QCD and Jets at the LHC

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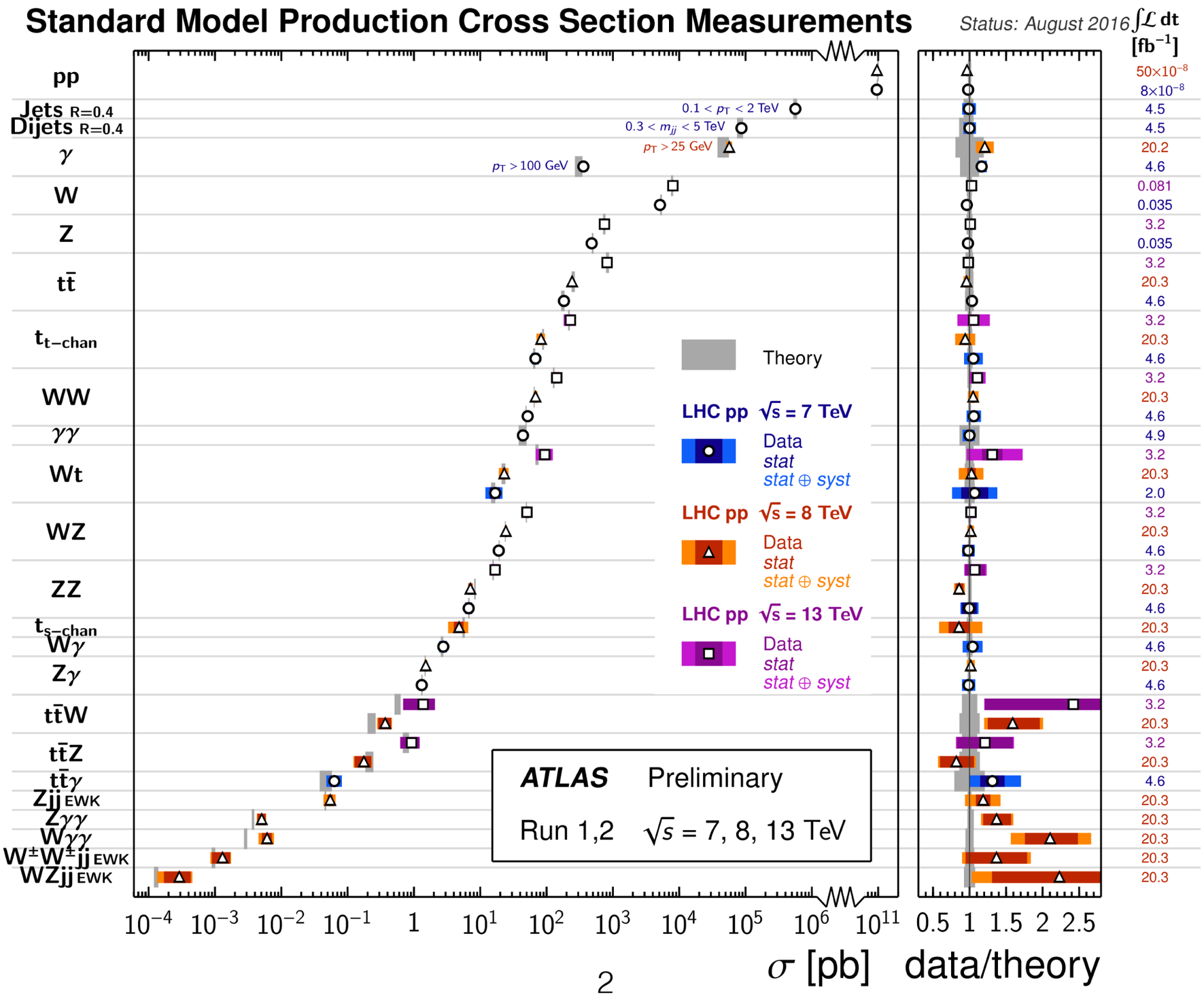
2nd CLHCP workshop, Peking University

QCD@LHC

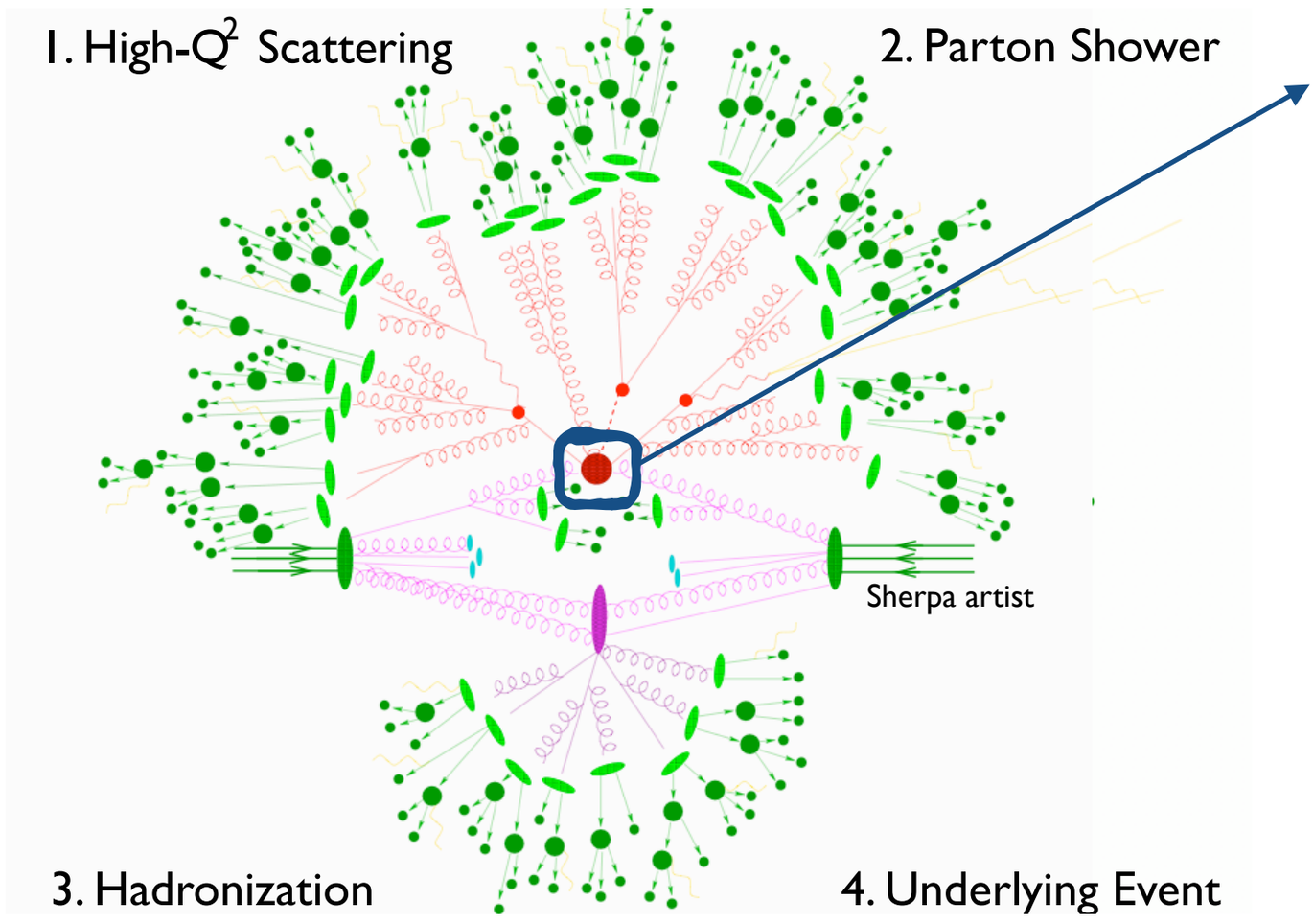
- Excellent agreement of data and theory at LHC not only prove successful of EW and flavor sectors of the SM, but also QCD



QCD@LHC

- Probe of the EW dynamics and any meaningful comparison of data and theory rely on precise knowledge on both perturbative and non-perturbative QCD

simplified picture of proton-proton collision



data vs. theory

- how to probe the EW dynamics and possible new physics in the primary interaction?

new resonance or higher dimension operators

QCD@LHC

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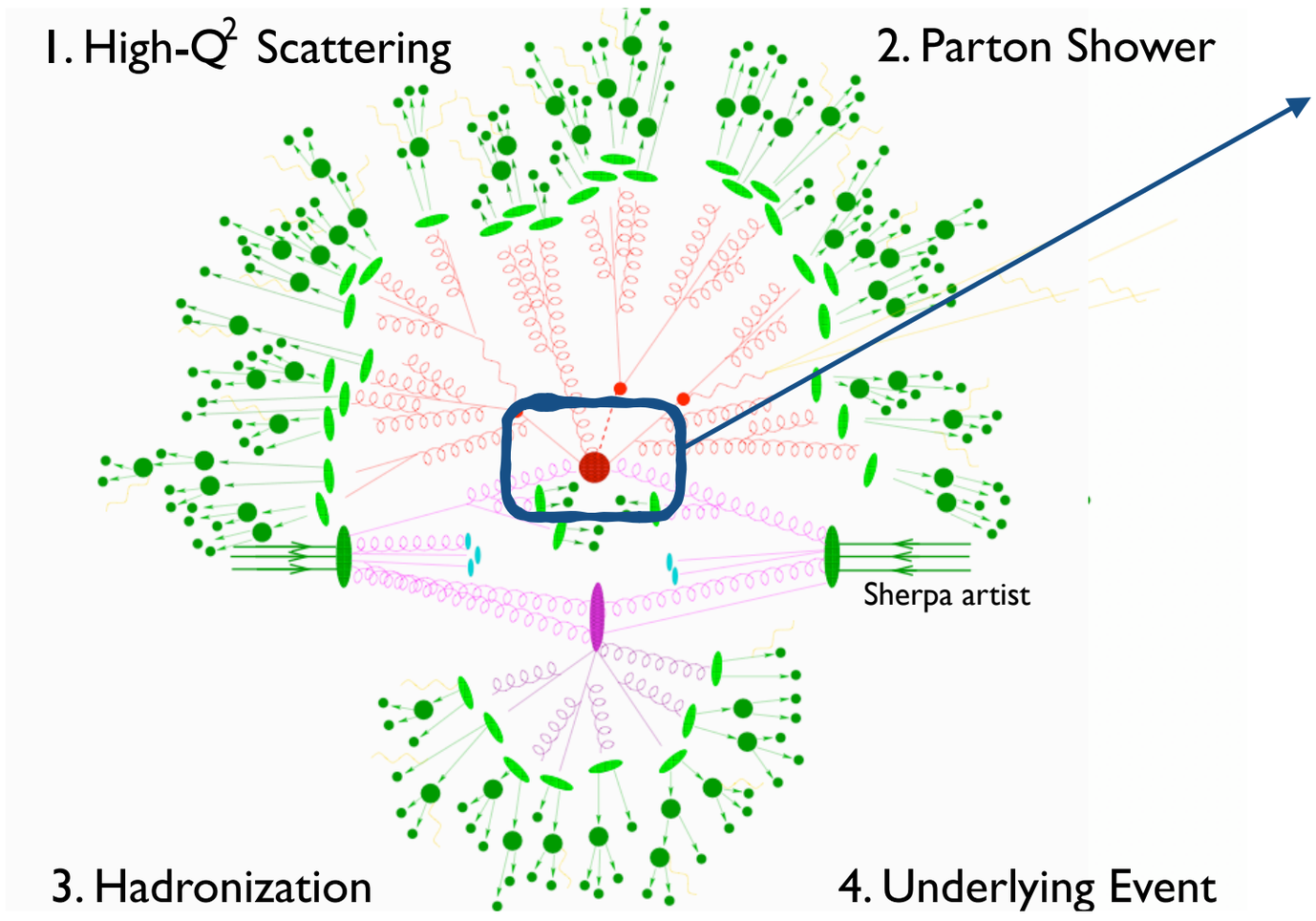

data vs. theory

- bottom up, unfold to parton level, e.g., jets (hadron)->jets (parton)

QCD fixed-order calculations, fully differential at parton level, frontier NNLO

QCD resummation, restricted phase space, pick important pieces from all orders in α_s, frontier N3LL

QCD@LHC

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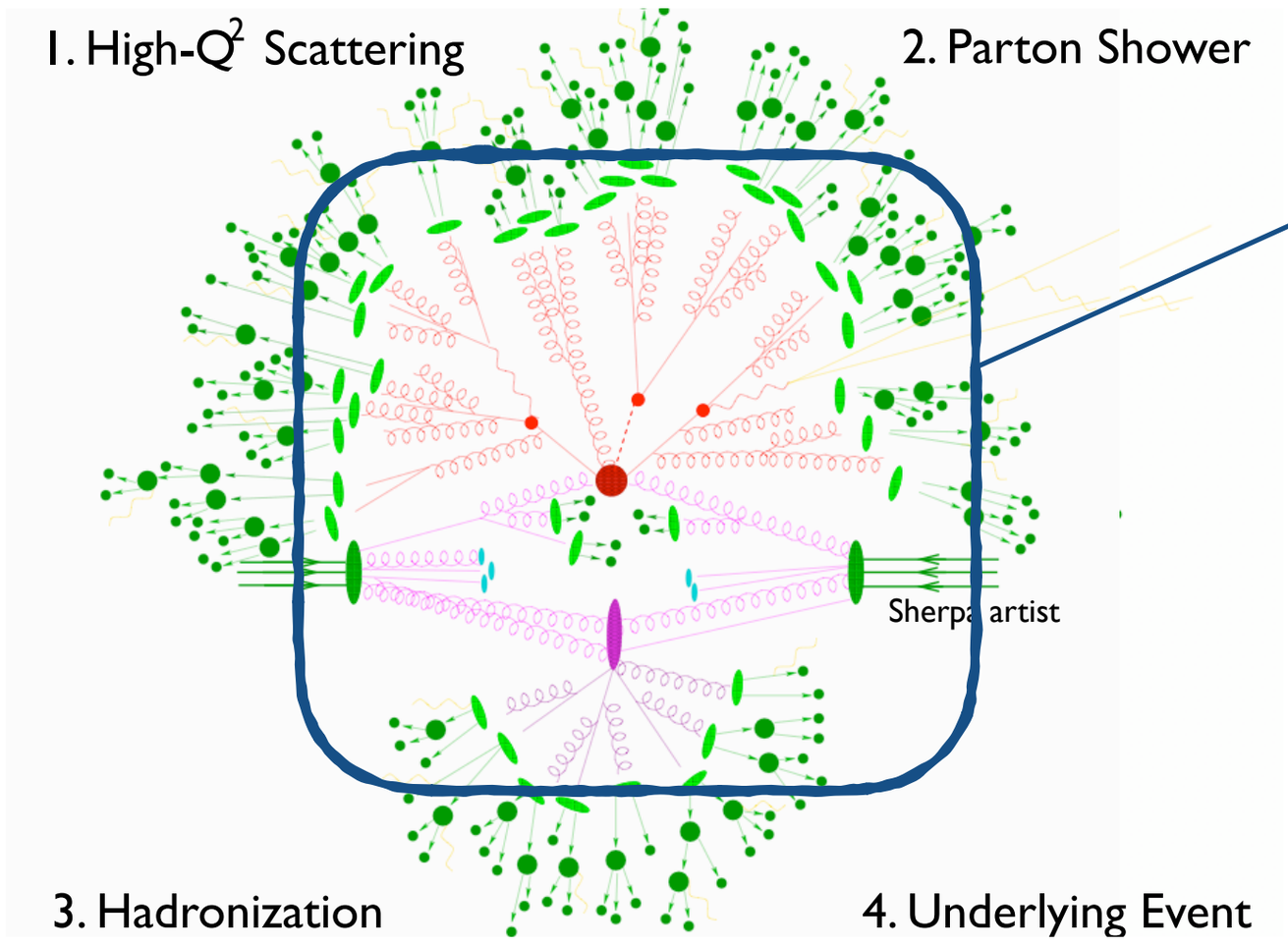


data vs. theory

- fully exclusive MC generators with higher order QCD corrections, both in hard emissions and in sub-leading logarithms

must have parton shower, and fragmentation models

need match (FO+PS) and merging (all multiplicities) to take advantage of fixed-order results

1. Parton Distribution Functions

2. Fixed Order Calculations

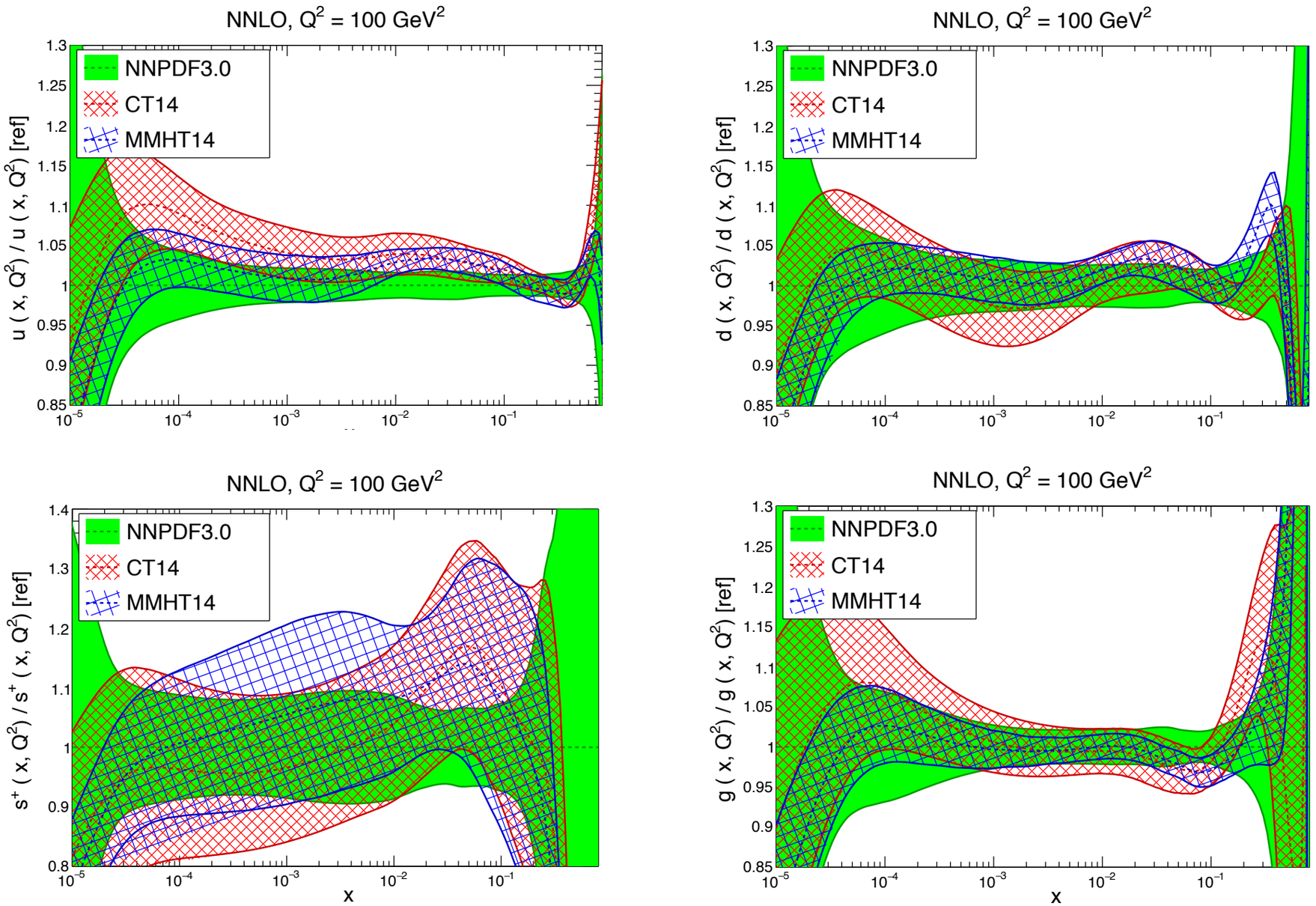
3. QCD Resummation

4. Parton Shower and Generator

New PDF4LHC recommendation

- Good agreements are found for the newest generation of three global analysis groups utilizing GM-VFN heavy-quark scheme; motivate a statistical combination at PDF level, i.e., PDF4LHC2015 PDFs

CT14, MMHT14, NNPDF3.0 NNLO PDFs with $\alpha_s(m_Z)$=0.118

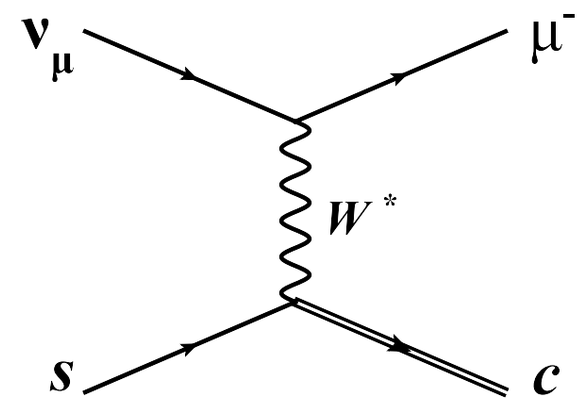


1401.0013, J Gao, Nadolsky

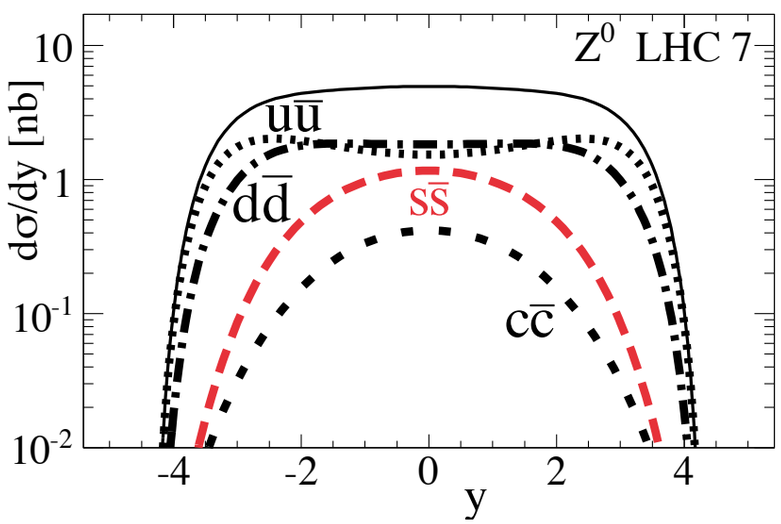
Puzzle on strangeness

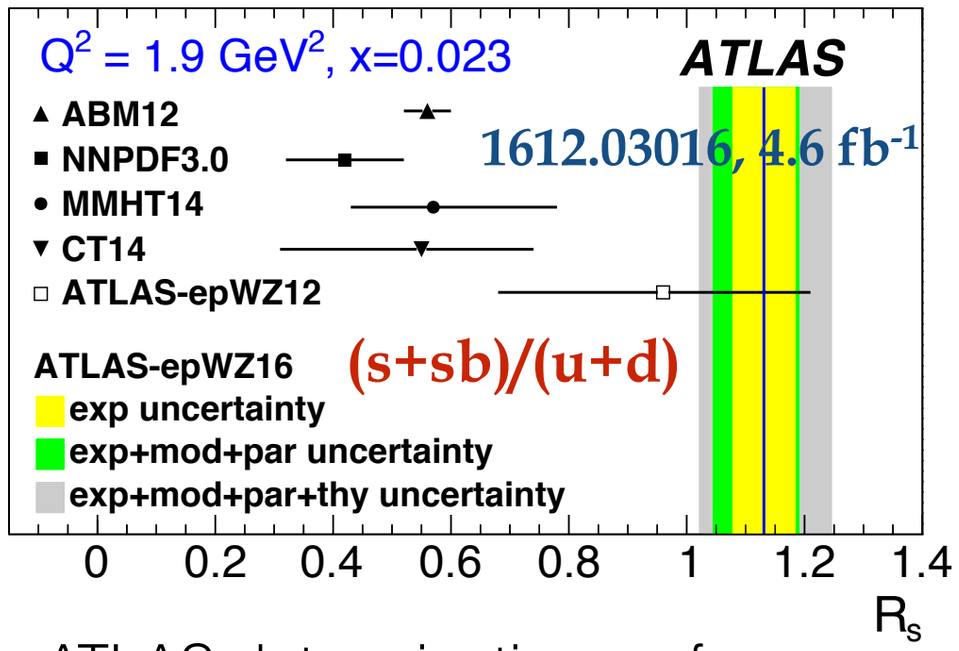
- It is still not clear whether the strangeness is suppressed comparing to u and d sea-quarks or not; tensions between DIS data and LHC W/Z data

Dimuon production in semi-inclusive CC DIS, e.g., NuTeV, CCFR, NOMAD, directly probe



LHC precise W/Z data can also disentangle different flavor seas





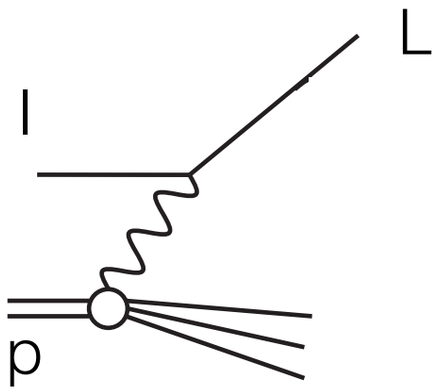
- ATLAS determination prefers unsuppressed strange sea in opposite to global fit
- previous dimuon data are only fitted using NLO theory
- NNLO QCD corrections to dimuon production are calculated recently; effects are under investigation

1601.05430, Berger, J Gao, CS Li et al.

Brightness of the proton

- A new approach for precision determination of photon PDF from electron proton scattering data, LUXqed

two diff. interpretations on imaginary exp. l+P->L+X, proton SFs vs. photon PDF

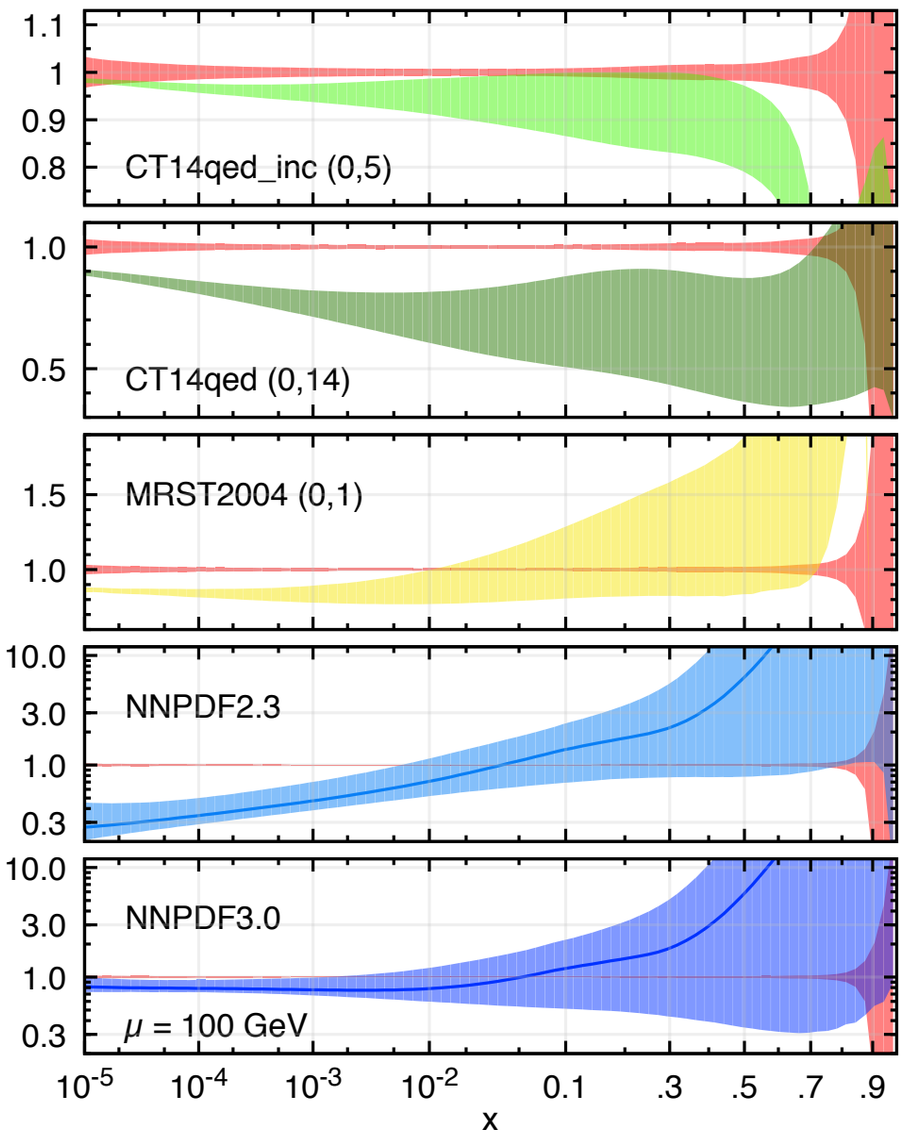


photon PDF directly from proton SFs

$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{ \int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2) \right.$$
$$\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right]$$
$$\left. - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}$$

1607.04266, Manohar et al.

comparison with previous results, normalized to LUXqed (in red)



1. Parton Distribution Functions

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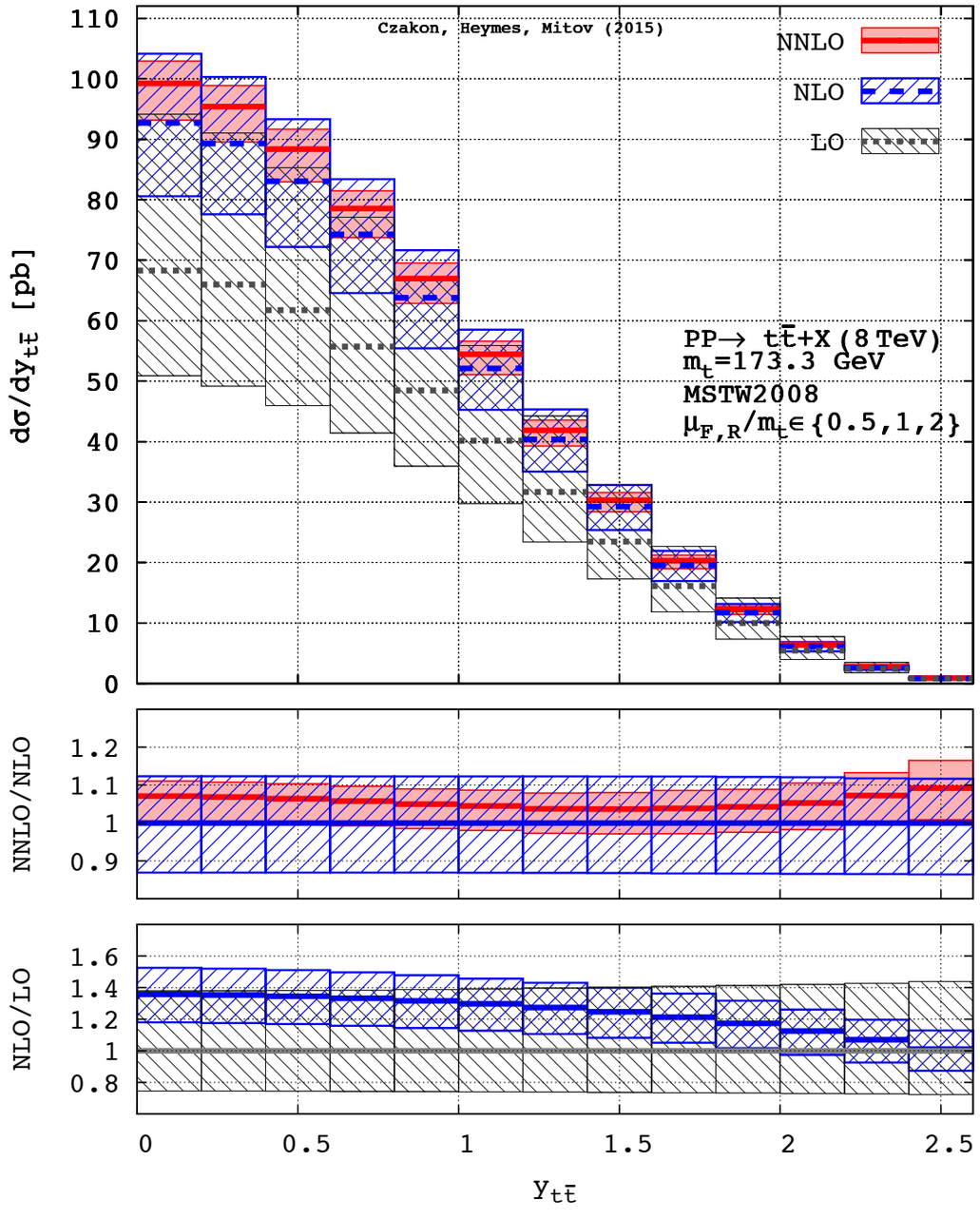
Top-quark pair distributions

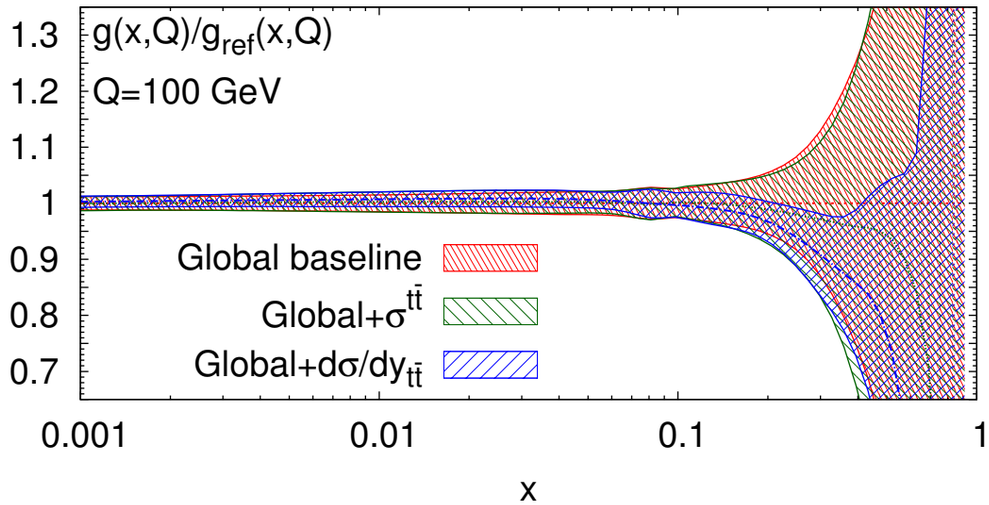
- Full NNLO QCD corrections for differential distributions based on sector improved phase space method and a numerical evaluation of the two-loop virtual amplitude

rapidity of top-quark pair



1511.00549, Czakon, Heymes, Mitov

1611.08609, Czakon et al.

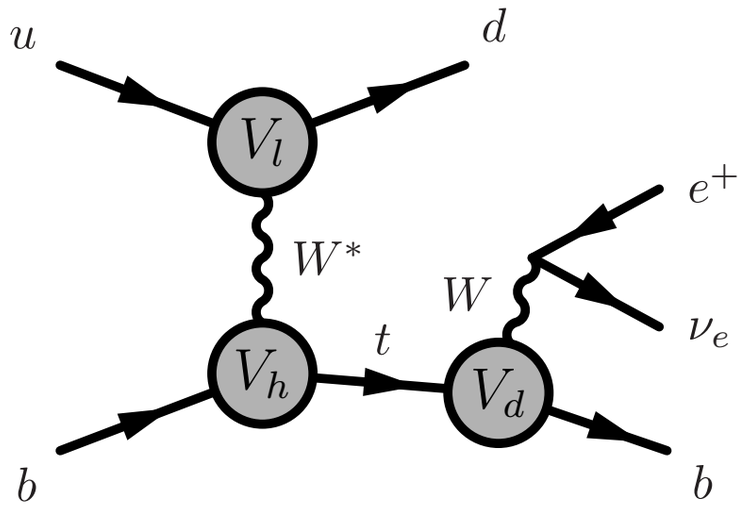


- improve agreement with data, reduce scale variations; show strong constraints on gluon PDF at large-x

- some tension found between CMS and ATLAS motivate further inclusion of top-quark decay at NNLO [J Gao, CS Li, HX Zhu 2012] similar to the NLO study by Bernreuther, ZG Si et al. 2004

Single top-quark fiducial cross section

- NNLO QCD corrections to fiducial cross sections in t-channel single top-quark production with leptonic decay in double DIS approach



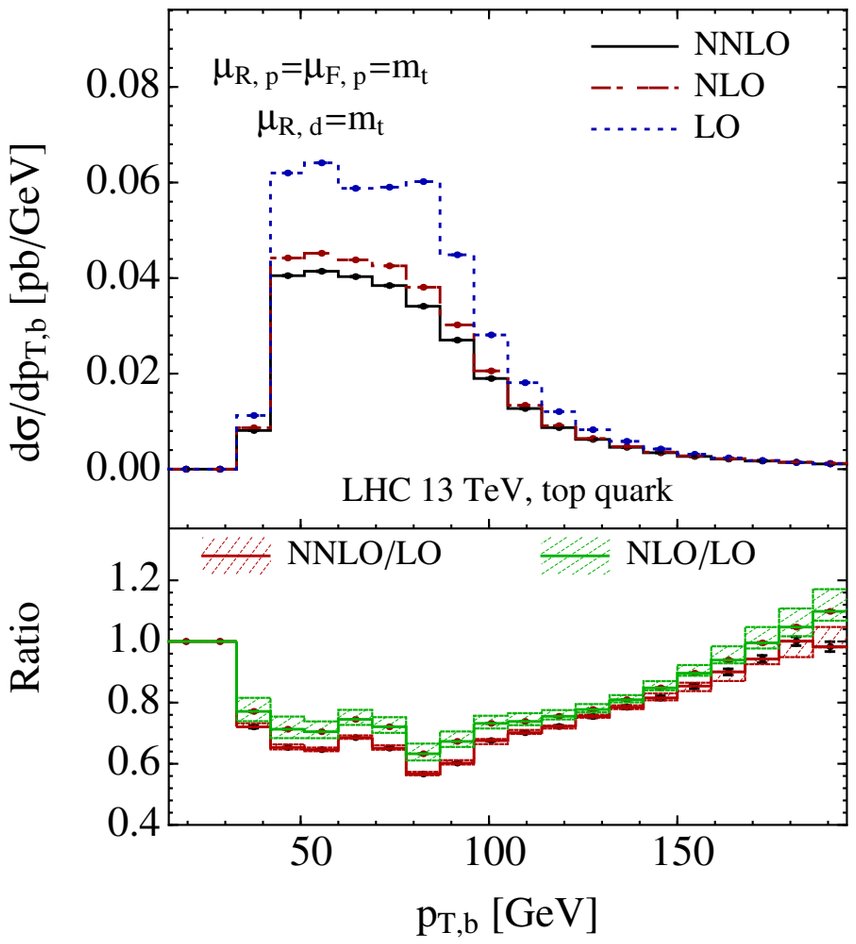
- neglecting cross talks in heavy and light-quark lines [color suppressed, ~$1/N_C^2$]
- NNLO top decay included using NWA
- apply similar fiducial cuts as in CMS 8 TeV analysis, including requiring exact two jets

1606.08463, Berger, J Gao, CP Yuan, HX Zhu

large negative QCD corrections

fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13

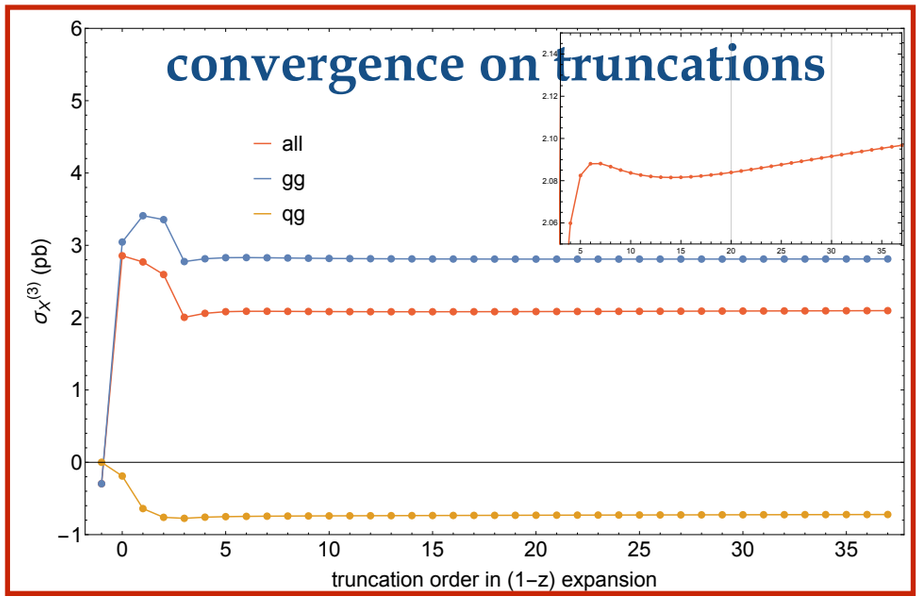
b-jet pT distribution

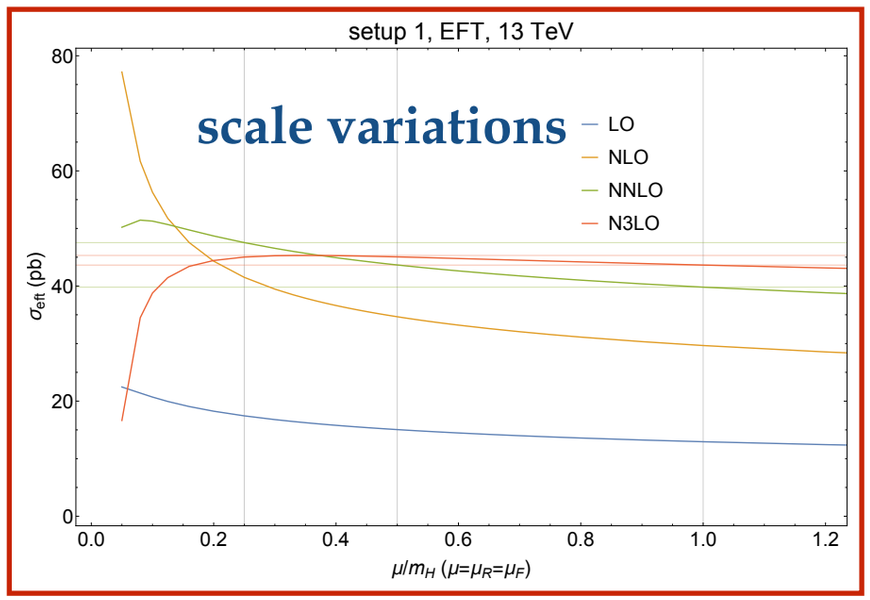


Higgs boson total cross section

- The state of art N3LO calculations for the total rate of Higgs boson production via gluon fusions in the infinite top-quark limit

1602.00695, Anastasiou et al.





$$\hat{\sigma}_{ij}^{(3,N)} = \delta_{ig}\,\delta_{jg}\,\hat{\sigma}_{\rm SV}^{(3)} + \sum_{n=0}^{N} c_{ij}^{(n)}\,(1-z)^n$$

- expand the N3LO partonic cross sections in threshold parameter z
- soft-virtual part also calculated in 1404.4839, by Y Li, HX Zhu et al.
- analytical results are calculated for c^n up to n=37

LHC 13 TeV full predictions

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}{+}\alpha_s)$$

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\ \text{pb}}_{-1.15\ \text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

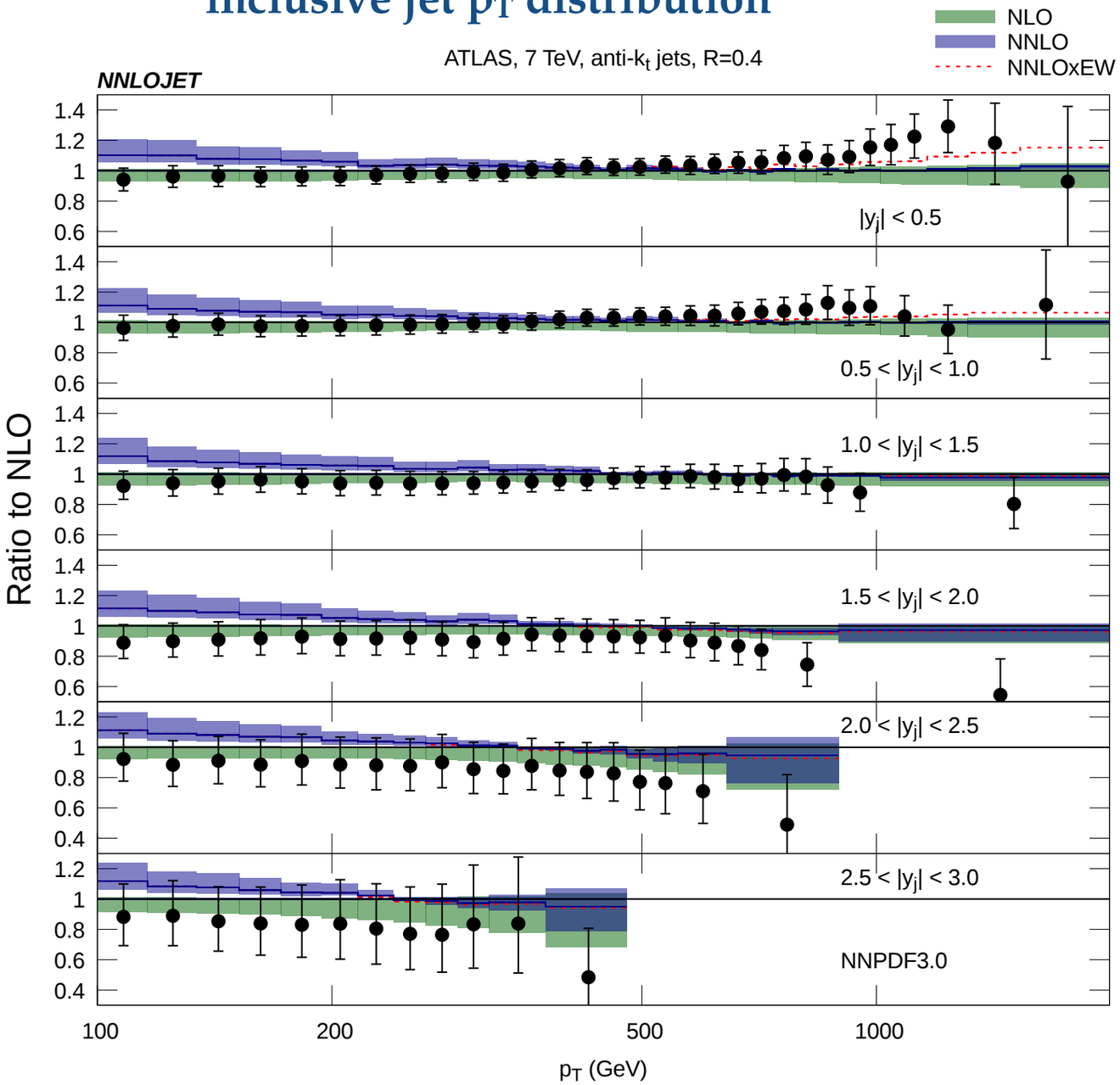
δ(PDF)	$\delta(\alpha_s)$
± 0.90 pb	$^{+1.27\text{pb}}_{-1.25\text{pb}}$
$\pm 1.86\%$	$^{+2.61\%}_{-2.58\%}$

breakdown of unc.

Inclusive jet production

- Calculations on NNLO QCD corrections including all partonic channels based on antenna subtraction method [not included subleading color contributions expected to be small]

inclusive jet p_T distribution

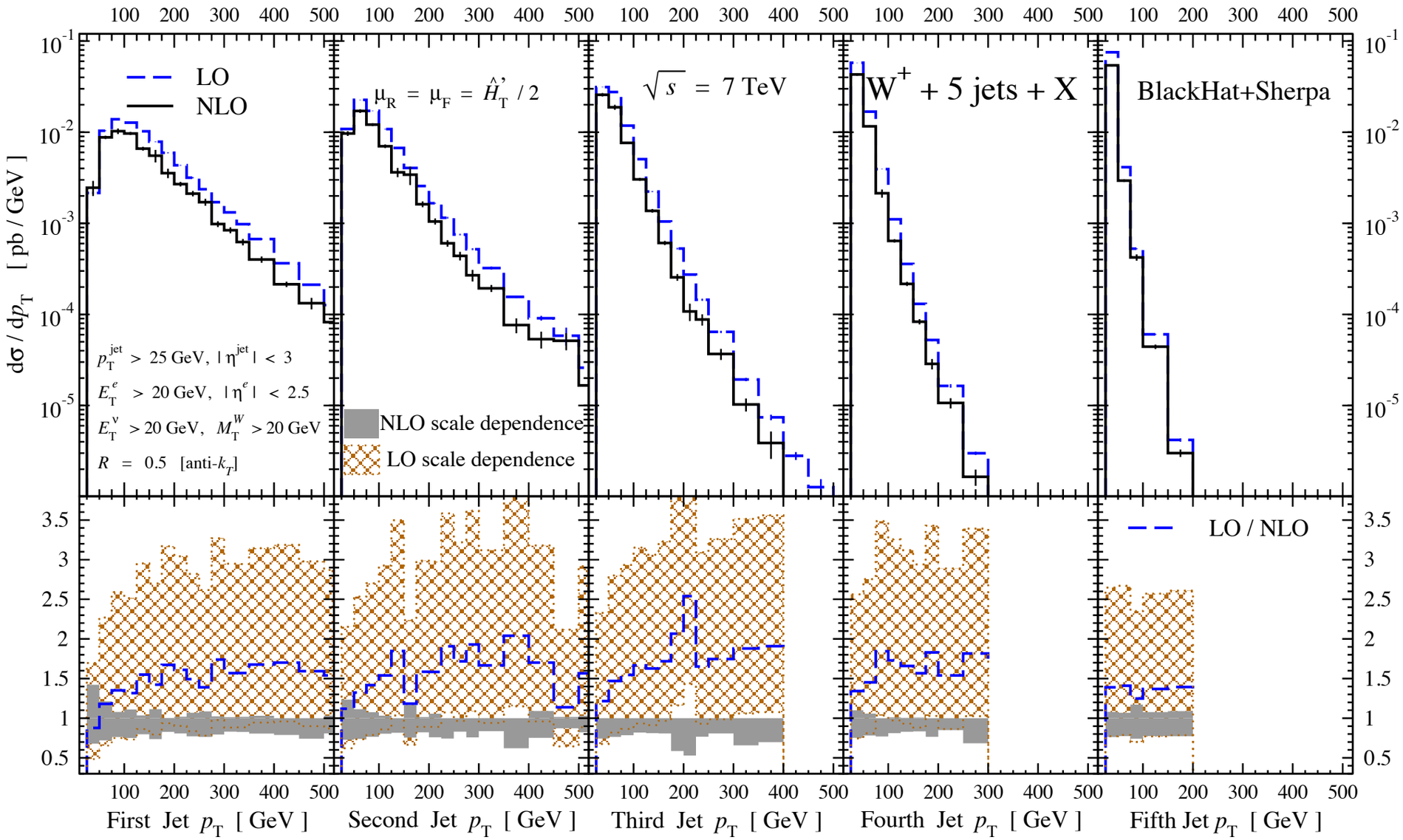


- corrections are found to be large in small pT region
- a reduction of scale variations at large pT, but not small pT
- possible bias in current NNLO PDF analyses
- EW corrections are important at large pT

1611.01460, Currie, Glover, Pires

W/Z boson plus jet(s)

- NLO predictions available for W plus up to 5 jets production from BLACKHAT+SHERPA

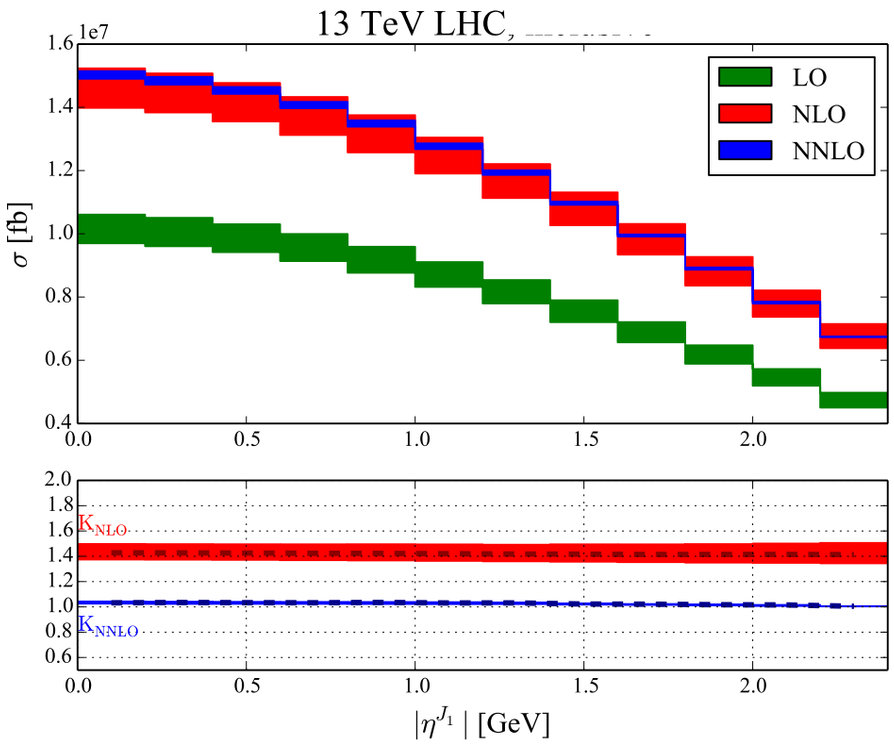


1304.1253, Bern et al.

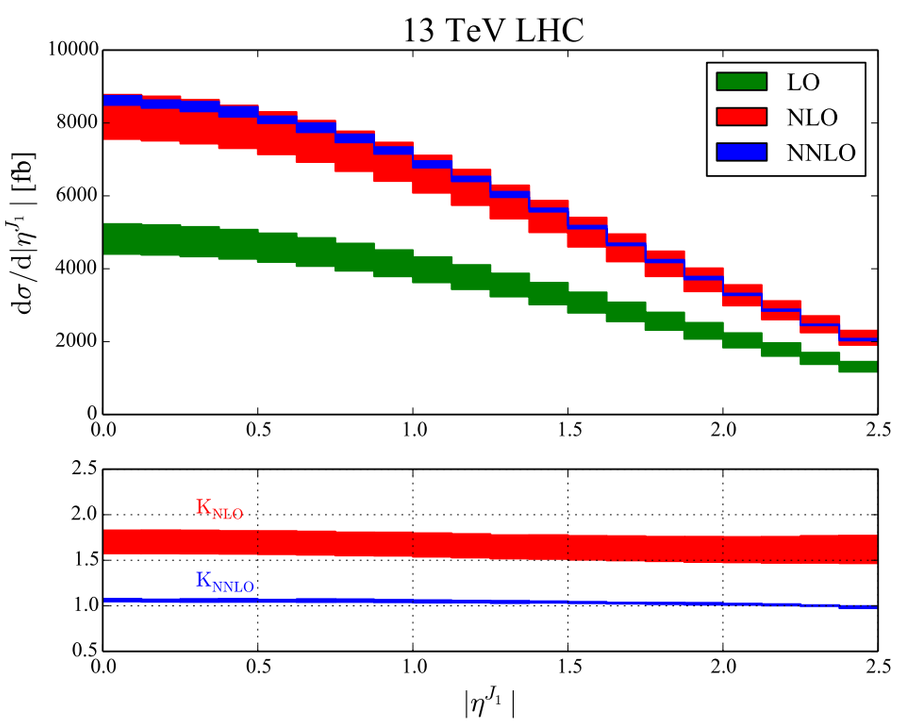
W/Z boson plus jet(s)

- NNLO predictions for W/Z plus jet production have been calculated by using both the jettiness cutoff and the antenna subtraction method

leading jet pseudo rapidity dis. in W+jet production



leading jet pseudo rapidity dis. in Z+jet production



1602.02695, 1602.08140, Boughezal, XH Liu, Petriello

- generalized phase-space cutoff method up to NNLO based on N-jettiness variable as the regulator and factorization in SCET, motivated by the Q_T cutoff method from Catani et al.

similar SCET approach, J Gao, CS Li, HX Zhu, 2012

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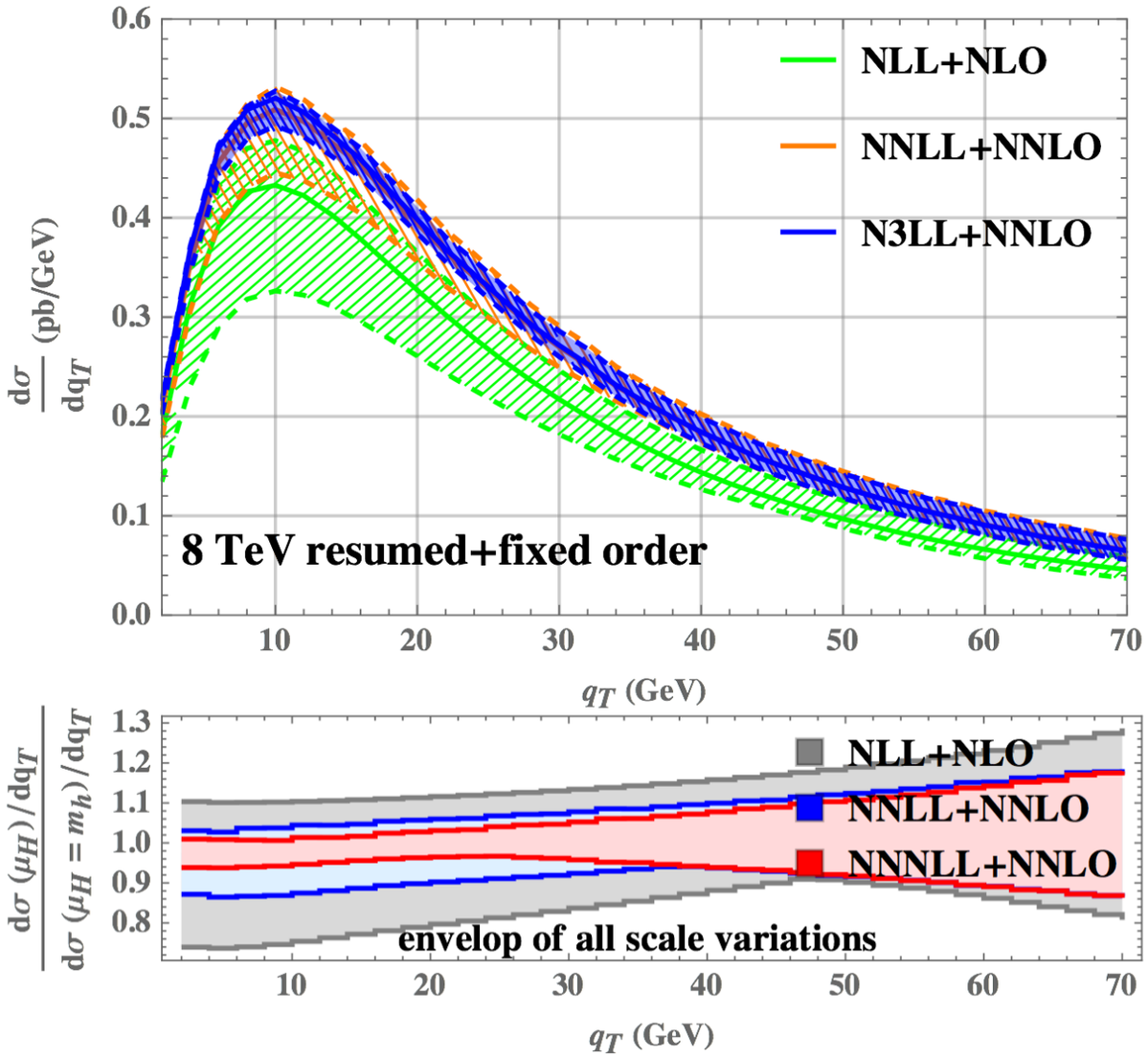
Higgs boson production at small Q_T

- N3LL resummation on transverse momentum distribution of the Higgs boson at small Q_T in gluon fusion is recently achieved and matched with NLO calculation at finite Q_T

Higgs boson p_T distribution



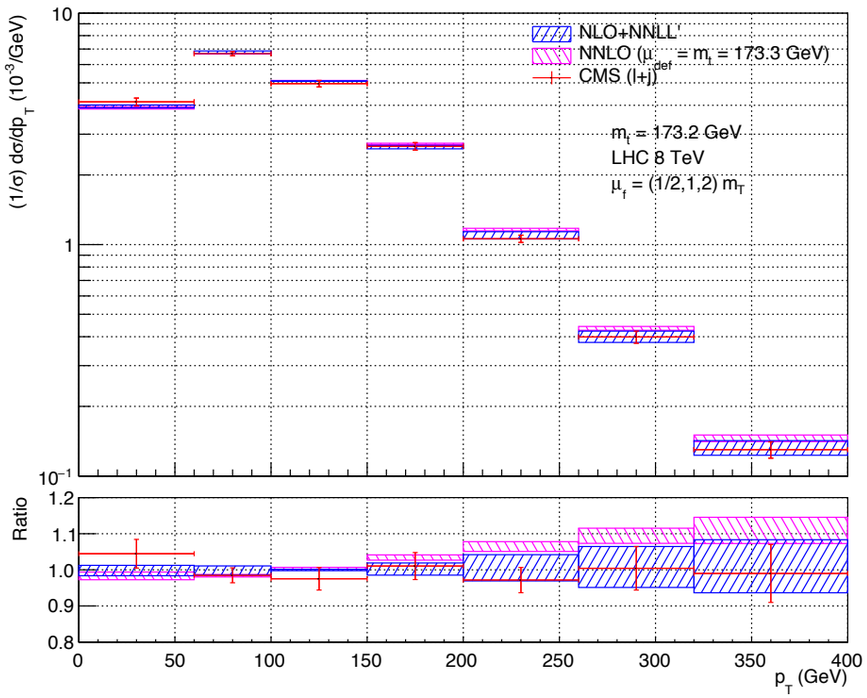
Y Li, Steward, HX Zhu et al., 2016

- The resummation is carried out in the rapidity renormalization group framework
- soft functions relevant for Q_T resummation of Higgs or W/Z boson production are calculated to 3-loop level
- the rapidity anomalous dimensions are extracted to the same order and allows a N3LL resummation; also derived 3-loop B function in CSS framework

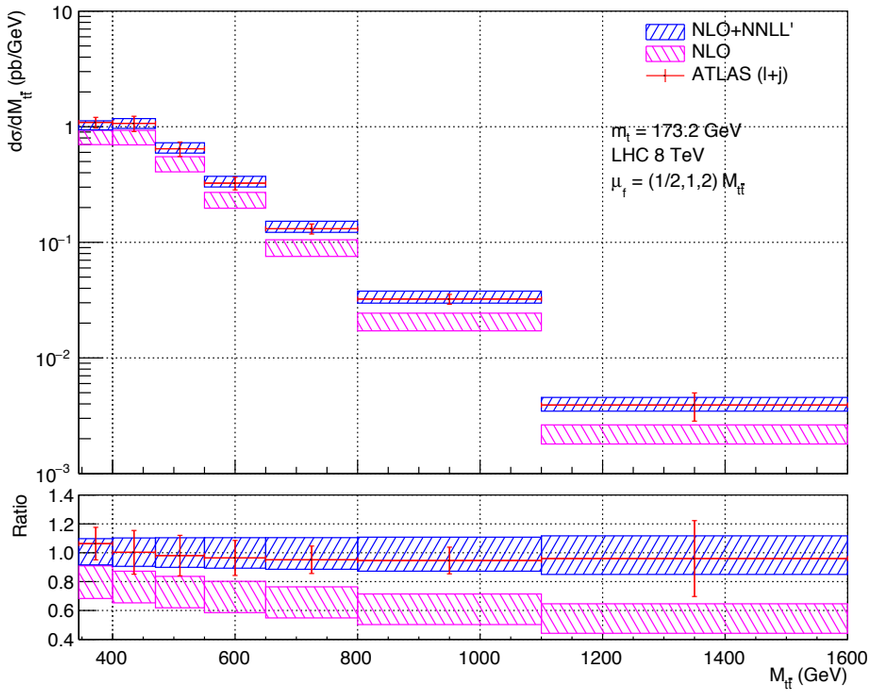
Boosted top-quark pair production

- Simultaneous resummation of Sudakov-type double logarithm and the logarithm from top-quark mass at NNLL'+NLO level

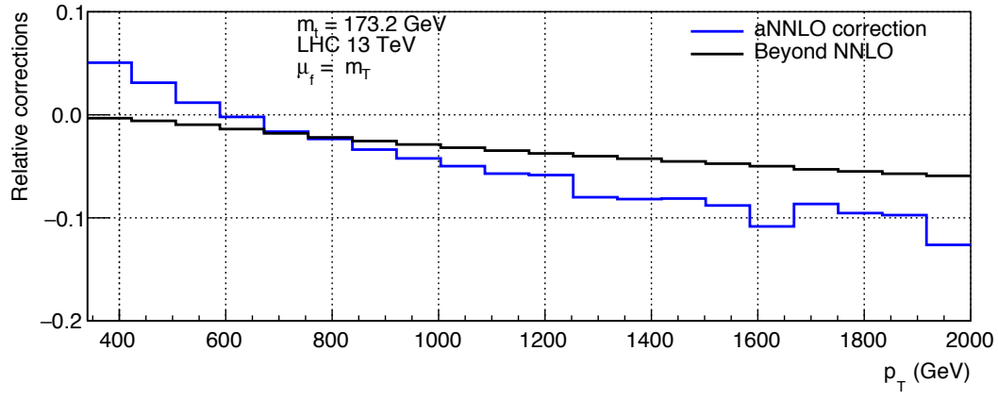
top quark p_T distribution



top pair invariant mass distribution



corrections from beyond NNLO



- there are the usual soft gluon double logarithm as well as terms of ~Log(pT/mt) needs to be resummed
- resummed results show a better agreements with data in boost region
- resummed corrections beyond NNLO are found to be large in tail region

1601.07020, Pecjak, Scott, X Wang, LLYang

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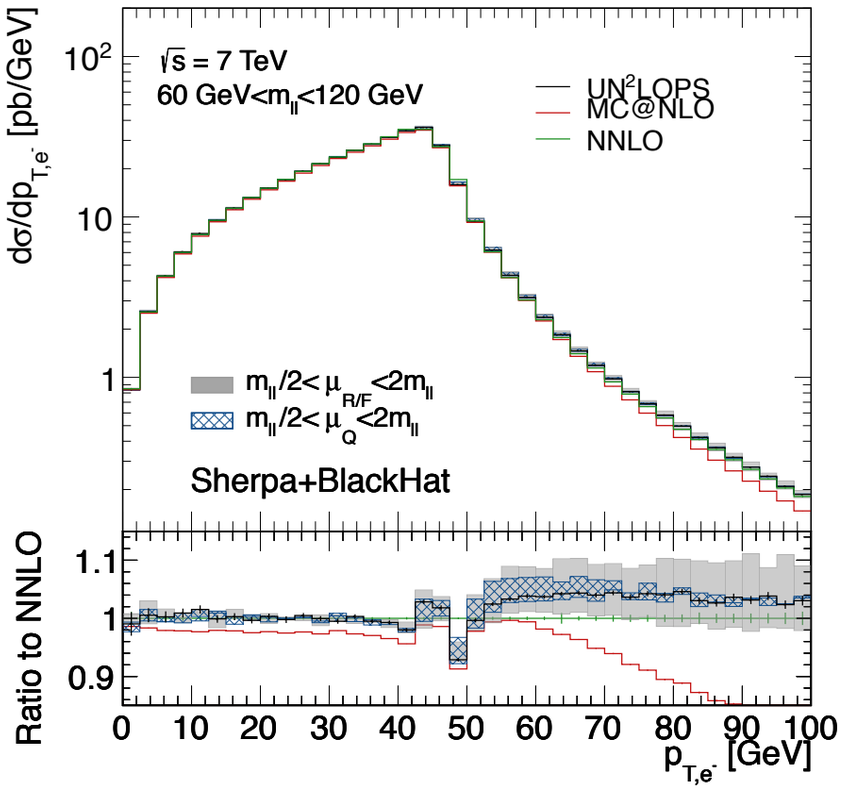
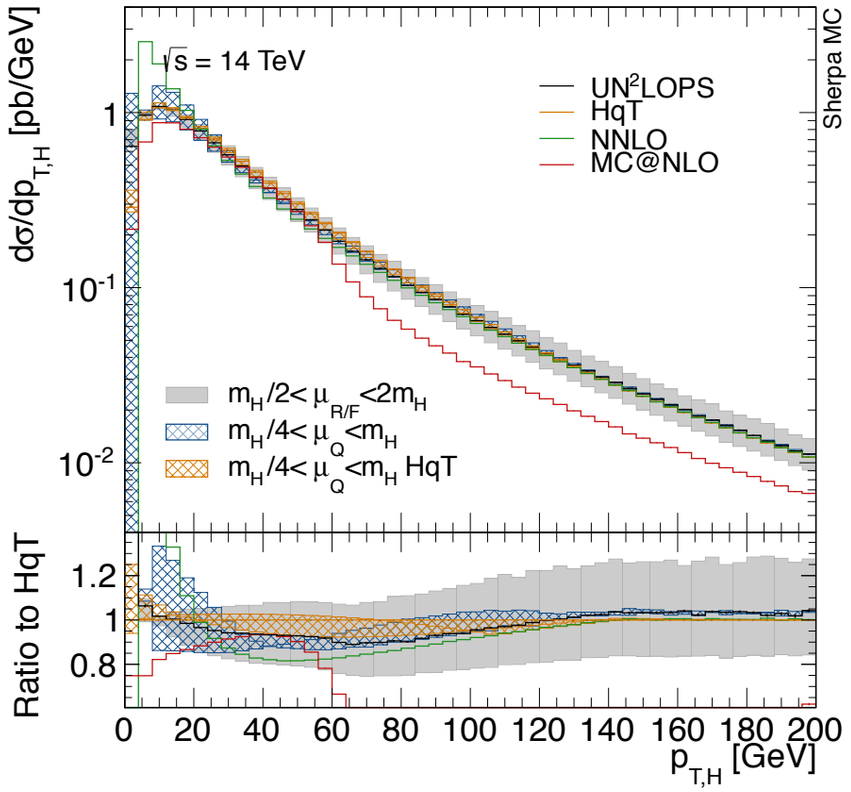
Matching NNLO with parton shower

- Attempts for matching NNLO fixed-order corrections of Higgs boson production via gluon fusion, or W/Z production, with parton shower

lepton p_T dis. in Z boson production



Higgs boson p_T dis. in gluon fusion



1405.3607, 1407.3773, Hoche, Y Li, Prestel

- matched results benefit from both exclusive resummation in PS and the hard emissions in FO; similar approach HJ-MINLO by Hamilton, Nason et al. 2013

- a possible framework on including NLO corrections into Sudakov form factor for final state shower, HT Li, Skands, 1611.00013

Summary

- Understanding in various topics of QCD ensures precision test of the standard model and also searches of new physics

- Tremendous theoretical progress have been made in the past few years especially on the perturbative calculations at NNLO and beyond

- Also improvements are still needed, like the knowledge on PDFs at large-x, NNLO corrections for specific 2 to 3 processes, NLO parton shower, PS matching with NNLO for general cases, and so on

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- Also improvements are still needed, like the knowledge on PDFs at large-x, NNLO corrections for specific 2 to 3 processes, NLO parton shower, PS matching with NNLO for general cases, and so on

Thanks for your attention!

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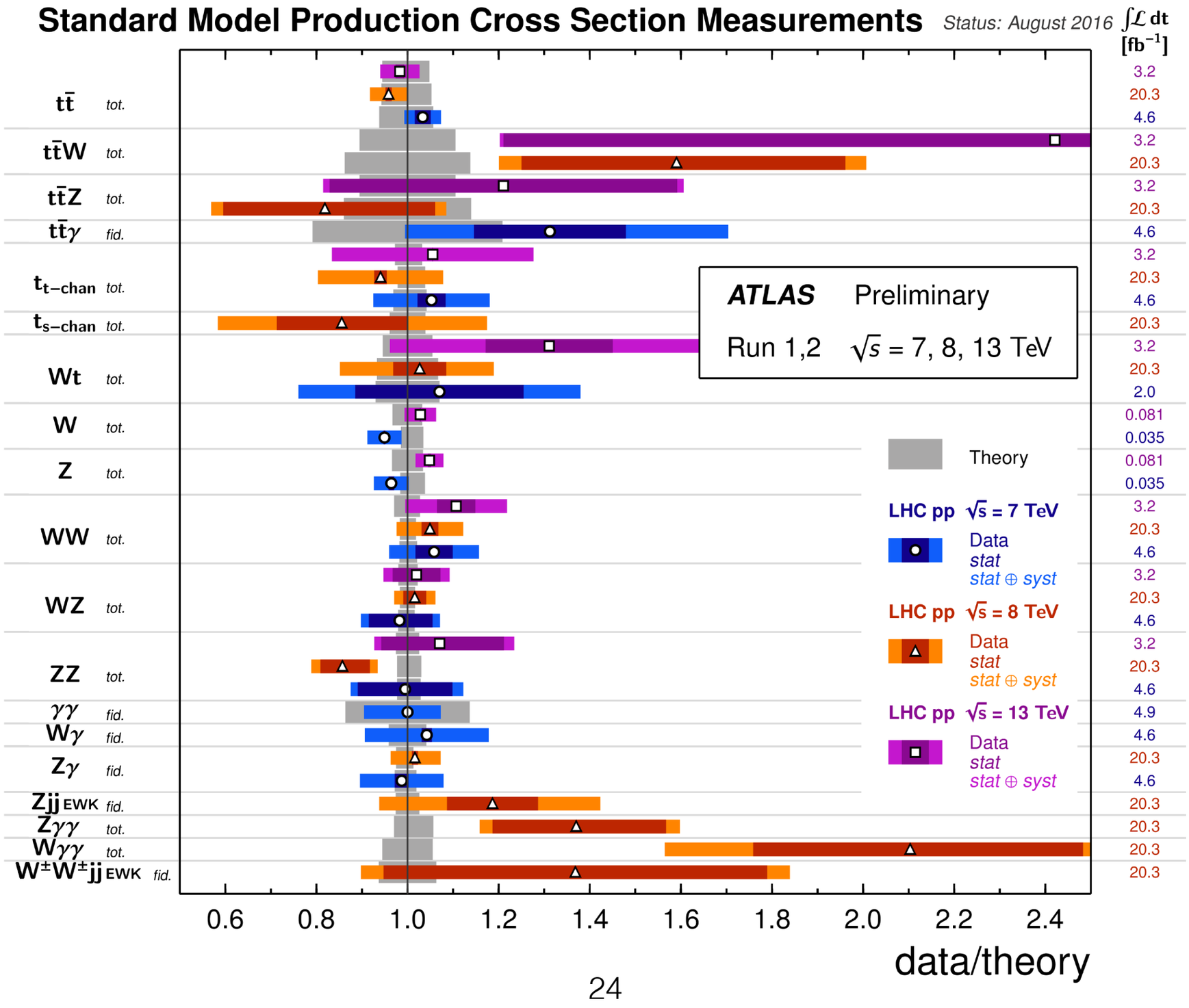
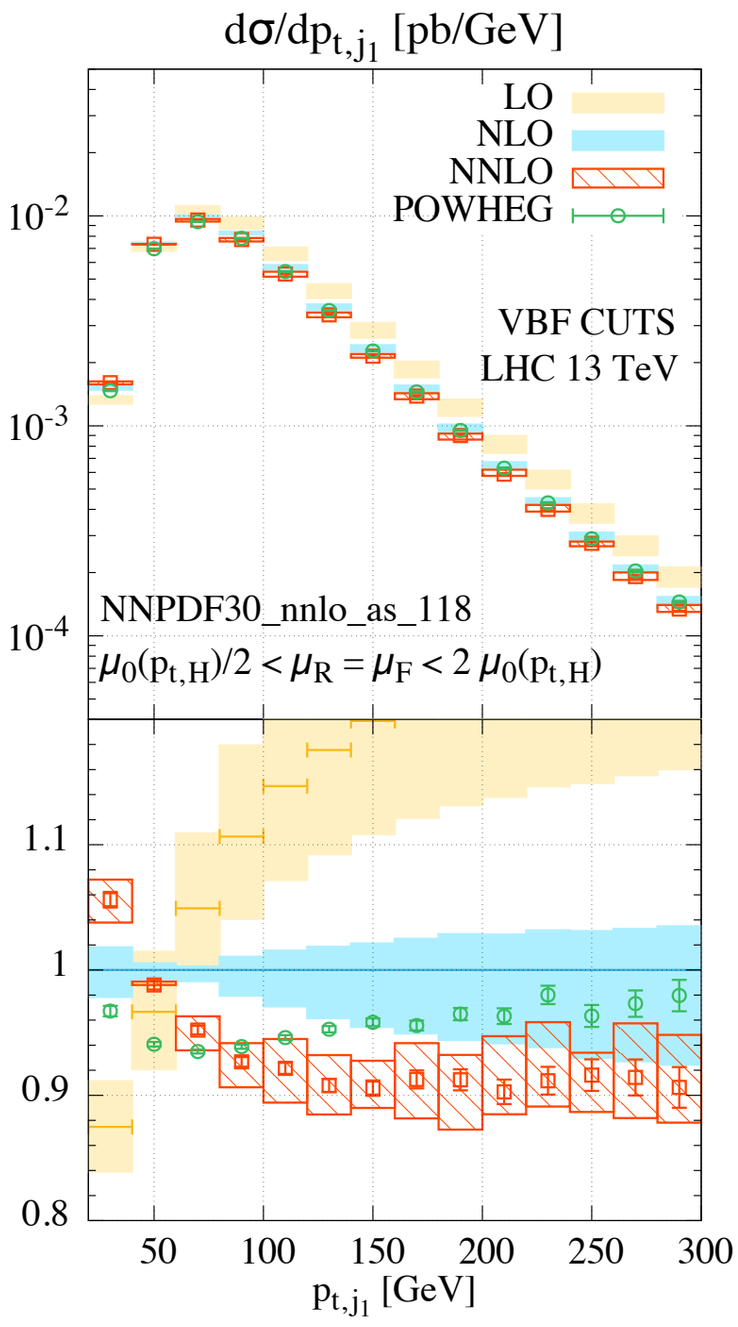


Higgs boson fully differential cross section in VBF

- NNLO QCD corrections to Higgs boson production via vector boson fusion in double DIS approximation with VBF cuts

leading jet pT after applying cuts



1506.02660, Cacciari et al.

QCD effects differ largely for inclusive and with VBF cuts

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.826\,^{+0.013}_{-0.014}$

- neglecting cross talks in two quark lines [color suppressed,~$1/N_C^2$]
- a new method, projection to born, is introduced for NNLO fully differential case, based on analytical results on DIS structure functions
- similar approach was used in Higgs pair production by LL Sheng, RY Zhang, WG Ma et al. 2013

W/Z boson plus jet(s)

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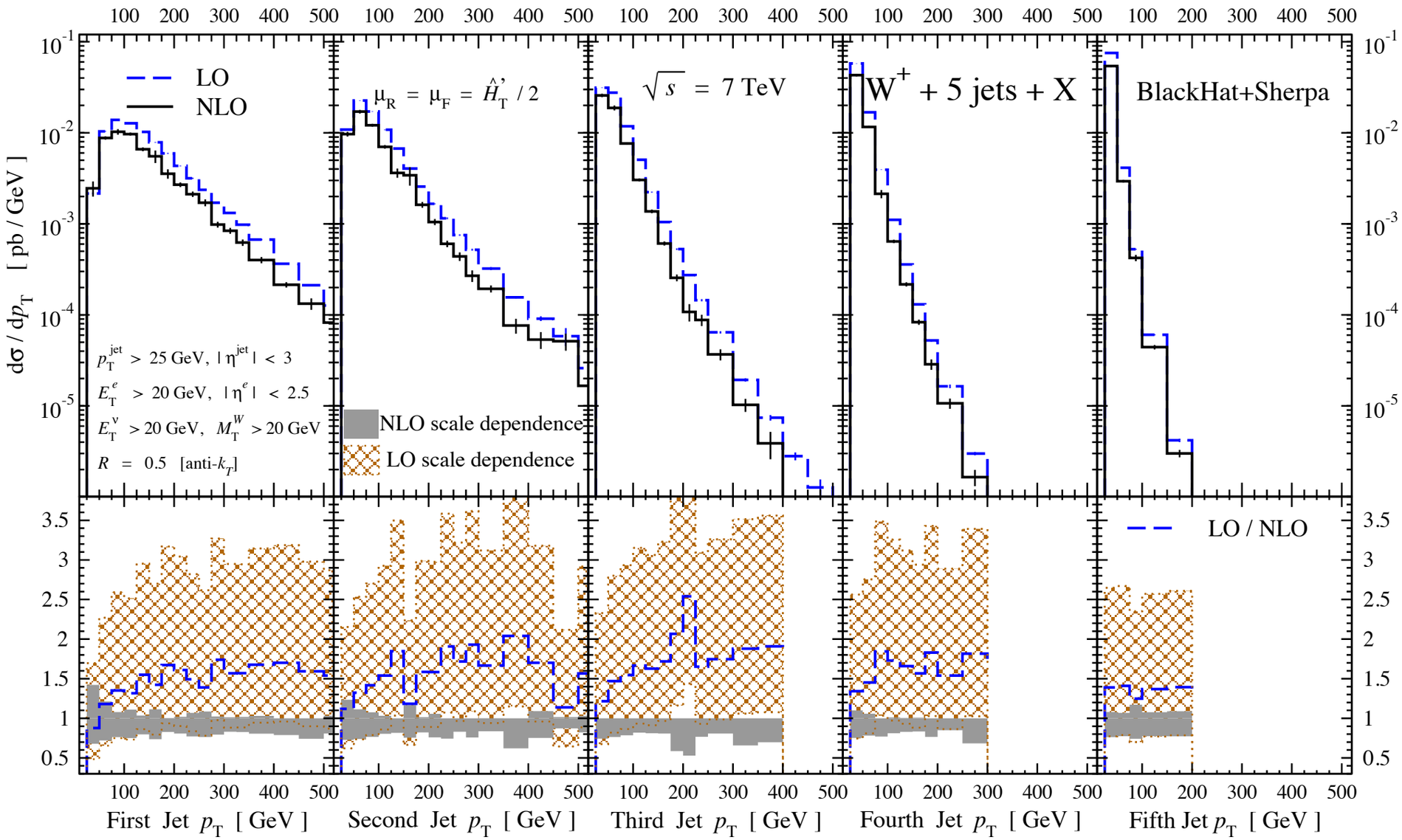

1304.1253, Bern et al.