Overview of the Latest Developments in Precision QCD

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Guido Altarelli

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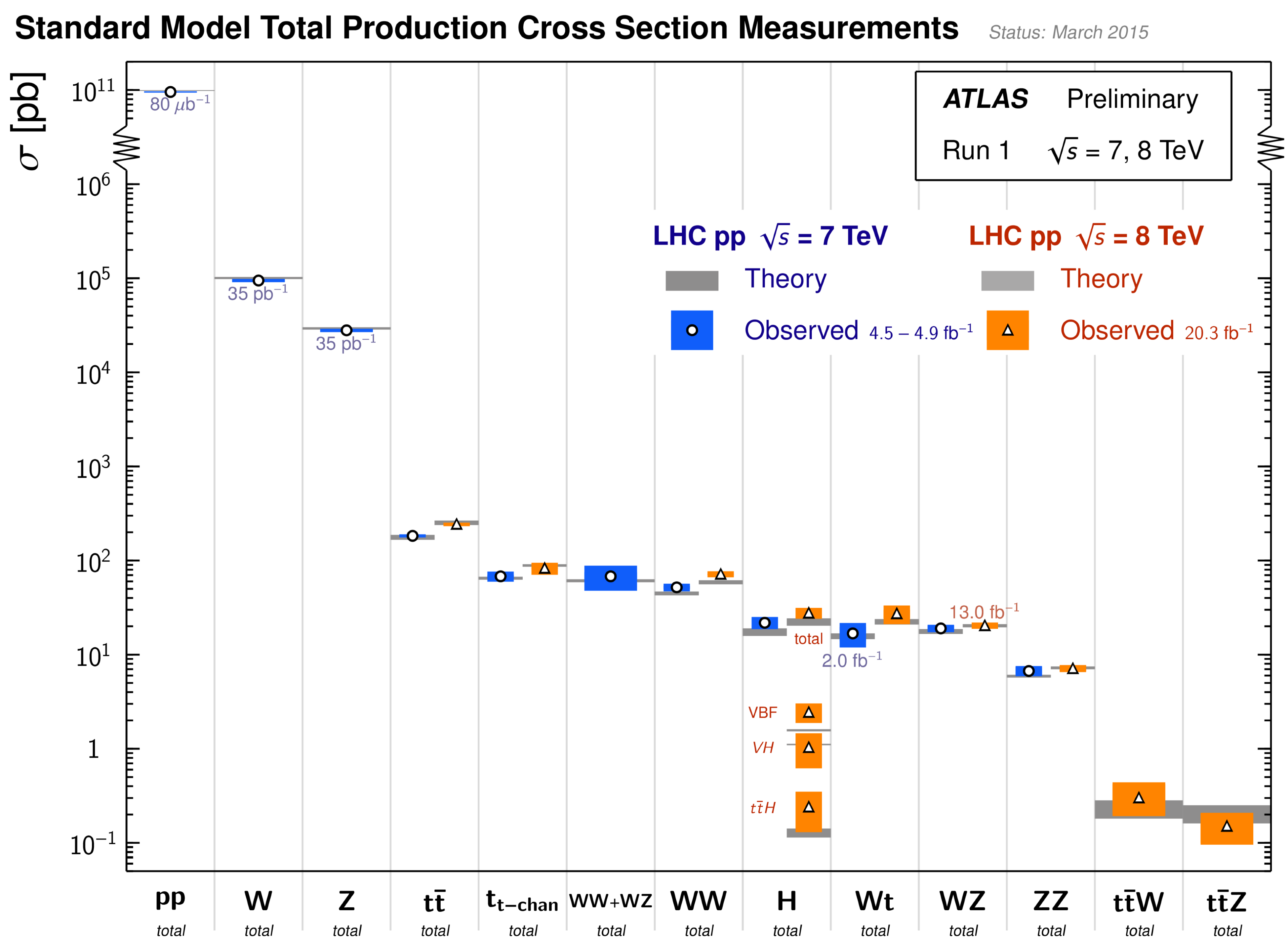
Tribute to a hero of QCD

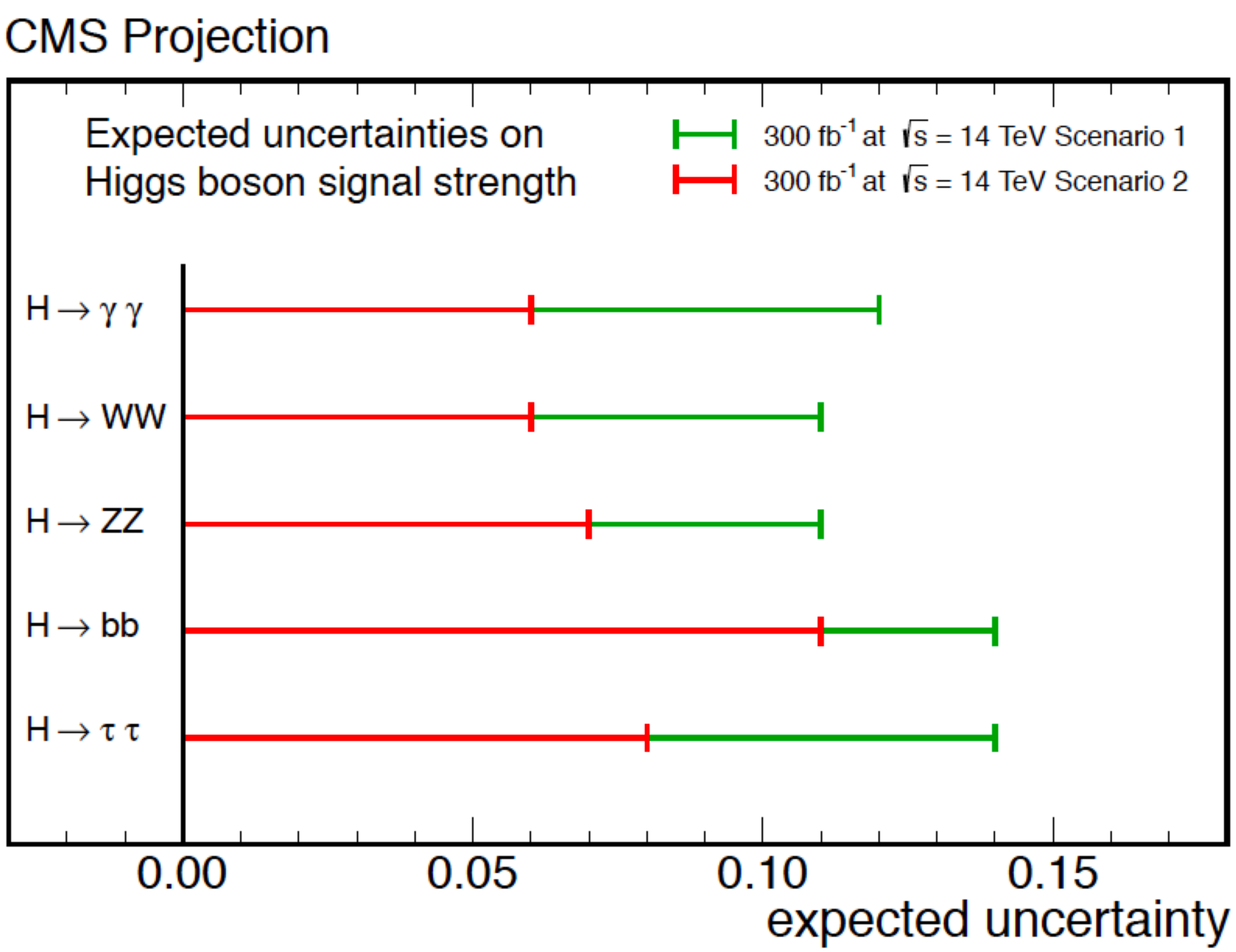
The LHC circa 2015

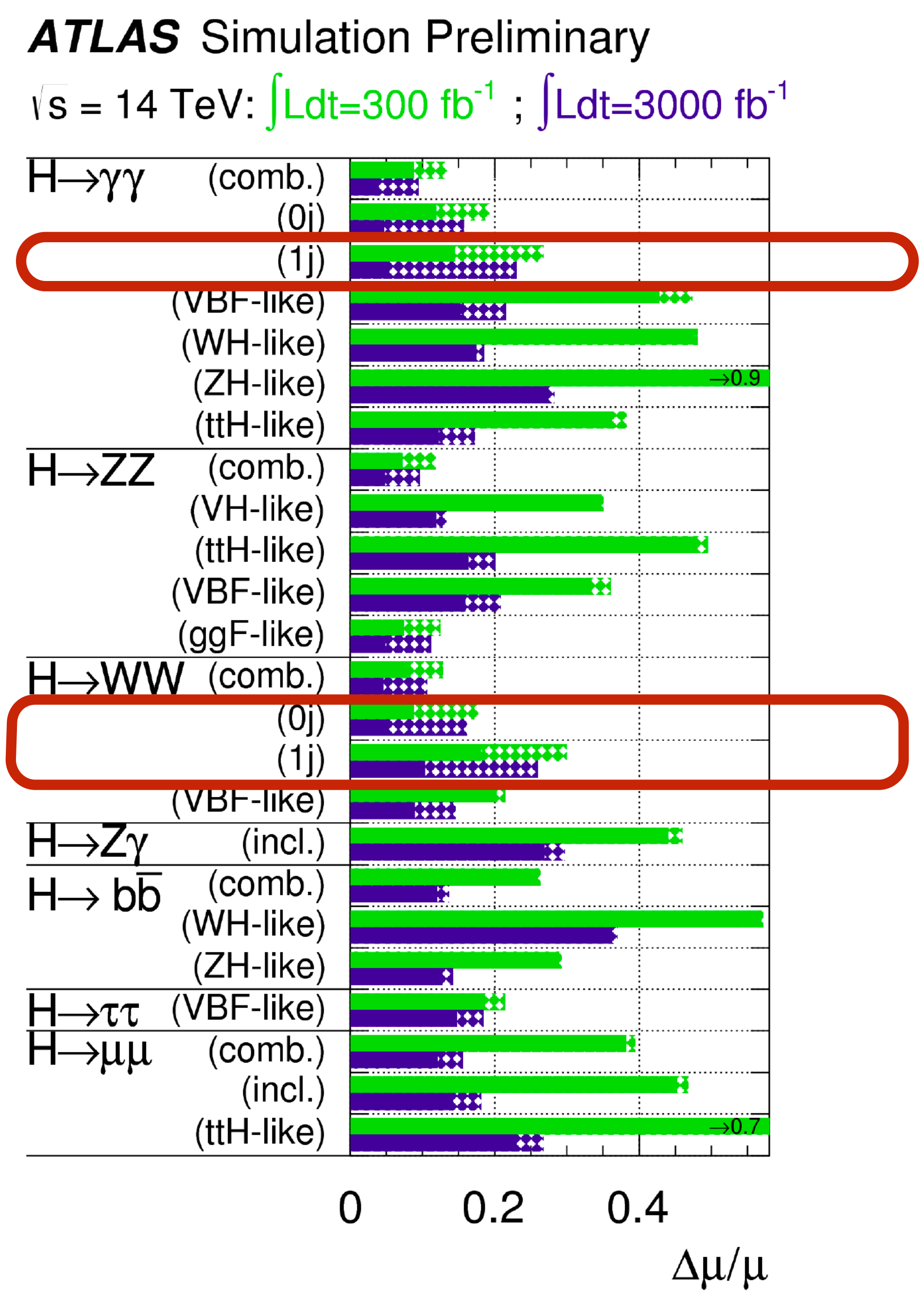


Very good overall agreement between theory and experiment

LHC Run 2: Prospects

- High expectations from the higher energy (13-14 TeV) and luminosity (~300fb^{-1})





Scenario 1: all systematic uncertainties same as now

Scenario 2: scale theory unc. by 1/2, experimental sys. by 1/sqrt(L)

Large impact from theory uncertainties (dashed) coming from QCD scale, jet binning, PDF+α_s

LHC Run 2 & Theory

$H \to ZZ^*$

ATLAS

Source of uncertainty	4μ	$2e2\mu$	$2\mu 2e$	$4e$	combined
Electron reconstruction and identification efficiencies	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiencies	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_s uncertainty					6.0%
$H \to ZZ^*$ branching ratio uncertainty					4.0%

LHC Run 2 & Theory

ATLAS

$H \to ZZ^*$

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$H \to ZZ^*$ branching ratio u			4.0%

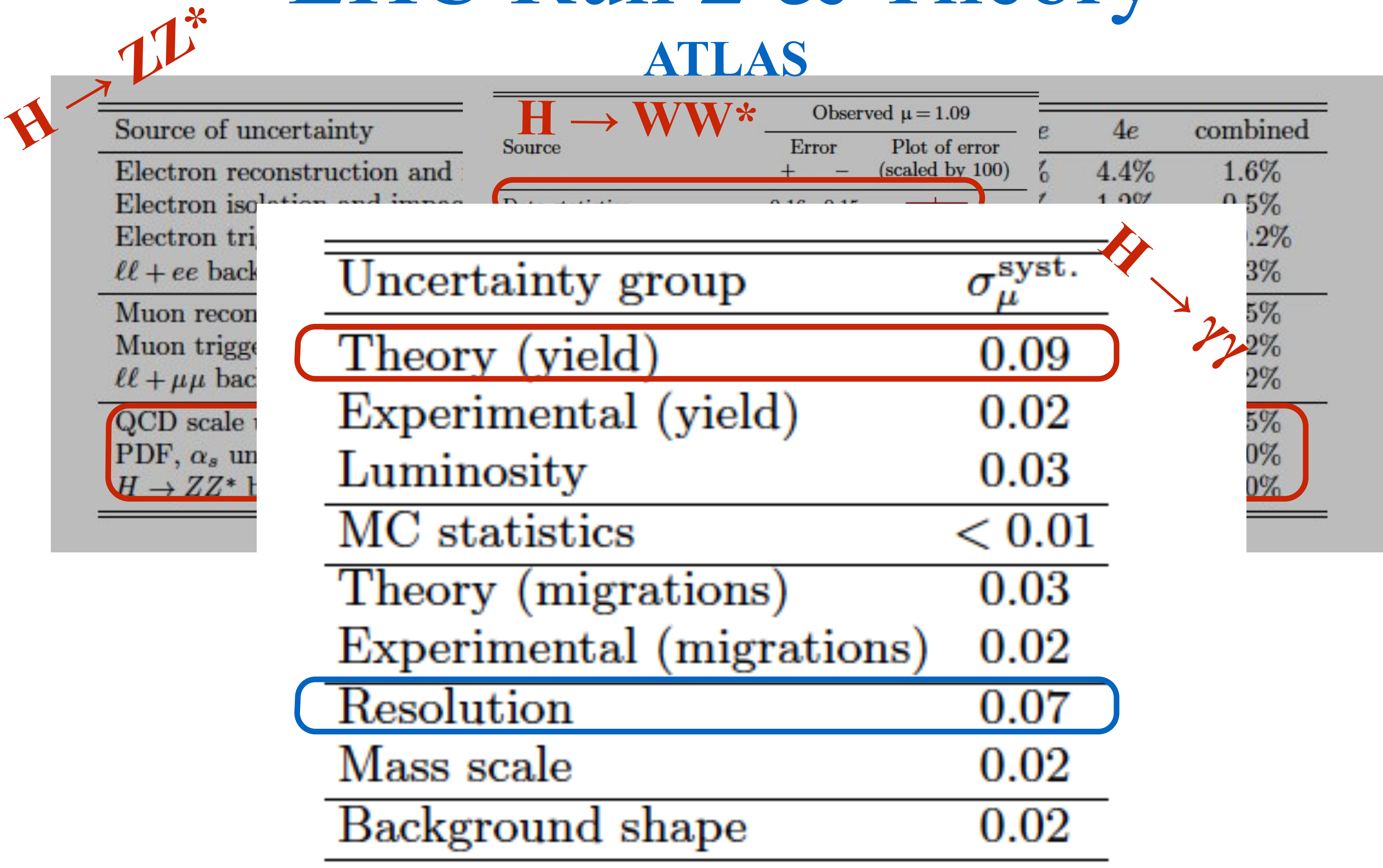
$H \to WW^*$

Source	Observed $\mu = 1.09$ Error +	–	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \to ee, \mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	
Integrated luminosity	0.03	0.03	
Total	0.23	0.21	

-30 -15 0 15 30

LHC Run 2 & Theory

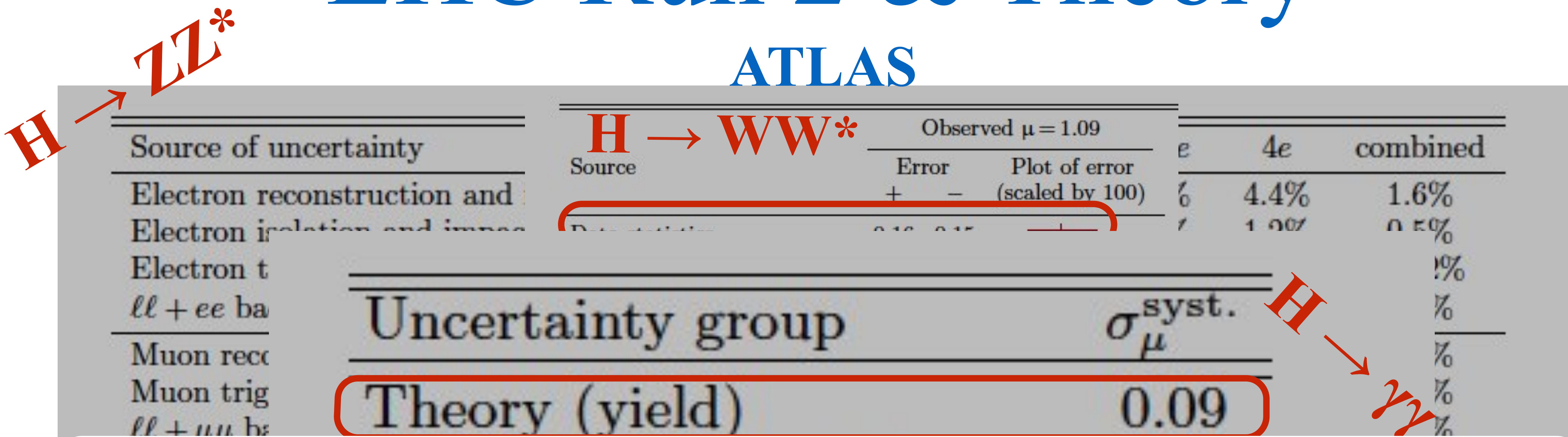
ATLAS



Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

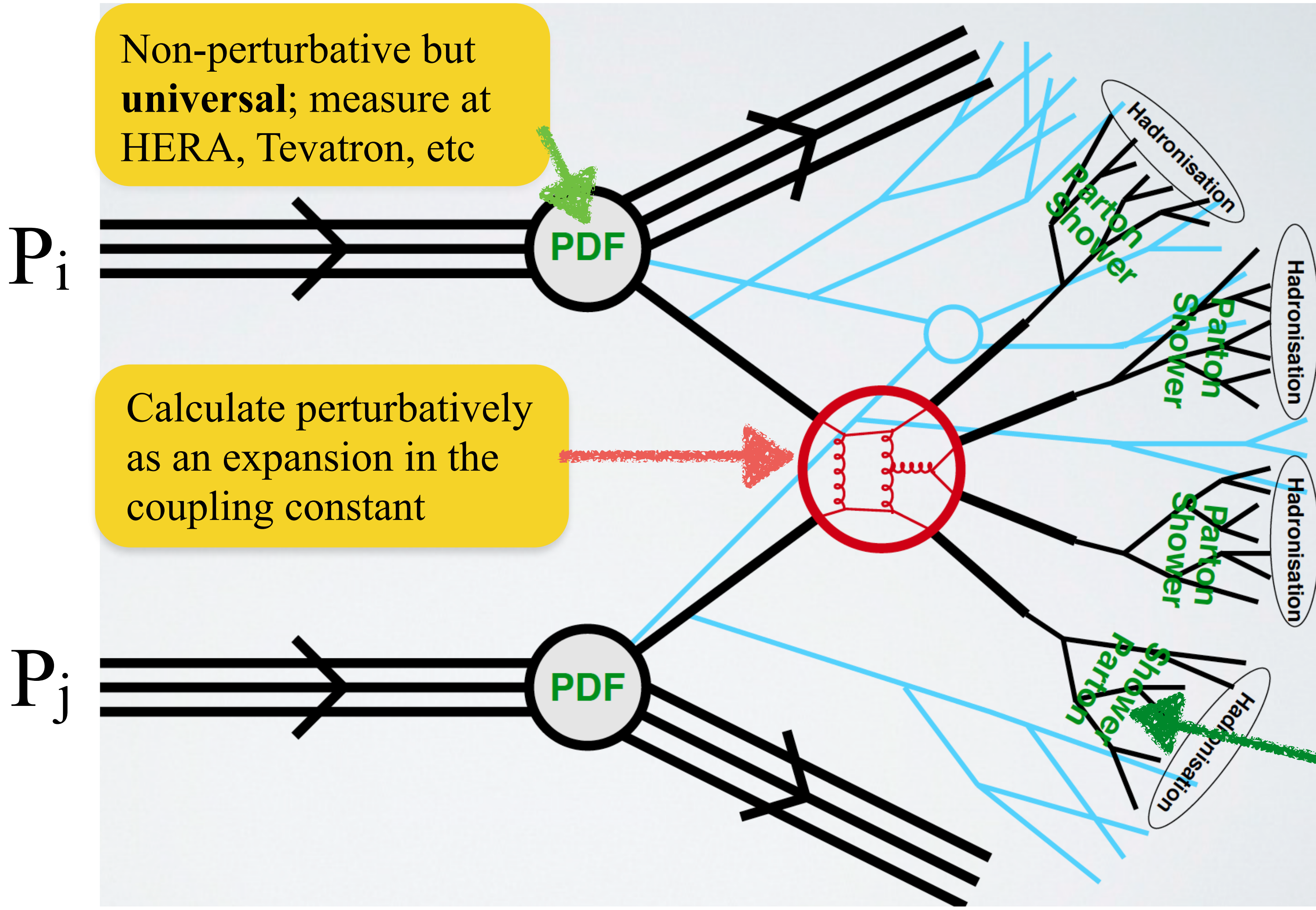
LHC Run 2 & Theory

ATLAS



For all three Higgs ‘precision’ channels, theory uncertainty is the dominant source of systematic uncertainty !

Theoretical Framework



How does theory allow us to peer into the inner hard-scattering in a typical hadron collider process?

Hadronization turns partons to hadrons using models obtained from data

parton shower evolution from high scales to low scales

Factorization: divide and conquer

$$\sigma(Q^2) = \int \sum_{i,j} d\hat{\sigma}_{ij}(\alpha_s(\mu_R), \mu_R^2/Q^2, \mu_F^2/Q^2) \otimes f_i^p(\mu_F) \otimes f_j^p(\mu_F) \quad \left[+ \mathcal{O}\left(\frac{1}{Q^2}\right) \right]$$

partonic cross section, process dependent

μ_R: renormalization scale

parton distributions

μ_F: factorization scale

power corrections

Q: hard scale of the process

Hadronic Cross Sections

- Check list for obtaining a high precision hadronic cross section

☑ Partonic cross sections:

Calculated perturbatively and truncated at some order in the couplings

Uncertainties systematically improvable by including missing higher orders.

☑ Parton Distribution Functions (PDF) and parametric inputs:

Include high precision benchmark processes in the PDF fit

Improve the extraction of input parameters, e.g. $\boldsymbol{\alpha}_s(M_Z)$, M_W, M_H

☑ Parton Showers, Fragmentation and Hadronization:

Needed to match the experimentally observed final state

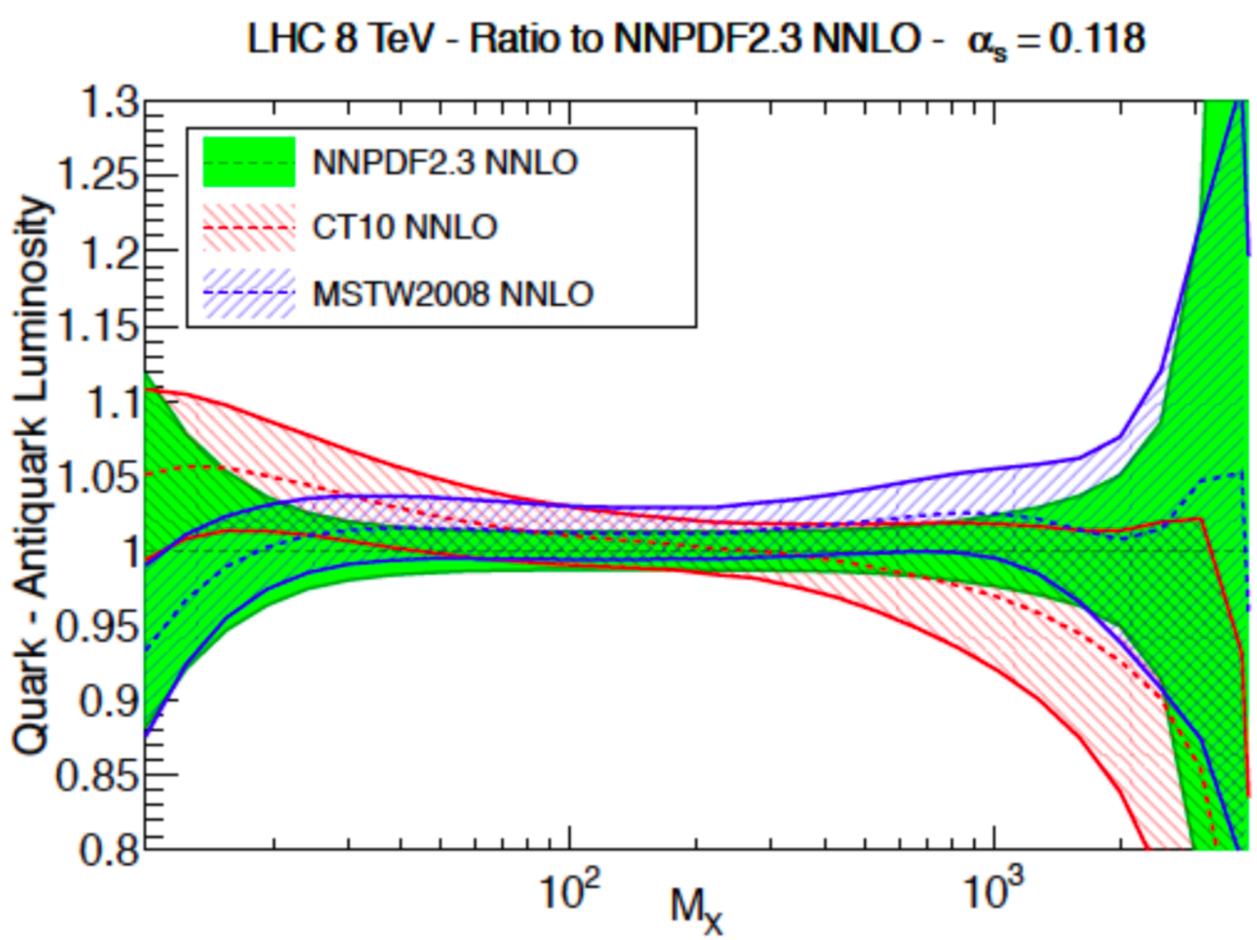
Parton showers improvable by matching/merging with higher orders.

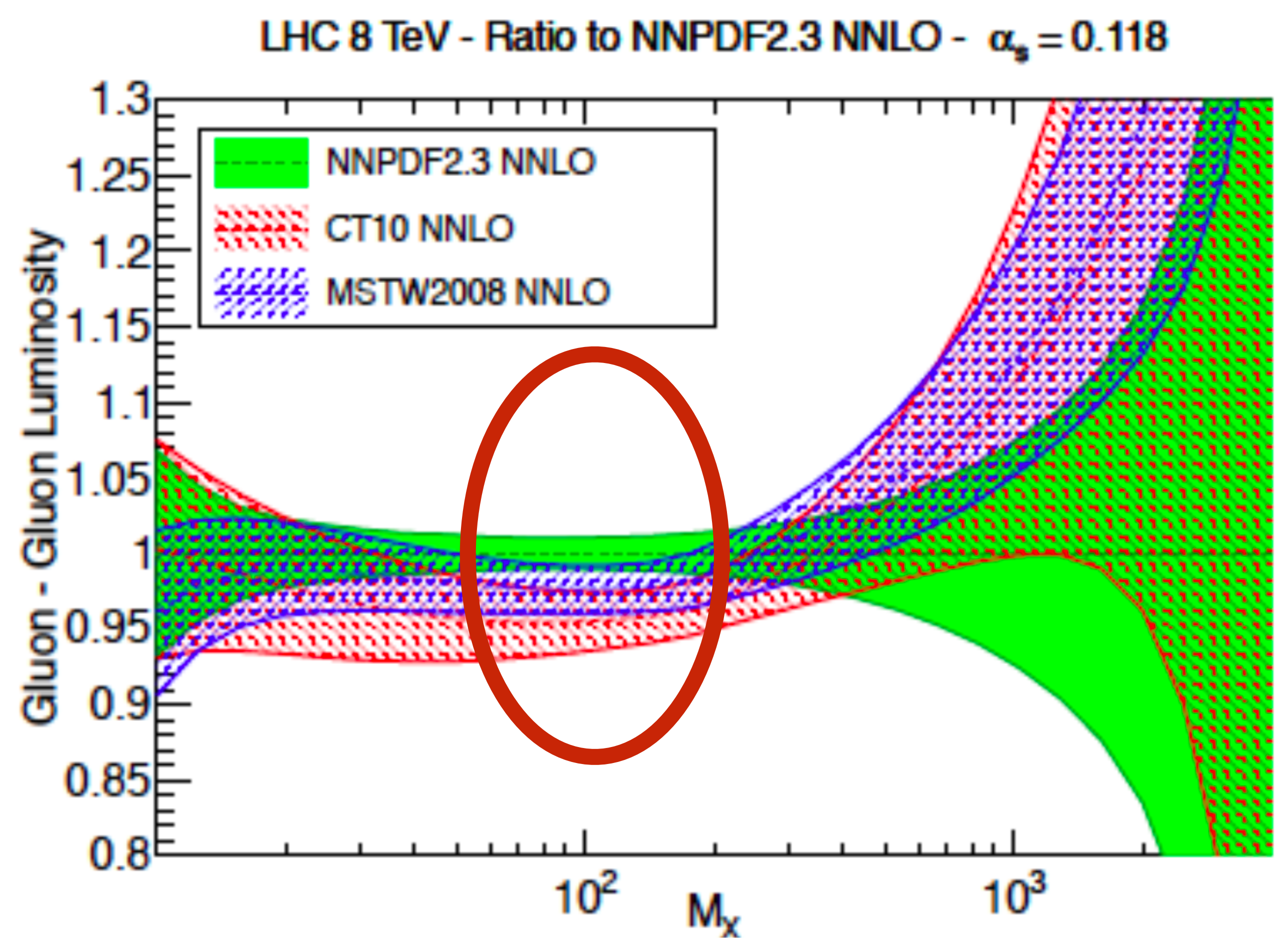
Fragmentation and hadronization models extracted from data.

All the three aspects need improvements to reduce the theory uncertainty!

NNLO PDFs

pre-2015



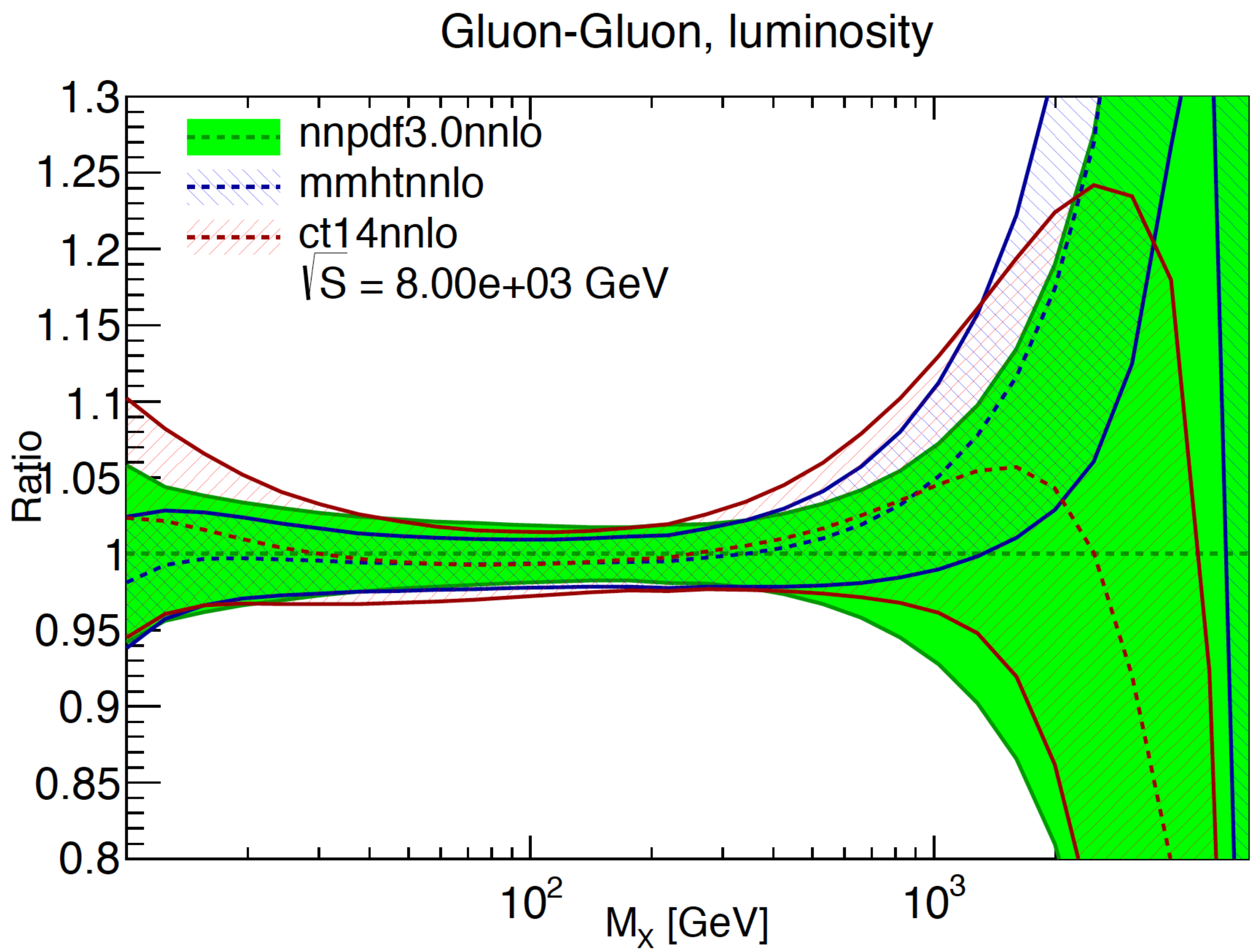


- Not so nice convergence of gg PDF luminosities around 125GeV at 8TeV
- PDF+α_s error dominate the theory uncertainty for Higgs production

$\boxed{\pm 7\% \text{ at a 13 TeV LHC}}$

NNLO PDFs

NEW 2015



- Much nicer convergence for new generations of PDFs (updated HERA data included, improved fit methodology).
- PDF uncertainty on Higgs production down to about 2%
- New LHCHXSWG recommendations: conservative envelope no longer needed, PDF and α_s uncertainties to be kept separate (combine in quadrature if needed), PDFs delivered for each value of α_s.

The Strong Coupling

- The world average in recent years:

Year	$\alpha_s(M_Z)$
2008	0.1176 ± 0.0009
2012	0.1184 ± 0.0007
2014	0.1185 ± 0.0006

- Obtained by averaging results of several measurements:
  DIS, τ-decays, e^+e^- data,
  Z-resonance fits, Lattice
- World average dominated by lattice

- Global PDF fits lead in some cases to different values of α_s:

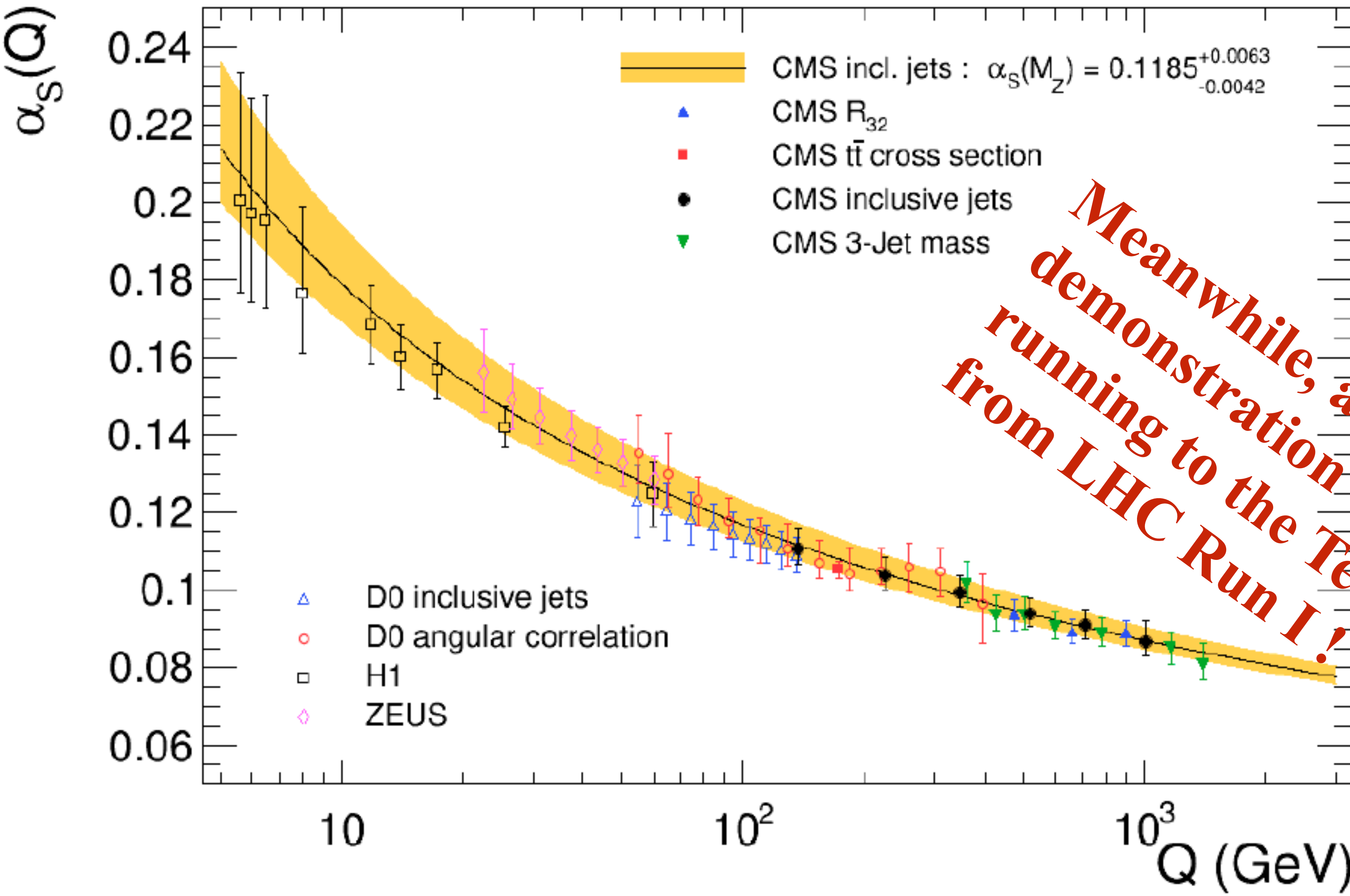
$\alpha_s(M_Z) \sim 0.1132 \pm 0.0011$ Alekhin, Blumlein, Moch (14)

- As well as other theoretical ideas eg. (SCET):

$\alpha_s(M_Z) \sim 0.1112 \pm 0.0015$ (Hoang et al, 2015, e+e- event shapes)

More work is needed to reach a more precise determination of α_s

The Strong Coupling



Meanwhile, an impressive demonstration of α_s running to the TeV range from LHC Run I !

Partonic Cross Sections

$$\boxed{\hat{\sigma} = \hat{\sigma}^{LO} \quad + \alpha_s/\pi \; \hat{\sigma}^{NLO}_{QCD} + (\alpha_s/\pi)^2 \; \hat{\sigma}^{NNLO}_{QCD} + (\alpha_s/\pi)^3 \; \hat{\sigma}^{N^3LO}_{QCD} + \cdots + \hat{\sigma}_{EW}}$$

- $\hat{\sigma}^{LO}_{QCD}$: known for all processes of interest, has large renormalization and factorization scale dependence
- $\hat{\sigma}^{NLO}_{QCD}$: first reliable prediction (correct shape and normalization, accounts for effects of extra radiation, smaller scale dependence)
- $\hat{\sigma}^{NNLO}_{QCD}$: required for precise theoretical description of few observables; needed in the precise extraction of PDFs, input parameters such as masses and α_s, or when perturbative corrections are large
- $\hat{\sigma}^{N^3LO}_{QCD}$: currently available only for gg→H where QCD corrections are sizable
- $\hat{\sigma}_{EW}$: becomes particularly important at high energies

QCD @ NLO

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

$$\boxed{\sigma^{NLO}_{(m)} = \int_{\Phi_m} \left[d\sigma^{Born} + d\sigma^{V}_{\rm NLO} + \int_{\Phi_1} d\sigma^{S}_{\rm NLO} \right] + \int_{\Phi_{m+1}} \left[d\sigma^{R}_{\rm NLO} - d\sigma^{S}_{\rm NLO} \right]}$$

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

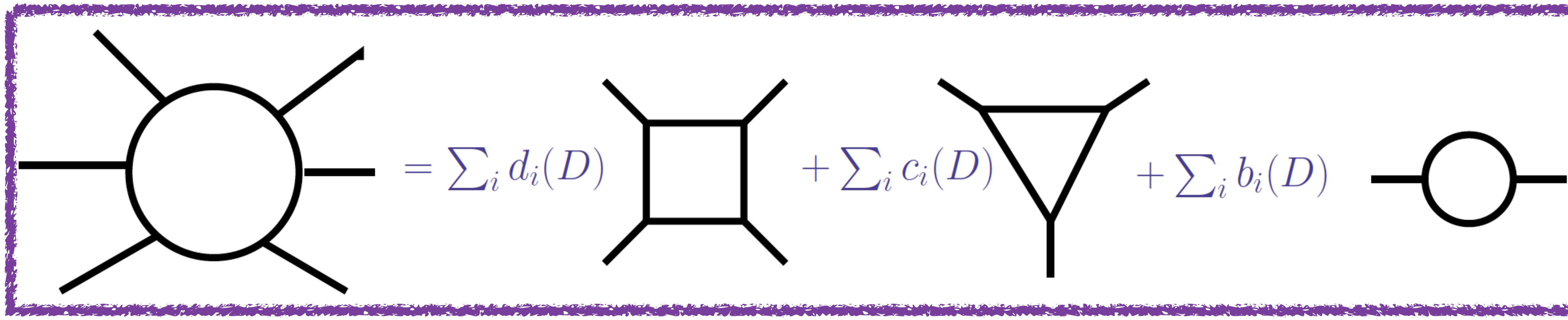
Approximates real-emission matrix elements in all singular limits so this difference is numerically integrable

- Extracting implicit IR poles from real radiation ME is well understood at NLO with various methods, most popular are dipole subtraction (Catani, Seymour) and FKS (Frixione, Kunszt, Signer)

- Automated and implemented in several dedicated codes: AutoDipole, Helac, MadFKS, Sherpa, TeVJet

QCD @ NLO

- Virtual corrections obtained as coefficients times 1-loop scalar integrals



Several breakthroughs in obtaining the coefficients in a clever way

Sew tree level amplitudes to compute the coefficients of scalar loop integrals (generalized unitarity, D-dimensional unitarity, …)

OPP method: reduce the integrand to master integrals. Coefficients of masters extracted by evaluating the amplitudes at specific values of loop momenta

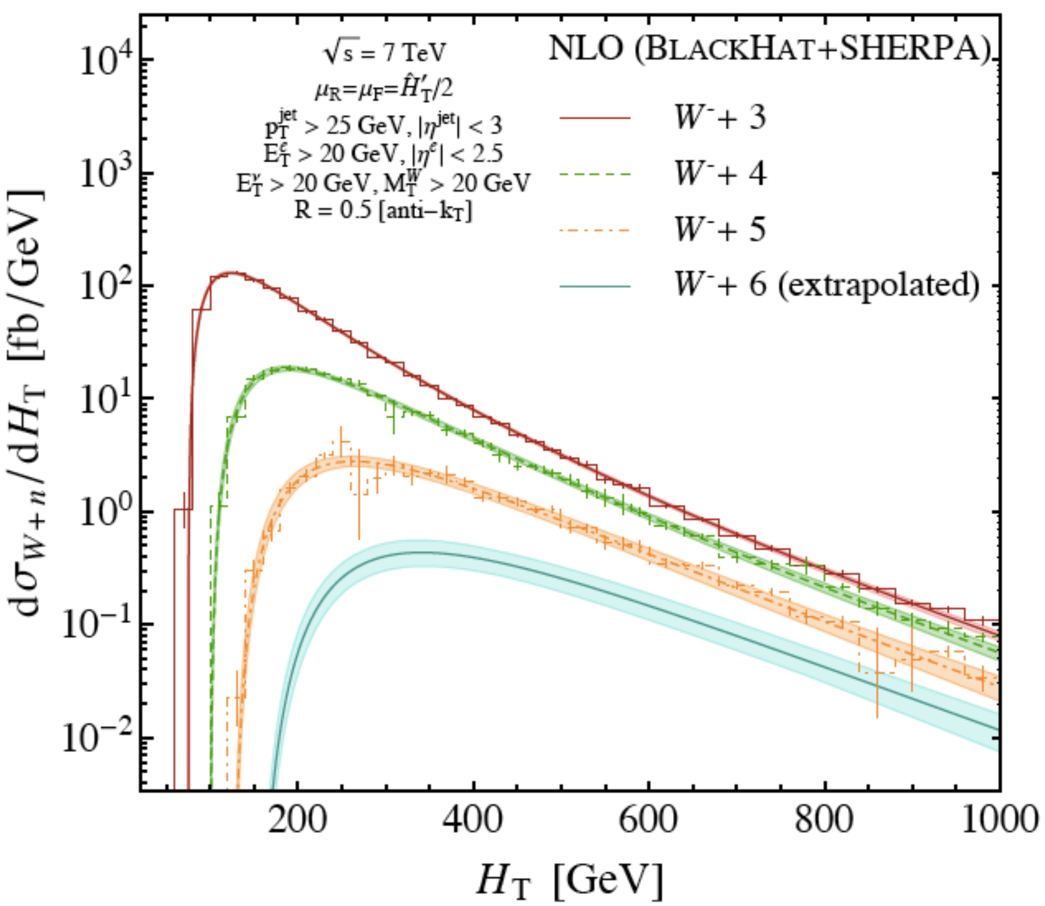
Bern, Dixon, Kosower; Britto, Cachazo, Feng; Ossola, Pittau, Papadopoulos; Ellis, Giele, Kunszt, Melnikov,…

- Automated in many codes:

HELAC-NLO, Blackhat+SHERPA, GoSam+SHERPA/MADGRAPH, NJet+SHERPA, Madgraph5_aMC@NLO, OpenLoops+SHERPA,….

QCD @ NLO

- Automation of NLO QCD processes is mostly a solved problem. Numerical stability and efficiency still depend on the multiplicity of the process (4-6 particles in the final state are still tough numerically….).
- Programs with analytic representations of the amplitudes (such as MCFM) remain extremely important for speed/efficiency and as input to NNLO.
- Example phenomenology: W+2 through 5 jets known to NLO (Blackhat + Sherpa). Can these be used to predict higher multiplicity?



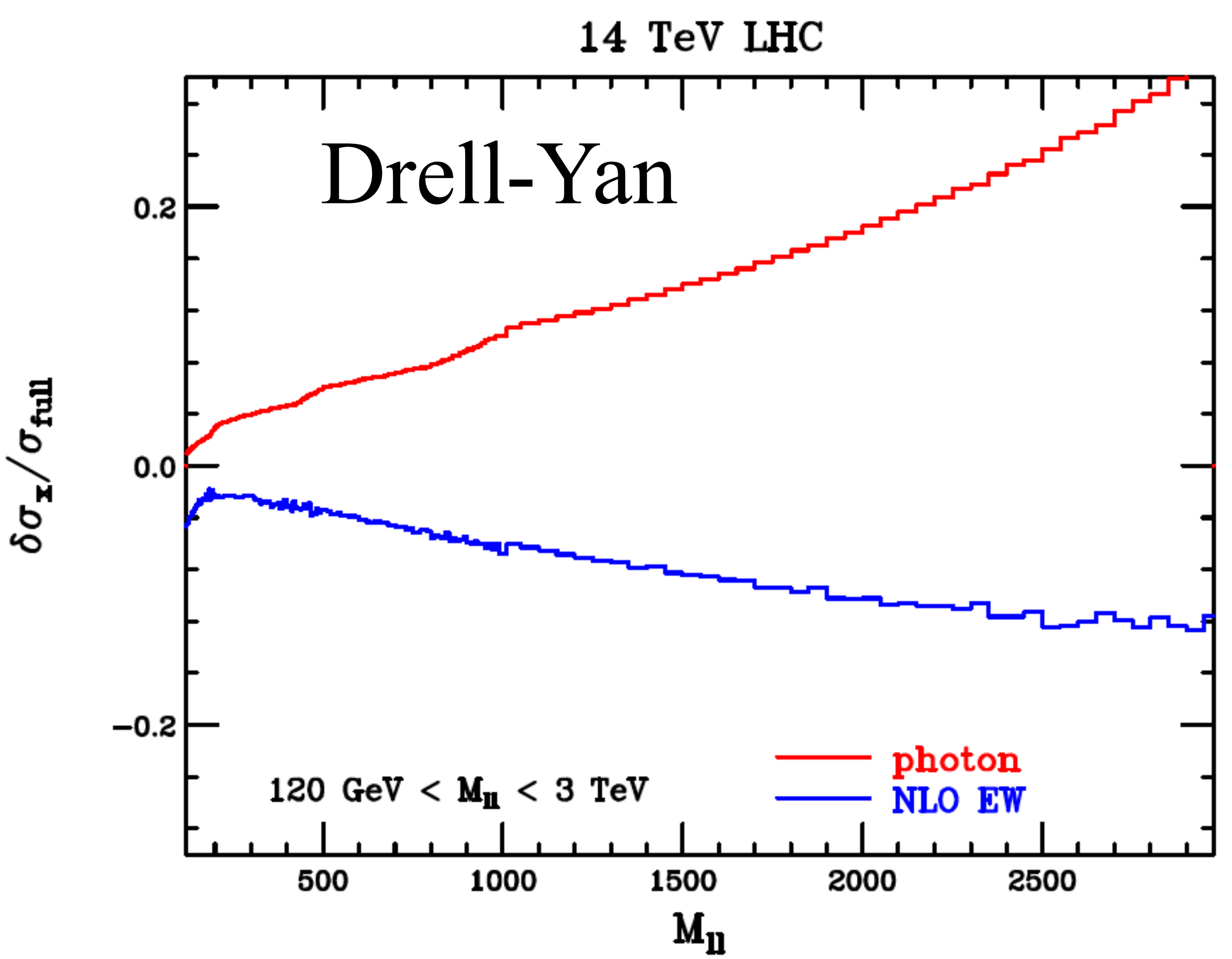
Bern, Dixon, Febres Cordero, Hoeche, Kosower, Ita, Maitre 1412.4775

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

- Validate fit methodology on n = 3-5 before extrapolation to six jets
- Will help control backgrounds to BSM in multi-jet final states

NLO EW Corrections

- NLO EW corrections are particularly important for LHC Run II where new phase space regions open up due to the large energy.
- Generic size $O(\alpha) \sim O(\alpha s^2)$ suggests that NLO EW ~ NNLO QCD



R.B., Li, Petriello, 2013

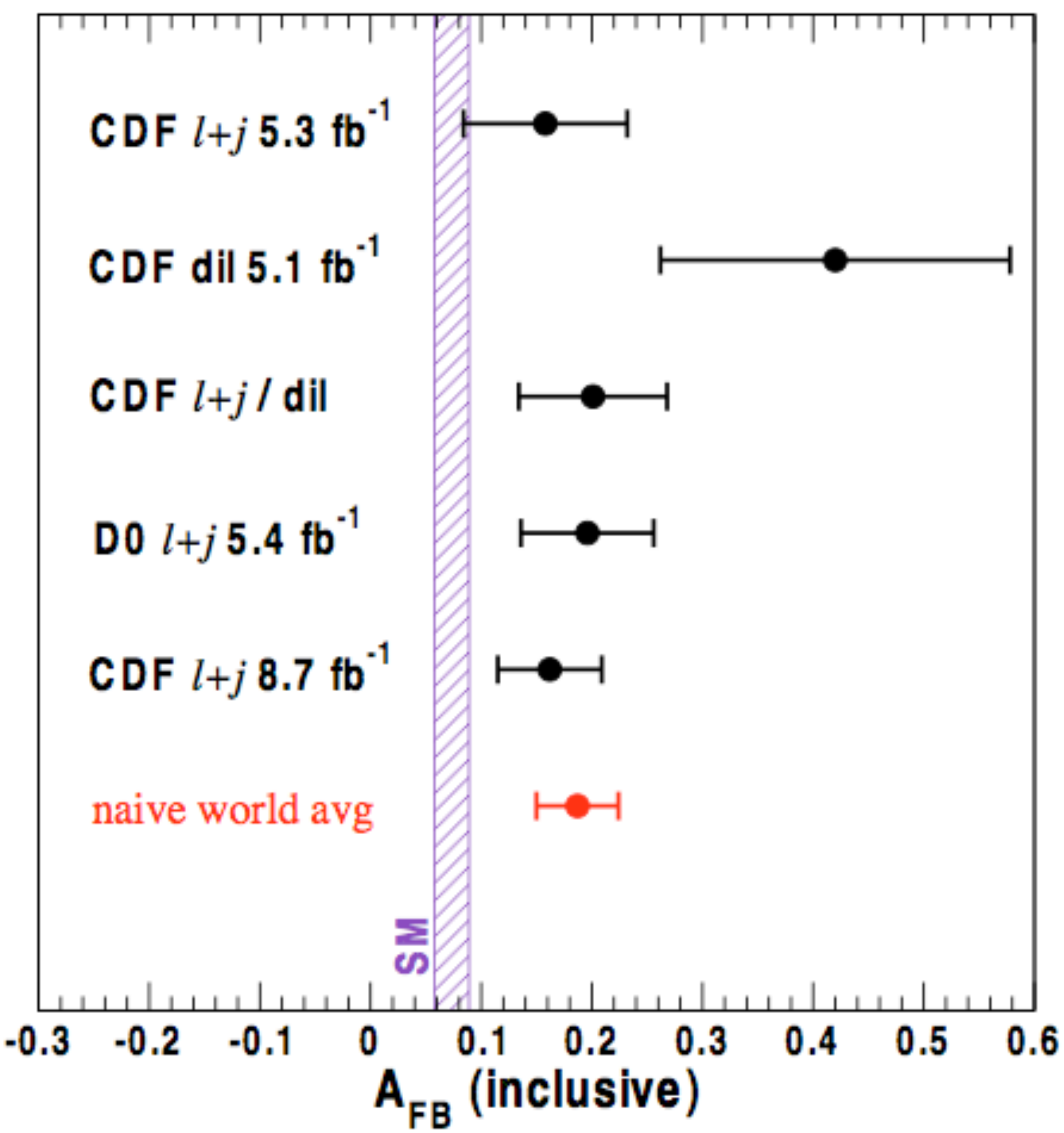
Possible large enhancements due to:

- EW Sudakov logarithms which become large at high energy: $\sim \alpha \log^2(M_W/Q)$
- Contributions from photon initiated processes can become large at high invariant mass
- Mass singular logarithms from QED emission $\sim \alpha \log(M_l/Q)$

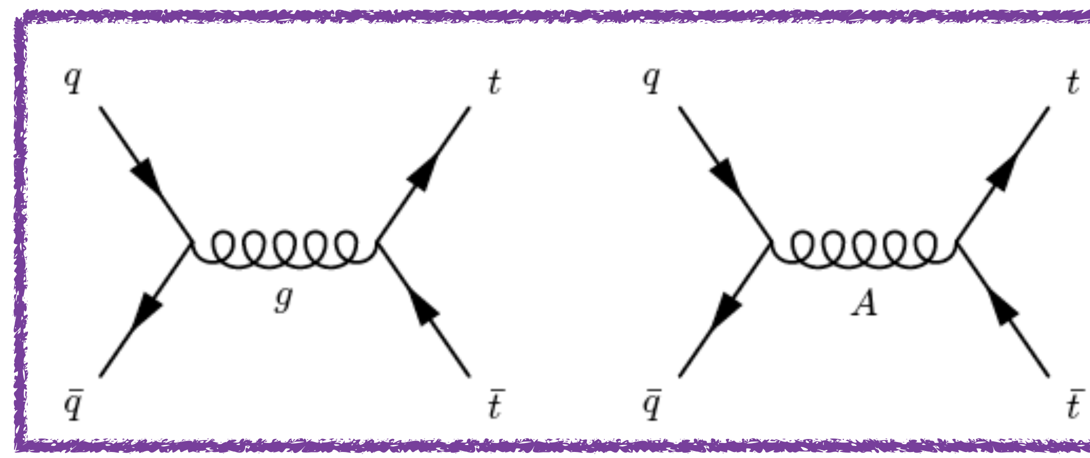
All these effects must be accounted for in precision predictions

Motivations for QCD @ NNLO

• **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?

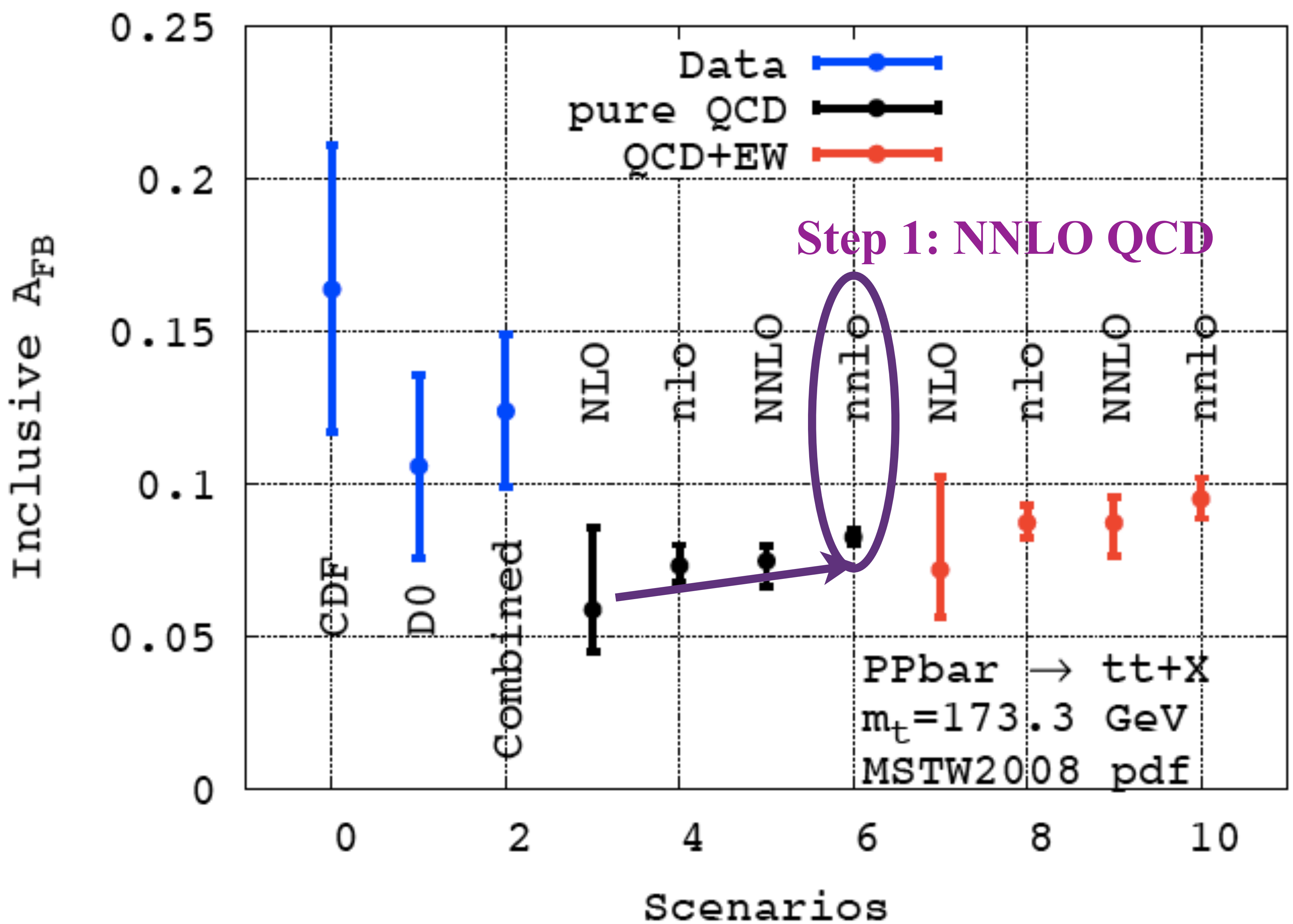


(Many authors)

Motivations for QCD @ NNLO

- **The ttbar asymmetry now:** large NNLO QCD corrections!

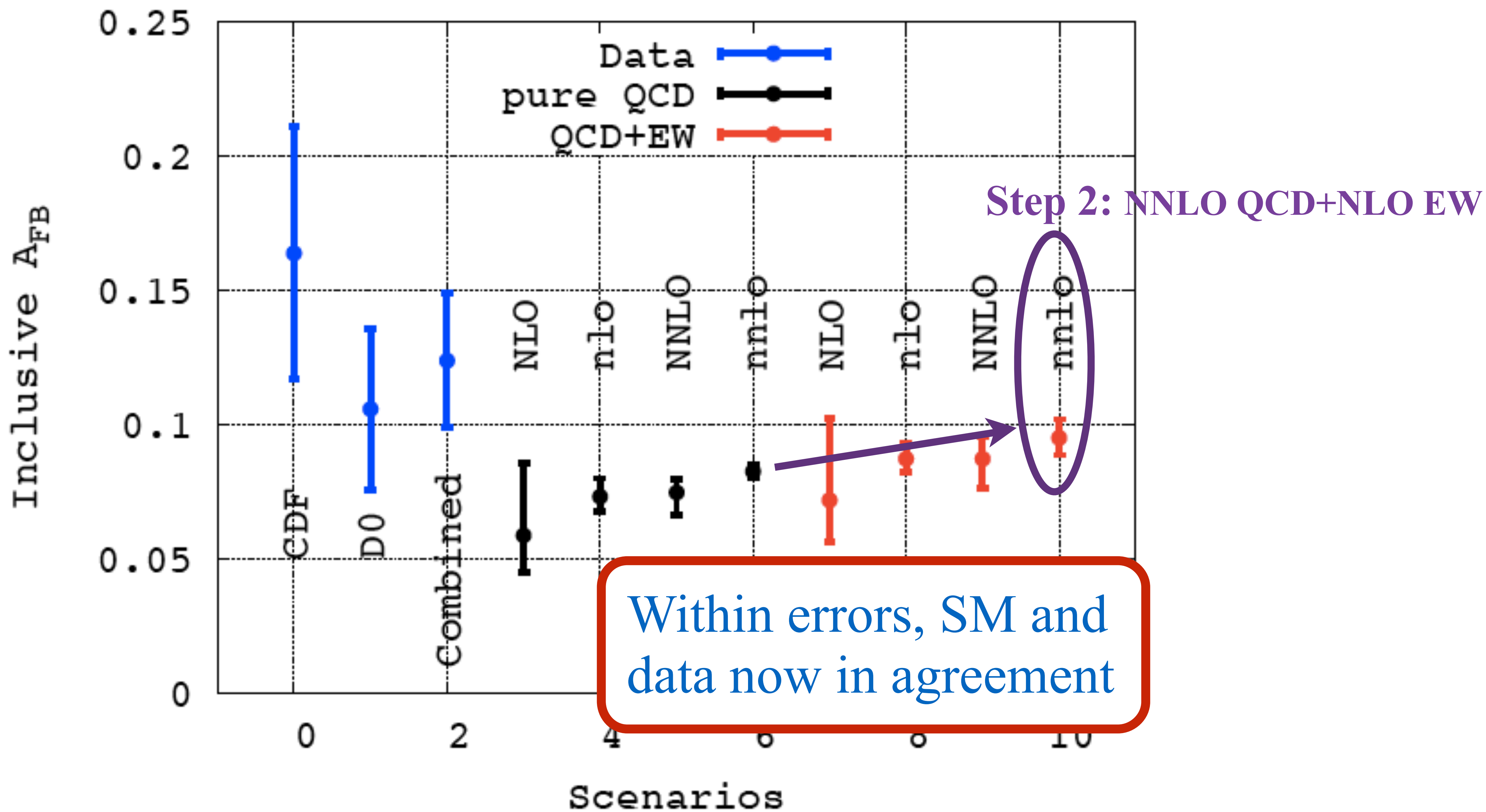
Not predicted by soft-gluon resummation, required a genuine NNLO prediction (Czakon, Fiedler, Mitov 1411.3007)



Motivations for QCD @ NNLO

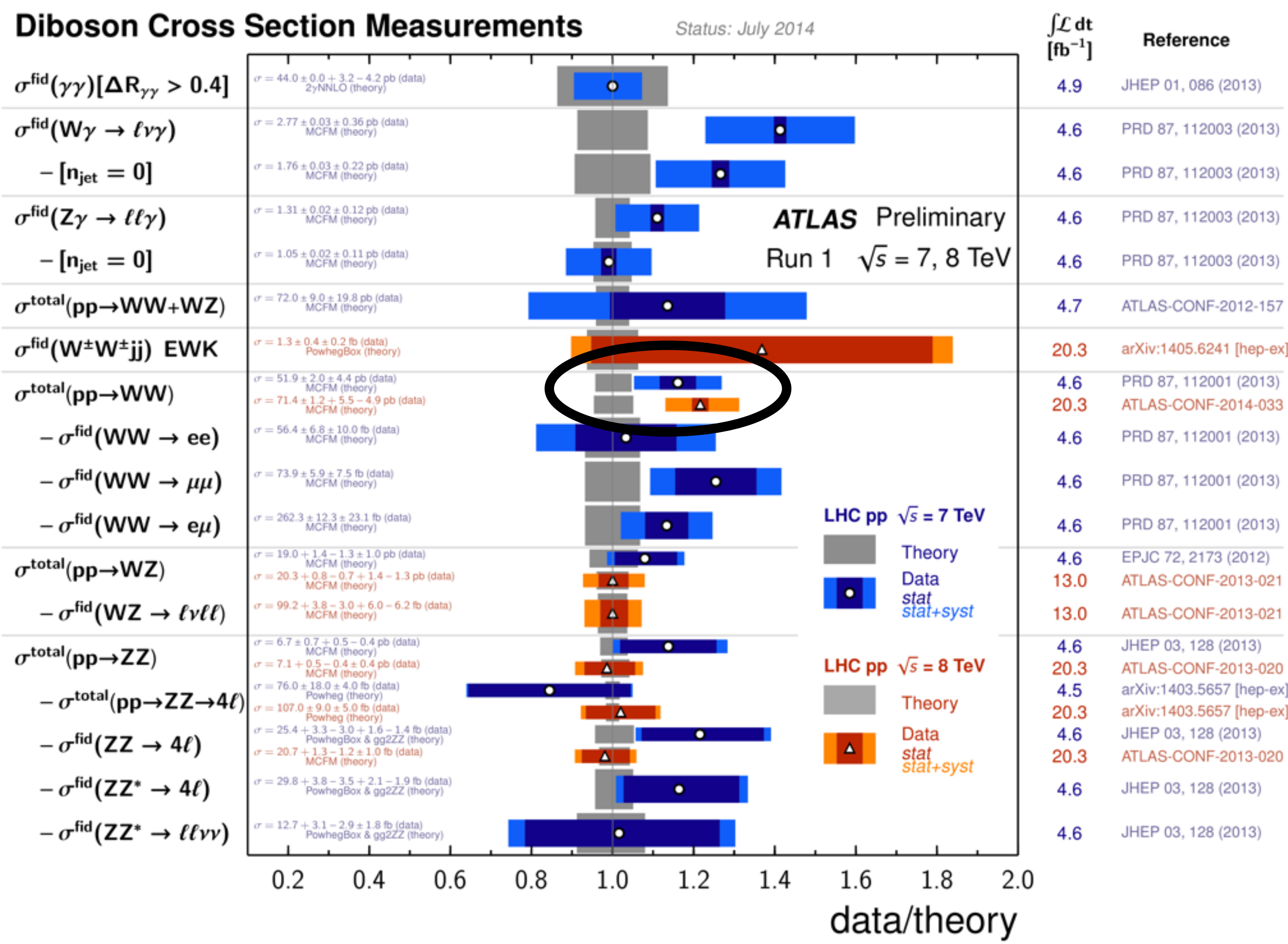
- **The ttbar asymmetry now:** large EW corrections!

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



Motivations for QCD @ NNLO

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



Could it be light charginos?

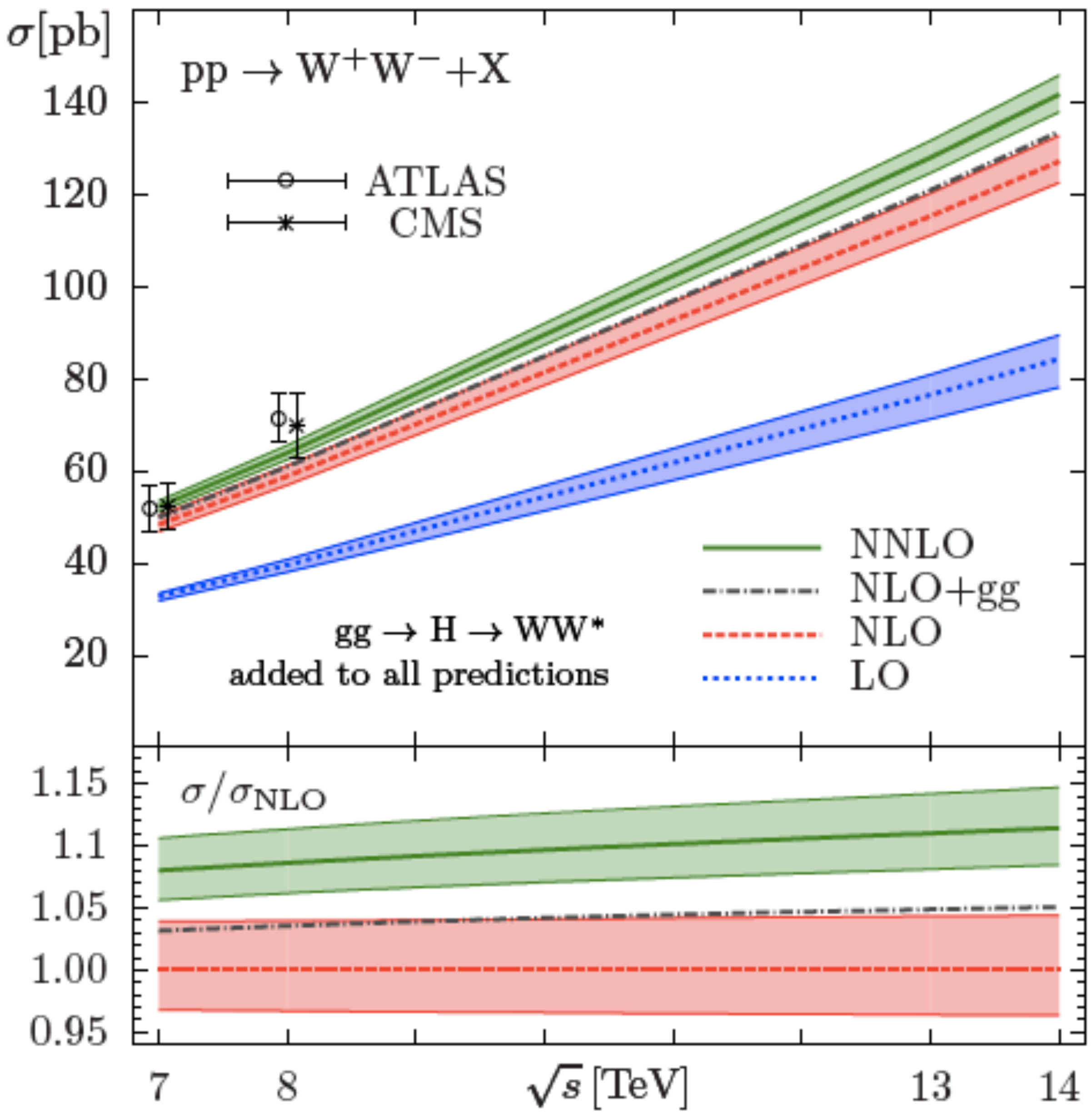
Curtin, Jaiswal, Meade 1206.6888, and others

Motivations for QCD @ NNLO

- **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

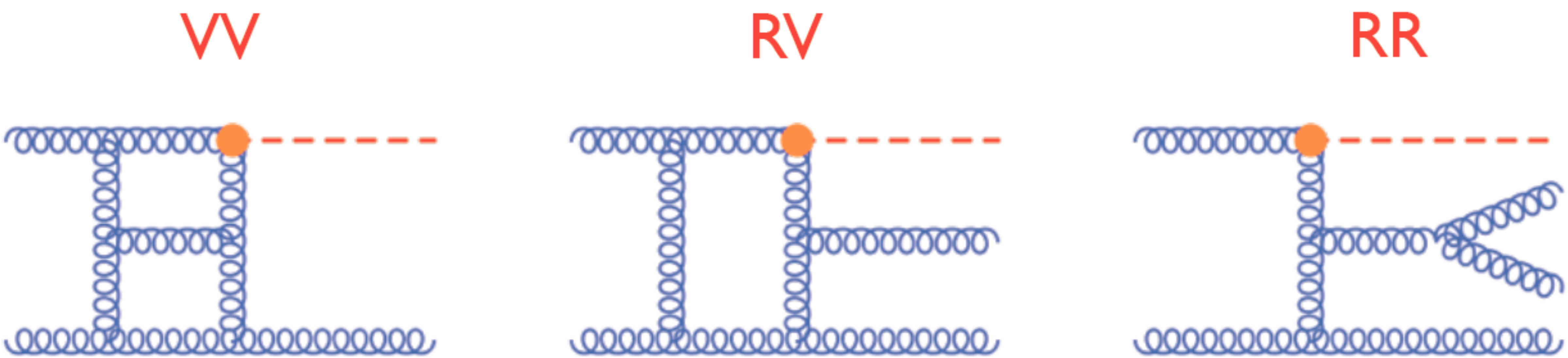


- Enhancement of theory is expected when the extrapolation from the fiducial region is properly modeled, further improving agreement

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

Ingredients for NNLO Calculations

- Need the following ingredients for NNLO cross sections



- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

Ingredients for NNLO Calculations

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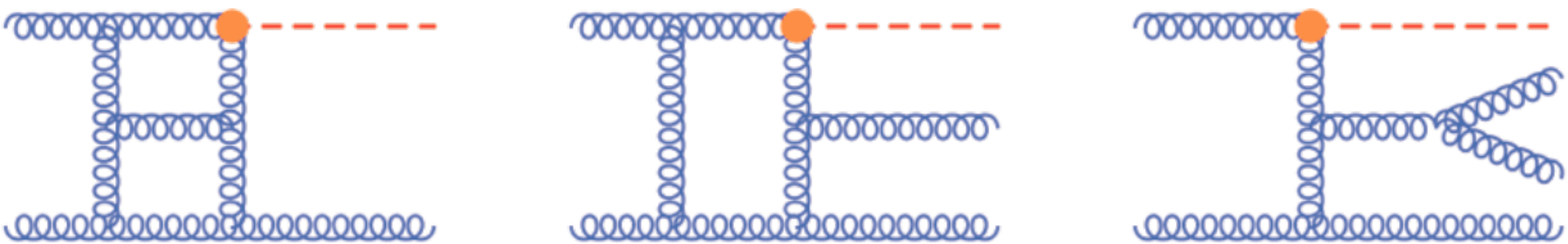
VV RV RR



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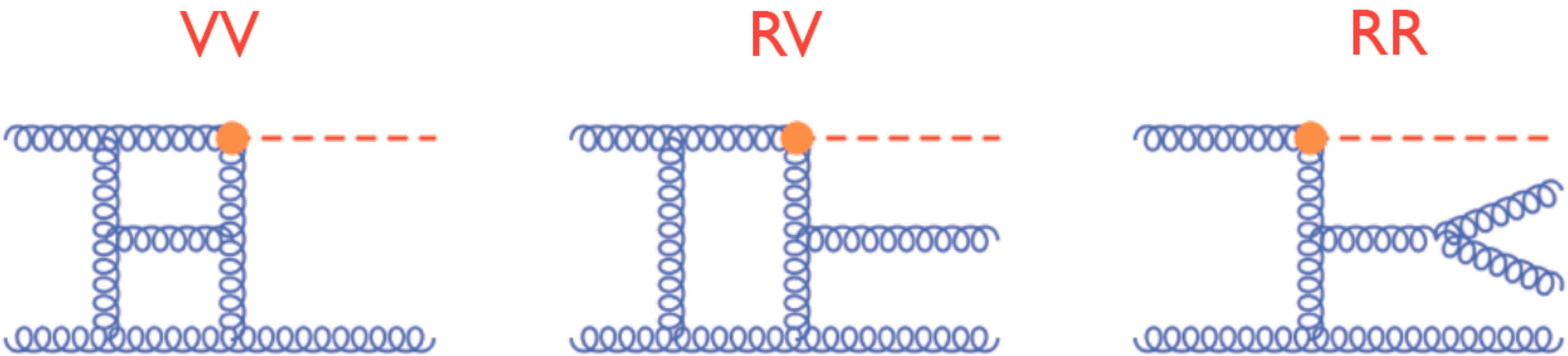
$$\int \left[\frac{vv_4}{\epsilon^4} + \frac{vv_3}{\epsilon^3} + \frac{vv_2}{\epsilon^2} + \frac{vv_1}{\epsilon} + vv_0\right] \, d\Phi_2 \qquad \int \left[\frac{rv_2}{\epsilon^2} + \frac{rv_1}{\epsilon} + rv_0\right] \, d\Phi_3 \qquad \int [rr_0] \, d\Phi_4$$

Ingredients for NNLO Calculations

- Need the following ingredients for NNLO cross sections



- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations.

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

- A generic procedure to extract IR singularities from RR and RV was unknown when jets in the final state are involved, until very recently.

Extracting IR Singularities @ NNLO

Two primary approaches

Subtraction: add and subtract counterterms that approximate real-emission matrix elements in all singular limits. Made difficult at NNLO by the overlapping singularities. **Subtraction terms can be integrated either analytically or numerically.**

Resummation: use a small cutoff to partition the phase space so that double unresolved singularities are all below the slicing cutoff. **Resummation provides analytic expressions for the region below the cut.** Above the cut is just an NLO+1 additional parton process.

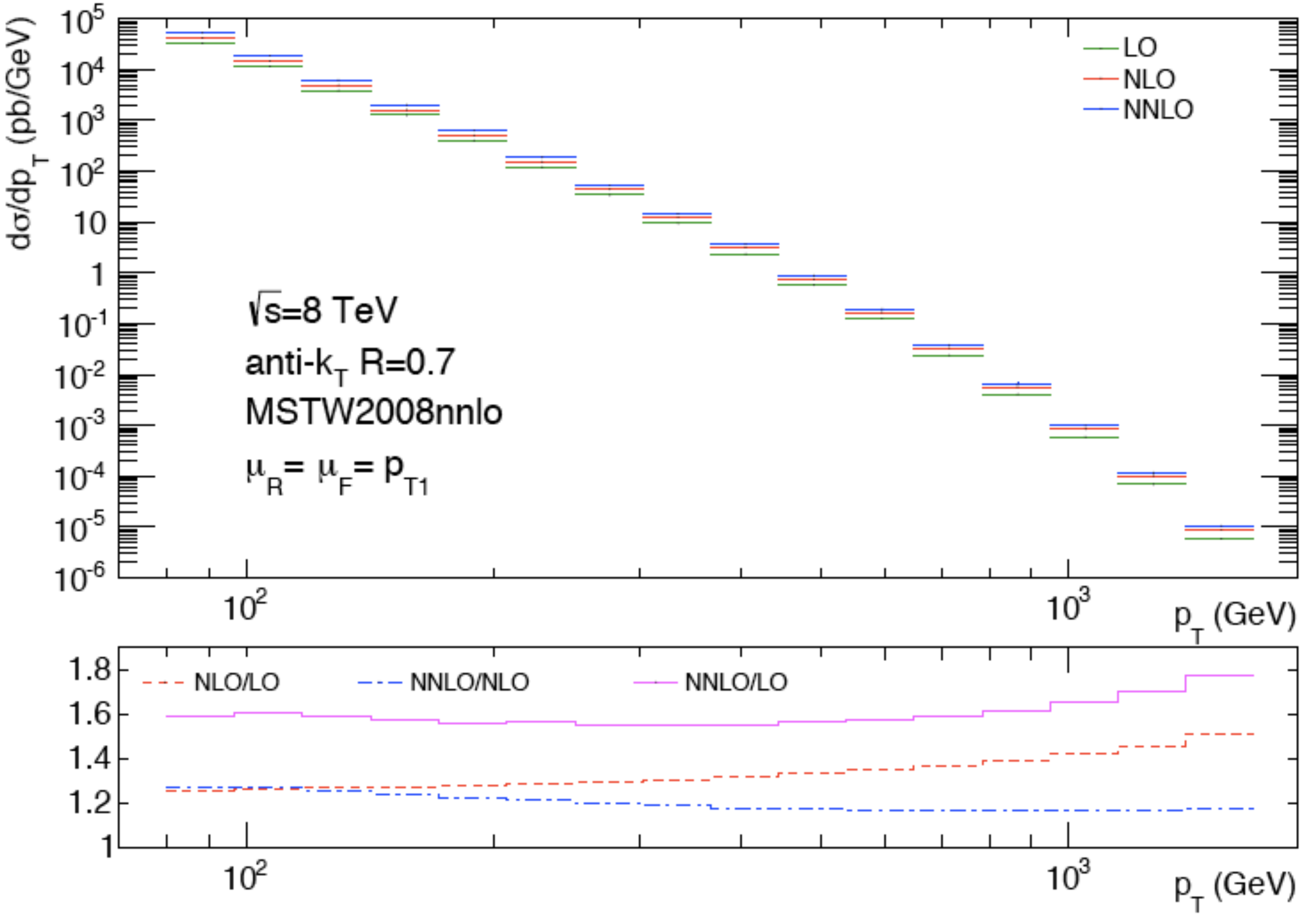
- Several methods, but only a few have been demonstrated to work for a generic hadron collider process
  - Sector decomposition Anastasiou, Melnikov, Petriello (03)
  - Antenna subtraction Gehrmann, Gehrmann-De Ridder, Glover (05)
  - qT subtraction Catani, Grazzini (07)
  - Sector-improved residue subtraction Czakon (10); R.B., Melnikov, Petriello (11)
  - N-jettiness subtraction R.B. Focke, Liu, Petriello (15); Gaunt, Stahlhofen, Tackmann, Walsh (15)
  - Colourful subtraction Del Duca, Somogyi, Trocsanyi (05)
  - Projection to Born (P2B) Cacciari, Dreyer, Karlberg, Salam, Zanderighi (15)

Antenna Subtraction

- Antenna subtraction: analytic cancellation of poles. Can handle a generic LHC process and so far applied to:
  - e+e- → 3 jets Gehrmann-De Ridder, Gehrmann Glover, Heinrich (07)
  - dijet production (partial) Gehrmann-De Ridder, Gehrmann, Glover, Pires (13); Currie, Gehrmann-De Ridder, Gehrmann, Glover, Pires (13); Currie, Gehrmann-De Ridder, Glover, Pires (13)
  - Z+jet (leading color, dominant channels) Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan (15)
  - Higgs + 1 jet (gluon only) Chen, Gehrmann, Glover, Jacquier (14)
  - top-pair production (partial, quarks only) Abelof, Gehrmann, Majer (14)

Antenna Subtraction

- Phenomenology example: inclusive jet production, important for high-x gluon PDF.



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

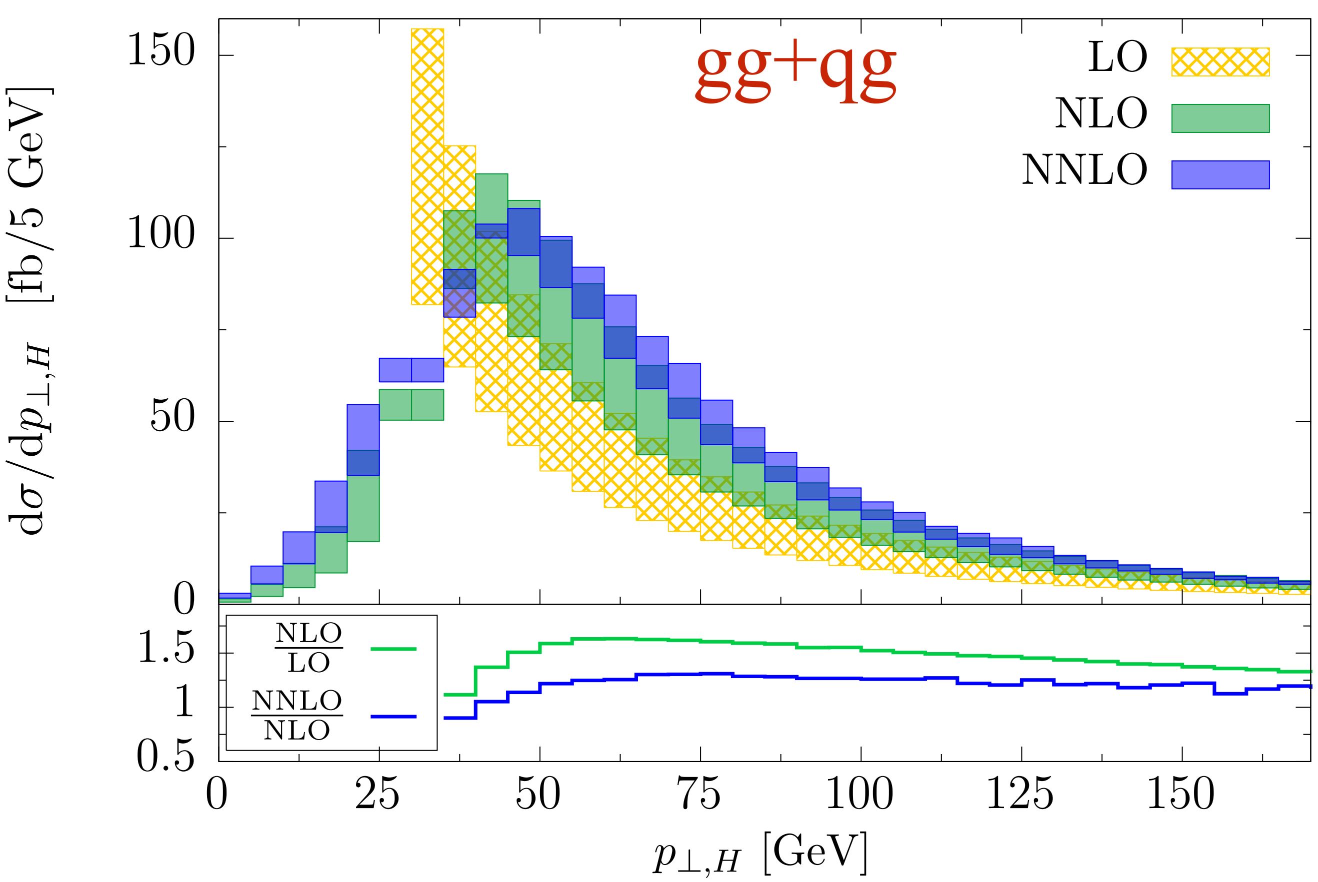
Currie, Gehrmann-De Ridder, Glover, Pires 1310.3993

Sector-improved Residue Subtraction

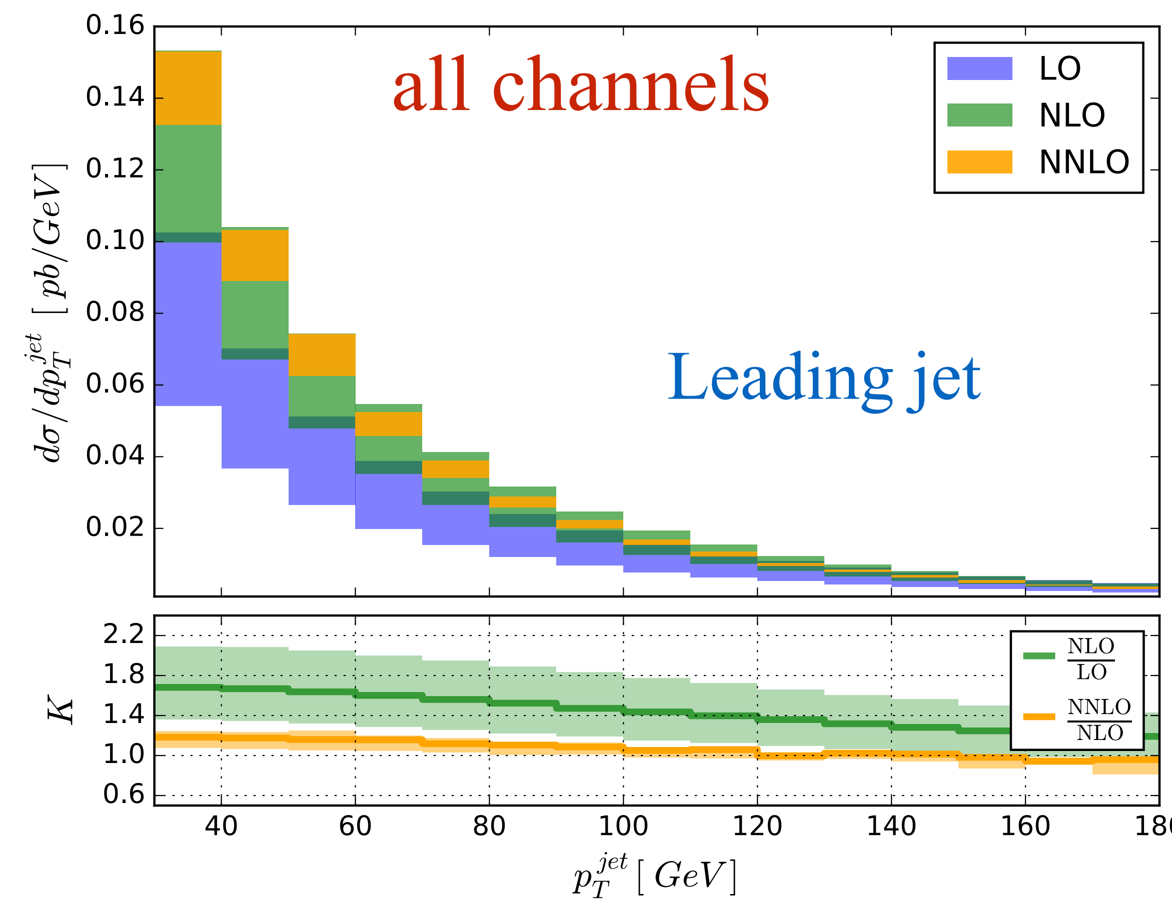
- Sector-improved residue subtraction: numerical cancellation of poles. Can handle a generic LHC process and so far applied to:
  - $Z \longrightarrow e+e-$ R.B, Melnikov, Petriello (11)
  - top-pair production (inclusive and differential) Bernreuter, Czakon, Fiedler, Mitov (12-13); Czakon, Fiedler, Mitov (14)
  - $b \longrightarrow X_\mu\ e\ \nu$ Bruchseifer, Caola, Melnikov (13)
  - Higgs + jet R.B., Caola, Melnikov, Petriello, Schulze (13-15)
  - Single top Bruchseifer, Caola, Melnikov (14)
  - muon decay spin asymmetry Caola, Czarnecki, Liang, Melnikov, Szafron (14)

Example: Higgs+jet at NNLO

- Phenomenology example: Higgs+jet, needed for a description of Higgs p_T distribution; can help discriminate between BSM effects (Banfi, Martin, Sanz 1308.4771; Azatov, Paul 1309.5273)
- Two calculations available for comparing with data: a first based on sector-improved subtraction providing the relevant channels (gg and qg) (R.B, Caola, Melnikov, Petriello, Schulze) and a second one based on jettiness subtraction providing all channels (R.B, Focke, Giele, Liu, Petriello)



R.B, Caola, Melnikov, Petriello, Schulze, 1302.6216 and 1504.07922



R.B, Focke, Giele, Liu ,Petriello, 1505.03893

Example: Higgs+jet at NNLO

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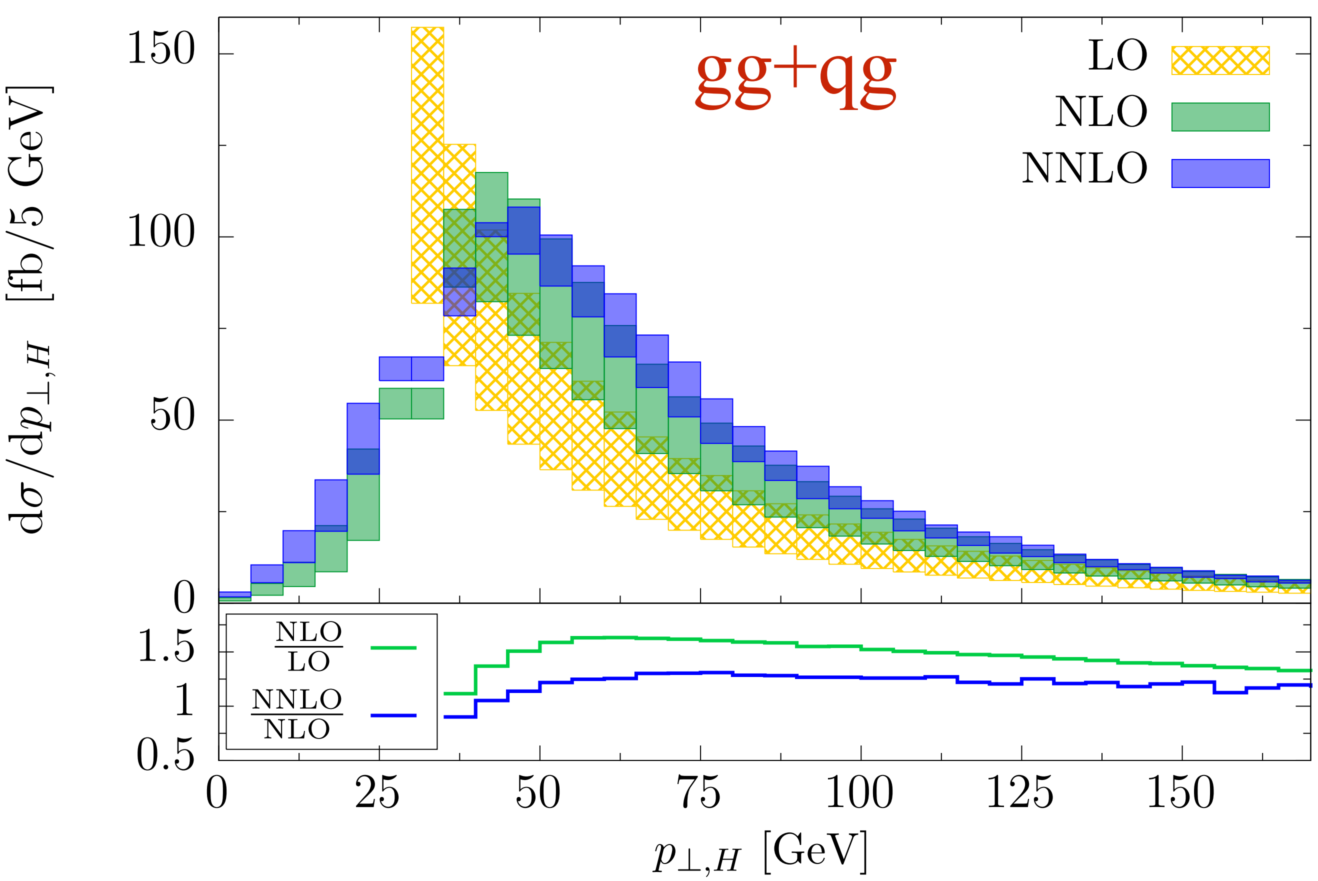
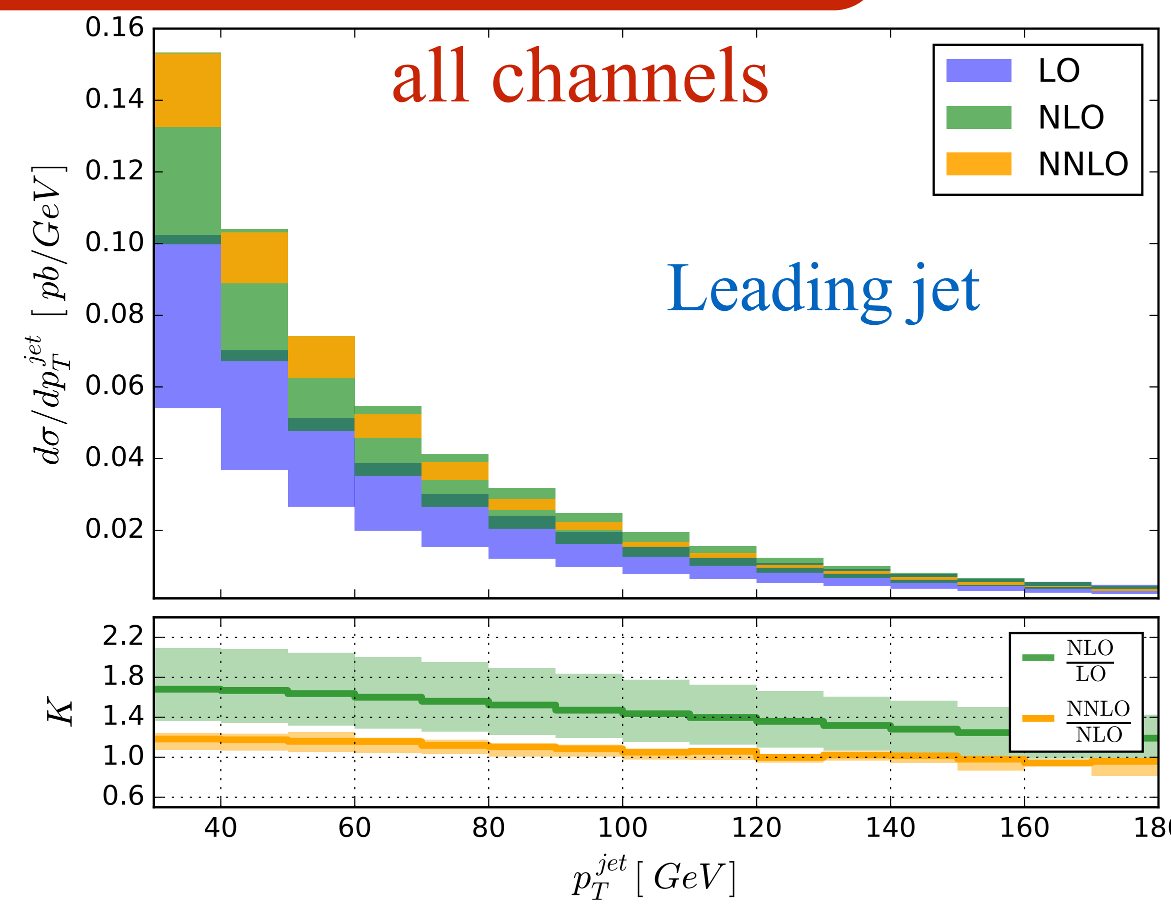
Sanz 1308.
- Two calc
sector-im
(R.B, Caola
subtracti

- Non-trivial K-factor shape as a function of p_{Tj} and p_{TH}
- Good perturbative behavior and smaller uncertainties for all differential distributions
- Corrections in inclusive σ are 20% for for $\mu = m_H$ and 4% for for $\mu = m_H/2$.



R.B, Caola, Melnikov, Petriello, Schulze, 1302.6216 and 1504.07922



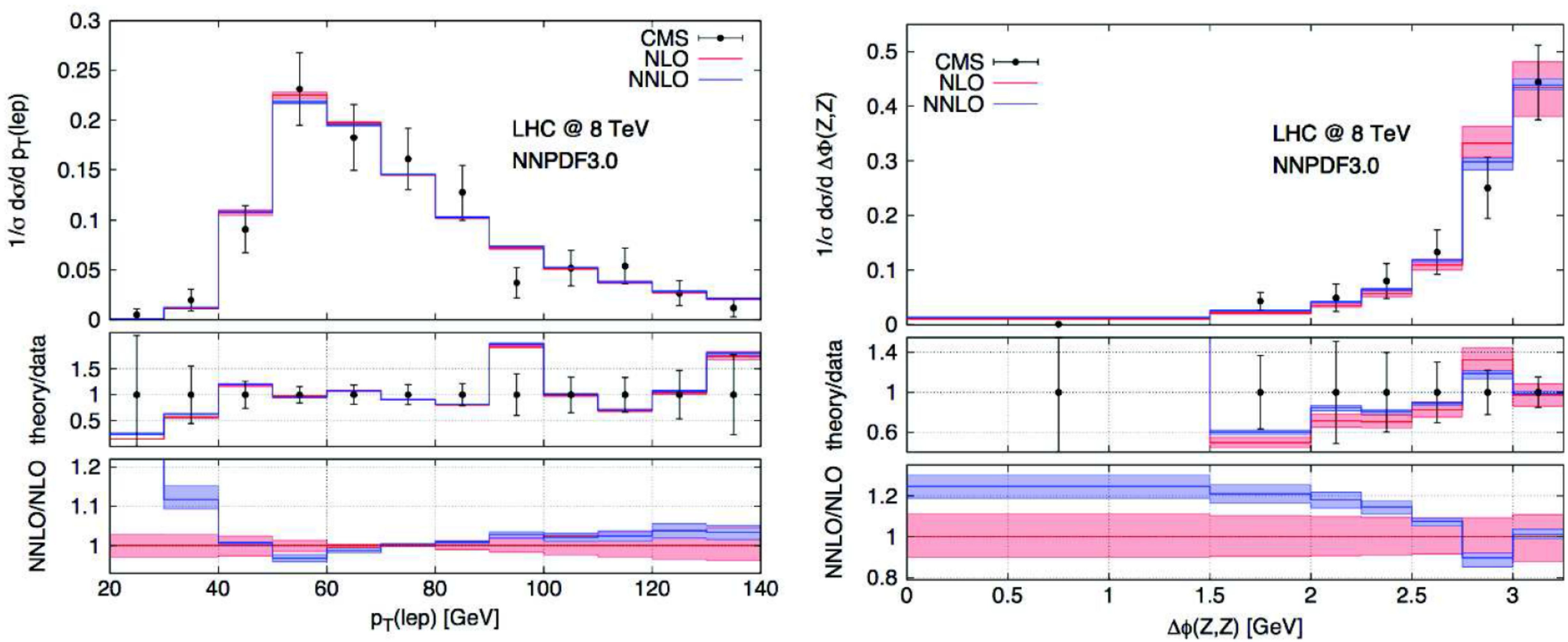
R.B, Focke, Giele, Liu ,Petriello, 1505.03893

q_T Subtraction

- q_T subtraction: uses resummation, singularities are subtracted analytically. Applied mostly to colorless final state, and recently to top quark pair production at hadron colliders:
  - **γγ** Catani, Cieri, De Florian, Ferrera, Grazzini (11)
  - WH and ZH Ferrera, Grazzini, Tramontano (11-14)
  - W**γ** and Z**γ** Grazzini, Kallweit, Rathlev, Torre (13); Grazzini, Kallweit, Rathlev (15)
  - ZZ Cascioli, Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs, (14); Grazzini, Kallweit, Rathlev (15)
  - WW Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi (14)
  - top-pairs (partial) Bonciani, Catani, Grazzini, Hargsyan, Torre (15)

q_T Subtraction

- Phenomenology example: Z boson pair production with decays. Leads to improved agreement with data for $\Delta\phi$.



Grazzini, Kallweit, Rathlev, 1507.06257

q_T Subtraction

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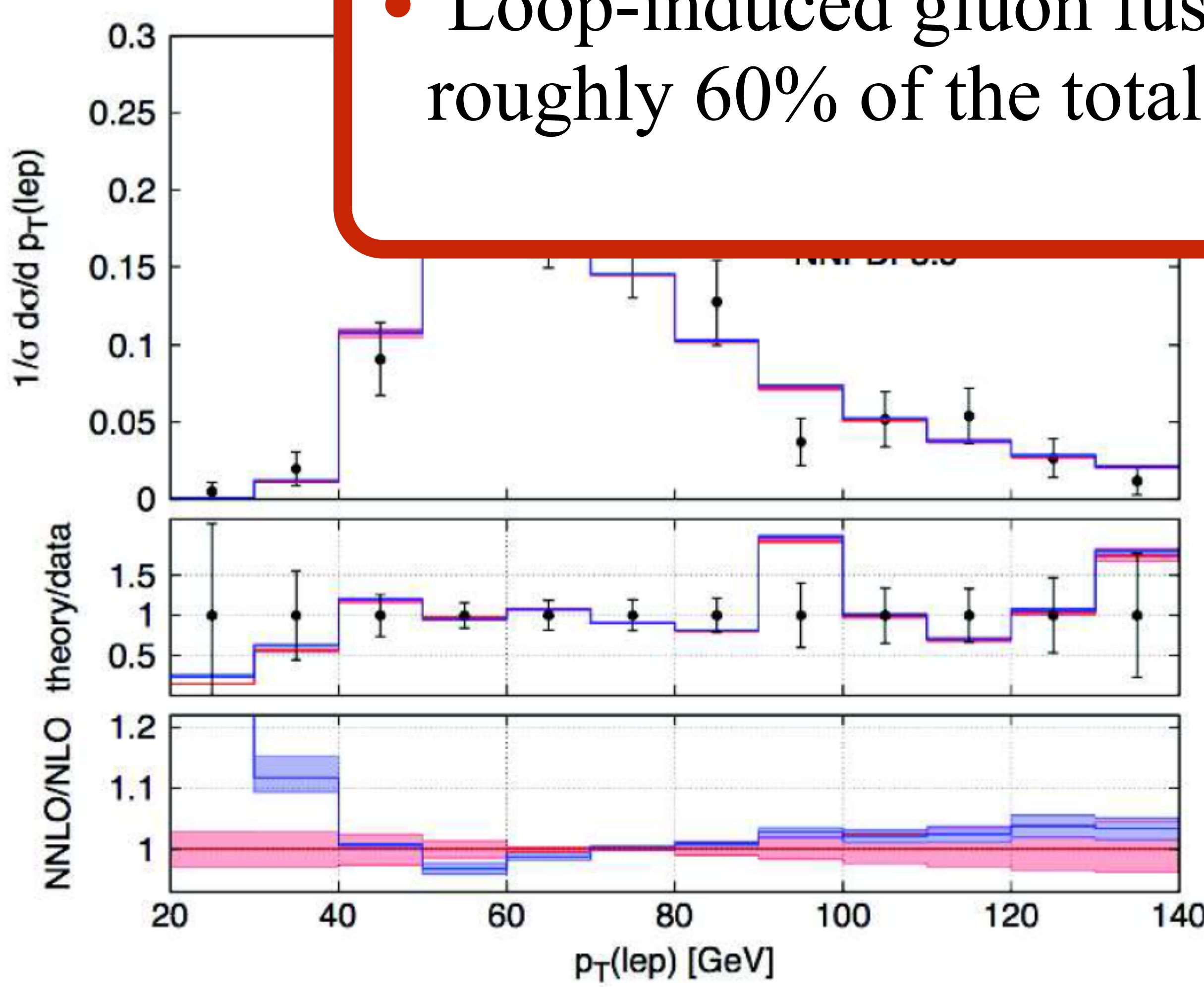
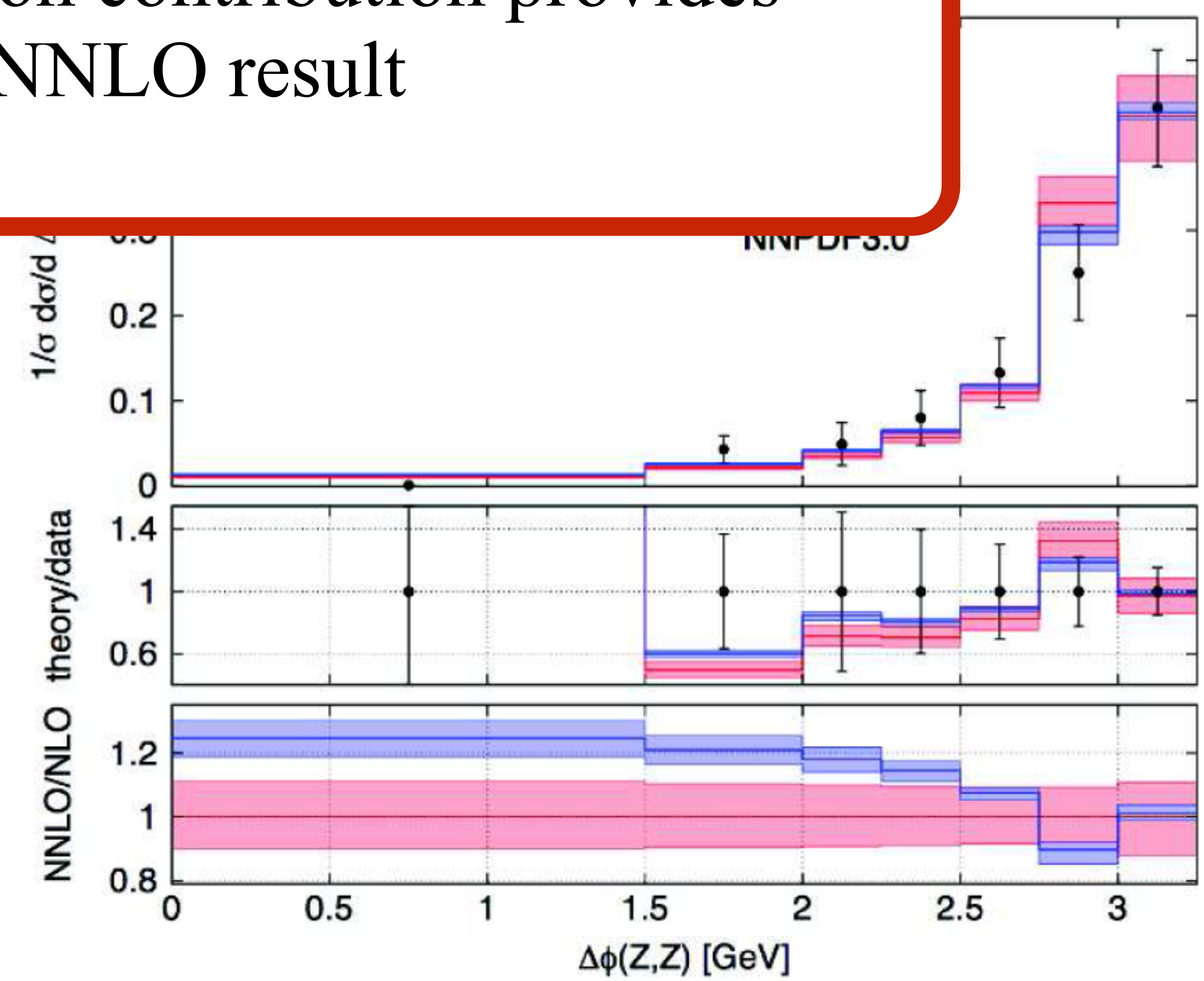
- NNLO corrections increase the NLO result by 11%-17% as sqrt(s) increases from 7 to 14 TeV
- Loop-induced gluon fusion contribution provides roughly 60% of the total NNLO result





Grazzini, Kallweit, Rathlev, 1507.06257

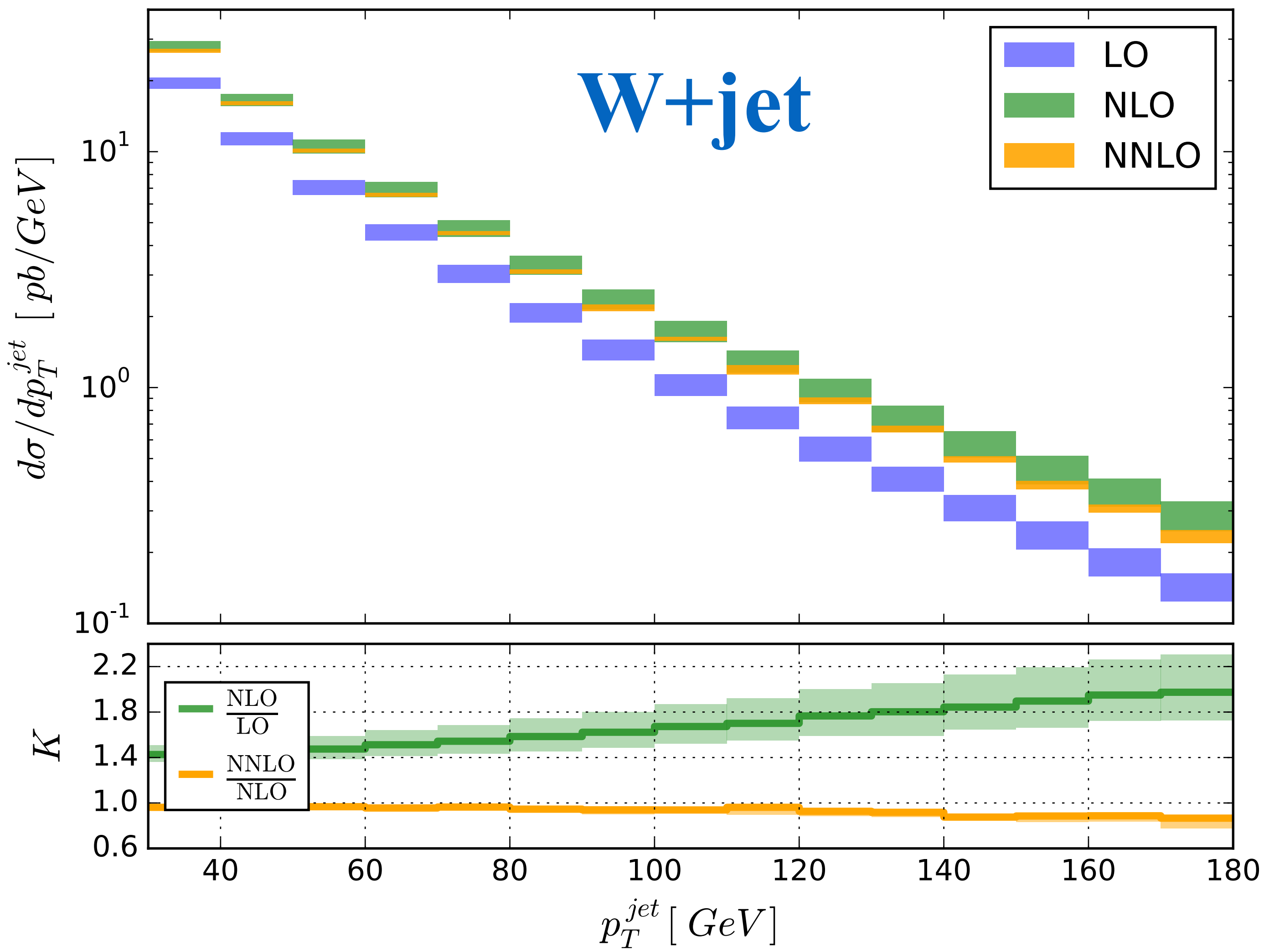
N-jettiness Subtraction

- Jettiness subtraction: uses resummation to remove double unresolved singularities. Can handle a generic LHC process and so far applied to:

  - W+jet R.B., Focke, Liu, Petriello (15)
  - Higgs+jet R.B., Focke, Giele, Liu, Petriello (15)
  - Higgs/Drell-Yan Gaunt, Stahlhofen, Tackmann, Walsh (15)

- Sample phenomenology example: W+jet, benchmark process in the SM. Required for precision prediction of W p_T, and will be used as a constraint on gluon PDF at large x.

N-jettiness Subtraction



R.B, Focke, Liu, Petriello 1504.02131

$p_T^{jet} > 30$ GeV, $\lvert\eta_{jet}\rvert < 2.4$	
Leading order:	533^{+39}_{-38} pb
Next-to-leading order:	797^{+63}_{-49} pb
Next-to-next-to-leading order:	791^{+0}_{-6} pb

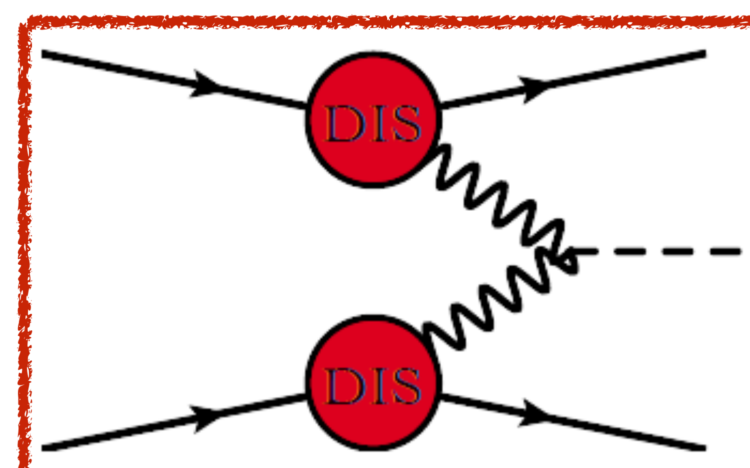
Very mild shift from NLO to NNLO and almost flat dependence on p_{Tj}

Corrections: LO $\xrightarrow{+40\%}$ NLO $\xrightarrow{-1\%}$ NNLO for $\mu = m_W$

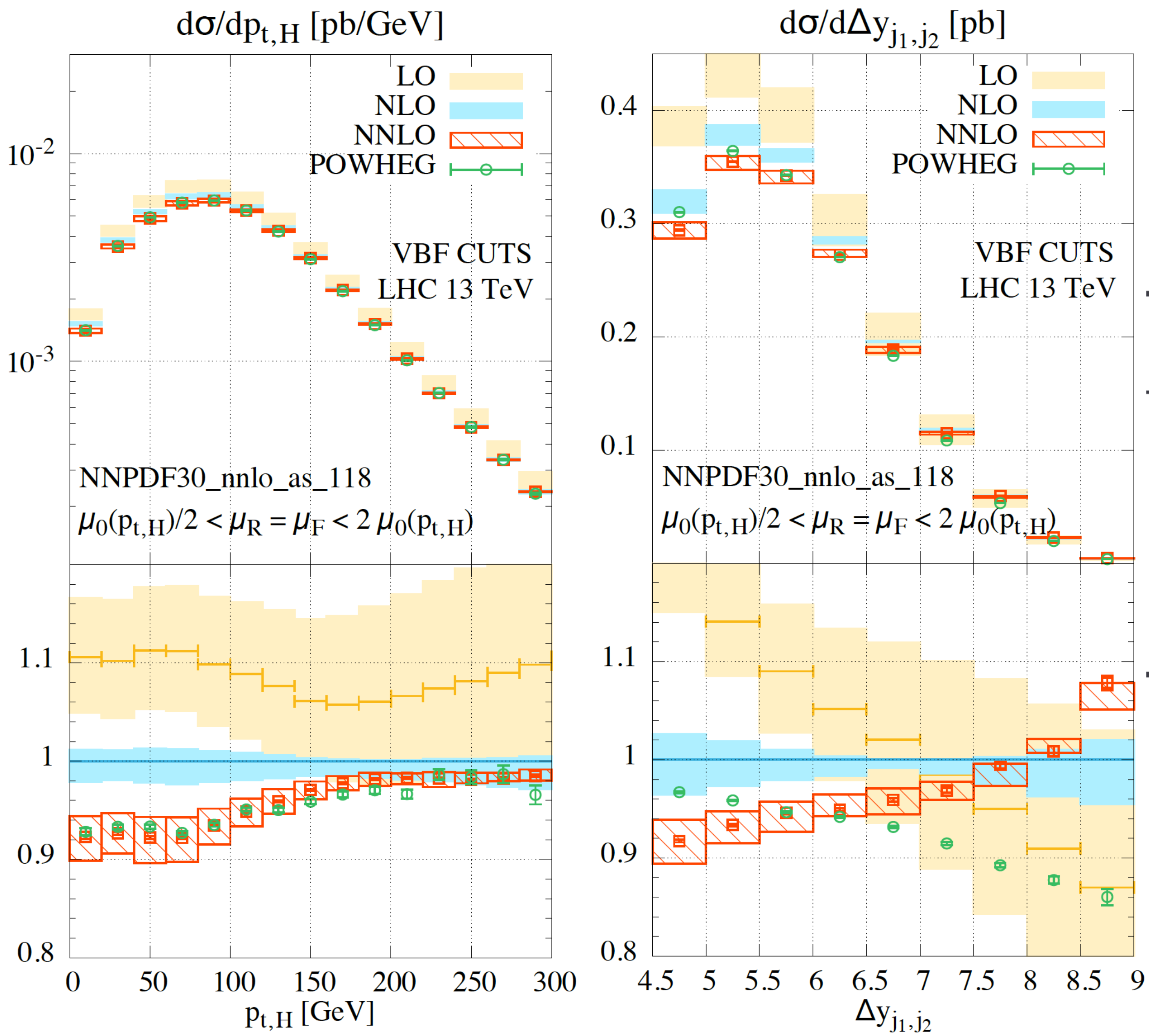
Scale uncertainties: 7% LO 7% NLO ~ <1% NNLO

Colourful Subtraction and P2B

- Colorful subtraction: analytical cancellation of poles. First application to $H \to bb$ (Del Duca, Duhr, Somogyi, Tramontano, Trocsanyi, (15))
- Projection to Born (P2B): uses simple kinematics of DIS to project double-real emission singularities to Born phase space. Not general, so far applied to differential VBF Higgs (Cacciari, Dreyer, Karlberg, Salam, Zanderighi (15)).
- Differential VBF@NNLO calculated in the structure function approach (2loop virtuals unknown for the $2 \to 3$ process) Bolzoni, Maltoni, Moch, Zaro
  - ✦ Structure function approach: no color exchange between the two quark lines
    - Exact at NLO
    - VBF = $(\mathrm{DIS})^2$
  - ✦ Small Corrections for the inclusive case: 1-2%



P2B



13TeV, anti-KT, R=0.4, NNPDF

	$\sigma^{(\text{no cuts})}$ [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	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$
	~ -1%	~ -5%

NNLO corrections outside the NLO band after VBF cuts

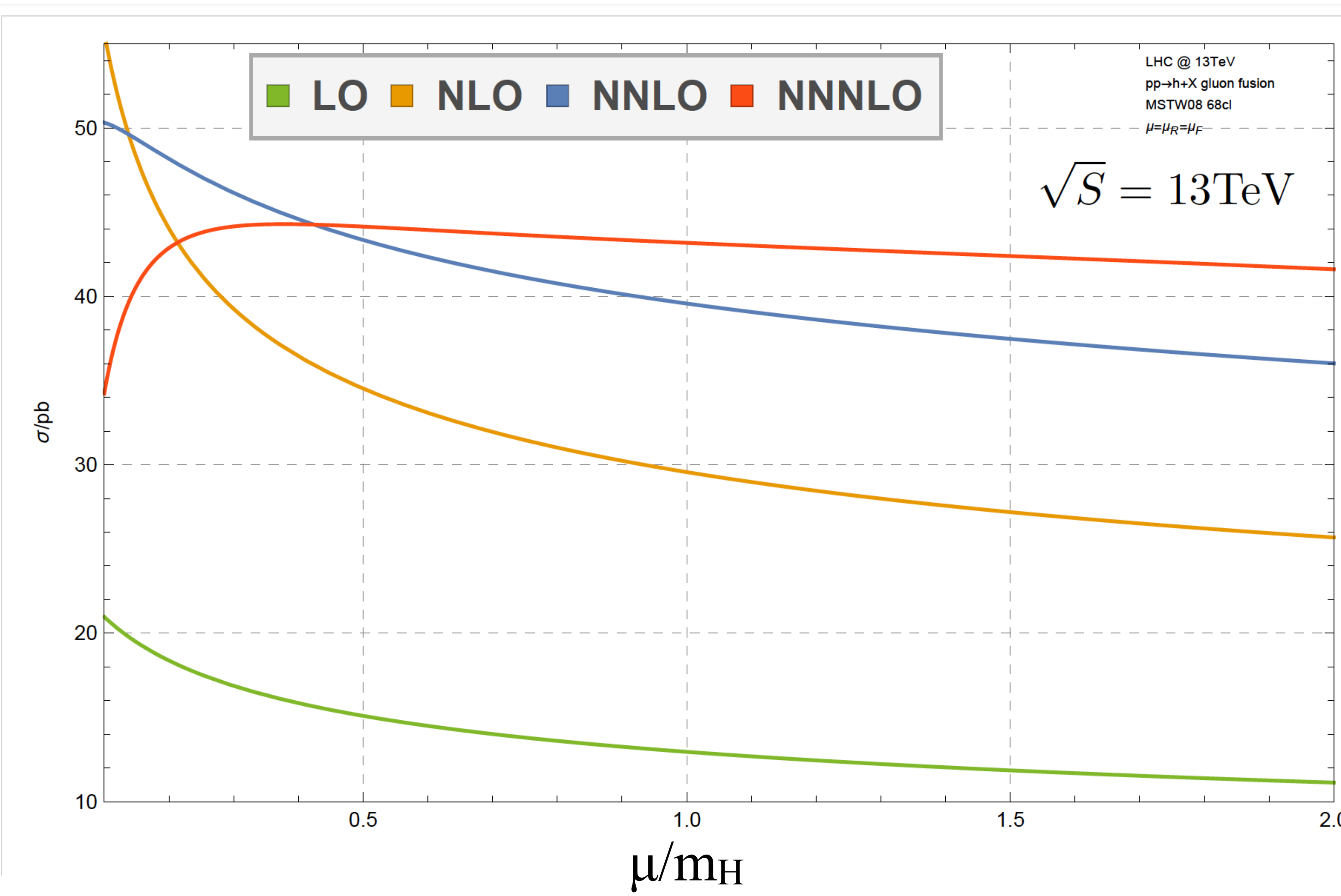
Cacciari, Dreyer, Karlberg, Salam, Zanderighi, 1506.02660

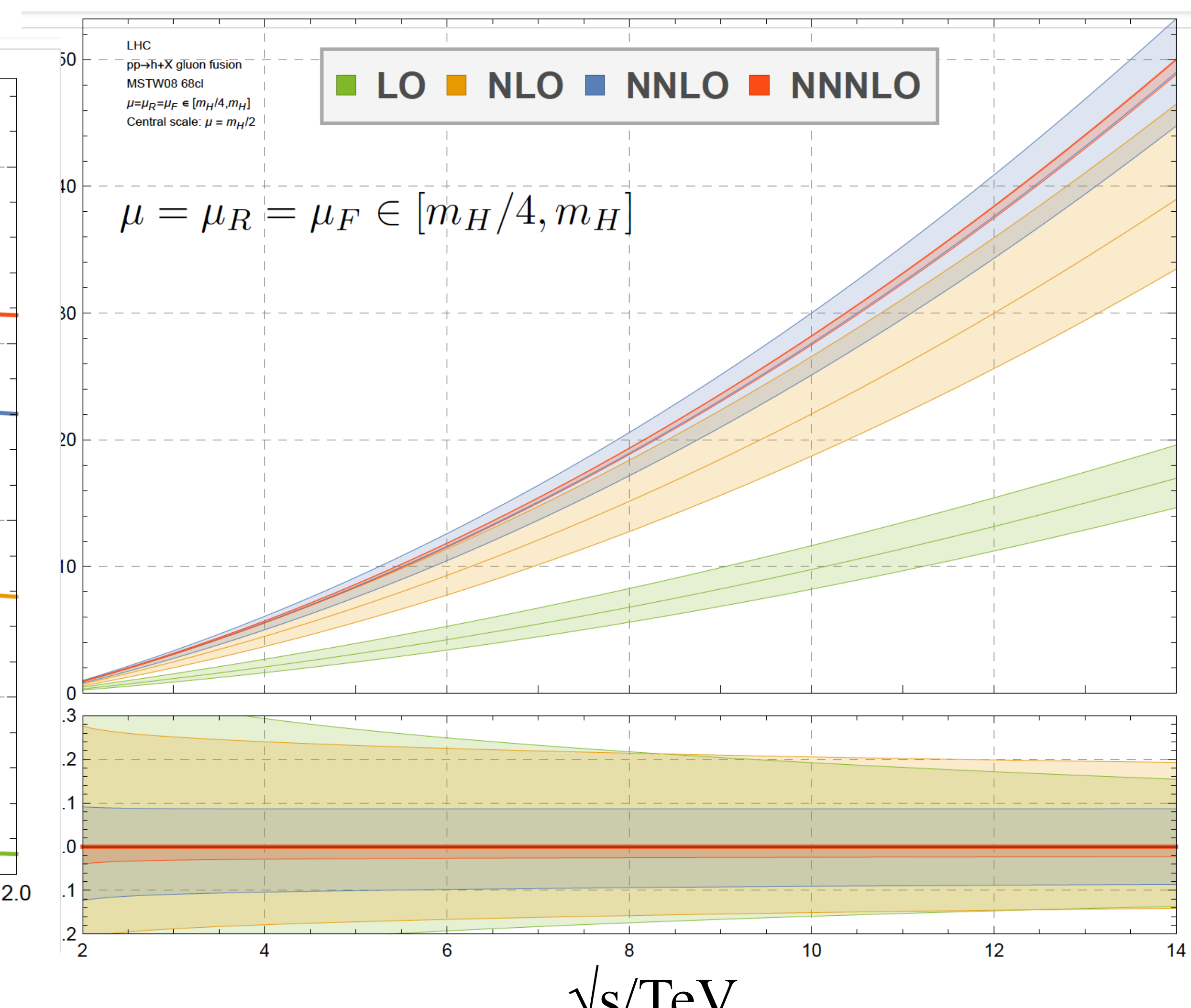
- NLO+parton shower agrees well with NNLO for P_{TH} but not for $\Delta y_{j1,j2}$
- Non trivial kinematic dependence of the K-factors

Beyond NNLO

- Inclusive Higgs production in gluon fusion is now known at N^3LO in QCD (infinite top mass limit approximation)
- Calculation motivated by the large QCD corrections to $\boldsymbol{\sigma}$ and slow perturbative convergence.
- Impacts directly the overall signal strength

Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)

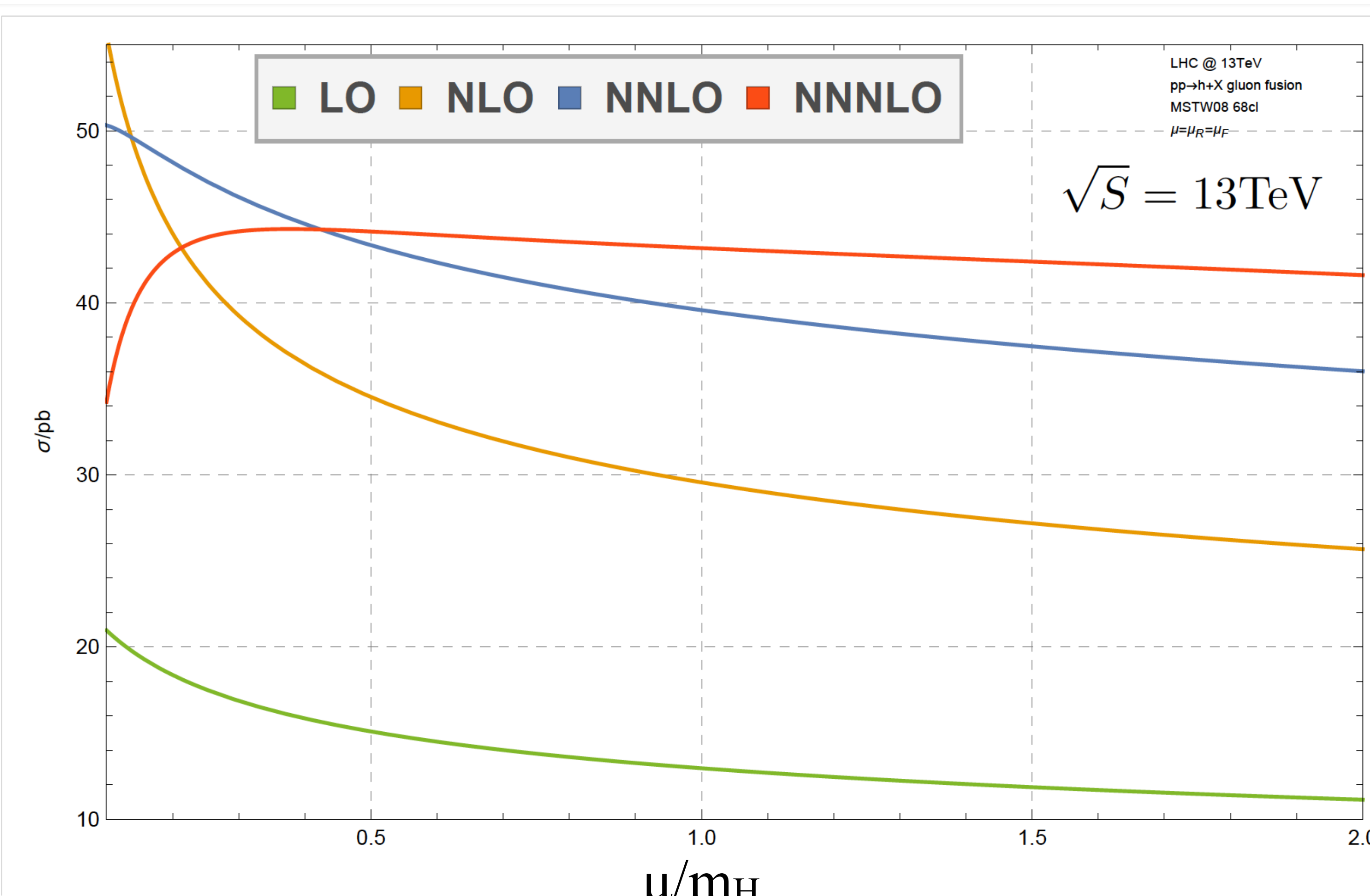


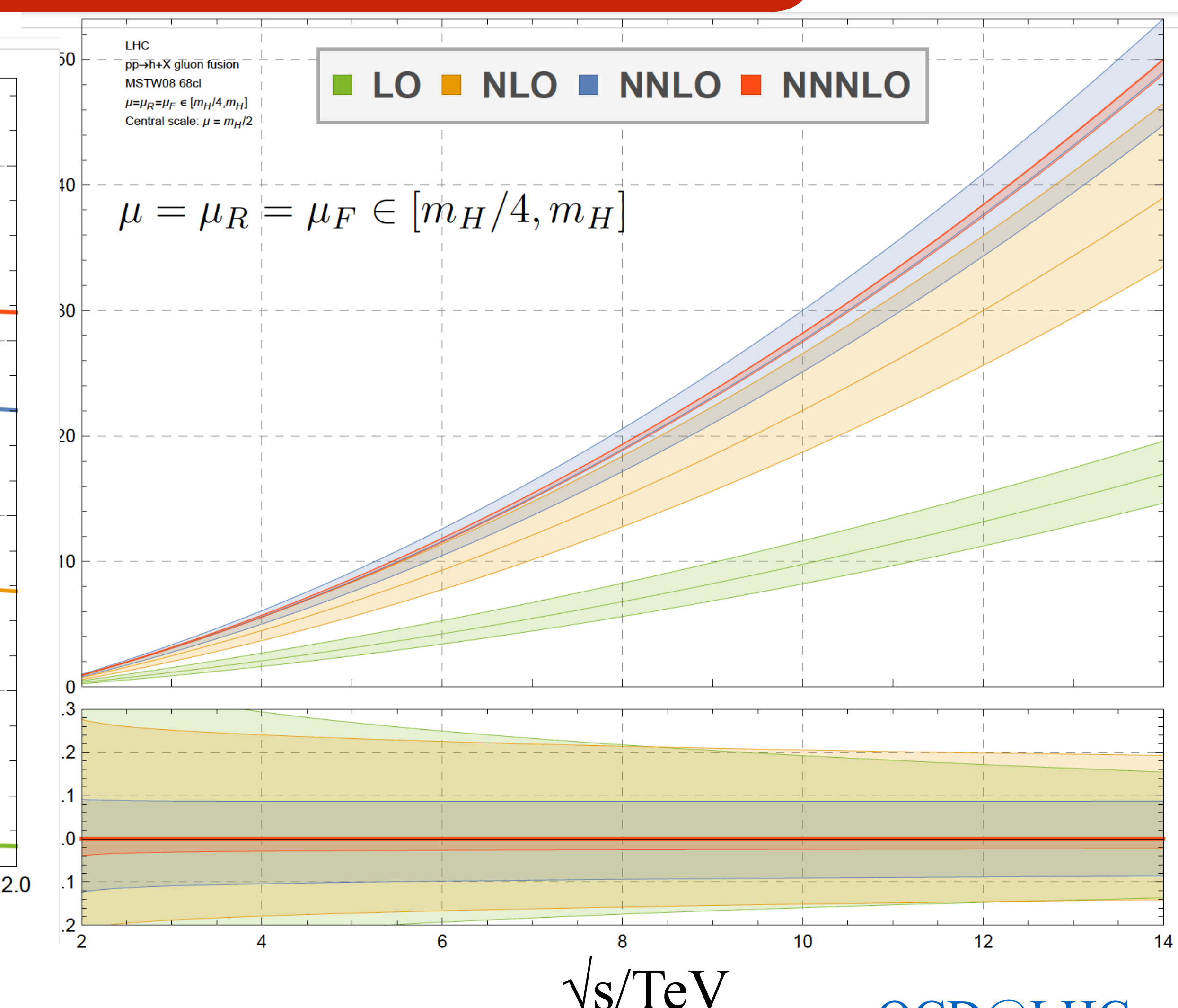


Beyond NNLO

- Inclusive Higgs production in gluon fusion is now known at N
QCD (inf
- Calculat
perturbat
- Affects c

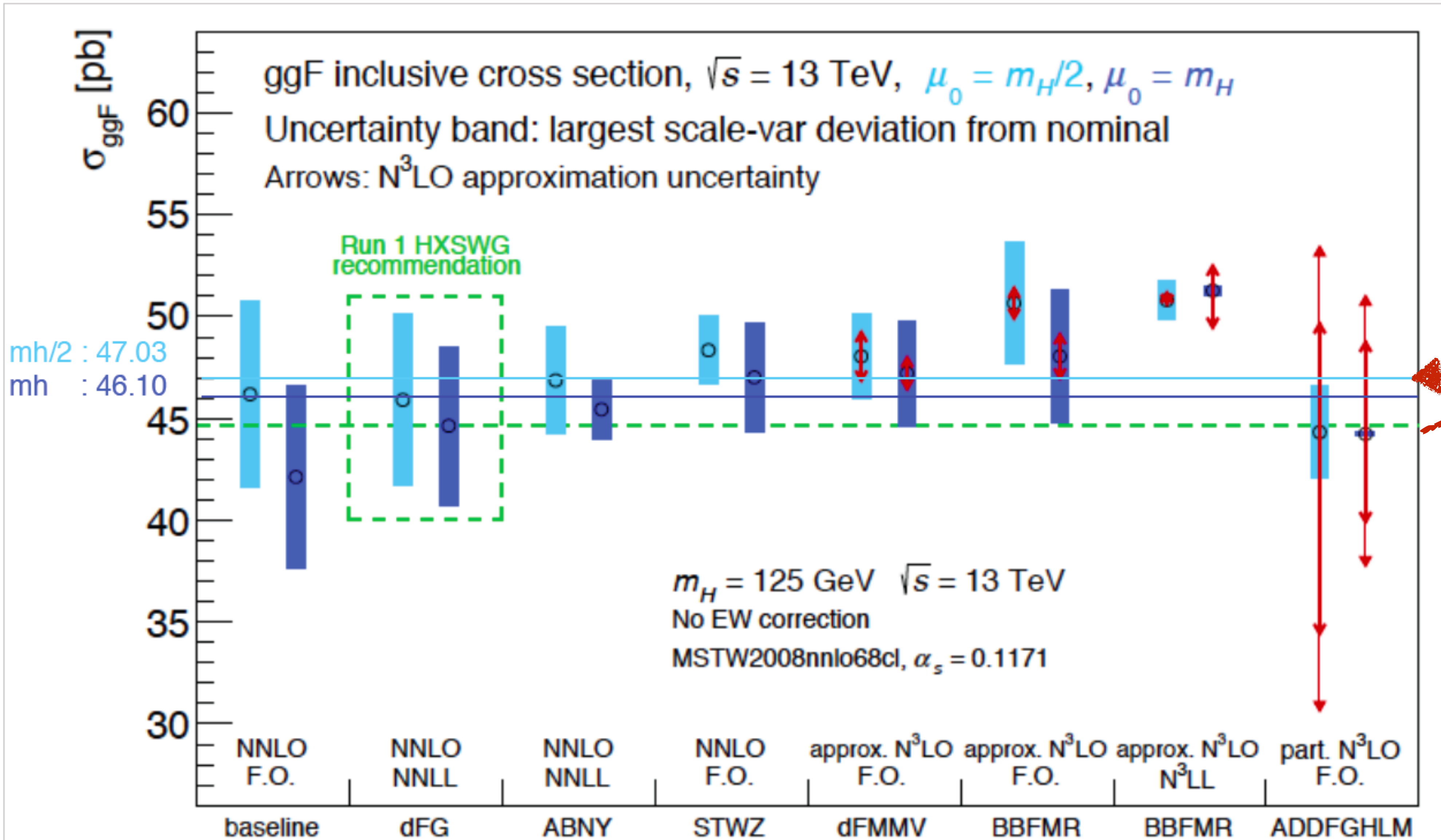
- An additional 2.2% correction for $\mu_F = \mu_R = m_H/2$ w.r.t. NNLO (8.9% for $\mu_F = \mu_R = m_H$)
- Uncertainties from missing higher order corrections reduced down to ~ 3%





Beyond NNLO

Duhr, Higgs Hunting 2015

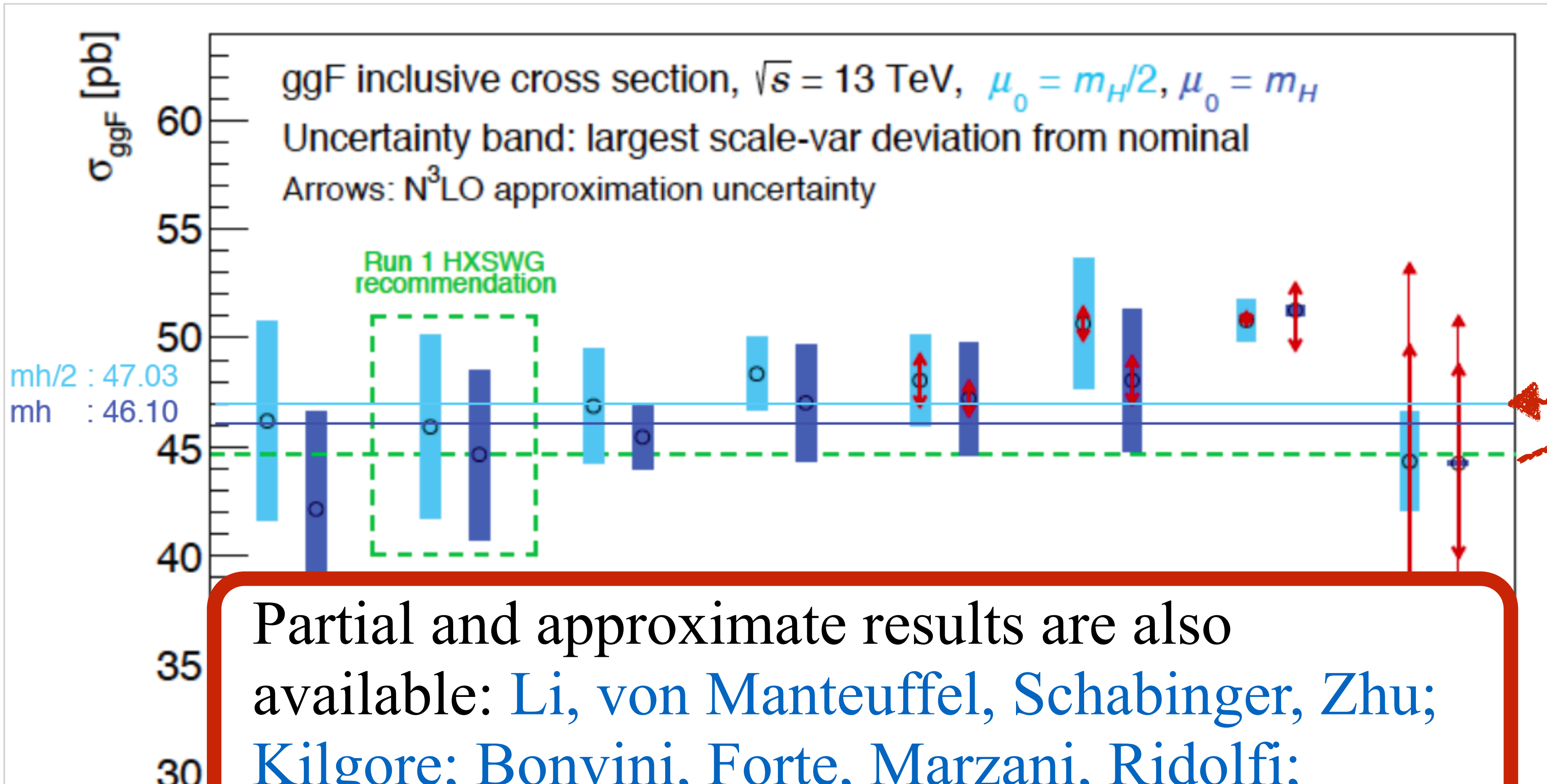


~ 4% increase in σ from Run 1 HXSWG recommendation

- Note: impact of soft-gluon resummation negligible for $\mu = m_H/2$ but necessary to take into account for $\mu = m_H$
- Attention shifting to other uncertainties: top-bottom interference in loops, heavy top-mass approximation, EW effects and treatment of mixed QCD-EW effects

Beyond NNLO

Duhr, Higgs Hunting 2015



~ 4% increase in σ from Run 1 HXSWG recommendation

Partial and approximate results are also available: Li, von Manteuffel, Schabinger, Zhu; Kilgore; Bonvini, Forte, Marzani, Ridolfi; Buehler, Lazopoulos; Hoeschele, Hoff, Ball, Pak, Steinhauser, Ueda

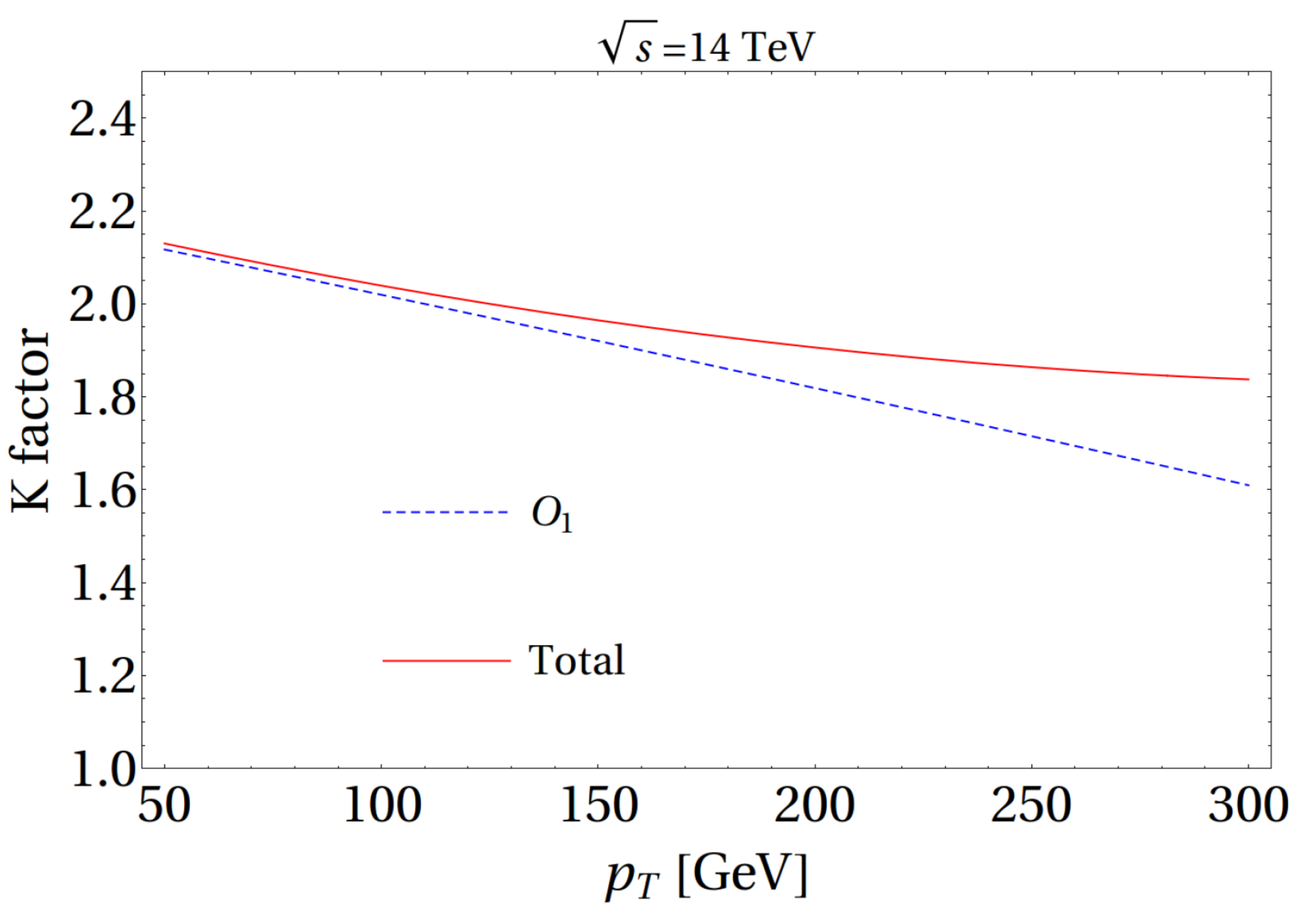
- Note: impact of soft-gluon resummation negligible for μ = m account for
- Attention shifting to other uncertainties: top-bottom interference in loops, heavy top-mass approximation, EW effects and treatment of mixed QCD-EW effects

Beyond Infinite m_{top}: H+j as an Example

- The infinite top-mass limit was shown to work well up to $p_{TH} \leq 150$GeV (Harlander, Neumann, 2013).
- Can go beyond the infinite top-mass limit @ NLO to get improved SM prediction for $p_{TH} \geq 150$GeV

$$\mathcal{L}_{\rm eff} = \hat{C}_1 O_1 + \frac{1}{\Lambda^2}\Sigma_{i=2,3,4,5}\hat{C}_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$ (in SM, $\Lambda = m_{top}$)

Dawson, Lewis, Zeng, 2014



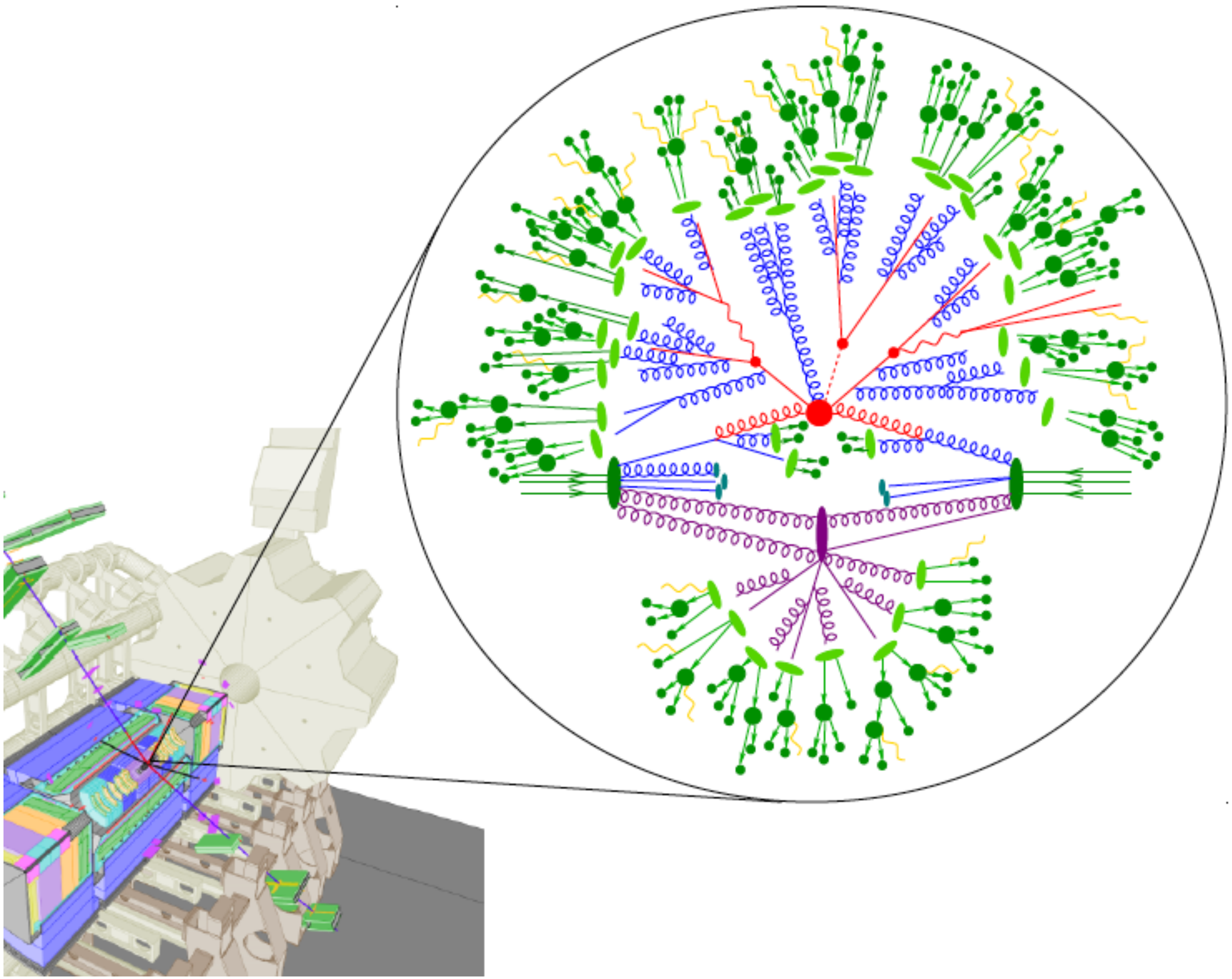
see I. Lewis's talk

$$\boxed{O_1 = G^A_{\mu\nu}G^{\mu\nu,A}h}$$ dim. 5, SM operator

$$\begin{aligned}
O_2 &= D_\sigma G^A_{\mu\nu} D^\sigma G^{A,\mu\nu}\, h \\
O_3 &= f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu\, h \\
O_4 &= g_s^2\, \Sigma^{n_{lf}}_{i,j=1} \overline{\psi}_i \gamma_\mu T^A \psi_i\, \overline{\psi}_j \gamma^\mu T^A \psi_j\, h \\
O_5 &= g_s \Sigma^{n_{lf}}_{i=1} G^A_{\mu\nu} D^\mu\, \overline{\psi}_i \gamma^\nu T^A \psi_i\, h\,,
\end{aligned}$$

dim. 7 operators

Accurate Event Simulation



Accurate Event Simulation

- Fixed order results describe correctly the hard radiation. Final state jets are described by partons.
- At NLO a jet can have up to two partons, while at NNLO it can have up to three
- Soft and collinear radiation is poorly described.

- Parton shower describes multi-particle dynamics and jet substructure. Allows the generation of full events (i.e. hadronization is accounted for).
- Exponentiates multiple soft and collinear radiation (accounting for leading logarithms)
- Fails to account for hard emissions

✱ Goal: combine the best of the two worlds - NLO/NNLO accuracy for hard radiation with multiple soft emissions

☛ Matching with parton shower

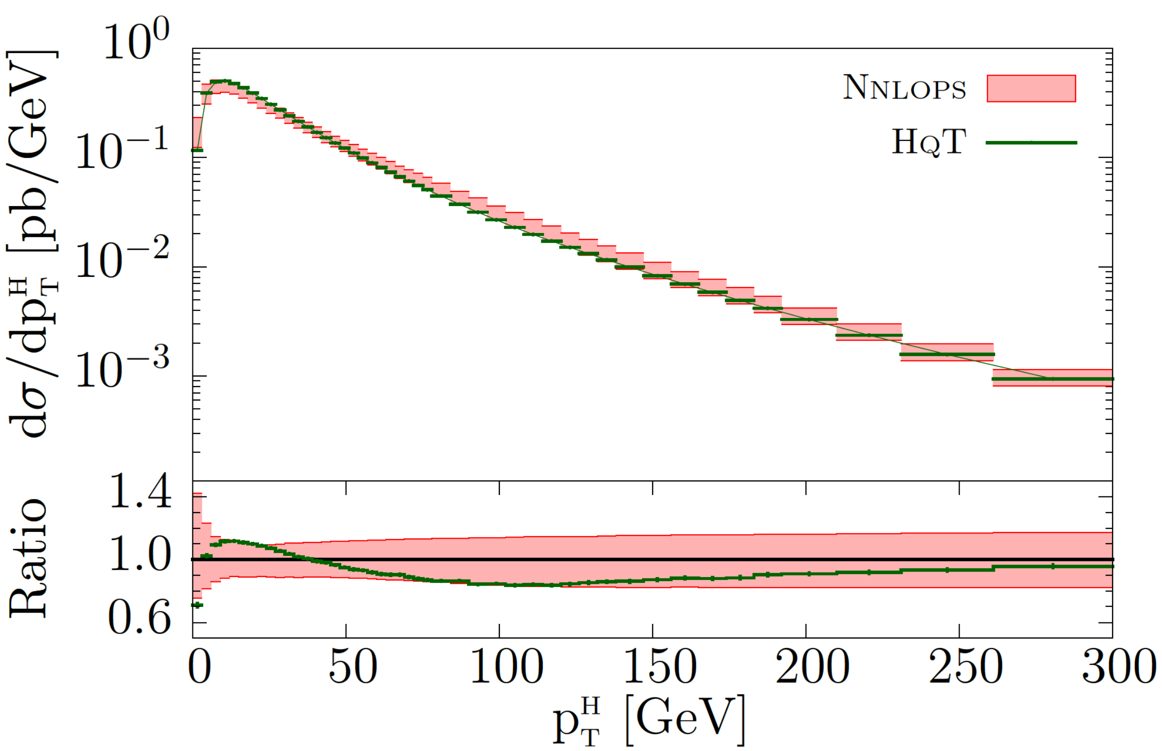
✱ Challenge: how to avoid double counting?

NLO/NNLO + Parton Shower

- Two established methods for NLO+PS:
  - MC@NLO (Frixione, Webber (02))
  - POWHEG (Nason (04); Frixione, Nason, Oleari (07))

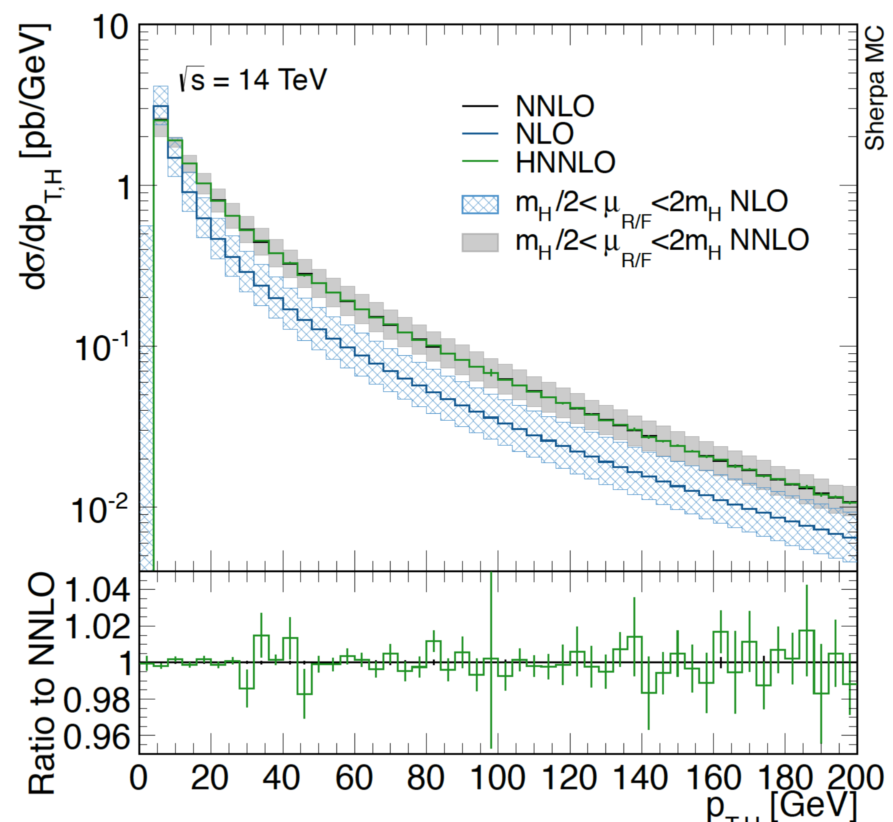
Automated in POWHEG BOX, MG5_aMC@NLO, Sherpa-MC@NLO, PowHel, Matchbox, …

- Current status: initial results for NNLO+PS for simple processes: H/DY



Hamilton, Nason, Re, Zanderighi (13)

Upgrade H+j@NLO+PS to H+0j@NNLO+PS in the singular region of the jet by reweighting the result using NNLO H+0j (MiNLO)

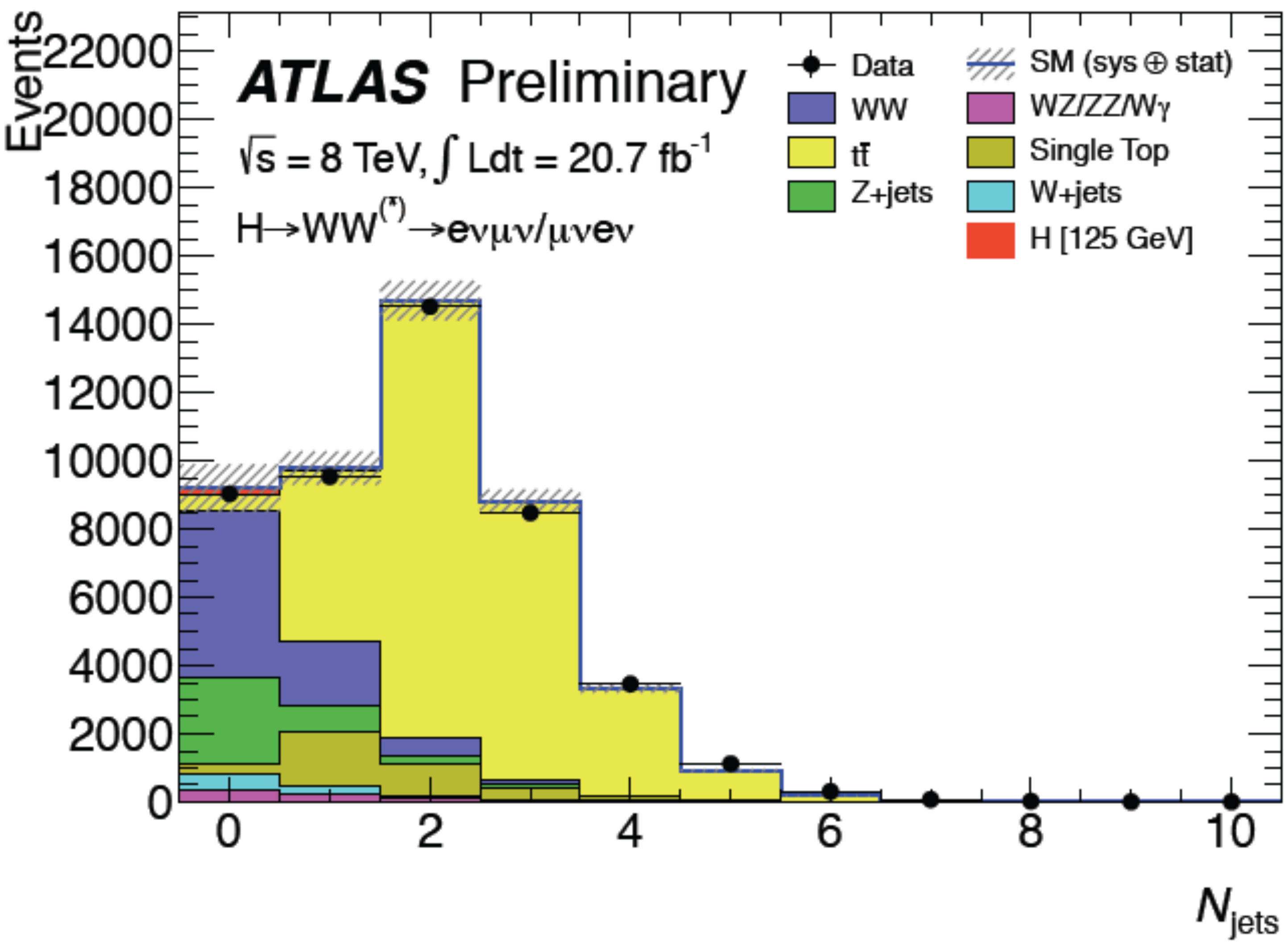


Hoeche, Li, Prestel (14)

Uses MC@NLO for H+1j and fills the zero-p$_T$ bin using knowledge of q$_T$-resummation (UNNLOPS)

Jet Binning and All-orders Resummation

- 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:

$p_{T,veto} \sim 25\text{-}30$ GeV $\ll M_H$

- Relevant term for gluon-fusion Higgs: $2C_A(\alpha_S/\pi)\ln^2(M_H/p_{T,veto}) \sim 1/2$

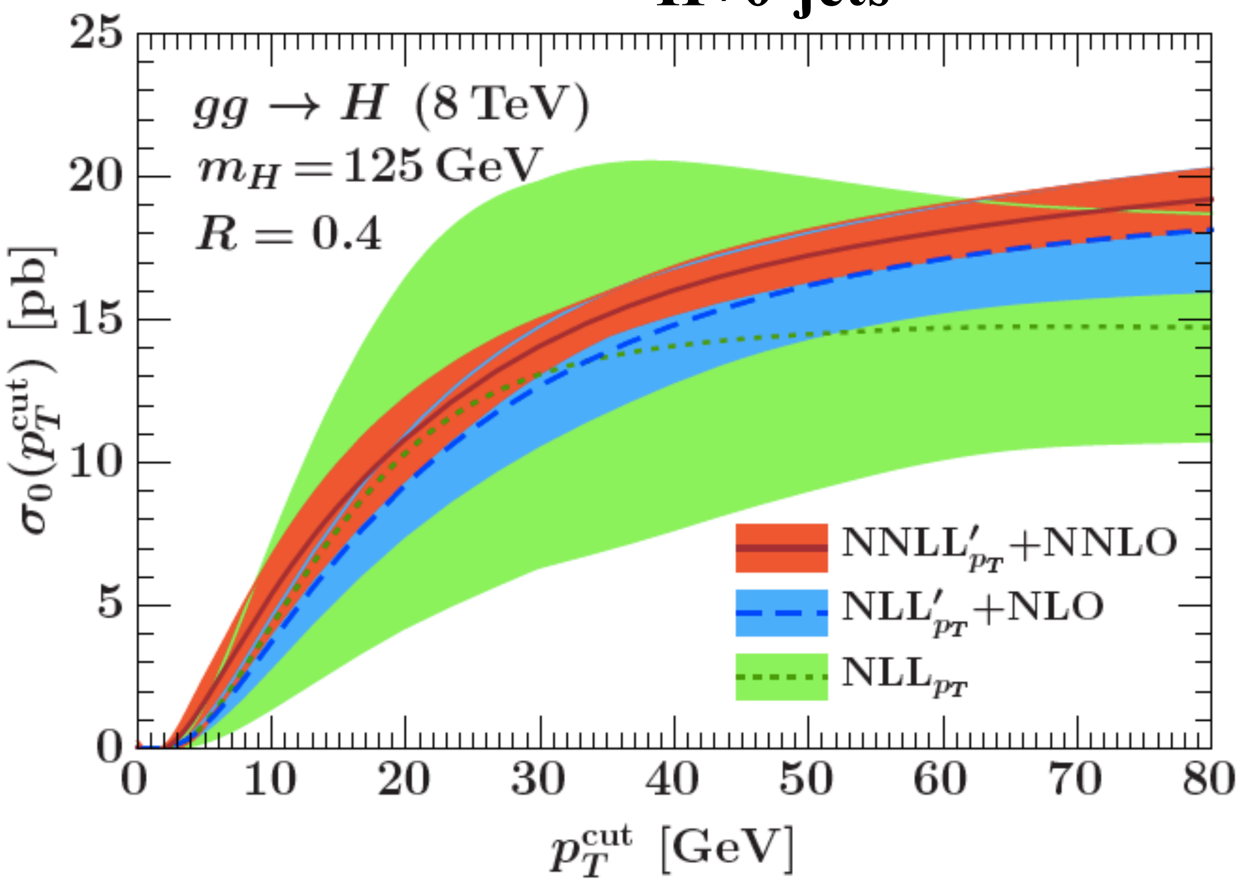
Need to resum these logs; they are a large source of theoretical systematic uncertainty in this channel!

Resummation of Jet Veto Logarithms

- Resummation of jet-veto logarithms in Higgs physics is a very active area

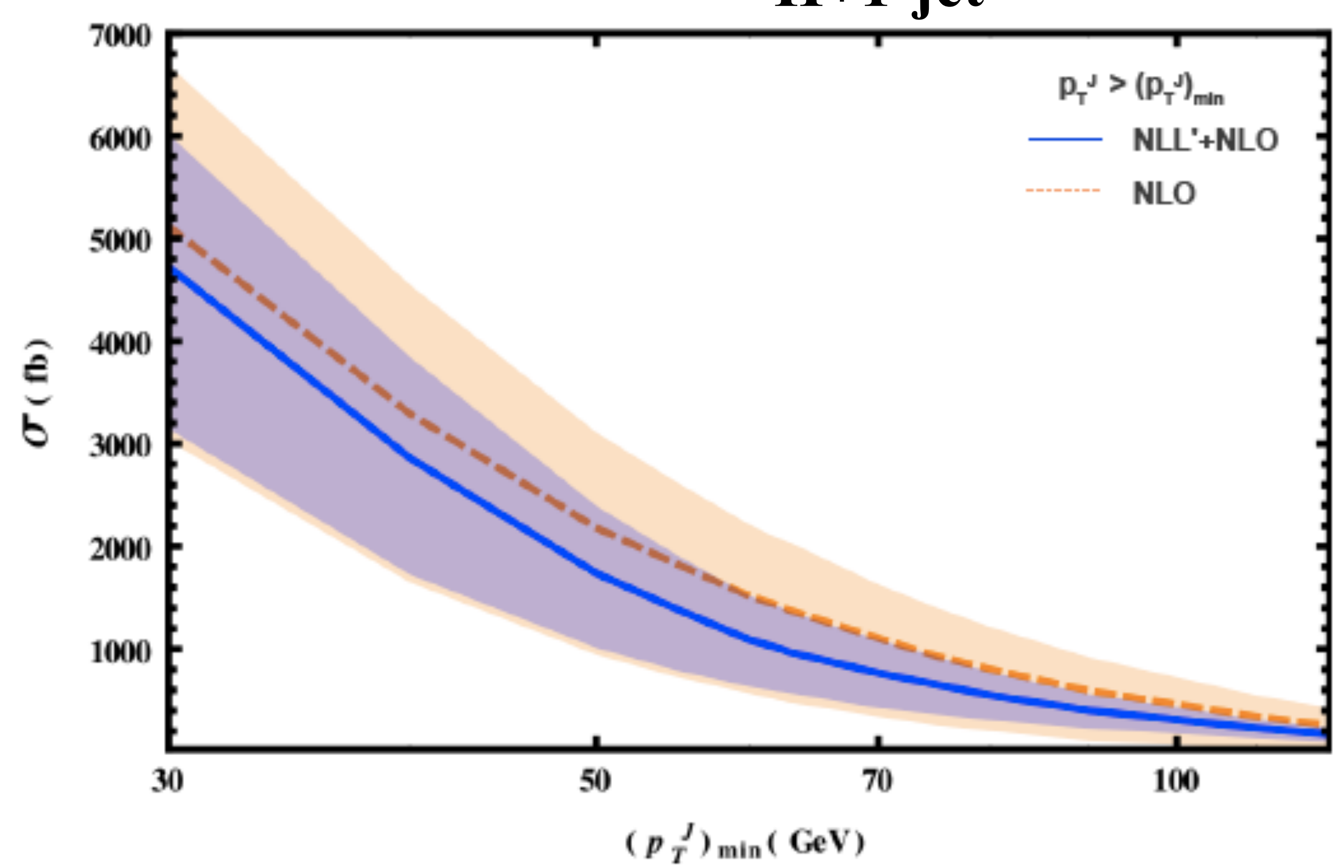
- H+0-jets in gluon fusion (Banfi, Monni, Salam, Zanderighi; Becher, Neubert; Stewart, Tackmann, Walsh, Zuberi)
- H+1-jet in gluon fusion (Liu, Petriello)
- Combination of the 0+1-jet bins (R.B., Liu, Petriello, Tackmann, Walsh)
- Associated VH production with a jet veto (Li,Liu)

H+0-jets



Stewart, Tackmann, Walsh, Zuberi (2013)

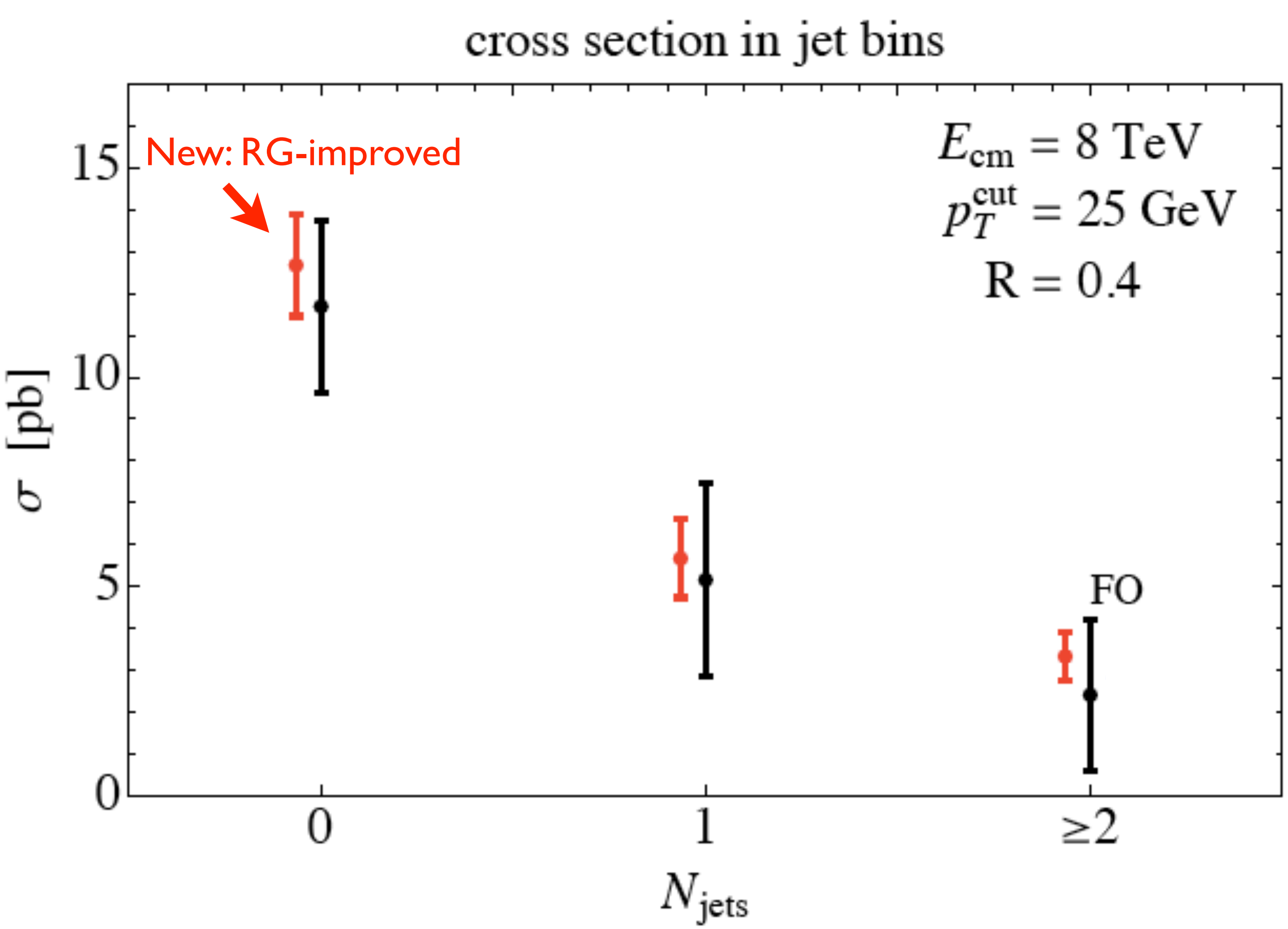
H+1-jet



Liu, Petriello (2013)

Resummation of Jet Veto Logarithms

- Can combine the resummation of the zero-jet and one-jet bins into a complete resummation of the global logarithms affecting the Higgs signal in gluon fusion R.B., Liu, Petriello, Tackmann, Walsh (2014)



- Greatly reduced uncertainties in all three bins used in the analysis
- Leads to a complete covariance matrix for experimental use
- Can translate into a reduced uncertainty in the signal-strength extraction:

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

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

Nearly a factor of 2 reduction in the theory uncertainty affecting the WW channel!

Summary

- The need for precise and reliable description of signals and backgrounds for LHC Run II has led to several remarkable achievements:
  - Multi-particle NLO has become a mature field. NLO+PS is becoming the standard tool for LHC analysis
  - NNLO has undergone rapid advances in the past year and merging with parton showers has already started. NNLO precision jet phenomenology is now possible!
  - High-precision resummation in the presence of final-state jets has become possible with important applications to Higgs predictions.

QCD theory is ready for the upcoming data!