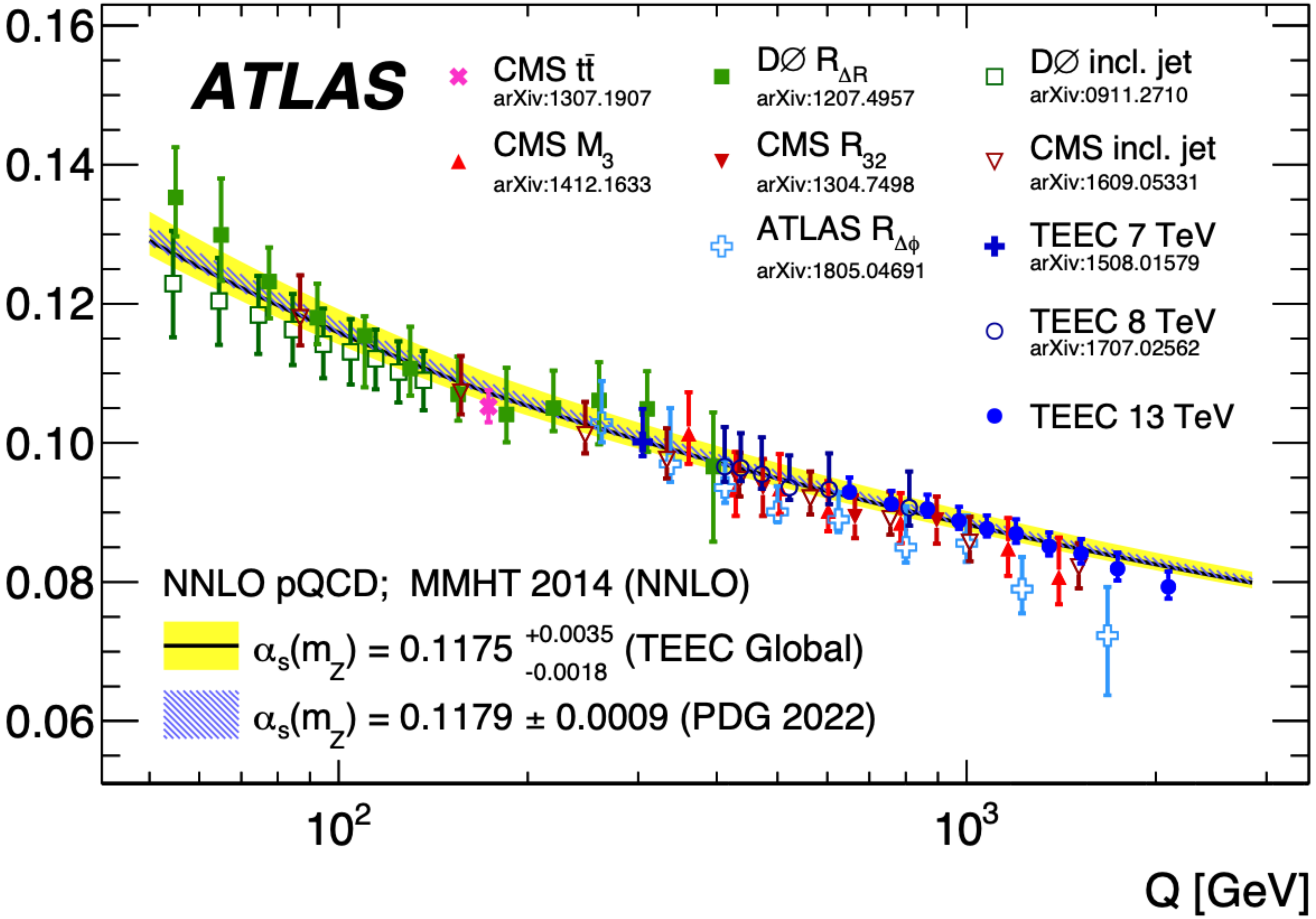
- Sensitive to strange quark PDF.
- The predicted fiducial cross section consistent with the measurement within uncertainties.
  - NNLO QCD and NLO EW corrections improve the agreement between theory and measurements.
- Inclusion of these measurements in PDF fits to improve modelling of strange PDF.

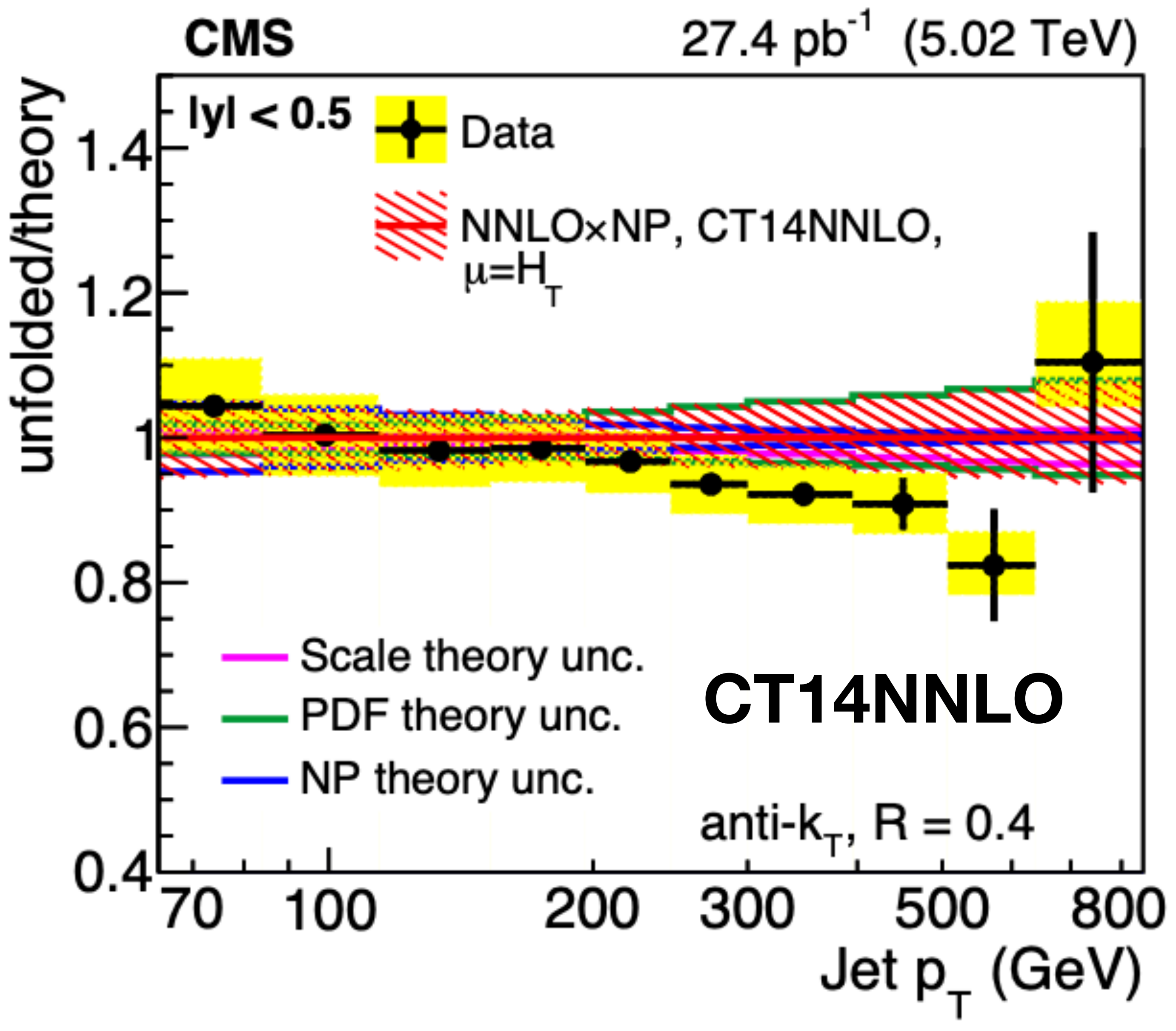
QCD order	EW order	σ^{OS}_{W+c}	σ^{SS}_{W+c}	$\sigma^{OS\text{-}SS}_{W+c}$	$\Delta^{OS\text{-}SS}_{stat}$	$\Delta^{OS\text{-}SS}_{scales}$	$\Delta^{OS\text{-}SS}_{PDF}$	$\Delta^{OS\text{-}SS}_{Total}$
LO	LO	137.4	0	137.4	± 0.1	$^{+16.6}_{-13.3}$	± 5.1	$^{+17.4}_{-14.3}$
NLO	LO	182.4	4.1	178.3	± 0.3	$^{+9.3}_{-9.4}$	± 6.8	$^{+11.6}_{-11.6}$
NNLO	LO	182.9	8.2	174.7	± 1.0	$^{+1.2}_{-2.8}$	± 6.8	$^{+7.0}_{-7.4}$
NNLO	NLO	179.1	8.0	171.1	± 1.0	$^{+1.2}_{-2.8}$	± 6.8	$^{+7.0}_{-7.4}$

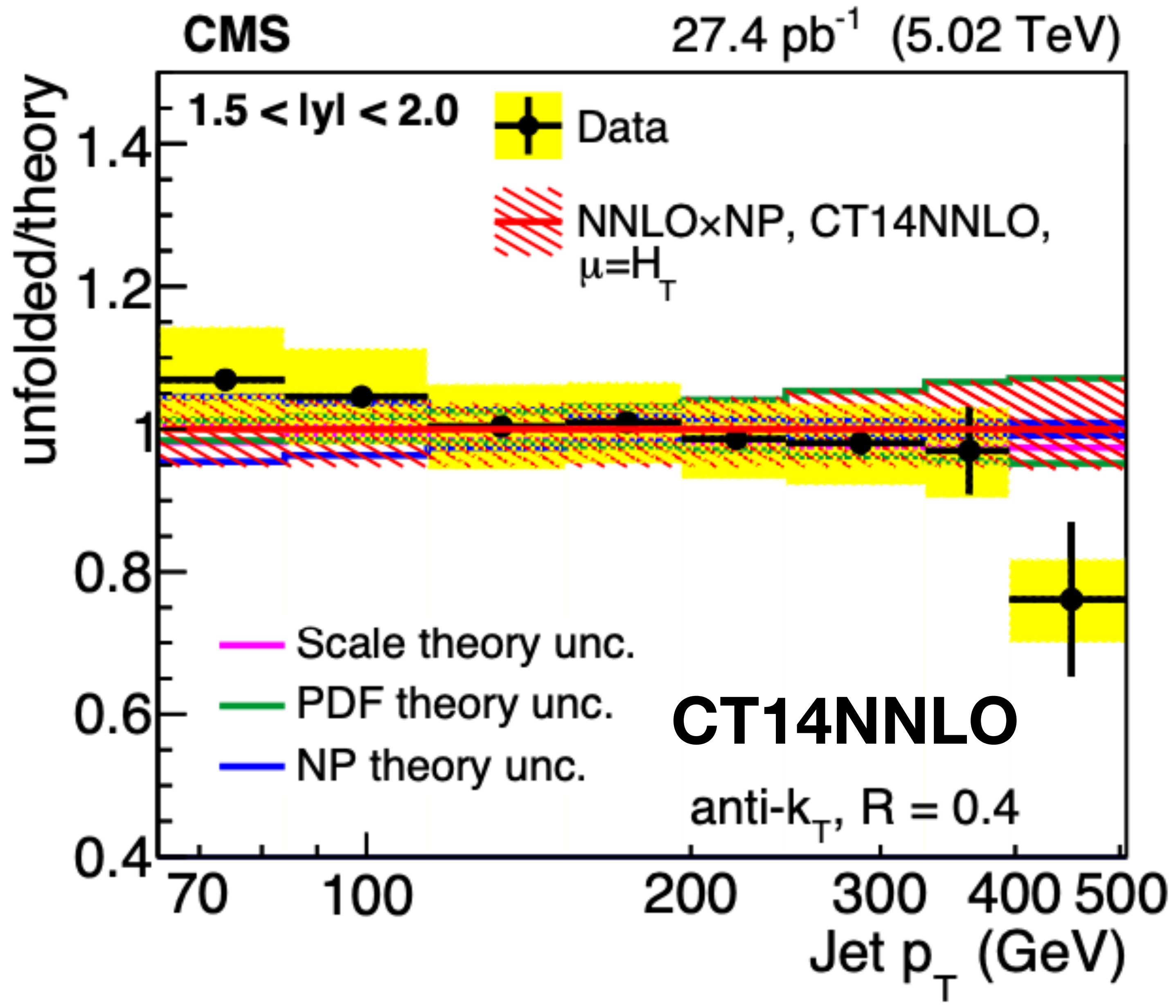
CMS: $163.4 \pm 0.5\,(\text{stat}) \pm 6.2\,(\text{syst})$ pb

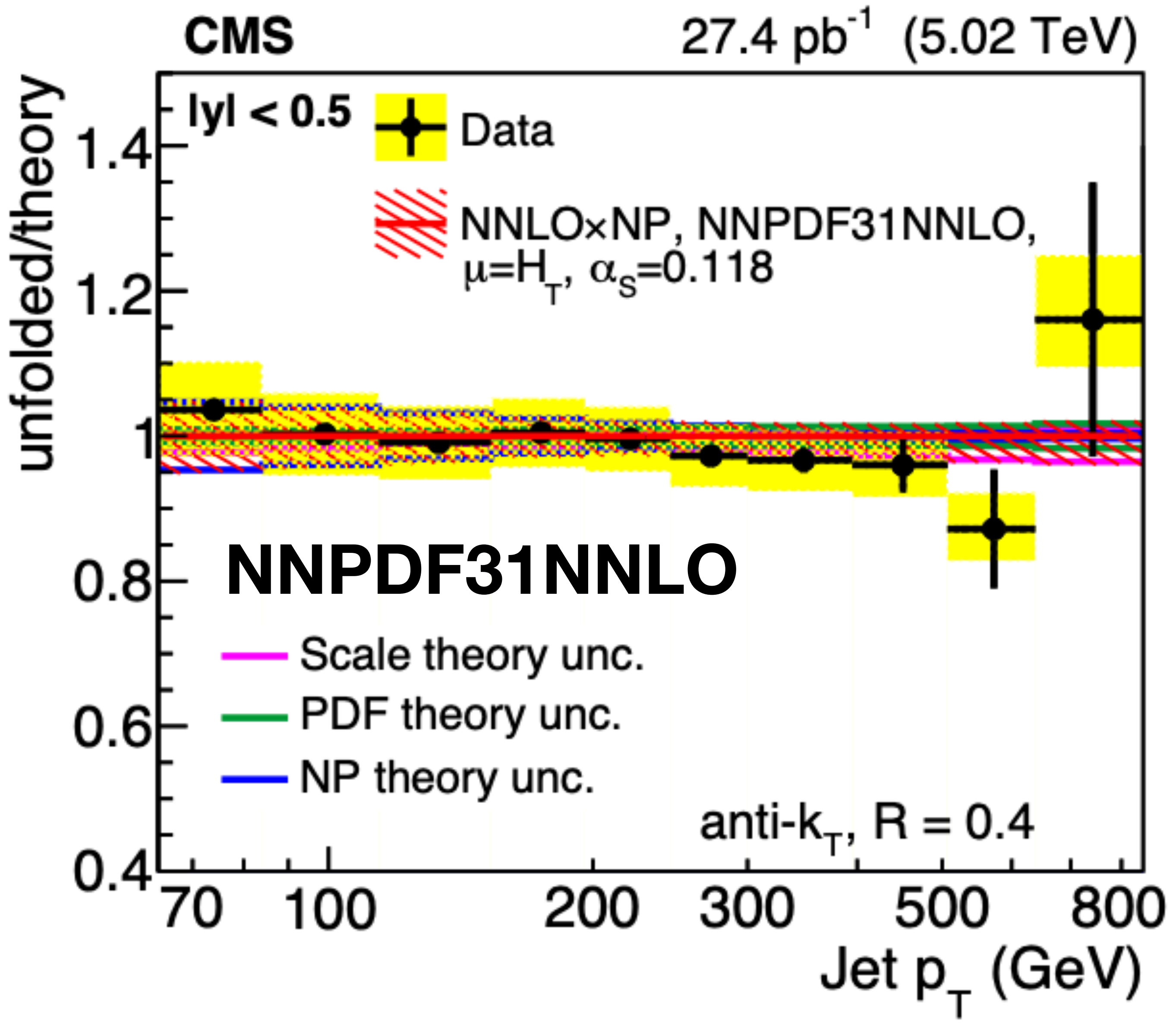
Hard QCD physics: inclusive jets

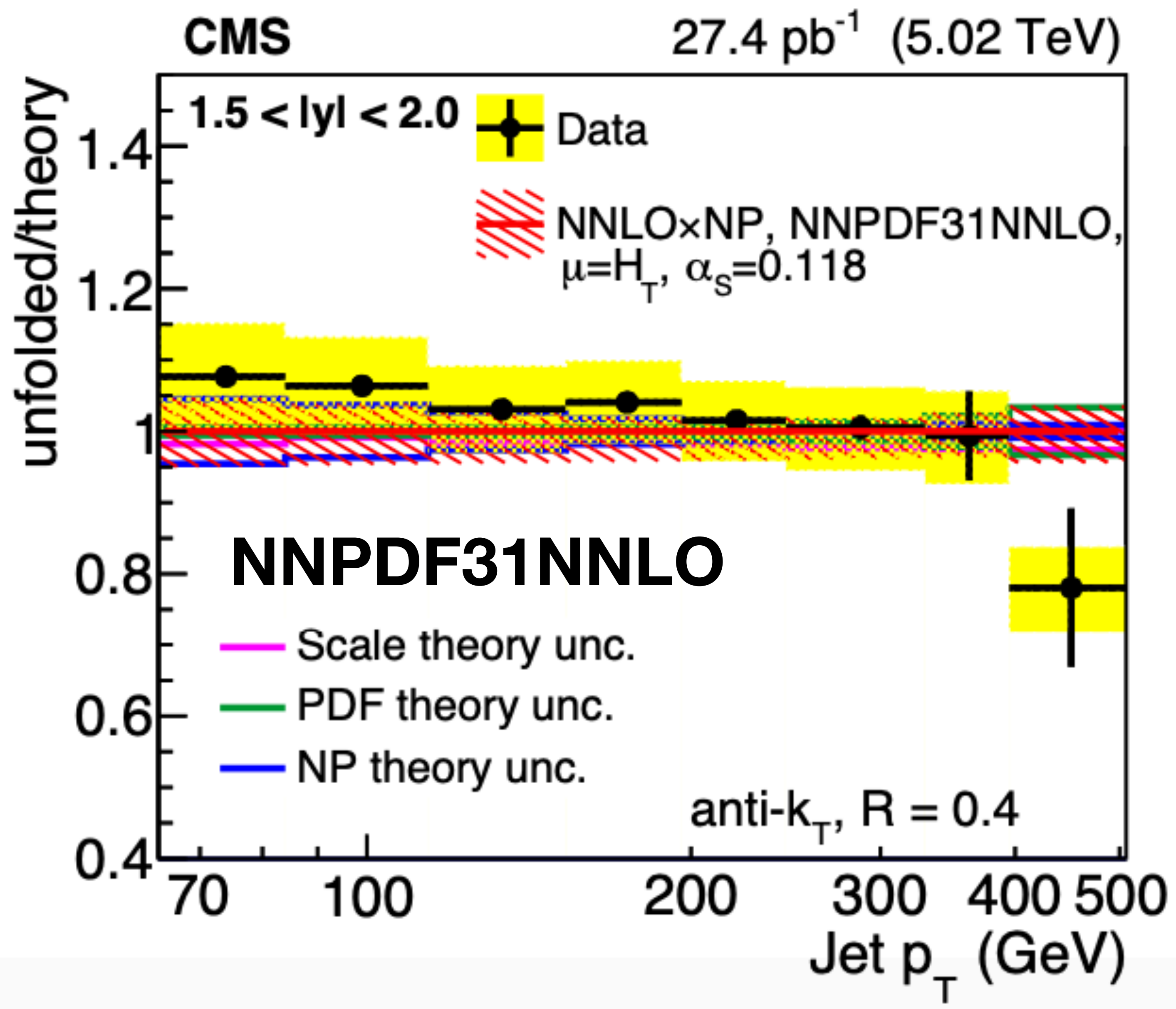




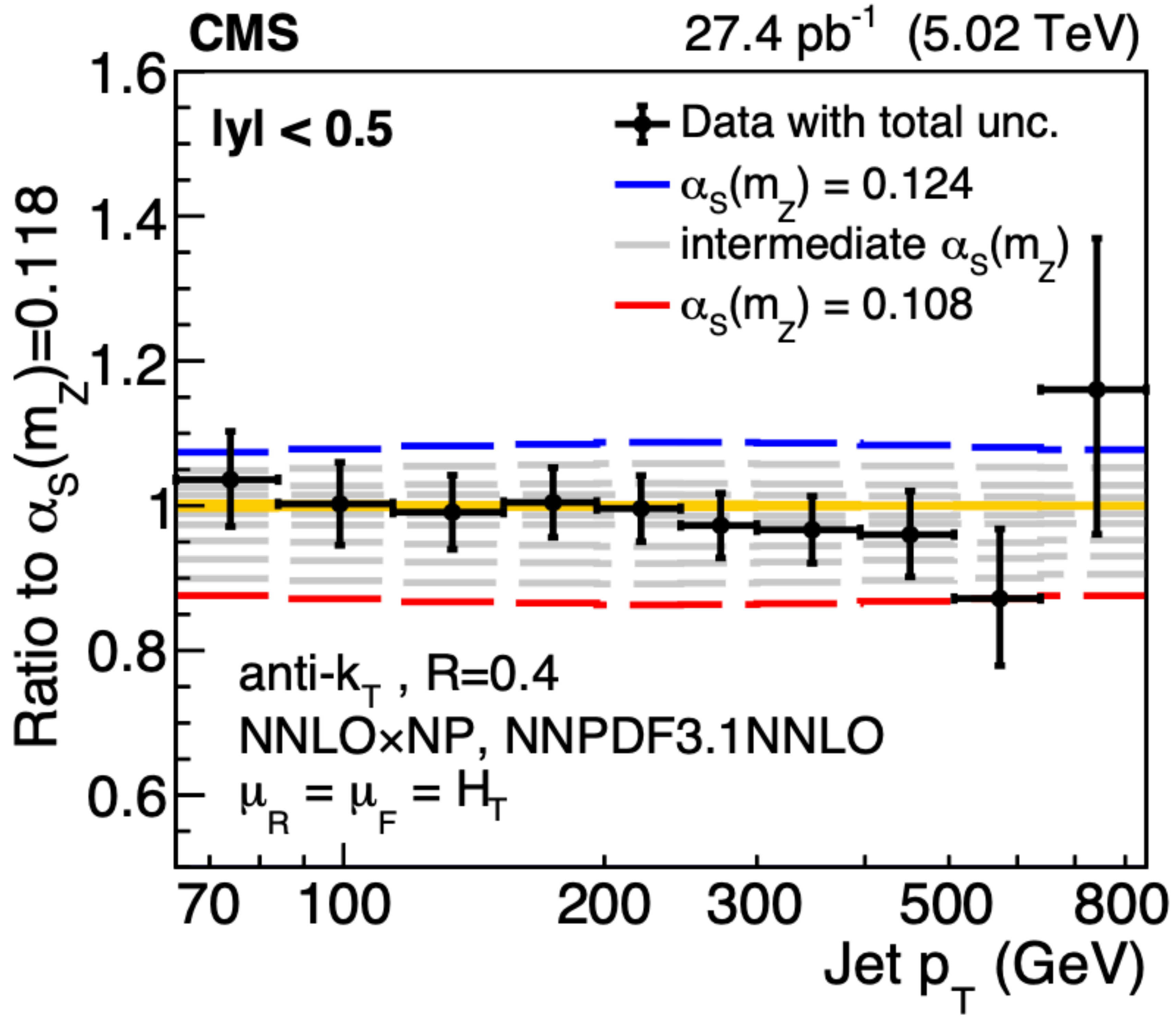






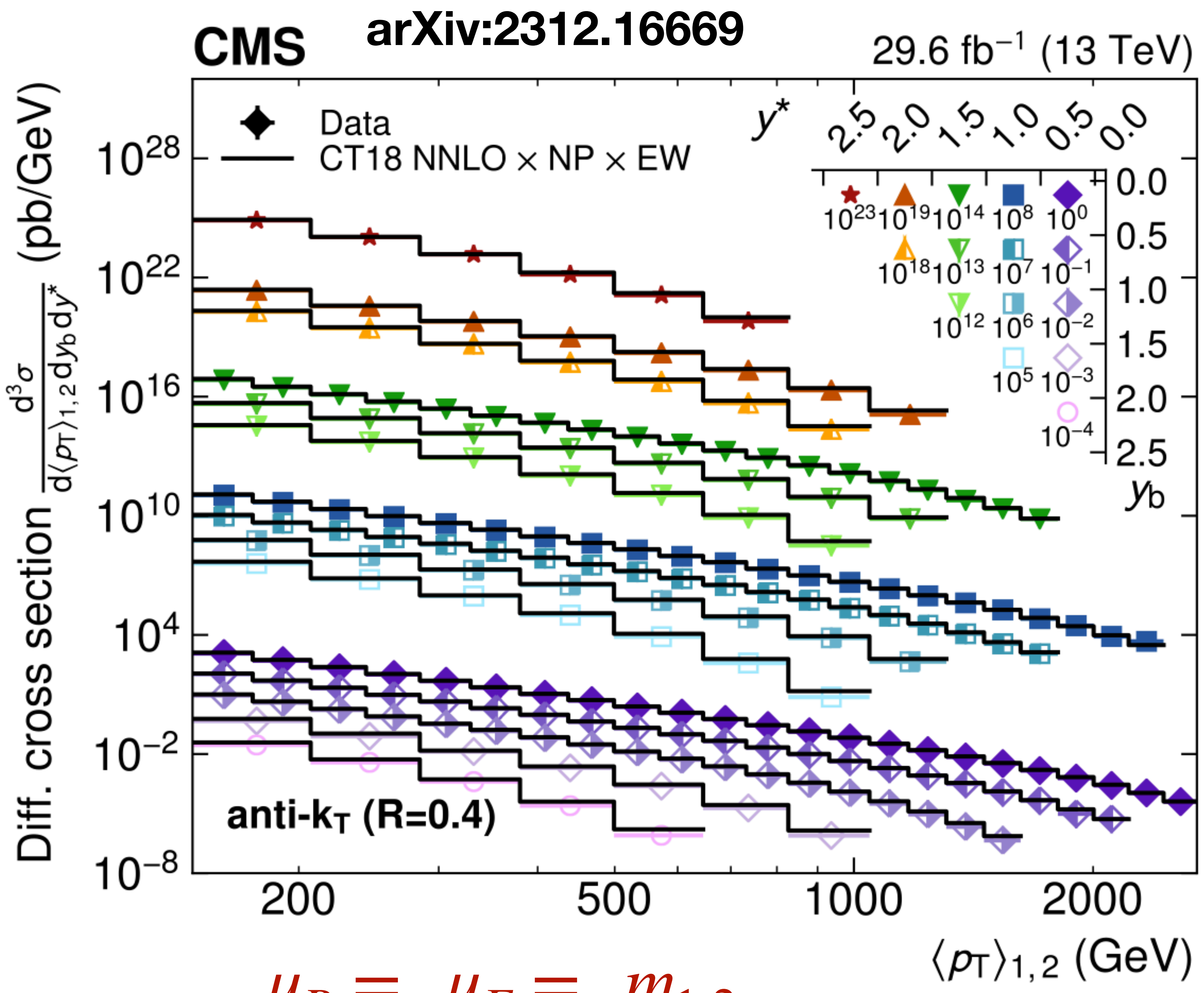


- Flatter ratio and smaller PDF uncertainty observed for the NNPDF31NNLO set.
  - O(1-2%) scale uncertainties (~ 5% in the tail).
- Sensitivity to α_S was studied.
  - Preference for $\alpha_S \sim 0.118$.



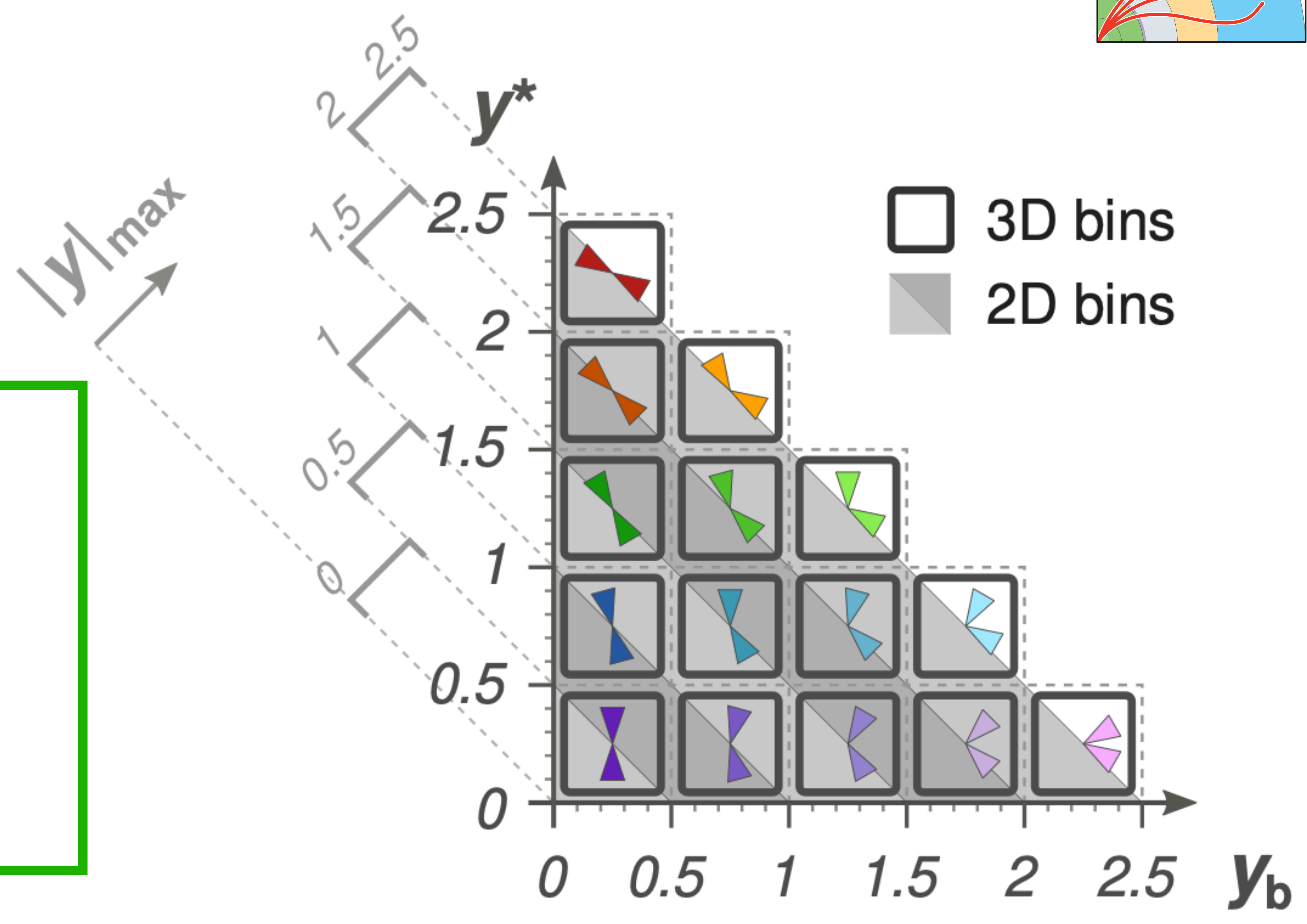
- Dijet cross-section measurements:
  - Test QCD dynamics:
    - double or triple differential cross-section measurements.
  - Sensitive to gluon PDF and α_S.

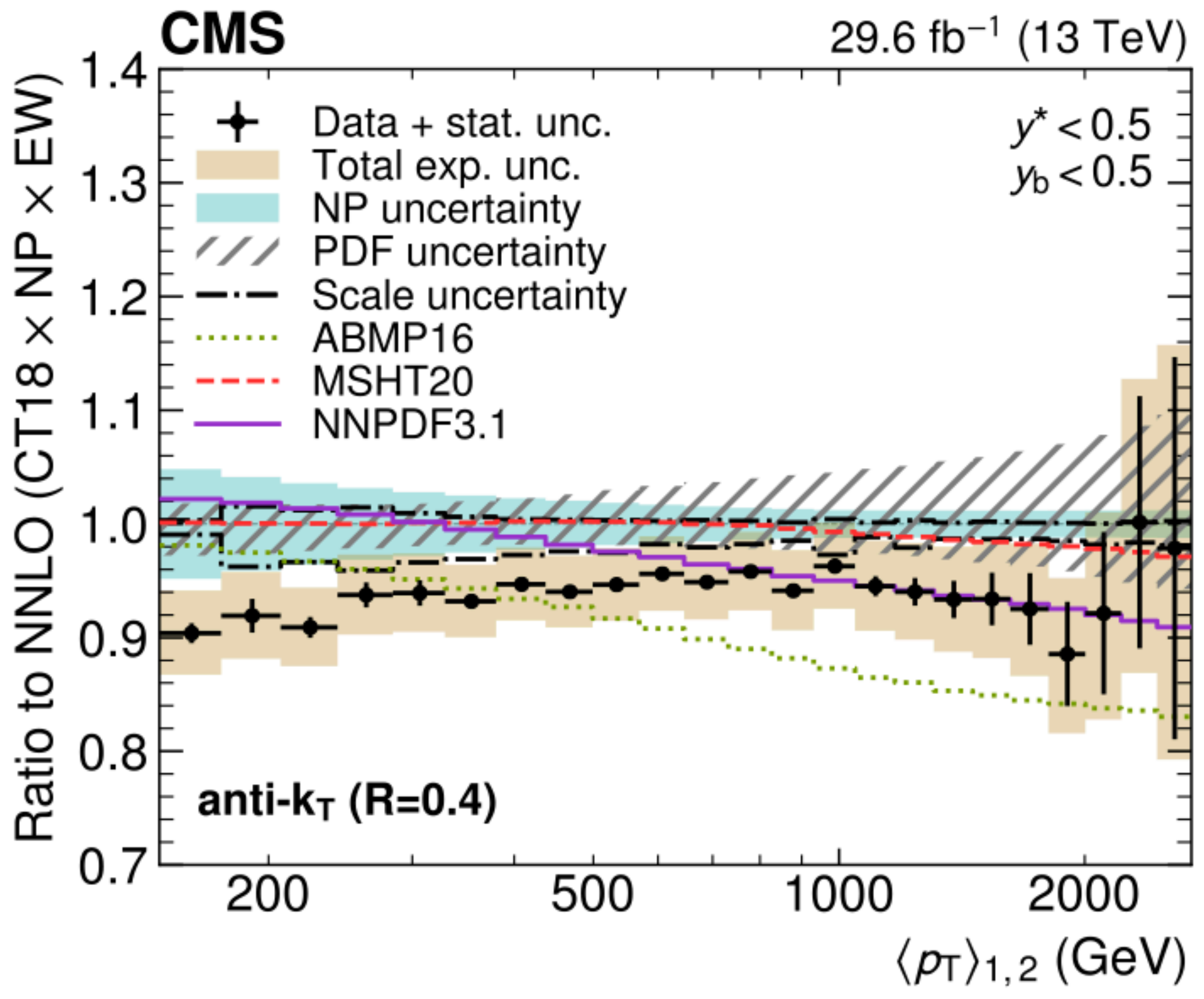
arXiv:2312.16669

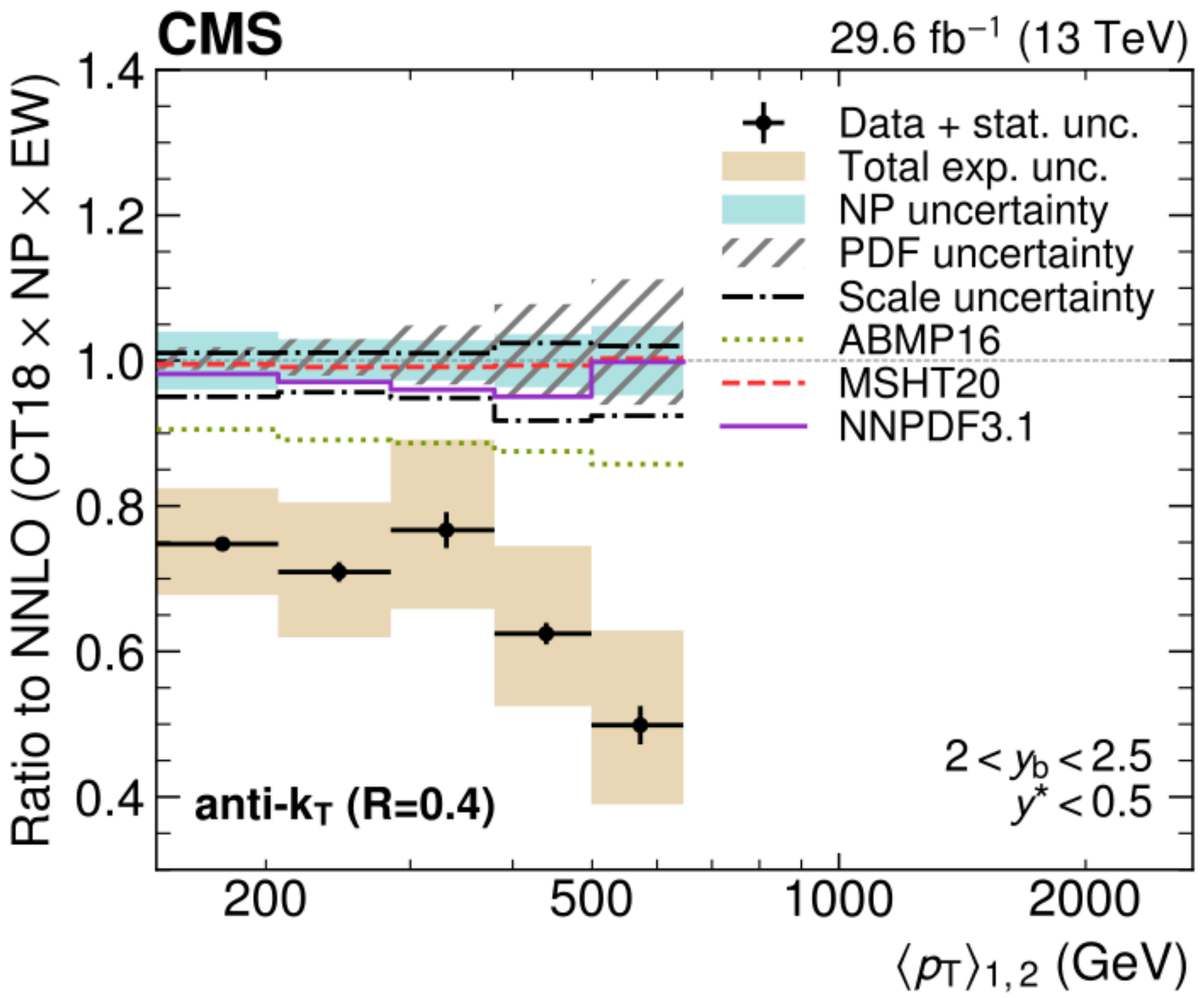


$\mu_R = \mu_F = m_{1,2}$

3D	2D
$y^* = \frac{1}{2}\lvert y_1 - y_2\rvert$	y_{max}
$y_b = \frac{1}{2}\lvert y_1 + y_2\rvert$	$m_{1,2}$
$\langle p_T\rangle_{1,2} = \frac{1}{2}(p_{T,1} + p_{T,2})$	





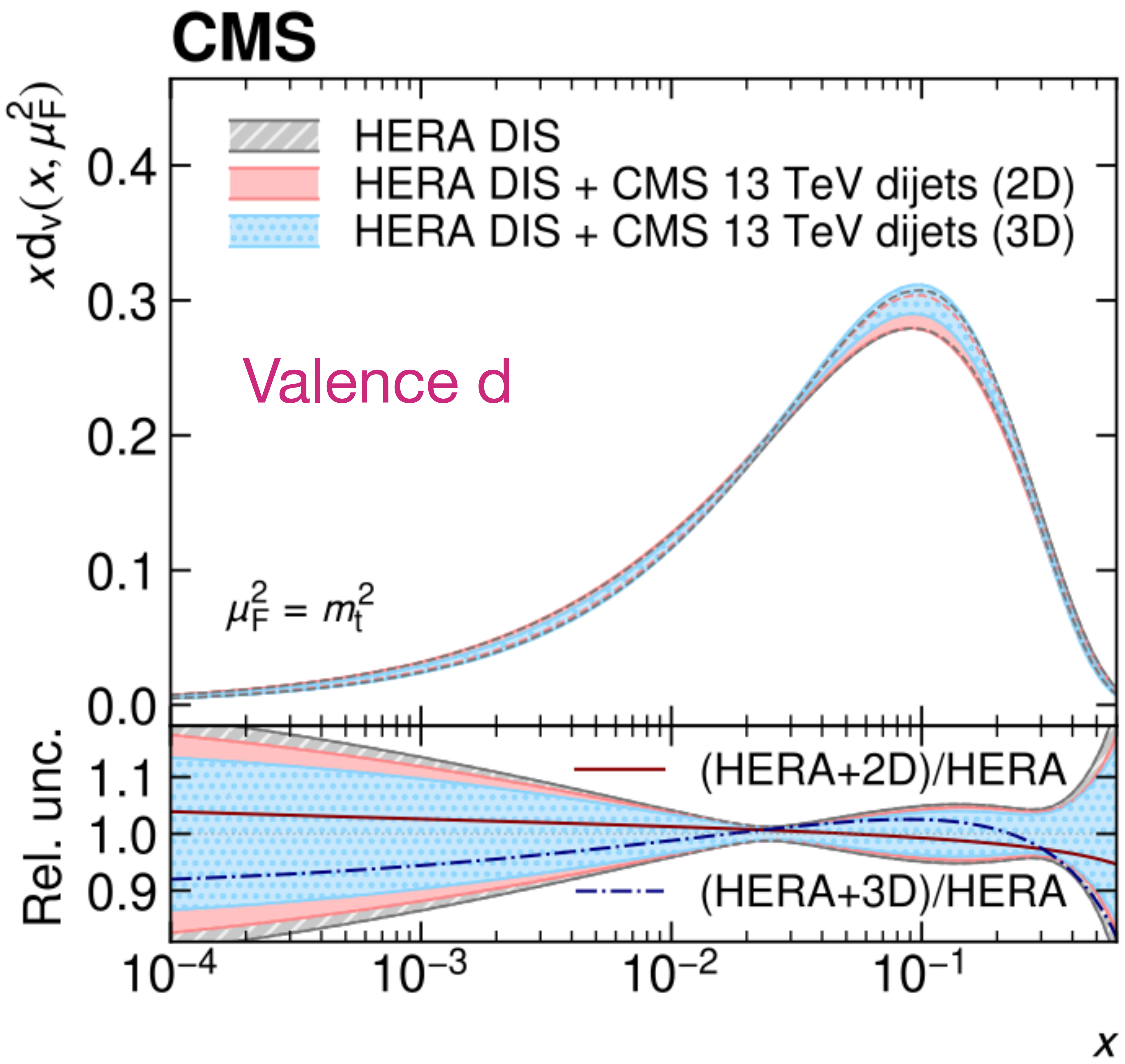


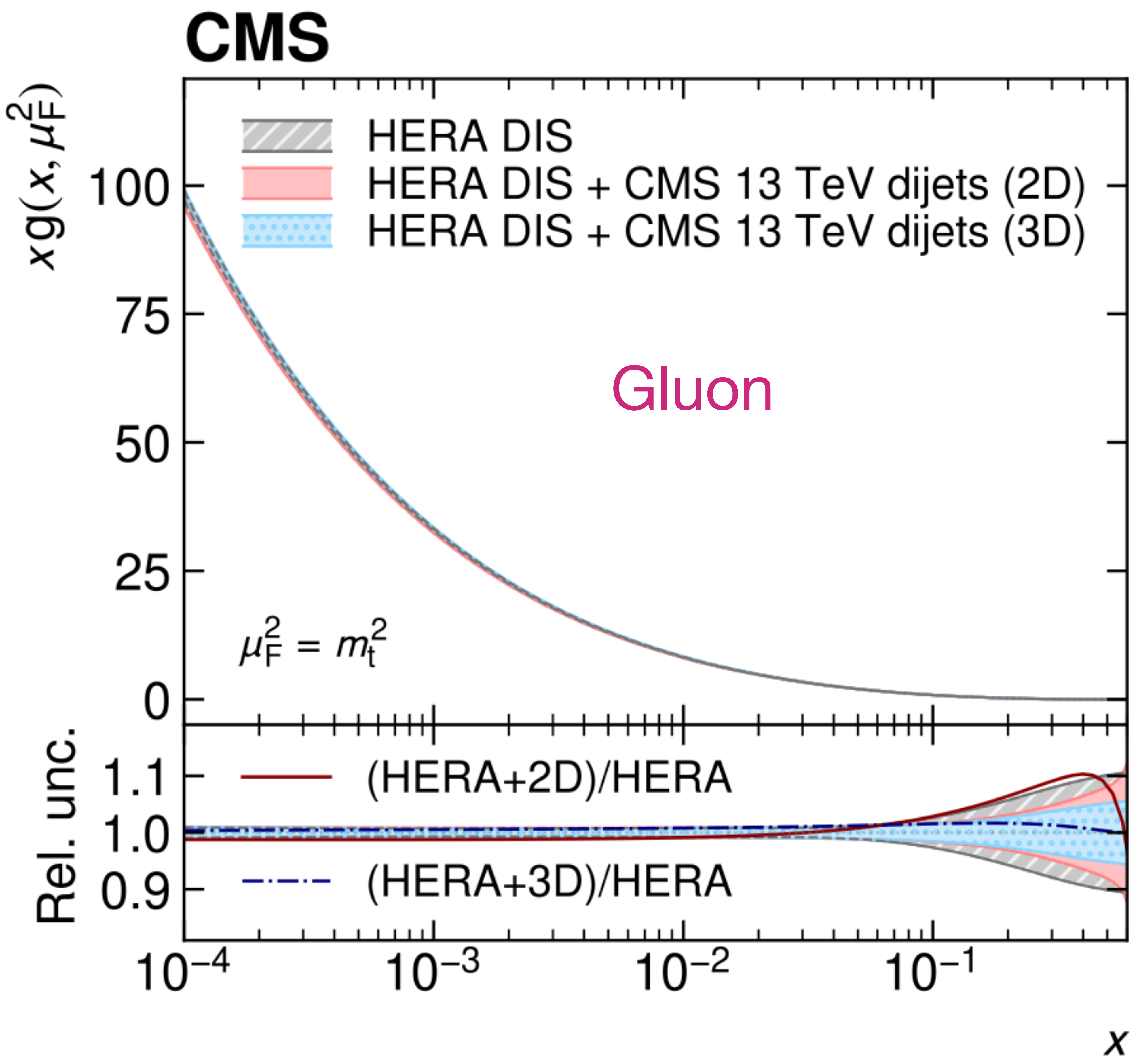
Hard QCD physics: di-jet production

- 10% underestimation by NNLO for small y^* and y_b.
  - 20% for large y_b and small y^*.
- PDF determination by performing $\mathrm{PDF} + \alpha_S$ fits:
  - Inclusion of dijet measurements leads to an improved determination of the PDFs.

$\alpha_S(m_Z) = 0.1179 \pm 0.0019$

- $\approx$ 1% coming from NNLO uncertainty!

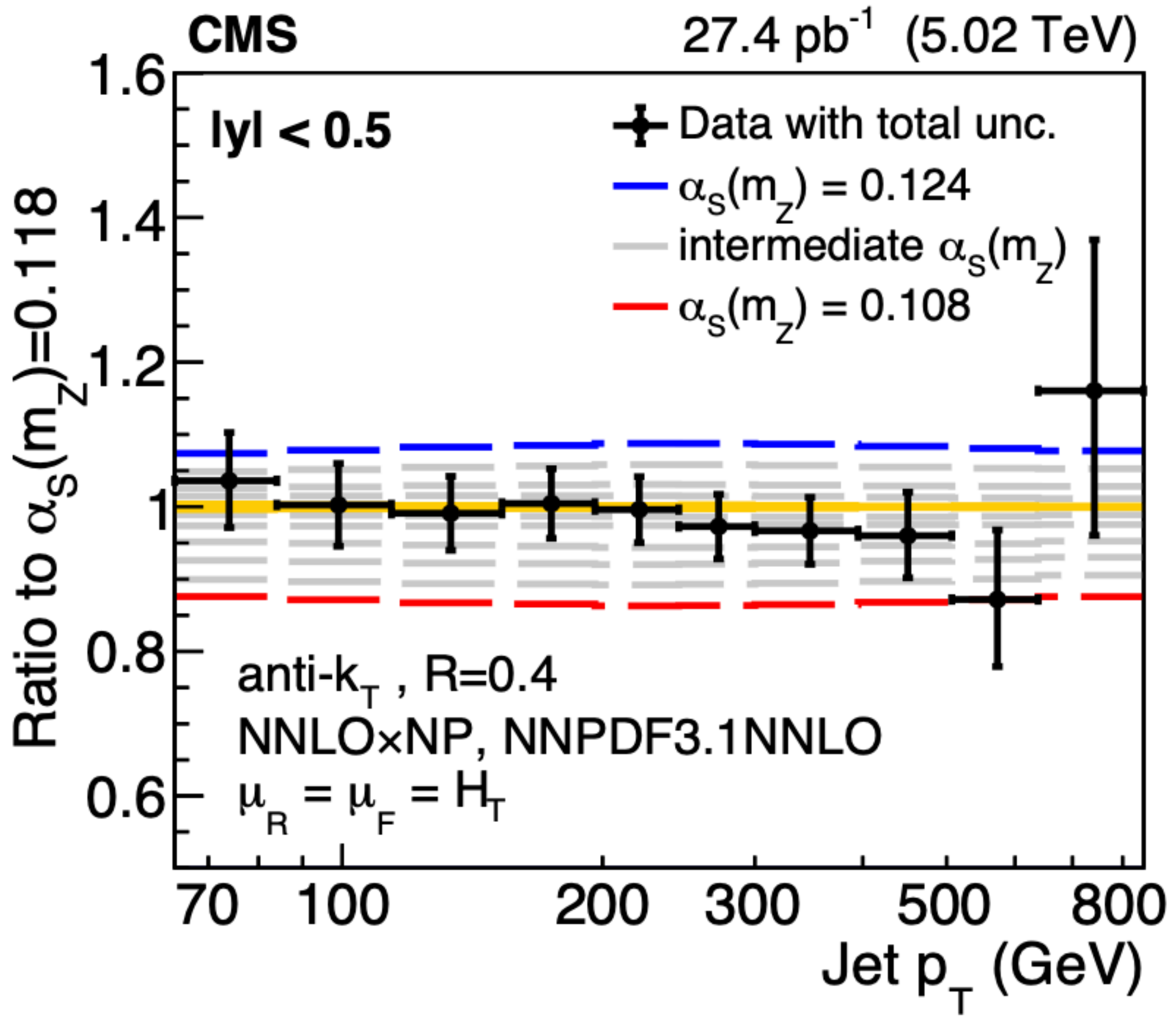




Hard QCD physics: inclusive jets production

- Inclusive jet cross section measurements:
  - Test QCD dynamics.
  - Sensitive to gluon PDF and α_S.
- Measurements compared to NLO and NNLO calculations.
  - Two scales compared at NLO: p_T and H_T.
- Sensitivity to α_S was studied.
  - Preference for $\alpha_S \sim 0.118$.

$p_T^{jet} > 60$ GeV, $|y^{jet}| < 2.0$



arXiv:2401.11355