NNLO QCD predictions for single jet inclusive production at the LHC

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Based on work in [Phys. Rev. Lett. 118, 072002 (2017)] and new results

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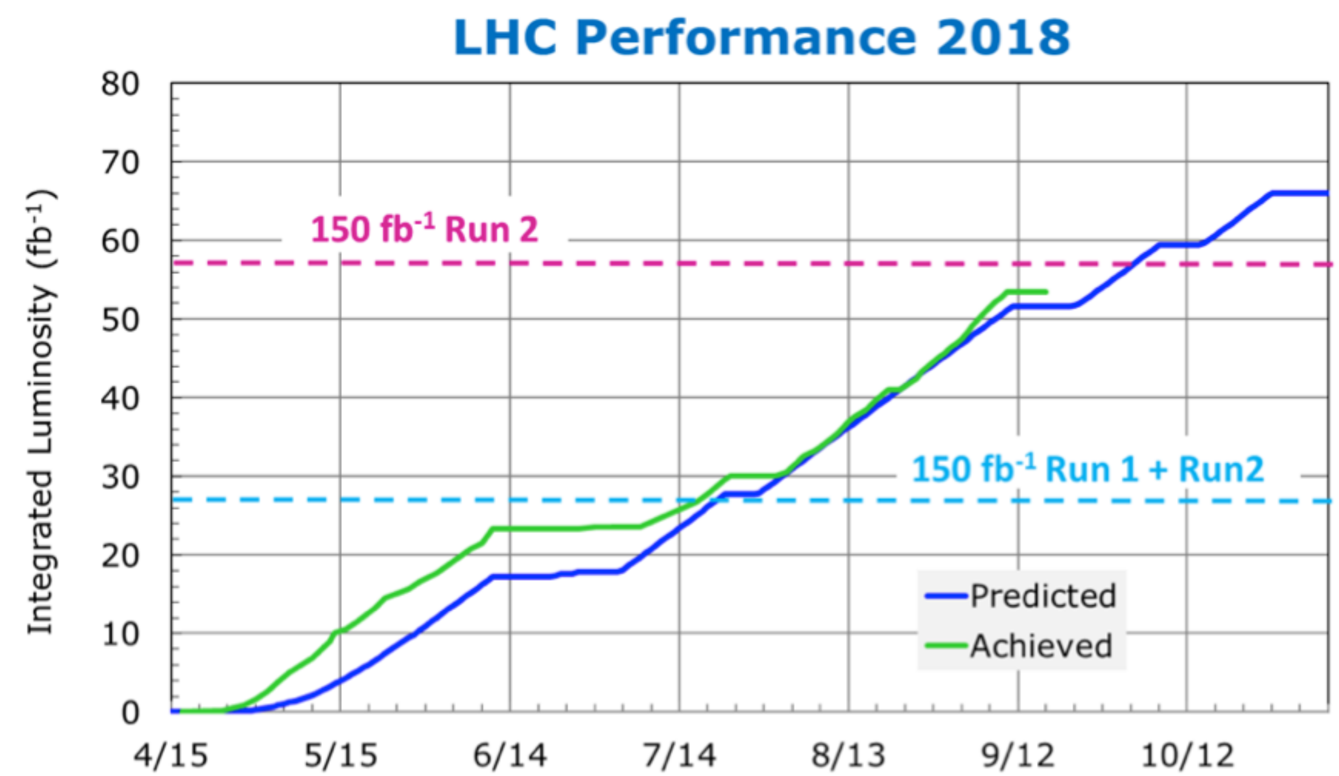
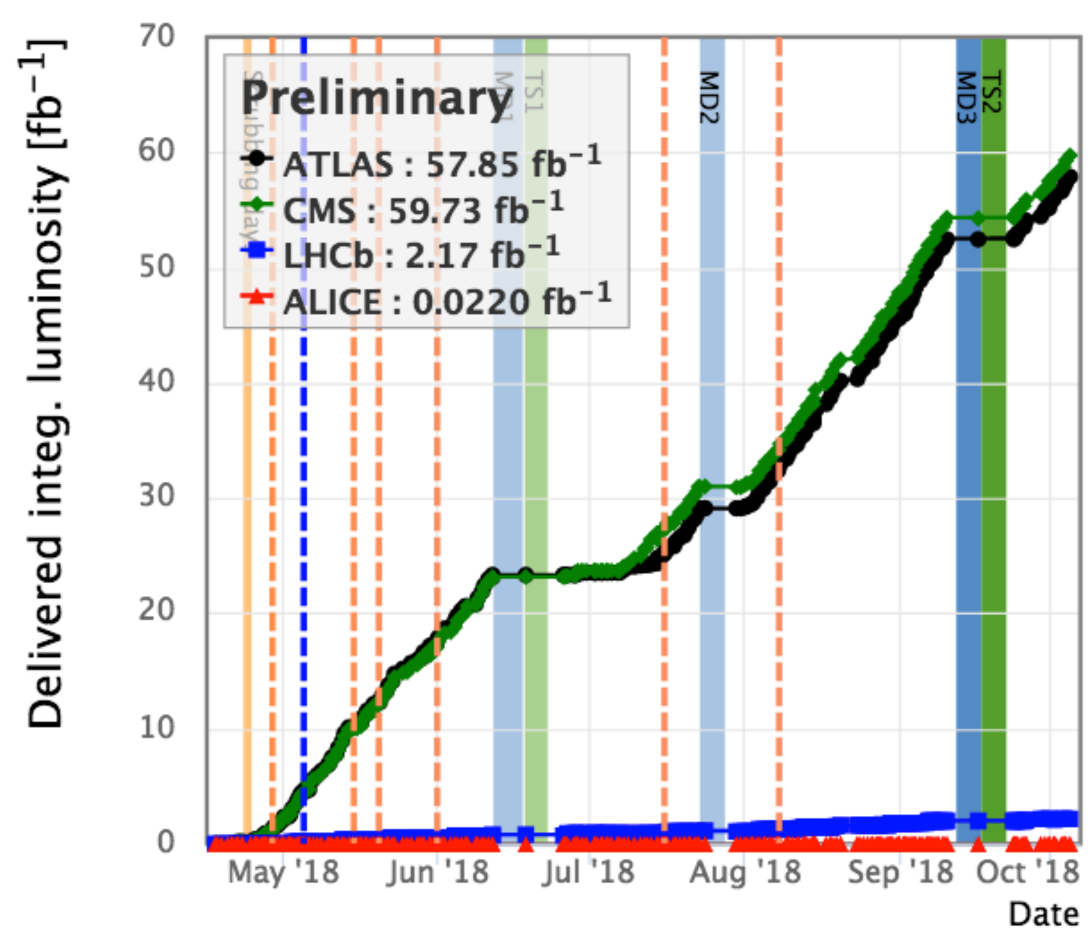
Centro de Física Teórica de Partículas

LHC performance

- coming to end of run II phase [2015-2018] with *pp* collisions at $\sqrt{s}$=13 TeV
- 2018: 1.3x increase factor in peak luminosity averaging ~ 2.0 10^{34} $cm^{-2}s^{-1}$
- **Luminosity targets for 2018 being met by all the collaborations → 10/10/2018**
  - **ATLAS: 59.73 fb^{-1} ; ALICE: 0.025 fb^{-1}**
  - **CMS: 61.43 fb^{-1} ; LHCb: 2.25 fb^{-1}**
- full run II exceeded **150 fb^{-1}** of integrated luminosity per experiment
- approaching Heavy Ion run in November/ 2018 before long shutdown 2
- expect to resume *pp* collisions in 2021 to begin LHC run III at $\sqrt{s}$=14 TeV





Outline

- *jet production at LHC*: motivation and phenomenological relevance of the final state
- Calculation of the NNLO QCD correction
- The *NNLOJET* parton-level event generator
- Numerical results for inclusive jet production at the LHC
- Comparison with ATLAS/CMS jet data
- Outlook and conclusions

Jet production at the LHC

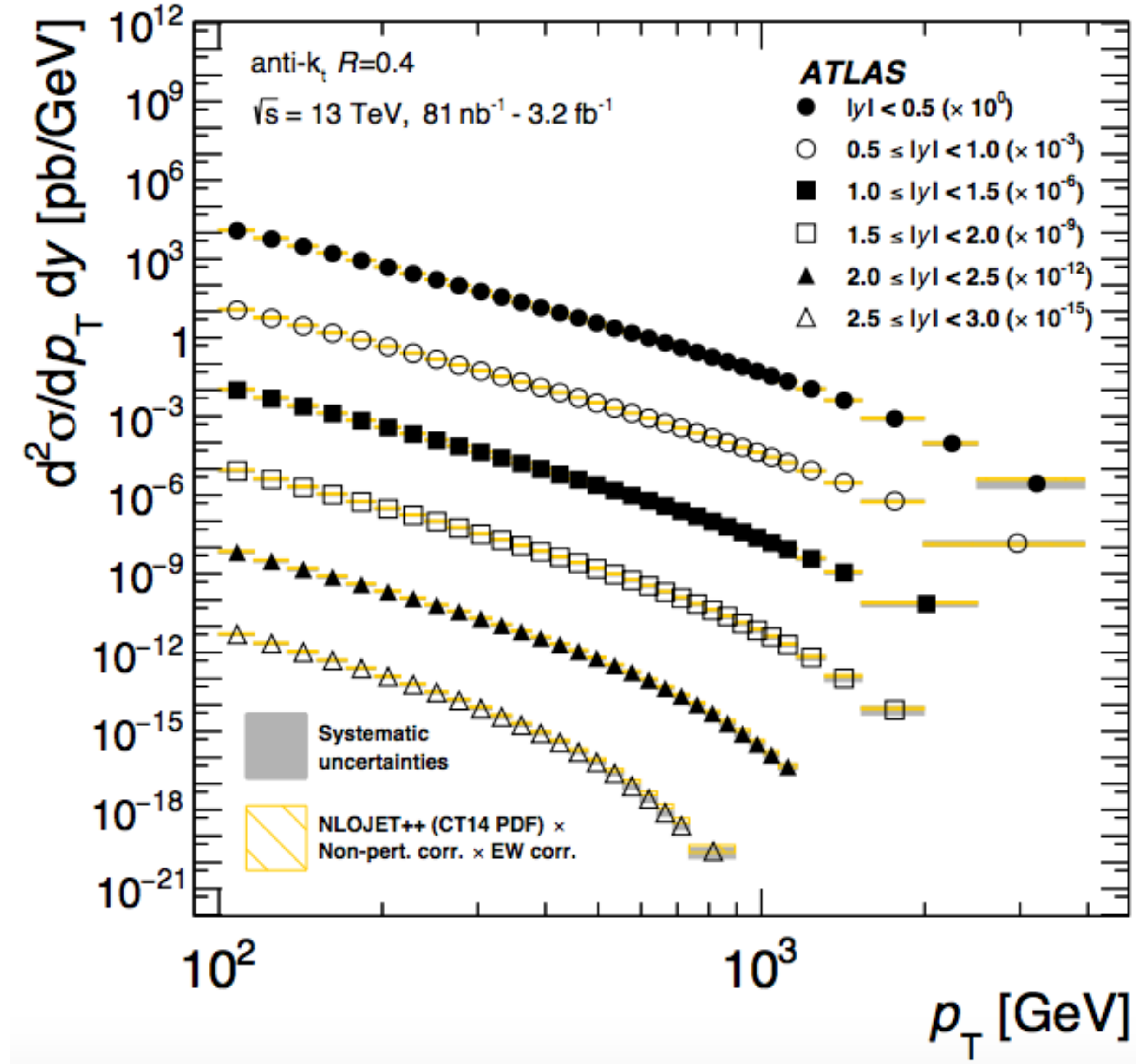
- look at production of jets of hadrons with large transverse energy

- for sufficiently high transverse momentum p_T > 20 GeV high rates and clean and simple cross section definition

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y}$$

Phenomenology of jet production at the LHC:

- test perturbative QCD
    - wide kinematical range in jet pT and rapidity covers 7 orders of magnitude in cross section



Single jet inclusive: (pp→jet+X)
ATLAS@13 TeV (arXiv:1711.02962)

Jet production at the LHC

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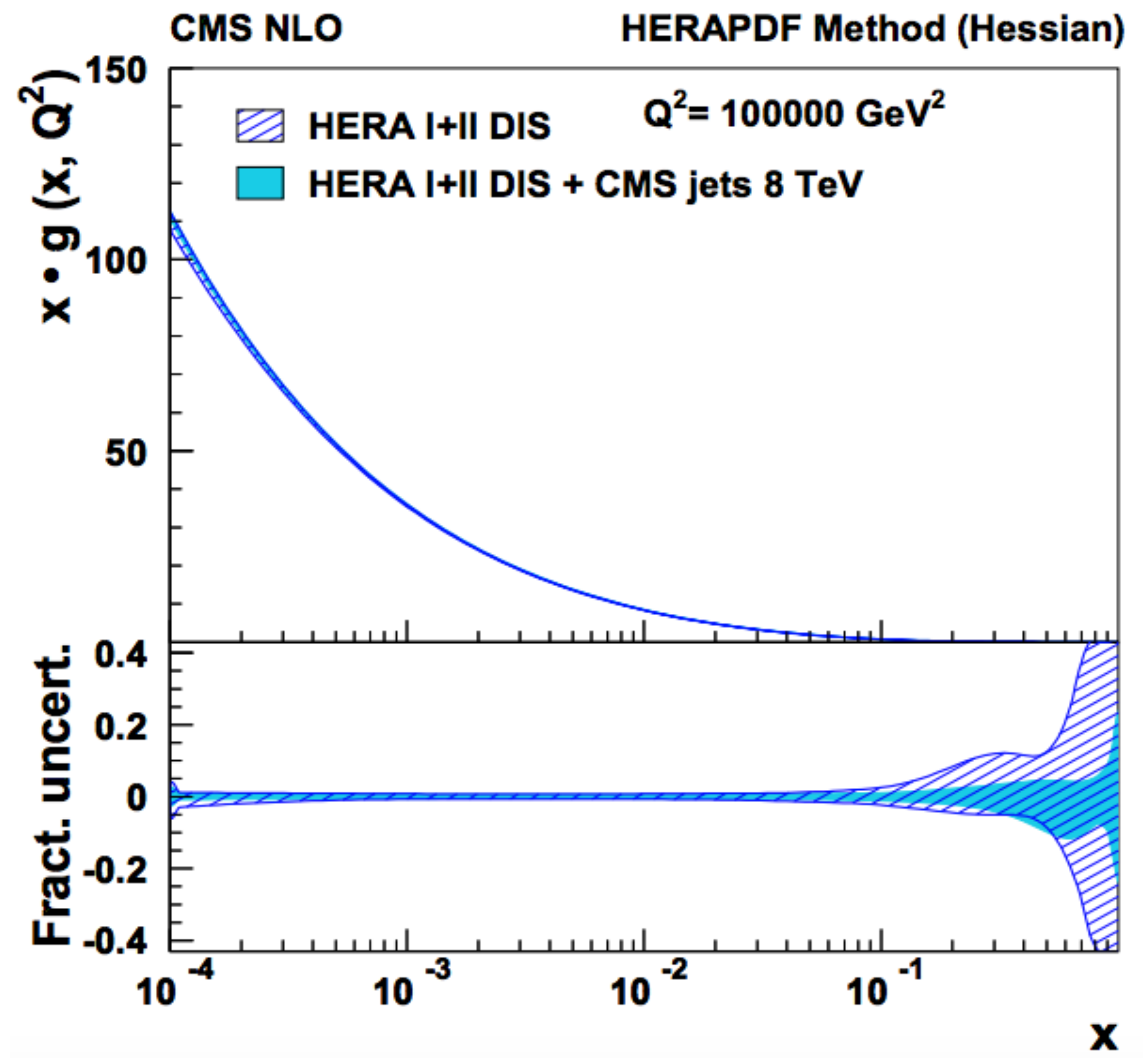

Gluon PDF fractional uncertainty with LHC jet data included CMS (arXiv:1609.5331)

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$$\frac{d\sigma}{dp_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y}$$

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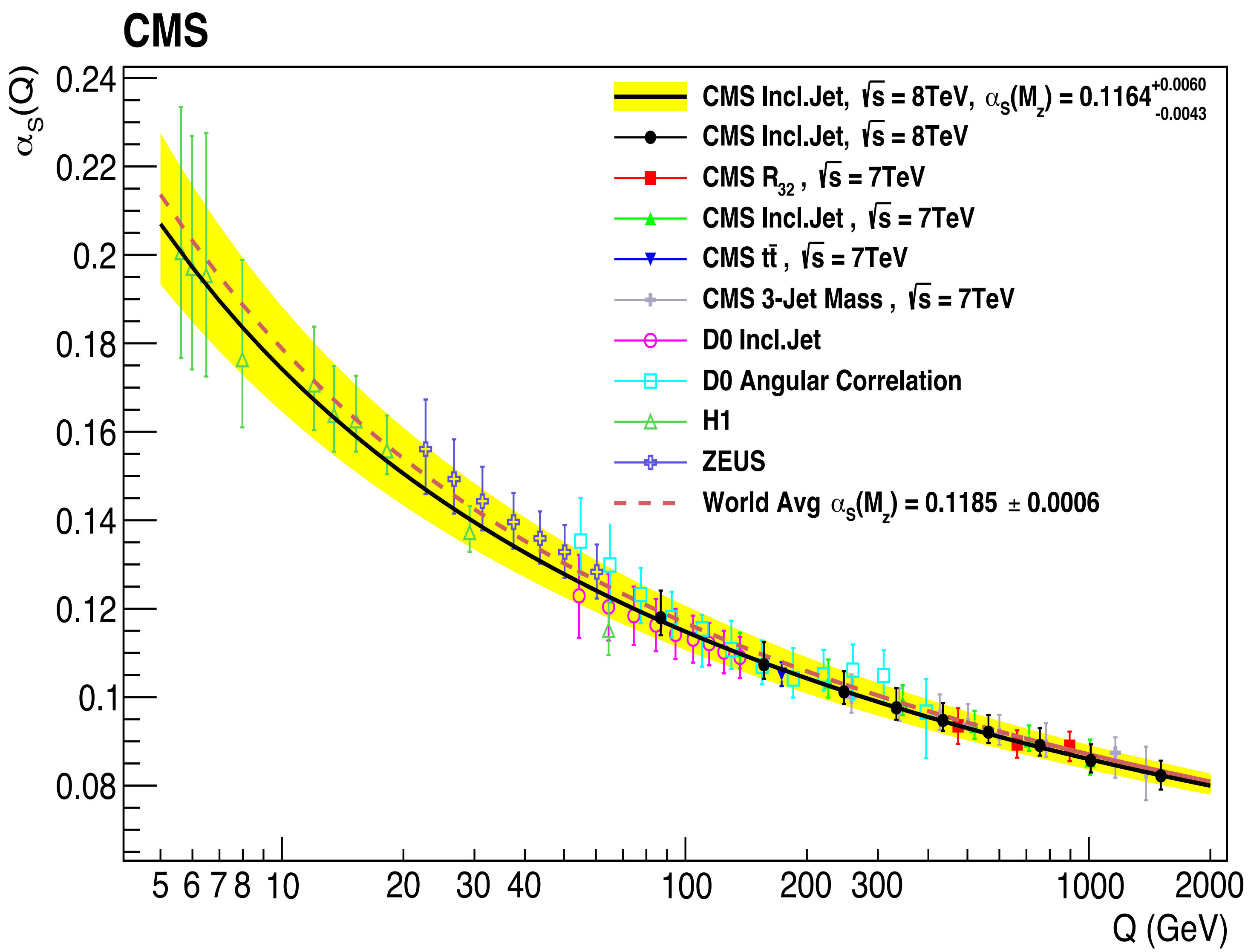

α_s running in the TeV range from LHC jet data

Jet production at the LHC

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Phenomenology of jet production at the LHC:

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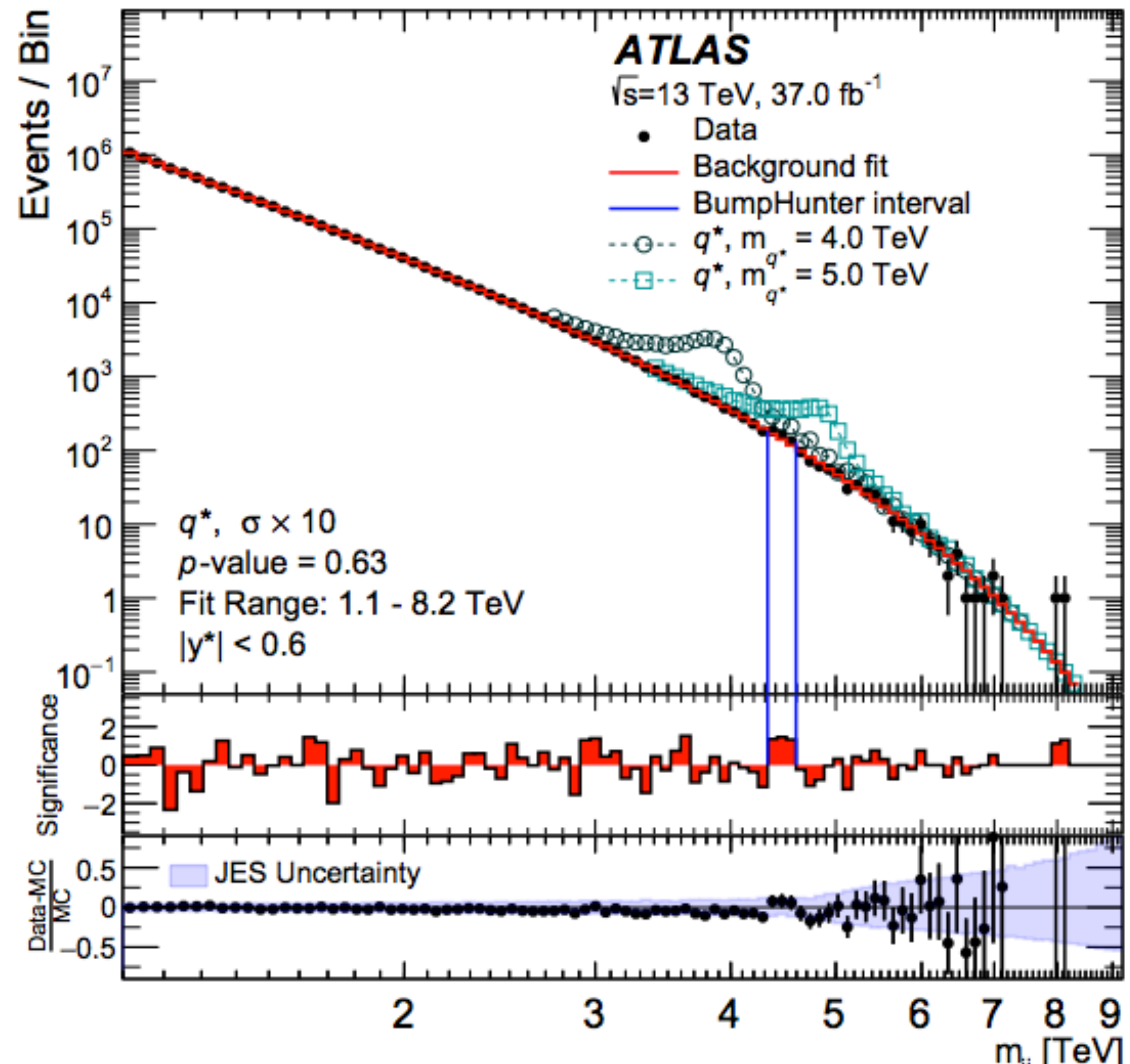
- search for BSM physics in resonances



High mass BSM resonance decaying to jets search by ATLAS@13 TeV (arXiv:1703.09127)

Jet production at the LHC

- look at production of jets of hadrons with large transverse energy
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$$\frac{d\sigma}{dp_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y}$$

Phenomenology of jet production at the LHC:

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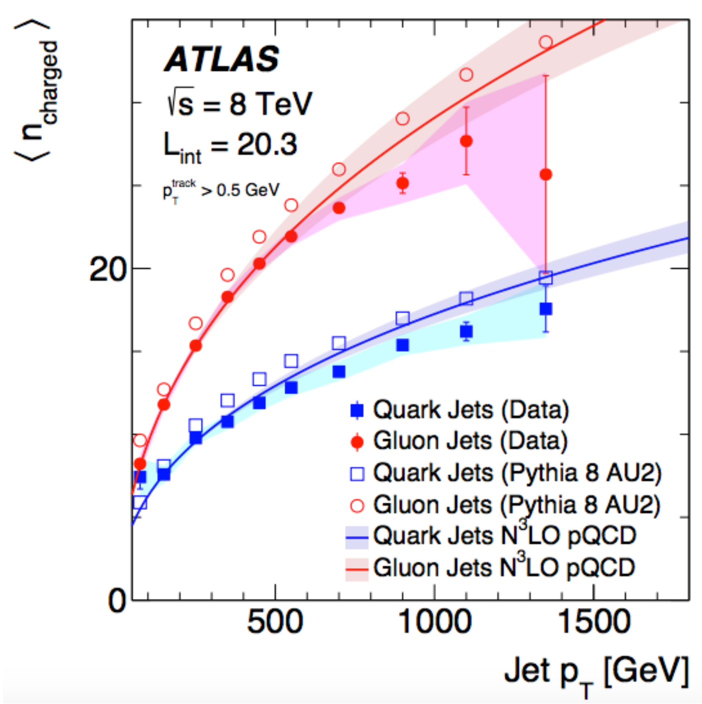
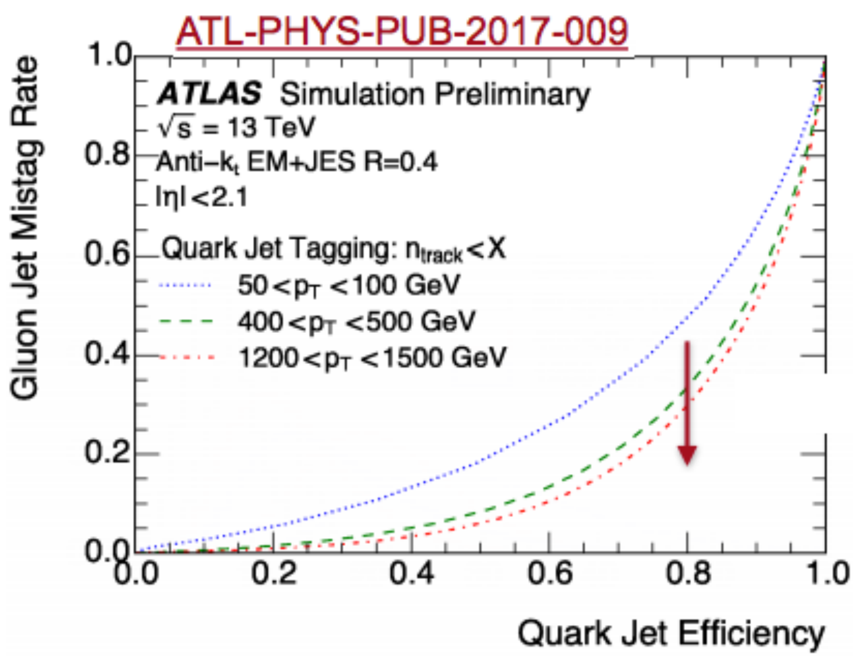
- determine structure of the proton →PDFs (sensitivity to the gluon medium to high-x)
- determine α_s and running of α_s from a single experiment
- jet substructure and quark/gluon jet identification





Improved gluon rejection at higher p_T

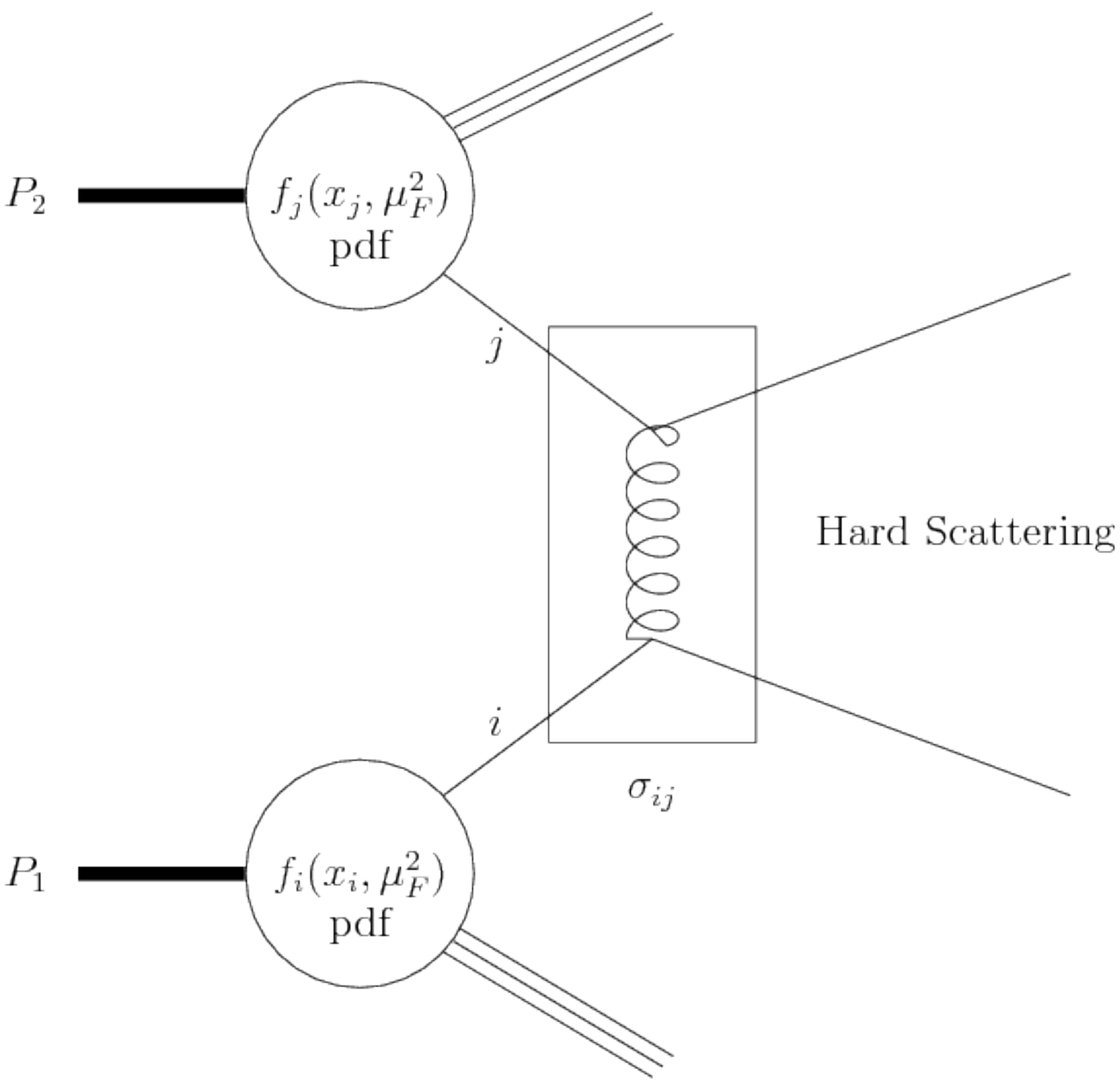
Squarks decay to ligh-quark jets while SM backgroung is dominated by gluon initiated jets

Average charged-particle multiplicity as q/g jet tagger ATLAS@8 TeV (arXiv:1602.00988)

Theoretical framework

- Improved parton model formula

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), s/\mu^2, s/\mu_F^2)$$



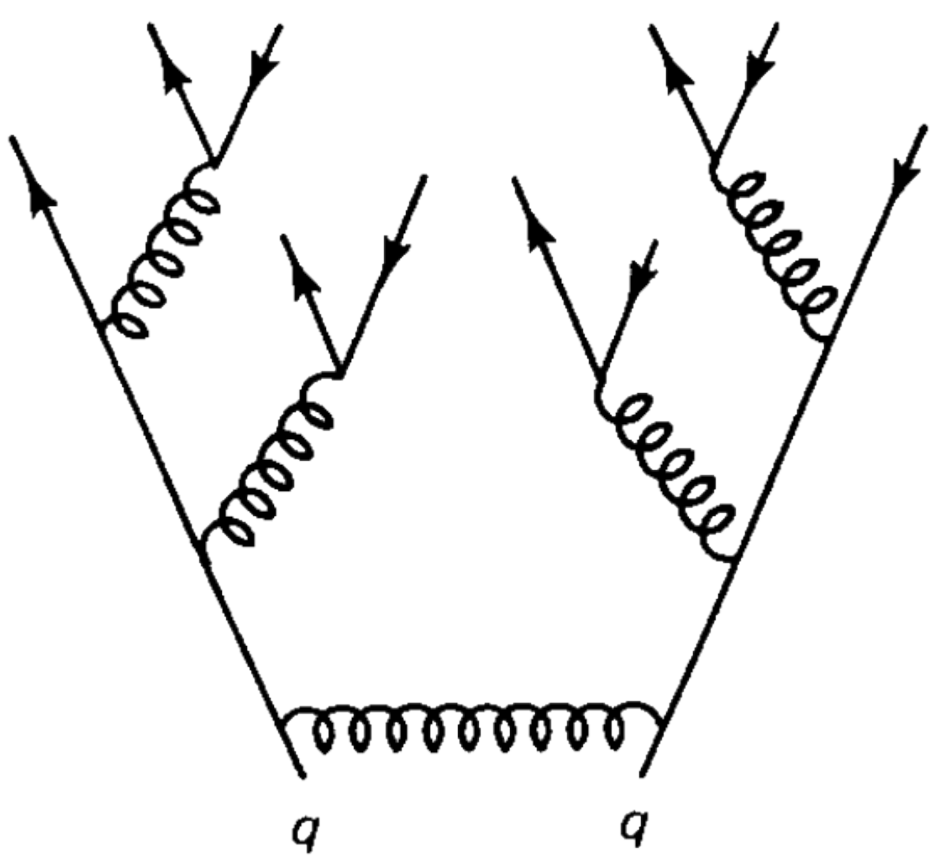
To apply:

- require large momentum transfer
- scale of the reaction $Q^2 \gg \Lambda_{\text{hadronic}}$
- quarks and gluons behave as free particles in the collision
- running coupling $\alpha_s(Q^2)$ decreases at high-scales
- compute partonic cross section σ_{ij} in perturbation theory from first principles → QCD Lagrangian

Theoretical framework

After hard scattering respect *quark confinment*:

- individual quarks cannot be observed directly



- force between quarks increases as they are separated
- I - soft and collinear radiation produces new $q\bar{q}$ pairs
- higher order corrections and parton shower matched to ME calculation simulate QCD radiation from the scattering scale Q^2 to the hadronization scale $\Lambda_{\text{hadronic}}$
- II - hadronization of quarks and gluons to form collimated bound states of baryons and mesons → final state jet

- properties of the final state jet follow closely the properties of the parton that initiated it local *parton-hadron duality*

Jet algorithms

Jet algorithms standardise the definition of jets and reduce the complexity of the final state to simpler calculable objects

- find the smallest distance measure d_{ij} between two particles and combine them if d_{ij} smaller than the jet resolution size R

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}\,, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{ti}^{2p}\,,$$

- CMS and ATLAS have settled on anti-k_T jets (p=-1)

$$\mathcal{J}_{n+1}(p_1, \ldots, p_i, p_j) \stackrel{p_i//p_j}{=} \mathcal{J}_n(p_1, \ldots, p_{ij})$$

$$\mathcal{J}_{n+1}(p_1, \ldots, p_n, p_i) \stackrel{p_i \to 0}{=} \mathcal{J}_n(p_1, \ldots, p_n)$$

- infrared-safe jet definition → allows inclusion of higher order perturbative corrections to the inclusive jet cross section

Inclusive jet cross section: theory status

Much progress in fixed-order calculations/resummed and parton-shower predictions

- NLO QCD *[Ellis, Kunszt, Soper ’92] [Giele, Glover, Kosower ’94] [Nagy 02]*

- NLO EW *[Dittmaier, Huss, Speckner ’13]* *[Frederix, Frixione, Hirschi, Pagani, Shao, Zaro ’17]*

- NLO QCD + PS (POWHEG) *[Alioli, Hamilton, Nason, Oleari, Re ’11]*

  NLO QCD + PS (MC@NLO) *[Hoeche, Schonherr ’12]*

- NLO QCD + Resummation (threshold+jet radius) *[Dasgupta, Dreyer, Salam, Soyez ’14] [Liu, Moch, Ringer ’17]*

- NNLO QCD *[Gehrmann-De Ridder, Gehrmann, Glover, JP ’13] [Currie, Glover, JP ’16]* *[Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP ’17]*

Jet observables: uncertainties

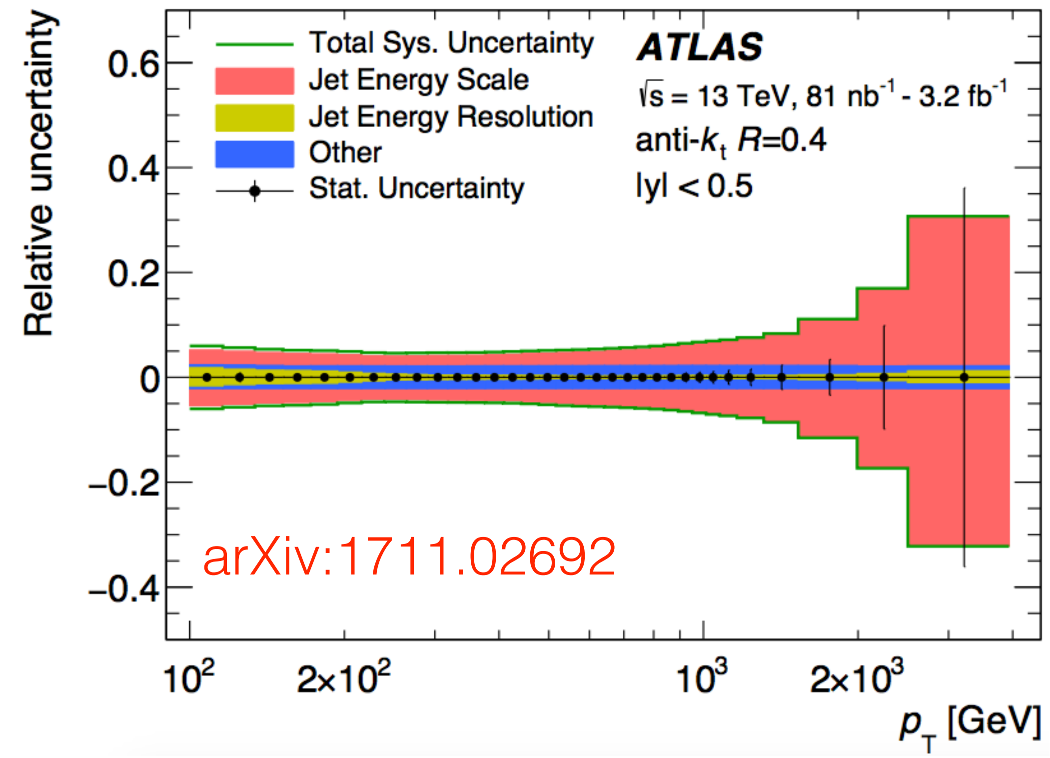
Experimental uncertainties:

- observables measured differentially with percent level uncertainties, dominated by systematics, jet energy scale

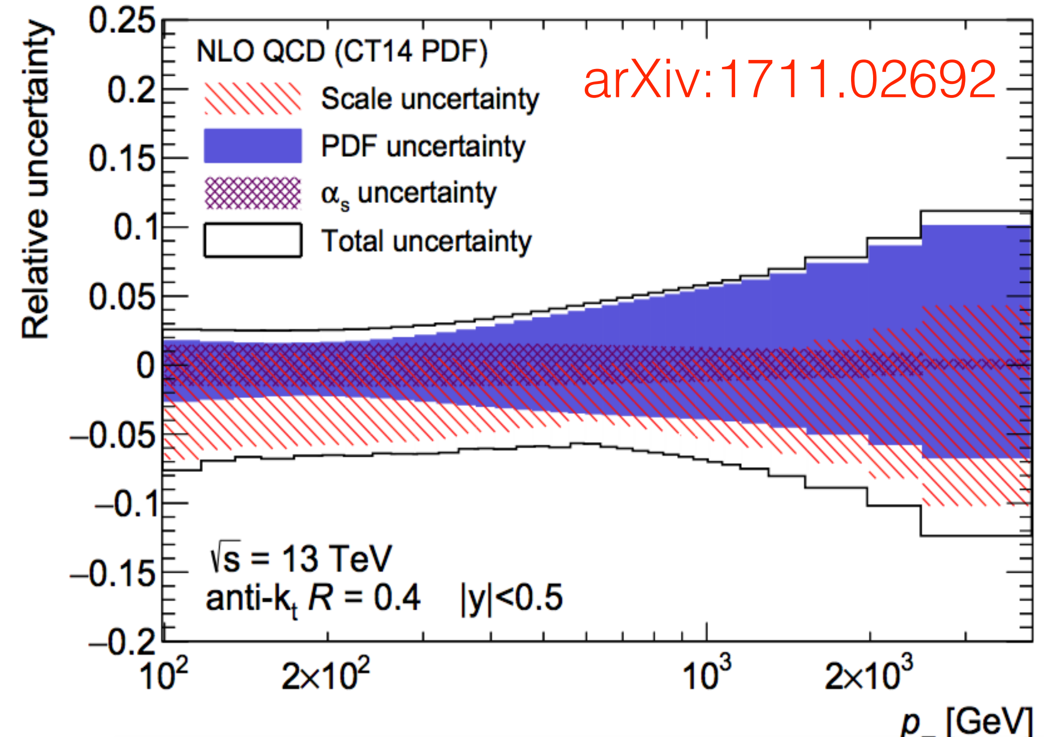
Theoretical uncertainties:

- parametric dependence on PDF and α_S
- perturbative uncertainty: truncation of the fixed order calculation to NLO and NNLO
- NNLO prediction needed to improve our understanding of inclusive jet data produced at the LHC

New results for jet production at NNLO (this talk)



dominant exp. systematic uncertainty jet energy scale: ±5-10%



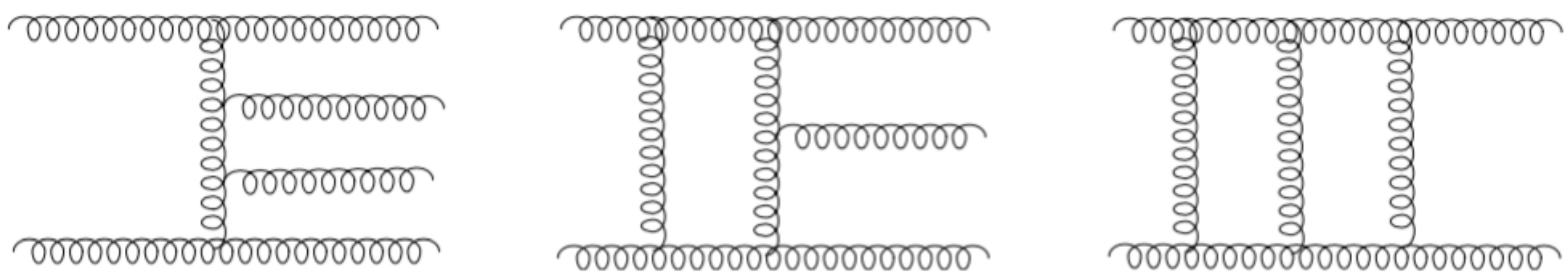
NLO scale uncertainty ~10% NNLO needed

NNLO contributions

- Perturbative QCD expansion of the inclusive jet cross section at hadron colliders

$$d\sigma = \sum_{i,j} \int \left[d\hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s}{2\pi}\right) d\hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s}{2\pi}\right)^2 d\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3) \right] f_i(x_1) f_j(x_2) dx_1 dx_2$$

- NNLO gluonic contributions

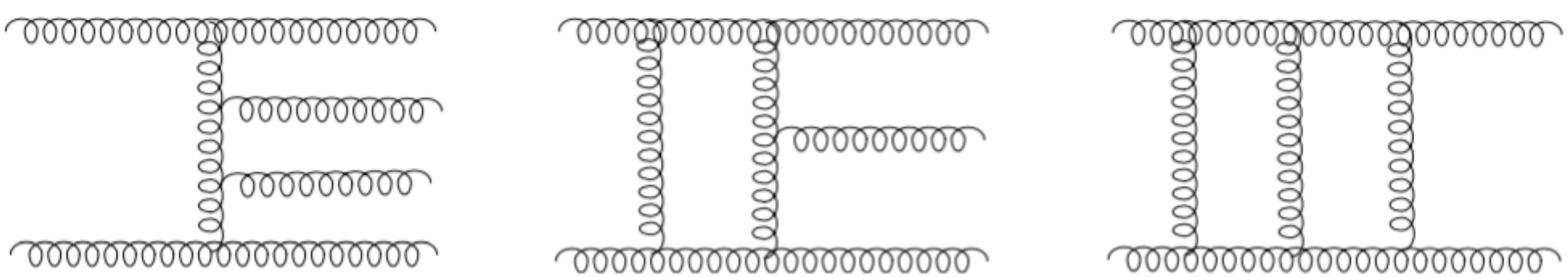


$A_6^{(0)}(gg \to gggg)$ $A_5^{(1)}(gg \to ggg)$ $A_4^{(2)}(gg \to gg)$

- tree-level 2→4 matrix elements *[Berends, Giele '87] [Mangano, Parke, Xu '87] [Britto, Cachazo, Feng '06]*
- one-loop 2→3 matrix elements *[Bern, Dixon, Kosower '93] [Kunszt, Signer, Trocsanyi '94]*
- two-loop 2→2 matrix elements *[Anastasiou, Glover, Oleari, Tejeda-Yeomans '01] [Bern, De Freitas, Dixon '02]*
- NNLO DGLAP evolution *[Moch, Vermaseren, Vogt '04]*
- NNLO PDF's *[ABMP, CT, NNPDF, MMHT]*

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4} \mathrm{d}\hat{\sigma}^{RR}_{NNLO} + \int_{\mathrm{d}\Phi_3} \mathrm{d}\hat{\sigma}^{RV}_{NNLO} + \int_{\mathrm{d}\Phi_2} \mathrm{d}\hat{\sigma}^{VV}_{NNLO}$$

$$\begin{aligned}
\mathrm{d}\hat{\sigma}^{RR}_{NNLO} &= \mathcal{N}\, \mathrm{d}\Phi_4(p_3,p_4,p_5,p_6;p_1,p_2)|\mathcal{M}^{(0)}_{gg\to gggg}|^2\, J_2^{(4)}(p_3,p_4,p_5,p_6) \\
\mathrm{d}\hat{\sigma}^{RV}_{NNLO} &= \mathcal{N}\, \mathrm{d}\Phi_3(p_3,p_4,p_5;p_1,p_2) \\
&\quad \left(\mathcal{M}^{(0)\star}_{gg\to ggg}\mathcal{M}^{(1)}_{gg\to ggg} + \mathcal{M}^{(0)}_{gg\to ggg}\mathcal{M}^{(1)\star}_{gg\to ggg}\right)\, J_2^{(3)}(p_3,p_4,p_5) \\
\mathrm{d}\hat{\sigma}^{VV}_{NNLO} &= \mathcal{N}\, \mathrm{d}\Phi_2(p_3,p_4;p_1,p_2) \\
&\quad \left(\mathcal{M}^{(2)\star}_{gg\to gg}\mathcal{M}^{(0)}_{gg\to gg} + \mathcal{M}^{(0)}_{gg\to gg}\mathcal{M}^{(2)\star}_{gg\to gg} + |\mathcal{M}^{(1)}_{gg\to gg}|^2\right)\, J_2^{(2)}(p_3,p_4)
\end{aligned}$$



$A_6^{(0)}(gg \to gggg)$ $A_5^{(1)}(gg \to ggg)$ $A_4^{(2)}(gg \to gg)$

- explicit infrared poles from loop integrations
- implicit poles in phase space regions corresponding to single and double unresolved gluon emission
- procedure to extract the infrared singularities and assemble all the parts

NNLO antenna subtraction

Glover, JP ***[arXiv: 1003.02824] JHEP 1006 (2010) 096***
Glover, De-Ridder, JP ***[arXiv: 1112.3613] JHEP 1202 (2012) 141***
Glover, De-Ridder, Gehrmann, JP ***[arXiv: 1211.2710] JHEP 1302 (2013) 026***

$$\begin{aligned} d\hat{\sigma}_{NNLO} &= \int_{d\Phi_4}\left(d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^{S}_{NNLO}\right) \\ &+ \int_{d\Phi_3}\left(d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^{T}_{NNLO}\right) \\ &+ \int_{d\Phi_2}\left(d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^{U}_{NNLO}\right) \end{aligned}$$

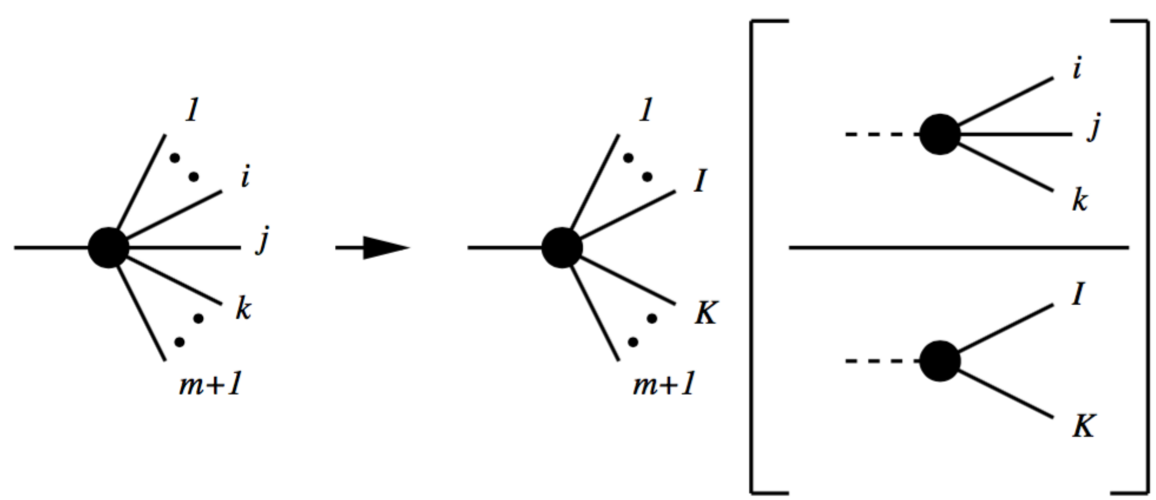
$d\hat{\sigma}^{S}_{NNLO}$ $d\hat{\sigma}^{T}_{NNLO}$

- mimic RR,RV in unresolved limits

$d\hat{\sigma}^{T}_{NNLO}$ $d\hat{\sigma}^{U}_{NNLO}$

- analytically cancel the poles in RV and VV matrix elements

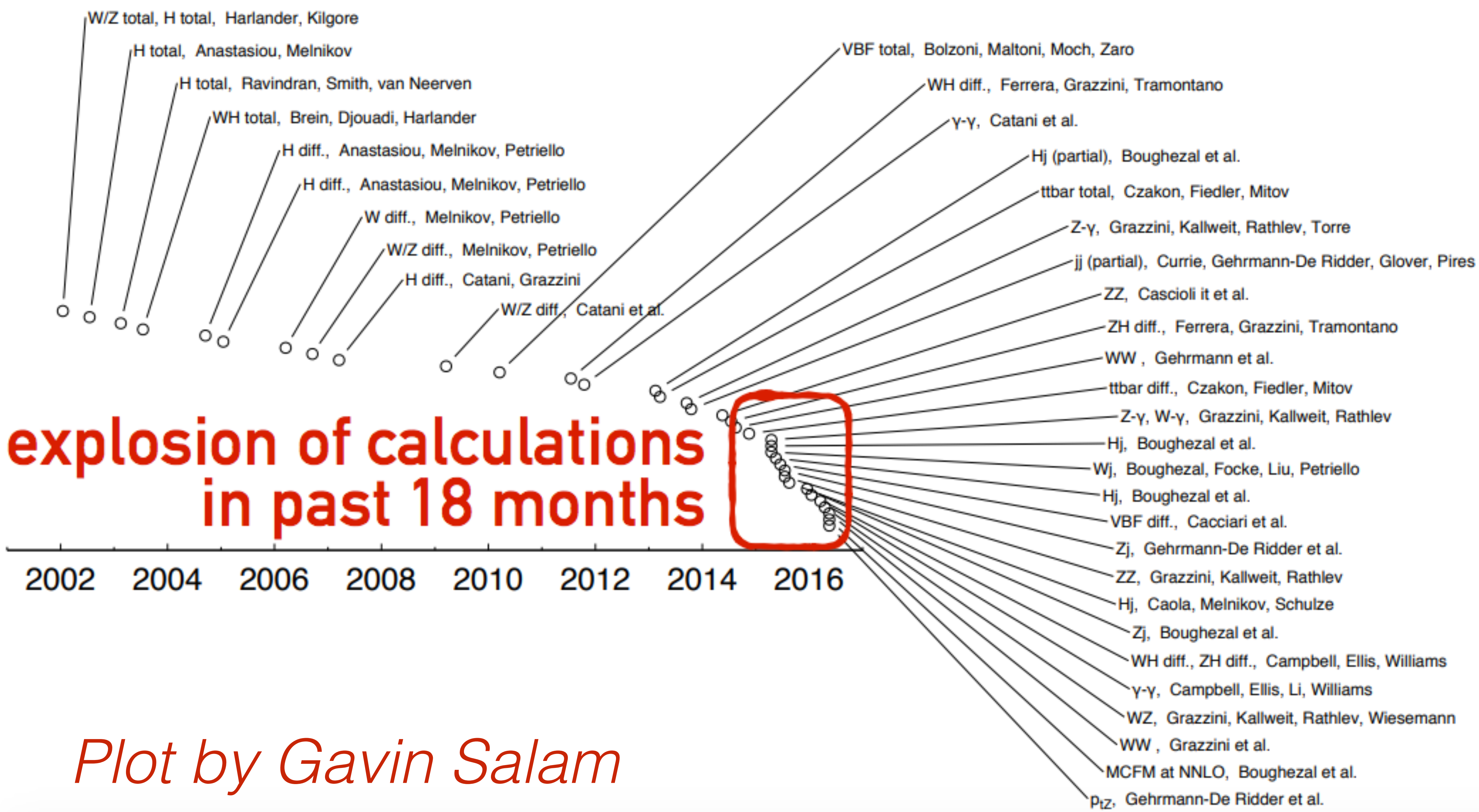
- matrix elements: universal factorization properties in IR limits



- phase space factorization

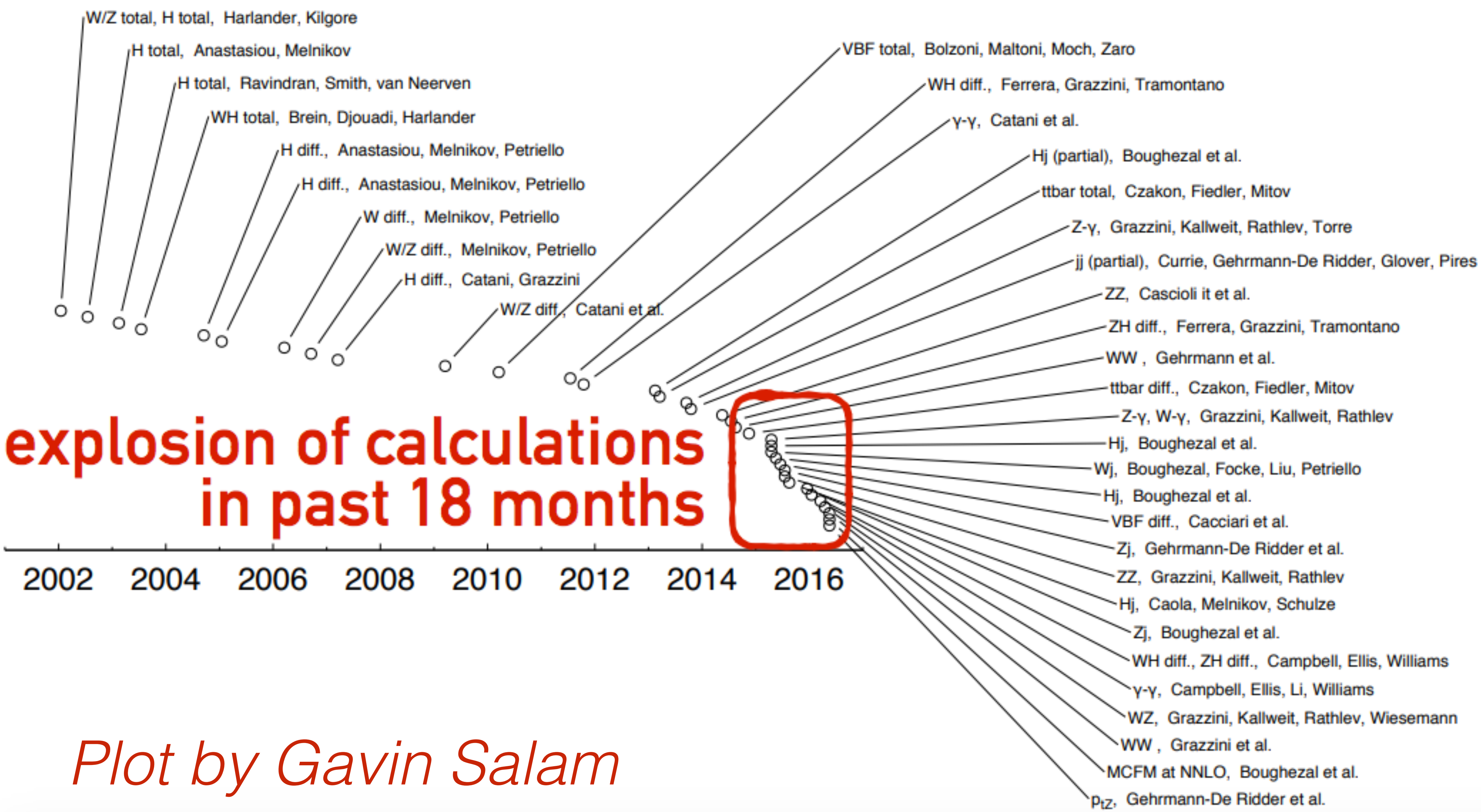
$$d\Phi_{m+1}(p_1,\ldots,p_{m+1};q) = d\Phi_m(p_1,\ldots,\tilde{p}_I,\tilde{p}_K,\ldots,p_{m+1};q)\cdot d\Phi_{X_{ijk}}(p_i,p_j,p_k;\tilde{p}_I+\tilde{p}_K)$$

Current state of the art/ NNLO hadron-collider calculations v. time



- summary on progress on NNLO calculations at LHC

Current state of the art/ NNLO hadron-collider calculations v. time



Plot by Gavin Salam

- **current frontier:** 2->2 crucial benchmark processes known theoretically from first principles at the few percent level

NNLOJET

NNLO fully differential parton-level generator*

- Based on antenna subtraction for the analytic cancellation of IR singularities at NNLO

Infrastructure

- Process management
- Phase space, histogram routines
- Validation and testing
- Applgrid and FastNLO interface in progress

Processes implemented at NNLO

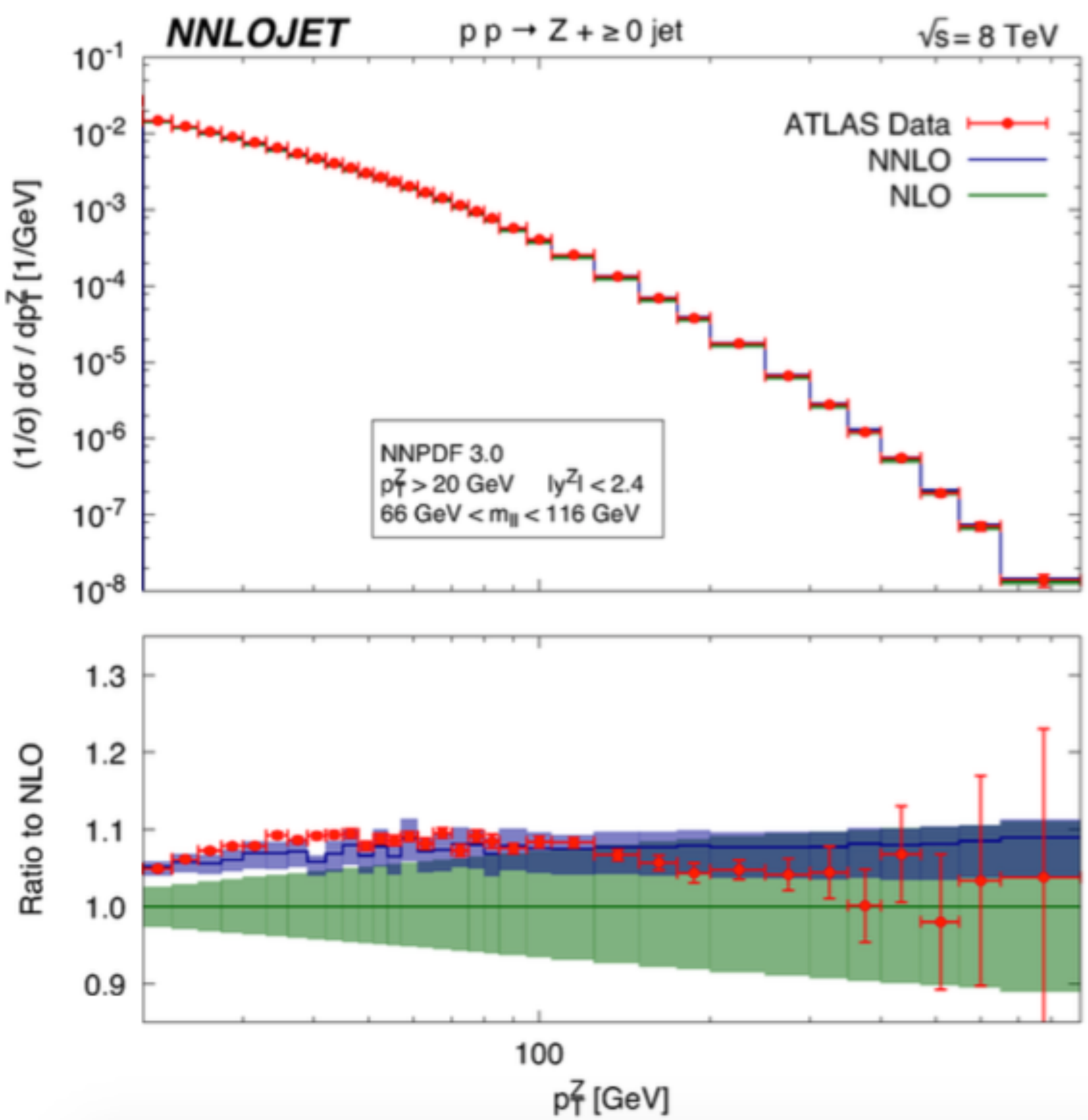
- Z+(0,1) jet, W+(0,1) jet
- H+(0,1) jet
- DIS-2jet
- VBF H+2jet
- Inclusive jet production

- In use by the experimental collaborations ATLAS and CMS

X.Chen,J.Cruz-Martinez, J.Currie, R.Gauld, T.Gehrmann, A.Gehrmann-De Ridder,E.W.N.Glover, M.Höfer, A.Huss, T.Morgan, I.Majer, J.Niehues, D.Walker, JP* *[arXiv: 1801.06415]*** *and references therein*

NNLOJET parton level generator

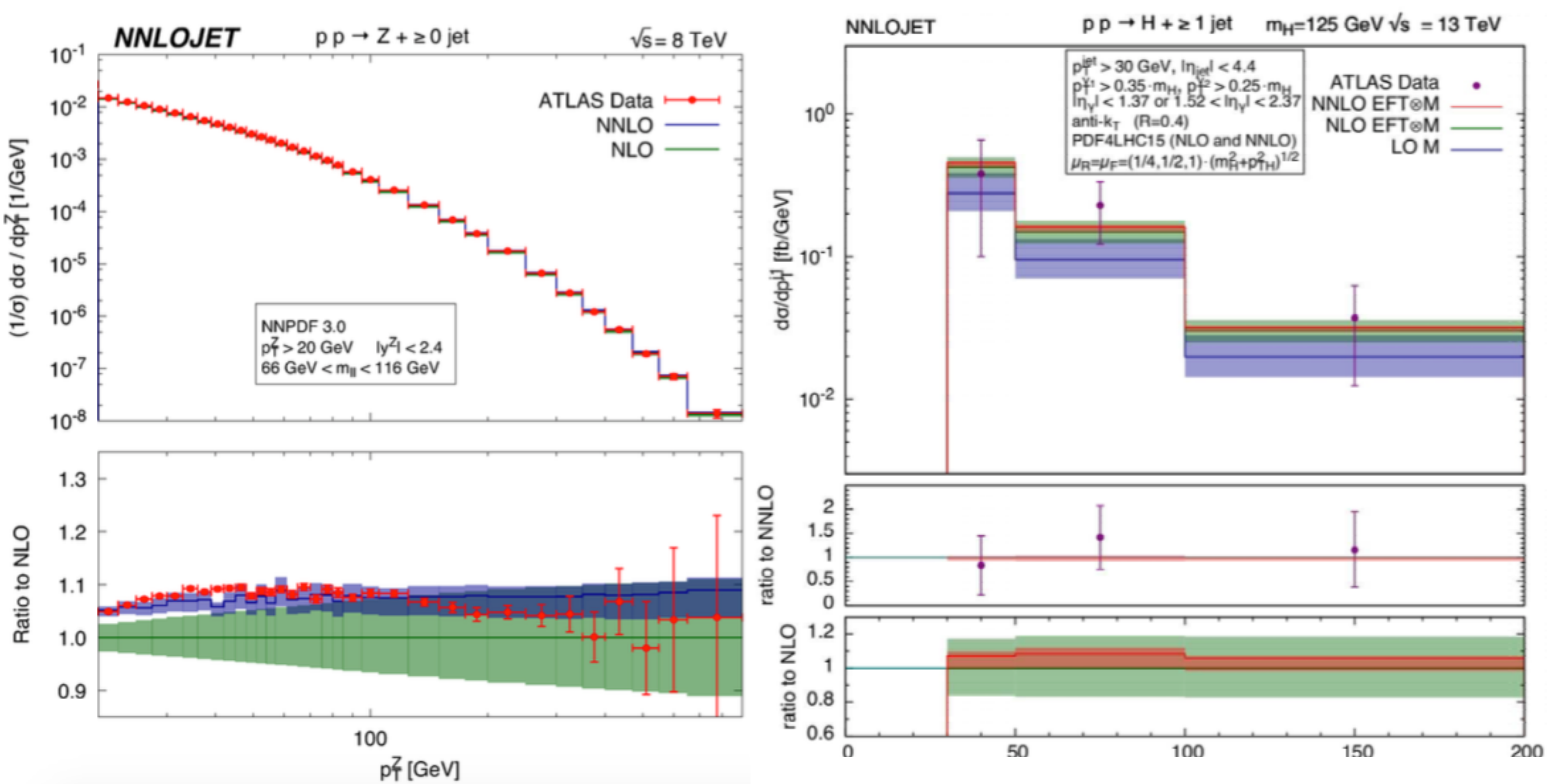
[X.Chen, J.Cruz-Martinez, J.Currie, R.Gauld, T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover, M.Höfer, A.Huss, T.Morgan, I.Majer, J.Niehues, D.Walker, JP **[arXiv: 1801.06415]** and references therein]



- Ex1: Z-boson p_T at NNLO: improved agreement with data with significant reduction in the scale uncertainty with respect to NLO

NNLOJET parton level generator

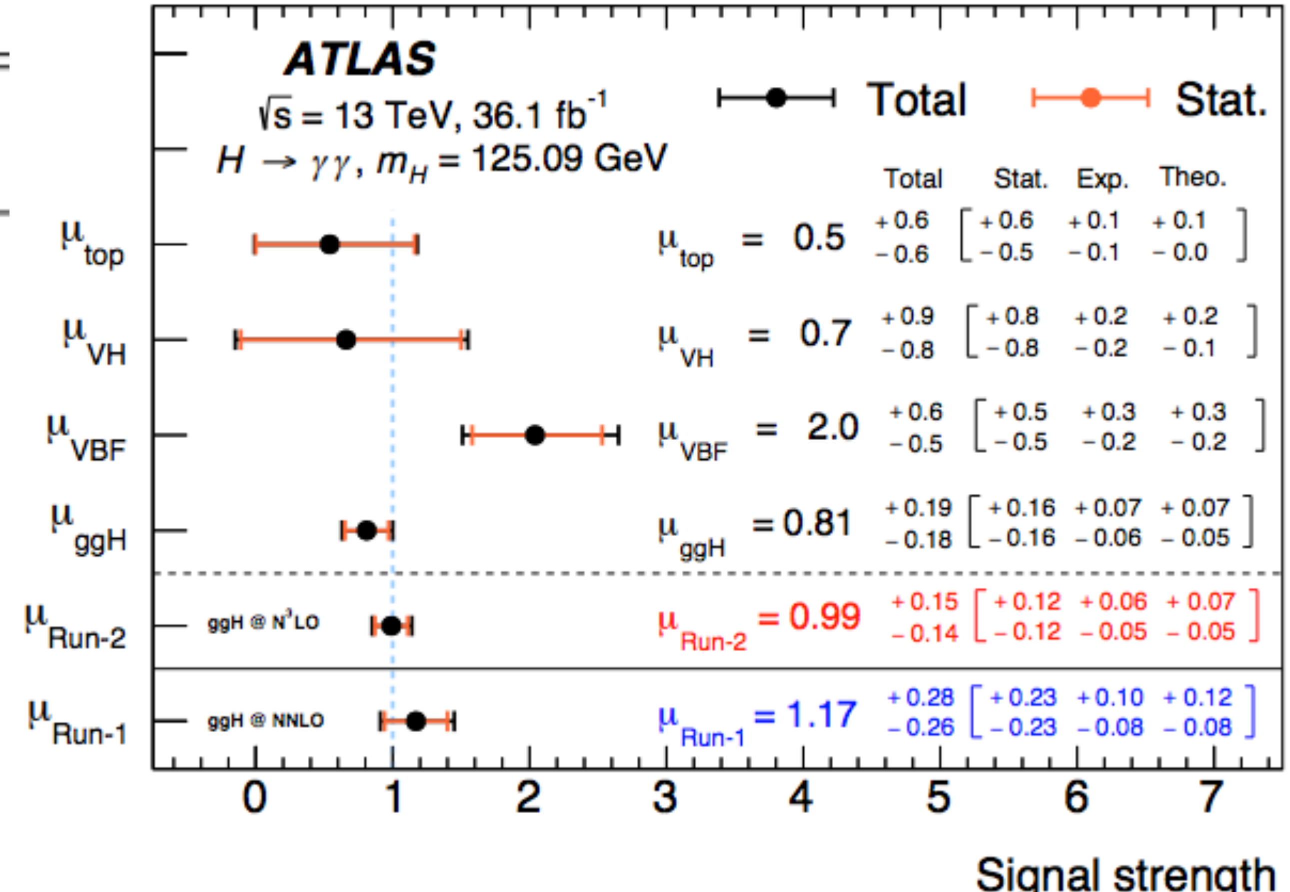
[X.Chen, J.Cruz-Martinez, J.Currie, R.Gauld, T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover, M.Höfer, A.Huss, T.Morgan, I.Majer, J.Niehues, D.Walker, JP **[arXiv: 1801.06415]** and references therein]



- Ex2: Leading jet p_T in association with a Higgs boson: ATLAS measurement agrees well with the NNLO prediction in shape and normalisation

Higgs production at the LHC

Process	σ [pb] $\sqrt{s}$ = 13 TeV	Order of calculation of σ
ggH	48.52	N^{3}LO(QCD)+NLO(EW)
VBF	3.78	NNLO(QCD)+NLO(EW)
WH	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}' \to ZH$	0.76	NNLO(QCD)+NLO(EW)
$gg \to ZH$	0.12	NLO+NLL(QCD)
$t\bar{t}H$	0.51	NLO(QCD)+NLO(EW)



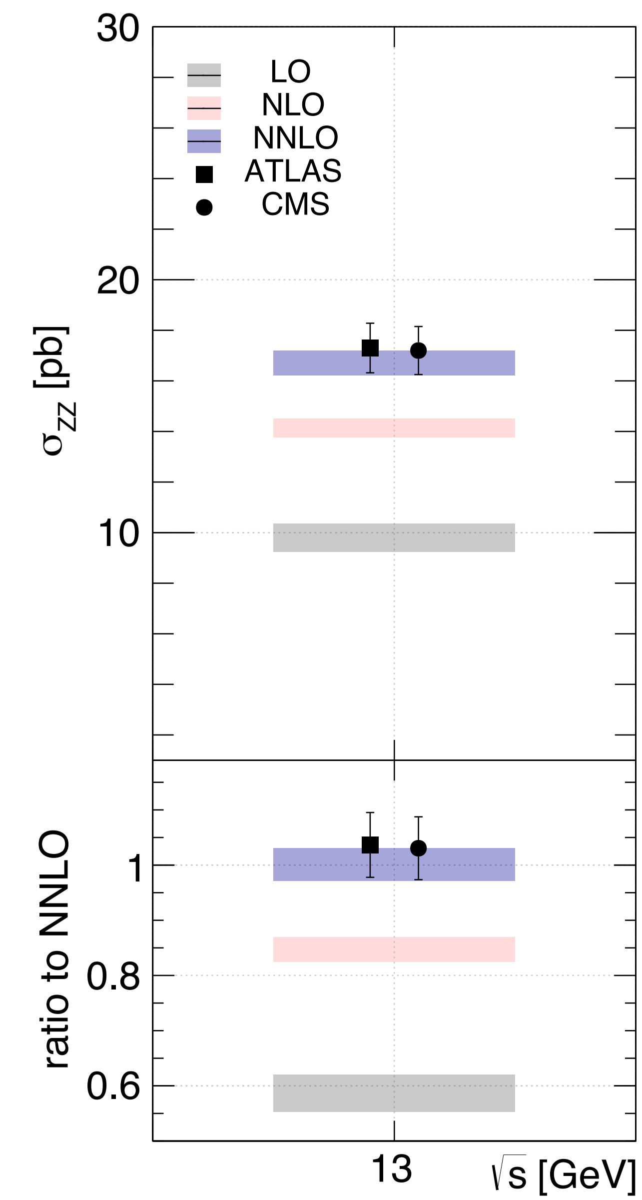
[ATLAS arXiv:1802.04146] Phys.Rev. D98 (2018) 052005

<u>Ex3:</u> Higgs cross section at the LHC, perturbative accuracy and ATLAS √s=13 TeV measurement

- Dominated by the experimental statistical uncertainties, theory error under control at NNLO

Diboson ZZ production at the LHC

	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]
Our Result			
MSWT2008	$9.890^{+4.9\%}_{-6.1\%}$	$14.508^{+3.0\%}_{-2.4\%}$	$16.92^{+3.2\%}_{-2.6\%}$
NNPDF3.0	$9.845^{+5.2\%}_{-6.2\%}$	$14.100^{+2.9\%}_{-2.4\%}$	$16.69^{+3.1\%}_{-2.8\%}$
ATLAS [7]	$17.3 \pm 0.6(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.6(\text{lumi.})$		
CMS [8]	$17.2 \pm 0.5(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{theo.}) \pm 0.4(\text{lumi.})$		



G.Heinrich, S.Jahn, S.P.Jones, M.Kerner, JP
[arXiv:1710.06294] JHEP 1803 (2018) 142

Ex4: ZZ inclusive cross section at the LHC and ATLAS and CMS $\sqrt{s}$=13 TeV measurement

- clean signature from fully leptonic decay mode to electron/muon final states $\mathcal{O}(5\%)$ experimental erros
- **large** NNLO effects $\mathcal{O}(20\%)$ from opening of new channels at higher order *qg* at NLO and *gg* at NNLO
  - eliminate 3σ tension between the measurement and NLO SM prediction

NNLO generators are becoming indispensable for data analysis at the LHC and crucial for the success of the physics programme in the understanding of high energy particle physics at hadron colliders

Phenomenology of inclusive jet production at the LHC

Jet phenomenology at the LHC

On-going pheno studies of jet production at the LHC

(CERN, ETH, Zurich, Durham, Lisbon) authors of NNLOJET

- concentrate on two observables:
    - *inclusive dijet production and dijet mass*
    - *single jet inclusive pT spectrum*
- mention **scale choice** for the theory prediction to assess perturbative scale uncertainty of the result
- present results and comparisons with LHC data
- present an outlook for inclusive jets at the LHC and future directions

Dijet inclusive production $\sqrt{s}=7$ TeV

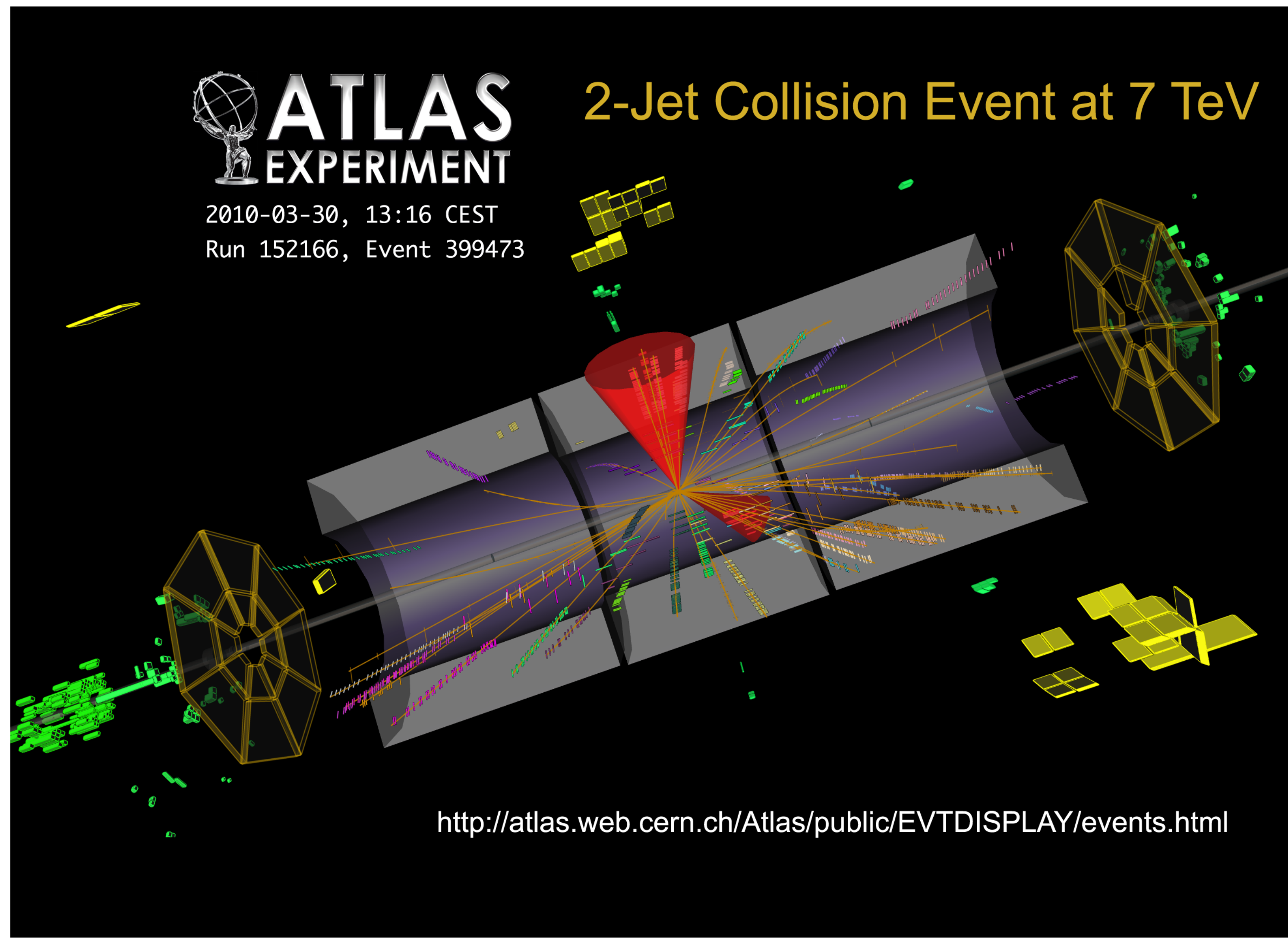
J.Currie, T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover, A.Huss, JP ***[arXiv: 1705.10271] Phys. Rev. Lett. 119, 152001 (2017)***

Theory setup

- MMHT2014 nnlo
- anti-k_T jet algorithm
- $p_{T1}>100$ GeV; $p_{T2}>50$ GeV;*
- $|y_{j1}|$, $|y_{j2}| < 3.0$
- $\mu_R=\mu_F=\{m_{jj}, <p_T>\}$
- vary scales by factors of 2 and 1/2

Comparison to data

- ATLAS 7 TeV ; $L=4.5$ fb^{-1}
- R=0.4



[ATLAS data, arXiv:1312.3524] JHEP 1405 (2014) 059

**measurement requires observation of a dijet system in the final state; asymmetric p_T cuts increase phase space available for real-gluon emission suppressing large logs in the QCD perturbative expansion of the observable*

Dijet inclusive production: scale choice

<u>*pp->2jets +X:*</u>

- cross section measured differentially in:

$$m_{jj}^2 = (p_{j1} + p_{j2})^2 \qquad y^* = \frac{1}{2}(y_{j1} - y_{j2})$$

- compare behaviour of the scales (normalised to data)

$$\mu = m_{jj} \quad ; \quad \mu = \langle p_T \rangle = \frac{1}{2}(p_{T1} + p_{T2})$$

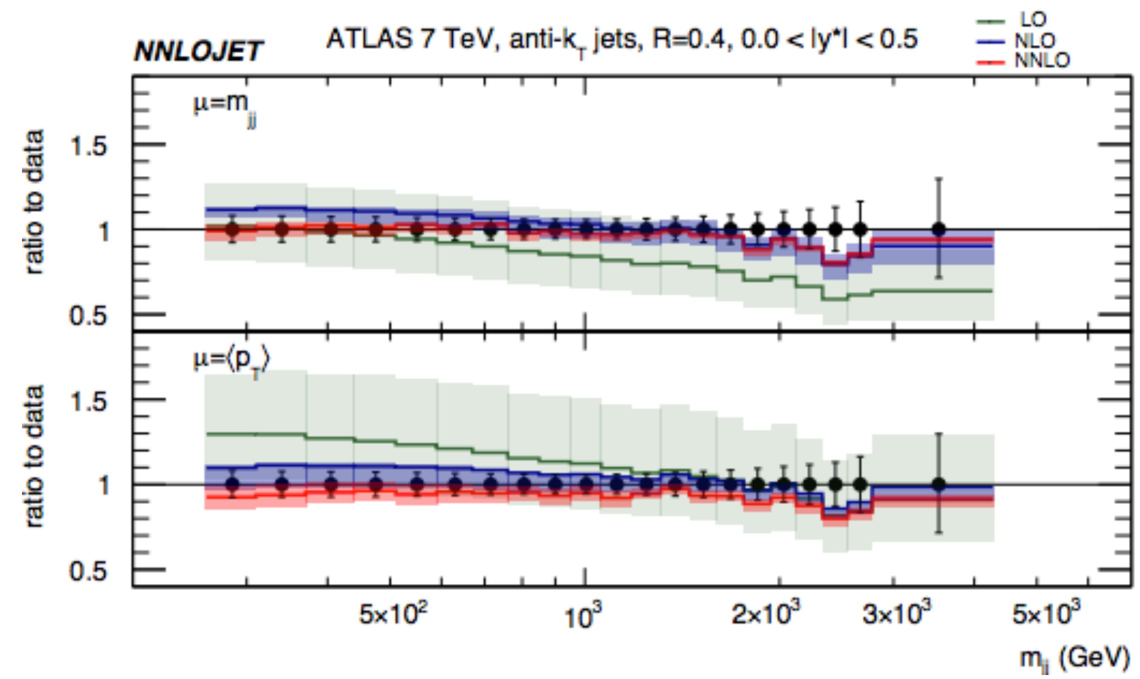
<u>*small |y*|:*</u>

- both scales give reasonable predictions

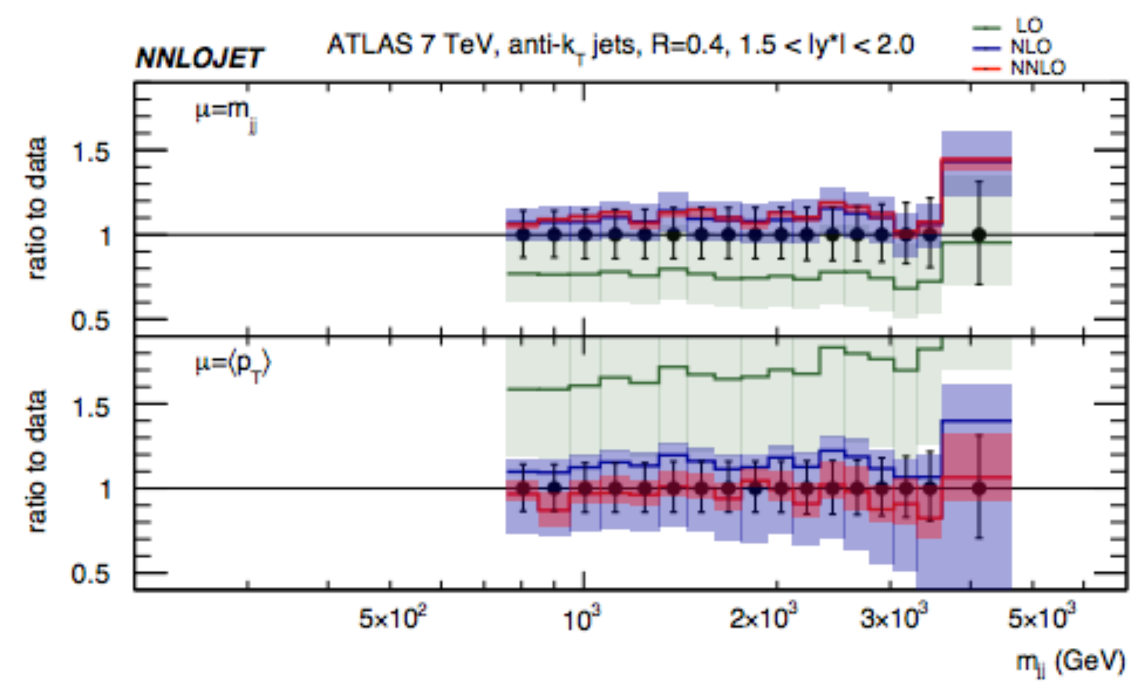
<u>*large |y*|:*</u>

- large negative NLO corrections, non-overlapping scale bands and residual NLO, NNLO scale uncertainties of ~100%, ~20% with $\mu = \langle p_T \rangle$

- **stable prediction with** $\mu = m_{jj}$

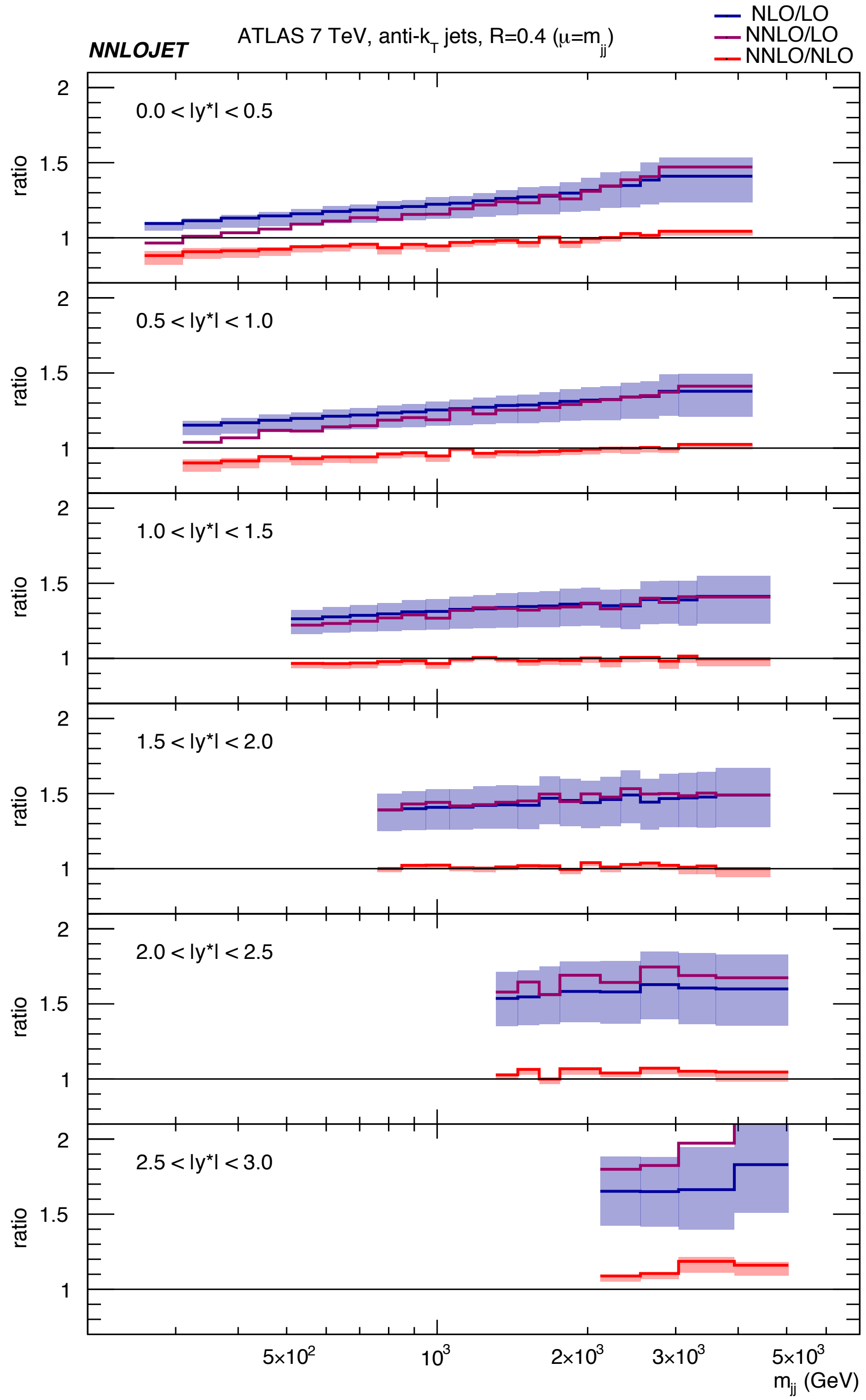


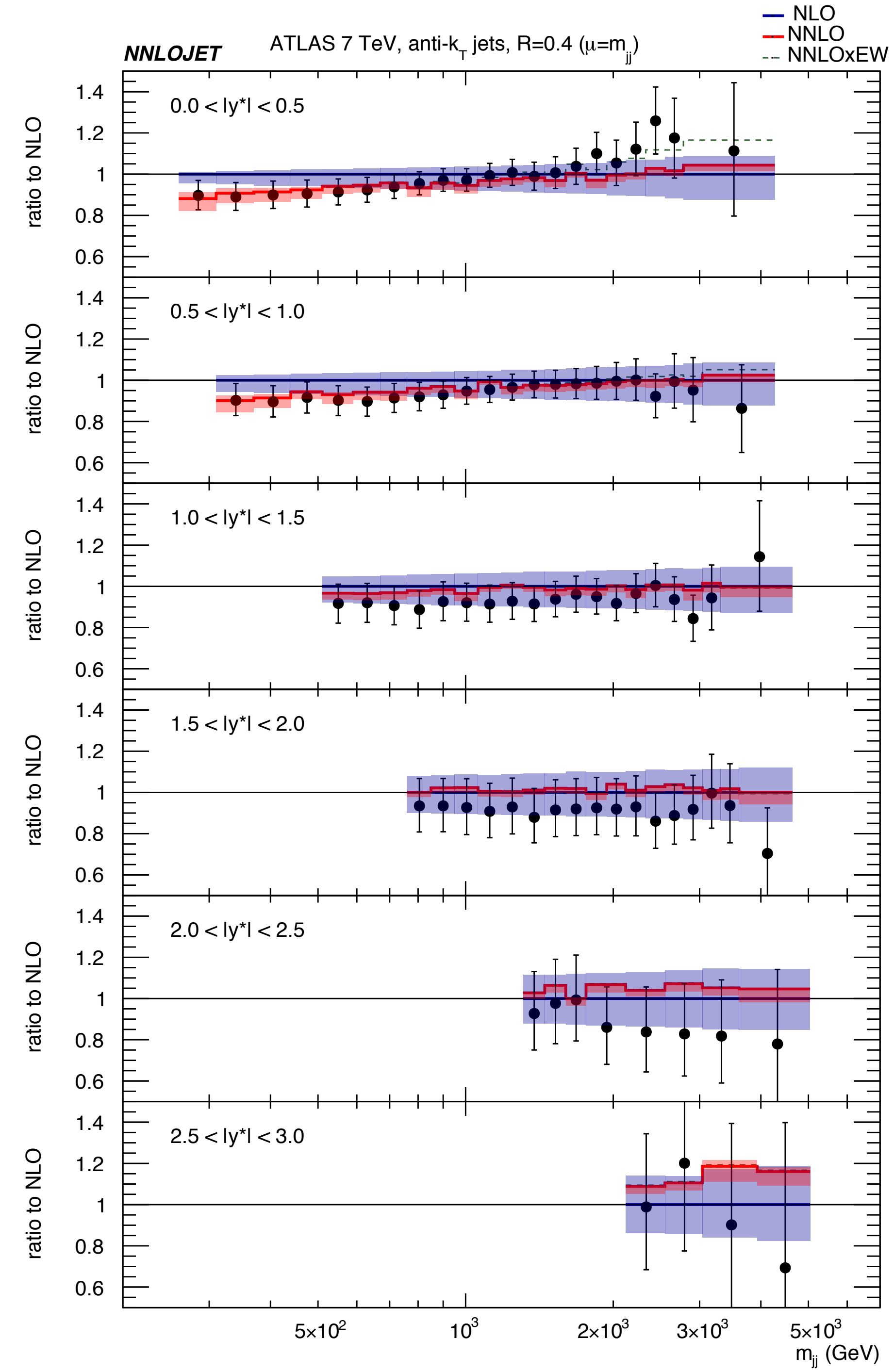
0.0<|y*|<0.5



1.5<|y*|<2.0

ATLAS dijet inclusive production √s=7 TeV





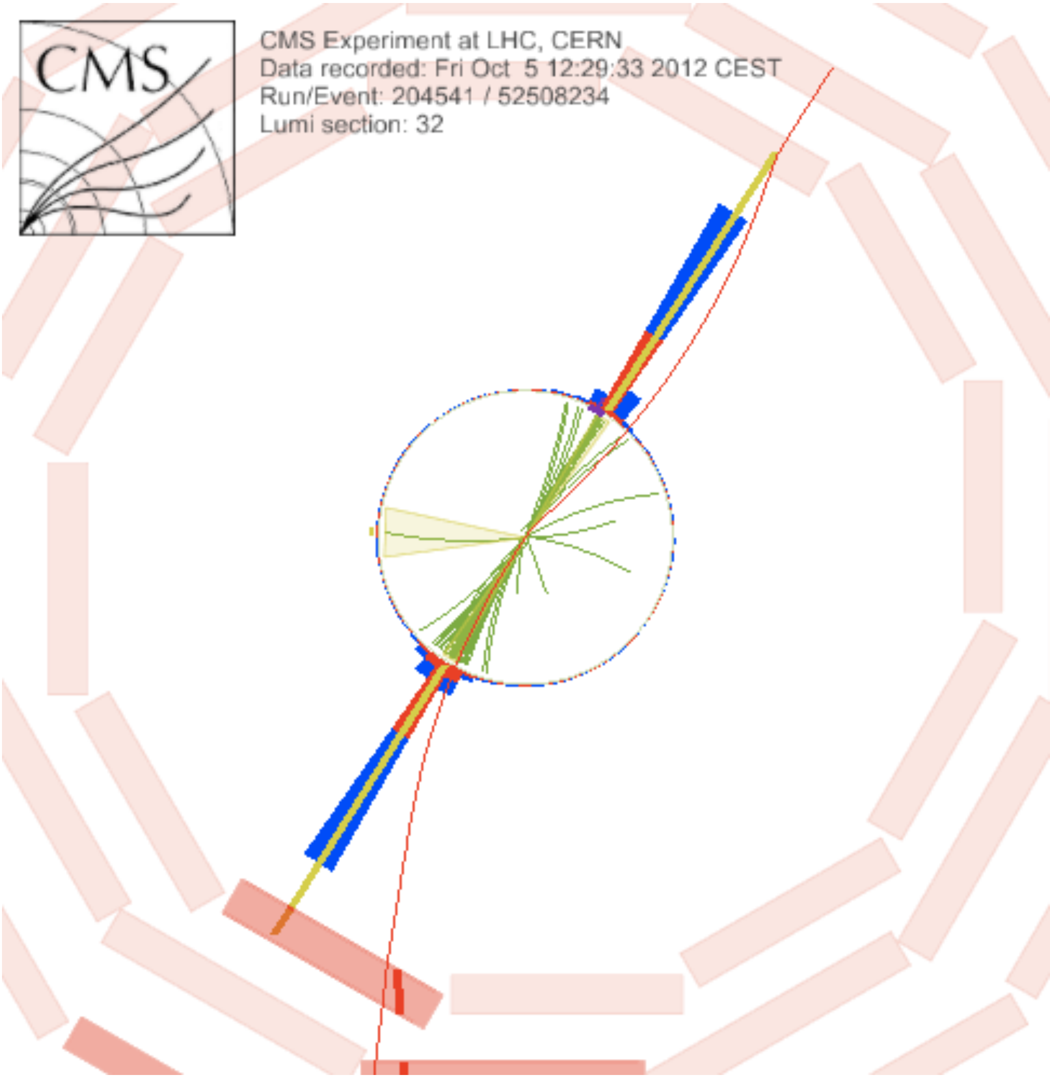
- Excellent convergence of the perturbative expansion; NNLO/NLO < 10% and flat
- **Improved description** of the dijet data at NNLO with theoretical uncertainties below the experimental error

Single jet inclusive production

J.Currie, E.W.N.Glover, JP ***[arXiv: 1611.01460] Phys. Rev. Lett.118, 072002 (2017)***
J.Currie, T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover, A.Huss, JP
[arXiv: 1807.03692] *to appear in JHEP*

Theory setup

- PDF4LHC15nnlo
- anti-k_T jet algorithm
- R=0.4 ; R=0.7 ;
- p_T>114 GeV*
- $|y_j| < 4.7$*
- theory uncertainty: vary renormalization μ_R and factorization μ_F scales by factors [1/2,2] around pre-defined central scale



Comparison to data

- CMS $\sqrt{s}$ = 13 TeV ; L=71 pb^{-1}
- R=0.4 and R=0.7

[CMS, arXiv:1605.04436]
Eur.Phys.J. C76 (2016) no.8, 451

**single jet inclusive observable obtained by summing over all jets that are observed in the event*

Scale choices $\mu_{R,}$ μ_F

- p_T → transverse momentum of the individual jets
- p_{T1} → transverse momentum of the leading jet
- H_T → scalar sum of the transverse momenta of the reconstructed jets
- $\check{H}_T$ → scalar sum of the transverse momenta of all partons
- $\mu_{R,}$ μ_F are arbitrary and unphysical parameters and are absent from the true result → *a priori* each scale above is an equally valid scale choice

$$\mu \sim p_T$$

$$\mu \sim p_{T1}$$

$$\mu \sim H_T$$

$$\mu \sim \hat{H}_T$$

However, a suitable scale choice would

- minimize ratios of Q^2/μ^2 ,i.e, faster perturbative convergence and smaller scale uncertainties
- avoid scales that introduce pathological behaviours in the prediction, i.e, $\sigma < 0$
- avoid scales that are discontinuous on the phase space of the observable, i.e, no kinks in k-factors

→ recently derived NNLO predictions for inclusive jet production allow for the first time a robust study on scale setting, making use of the knowledge of three orders in the perturbative expansion of the observable

Define scale choice criteria for single jet inclusive cross section

Studied the IR sensitivity of the different ingredients and introduced an extended set of criteria to help identify the most appropriate scale choice for the perturbative description of single jet inclusive production

- **(a) *perturbative convergence:*** size of the corrections to the inclusive cross section reduces at each successive order
- **(b) *scale uncertainty as theory estimate:*** overlapping scale uncertainty bands between the last two orders, i.e., between NLO and NNLO
- **(c) *perturbative convergence of the individual jet spectra:*** perturbative convergence of the corrections to the individual p_{T1} and p_{T2} distributions
- **(d) *stability of the second jet distribution:*** require the predictions and associated scale uncertainty to provide physical, positive cross sections

Singled out $\mu = 2p_T$ and $\mu = \hat{H}_T$ as scales that satisfy all the criteria above for both cone sizes R=0.4 and R=0.7 $\Rightarrow$ $\mu = p_{T,1}$ **strongly disfavoured**

J.Curries, T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover, A.Huss, JP ***[arXiv: 1807.03692]***

J.Currie, T.Gehrmann, A.Gehrmann-De Ridder, E.W.N.Glover, A.Huss, JP ***[arXiv: 1807.03692]***

scale	criterion (a)	(b)	(c)	(d)
$p_{T,1}$	–	–	✓	✓
$2\,p_{T,1}$	✓	–	✓	✓
p_T	–	✓	✓	✓
$2\,p_T$	✓	✓	✓	✓
$\hat{H}_T/2$	✓	✓	✓	–
$\hat{H}_T$	✓	✓	✓	✓

(a) $R = 0.7$

scale	criterion (a)	(b)	(c)	(d)
$p_{T,1}$	–	–	–	–
$2\,p_{T,1}$	✓	–	✓	(✓)
p_T	–	–	–	–
$2\,p_T$	✓	✓	✓	✓
$\hat{H}_T/2$	✓	✓	–	–
$\hat{H}_T$	✓	✓	✓	(✓)

(b) $R = 0.4$

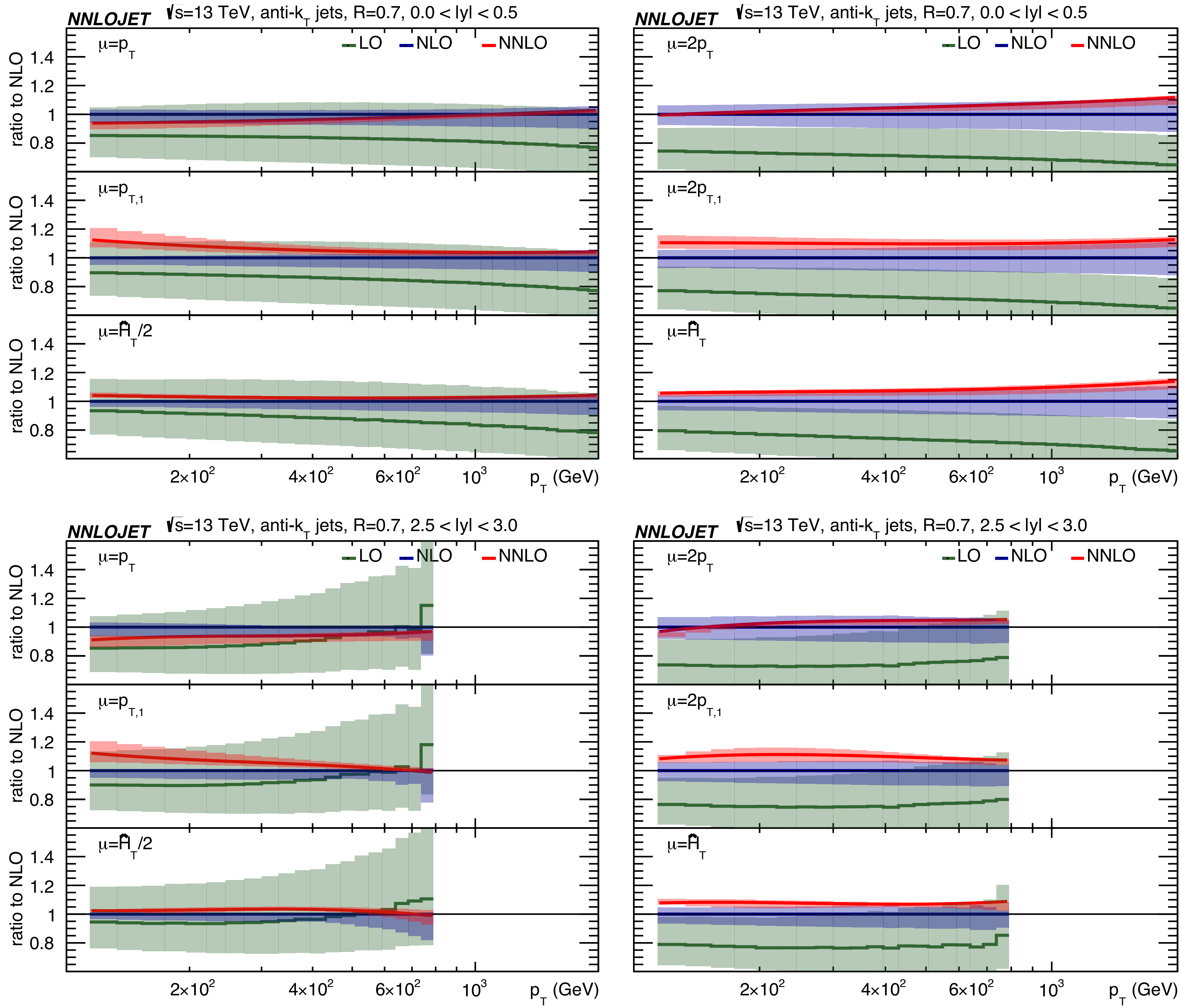
Table 2: Summary of scales vs. criteria for (a) R=0.7 and (b) R=0.4 cone sizes.

Differential single jet inclusive k-factors: CMS cuts and scale choices

0.0<|y|<0.5

$\mu = 2p_T$

$\mu = \hat{H}_T$



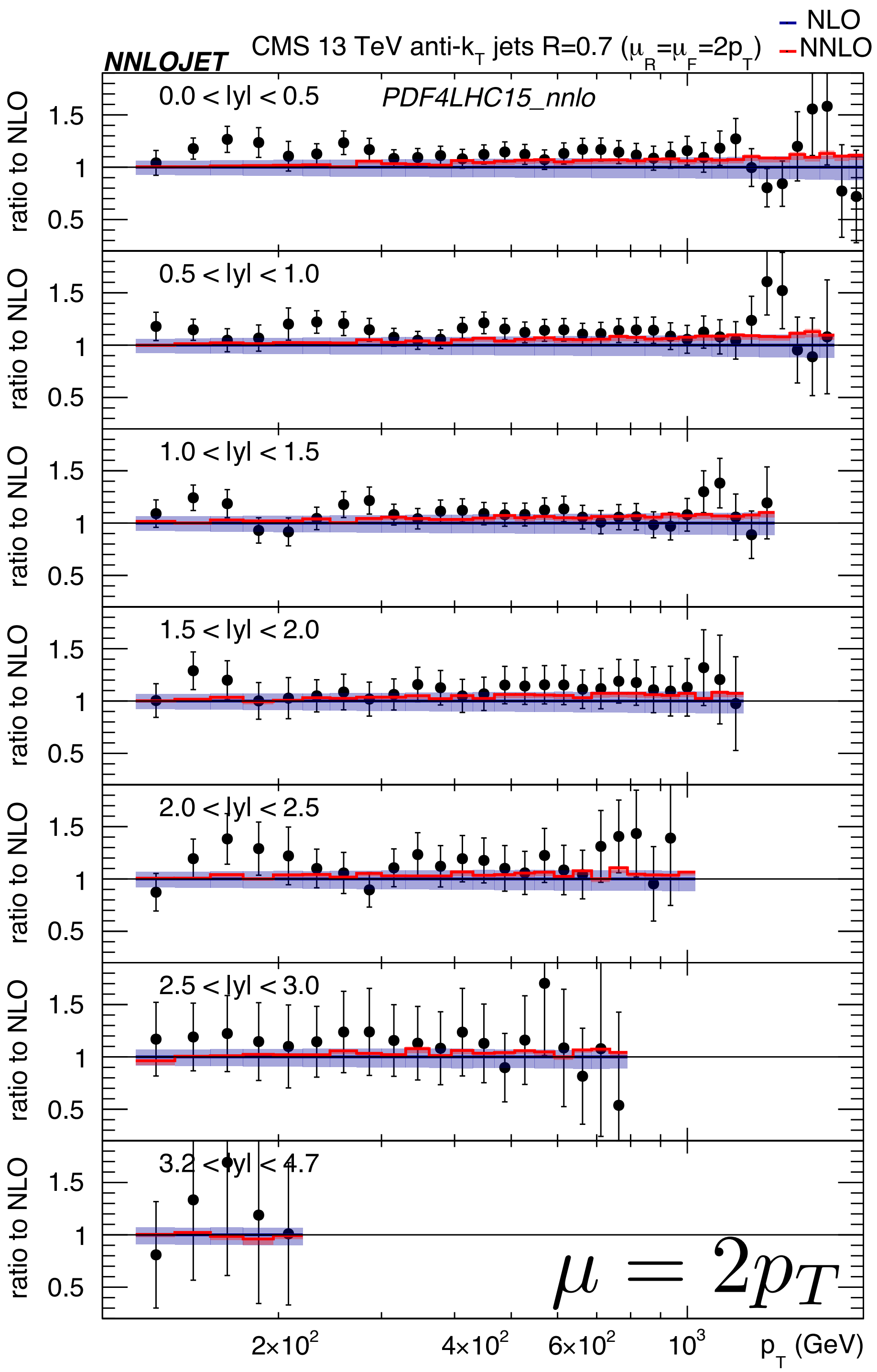
2.5<|y|<3.0

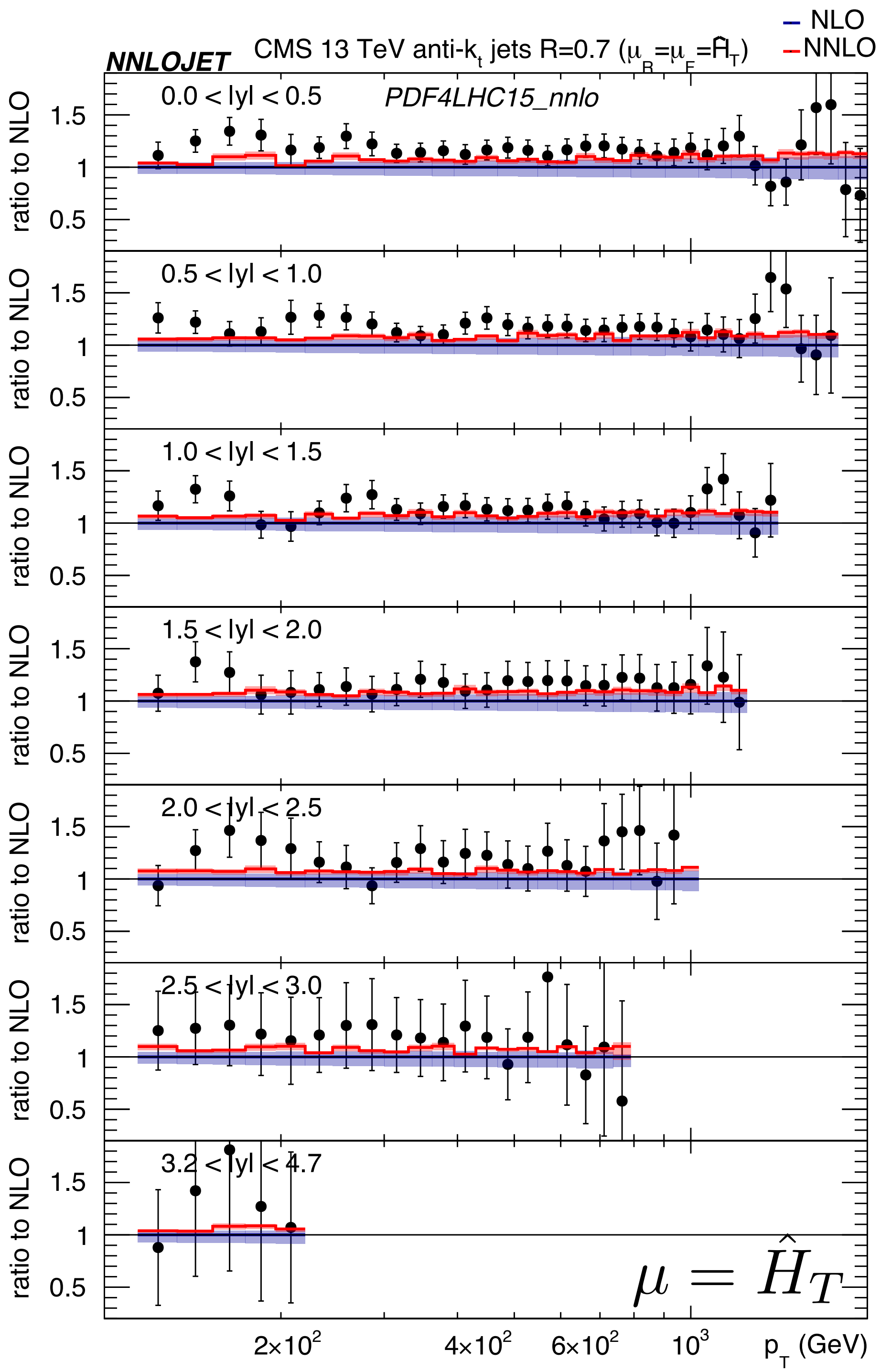
$\mu = 2p_T$

$\mu = \hat{H}_T$

- Excellent convergence of the perturbative expansion and overlapping scale uncertainty bands observed for $\mu = 2p_T$ and $\mu = \hat{H}_T$

Comparison with CMS $\sqrt{s}$=13 TeV data R=0.7

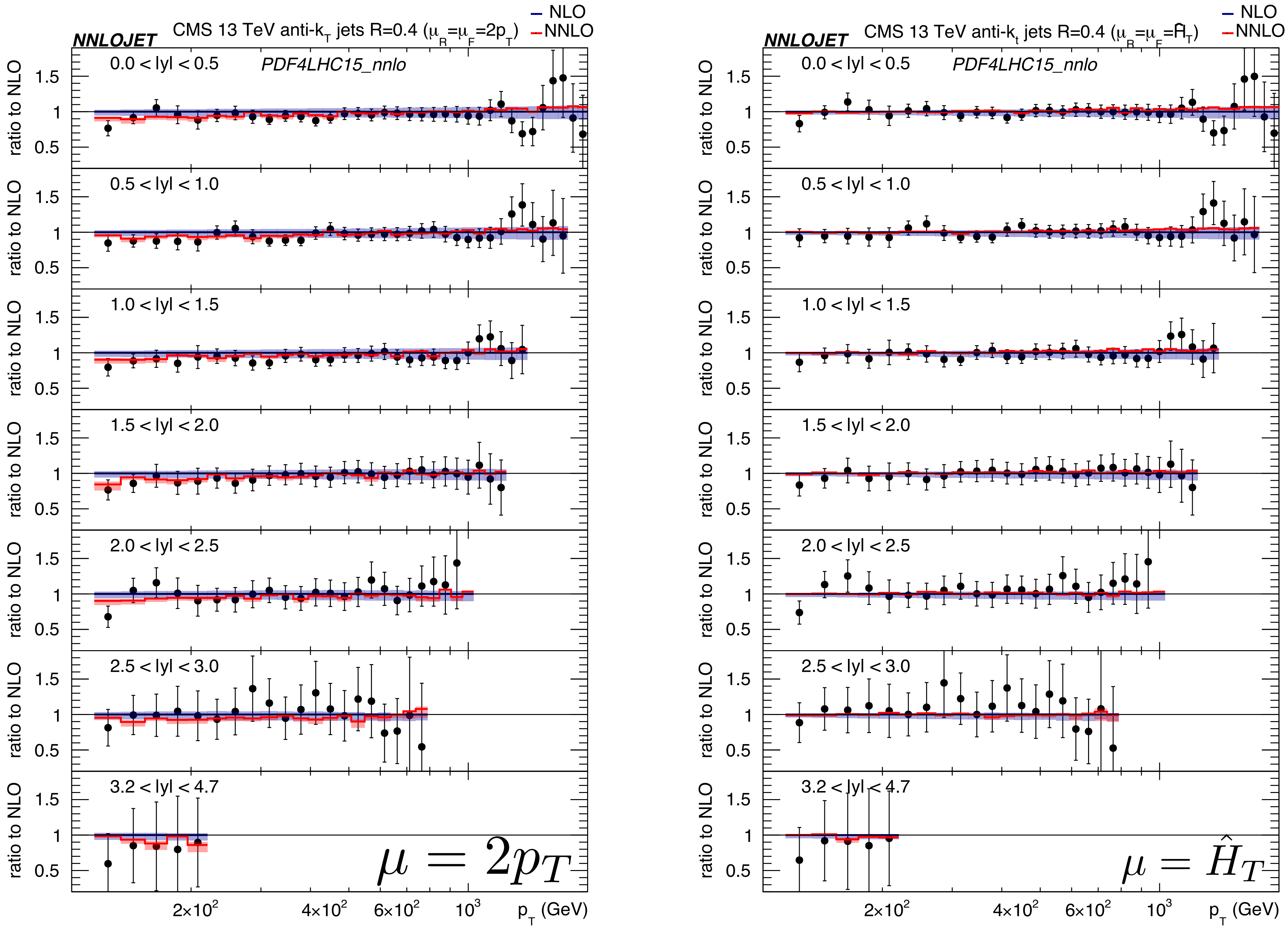




- small positive NNLO corrections improve the agreement with CMS data with respect to NLO
- **significant reduction in scale uncertainty** from NLO to NNLO → roughly more than a factor of 2 in a wide range of p_T and rapidity $\delta_{\text{scale}} \sim \mathcal{O}(<5\%)$

J.Currie, T.Gehrmann, A.Gehrmann-De Ridder
E.W.N.Glover, A.Huss, JP ***[arXiv: 1807.03692]***

Comparison with CMS √s=13 TeV data R=0.4



- improved agreement with data at NNLO with respect to NLO
- **both scale choices are stable** and provide reasonable predictions for jet sizes R=0.7 and R=0.4
- opens the path towards precision jet physics at the LHC

J.Currie, T.Gehrmann, A.Gehrmann-De Ridder E.W.N.Glover, A.Huss, JP ***[arXiv: 1807.03692]***

Summary

1. LHC had a successful run II experimental run producing data above the target expectations

   - excellent performance from both the accelerator and the detectors

   - increasing paradigm shift in the experimental analysis: hadron collider is a precision machine

2. On the theory side NNLO calculations and generators are becoming indispensable tools for data analysis and crucial to fully explore and understand the TeV region with the LHC and future HE/HL upgrades *(Higgs, Drell-Yan, inclusive jets, Diboson production, top-pair production, …)*

   - No physics beyond the Standard Model has been observed in the analysed datasets ➝ can expect new physics hiding at large energy scales that will manifest as small deviations from the SM background at the LHC ➝ need the best theoretical calculations to maximize the sensitivity to small BSM effects and to search for BSM scenarios. Even more at large luminosities, currently siting at 1% of the full HL-LHC full dataset L=3000 fb-1

3. NNLOJET framework developed to perform the computation of hadron-collider processes to high perturbative accuracy

   - Observed remarkable improvement in the description of LHC data at NNLO in a variety of processes and a significant reduction in the theory uncertainty with respect to NLO

   - Many new encouraging phenomenological results available not possible a few years ago

4. Possibility to add new final states/processes to NNLOJET ➝ to be done in coordination with the needs of the experimental community ➝ goal to work on specific phenomenological analyses relevant in LHC physics

Jet phenomenology outlook

1. Perform further quantitative comparisons between data and theory (different center of mass energies, covering wide jet p_T and rapidity to jet cone sizes) → goal to have a consistent description of all jet datasets

2. Study the sensitivity of jet-based observables to α_s and PDFs and assess ultimate precision in their extraction in a combined fit

   - Request from Review of Particle Physics (*S.Bethke, G.Dissertori*) to provide an extraction of the strong coupling constant from LHC jet data at NNLO to enter world average determination of α_s (On-going work with *D.Britzger, K.Rabbertz (CMS)* and *C.Gwenlan, M.Sutton (ATLAS)* to provide the necessary APPLfast grids)

   - Study with the PDF fitters to perform PDF extractions with LHC data and assess the impact from LHC jet data on the determination of gluon PDF at NNLO. On-going work with *S.Forte, J.Rojo, S.Carrazza (NNPDF)*, *CTEQ, MMHT*

3. Comparison between fixed-order NNLO calculation and the matched NLO+PS inclusive jet shape description

   - On-going work with *Joey Huston (ATLAS)* → goal to understand Jet Shapes at the LHC and Non-Perturbative (NP) uncertainties in inclusive jets in Showers and at fixed-order

4. Request from the HE/HL-LHC working group to investigate the reach in cross section at the HL/HE stages of the LHC

   - *Yellow Report* in preparation for release by December 2018 and send to the *European Strategy Council*

5. Match the NNLO calculation to the parton shower → NNLO+PS hadron level prediction for inclusive jets

6. Study jet production in heavy ion collisions for Nuclear PDFs New MCs and comparisons with jets in *pp*

7. Include contributions from EFT higher-dimensional operators beyond the SM in the NNLO prediction and constrain them with LHC data

Thank you for your attention