TMD densities at leading and higher order from the Parton Branching method

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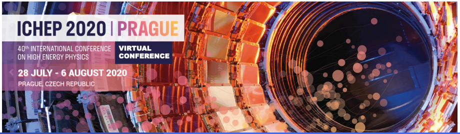
A. Bermudez Martinez, P.L.S. Connor, D. Dominguez Damiani, L.I. Estevez Banos, F. Hautmann, H. Jung, J. Lidrych, A. Lelek, M. Schmitz, Q. Wang, H. Yan



Outline

1. **Recap of Parton Branching method**
2. **Determination of PDFs at 5FL-LO, 5FL-NLO & 4FL-NLO**
3. **What is the gain with exclusive evolution?**

Recap of Parton Branching method

- Including the Δ_s in to the differential form of the DGLAP eq.

$$\mu^2 \frac{\partial}{\partial \mu^2} \frac{f(x,\mu^2)}{\Delta_s(\mu^2)} = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} \frac{\mathcal{P}(z)}{\Delta_s(\mu^2)} f(\frac{x}{z},\mu^2)$$

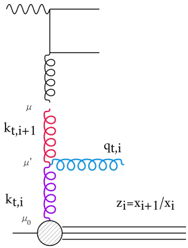
- Integral form with a very simple physical interpretation:

$$f(x,\mu^2) = f(x,\mu_0^2)\Delta_s(\mu^2) + \int \frac{dz}{z} \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^R(z) f(\frac{x}{z},\mu'^2)$$

- Solve integral equation via iteration:

$$f_0(x,\mu^2) = f(x,\mu_0^2)\ \Delta_s(\mu^2)$$

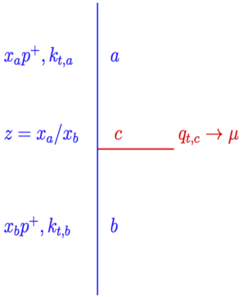
$$f_1(x,\mu^2) = f(x,\mu_0^2)\ \Delta_s(\mu^2) + \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} \int \frac{dz}{z} P^R(z) f(x/z,\mu_0^2)\Delta(\mu'^2)$$



- iterating with second branching and so on to get the full solution

Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step
- give physics interpretation of evolution scale:
  - in high energy limit: p_T-ordering: $\mu = q_T$
  - angular ordering: $\mu = q_T/(1-z)$



Determination of PDFs

PDFs from PB method: fit to HERA data

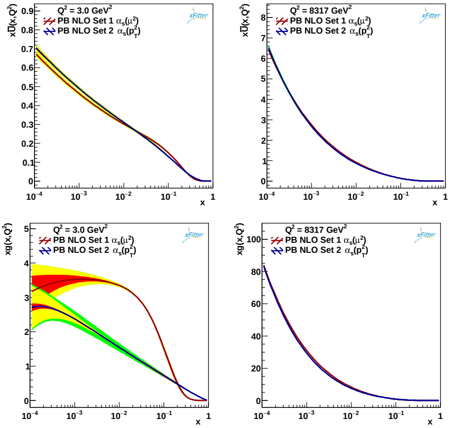
- A kernel obtained from the MC solution of the evolution equation for any initial parton
- Kernel is folded with the non-perturbative starting distribution

$$
\begin{aligned}
xf_a(x,\mu^2) &= x \int dx' \int dx'' \mathcal{A}_{0,b}(x')\, \tilde{\mathcal{A}}_a^b(x'',\mu^2)\, \delta(x'x''-x) \\
&= \int dx'\, \mathcal{A}_{0,b}(x') \cdot \frac{x}{x'}\, \tilde{\mathcal{A}}_a^b(\frac{x}{x'},\mu^2)
\end{aligned}
$$

- Fit performed using xFitter frame (with collinear Coefficient functions at both **LO & NLO**)
- LO PDFs are of especial interest for MC event generators, based on LO ME + PS.
  - full coupled-evolution with all flavors
  - using full HERA I+II inclusive DIS (neutral current, charged current) data
  - $3.5 < Q^2 < 50000$ GeV^2 & $4.10^{-5} < x < 0.65$
- Can be easily extended to include any other measurement for fit.

A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).

Standard 5FL-NLO full fit with different scale in α_s



- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.21$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.21$

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- fits are as good as HERAPDF2.0.
- very different gluon distribution obtained at small Q^2
- the differences are washed out at higher Q^2

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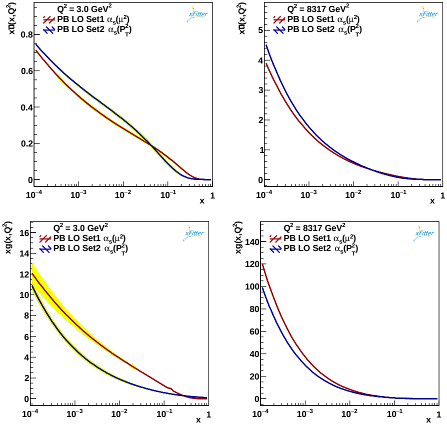
Standard 5FL-LO full fit with different scale in α_s

LO TMDs are important for LO multi-jet merging $\rightarrow$ **will be presented by Armando**



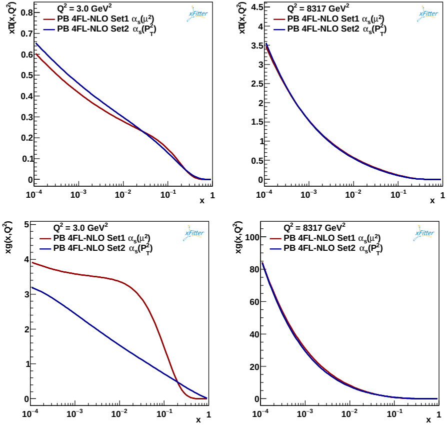
- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.24$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.37$

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- very different gluon distribution obtained at small and large Q^2
- the uncertainty is smaller at LO compared to NLO

Standard 4FL-NLO full fit with different scale in α_s

NEW

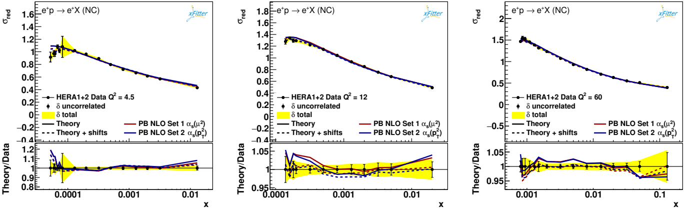


- Set1-$\alpha_s(\mu^2) \to \chi^2/dof = 1.20$
- Set2-$\alpha_s(p_T^2) \to \chi^2/dof = 1.23$

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\,(1+E_{u_v}x^2)\,,$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}\,,$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\,(1+D_{\bar{U}}x)\,,$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}\,.$$

- very different gluon distribution obtained at small Q^2
- the differences are washed out at higher Q^2

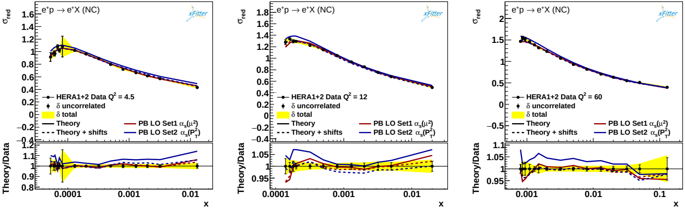
How well can we describe inclusive DIS cross section with the two sets at NLO?



A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).

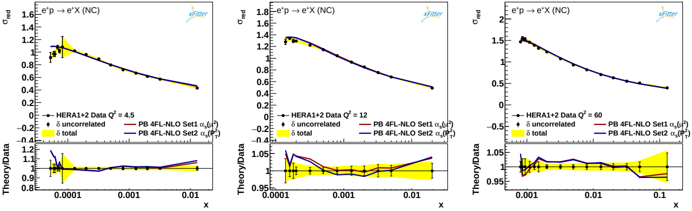
Fit to DIS x-section at 5FL-LO: F_2

How well can we describe inclusive DIS cross section with the two sets at LO?



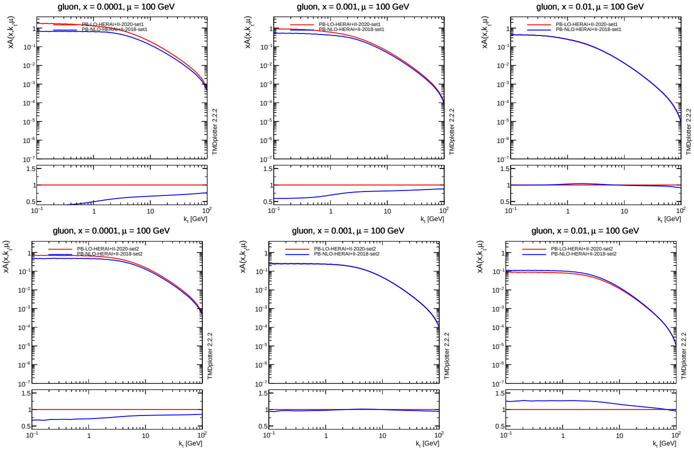
Fit to DIS x-section at 4FL-NLO: F_2

How well can we describe inclusive DIS cross section with the two sets at 4FL-NLO?



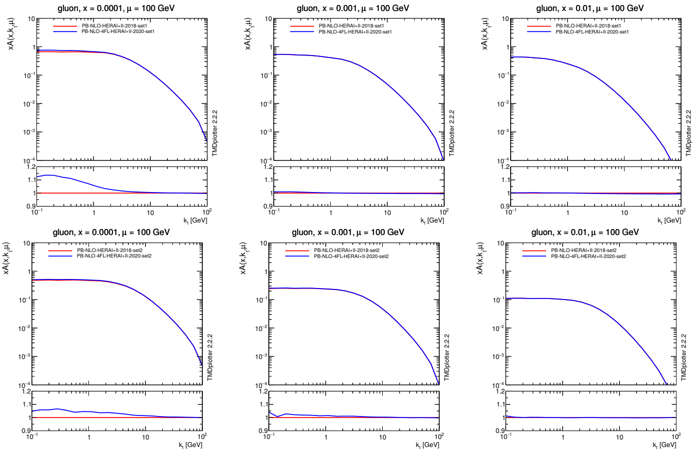
What is the gain with exclusive evolution?

k_t behavior at LO and NLO



- difference coming from different starting distribution and also the evolution
- with the same starting distribution we still get differences at small k_t
- at larger k_t, more splitting → The differences between LO and NLO are washed out

k_t behavior at 4FL-NLO and 5FL-NLO

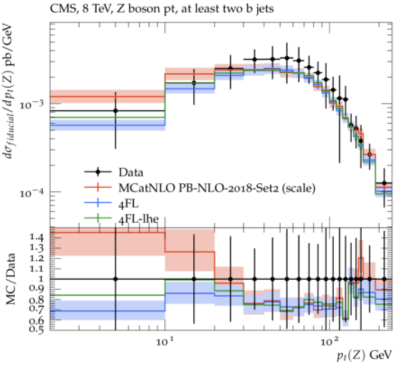


- 4-FL gluon is larger than 5-FL gluon at small kt region.
- at small k_t $\rightarrow$ starting distribution
- at large k_t $\rightarrow$ the differences are washed out due to having more splittings.

PB-TMD, PB-TMD shower & MC@NLO : Z+b jets

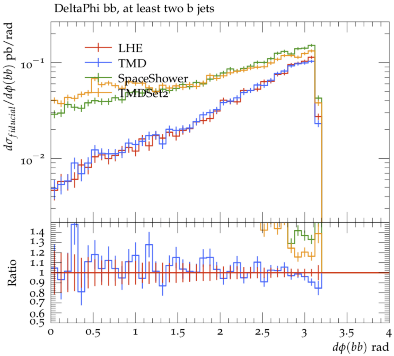
CMS Measurements of the associated production of a Z boson and b jets in pp collisions at 8 TeV, Eur. Phys. J., C77(11), 751, CMS-SMP-14-010, arxiv:1611.06507

- cuts:
  - leptons: $|\eta| < 2.4$, $p_T > 20$ GeV, 71 GeV $< m_{ll} < 111$ GeV
  - jets: anti-k_T, R=0.5, $|\eta| < 2.4$, $p_T > 30$GeV, b-Hadron



- p_t spectrum of z boson is nicely described with the 4FL scheme

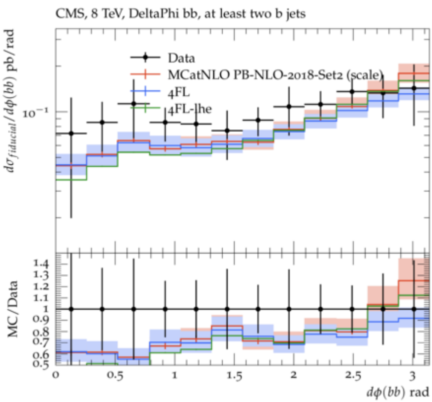
Z+2 jets: sensitivity to initial state shower



- TMD has little impact
- **Initial state PS has significant large effect**
- FSR has contribution at small $\Delta\phi$: $g \to bb$

Z+2b-jets: $\Delta\phi(bb)$ - comparison to measurement

- $\Delta\phi$ between the b-b system is well described with the 4FL scheme



- bb correlation tests space shower
- Space shower is important
- Time shower only at small $\Delta\phi(bb)$
- sensitive to b-quark TMD density and b-quark TMD-shower

Conclusion

- PB method to solve DGLAP equation at LO, NLO, NNLO.
  - advantages of PB method (angular ordering)
- method directly applicable to determine k_t distribution (as would be done in PS)
  - TMD distributions for all flavors determined at LO & NLO
- Application to pp processes:
  - NEW: application to Z+b-jets
  - Z+b-jets interesting tool for studying initial state parton radiation in very detail: TMD and TMD showers

Backup

Evolution equation and parton branching method

- use momentum weighted PDFs with real emission probability

$$
\begin{aligned}
xf_a(x,\mu^2) &= \Delta_a(\mu^2) xf_a(x,\mu_0^2) \\
&+ \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_s(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz \; P_{ab}^R(\alpha_a, z) \, \frac{x}{z} \, f_b(x/z, \mu^2)
\end{aligned}
$$

- due to step by step individual branchings, all kinematics can be calculated exactly.
- z_M introduced to separate real from virtual and non-resolvable branching
- reproduces DGLAP up to $\mathcal{O}(1 - z_M)$
- make use of momentum sum rule to treat virtual corrections
- use Sudakov form factor for non-resolvable and virtual corrections

$$
\Delta_a(z_M, \mu^2, \mu_0^2) = exp\left(- \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz \; z \; P_{ba}^R(\alpha_s, z) \right)
$$

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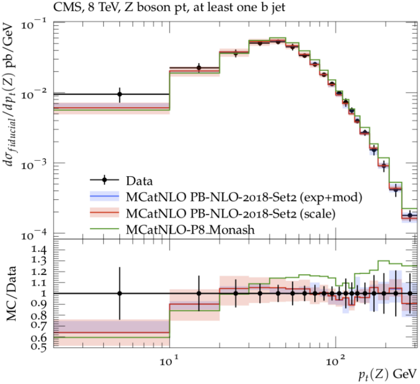
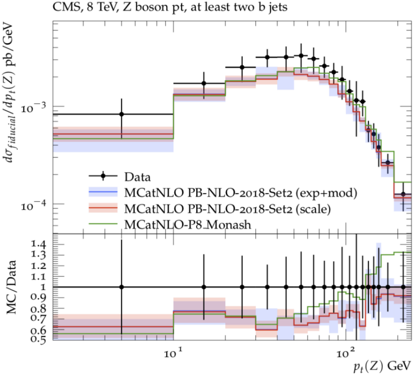
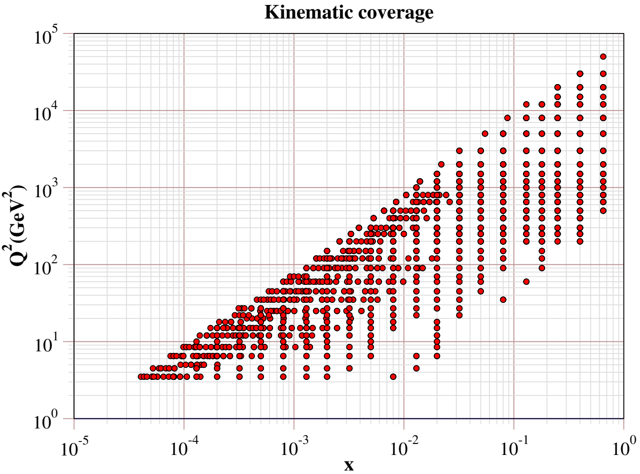




- comparison PB-TMD and P8 shower shows good agreement
- differences in details

Kinematic coverage of the HERA data in the (x, Q^2) plane

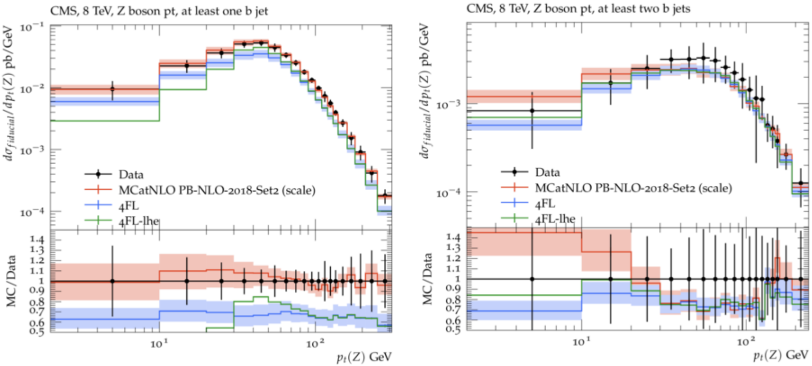
- This is mainly small Q^2 effects rather than small x one.



- Going from $Q_{min} = 3.5$ to 5 GeV^2, no obvious change on x while χ^2 change significantly.
- No x dependence $\rightarrow$ No direct need for any small-x modification

PB-TMD, PB-TMD shower & MC@NLO : Z+b jets

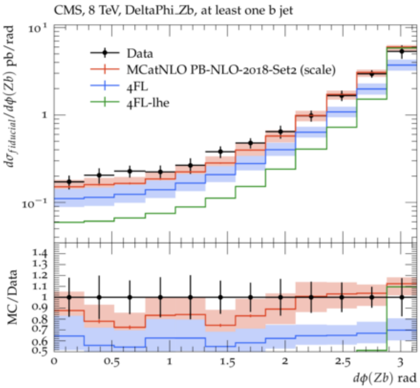
comparison between 4FL-PB-TMD and 5FL-PB-TMD



- 5 FL is better for one b jet
- TMD important at large $\Delta\phi$

z+b-jets: $\Delta\phi(Zb)$-comparison to measurements II

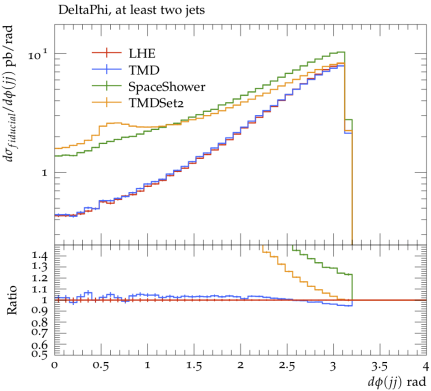
comparison between 4FL-PB-TMD and 5FL-PB-TMD



PB-TMD, PB-TMD shower & MC@NLO : Z+b jets

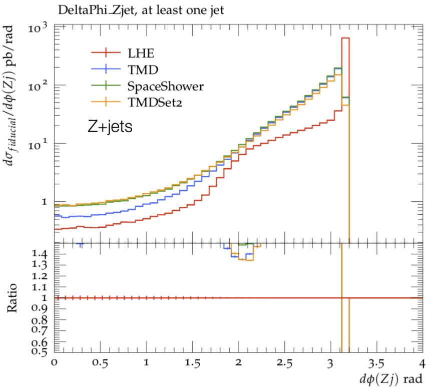
- MC@NLO for Z+b : (**5-FL scheme** & **4-FL scheme**)
- using herweg6 subtraction terms
- PB-TMD to generate initial state k_T
- initial state parton shower following PB TMD
- uncertainties:
  - MC@NLO for Z+b : (5-FL scheme & 4-FL scheme)
  - using herweg6 subtraction terms
  - PB-TMD to generate initial state k_T
  - initial state parton shower following PB TMD

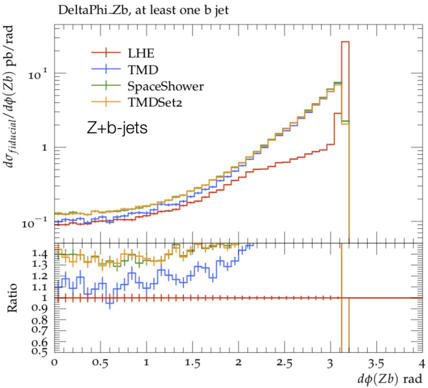
Z+2 jets: sensitivity to initial state shower



- TMD has little impact
- Initial state PS has only small effect
- FSR has significant contribution at small $\Delta\phi$: $g \to bb$

Z+jets: sensitivity to initial state k_T





- TMD important at large & small $\Delta\phi$
- Initial state PS at small $\Delta\phi$
- FSR only small effect at large $\Delta\phi$

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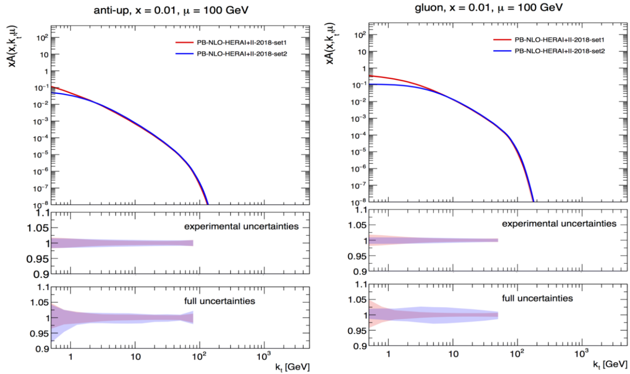
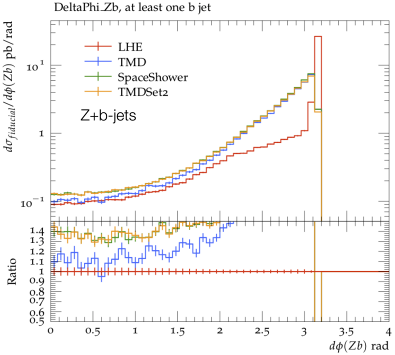
TMD distributions from fit to HERA data



- Different shape and dependence of the uncertainty as a function of k_t.
- Model dependence larger than experimental uncertainties.
- Difference essentially in low k_t region.
- Introducing p_T instead of μ suppresses further soft gluons at low k_t.

A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).

Z+b-jets: sensitivity to initial state k_T

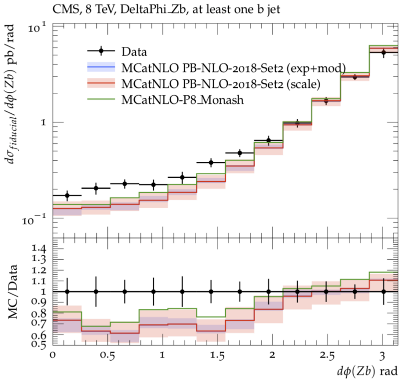


- **TMD important at large $\Delta\phi$**
- Initial state PS only small effect
- FSR only small effect at large $\Delta\phi$

z+b-jets: $\Delta\phi(Zb)$-comparison to measurements

- Good description in large $\Delta\phi$ region where TMD effects are relevant

Z+b correlation tests TMD

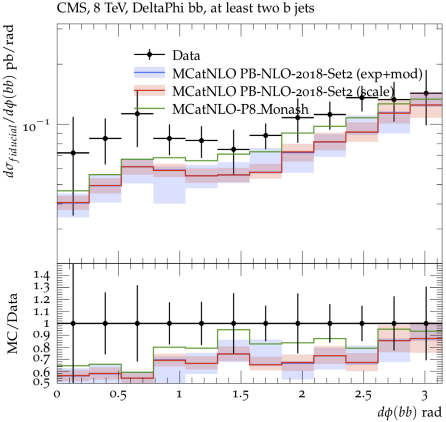


- decorrelation comes essentially from k_T from initial evolution
- details of shower are less important (see slide before)
- distributions essentially determined by TMD distribution
- uncertainties only from TMD

Z+2b-jets: $\Delta\phi(bb)$ - comparison to measurement

- Good description

bb correlation tests space shower



- decorrelation comes essentially from k_T from initial evolution
- Space shower is important
- Time shower only at small $\Delta\phi(bb)$
- sensitive to b-quark TMD density and b-quark TMD-shower

PDFs from PB method: fit to HERA data

- two angular ordered sets with different argument in α_s (either μ or q_t)
- q_{cut} in, $\alpha_s(max(q^2_{cut}, |q^2_{t,i}|))$, to avoid the non-perturbative region, $|q^2_{t,i}| = (1 - z_i)^2 \mu_i^2$
- for both LO & NLO:
  - $\mu_0^2 = 1.9$ GeV^2 for set1 (as in HERAPDF)
  - $\mu_0^2 = 1.4$ GeV^2 for set2 (the best χ^2/dof)
- fits to HERA measurements performed using χ^2/dof minimization
- the experimental uncertainties defined with the Hessian method with $\Delta\chi^2 = 1$.
- the model dependence obtained by varying charm and bottom masses and μ_0^2.
- the uncertainty coming from the q_{cut} in set2

	Central value	Lower value	Upper value
PB Set1 μ_0^2 (GeV^2)	1.9	1.6	2.2
PB Set 2 μ_0^2 (GeV^2)	1.4	1.1	1.7
PB Set 2 q_{cut} (GeV)	1.0	0.9	1.1
m_c (GeV)	1.47	1.41	1.53
m_b (GeV)	4.5	4.25	4.75

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