MiNNLOPS

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Outline

- History
- MiNLO and NNLOPS
- MiNNLOPS: the method
- MiNNLOPS: recent results
- Ongoing work in MiNNLOPS

The beginning

Original goal was to find a procedure to set scale in an unbiased and à-priori way in NLO calculations involving many scales (in essence extending the CKKW procedure to NLO)

Hamilton, Nason, GZ ' *JHEP* 10 (2012) 155

Conclusions

Cortona, 2012

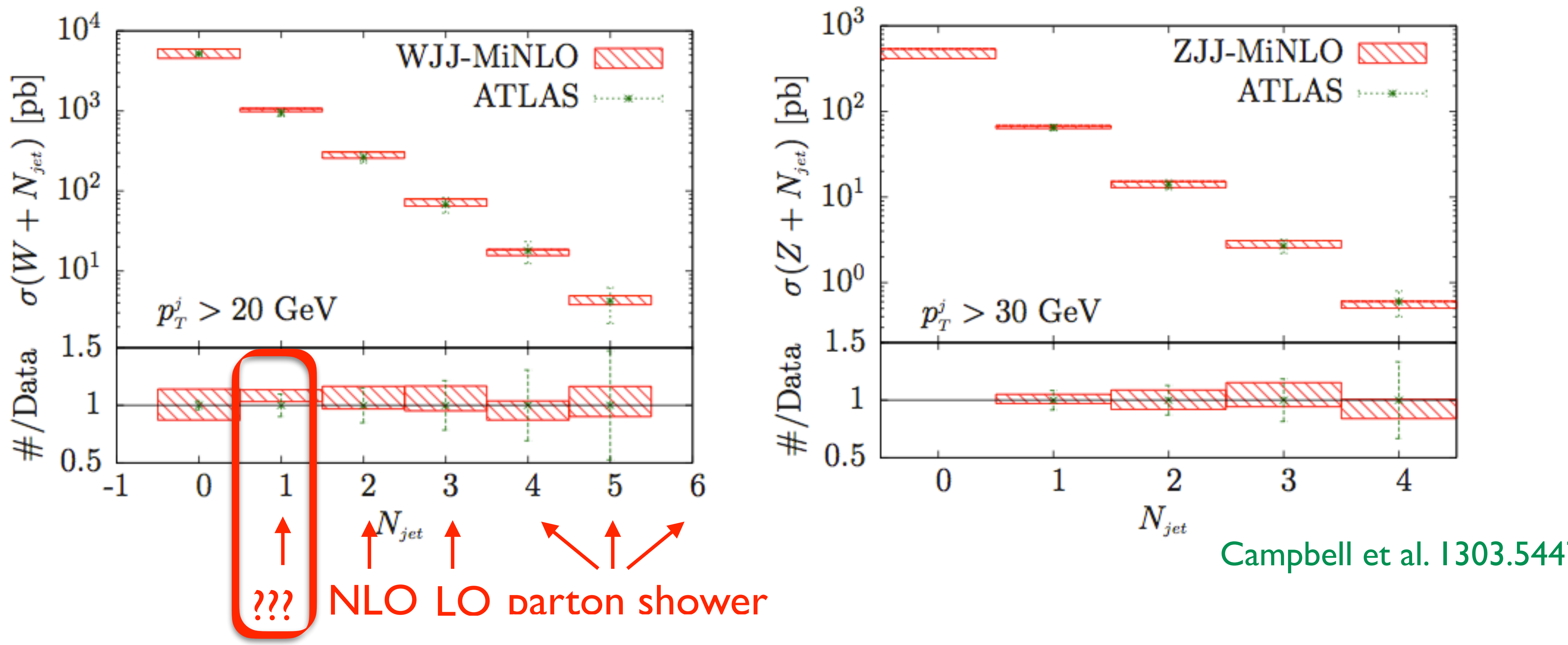
The choice of scale in NLO calculation has since a while being a debated issue

Matrix element calculations have a natural choice via the CKKW procedure, but they also include double logs from Sudakov form factors

SINLO is a simple procedure to extend the CKKW method to NLO

- the result is accurate at NLO, i.e. the scale dependence is NNLO
- the accuracy in the Sudakov region is Leading Log (LL) or better, according to the form of the Sudakov used
- the smooth behaviour of the CKKW scheme in the singular regions is preserved (X+n-jet cross-sections are finite even without jet cuts, and reproduce inclusive cross-section accurate to LO)
- the procedure is simple to implement in any NLO calculation, i.e. the improvement requires only a very modest amount of work

MiNLO: W+jets



Results for W+2jets with original MiNLO turned on versus ATLAS data for 0,1... 5 jets

Note: predictions are NLO accurate only in the 2-jet bin but one and zero-jet bin are described very well.

Does MiNLO catch the bulk of the NLO corrections … ?

MiNLO'

Hamilton, Nason, GZ *JHEP* 05 (2013) 082

Insight from resummation was crucial to address the question

$NNLL_\Sigma$ q_T resummation (e.g. for Higgs) at fixed rapidity can be written as

$$\frac{d\sigma}{dy dq_T^2} = \sigma_0 \frac{d}{dq_T^2}\left\{\left[C_{ga}\otimes f_{a/A}\right](x_A,q_T)\times\left[C_{gb}\otimes f_{b/B}\right](x_B,q_T)\right\}\times\Delta_g^2(M_H,q_T)+R_f$$

Integrating in q_T one gets

$$\frac{d\sigma}{dy} = \sigma_0 \left\{\left[C_{ga}\otimes f_{a/A}\right](x_A,q_T)\times\left[C_{gb}\otimes f_{b/B}\right](x_B,q_T)\right\}\times\Delta_g^2(M_H,q_T)+\int dq_T^2 R_f$$

the formula is NLO accurate for Higgs production if $O(\alpha_s)$ corrections to the coefficient functions are included and R_f is LO accurate

Now, one can take the derivative explicitly and see which terms are needed to maintain NLO accuracy after integration over q_T

MiNLO'

The Sudakov form factor for Higgs production has the form

$$\Delta_g(M_H, q_T) = \exp\left\{ -\int_{q_T^2}^{M_H^2} \left[\frac{dq^2}{q^2} A(\alpha_s(q^2)) \ln \frac{M_H^2}{q^2} + B(\alpha_s(q^2)) \right] \right\}$$

$$A(\alpha_s) = \sum_i A_i \left(\frac{\alpha_s}{2\pi} \right)^i \qquad B(\alpha_s) = \sum_i B_i \left(\frac{\alpha_s}{2\pi} \right)^i$$

$$A_1 = C_A \qquad B_1 = -\frac{\beta_0}{2} \qquad A_2 = K_{\rm CMW}$$

MiNLO'

Use the simple gaussian integrals

$$\int_0^\infty dL e^{-\alpha L^2} = \frac{1}{2}\sqrt{\frac{\pi}{\alpha}} \qquad \int_0^\infty dL L e^{-\alpha L^2} = \frac{1}{2} \qquad \ldots$$

To obtain

$$I(m,n) \equiv \int_{\Lambda^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2} \left(\log\frac{Q^2}{q^2}\right)^m \alpha_s^n\left(q^2\right) \exp\left\{-\int_{q^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2} A\,\alpha_s(\mu^2)\log\frac{Q^2}{\mu^2}\right\}$$

$$\approx \left[\alpha_s(Q^2)\right]^{n-\frac{m+1}{2}}$$

i.e. each log "counts" as a square-root of $1/\alpha_s$ after integration over the transverse momentum, when the Sudakov weight is present

$$dL \sim L \sim \frac{1}{\sqrt{\alpha_s}}$$

MiNLO'

Taking the derivative one gets

$$\sigma_0 \frac{dq_T^2}{q_T^2}\left[A_1 \alpha_s L, B_1 \alpha_s, A_2 \alpha_s^2 L, B_2 \alpha_s^2, C_1 \times C_1 \times A_1 \alpha_s^3 L, \dots \right] \exp\{\Delta_g(M_H, q_T)^2\}$$

After integration with the Sudakov weight, the counting is set by $L \sim dL \sim 1/\sqrt{\alpha_s}$. So these terms contribute, as

$$\int dL\, A_1\, \alpha_s L \exp\{\Delta_g(M_H, q_T)^2\} \sim A_1$$

$$\int dL\, B_1\, \alpha_s \exp\{\Delta_g(M_H, q_T)^2\} \sim B_1 \sqrt{\alpha_s}$$

LO

$$\int dL\, A_2\, \alpha_s^2 L \exp\{\Delta_g(M_H, q_T)^2\} \sim A_2 \alpha_s$$

$$\int dL\, B_2\, \alpha_s^2 \exp\{\Delta_g(M_H, q_T)^2\} \sim B_2 \alpha_s^{3/2}$$

NLO

To claim NLO accuracy one needs to include B_2 in the Sudakov (neglected terms must be $O(\alpha_s^2)$ and not $O(\alpha_s^{3/2})$)

MiNLO'

Conclusion:

Hamilton, Nason, GZ *JHEP* 05 (2013) 082

☛ The original MiNLO procedure is not NLO accurate for inclusive quantities, in that it neglects O($\alpha_s^{3/2}$) terms

☛ achieve NLO accuracy from HJ also for inclusive H by

✔ including the B_2 term in the Sudakov form factors

✔ taking the scale in the coupling in the real and virtual equal to the Higgs transverse momentum (effect of same size as B_2)

Provided this is done, the HJ-MiNLO describes both H and H+jet at NLO, i.e. merging of H and H+jet is achieved without any merging scale

NNLOPS

Hamilton, Nason, GZ *JHEP* 05 (2013) 082

It was soon realised that, since MiNLO' is NLO accurate for X+jet, an à-posteriori reweighing of MiNLO' results with the ratio of NNLO/ MiNLO' result, differential in the Born kinematics of X, leads to NNLOPS accurare results for X (X=H, W, Z …)

E.g. for Higgs production

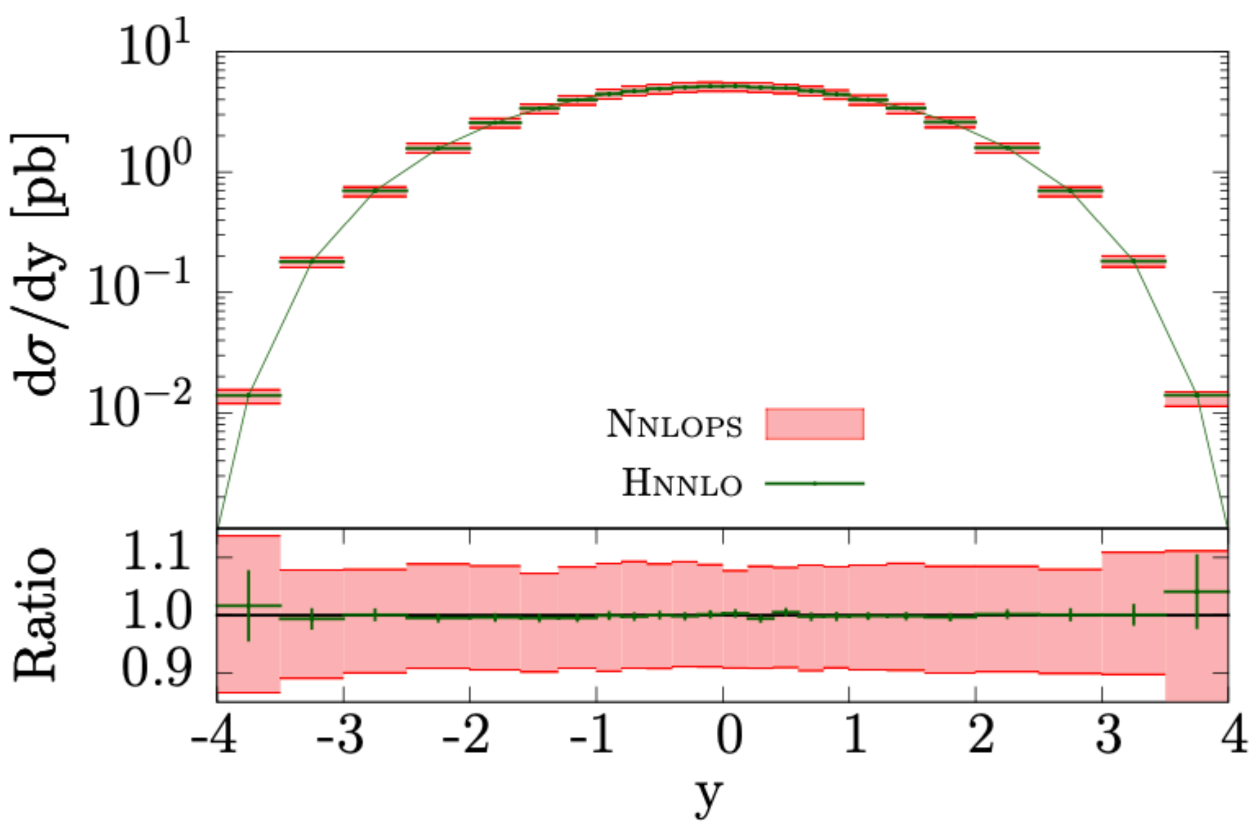
$$\frac{\left(\frac{d\sigma}{dy}\right)_{\text{NNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\text{HJ-MiNLO}}} = \frac{c_2\alpha_s^2 + c_3\alpha_s^3 + c_4\alpha_s^4}{c_2\alpha_s^2 + c_3\alpha_s^3 + d_4\alpha_s^4} \approx 1 + \frac{c_4 - d_4}{c_2}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

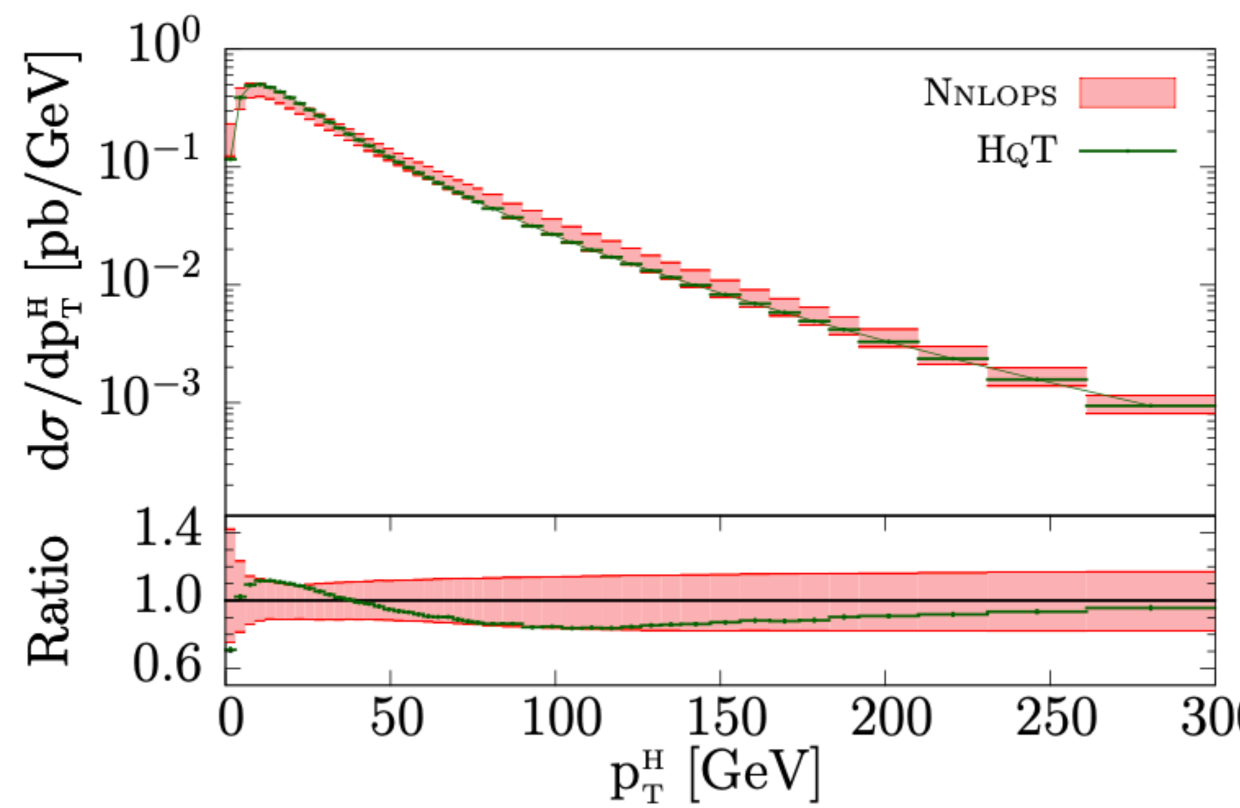
Thus, reweighing HJ-MINLO results with this factor one obtains NNLO+PS accuracy, without spoiling the NLO accuracy of HJ

NNLOPS

Sample NNLOPS results for Higgs:

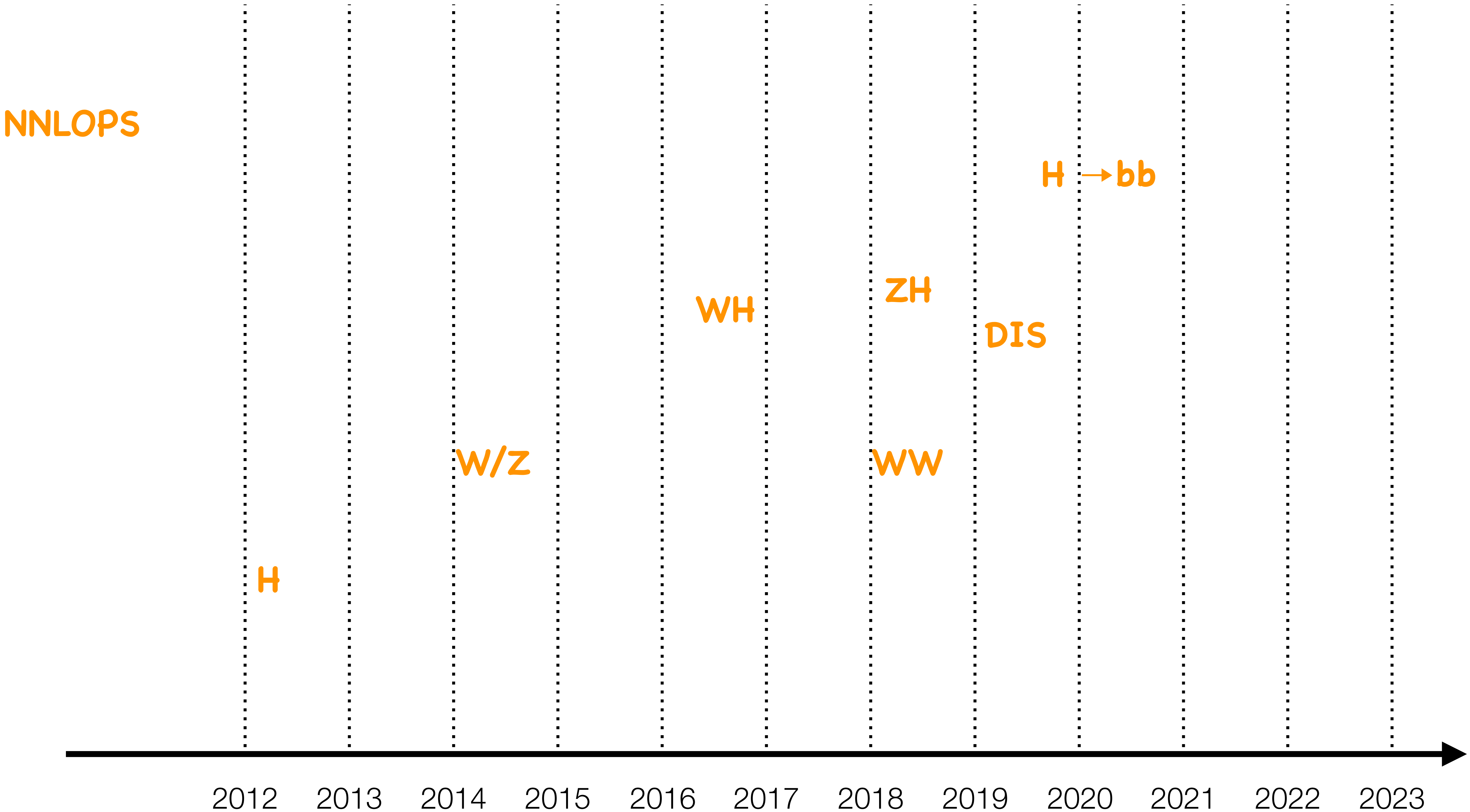
Hamilton, Nason, GZ *JHEP* 10 (2013) 222





NNLOPS method pushed numerically to the boundaries with Drell Yan, HW and WW, because of high dimensionality of Born phase space

NNLOPS timeline



MiNNLOPS

MiNNLOPS extends the original MiNLO idea by including directly all terms required to achieve NNLO accuracy. Key ingredient is a NNLO matched resummed prediction.

Starting point:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}}{\mathrm{d}p_{\mathrm{T}}}\left\{\exp[-\tilde{S}(p_{\mathrm{T}})]\mathcal{L}(p_{\mathrm{T}})\right\} + R_f(p_{\mathrm{T}})$$

Which can be written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}\sigma^{\mathrm{sing}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} + R_f(p_{\mathrm{T}}) \qquad \frac{\mathrm{d}\sigma^{\mathrm{sing}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]D(p_{\mathrm{T}})$$

With

$$D(p_{\mathrm{T}}) \equiv -\frac{\mathrm{d}\tilde{S}(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\mathcal{L}(p_{\mathrm{T}}) + \frac{\mathrm{d}\mathcal{L}(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}$$

MiNNLOPS

Writing
$$R_f(p_T) = \frac{d\sigma_{FJ}^{(NLO)}}{d\Phi_F dp_T} - \frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma^{sing}}{d\Phi_F dp_T}\right]^{(1)} - \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 \left[\frac{d\sigma^{sing}}{d\Phi_F dp_T}\right]^{(2)}$$

With
$$\frac{d\sigma_{FJ}^{(NLO)}}{d\Phi_F dp_T} = \frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)} + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2 \left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)}$$

Factoring out the Sudakov form factor

$$\frac{d\sigma}{d\Phi_F dp_T} = \exp[-\tilde{S}(p_T)]\left\{D(p_T) + \frac{R_f(p_T)}{\exp[-\tilde{S}(p_T)]}\right\}$$

Expanding,

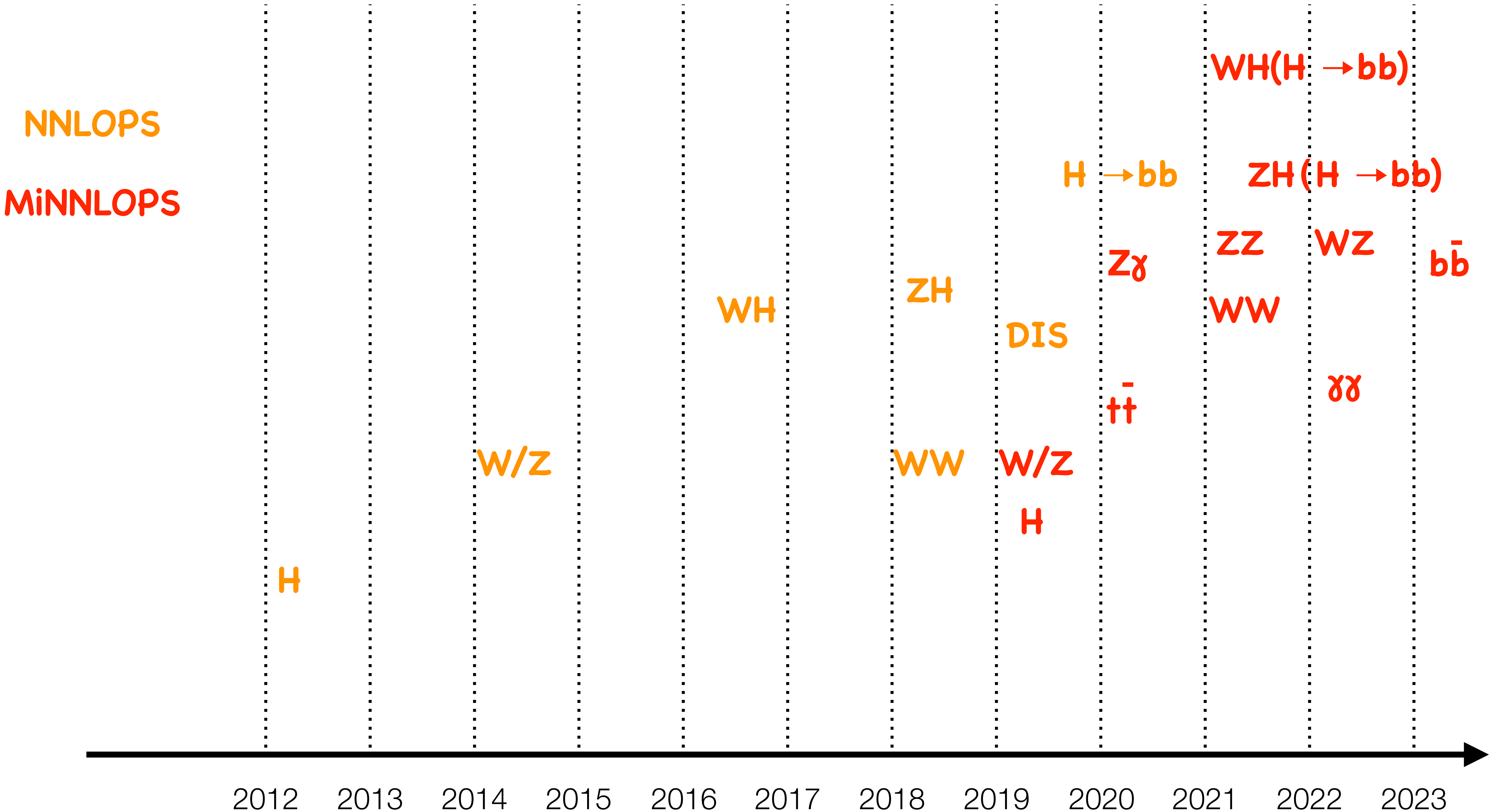
$$\frac{d\sigma}{d\Phi_F dp_T} = \exp[-\tilde{S}(p_T)]\left\{\frac{\alpha_S(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)}\left(1 + \frac{\alpha_S(p_T)}{2\pi}[\tilde{S}(p_T)]^{(1)}\right) + \left(\frac{\alpha_S(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)}\right.$$

$$\left. + \left[D(p_T) - \frac{\alpha_S(p_T)}{2\pi}[D(p_T)]^{(1)} - \left(\frac{\alpha_S(p_T)}{2\pi}\right)^2 [D(p_T)]^{(2)}\right] + \text{regular terms of } \mathcal{O}(\alpha_S^3)\right\}$$

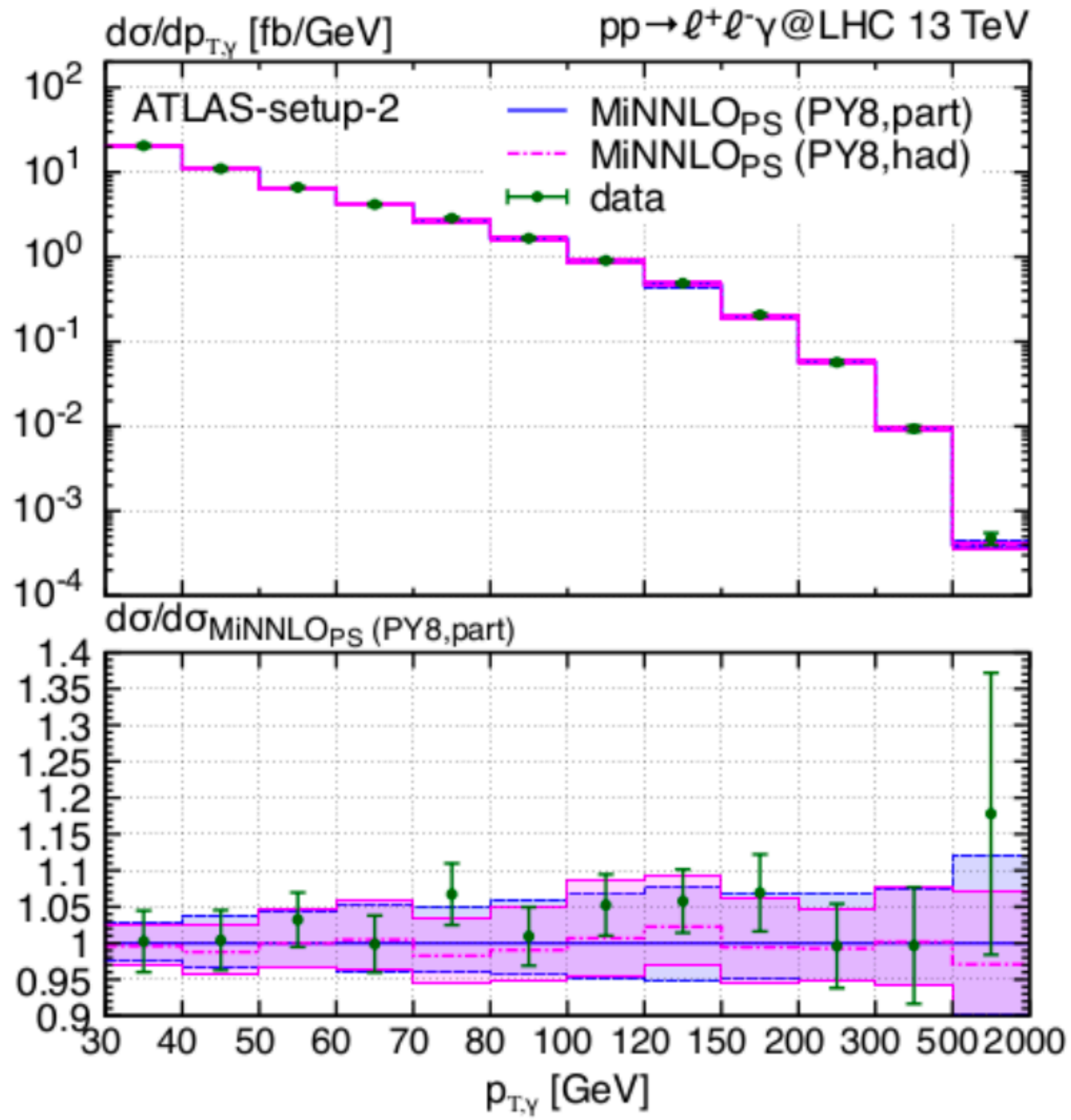
MiNLO'

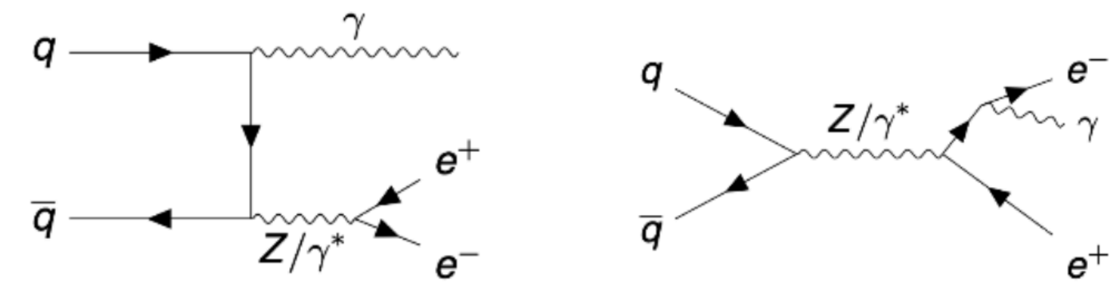
Extra terms in MiNNLO

NNLO+PS timeline



MiNNLOPS: Z +photon



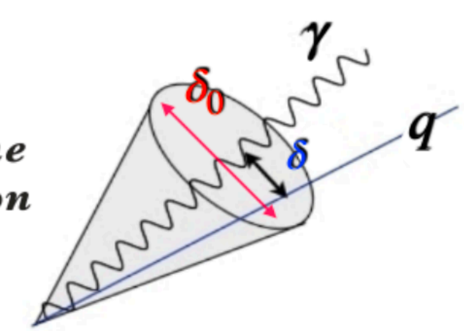


Photon isolation requirement:

- *Experimentally needed to identify hard photons*
- *Theoretically delicate definition of an infrared-safe cross section*

$$\sum_{had/part \in \delta} E_T^{had/part} \leq E_T^{max}(\delta) = E_T^{ref} \cdot \left(\frac{1-cos\delta}{1-cos\delta_0}\right)^n, \quad \forall \delta \leq \delta_0$$

Frixione isolation



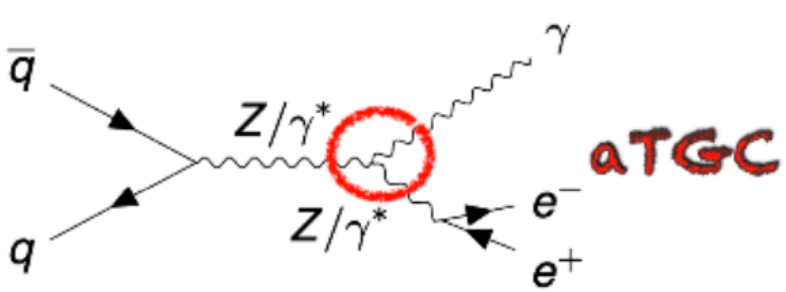
Lombardi, Wiesemann, GZ *JHEP* 06 (2021) 095

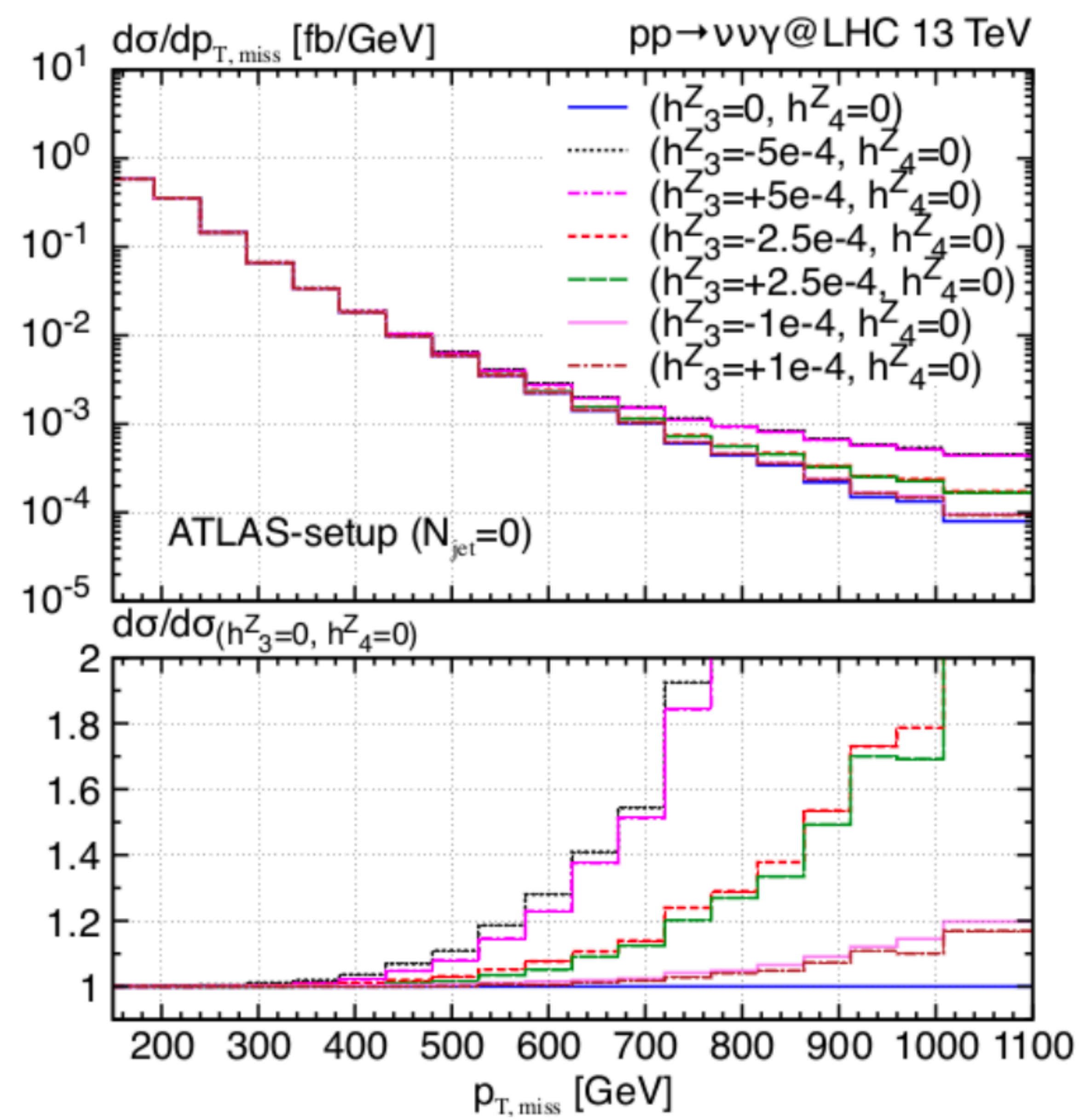
MiNNLOPS: Z +photon

Important probe of BSM:

- Anomalous triple gauge couplings
- Background to mono-photon Dark Matter searches ($Z \rightarrow \bar{\nu}\nu$)

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,p) = \frac{i(p^2-m_V^2)}{\Lambda^2}\left(h_1^V \left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{\Lambda^2} p^\alpha \left(p\cdot q_2\; g^{\mu\beta} - q_2^\mu p^\beta\right) - h_3^V \varepsilon^{\mu\alpha\beta\nu} q_{2\nu} - \frac{h_4^V}{\Lambda^2}\varepsilon^{\mu\beta\nu\sigma}p^\alpha p_\nu q_{2\sigma}\right)$$

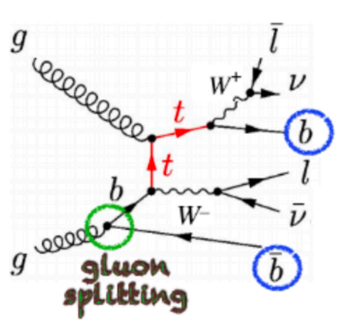




Lombardi, Wiesemann, GZ Phys.Lett.B 824 (2022)

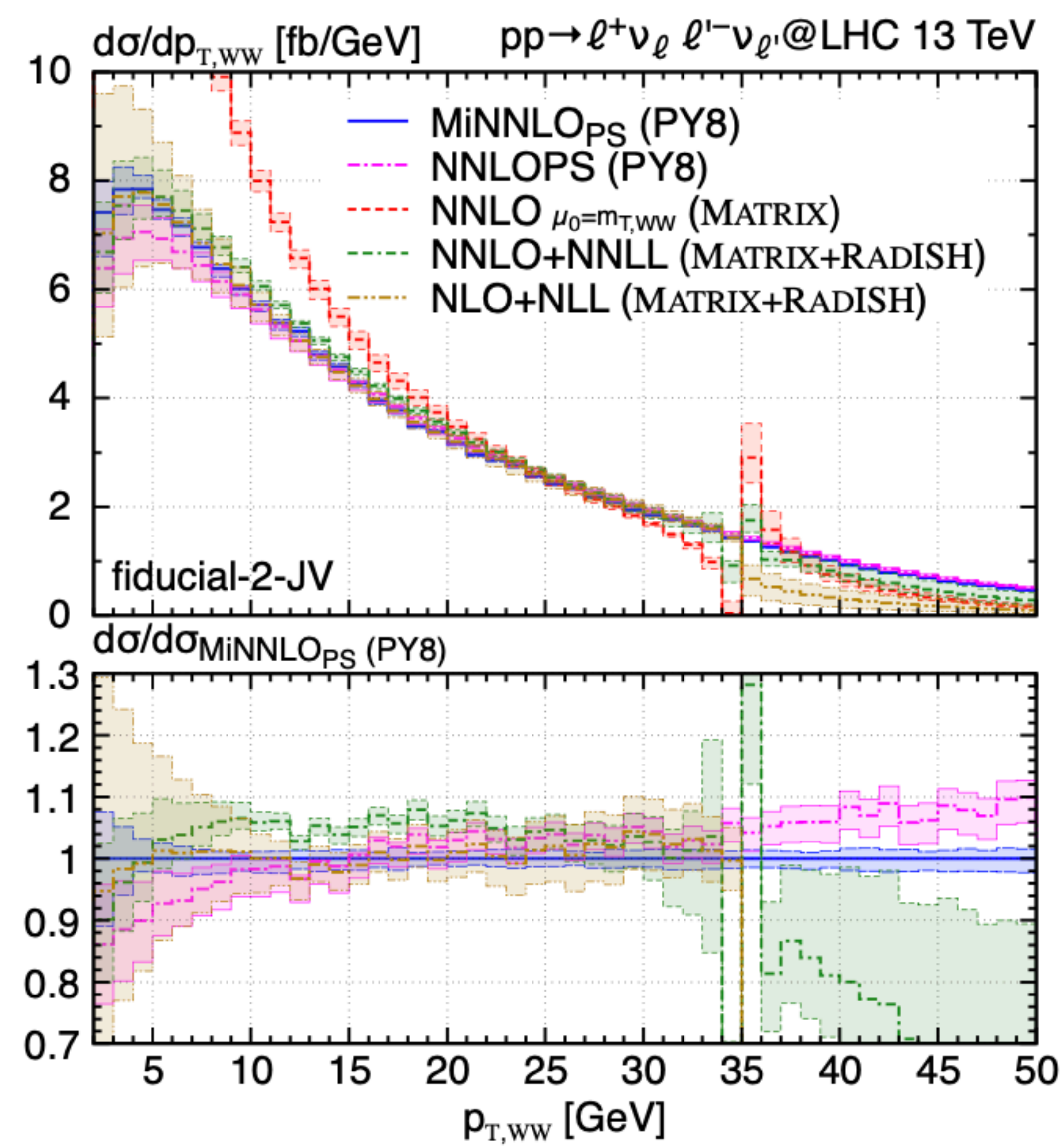
MiNNLOPS: WW

- Largest of diboson processes
- Access to anomalous triple gauge couplings
- No full event reconstruction due to neutrinos → high-precision theory required
- Jet-veto required → theoretical modelling important



Jet-veto requirement:

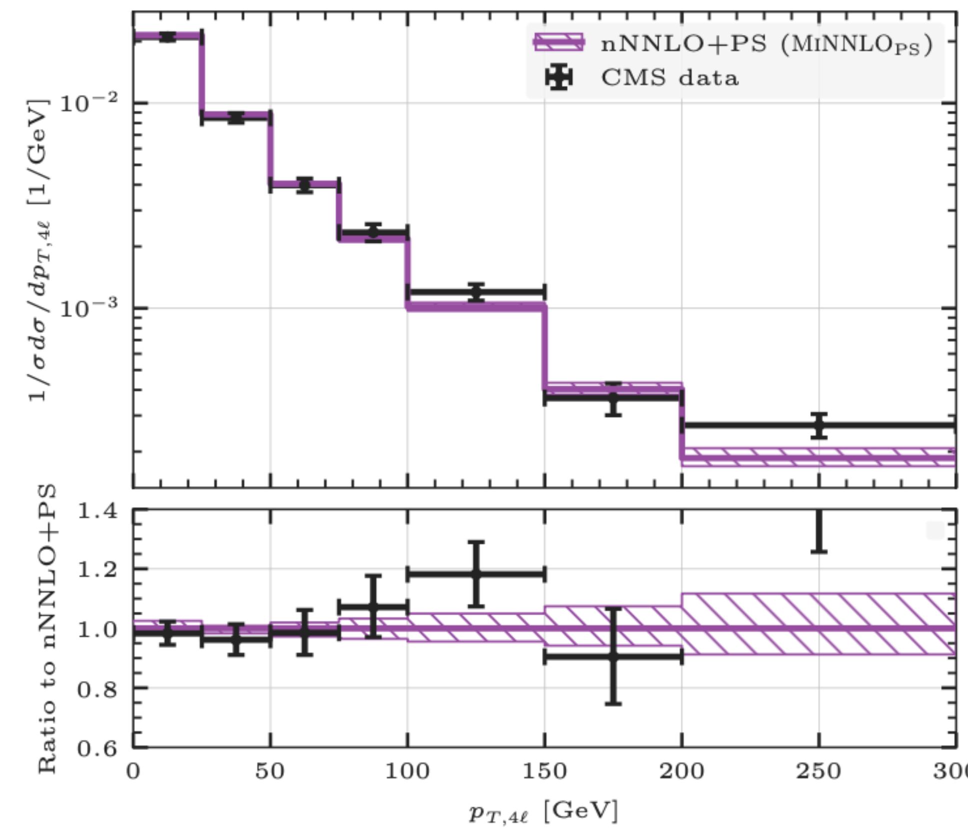
- *Experimentally needed to reduce top background*
- *Theoretically involved definition of WW cross section, due to diagrams with resonant top quarks and b final states:*
  - *Interference with double-real diagrams*
  - *Not separately finite for massless b quarks*

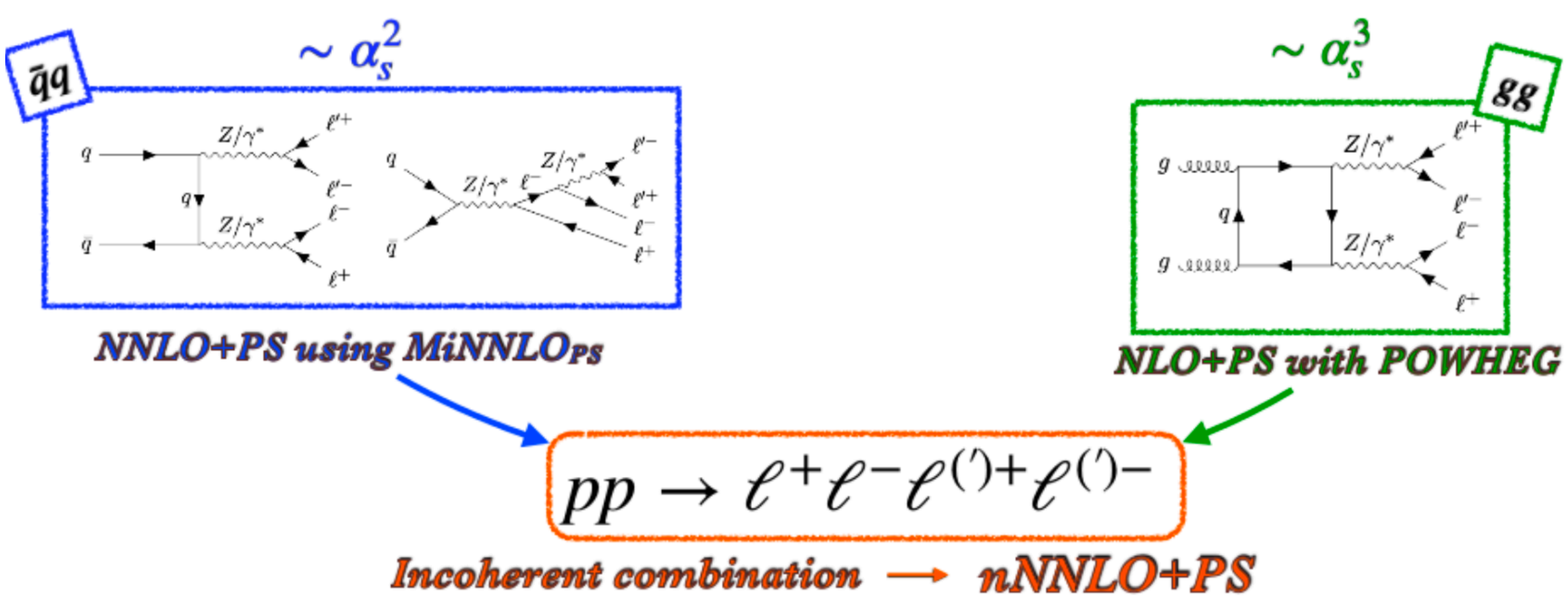


Lombardi, Wiesemann, GZ *JHEP* 11 (2021) 230

MiNNLOPS: ZZ

- Smallest cross-section of diboson processes
- Access to anomalous triple gauge couplings
- Important for constraining Higgs width and couplings

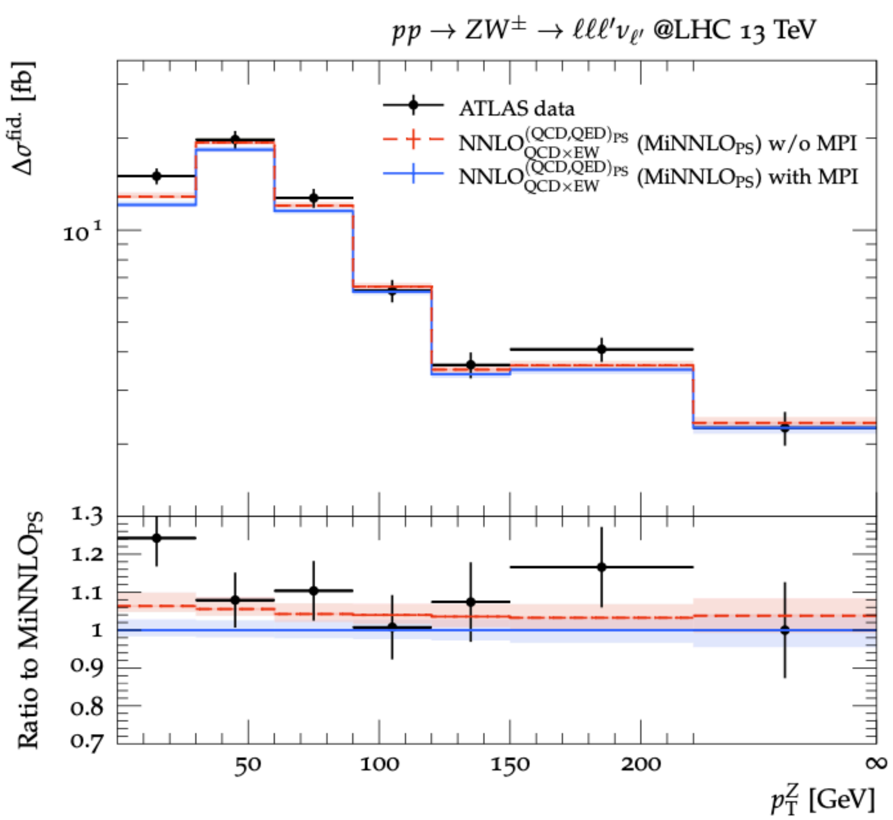


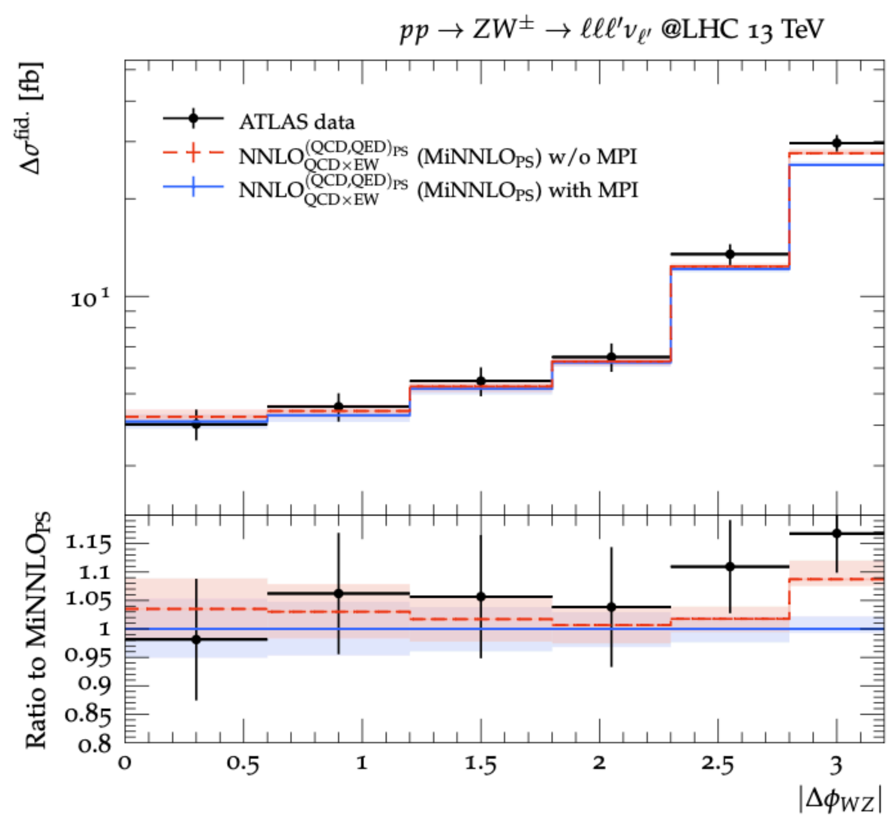


Buonocore, Koole, Lombardi, Rottoli, Wiesemann, GZ
JHEP 11 (2022) 072

MiNNLOPS: WZ

- Including approximate EW corrections using different schemes
- Default scheme: $\mathrm{NNLO}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K\text{-}NLO}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}}_{\mathrm{EW}} = \mathrm{NNLO}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}}_{\mathrm{QCD}\times\mathrm{EW}}$





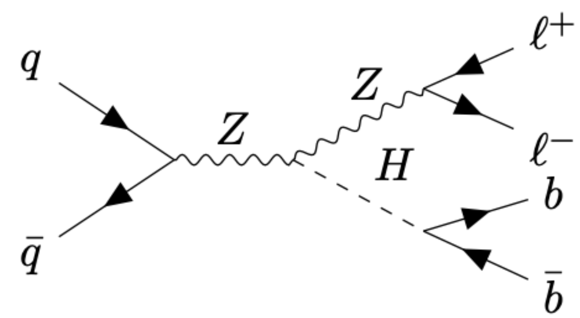
Lindert, Lombardi, Wiesemann, Zanoli, GZ *JHEP* 11 (2022) 036

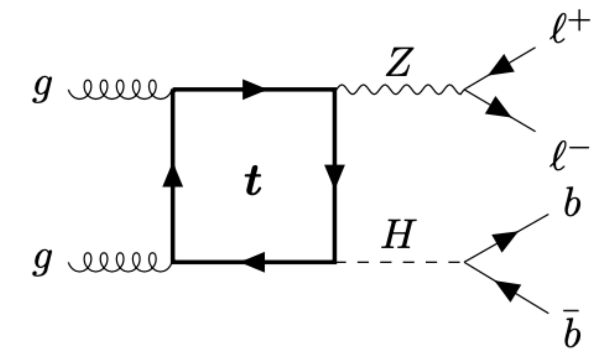
In progress: a priori combination of QCD and EW corrections

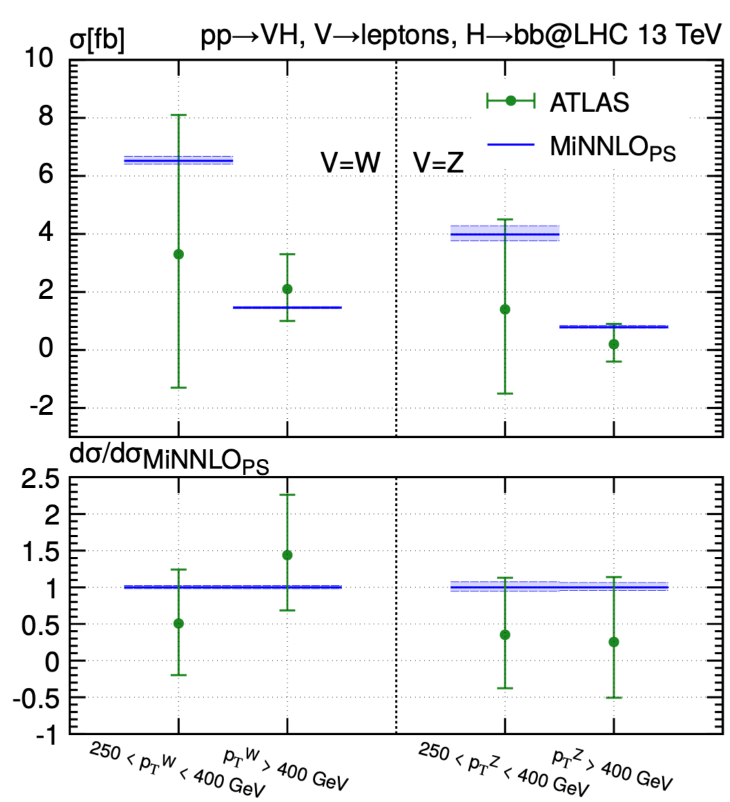
Lombardi, Pelliccioli, Wiesemann, Zanoli, GZ in progress

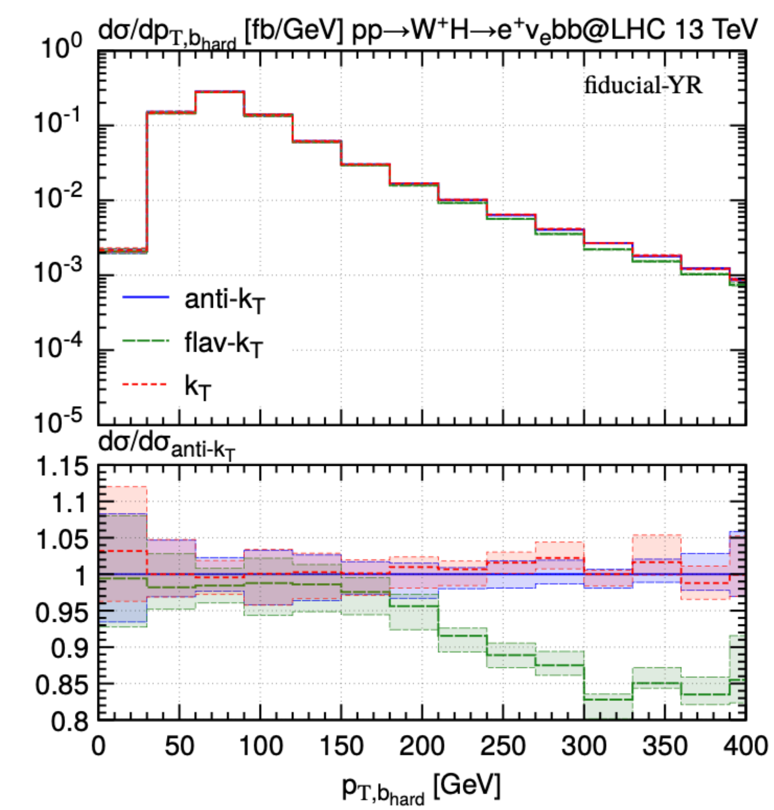
MiNNLOPS: ZH with H → bb

- Needed for precision in the Higgs sector
- One of the main production channels + largest branching fraction in decay
- NNLO+PS accuracy in production of decay









Zanoli, Chiesa, Re, Wiesemann, GZ *JHEP* 11 (2022) 072

ZH with SMEFT H → bb

https://twitter.com/AlessandroStru4/status/1662008330439606272

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Critical review about SMEFT generated via ChatGPT in Trump style.

The Standard Model Effective Field Theory

Let me tell you, folks, this SMEFT thing, okay? It's supposed to be a fancy framework in theoretical physics, but let me tell you, it's a disaster, a total disaster. The academics who came up with this stuff, they must have been really bored or something, they're listing all these operators with ridiculous long names, operators nobody can even pronounce. The Non-Universal Left-Handed Quark Dipole Operator with Chromomagnetic Moments (NUQDOWCMDM). It's like they're just throwing random words together and hoping it sounds smart. I mean, seriously, who comes up with this stuff? At dimension 6 they got 2499 operators, the $\mathcal{O}_{HWB}$, $\mathcal{O}^{(3)}_{Hb_L}$, $[\mathcal{O}^{(3)}_{LQ}]_{3323}$, and it goes on and on and on.

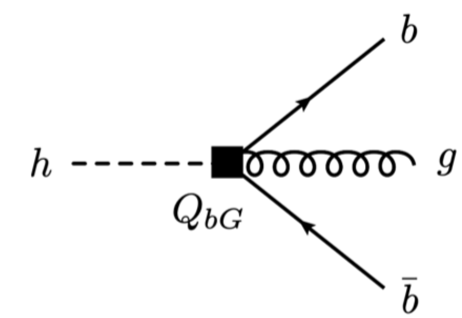
Who needs that many operators? It's ridiculous. They've got operators for everything. Operators for quarks, operators for leptons, operators for gauge bosons. They even got operators to count operators at higher dimension. It's crazy! They keep adding more operators. They just can't stop

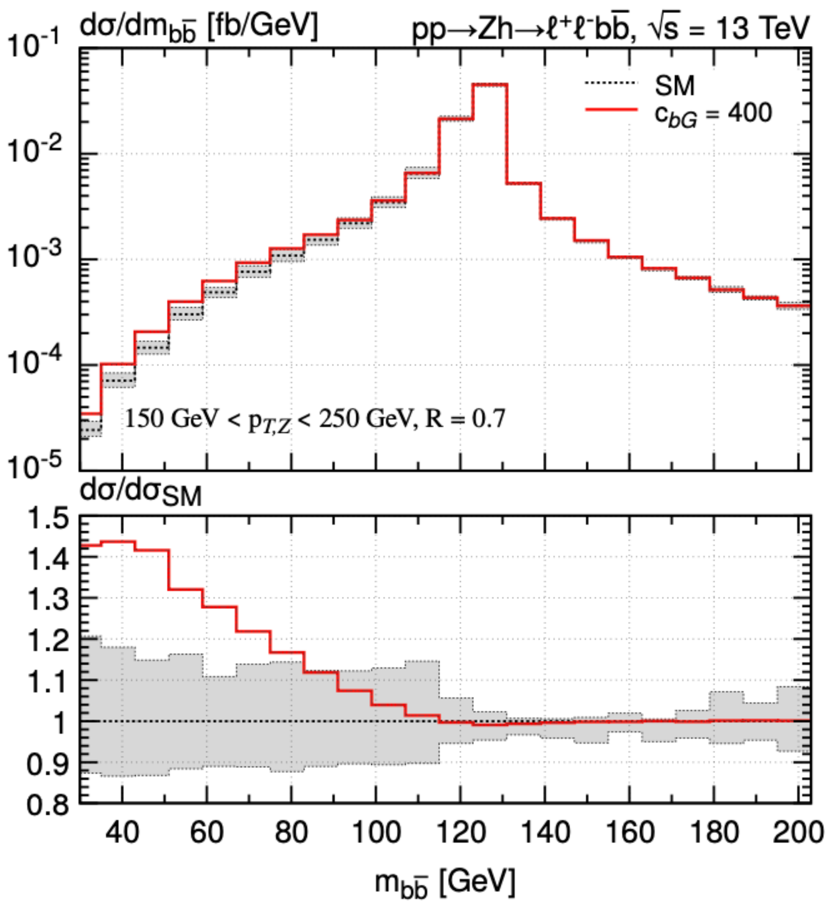
ZH with SMEFT H → bb

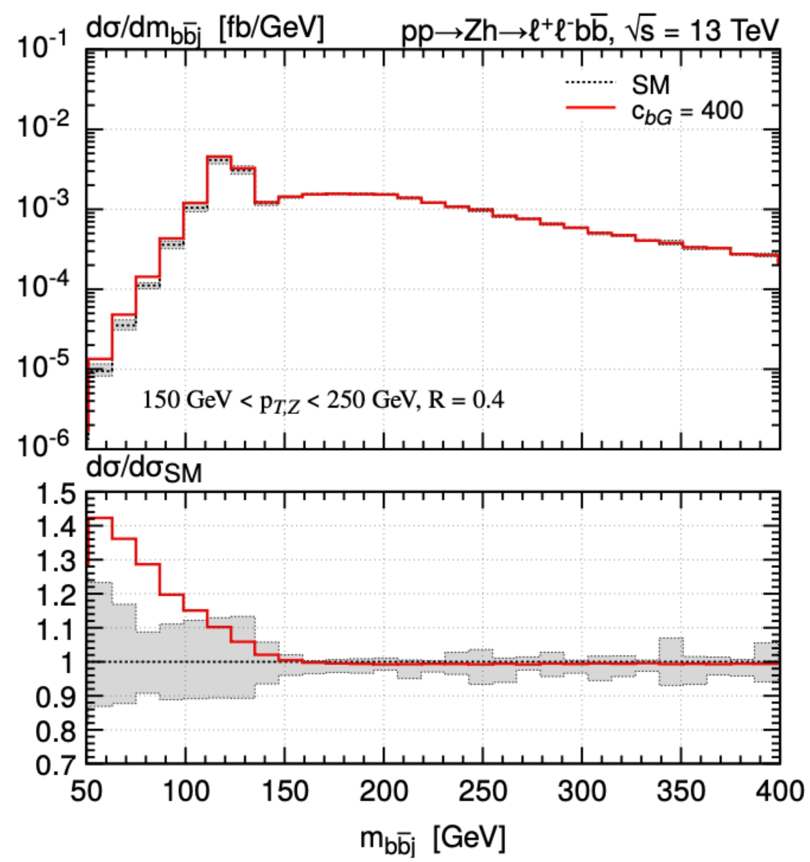
$$Q_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)\,, \qquad Q_{HD} = (H^\dagger D_\mu H)^*\,(H^\dagger D^\mu H)\,,$$

$$Q_{bH} = y_b (H^\dagger H)\,\bar{q}_L b_R H\,, \qquad Q_{bG} = \frac{g_s^3}{(4\pi)^2}\, y_b\, \bar{q}_L \sigma_{\mu\nu} T^a b_R H\, G^{a,\mu\nu}\,,$$

$$Q_{HG} = \frac{g_s^2}{(4\pi)^2}\,(H^\dagger H)\, G^a_{\mu\nu} G^{a,\mu\nu}\,, \qquad Q_{3G} = \frac{g_s^3}{(4\pi)^2}\, f^{abc} G^{a,\nu}_{\mu} G^{b,\sigma}_{\nu} G^{c,\mu}_{\sigma}\,,$$







$$\Gamma(h \to b\bar{b})^{\rm NNLO,non}_{\rm SMEFT} = \Delta_{\rm non}\, c_{bG}\, \Gamma(h \to b\bar{b})^{\rm LO}_{\rm SM}\,,$$

$$\Delta_{\rm non} = \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_h^2}{3v^2}$$

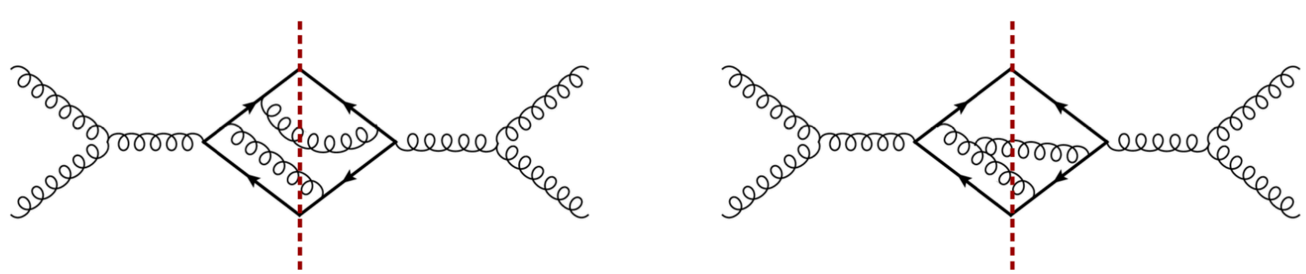
⇒ very interesting and distinctive shape differences

Haisch, Scott, Wiesemann, Zanoli, GZ *JHEP* 07 (2022) 054

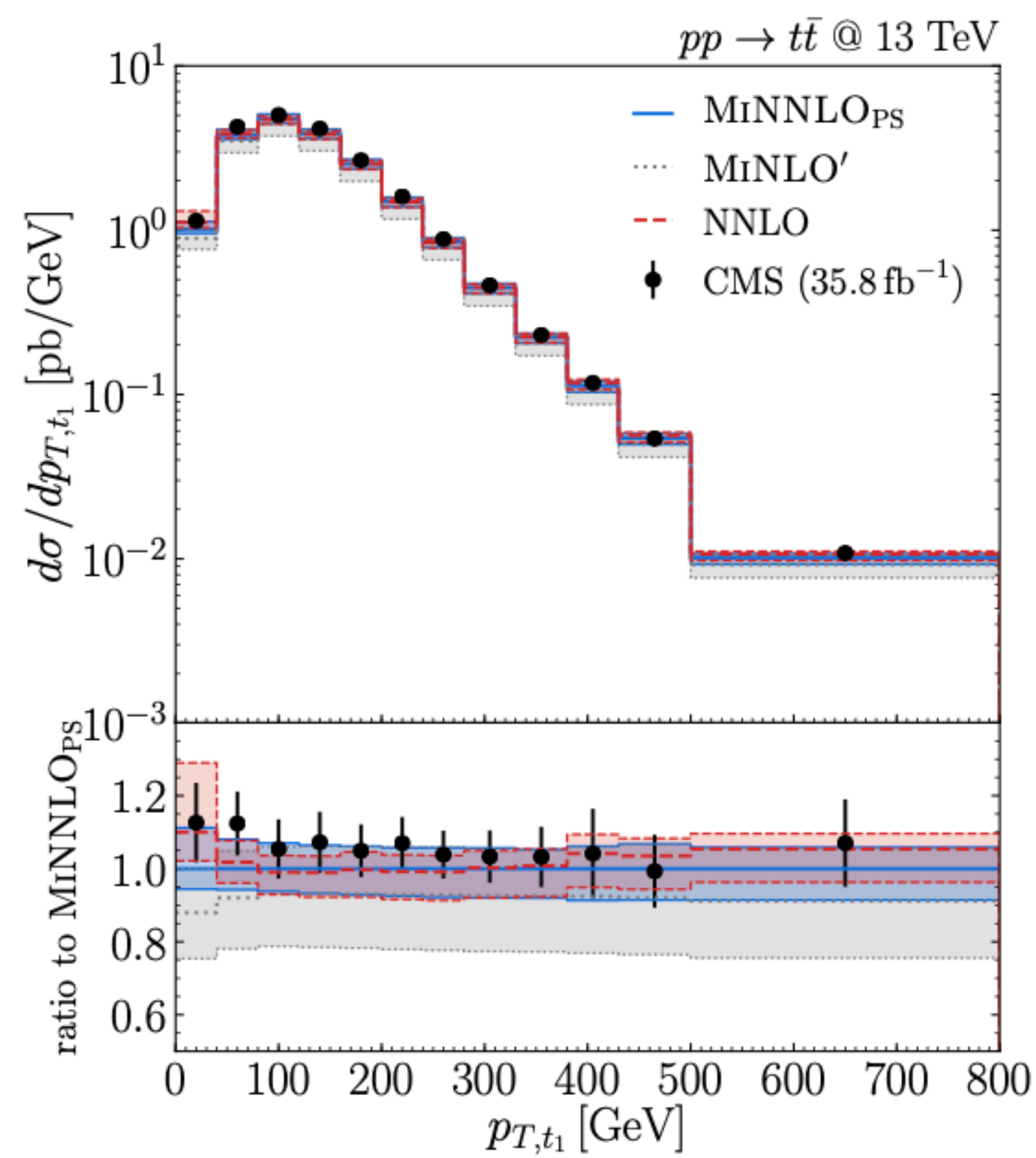
MiNNLOPS: top-pairs

- Breakthrough: first application beyond colour singlet: top-pair production
- Extremely relevant for phenomenology: 40% of LHC analyses use $t\bar{t}$ predictions

More complicated structure due to final-state soft radiation...



… leading to colour interference effects



Mazzitelli, Monni, Nason, Re, Wiesemann, GZ Phys.Rev.Lett. 127 (2021) 6; *JHEP* 04 (2022) 079

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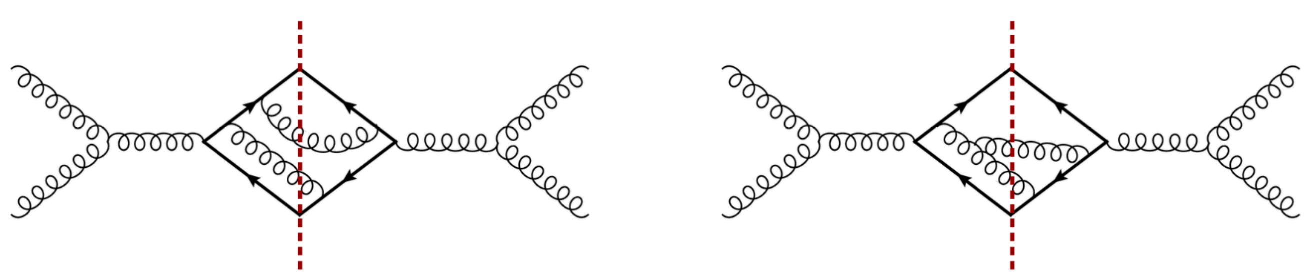
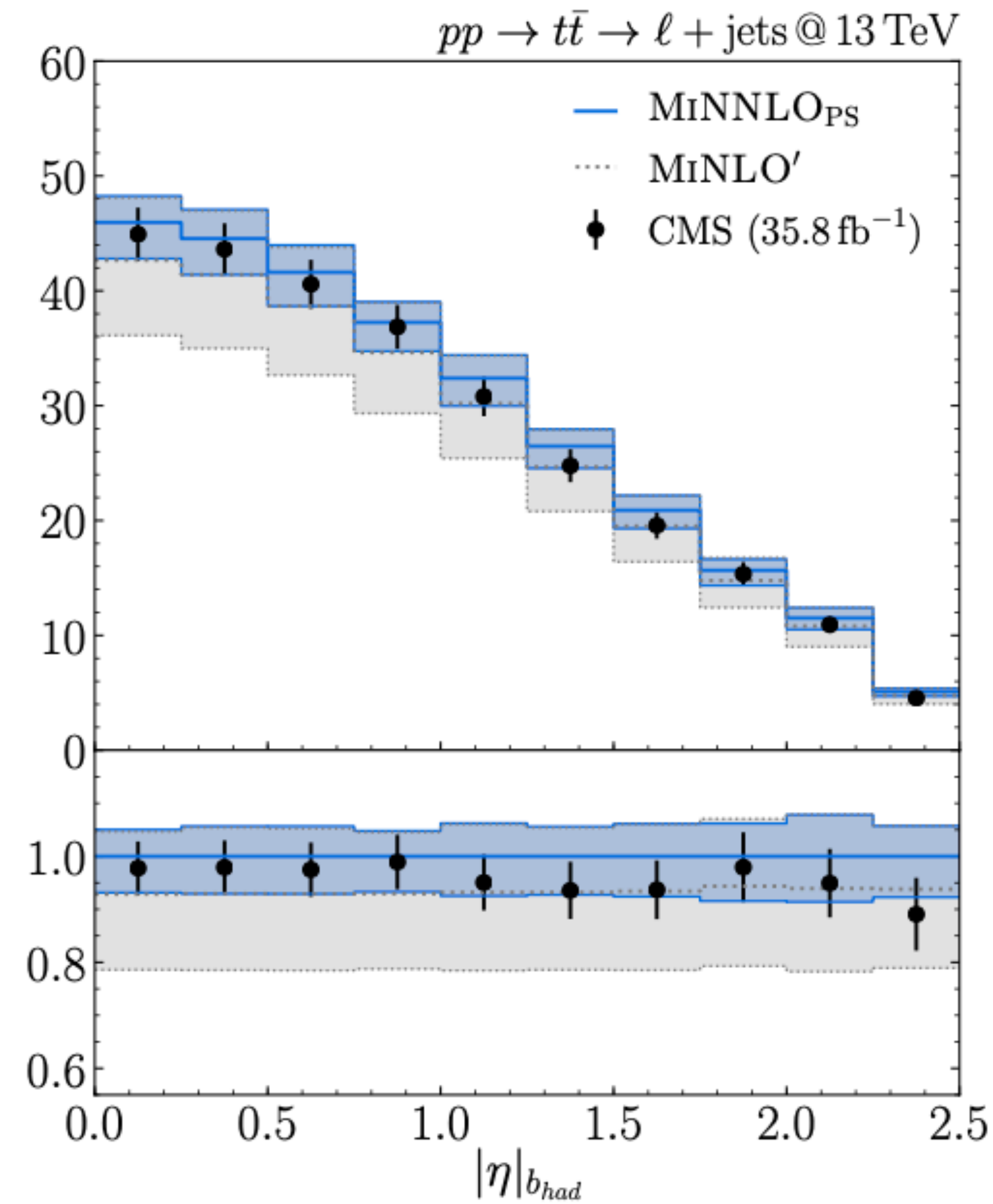


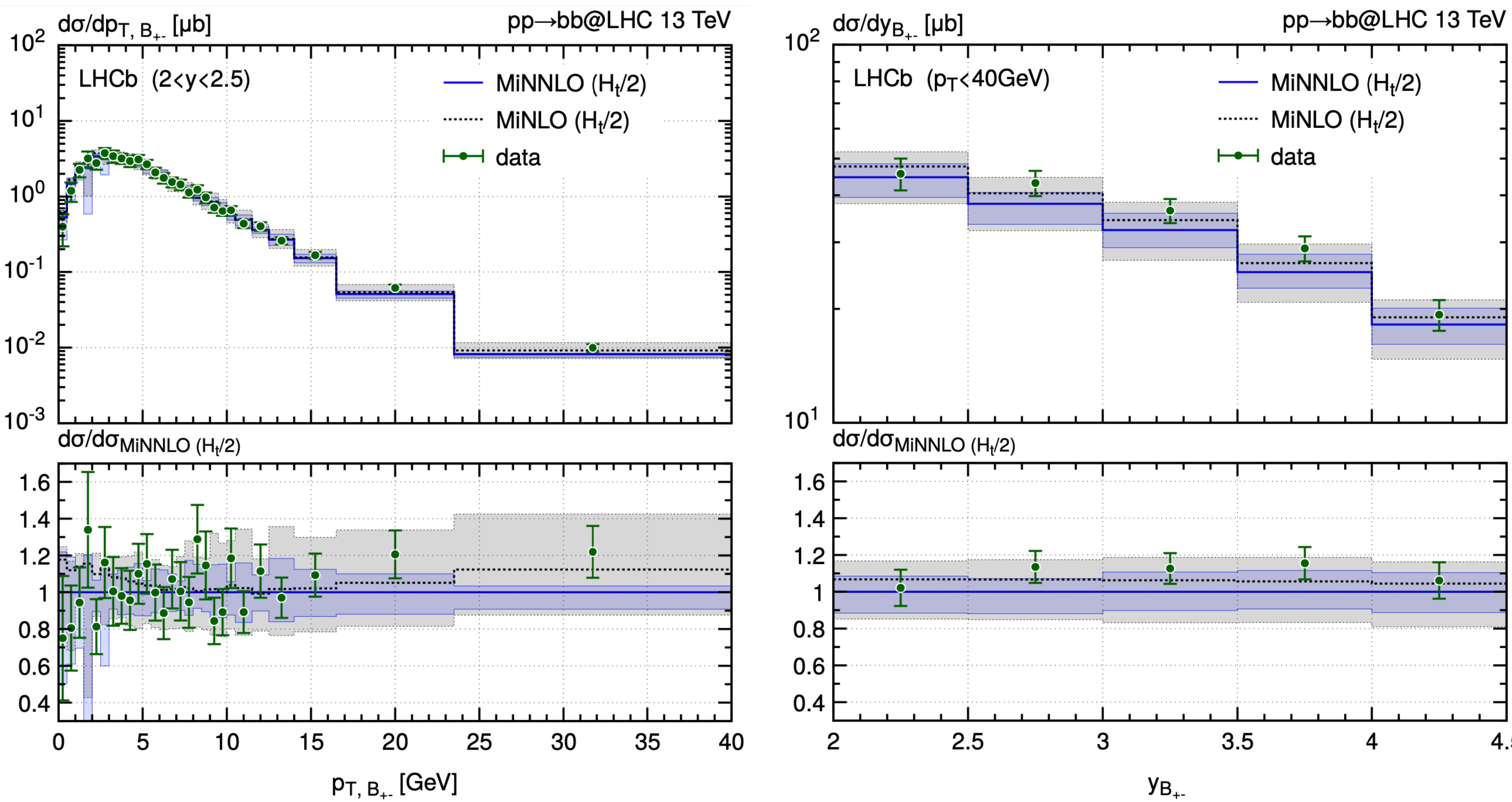
... leading to **colour** interference effects



Including tree-level decays of top quarks

Mazzitelli, Monni, Nason, Re, Wiesemann, GZ Phys.Rev.Lett. 127 (2021) 6; *JHEP* 04 (2022) 079

MiNNLOPS: B-hadrons

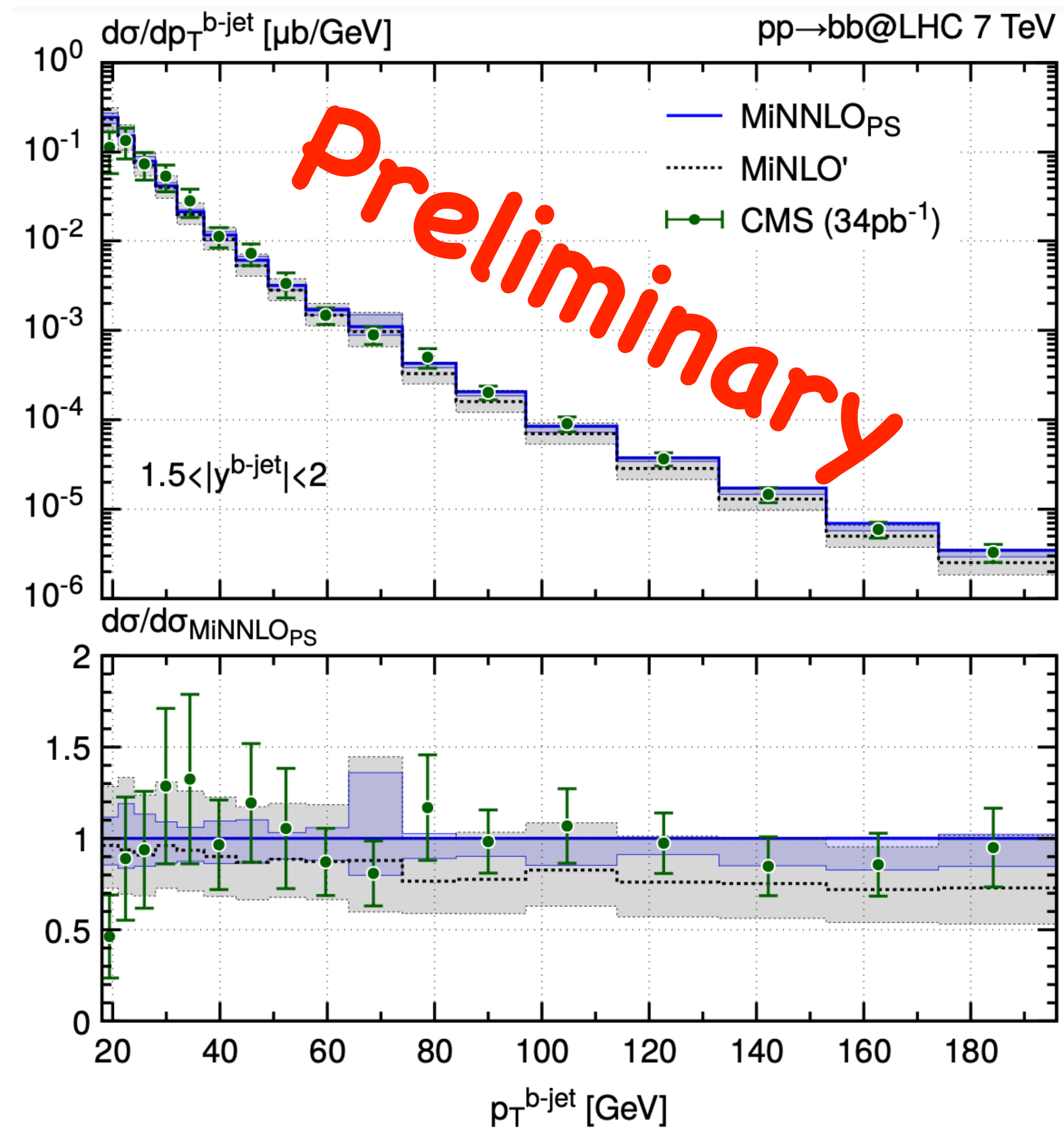


Mazzitelli, Ratti, Wiesemann, GZ 2302.01645

Ongoing

MiNNLOPS: bjets

- Comparison with b-jets measured at CMS
- Issue of b-jet definition must be further investigated

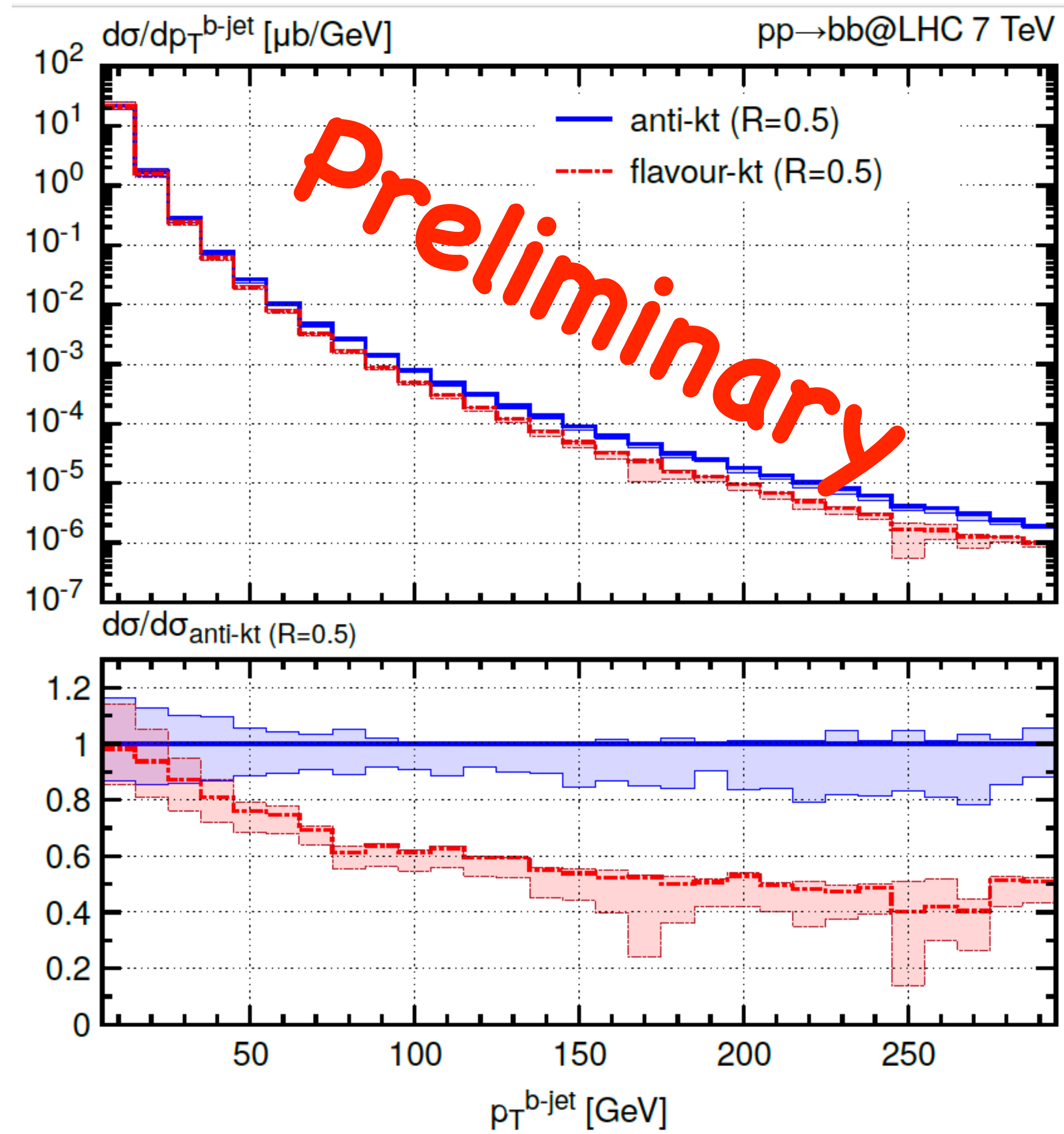


Extension to $c\bar{c}$ also in progress

Mazzitelli, Ratti, Wiesemann, GZ in preparation

MiNNLOPS: bjets

- Comparison with b-jets measured at CMS
- Issue of b-jet definition must be further investigated



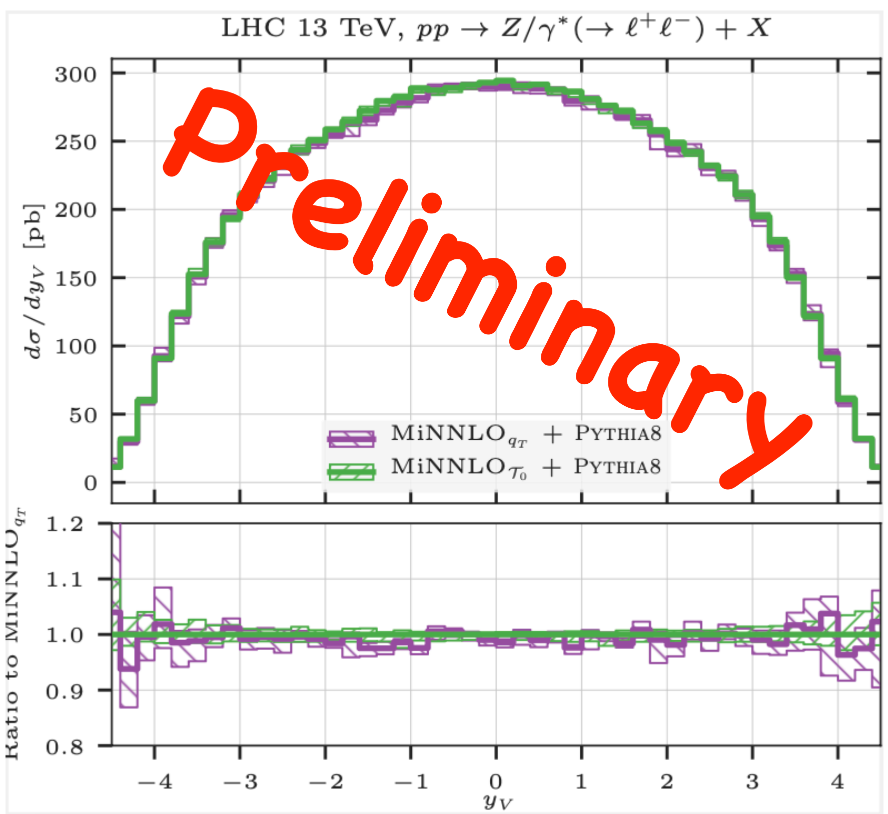
Extension to $c\bar{c}$ also in progress

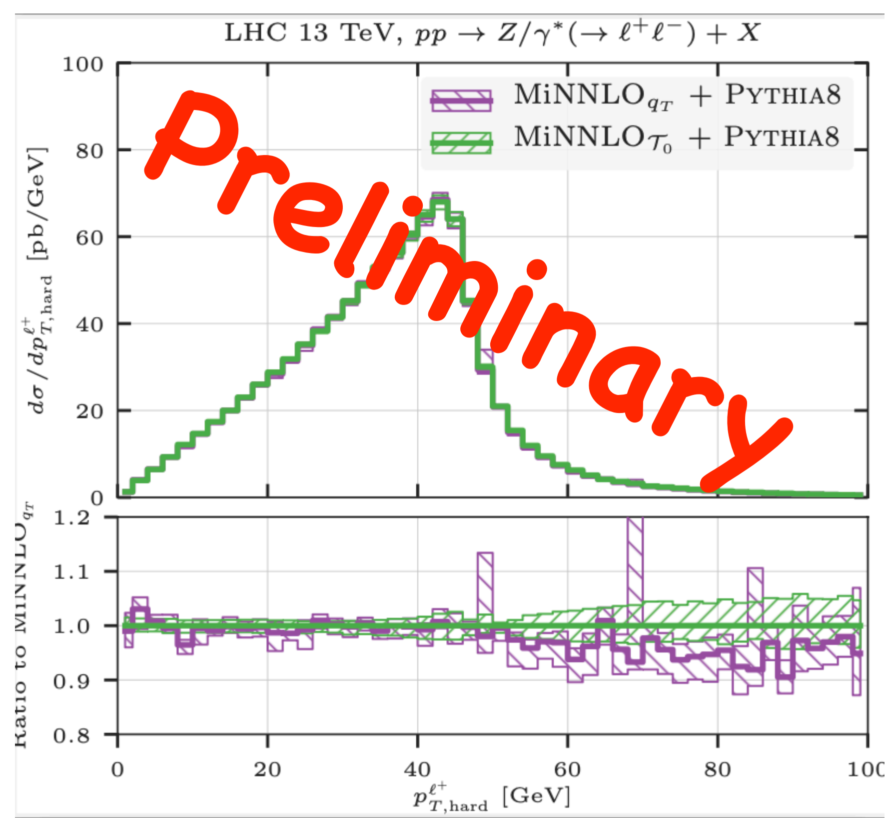
Mazzitelli, Ratti, Wiesemann, GZ in preparation

MiNNLOPS: using τ_0

- Resummation for τ_1 useful to formulate a MiNNLOPS for X+1 jet
- First step: formate a τ_0-MiNNLOPS for Higgs and Drell Yan

Preliminary results for Drell-Yan:





(worse agreement for Higgs production)

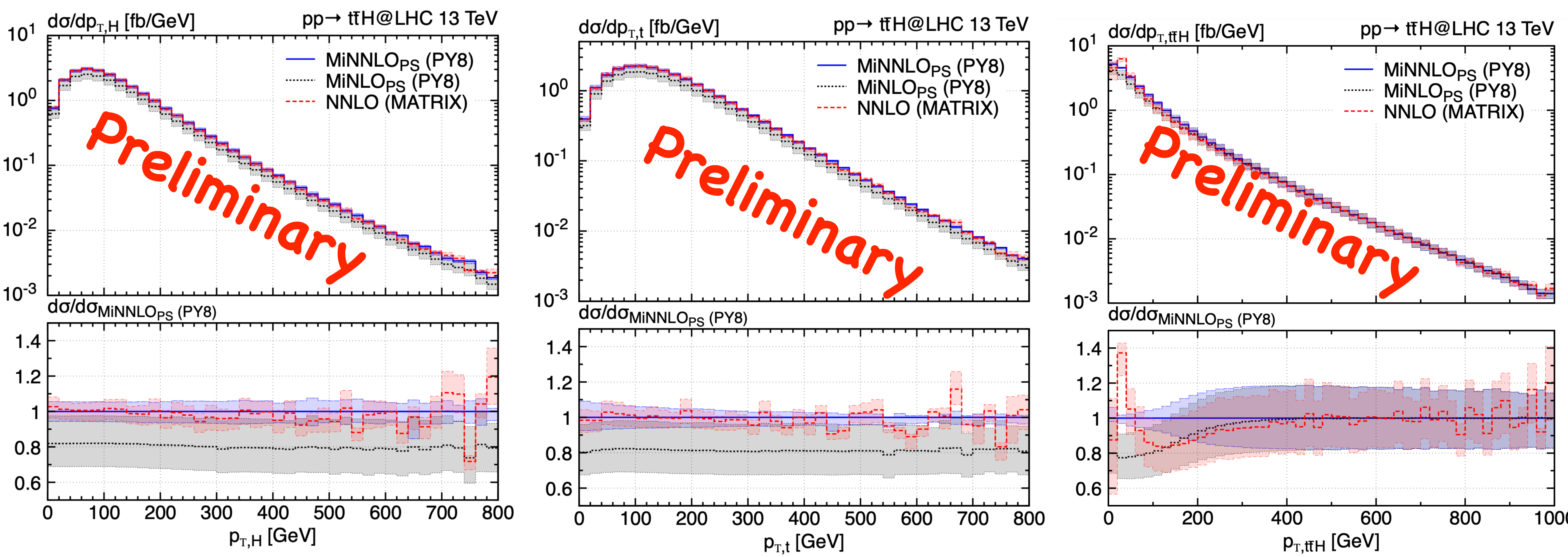
Ebert, Rottoli, Wiesemann, GZ, Zanoli in preparation

MiNNLOPS: ttH

Recent approx. NNLO calculation of ttH can be used to build a MiNNLOPS ttH generator

Catani et al 2210.04846

<u>Preliminary results:</u>



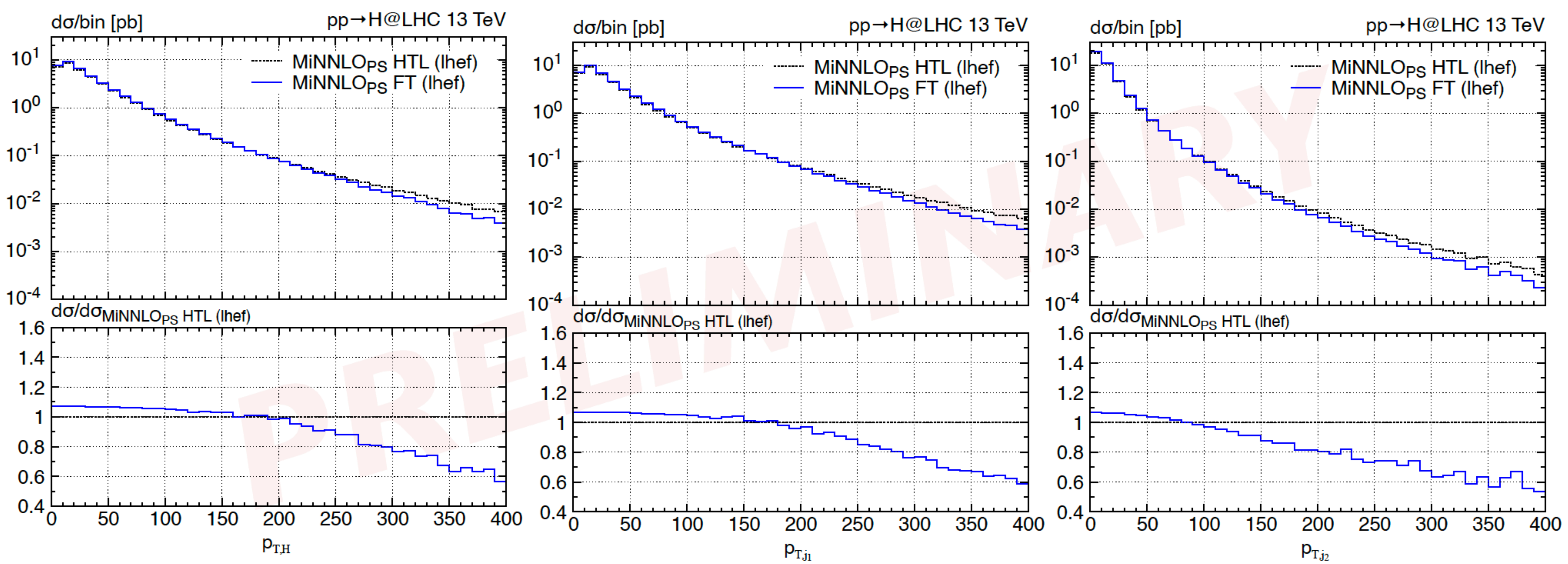
Mazzitelli, Wiesemann in preparation

MiNNLOPS: ggH in FT

Recent progress in NNLO calculation in full theory (i.e. beyond large m_t) paves the easy for a MiNNLOPS generator for ggH in full theory

Czakon, Harlander, Klappert, Nieggetiedt '20

Heavy Top Loop (HTL) vs Full Theory (FT) results



Czakon, Harlander, Nieggetiedt, Wiesemann in preparation

Also in progress MiNNLOPS for bb → H production

Biello, Sankar, Wiesemann, GZ in preparation

Conclusions

<u>Considerable process in MiNNLOPS in the last years:</u>

- Colour singlet processes done in MiNNLOPS ($2 \to 1$ and $2 \to 2$)
- MiNNLOPS for Heavy-flavour $Q\bar{Q}$ also available
- Public codes available in the POWHEG BOX, or upon request

<u>Future: many extensions ongoing/planned</u>

- QCD MiNNLOPS × MiNLO EW
- X+jet (HJ, ZJ, …)
- $2 \to 3$ colour singlet
- $Q\bar{Q}$+X (ttH, bbH, ttZ, ttZ, bbZ, …)
- MiNNLOPS for VBF processes