QCD Physics at the LHC

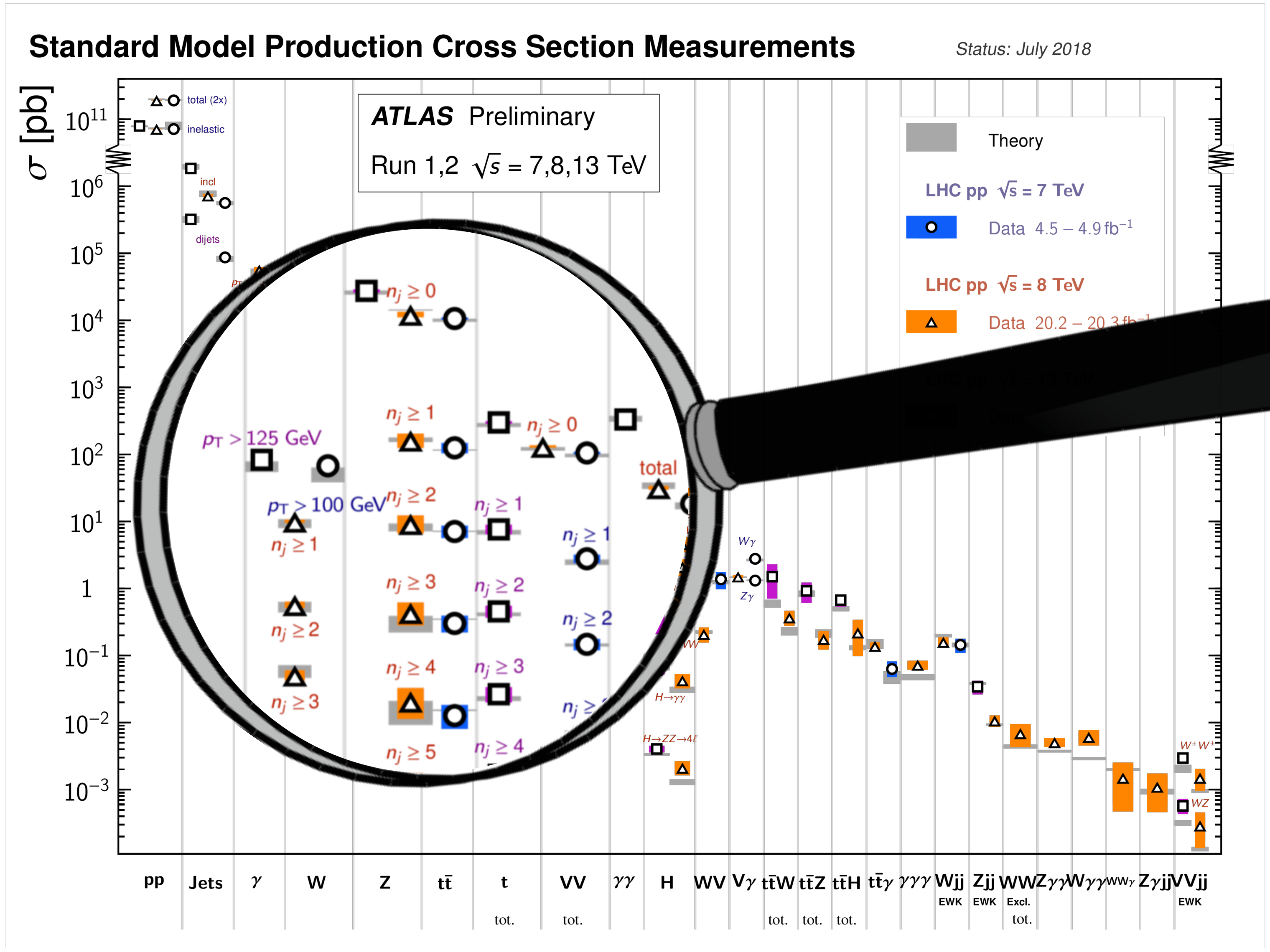
Xiaohui Liu

CLHCP 2018 @ CCNU

北京師範大學
BEIJING NORMAL UNIVERSITY

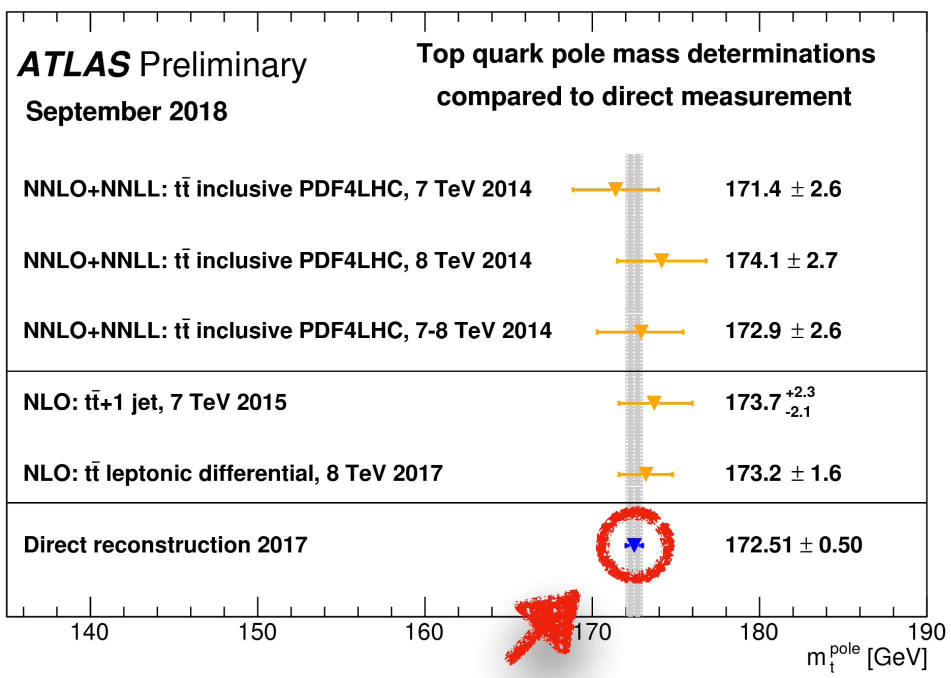
Remarkable experimental performance

- Overall good agreement with the SM, over 14 orders of magnitude!
- Many differential/inclusive cross-sections are known at per-mil precision! i.e. better than the theories.



A precision era!

Limitations due to QCD predictions



How to turn to the pole mass?
Theory error could be ~ 1GeV

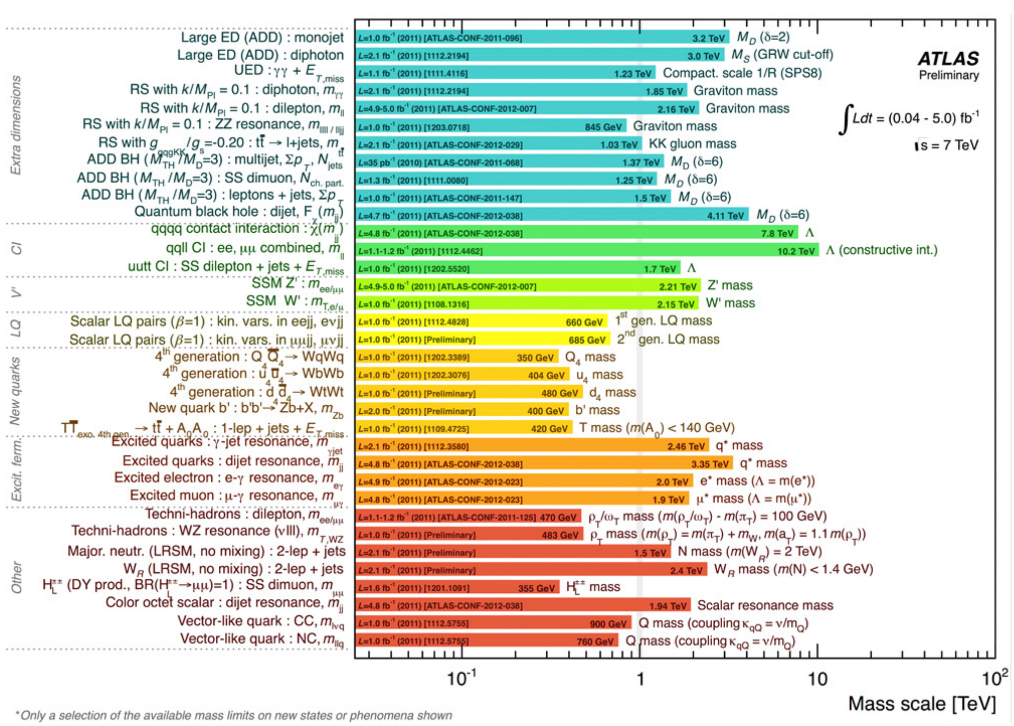
Precision measurements of the SM param.

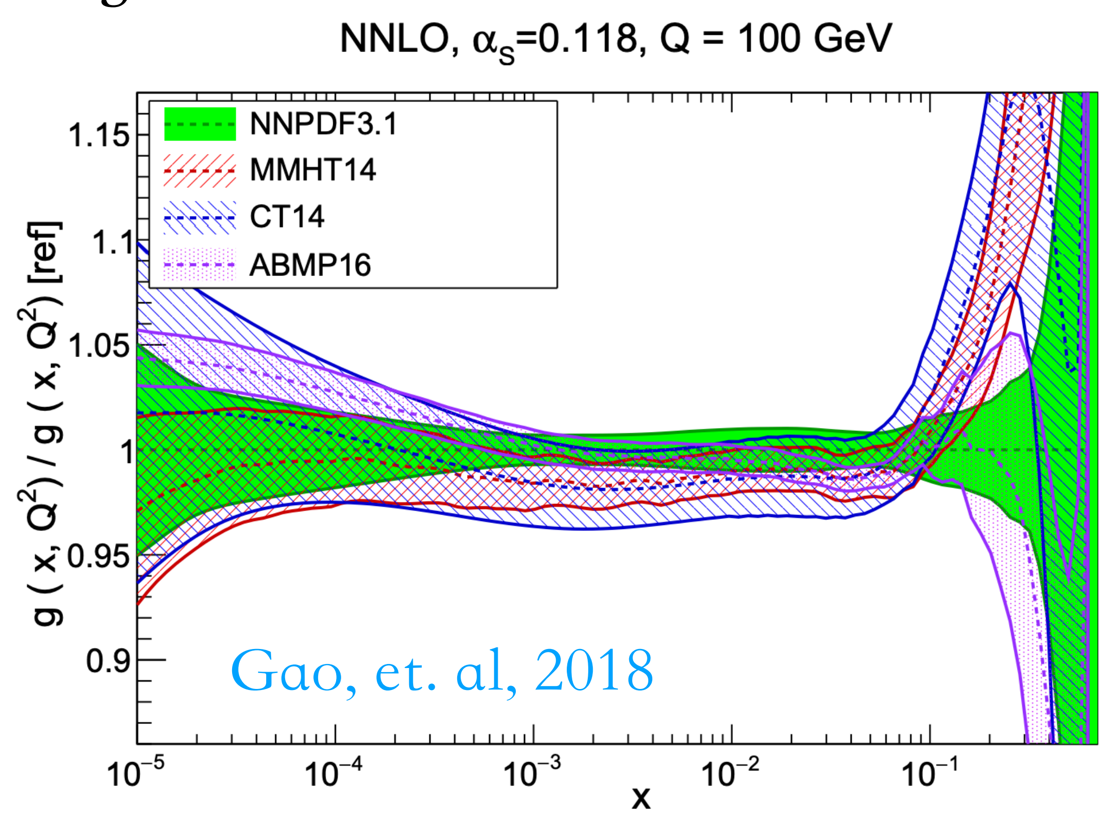
- $m_{\mathrm{top}}, m_W, \sin^2\theta_w\,, \ldots$
- (partially) dominated by the QCD uncertainties

$$m_t^{\mathrm{pole}} = 173.2 \pm 0.9(\mathrm{stat}) \pm 0.8(\mathrm{syst}) \pm 1.2(\mathrm{theory})\ \mathrm{GeV}$$

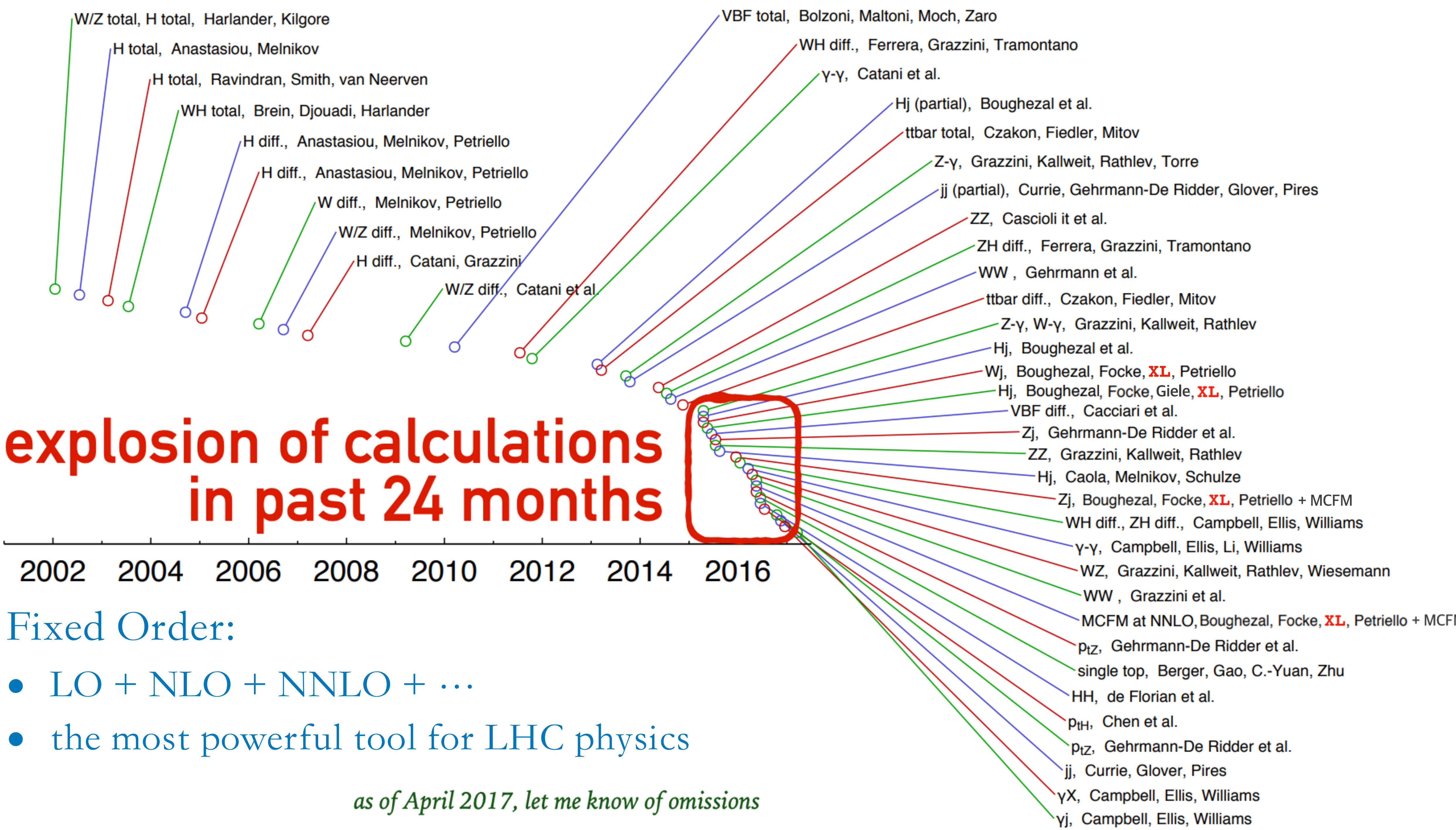
Indirect

Similar story for constraining new physics and hard probing hadrons





Theorists are catching up



Fixed Order:

- LO + NLO + NNLO + ···
- the most powerful tool for LHC physics

as of April 2017, let me know of omissions

Gavin P. Salam, 2017

Fixed Order Calculations

Virtual

- IBP + improvements Larporta , + $\cdots$
- Differential eqn. Kotikov
- Difference eqn. Larporta
- SecDec. Binoth, Heinrich
- Mellin Barnes Usyukina, Smirnov
- Series representation Ma, et.al
- Parameter expansions Yang, et.al
- Quasi-Monte Carlo Li, et. al.
- $\cdots$

Real

- Antenna subtraction Gehrmann, Glover, et.al
- STRIPPER Czakon, et.al
- N-jettiness subtraction Boughezal, **XL**, et.al
- qT-subtraction Catani, et.al
- Inclusive jet mass subtraction Gao, Li , Zhu
- P2B Salam, et. al.
- $\cdots$

Both loops and real corrections are important for predictions at the LHC

e.g., 2- loops for di-jet production are known for long (~2001), but no methods to deal with the real before 2015.

Resummation

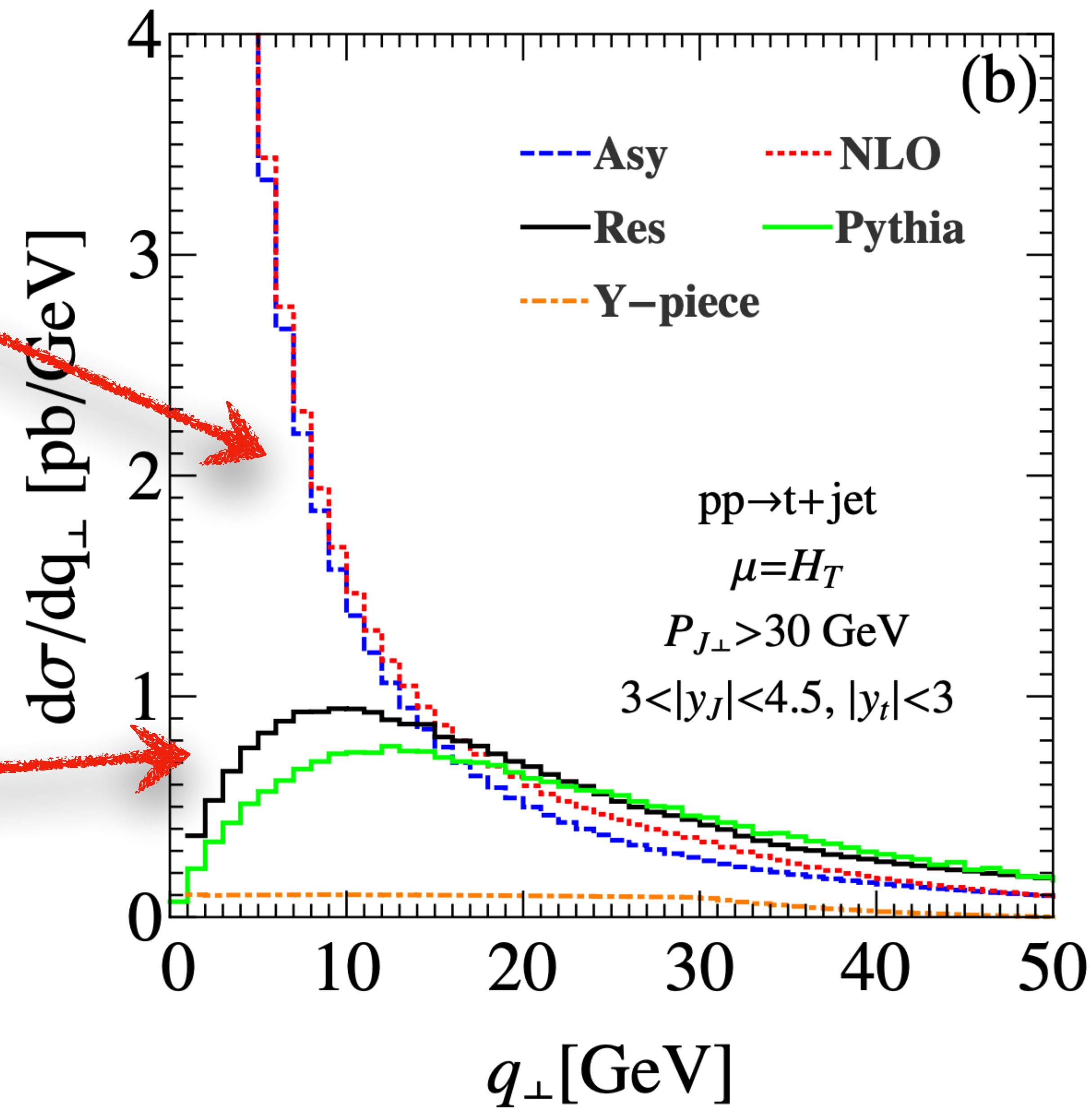
Standard approaches to the predictions: FO + Res.

Fixed order

- Breaks down in the soft-collinear dominated regions

Resummation to rescue

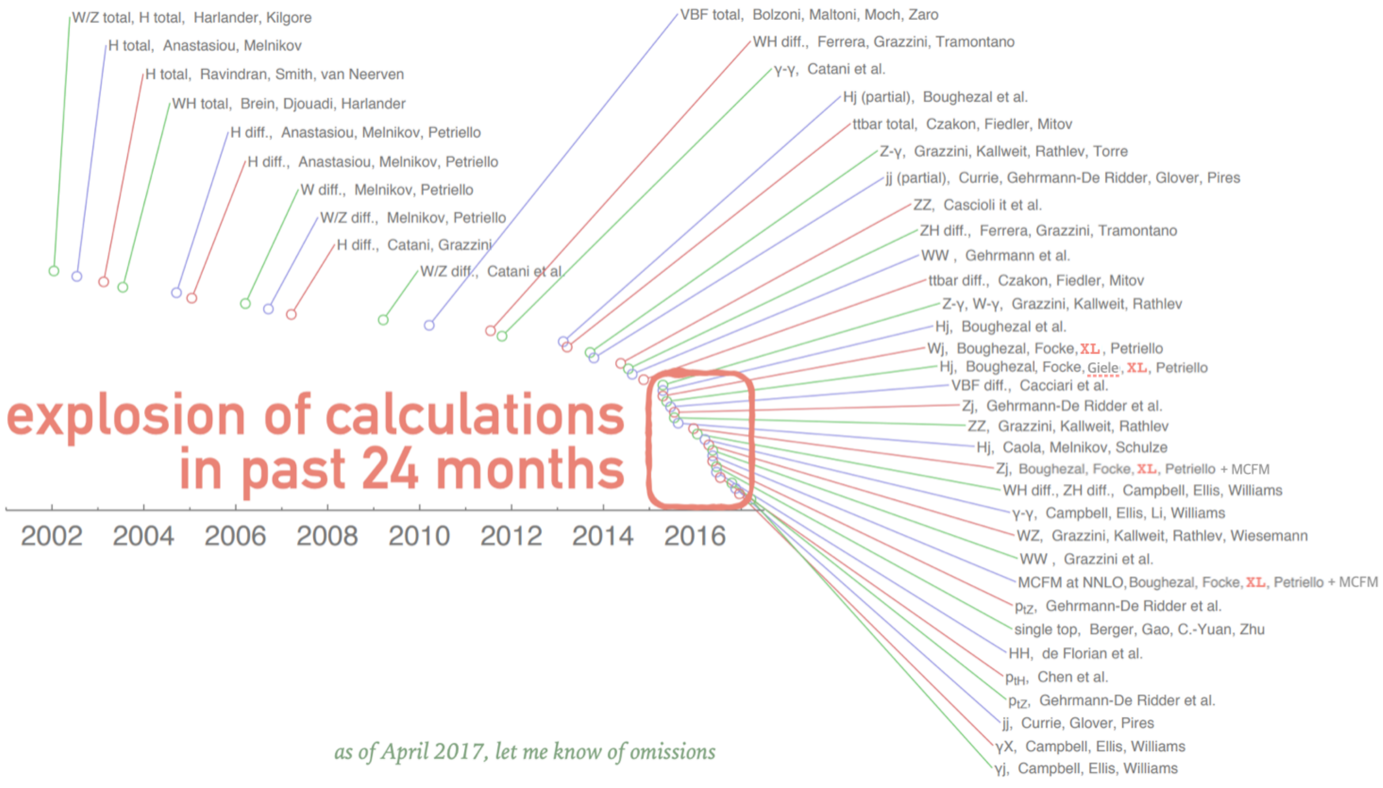
- LL + NLL + NNLL + ⋯
- Parton shower (~ LL)
- Analytic — SCET ⋯



Cao, Sun, Yan, Yuan, Feng 2018

Outlines

- LHC phenomenology and available tools
  - Higgs, vector bosons and jets
- Summary

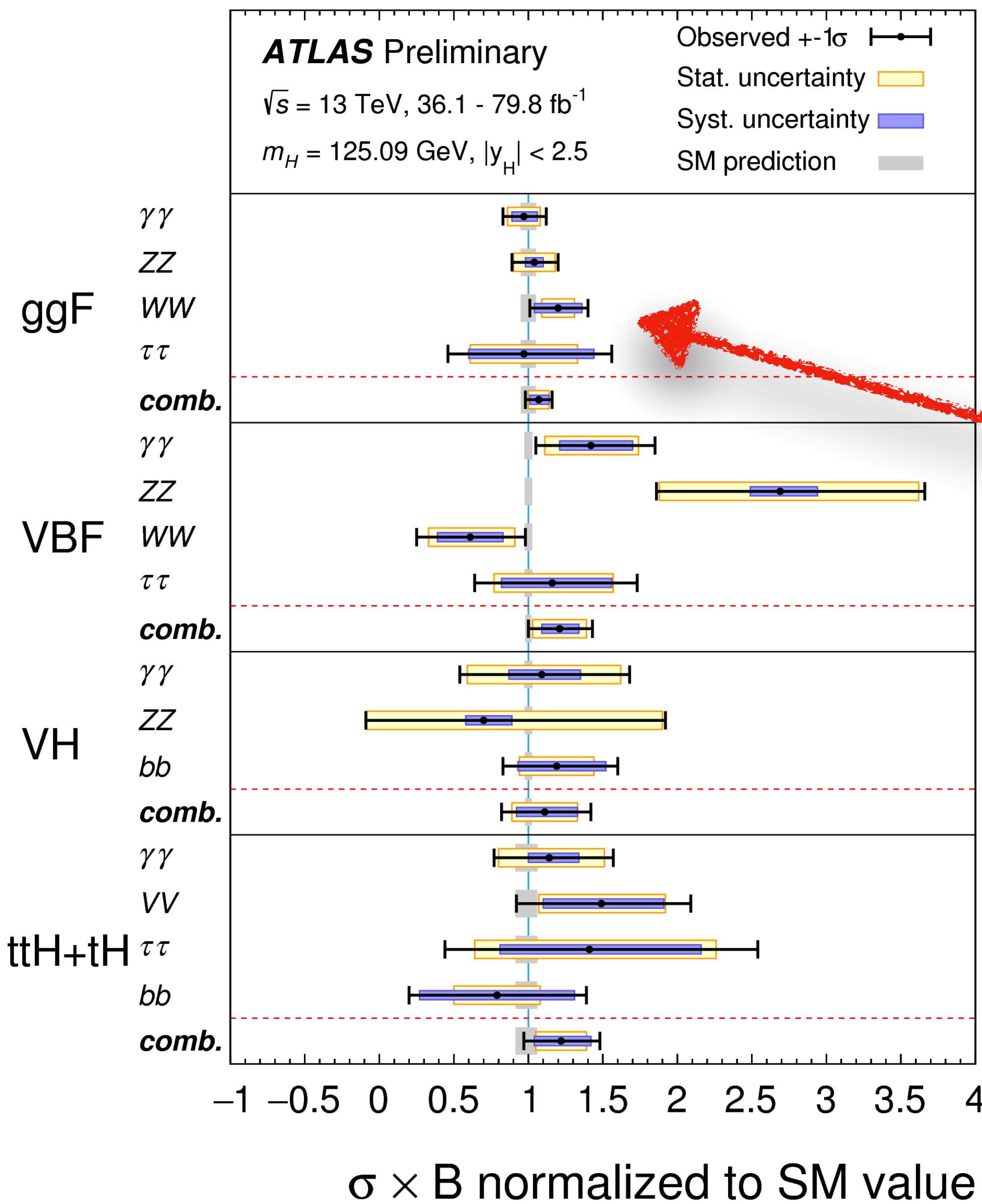


Higgs

ggH — the frontier of the precision frontier

- The only fundamental scalar in the SM
- Potential? Completely unknown!
- Yukawa? Only on the 3rd generations
- Portals to New physics
- $\cdots$

ggH — the frontier of the precision frontier



All measurements are consistent with the SM

$$\sigma_{ggH} = 48.58\,\text{pb}^{+4.56\%}_{-6.72\%}(\text{theory}) \pm 3.2\%(\text{PDF} + \alpha_s)$$

Anastasou, et.al., 2016

Precision is the key!

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	LO, rEFT
	$+\ 20.84\,\text{pb}$	$(+42.9\%)$	NLO, rEFT
	$-\ 2.05\,\text{pb}$	(-4.2%)	Exact NLO
	$+\ 9.56\,\text{pb}$	$(+19.7\%)$	NNLO, rEFT
	$+\ 0.34\,\text{pb}$	$(+0.2\%)$	NNLO, 1/mt
	$+\ 2.40\,\text{pb}$	$(+4.9\%)$	EW, QCD-EW
	$+\ 1.49\,\text{pb}$	$(+3.1\%)$	N3LO, rEFT

ggH — the frontier of the precision frontier

Frontier of the Precision Frontier, from 2016 to 2018

$$\sigma_{ggH} = 48.58\,\mathrm{pb}^{+4.56\%}_{-6.72\%}(\text{theory}) \pm 3.2\%(\text{PDF} + \alpha_s)$$

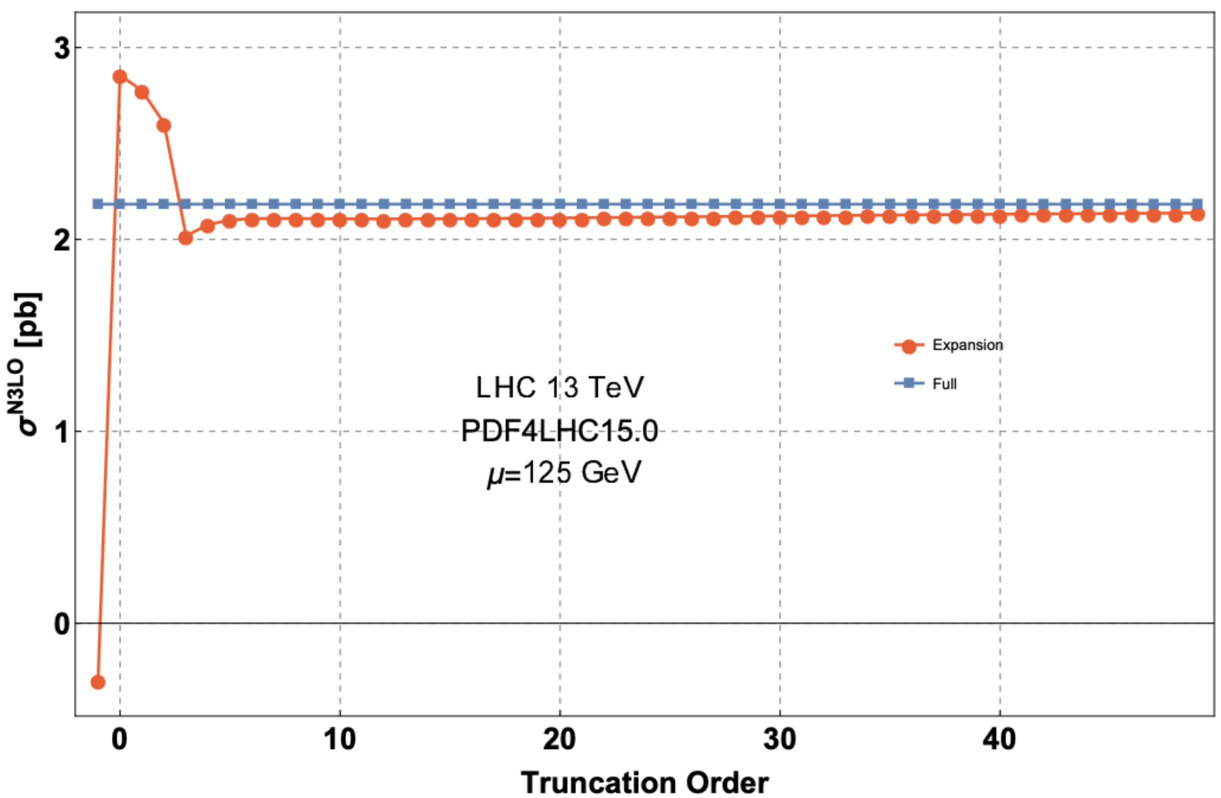
2016: soft expansion

Anastasou, et.al., 2014 - 2016

See also Li, Zhu, et. al., 14 for the 0th order

2018: EXACT, Fully analytic

Mistlberger, 2018

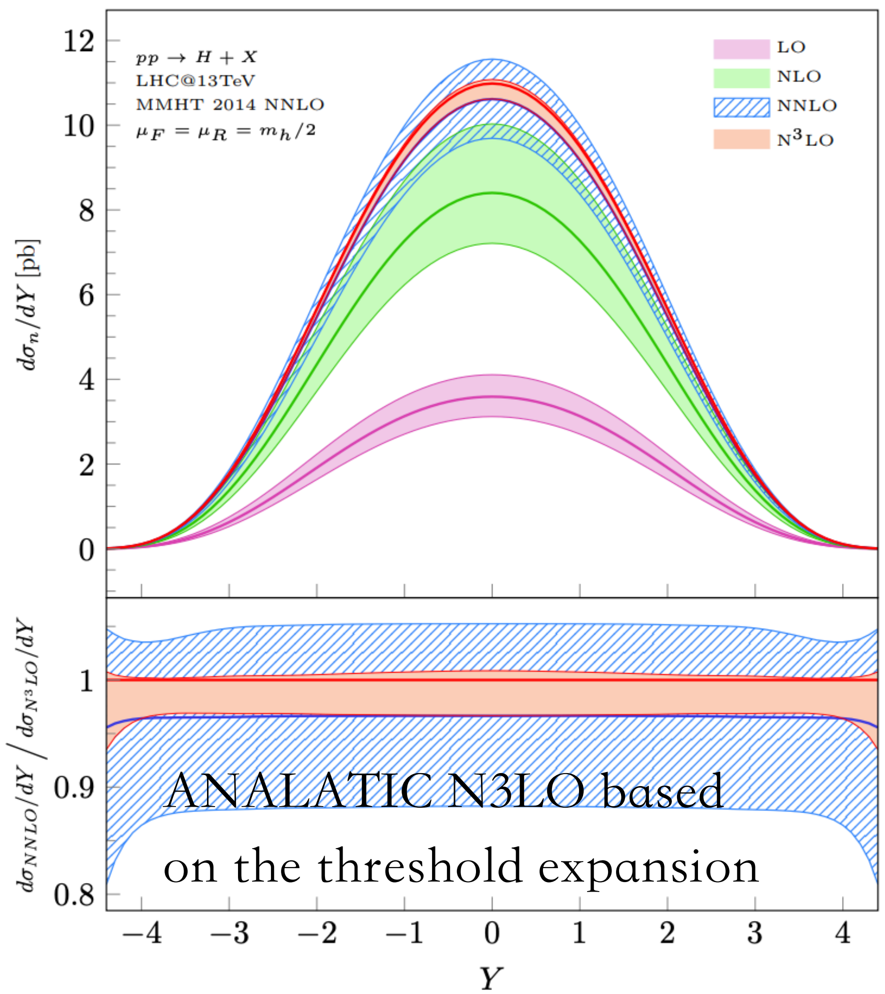


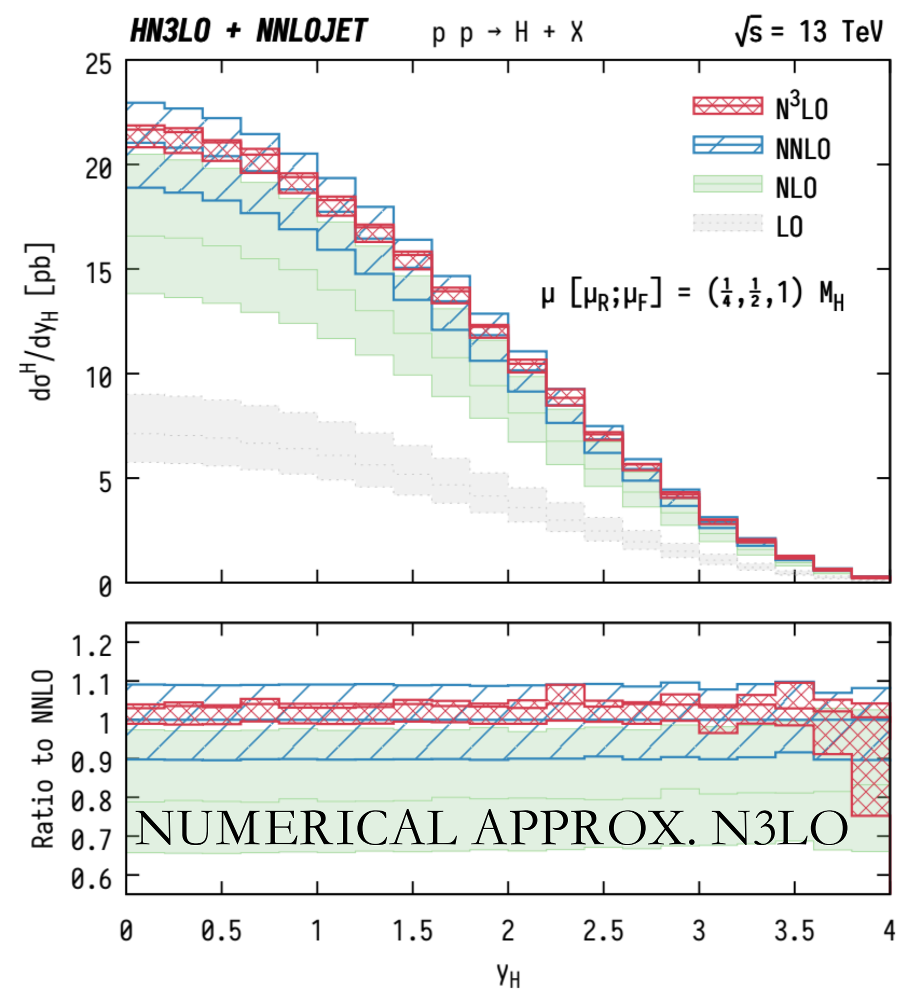
Small discrepancies mainly due the slow soft convergence of the qq channels

ggH — the frontier of the precision frontier

Frontier of the Precision Frontier, from 2016 to 2018

NOT ONLY inclusive x-sec!





Dulat, et.al. , 2018

Cieri, et.al. , 2018

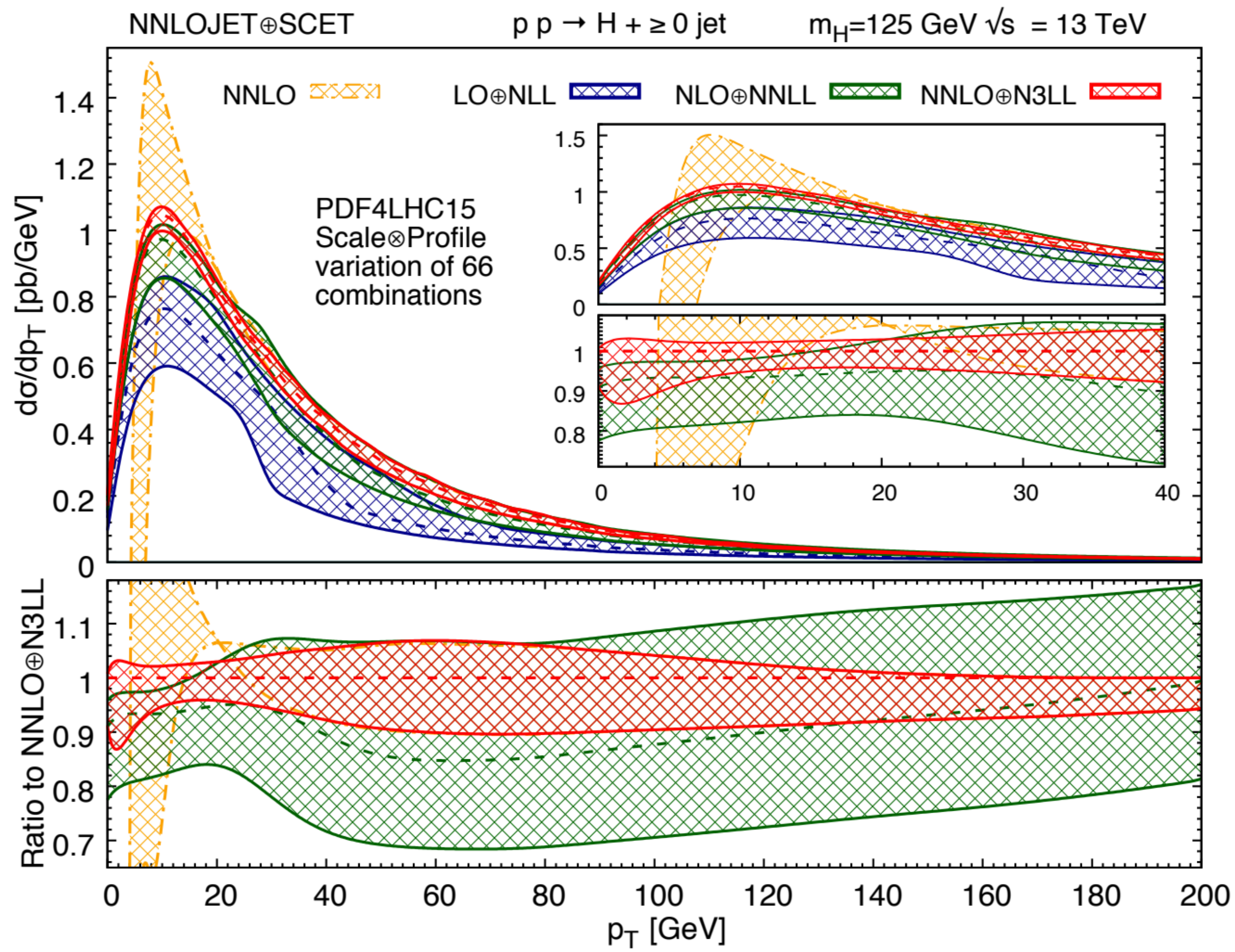
- Fully exclusive N3LO available
- Perturbative uncertainties reduced to 4%
- N3LO distribution (left) well reproduced by assuming a flat correction (right)

ggH — the frontier of the precision frontier

Frontier of the Precision Frontier, from 2016 to 2018

pT spectrum at NNLO + N3LL

- Res. is crucial for small pT
- Further reduce the theory errors



Li, Neill, Schulz, Stewart, Zhu + NNLOJET, 2018

See also, Bizon, Monni, Re, Rottoli, Torrielli + NNLOJET

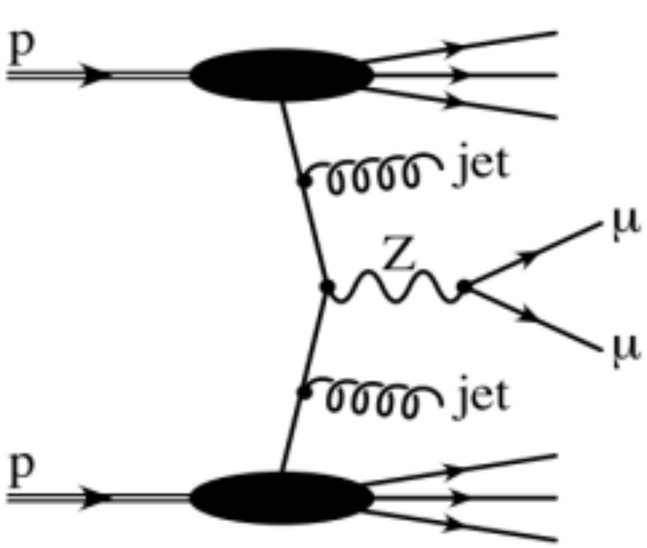
NNLO see also Boughezal, et. al., 2015

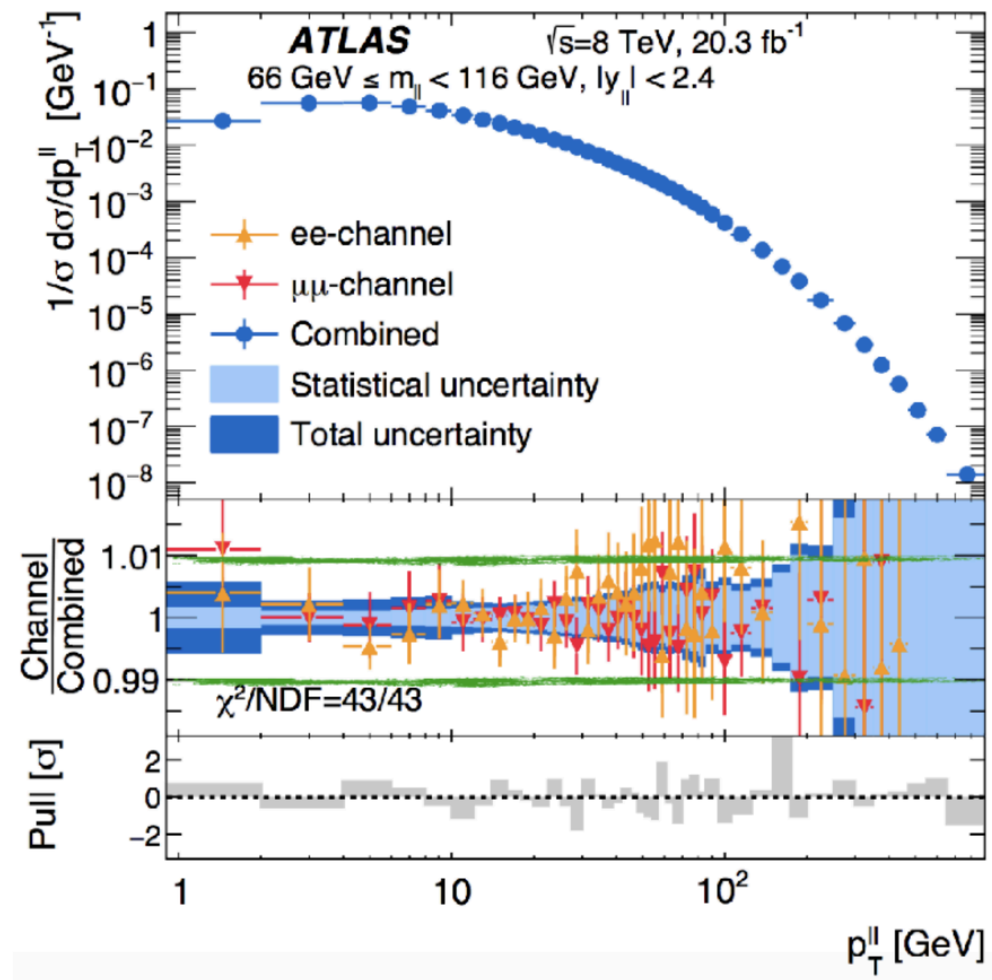
Boughezal, Focke, Giele, **XL**, Petrillo, 2015

Vector Bosons

Vector boson spectrums @ N2LO

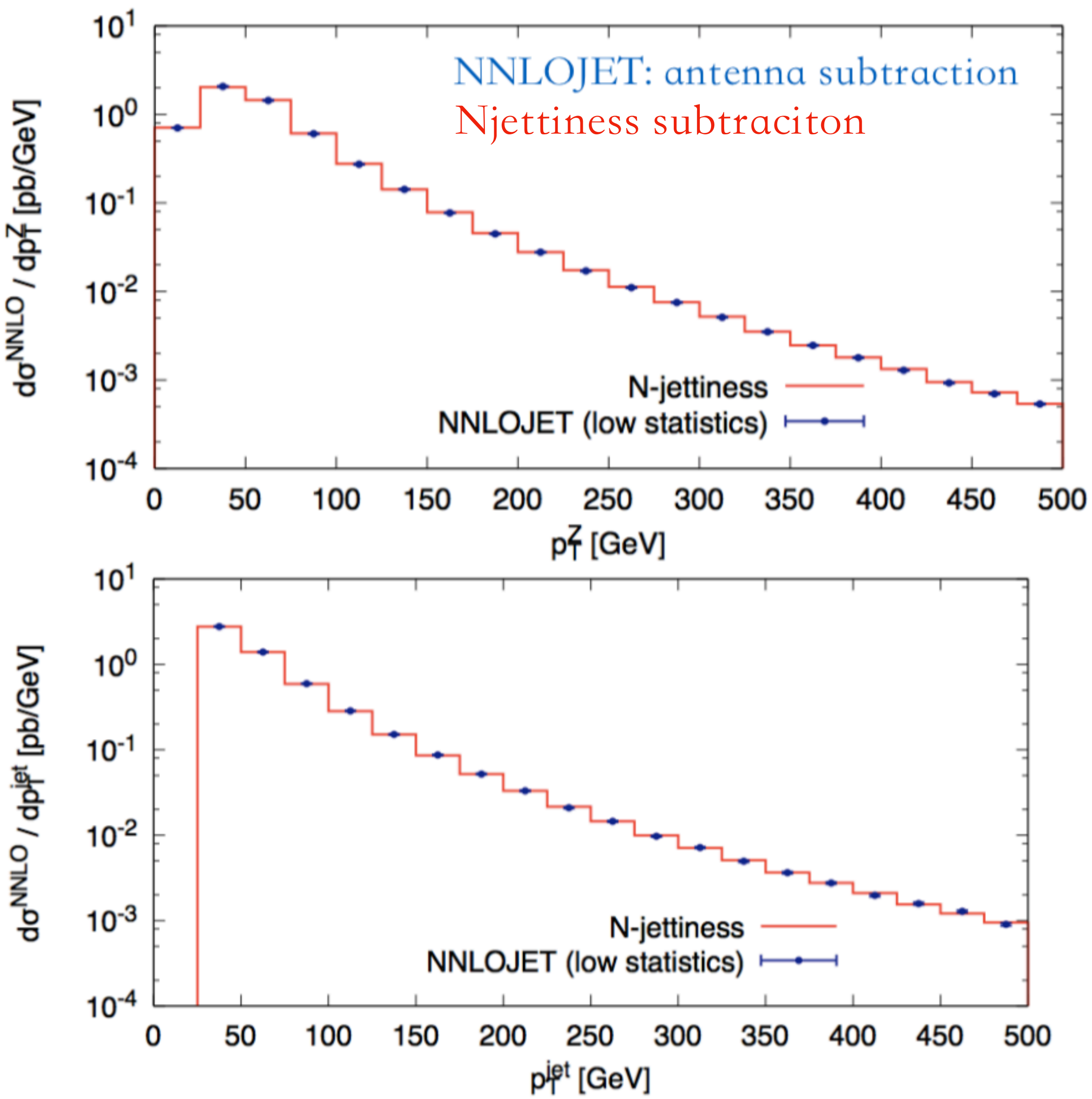
- Benchmark process at the LHC
- Clean signature, exp. uncertainty < 1%
- Irreducible background for NP searches
- Sensitive to PDFs

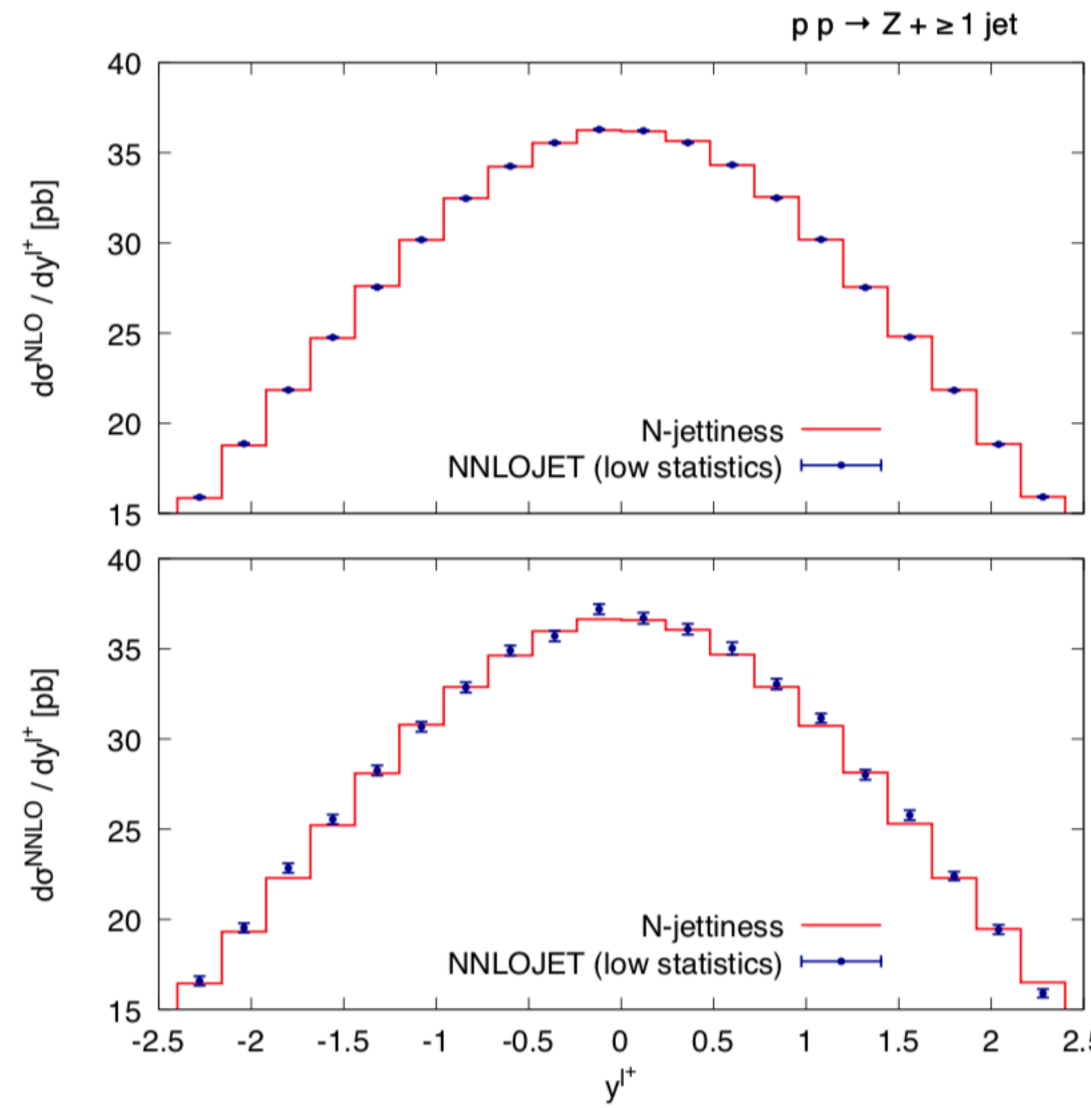




Vector boson spectrums @ N2LO

Independent calculations by different groups with different methods

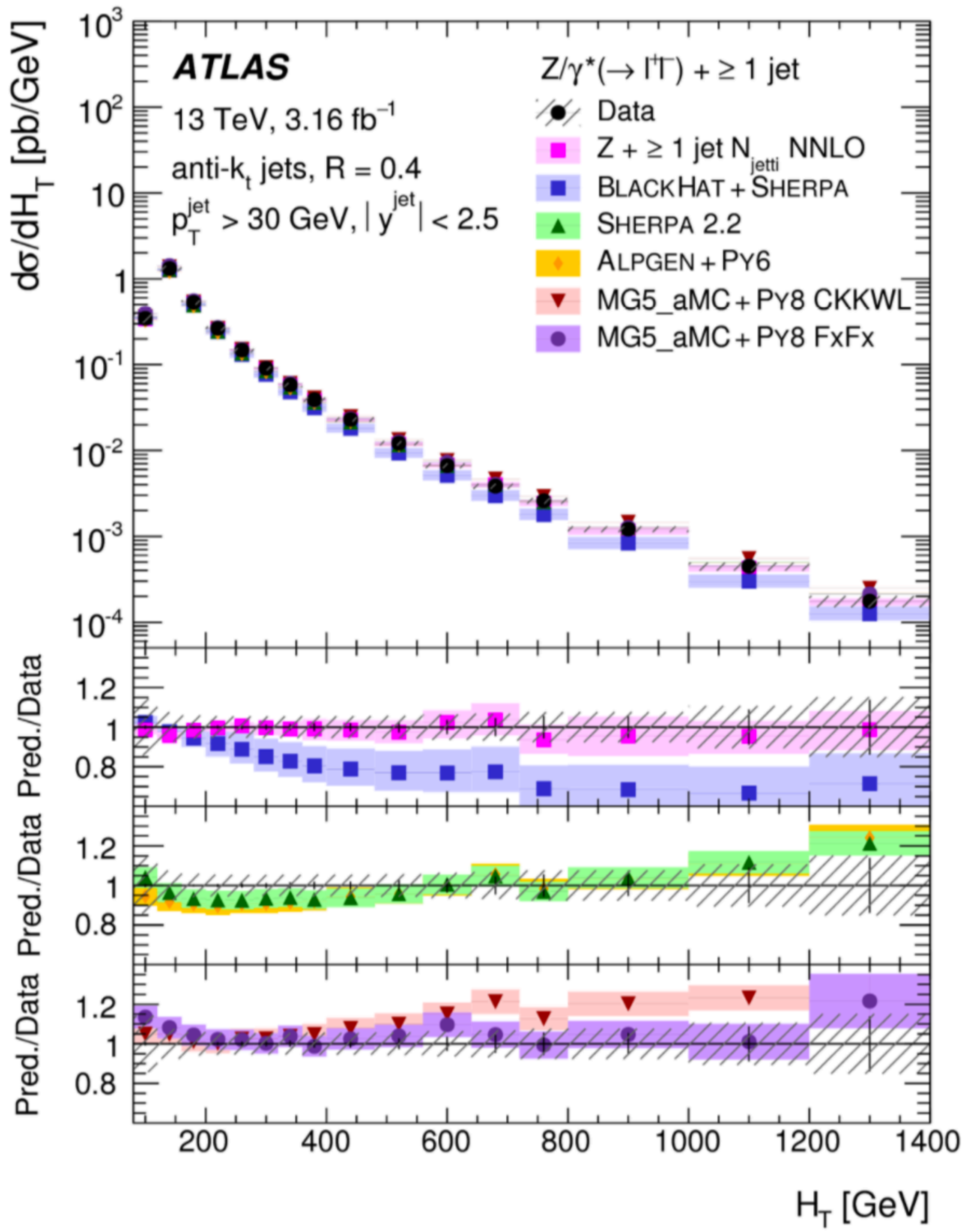




Gehrmann, et. al., 2016

Boughezal, Focke, **XL**, Petriello + MCFM, 2016

Vector boson spectrums @ N2LO

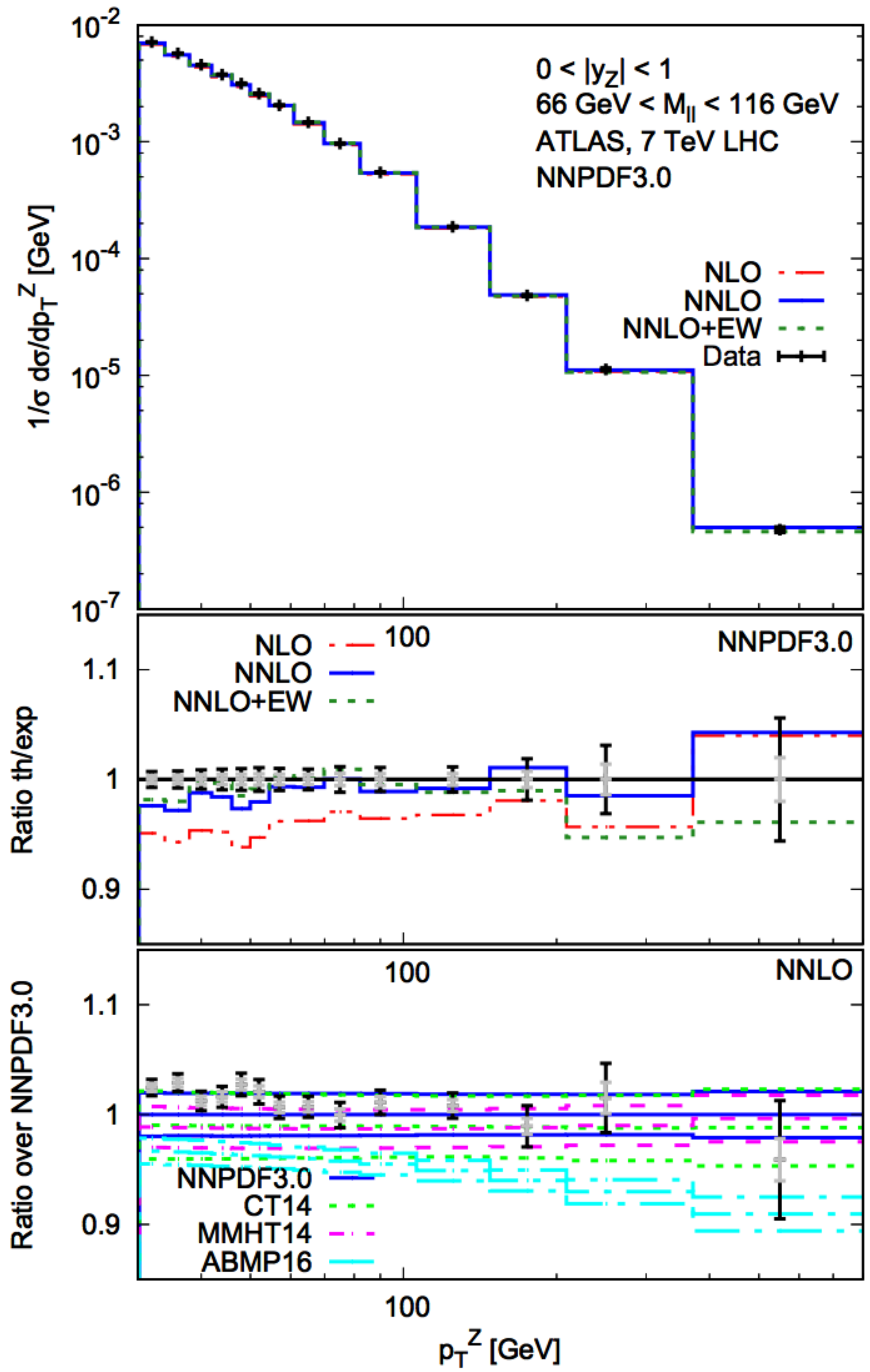


NLO underestimates the data by 50% !

NNLO recovers agreement with data by add on missing high orders.

Boughezal, Focke, **XL**, Petriello + MCFM, 2016

Vector boson spectrums @ N2LO

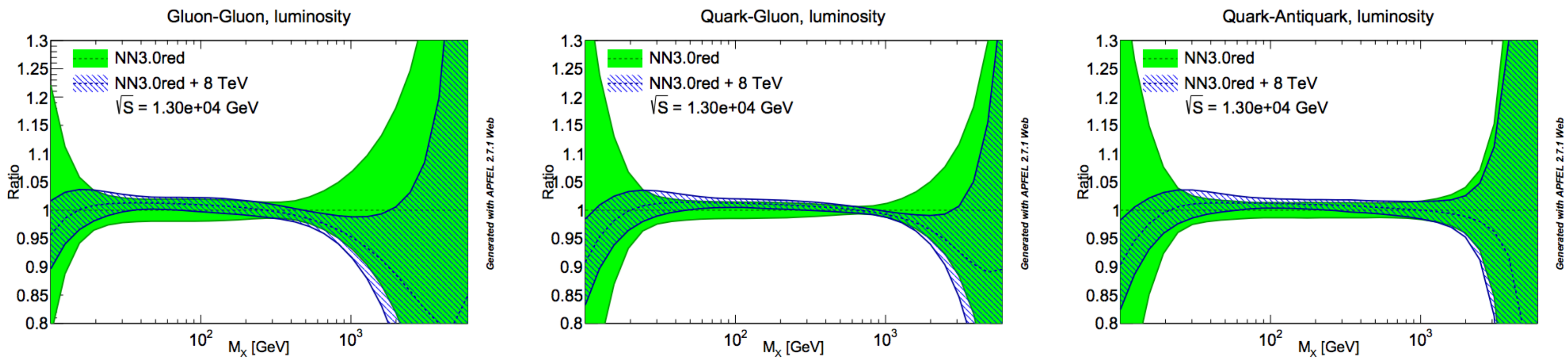


Z pT distribution

- Clean and very small exp. uncertainty ~ 1%
- therefore standard candle at the LHC

NNLO agrees much better than NLO.

Vector boson spectrums @ N2LO



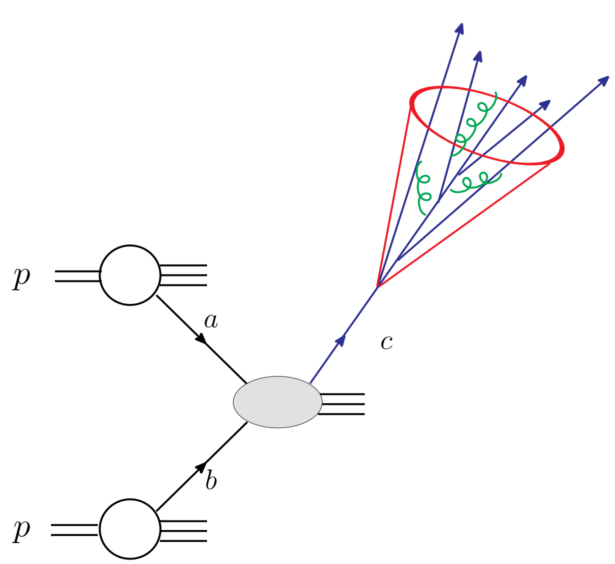
	Before p_T^Z data	After p_T^Z data
$\sigma_{gg\to H}$ [pb]	48.22 ± 0.89 (1.8%)	48.61 ± 0.61 (1.3%)
σ_{VBF} [pb]	3.92 ± 0.06 (1.5%)	3.96 ± 0.04 (1.0%)

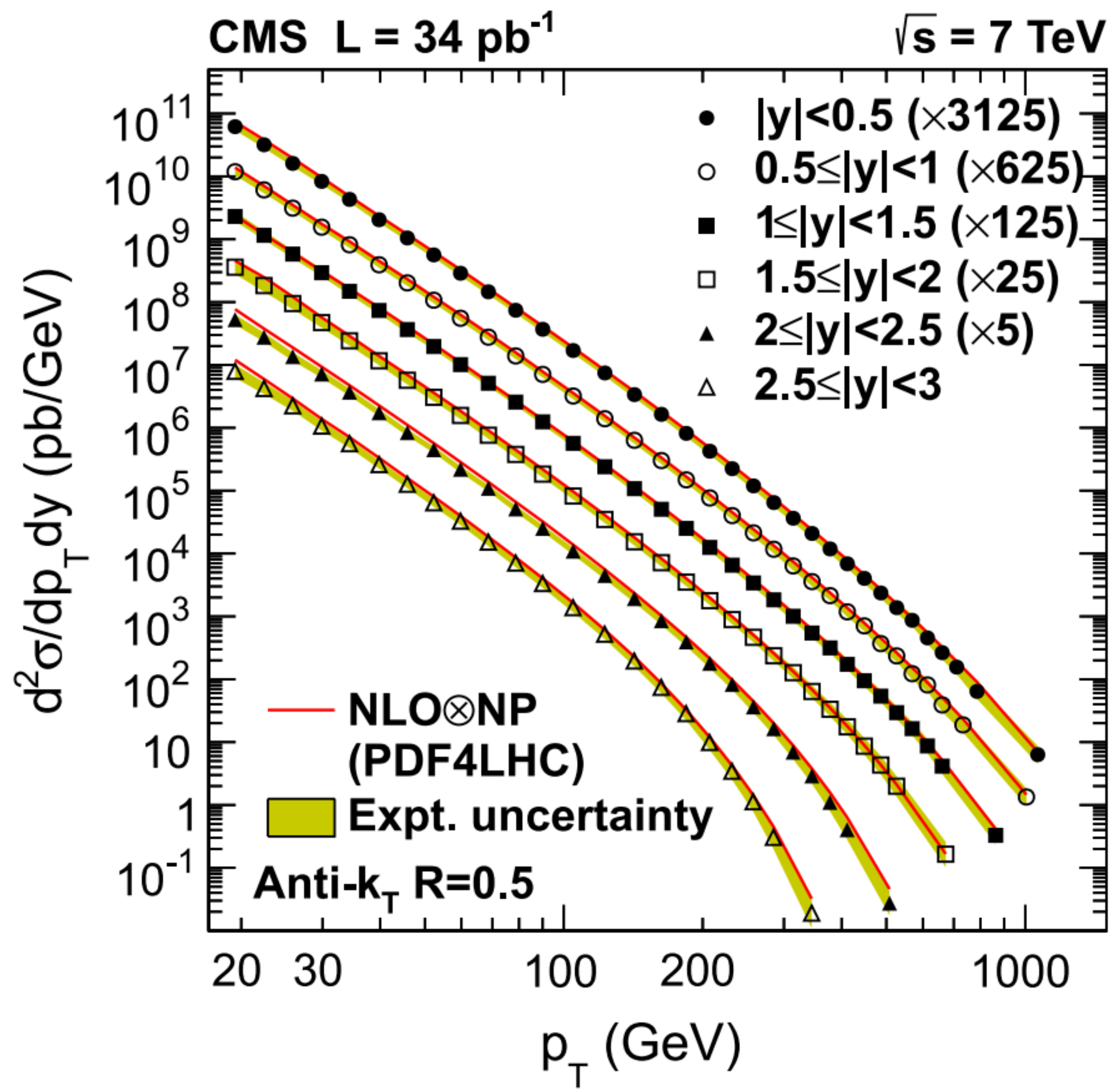
Error reduced by 30% when NNLO Z pT included

Jet

Inclusive jet production — where FO is not enough

- Anther benchmark process at the LHC
- Related to new physics searches, PDF fitting ⋯



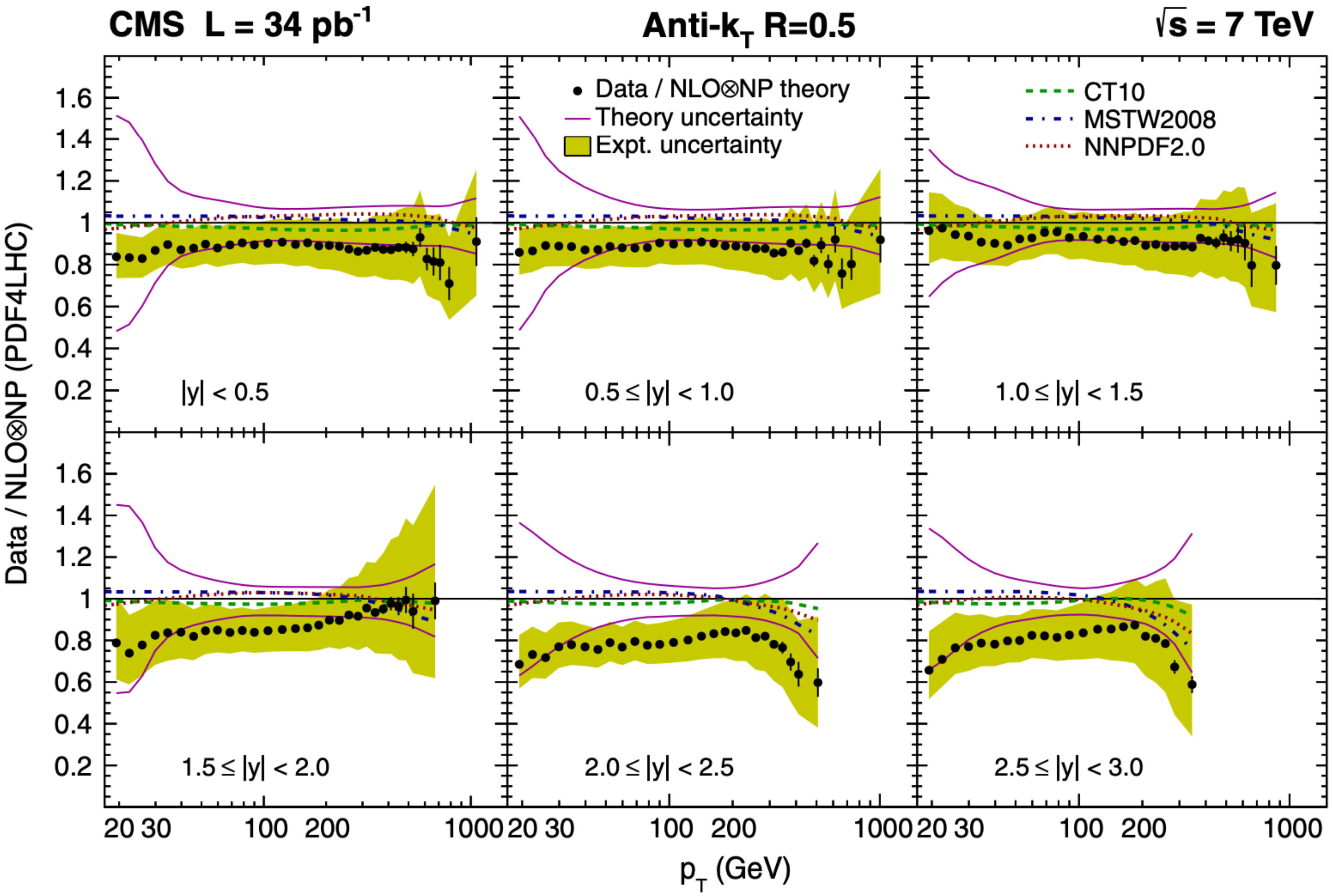


Overall good agreements with data, but ⋯

Inclusive jet production — where FO is not enough

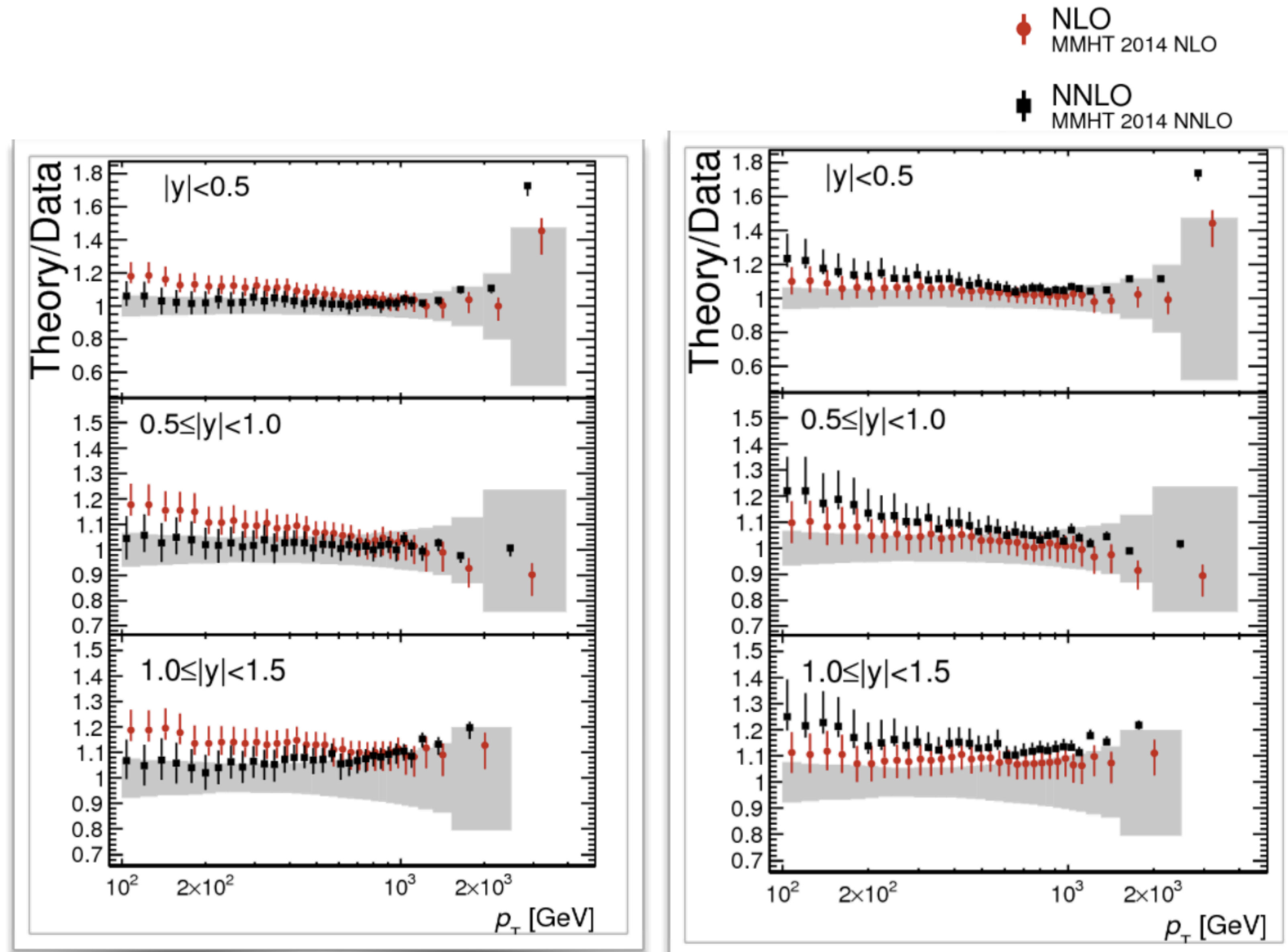
Long time systematic discrepancies between theory and the data

Holds for 7, 8, 13, ⋯ TeV



Inclusive jet production — where FO is not enough

NNLO seems to help,
but Strongly depends on the scale choices!



scale = individual jet pT

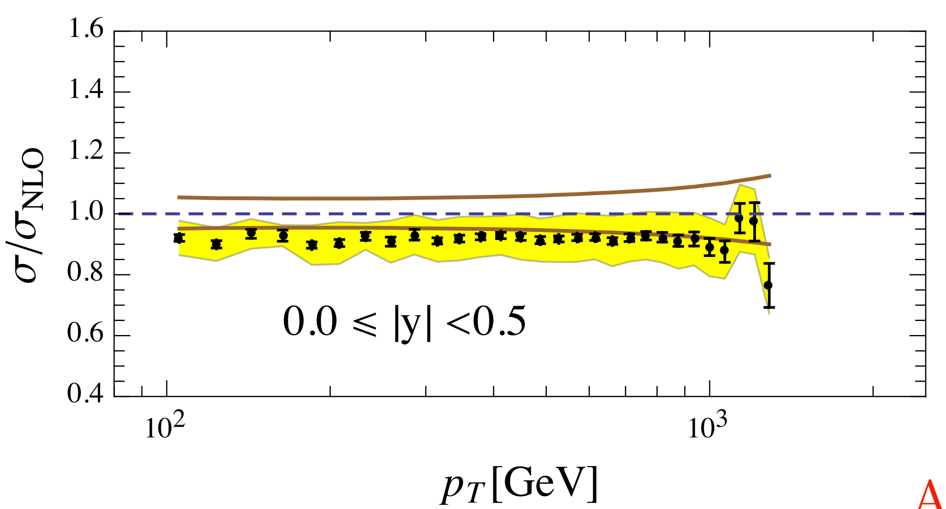
scale = leading jet pT

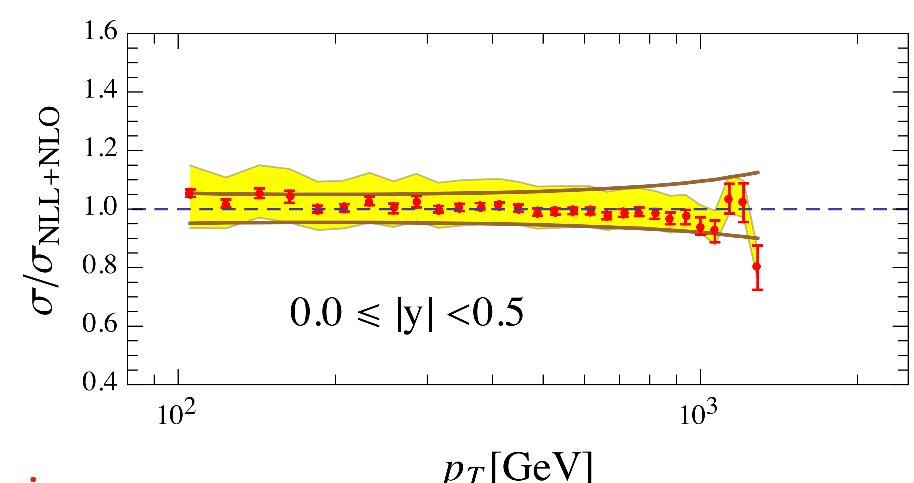
Currie, Glover, Pires, 2018

Inclusive jet production — where FO is not enough

Resummation (small R + threshold) helps here

- Small R res. reduces the cross section
- Threshold enhances the cross section
- After resummation, the theory describes the data well





After resummation

XL, Moch, Ringer, 2018

Tools

Available tools for NNLO predictions   Grazzini, et.al.

- MATRIX (qT-subtraction, public)
  - zero-jet — ggH, Drell-Yan $\cdots$
- MCFM 8.0 @ NNLO (N-jettiness-subtraction)   Boughezal, Focke, **XL**, Petriello + MCFM
  - zero-jet — ggH, Drell-Yan $\cdots$ (public)
  - Z/W/photon/H+1-jet (private)
- NNLOJET (antenna subtraction, private)   Gehrmann et. al.
  - Lots of NNLO and N3LO + res. Results
- $\cdots$

Already used in experimental analysis
In general, good agreements are found

Sorry for not covering

- Inclusive VBF @ N3LO Dreyer, Karlberg, 18
- VBF distribution @ N2LO Cacciari, et.al., 15, Cruz-Martinez, et. al., 18
- Full top mass dependent NLO HH Borowka, et. al., 16
- Full top mass dependent NLO H + jet production Jones, et. al., 18
- Top quarks Czakon, et, al; Li, Gao, Zhu; Wang, Yang; Gao, Liu ⋯
- VV' productions a lot since 2014
- Jet substructures Kang, Marzani, Larkoski, Lee, **XL**, Ringer, Salam, Soyez, Thaler, Wang, ⋯
- Other relevant topics, e.g. DIS @ N3LO, N2LO ⋯

  Gehrmann, et.al.; Berger, Li, Liu, Zhu, Abelof, Boughezal, **XL**, Petriello ⋯

Summaries

- A competitive and highly active area
- Precision is important (test QCD + new physics searches)
- A lots for 2 -> 2 processes have been pushed to NNLO or even beyond, public tools are also available now
- Beyond that, the predictions are limited by the unknown virtual corrections, e.g., 3jet, V + 2j $\cdots$

Thanks!