Recent Highlights of Precision QCD at the LHC

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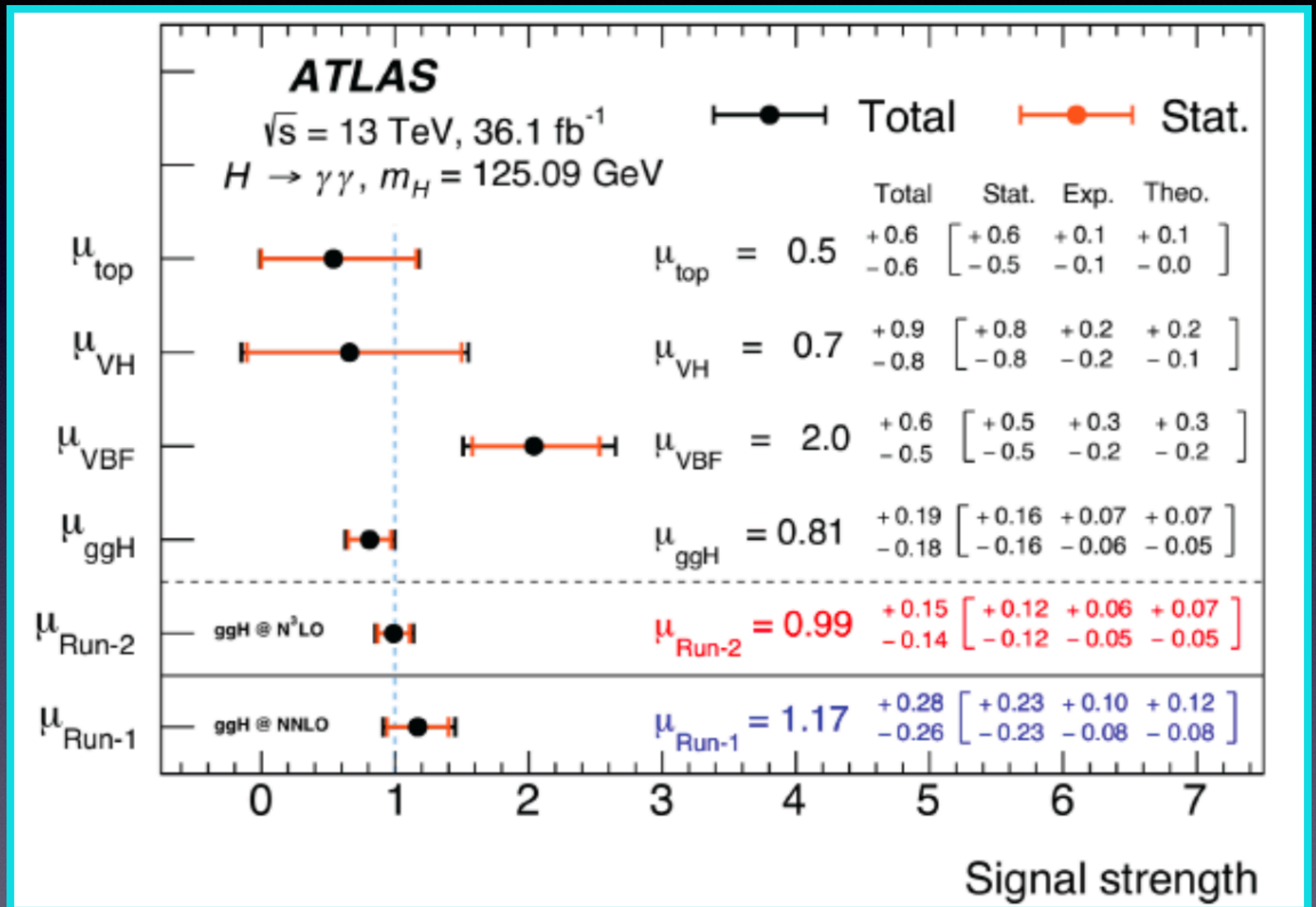
DIS 2021 , Stony Brook University, New York, April 12-16, 2021

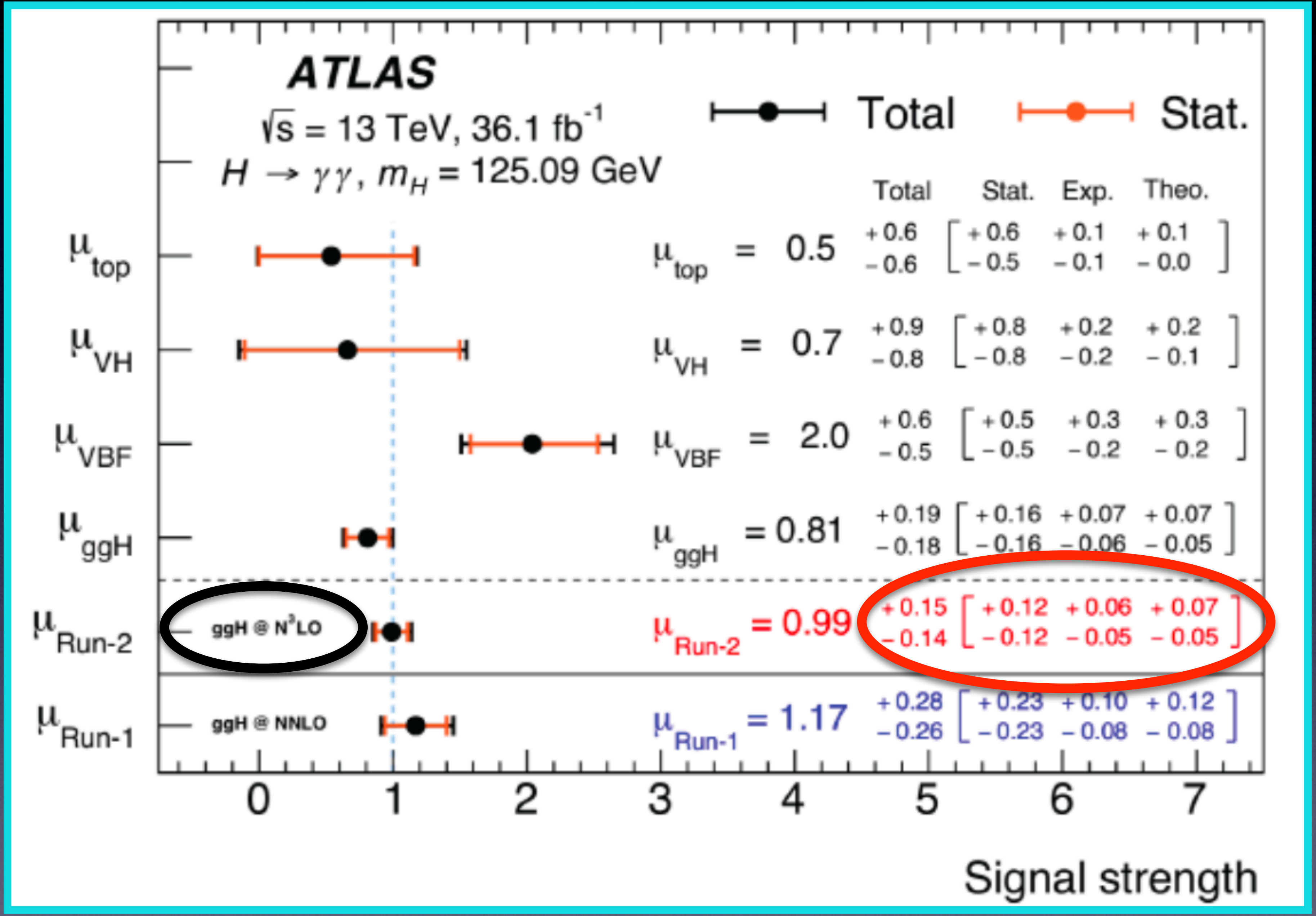
Major theme of this talk is precision QCD at the LHC and potential future machines. Why is precision relevant now more than ever?

Precision QCD



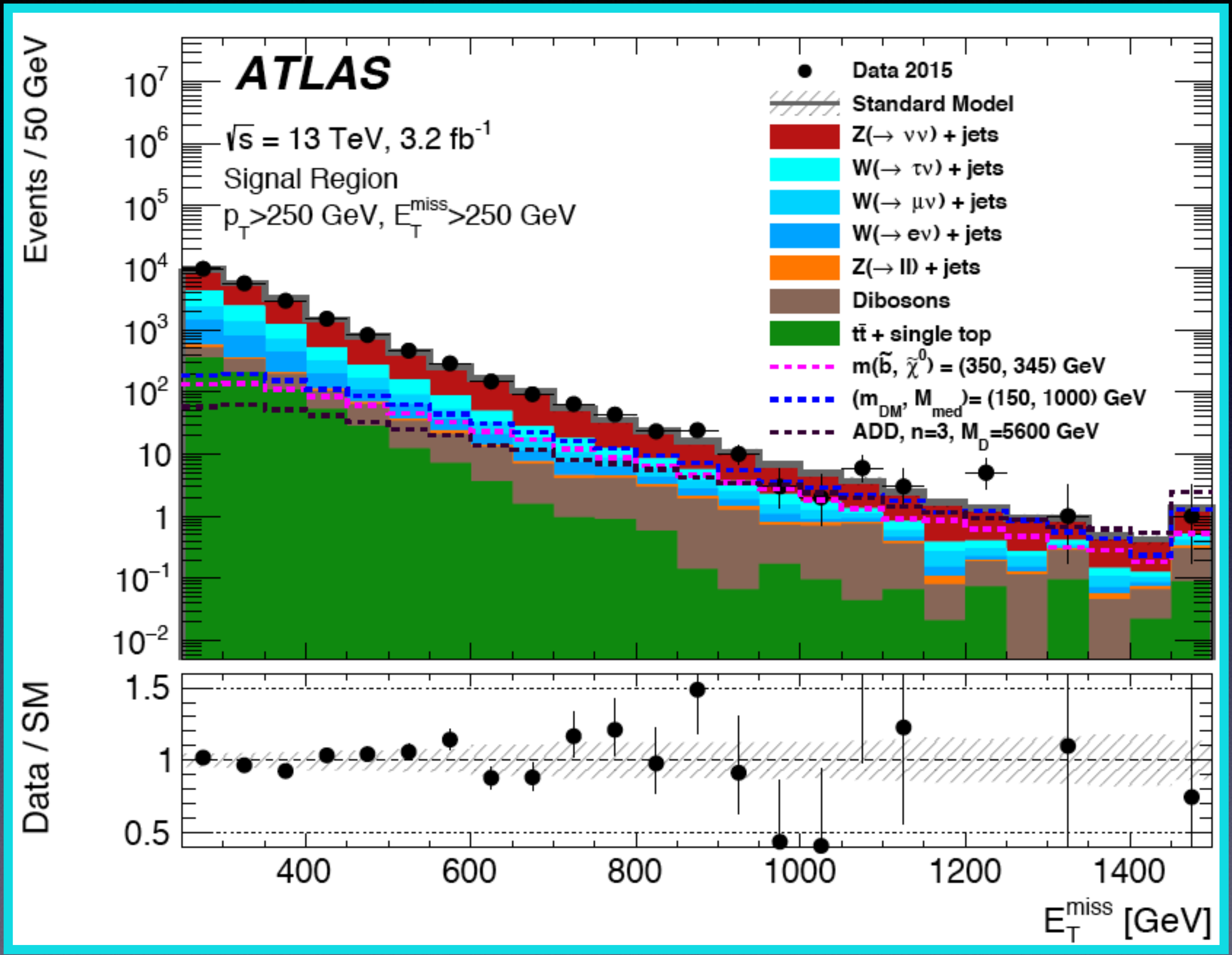
Indispensable in understanding measurements at the LHC and whether they agree with the Standard Model. Poised to become more so with higher integrated luminosity.

Precision QCD



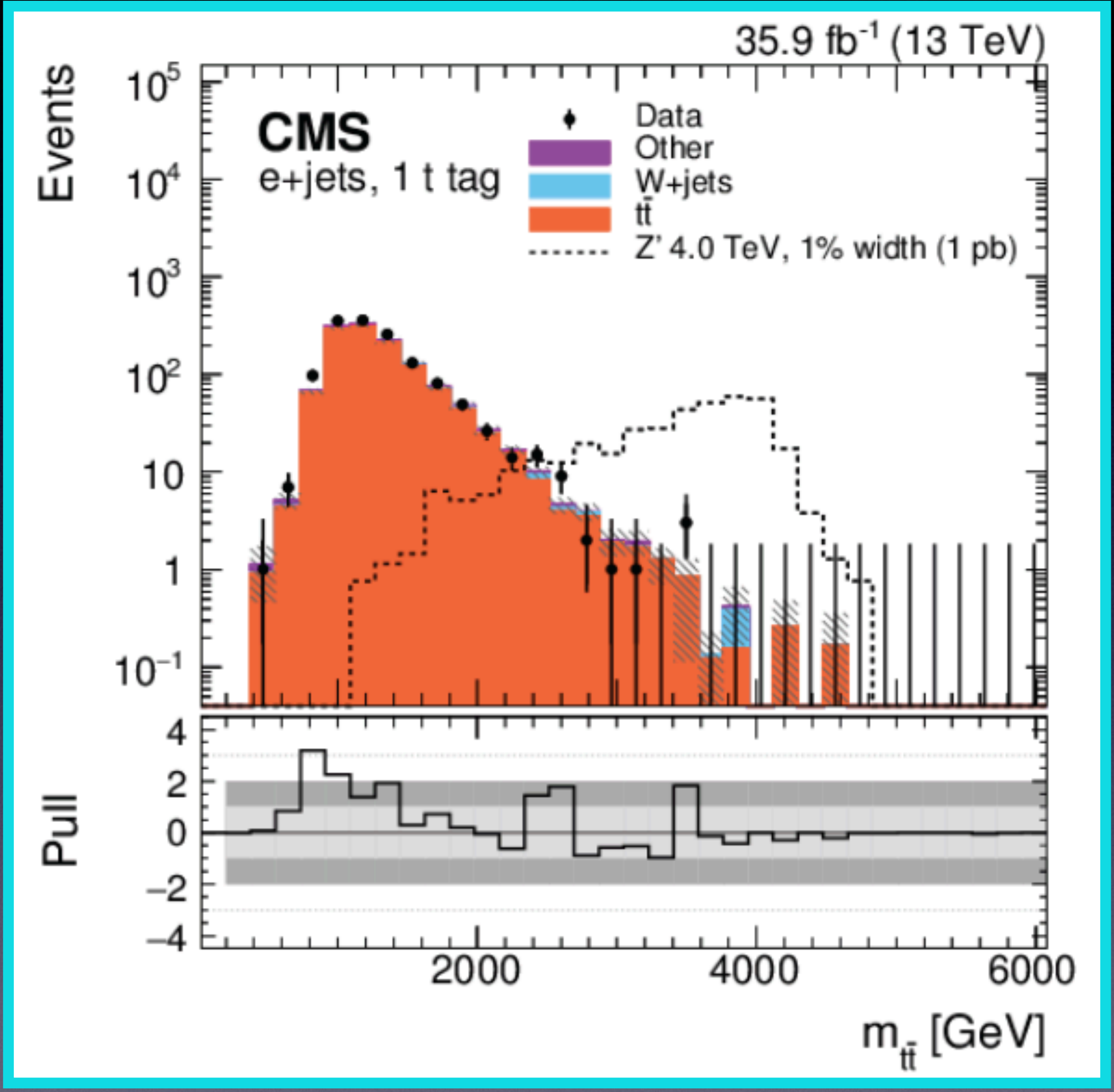
Even with N^3LO pQCD prediction (Anastasiou et al. 1602.00695) theory uncertainties still substantial!

QCD tools for BSM searches



QCD tools are needed to understand sometimes subtle kinematic differences between background and signal in BSM searches

QCD tools for BSM searches



New ideas: understanding of QCD has led to new tools to search for physics beyond the SM, such as jet substructure

Precision QCD @ LHC

QCD at Hadron Colliders

- Our formalism for predicting hadronic cross sections:

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2; \mu_F^2, \mu_R^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)$$

Parton density functions, universal, non-perturbative

Parton level cross sections, process dependent, perturbative

Power suppressed contributions

- Partonic cross sections: computed perturbatively as an expansion in the coupling constant, for example the strong coupling:

$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \dots \right)$$

LO predictions

NLO corrections

NNLO corrections

NNNLO corrections

QCD at Hadron Colliders

- Current state-of-the-art in a nutshell:

  - NNLO predictions for most 2→2 SM cross sections, including jets in the final state.
  - NNLO prediction for pp→$\gamma\gamma\gamma$
  - A few N3LO cross sections: ggH, VBF, Drell-Yan

- Our goal: increase the precision of the predictions both for signals as well as SM backgrounds. This is especially relevant when looking for BSM signals indirectly through precision tests of the SM.

I will present highlights of these advances and I apologize for not having time to cover all the important results!

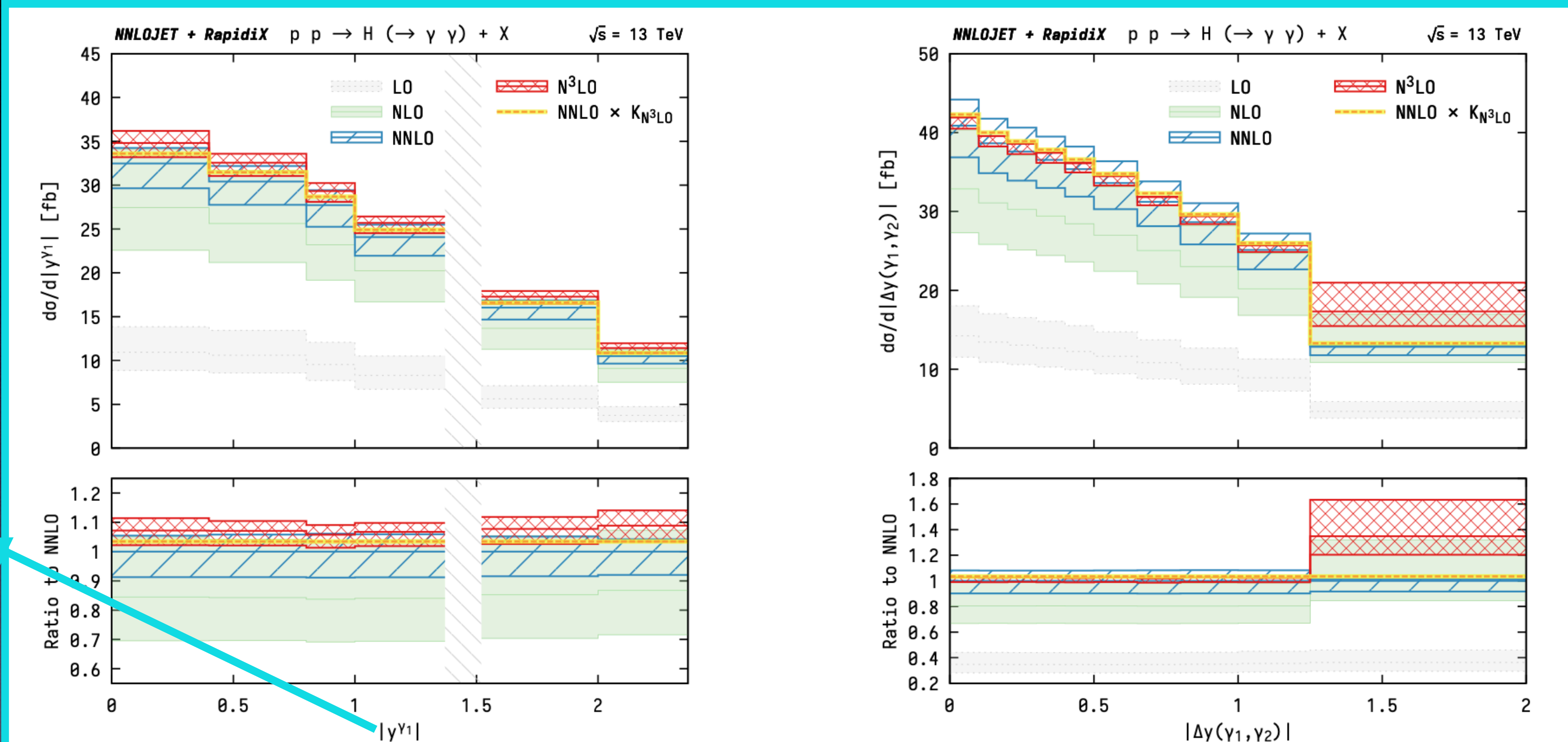
Fully differential $gg \to H \to \gamma\gamma$ @ N^3LO

- Fiducial cross section predictions with realistic selection cuts on the final-state decay products allow for a direct comparison with experimental results. They present a unique window into the Higgs properties.

- **New:** fully differential result for $gg \to H \to \gamma\gamma$ @ N^3LO has just become available. Obtained using the Projection-to-Born method for dealing with intermediate infra-red singularities (Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2021).

Fully differential gg→H→γγ @ N^{3}LO

$m_{\gamma\gamma} \equiv M_H$=125GeV



Photon with leading pT

$$K_{\mathrm{N^3LO}} \equiv \sigma^{\mathrm{N^3LO}}_{\mathrm{incl.}} / \sigma^{\mathrm{NNLO}}_{\mathrm{incl.}}$$

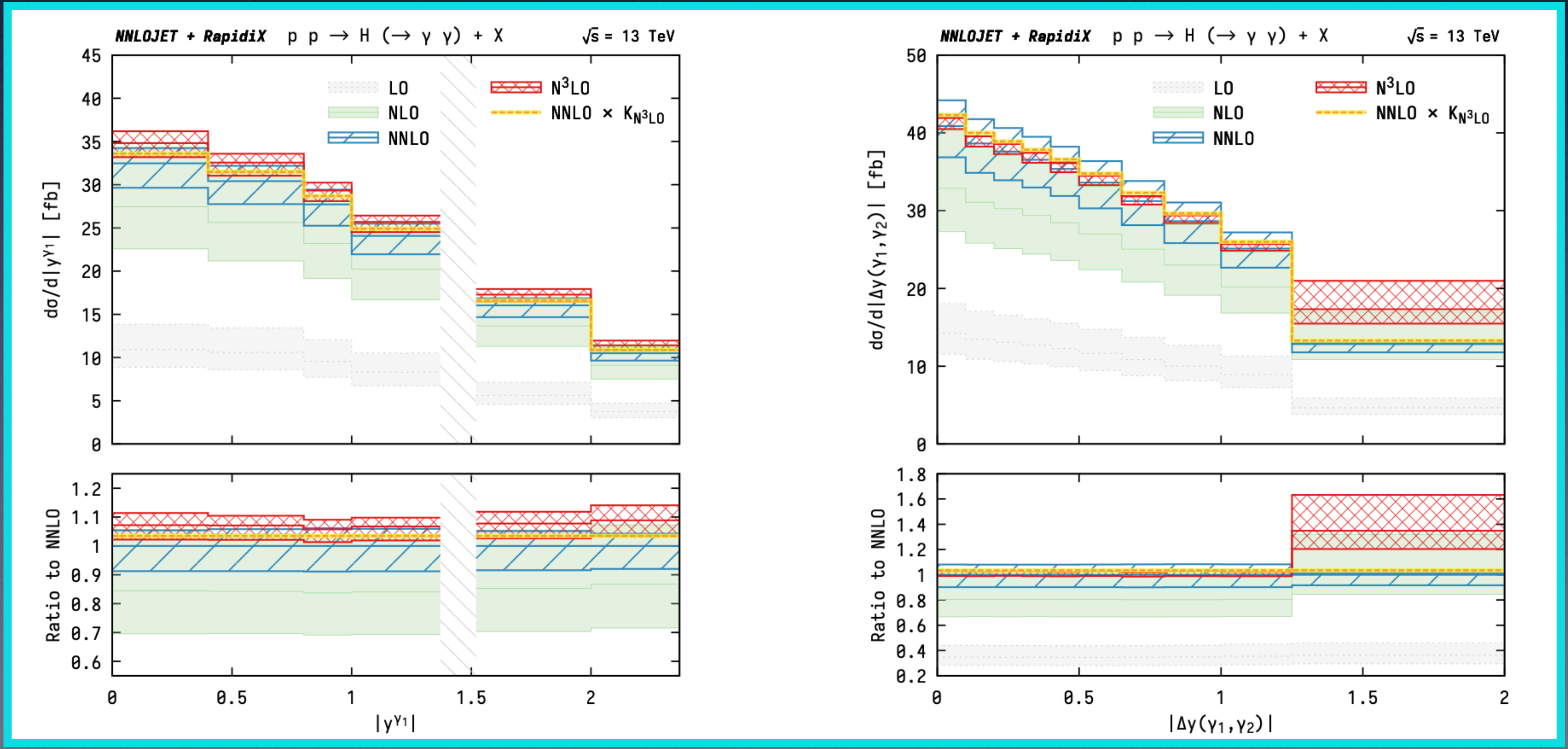
$$p_T^{\gamma_1} > 0.35 \times m_{\gamma\gamma}, \qquad p_T^{\gamma_2} > 0.25 \times m_{\gamma\gamma},$$
$$|\eta^\gamma| < 2.37 \text{ excluding } 1.37 < |\eta^\gamma| < 1.52,$$

Scale uncertainty obtained by independently varying μ_F and μ_R around the central value $M_H/2$ by (1/2,2) with $1/2 \lesssim \mu_F/\mu_R \lesssim 2$

Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2021

Fully differential gg→H→γγ @ N³LO

- *Leading photon case:* the naive treatment of scaling the NNLO result with an inclusive K_{N3LO} factor to get fiducial N3LO results is not accurate. Genuine N3LO fiducial results are larger.
- *Rapidity difference of the two photons:* inclusive K-factor rescaling agrees with the N3LO fiducial result, except in the last bin where a perturbative instability is observed.



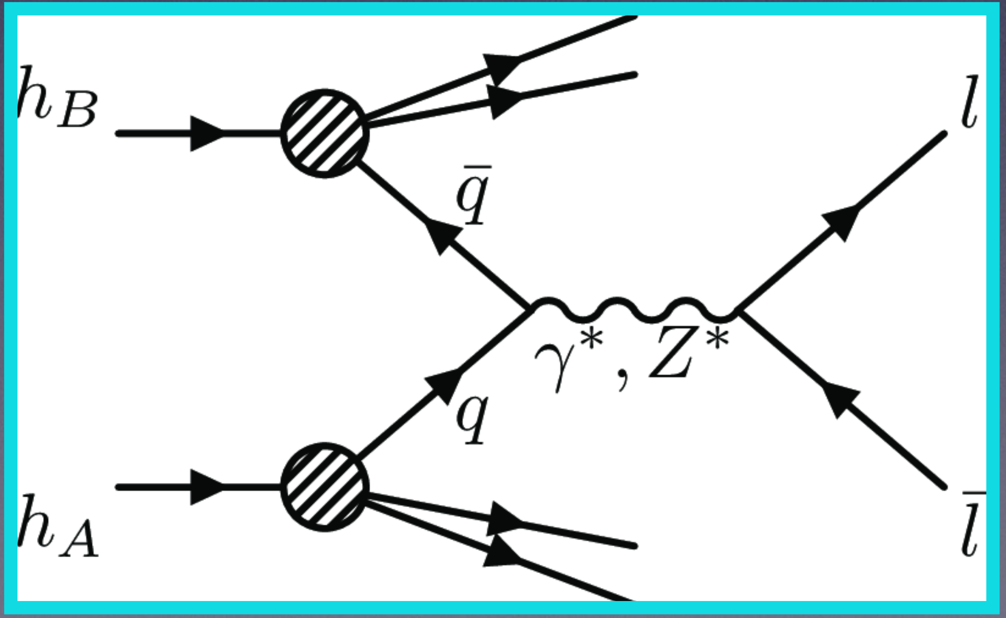
Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2021

Drell-Yan @ N^3LO

- Has a clean final-state signature making it an ideal candidate for luminosity measurements and detector calibration.
- An important input for proton PDFs determination.
- A lot of work was done over the years to predict it precisely including NNLO QCD corrections supplemented with electroweak effects, as well as the mixed QCD-QED corrections.

Recently the inclusive N^3LO QCD corrections to DY due to a γ^* exchange and charged current became available!

Duhr, Dulat, Mistelberger, 2020



Drell-Yan @ N^{3}LO: γ^*

Q/GeV	$K_{QCD}^{N^3LO}$	δ(scale)	$\delta(\text{PDF}+\alpha_S)$	δ(PDF-TH)
30	0.952	$^{+1.5\%}_{-2.5\%}$	$\pm 4.1\%$	$\pm 2.7\%$
50	0.966	$^{+1.1\%}_{-1.6\%}$	$\pm 3.2\%$	$\pm 2.5\%$
70	0.973	$^{+0.89\%}_{-1.1\%}$	$\pm 2.7\%$	$\pm 2.4\%$
90	0.978	$^{+0.75\%}_{-0.89\%}$	$\pm 2.5\%$	$\pm 2.4\%$
110	0.981	$^{+0.65\%}_{-0.73\%}$	$\pm 2.3\%$	$\pm 2.3\%$
130	0.983	$^{+0.57\%}_{-0.63\%}$	$\pm 2.2\%$	$\pm 2.2\%$
150	0.985	$^{+0.50\%}_{-0.54\%}$	$\pm 2.2\%$	$\pm 2.2\%$

Duhr, Dulat, Mistelberger, 2020

Current PDF+α_s errors combined quadratically

uncertainty due to missing N3LO PDFs

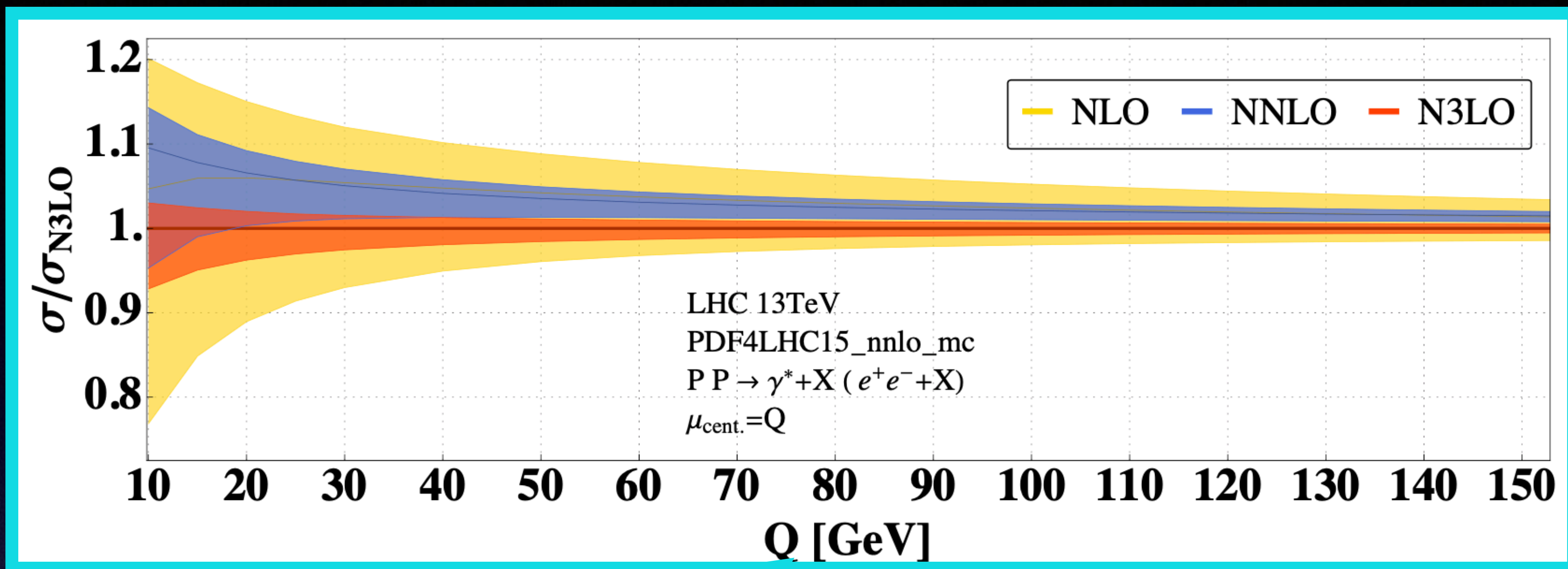
$$K_{QCD}^{N^3LO} = \frac{\sigma^{(3)}(\mu_f = \mu_r = Q)}{\sigma^{(2)}(\mu_f = \mu_r = Q)}$$

$$\delta(X) = \frac{\delta_X(\sigma^{(3)})}{\sigma^{(3)}(\mu_f = \mu_r = Q)}$$

- Central scale = Q, where Q is the leptons invariant mass
- μ_F and μ_R varied independently by a factor of 2 around Q with $1/2 \leq \mu_{R/F} \leq 2$

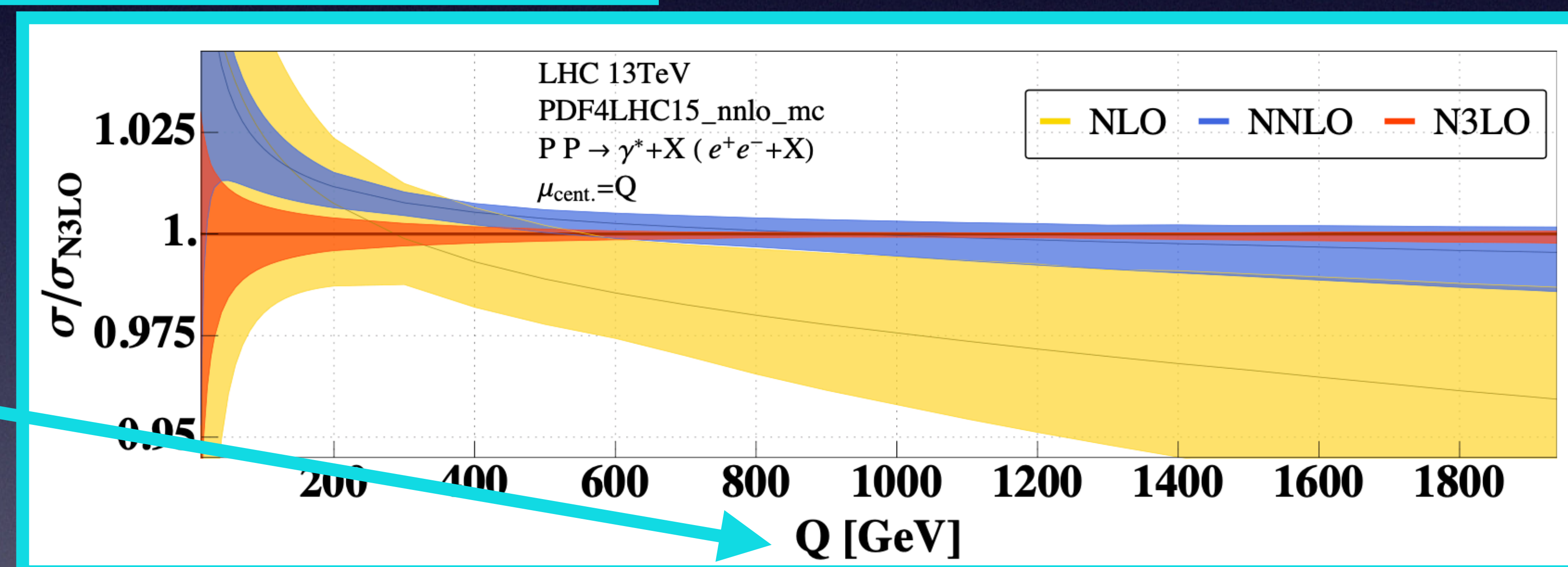
- Up to 5% percent correction at low Q in going from NNLO to N3LO in α_s
- The estimated uncertainty associated with missing N3LO PDFs is comparable in size to current PDF+α_s uncertainty and is roughly 2%

Drell-Yan @ N^3LO: γ^*



Duhr, Dulat, Mistelberger, 2020

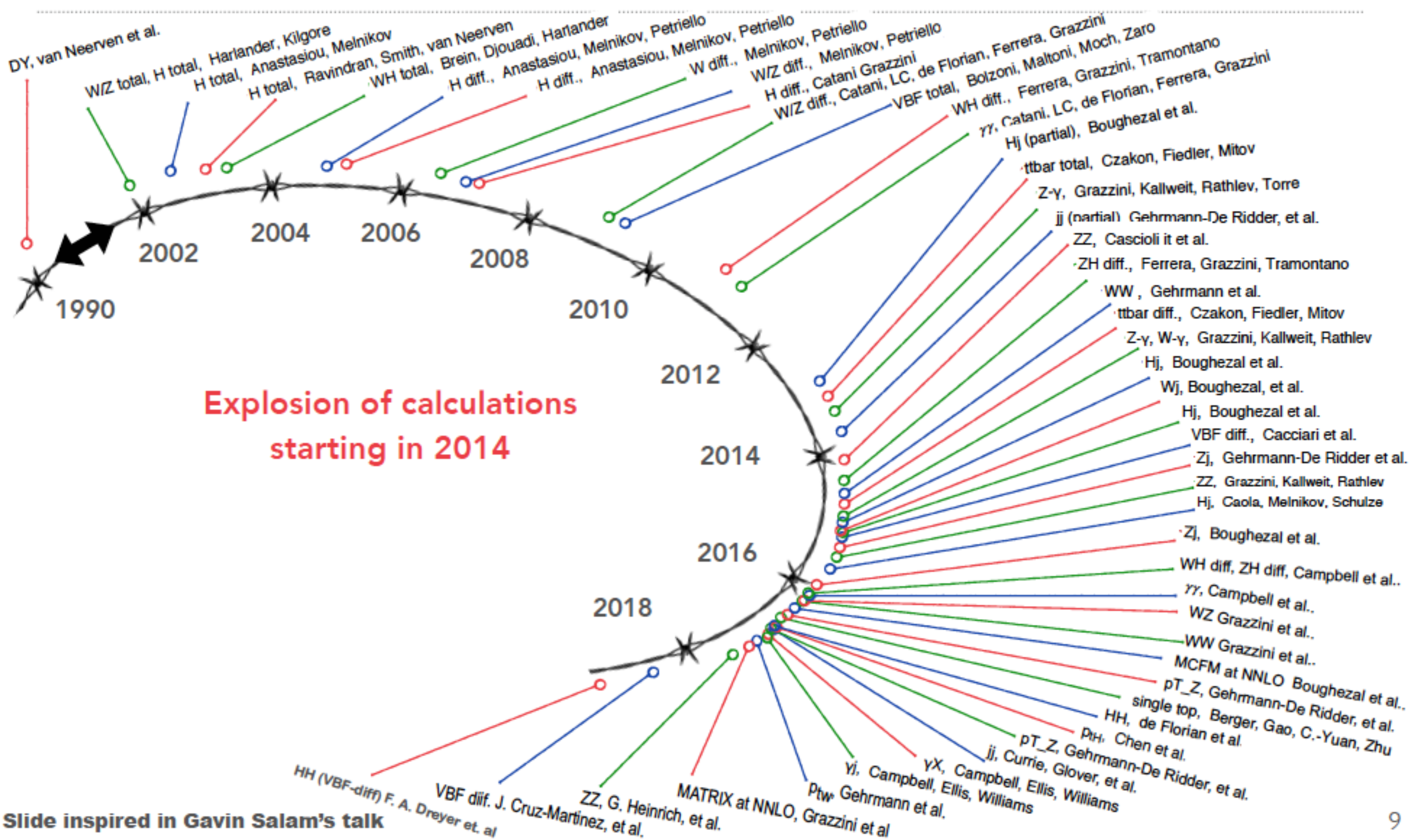
$\mu_R = \mu_F = Q$



- While the N3LO cross section depends only mildly on the scale Q, the scale error bands for NNLO and N3LO do not overlap for 50GeV ≤Q ≤400GeV
- This emphasizes the need for a better approach to estimate missing higher order uncertainties.

NNLO

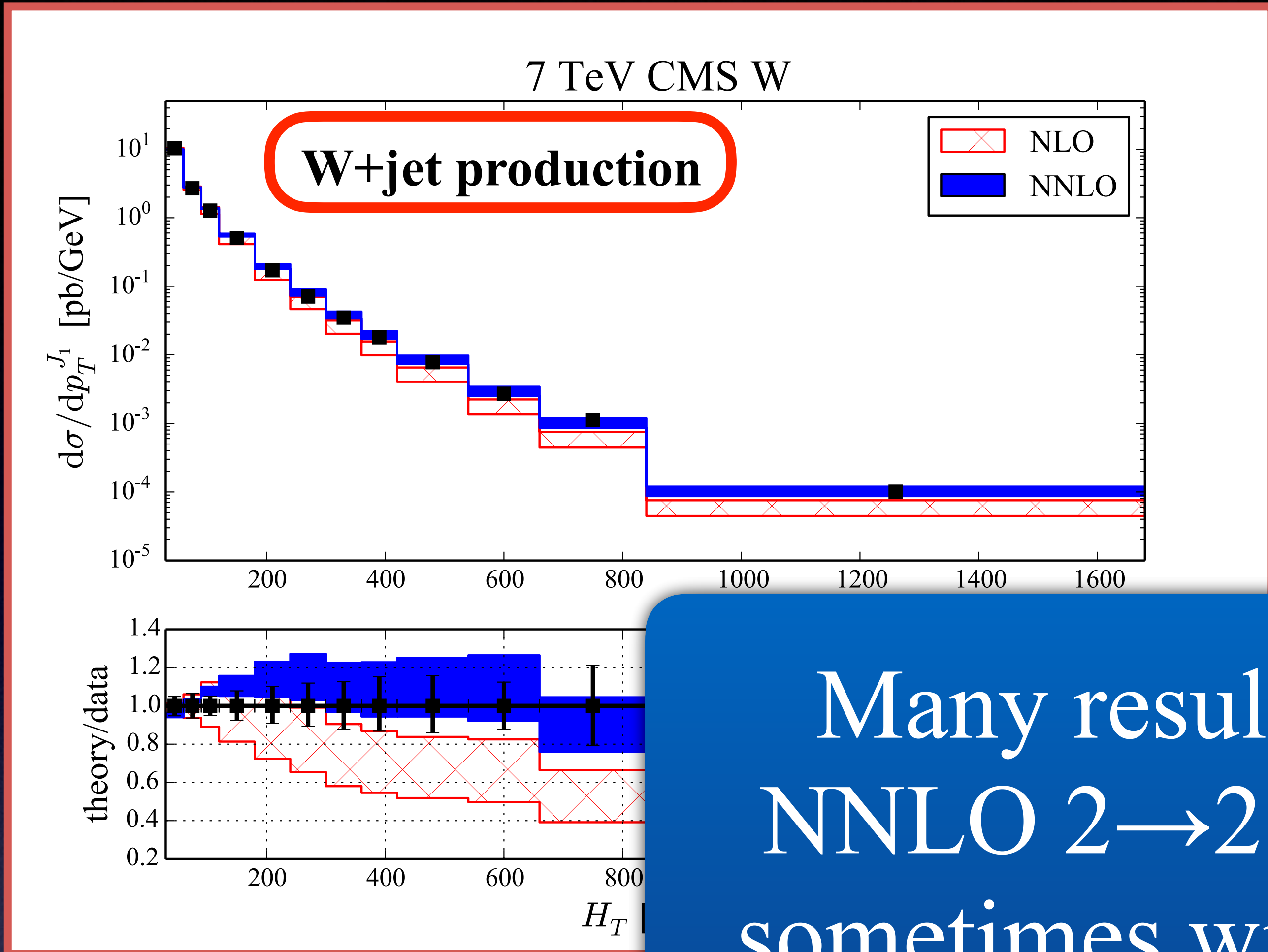
NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



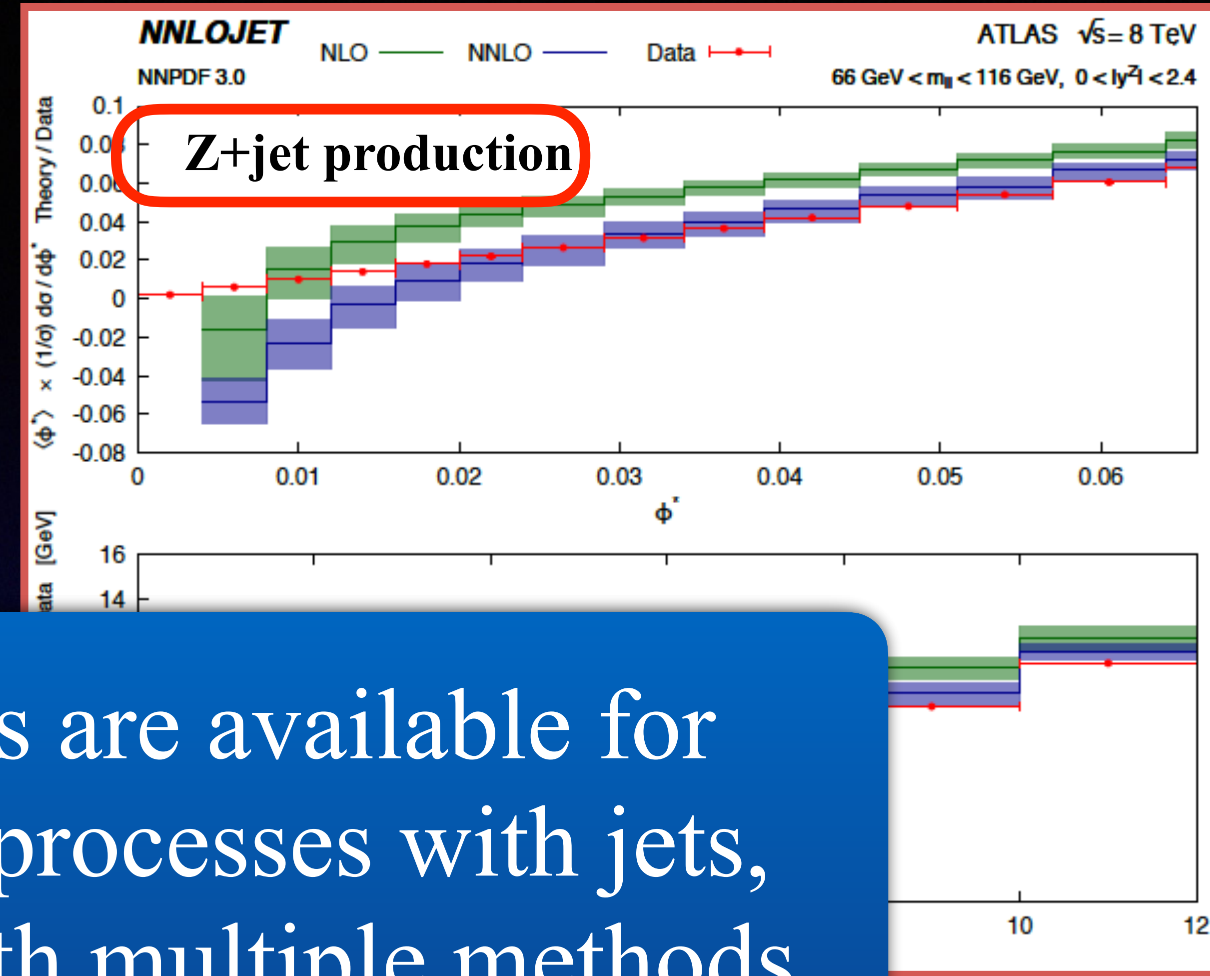
Slide inspired in Gavin Salam's talk

L. Cieri, Moriond 2019

RB, Liu, Petriello, 2016

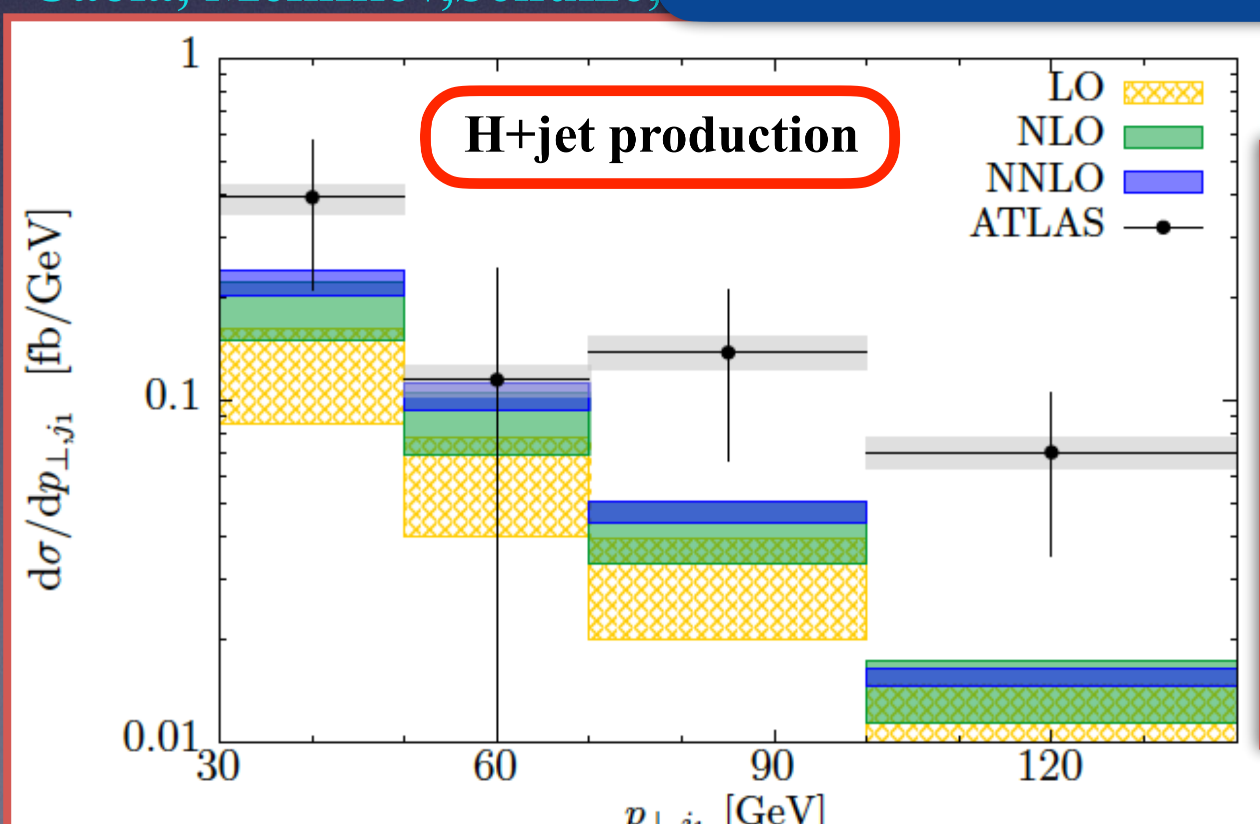


A. Gehrmann, T. Gehrmann, Glover, Huss, Morgan, 2016

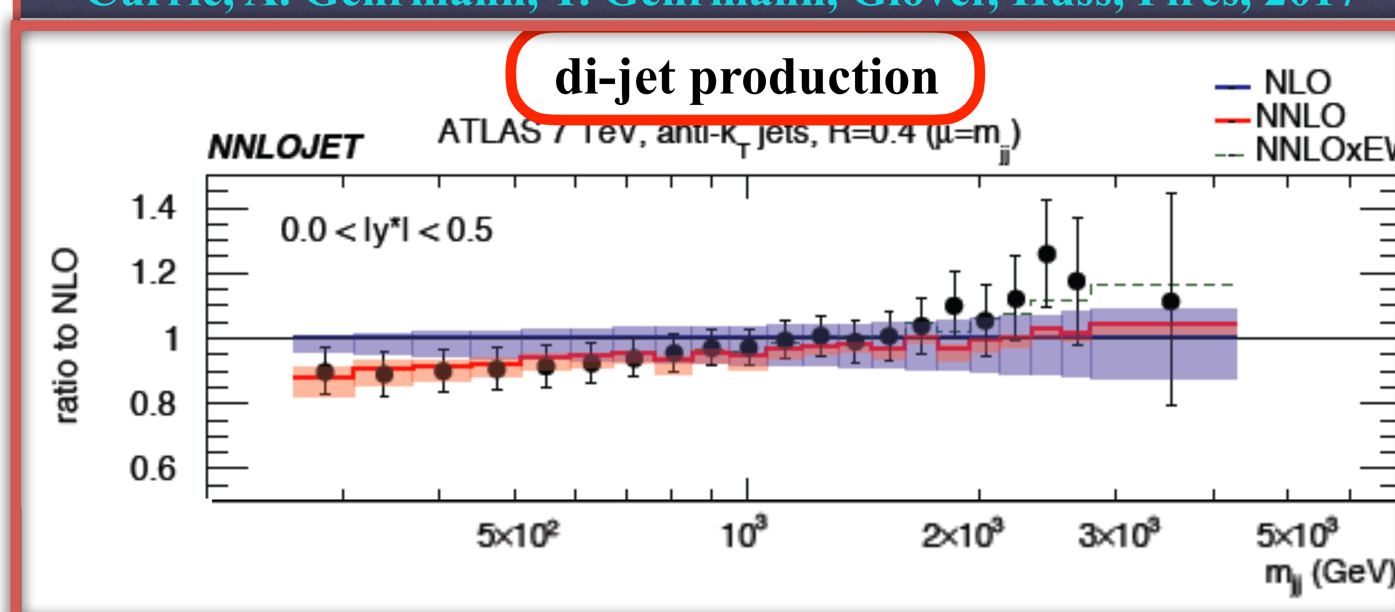


Many results are available for NNLO 2→2 processes with jets, sometimes with multiple methods

Caola, Melnikov,Schulze,



Currie, A. Gehrmann, T. Gehrmann, Glover, Huss, Pires, 2017



NNLO progress

- Many important fully differential cross sections are available, in some cases with multiple methods.

  - ***Color singlet processes:***

    pp→H, pp→V, pp→ ɣɣ, pp→VH, pp→ VV, pp→ 3ɣ

    (Anstasiou, Melnikov, Petriello; Catania, Cieri, de Florian, Ferrera, Grazzini, Tramontano; RB, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams; Heinrich, Jahn, Jones, Kerner, Pires; Chowdhry, Czakon, Mitov, Poncelet).

  - ***Heavy quark final state:***

    pp→tt (Czakon, Fiedler, Mitov; Catani, Devoto, Grazzini, Kallweit, Mazzitelli)

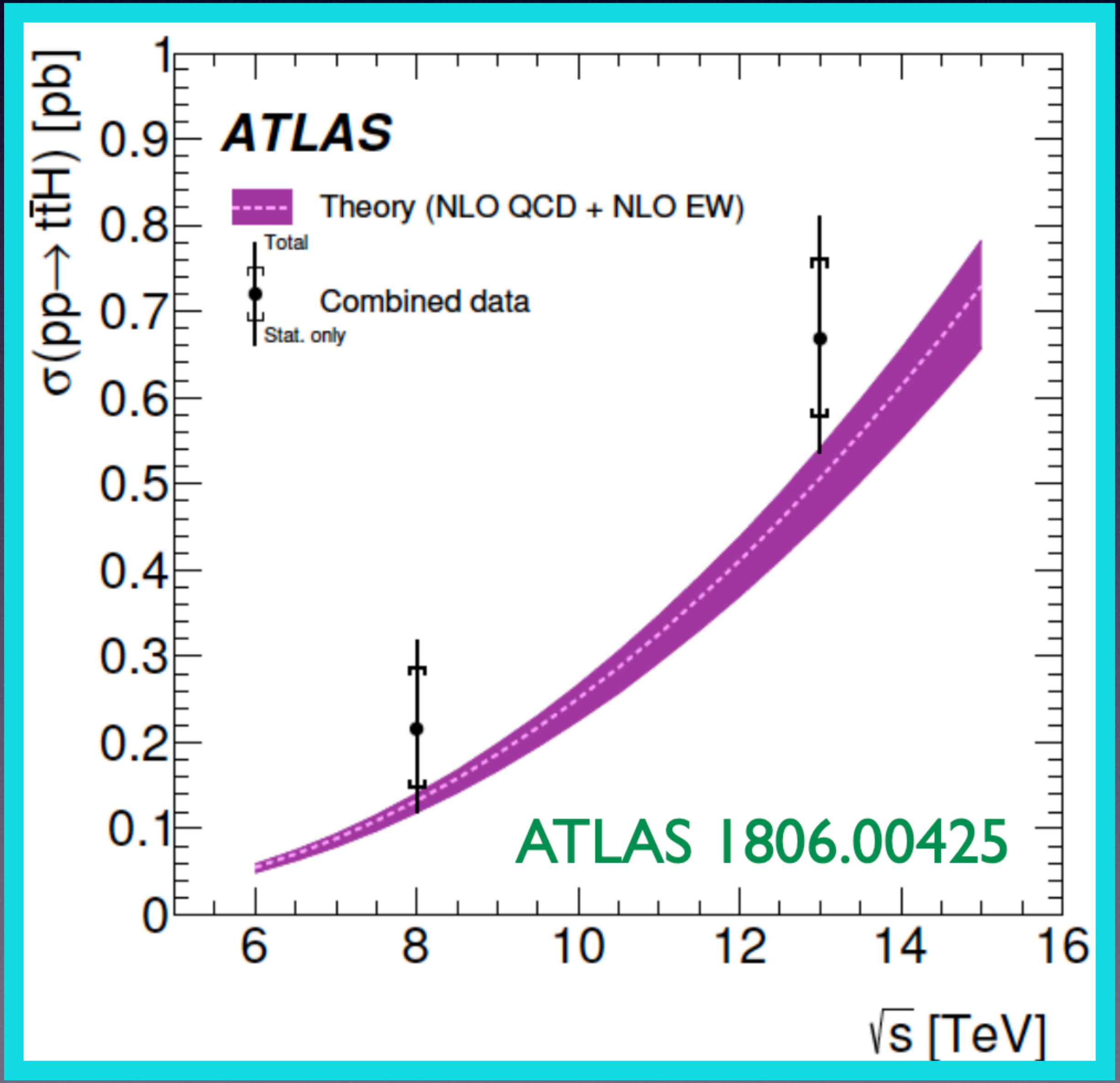
  - ***Processes with jets in the final state:***

    pp→H+j, pp→W+j, pp→Z+j, pp→ɣ+j, pp→jj, pp→H+2j (VBF), pp→HH+2j (VBF), ep→ 2j

    (RB, Caola, Melnikov, Petriello, Schulz; Caola, Melnikov, Schulze; Cacciari, Dreyer, Karlberg, Salam, Zanderighi; RB, Liu, Petriello; Czakon, Van Hameren, Mitov, Poncelet; Chen, Cruz-Martinez, Currie, Gauld, A. Gehrmann, T. Gehrmann, Glover, Hoefer, Huss, Majer, Mo, Morgan, Niehues, Pires, Walker, Whitehead; Campbell, Ellis, Williams)

Beyond 2→2 cross sections

- Most relevant SM 2→2 processes are known at NNLO today, some in approximations that need further improvement (eg. leading color, infinite m_{top}). Some cross sections for 2→3 processes are also needed at this accuracy to match the anticipated experimental precision. An example is ttH.



At the end of the HL-LHC, ttH is expected to have 2% statistical uncertainty. Current theory predictions will be a limiting factor when comparing with data. Need NNLO QCD combined with NLO electroweak corrections.

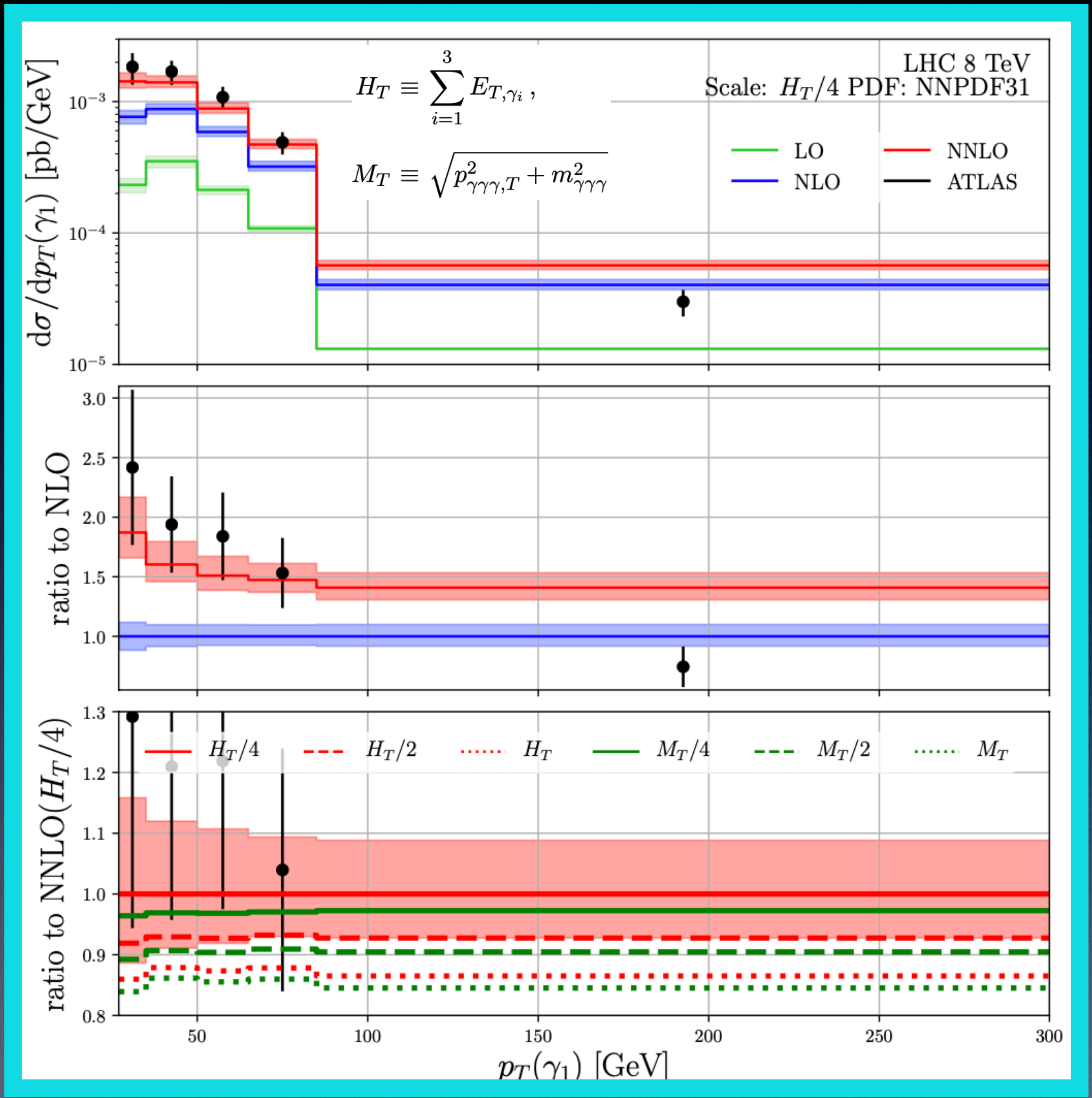
Need to extend NNLO QCD techniques to handle 2→3 processes

Beyond 2→2 cross sections

- **Five particle 2-loop amplitudes**: currently an active subject of study, with various analytical and numerical results (Abreu, Dormans, Febres Cordero, Ita, Page '18; Badger, Bronnum-Hansen, Hartanto, Peraro '17; Abreu, Febres Cordero, Ita, Page, Zeng '17; Abreu, Febres Cordero, Ita, Page, Sotnikov '18/21; Gehrmann, Henn, Lo Presti '16; Badger, Bronnum-Hansen, Hartanto, Peraro' 19; Badger, Chicherin, Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zoia '19; Herschel, Chowdhry, Czakon, Mitov, Poncelet '21; Agarwal, von Manteuffel, Panzer, Schabinger, '21, …)

- **Multi-scale 2-loop amplitudes with massive internal particles:** relevant for Higgs, top, vector boson production. New mathematical structures beyond multiple polylogarithms appear (Remiddi, Tancredi '16; Bonciani et al '16; Weinzierl et al '16-17; Ablinger et al '17; Broedel, Duhr, Dulat, Tancredi '17; Caola, Lindert, Melnikov, Monni, Tancredi, Wever '18; Adams, Chaubey, Weinzierl '18; Bonciani et al '19; Becchetti, Bonciani, Casconi, Ferroglia, Lavacca, von Manteuffel '19; Bogner, Mueller-Stach, Weinzierl '19; Badger, Chaubey, Hartanto, Marzucca '21; Badger, Hartanto, Zoia '21; Chen, Heinrich, Jones, Kerner, Klappert, Schlenk '21;…)

First 2→3 result: pp→γγγ+X



Chawdhry, Czakon, Mitov, Poncelet, 2019

- The cross section for 3 isolated photons was measured in detail by ATLAS and was found to deviate from the existing NLO prediction for this process
- The missing scale independent finite contribution of the two-loop 5-point amplitudes was included in the leading-color approximation
- Including NNLO removes the discrepancy w.r.t data

- While this is technically a simpler calculation than ttH (no external mass scales and no final state IR singularities), this is still an interesting advance for 2→3 predictions.

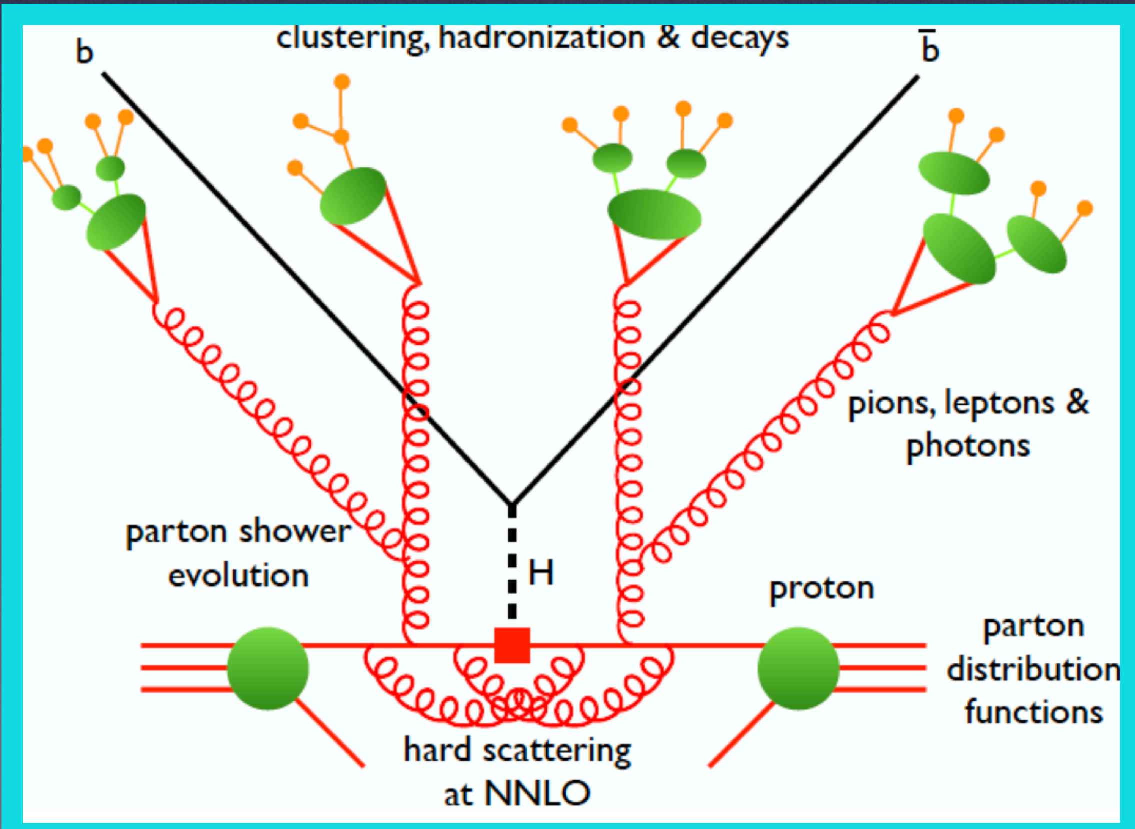
Matching NNLO and parton shower

NNLO: provides precise predictions but limited to low multiplicity final states and parton level.

Parton Showers (PS): less precise but more realistic, including hadronization effects, and multi-patron interactions.

NNLOPS

Achieving a good perturbative accuracy while maintaining a realistic description of the final state requires matching NNLO to PS **(NNLOPS)**



Matching NNLO and parton shower

- **NNLOPS:** Currently three methods exist for matching NNLO with PS for color-singlet production.

UNNLOPS: Hoeche, Li, Prestel

MiNNLOps: Monni, Nason, Re, Wiesemann, Zanderighi

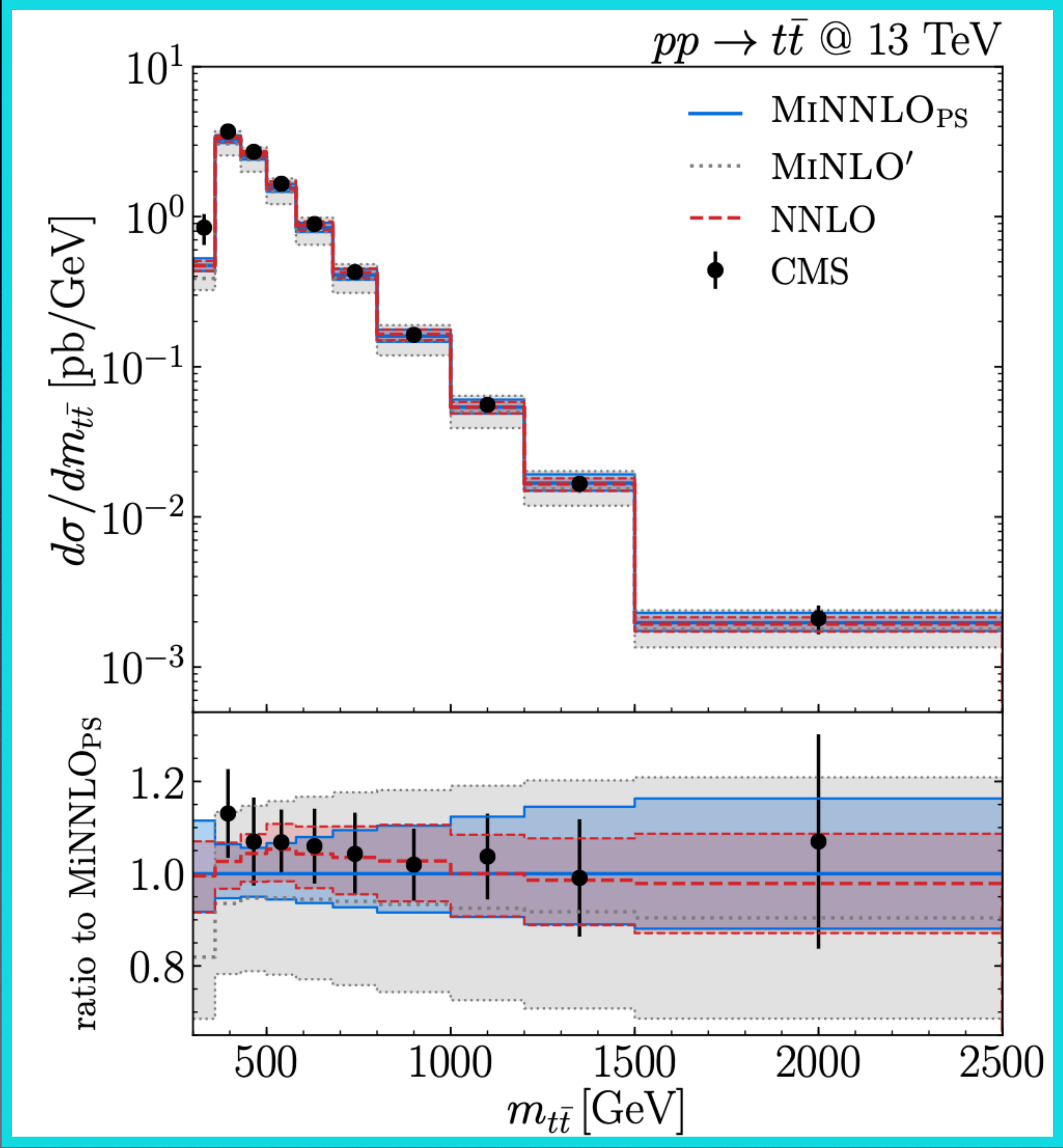
Geneva: Alioli, Bauer, Berggren, Guns, Tackmann, Walsh

- Recently the MiNNLOps approach was also extended for heavy quarks production (pp ⟶ ttbar, Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi, 2020). However the path to extending these methods to generic 2⟶2 processes is not yet clear.

Going beyond the current state-of-the art for NNLOPS would require new approaches or extensions of the current ones.

Example: NNLOPS for ttbar

- For m_{ttbar} MiNNLOps and NNLO yield consistent results with overlapping error bands.
- Larger MiNNLOps error band is due to additional scales present in the shower.
- The inclusion of NNLO corrections through MiNNLOps has an impact of **10%-20%** on this distribution. It substantially reduces the perturbative uncertainty compared to MiNLO'.



Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi, 2020

Precision PDFs

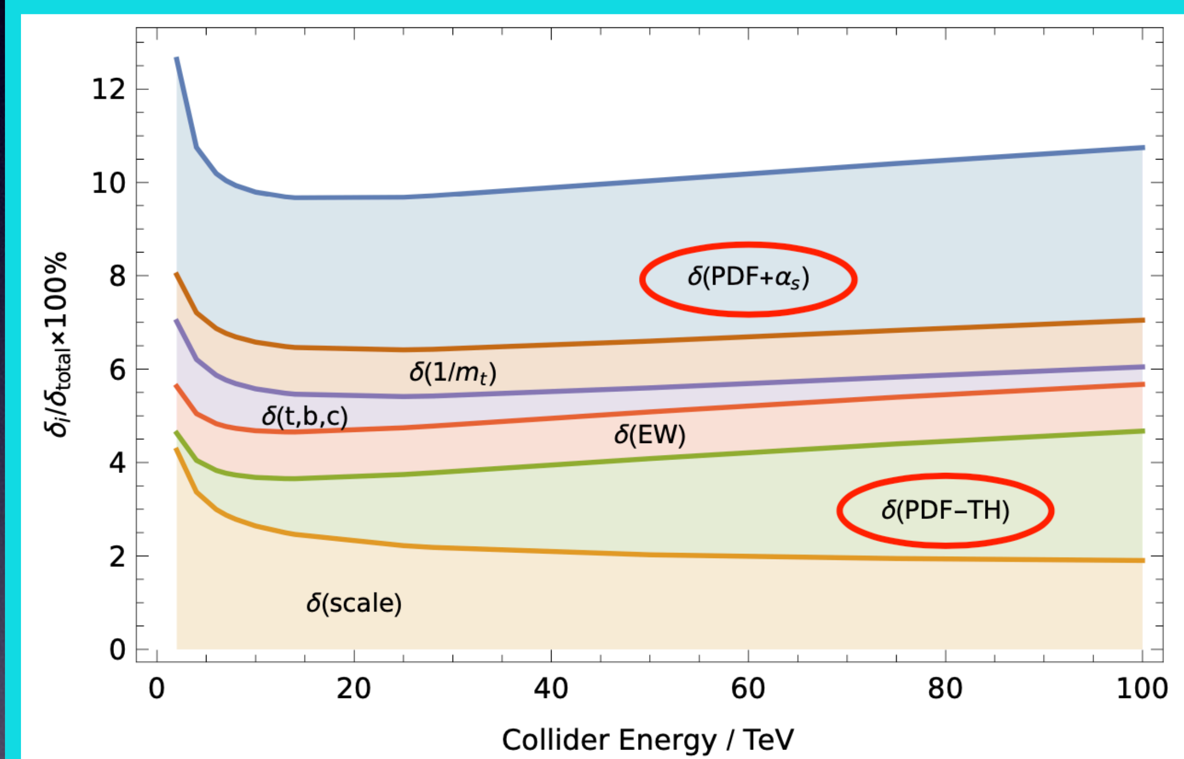
- PDFs are a critical component of the LHC precision program. They are needed for all aspects, from measurements to searches.

M_W

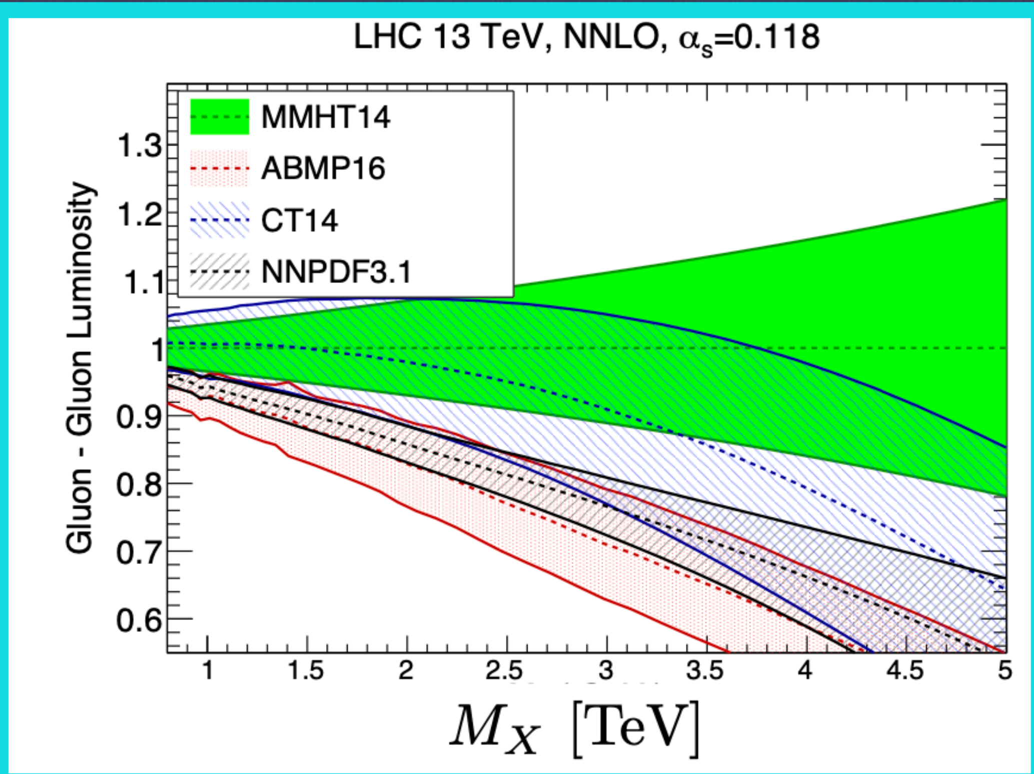
Value [MeV]	PDF Unc.	Total Unc.
80369.5	9.2	18.5

Large component of W mass uncertainty

Dulat, Lazopoulos, Mistlberger, 2018



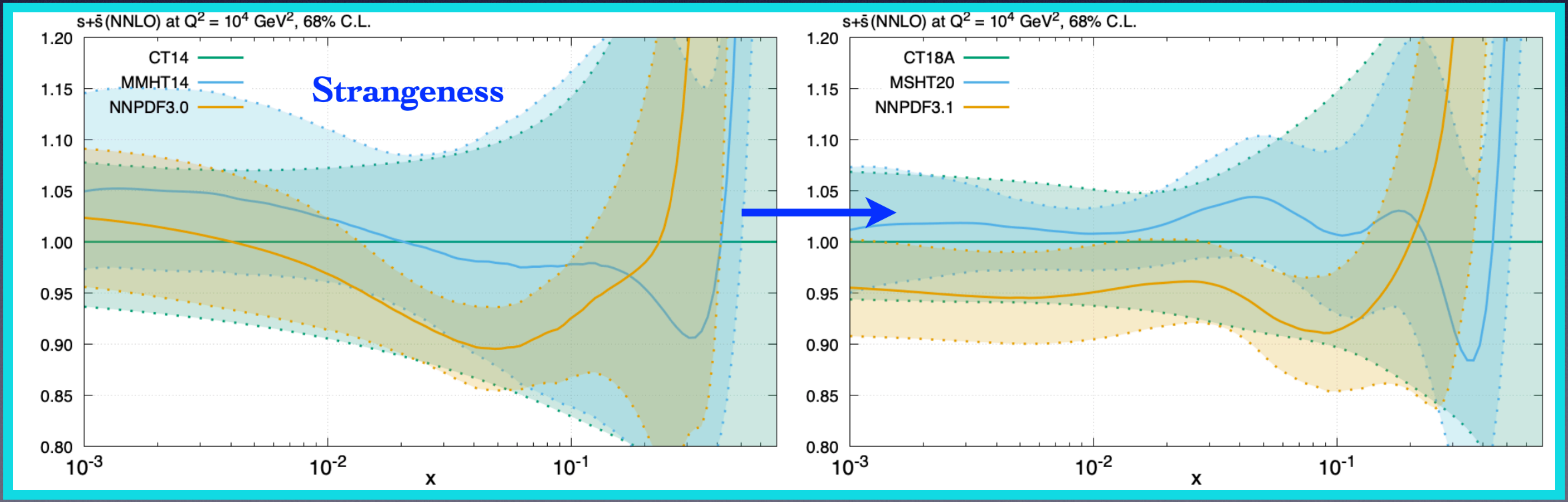
Limiting uncertainty for Higgs cross section predictions



PDFs error becomes significant for high mass resonance searches

Current status of PDF fits

- The three major global fitting groups (CTEQ, MSHT, NNPDF) have incorporated multi-differential W/Z and ttbar data from the LHC, as well as final H1+ZEUS combined DIS data.
- ABMP16 updated to include non-resonant γ*Z data for the first time (2019)
- Most processes are incorporated with full NNLO QCD corrections; NLO EW included when available.
- Methodological improvements such as parameterization dependence studied by all groups.



Reduced uncertainties and agreement between different approaches for some PDFs…

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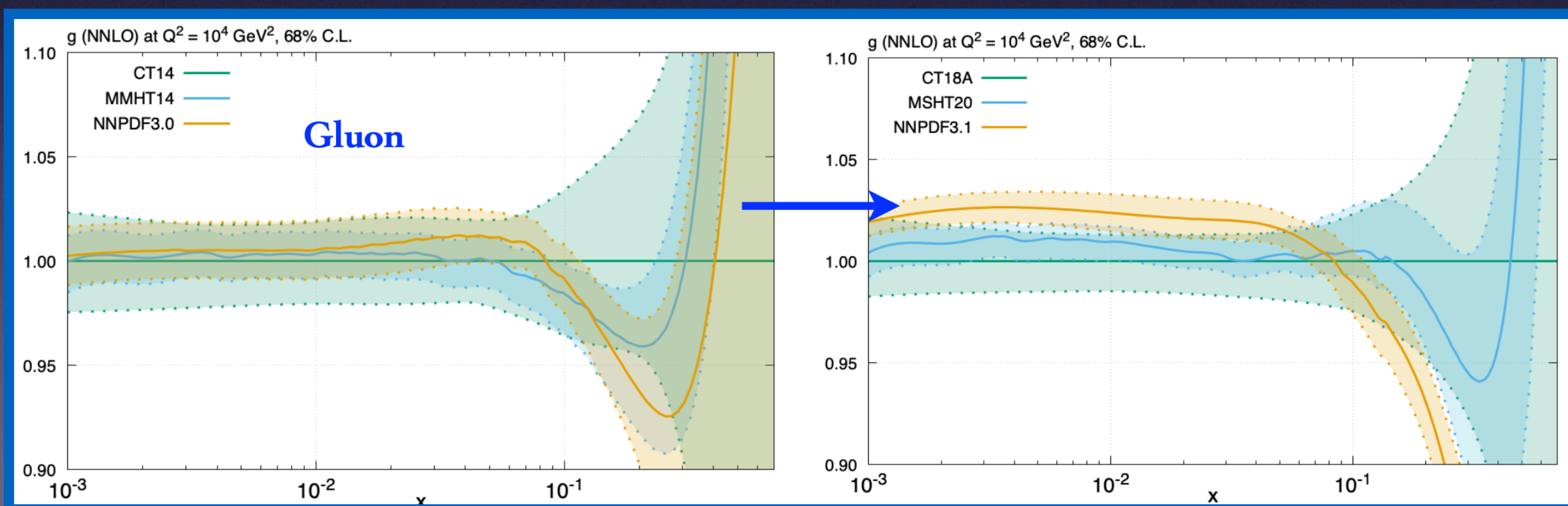


…but not all! Further understanding and benchmarking needed to prepare for future LHC data

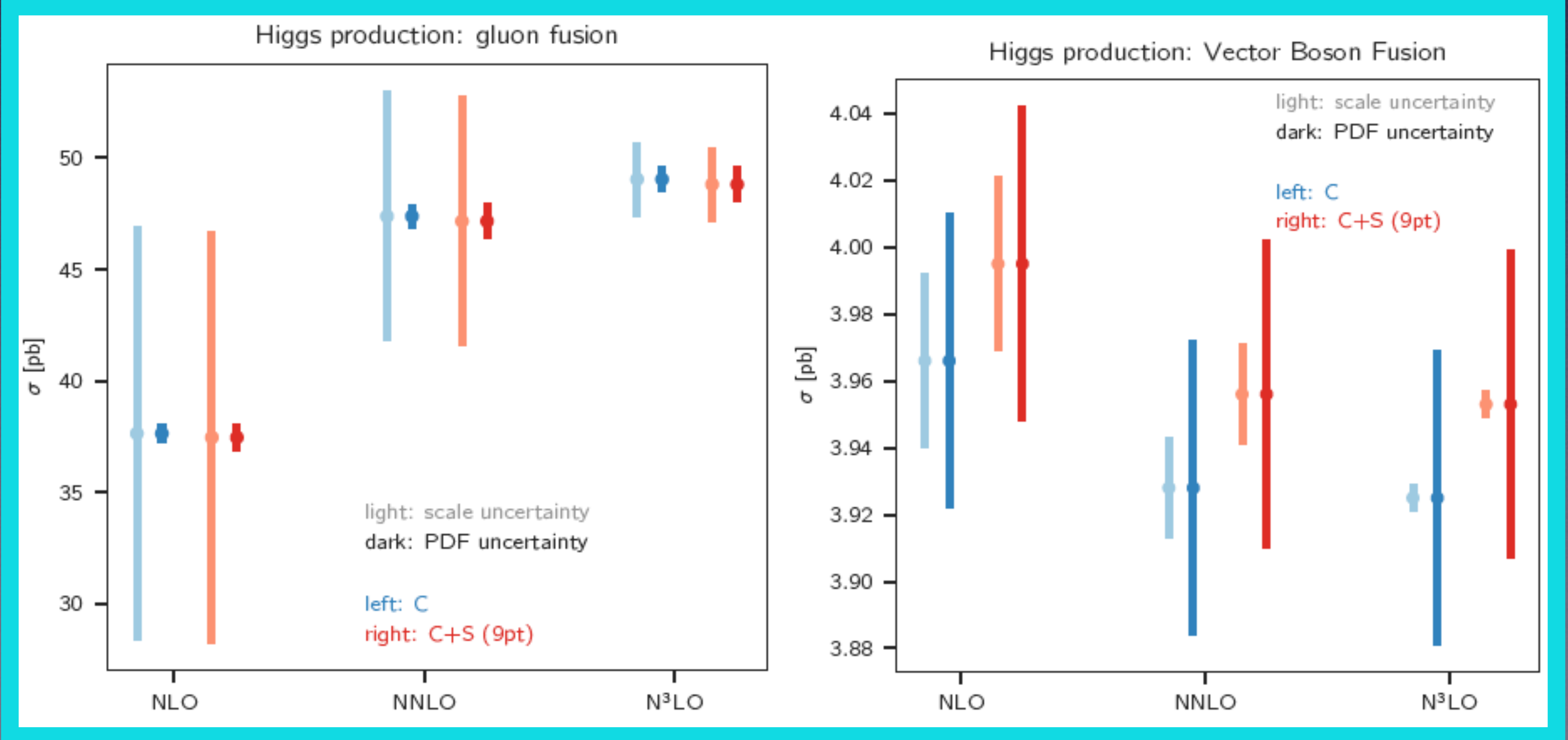
Theory uncertainties in PDFs

- New: extend PDF uncertainties to include theoretical uncertainties from the underlying process from which they're fit, not just the experimental errors (NNPDF 1905.04311, 1906.10698).

- *Preliminary* pheno implications:

  ggH: few per-mille increase of PDF uncertainty, <1% cross section shift

  VBF: PDF uncertainty almost unchanged, 1% upwards cross section shift



Interplay between precision QCD and BSM searches

Going beyond the SM in a model independent way

- With no direct evidence of new physics at the LHC so far, a reasonable assumption is that it is likely heavy.

- A minimal extension of the SM that still respects SM gauge symmetries, while benefitting from LHC's energy reach and low energy experiments is SMEFT.

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_{6,i}\mathcal{O}_{6,i} + \frac{1}{\Lambda^4}\sum_i C_{8,i}\mathcal{O}_{8,i}$$

Assumption: all new states are heavier than the energy probed by experiments $\sqrt{s}<\Lambda$

- The higher-dimension operators could lead to larger effects at high energy.

Dim-8 effects in Drell-Yan lepton production

- Current precision of the DY process provides a powerful probe of BSM effects. An extension of the 40-year old angular basis used to describe DY is needed for a smoking-gun probe of dimension-8 effects in the Standard Model EFT.

Alioli, RB, Mereghetti, Petriello, 2020

$$
\begin{aligned}
\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\Bigg\{&(1+c_\theta^2)+\frac{A_0}{2}(1-3c_\theta^2)\\
&+A_1 s_{2\theta}c_\phi+\frac{A_2}{2}s_\theta^2 c_{2\phi}+A_3 s_\theta c_\phi+A_4 c_\theta\\
&+A_5 s_\theta^2 s_{2\phi}+A_6 s_{2\theta}s_\phi+A_7 s_\theta s_\phi\\
&+B_3^e s_\theta^3 c_\phi+B_3^o s_\theta^3 s_\phi+B_2^e s_\theta^2 c_\theta c_{2\phi}\\
&+B_2^o s_\theta^2 c_\theta s_{2\phi}+\frac{B_1^e}{2}s_\theta(5c_\theta^2-1)c_\phi\\
&+\frac{B_1^o}{2}s_\theta(5c_\theta^2-1)s_\phi+\frac{B_0}{2}(5c_\theta^3-3c_\theta)\Bigg\}
\end{aligned}
$$

New Bi coefficients a hallmark of s^2/Λ^4 effects beyond the SM; can't be generated by QCD at any order!

$$
\begin{aligned}
\mathcal{O}_{8,lq\partial 1} &= (\bar{l}\gamma_\mu l)\partial^2(\bar{q}\gamma^\mu q),\\
\mathcal{O}_{8,lq\partial 2} &= (\bar{l}\tau^I\gamma_\mu l)\partial^2(\bar{q}\tau^I\gamma^\mu q),\\
\mathcal{O}_{8,lq\partial 3} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q),\\
\mathcal{O}_{8,lq\partial 4} &= (\bar{l}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q)
\end{aligned}
$$

SMEFT

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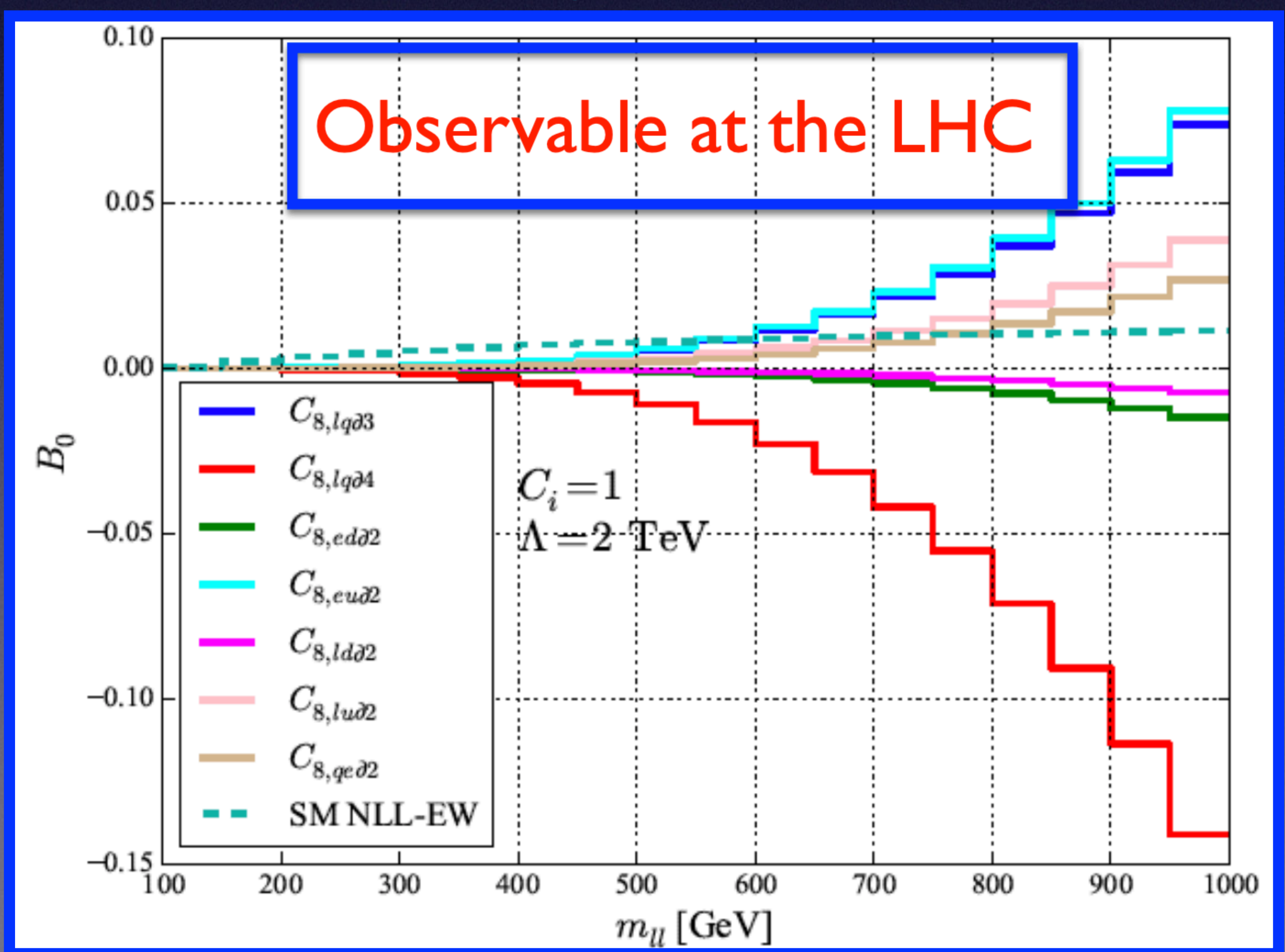
Alioli, RB, Mereghetti, Petriello, 2020



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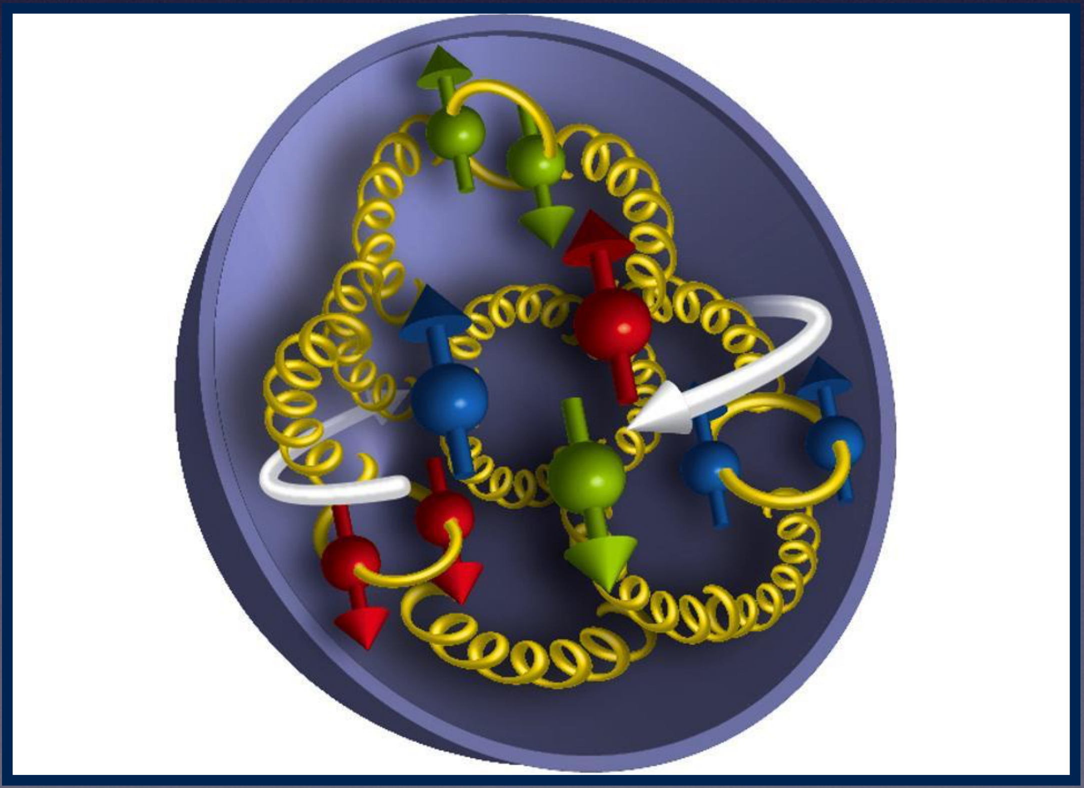
Puzzles in proton structure

- Even after several decades of study, simple aspects of QCD still surprise us

How is the proton spin formed from its microscopic constituents?

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



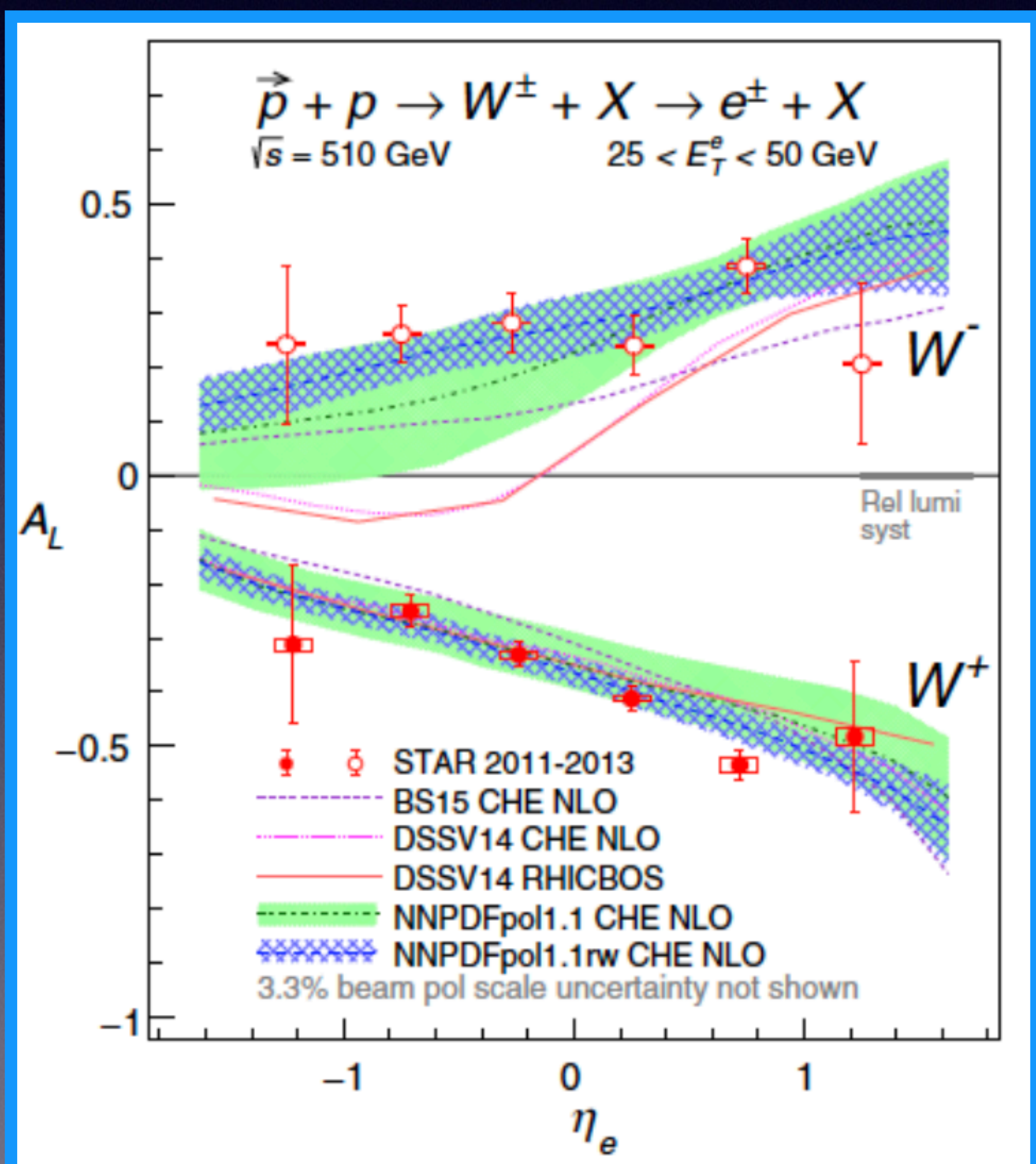
Quark spin **Gluon spin** **Orbital**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{G+q}$$

Goal: precision determination of polarized PDFs

Recent progress: W production at RHIC

- Longitudinal spin asymmetries in W production provide the first glimpse of flavor structure in the polarized quark sea.



$$A_L \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

$$y_W \gg 0 \to x_1 \gg x_2 : A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)}, A_L^{W^-} \approx -\frac{\Delta d(x_1)}{d(x_1)}$$

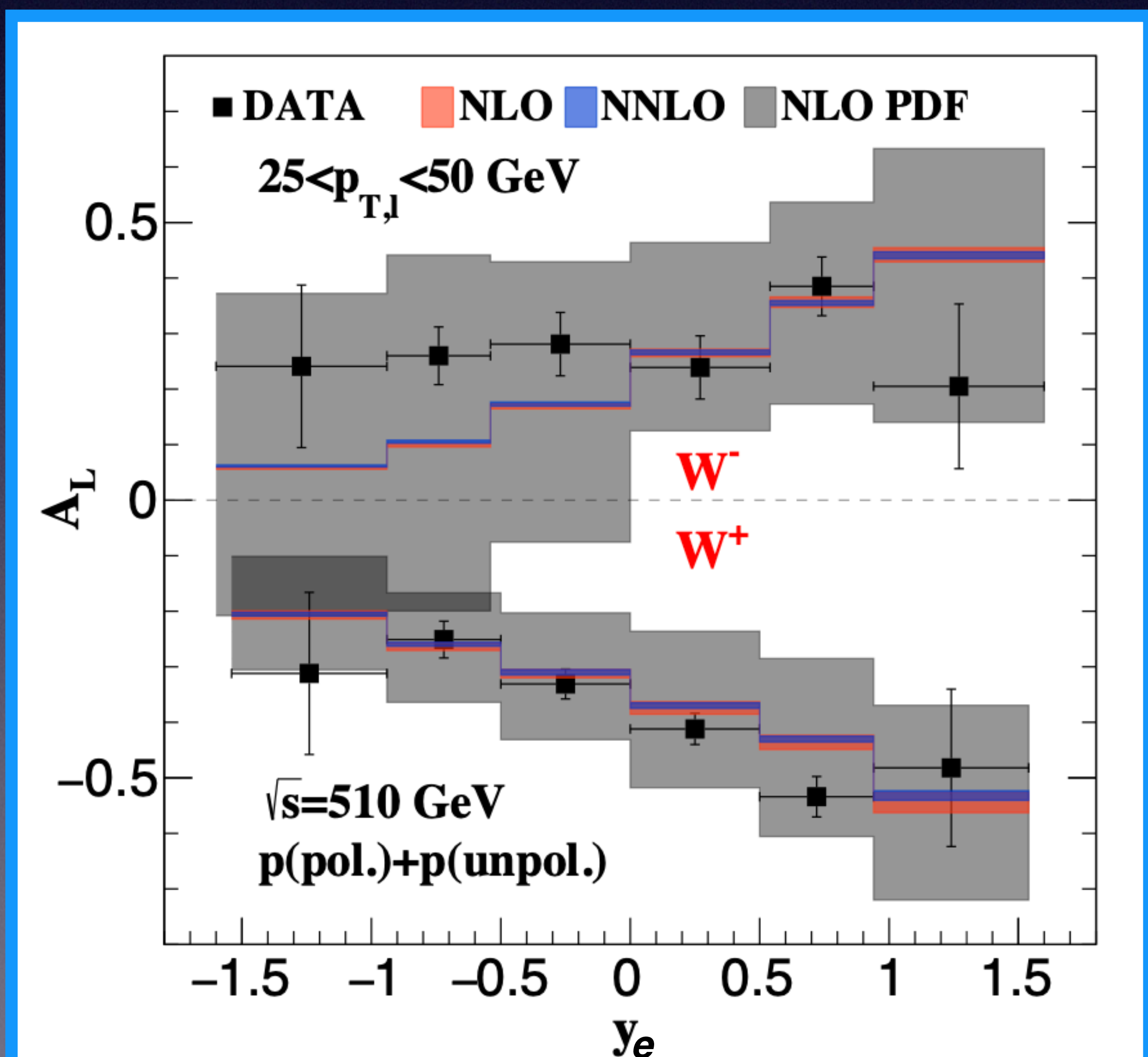
$$y_W \ll 0 \to x_2 \gg x_1 : A_L^{W^+} \approx \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, A_L^{W^-} \approx \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}$$

$A_L^{W-} > 0$ and $A_L^{W+} < 0$ at negative η_e indicate a positive $\Delta\bar{u} - \Delta\bar{d}$

Recent progress: W at RHIC

- Longitudinal spin asymmetries in W production provide the first glimpse of flavor structure in the polarized quark sea.

RB, H.T.Li, Petriello, 2021



$$A_L \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

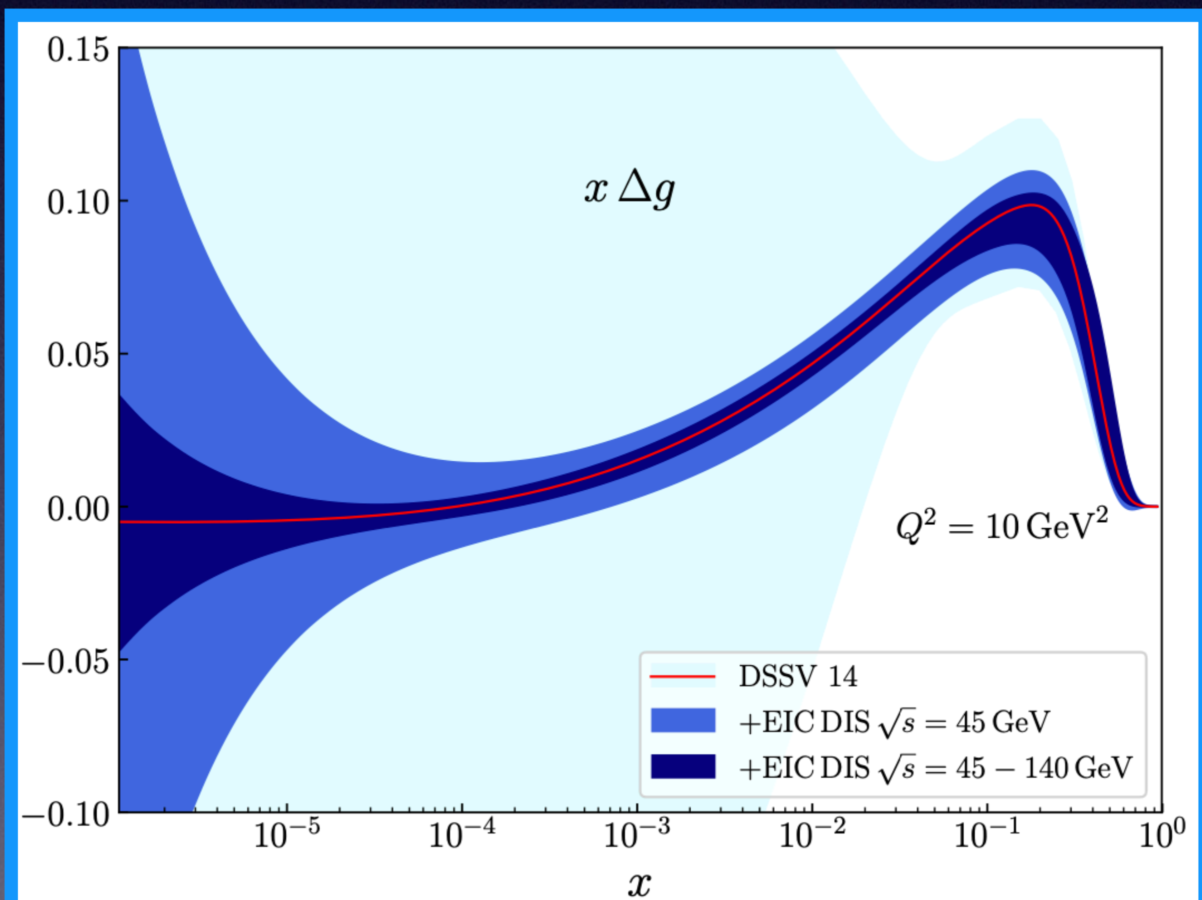
$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

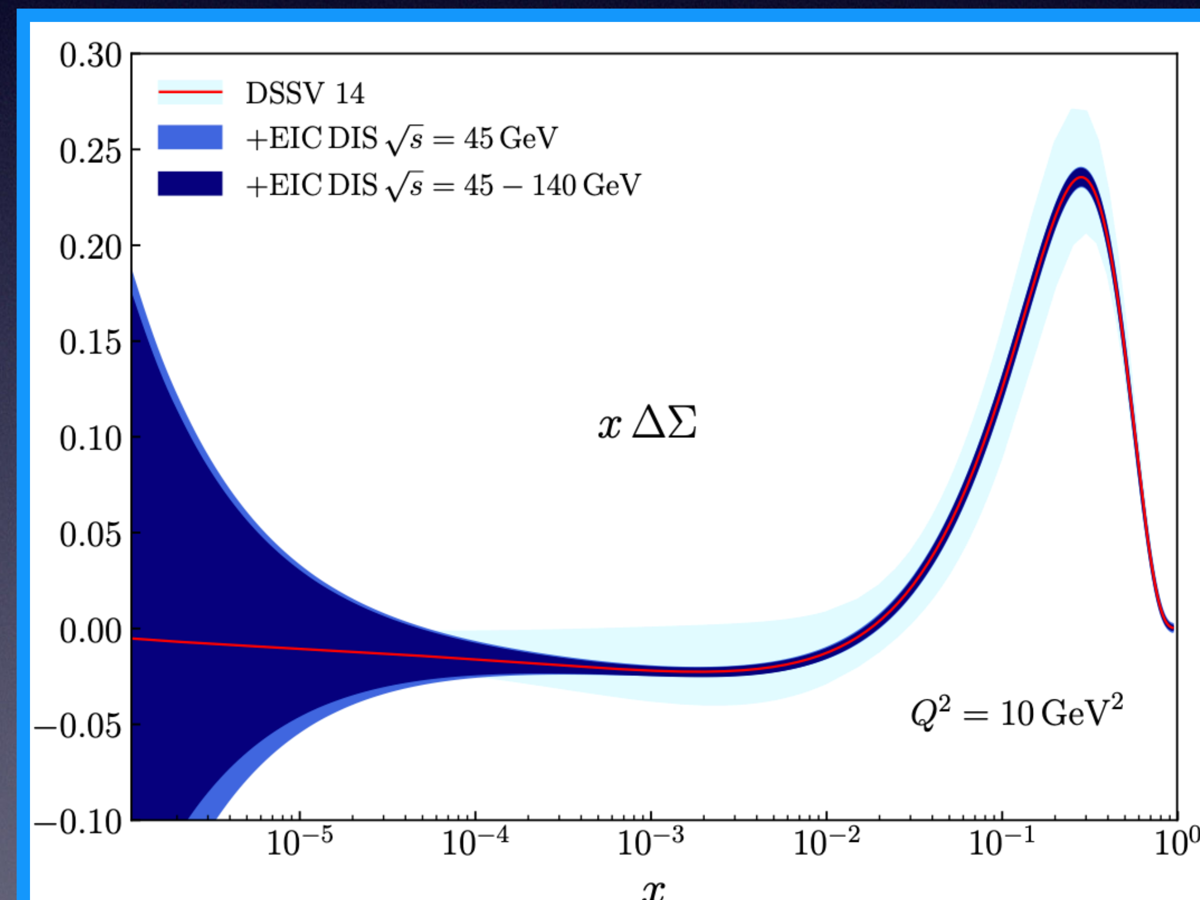
Now known at NNLO. Excellent stability under pQCD makes this a powerful probe of polarized sea PDFs.

Future projections at the EIC

- A precision determination of polarized PDFs will first come from the EIC.

Borsa, Lucero, Sassot, Aschenauer, Nunes, 2020





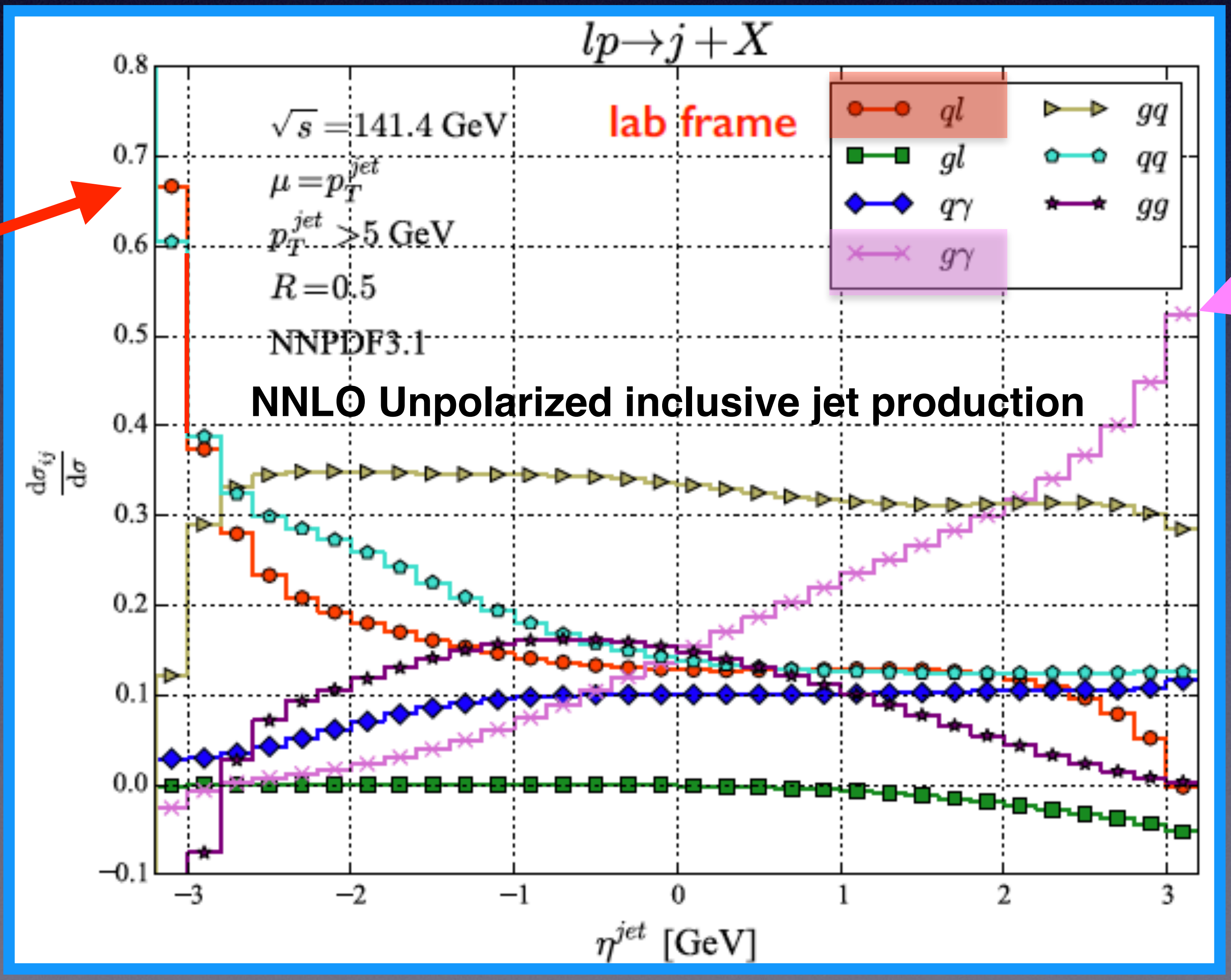
Long-term goal: NNLO extraction of polarized PDFs. Our understanding of unpolarized PDFs at this level has had a profound impact on our ability to understand LHC data.

Jets and longitudinal proton structure

- Jets can play an important role in disentangling the structure of the proton.

Abelof, RB, Liu, Petriello, 2016

quark-dominated



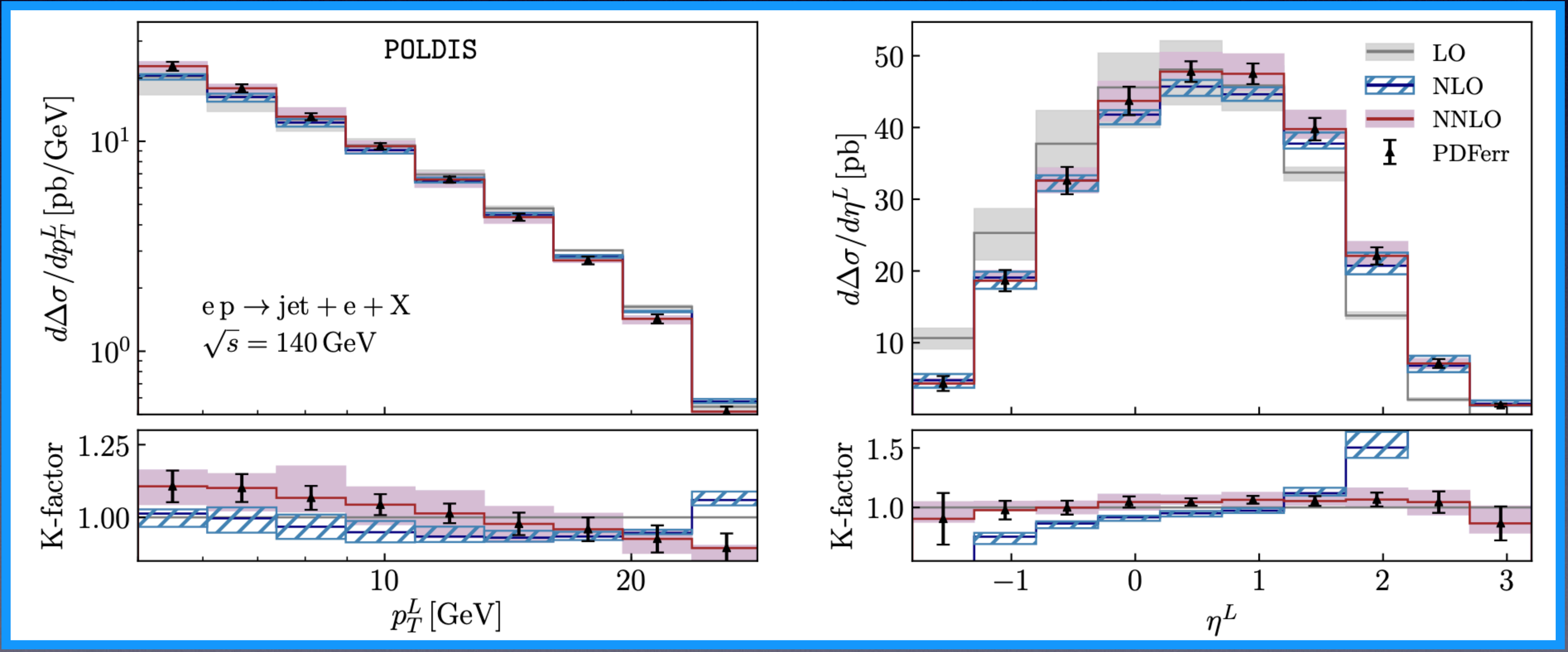
gluon-dominated

Different regions of jet phase space give access to different parton distributions

Jets and longitudinal proton structure

- **New result:** jet production in polarized DIS through NNLO (n.b. no direct or resolved photon contributions).

Borsa, de Florian, Pedron, 2020



Good perturbative behavior of the DIS process observed

Summary

- In the last few years we have witnessed significant improvements in the accuracy of SM predictions for a host of important processes.
- NNLO accuracy for differential distributions has become the standard for relevant $2 \rightarrow 2$ LHC processes and N3LO is becoming the new precision frontier.
- A continuous progress of precision theory is crucial for a full exploitation of the upcoming precision LHC data.
- Can gauge sensitivity to heavy new physics through EFT approaches such as SMEFT. Such studies combined with the anticipated HL-LHC precision can lead to novel experimental signatures.
- Great synergy and cross talk between the precision program at the LHC and future colliders such as the EIC. Looking forward to exciting new results and advances!