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NNLO QCD Predictions

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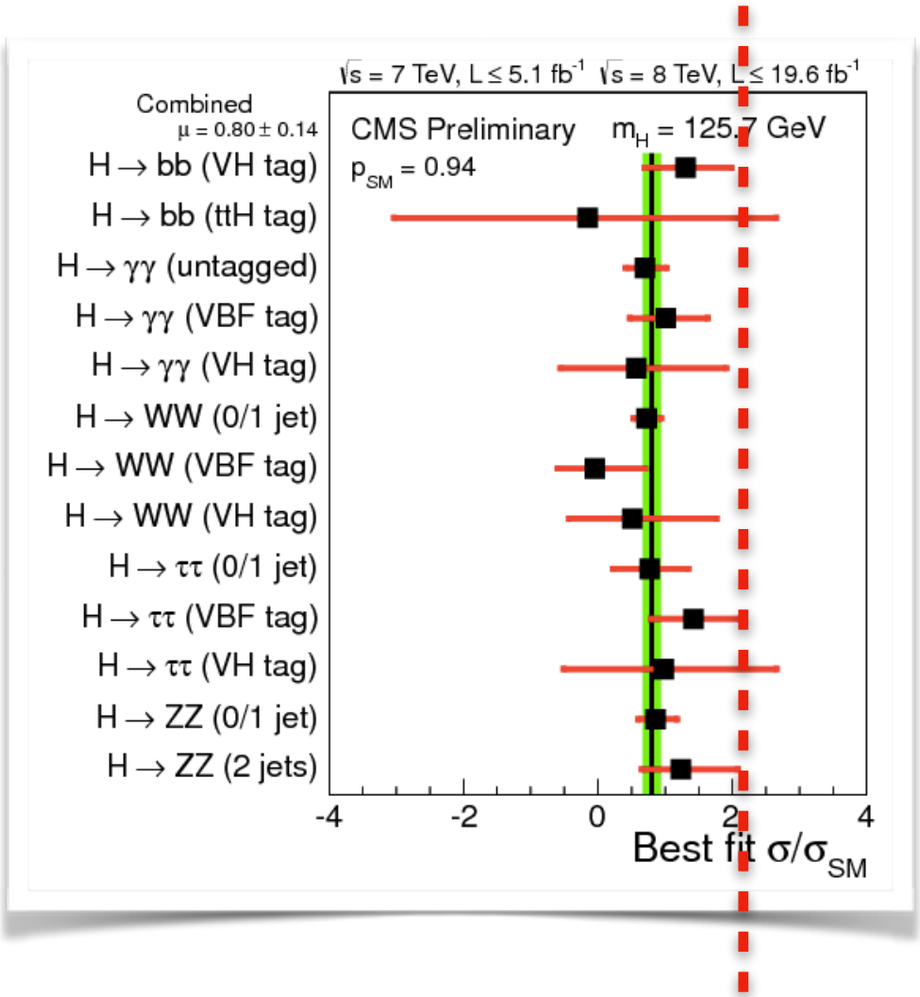
Meeting of the APS Division of Particles and Fields 2017 @ Fermi Lab

Why Precision Calculations?



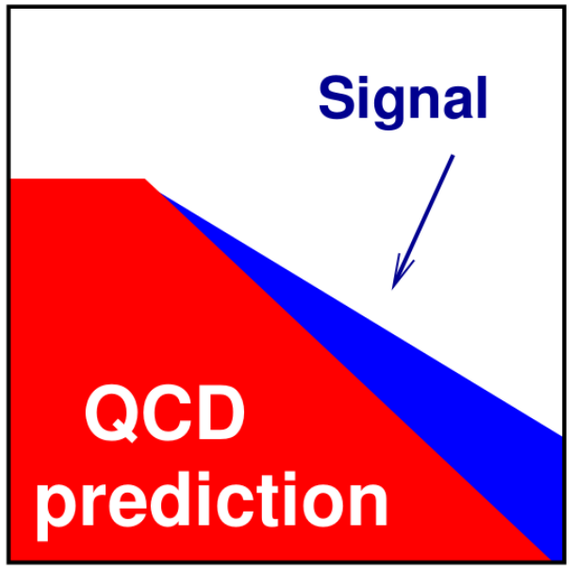
LO @ 8 TeV: 9.6 +/- 25% pb

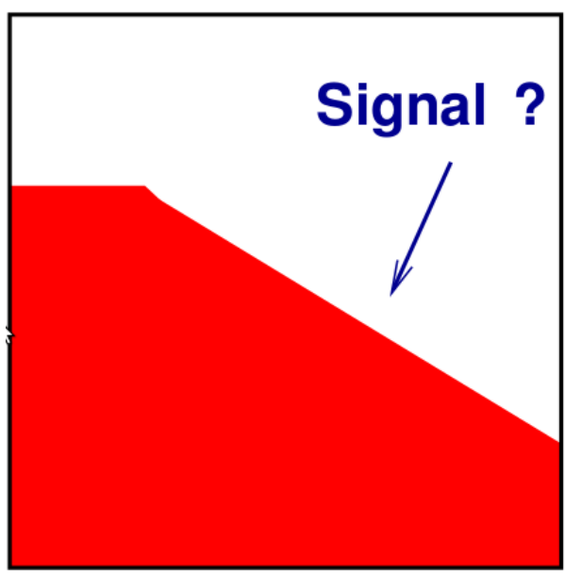
N3LO @ 8 TeV: 19.47 + 0.32% - 2.99% pb

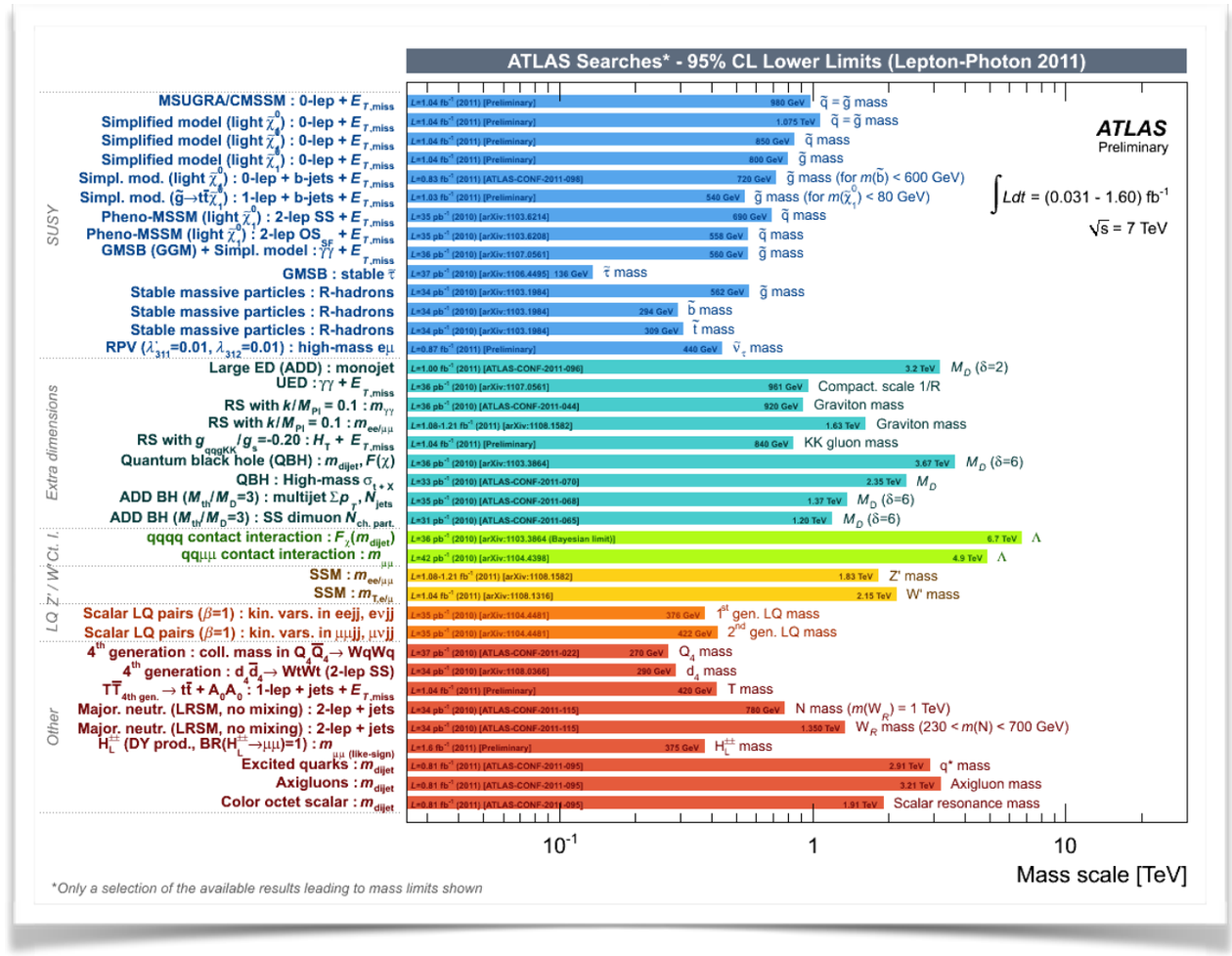
Anatasiou, Duhr, Dulat, Herzog, Mistlberger '15

If w/o higher order results,
we can NOT interpret the Higgs properly

Why Precision Calculations?



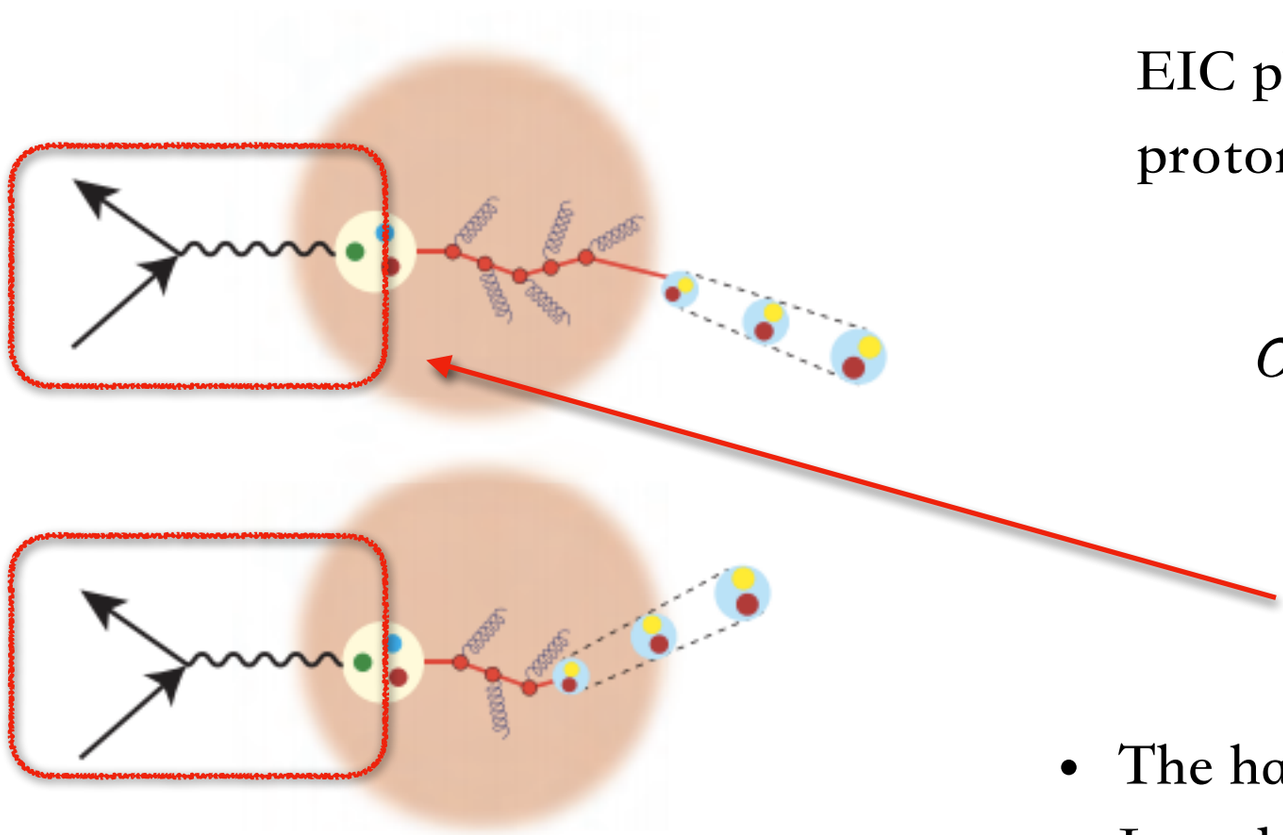




- NP resonance may likely be out of the LHC reach, and we may only see excess in the tail of spectrums
- Predicting the shape correctly is crucial

New Physics = Data - SM Prediction!!

Why Precision Calculations?



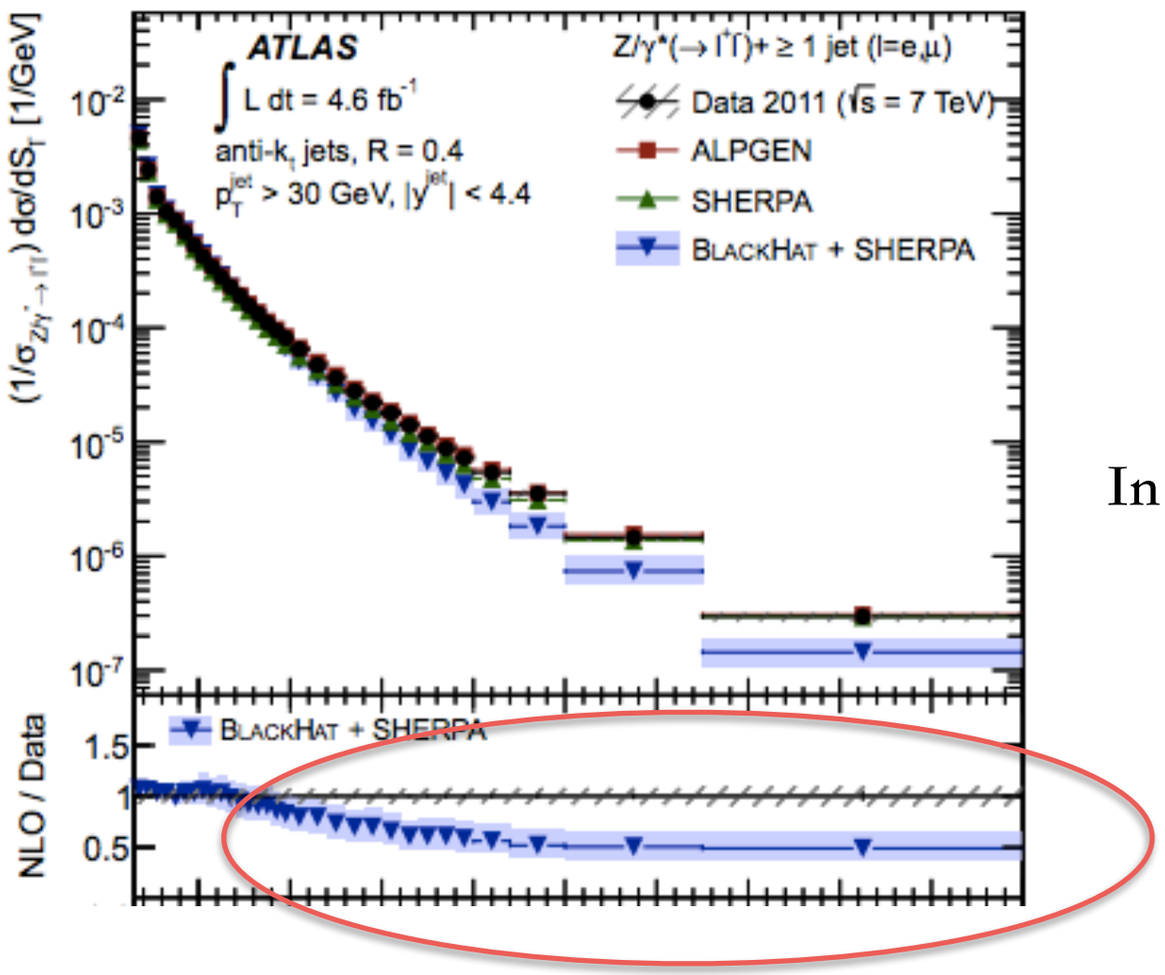
EIC physics: hard probe of the proton/nucleon internal dynamics

$$\sigma = \hat{\sigma}_i \otimes \mathcal{D}_{i/N} + \ldots$$

hard probe

- The hard part can be calculated perturbatively
- In order to extract the universal non-perturbative information, the hard part should be calculated as accuracy as possible, e.g. PDF fitting

Why Precision Calculations?



NLO is NOT always sufficient

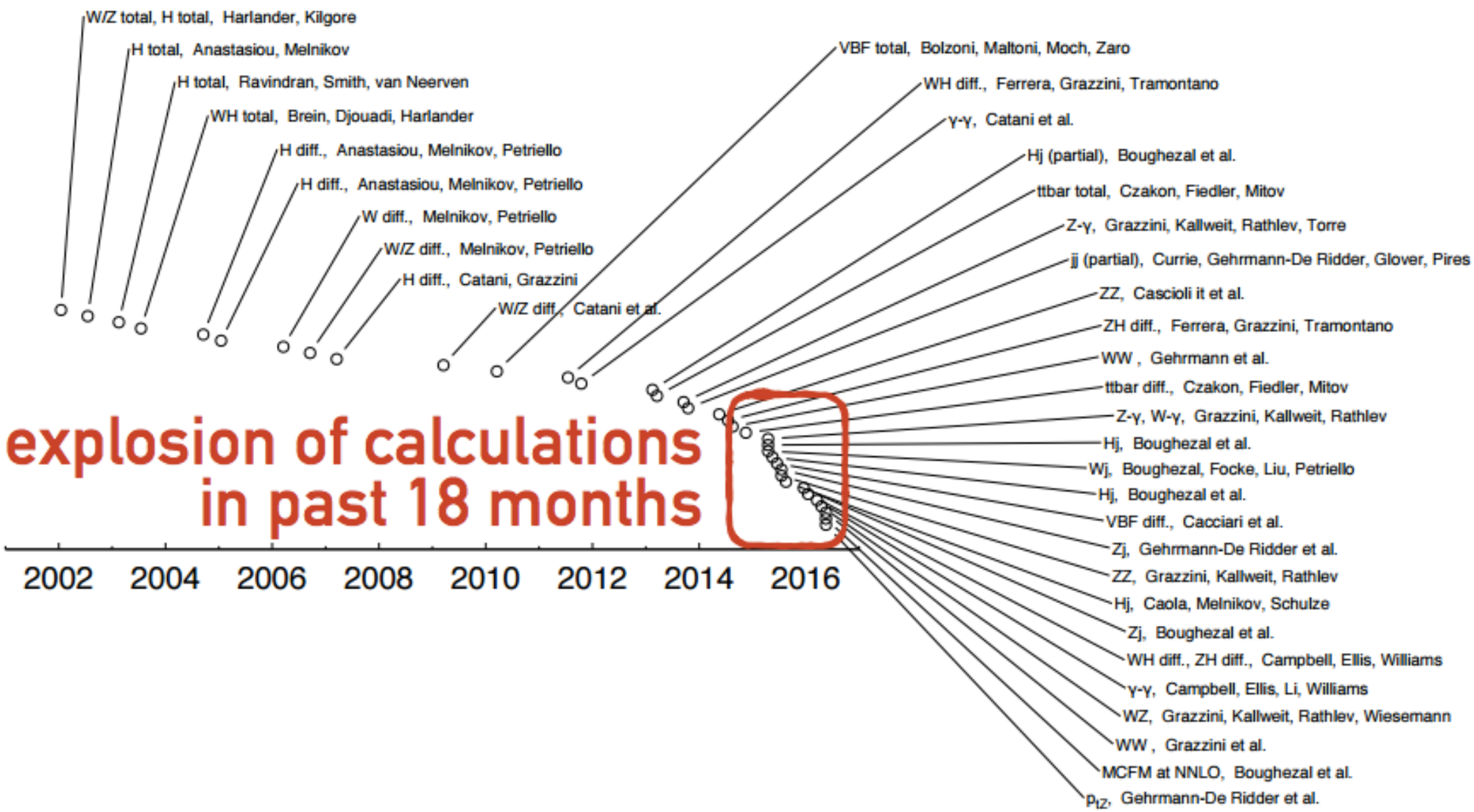
In lots of scenarios, we need NNLO and more

CERN-PH-EP-2013-023

Outlines

- Why Precision Calculations?
- Current Status of NNLO predictions
- Collider Phenomenology
  - Z+jet
  - inclusive jet
- Conclusions

Current Status of NNLO Predictions



Current Status of NNLO Predictions

- Big progress in understanding IR in real corrections

$$\int \mathrm{d}z \frac{f(z)}{z^{1+a\epsilon}}$$

Local Subtraction:

$$\int \mathrm{d}z \frac{f(z)-f(0)}{z} + \int \mathrm{d}z z^{-1-a\epsilon} f(0)$$

- improved Sector Decomposition Czakon; Boughezal,et. al.; Caola, et. al.
- antenna subtraction Kosower; Gehrmann-De Ridder, et. al.

- relatively more smooth integrand
- but still numerically challenging at NNLO
- conceptually hard to implement

Current Status of NNLO Predictions

- Big progress in understanding IR in real corrections

$$\int \mathrm{d}z \frac{f(z)}{z^{1+a\epsilon}}$$

Global Scheme:

$$\int \frac{f(z)}{z}\theta(z > z_0) - f(0)\frac{z_0^{-a\epsilon}}{a\epsilon} + \ldots$$

Power corrections, vanishes as z_0 -> 0. Can be added systematically

Moult et.al.; Boughezal, et. al.

- qT subtraction (W/H $\cdots$) Catani et. al.
- jet mass (top quark physics) Gao et. al.
- N-jettiness scheme (generic jet process)

Boughezal, et. al.; Gaunt, et. al.

Achieves the most NNLO calculations so far

- numerical challenging
- conceptually easy to implement

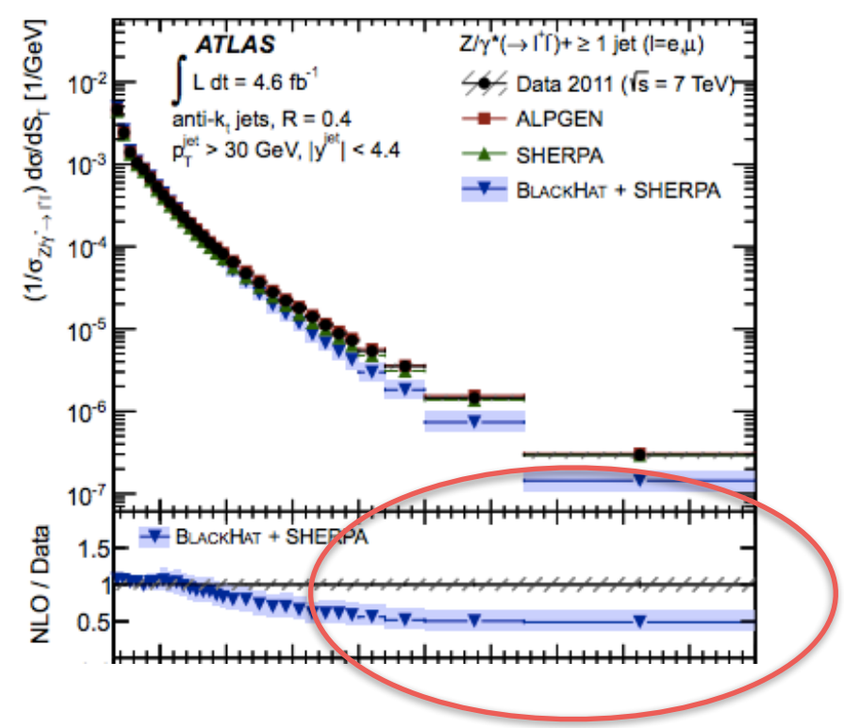
Collider Phenomenology

V+1jet

- SUSY, dark matter mono jet search Background

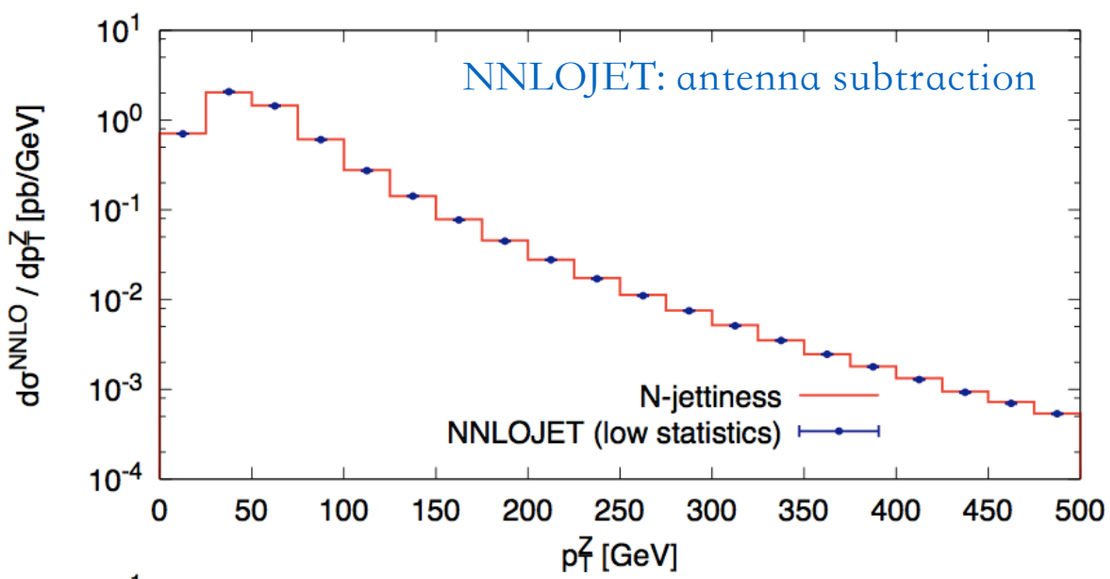
Background process	Method
$Z(\to \nu\bar{\nu})$+jets	MC and control samples in data
$W(\to e\nu)$+jets	MC and control samples in data
$W(\to \tau\nu)$+jets	MC and control samples in data
$W(\to \mu\nu)$+jets	MC and control samples in data
$Z/\gamma^*(\to \ell^+\ell^-)$+jets ($\ell = e, \mu, \tau$)	MC-only
$t\bar{t}$, single top	MC-only
Diboson	MC-only
Multijets	data-driven
Non-collision	data-driven

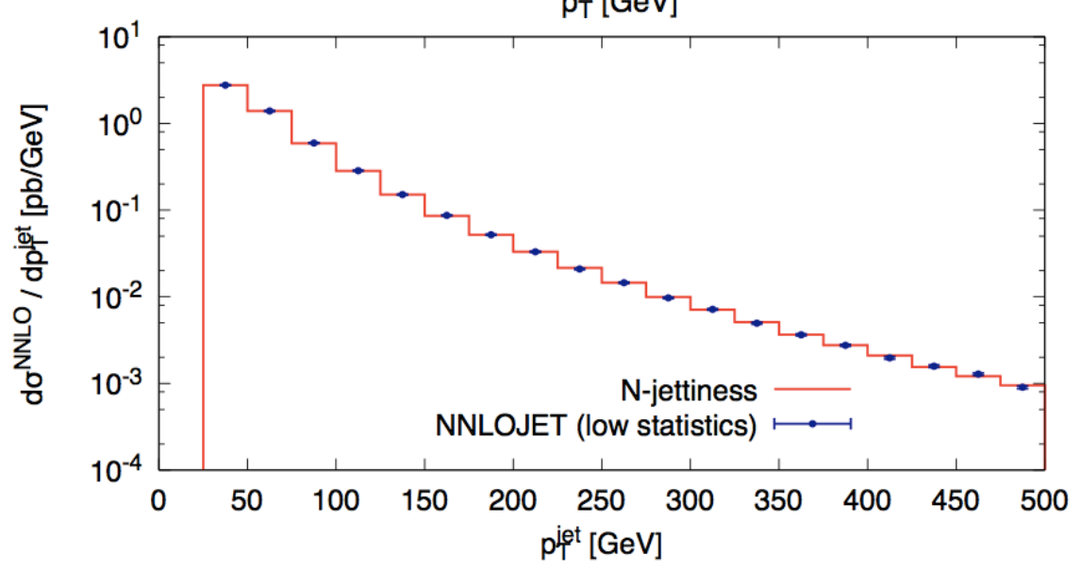
- Standard Candle at the LHC
  - Exp.: very small uncertainty
  - Exp.: jet energy scale calibration
  - Theory: tune Parton Shower
  - Theory: PDF fitting

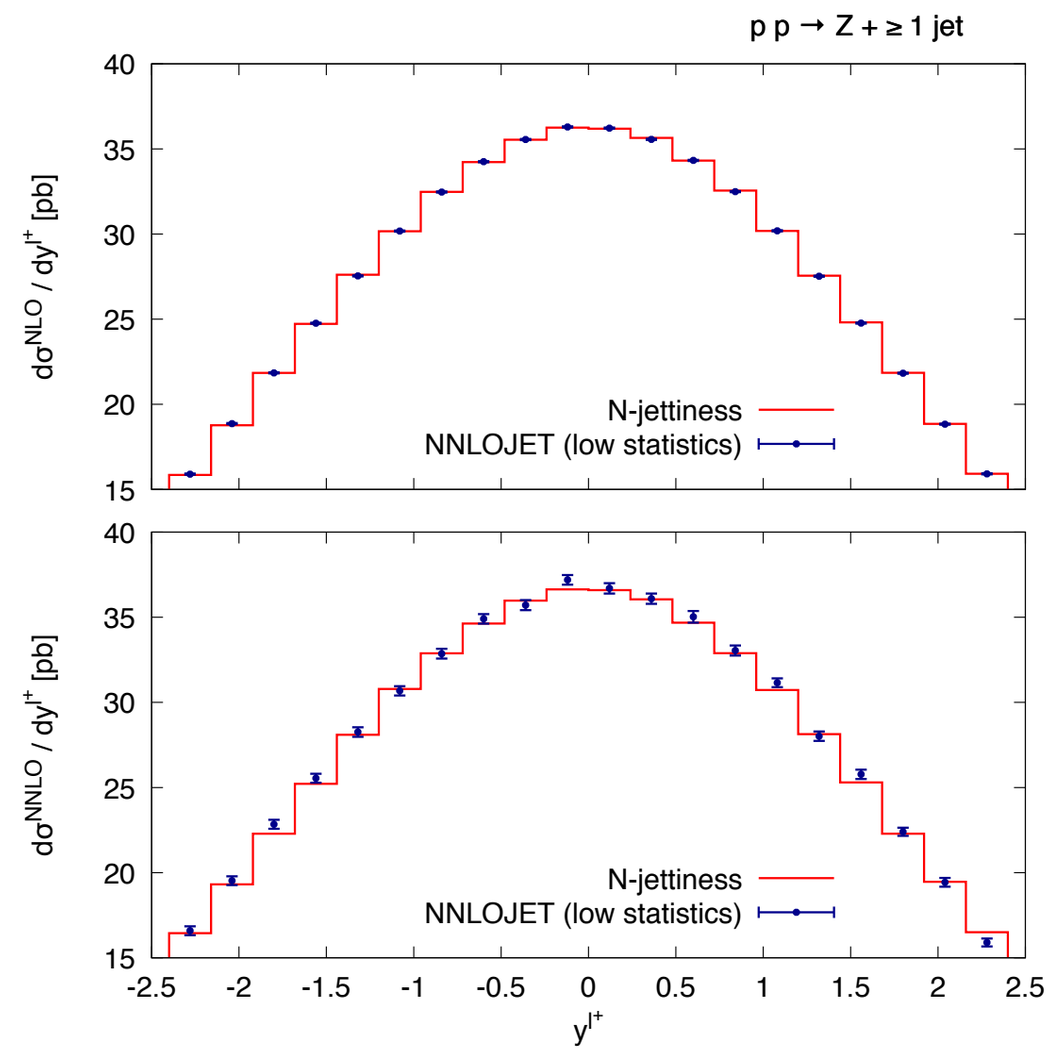


V+1jet

- Validations Boughezal, et. al. Gehrmann-De Ridder, et. al.
  - Good agreement between independent calculations

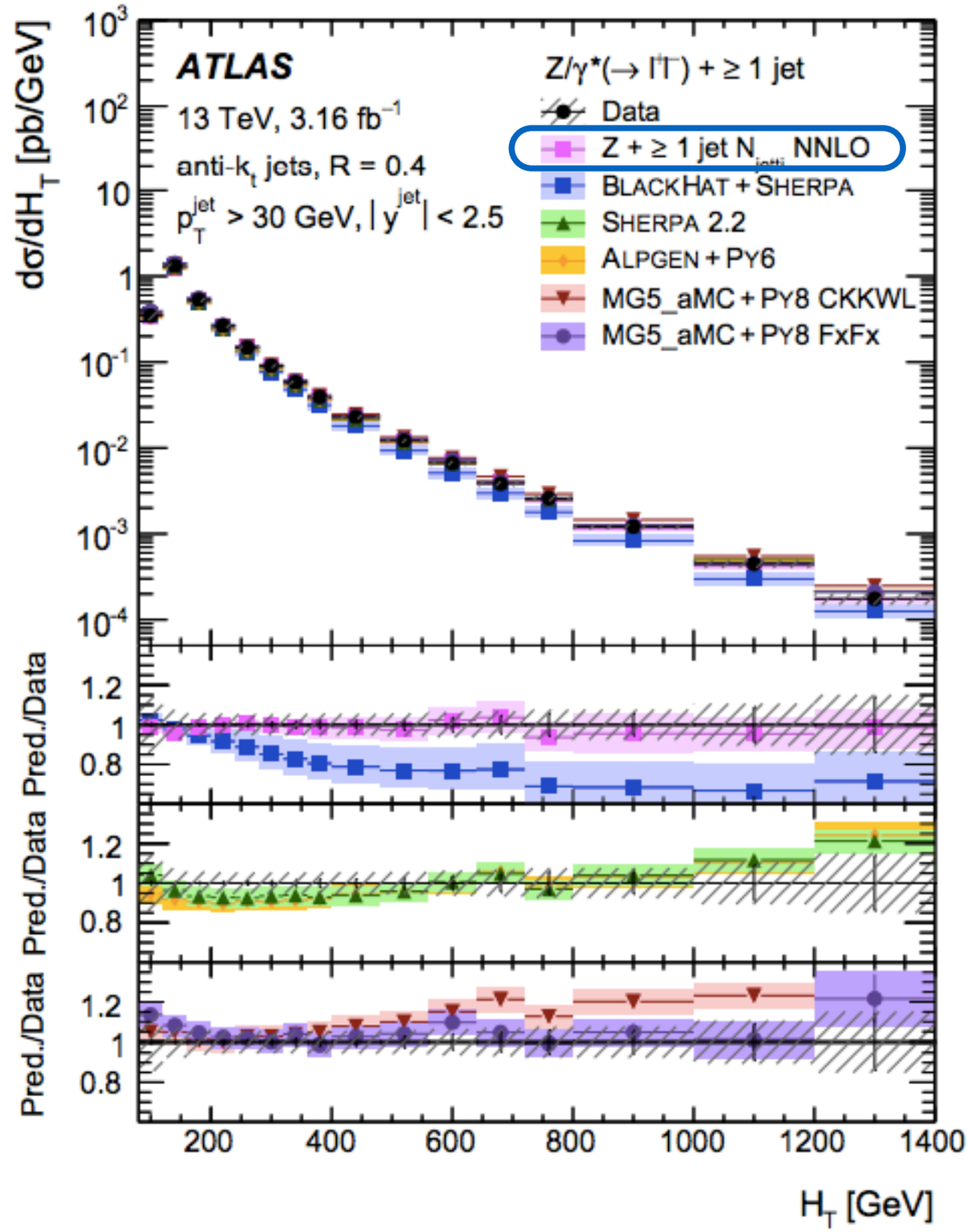






V+1jet

- Comparison with data
  - agreements get dramatically improved



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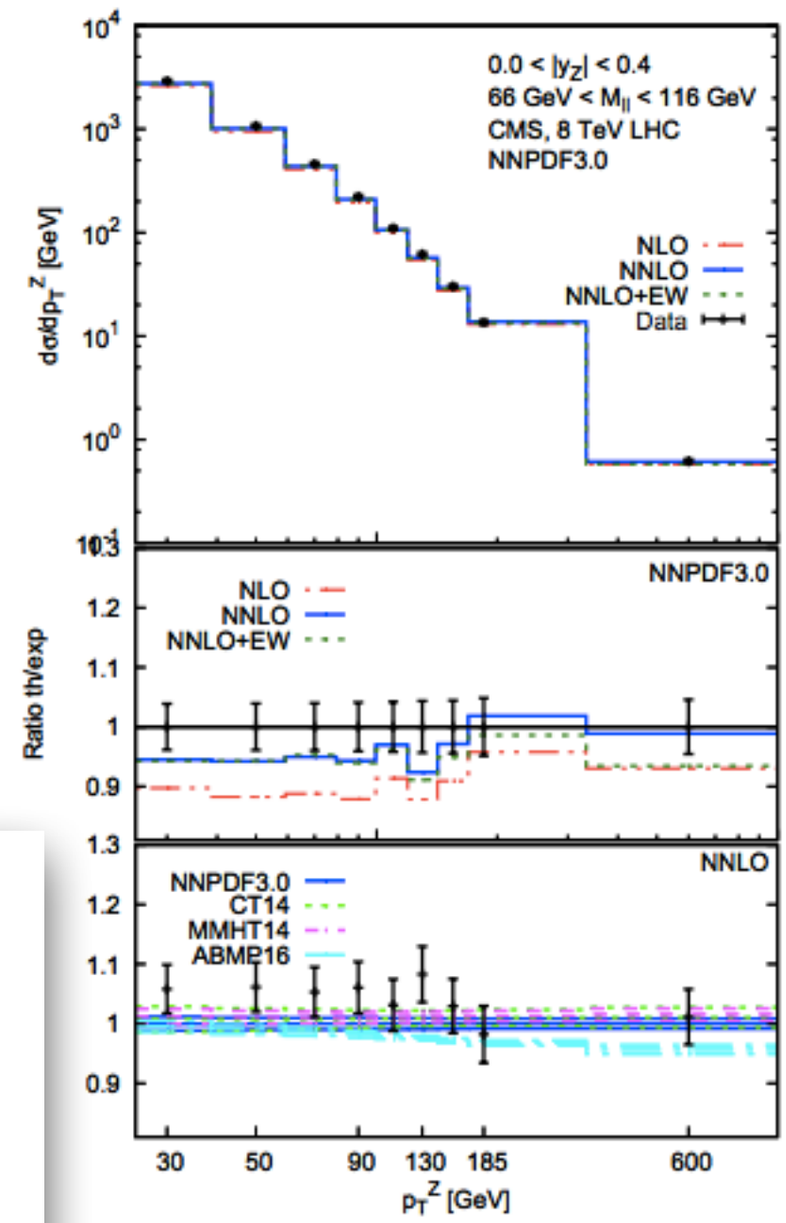
V+1jet

- Impact on PDF fittings
  - Z pT: one of the most accurate measurements at the LHC, exp err < 1%
  - Improved agreement when NNLO included

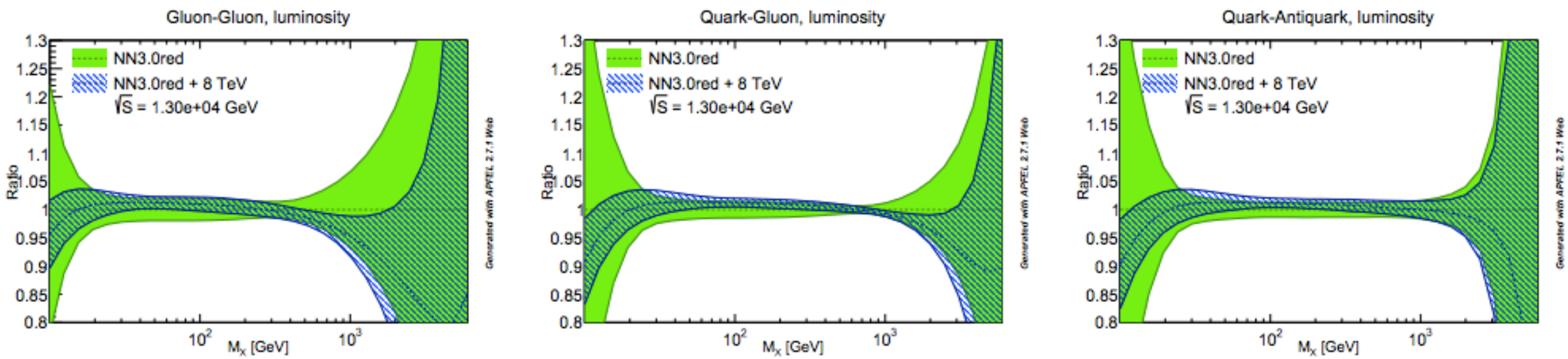


Bin	Order	$N_{\rm dat}$	$\chi^2_{\rm d.o.f.}$ (NN30)	$\chi^2_{\rm d.o.f.}$ (CT14)	$\chi^2_{\rm d.o.f.}$ (MMHT14)
$0.0 < y_Z < 0.4$ GeV	NLO	9	3.1	2.6	2.2
	NNLO	9	2.2	2.4	2.3
	NNLO+EW	9	1.4	1.4	1.3
$0.4 < y_Z < 0.8$ GeV	NLO	9	2.4	1.9	1.5
	NNLO	9	1.4	1.4	1.3
	NNLO+EW	9	1.9	1.9	1.7
$0.8 < y_Z < 1.2$ GeV	NLO	9	2.3	2.0	1.6
	NNLO	9	1.6	1.4	1.4
	NNLO+EW	9	1.2	1.2	1.0
$1.2 < y_Z < 1.6$ GeV	NLO	9	1.6	2.0	1.9
	NNLO	9	1.4	1.4	1.3
	NNLO+EW	9	2.8	3.1	2.8
All bins	NLO	36	3.3	3.2	3.3
	NNLO	36	3.5	3.5	3.7
	NNLO+EW	36	3.9	4.0	4.0

Boughezal, et. al.

V+1jet

- Impact on PDF fittings



a significant reduction of the 13 TeV gluon-gluon, quark-gluon and quark-antiquark luminosity errors

Immediate impact on Higgs x-section

	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%)
$\sigma_{\rm VBF}$ [pb]	3.92 ± 0.06 (1.5%)	3.96 ± 0.04 (1.0%)

Error reduced by 30% for ggh

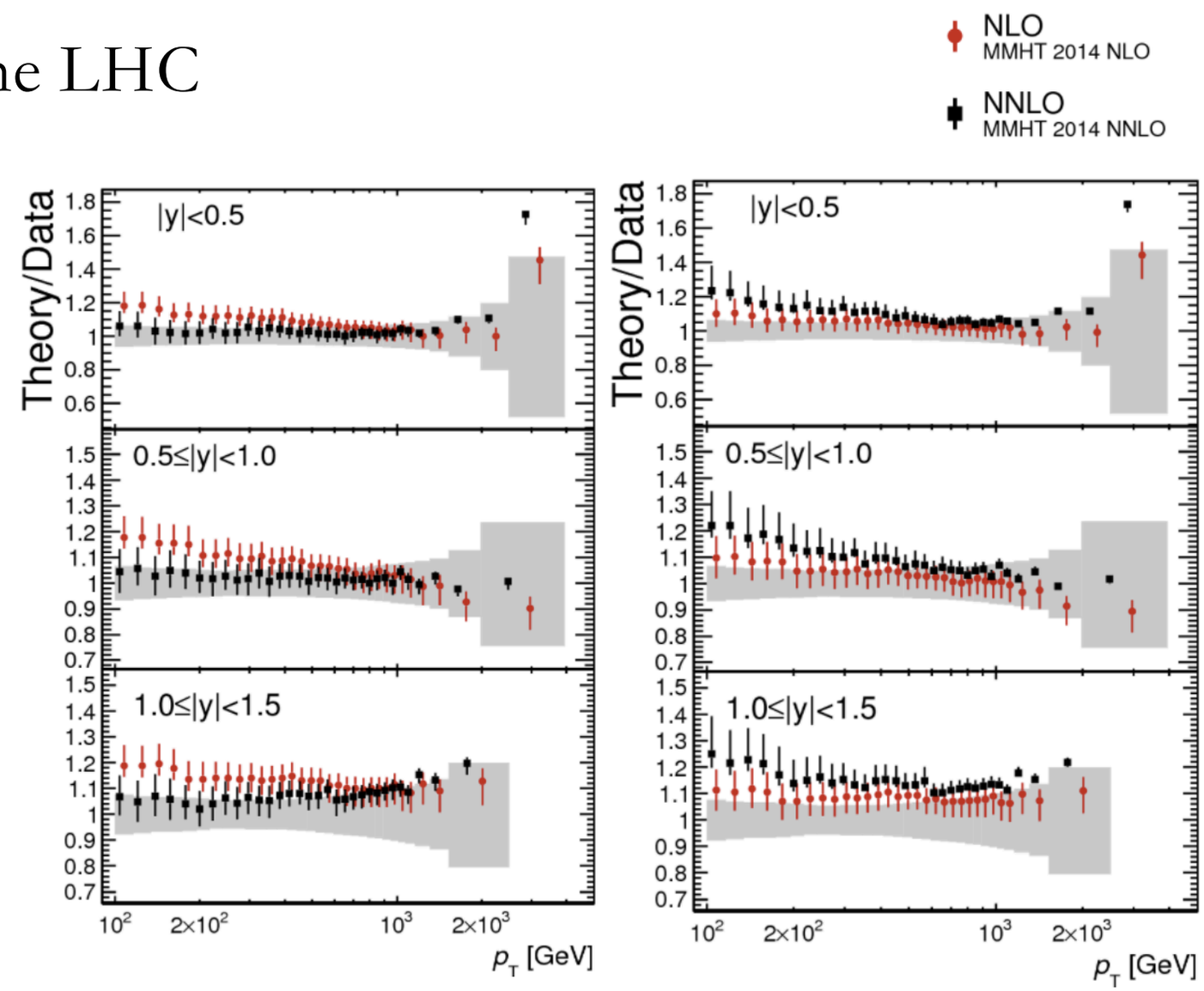
Boughezal, et. al.

inclusive jet production

- Another benchmark process at the LHC
  - PDF fitting
  - alphas extraction
  - New physics searches

inclusive jet production

- benchmark process at the LHC
  - NNLO with leading color approximation



scale = individual jet pT

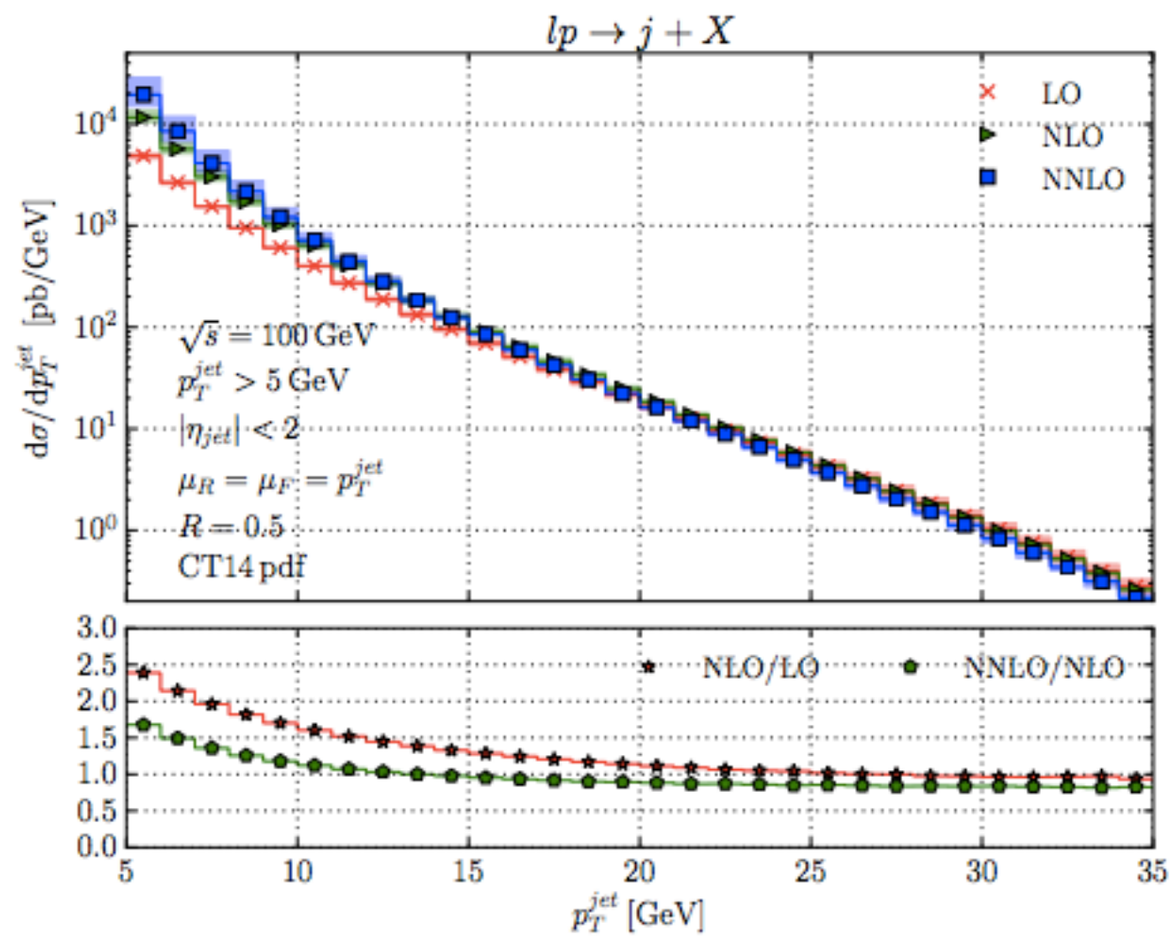
scale = leading jet pT

James Currie, et al.

different scale choices lead to
different behavior
large higher order corrections ?

inclusive jet production at EIC

- First step toward precision prediction of jet physics at EIC
  - unpolarized beam
  - large NNLO correction in the small pT region.
  - New channels (qq and gq) open up at NNLO, which have large impact in scale variation.



Abelof, et. al.

Conclusion

- We have entered a precision NNLO era
  - IR subtraction schemes (Antenna, N-jettiness ⋯) have been successfully applied to collider phenomenology
  - Direct impact on precision measurements including PDF fittings
  - Will also play its role in EIC physics

Thanks