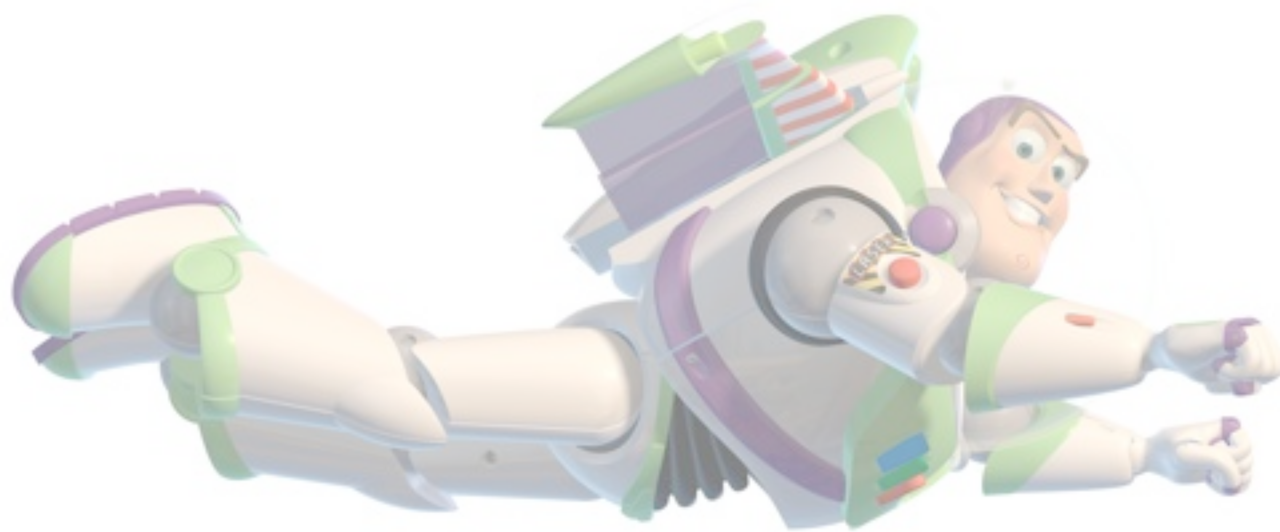

QCD to NNLO... and beyond!

Frank Petriello

DIS 2015

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NORTHWESTERN UNIVERSITY

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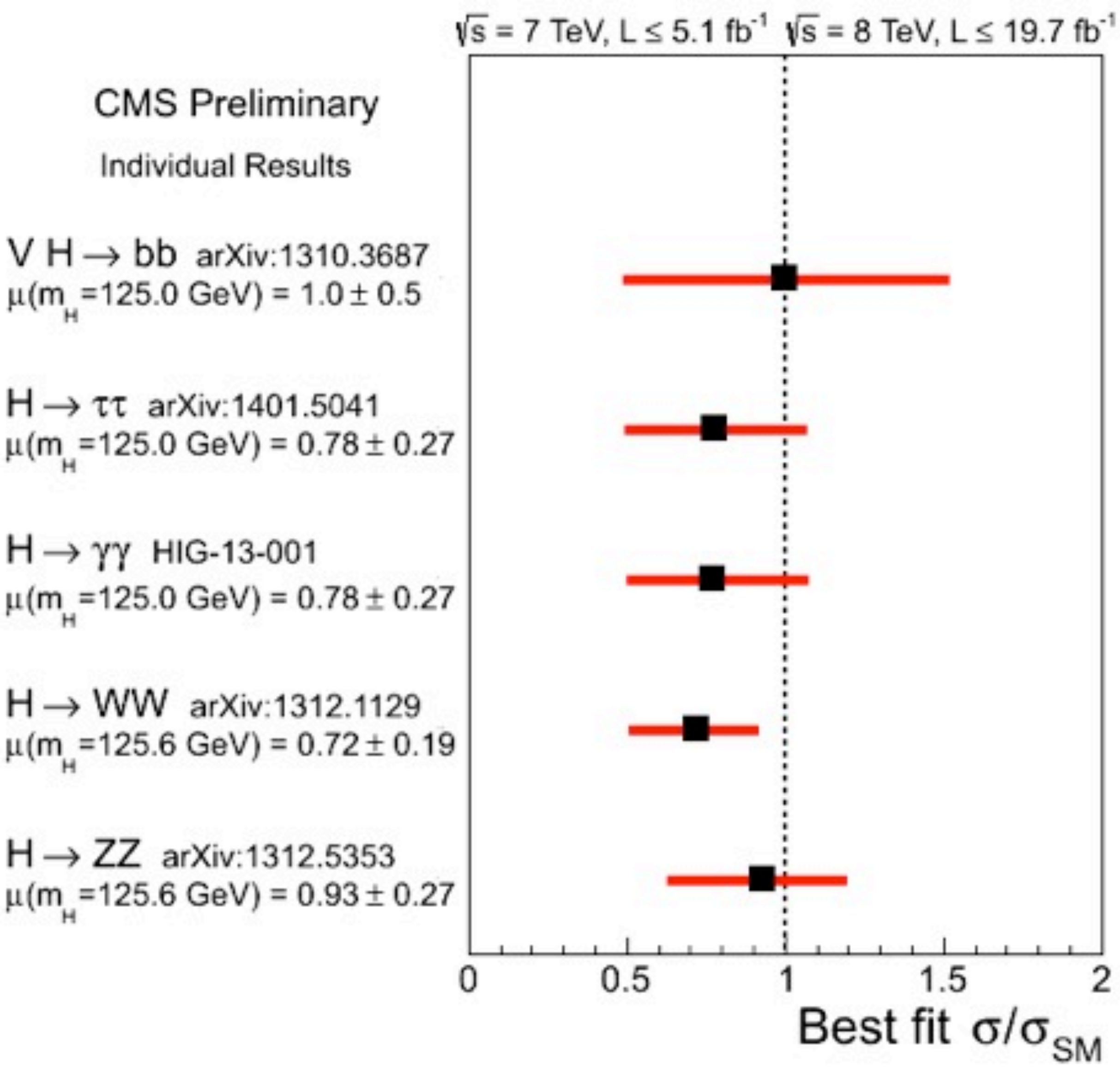
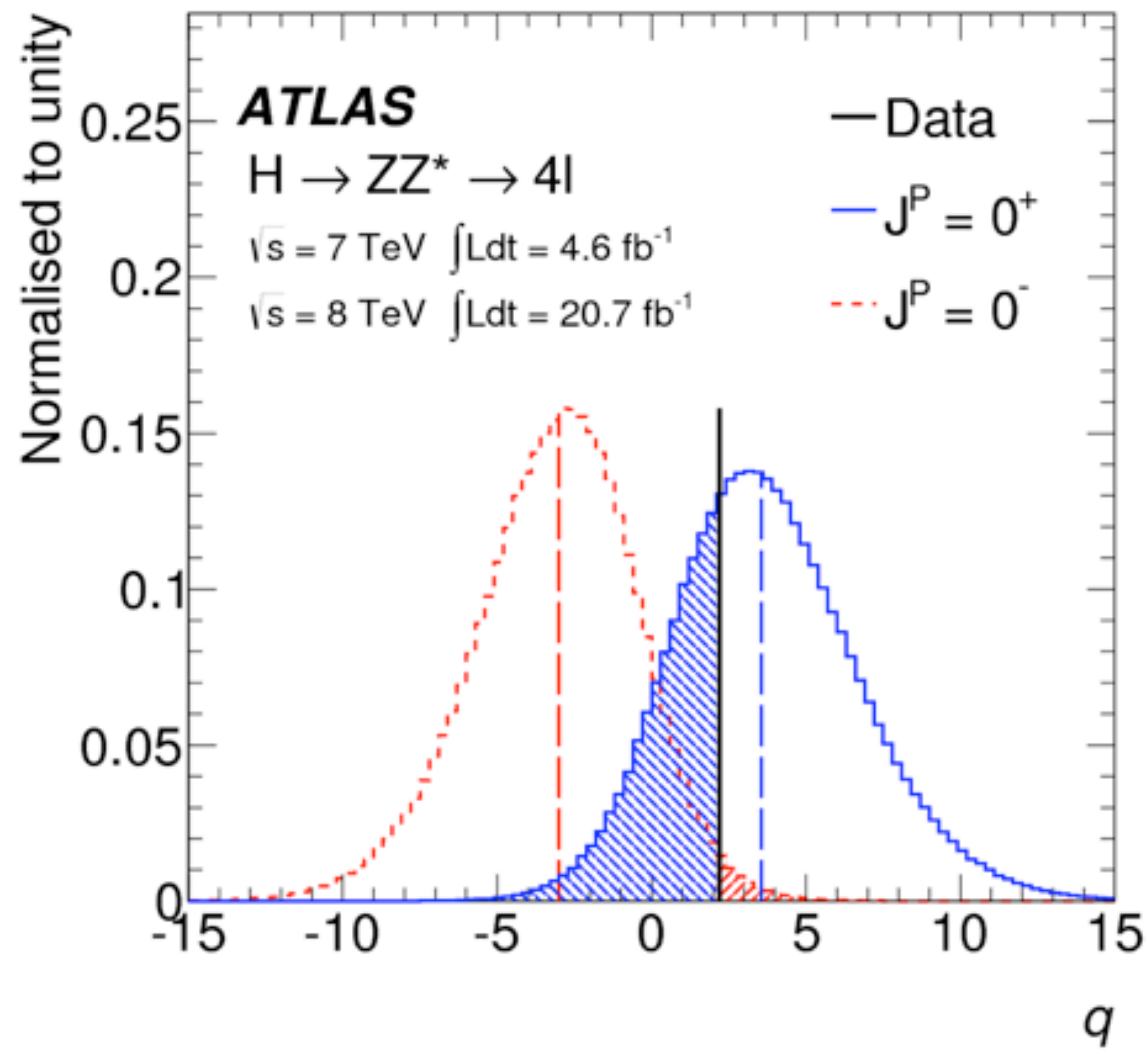
Outline

- Overview and the motivation for precision QCD
- QCD at NLO and W+many jets
- The role of NNLO QCD at the LHC
- Precision jet phenomenology
- Jet binning to all-orders and the Higgs
- The curious case of the Z+1-jet exclusive cross section

What have we learned from LHC Run I?

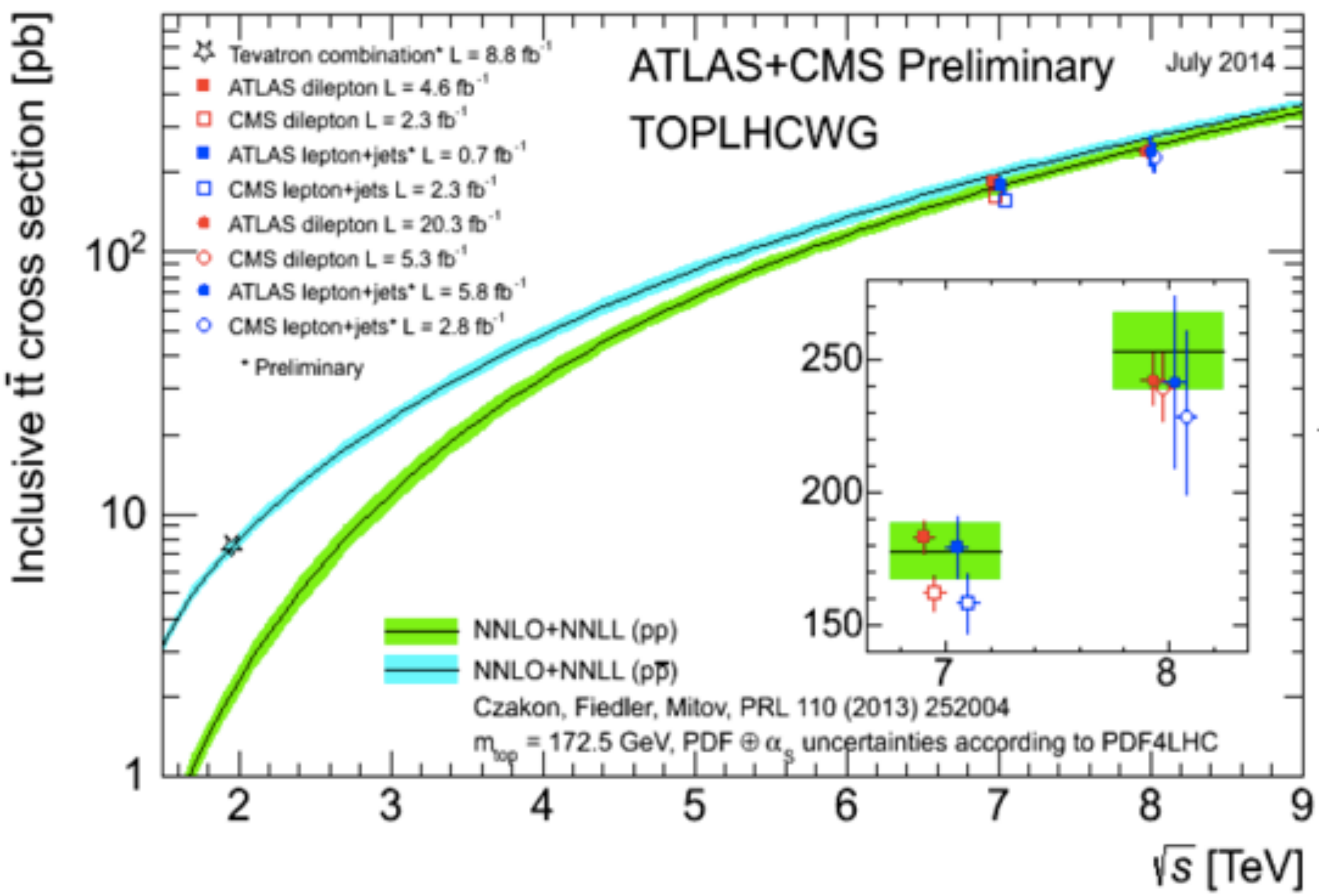
- We have a Higgs boson! It is a predominantly 0^+ state whose couplings agree roughly with SM predictions





What have we learned from LHC Run I?

- The ttbar cross section is known at NNLO (Czakon, Fiedler, Mitov 1303.6254) and is in good agreement with data; the error on the mass is below a GeV



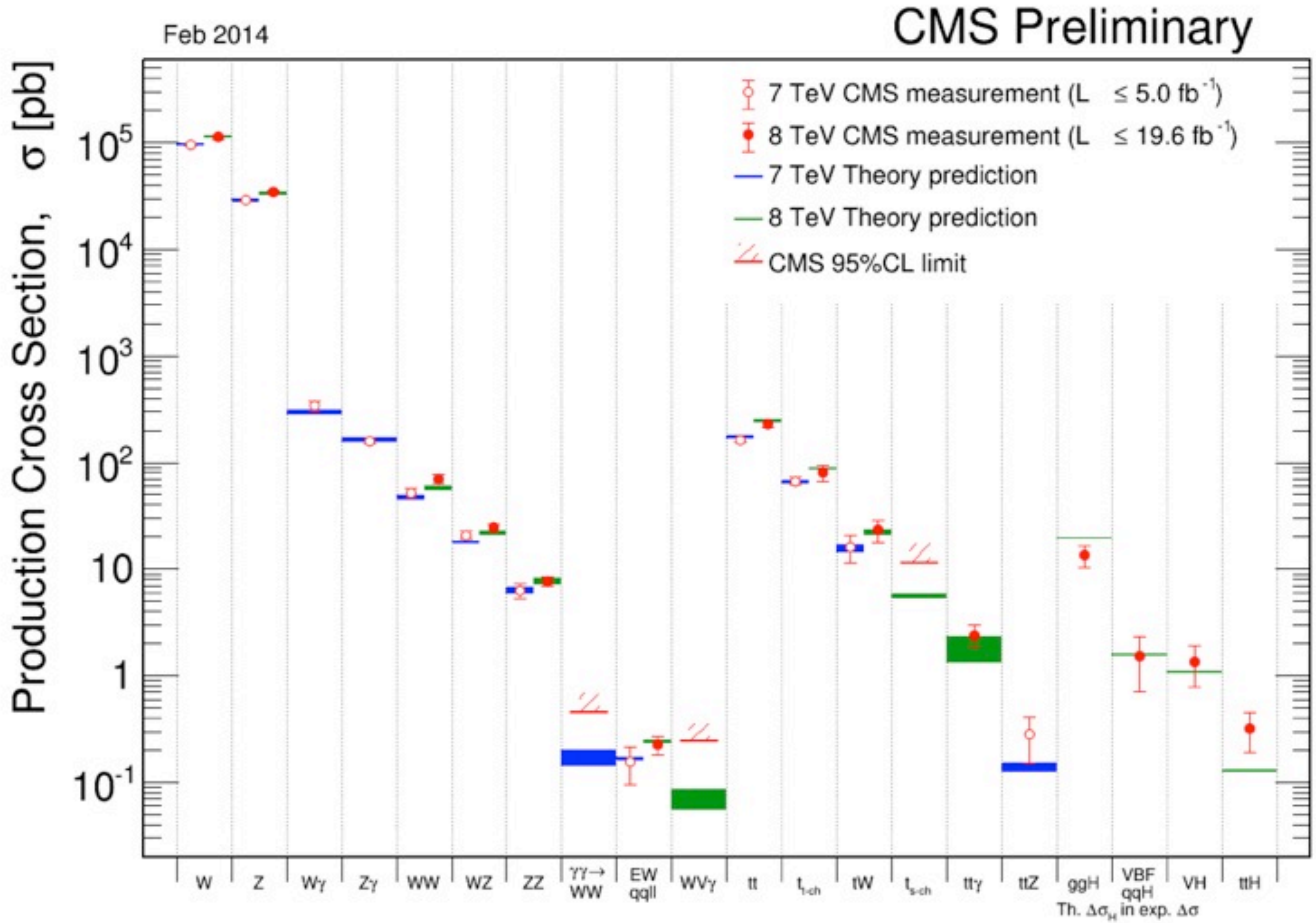
Precision	Tevatron D0	Tevatron CDF	LHC 8 TeV ATLAS	LHC 8 TeV CMS
total	7.8%	6.5%	4.3%	5.5%
stat	2.6%	4.0%	0.7%	0.8%
syst	4.3%	4.7%	2.3%	4.7%
lumi	6.1%	2.0%	3.1 %	2.6%

$$m_{top} = 173.34 \pm 0.27\ (\text{stat}) \pm 0.24\ (\text{iJES}) \pm 0.67\ (\text{syst})\ \text{GeV}$$

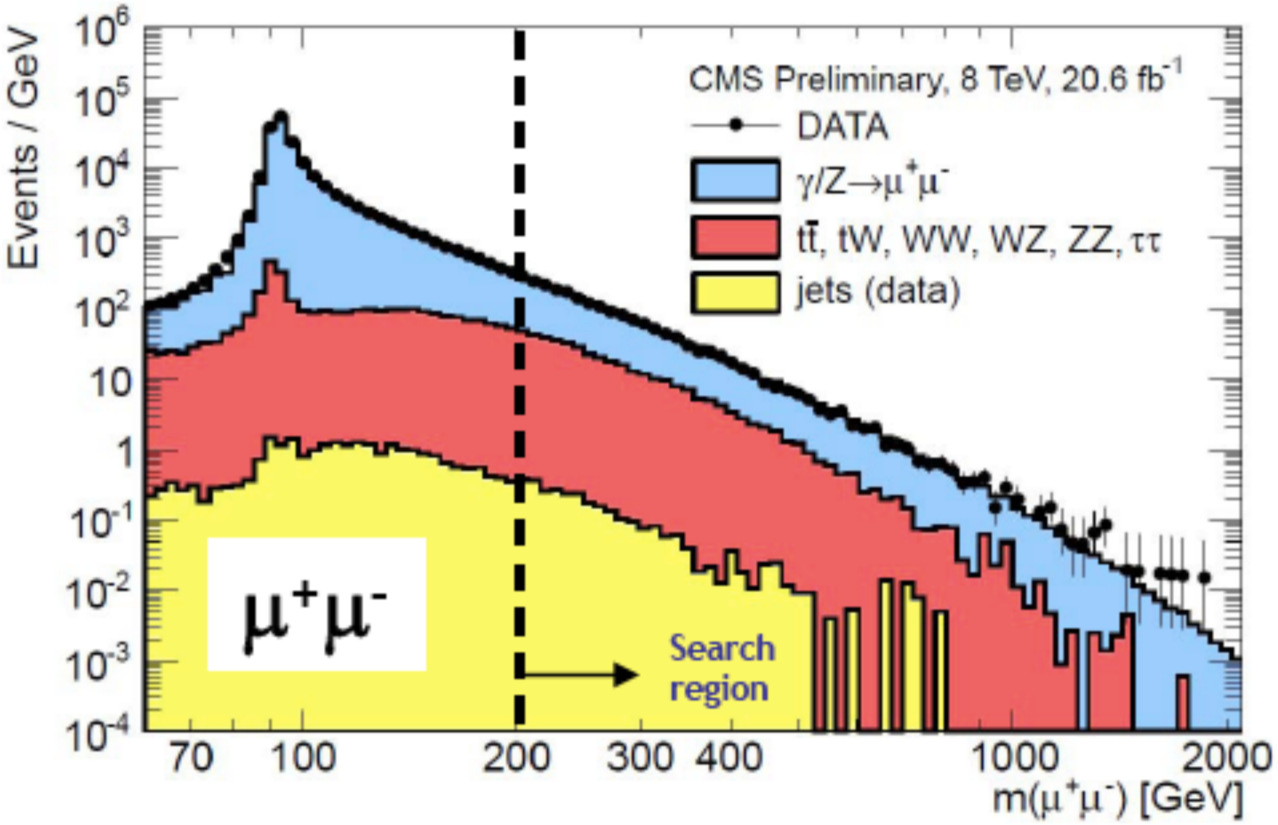
Combination from 1403.4427

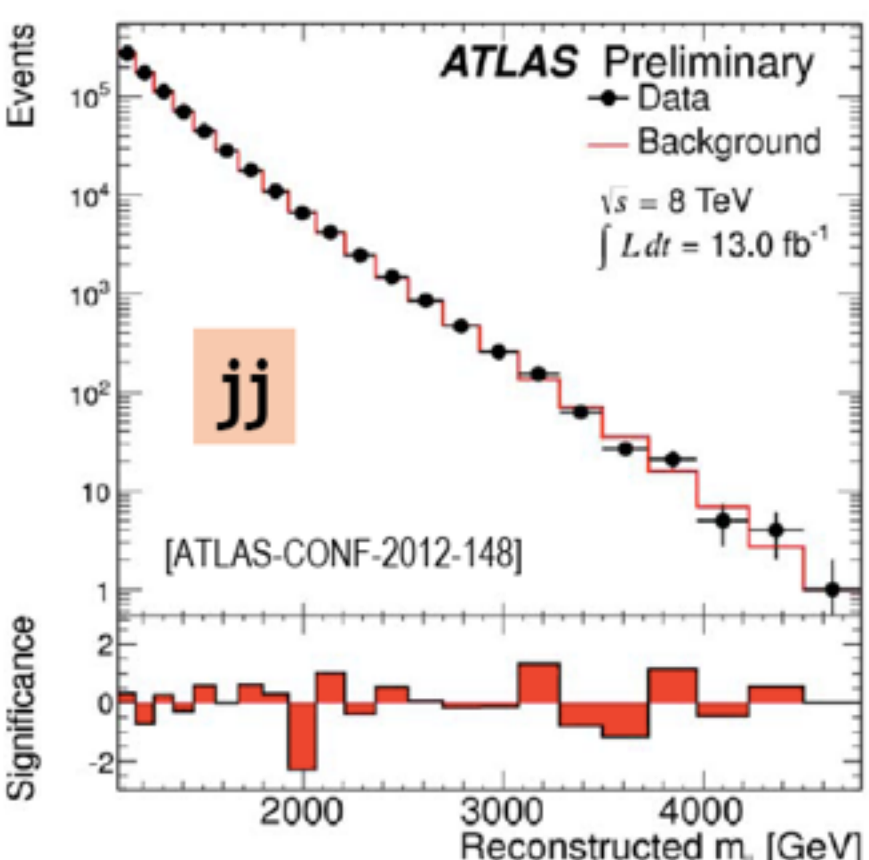
What have we learned from LHC Run I?

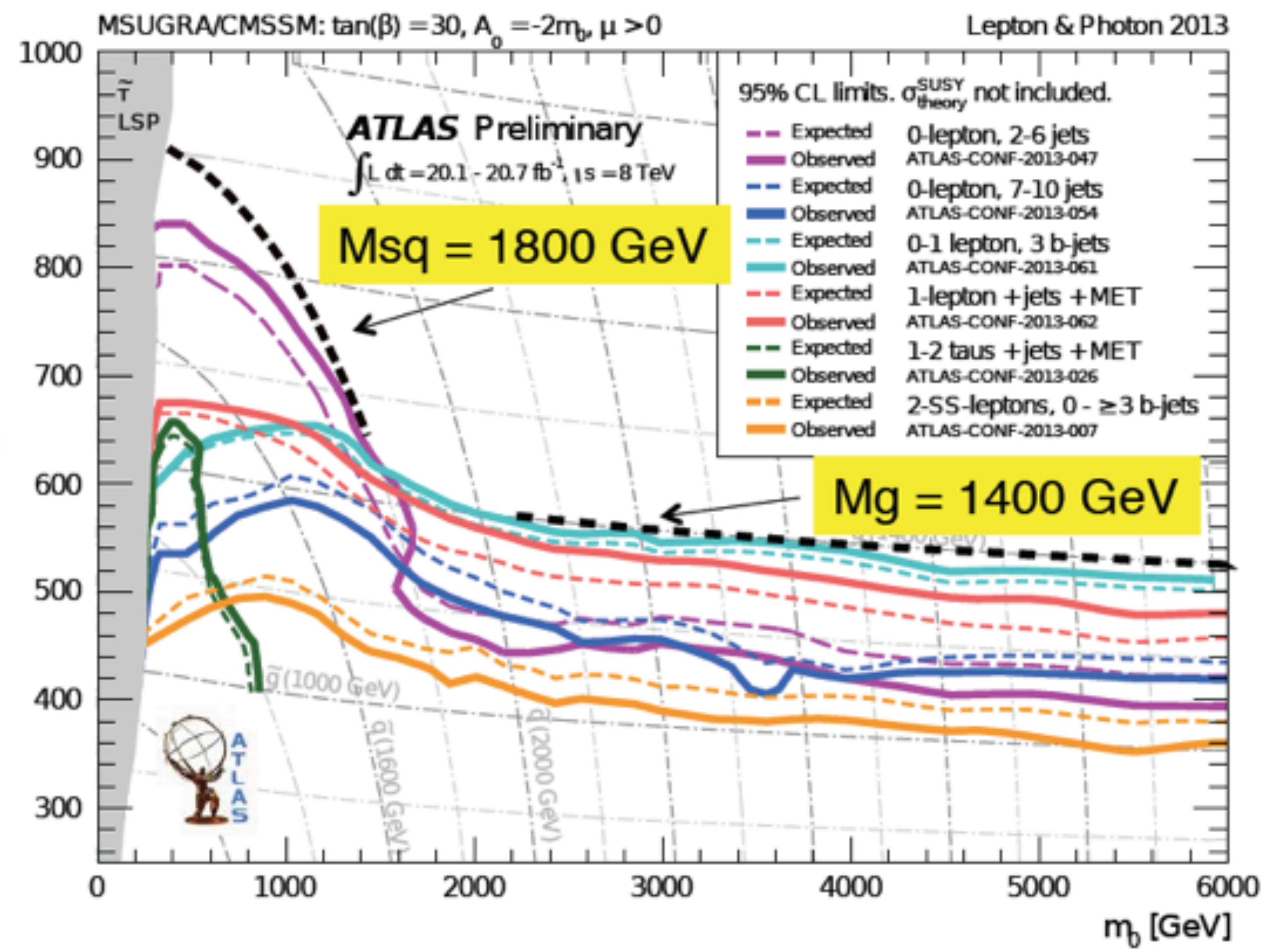
- EW gauge boson production cross sections spanning six orders of magnitude have been measured, and are in good agreement with theory



Global summary of high-p_T Run I results







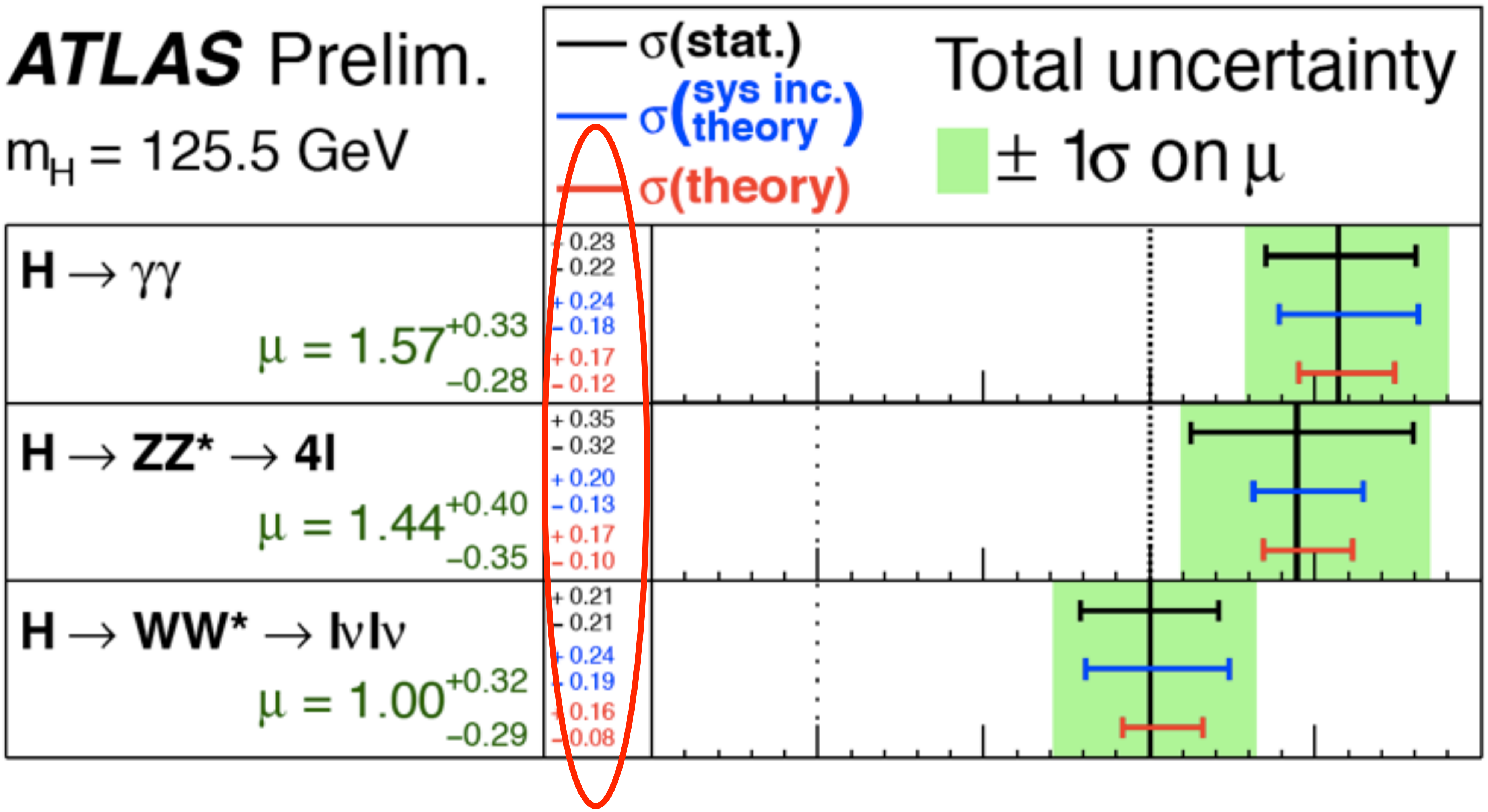
• Nothing found besides the Higgs; limits reaching multi-TeV in some channels

Everything we've measured so far is consistent with the following picture of fundamental physics at a few/tens of TeV

- There can be fascinating life hidden in a desert!
- We must be ready for the challenge if there is no obvious discovery at Run II
- There can be fascinating life hidden in a desert… but it can be rare and difficult to find

Precision physics may be the path to an oasis in the desert!

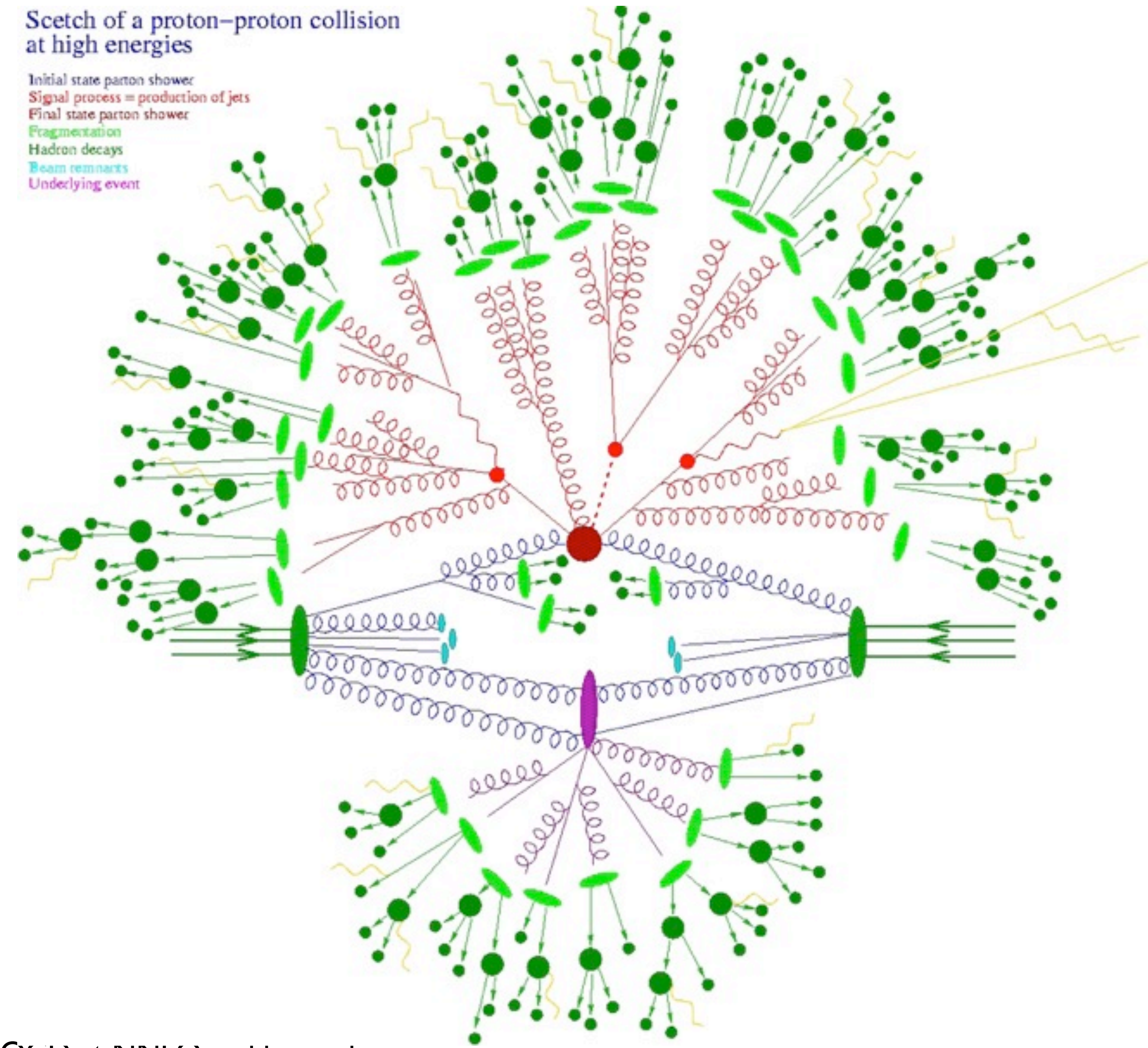
Precision and the Higgs



- The dominant component of the systematic error on the signal strength is theory.
- This will become a limiting factor in interpretation in Run II as statistical errors decrease.

Need better theory to sharpen our probes of BSM physics
in the Higgs sector!

QCD at the LHC



- Theory at hadron colliders is driven by our understanding of QCD
- How does theory allows us to peer into the inner "hard-scattering" in this mess?

Factorization: divide and conquer

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

Collins, Soper, Sterman (1988)

Factorization: divide and conquer

How do we get a quark/gluon from the proton?
Non-perturbative but *universal*; measure at HERA, Tevatron, etc. → Alberto Accardi's talk

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

Collins, Soper, Sterman (1988)

Calculate! $\sigma = \sigma^{(0)} + \frac{\alpha_s}{\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \sigma^{(2)}$

- Leading-order (LO)
- Next-to leading-order (NLO)
- Next-to-next-to leading-order (NNLO)
- +parton shower → Frank Siegert's talk

or even N^3LO for Higgs! → Stefano Forte's talk

Multi-jet QCD at NLO

QCD@NLO

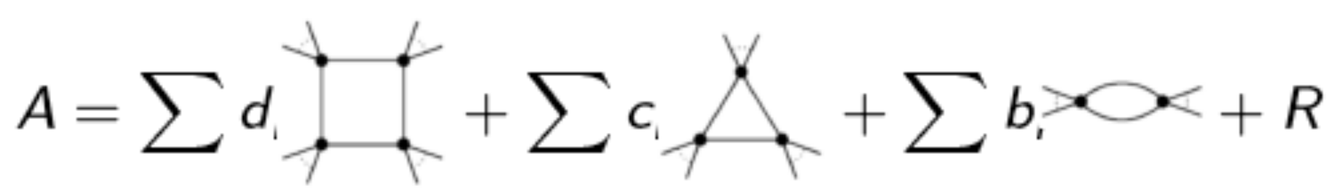
- Well-honed techniques for calculating and combining real+virtual at NLO

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

$$d\sigma_{NLO} = \int_{d\Phi_{m+1}} \left(d\sigma^R_{NLO} - d\sigma^S_{NLO}\right) + \left[\int_{d\Phi_{m+1}} d\sigma^S_{NLO} + \int_{d\Phi_m} d\sigma^V_{NLO}\right]$$

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

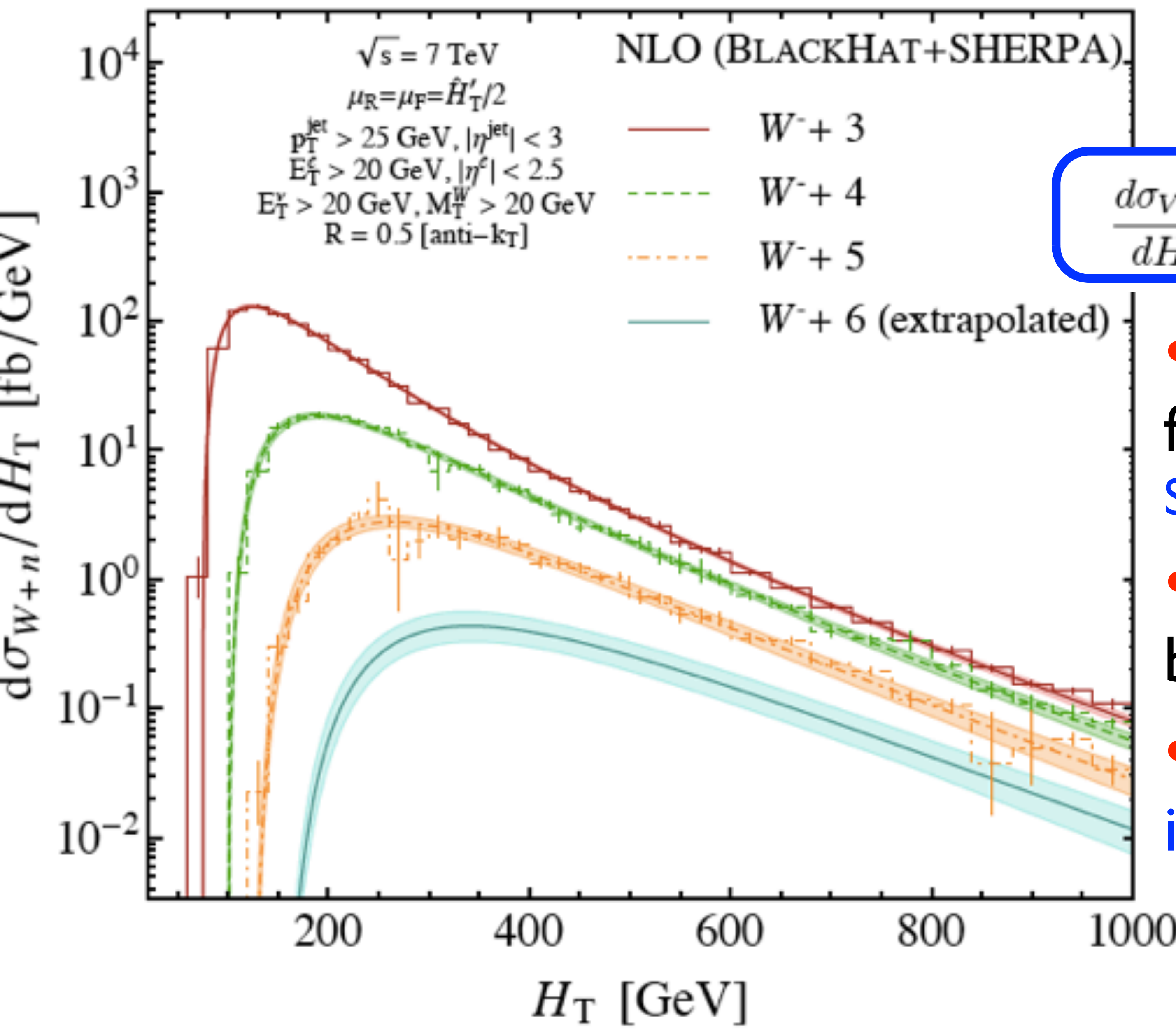
- Can use dipole subtraction (Catani, Seymour 1996); FKS subtraction (Frixione, Kunszt, Signer 1996)
- Implemented in several dedicated codes Autodipole, Helac, MadDipole, MadFKS, Sherpa, TeVJet
- Virtual corrections obtained as coefficients times 1-loop scalar integrals



- 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

Recent NLO phenomenology

- W+2 through 5 jets known to NLO (higher-multiplicity process via BLACKHAT +SHERPA). Can these be used to predict even higher multiplicities?



$$\frac{d\sigma_{V+n}}{dH_T} = (2a_s(H_T/2))^n f^H(H_T) N_n^H \ln^{\tau_n^H} \rho_{H,n} (1 - H_T/H_T^{\max})^{\gamma_n^H}$$

- Such universal behavior can be atgued formally for some observables Gerwick, Schichtel 1412.1806
- Validate fit methodology on n=2-5 before extrapolation to six jets
- Will help control backgrounds to BSM in multi-jet final states

Bern, Dixon, Febres Cordero, Hoeche, Kosower, Ita, Maitre 1412.4775

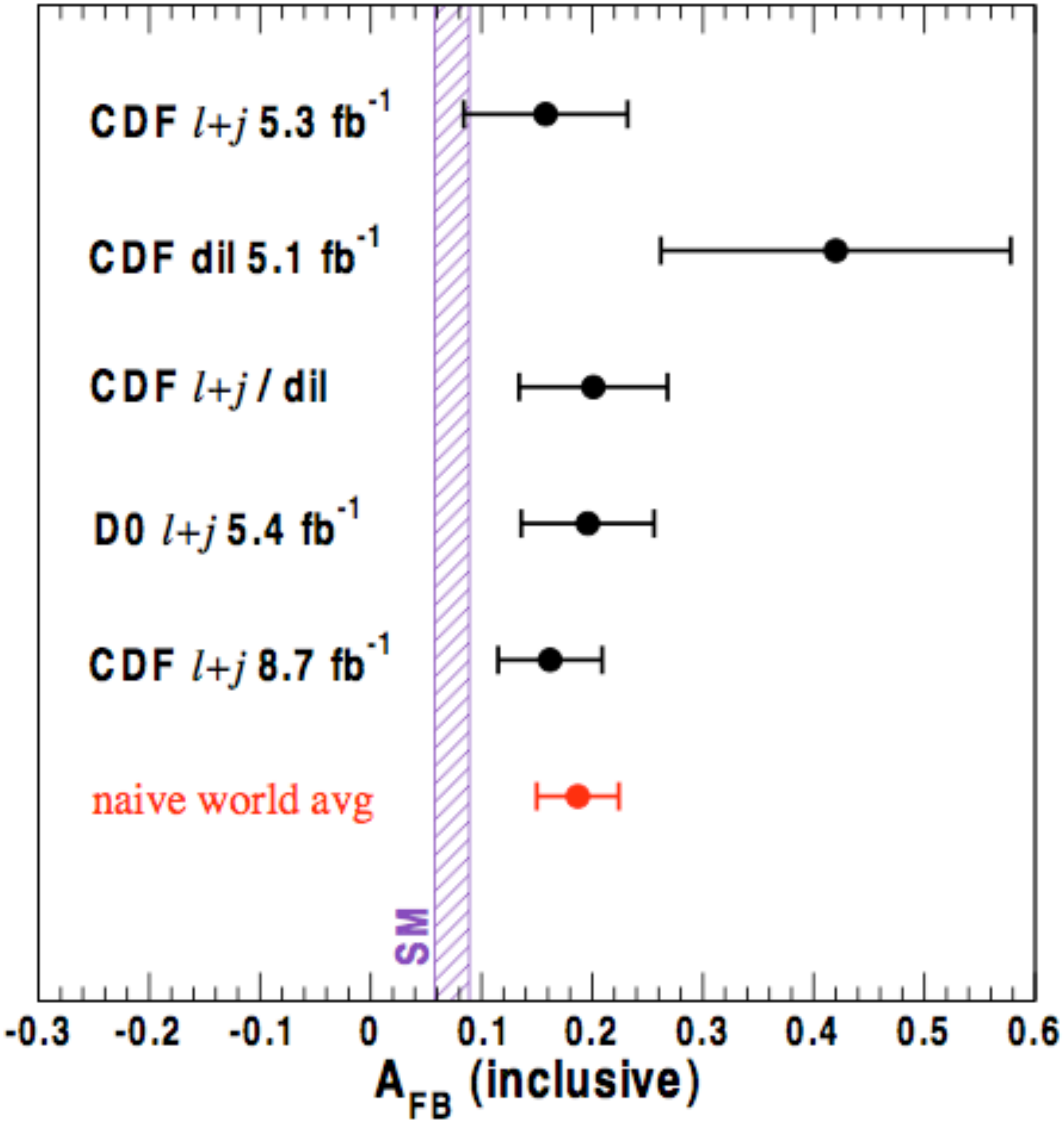
NNLO QCD at hadron colliders

- From Merriam-Webster:

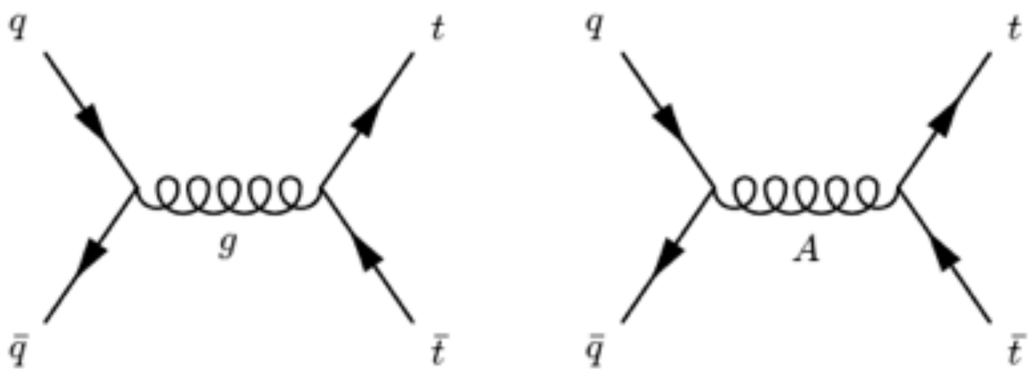
> **spoil·sport** *noun* \'spȯi(-ə)l-ˌspȯrt\
>
> : someone who spoils other people's fun or enjoyment

The ttbar asymmetry

- For several years the forward-backward asymmetry of top quarks measured at the Tevatron has differed from SM predictions



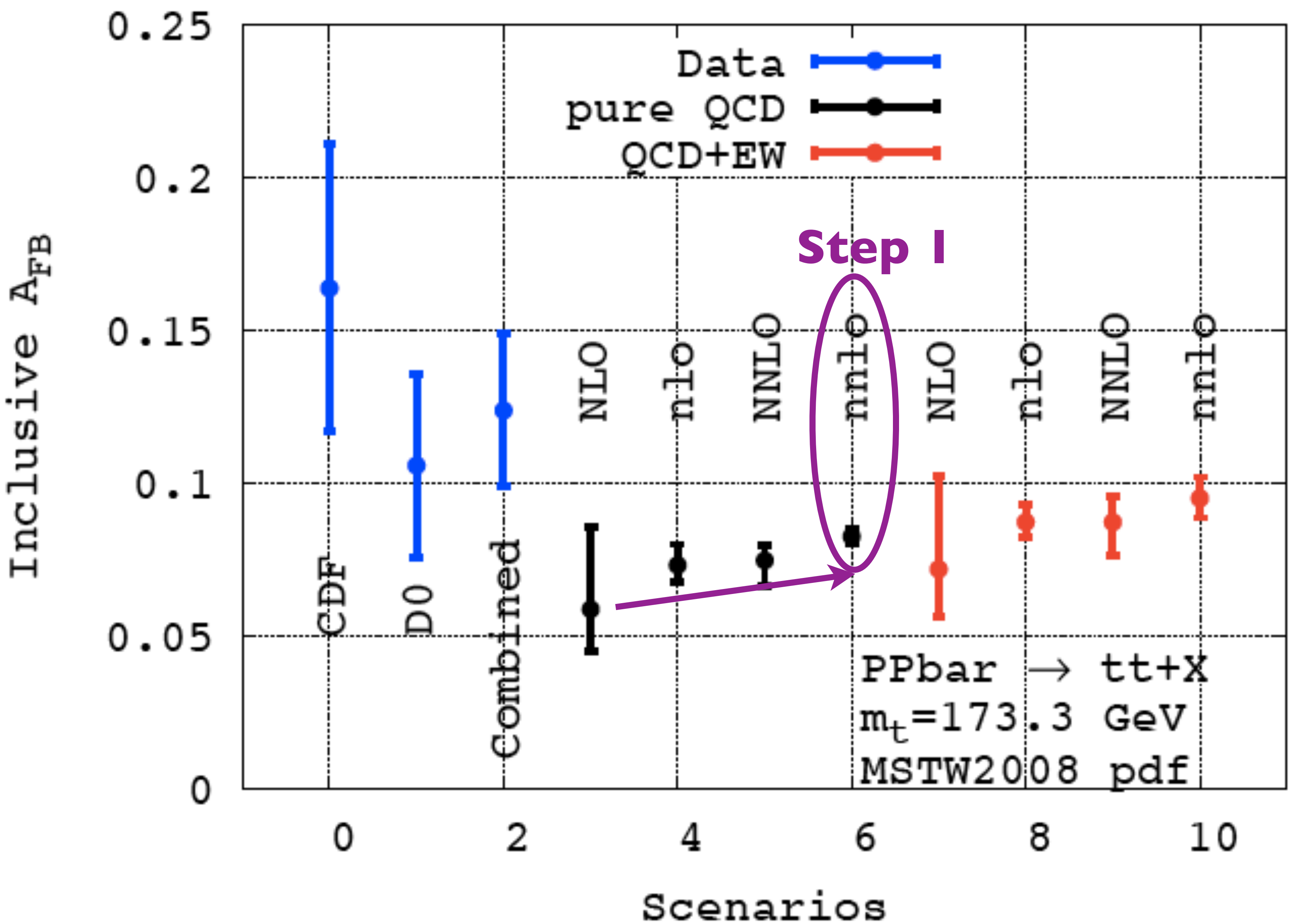
Could it be a light axigluon?



(many authors)

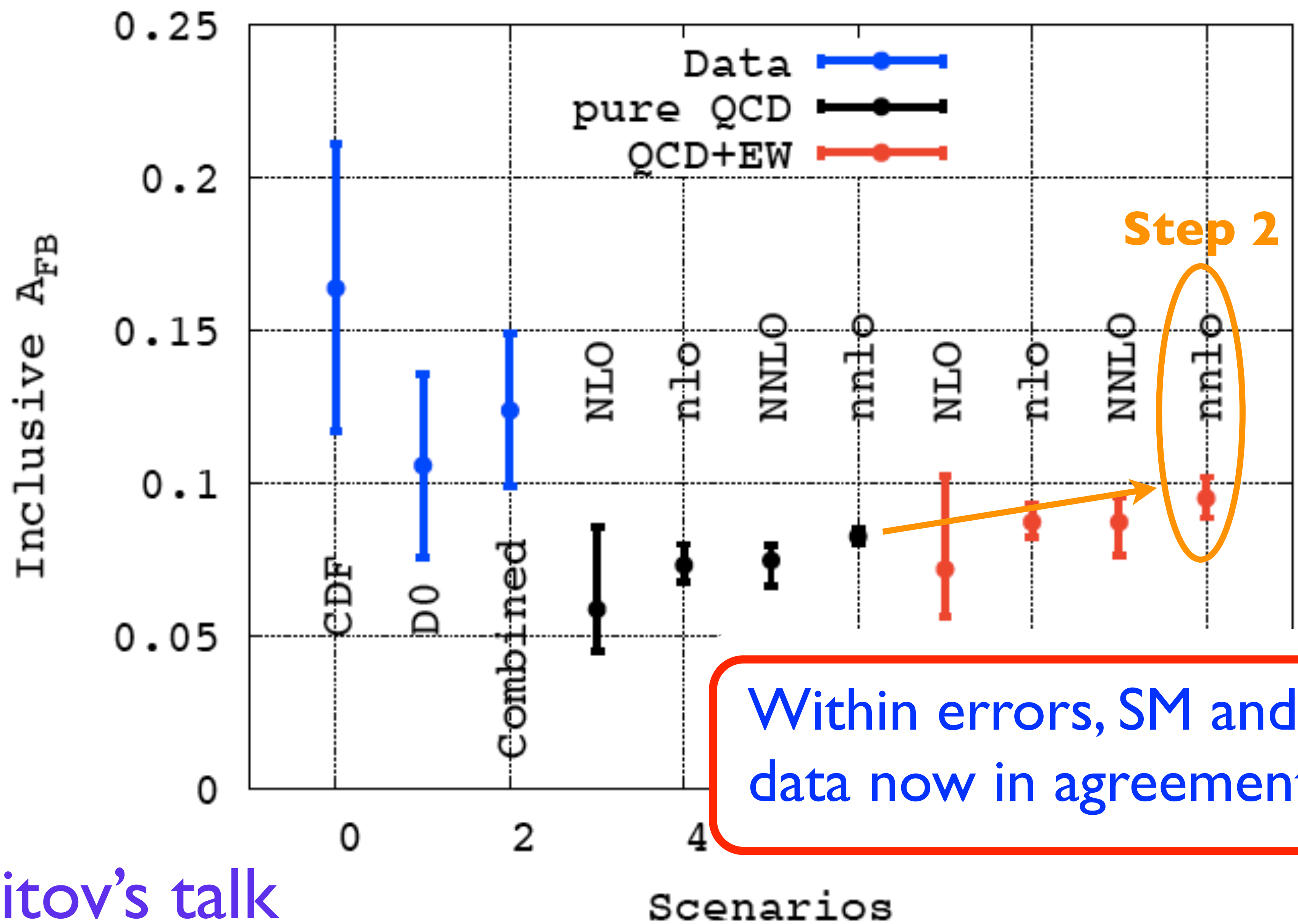
The ttbar asymmetry now

- Large NNLO QCD corrections! Not predicted by soft-gluon resummation, required a genuine NNLO prediction (Czakon, Fiedler, Mitov 1411.3007)



The ttbar asymmetry now

- Large electroweak corrections! QED generates an asymmetry via the same mechanism as QCD (Hollik, Pagani 1107.2606; Kuhn, Rodrigo 1109.6830)

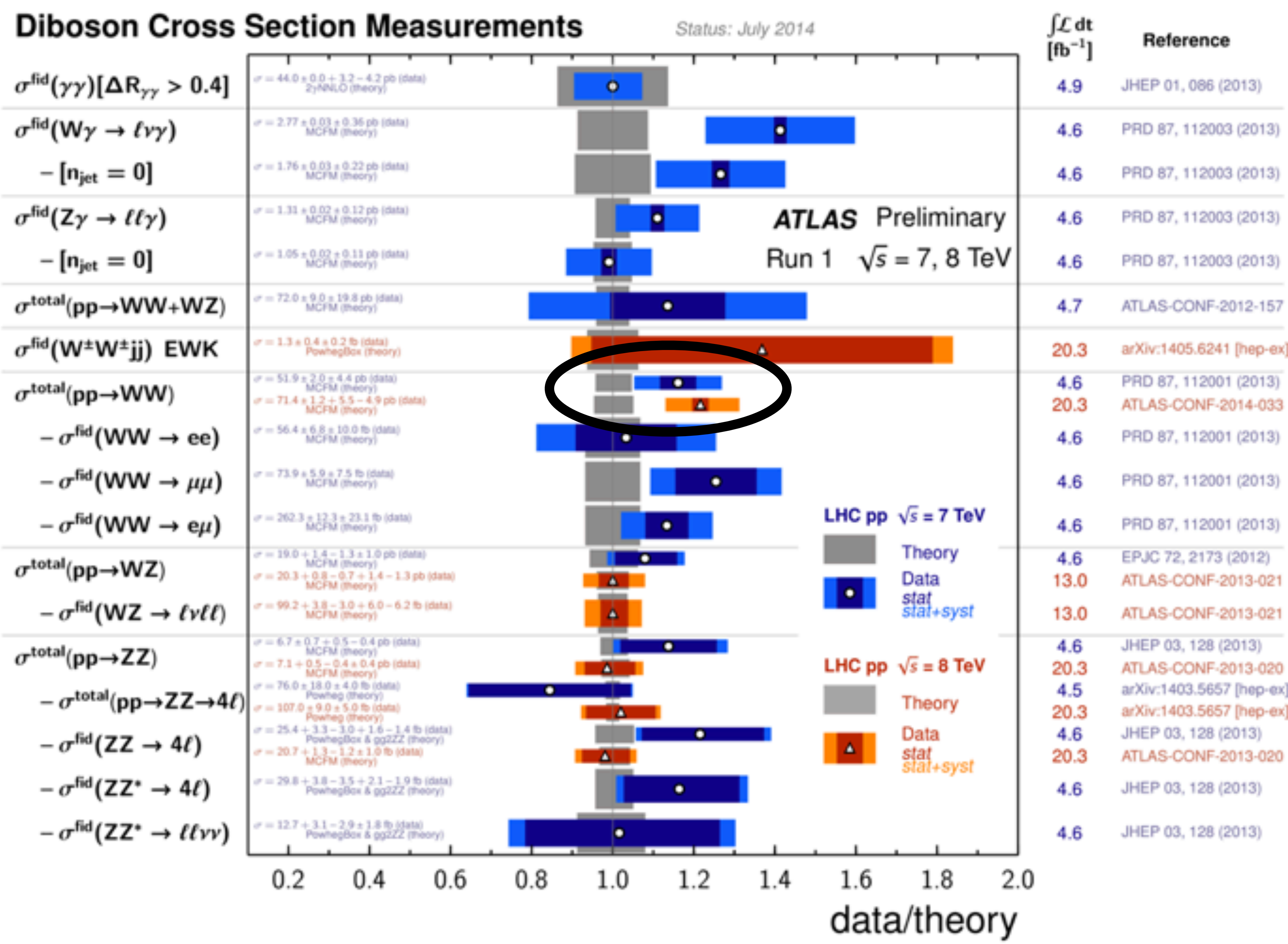


Within errors, SM and data now in agreement

see Alex Mitov's talk

The WW cross section

- Disagreement between the measured WW cross section and NLO theory seen by both ATLAS and CMS, at both 7 and 8 TeV

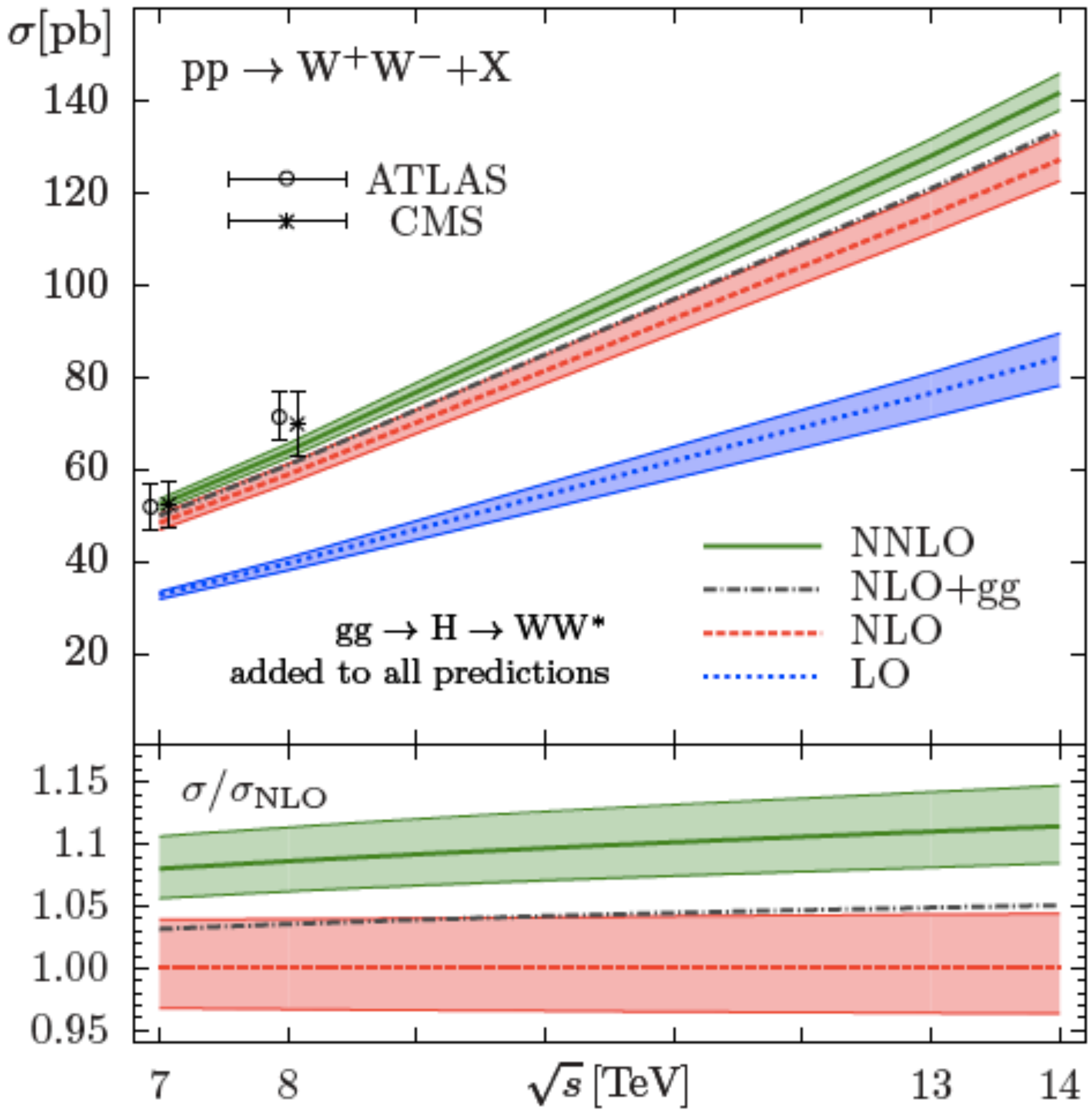


Could it be light charginos?

(Curtin, Jaiswal, Meade 1206.6888, and others)

The WW cross section now

- Sizable NNLO QCD corrections! Theory within 1σ agreement of ATLAS and CMS for both CM energies Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi 1408.5243

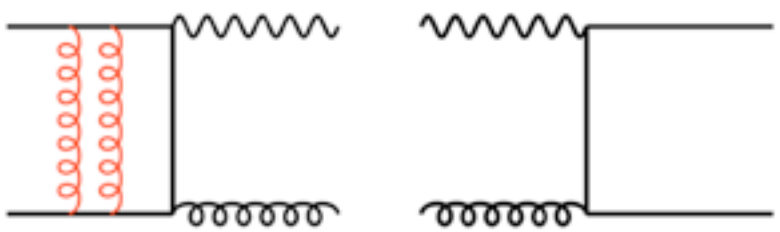


- Enhancement of theory is expected when the extrapolation from the fiducial region is properly modeled, further improving agreement

Monni, Zanderighi 1410.4745 (see also Jaiswal, Okui, 1407.4537; Curtin, Meade, Tien 1406.0848)

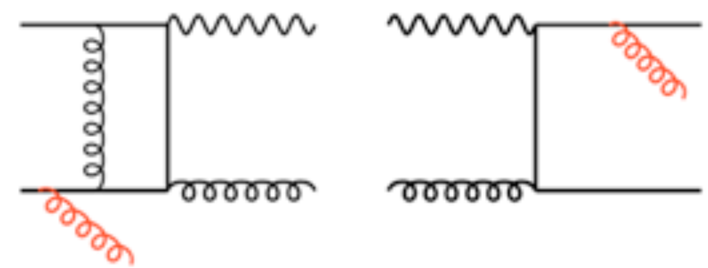
Ingredients at NNLO

2-loop matrix elements, m partons



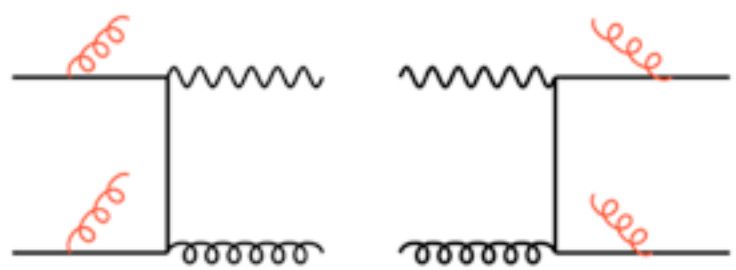
- Explicit IR poles from loop integrals

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

The next frontier: NNLO for light jets

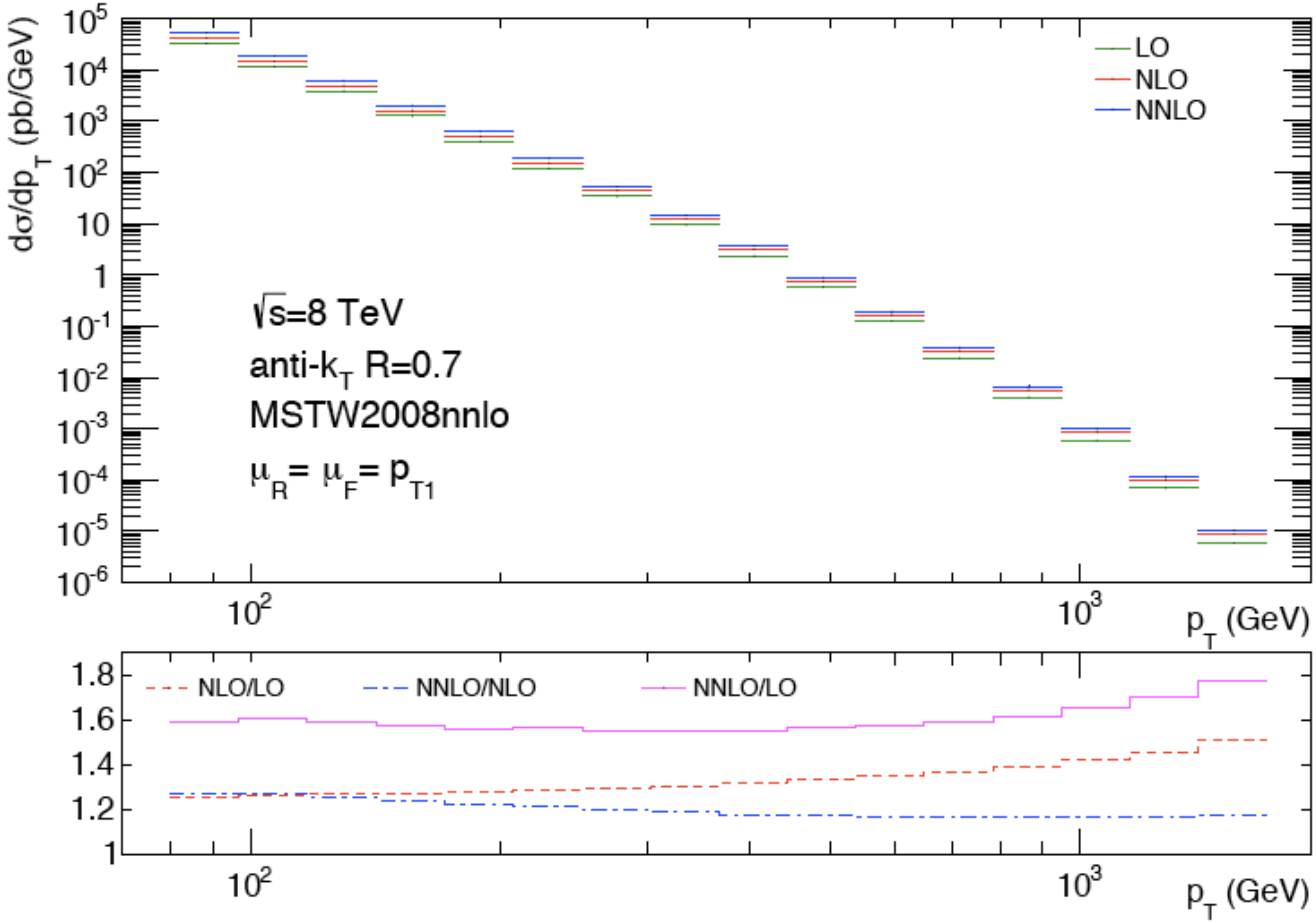
- Until recently, only colorless initial states or colorless (or massive, such as ttbar) final states were known at the differential level to NNLO using available techniques
  - Sector decomposition: Anastasiou, Melnikov, FP
  - q_T-subtraction: Catani, Grazzini

- Three methods have been extended to allow for NNLO corrections to jets at hadron colliders:
  - Antennae subtraction: Gehrmann, Gehrmann-deRidder, Glover
  - Sector-improved subtraction: Czakon; Boughezal, Melnikov, FP
  - Jettiness subtraction: Boughezal, Focke, Liu, FP

- The past couple of years have seen the emergence of NNLO jet phenomenology, in time for Run II!

Inclusive jets at NNLO

- Important for high-x gluon; uses antennae subtraction, initial gluons only

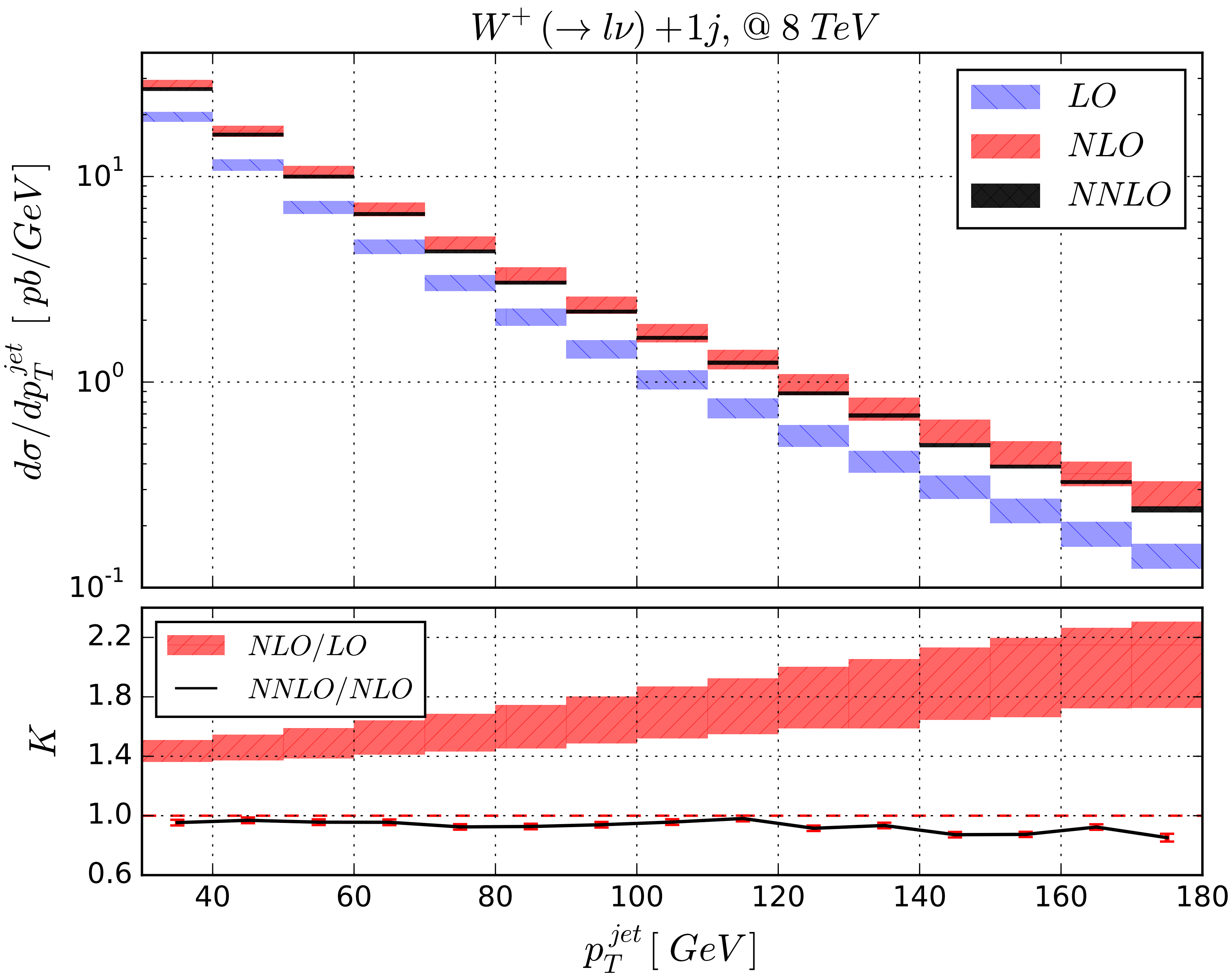


- 20% corrections beyond NLO, flat as a function of p_T
- Needed to control backgrounds to high-mass searches in Run II

Currie, Gehrmann-De Ridder, Glover, Pires 1310.3993

W+jet at NNLO

- Jettiness subtraction: resummation of jettiness allows a NNLO subtraction scheme to be constructed, similar to q_T-subtraction for colorless final states



$$\mathcal{T}_N = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i} \right\}$$

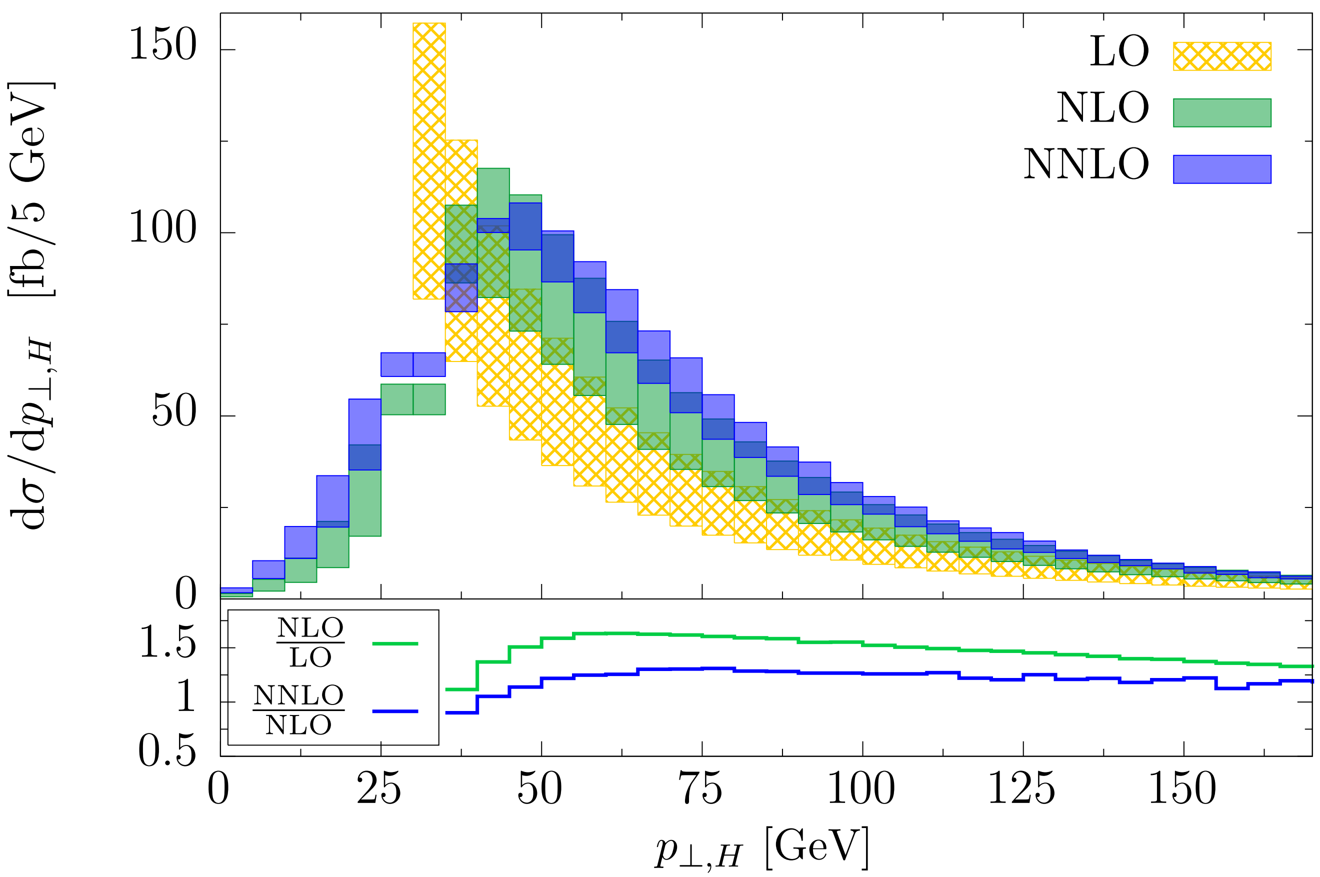
$$\sigma(\mathcal{T}_N < \mathcal{T}_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n \right].$$

- Corrections of 2% which decrease NLO, flat with $p_{T,jet}$
- Ready for precision phenomenology in Run II!

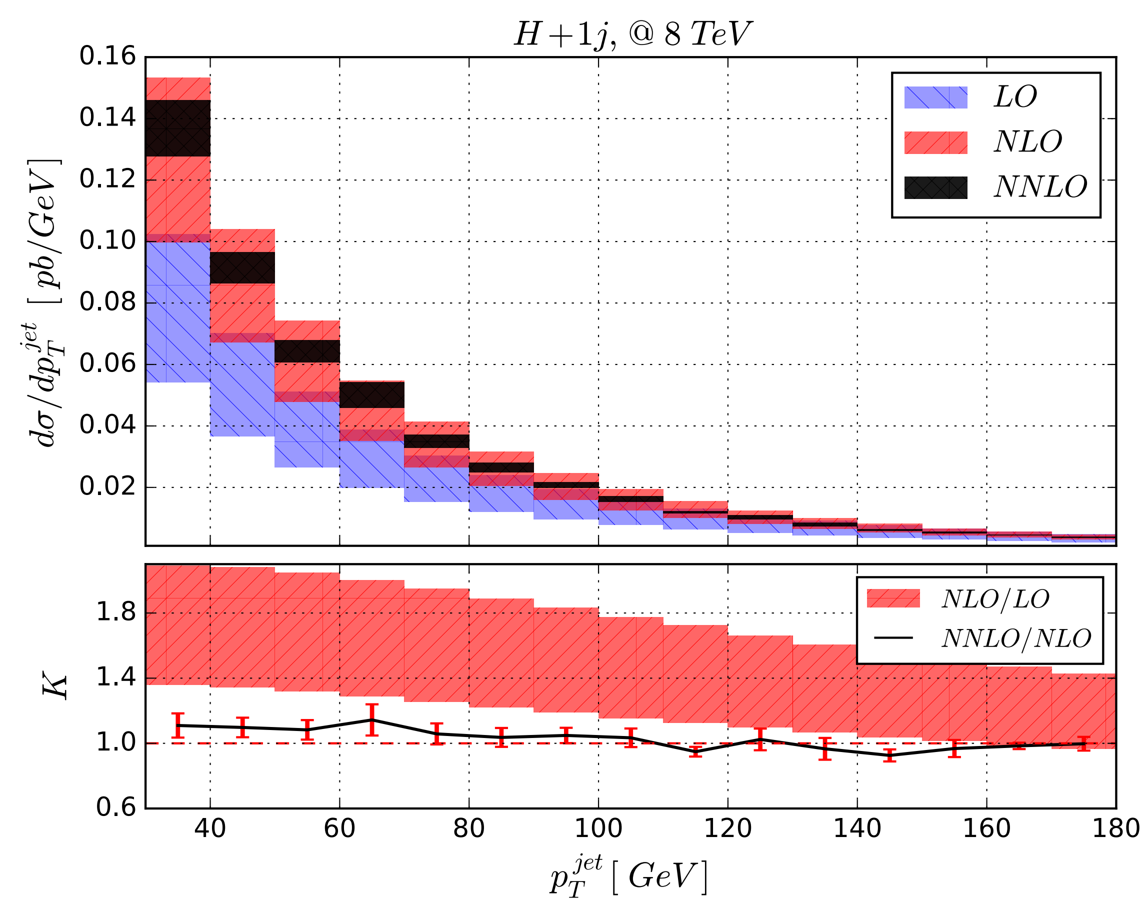
Boughezal, Focke, Liu, FP 1504.02131

H+jet at NNLO

- Needed for a description of Higgs p_T distribution; can help discriminate between BSM effects (Banfi, Martin, Sanz 1308.4771; Azatov, Paul 1309.5273)
- Calculations based on sector-improved subtraction (Boughezal, Caola, Melnikov, FP, Schulze) and jettiness subtraction (Boughezal, Focke, Liu, FP); gluons-only results with antennae subtraction (Chen, Gehrmann, Glover, Jaquier)



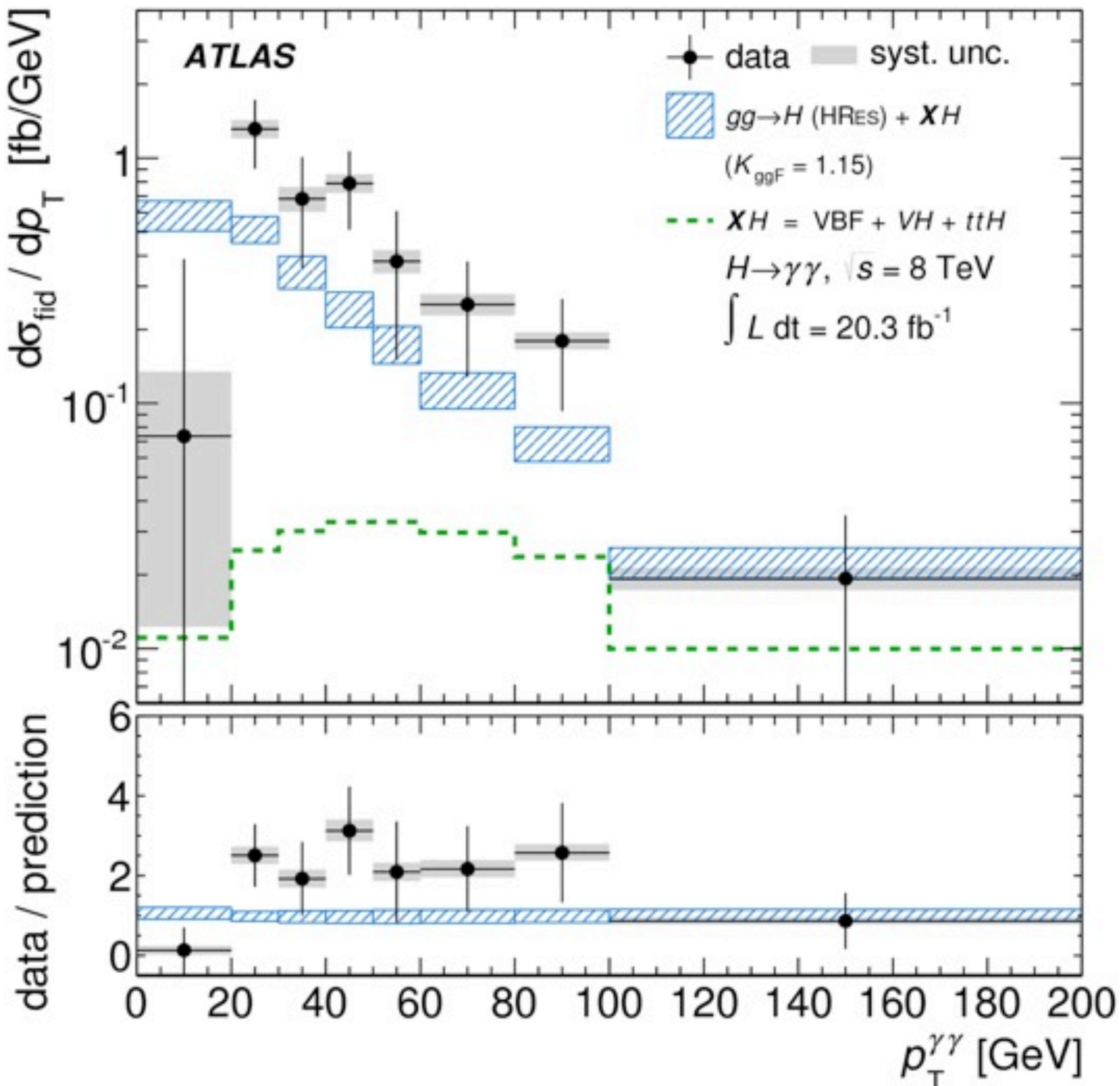
Boughezal, Caola, Melnikov, FP, Schulze, 1302.6216 and to appear



Boughezal, Focke, Liu FP, to appear

H+jet at NNLO

- Needed for a description of Higgs p_T distribution; can help discriminate between BSM effects (Banfi, Martin, Sanz 1308.4771; Azatov, Paul 1309.5273)

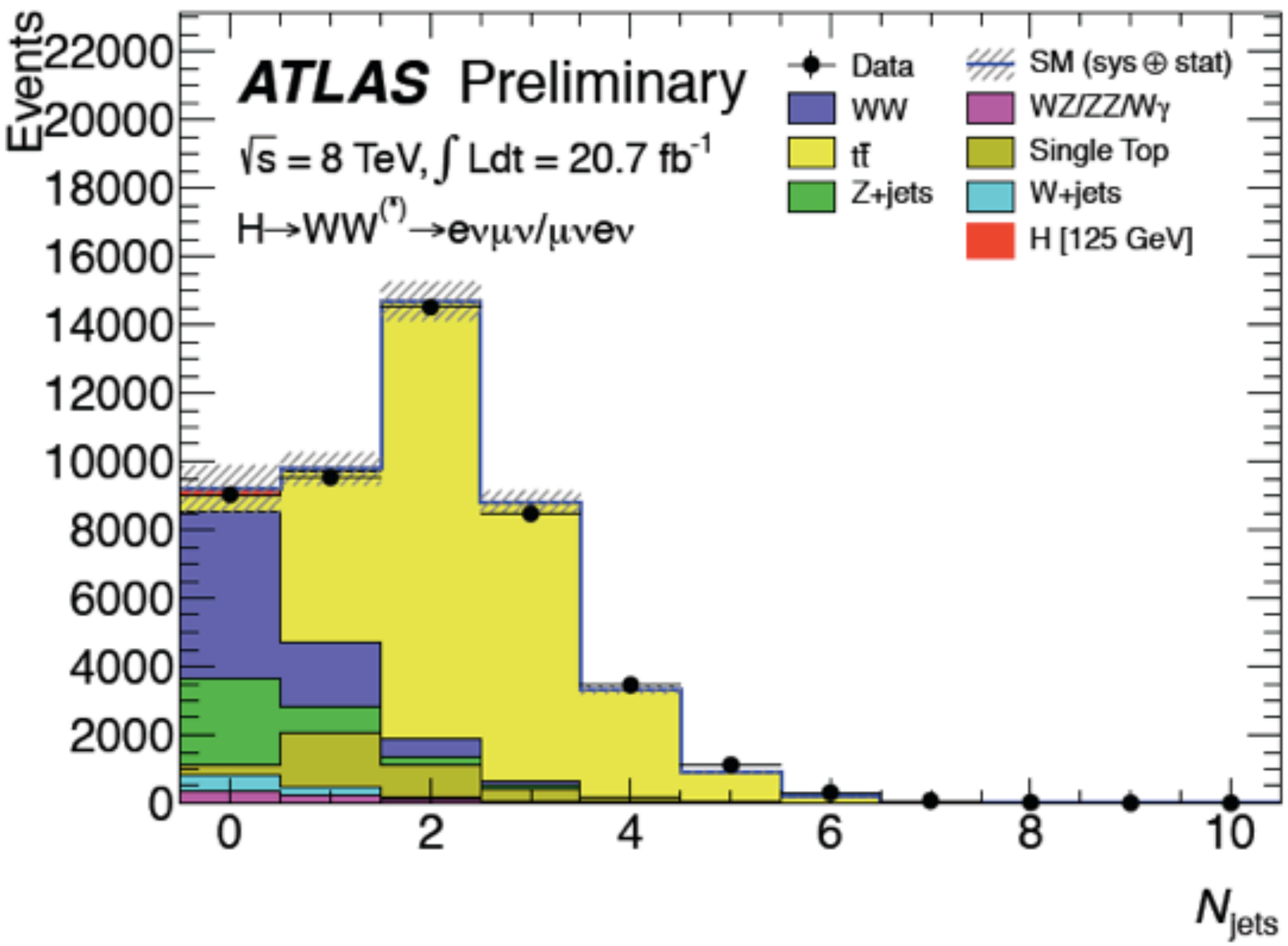


- Waiting for the next measurements from Run II!

Jet binning and all-orders resummation

Jet binning

- No mass peak in WW; theory especially crucial for search and interpretation
- A major issue in this channel is the division into exclusive jet bins

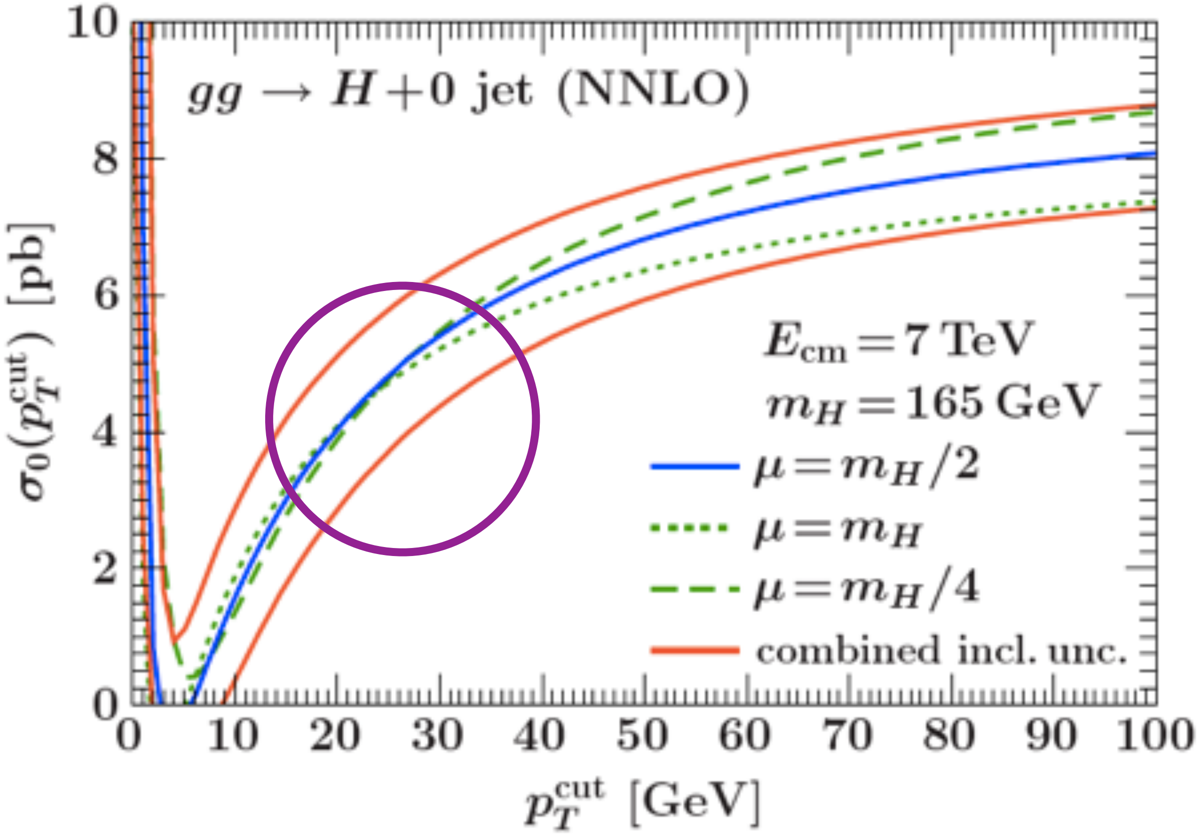


- Required by background composition
- Large logs from soft/collinear radiation
- Typical parameters: $p_{T,veto}$~25-30 GeV$\ll M_H$
- Relevant term for gluon-fusion Higgs: $2C_A(\alpha_S/\pi)\ln^2(M_H/p_{T,veto})$~1/2

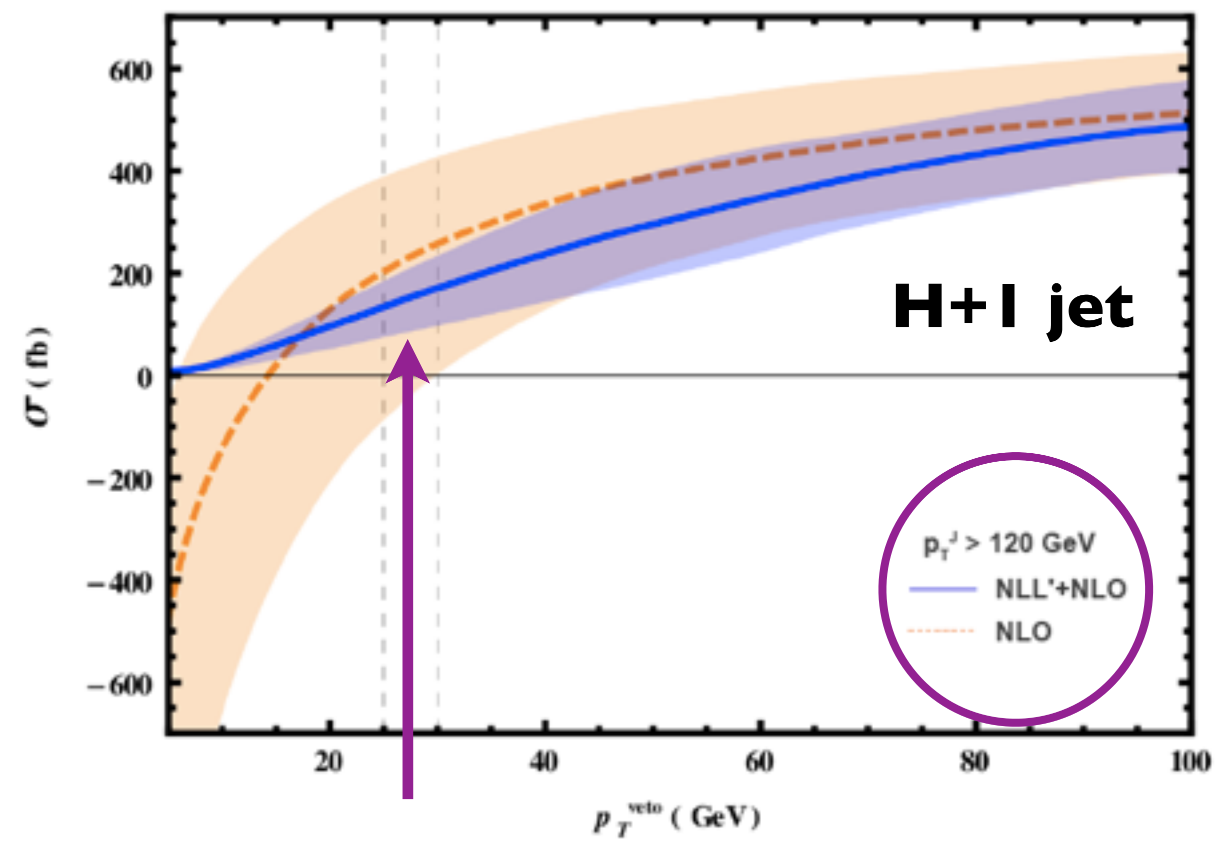
Effects of the jet binning

- These large logarithms induce several problems in the theory predictions

Stewart, Tackmann 1107.2117



Liu, FP 1303.4405



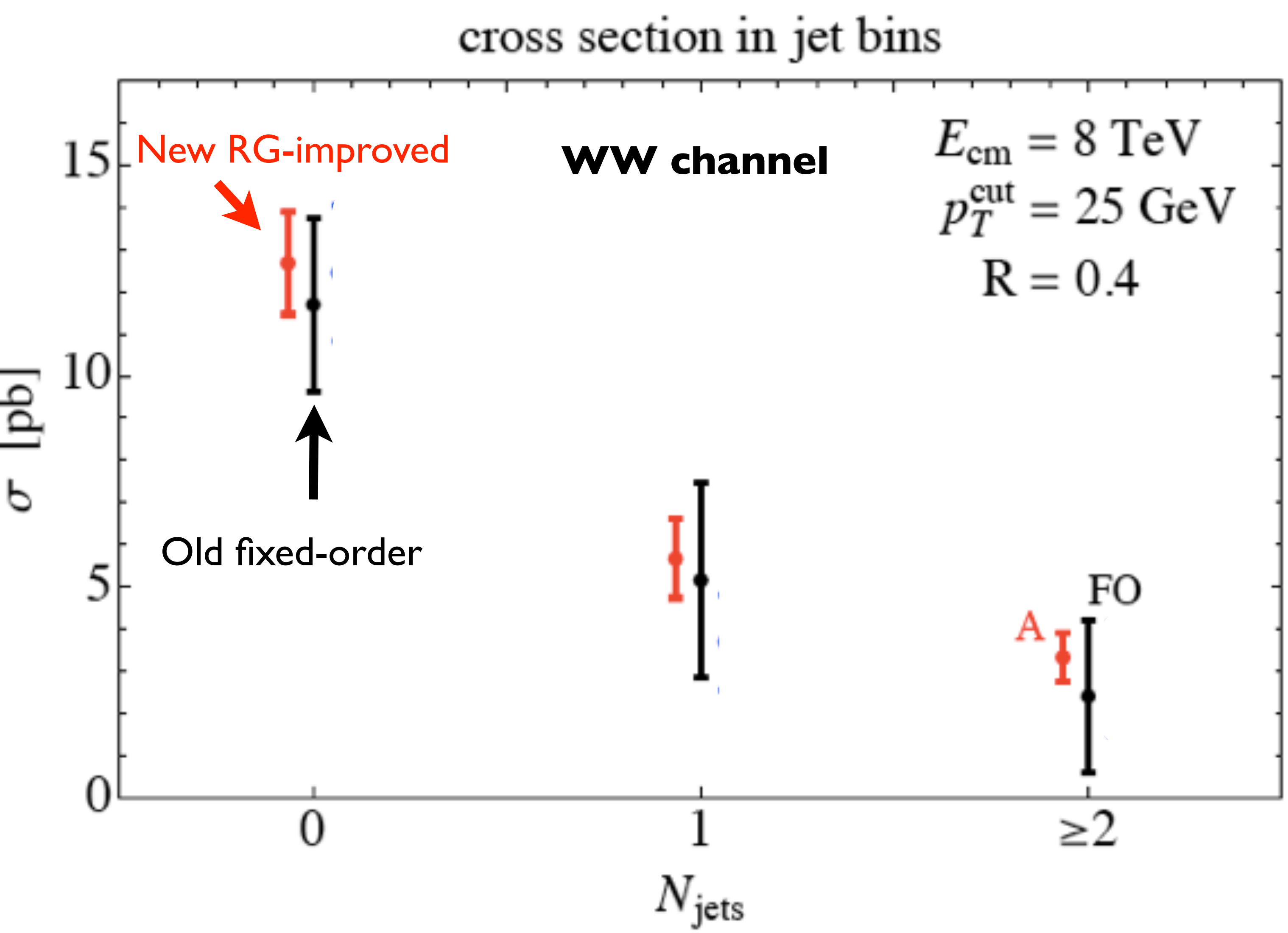
- Scale variation no longer estimates theory uncertainties (green band); use the ST prescription to get the much larger red band

- Deviations from fixed-order, especially in new kinematic regions that will be first probed in Run II

Very active area! Banfi, Monni, Salam, Zanderighi; Becher, Neubert; Liu, FP; Stewart, Tackmann, Walsh, Zuberi; Li, Liu

Numerical results for the LHC

•The goal: completely replace fixed-order perturbation theory with renormalization-group improvement that resums the large jet-veto logs



Boughezal, Liu, Petriello, Tackmann, Walsh 1312.4535

•Can accomplish this using SCET framework for all jet bins

•Improved signal-strength error:

$$(\Delta\mu/\mu)_{FO} = 13.3\%$$

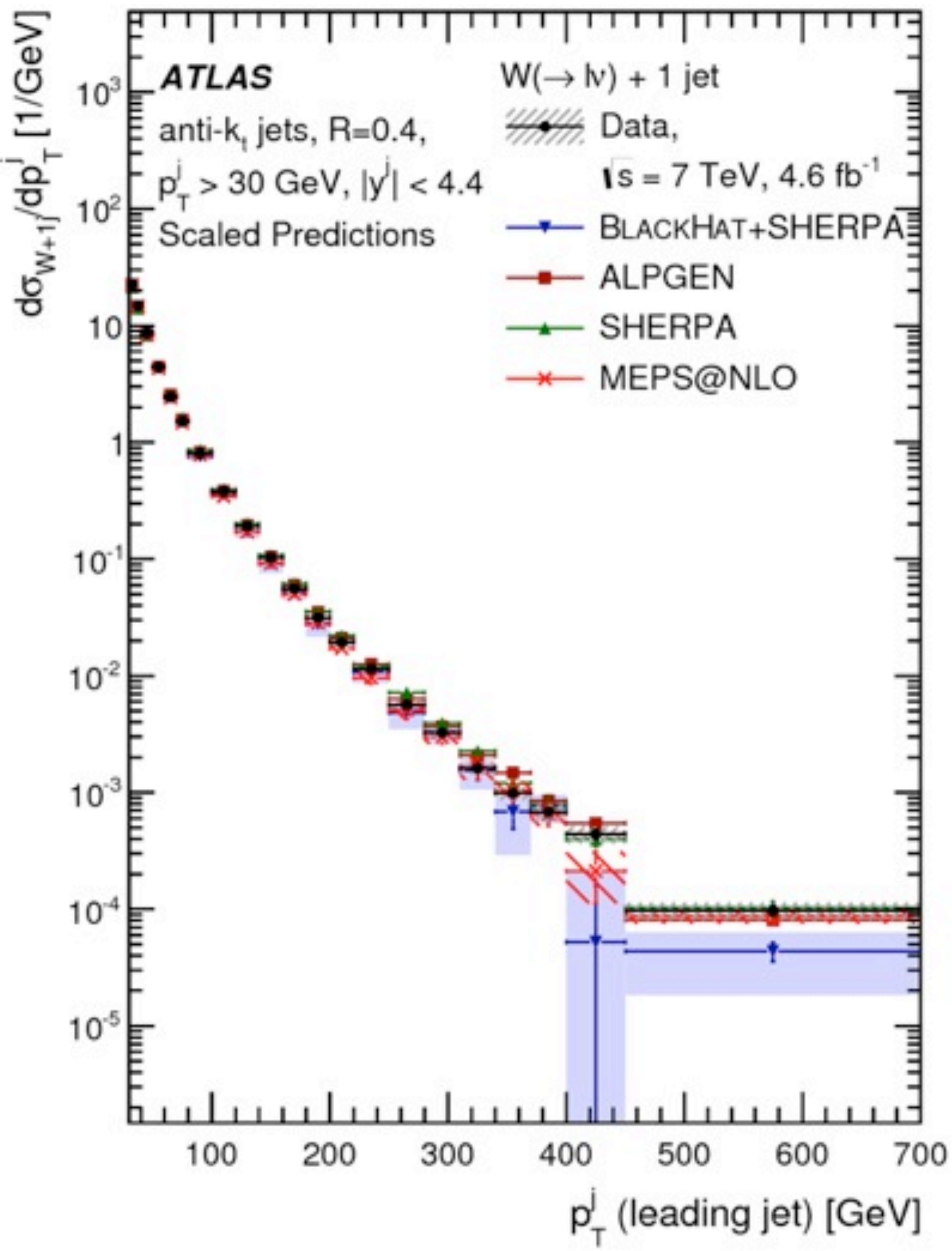
$$(\Delta\mu/\mu)_{RG} = 6.9\%$$

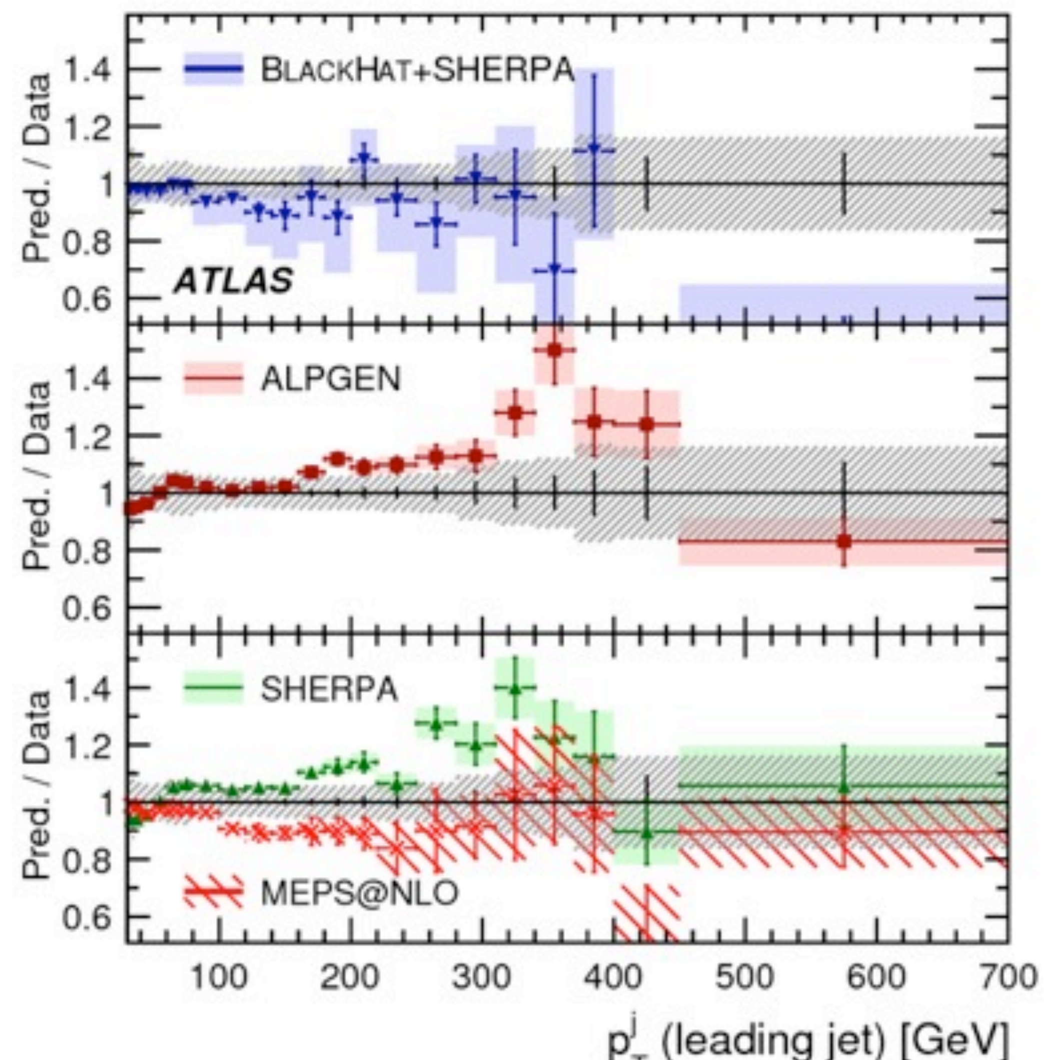
•WW theory uncertainty down by nearly a factor of 2!

•ATLAS finds agreement between this framework and their γγ, γγ+ZZ data: 1407.4222, 1504.05833

The exclusive Z+1-jet puzzle

- Validate resummation formalism with exclusive V+1-jet. Color factor is smaller (C_F vs. C_A), but at p_T=few hundred GeV logs should dominate.

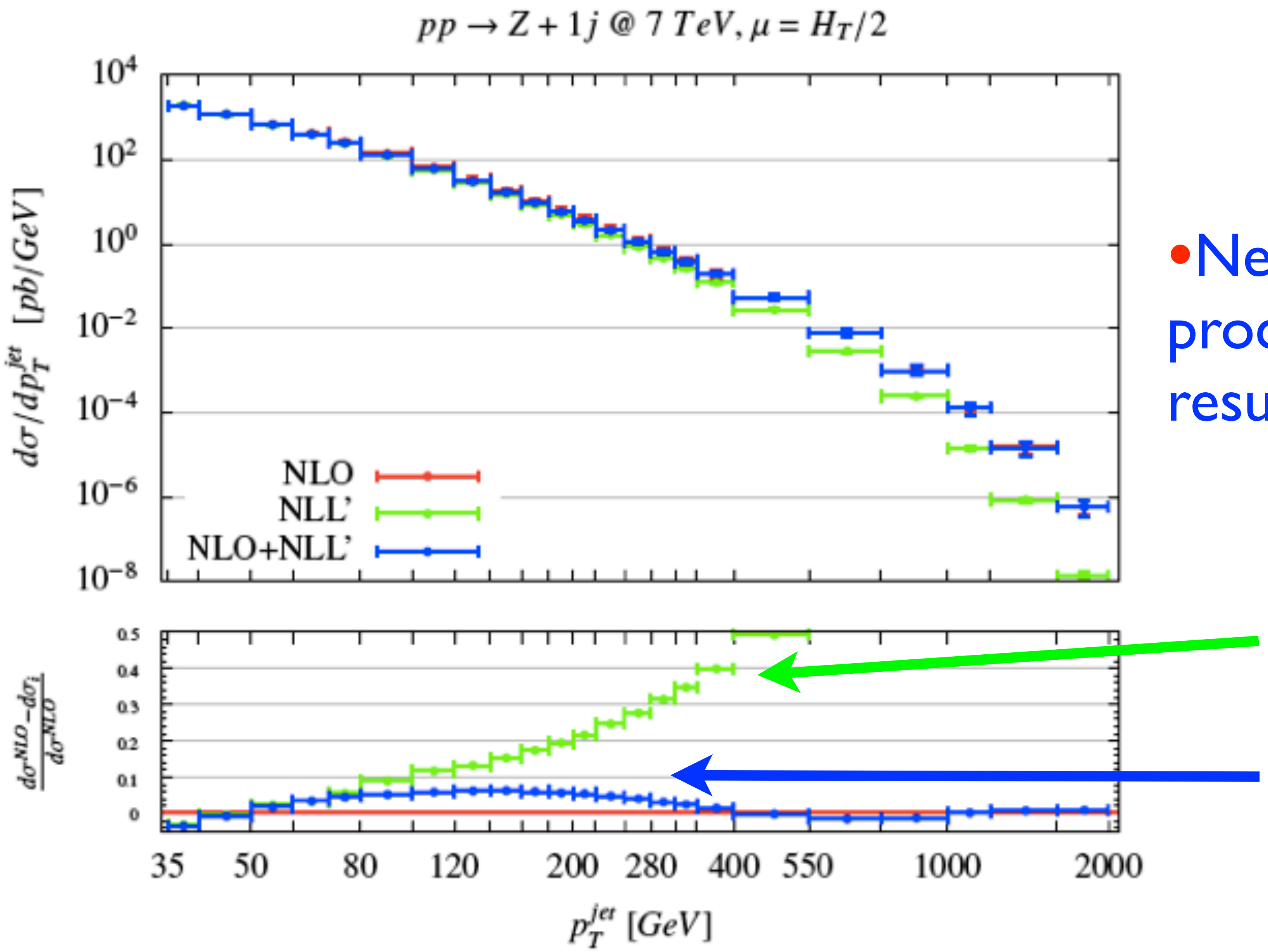




- Agreement with NLO up to 500 GeV!
- Seemingly contradicts expectation that logs dominate the cross section

The exclusive Z+1-jet puzzle

- Two competing effects: jet-veto logarithms and a giant K-factor
- ATLAS unfolding procedure reintroduces 2-jet events with one jet collinear to a final-state lepton, via a Monte-Carlo correction; very large at high p_T!



- Need to modify the unfolding procedure in order to access the resummation region

large correction from jet-veto logs

reduced by 2-jet events at high p_T

Boughezal, Focke, Liu 1501.01059

Conclusions

- There can be flowers in the desert if one looks carefully; we have the tools to do so!
- Multi-particle NLO has become a mature field
- NNLO has undergone rapid advances in the past year; NNLO precision jet phenomenology now possible!
- High-precision resummation in the presence of final-state jets has become possible
- QCD theory is ready for the upcoming data!