B-jet production at the LHC using PBTMD

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

OUTLINE

- PBTMD method
  - DGLAP evolution solution
  - Transverse momentum dependence
  - PB-TMD, TMD shower & MCatNLO: $\boldsymbol{Z+b}$ jets
- Z + bjet production at LHC (4FL and 5FL) (8TeV CMS measurement)
  arXiv:1611.06507
  - Z pT spectrum for Z+b and Z+bb
  - Leading b-jet and subleading b-jet spectrum Z+b and Z+bb
  - $\Delta\phi(\mathrm{Z},\mathrm{b})$: sensitivity to initial state kT
  - $\Delta\phi(\mathrm{b},\mathrm{b})$: sensitivity to TMD initial state shower

PB-TMD : DGLAP evolution solution

$$f(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2) + \int \frac{dz}{z}\int \frac{d\mu'^2}{\mu'^2}\frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)}\,P^{(R)}(z)\,f\left(\frac{x}{z},\mu'^2\right)$$

- Solve integral equation via iteration:

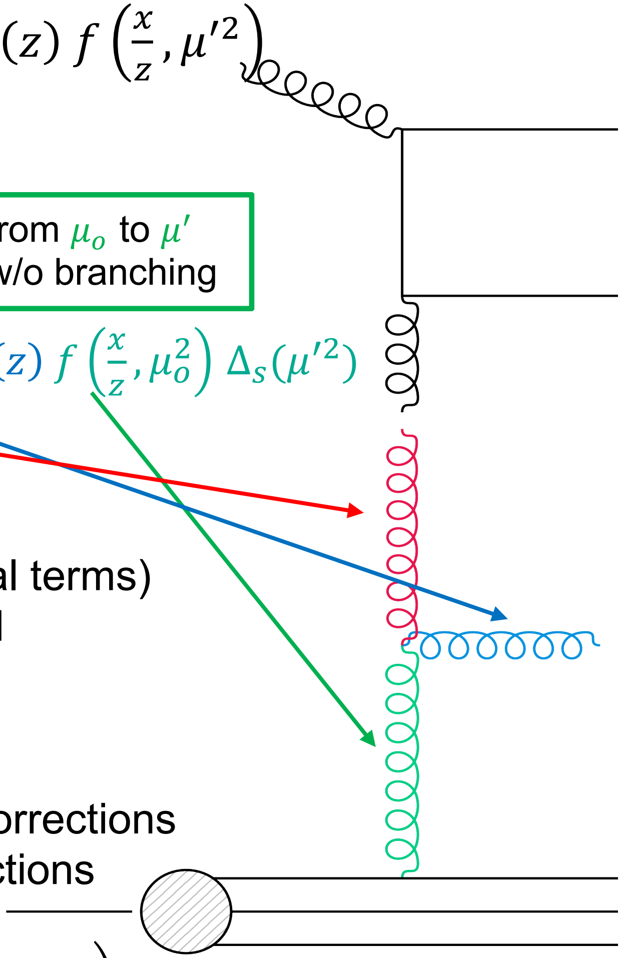
$$f_o(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2)$$

Branching at μ'

from μ_o to μ'
w/o branching

$$f_1(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2) + \int_{\mu_o^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)}\int^{z_M}\frac{dz}{z}\,P^{(R)}(z)\,f\left(\frac{x}{z},\mu_o^2\right)\Delta_s(\mu'^2)$$

from μ' to μ
w/o branching



- $P^{(R)}(z)$ real emission probability (without virtual terms)
- z_M introduced to separate real from virtual and non-emission probability.
- reproduces DGLAP up to $\mathcal{O}(1-z_M)$

- Make use of momentum sum rule to treat virtual corrections
  - Sudakov for non-resolvable and virtual corrections

$$\Delta_a(z_M,\mu^2,\mu_o^2) = exp\left(-\sum_b \int_{\mu_o^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\int_0^{z_M} dz\;P_{ab}^{(R)}(\alpha_s\,,z)\right)$$

PB-TMD : Transverse Momentum Dependence

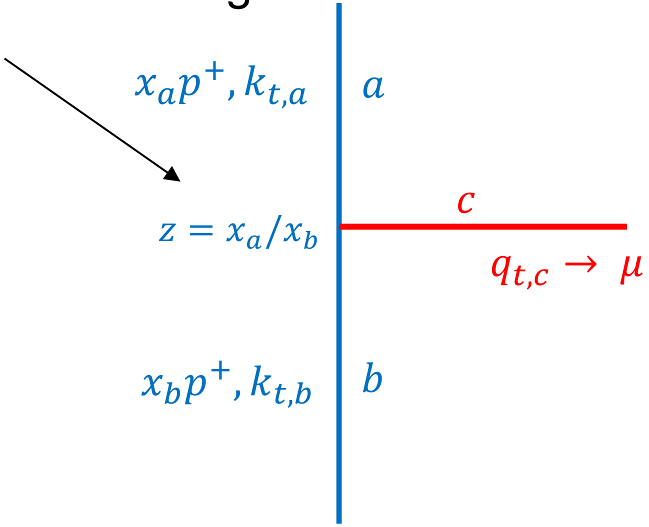
- PB-TMD obtained from NLO fit to inclusive HERA data
  - parameters of collinear initial distribution obtained
  - intrinsic Gauss distribution with:

    $\mathcal{A}_{0,b}(x, k_T^2, \mu_0^2) = f_{0,b}(x, \mu_0^2)\exp(-|k_T^2|/2\sigma^2)/\ (2\pi\sigma^2)$

    constrained width $\sigma^2 = q_s^2/2$ of Gauss distribution (default $q_s = 0.5\ GeV$)

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step

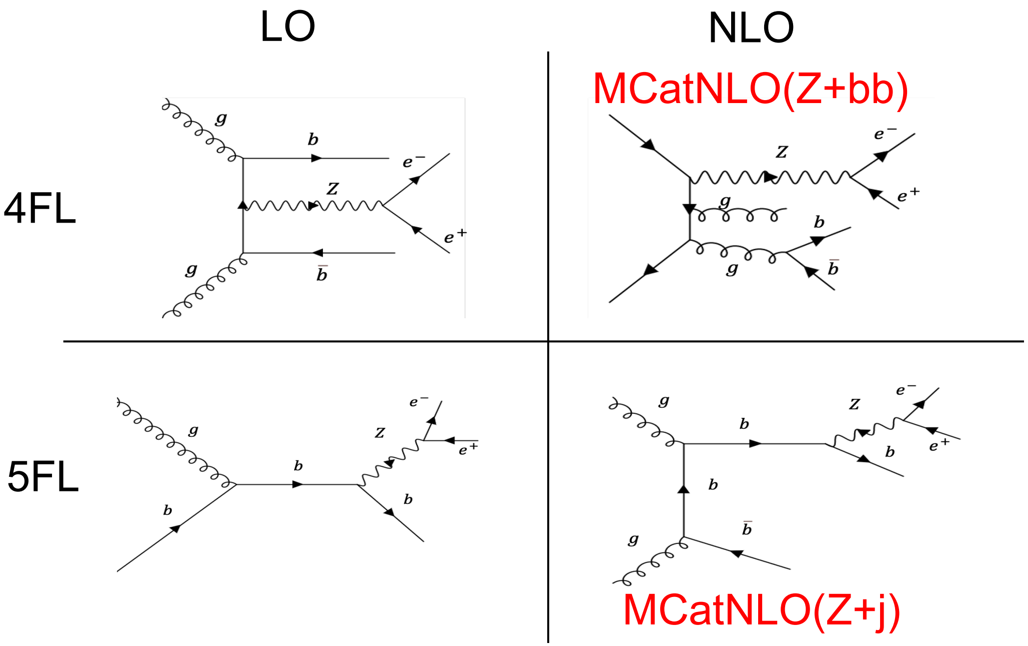
- Give physics interpretation of evolution scale:
  - angular ordering: $\mu = \ q_T/(1-z)$



- No further free parameters !

[1] 10.1007/JHEP01(2018)070 , arXiv:1708.03279v1
[2] 10.1016/j.physletb.2017.07.005 , arXiv:1704.01757
[3] 10.1103/PhysRevD.99.074008 , arXiv:1804.11152

PB-TMD, TMD shower & MCatNLO: $Z + b$ jets



LO

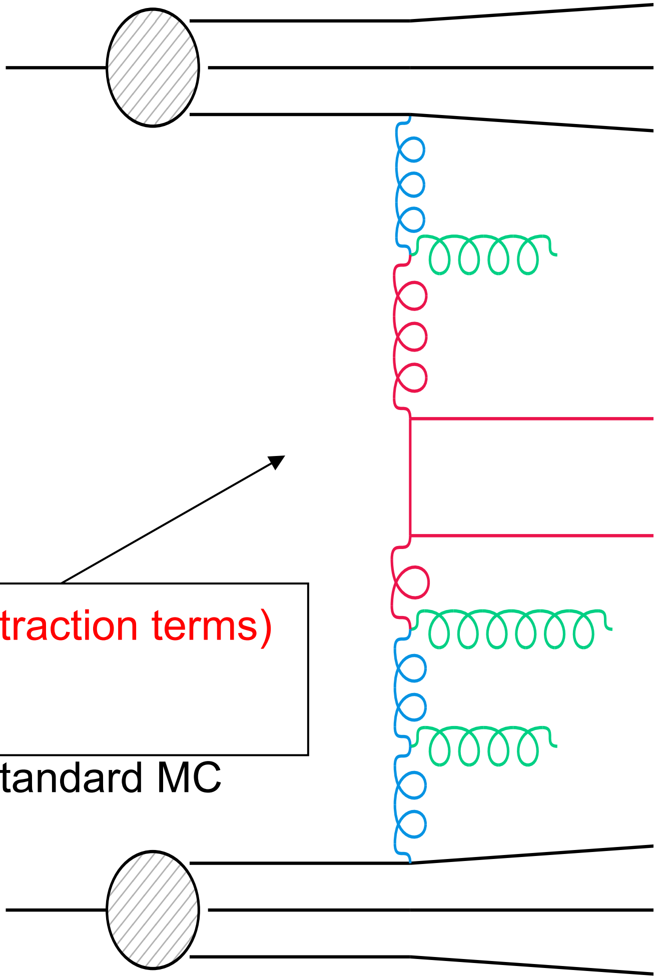
NLO

4FL

5FL

MCatNLO(Z+bb)

MCatNLO(Z+j)

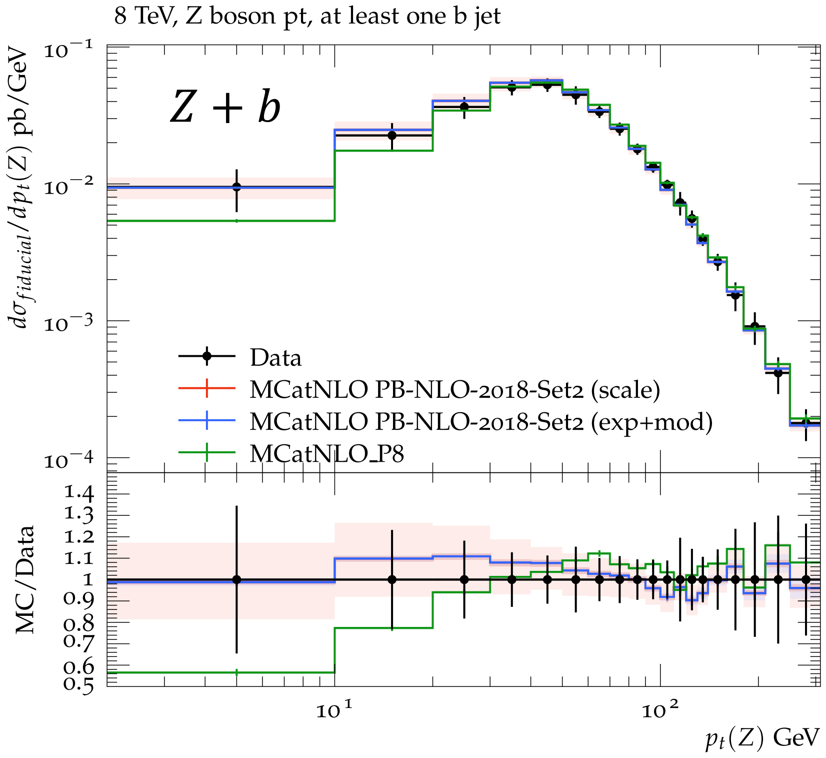


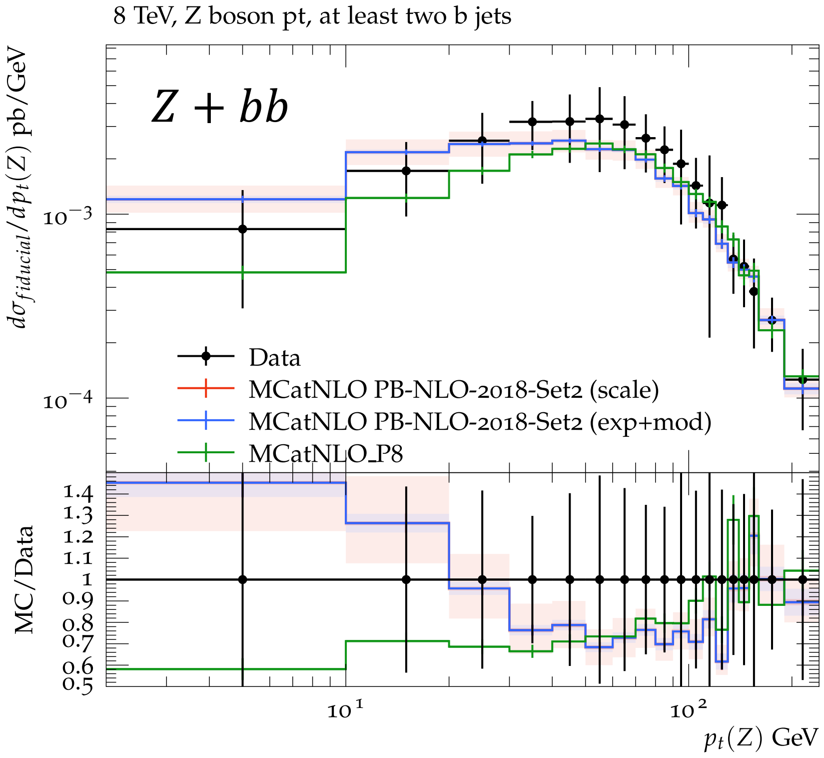
- ○ Matrix elements from MCatNLO (using Herwigh6 subtraction terms)
- ○ PDFs : TMDs (4FL and 5FL)
- ○ Parton shower following TMDs for initial state
- ○ Proton remnant , FSR and hadronization treated by standard MC (PYTHIA6)
- ○ Uncertainties:
  - Scale unc. from MCatNLO.
  - PDF (TMD) uncertainties.

Z pT spectrum for Z+b and Z+bb (5FL)

- **Phase space cuts:**
  - ***Leptons :*** $|\eta| < 2.4$, $p_T > 20\ GeV$, $71\ GeV < m_{ll} < 111\ GeV$
  - ***Jets :*** anti$-k_T$, $R = 0.5$, $|\eta| < 2.4.$, b-Hadron $p_T > 30\ GeV$

Data points in this presentation from 8TeV Z+bjet CMS measurement arXiv:1611.06507

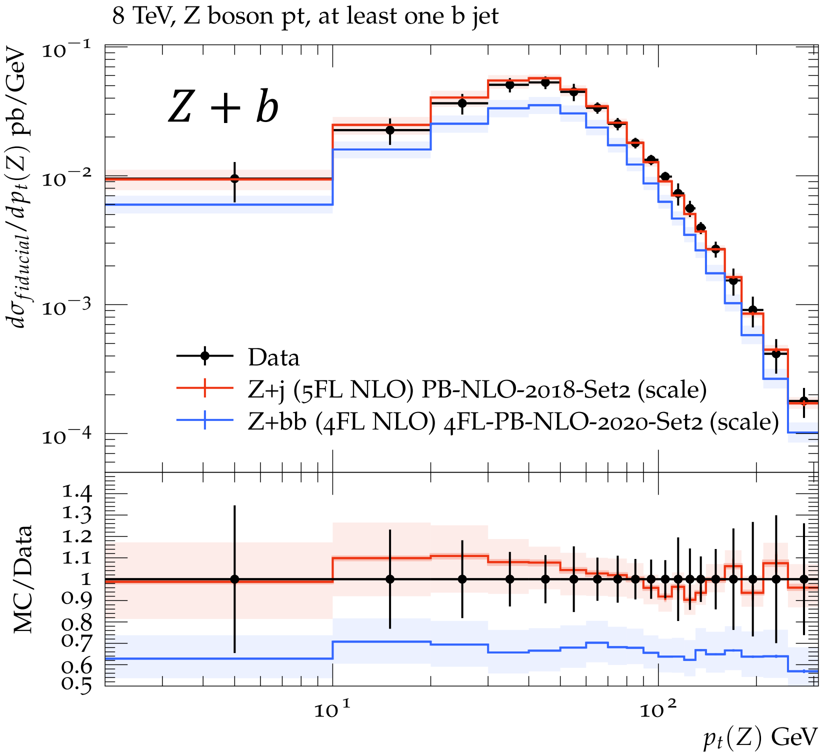

8 TeV, Z boson pt, at least one b jet

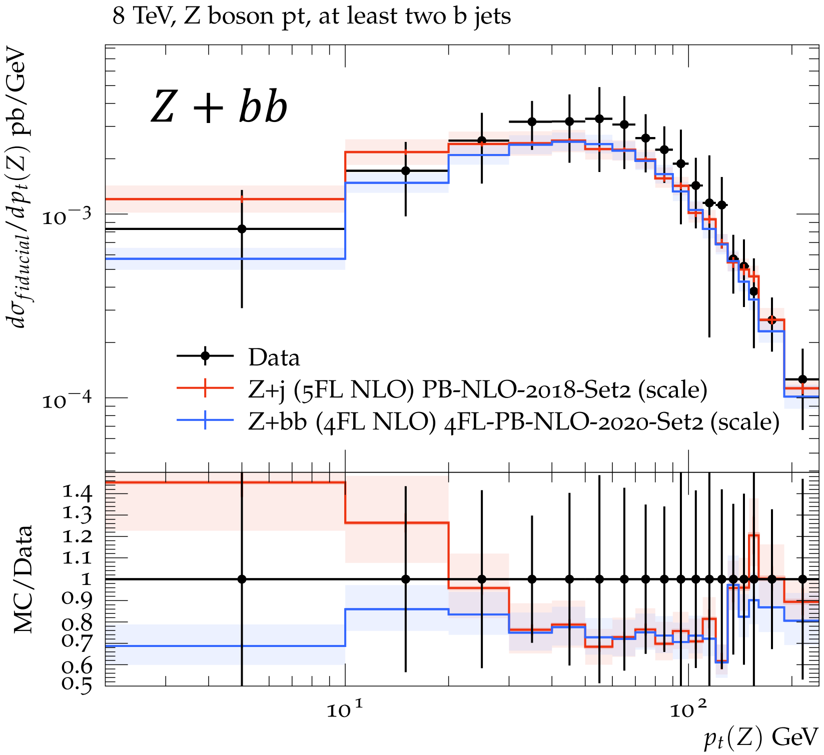

8 TeV, Z boson pt, at least two b jets

- PB-TMD shows better description (wrt. P8) at low pT from PB-TMD in $Z + b$.
- Scale uncertainty dominates (red band).

Z pT spectrum for Z+b and Z+bb (5FL vs 4FL)

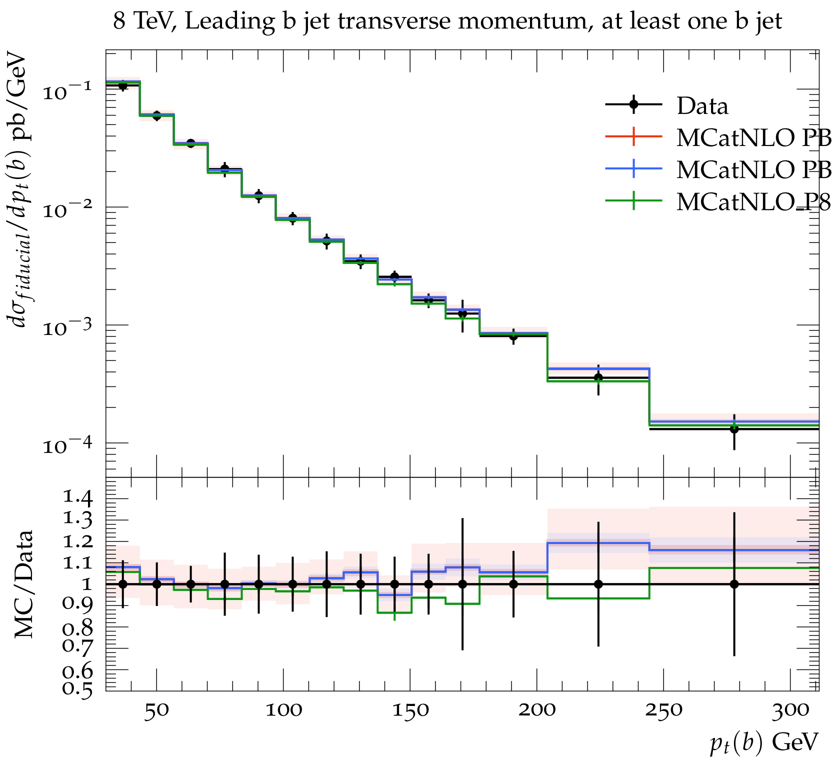
- **Phase space cuts:**
  - ***Leptons :*** $|\eta| < 2.4$, $p_T > 20\ GeV$, $71\ GeV < m_{ll} < 111\ GeV$
  - ***Jets :*** $\text{anti}-k_T$, $R = 0.5$, $|\eta| < 2.4.$, b-Hadron $p_T > 30\ GeV$

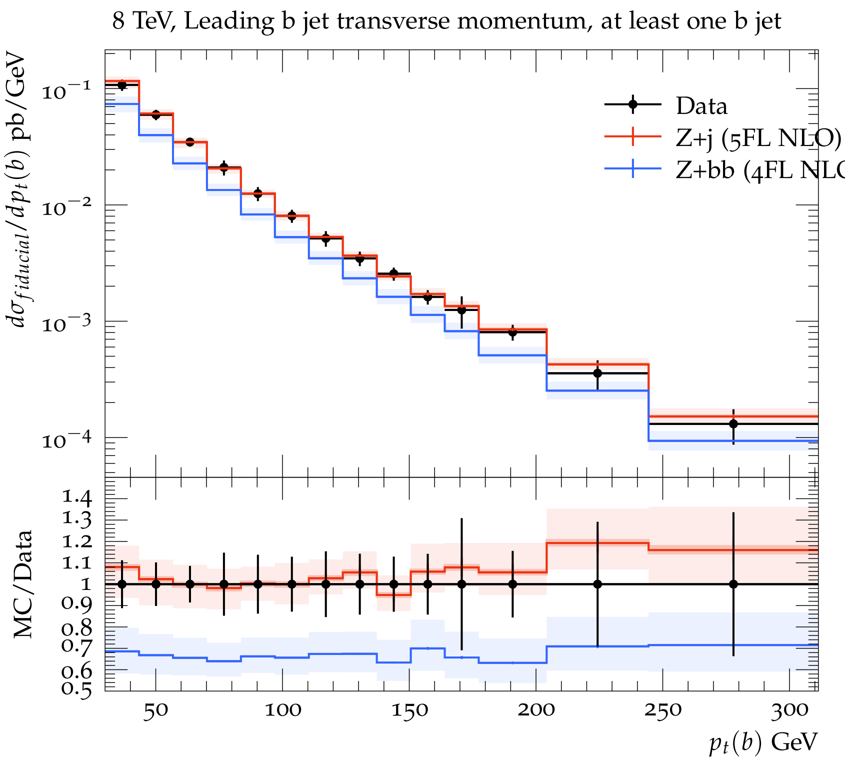




- 4FL shows a deficit in the description of $Z + b$ data.
- 4FL and 5FL schemes agree within uncertainties in the description of $Z + bb$ data.
- Scale uncertainty is shown (red and blue band).

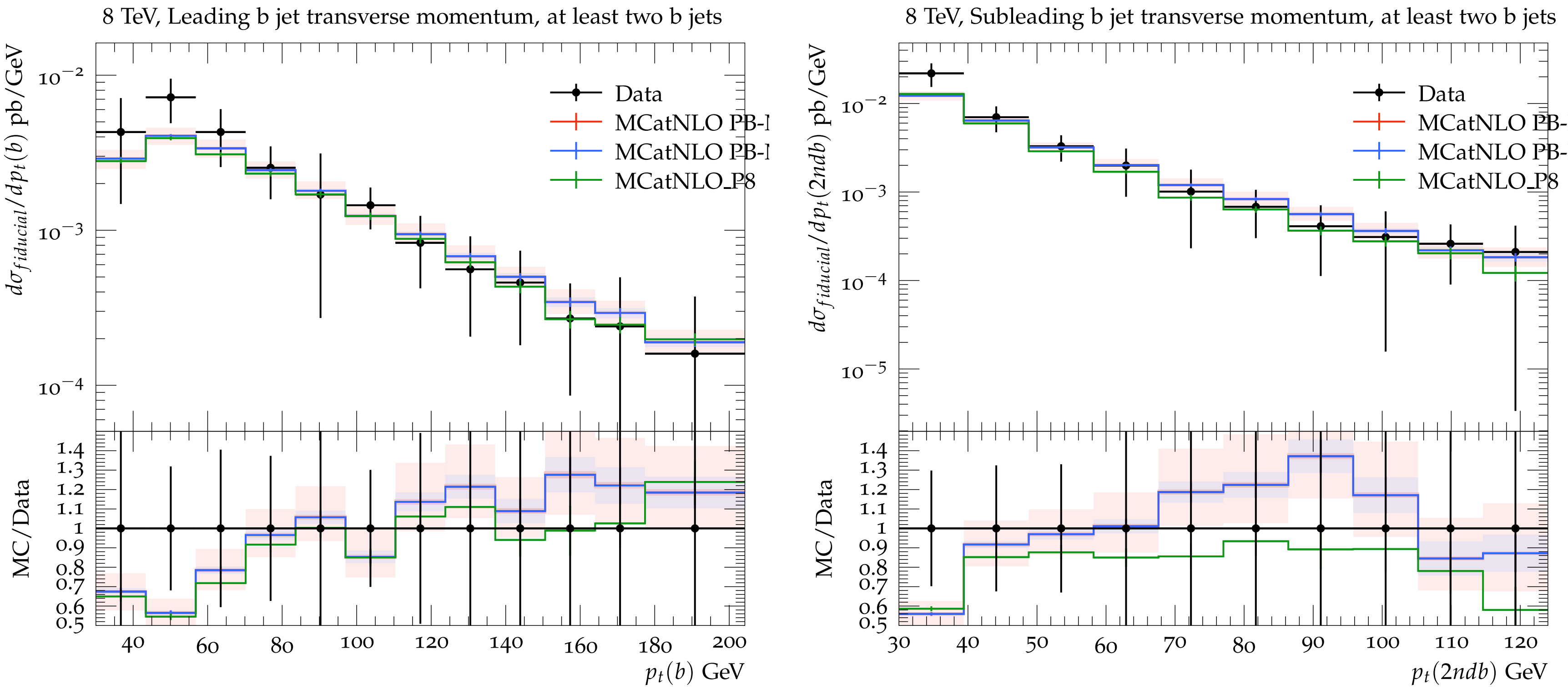
Leading b-jet pT for Z+b (4FL vs 5FL)


8 TeV, Leading b jet transverse momentum, at least one b jet


8 TeV, Leading b jet transverse momentum, at least one b jet

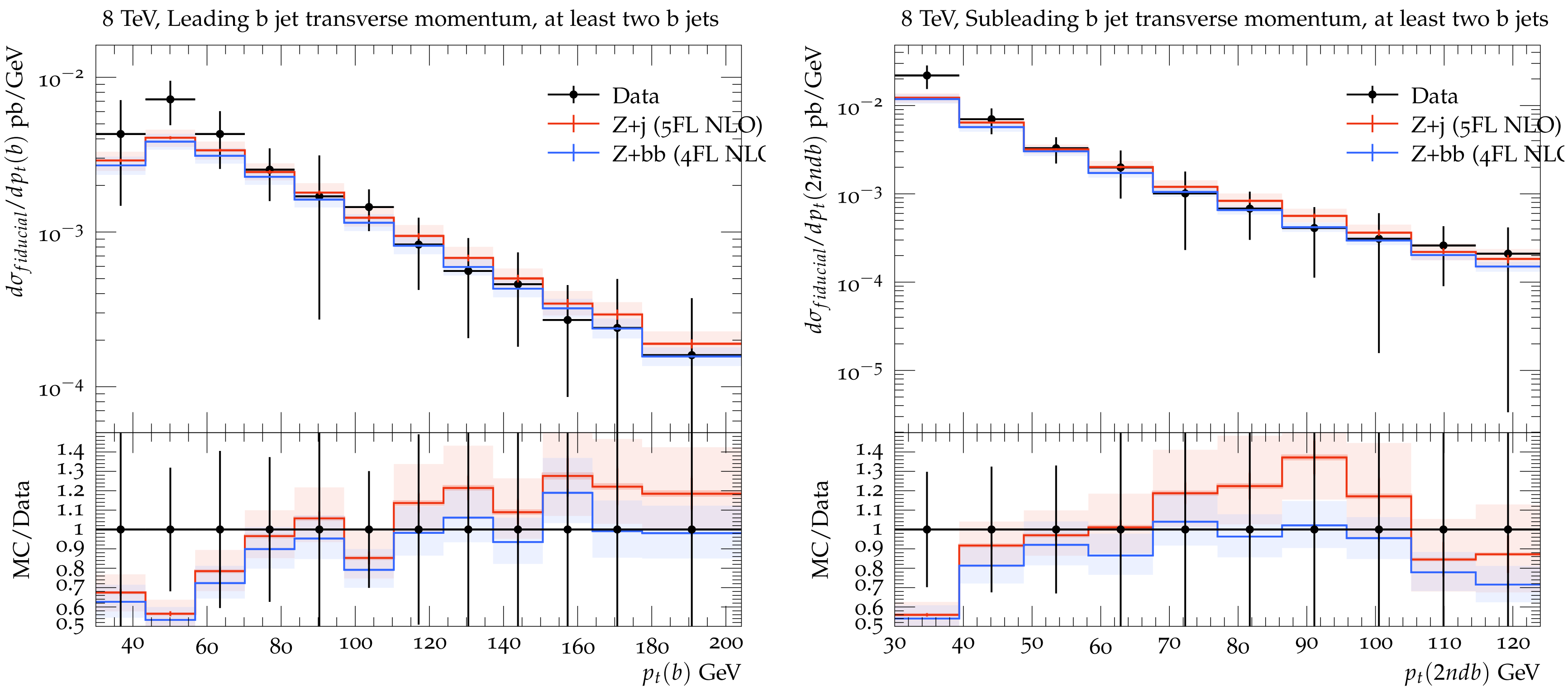
- Good description from 5FL PB-TMD and Pythia8 (left plot).
- 4FL PBTMD calculation around 30% below data and prediction mainly due to missing contribution from TMD b-quark content.

Leading and subleading b-jet pT for Z+bb (5FL)



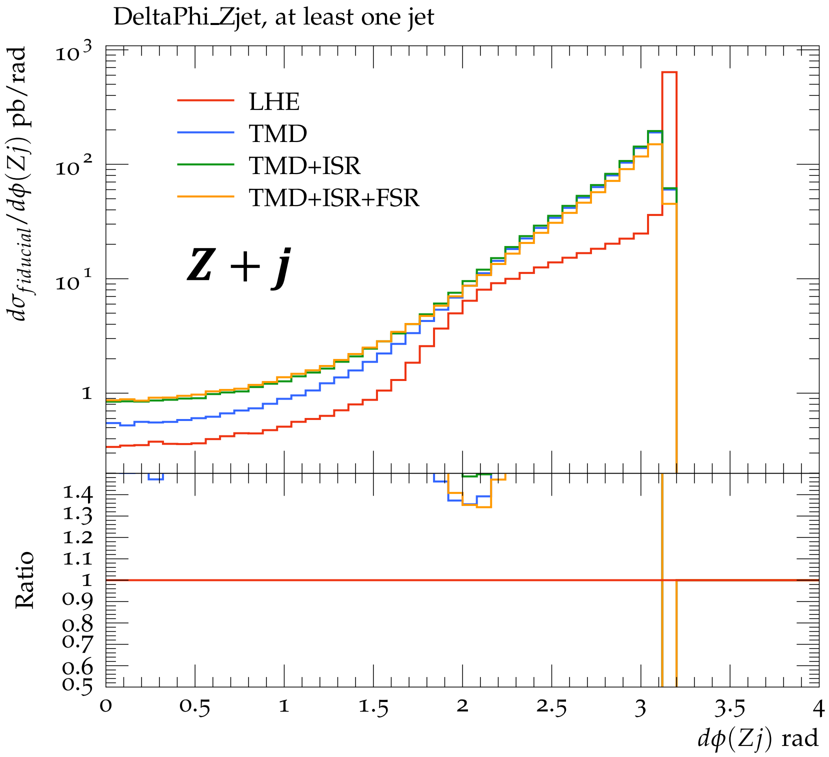
- Consistent descriptions from PB-TMD and P8.
- Scale uncertainty dominates (red band) over experimental uncertainty (blue band).

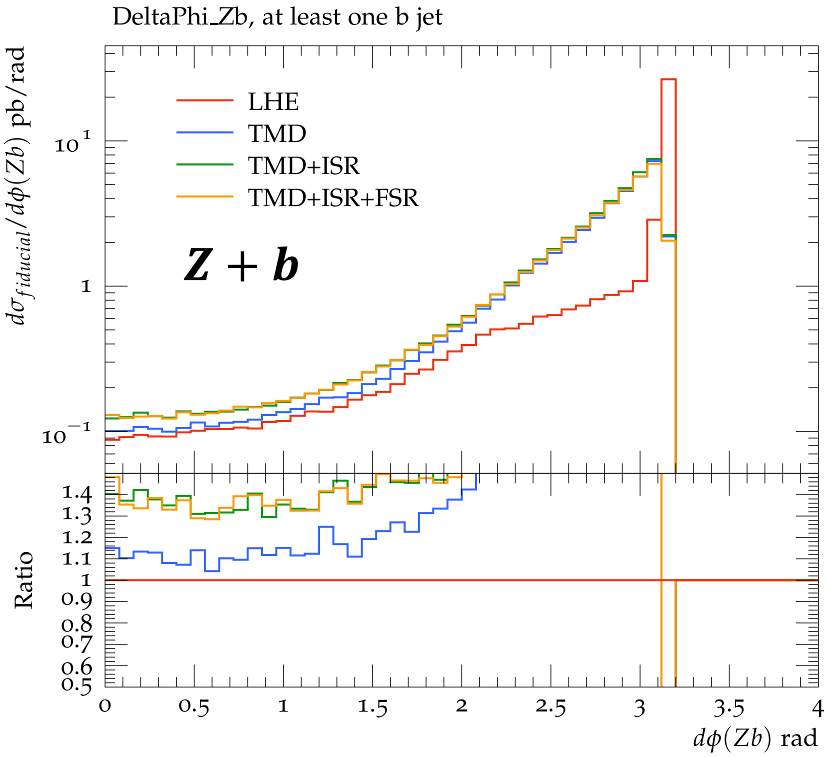
Leading and subleading b-jet pT Z+ bb (4FL vs 5FL)



- Consistent descriptions from PB-TMDs 4FL and 5FL approaches.
- Scale uncertainty show as a band.

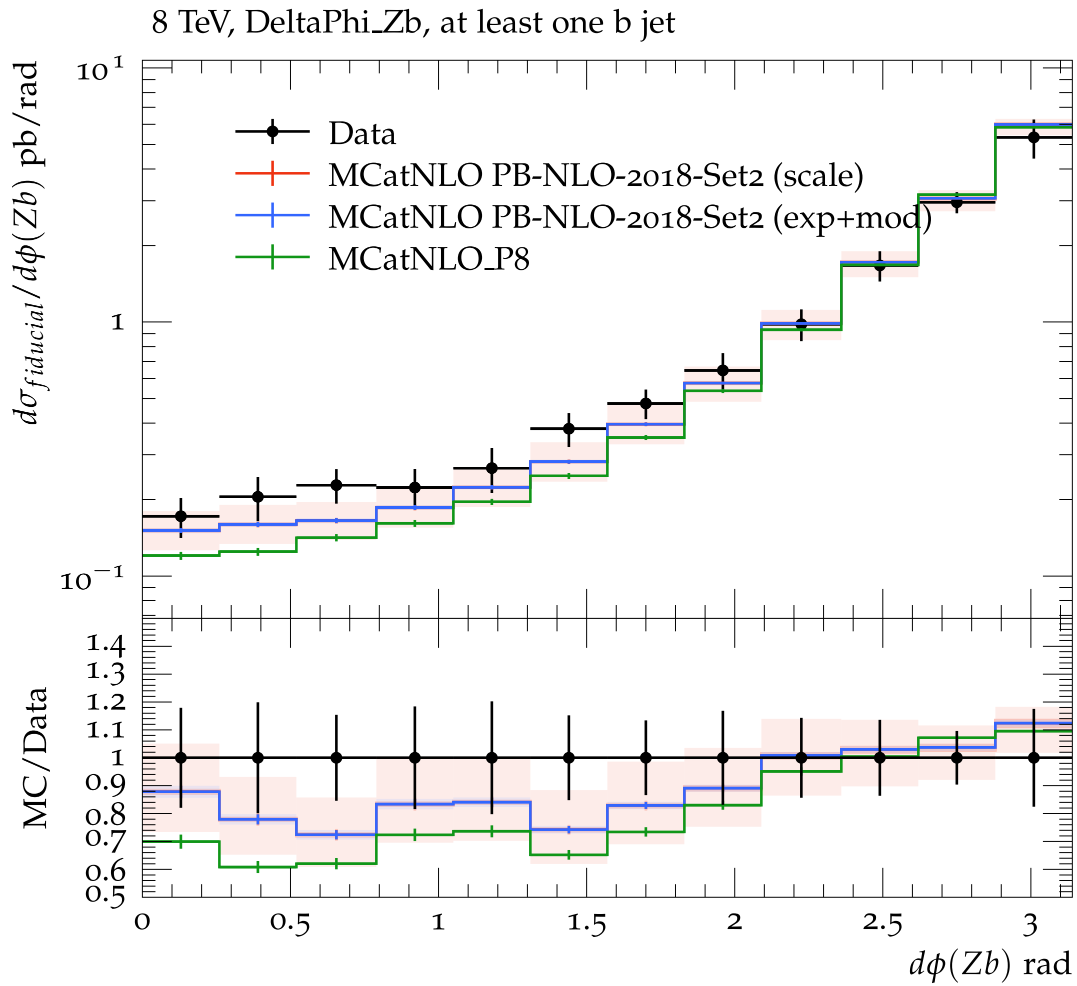
$Z + b\ \Delta\phi$: sensitivity to initial state kT





- ○ **TMD** is clearly important at large $\Delta\phi$ specially in $\boldsymbol{Z + b}$.
- ○ **ISR** (TMD space shower) only small effect at small $\Delta\phi$ on top of **TMD**.
- ○ **FSR** (Pythia6 time shower) almost no effect on top of **TMD** and **ISR**.

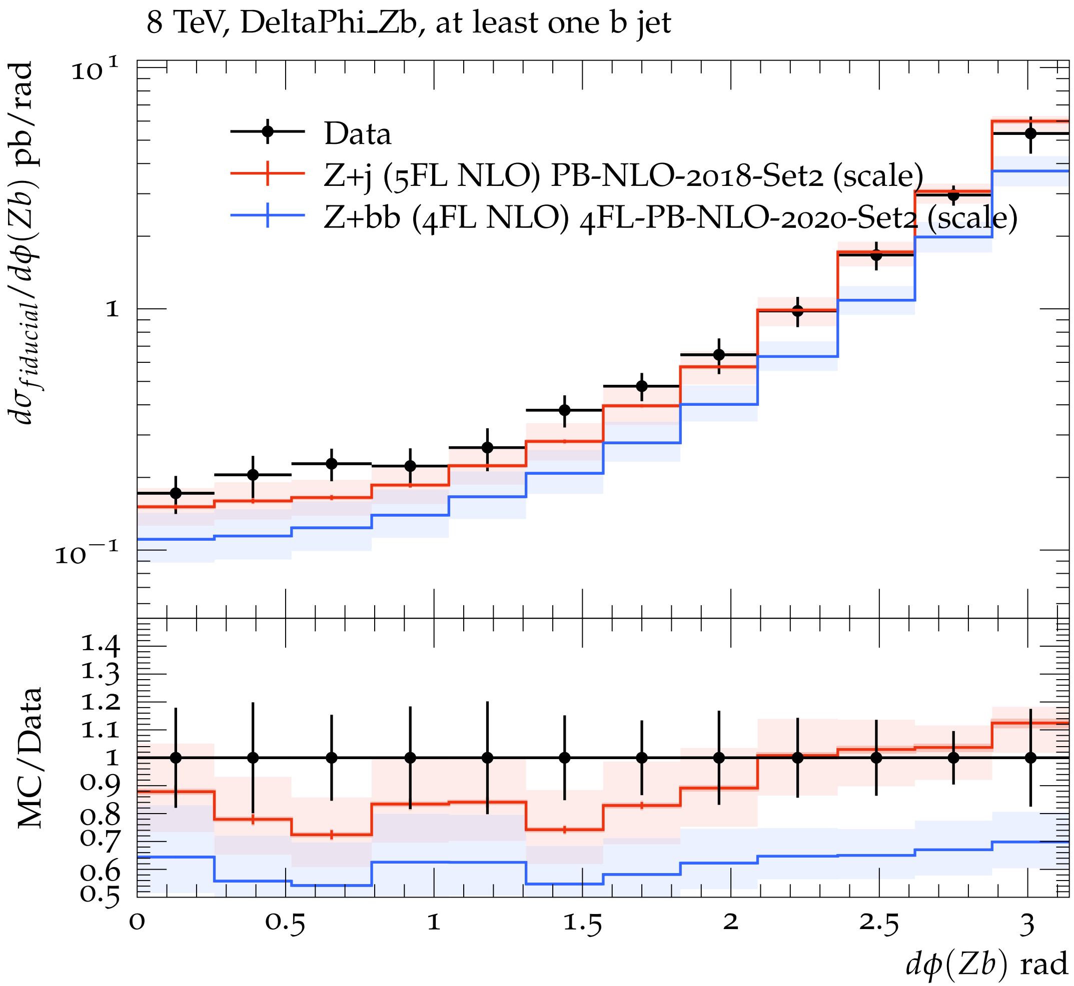
$Z + b\ \Delta\phi$: comparison to measurement



- Good description in the back-to-back region where TMD effects are relevant.
- Decorrelation comes essentially from the kT in the initial evolution.
- Initial and final showers are less important (see previous slides)
- Distribution essentially determined from PBTMD evolution.

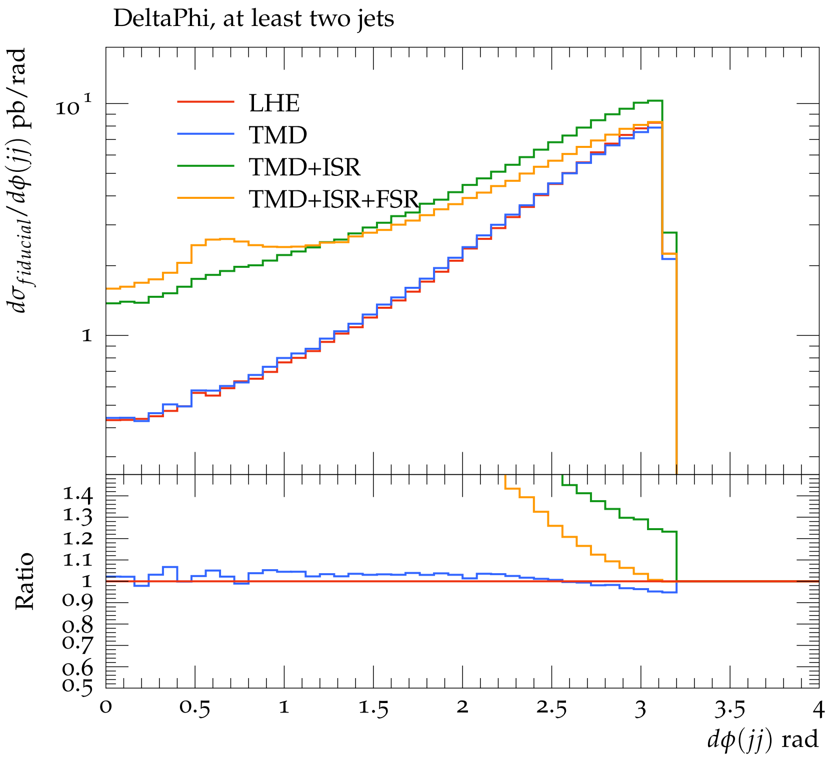
Z + b-jet correlation tests TMD

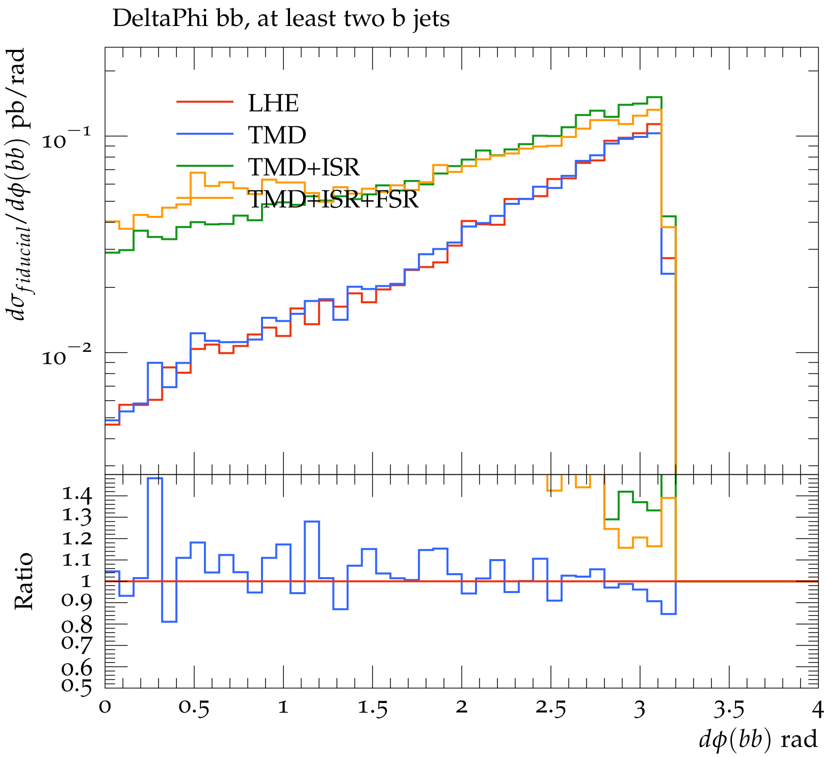
$Z + b$ $\Delta\phi$: comparison to measurement



- Good description in the back-to-back region where TMD effects are relevant.
- Decorrelation comes essentially from the kT in the initial evolution.
- From the difference between the predictions (5FL and 4FL) we can clearly see the contribution from the b-quark content of the proton.
- Scale uncertainty dominates.

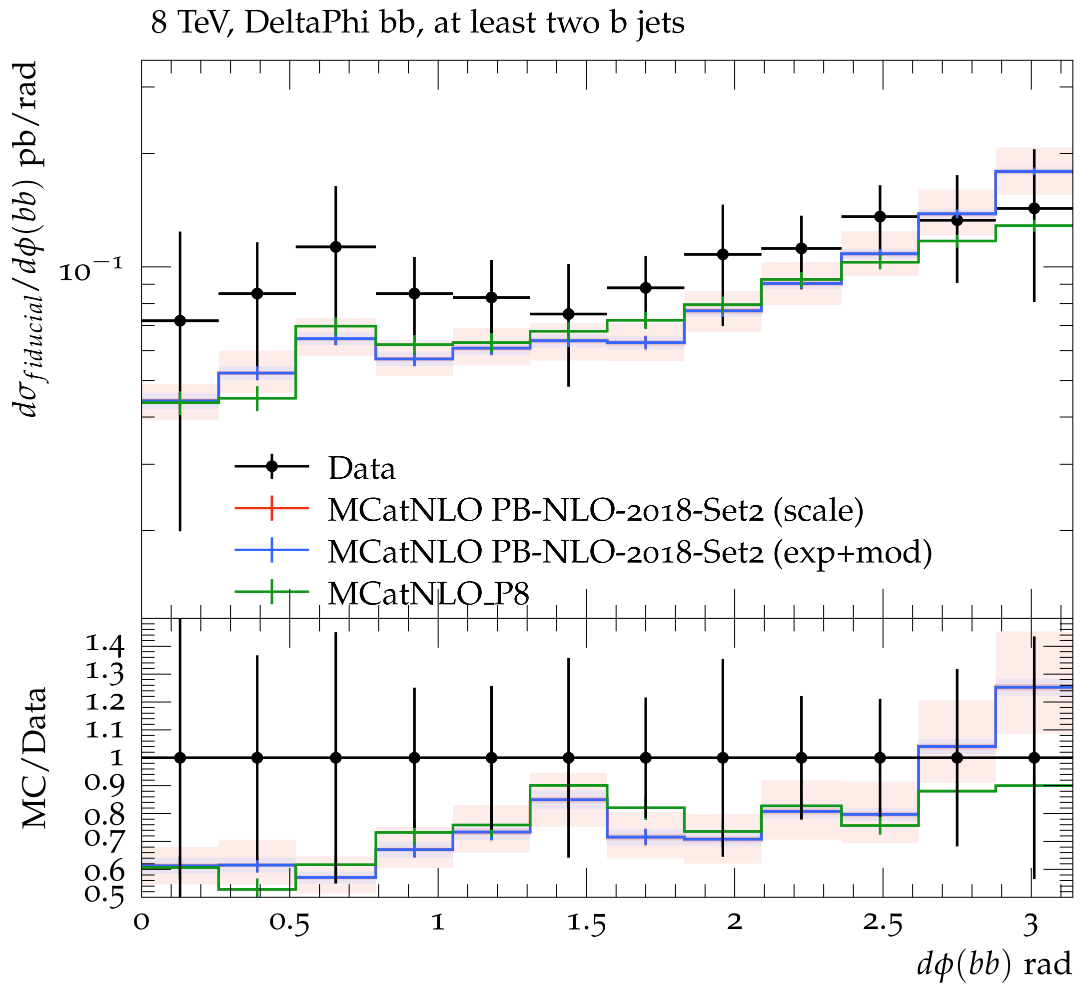
$Z + bb$: sensitivity TMD initial state shower


DeltaPhi, at least two jets


DeltaPhi bb, at least two b jets

- **TMD** has almost no effect.
- **ISR** (TMD initial state shower) has a large effect on top of **TMD**.
- FSR (Pythia6 time shower) significant at small $\Delta\phi$ on top of **TMD** and **ISR**.

$Z + bb$: Comparison to data (5FL)

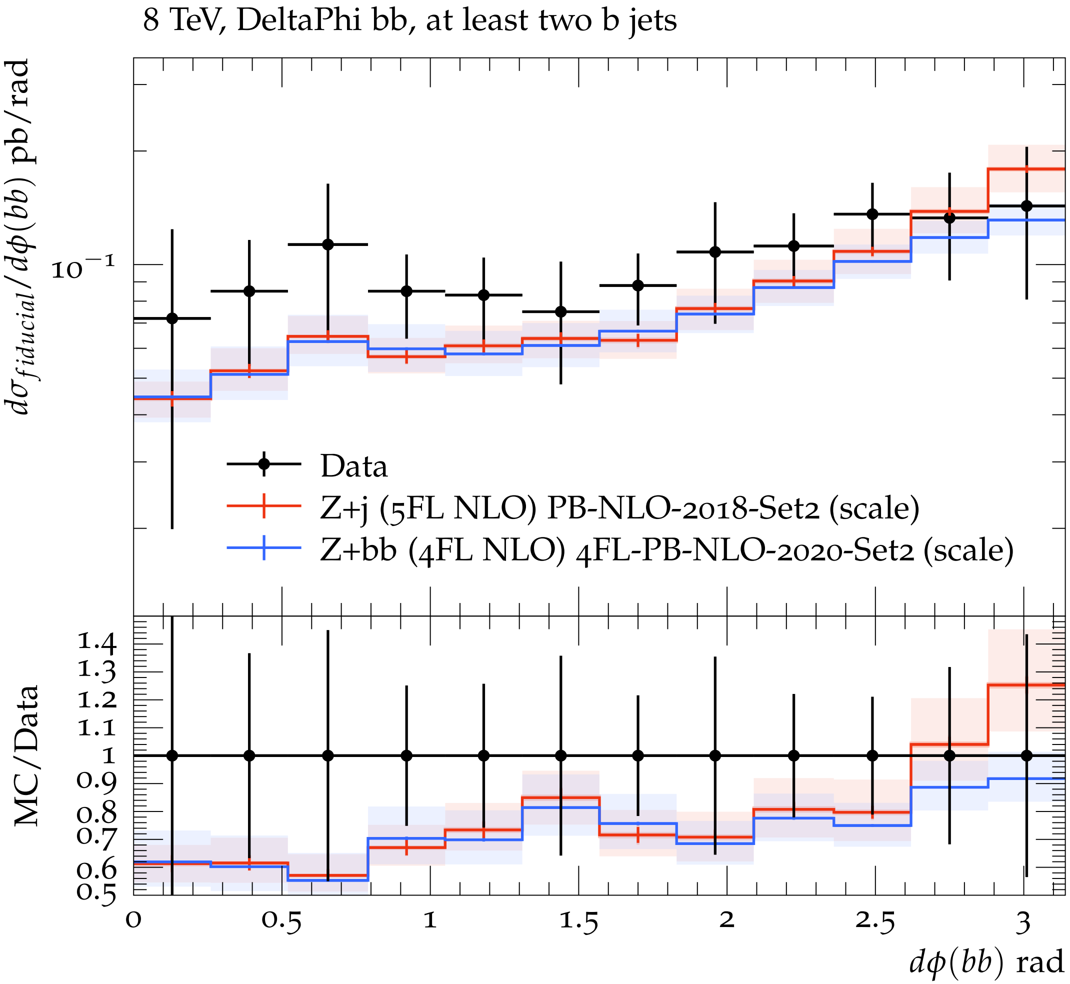


- ○ Good description in the back-to-back region where TMD effects are relevant.
- ○ Decorrelation comes essentially from the kT in the initial evolution.
- ○ Space shower (ISR) is important
- ○ Time shower (FSR) only at small $\Delta\phi$(bb)
- ○ Scale uncertainty dominates.

Sensitive to b-quark TMD density and b-quark TMD shower

bb correlation tests space shower

$Z + bb$: Comparison to data (4FL vs 5FL)



- Good description in the back-to-back region where TMD effects are relevant.
- Decorrelation comes essentially from the kT in the initial evolution.
- Nice consistency between 5FL and 4FL schemes since this measurement is mainly sensitive to ISR.

Conclusions

- New application to Z + b jets with PBTMD 4FL and 5FL scheme.
- Distributions well described (scale uncertainty dominates over experimental uncertainties)
- Regions of sensitivity to TMD and space shower identified:
    - B-quark TMD density AND b-quark TMD shower.
- Z + b jets interesting analysis for studying initial state parton radiation in very detail: TMDs and TMD showers.

Thank you

BACKUP : DGLAP evolution solution

- Differential form of DGLAP equation:

$$\mu^2 \frac{\partial f(x,\mu^2)}{\partial \mu^2} = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P_+(z) f\left(\frac{x}{z}, \mu'^2\right)$$

$$\Delta_s(\mu^2) = exp\left(-\int^{z_M} dz \int_{\mu_o^2}^{\mu^2} \frac{\alpha_s}{2\pi} \frac{d\mu'^2}{\mu'^2} P^{(R)}(z)\right)$$

- Then using f / Δ_s in the differential DGLAP we can get the integral form:

$$f(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2) + \int \frac{dz}{z} \int \frac{d\mu'^2}{\mu'^2} \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^{(R)}(z)\, f\left(\frac{x}{z}, \mu'^2\right)$$

BACK UP: DGLAP evolution solution

$$f(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2) + \int \frac{dz}{z}\int \frac{d\mu'^2}{\mu'^2}\,\frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)}\,P^{(R)}(z)\, f\left(\frac{x}{z},\mu'^2\right)$$

- Solve integral equation via iteration:

$$f_o(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2)$$

$$f_1(x,\mu^2) = f(x,\mu_o^2)\,\Delta_s(\mu^2) + \int_{\mu_o^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\,\frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)}\int^{z_M}\frac{dz}{z}\,P^{(R)}(z)\, f\left(\frac{x}{z},\mu_o^2\right)\Delta_s(\mu'^2)$$

Branching at μ'

from μ_o to μ'
w/o branching

from μ' to μ
w/o branching