NNLO predictions for three-jet cross sections at the LHC

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in collaboration with Michal Czakon and Alexander Mitov

based on: [1907.12911] and [2106.05331]

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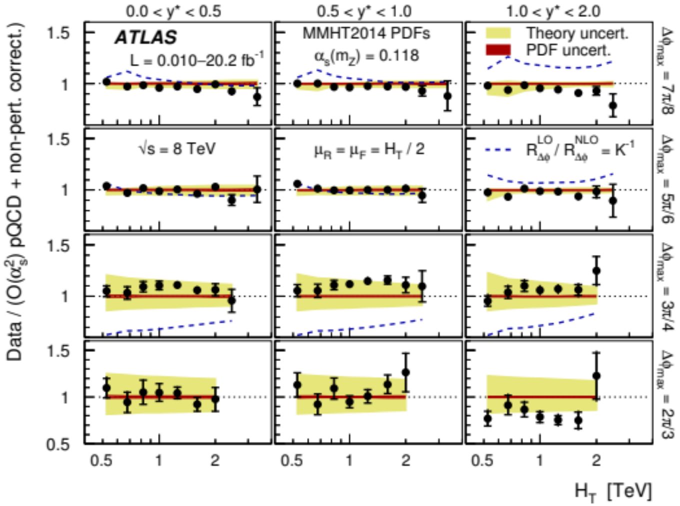
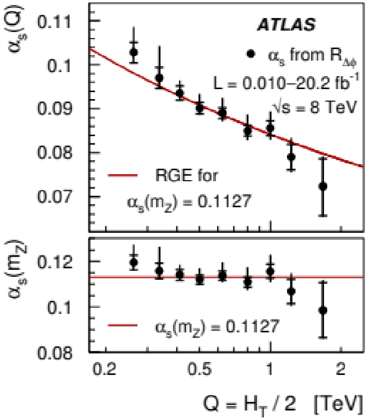
Jet observables at the LHC

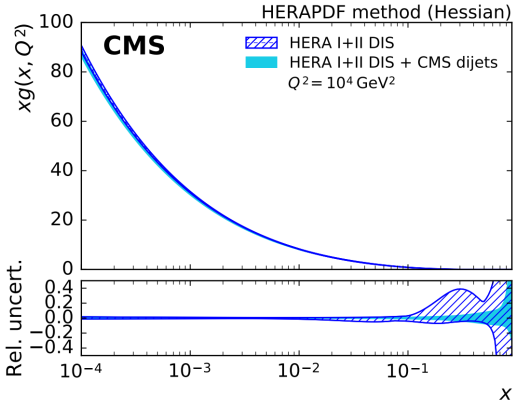
Tests of pQCD, α_s extraction:
R32 ratios, event-shapes





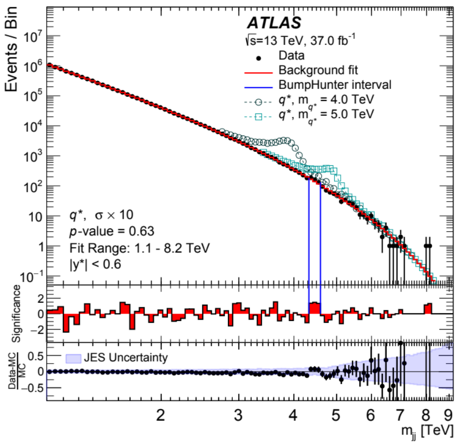
[1805.04691]

PDF determination:
Single inclusive,
Multi-differential dijet



[1705.02628]

NP searches:
dijet mass



[1703.09127]

Precision theory required!

Data driven

Precision predictions

Resummation

Fixed order
perturbation theory

Parton-showers

Precision theory predictions

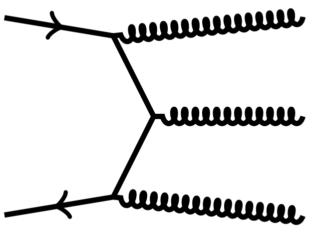
Parametric input:
PDFs and alphaS

Soft physics:
MPI, colour reconnection,
...

Fragmentation/hadronisation

Three jet production

Advances in perturbative QCD allow to tackle the most complicated 2→3 process



$pp \to ggg + X$

Bottlenecks:

- Handling of real radiation:
  - Sector-improved residue subtraction [Czakon'10'14'19]
  - Computationally very challenging! → O(1M CPUh)
- Double virtual amplitudes in leading colour approximation [Abreu'21]
  - Fast numerical evaluation → very small contribution to computational cost

Only Approximation made:
→ taken from [Abreu'21]

$$\mathcal{R}^{(2)}(\mu_R^2) = 2\,\mathrm{Re}\left[\mathcal{M}^{\dagger(0)}\mathcal{F}^{(2)}\right](\mu_R^2) + \left|\mathcal{F}^{(1)}\right|^2(\mu_R^2) \equiv \mathcal{R}^{(2)}(s_{12}) + \sum_{i=1}^{4} c_i \ln^i\left(\frac{\mu_R^2}{s_{12}}\right)$$

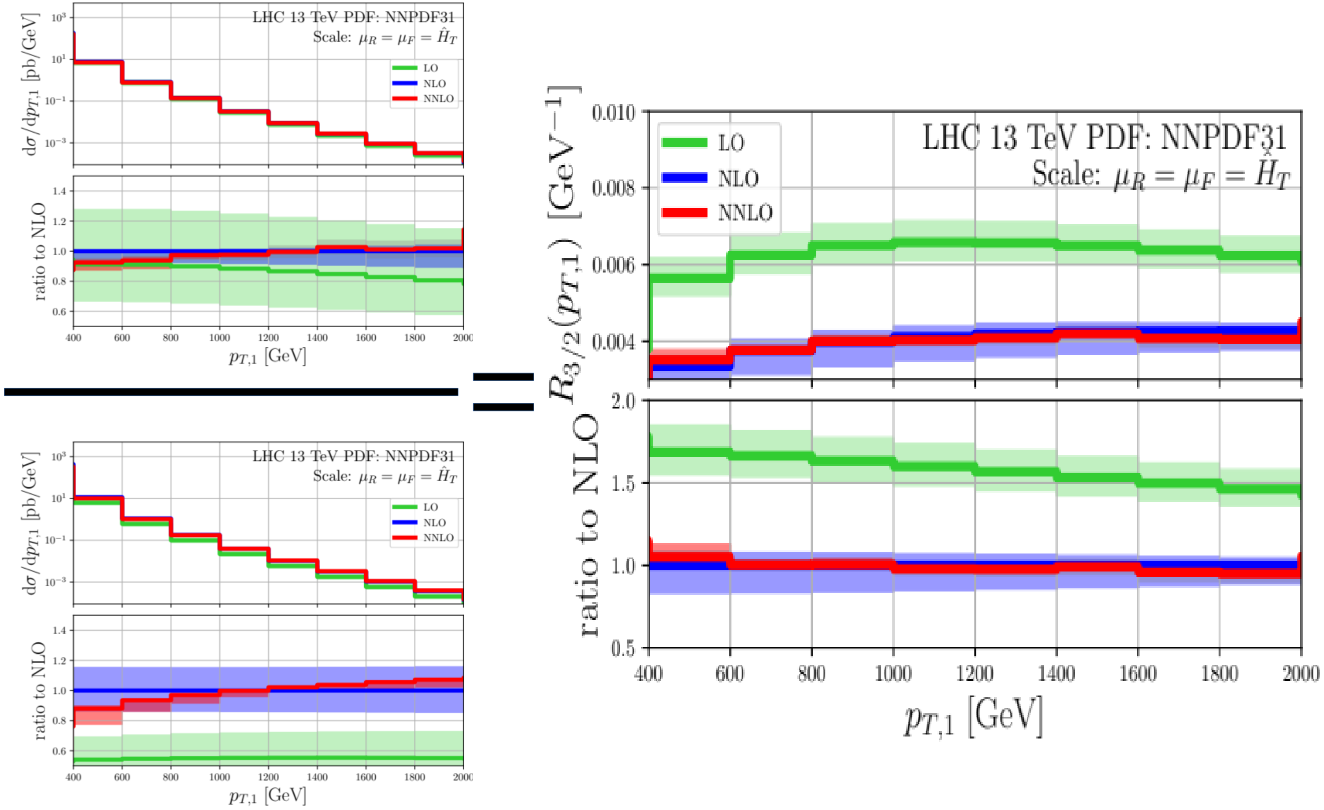
$$\mathcal{R}^{(2)}(s_{12}) \approx \mathcal{R}^{(2)l.c.}(s_{12})$$

Three jet production - R32(pT1)

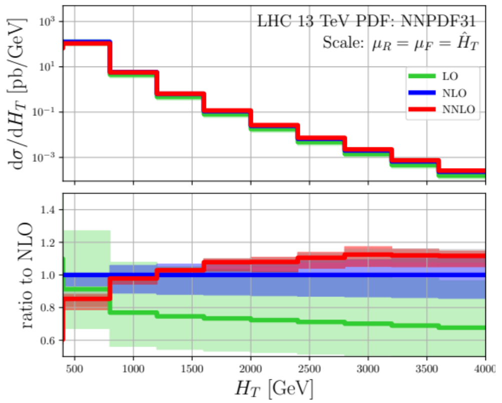
- LHC @ 13 TeV, NNPDF31
- Require at least three (two) jets:
  - $p_T(j) > 60$ GeV and $|y(j)| < 4.4$
  - $H_{T,2} = p_T(j_1) + p_T(j_2) > 250$ GeV
- Scales:

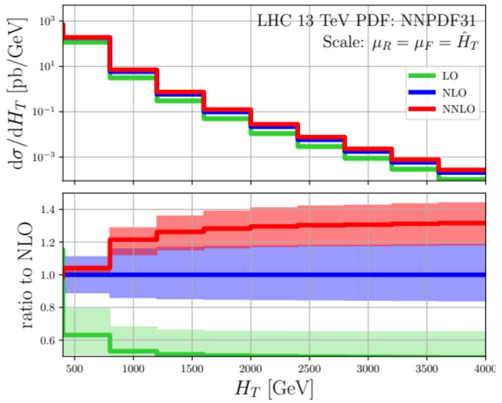
$$\mu_R = \mu_F = \hat{H}_T = \sum_{\text{partons}} p_T$$

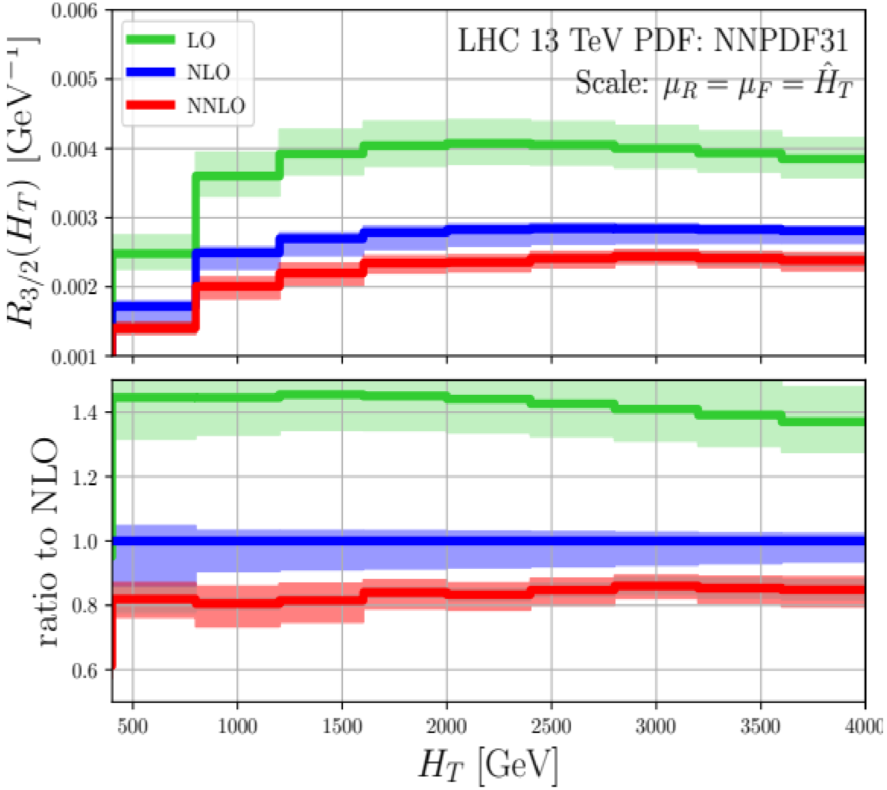
$$R_{3/2}(X, \mu_R, \mu_F) = \frac{\mathrm{d}\sigma_3(\mu_R, \mu_F)/\mathrm{d}X}{\mathrm{d}\sigma_2(\mu_R, \mu_F)/\mathrm{d}X}$$



Three jet production - R32(HT)







$$H_T = \sum_{\text{jets}} p_T$$

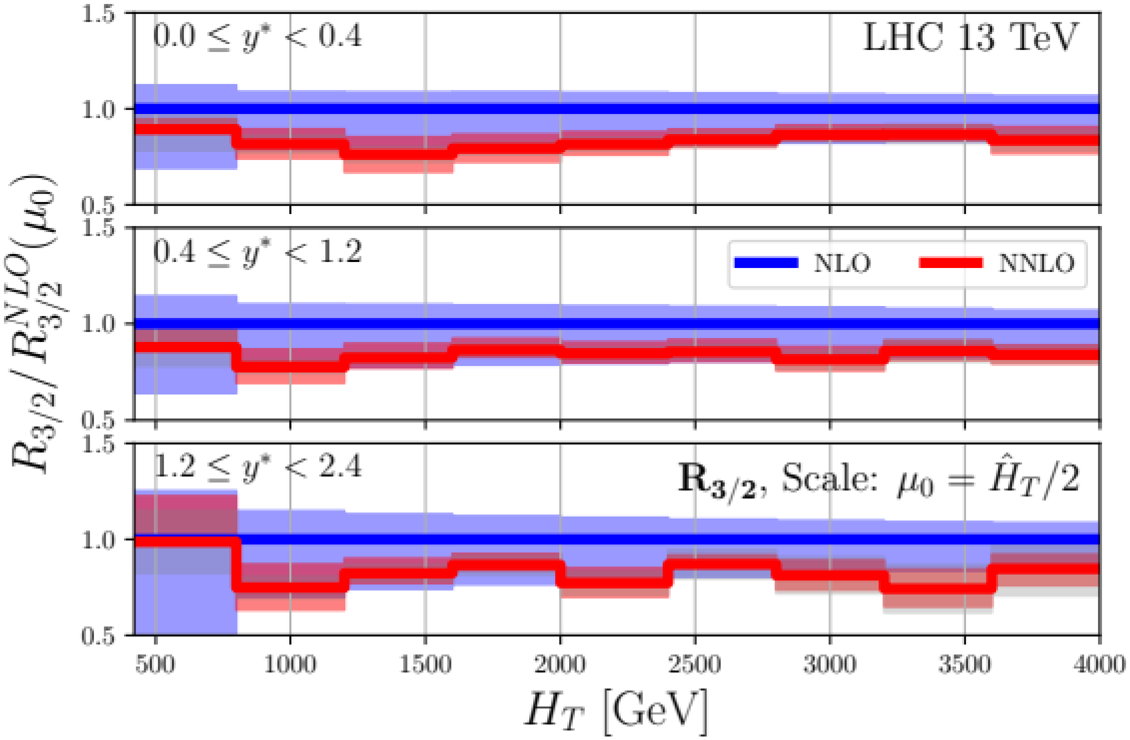
Scale dependence correlated in ratio

→ reduction of scale dependence

→ flat k-factor

→ scale bands in ratio barely overlap

Three jet production – R32(HT,y*)



Double differential w.r.t. $y^* = |y(j_1) - y(j_2)|/2$

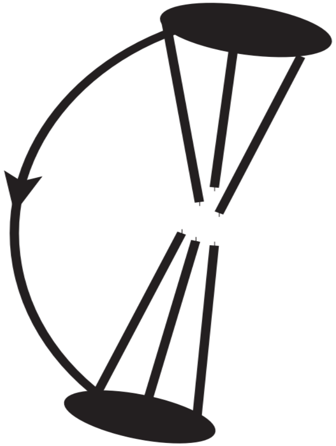
Different central scale choice: $\hat{H}_T/2$

Three jet production – azimuthal decorrelation

Kinematic constraints on the azimuthal separation between the two leading jets (ϕ_{12})

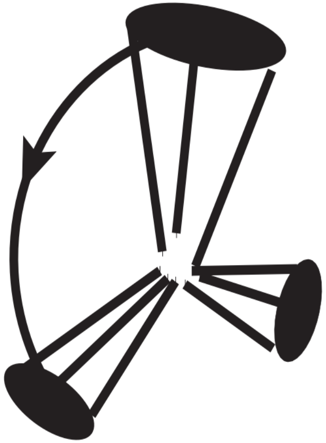
Dijet:

$\phi_{12} = \pi$



Trijet:

$\phi_{12} > \frac{2\pi}{3}$



φ12 sensitive to the jet multiplicity:

2j: $\phi_{12} = \pi$

3j: $\phi_{12} > \frac{2\pi}{3}$

4j: unconstrained

Study of the ratio:

$$R_{32}(H_T, y^*, \phi_{\max}) = \frac{\mathrm{d}\sigma_3(H_T, y^*, \phi_{12} < \phi_{\max})}{\mathrm{d}\sigma_2(H_T, y^*)}$$

Three jet production - azimuthal decorrelation

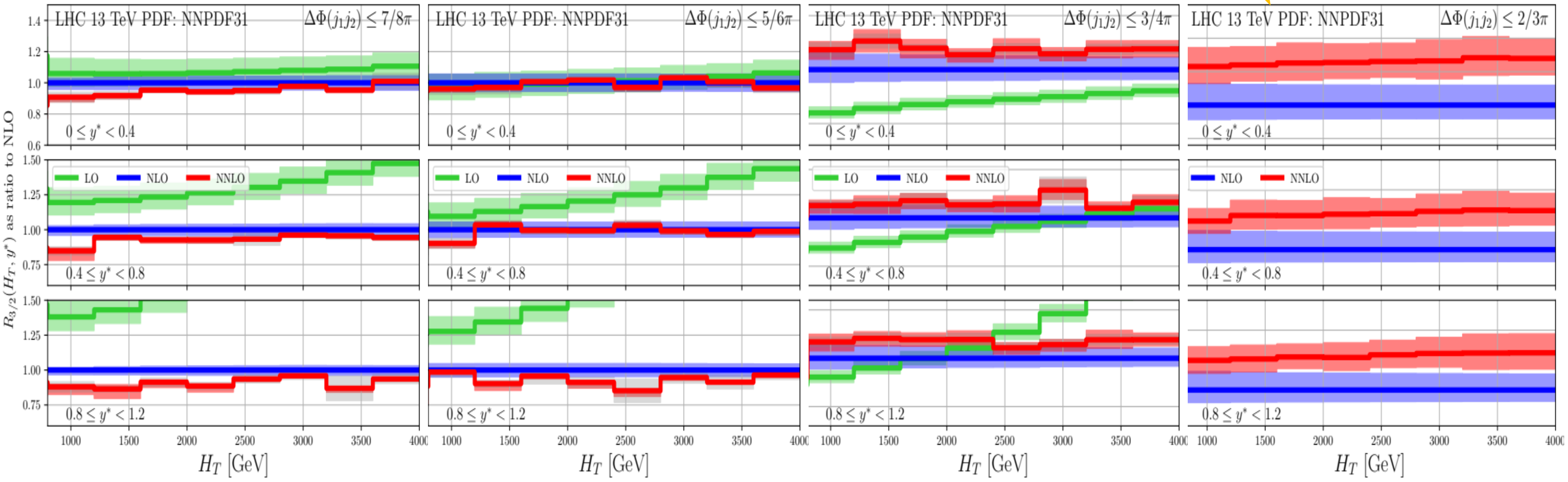
NNLO/NLO K-factor smaller than NLO/LO
Scale dependence is reduced

Work in progress: phasespace in [1805.04691]

NLO 4-jet

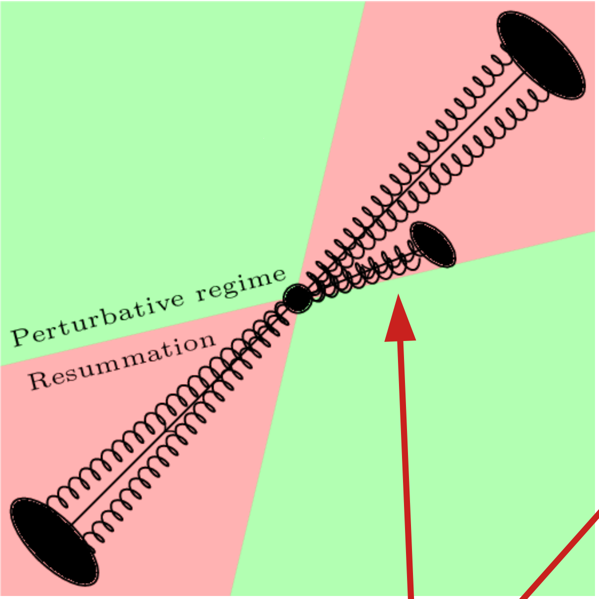
$\phi_{\max}$

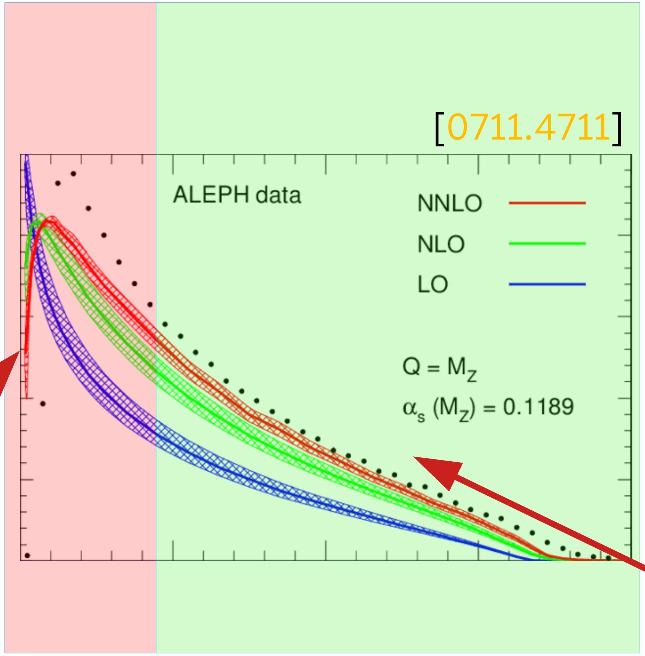
y^*

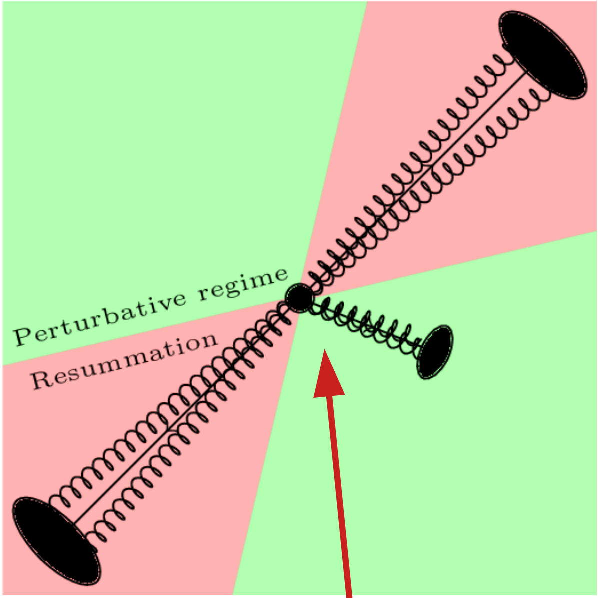


Event-shapes regimes

Typically event-shapes measure departure from dijet topologies







Anisotropic, dijet like

Sensitivity to resummation, non-perturbative effects

Example: 1-Thrust at LEP

Isotropic, multi-jet

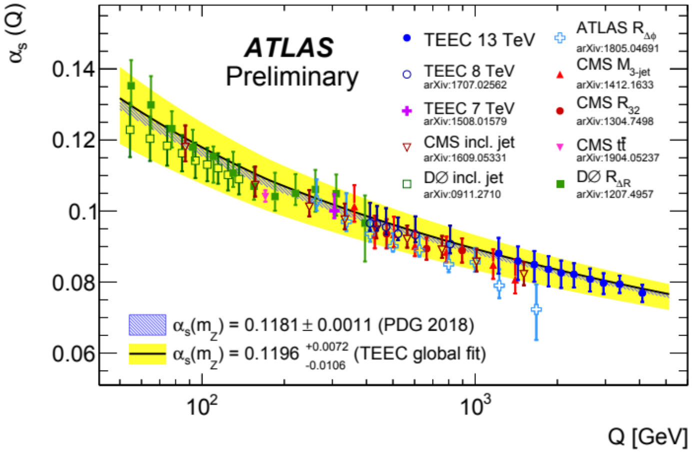
Sensitive to hard matrix elements

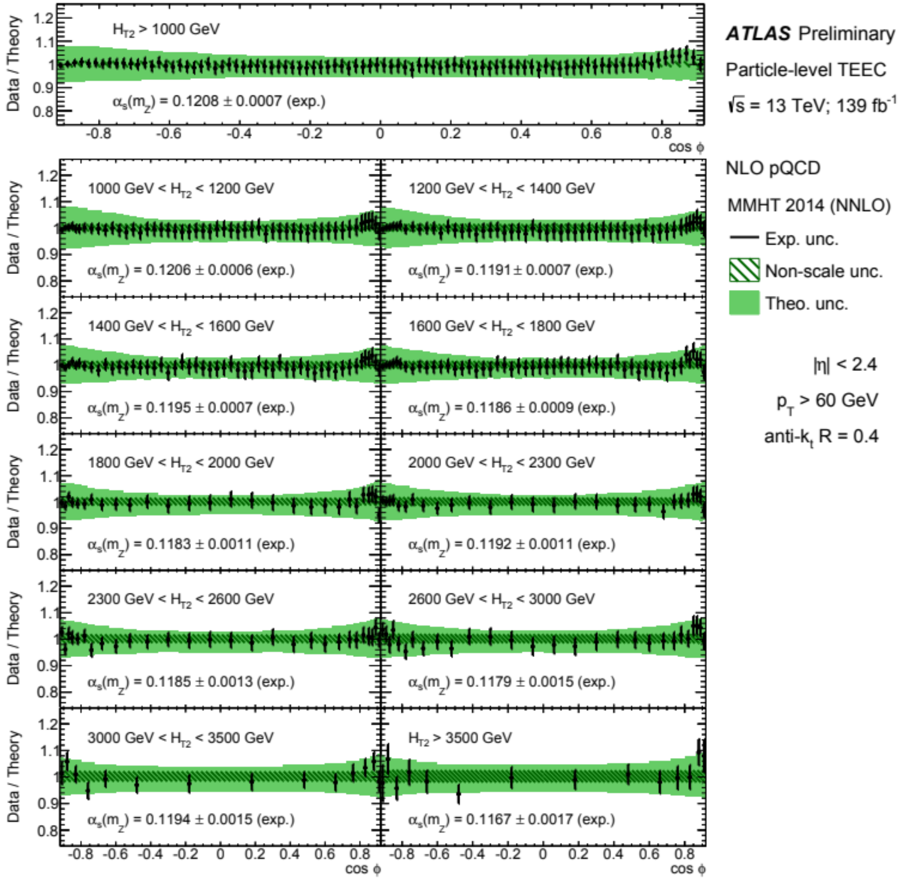
Event-shapes at the LHC

Strong coupling measurements from event-shapes:
→ three jet is leading contribution
→ normalization through dijet rates

TEEC: Transverse Energy-Energy Correlation

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





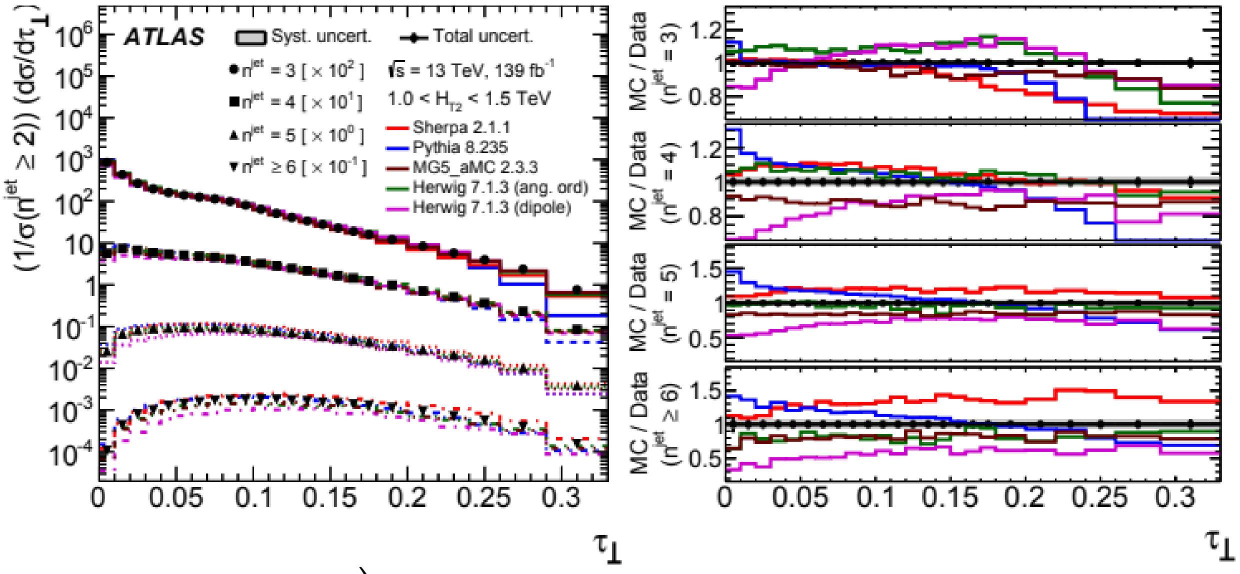
[ATLAS-CONF-2020-025]

Event-shapes at the LHC

ATLAS measurement of event shapes [2007.12600]

Transverse Thrust:

$$\tau_T = 1 - \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum |\vec{p}_{T,i}|}$$



Sphericity tensor:

$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}$$

Summary and Outlook

R32 ratios with the sector-improved residue subtraction framework

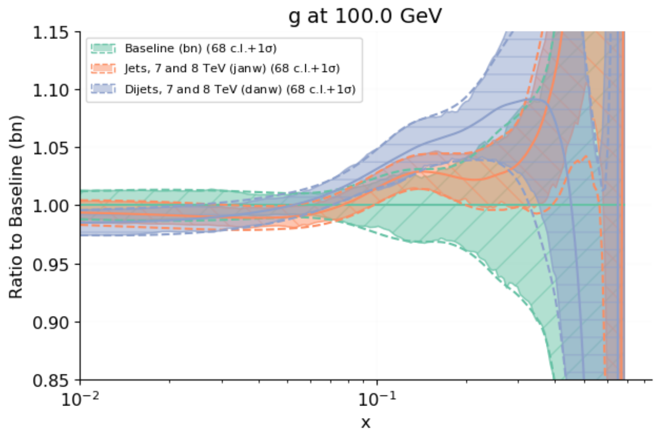
- Full NNLO QCD predictions for dijet production available
  → scale choice important
  → sub-leading colour contributions small
- Three jets @ the LHC:
  - First predictions available with approximate two-loop contribution!
    → improved scale dependence and stabilized K-factors
    → pT spectra, HT, double differential
  - Real radiation for 2→3 can be handled.
    But efficiency is a concern and needs some attention!

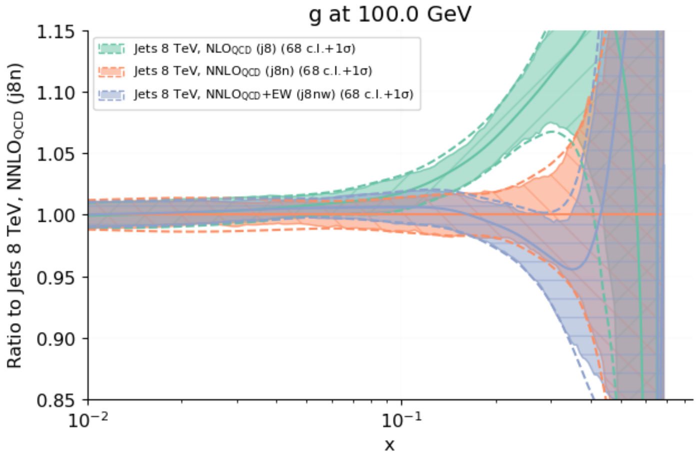
Many interesting applications ahead! → Event-shapes
Stay tuned!

Thank you for your attention!

Backup

Higher order pQCD: PDF fits with jets





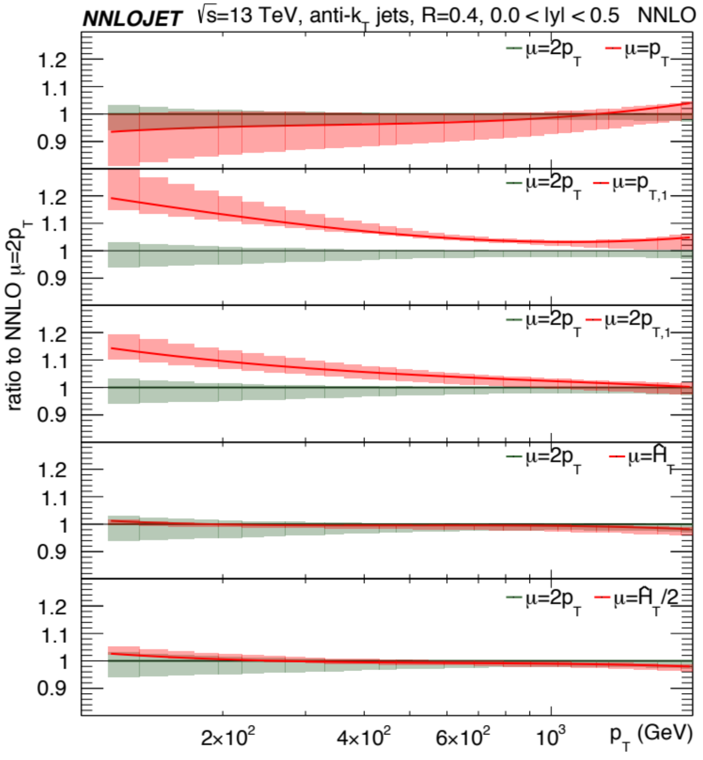
Idea (quite old actually [Giele'94]):

Here by a collaboration of NNLOJet and NNPDF [Khalek'20]:

Combine single inclusive and dijet triple differential measurements by ATLAS and CMS to constrain the large gluon-x

- Reduced uncertainty in large-x gluon PDF
- NNLO QCD corrections crucial to obtain consistent results between data sets
- NLO EW [Dittmaier'12] or
  full NLO corrections [Frederix'17,Reyer'19]

Higher order pQCD: lessons from dijet



Detailed studies of
scale dependence:
Event-based choices vs.
single jet choices
[Currie'18]

Study of
sub-leading colour
effects
in quark channels:
smaller than O(1%)
[Czakon'19]