MAX-PLANCK-INSTITUT
FÜR PHYSIK

Alessandro Ratti

# NNLO predictions for bottom quark pair production in MiNNLO$_{\text{PS}}$

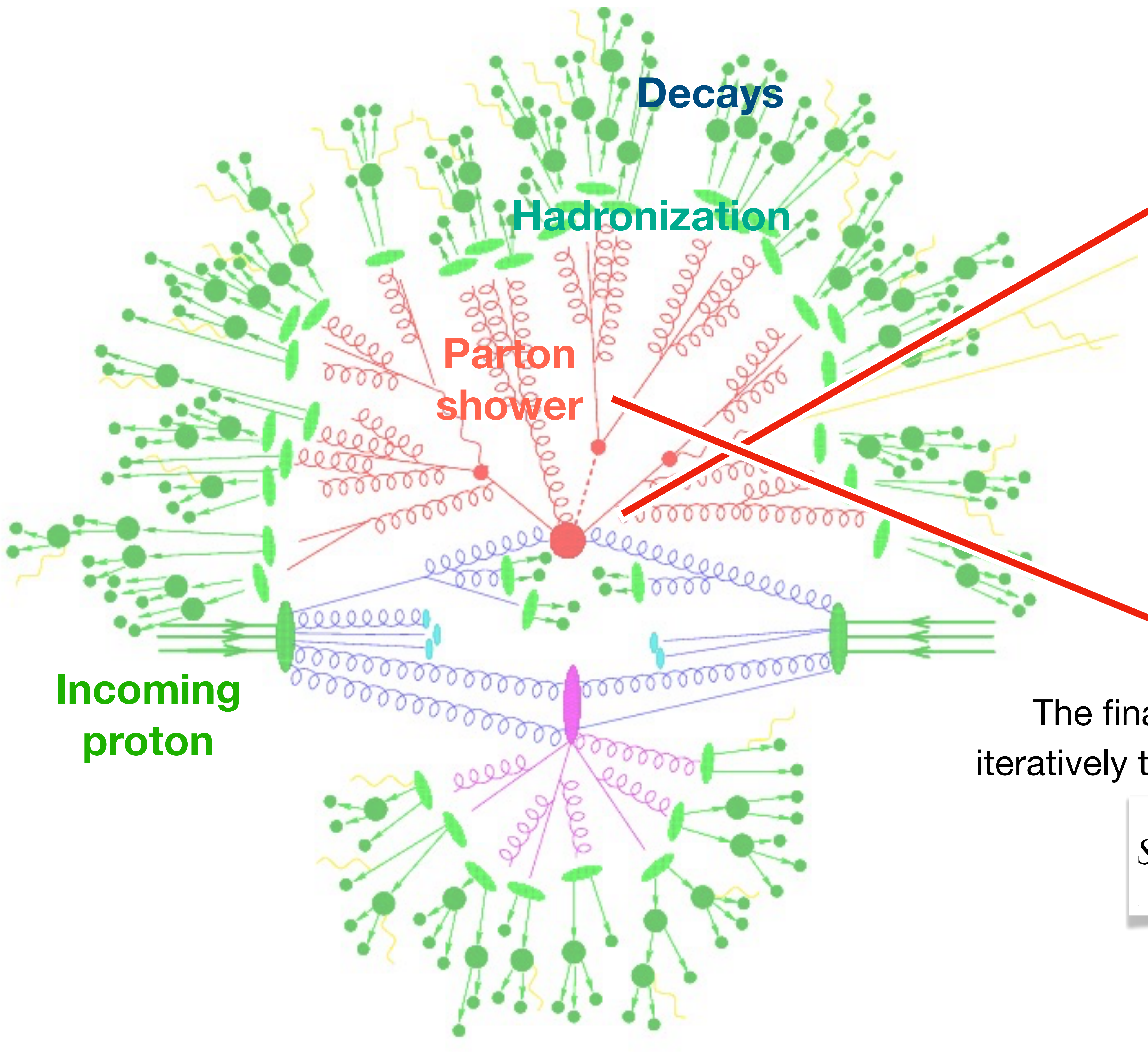
***Workshop on Tools for High Precision LHC Simulations***
*Schloss Ringberg, November 1st 2022*

# Outlook

- **Event generation with MiNNLOps**

- **Motivations and status**
  - Gluon PDFs constraints through the analysis ratio of rapidity distributions
  - Some experimental results
  - NNLO fixed order computations
- **Bottom pair production in MiNNLOps** (in progress)
  - Validation against fixed order NNLO results
  - Preliminary results for B meson distributions

# Events at LHC: theoretical perspective



**Hard scattering**

Described through the **factorization formula** for hadron collisions

$$\sigma = \sum_{a,b} \int dx_1 dx_2 \; f_{1,a}(x_1) f_{2,b}(x_2) \; \sigma_{ab}(x_1, x_2) \quad + \quad O(1/\Lambda)$$

Differential cross section for the elementary parton process (evaluated in perturbation theory)

The final state multiplicity for the hard scattering is then increased iteratively trough a **Parton shower algorithm** (down to a certain scale $t_0$)

$$S(t_I) \;=\; \Delta(t_I, t_0)\langle 1 | + \int_{t_0}^{t_I} dt \int_0^1 dz \; \Delta(t_I, t) \, F(t, z) \, S(z^2 t) \, S((1-z)^2 t)$$

$$S(t_I) \cdot |\Psi\rangle \;\longrightarrow$$

Probability to generate some final state configuration from PS

# The POWHEG method

**Matching** leading order calculations to Parton showers is quite straightforward…

… But when it comes to matching NLO calculations, things become a bit more cumbersome

Nason P. (2005)

Frixione S., Nason P., Oleari C. (2007)

Amplitudes for a 2 -> n inclusive process

$$A_n = A_n^{(0)} + g_s A_n^{(1)} + O(g_s^2)$$

$$A_{n+1} = g_s A_{n+1}^{(0)} + O(g_s^2)$$

**Born matrix element**

$$B \equiv |A_{2\to n}^{(0)}|^2$$

**Real correction**

$$R \equiv \alpha_s |A_{2\to n+1}^{(0)}|^2$$

**Virtual correction**

$$V \equiv \alpha_s 2\, Re\left(A_{2\to n}^{(0)} \cdot A_{2\to n}^{(1)\,*}\right)^{*}$$

*Note: real and virtual corrections display IRC singularities: a subtraction scheme is required when numerically computing phase space integrations (e.g. FKS, CS)

The POWHEG approach: generating the **hardest radiation first and with NLO accuracy**, then attaching a pt-ordered Parton shower

$$d\sigma = d\Phi_n\, B(\Phi_n) \left[\Delta(t_I, t_0) + d\phi_{rad} F(z,t)\Delta(t_I, t) + \dots\right]$$

$$\Downarrow$$

$$\boxed{d\sigma = d\Phi_n\, \overline{B}(\Phi_n) \left[\Delta^{(NLO)}(t_I, t_0) + d\phi_{rad} \frac{R}{B} \Delta^{(NLO)}(t_I, t)\right]}$$

**POWHEG master formula**

$$\overline{B} \equiv B + V^{(fin)} + \int d\phi_{rad}\, R^{(sub)}$$

$$\Delta^{NLO} = e^{-\int d\phi_{rad} R/B}$$

# The MiNNLO$_{\text{PS}}$ method

Let us consider the POWHEG event generator for the process

$$pp \rightarrow F + J$$

(Color singlet production with one jet)

In this case, the POWHEG B function will be computed at **NLO fixed order** as:

$$\bar{B}(\Phi_{FJ}) = B(\Phi_{FJ}) + \alpha_s \left\{ V(\Phi_{FJ}) + \int d\phi_{rad} R(\Phi_{FJJ}) \right\} + O(\alpha_s^2)$$

But the matrix elements used in this formula show large logarithmic enhancements in the phase space regions where the jet is collinear to its emitter…

**We loose predictivity in the low jet transverse momentum region!**

How can we recover NLO accuracy for exclusive distributions in F+J?

**Implementing Pt-resummation in the definition of the B function**

# The MiNNLO$_{\text{PS}}$ method

Sudakov form factor suppresses $\overline{B}$ at low $p_T$

Couplings evaluated at the $p_T$ scale

**MiNLO'**

Hamilton K., Nason P., Oleari C., Zanderighi G. (2012)

$$\bar{B}(\Phi_{\rm FJ}) = e^{-\tilde{S}(p_{\rm T})}\left[B(\Phi_{\rm FJ})\left(1+\frac{\alpha_s(p_{\rm T})}{2\pi}[\tilde{S}(p_{\rm T})]^{(1)}\right)+V(\Phi_{\rm FJ})\right] + \int {\rm d}\Phi_{\rm rad} R(\Phi_{\rm FJ},\Phi_{\rm rad}) e^{-\tilde{S}(p_{\rm T})}\,.$$

**Accuracy for the F and F+J inclusive observables**

| | MiNLO' | MiNNLO$_{\text{PS}}$ |
|---|---|---|
| **F** | NLO | **NNLO** |
| **F+J** | NLO | **NLO** |

**MiNNLOps For FJ**

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

$$\tilde{B}(\Phi_{\rm FJ},\Phi_{\rm rad}) = \exp[-\tilde{S}(\Phi_{\rm F},p_{\rm T})]\left[B(\Phi_{\rm FJ})\left(1+\frac{\alpha_s(p_{\rm T})}{2\pi}[\tilde{S}(\Phi_{\rm F},p_{\rm T})]^{(1)}\right)+V(\Phi_{\rm FJ}) + R(\Phi_{\rm FJ},\Phi_{\rm rad}) + D^{(\geq 3)}(\Phi_{\rm F},p_{\rm T})F^{\rm corr}(\Phi_{\rm FJ})\right],$$

Additional terms necessary to reach NNLO accuracy for inclusive distributions in F

**MiNNLOps For QQJ**

Mazzitelli J., Monni P., Nason P., Re E., Wiesemann M., Zanderighi G. (2020)

*[Javier Mazzitelli's talk]*

$$\begin{aligned}\tilde{B}_{Q\bar{Q}}(\Phi_{\rm FJ},\Phi_{\rm rad}) \equiv \sum_{c_{\rm FJ}}\Bigg\{ & \sum_{i=1}^{n_{c_{\rm F}\leftarrow c_{\rm FJ}}} \mathcal{C}^{[\gamma_i]}_{c_{\rm F}\leftarrow c_{\rm FJ}}(\Phi_{\rm F})\exp[-\tilde{S}^{[\gamma_i]}_{c_{\rm F}\leftarrow c_{\rm FJ}}(\Phi_{\rm F},p_{\rm T})] \\ & \times\left[B_{c_{\rm FJ}}(\Phi_{\rm FJ})\left(1+\frac{\alpha_s(p_{\rm T})}{2\pi}[\tilde{S}^{[\gamma_i]}_{c_{\rm F}\leftarrow c_{\rm FJ}}(\Phi_{\rm F},p_{\rm T})]^{(1)}\right)+V_{c_{\rm FJ}}(\Phi_{\rm FJ})\right]\Bigg\} \\ & + \sum_{c_{\rm FJJ}}\left\{\sum_{i=1}^{n_{c_{\rm F}\leftarrow c_{\rm FJJ}}} \mathcal{C}^{[\gamma_i]}_{c_{\rm F}\leftarrow c_{\rm FJJ}}(\Phi_{\rm F})\exp[-\tilde{S}^{[\gamma_i]}_{c_{\rm F}\leftarrow c_{\rm FJJ}}(\Phi_{\rm F},p_{\rm T})]\right\} R_{c_{\rm FJJ}}(\Phi_{\rm FJ},\Phi_{\rm rad}) \\ & + \sum_{c_{\rm FJ}}\left\{\sum_{c_{\rm F}}\sum_{i=1}^{n_{c_{\rm F}}} \mathcal{C}^{[\gamma_i]}_{c_{\rm F}}(\Phi_{\rm F})\exp[-\tilde{S}^{[\gamma_i]}_{c_{\rm F}}(\Phi_{\rm F},p_{\rm T})] D^{[\gamma_i],\,(\geq 3)}_{c_{\rm F}}(\Phi_{\rm F},p_{\rm T})\right\} F^{\rm corr}_{c_{\rm FJ}}(\Phi_{\rm FJ})\end{aligned}$$

# Bottom pair production

## Motivations and status

# Bottom pair production

## Why is this process interesting?

- ✦ Very large cross section —> relevant background to various processes (both SM and BSM)
- ✦ Heavy quark pair production at LHC can be exploited to find **constraints on the gluon PDF**
- ✦ Event generators for processes like $pp \to b\bar{b}$ and $pp \to c\bar{c}$ can be exploited when studying the **prompt atmospheric neutrino flux** for backgrounds in neutrino telescopes (e.g., IceCube)

**BUT**

Available theoretical results for this process still affected by large uncertainties…

↓

**We need to improve the accuracy of our predictions!**

# Bottom pair production

## Constraining gluon PDF from rapidity ratio distributions at different c.o.m. energies

**Possible sources of theoretical uncertainties:**

- Uncertainties over **PDFs**
- Uncertainties over **pole mass value**
- (Uncertainties over coupling constant values)
- **7-point scale variation** for renormalization and factorization scale

# Bottom pair production

## Constraining gluon PDF from rapidity ratio distributions at different c.o.m. energies

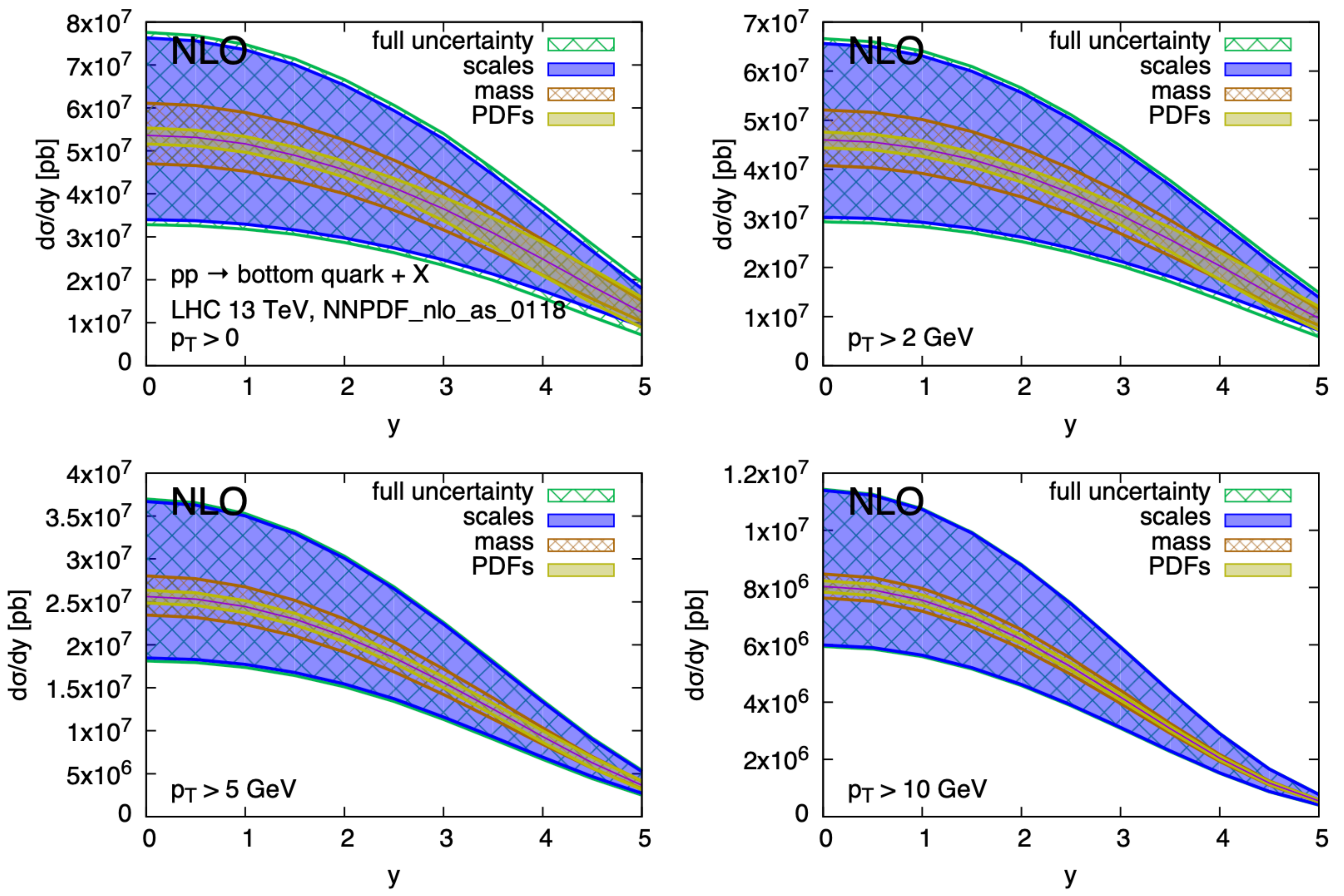


Figure 3: Bottom quark rapidity distributions at $\sqrt{S} = 13$ TeV.

Cacciari M., Mangano M., Nason P. (2015)

From fixed order results at **NLO**, it has been shown that:

- Uncertainties over PDFs
- Uncertainties over pole mass value
- (Uncertainties over coupling constant values)
- **7-point scale variation for renormalization and factorization scale**

↓

**Dominant source of uncertainty!**

(Even ~50% at low $p_T$ in the central rapidity range)

# Bottom pair production

## Constraining gluon PDF from rapidity ratio distributions at different c.o.m. energies

How can we deal with huge scale uncertainties? We can analyze observables where scale variation is **suppressed**

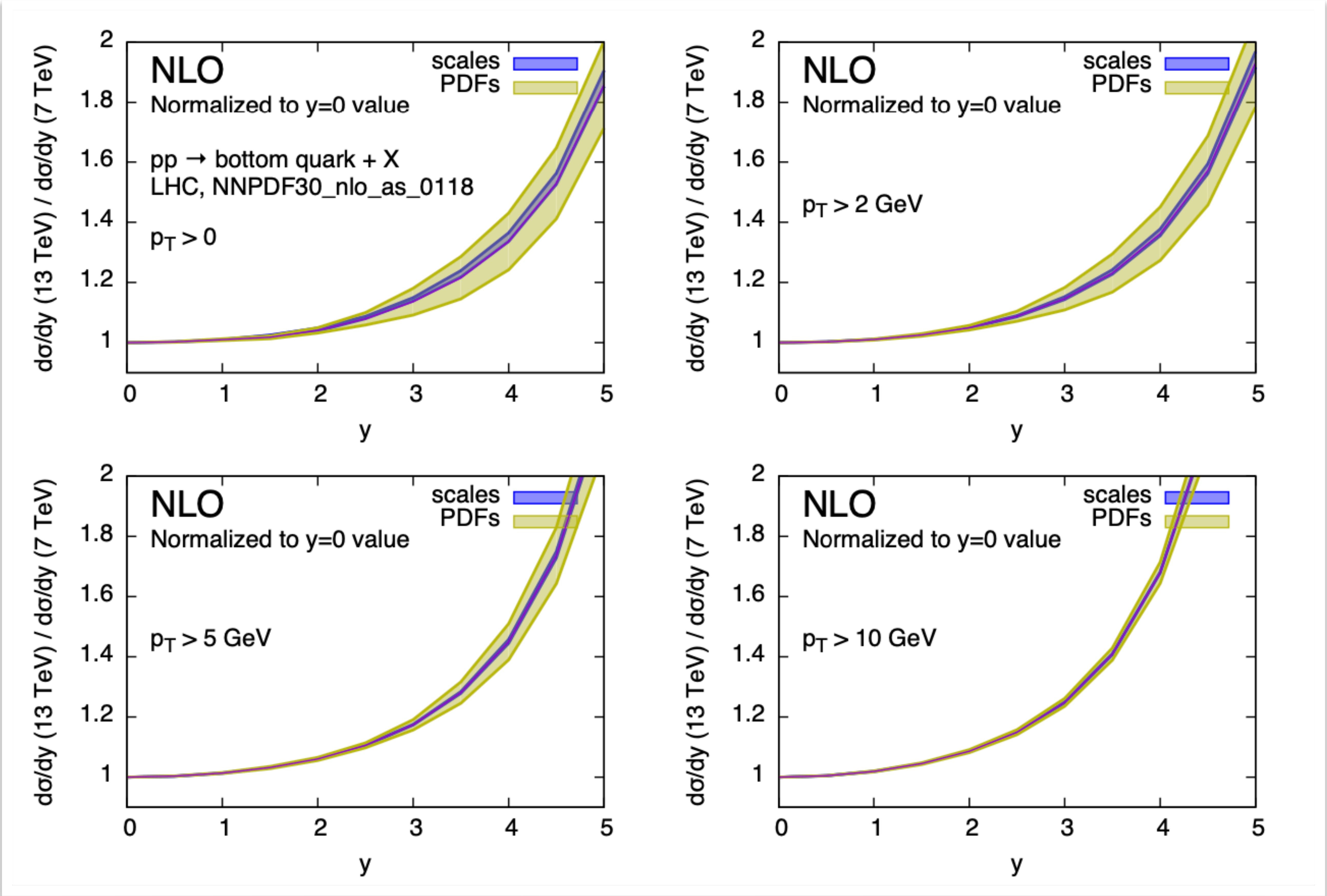
$$R(y) \equiv \frac{\frac{d\sigma}{dy}(13TeV)}{\frac{d\sigma}{dy}(7TeV)}$$

**Ratio** of rapidity distributions at different beam energies

- Beam energy and the scale choice are **not correlated** (most scales just depend on the Parton level kinematics)
- At different energies, the same $(p_T, y)$ kinematics selects **different values for x** (since $x \sim p_T/\sqrt{s}$)

Scale dependence is **more suppressed** than the one on PDFs, which become dominant!

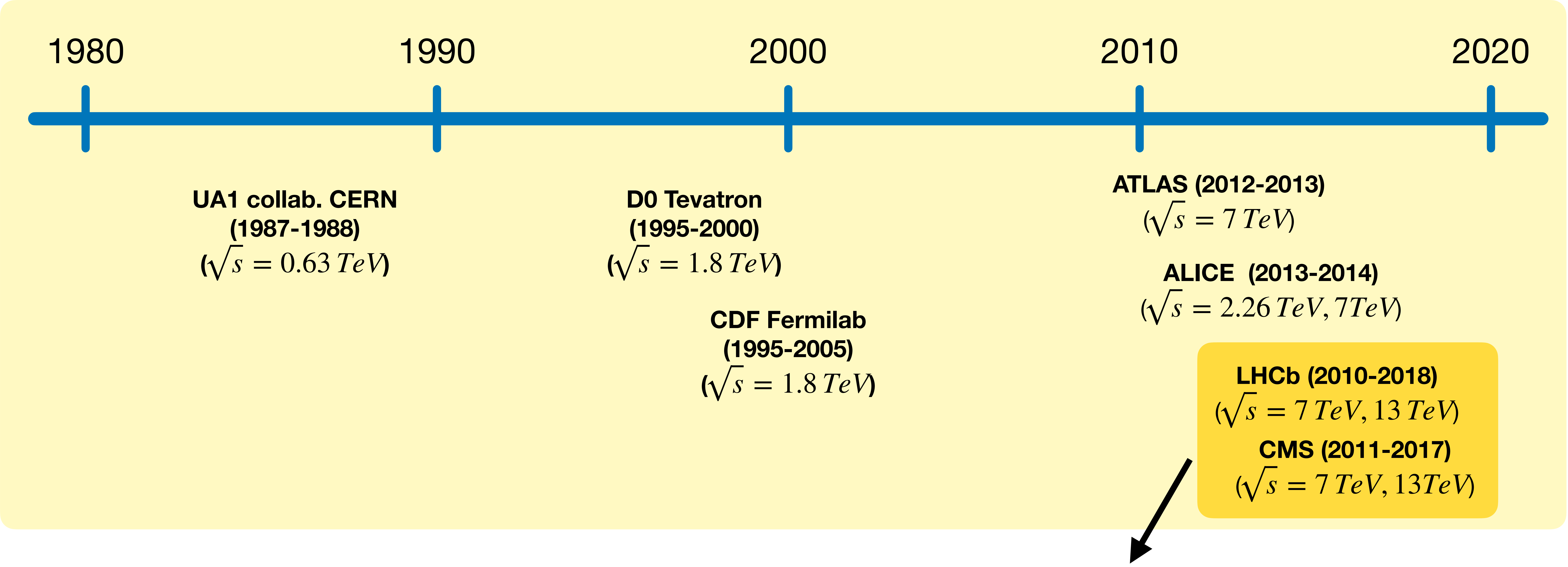
Especially gluon PDF



Cacciari M., Mangano M., Nason P. (2015)

# Experimental results for B meson production

Several experimental collaborations have addressed the physics of b pair production at high energies (through measurements for of **B mesons and their decays**)



**UA1 collab. CERN**
**(1987-1988)**
$(\sqrt{s} = 0.63\, TeV)$

**D0 Tevatron**
**(1995-2000)**
$(\sqrt{s} = 1.8\, TeV)$

**CDF Fermilab**
**(1995-2005)**
$(\sqrt{s} = 1.8\, TeV)$

**ATLAS (2012-2013)**
$(\sqrt{s} = 7\, TeV)$

**ALICE (2013-2014)**
$(\sqrt{s} = 2.26\, TeV, 7 TeV)$

**LHCb (2010-2018)**
$(\sqrt{s} = 7\, TeV, 13\, TeV)$
**CMS (2011-2017)**
$(\sqrt{s} = 7\, TeV, 13 TeV)$

**First results at 13TeV**

# Experimental results for B meson production

LHCb collaboration, 2018

Average B meson **pseudorapidity** distributions $d\sigma(pp \to H_b X)/d\eta$, compared to FONLL predictions

Here it has been defined:

$$\sigma(pp \to H_b X) = \frac{1}{2}\left[\sigma(B^0) + \sigma(\overline{B}^0)\right] + \frac{1}{2}\left[\sigma(B^+) + \sigma(B^-)\right] + \frac{1}{2}\left[\sigma(B_s^0) + \sigma(\overline{B}_s^0)\right] + \frac{1+\delta}{2}\left[\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)\right]$$

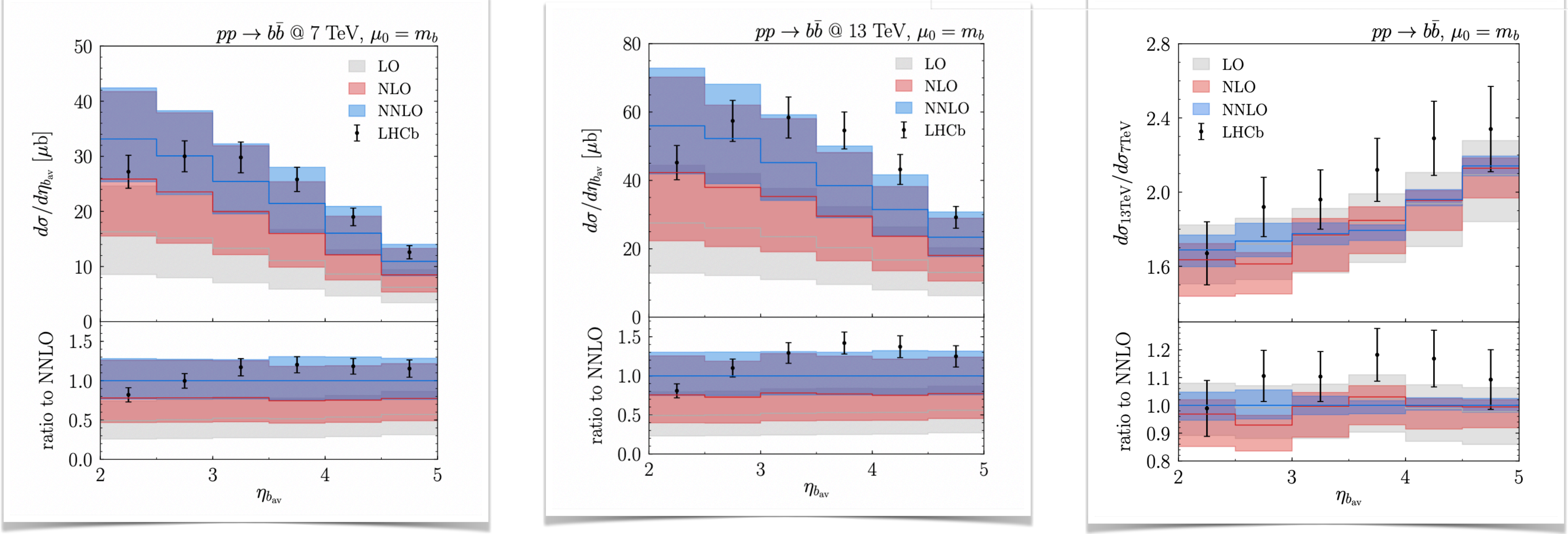
We notice that:

- Data and FONLL predictions are **compatible** within their respective uncertainties
- There are some **shape differences** between data and experimental predictions
- Such shape disagreements compensate in the ratio of distributions

→ **Does the situation improve at NNLO?**

# Fixed order NNLO bottom pair production

S. Catani, S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli; JHEP 03 (2021) 029



*Average bottom and anti-bottom pseudorapidity distributions at 7TeV and 13TeV (LO, NLO, NNLO) with* $\mu_F = \mu_R = m_b$

# Bottom pair production with MiNNLO$_{PS}$

# Bottom pair production with MiNNLO$_{PS}$

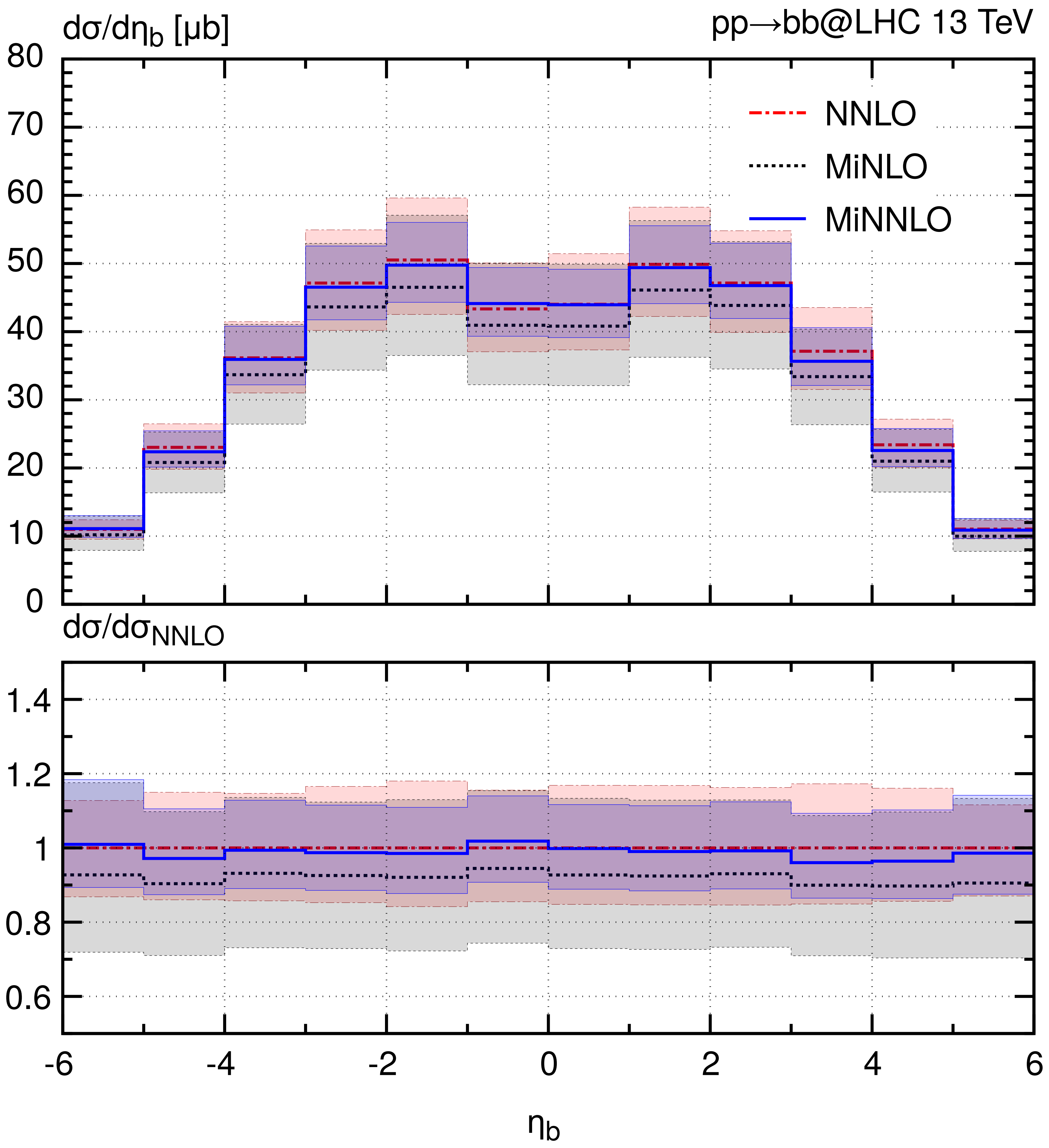
## Settings

- We consider **7 and 13 TeV** LHC collisions
- Four-flavour scheme, with **pole mass** of bottom quarks set to $m_b = 4.92\,GeV$
- PDF choice: NNPDF31_nnlo_as_0118_nf_4
- For the two overall couplings in the MiNNLOps formula, we tested different scale choices, namely $m_{bb}$, $m_{bb}/2$, $H_t/2$ and $H_t/4$
- OpenLoops2 for tree level and 1-loop contributions, and evaluated the genuinely 2-loops contributions using analytical grids

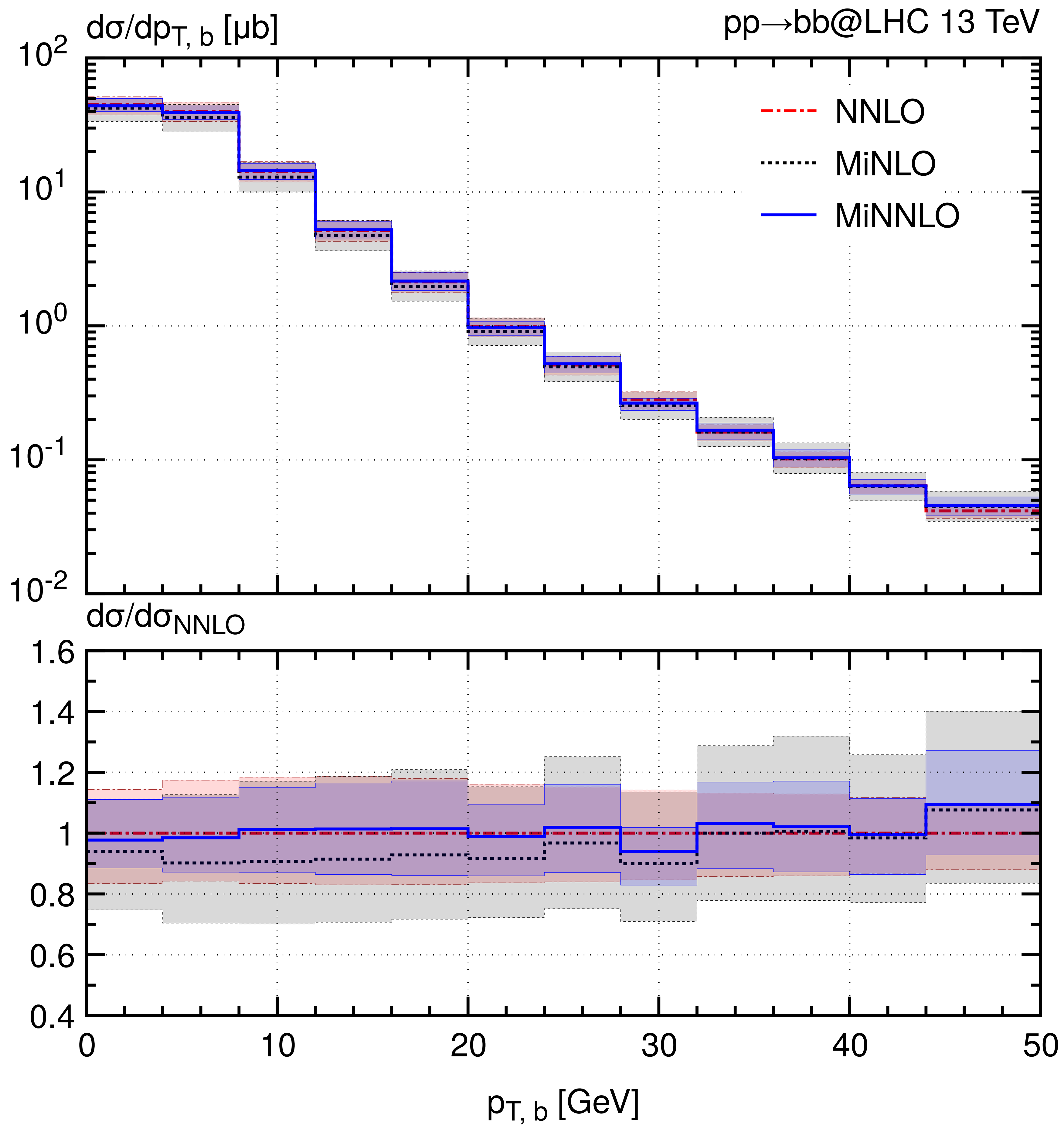
# Comparison to fixed order results

## Inclusive observables in bb

**Bottom quark pseudorapidity**



**Bottom transverse momentum**



**Total cross section**

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

Comparison with fixed order NNLO predictions from MATRIX. 7-point scale variation has been performed choosing the central scale:

$$\mu_R = \mu_F = m_{b\bar{b}}$$

# Comparison to experimental data

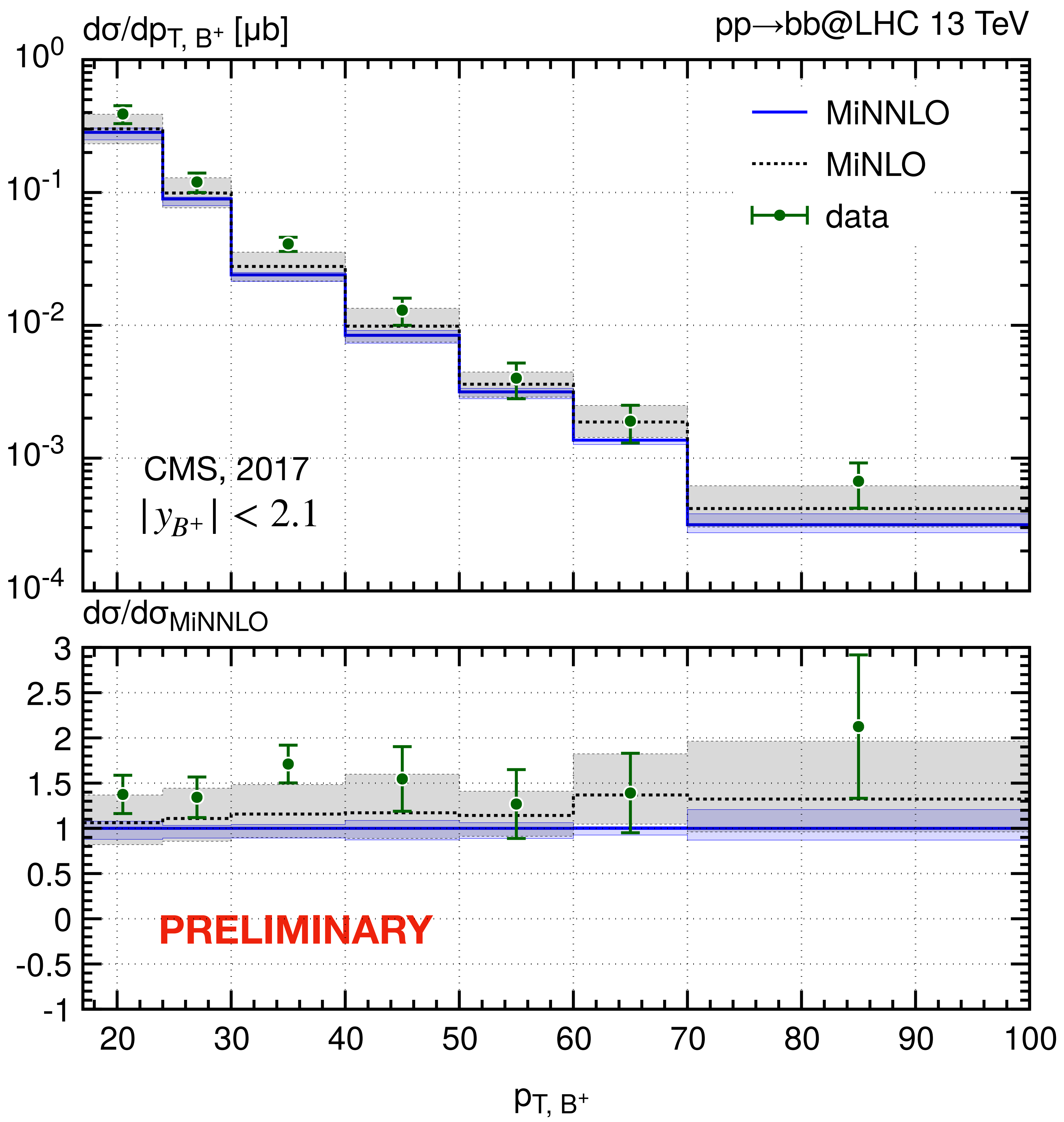
We show some preliminary results for the comparison of predicted B meson distributions with experimental data.
Events have been generated interfacing POWHEG to **PYTHIA8** (both for PS and hadronization)

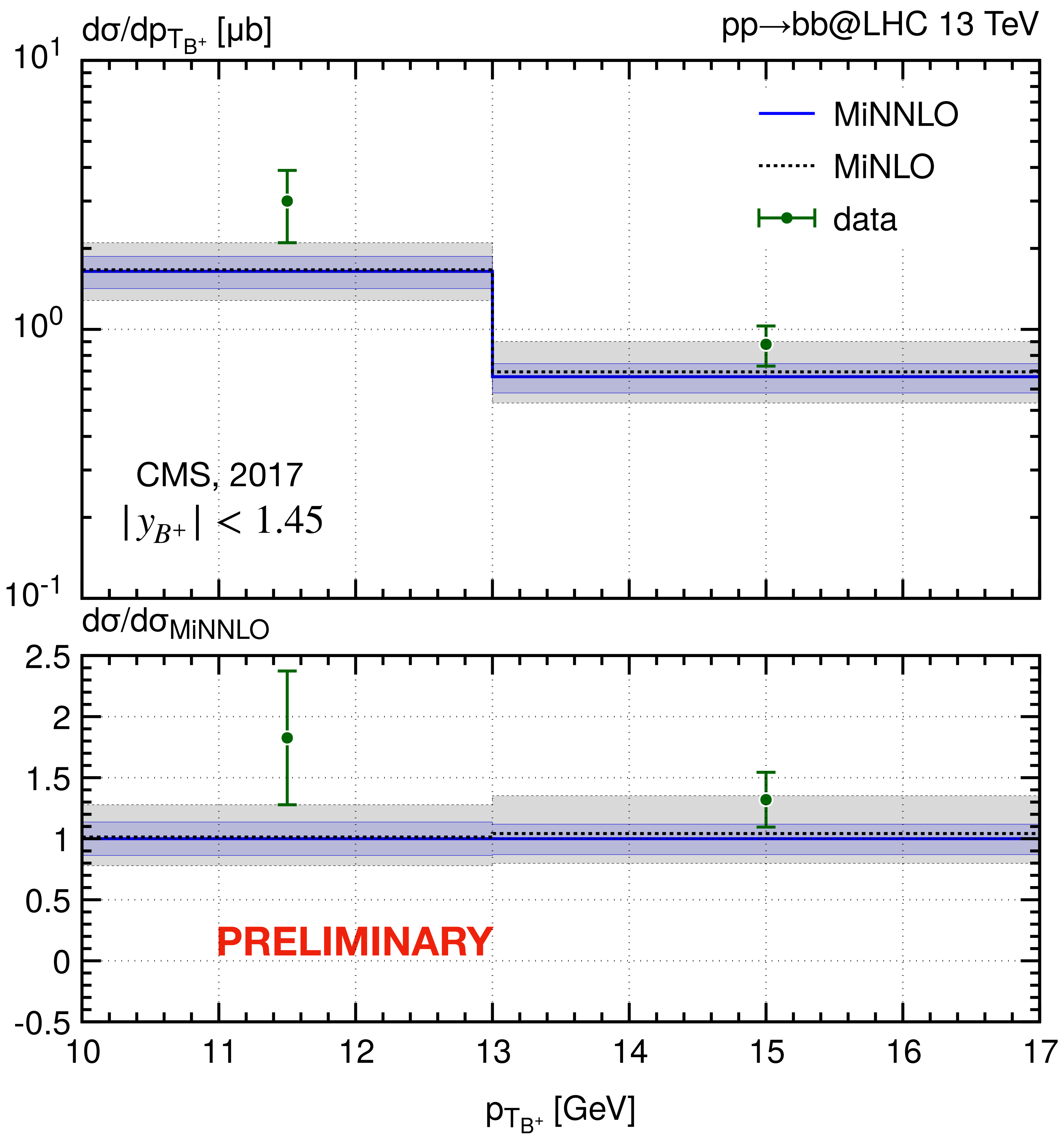
NOTE:
uncertainties here are only estimated with 7-point scale variation around

$$\mu_R = \mu_F = H_T/2$$

Where

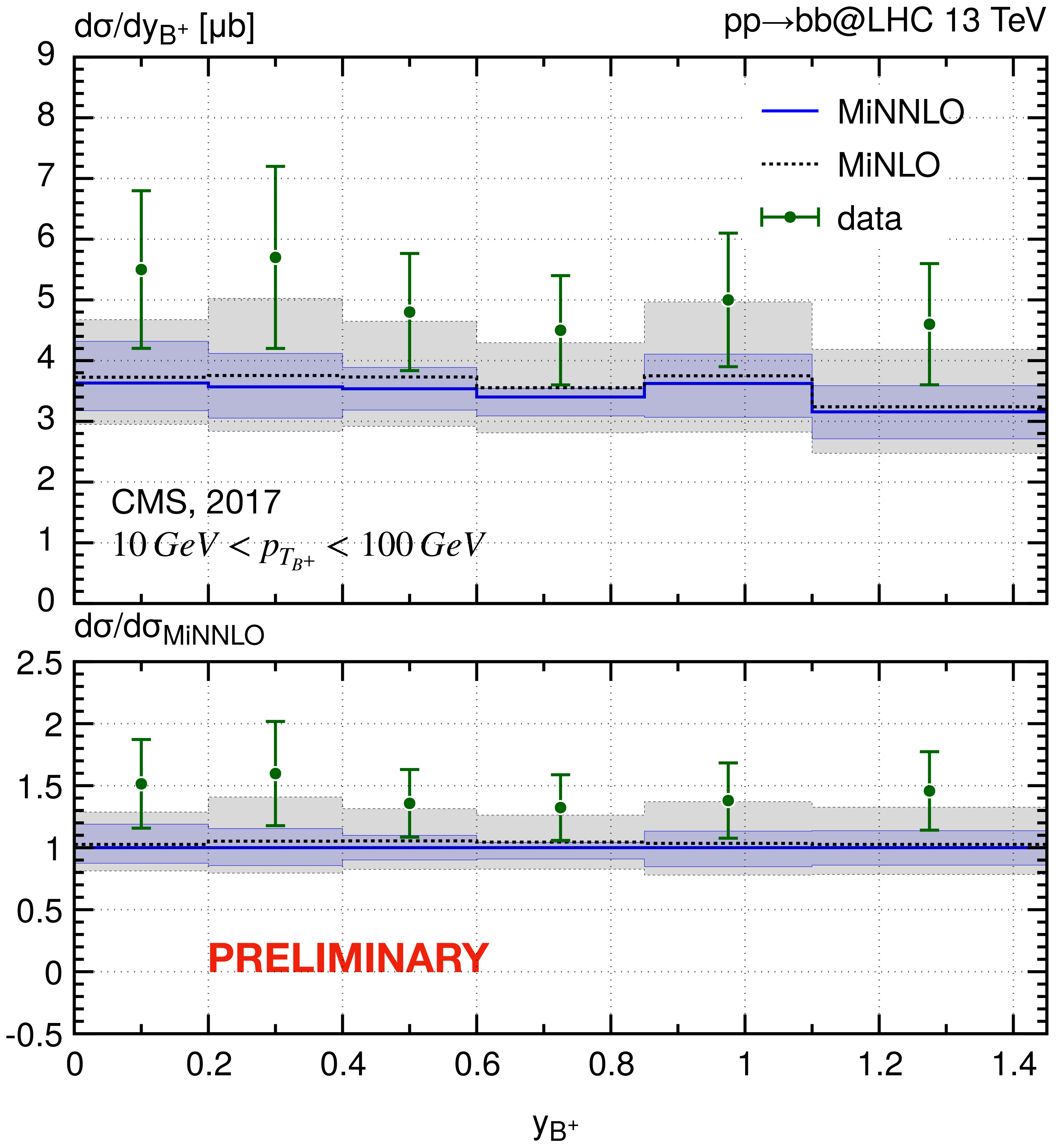
$$H_T = \sqrt{m_b^2 + p_{T,b}^2} + \sqrt{m_{\bar{b}}^2 + p_{T,\bar{b}}^2}$$

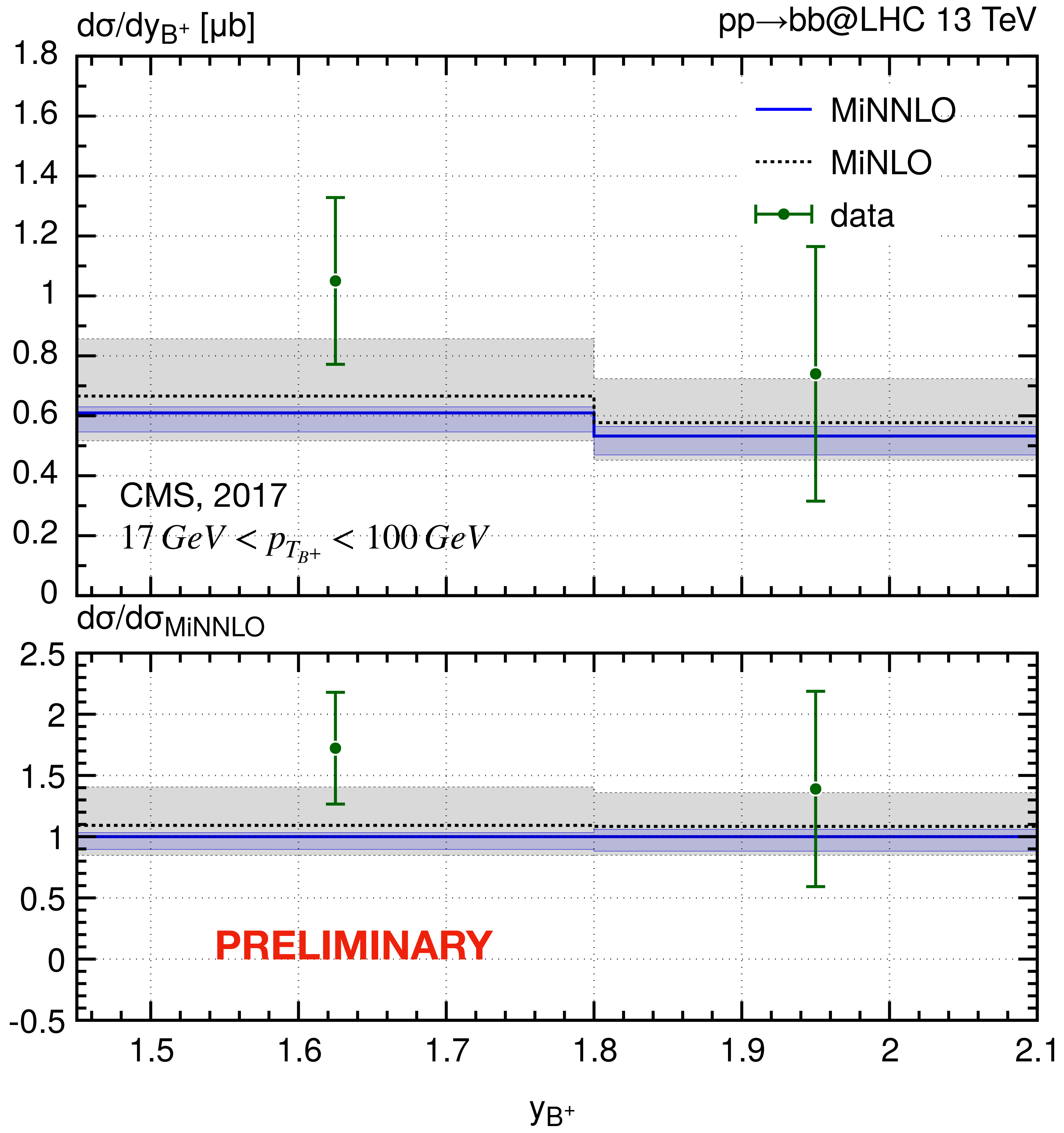




# Comparison to experimental data

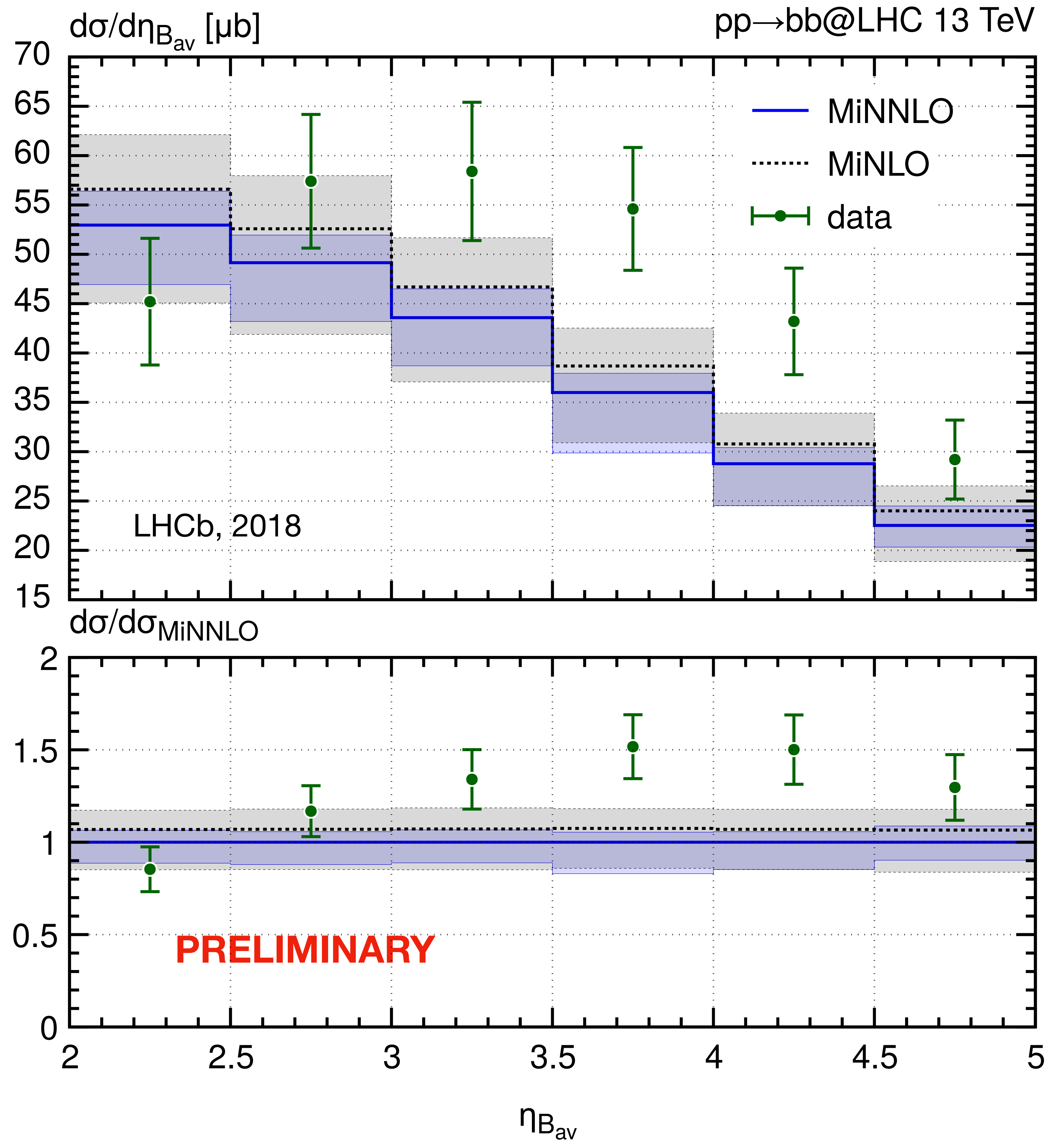
We show some preliminary results for the comparison of predicted B meson distributions with experimental data.
Events have been generated interfacing POWHEG to **PYTHIA8** (both for PS and hadronization)





# Comparison to experimental data

We show some preliminary results for the comparison of predicted B meson distributions with experimental data.
Events have been generated interfacing POWHEG to **PYTHIA8** (both for PS and hadronization)



# Summary

- **Status of bottom pair production in MiNNLOps**
    - The code has been validated against NNLO fixed order predictions
    - Preliminary comparisons to experimental B meson distributions at 13 TeV
- **Further developments**
    - Comparison to 7 TeV data
    - Ratio analysis for rapidity distributions at 7 and 13 TeV
    - Analysis for b-jets and comparison to experimental results
    - NNLO fixed order computations

# Thank you!

# Backup