Higgs-2021

Fully Differential Prediction for Higgs Boson Production at N3LO

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WHY PRECISION?

Quests in the age of the Higgs:

- A new interaction: Yukawa!

- The mechanism of electro-weak symmetry breaking

- Generation of fundamental masses

- Determine couplings / interactions with established matter $H \heartsuit \mu$?

  $W \heartsuit W \heartsuit W \heartsuit W$?

- Explore the limitations of the Standard Model of particle physics

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The Method: Predict & Compare.

Precision is key!

PRECISION OBSERVABLES

- What precision can we expect from the LHC?

How many Higgs bosons are produced at the LHC?

$$\mu = \frac{\sigma_{\text{obs.}}}{\sigma_{\text{SM}}}$$

$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$ ATLAS

$\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat}) \pm 0.04(\text{exp.}) \pm 0.04(\text{sig.+bkg. th.})$ CMS

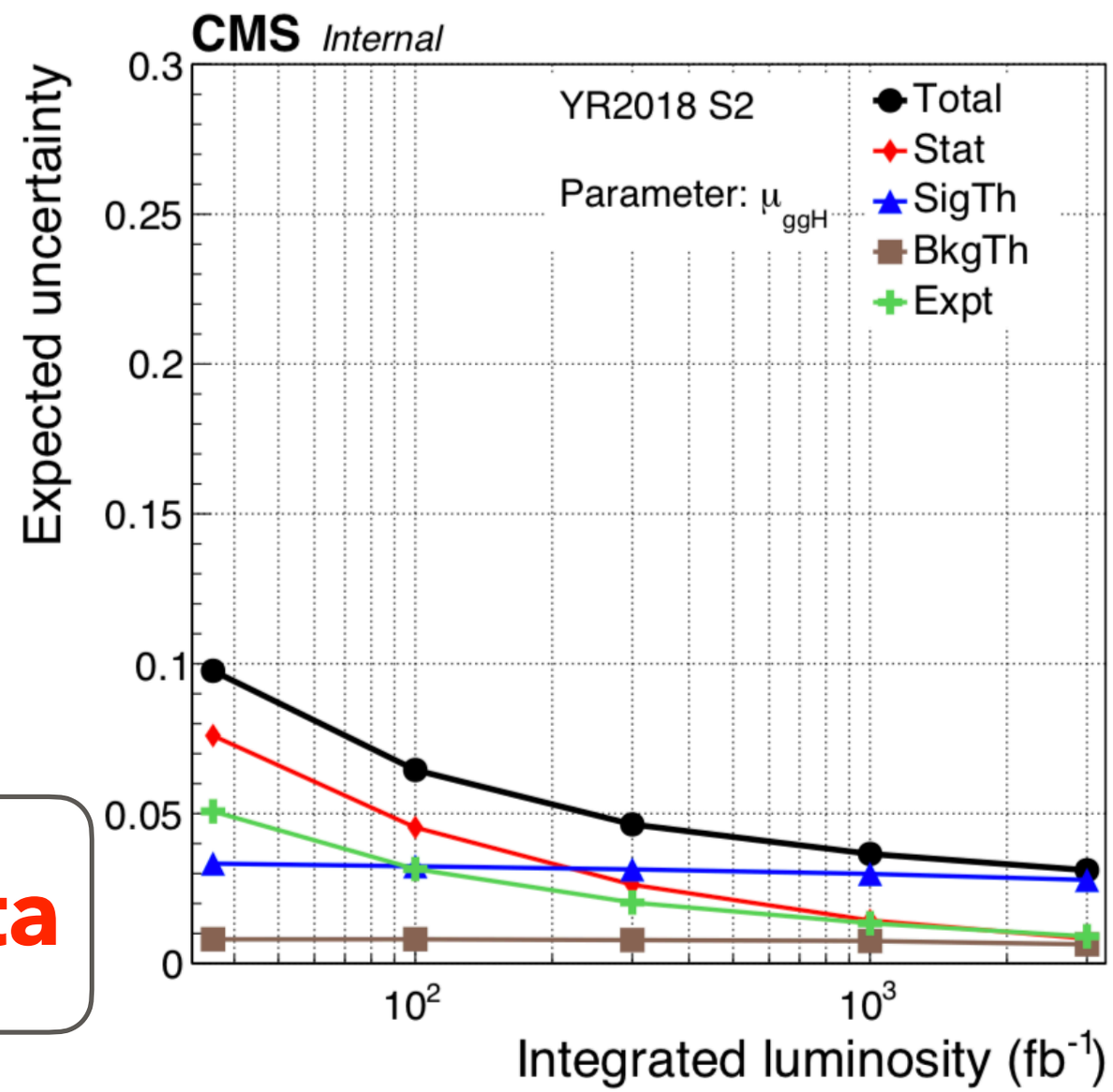
- Agreement of EXP and TH at ~ 7%!
- TH Uncertainty ~ Exp Uncertainty
- Key observable for coupling extraction, BSM scenarios …

PRECISION OBSERVABLES

- What precision can we expect from the LHC?

How many Higgs bosons are produced at the LHC?

$$\mu = \frac{\sigma_{\text{obs.}}}{\sigma_{\text{SM}}}$$



- Expected precision with HL-LHC: ~ 3 % TH+STAT+SYS
- Enormous challenge for TH to reach this level!

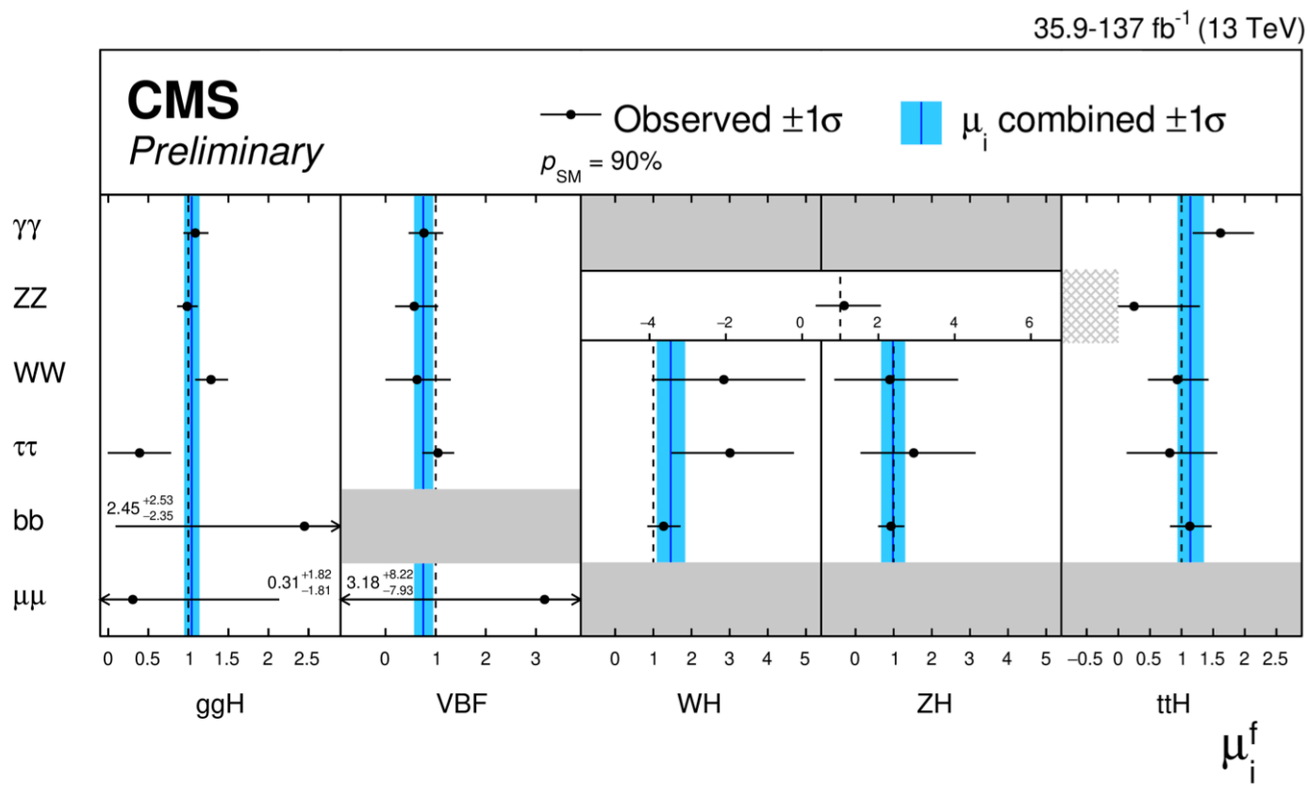
HL-LHC: 20 x current data

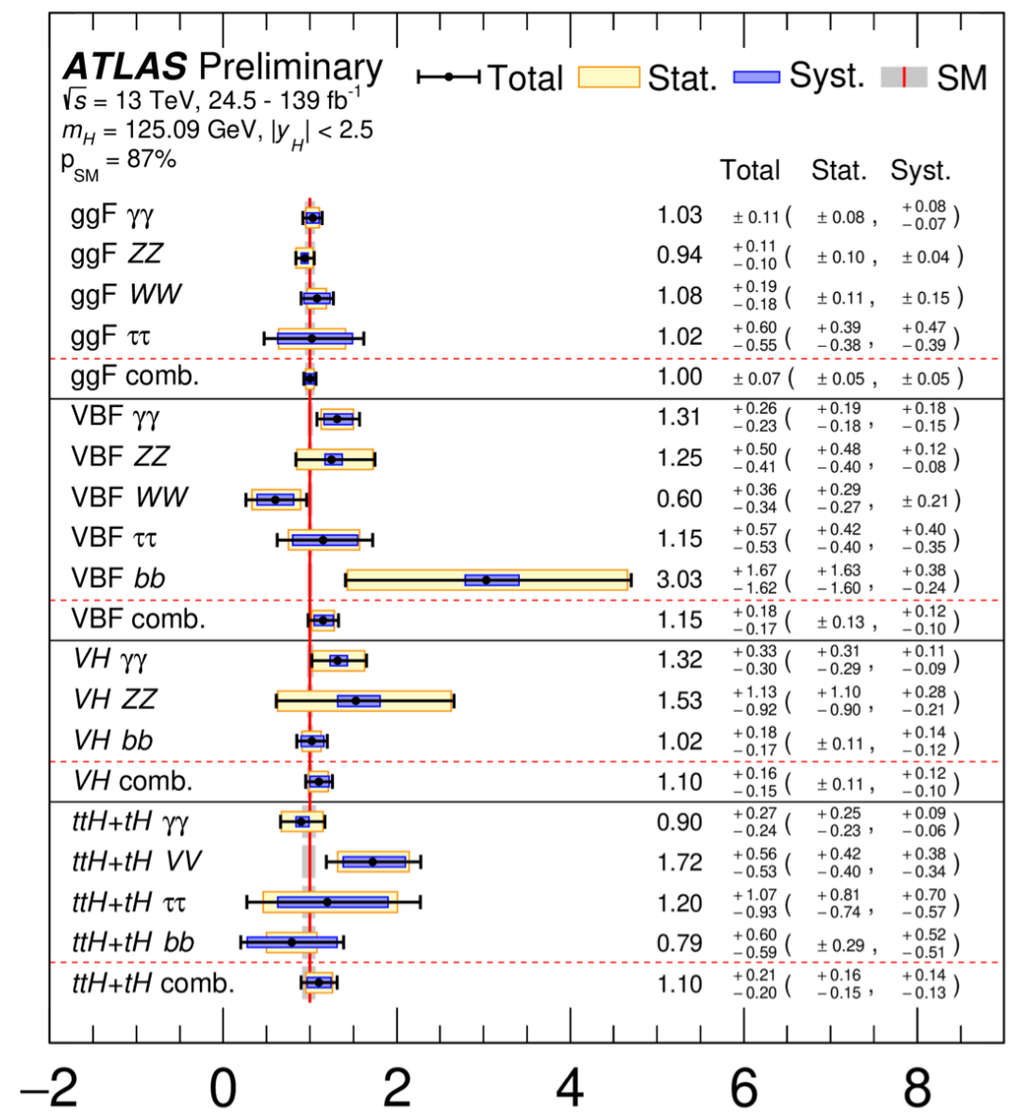
PRECISION OBSERVABLES

- What is precision in Higgs physics?

Separate in different production and decay modes:

- Precision channels: ~ 10 %
- More intricate - more information! Couplings!



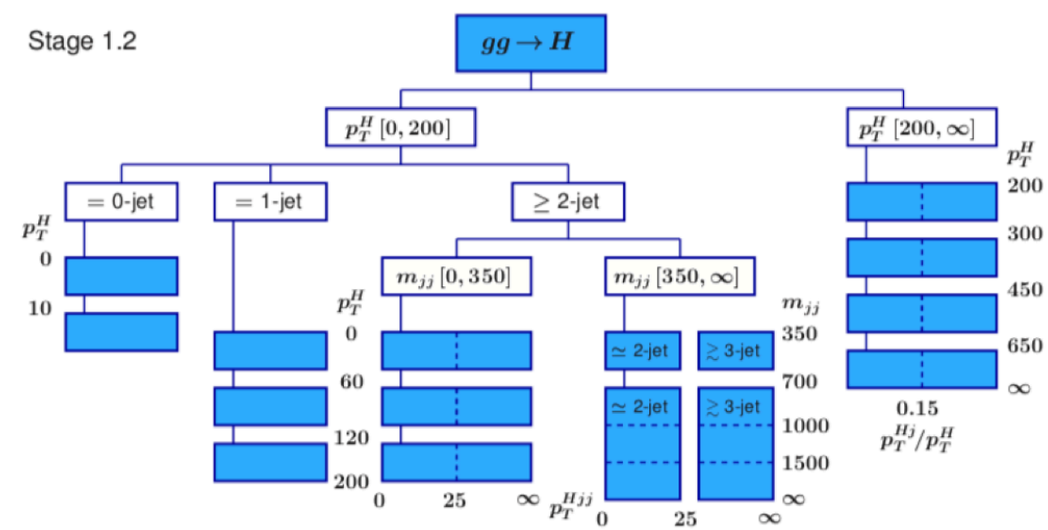


PRECISION OBSERVABLES

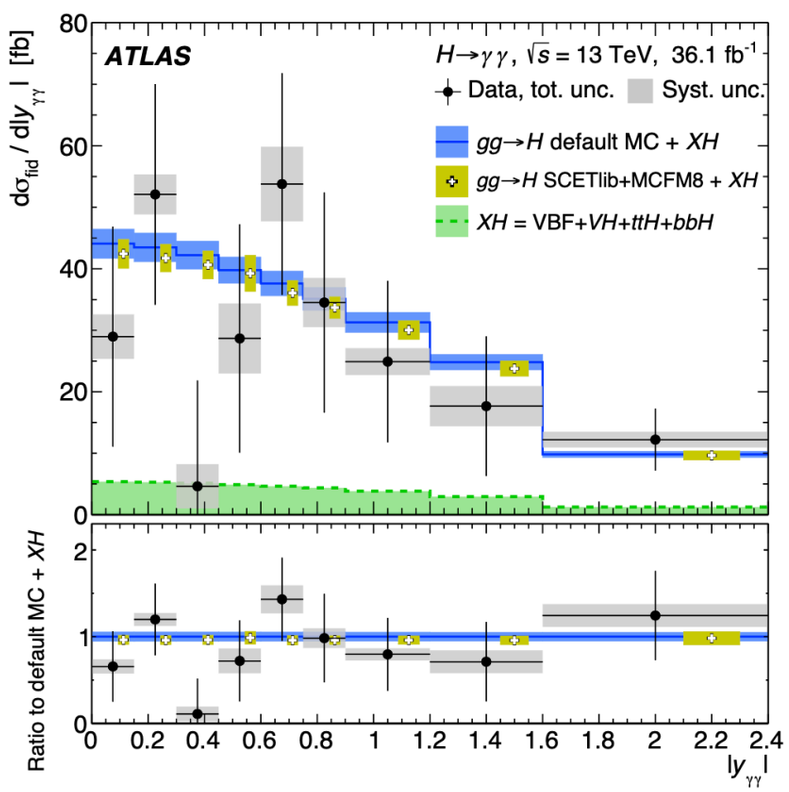
- What is precision in Higgs physics?

Differential Properties:

STXS



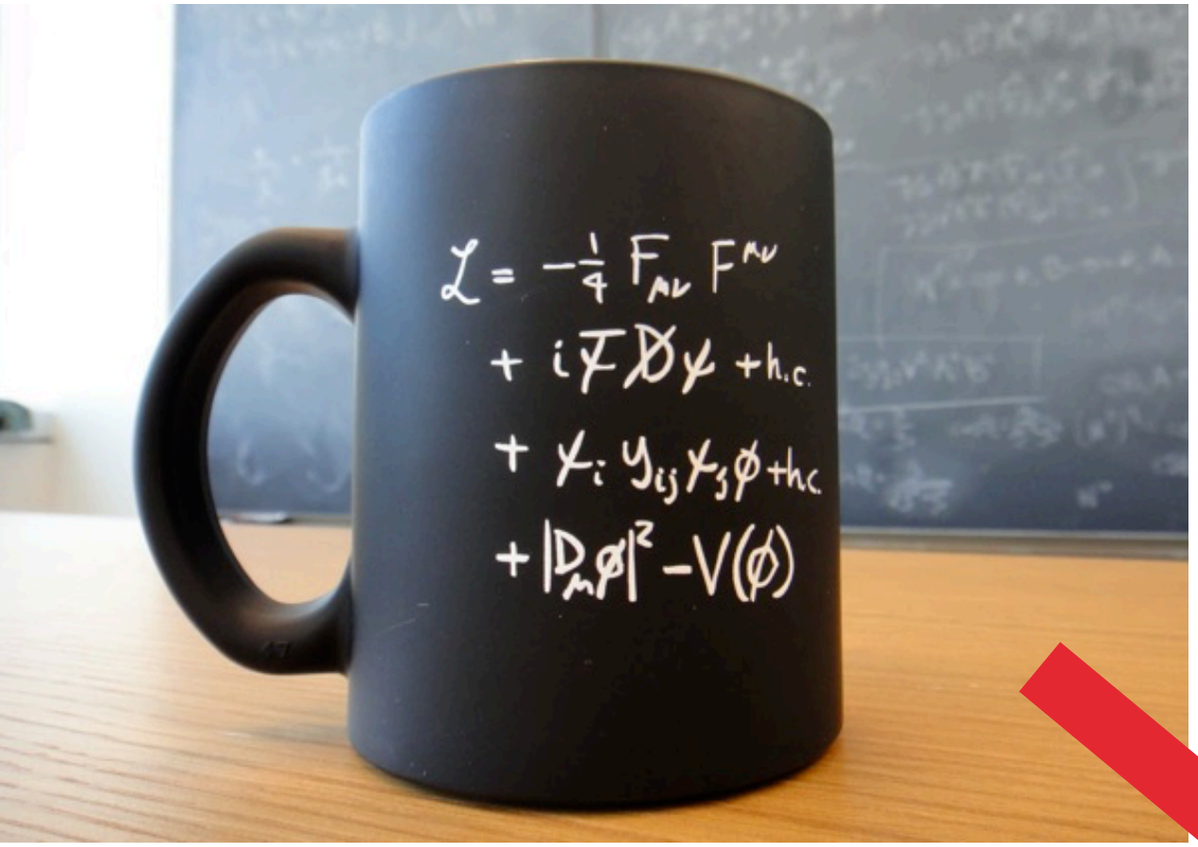
Differential Cross Sections



Other Combinations:

- Pseudo-Observables
- Observables Tailored for EFT fits.
- Ratios of Cross Sections
- …

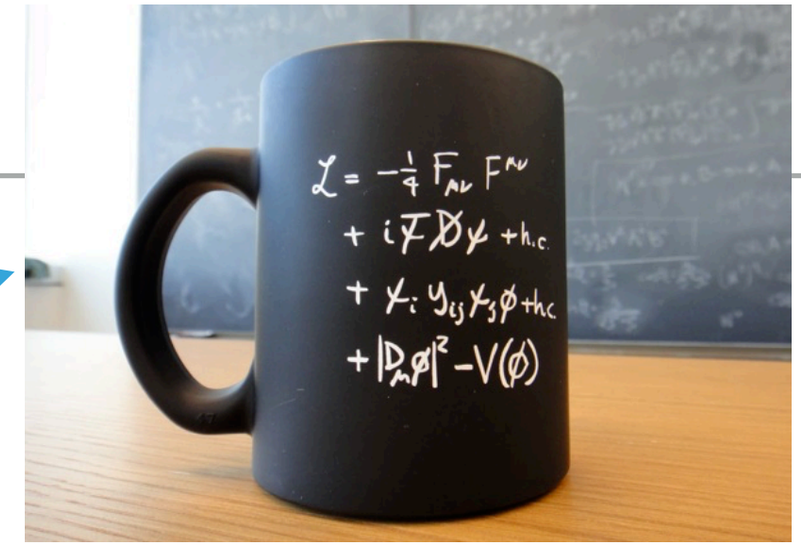
FROM THE STANDARD MODEL TO REAL LIFE OBSERVABLES



From first principle QFT …

… to real life measurement

THE WAY TO PRECISION LHC PREDICTIONS



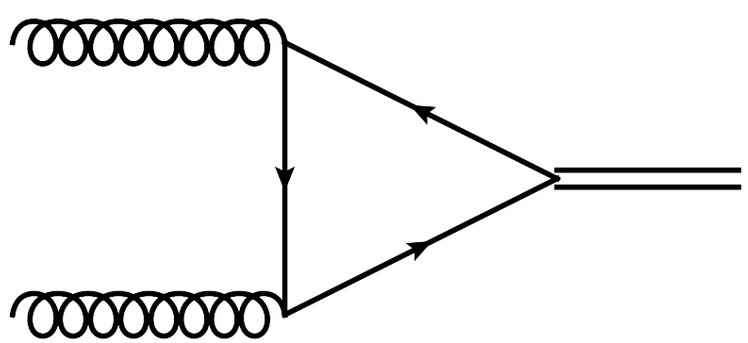
$$\sigma \sim \int dx dy f(x) f(y) \hat{\sigma} + \mathcal{O}\left(\frac{\Lambda}{Q}\right)$$

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

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

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

- Gluon fusion production mechanism in the limit of infinite top quark mass:

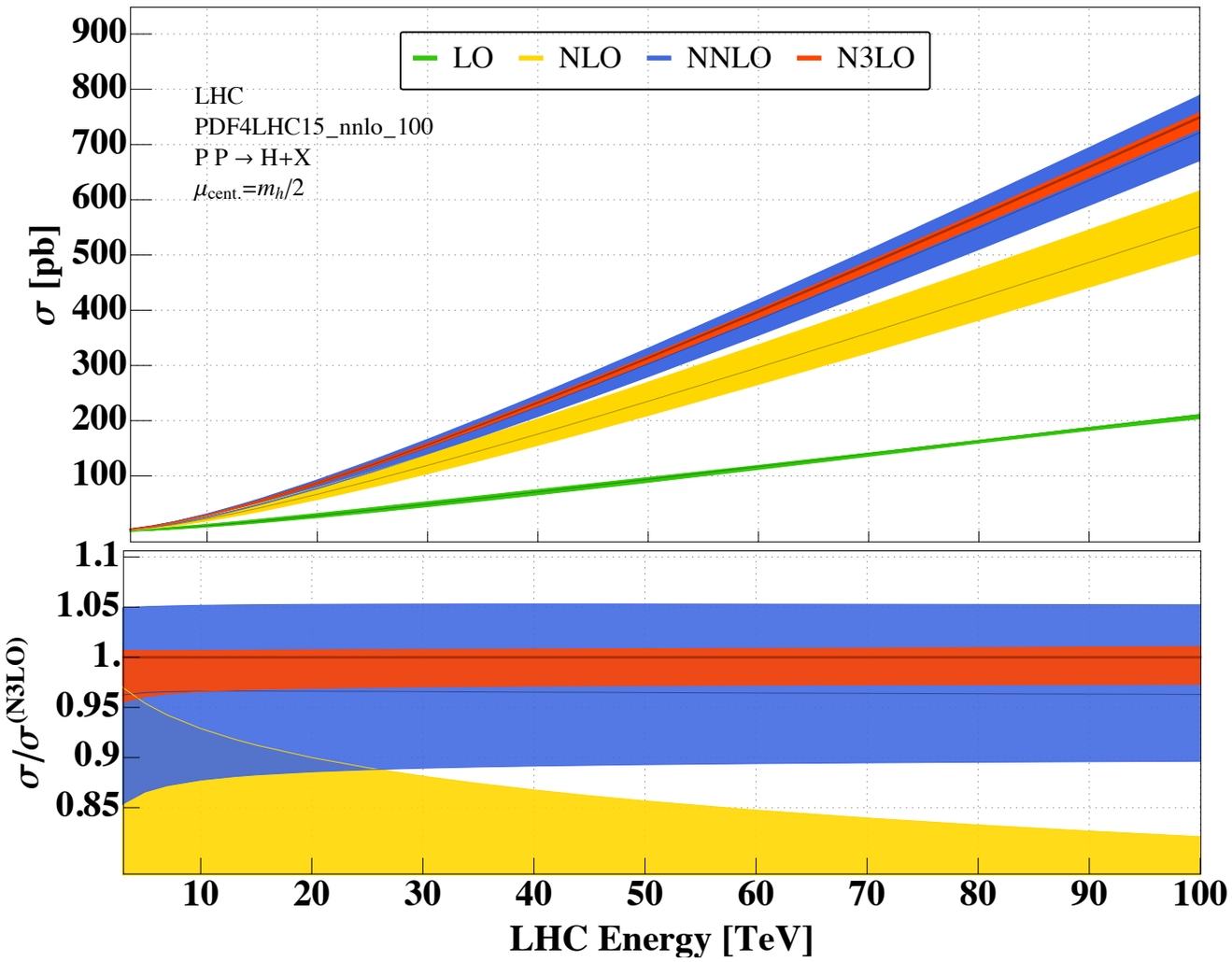


~88.2%

INCLUSIVE HIGGS PRODUCTION

ggF

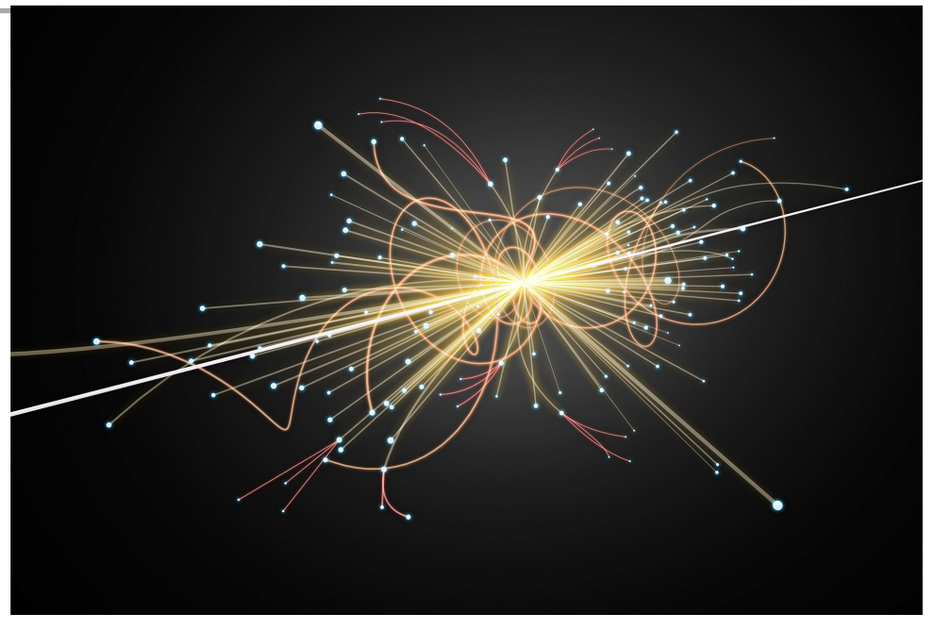
[Anastasiou,Duhr,Dulat,Herzog,BM, arXiv:1503.06056]



- N3LO accuracy
- ggF: > 2% QCD uncertainties
- Necessary for current state of the art.

DIFFERENTIAL HIGGS PRODUCTION

- We want to make predictions as close as possible to experimental observations!
    - Realistic cuts!
    - Observable final states!



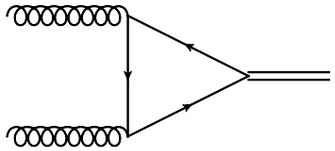
$$\boxed{PP \to H + X \to \gamma\gamma + X}$$

- 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

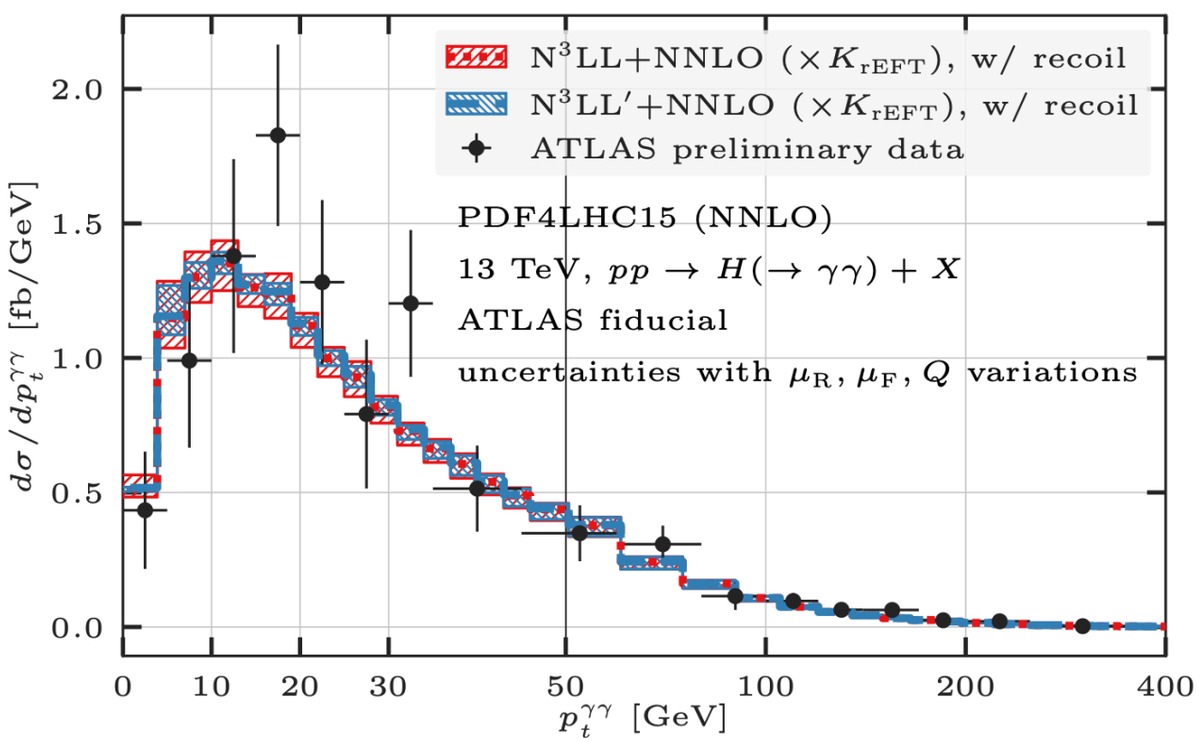
DIFFERENTIAL HIGGS BOSON PRODUCTION



- New perturbative ingredients:
  - ★ Cusp anomalous dimension at 4 loops [Henn, Korchemsky, BM, 1911.10174] [Manteuffel, Panzer, Schabinger, 2002.04617]
  - ★ qT Beam Functions at 3 loops [Luo et al.,1912.05778] [Ebert, BM, Vita, 2006.05329]
- Enable predictions at **N3LL` + NNLO** See also for DY production!

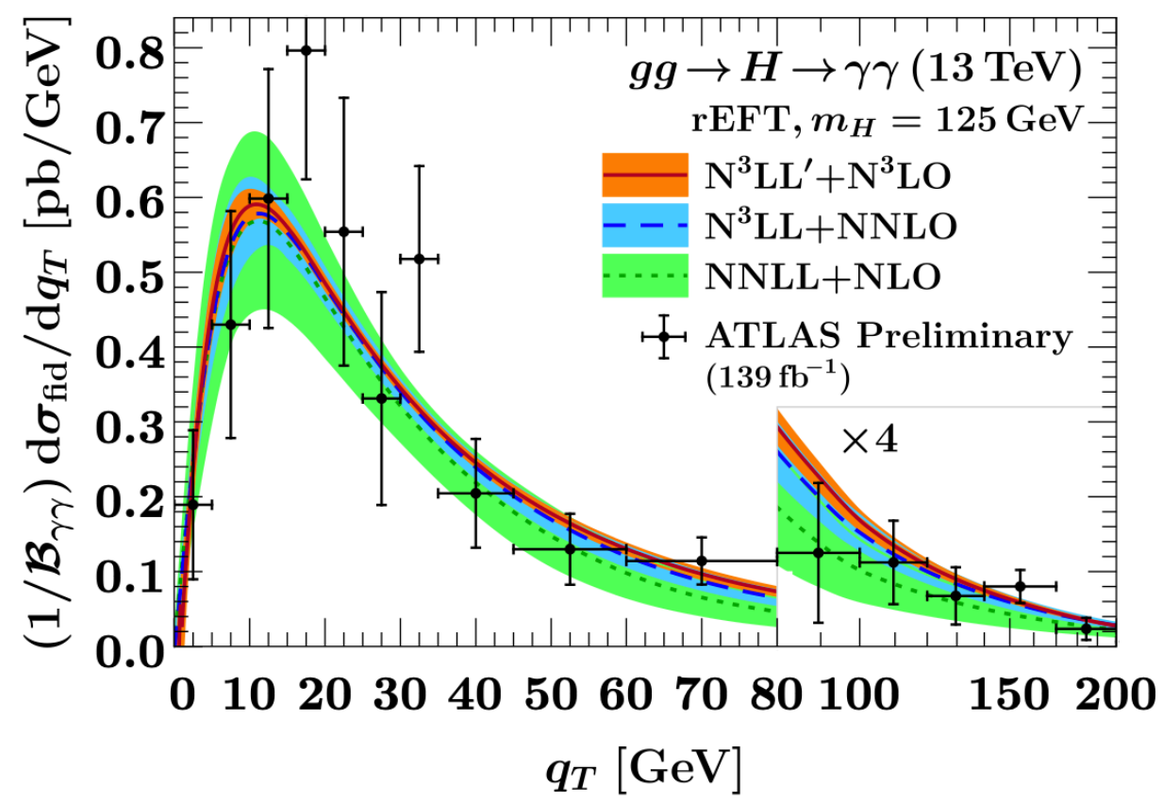
Differential: $$P\,P \to H + X \to \gamma\,\gamma + X$$

Re, Rottoli, Torielli [2104.07509]



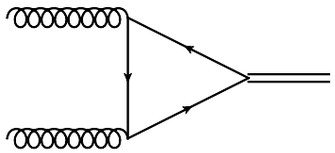
See Re's talk!

Billis, Dehnadi, Ebert, Michel Tackmann, [2102.08039]



See Michel's talk!

DIFFERENTIAL HIGGS BOSON PRODUCTION



See Michel's talk!

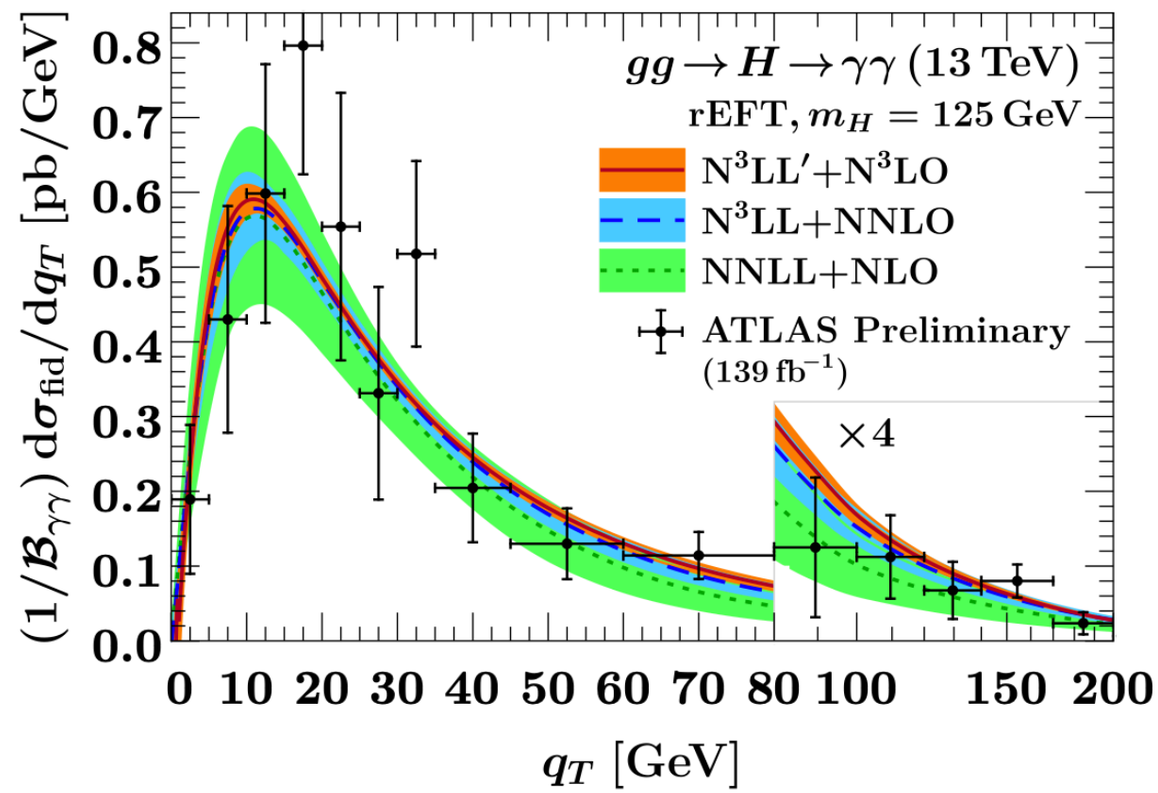
- Predictions at **N3LL` + NNLO**

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

Billis, Dehnadi, Ebert, Michel Tackmann, [2102.08039]

Integrate:

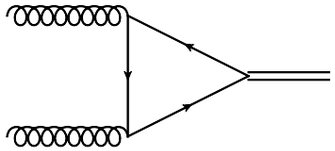
$$\sigma = \int dp_T \frac{d\sigma}{dp_T}$$



- **First** fiducial Cross Section at **N3LO** in perturbative QCD

$$\sigma_{\rm fid} = 57.69\,(1 \pm 2.7\%_{\rm pert} \pm 2.1\%_{\mathcal{B}} \pm 3.2\%_{{\rm PDF}+\alpha_s} \pm 2\%_{\rm EW} \pm 2\%_{t,b,c})\,{\rm fb}$$

DIFFERENTIAL HIGGS BOSON PRODUCTION



- Predict fully differential distributions at the LHC:

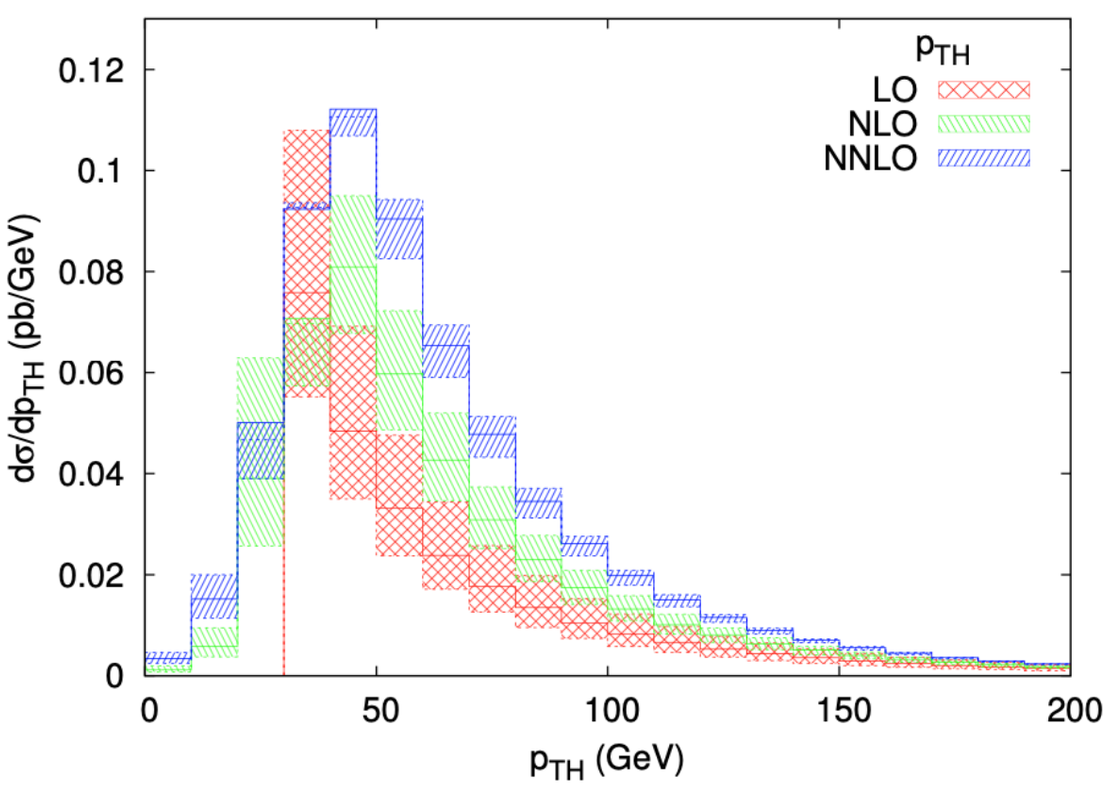
[Cacciari,Dreyer,Karlberg,Salam,Zanderighi; 15]

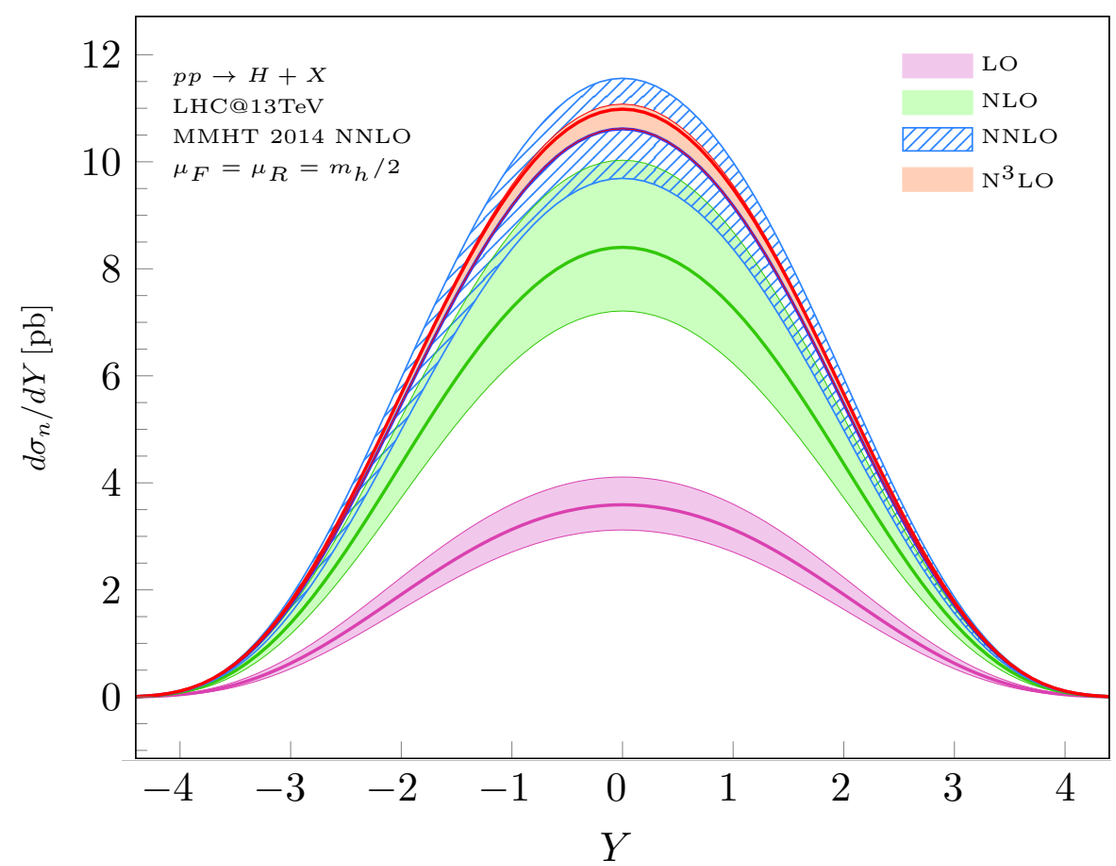
Projection-To-Born Subtraction

H+J at NNLO ∞ **Analytic Rapity Distribution of the Higgs**

[Chen, Gehrmann, Glover, Jaquier, 1408.5325]

[Dulat, BM,Pelloni,18]





SUBTRACTION ALGORITHMS

Fully Differential Cross Sections

Typical treatment of singularities in fixed order perturbation theory:
Example:

$$\sigma \sim \int_0^{q^2} dp_\perp^2 \frac{1}{(p_\perp^2)^{1+\epsilon}} (M(p_\perp^2) - \tilde{M}(0))$$

+Integrated Counter Term

Divergence

Local Counter Term

Matrix Element

SUBTRACTION ALGORITHMS

Fully Differential Cross Sections

Typical treatment of singularities in fixed order perturbation theory:
More general example:

Measurement Function

$$\sigma_J \sim \int d\phi_n (M(\phi_n, \phi_{\mathrm{Born}}) J(\phi_n, \phi_{\mathrm{Born}}) - \tilde{M}(\phi_n, \phi_{\mathrm{Born}}) J(0, \phi_{\mathrm{Born}}))$$

Integrate over n-partons

+Integrated Counter Term

Divergence

Local Counter Term

IRC - Safety: $J(\phi_n, \phi_{\mathrm{Born}}) \to J(0, \phi_{\mathrm{Born}})$ in singular limits

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

Fully Differential Cross Sections

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n (M(\phi_n, \phi_{\text{Born}}) J(\phi_n, \phi_{\text{Born}}) - \tilde{M}(\phi_n, \phi_{\text{Born}}) J(0, \phi_{\text{Born}}))$$

+Integrated Counter Term

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

Fully Differential Cross Sections

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n M(\phi_n, \phi_{\text{Born}}) \Big[J(\phi_n, \phi_{\text{Born}}) - J(0, \phi_{\text{Born}}) \Big]$$

+Integrated Counter Term

$$\tilde{M}(\phi_n, \phi_{\text{Born}}) = M(\phi_n, \phi_{\text{Born}})$$

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

Fully Differential Cross Sections

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n M(\phi_n, \phi_{\text{Born}}) \Big[J(\phi_n, \phi_{\text{Born}}) - J(0, \phi_{\text{Born}}) \Big]$$

+Integrated Counter Term

$$\tilde{M}(\phi_n, \phi_{\text{Born}}) = M(\phi_n, \phi_{\text{Born}})$$

- **Fully local subtraction**
- **No large numerical discrepancy between local CT and matrix element possible**
- **Successfully used in DIS - like processes (VBF H / HH @ N3LO, differential DIS)**
- **Need to know Integrated Counter Term exactly. Hard!!**

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

Fully Differential Cross Sections

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n M(\phi_n, \phi_{\text{Born}}) \Big[J(\phi_n, \phi_{\text{Born}}) - J(0, \phi_{\text{Born}}) \Big]$$

+Integrated Counter Term

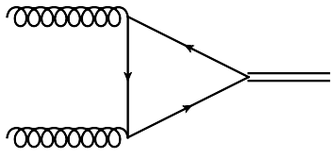
For Higgs Boson Production:

$$\phi_{\text{Born}} = \{z, Y\}$$

Integrated Counter Term

$$\frac{d\sigma}{dz dY}$$

DIFFERENTIAL HIGGS BOSON PRODUCTION

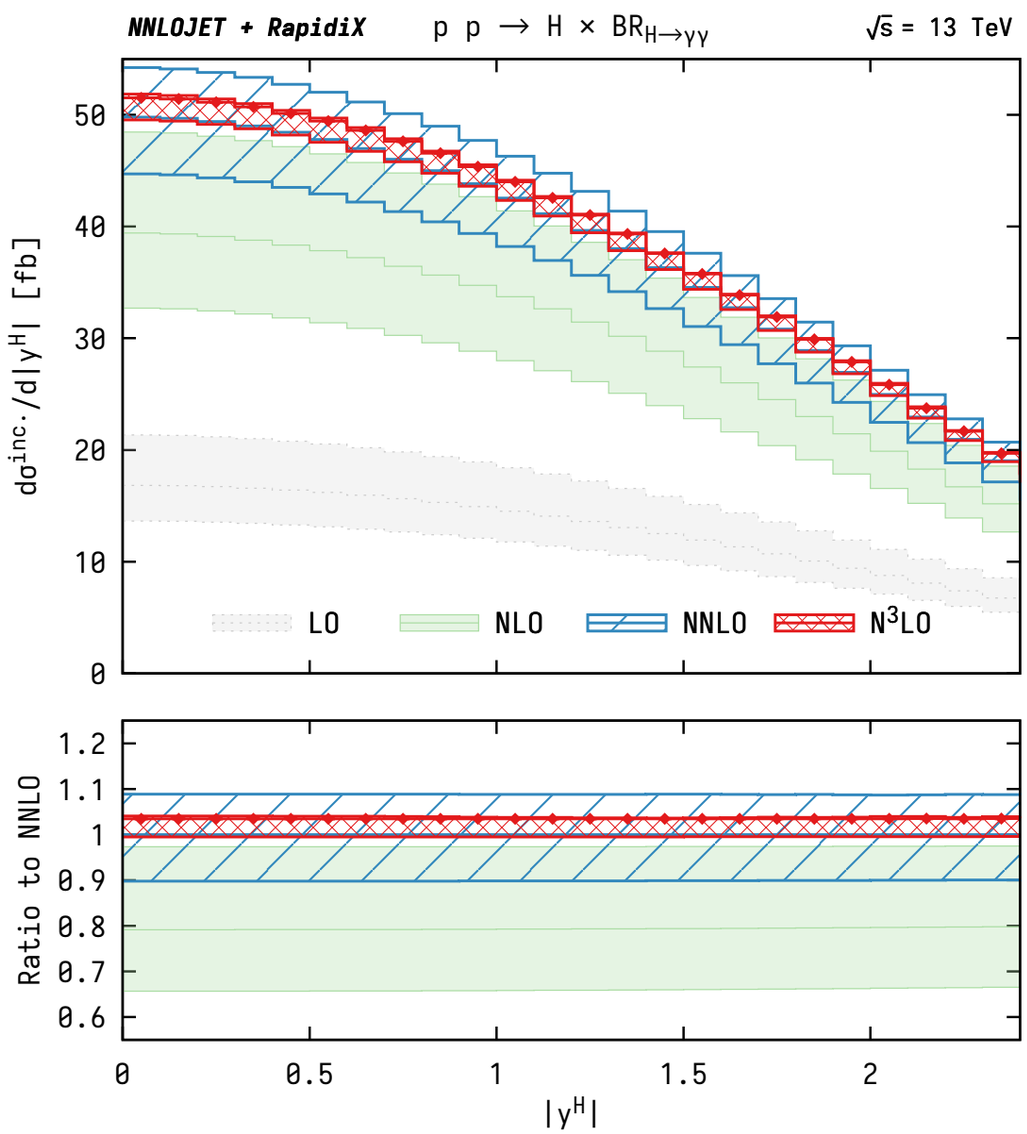


- Predict fully differential distributions at the LHC:

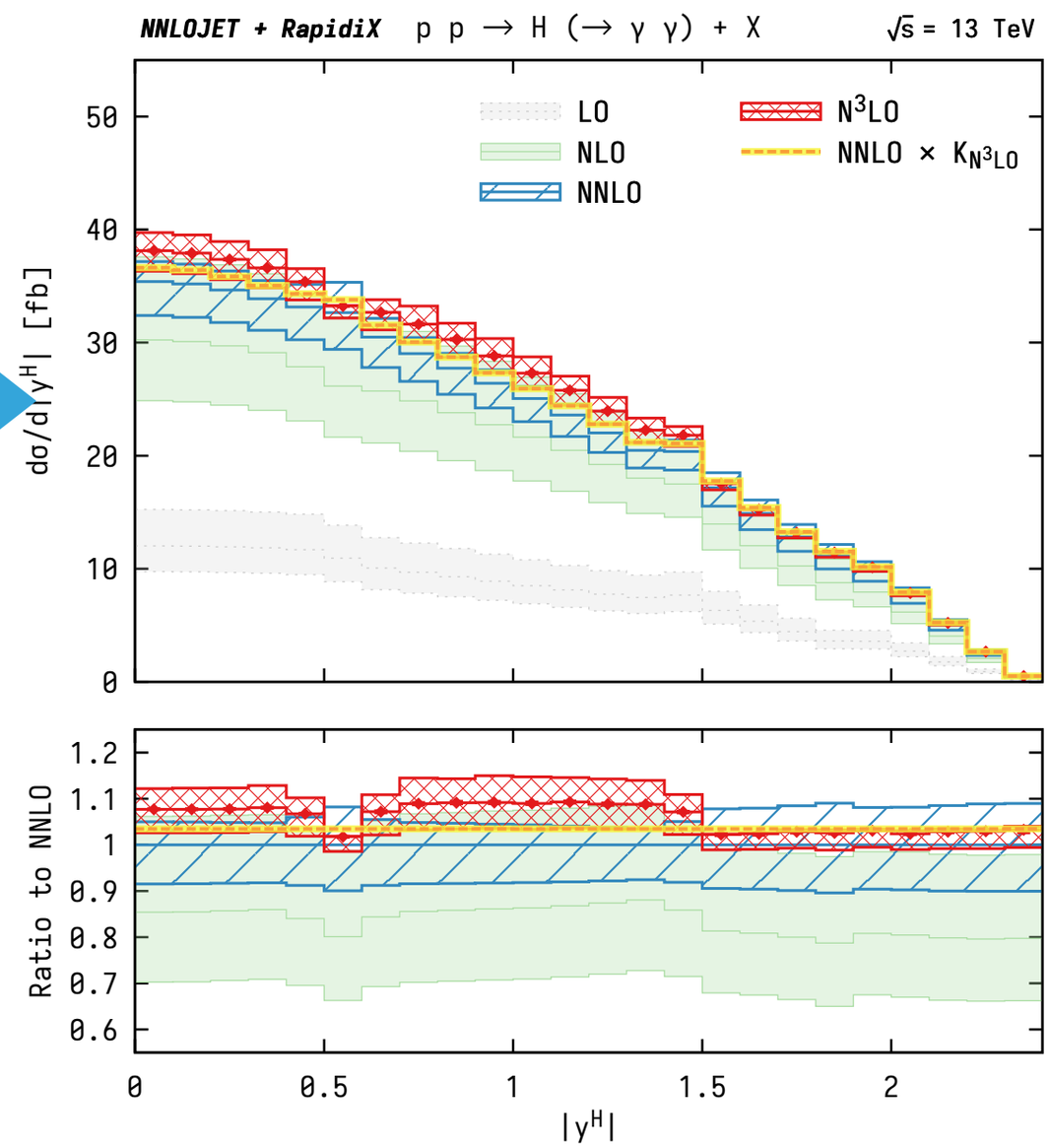
$$P\,P \to H + X \to \gamma\gamma + X$$

Chen, Gehrmann, Glover, Huss, BM, Pelloni [2102.07607]

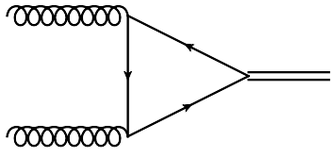
Inclusive Rapidity



Differential Rapidity



DIFFERENTIAL HIGGS BOSON PRODUCTION



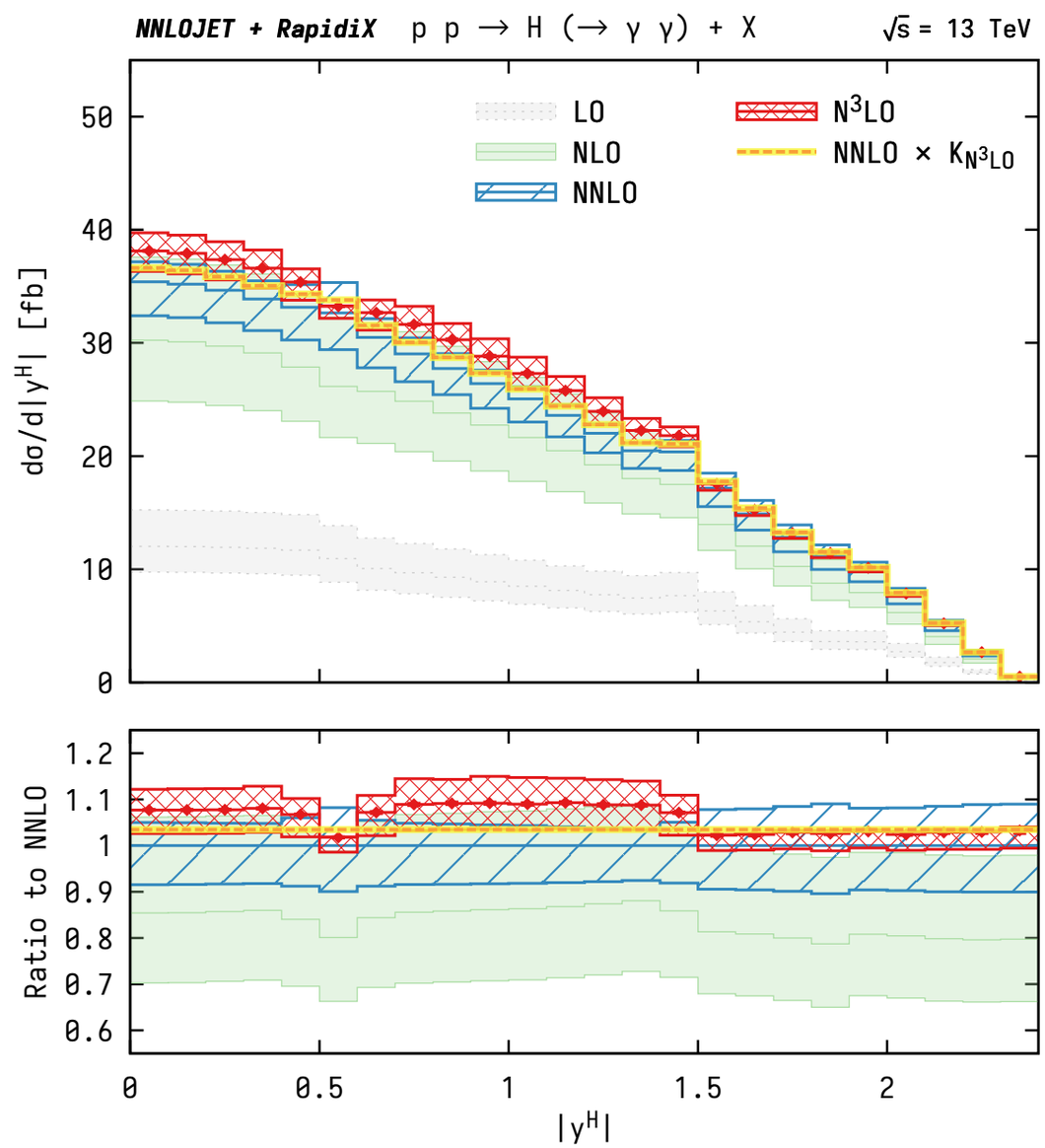
- Predict fully differential distributions at the LHC:

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

Chen, Gehrmann, Glover, Huss, BM, Pelloni [2102.07607]

- First predictions for fully differential distributions at N3LO in perturbative QCD at the LHC.
- Corrections slightly larger than inclusive K - factor.
- Interesting features due to photon cuts.

Differential Rapidity



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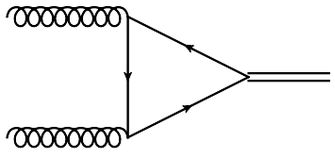
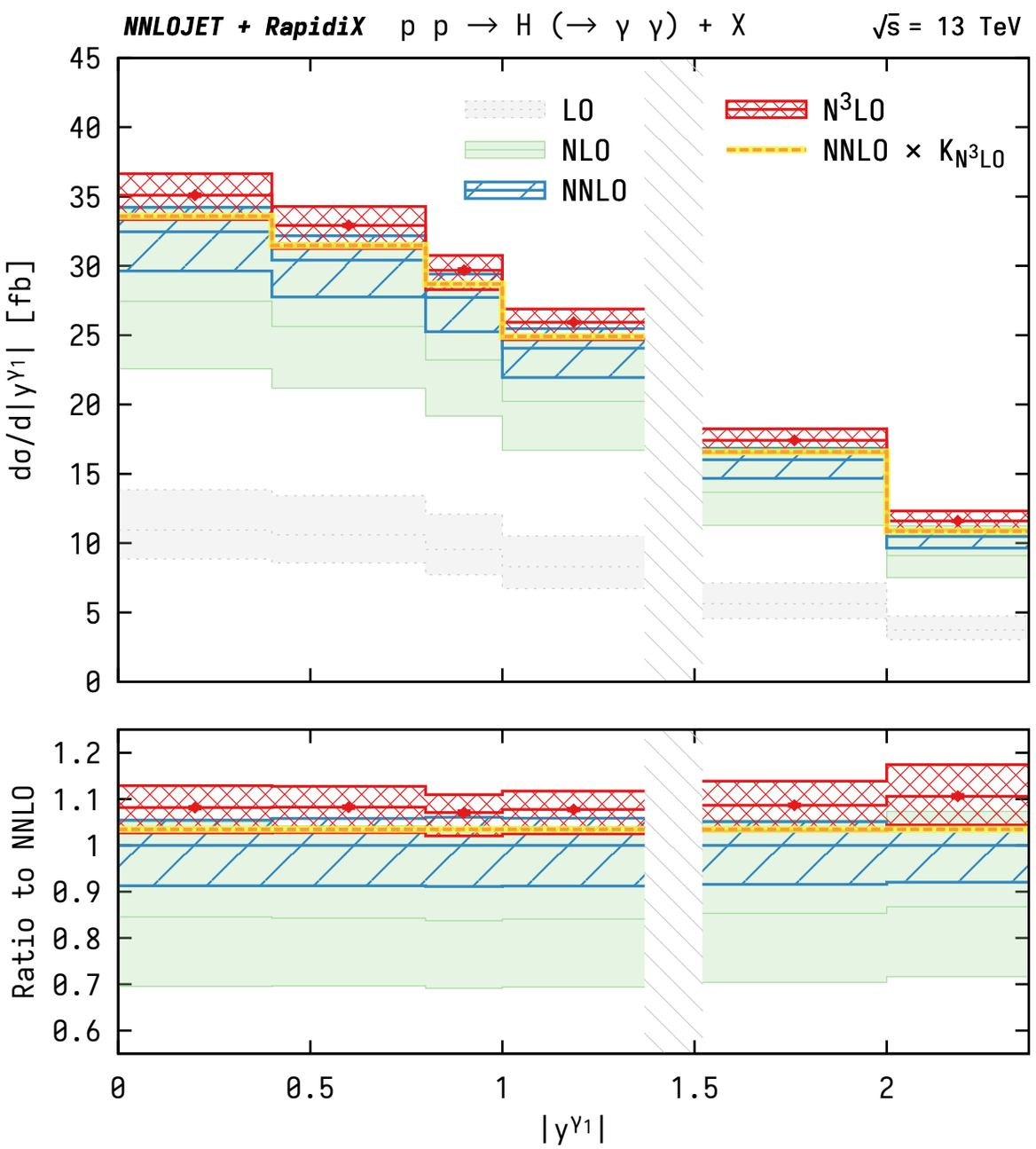
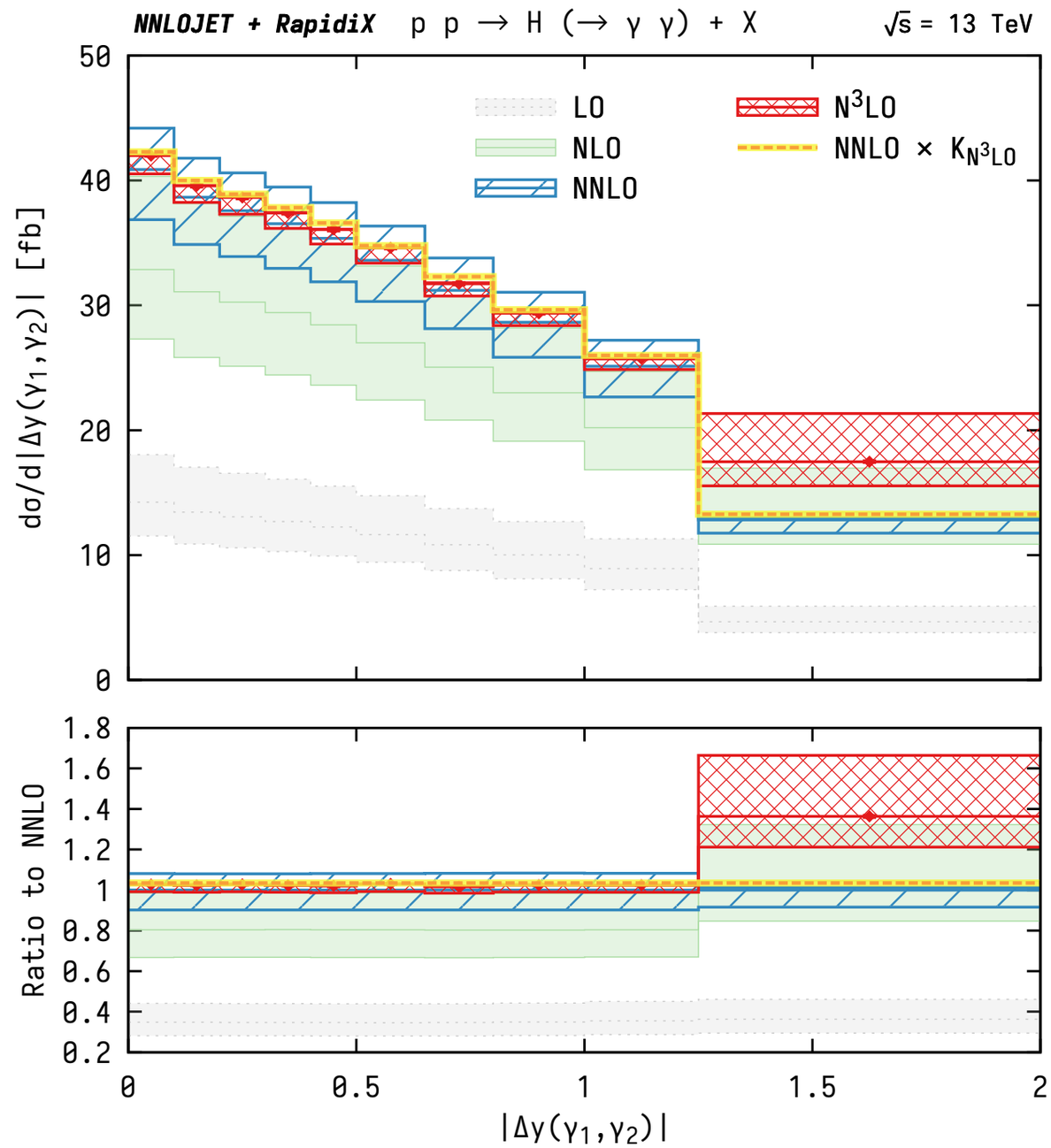


Chen, Gehrmann, Glover, Huss, BM, Pelloni [2102.07607]

Differential Photon Rapidity



Differential Rapidity Difference



FULLY DIFFERENTIAL PREDICTION FOR HIGGS BOSON PRODUCTION AT N3LO

- Technological and Theoretical advancements!
  - N3LO: Percent level predictions for Higgs Boson phenomenology
- First fully differential predictions at N3LO
  - Many challenges ahead!

THANK YOU!