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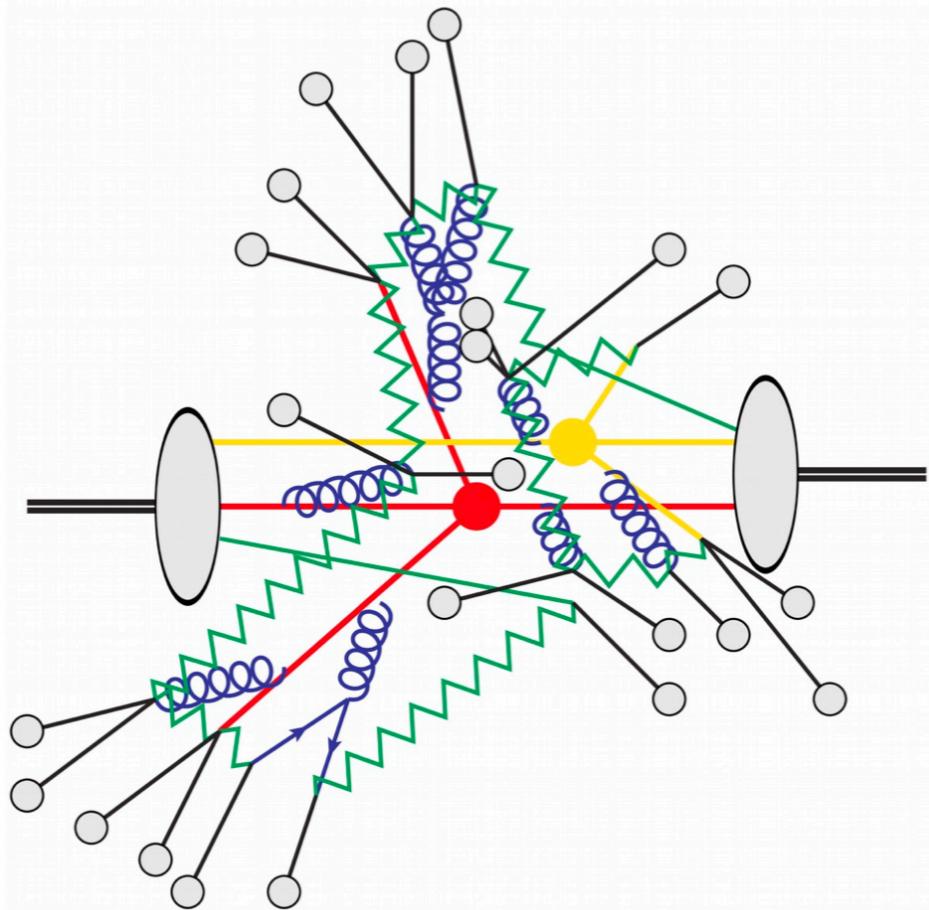


Alessandro Ratti

Heavy quark pair production at NNLO matched to Parton Shower

In collaboration with
J.Mazzitelli, M.Wiesemann, G.Zanderighi

Introduction



In this talk:

Analysis of MC generated events in proton-proton scatterings involving a pair of heavy quarks ($Q = t, b$) in the final state

$$pp \rightarrow t\bar{t} + X$$

[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi
JHEP 05 (2022) 079]

$$pp \rightarrow b\bar{b} + X$$

[Mazzitelli, A.R., Wiesemann, Zanderighi
arXiv:2302.01645v1]

NEW!

Implementation:

- Hard scattering matched to PS in POWHEG with MiNNLOps [Monni, Nason, Re, Wiesemann, Zanderighi JHEP 05 (2020) 143]
[Frixione, Nason, Oleari JHEP 11 (2007) 070]
- Tree level and 1 loop amplitudes ($Q\bar{Q} + j$ and $Q\bar{Q} + jj$) provided by OpenLoops2 [Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller Eur.Phys.J.C 79 (2019) 10, 866]
JHEP 12 (2012) 054, [1207.0236]
JHEP 01 (2013) 080, [1210.6832]
Phys. Rev. Lett. 116 (2016) 082003
- Two loop $gg \rightarrow Q\bar{Q}$ and $q\bar{q} \rightarrow Q\bar{Q}$ evaluated by grid interpolation
- PS and Hadronisation carried out by PYTHIA8 (Monash 2013 tune)

NNLO+PS event generation with MiNNLOps

POWHEG

One possible way to **match NLO hard events to Parton shower**

1. Generate a n particle configuration using $\bar{B}(\Phi_n)$
2. Generate first hardest radiation at NLO accuracy ($\Delta_{pwg}, R/B$)
3. Generate subsequent splittings at lower p_T using parton shower

$$\frac{d\sigma}{d\Phi_n} = \bar{B}(\Phi_n) \left[\Delta_{pwg}(p_T^{min}) + \frac{R(\Phi_n, \phi_{rad})}{B(\Phi_n)} \Delta_{pwg}(p_T) d\phi_{rad} \right]$$

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\phi_{rad} R(\Phi_{n+1})$$

$$\Delta_{pwg} \sim \exp(- \int d\phi_{rad} R/B)$$

MiNLO'

First implemented for color singlet + jet production (FJ).

Question: Can we **merge** the Powheg $F + J$ and F generators at NLO?

Answer: yes, if we properly modify $\bar{B}(\Phi_{FJ})$ beyond α_s (relative to B)

$$\bar{B}(\Phi_{FJ}) = e^{-\tilde{S}(p_T)} \left\{ B(\Phi_{FJ}) \left(1 + \frac{\alpha_s(p_T)}{2\pi} \tilde{S}^{(1)}(p_T) \right) + V(\Phi_{FJ}) \right\} + \int d\phi_{rad} e^{-\tilde{S}(p_T^{\text{rad}})} R(\Phi_{FJJ})$$

Where **Sudakov** form factor suppresses low color singlet p_T regions and **scales** are set to the p_T of F.



- NLO accuracy preserved for FJ **inclusive** observables
- NLO accuracy extended to F **inclusive** observables

NNLO+PS event generation with MiNNLOps

MiNNLOps

How can we modify again $\bar{B}(\Phi_{FJ})$ to get **NNLO** accuracy for $pp \rightarrow F$ inclusive observables?

We can look at the **resummation** formula in p_T :

$$\begin{aligned}
 & \text{summation} \quad \frac{d\sigma}{d\Phi_F dp_T} = \underbrace{\frac{d}{dp_T} \left\{ e^{-\tilde{S}(p_T)} L \right\}}_{\text{div.}} + \underbrace{R_f(p_T)}_{\text{fin.}}
 \end{aligned}$$

We can expand this formula into all the terms necessary to get **NNLO accuracy** for $d\sigma/d\Phi_E$, and plug them into the Powheg \bar{B} function. The result is:

$$\tilde{B}(\Phi_{FJ}) = \boxed{e^{-\tilde{S}(p_T)} \left[B(\Phi_{FJ}) \left(1 + \frac{\alpha_s(p_T)}{2\pi} \tilde{S}^{(1)} \right) + V(\Phi_{FJ}) + \int d\phi_{\text{rad}} R(\Phi_{FJJ}) \right]} + \boxed{D^{(\geq 3)}(\Phi_F, p_T) F^{(\text{corr.})}(\Phi_{FJ})}$$

First introduced for color singlet production, recently extended to **quark pair production**:

1. **Color algebra** accounted in the resummation formula
 2. Both gg **and** $q\bar{q}$ channels in the initial state (\tilde{S}_{gg} and $\tilde{S}_{q\bar{q}}$)
 3. Soft gluon exchanges between **final legs** and between **final and initial legs**

Top pair production

Motivations

- Top pair production is the **main source** of top quarks at LHC
- Important QCD test and for determination of top features
- $t\bar{t}$ is a background of some **SM** processes (e.g. tW)
- relevant background in **BSM** searches (e.g. H^\pm)

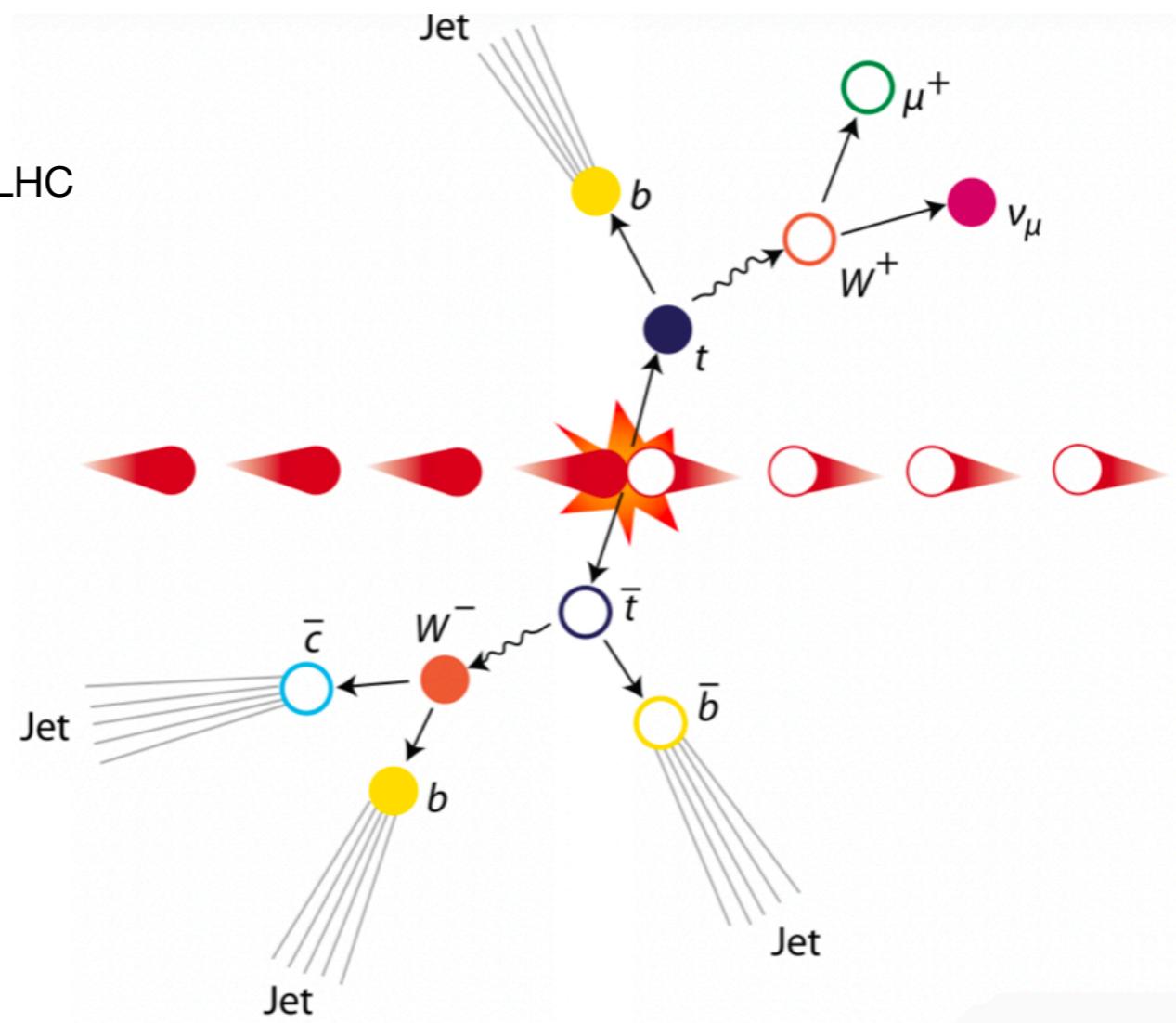
$$t\bar{t} \rightarrow b\bar{b} W^-W^+$$

Fully leptonic $W^+W^- \rightarrow l\bar{\nu}_l \bar{l}\nu_l$

Semi-leptonic $W^+W^- \rightarrow l\bar{\nu}_l q\bar{q}'$

Hadronic $W^+W^- \rightarrow q\bar{q}'q'\bar{q}$

(where $q = \{u, c\}$ and $q' = \{d, s\}$)



In the last few years

- **Top pair production at NNLO** (narrow-width approximation for the double-resonant channel)

[Czakon, Mitov '12], [Czakon, Fiedler, Mitov '13] [Czakon, Fiedler, Heymes, Mitov '15 '16]

[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19] [Catani, Devoto, Grazzini, Kallweit, Mazzitelli '19]

- **NLO+PS** (exact inclusion of off-shell and spin correlation effects)

[R. Frederix and S. Frixione '12] [S. Hoeche, F. Krauss, P. Maierhoefer, S. Pozzorini, M. Schonherr and F. Siegert '15] [K.

Cormier, S. Plätzer, C. Reuschle, P. Richardson and S. Webster '19] [T. Ježo and P. Nason '15] [T. Ježo, J. M. Lindert, P. Nason,

C. Oleari and S. Pozzorini '16] [R. Frederix, S. Frixione, A. S. Papanastasiou, S. Prestel and P. Torrielli '16] [S. Frixione, E.

Laenen, P. Motylinski and B. R. Webber '07]

Top pair production

[Mazzitelli, Monni, Nason, Re,
Wiesemann, Zanderighi JHEP
05 (2022) 079]

With MiNNLOps in POWHEG,
first NNLO+PS event generator for $pp \rightarrow t\bar{t} + X$

Results have been **validated** against fixed order predictions (13TeV)

MiNLO'	NNLO	MiNNLO _{PS}
$572.9(2)^{+21\%}_{-17\%}$ pb	$719.1(8)^{+7.0\%}_{-7.6\%}$ pb	$719.8(2)^{+7.6\%}_{-7.4\%}$ pb

- Uncertainty bands evaluated through standard **7-point scale variation** on μ_R and μ_F
- NNLO and MiNNLOps results are fully **compatible**
- MiNNLOps **uncertainty bands** remarkably smaller than MiNLO' ones

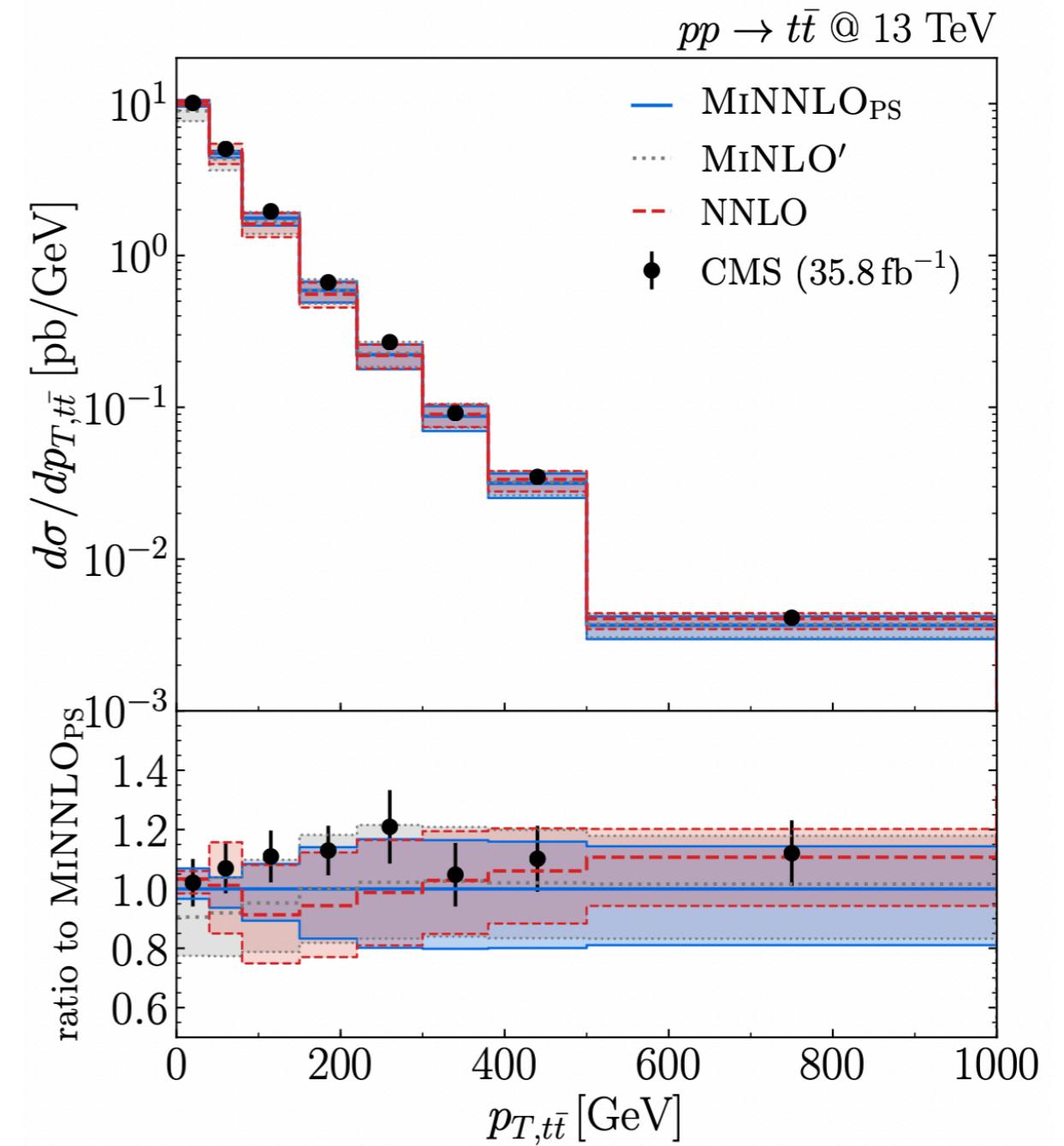
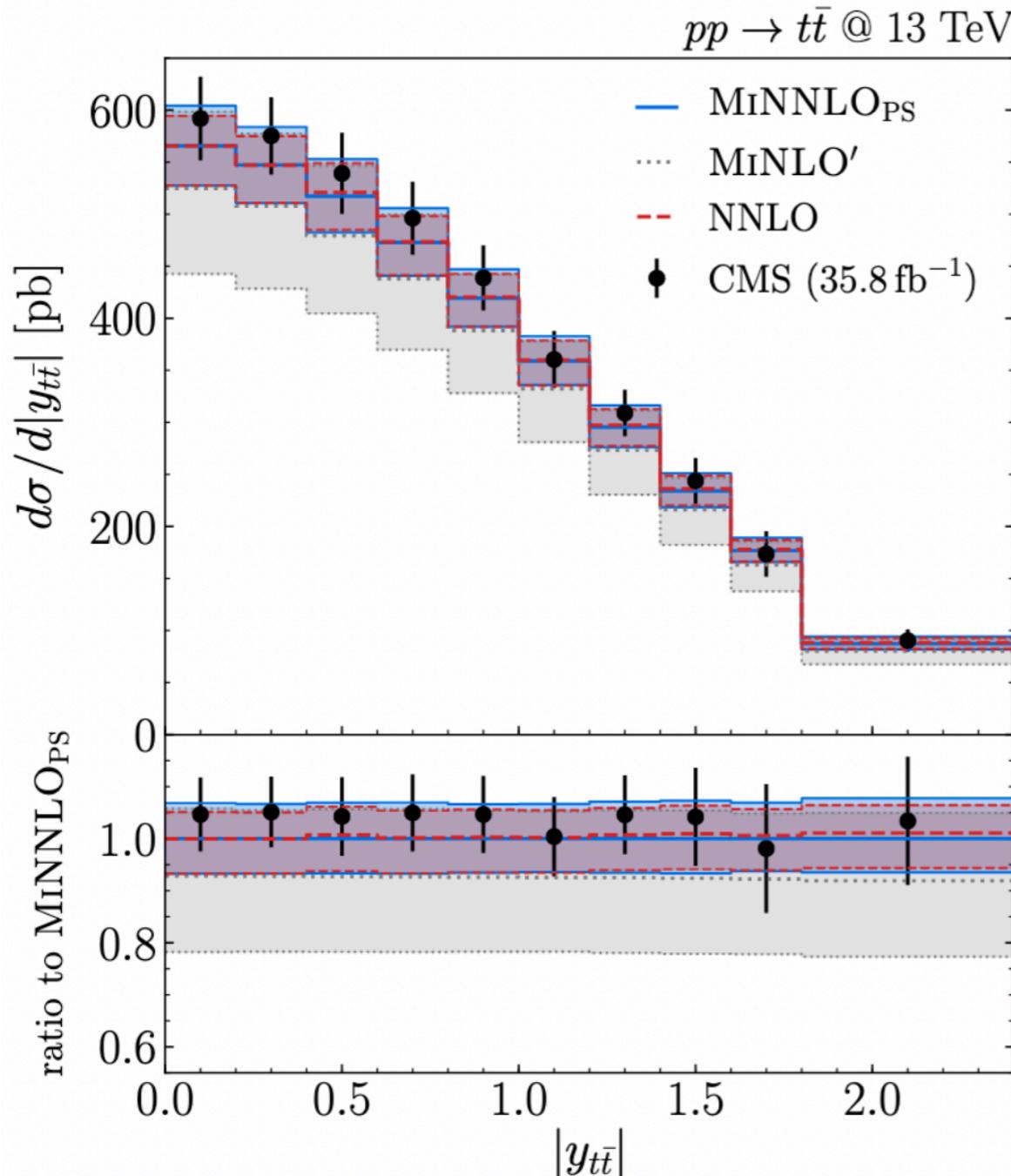
Phenomenological analysis:

1. Off-shell effects for the **double resonant** decay channel only included at **LO**
[As implemented in POWHEG $t\bar{t} + j$, Alioli, Moch, Uwer 1110.5251]
2. Data from CMS extrapolated on the **inclusive $t\bar{t}$ phase space**
3. Data from ATLAS and CMS for various **decay channels**

Top pair production

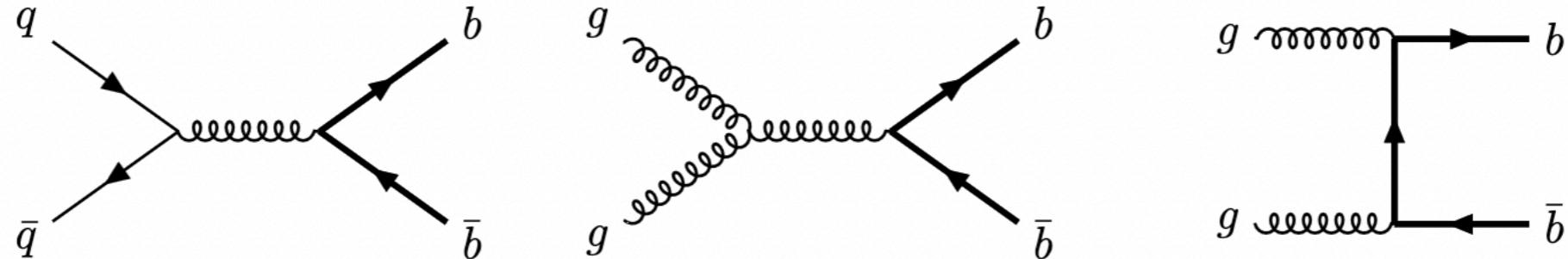
Comparison with data from CMS

$t\bar{t}$ inclusive distributions at 13TeV



Bottom pair production

[Mazzitelli, A.R.,
Wiesemann, Zanderighi
arXiv:2302.01645v1]



- Most relevant channel for **inclusive B hadron production** at LHC: $pp \rightarrow b\bar{b} + X \rightarrow B + X$
- **Slow convergence** of perturbative series due to high values of $\alpha_s(m_b) \sim 0.2$
- Fixed order results affected by **rather big scale uncertainties** ($\sim \pm 15\%$ for σ_{NNLO})
- **NNLO fixed order** differential results recently available [Catani, Devoto, Grazzini, Kallweit, Mazzitelli '21]

New NNLO+PS implementation
with MiNNLOps in POWHEG

(4 flavour scheme)

Validation against fixed order results from MATRIX

NLO	MiNLO'	NNLO	MiNNLOps
$348.5(3)^{+27\%}_{-24\%} \mu b$	$399.7(5)^{+22\%}_{-21\%} \mu b$	$435(2)^{+16\%}_{-15\%} \mu b$	$428.7(5)^{+13\%}_{-11\%} \mu b$

Bottom pair production

Comparison to fiducial cross sections from CMS, ATLAS, LHCb

Analysis	Energy	Process	Measured cross section (μb)	MINNLO _{PS} (μb)
ATLAS	7 TeV	$pp \rightarrow B^+ + X$	$10.6 \pm 0.3_{\text{(stat)}} \pm 0.7_{\text{(syst)}} \pm 0.2_{\text{(lumi)}} \pm 0.4_{\text{(bf)}}$	$10.17(5)^{+13.3\%}_{-14.0\%}$
CMS	13 TeV	$pp \rightarrow B^+ + X$	$15.3 \pm 0.4_{\text{(stat)}} \pm 2.1_{\text{(syst)}} \pm 0.4_{\text{(lumi)}}$	$11.47(6)^{+11.3\%}_{-13.2\%}$
LHCb-1	7 TeV	$pp \rightarrow B^\pm + X$	$38.9 \pm 0.3_{\text{(stat)}} \pm 2.5_{\text{(syst)}} \pm 1.3_{\text{(bf)}}$	$42.2(1)^{+13.9\%}_{-11.4\%}$
		$pp \rightarrow B^0 + X$	$38.1 \pm 0.6_{\text{(stat)}} \pm 3.7_{\text{(syst)}} \pm 4.7_{\text{(bf)}}$	$42.3(1)^{+14.7\%}_{-11.3\%}$
		$pp \rightarrow B_s^0 + X$	$10.5 \pm 0.2_{\text{(stat)}} \pm 0.8_{\text{(syst)}} \pm 1.0_{\text{(bf)}}$	$9.32(6)^{+13.6\%}_{-11.5\%}$
LHCb-2	7 TeV	$pp \rightarrow B^\pm + X$	$43.0 \pm 0.2_{\text{(syst)}} \pm 2.5_{\text{(stat)}} \pm 1.7_{\text{(bf)}}$	$42.2(1)^{+13.9\%}_{-11.4\%}$
	13 TeV	$pp \rightarrow B^\pm + X$	$86.6 \pm 0.5_{\text{(stat)}} \pm 5.4_{\text{(syst)}} \pm 3.4_{\text{(bf)}}$	$78.5(3)^{+9.0\%}_{-9.3\%}$
LHCb-3	7 TeV	$pp \rightarrow B + X$	$72.0 \pm 0.3_{\text{(stat)}} \pm 6.8_{\text{(syst)}}$	$65.3(1)^{+12.6\%}_{-10.5\%}$
	13 TeV	$pp \rightarrow B + X$	$144 \pm 1_{\text{(stat)}} \pm 21_{\text{(syst)}}$	$116.2(3)^{+7.6\%}_{-12.3\%}$

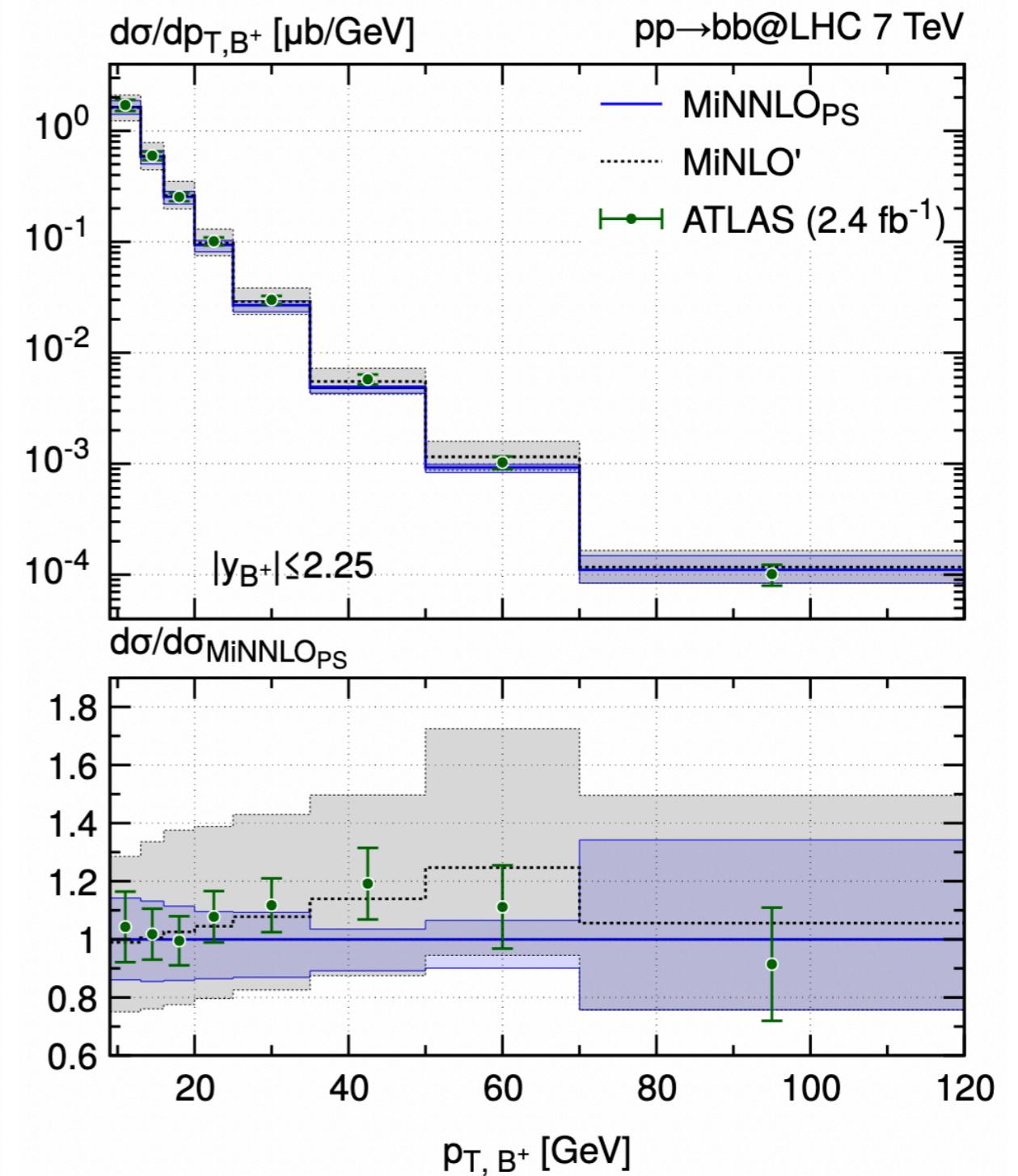
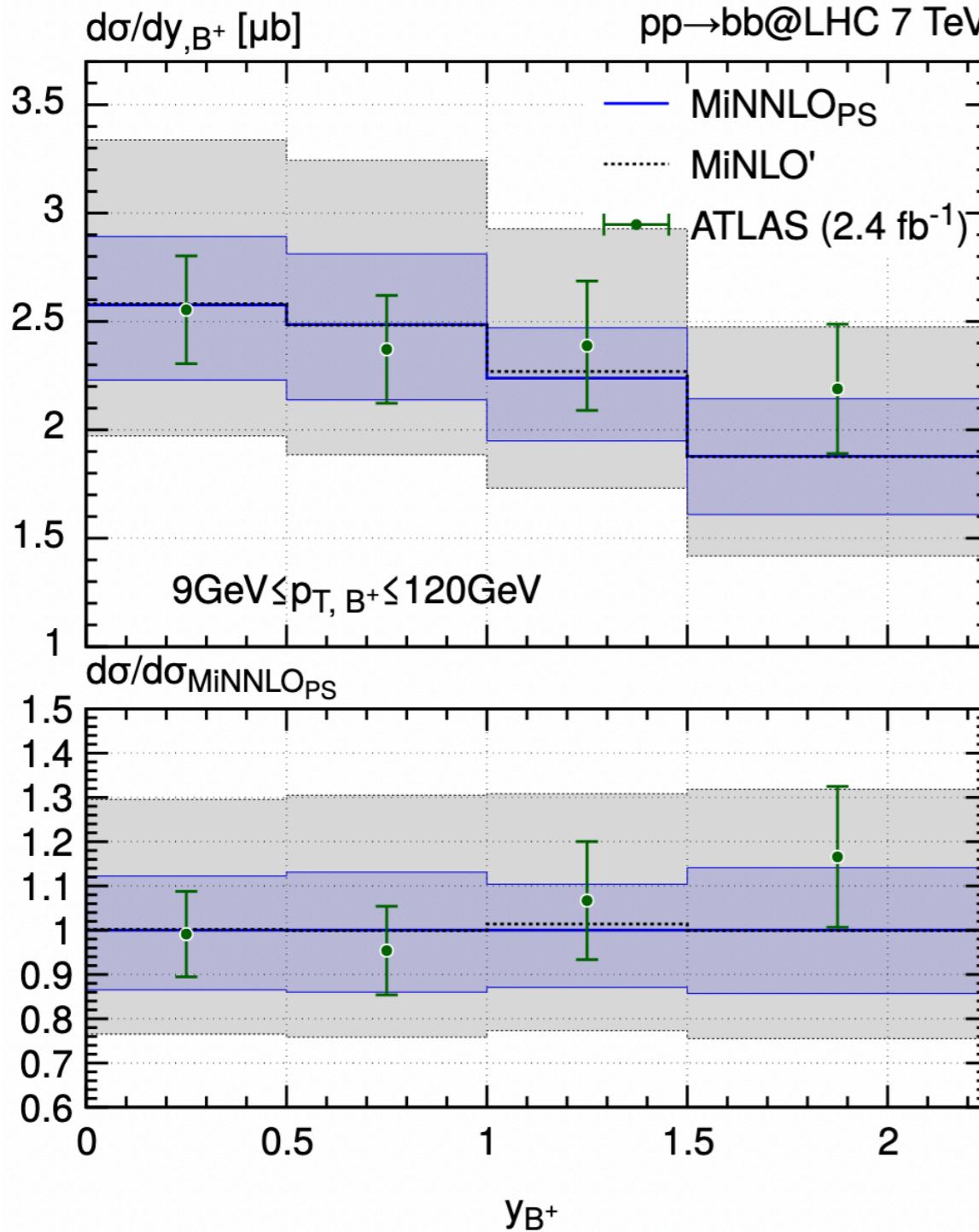
- ATLAS [G. Aad et al. (ATLAS), JHEP 10, 042 (2013)]
- CMS [V. Khachatryan et al. (CMS), Phys. Lett. B 771, 435 (2017)]
- LHCb-1 [R. Aaij et al. (LHCb), JHEP 08, 117 (2013)]
- LHCb-2 [R. Aaij et al. (LHCb), JHEP 12, 026 (2017)]
- LHCb-3 [R. Aaij et al. (LHCb), Phys. Rev. Lett. 118, 052002 (2017), [Erratum: Phys. Rev. Lett. 119, 169901 (2017)]]

Bottom pair production

Comparison with data from ATLAS

[G. Aad et al. (ATLAS),
JHEP 10, 042 (2013)]

B^+ hadron inclusive distributions at 7TeV

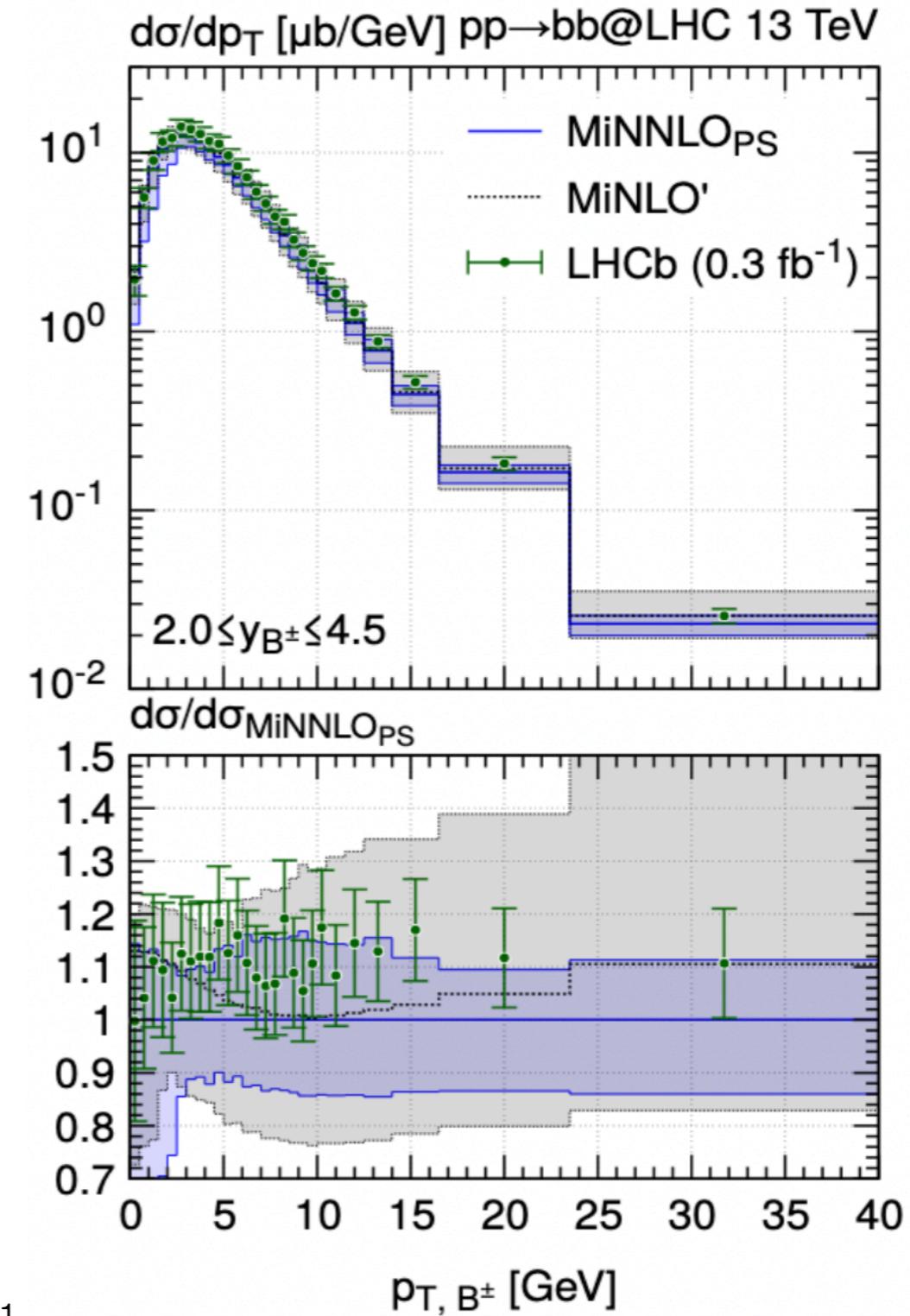
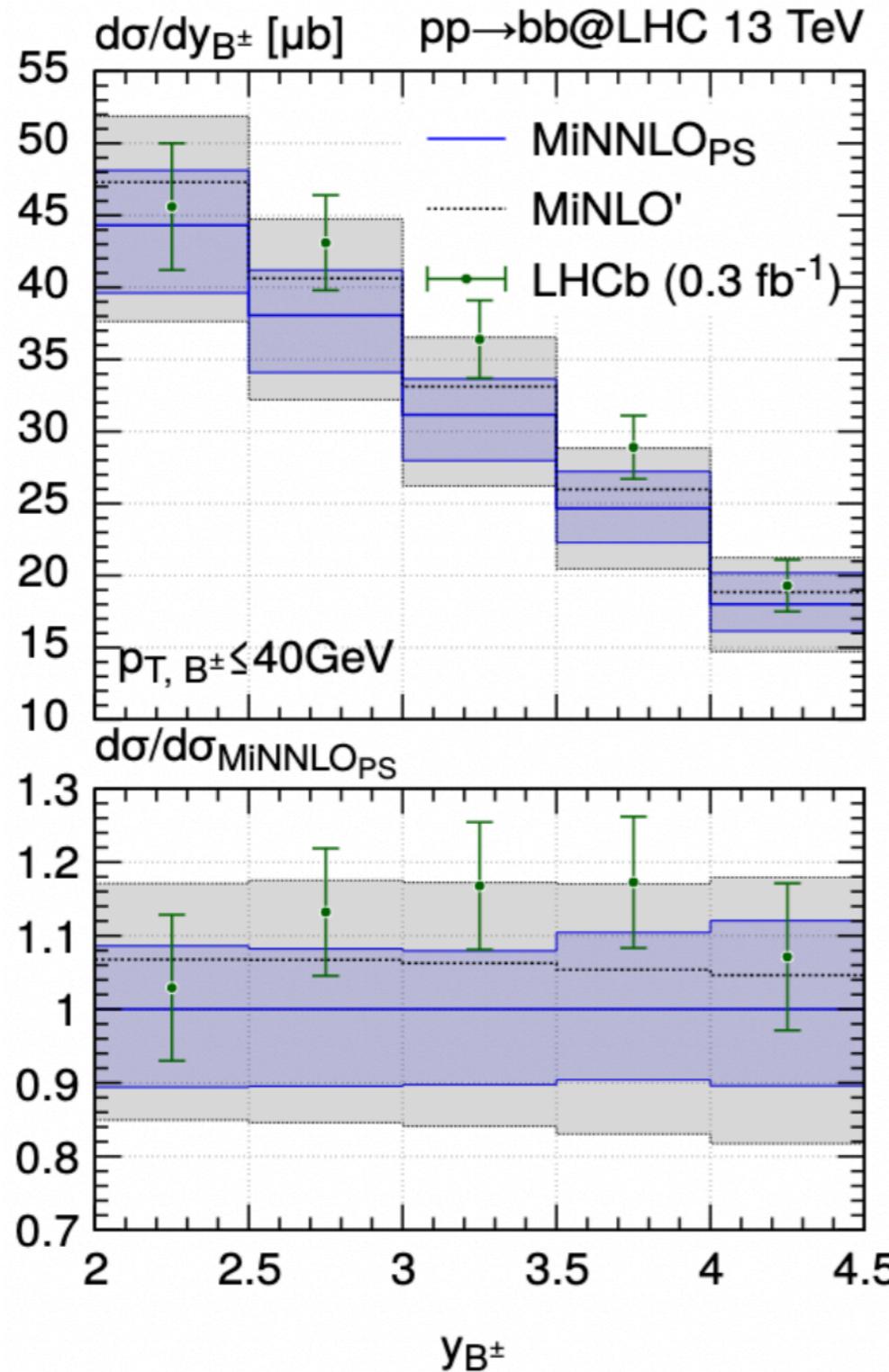


Bottom pair production

Comparison with data from LHCb

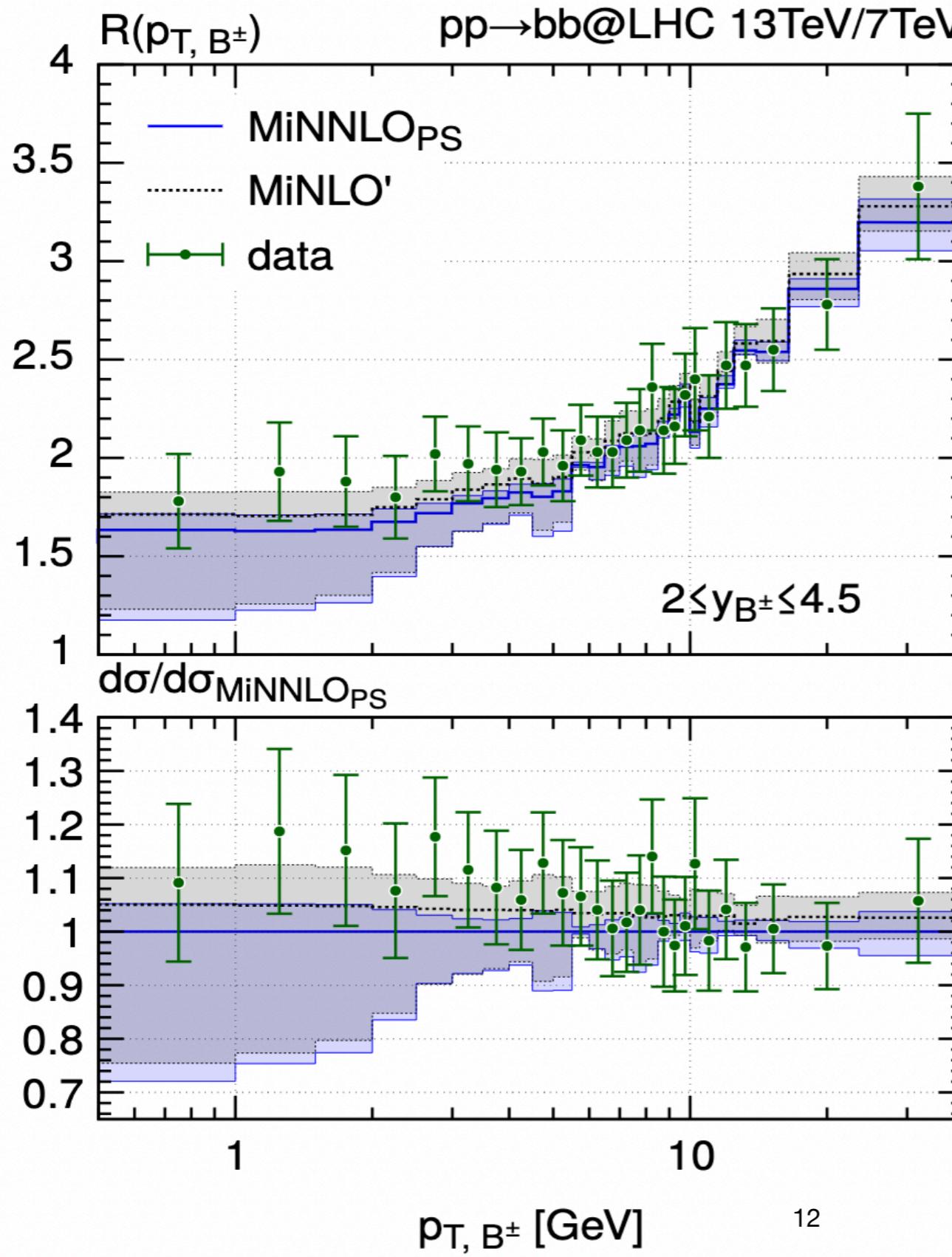
[R. Aaij et al.
(LHCb), JHEP 12,
026 (2017)]

B^+ and B^- inclusive distributions at 13TeV



Bottom pair production

Comparison with data from LHCb



Ratio of rapidity distributions
for 13TeV and 7TeV c.o.m. energy.
Inclusive over B^+ and B^-

$$R(p_{T,B^\pm}) = \frac{\frac{d\sigma}{dp_{T,B^\pm}}(13\text{TeV})}{\frac{d\sigma}{dp_{T,B^\pm}}(7\text{TeV})}$$

[R. Aaij et al.
(LHCb), JHEP 12,
026 (2017)]

Conclusions

Summary

- We reviewed the basic features of **POWHEG** and **MiNNLOps**
- We showed some results for **top pair production** at 13TeV, $t\bar{t}$ inclusive distributions
- We presented the recent results for B hadron distributions from **bottom pair events**

What's next?

- **b-jet analysis** on bottom pair production events
- Implementation of **charm pair production** with MiNNLOps
- Exploiting MiNNLOps implementation of bottom and charm pair production in the analysis of the **prompt atmospheric neutrino flux**

Thank you!

Backup

MiNNLO_{PS} method for color singlet production

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d}{dp_T} \left\{ e^{-\tilde{S}(p_T)} L \right\} + R_f(p_T)$$

$$\frac{d\sigma}{d\Phi_F dp_T} = \underbrace{e^{-\tilde{S}(p_T)} D(p_T)}_{\text{div}} + \underbrace{R_f(p_T)}_{\text{fin}}$$

We end up with:

$$\begin{aligned} \frac{d\sigma}{d\Phi_F dp_T} &= \exp[-\tilde{S}(p_T)] \left\{ \frac{\alpha_s(p_T)}{2\pi} \left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T} \right]^{(1)} \left(1 + \frac{\alpha_s(p_T)}{2\pi} [\tilde{S}(p_T)]^{(1)} \right) \right. \\ &\quad \left. + \left(\frac{\alpha_s(p_T)}{2\pi} \right)^2 \left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T} \right]^{(2)} + \left(\frac{\alpha_s(p_T)}{2\pi} \right)^3 [D(p_T)]^{(3)} + \text{regular terms} \right\} \end{aligned}$$

We expand the right-hand side so to get $O(\alpha_s^2)$ after integration over dp_T

$$\begin{aligned} \tilde{B}(\Phi_{FJ}, \Phi_{rad}) &= \exp[-\tilde{S}(\Phi_F, p_T)] \left[B(\Phi_{FJ}) \left(1 + \frac{\alpha_s(p_T)}{2\pi} [\tilde{S}(\Phi_F, p_T)]^{(1)} \right) + V(\Phi_{FJ}) \right. \\ &\quad \left. + R(\Phi_{FJ}, \Phi_{rad}) + D^{(\geq 3)}(\Phi_F, p_T) F^{\text{corr}}(\Phi_{FJ}) \right], \end{aligned}$$

MiNNLOps master formula

- $R_f(p_T)$: it's regular, we can just expand it up to $O(\alpha_s^2)$

$$R_f(p_T) = \frac{d\sigma}{d\Phi_F dp_T} - e^{-\tilde{S}} D \rightarrow \alpha_s \left(\frac{d\sigma}{d\Phi_F dp_T} \right)^{(1)} + \alpha_s^2 \left(\frac{d\sigma}{d\Phi_F dp_T} \right)^{(2)} + e^{-\tilde{S}} \left[\alpha_s D^{(1)} + \alpha_s^2 D^{(2)} \right]$$

- $e^{-\tilde{S}} D$ more subtle: not straightforward achieving $O(\alpha_s^2)$ after integration over p_T (divergent terms), but we can notice that:

$$\int_{\Lambda}^Q dp_T \alpha_s^M(p_T) \frac{1}{p_T} \ln^n \frac{Q}{p_T} e^{-\tilde{S}(p_T)} \approx O\left(\alpha_s^{m-\frac{n+1}{2}}(Q)\right)$$

	MiNLO'	MiNNLO _{PS}
F	NLO	NNLO
F+J	NLO	NLO

Monni P., Nason P., Re E.,
Wiesemann M., Zanderighi G.
(2019)

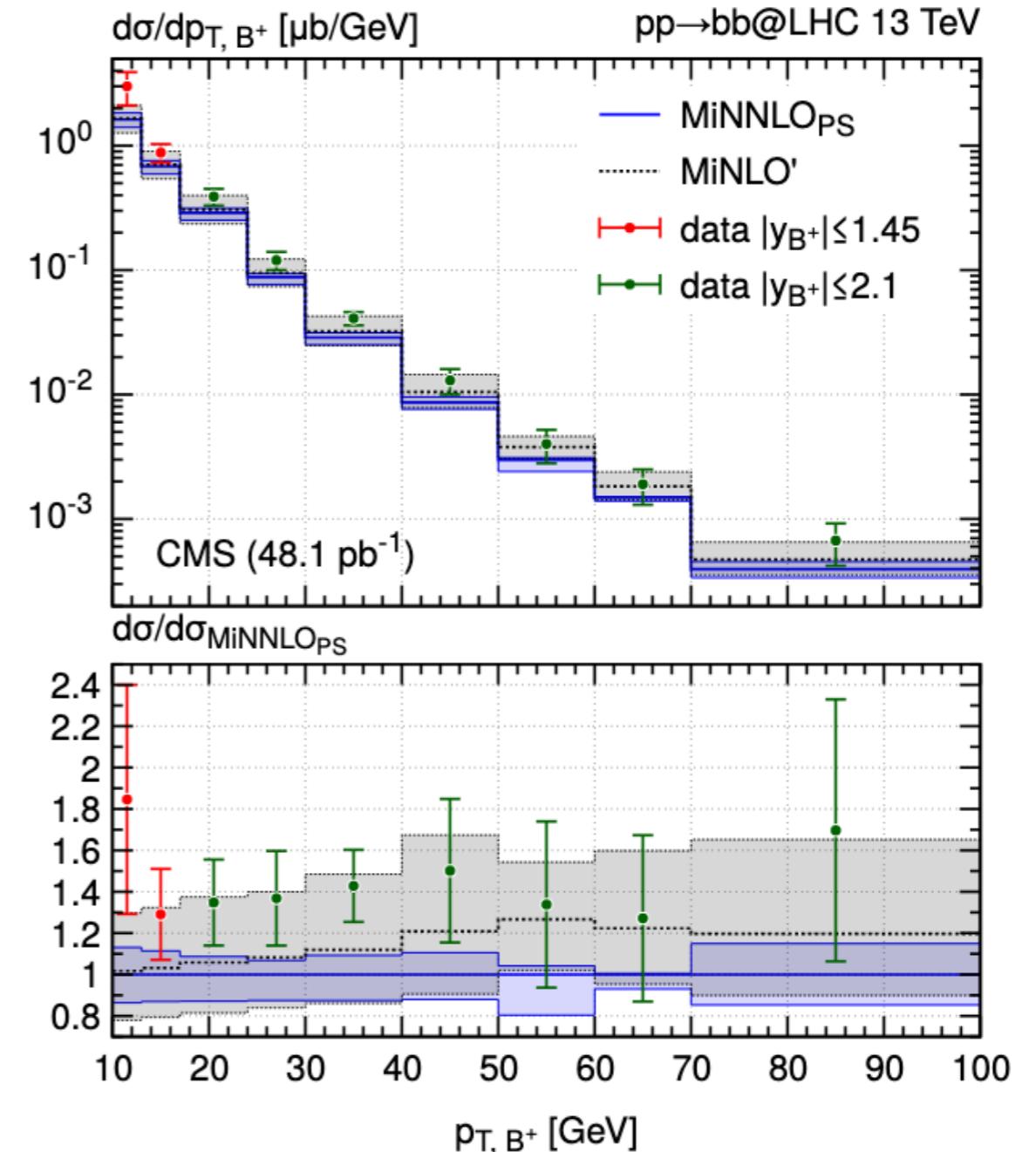
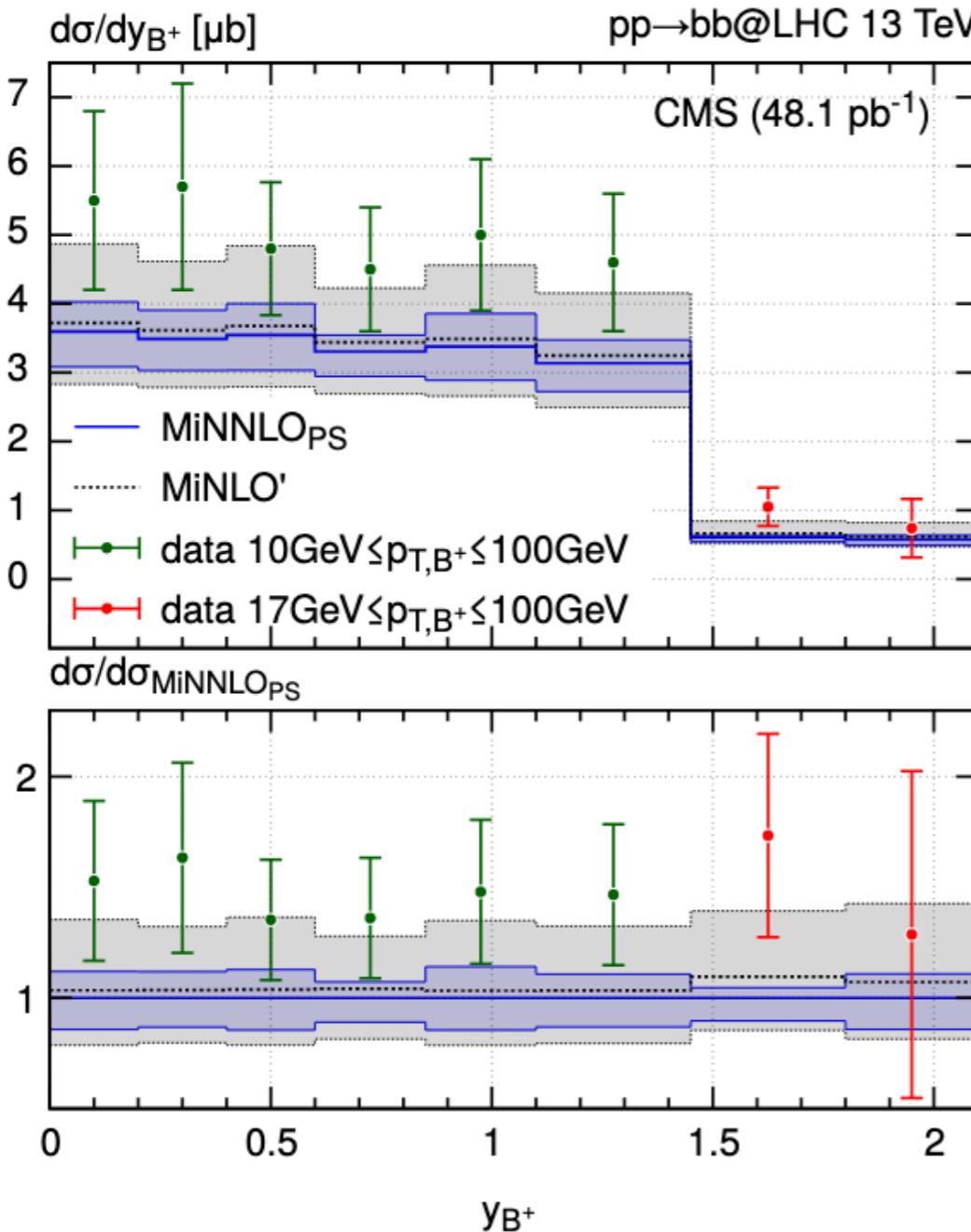
$b\bar{b}J$ generator: settings

- **Four-flavour scheme**
- **Pole mass** of bottom quarks set to $m_b = 4.92 \text{ GeV}$
- PDF choice: **NNPDF31_nnlo_as_0118_nf_4**
- For the factorization and renormalization scales entering the MiNNLOps formula, we tested m_{bb} , $m_{bb}/2$, $H_t/2$ and $H_t/4$ (where $H_T = \sqrt{m_b^2 + p_{T,b}^2} + (b \rightarrow \bar{b})$)
- OpenLoops2 for **tree level and 1-loop contributions**, and evaluated the genuinely **2-loops contributions** by grid interpolation

$pp \rightarrow Q\bar{Q}$	$A_{Q\bar{Q}} = A_{Q\bar{Q}}^{(tree)} + g_s A_{Q\bar{Q}}^{(1-loop)} + g_s^2 A_{Q\bar{Q}}^{(2-loops)} + \dots$
$pp \rightarrow Q\bar{Q} + J$	$A_{Q\bar{Q}J} = g_s A_{Q\bar{Q}J}^{(tree)} + g_s^2 A_{Q\bar{Q}J}^{(1-loop)} + \dots$
$pp \rightarrow Q\bar{Q} + JJ$	$A_{Q\bar{Q}JJ} = g_s^2 A_{Q\bar{Q}JJ}^{(tree)} + \dots$

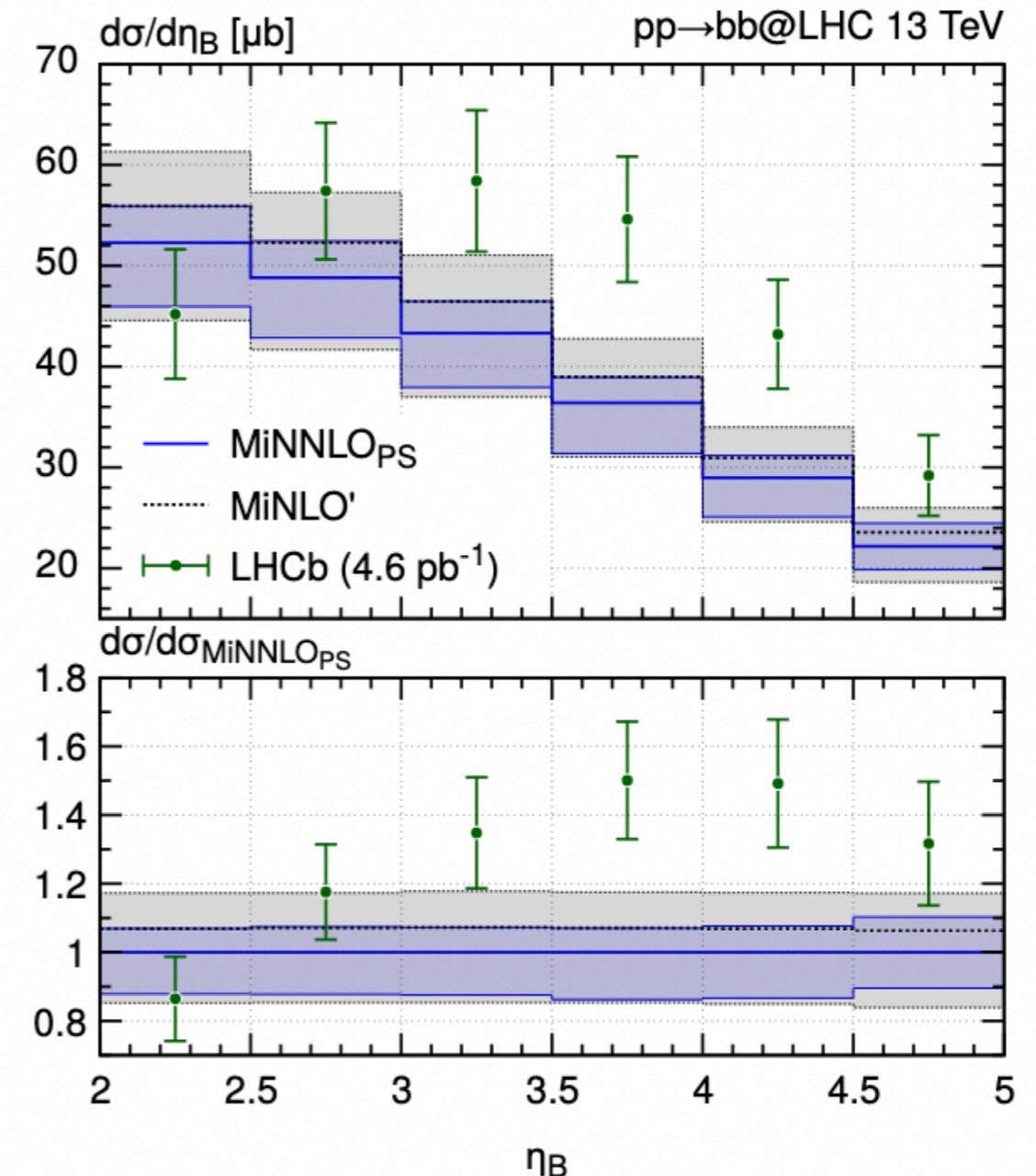
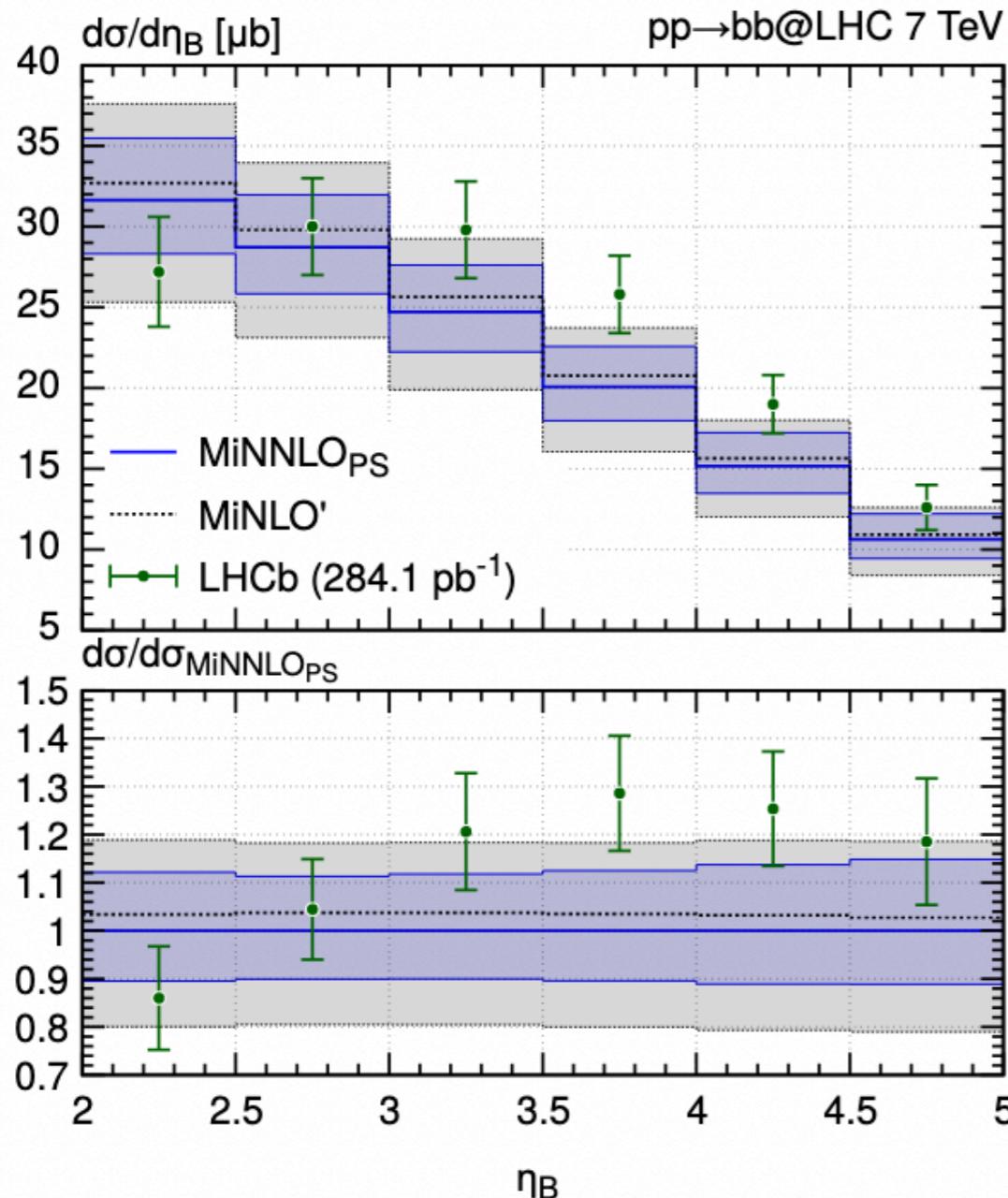
Bottom pair production

Comparison with data from CMS



Bottom pair production

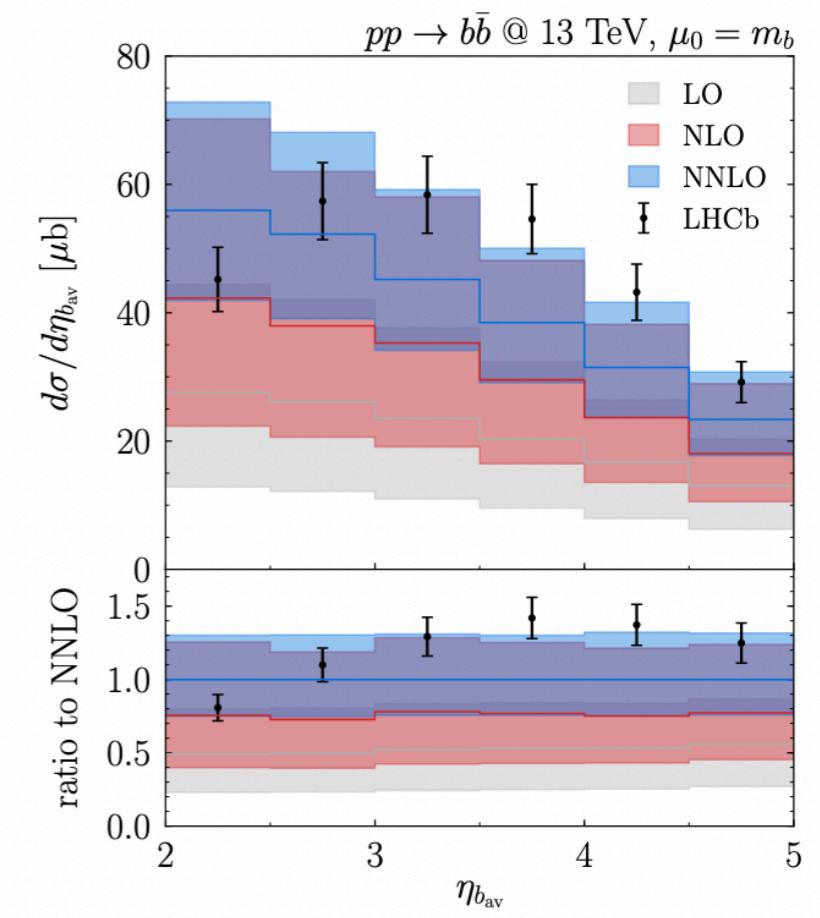
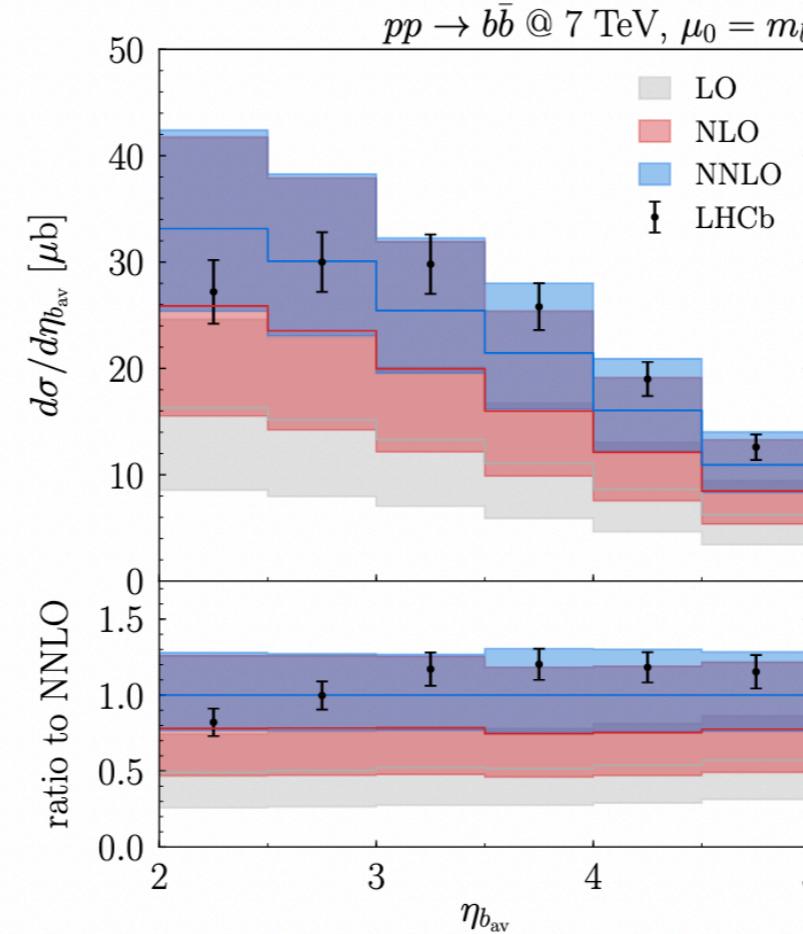
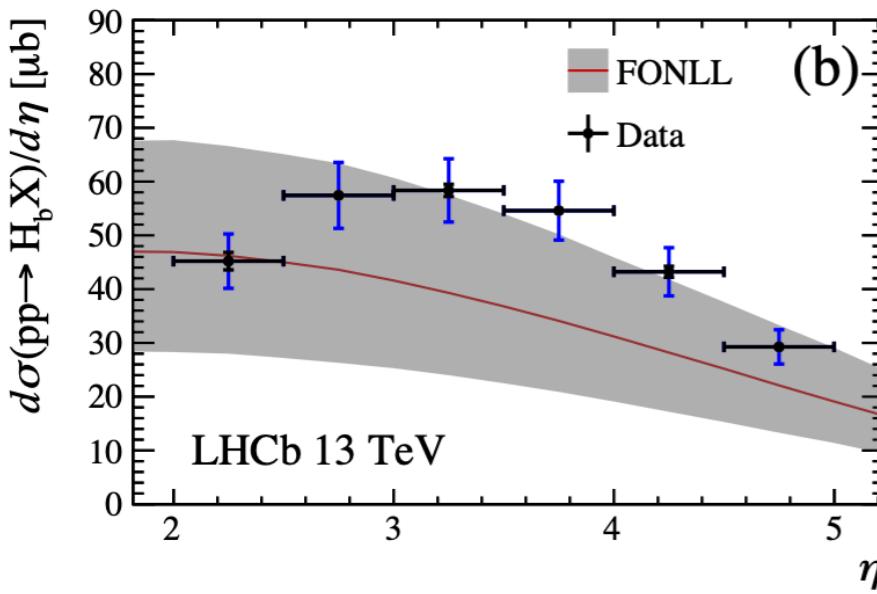
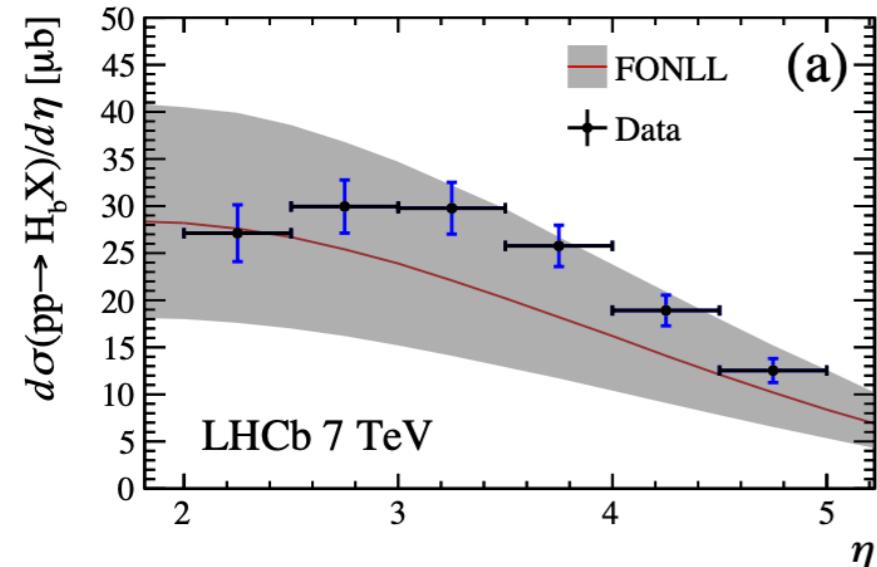
Comparison with data from LHCb



Bottom pair production

Pseudorapidity distributions from LHCb

$$\begin{aligned}\sigma(pp \rightarrow H_b X) = & \frac{1}{2} [\sigma(B^0) + \sigma(\bar{B}^0)] + \frac{1}{2} [\sigma(B^+) + \sigma(B^-)] \\ & + \frac{1}{2} [\sigma(B_s^0) + \sigma(\bar{B}_s^0)] + \frac{1+\delta}{2} [\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)]\end{aligned}$$



Bottom pair production

Ratio of differential distributions

