BERNHARD MISTLBERGER

COLOUR-SINGLET PRODUCTION AT N3LO

PRECISION LHC PHYSICS

- The large amount of LHC data allows us to measure some observables to astounding precision.
- Typically, such observables are characterised by clearly identifiable final states and involve very large final state particle momenta.

Higgs, Z, W, top quark:

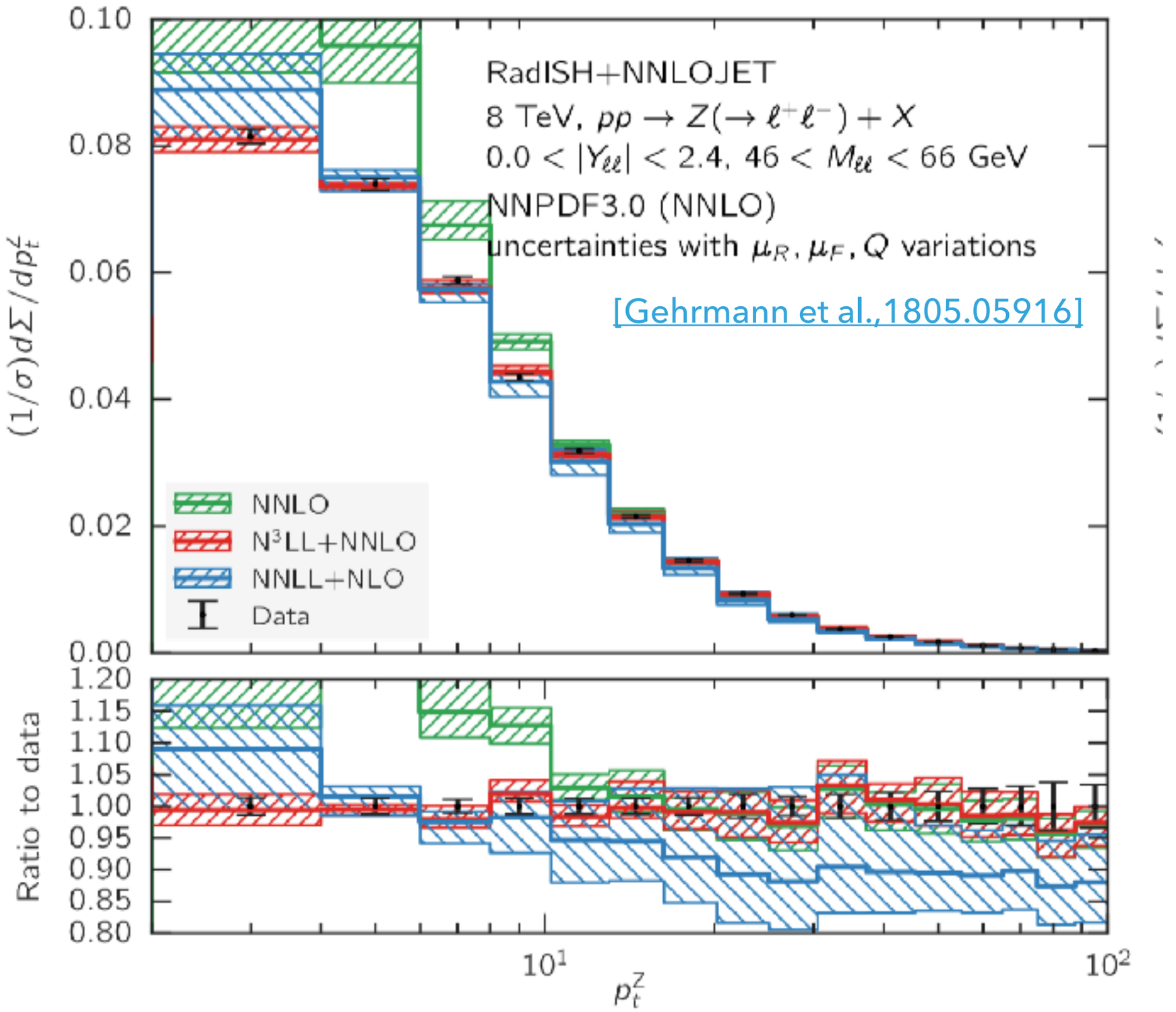
PRECISION LHC PHYSICS

Higgs, Z, W, top quark:

- **The quest nr 1:** What is the Higgs potential? What are the properties of the Higgs?
- Measuring their properties will allow us to systematically search for deviations from Standard Model Physics (with EFTs, with bumps).
- New physics aside: We can simple determine masses, couplings, parton distribution functions; study hadronisation, jets and interactions of highly energetic particles in general.

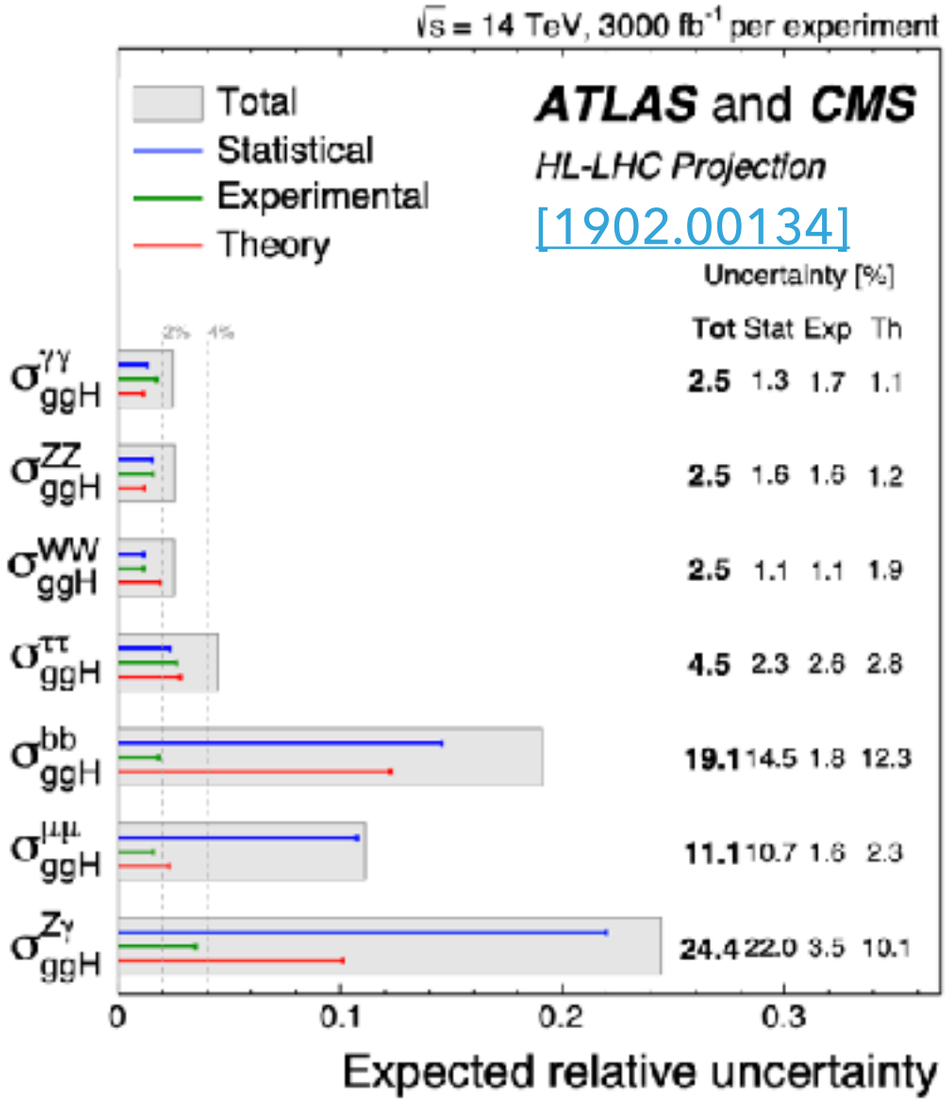
EXAMPLES OF PRECISION OBSERVABLES – Z-PT

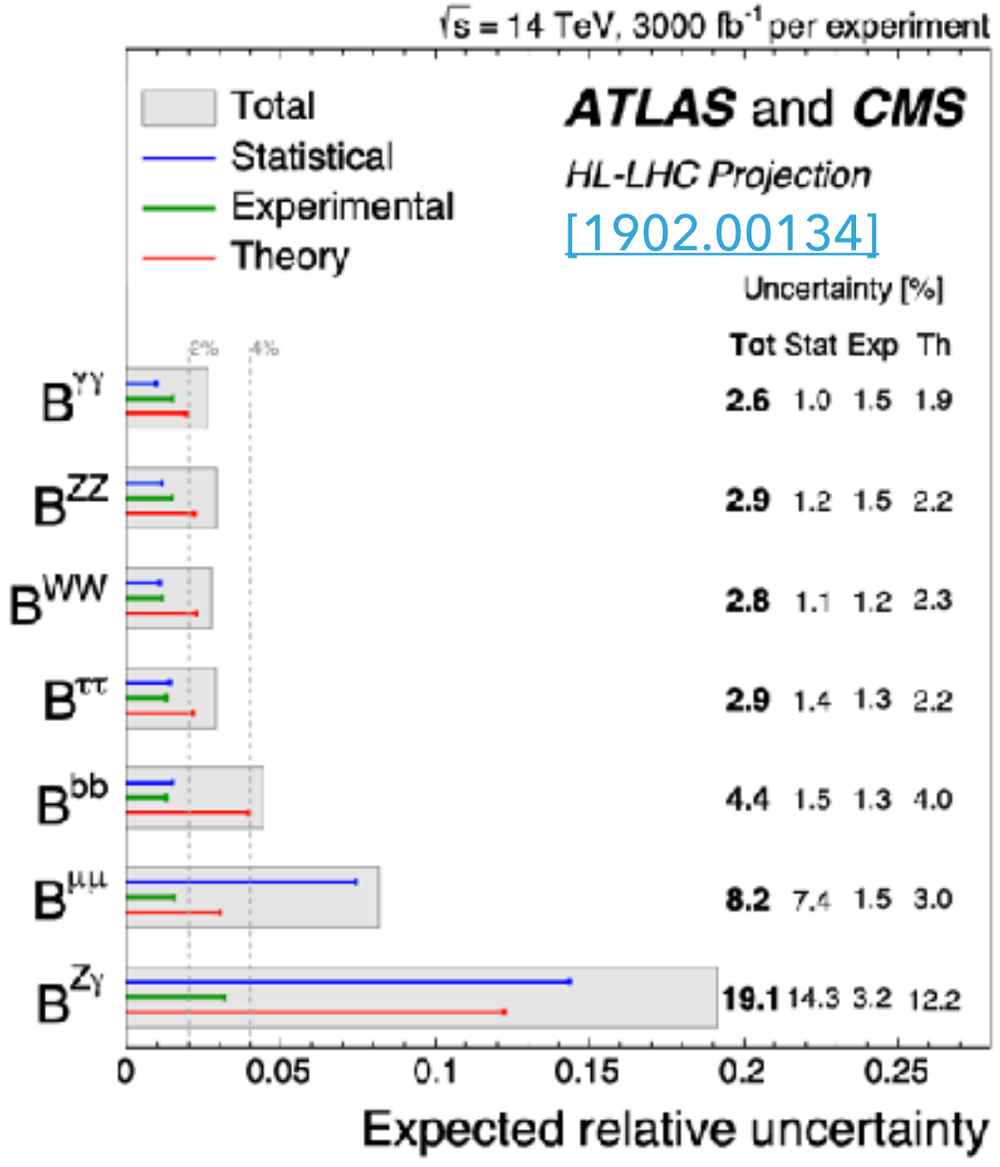
- Huge Cross Sections
- 2 - lepton final state
- Extremely Precise Measurements
- Here: 8 TeV Data.



EXAMPLES OF PRECISION OBSERVABLES – HIGGS

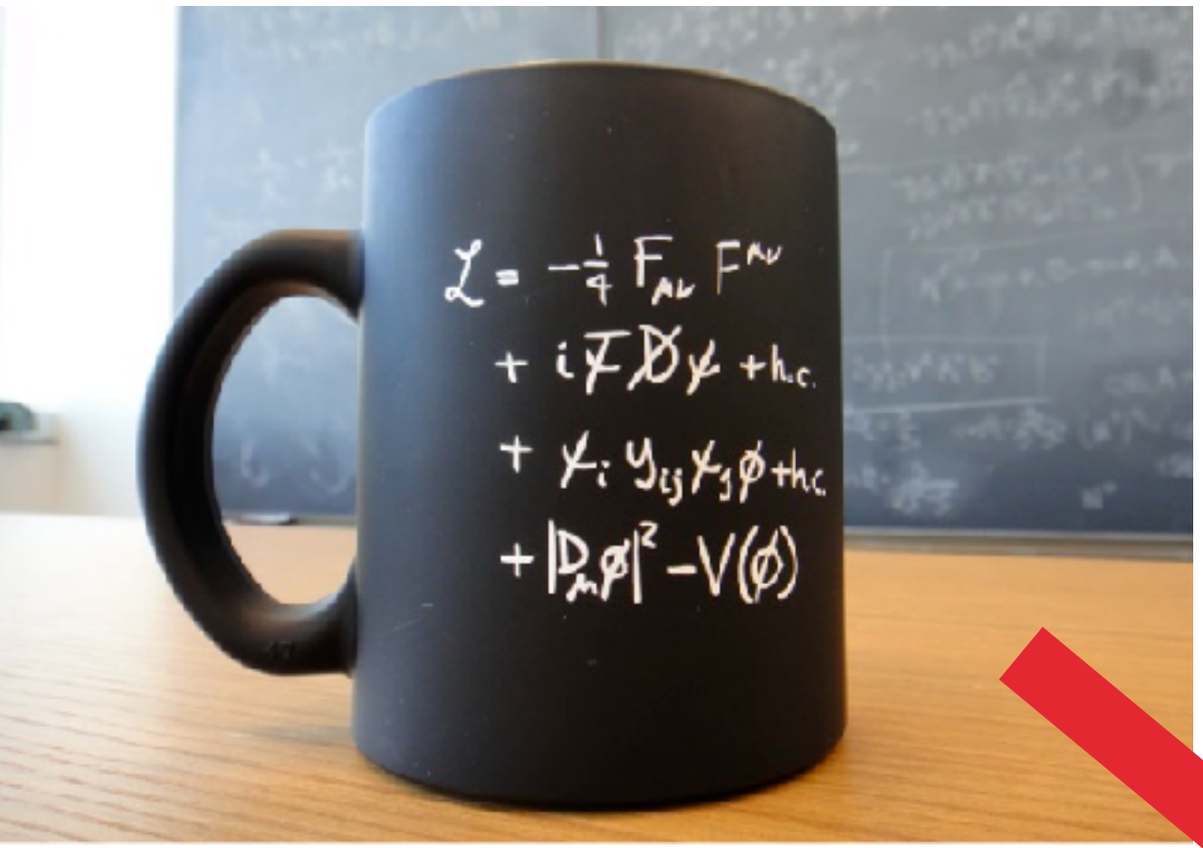
- 3000 fb^-1
- Determining Higgs properties at few percent!





COMPUTING AT N3LO

PRECISION LHC PHYSICS

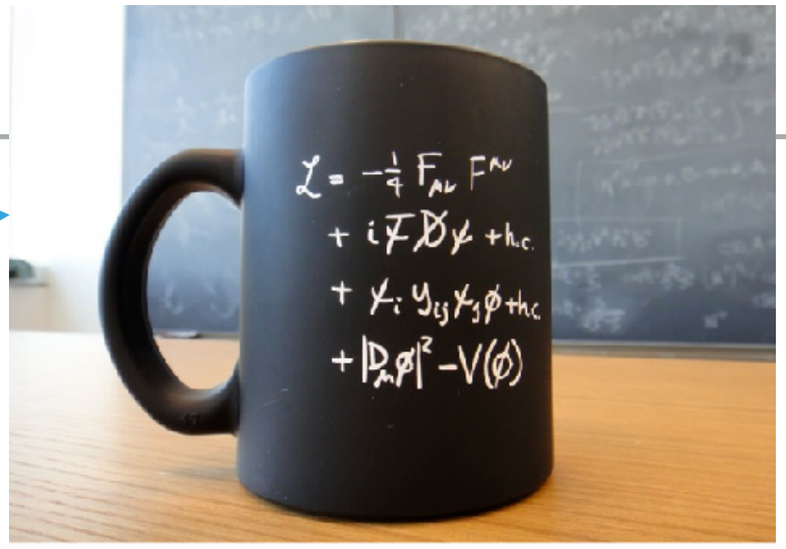


To learn about nature we need to connect

Theory and Experiment at the same level of precision.

PRECISION LHC PHYSICS

$$\sigma \sim \int dx dy f(x) f(y) \hat{\sigma} + \mathcal{O}\left(\frac{\Lambda}{Q}\right)$$



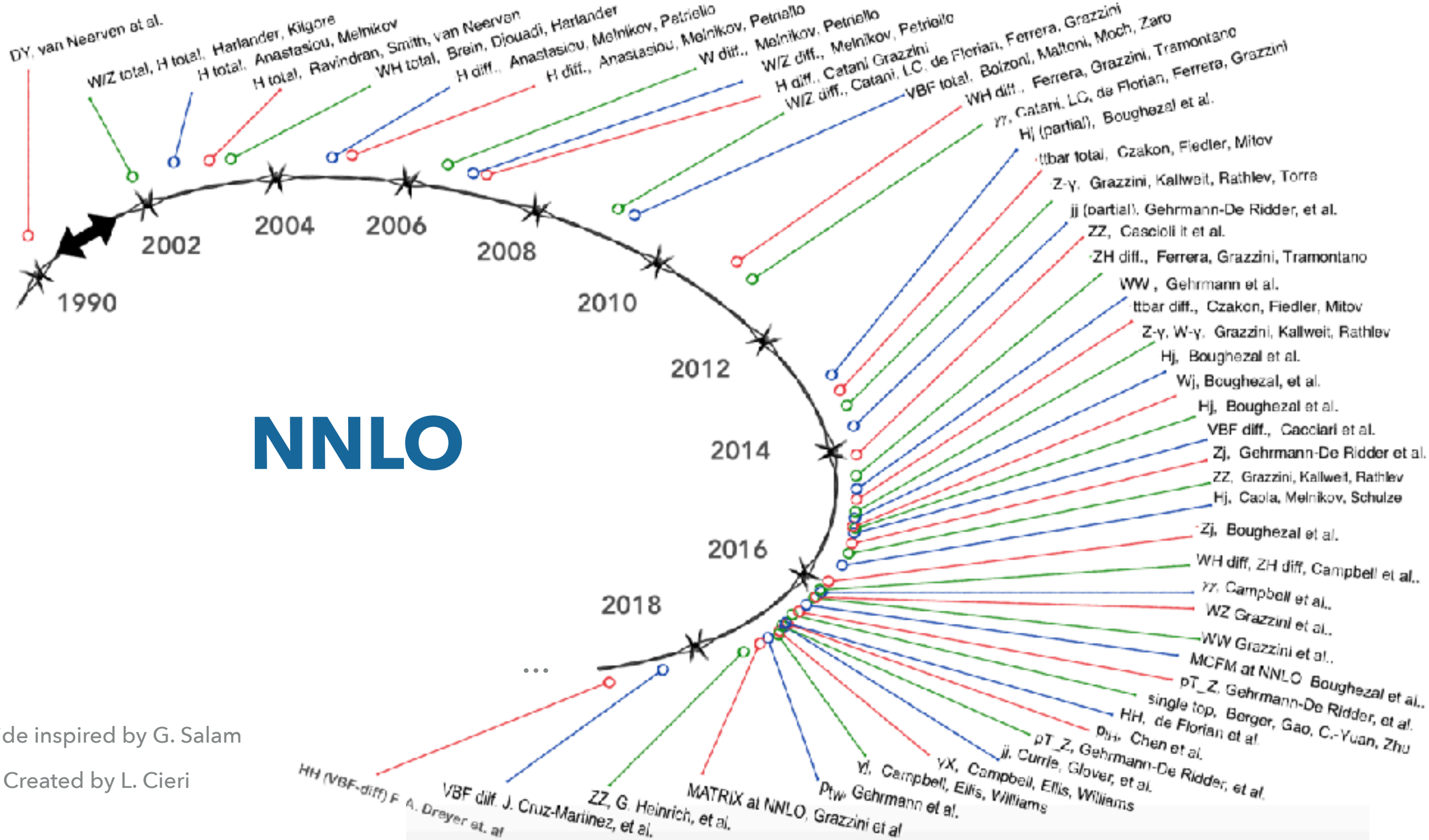
- Perturbative partonic cross sections
- QCD perturbation theory is dominant $\alpha_S = 0.118$
- Naively:

LO **NLO** **NNLO** **N3LO**

$$\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_S^1 \hat{\sigma}^{(1)} + \alpha_S^2 \hat{\sigma}^{(2)} + \alpha_S^3 \hat{\sigma}^{(3)} + \dots$$

- Resum, where this doesn't work!

NNLO OVER TIME



NNLO

Slide inspired by G. Salam

Created by L. Cieri

N3LO RESULTS OVER TIME

2015

Higgs Threshold Exp.
[Anastasiou, Duhr, Dulat, Herzog, BM, 15]

Higgs Jet Veto [Banfi, et al. 15]

2016

Drell-Yan [Dulat, Duhr, BM,20]

bbH 4FS+5FS [Dulat, Duhr, Hirschi, BM,20]

CCDY [Dulat, Duhr, BM,20]

2017

Higgs VBF [Dreyer, Karlberg,16]

Higgs Diff. Threshold App.
[Dulat, BM, A. Pelloni,17]

2018

Higgs Diff. qT [Cieri,Chen, Gehrmann, Glover,Huss,18]

HH (VBF) [Dreyer, Karlberg,18]

Higgs (Y approx.) [Dulat, BM,Pelloni,18]

2019

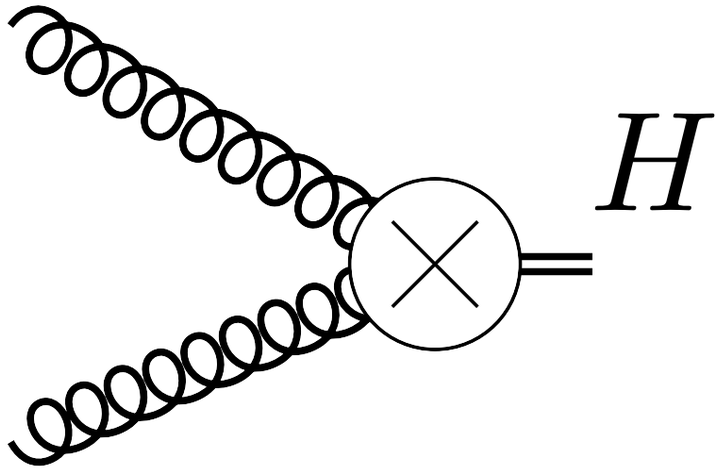
Higgs, [BM,18]

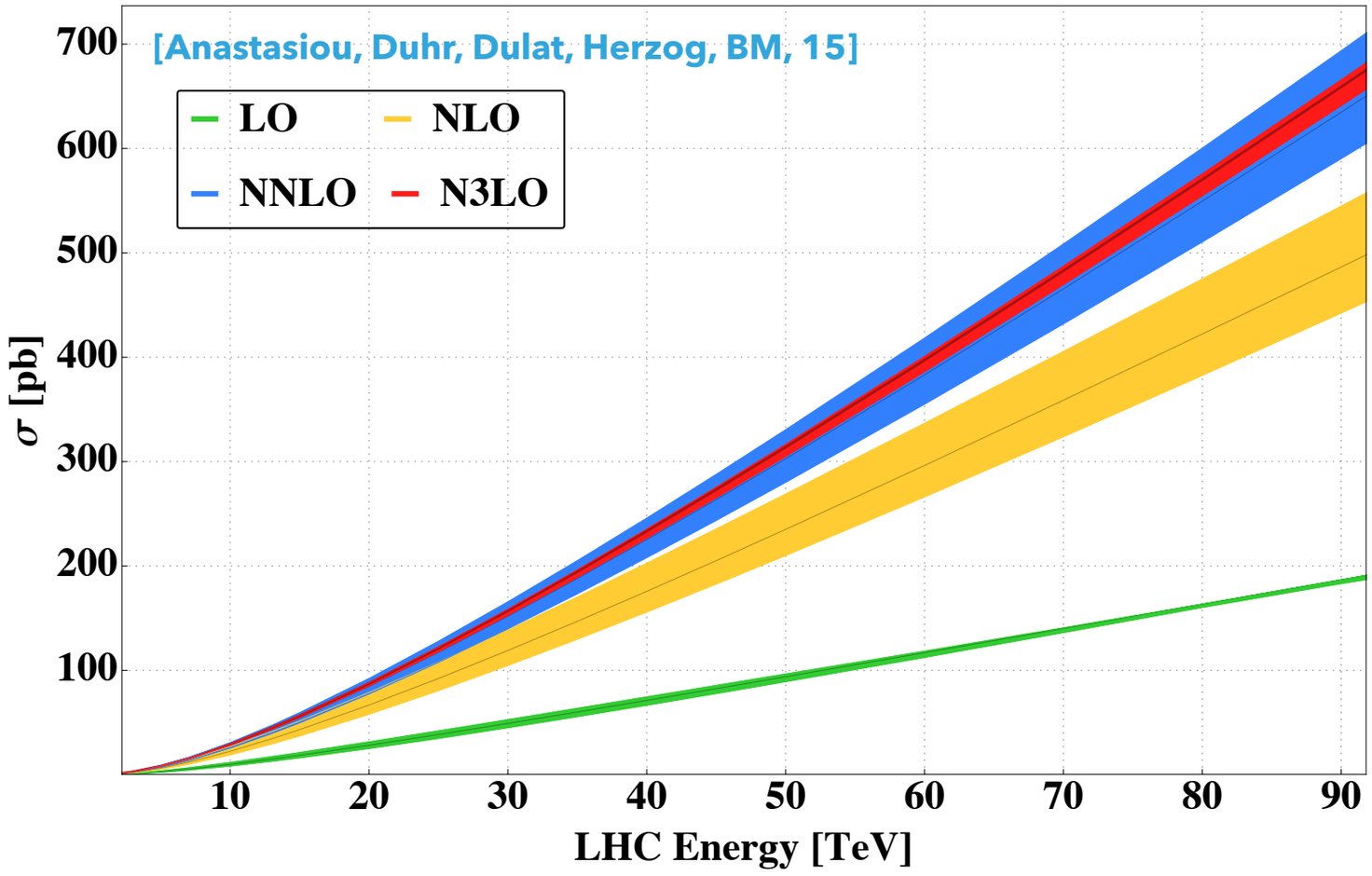
2020

bb->H [Dulat, Duhr, BM,19]

INCLUSIVE CROSS SECTIONS AT N3LO

HIGGS PRODUCTION





- Observable plagued by large corrections.
- N3LO stabilises the expansion.
- Here: Only QCD corrections with bands = scale variation

HIGGS PRODUCTION

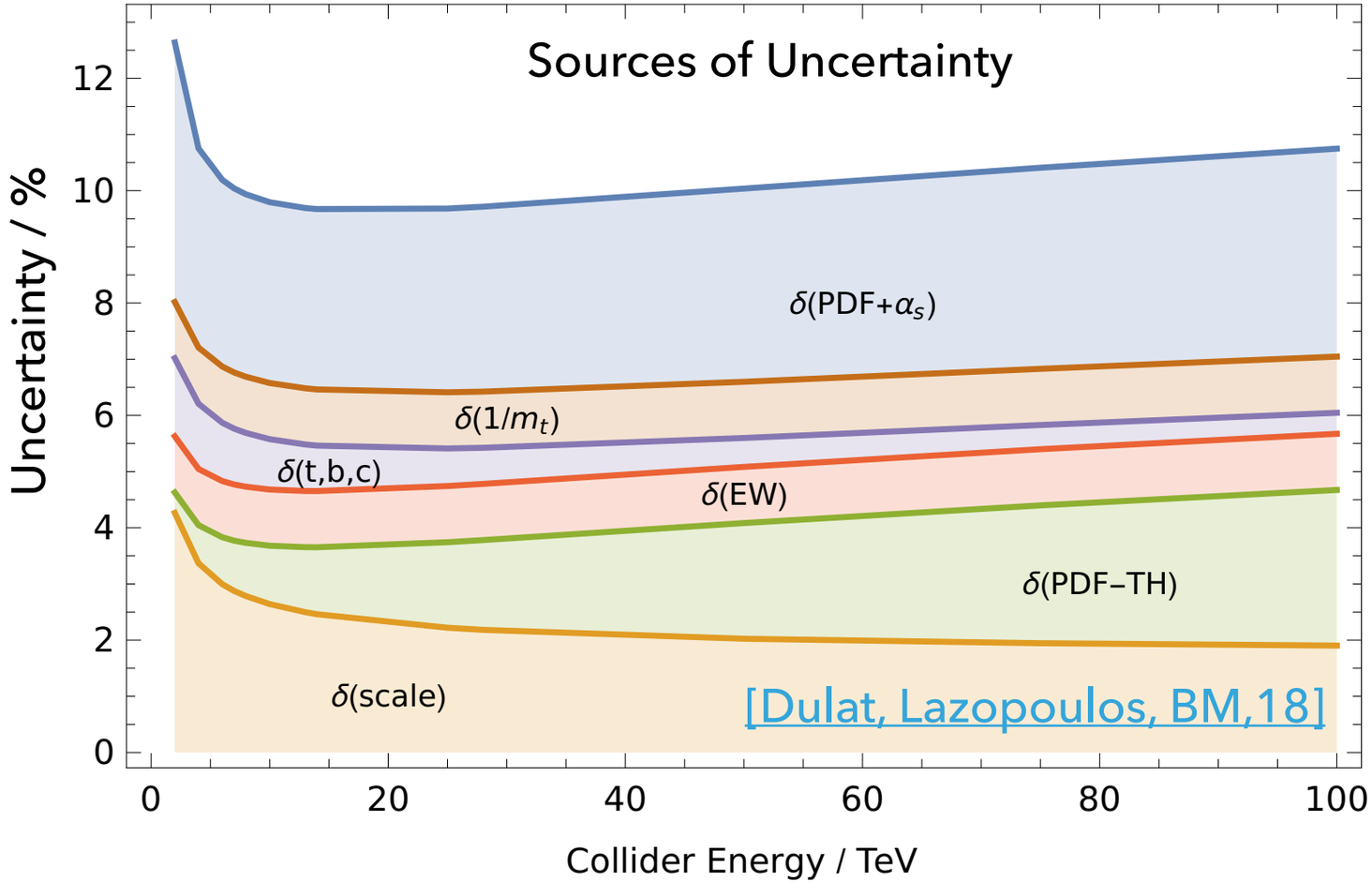
Much more than QCD corrections

- Electro-weak corrections.
- Neglected quark mass effects.
- Coupling to bottom, charm quarks.
- Estimate uncertainties.

  Truncation of perturbative series

  PDF, α_S

- …



HIGGS PRODUCTION

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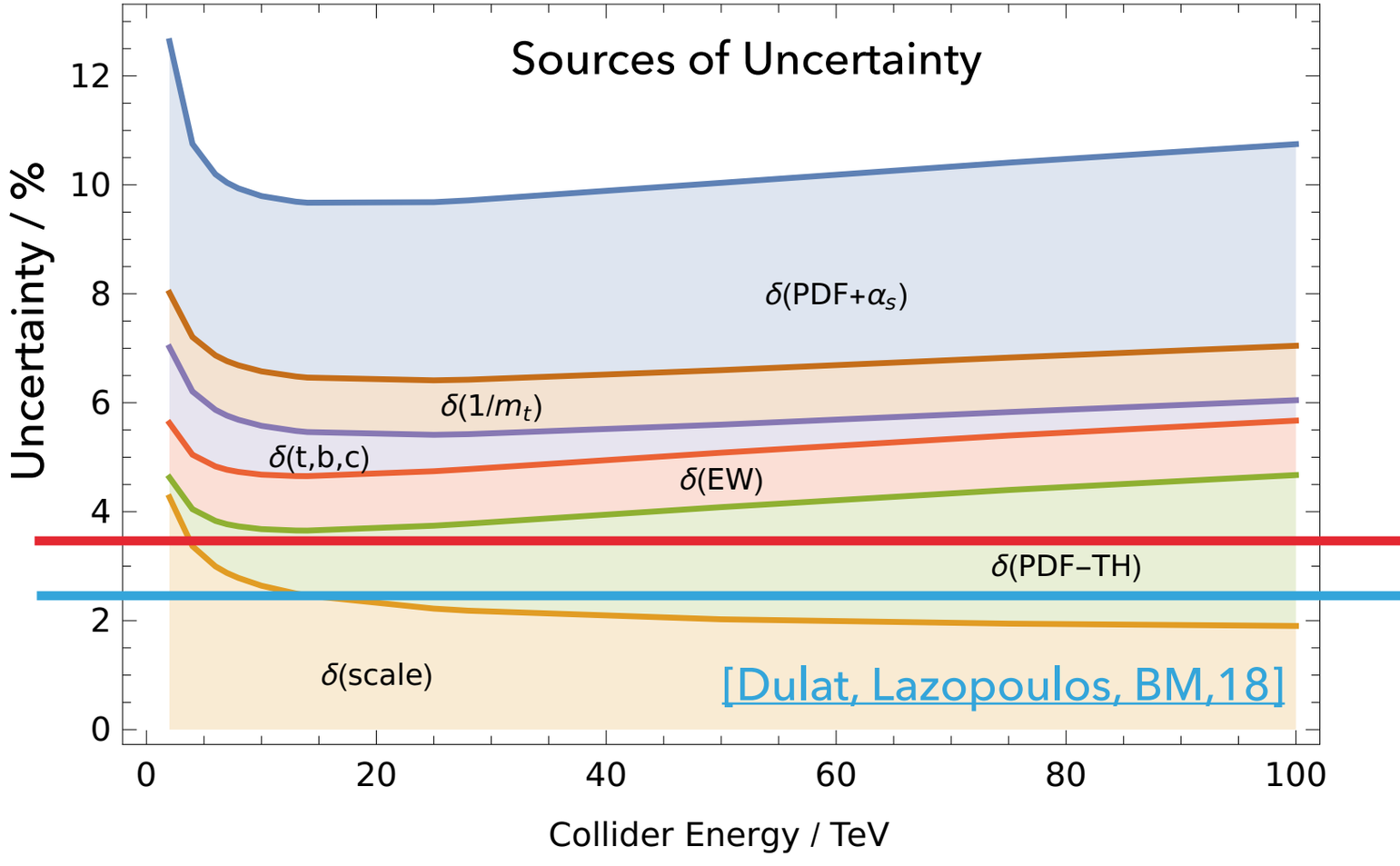
- ...

HL-LHC

$3000\ fb^{-1}$

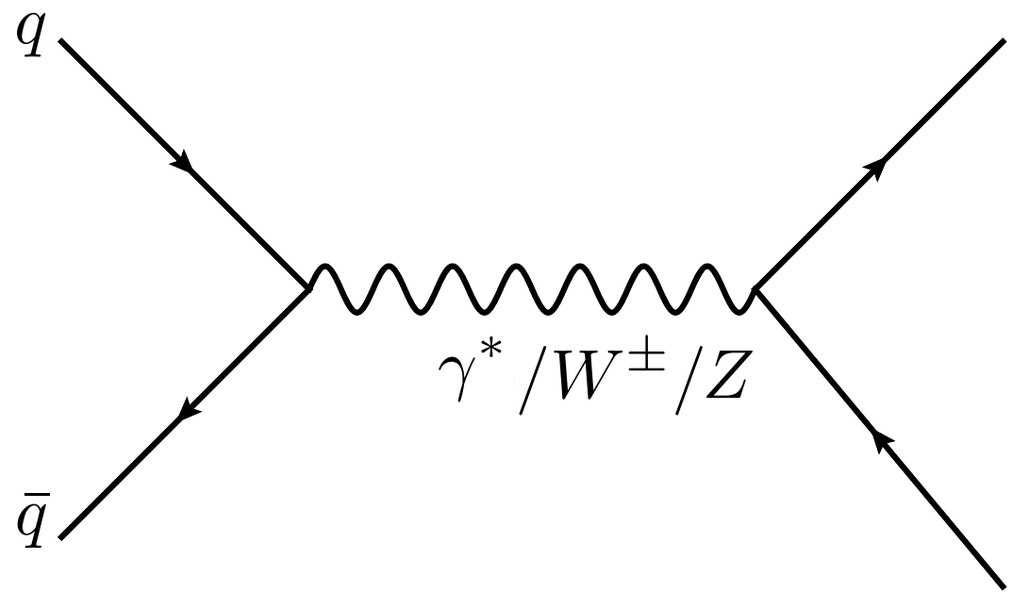
Pessimistic scenario

Optimistic scenario



$P\,P \to \gamma^*/W^{\pm}/Z$

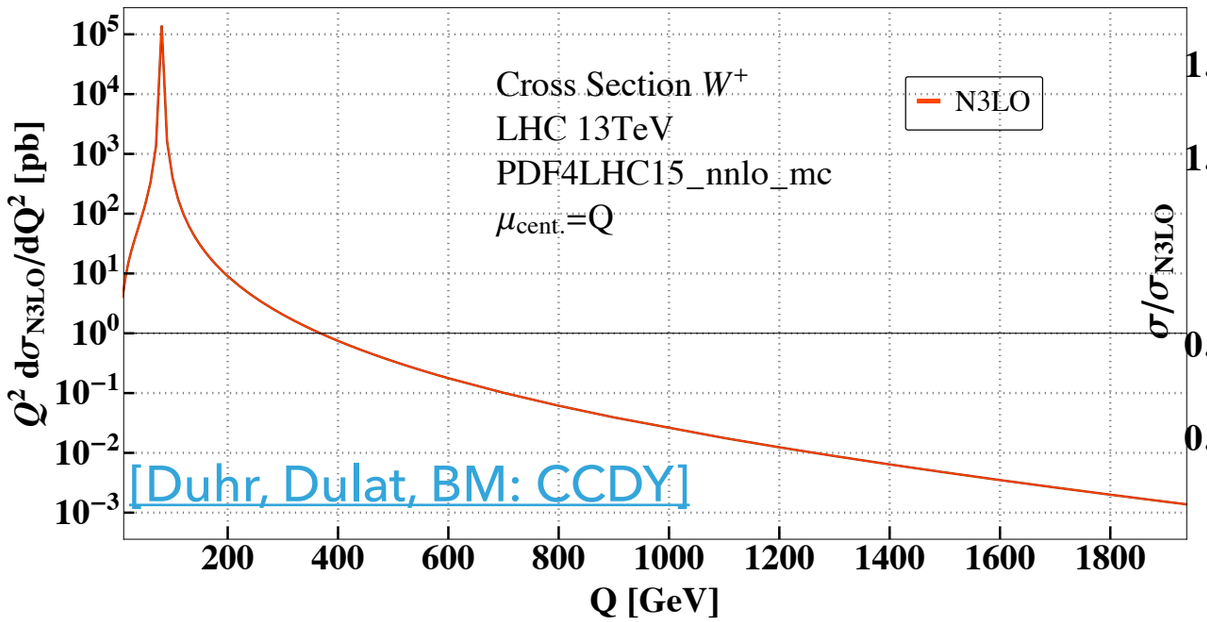
DRELL-YAN PRODUCTION



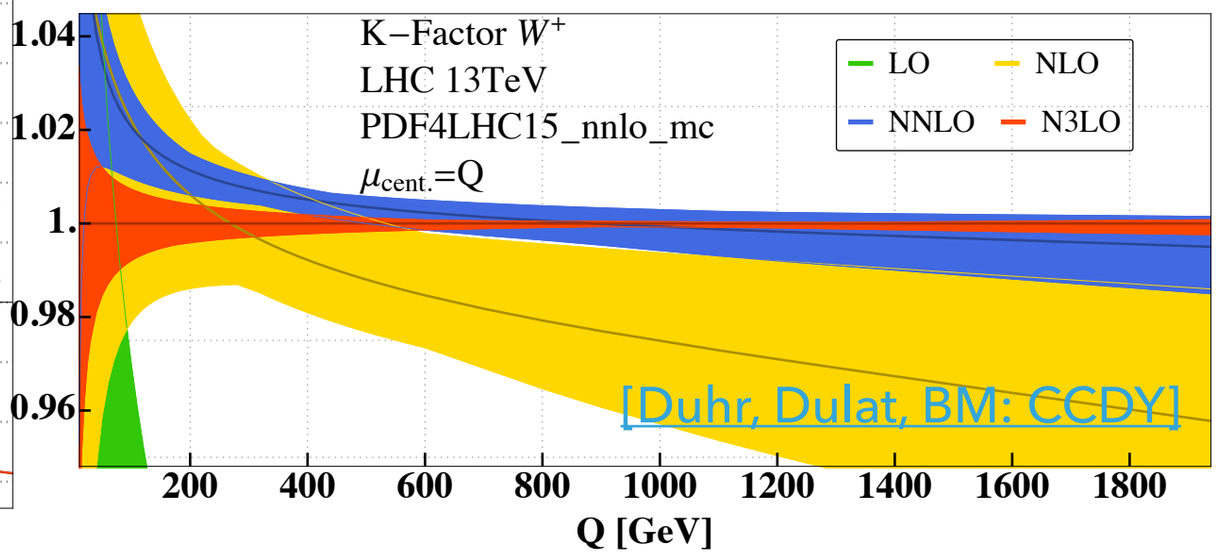
- Inclusive probability to produce a virtual vector boson that can decay into leptons or jets.
- Very clean final state measured with incredible statistics.
- Recently computed to **N3LO** in QCD perturbation theory
  - ★ K - Factors
  - ★ Learn about the progression of perturbation theory
  - ★ Learn about the precision achievable for such processes

$P\ P \to W^+$

Nominal XS:



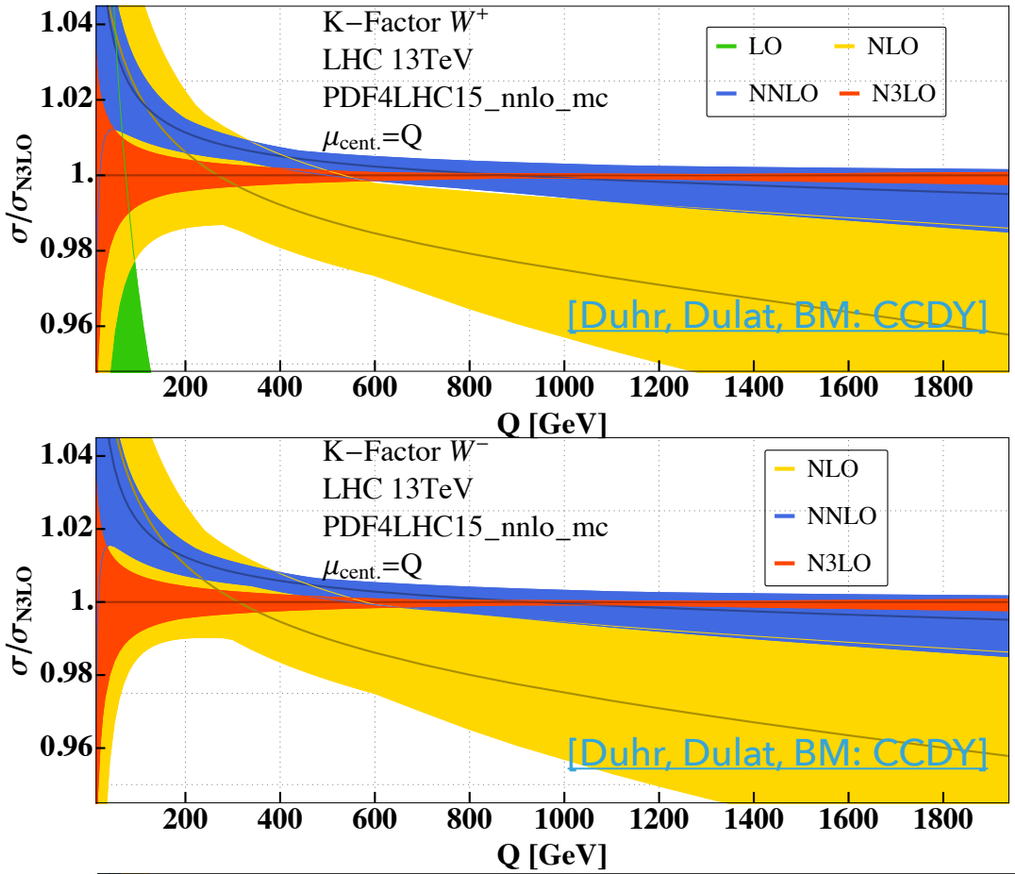
K-Factor



- Percent level corrections.
- Stable at large scales.
- Permille scale variations.

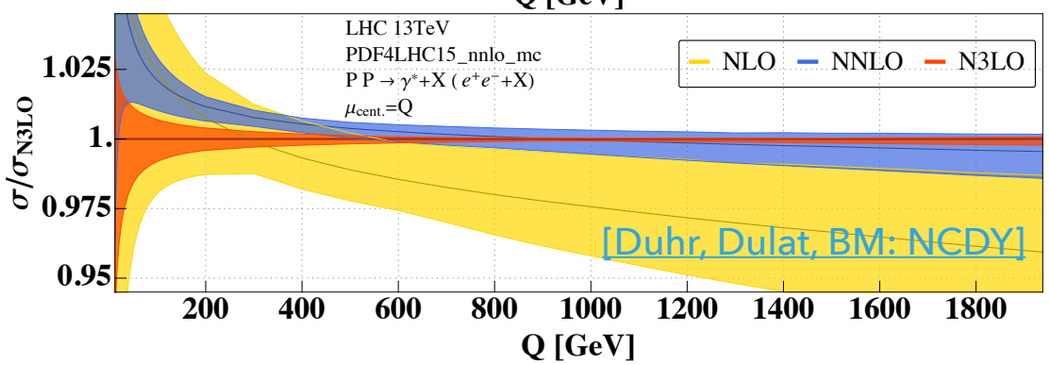
$P\,P \to \gamma^*/W^{\pm}$

K-Factor



W+

W-

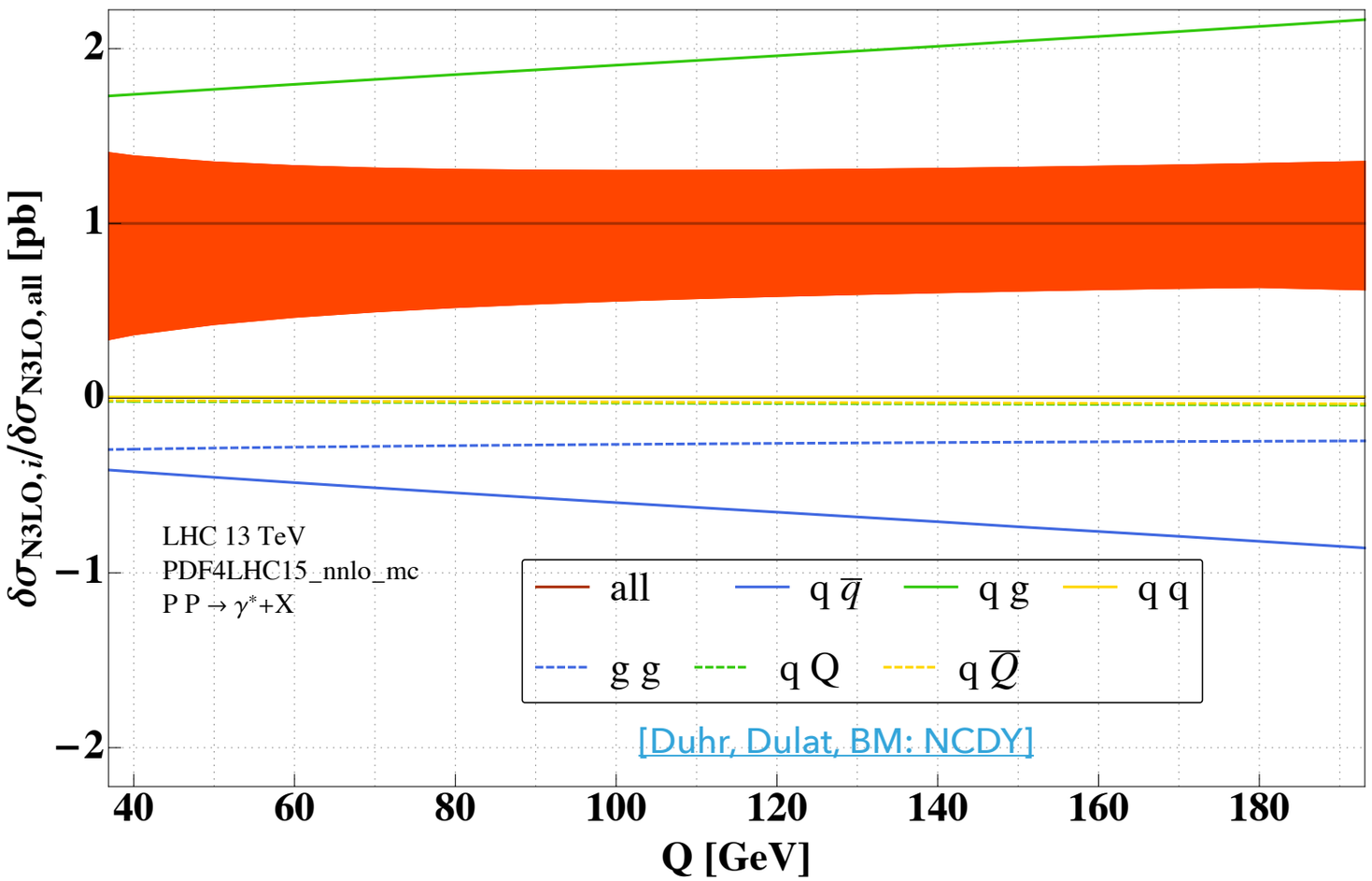


Photon

- Very similar corrections for CC and NC DY cross sections.
- Gap at ~ 100 GeV of NNLO and N3LO bands.

Non-overlapping scale bands: N3LO vs NNLO

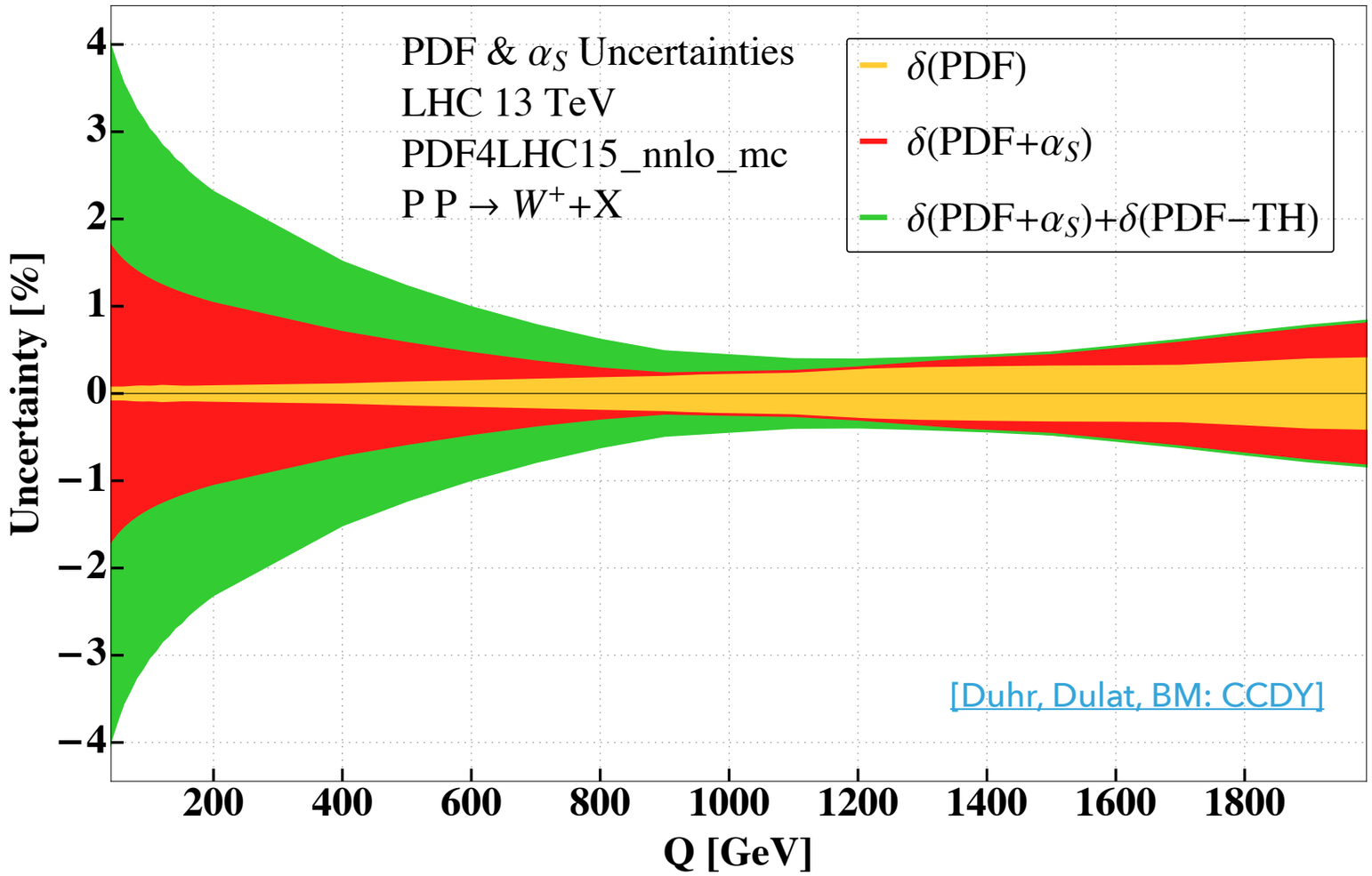
Decompose partonic initial states:



- Large cancellation of quark and gluon initial state.
- Compensated by N3LO PDFs?? - currently missing.
- Similar for W bosons.

Large uncertainties related to PDFs:

- Currently: no N3LO PDFs
- Strong Coupling Constant
- PDFs themselves are not known to the level of QCD predictions

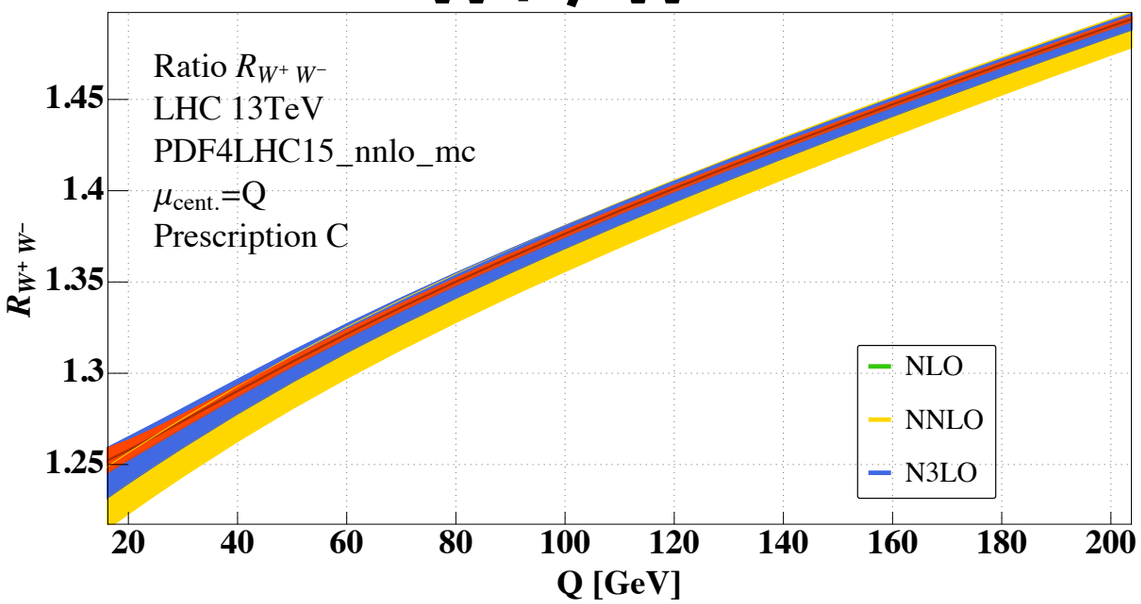


Opportunity to push for better PDFs.

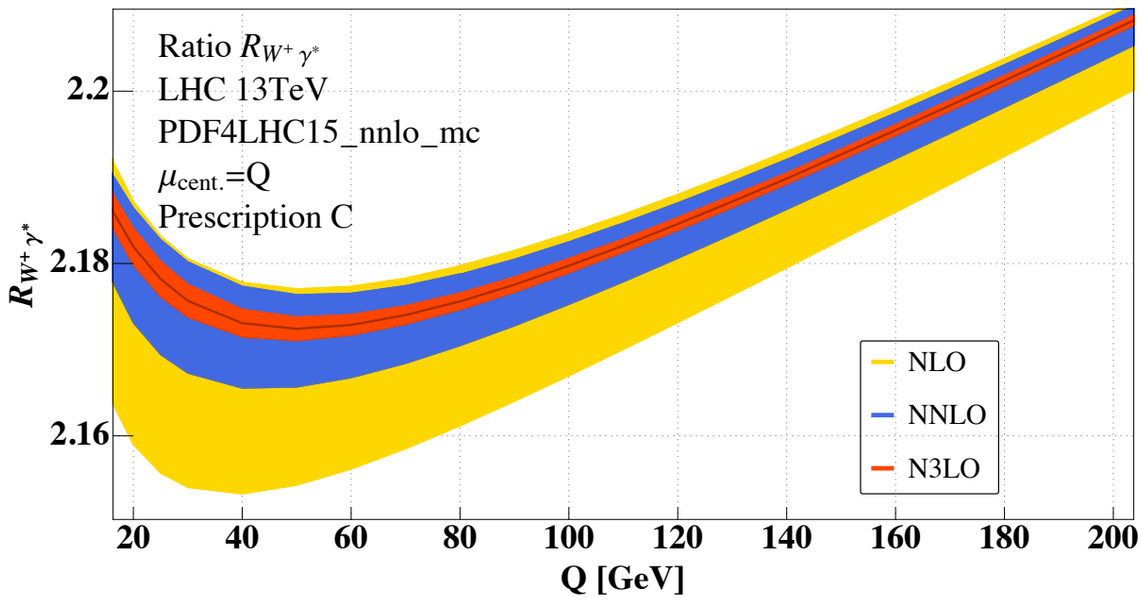
Per-Cent Level

RATIOS OF CROSS SECTIONS

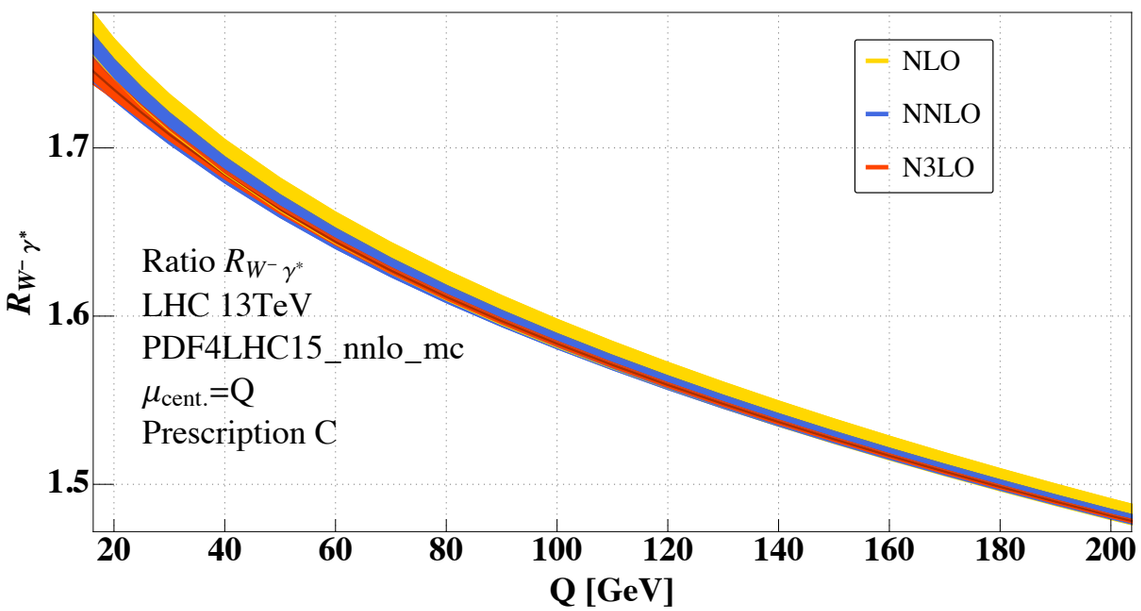
W+ / W-



W+ / Photon



W- / Photon

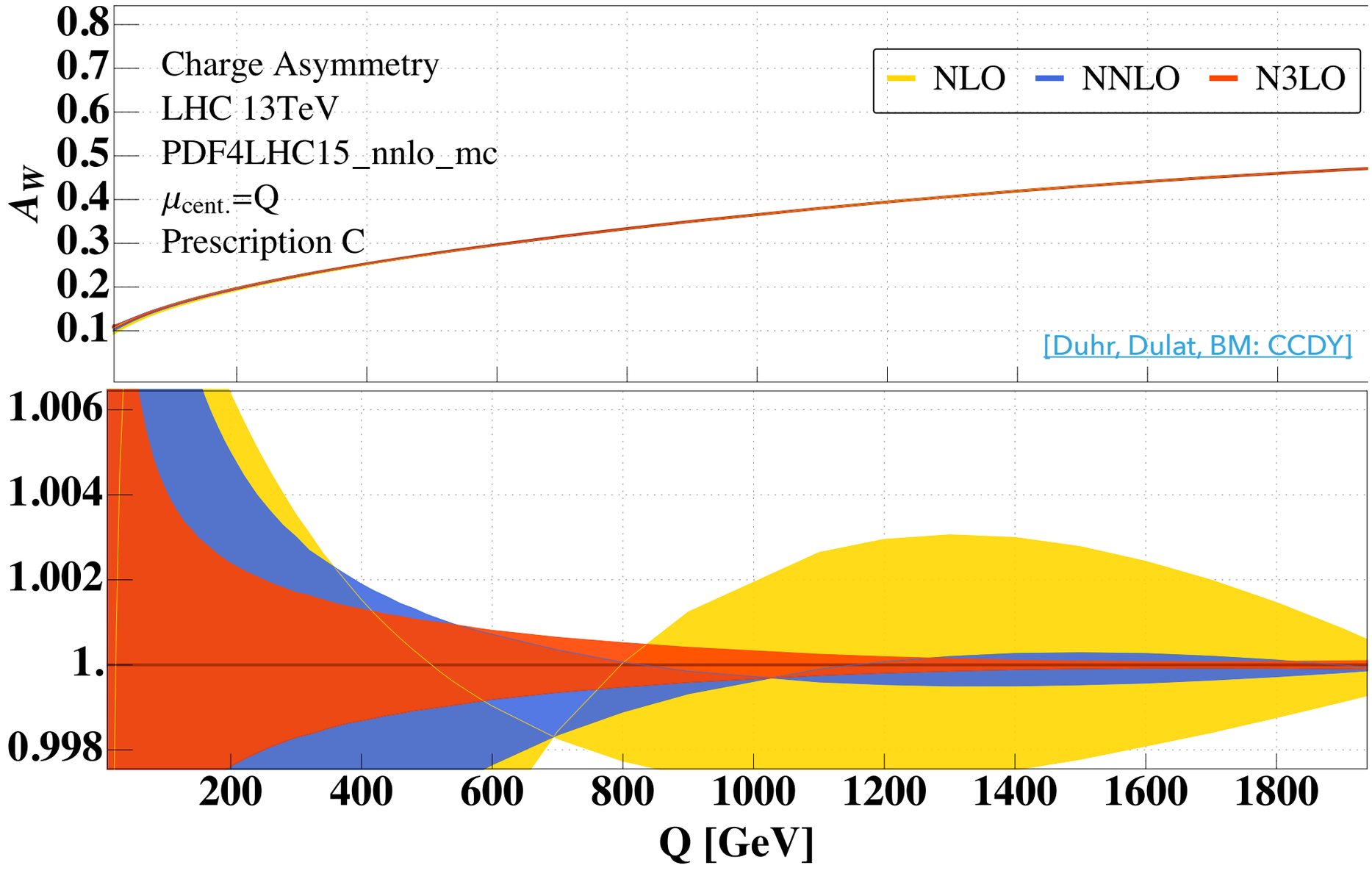


- Ratios of Cross Sections can be predicted very well.
- Reduce systematics: Lumi-Uncertainty, etc.

CHARGE ASYMMETRY

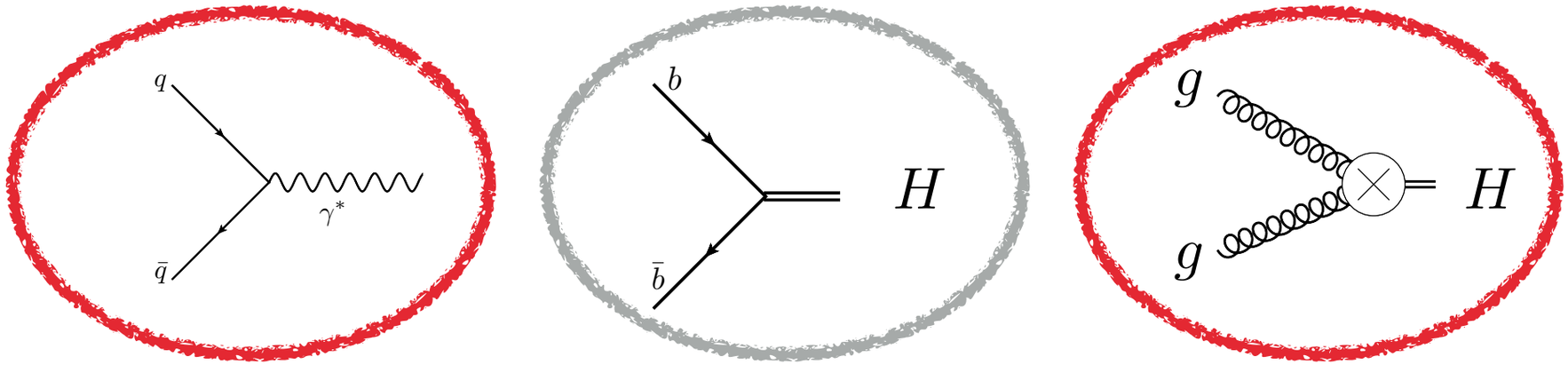
- One nice observable:

$$A_c = \left| \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}} \right|$$



THE EMERGING N3LO PICTURE

Processes at **N3LO**:



$$\frac{\delta\sigma_{N3LO}}{\sigma_{NNLO}} \qquad -1.4\% \qquad -2.3\% \qquad 3.5\%$$

- Corrections are at the order of a few percent.
- N3LO stabilises the perturbative expansion.
- Dependence on perturbative scales is reduced.
- Let’s not forget other uncertainties of comparable size: (PDF / EWK / AlphaS/ …).
- Interpretation of MHOU?

What would we wish for?

- Make theoretical uncertainty irrelevant.
- Easy framework to produce realistic predictions for any LHC observable with cutting edge precision.

- N3LO accurate perturbative predictions matched to parton showers and resumed in every possible corner.

What would we wish for?

- Make theoretical uncertainty irrelevant.
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We need better techniques, better algorithms, … , better everything!

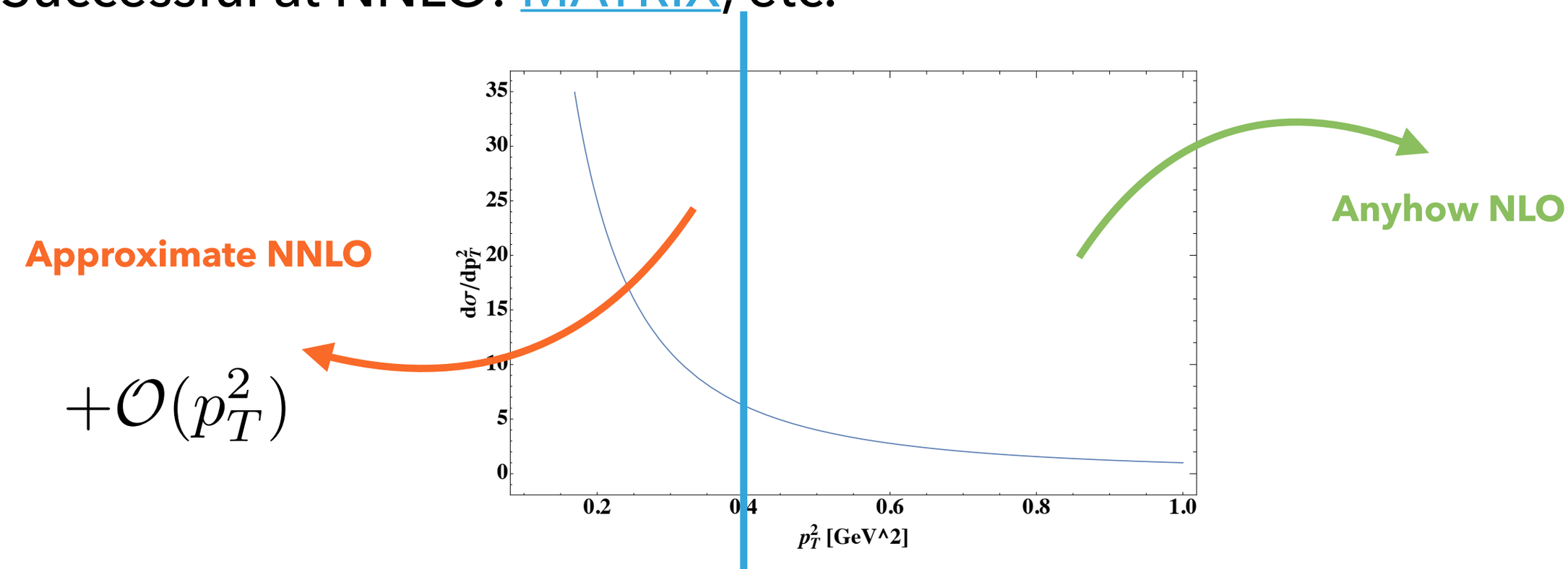
TOWARDS DIFFERENTIAL N3LO

$q_\perp$ AT N3LO:

- qT - Subtraction / Slicing: Algorithm to handle infrared singularities when integrating over final state partons.
- Relatively “simple”.
- Applied to colourless (+ ttbar) final states.

$$\gamma^* \; W \; Z \; H \quad bbH \quad H^* \; G \qquad WH \; ZH \quad ZZ \; WW$$

- Successful at NNLO: MATRIX, etc.

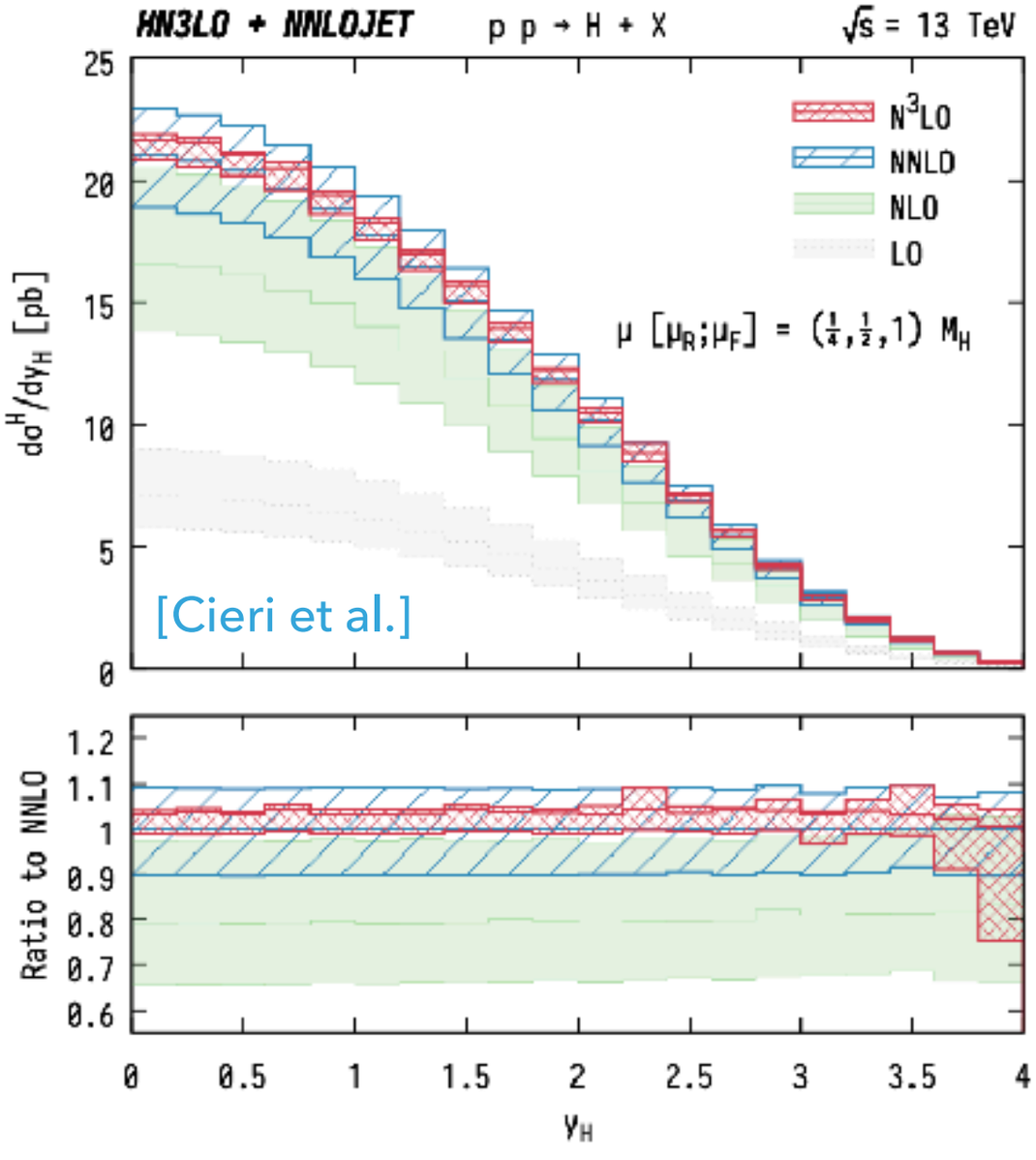


$q_\perp$ AT N3LO:

- Application to the Higgs Rapidity distribution in ggF!

- H+J at NNLO + approximate approximation below cut.
- Numerically very challenging!
- Nice perturbative progression at differential N3LO

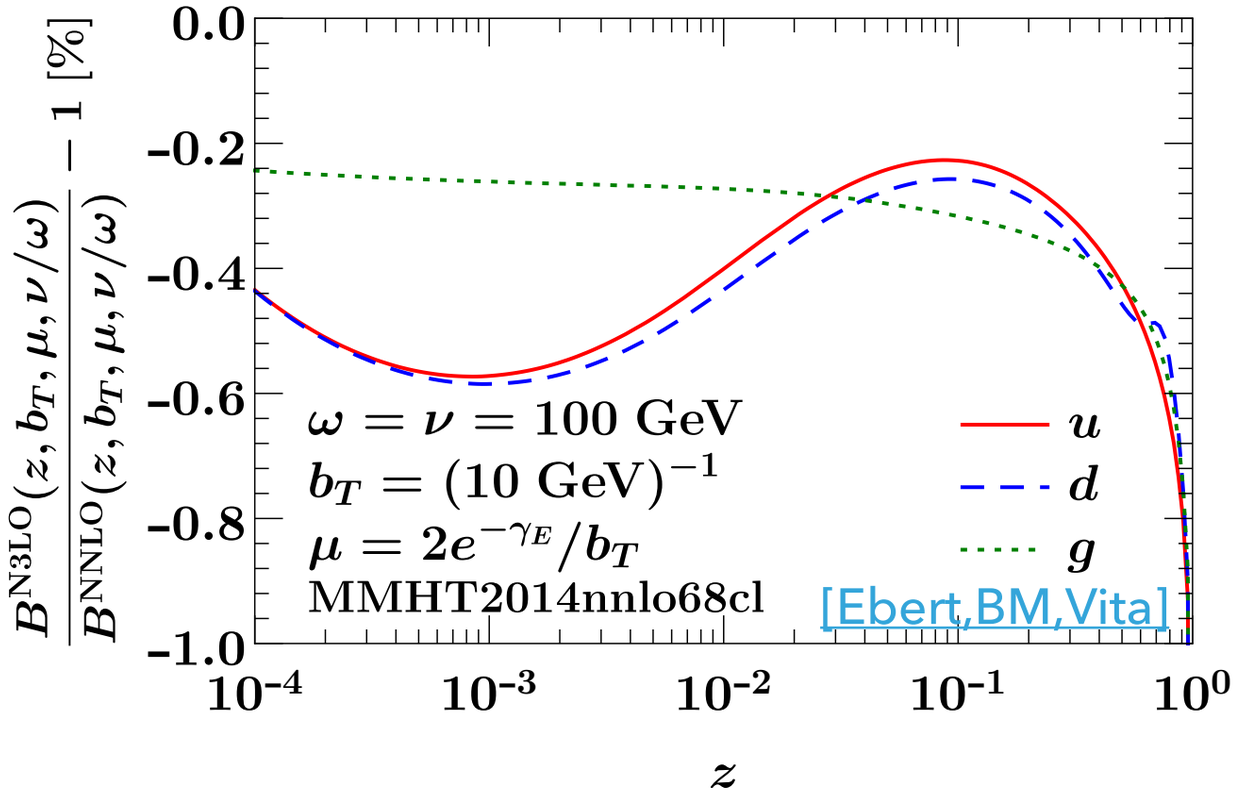
$$Y = \frac{1}{2}\log\left(\frac{2P_1 p_h}{2P_2 p_h}\right)$$



BEAM FUNCTIONS AT N3LO: $q_\perp$ [Ebert,BM,Vita]

- Last missing universal ingredient for qT subtraction at N3LO.
- All channels, fully analytic.

  See also [Luo et al.,1912.05778]
- Can be used to create fully differential predictions for arbitrary colour singlet processes at N3LO.



$\gamma^*\ W\ Z\ H\quad bbH\quad H^*\ G\qquad WH\ \ ZH\quad ZZ\ WW$

In other news: We also computed the N-Jettiness Beam Functions at N3LO.

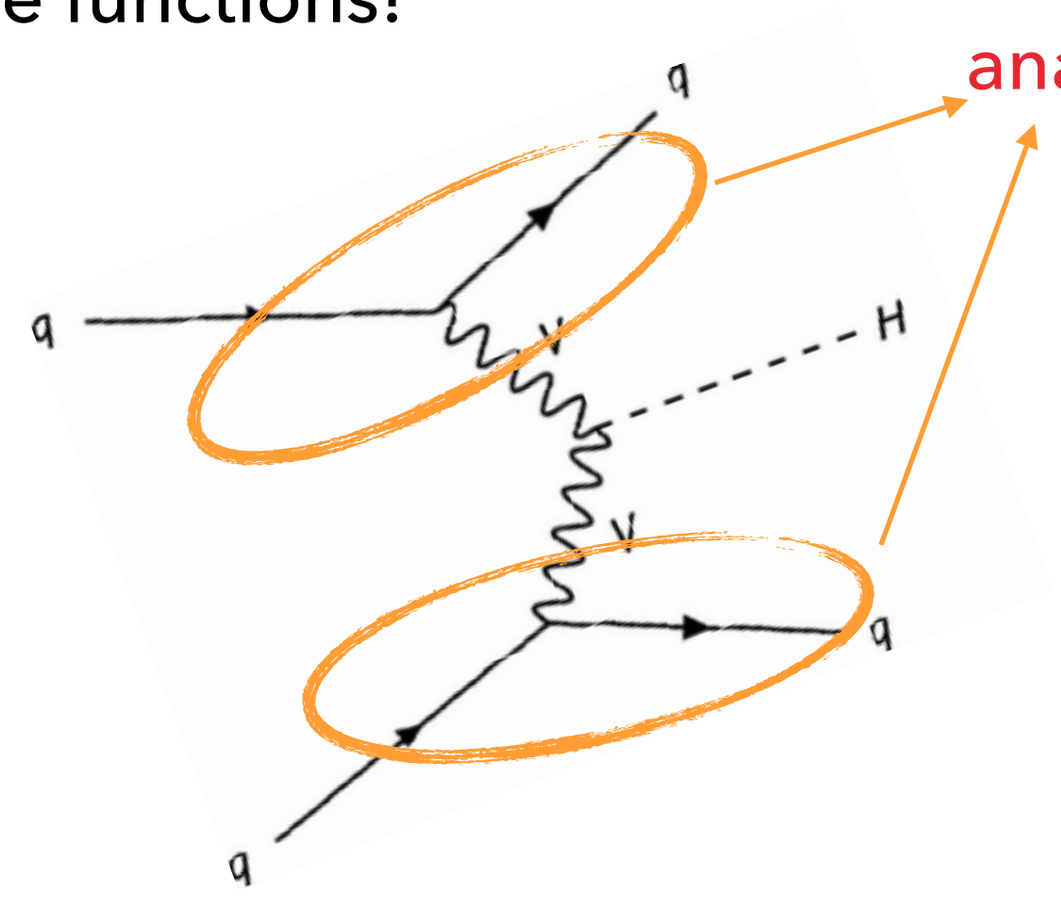
[Ebert,BM,Vita]

FOCUS ON CERTAIN DEGREES OF FREEDOM

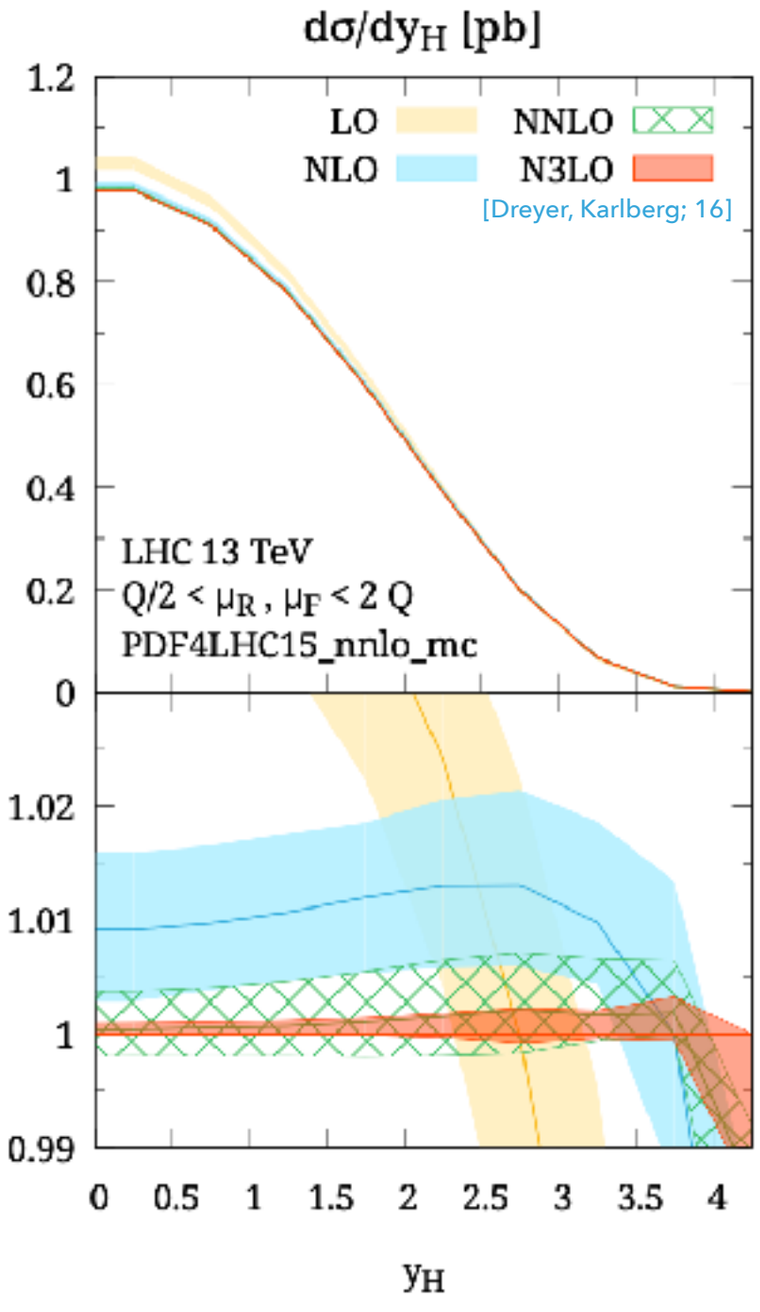
- Inclusive VBF Higgs production: [Dreyer, Karlberg; 16]

Still differential in Higgs momentum!

- Approximate N3LO cross section:
  Structure functions!



analytic!



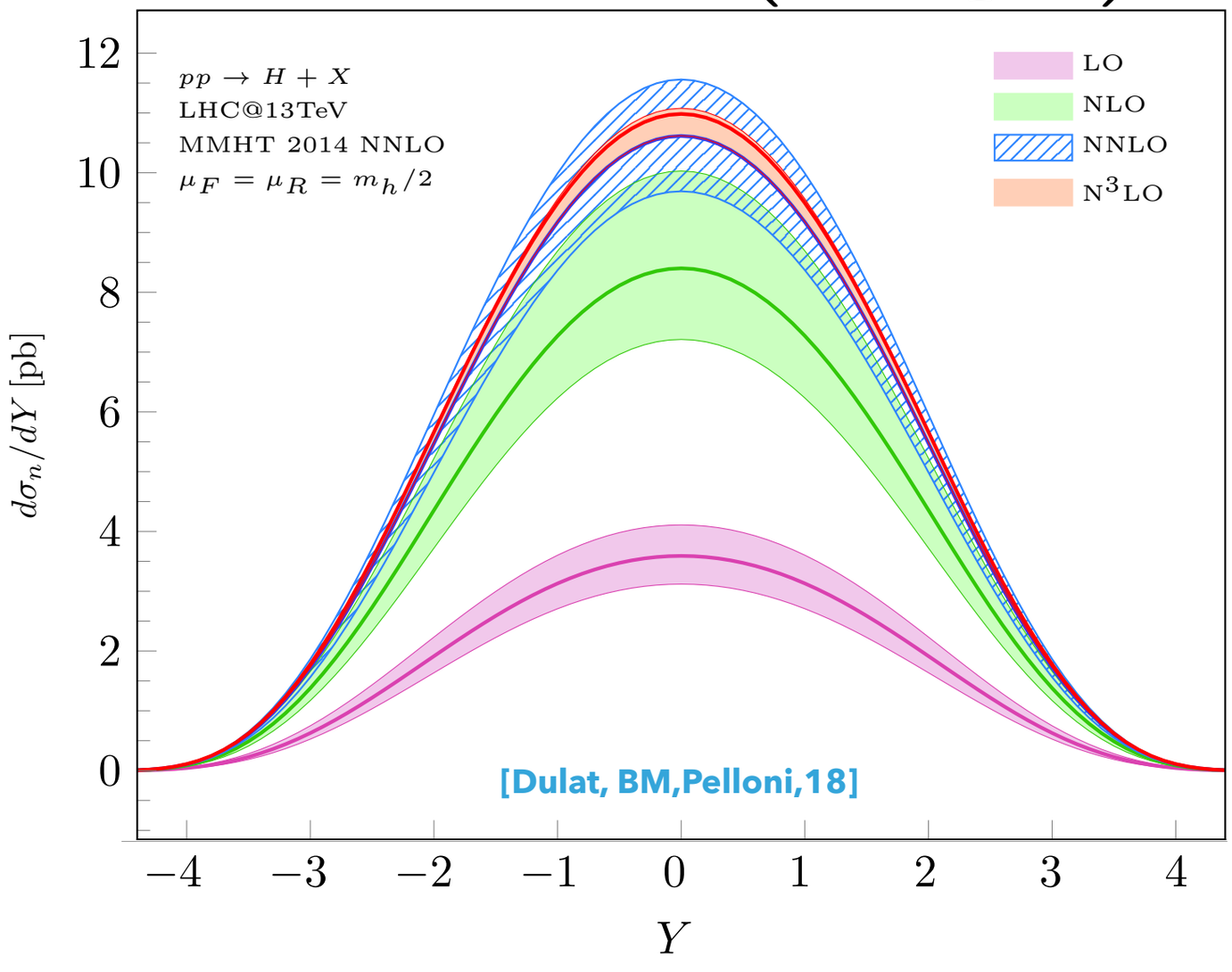
- Even VBF HH production at N3LO!

[Dreyer, Karlberg; 18]

FOCUS ON CERTAIN DEGREES OF FREEDOM

$$Y = \frac{1}{2}\log\left(\frac{2P_1 p_h}{2P_2 p_h}\right)$$

- Higgs boson rapidity distribution.
- Gluon - Fusion
- Analytic calculation: tailored for this observable.
- Differential K-factor is very similar to inclusive K-factor!



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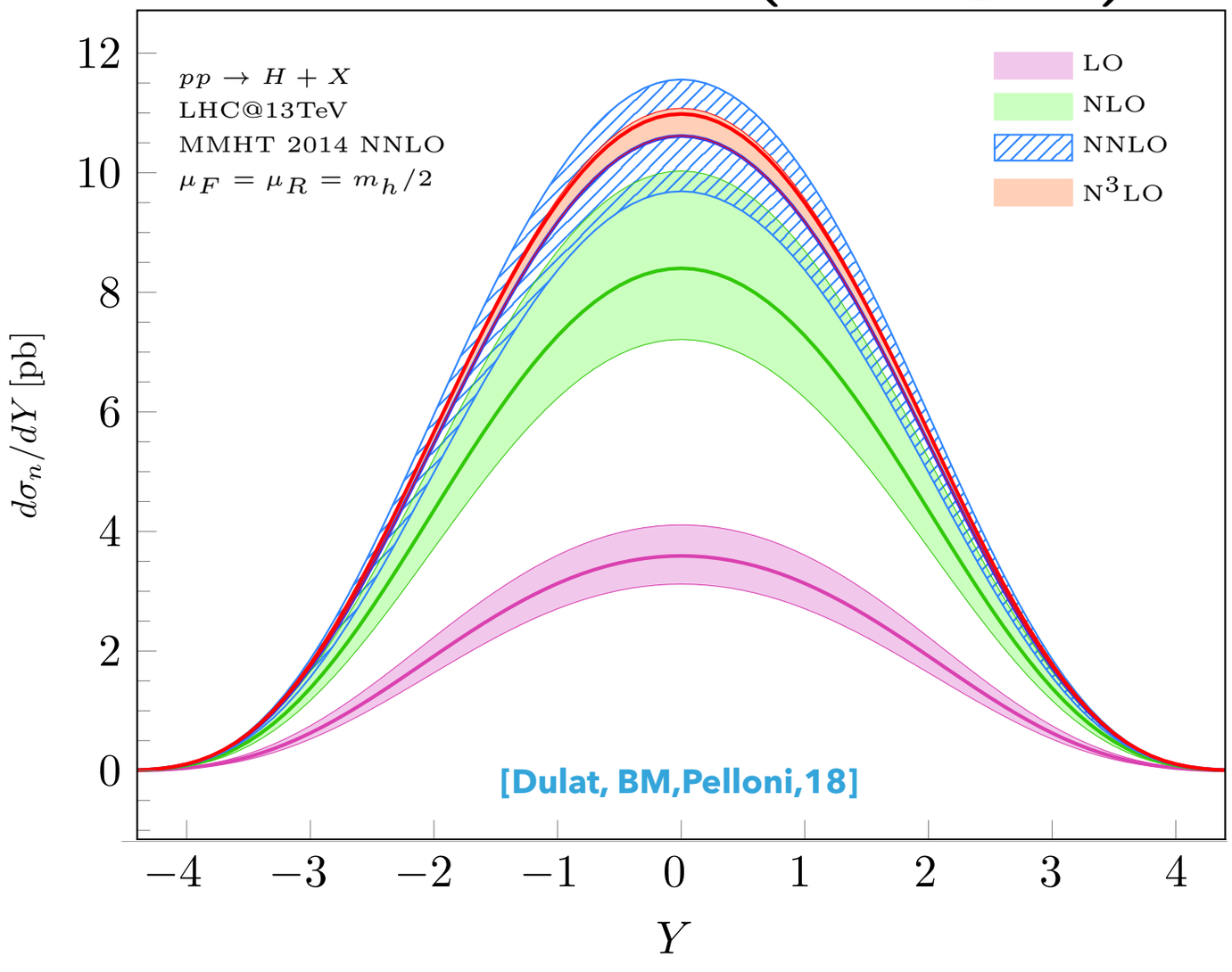


Evaluates in minutes!

NEW SUBTRACTION TECHNIQUES

PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi; 15]

$$\sigma \sim \int_0 \frac{dx}{x} F(x) \left[\mathcal{O}(x) - \mathcal{O}(0)\right] + \mathcal{O}(0)\sigma_{\text{integrated}}$$

The perfect subtraction method!

(Subtraction term always identically cancels divergences if applicable.)

N3LO Cross Section to produce F - Required ingredients:

★ Fully differential calculation of F+J at NNLO.

★ Inclusive N3LO F cross section differential in Born variables.

PROJECTION TO BORN

$$Y_H \quad \infty \quad H + J$$

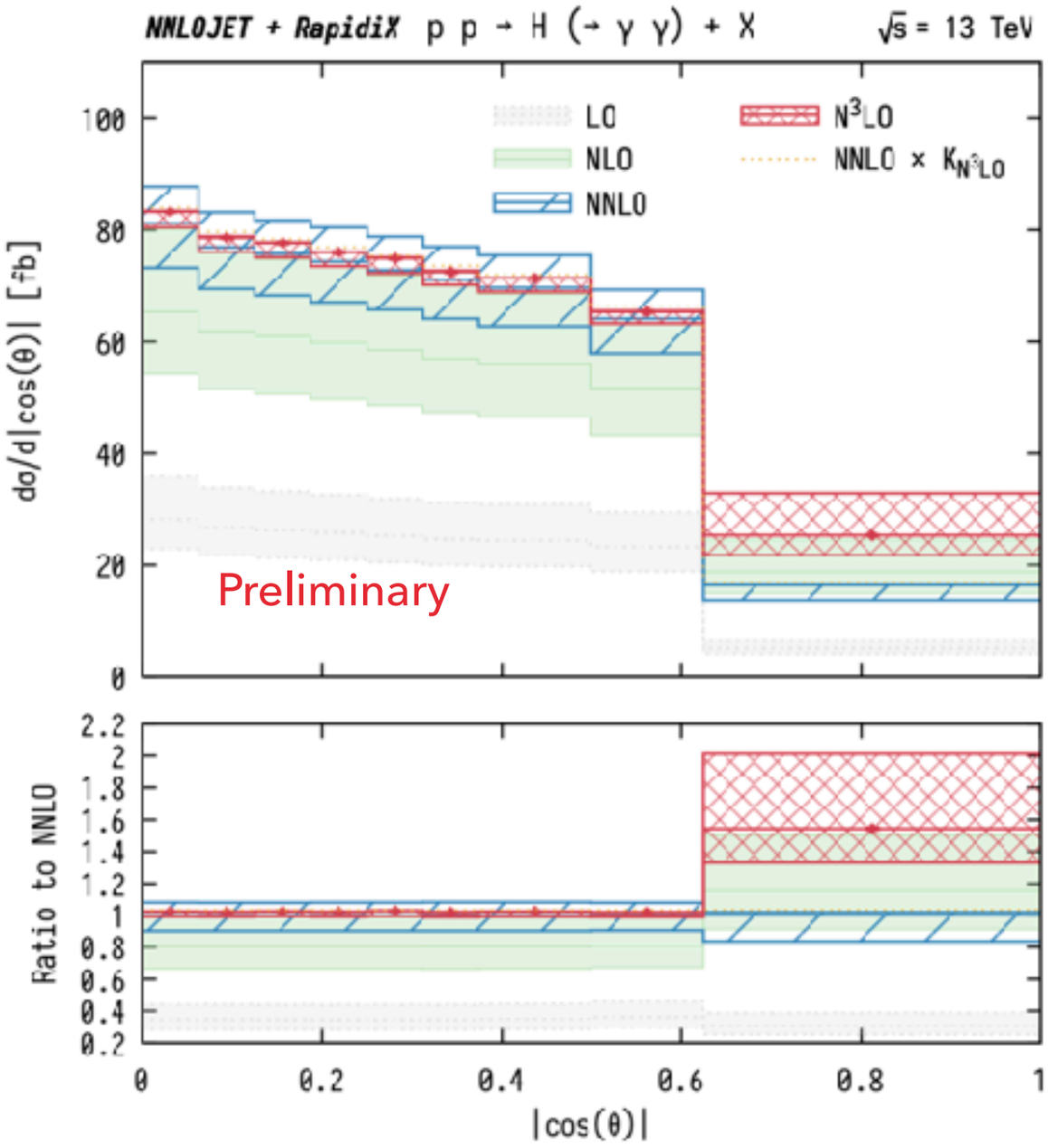
$$P\,P \to H + X \to \gamma\gamma + X$$

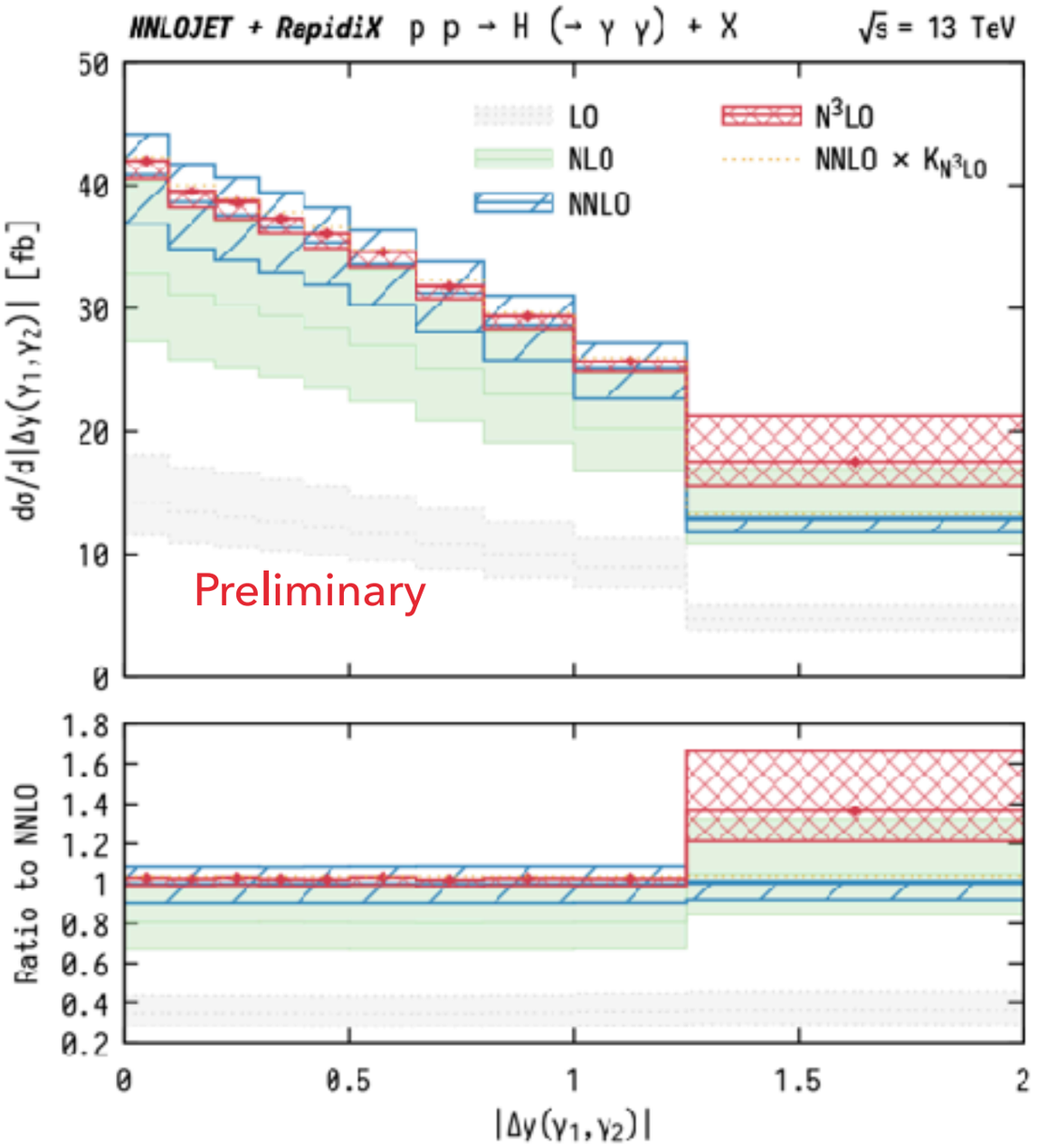
- Define a fiducial volume

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

+Photon Isolation

FULLY DIFFERENTIAL HIGGS BOSON CROSS SECTIONS





[Chen,Dulat,Gehrmann, Glover,Huss,**BM**,Pelloni, to appear]

CROSS SECTIONS AT N3LO

- **N3LO**
  is the precision frontier

- **Universal Picture:**
  Percent level corrections at N3LO

- **First steps to differential N3LO**

- **Many challenges ahead!**

THANK YOU!