Parton Branching TMD distributions

Sara Taheri Monfared

Deutsches Elektronen-Synchrotron (DESY)

xFitter workshop 2020-DESY

On be half of

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 LO and NLO**
3. **What is the gain with exclusive evolution?**
4. **Application of PB TMDs to DY production**

Recap of Parton Branching method

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

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

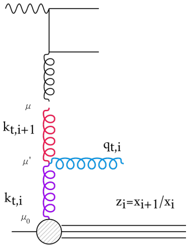
- Integral form with a very simple physical interpretation:

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

- 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

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

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

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

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

- 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).

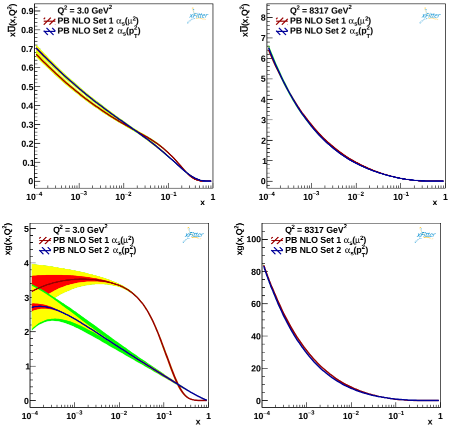
PDFs from PB method: fit to HERA data

- 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

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

Standard NLO full fit with different scale in α_s



- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.2$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.21$

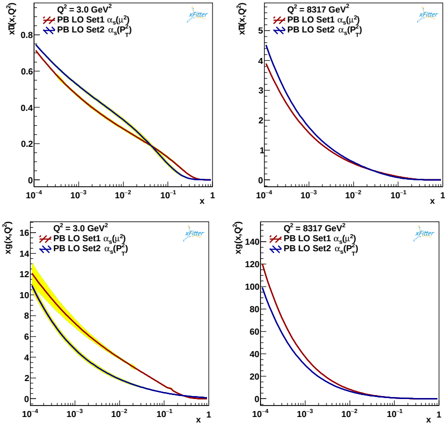
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right),\\
x\bar{D}(x)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

- 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

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

Standard LO full fit with different scale in α_s

NEW!



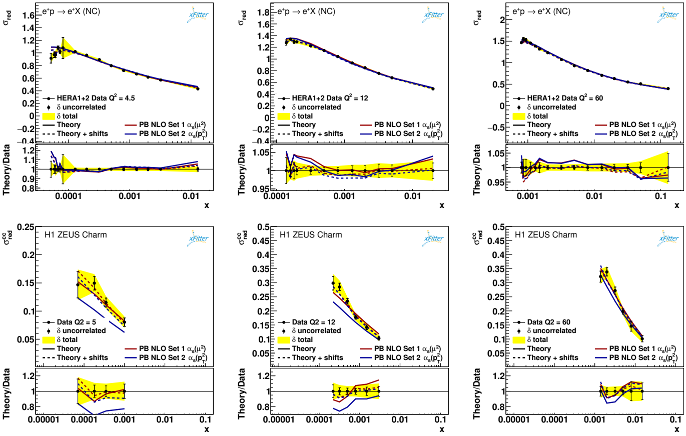
- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.24$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.37$

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

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

Fit to DIS x-section at NLO: F_2 and F_2^c

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

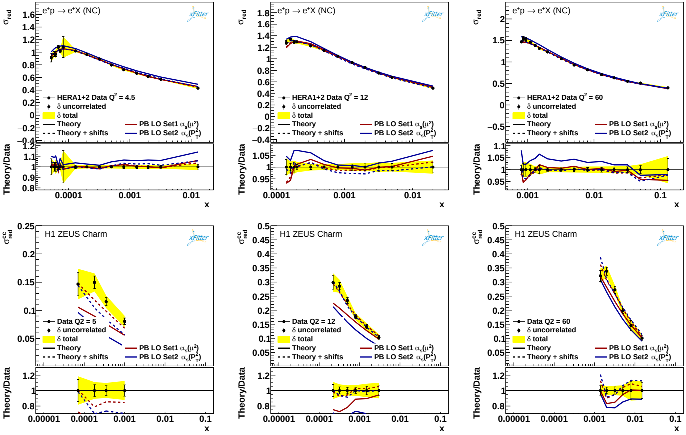


A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).

Fit to DIS x-section at LO: F_2 and F_2^c

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

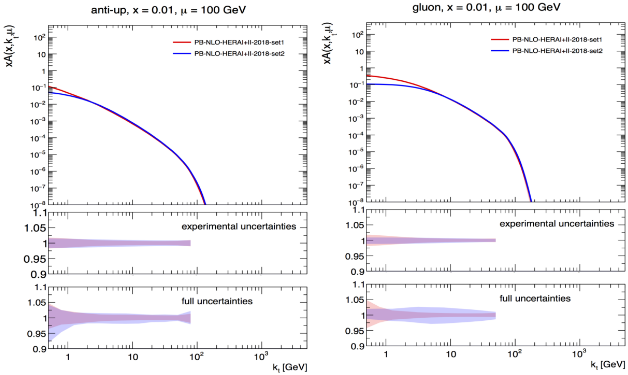
NEW!



- Inclusive charm production measurements are within systematic shifts in theory prediction.

What is the gain with exclusive evolution?

TMD distributions from fit to HERA data



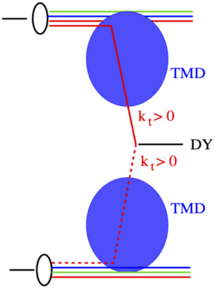
- Different shape and dependence of the uncertainty as a function of k_t.
- Model dependence larger than experimental uncertainties.
- Difference essentially in low k_t region.
- Introducing p_T instead of μ suppresses further soft gluons at low k_t.

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

Application to DY q_T- spectrum

- fixed-order purturbative calculations cannot describe transverse momentum spectrum of Z bosons in DY at small q_T.

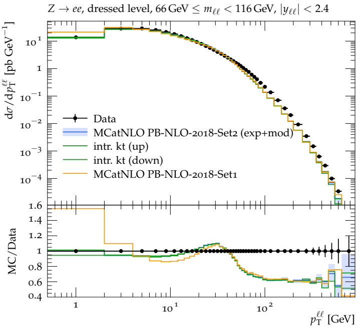
- Use collinear ME $q\bar{q} \to z_0$
- add k_t for each parton as function of x and μ according to TMD
- keep final state mass fixed:
  - x_1 and x_2 are different after adding k_t



Application to DY q_T- spectrum

Transverse momentum spectrum of Z-bosons obtained from two **NLO** TMDs, compared with ATLAS measurements. :

- TMD with angular ordering including $\alpha_s(\mu^2)$
- TMD with angular ordering including $\alpha_s(p_T^2)$



ATLAS Collaboration Eur. Phys. J. C76 (2016),291, arXiv:1512.02192 [hep-ph].
A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).
A. Bermudez Martinez *et al.*, Phys. Rev. D **100**, no. 7, 074027 (2019).

What happens at small m_{DY} and small $\sqrt{s}$?

- at low mass p_T of DY is dominated by **intrinsic** k_t and by **soft gluons**, which need to be resummed
- measurements available at low DY mass & at low energies:
  - latest measurements: PHENIX (PHYSRevD.99.072003) at $\sqrt{s} = 200$ GeV for $4.6 \leq m_{DY} \leq 8.2$ GeV
  - R209 (1982-PhysRevLett.48.302) at $\sqrt{s} = 62$ GeV (data read from plot in paper)
  - NUSEA (2003-hep-ex/0301031) at $\sqrt{s} = 38$ GeV (unpublished)
- Can PB method with MC@NLO be applied to small $\sqrt{s}$?
  - Is there a small p_T crisis?

The difficulties at small q_T and small $\sqrt{s}$

PHYSICAL REVIEW D **100,** 014018 (2019)

Difficulties in the description of Drell-Yan processes at moderate invariant mass and high transverse momentum

Alessandro Bacchetta,[1,2,*] Giuseppe Bozzi,[1,2,†] Martin Lambertsen,[3,‡] Fulvio Piacenza,[1,2,§] Julius Steiglechner,[3,∥] and Werner Vogelsang[3,¶]

[1]*Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy*
[2]*INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy*
[3]*Institute for Theoretical Physics, Tübingen University, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*

(Received 30 January 2019; published 22 July 2019)

Both regimes, $q_T \ll Q$ and $q_T \sim Q$, as well as their matching, must be under theoretical control in order to have a proper understanding of the physics of the Drell-Yan process. In the present work, we study the process at fixed-target energies for moderate values of the invariant mass Q and in the region $q_T \lesssim Q$. We focus on the predictions based on collinear factorization and examine their ability to describe the experimental data in this regime. We find, in fact, that the predicted cross sections fall significantly short of the available data even at the highest accessible values of q_T. We investigate possible sources of uncertainty in the predictions based on collinear factorization, and two extensions of the collinear framework: the resummation of high-q_T threshold logarithms, and transverse-momentum smearing. None of these appear to lead to a satisfactory agreement with the data. We argue that these findings also imply that the Drell-Yan cross section in the "matching regime" $q_T \lesssim Q$ is presently not fully understood at fixed-target energies.

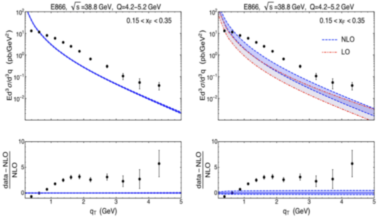
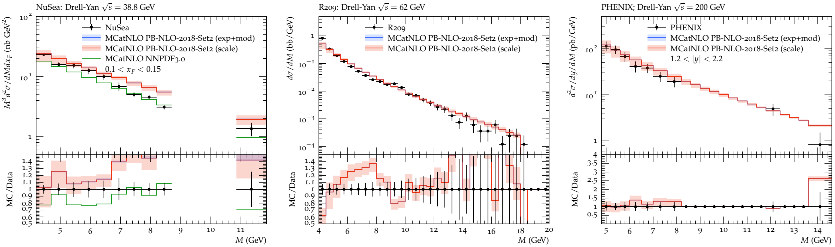


FIG. 2. Transverse-momentum distribution of Drell-Yan dimuon pairs at $\sqrt{s} = 38.8$ GeV in a selected invariant mass range and Feynman-x range: experimental data from Fermilab E866 (hydrogen target) [41] compared to LO QCD and NLO QCD results. (Left panels) NLO QCD $[\mathcal{O}(\alpha_s^2)]$ calculation with central values of the scales $\mu_R = \mu_F = Q = 4.7$ GeV, including a 90% confidence interval from the CT14 PDF set [39]. (Right panels) LO QCD and NLO QCD theoretical uncertainty bands obtained by varying the renormalization and factorization scales independently in the range $Q/2 < \mu_R, \mu_F < 2Q$.

Is there a way to solve this problem?

Comparison with DY mass measurements

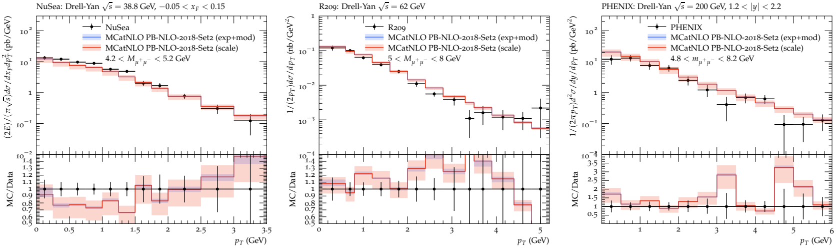
- DY mass distribution well described with PB pdfs



- sensitive only to collinear pdf (nothing to do with TMD)
- at smallest $\sqrt{s}$, large x probed
- pdfs are fitted to HERA data and not well constrained at large x

A. Bermudez Martinez *et al.*, arXiv:2001.06488 [hep-ph].

The DY p_T- spectrum



- DY p_T spectrum well described with MC@NLO+PB-TMDs
- good agreement within uncertainties

	NuSea	R209	PHENIX
χ^2/ndf	1.08	1.27	1.04

- no hint for p_T crisis!

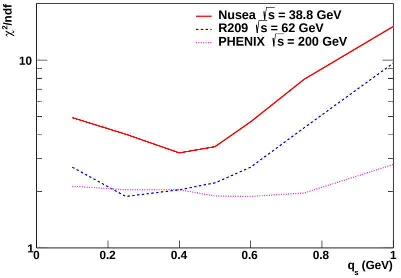
A. Bermudez Martinez *et al.*, arXiv:2001.06488 [hep-ph].

Constraints on intrinsic k_T

- intrinsic k_T is included in starting distribution, for simplicity Gauss is assumed

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

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

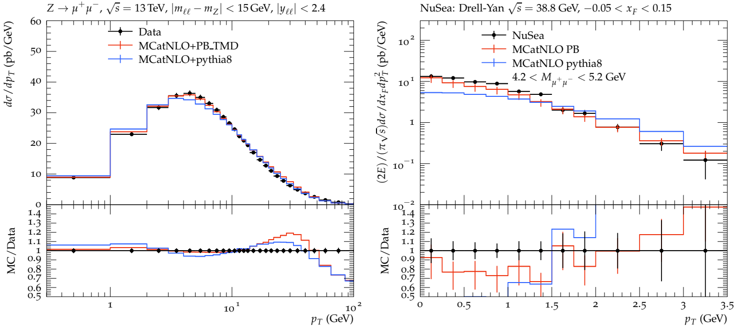


- only at low energies,sensitivity to intrinsic Gauss observed ...
- the scan shows that the guess value of $q_s = 0.5$ GeV is reasonable, although the tendency is a bit smaller value.

A. Bermudez Martinez *et al.*, arXiv:2001.06488 [hep-ph].

Predictions from MC@NLO+PYTHIA8

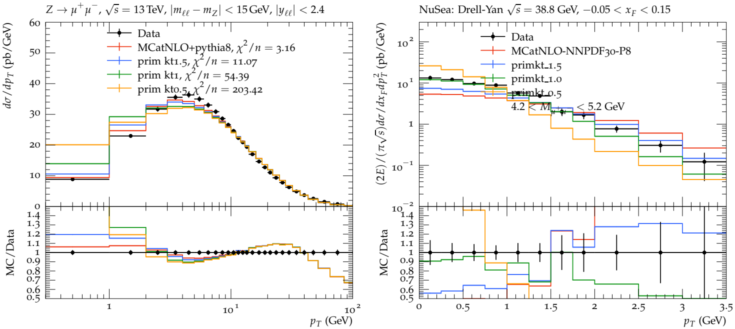
- Do we get the same results if we would run MC@NLO with pythia?



- the MC@NLO calculation is different for different parton shower.
- differences observed using Monash tune in P8
- P8 too high at high energy
- P8 too low at low energy
  - can it be tuned?

Application to DY q_T- spectrum

- We get a significant dependence on intrinsic k_t width.



- the low DY energy is very sensitive to intrinsic k_t width (different shape with different k_t).
- differences observed using Monash tune in P8
- intrinsic kt in P8 cannot be simply tuned to describe both high and low energy data

xFitter: Releases and Updates

The PB in implemented in the the recent xFitter, version 2.1.X.

Conclusion

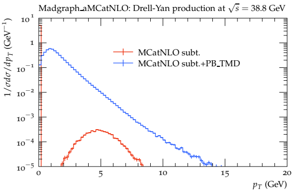
- PB method to solve DGLAP equation at LO, NLO, NNLO.
  - consistent for collinear (integrated) PDFs shown
  - advantages of PB method (angular ordering)
- method directly applicable to determine k_t distribution (as would be done in PS)
  - TMD distributions for all flavors determined at LO & NLO
  - TMD evolution implemented in xFitter -fits to processes at the moment
- Application to pp processes:
  - DY q_T-spectrum without new parameters for z and low mass DY
  - matching TMD with MC@NLO
  - DY q_T-spectrum at low mass and low energies well described (in contrast with pythia predictions)
  - PB TMDs with MC@NLO well describe DY production over wide range
  - proper prediction of low p_T spectrum - needed for m_W determination

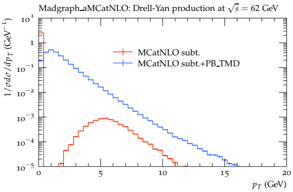
Thank you for your attention

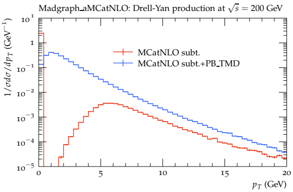
Backup

MC@NLO for small m_{DY} and small $\sqrt{s}$

- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and/or parton shower)
- MC@NLO without shower is unphysical.





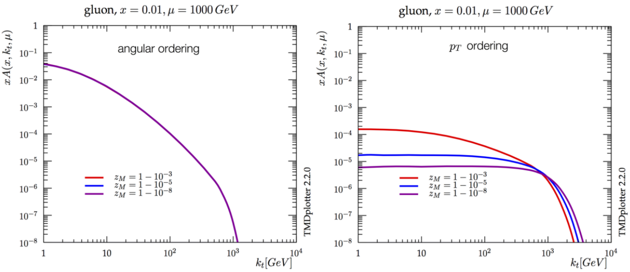


- In very low CM energy, contribution from real 1 parton emission is small
- Contribution of real 1 parton emission increases with $\sqrt{s}$
- NLO corrections are large at small m_{DY} (factor of 2 or more) because scale (m_{DY}) is small and $\alpha_s(m_{DY})$ is large!

A. Bermudez Martinez *et al.*, arXiv:2001.06488 [hep-ph].

Transverse Momentum Dependence

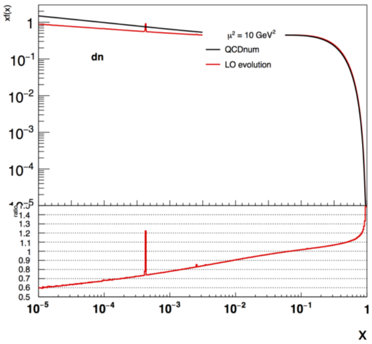
- Parton Branching evolutions generates every single branching. Kinematics can be calculated at every step.
- Give physics interpretation of evolution scale:
  - p_T-ordering : $\mu = q_T$
  - angular ordering : $\mu = q_T/(1-z)$

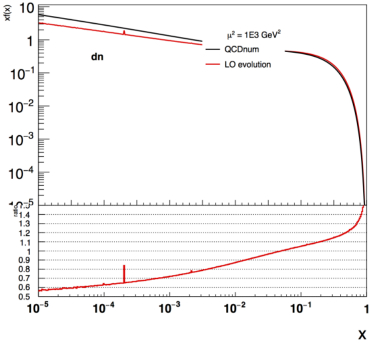


- p_T-ordering shows significant dependence on Z_M: Unstable results because of soft gluon contribution.
- angular ordering is independent of Z_M: stable results since soft gluons are suppressed.

Effect of LO vrs NLO evolution

Using the same starting distribution, but LO or NLO splitting functions





- effect of NLO evolution (α_s and P_{ij}) is very large:$\sim$ 50% for quarks

NB: spikes in plots come from fluctuations in MC solution.