Recent results in QCD theory

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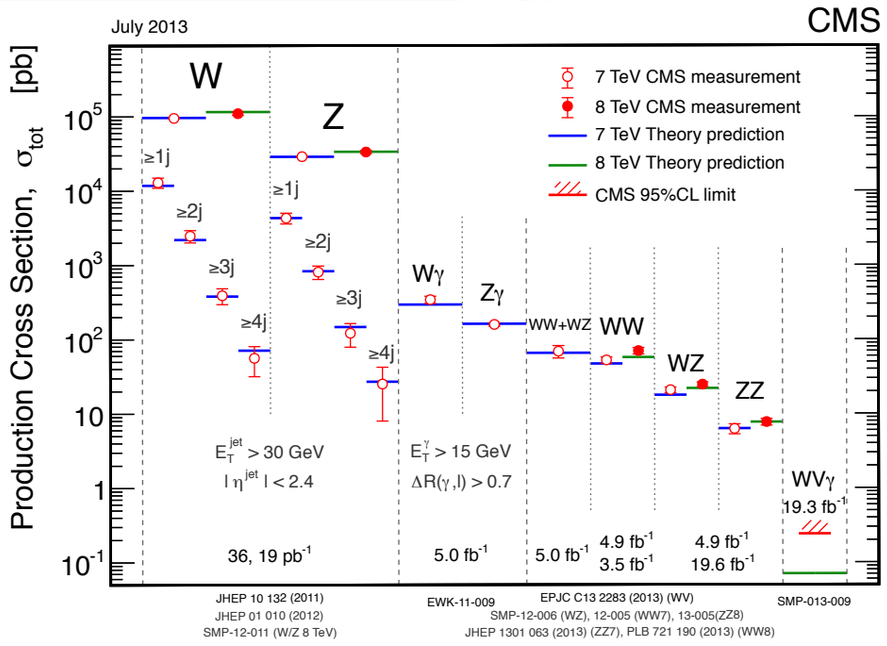
2014 Aspen Winter Conference on Particle Physics:
From Dark Matter to the LHC and Beyond

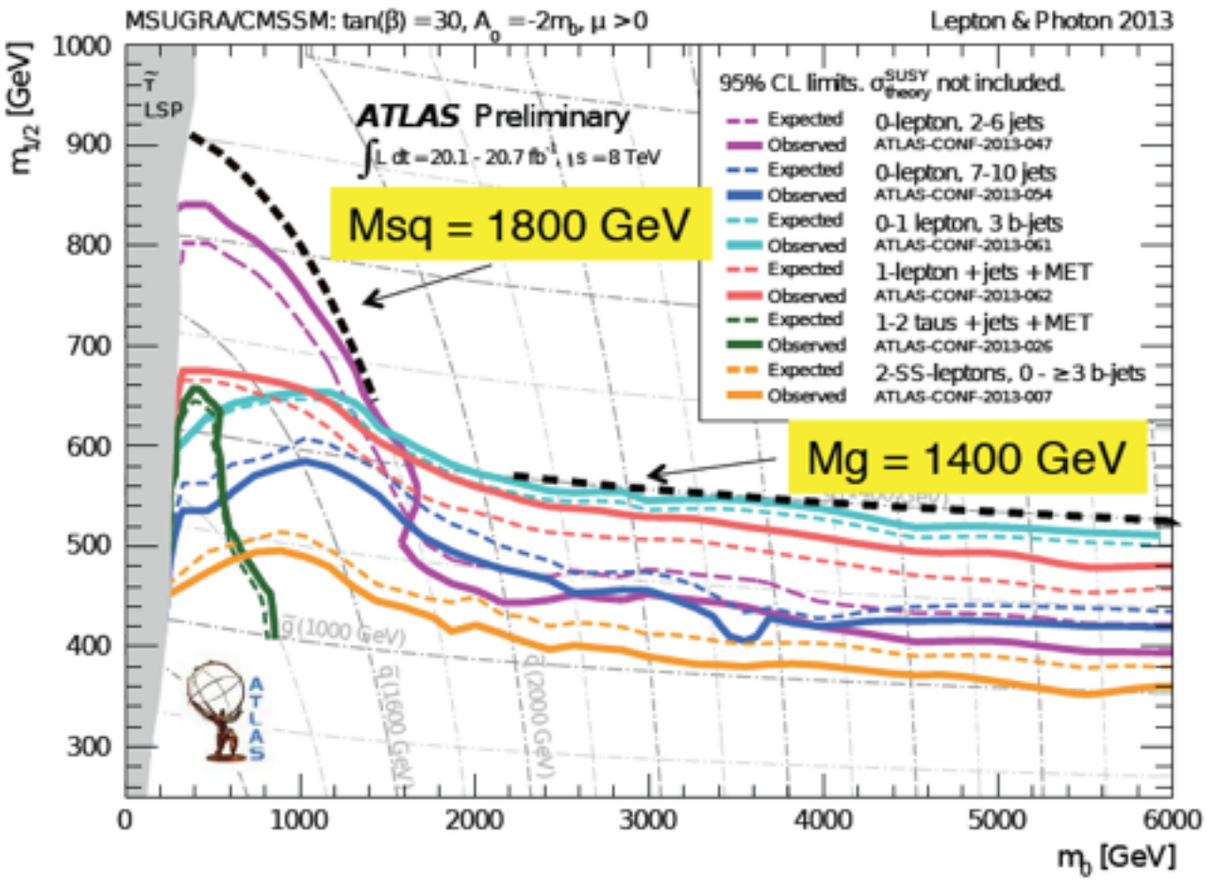
NORTHWESTERN
UNIVERSITY

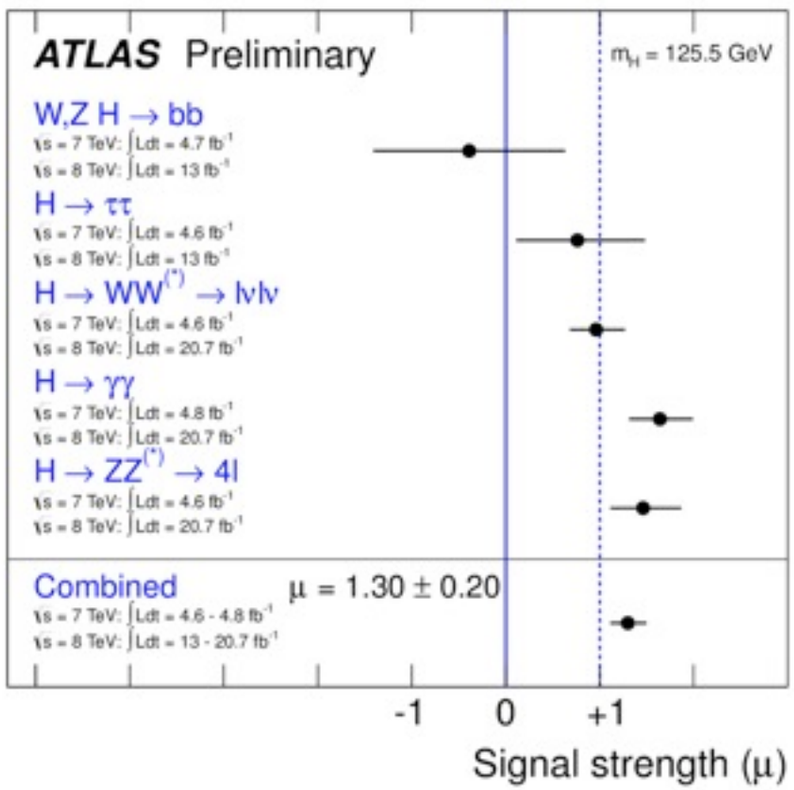
Outline

- Motivation and introduction: QCD in the LHC era
- Status of NLO calculations and recent NLO phenomenology
- Matching and merging fixed-order and parton showers
- 2013: the year of NNLO
- Going beyond fixed-order with analytic resummation

The LHC circa 2013





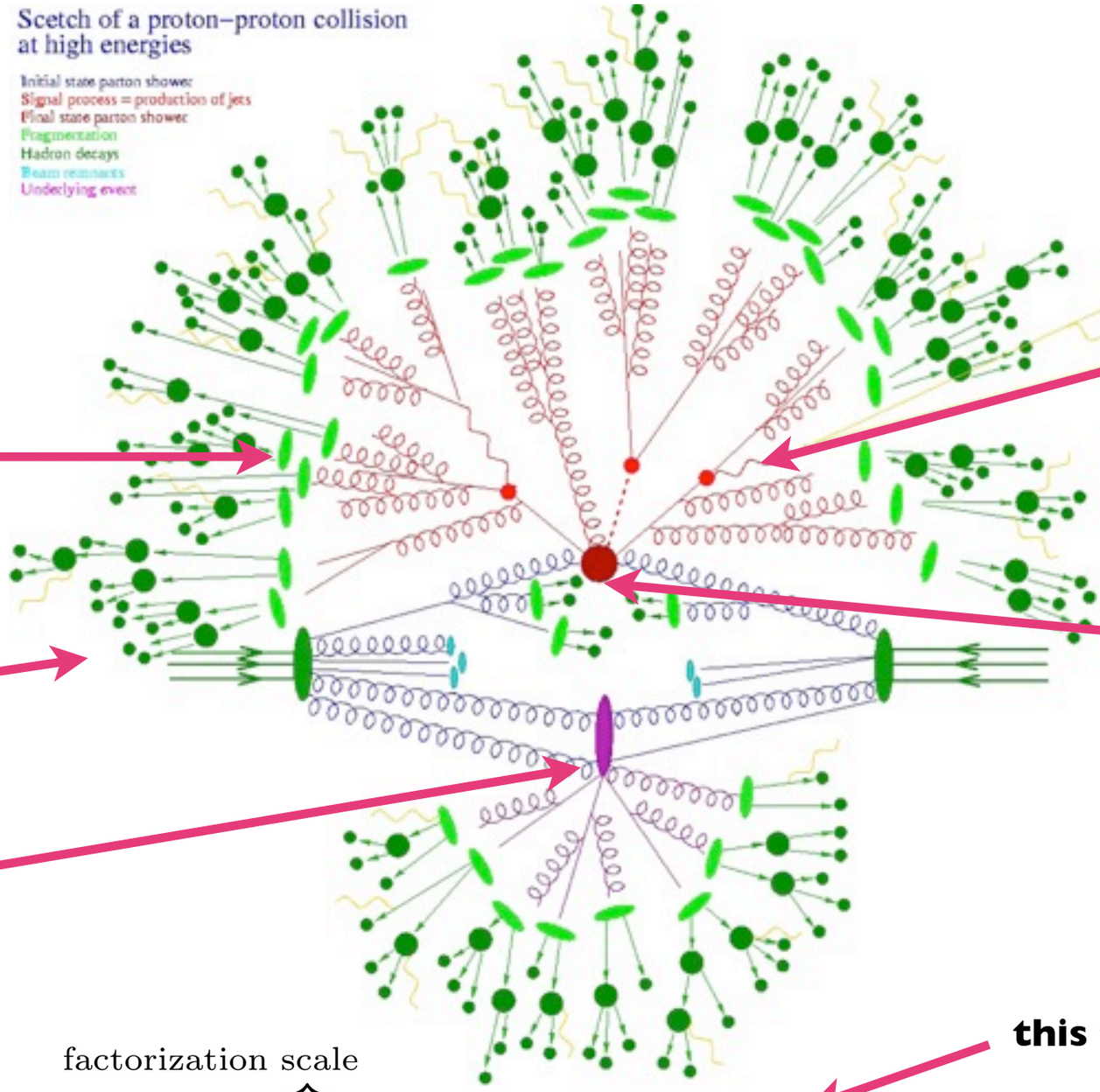


- Remarkable in both breadth and depth of coverage
- Underlying identity of the Higgs being revealed
- Nothing besides the Higgs; limits reaching multi-TeV in some channels

- Everything we've measured so far is consistent with a desert beyond the Higgs at a few/tens of TeV
- There can be fascinating life hidden in a desert... but it can be rare and difficult to find (the background to SUSY is *not* SUSY)
- Takes persistence and the ability to sift through lots of background to find what is new and exciting
- Hopefully LHC_{14} resurrects the SUSY background problem, but if not we should be ready for the challenge

QCD at the LHC

- From a theorist's perspective, the challenge is dealing with QCD



Hadronization at Λ_{QCD}

Hadron decays

Multiple parton interactions

Parton-shower evolution to low energies

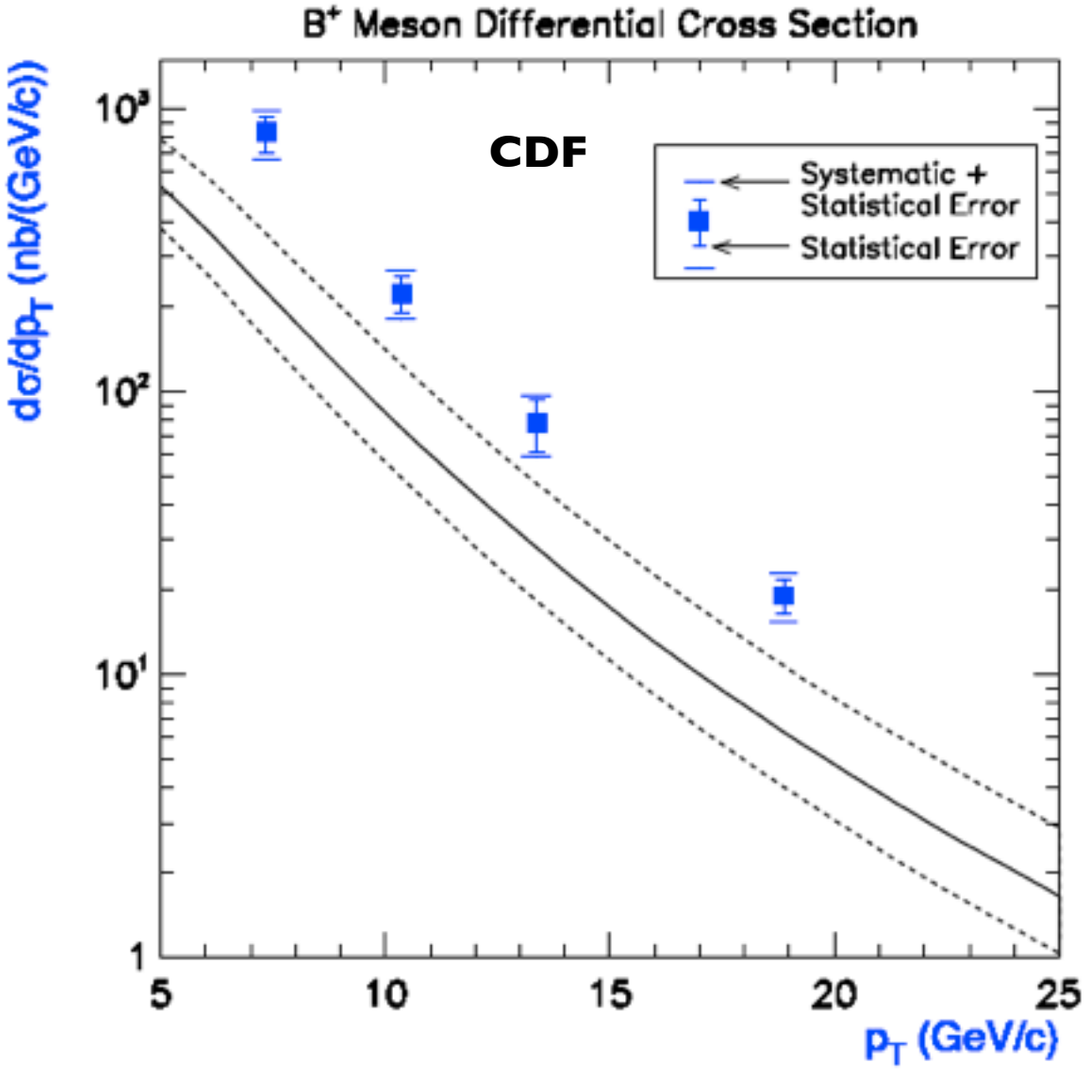
Hard collision (Higgs production) at short distances/ high energies

this talk

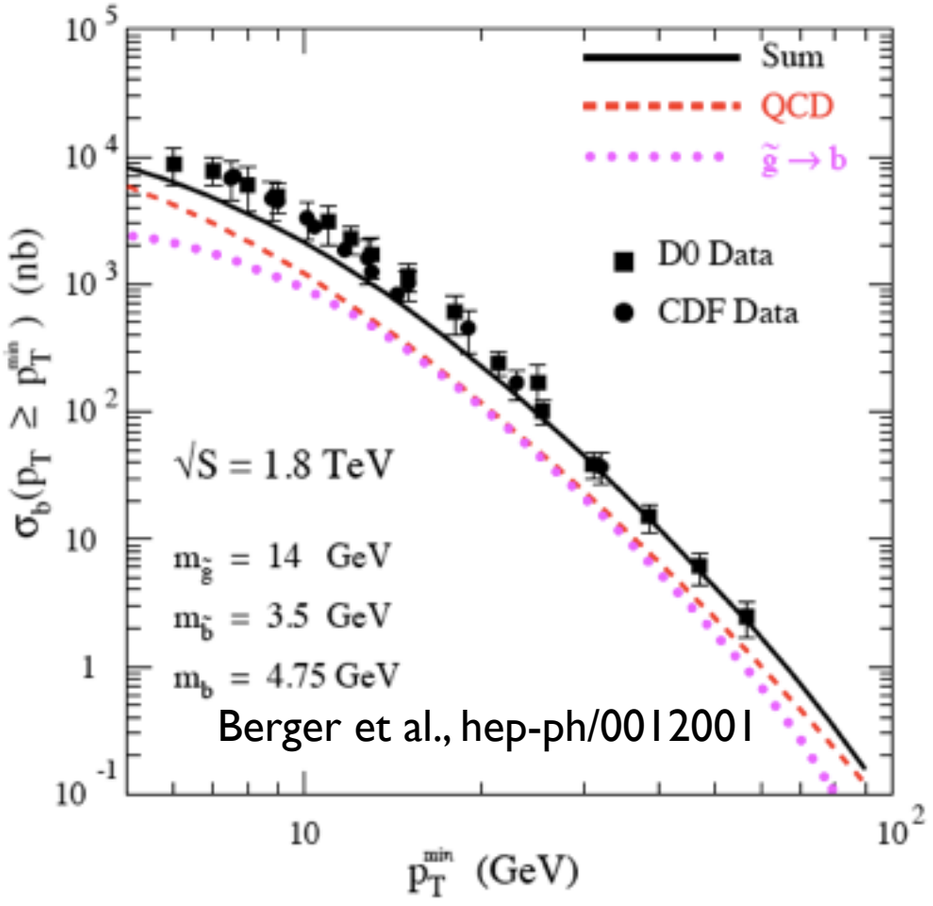
Joey's talk

$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij\to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

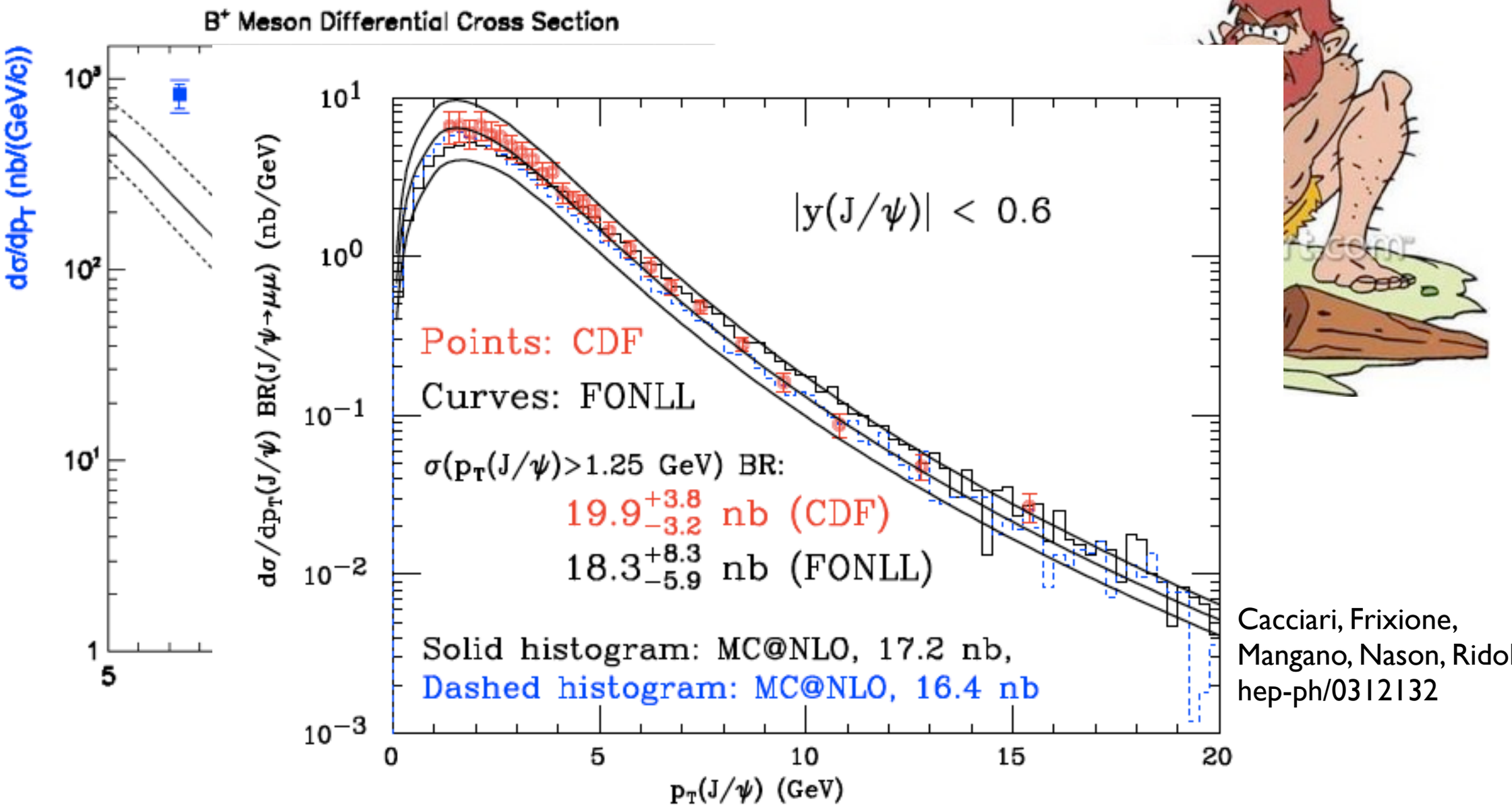
QCD simulation circa 2001



"The differential cross section is measured to be 2.9±0.2±0.4 times higher than the NLO QCD predictions with agreement in shape."



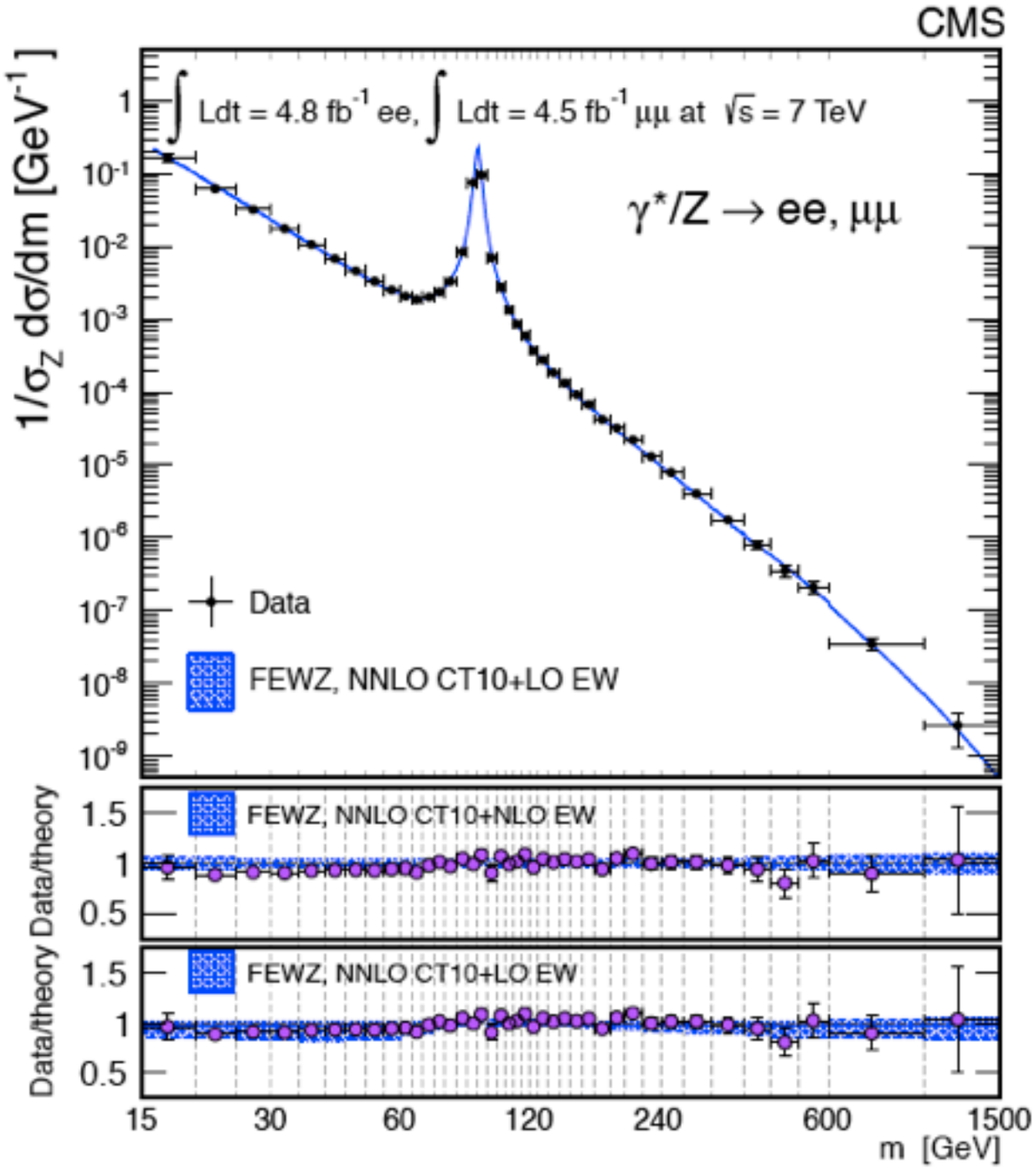
QCD simulation circa 2001



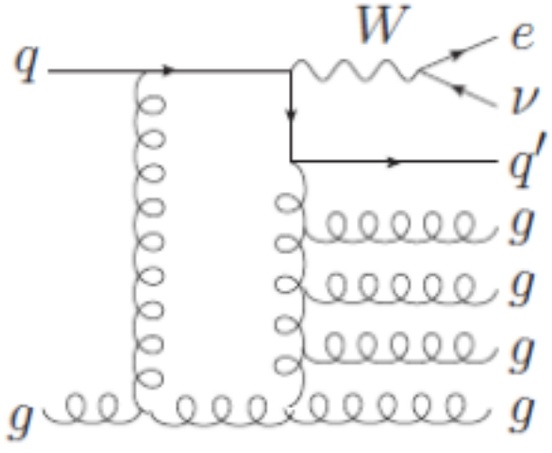
Cacciari, Frixione, Mangano, Nason, Ridolfi hep-ph/0312132

- Consistent combination of fragmentations functions and pQCD, more proper accounting of theoretical errors, better PDFs, all reduce the discrepancy

QCD today



- NLO+parton shower tools now standard tools used in analyses
- NNLO QCD, sometimes with NLO EW combined, is becoming available for more and more channels
- Several global NNLO PDF extractions with robust errors now available



W+5 jets from BLACKHAT, Bern et al. 1304.1253

QCD@NLO

- Well-honed techniques for calculating and combining real+virtual at NLO

Simple enough to integrate analytically so that 1/ε poles can be cancelled against virtual corrections

$$\mathrm{d}\sigma_{NLO} = \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{R}_{NLO} - \mathrm{d}\sigma^{S}_{NLO}\right) + \left[\int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{S}_{NLO} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{V}_{NLO}\right]$$

Approximates real-emission matrix elements in all singular limits so this difference is numerically integrable

- Can use dipole subtraction (Catani, Seymour 1996); FKS subtraction (Frixione, Kunszt, Signer 1996)
- Implemented in several dedicated codes Autodipole, Helac, MadDipole, MadFKS, Sherpa, TeVJet
- Virtual corrections obtained as coefficients times 1-loop scalar integrals, either using Feynman diagrams or unitarity techniques

$$A = \sum d_i \square + \sum c_i \triangle + \sum b_i \text{⋈} + R$$

- Several semi-numerical codes exist for high-multiplicity final states (2→4 or more) : BlackHat, GoSam, HelacNLO, MadLoop, NJet, OpenLoops, Rocket
- Programs with analytic representations of the amplitudes (such as MCFM) remain extremely important for speed/efficiency, and as input to NNLO

The new wishlist

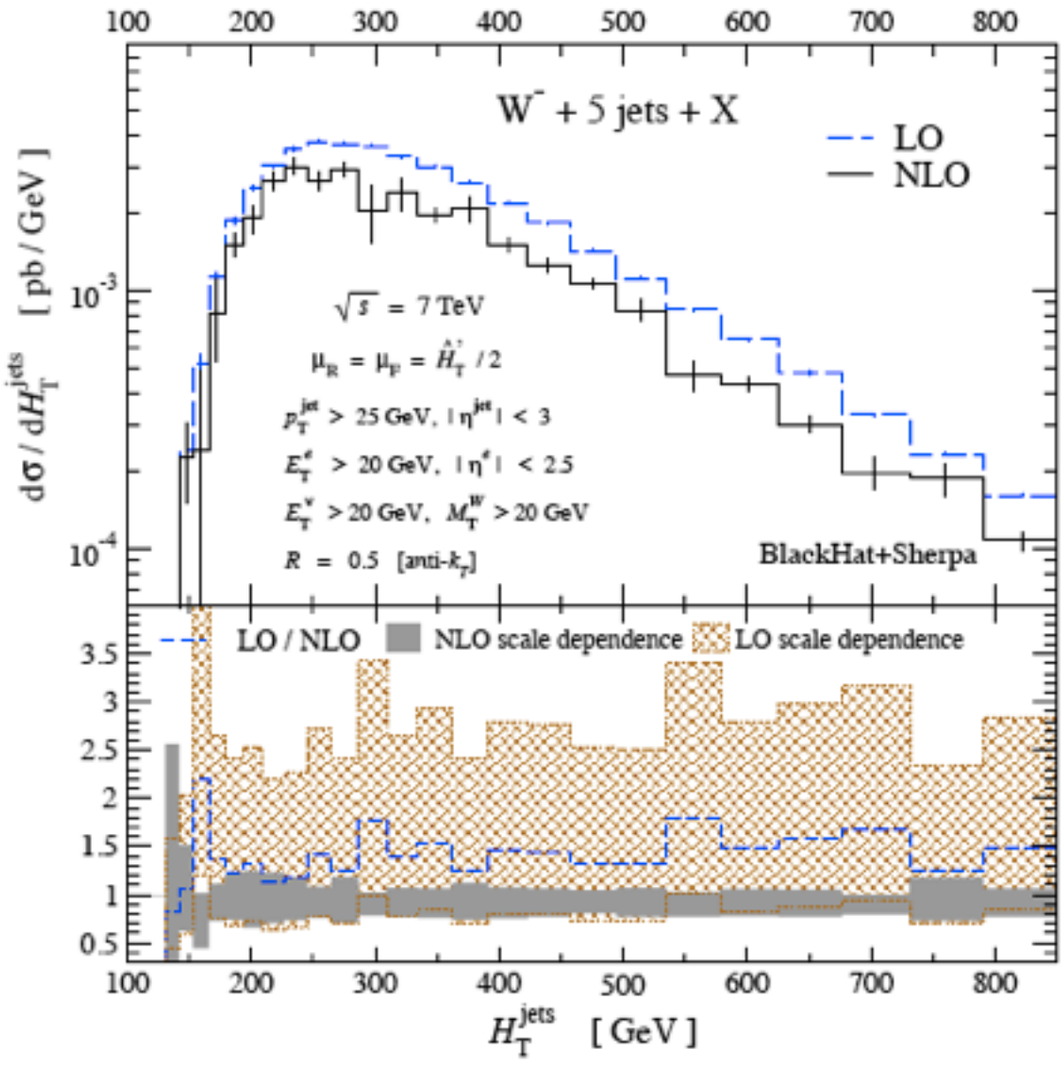
Process ($V \in \{Z, W, \gamma\}$)	Comments
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti WZ jet, $W\gamma$ jet completed by Campanario et al.
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier Interference QCD-EW in VBF channel
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld see also Binoth/Ossola/Papadopoulos/Pittau VBFNLOmeanwhile also contains $WWW, ZWW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma, W\gamma\gamma j$
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa and Rocket collaborations Z+3jets by Blackhat/Sherpa
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al.Bevilacqua et al.
8. $pp \to VV$+2jets	W^+W^++2jets, W^+W^-+2jets, relevant for VBF $H \to VV$ VBF contributions by (Bozzi/)Jäger/Oleari/Zeppenfeld
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al.
10. $pp \to V + 4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets, Z+4jets see also HEJfor $W + n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures, Bevilacqua/Worek
$pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld
$pp \to 4$ jets	Blackhat/Sherpa

- The NLO wishlist of desired processes, created in Les Houches nearly a decade ago, was closed last year; everything is known!
- Replace with a new NNLO+EW wishlist (see Snowmass QCD report, 1310.5189)
- Increased importance of higher-order electroweak Sudakov logs at LHC Run II (see Mishra et al, 1308.1430)

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

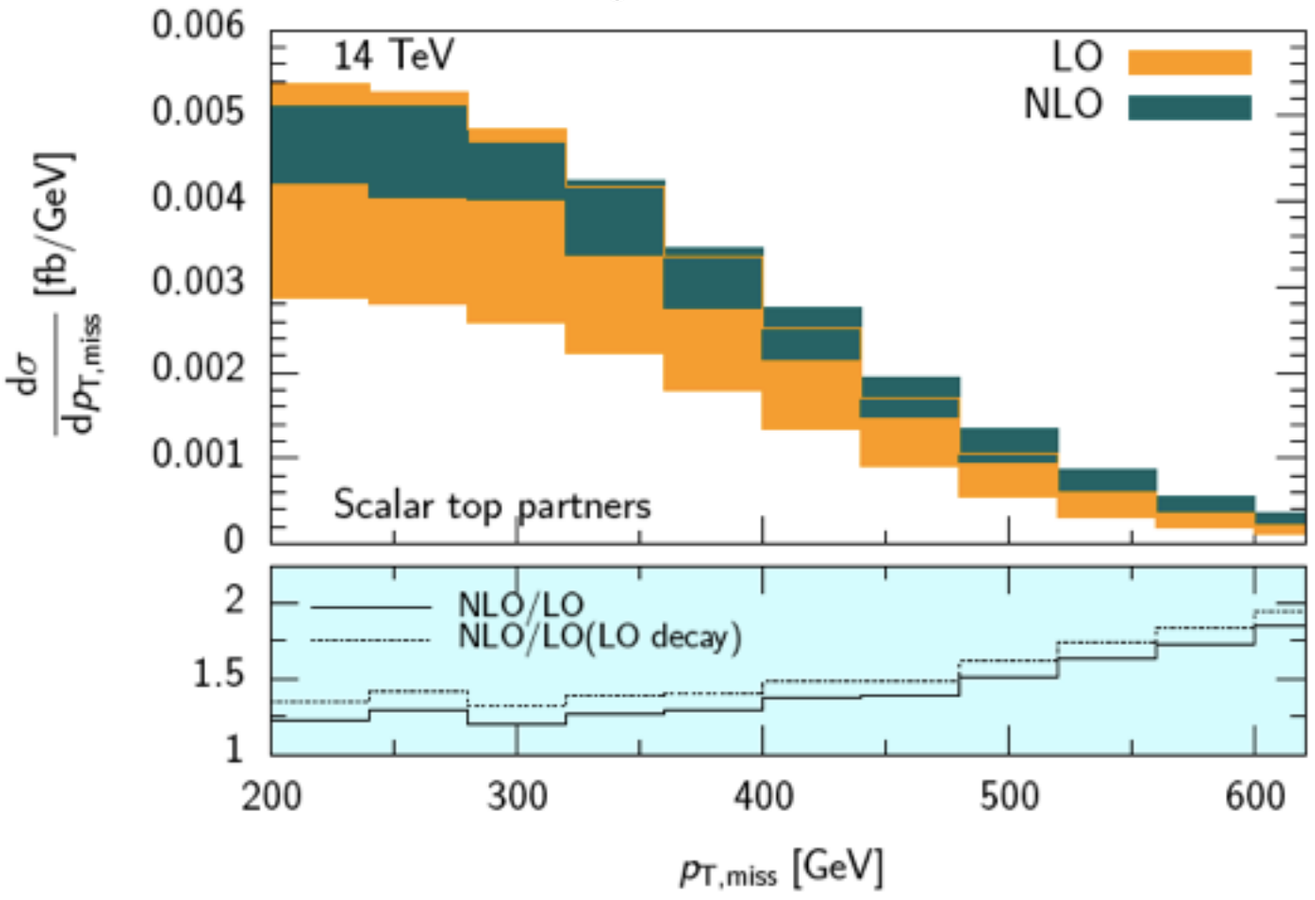
Recent NLO phenomenology

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren 1304.1253



- First 2→6 NLO hadron collider calculation
- Reduced NLO scale dependence
- $H_T/2$ scale choice at LO gets distribution shapes correct

Boughezal, Schulze 1309.2316

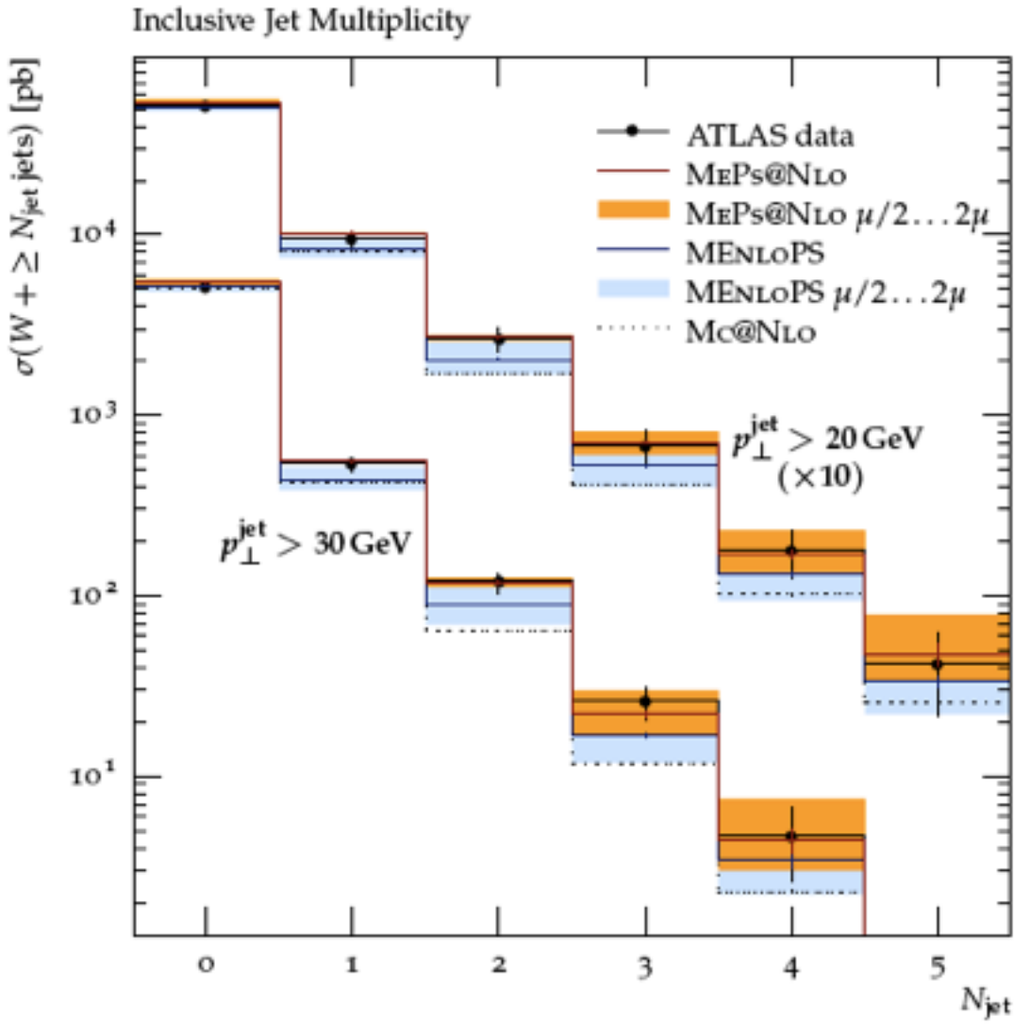


	LO	NLO	MG+Pythia	MG+PS merged
acceptance	0.19^{+0}_{-0}	$0.27^{+0.3}_{-0.2}$	0.46	0.27

- Techniques applicable to BSM theories also
- Stop pairs to ttbar+missing E_T with QCD corrections included throughout decay chain; strong kinematic dependence of K-factors
- Out-of-the-box parton showers can get acceptances very wrong!

NLO+parton showers

- NLO provides normalization and exact treatment of 1st jet; shower provides leading-log resummation plus realistic high-multiplicity partonic final states
- Two methods: MC@NLO (Frixione, Webber 2002), POWHEG (Nason 2004; Frixione, Nason, Oleari 2007)
- Other public implementations: aMC@NLO, Sherpa



Hoeche, Krauss, Schonherr, Siegert 1207.5030

- Can now do NLO+PS consistently for several jet multiplicities simultaneously:

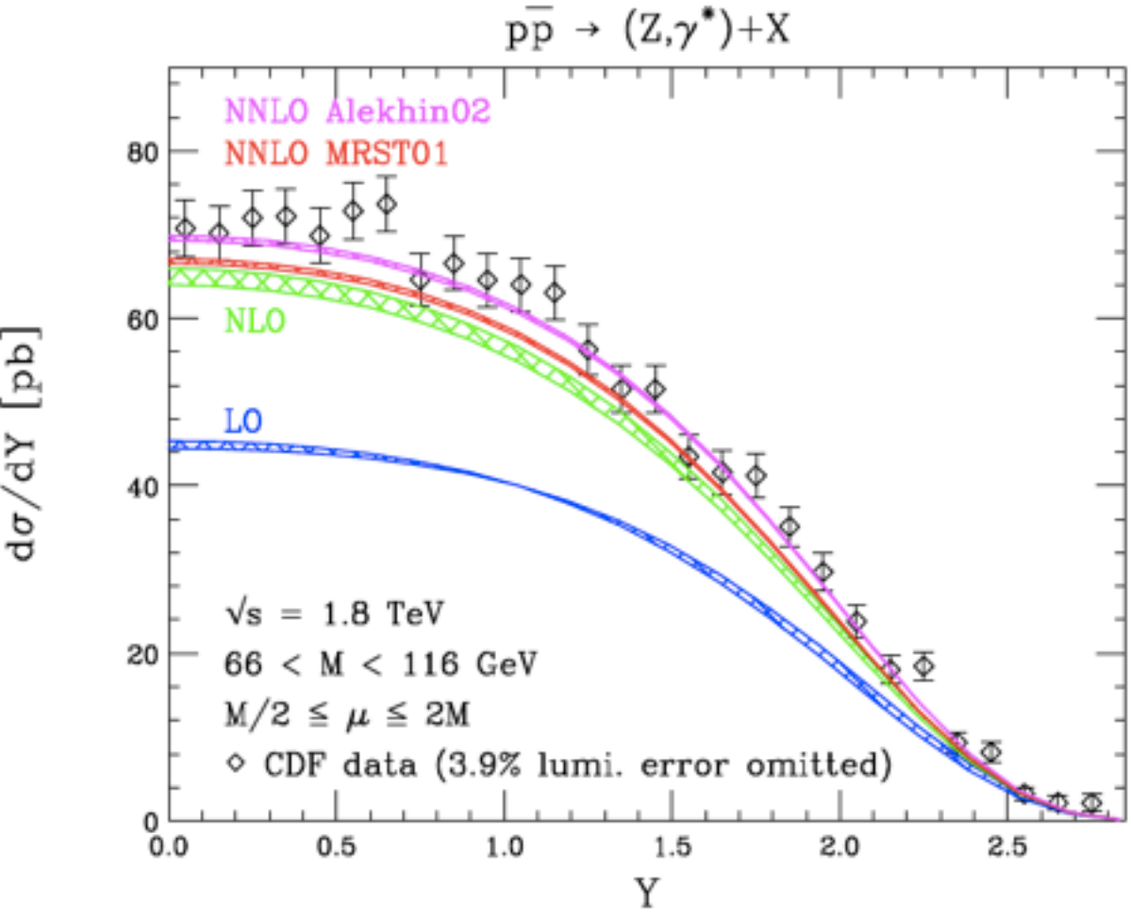
Lavesson, Lonnblad 2008; Lonnblad, Prestel 2012; Gehrmann, Hoeche, Krauss, Schonherr, Siegert 2012; Frixione, Frederix 2012; GENEVA (Alioli et al.) 2012

- Initial work on combining NNLO+PS

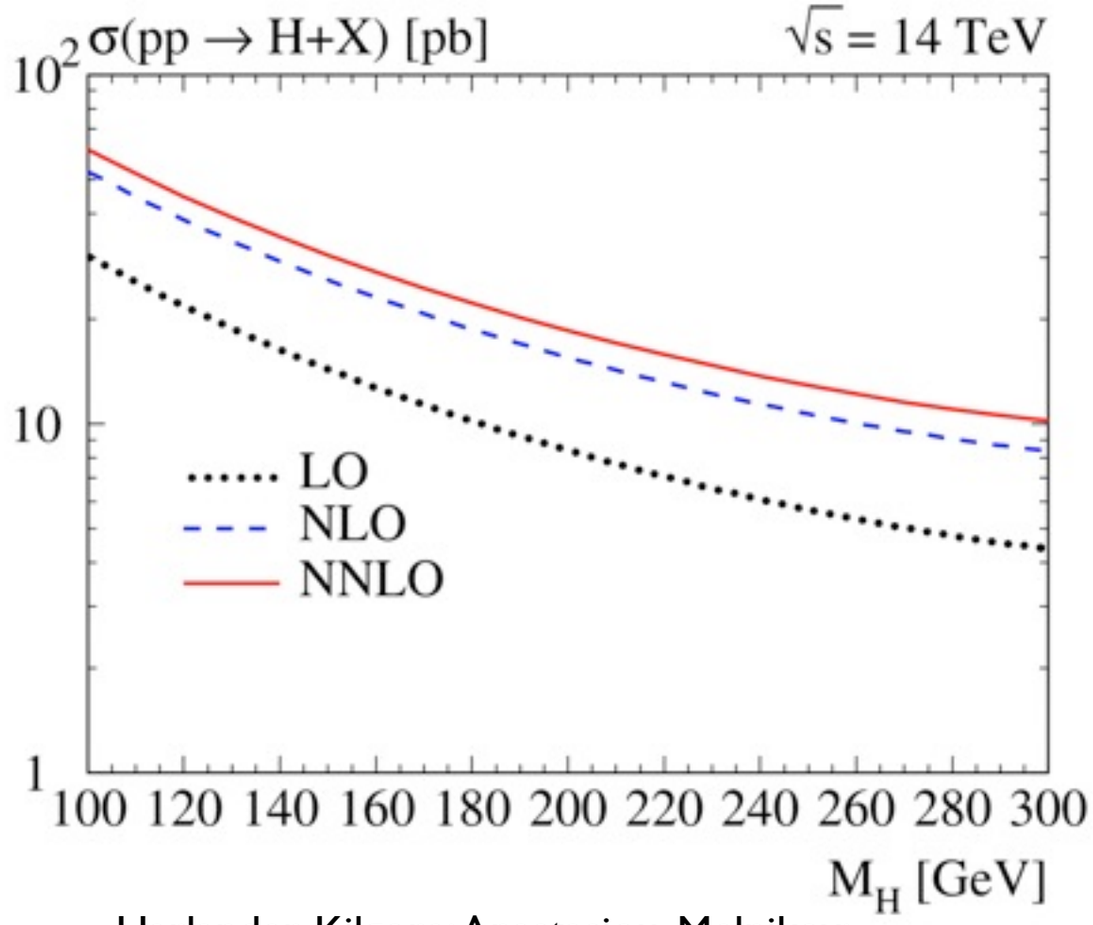
Lonnblad, Prestel 1211.7278; Hamilton, Nason, Re, Zanderighi 1309.0017; GENEVA (Alioli et al.) 1311.0286

The NNLO frontier

- The need to go to NNLO or beyond for certain analyses is well-established; needed for benchmark high-precision measurements, and when corrections unusually large



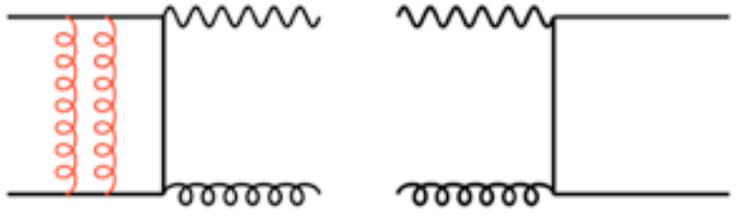
Anastasiou, Dixon, Melnikov, FP 2004



Harlander, Kilgore; Anastasiou, Melnikov;
Ravindran, Smith, van Neerven 2002-2003

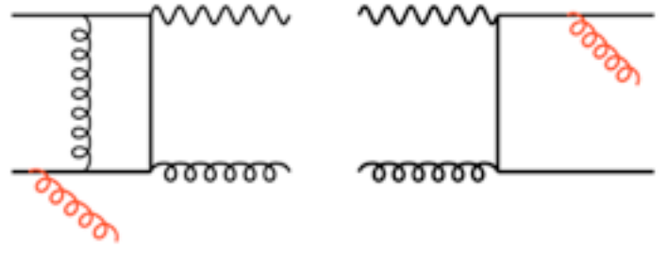
Ingredients at NNLO

2-loop matrix elements, m partons



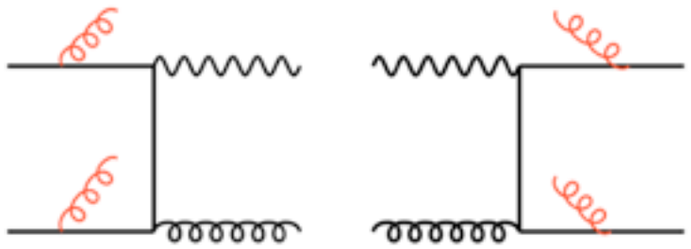
- Explicit IR poles from loop integrals

1-loop matrix elements, m+1 partons



- Explicit IR poles from loops
- Implicit IR poles from single unresolved radiation

Tree level matrix elements, m+2 partons



Implicit IR poles from double unresolved radiation

- Need a subtraction scheme to account for all singular configurations, like at NLO
- Understanding how to parameterize and integrate the subtraction terms much more difficult at NNLO

What is known at NNLO

- Until recently, only special processes with colorless initial states or colorless final states were known at the differential level to NNLO

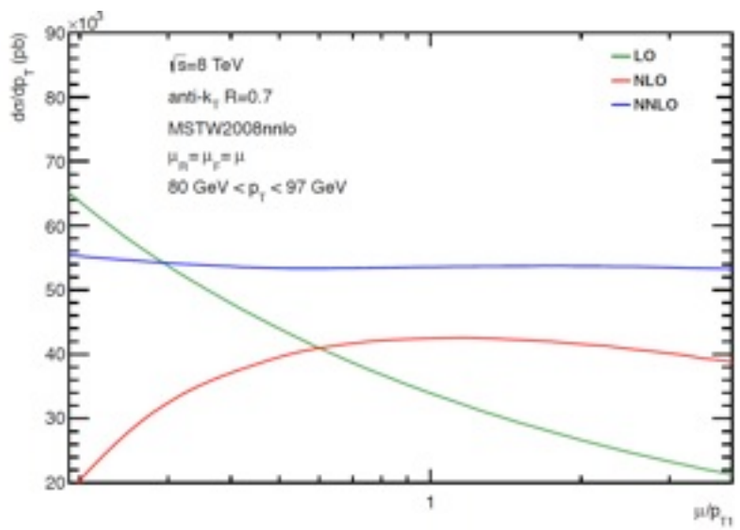
  - $pp \to H$: Anastasiou, Melnikov, FP 2005; Catani, Grazzini 2007
  - $pp \to V$: Melnikov, FP 2006; Catani, Cieri, Ferrera, de Florian, Grazzini 2009
  - $e^+e^- \to 3$ jets: Gehrmann-De Ridder, Gehrmann, Glover, Heinrich 2007; Weinzierl 2008
  - $pp \to \gamma\gamma, VH$: Catani et al. 2011; Ferrera, Grazzini, Tramontano 2011

- Processes with both initial and final-state colored particles were terra incognita
- Two methods have been extended to allow for NNLO corrections to colored final states at hadron colliders:

  - Antennae subtraction: Gehrmann, Gehrmann-deRidder, Glover
  - Sector-improved subtraction: Czakon; Boughezal, Melnikov, FP

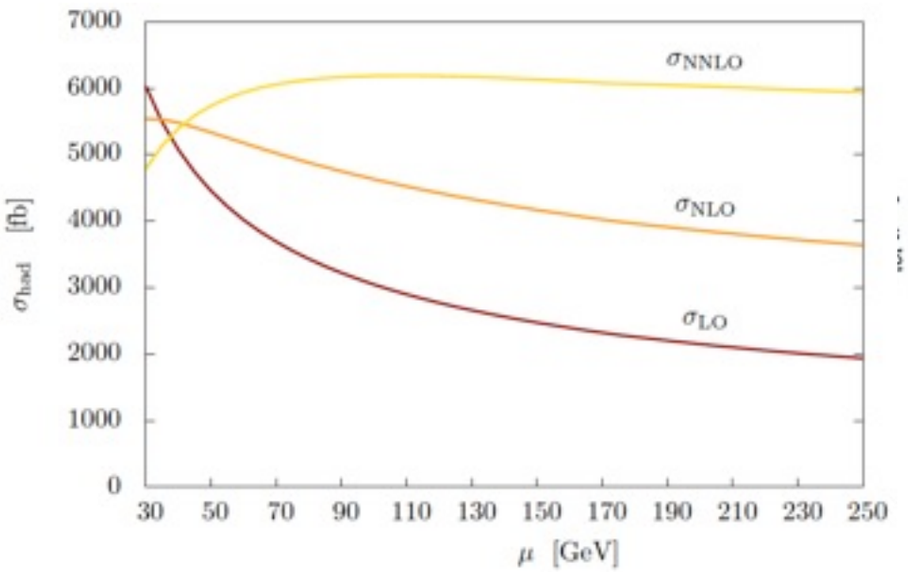
2013: the year of NNLO

- After more than a decade of research we finally know how to generically handle NNLO QCD corrections to processes with both colored initial and final states



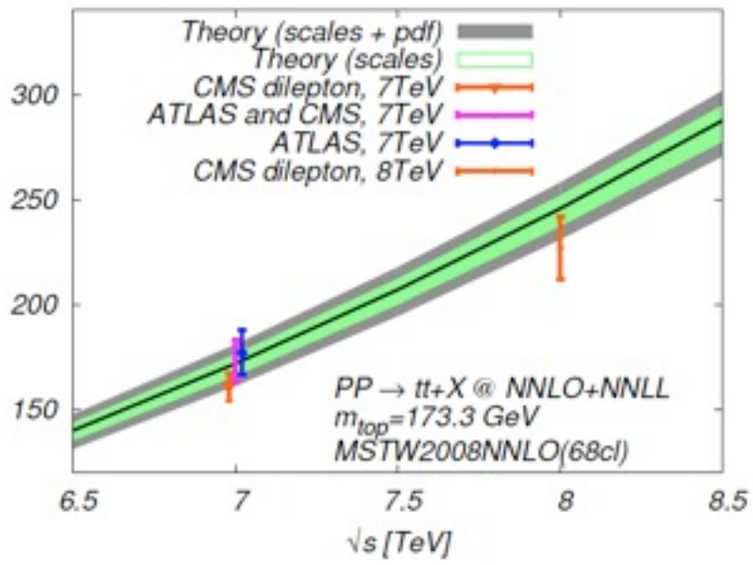
Gehrmann-de Ridder, Gehrmann, Glover, Pires 1301.7310

dijet: gg-channel



Boughezal, Caola, Melnikov, FP, Schulze 1302.6216

H+1j:gg-channel



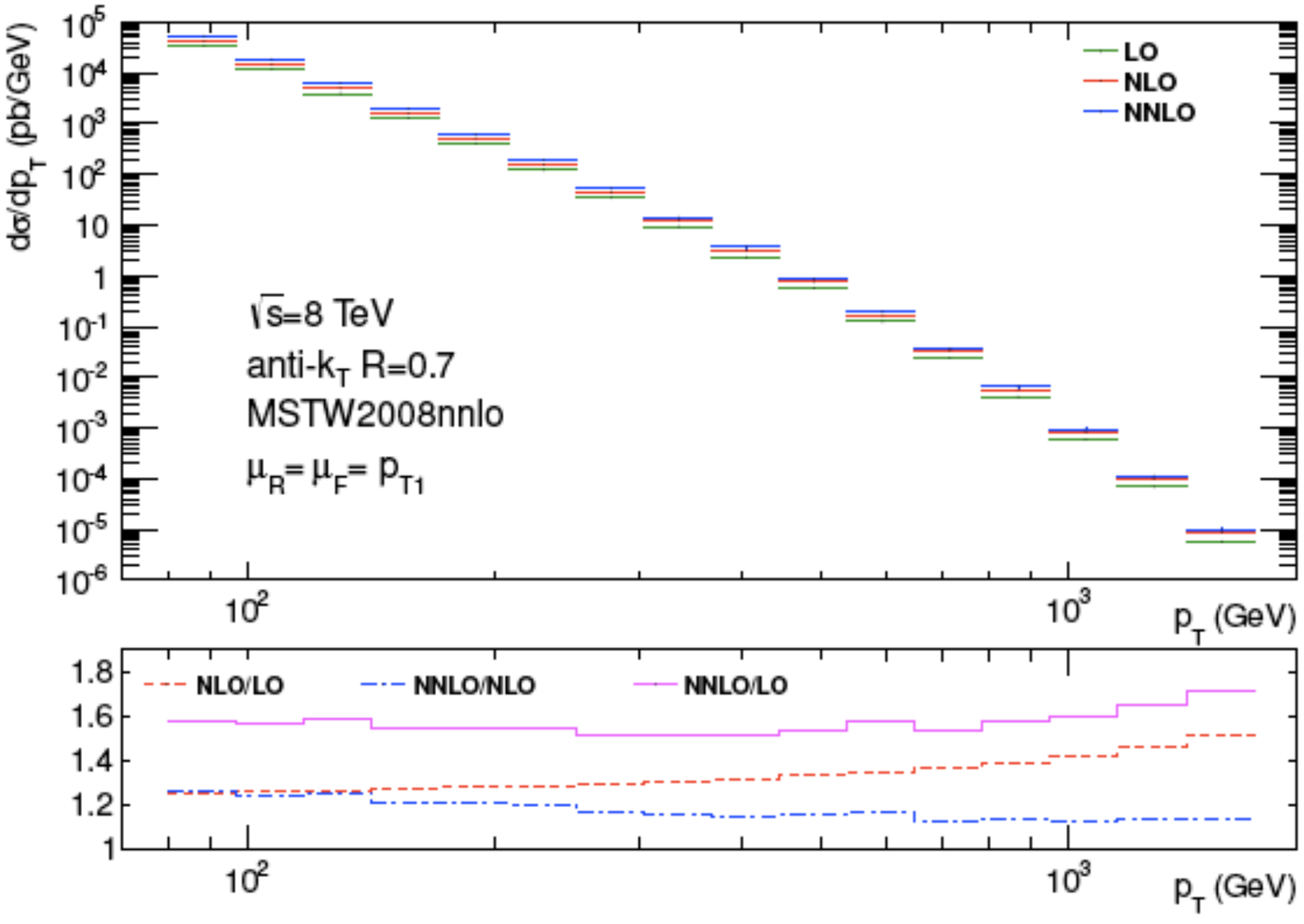
Czakon, Fiedler, Mitov 1303.6254

ttbar: all-channels

Based on Antenna subtraction scheme

Based on sector-improved subtraction scheme

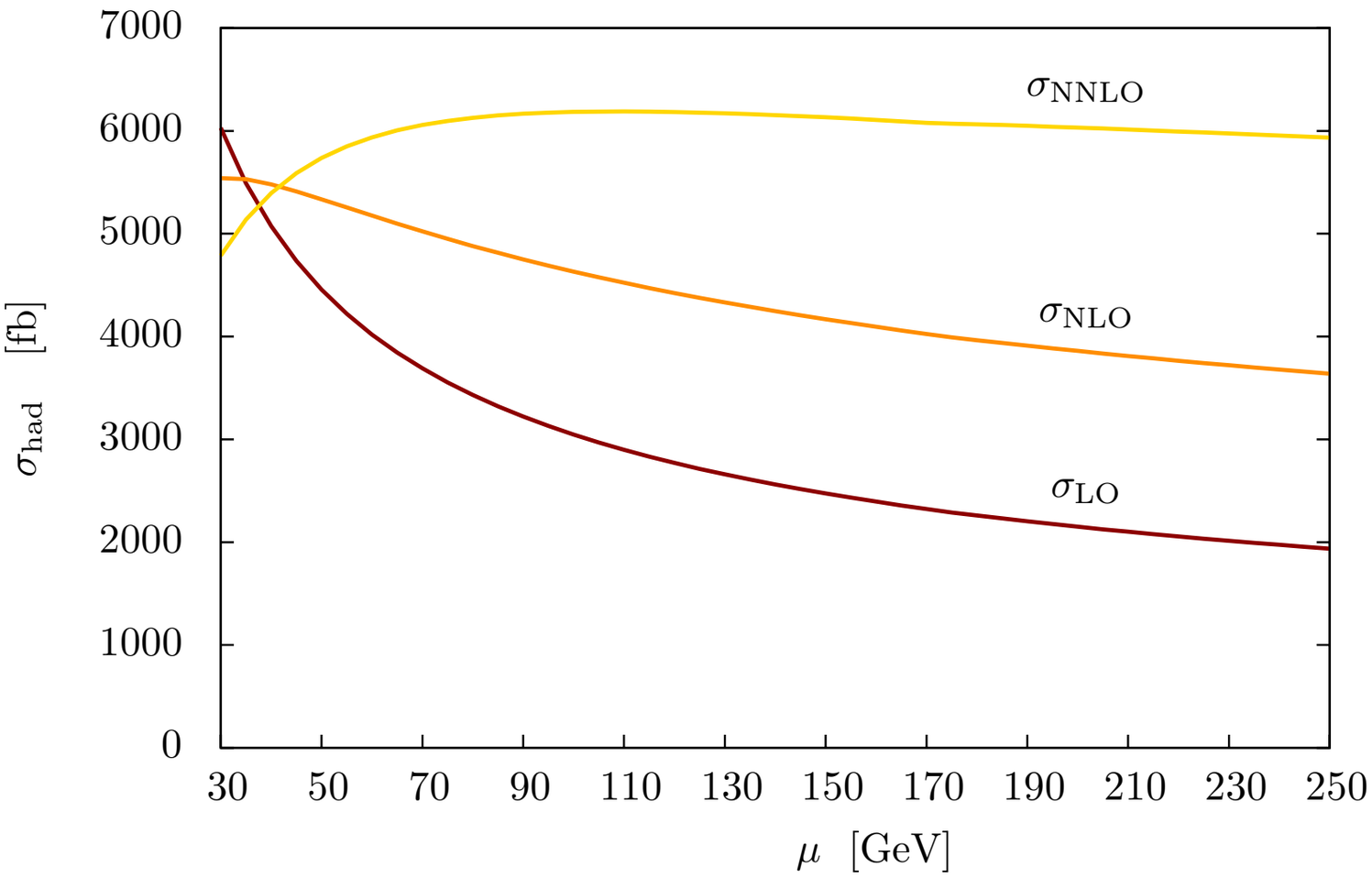
Dijets@NNLO



Gehrmann-de Ridder, Gehrmann, Glover, Pires 1301.7310

- Leading-color gg→gg channel
- 10-20% corrections going from NLO to NNLO, with a kinematic dependence
- Stabilization of the scale dependence
- Implementation of remaining partonic processes expected soon

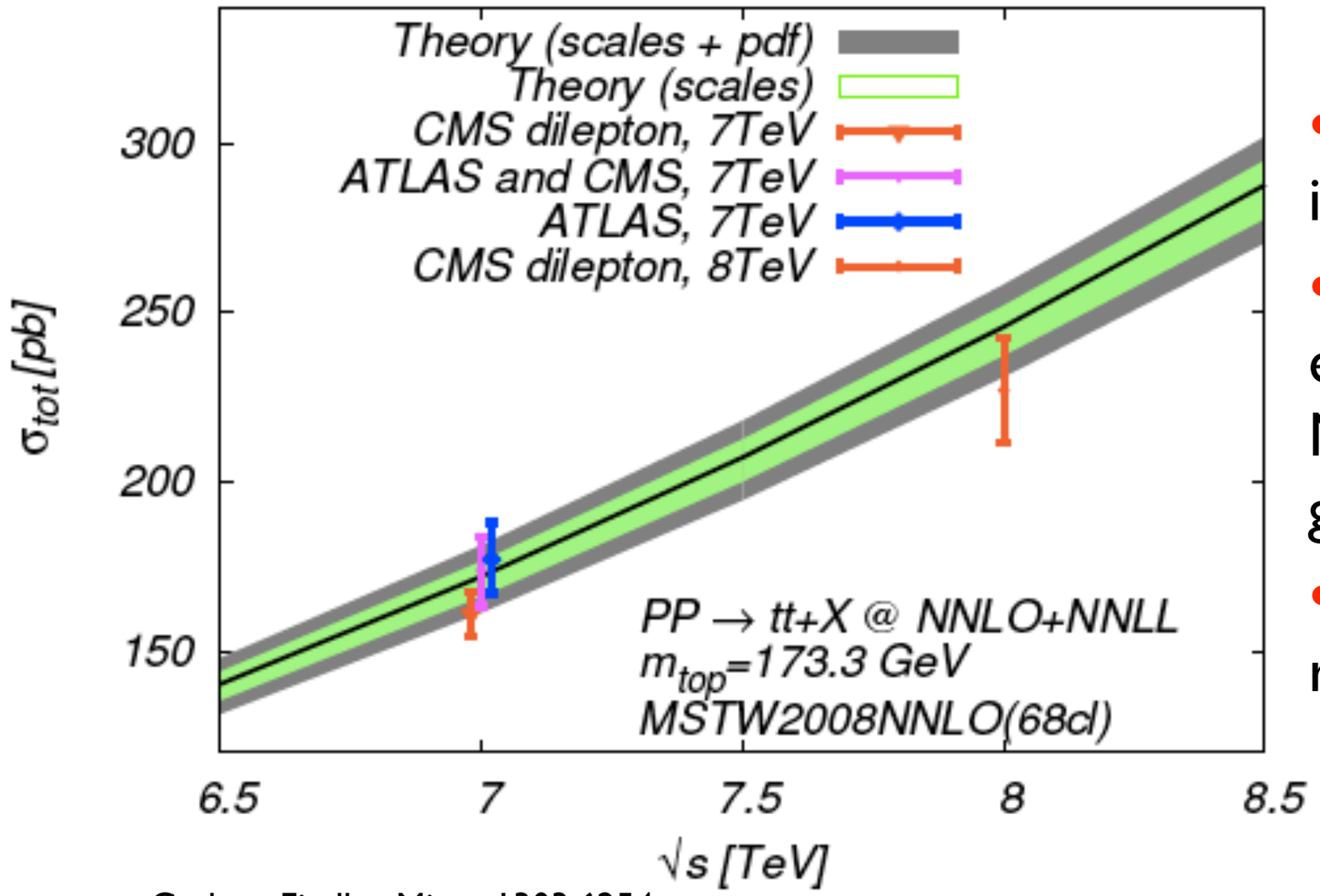
H+j@NNLO



Boughezal, Caola, Melnikov, FP, Schulze 1302.6216

- Full result for the gg→gh channel
- Large corrections! 30% from NLO to NNLO at $\mu=m_H$
- Preference for scales smaller than m_H shown
- Remaining partonic channels being completed

Tops@NNLO

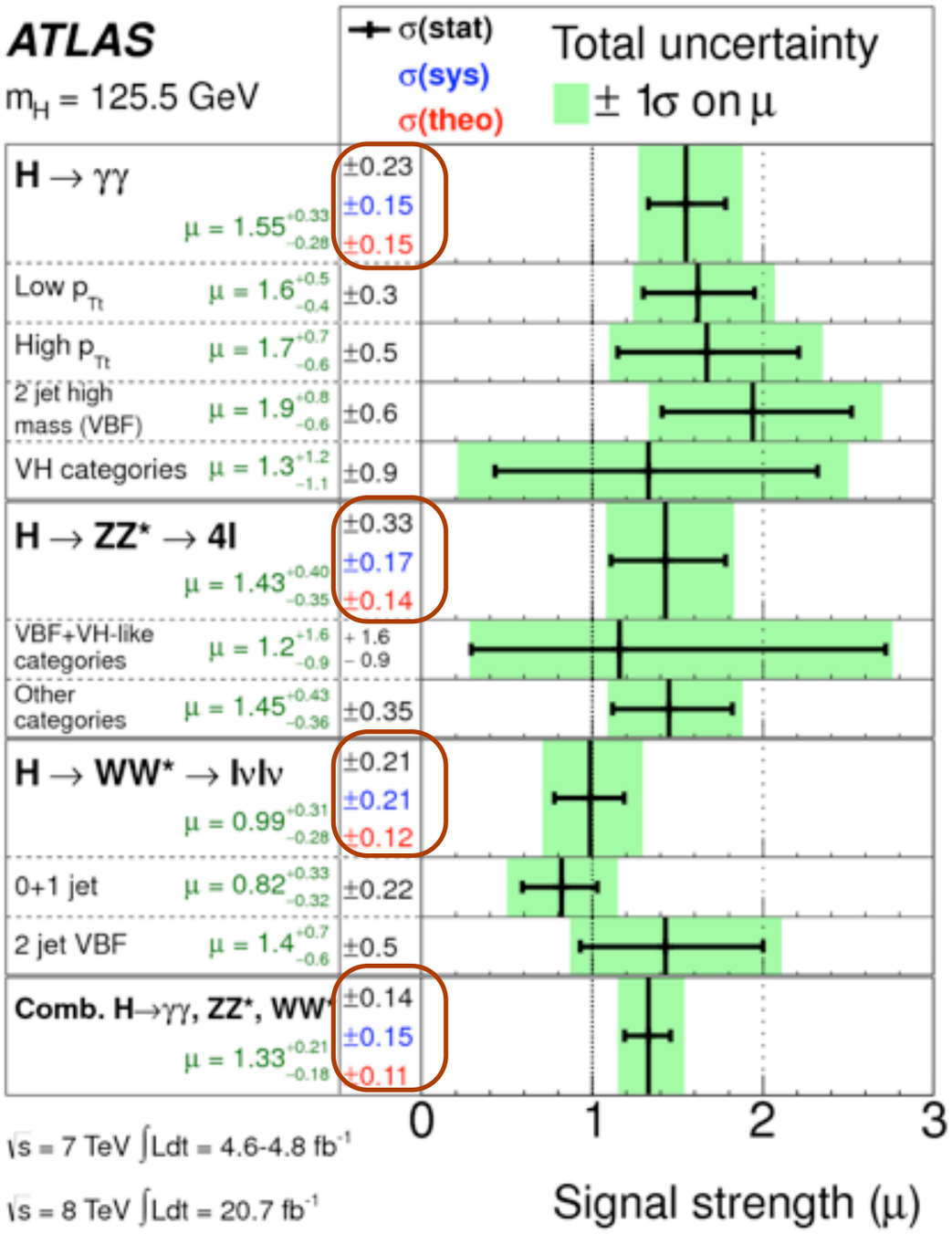


Czakon, Fiedler, Mitov 1303.6254

- Full calculation available, for the inclusive cross section
- Needed to match the expected experimental precision of ±5%; NLO+threshold resummation gives ±10%
- Calculation of differential results ongoing

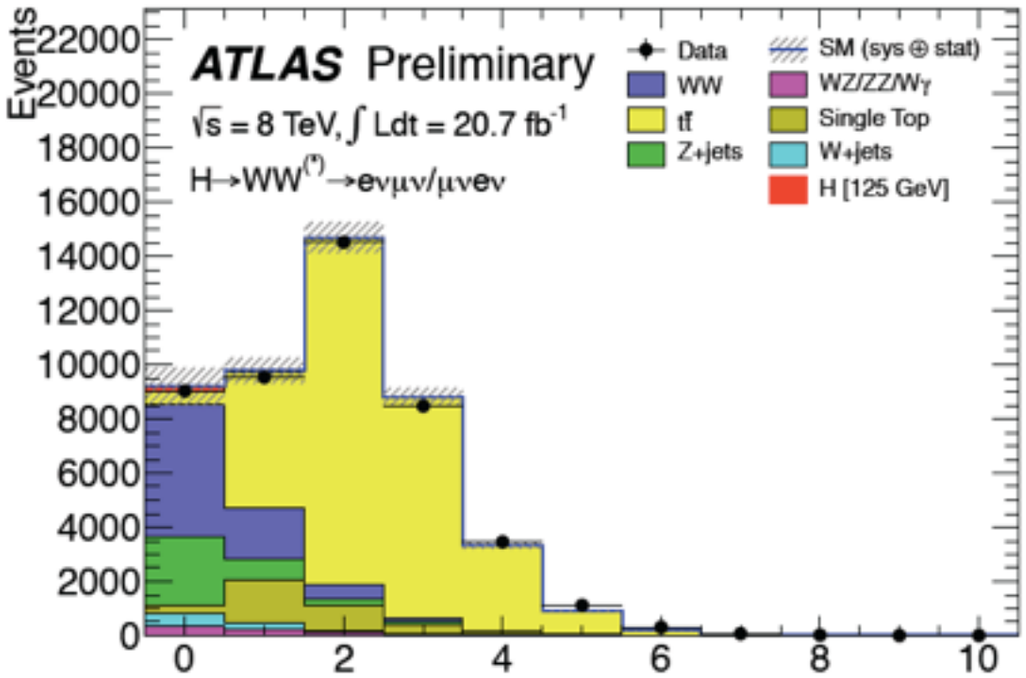
A two-front war

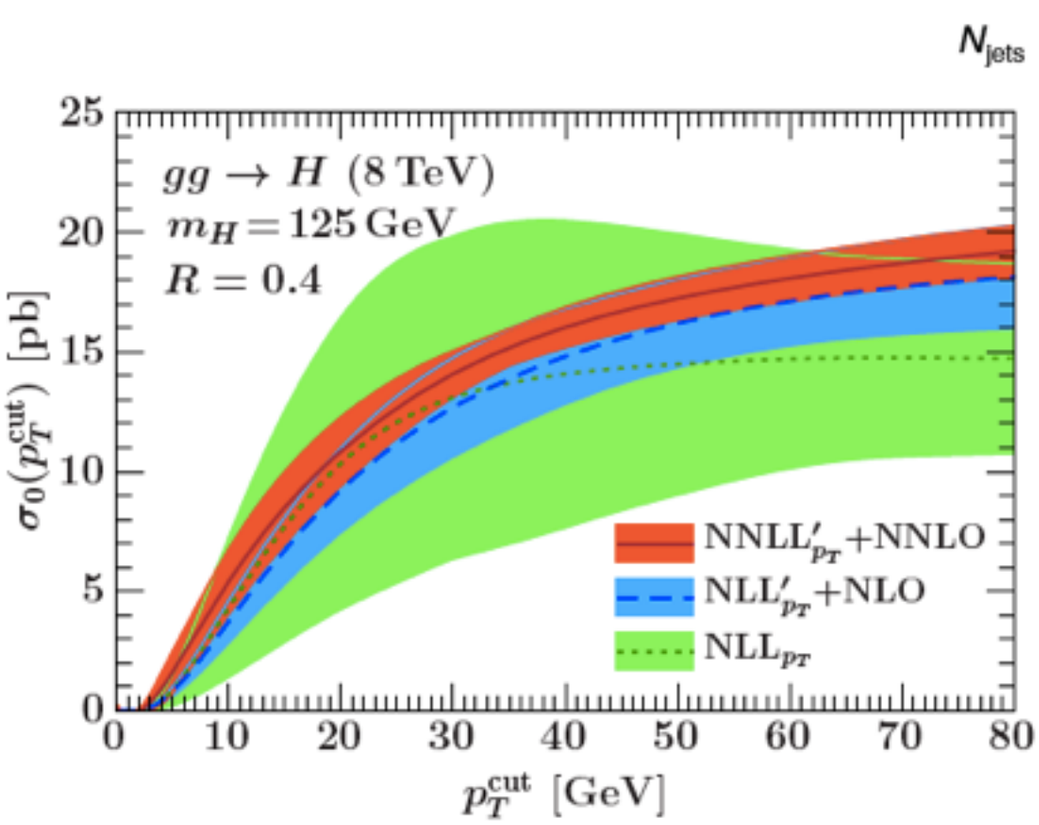
- Fixed-order not enough when experimental cuts are severe, as for Higgs



- Systematic errors, especially theory, on Higgs analyses already approaching statistical ones; will overtake with 14 TeV data
- Two reasons for the large theory errors:
  - Large fixed-order corrections, which need further NNLO fixed-order results
  - Some analyses, particularly WW, require a division into exclusive jet bins that introduces large logarithms which must be resummed
- Progress on both fronts needed to improve Higgs-signal modeling for Run II of the LHC

Exclusive jet bins





Stewart, Tackmann, Walsh, Zuberi

- Required experimentally in the WW channel due to the background composition
- Typical jet-p_T cuts: 25-30 GeV; $m_H/p_{cut} \gg 1$, leading to large logarithms
- Significant recent theory activity on resumming these terms to all orders

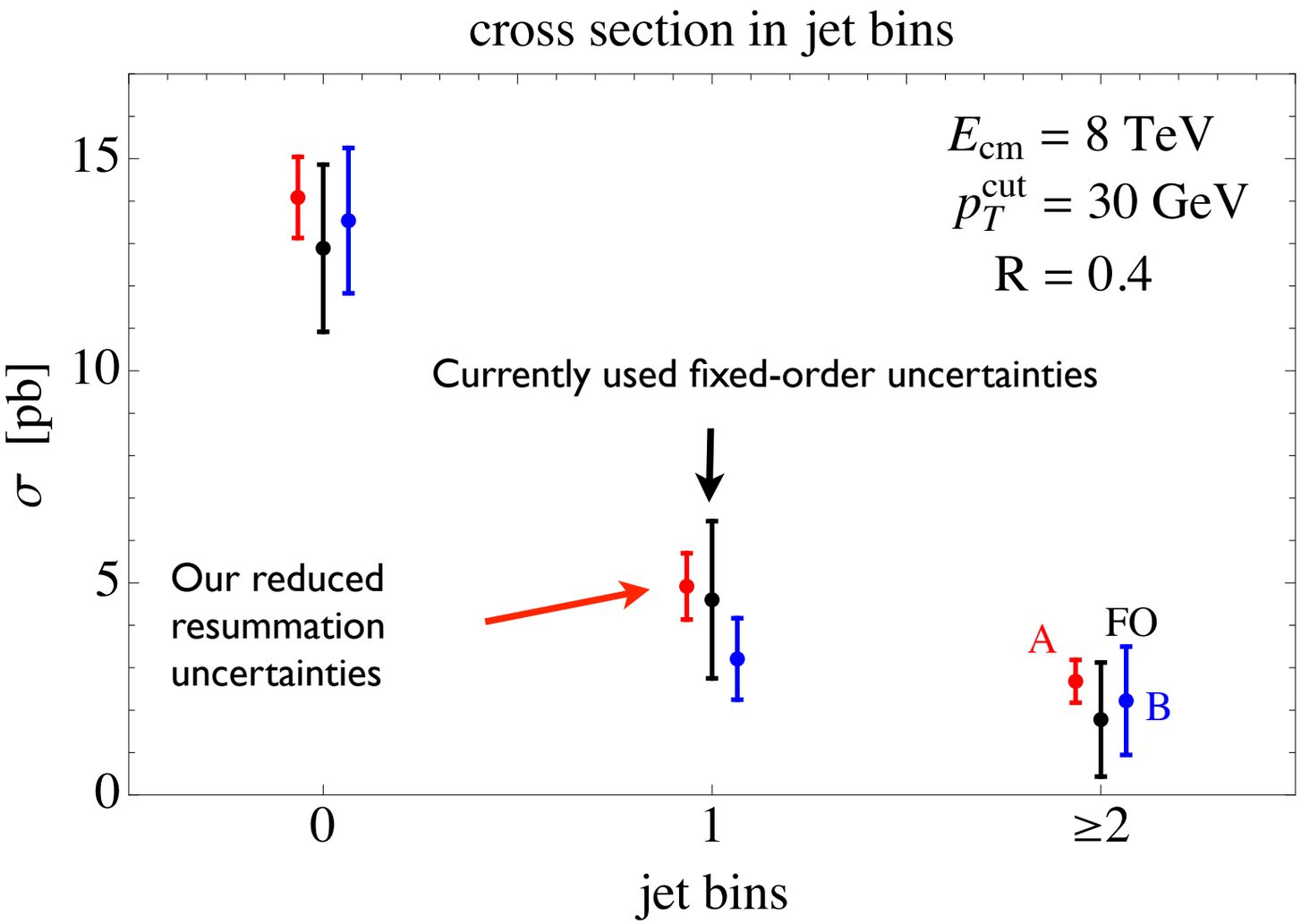
- 0-jet bin:
  - Banfi, Monni, Salam, Zanderighi: NNLL+NNLO 1203.5573, 1206.4998
  - Becher, Neubert NNLL+NNLO 1205.3806, partial N^{3}LL +NNLO 1307.0025
  - Stewart, Tackmann, Walsh, Zuberi NNLL'+NNLO 1307.1808

  (N.B.: accuracy of all three calculations basically equivalent)
- 1-jet bin for high-p_T ($p_T \sim m_H$) jets: Liu, FP 1210.1906, 1303.4405
- Resummation important for boosted VH production also: Li, Liu 1401.2149

Combining the 0+1 jet bins

- New result gives a consistent resummation-improved treatment of the entire combined 0+1 jet bins with all theoretical error correlations

Boughezal, Liu, Tackmann, FP, Walsh 1312.4535



- Direct resummation of jet-veto logarithms for the 0-jet and high-p_T 1-jet results
- Low-p_T 1-jet bin is a difficult 3-scale problem (m_H,p_{jet},p_{cut})
- Can indirectly obtain as a difference of 2-scale cross sections that can be directly resummed, plus a small (5-10%) genuine 3-scale piece known through NLO
- All pieces treated within a consistent SCET formalism which maintains all error correlations

Estimate a factor of 2 reduction in the theory uncertainty on the WW signal strength from this analysis; ±12%→±6%!

- There can be flowers in the desert if one looks carefully; we have the tools to do so
- Multi-particle NLO and NLO+PS have become mature fields
- NNLO has undergone rapid advances in the past year
- High-precision resummation in the presence of final-state jets has become possible in the past year
- QCD theory is ready for Run II!