Workshop on “Monte Carlo Event Generators for Future ep and eA Facilities”
Vienna, November 2019

F Hautmann

Parton Branching TMDs and Collider Cross Sections

based on

- Nucl. Phys. B 949 (2019) 114795 [arXiv:1908.08524]
  F Hautmann, L Keersmaekers, A Lelek and A M van Kampen
- Phys. Rev. D 100 (2019) 074027 [arXiv:1906.00919]
  A Bermudez, P Connor, D Dominguez, L Estevez, F Hautmann, H Jung, J Lidrych, M Schmitz, S Taheri, Q Wang and R Zlebcik

Contents

- Introduction to Parton Branching (PB) TMDs
- Matching PB TMDs with NLO in MC@NLO
- Applications to Drell-Yan production at the LHC and at low-energy fixed target experiments

Transverse momentum dependent (TMD) parton distribution functions

- Nonperturbative correlation functions of parton fields needed in QCD factorization theorems to sum classes of logarithmic radiative corrections to all orders in the strong coupling alpha_s

EXAMPLES:

low q_T : $q_T \ll Q$

$\alpha_s^n \ln^m Q/q_T$

low-qT factorization

high $\sqrt{s}$: $\sqrt{s} \gg M$

$(\alpha_s \ln \sqrt{s}/M)^n$

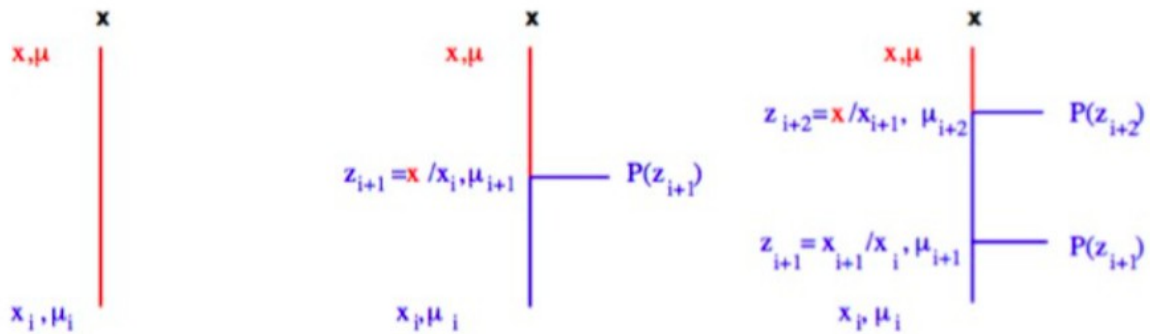
high-energy factorization

- See e.g. R. Angeles-Martinez et al., “Transverse momentum dependent (TMD) parton distribution functions: status and prospects”, Acta Phys. Polon. B46 (2015) 2501

Parton Branching (PB) approach to TMDs

- The evolution of TMD distributions has been recently formulated in a parton branching formalism:

Jung, Lelek, Radescu, Zlebcik & H, "Collinear and TMD quark and gluon densities from parton branching", JHEP 1801 (2018) 070



PB evolution equation motivated by

– applicability over large kinematic range from low to high transverse momenta

– applicability to exclusive final states and Monte Carlo event generators

- connection with DGLAP evolution of collinear parton distributions

PB evolution equation

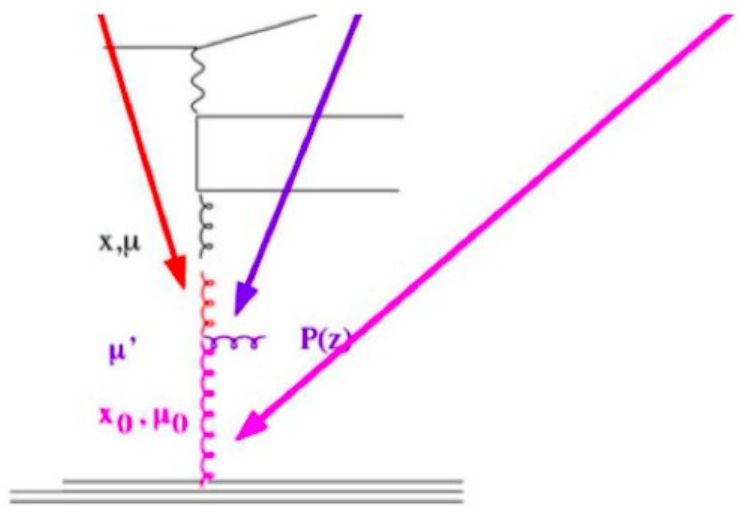
$$\widetilde{A}_a\left(x,\boldsymbol{k},\mu^2\right)=\Delta_a\left(\mu^2,\mu_0^2\right)\widetilde{A}_a\left(x,\boldsymbol{k},\mu_0^2\right)+\sum_b\int\frac{\mathrm{d}^2\boldsymbol{\mu}'}{\pi\mu'^2}\Theta\left(\mu^2-\mu'^2\right)\Theta\left(\mu'^2-\mu_0^2\right)$$

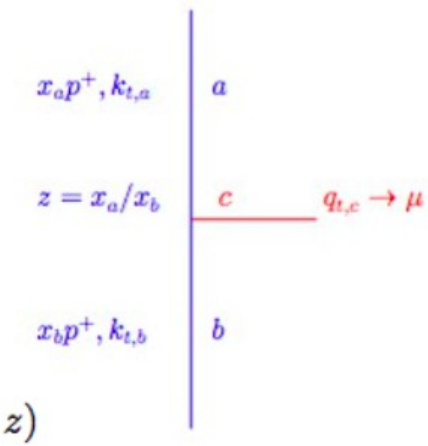
$$\times\quad\int_x^1\mathrm{d}z\,\Theta\left(z_M(\mu')-z\right)\frac{\Delta_a\left(\mu^2,\mu_0^2\right)}{\Delta_a\left(\mu'^2,\mu_0^2\right)}\,P_{ab}^R\left(z,\alpha_s(b(z)^2\mu'^2)\right)\widetilde{A}_b\left(\frac{x}{z},\boldsymbol{k}+a(z)\boldsymbol{\mu}',\mu'^2\right)$$

$$z_M(\mu')=1-q_0/\mu' \qquad b(z)=1-z \qquad a(z)=1-z$$

NB: angular ordering

- solvable by iterative MC technique





$$\mu=|\mathbf{q}_c|/(1-z)$$

where

$$\Delta_a(\mu^2,\mu_0^2)=\exp\left[-\sum_b\int_{\mu_0^2}^{\mu^2}\frac{\mathrm{d}\mu'^2}{\mu'^2}\int_0^1\mathrm{d}z\,\Theta\left(z_M(\mu')-z\right)\,z\,P_{ba}^R\left(z,\alpha_s\left(b(z)^2\mu'^2\right)\right)\right],\qquad P_{ba}^{(R)}(\alpha_s,z)=\delta_{ba}k_b(\alpha_s)\,\frac{1}{1-z}+R_{ba}(\alpha_s,z)$$

$$k_b(\alpha_s)=\sum_{n=1}^{\infty}\left(\frac{\alpha_s}{2\pi}\right)^n k_b^{(n-1)},\quad R_{ba}(\alpha_s,z)=\sum_{n=1}^{\infty}\left(\frac{\alpha_s}{2\pi}\right)^n R_{ba}^{(n-1)}(z)$$

Dynamical soft-gluon resolution scale

- The resolution parameter zM separates hard ("resolvable") color radiation *(yellow regions)* and soft ("non-resolvable") color radiation *(grey regions)*
- This separation depends on the branching scale for evolution. The boundary between "hard" and "soft" varies with mu *(red curve)*.
- Angular-ordered evolution requires that zM varies with mu as

  zM = 1 – q0 / mu.
- q0 has the meaning of minimum transverse momentum with which any emitted parton can be resolved.

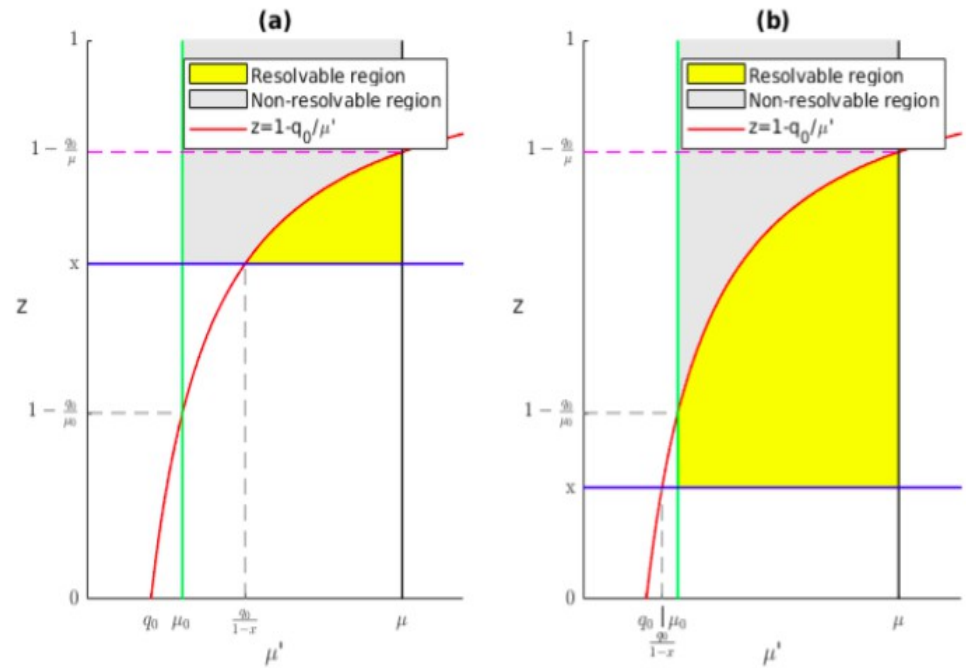


Figure 2: The angular ordering condition $z_M(\mu') = 1 - q_0/\mu'$ with the resolvable and non-resolvabl emission regions in the (μ', z) plane: a) the case $1 > x \geq 1 - q_0/\mu_0$; b) the case $1 - q_0/\mu_0 > x > 0$.

- For x < 1 – q0 / mu0: evolution down to mu0
- For x > 1 – q0 / mu0: evolution down to q0 / (1 – x)

Nucl. Phys. B 949 (2019) 114795

Integrated PB-TMD with angular ordering:

$$\tilde{f}_a(x,\mu^2) = \Delta_a(\mu^2,\mu_0^2)\tilde{f}_a(x,\mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_x^1 dz$$

$$\times \quad \Theta(1-q_0/\mu'-z)\,\frac{\Delta_a(\mu^2,\mu_0^2)}{\Delta_a(\mu'^2,\mu_0^2)}\,P_{ab}^R\left(z,\alpha_s\left((1-z)^2\mu'^2\right)\right)\tilde{f}_b\left(\frac{x}{z},\mu'^2\right)$$

- coincide with CMW result for coherent branching

[Catani-Marchesini-Webber, Nucl. Phys. B349 (1991) 635;

Marchesini-Webber, Nucl. Phys. B310 (1988) 461.]

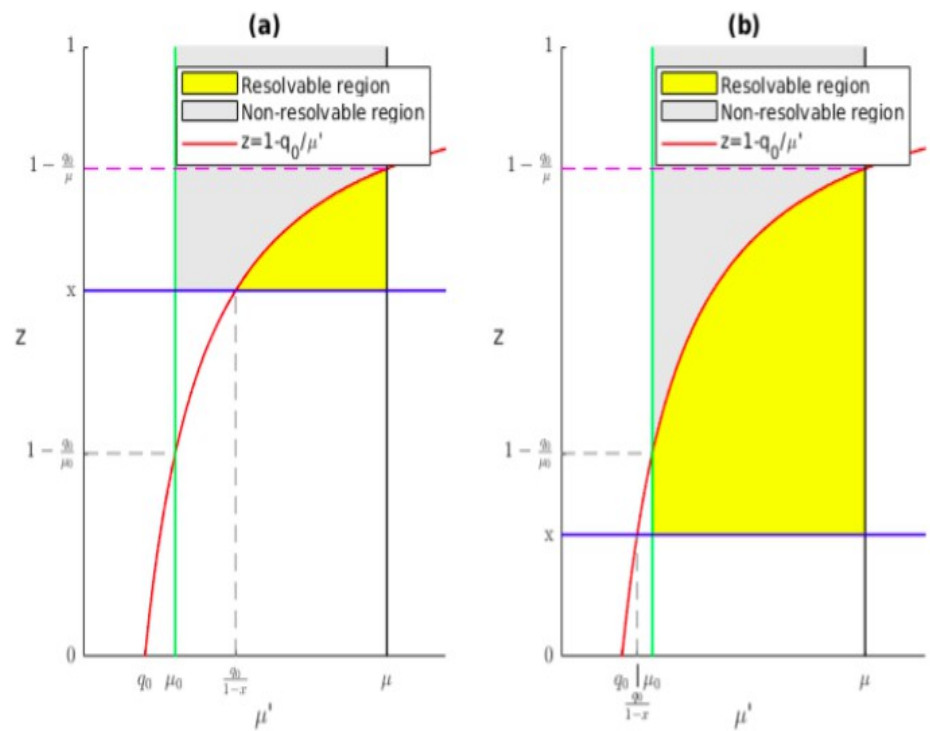
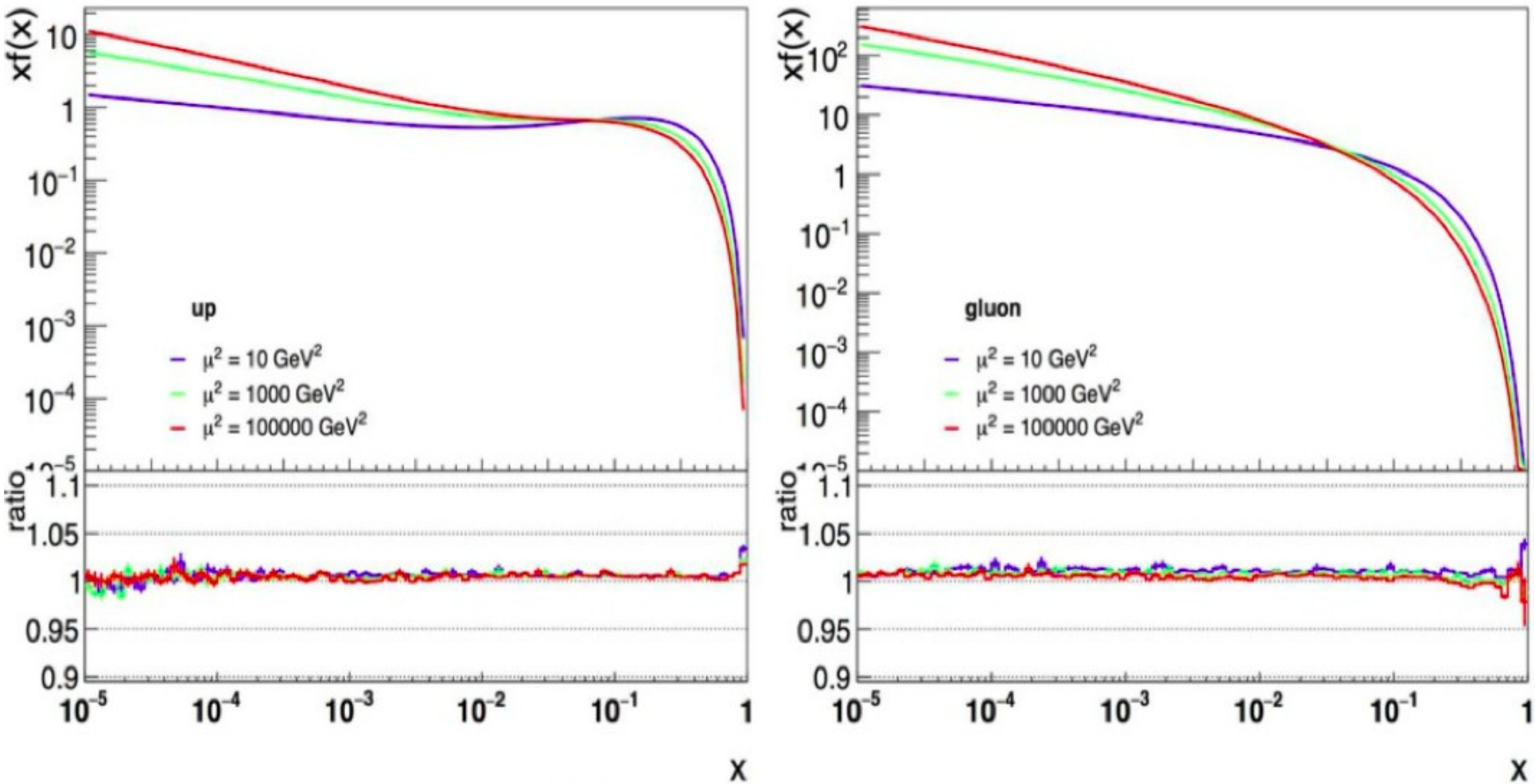


Figure 2: The angular ordering condition $z_M(\mu') = 1 - q_0/\mu'$ with the resolvable and non-resolvable emission regions in the (μ', z) plane: a) the case $1 > x \geq 1 - q_0/\mu_0$; b) the case $1 - q_0/\mu_0 > x > 0$.

Integrated PB-TMD with $z_M \to 1$ and $\alpha_s \to \alpha_s(\mu'^2)$ ---> collinear PDFs



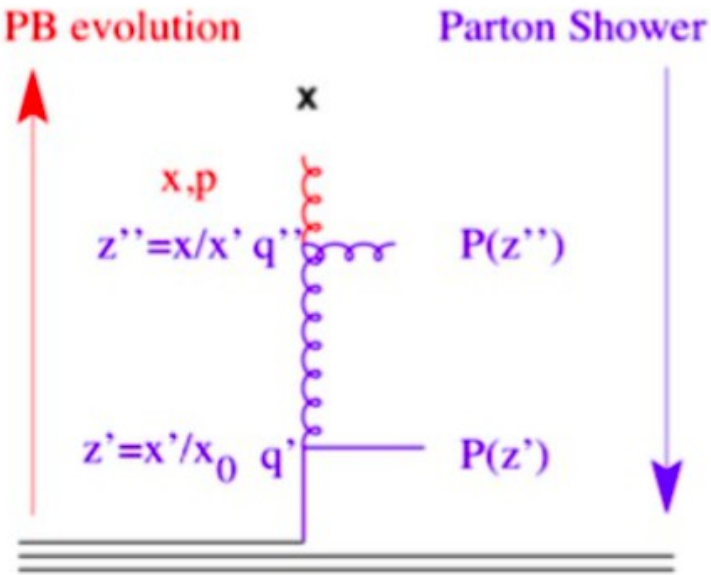
Very good agreement at NLO over all x and mu.
NB: the same approach is designed to work at NNLO.

- Equivalent to DGLAP evolution equation for zM → 1

3D Imaging and Monte Carlo

- **Parton Branching evolution**
  - start from hadron side and evolve from small to large scale μ^2

$$\Delta_s = \exp\left(-\int^{z_M} dz \int_{\mu_0^2}^{\mu^2} \frac{\alpha_s}{2\pi}\frac{d\mu'^2}{\mu'^2}P(z)\right)$$



- **Parton Shower**
  - backward evolution from hard scale μ^2 to hadron scale $\mu^2{}_0$ (for efficiency reasons)

$$\Delta_s = \exp\left(-\int^{z_M} dz \int_{\mu_0^2}^{\mu^2} \frac{\alpha_s}{2\pi}\frac{d\mu'^2}{\mu'^2}P(z)\frac{\frac{x}{z}\mathcal{A}\left(\frac{x}{z},k'_\perp,\mu'\right)}{x\mathcal{A}(x,k_\perp,\mu')}\right)$$

➔ in backward evolution, parton density (TMD) imposed further constraint !

APPLICATIONS to DIS and DY

PB method in xFitter

TMD distributions from fits to precision inclusive-DIS data from HERA using the open source QCD platform xFitter [*S. Alekhin et al., E. Phys. J. C 75 (2014) 304*]

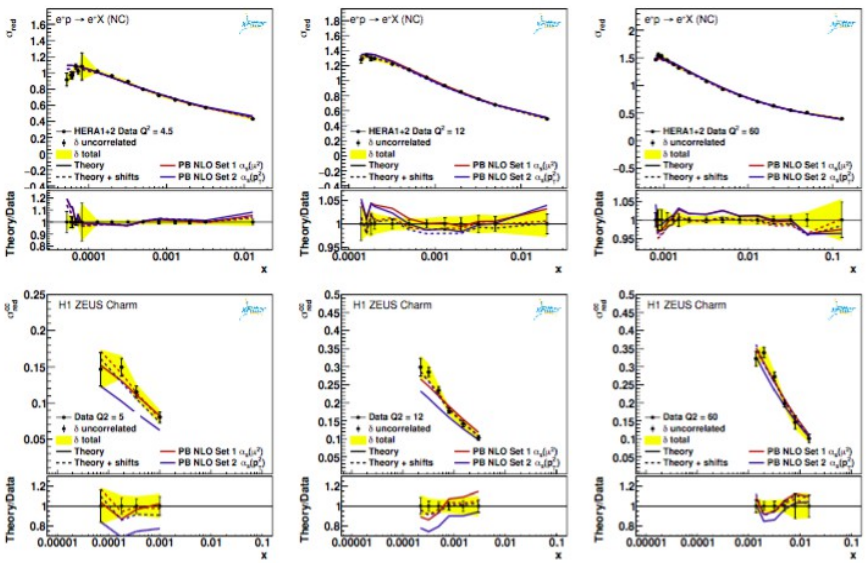


Figure 5: Measurement of the reduced cross section obtained at HERA compared to predictions using Set 1 and Set 2. Upper row: inclusive DIS cross section [11], lower row: inclusive charm production [38]. The dashed lines include the systematic shifts in the theory prediction.

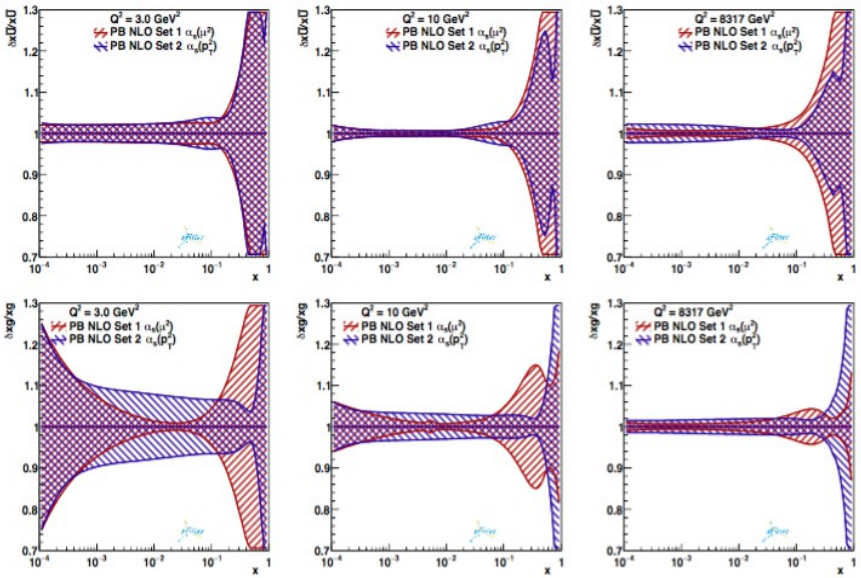


Figure 4: Total uncertainties (experimental and model uncertainties) for the two different sets at different values of the evolution scale μ^2.

A. Bermudez et al., Phys. Rev. D99 (2019) 074008

- NLO determination of TMDs including uncertainties

TMD distribution functions from precision DIS data fits

- NLO determination of TMDs including uncertainties

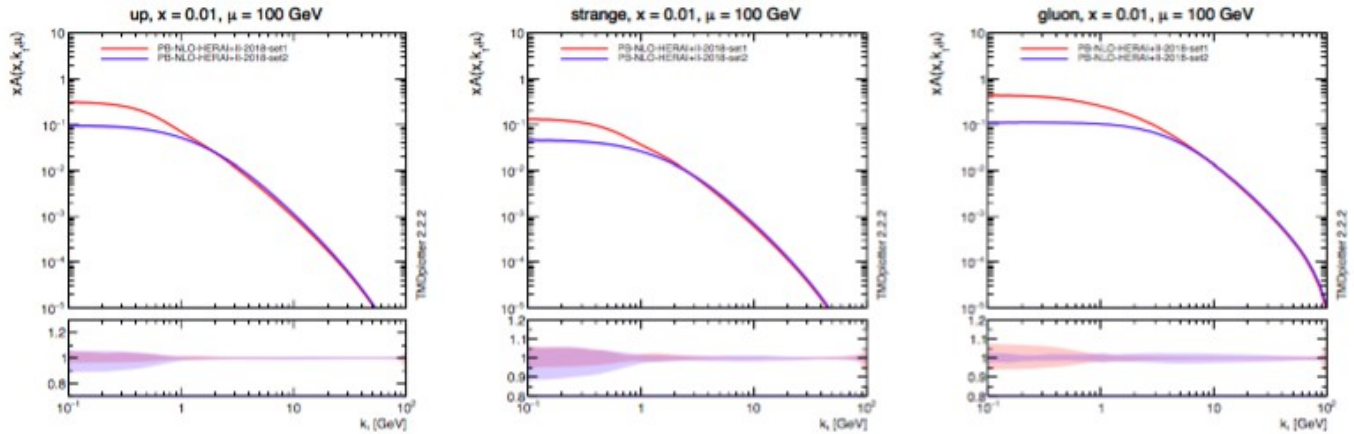


Figure 2: TMD parton distributions for up, strange and gluon (PB-NLO-2018-Set1 and PB-NLO-2018-Set 2) as a function of k_t at $\mu = 100$ GeVand $x = 0.01$.

A. Bermudez et al., Phys. Rev. D99 (2019) 074008

- can improve sensitivity at low kT by precise semi-inclusive DIS measurements at future ep/eA colliders

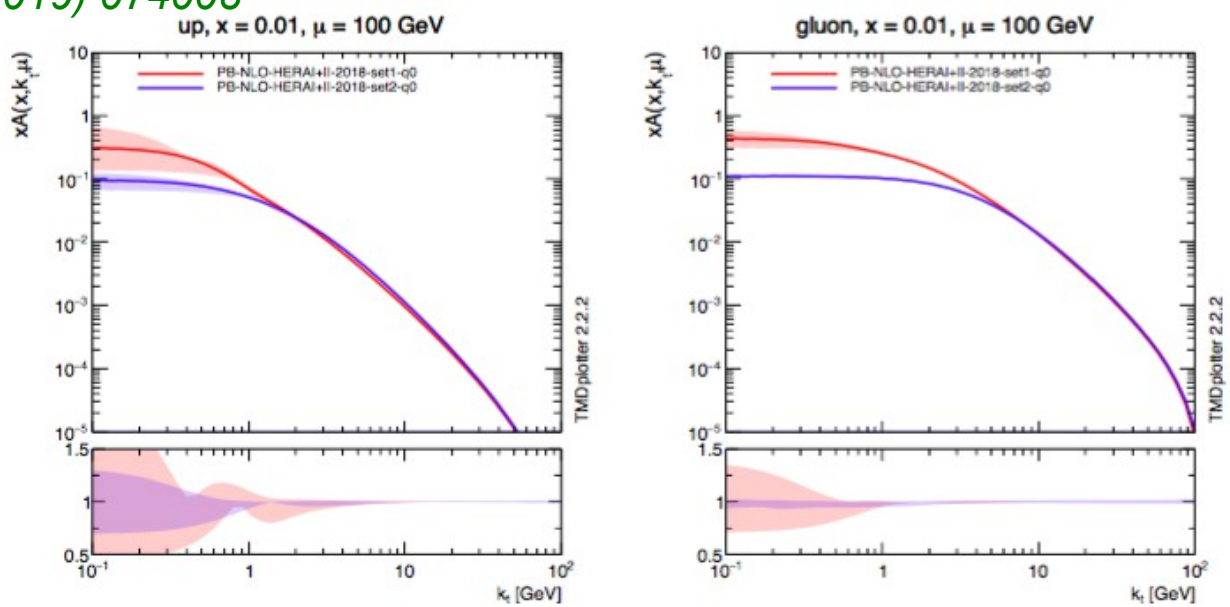


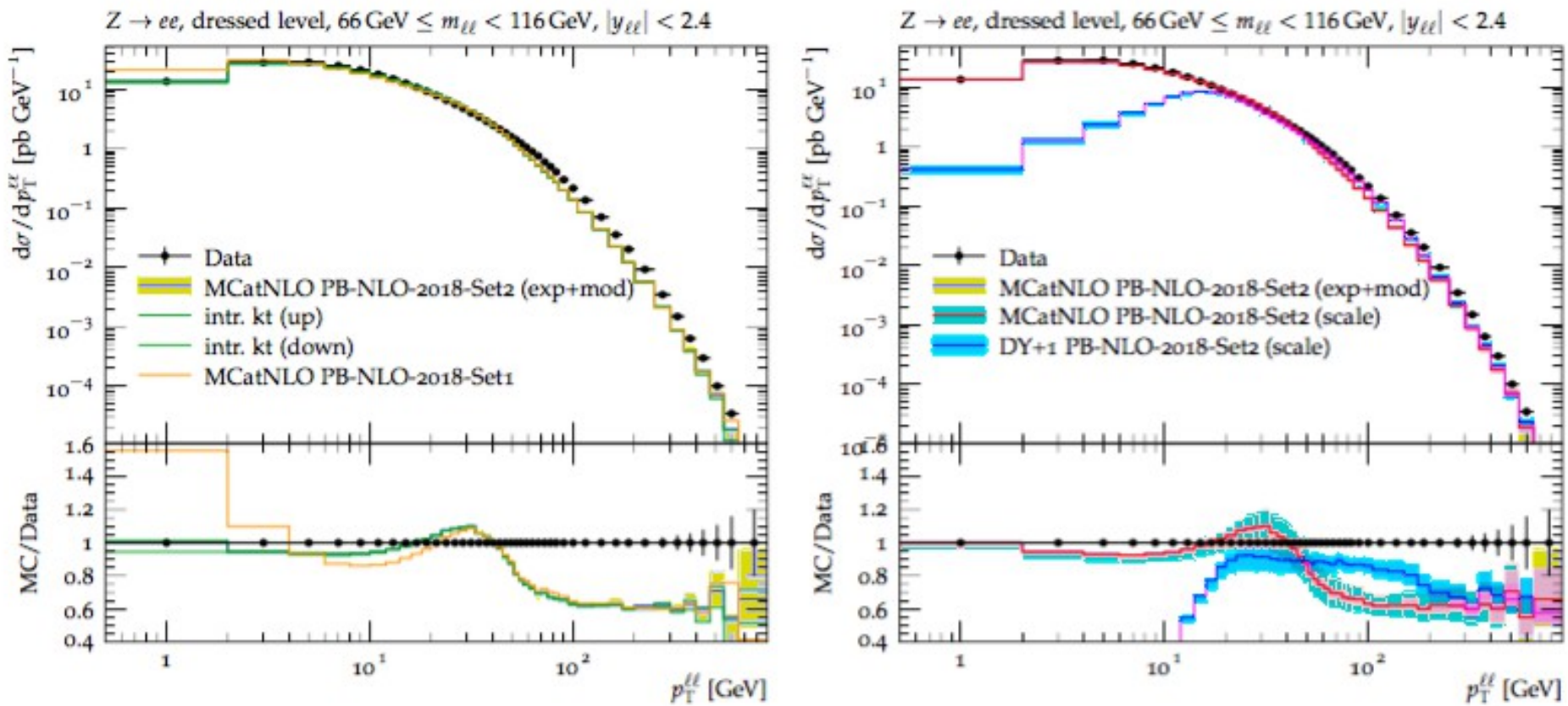
Figure 3: TMD parton distributions for up-quark and gluon (PB-NLO-2018-Set1 and PB-NLO-2018-Set 2) as a function of k_t at $\mu = 100$ GeVand $x = 0.01$ with a variation of the mean of the intrinsic k_t distribution.

Z-boson DY production at the LHC:
TMDs fitted to inclusive DIS + NLO DY calculation

A Bermudez et al, PRD 100 (2019) 074027 [arXiv:1906.00919]

- Use MadGraph5_aMC-at-NLO
- Apply PB-TMD
- Set matching scale mu_m (kT < mu_m)

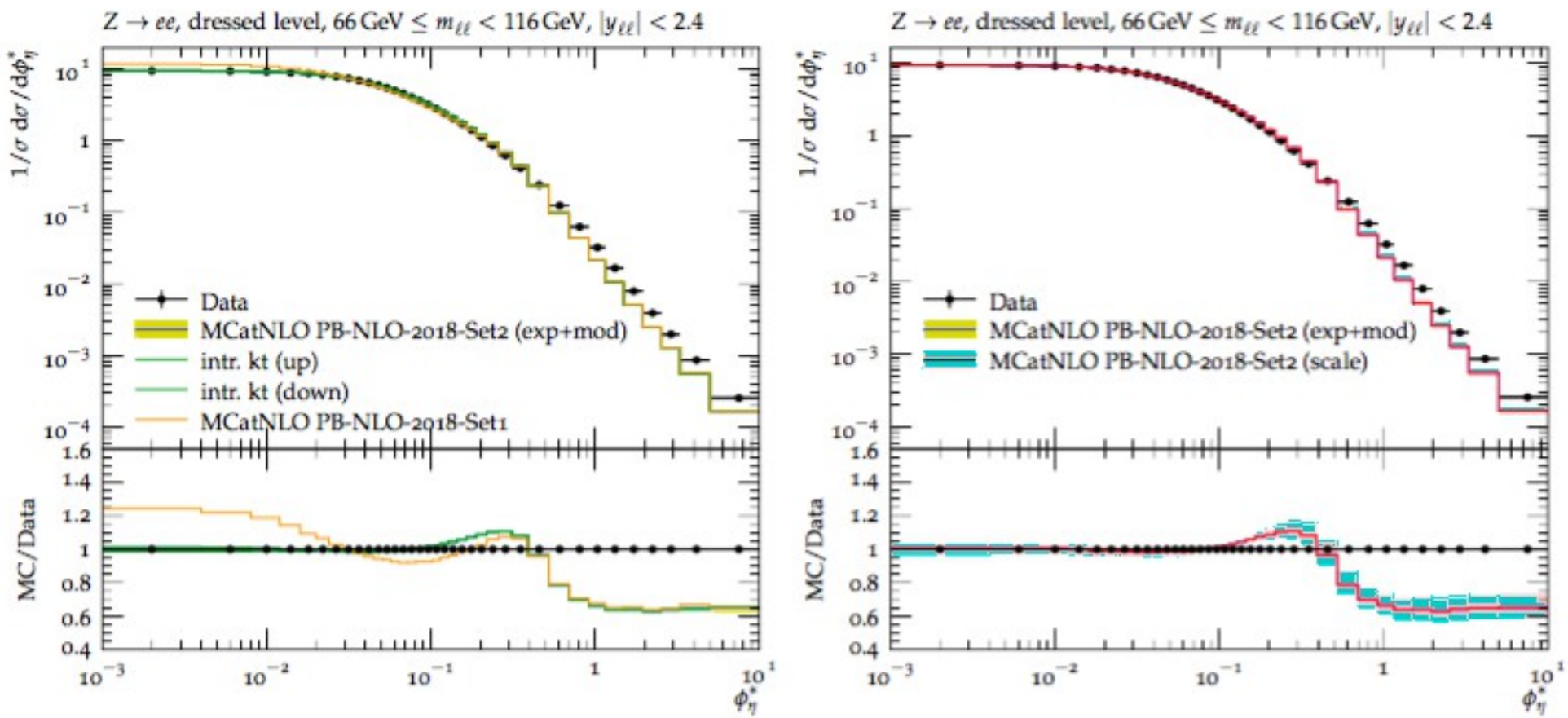
ATLAS 8 TeV data [E. Phys. J. C76 (2016) 291]



- Theoretical uncertainties dominated by scale dependences; TMD uncertainties moderate
- Low-pT spectrum sensitive to angular ordering (PB-TMD Set 2)
- Missing higher orders at high pT: see DY + 1 jet contribution

Z-boson DY production at the LHC:
TMDs fitted to inclusive DIS + NLO DY calculation

A Bermudez et al, PRD 100 (2019) 074027
[arXiv:1906.00919]



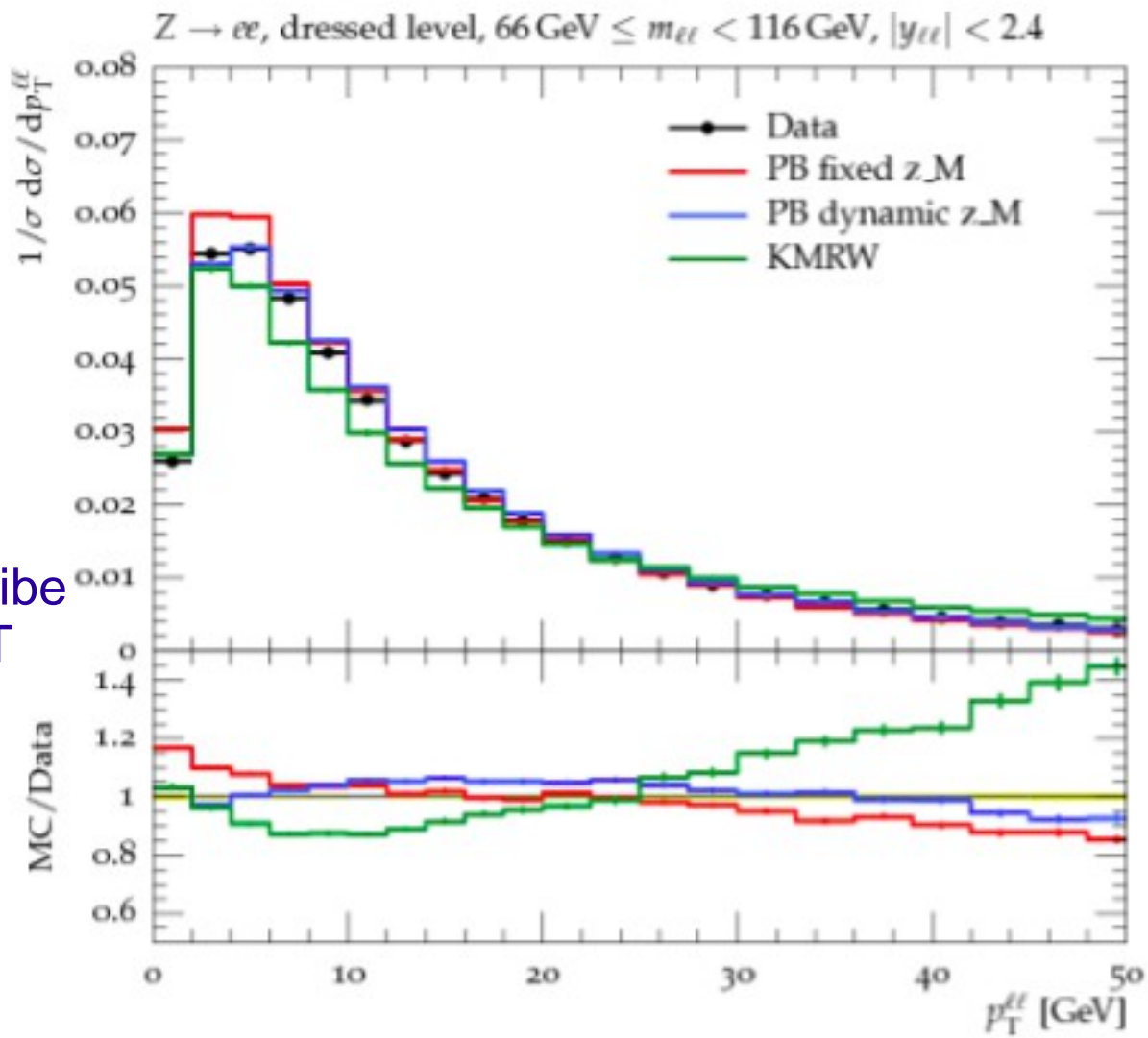
ATLAS 8 TeV data [E. Phys. J. C76 (2016) 291]

Sensitivity to branching-scale dependent soft-gluon resolution scales

Keersmaekers, Lelek, van Kampen & H, Nucl. Phys. B 949 (2019) 114795

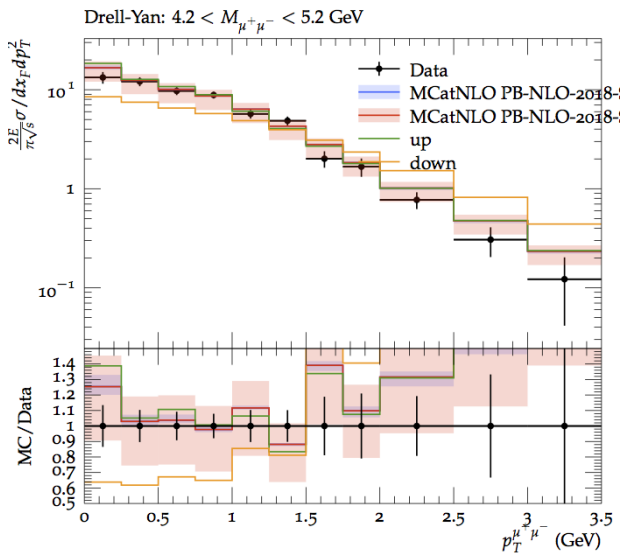
- low-pT DY spectrum sensitive to dynamical soft-gluon resolution scale

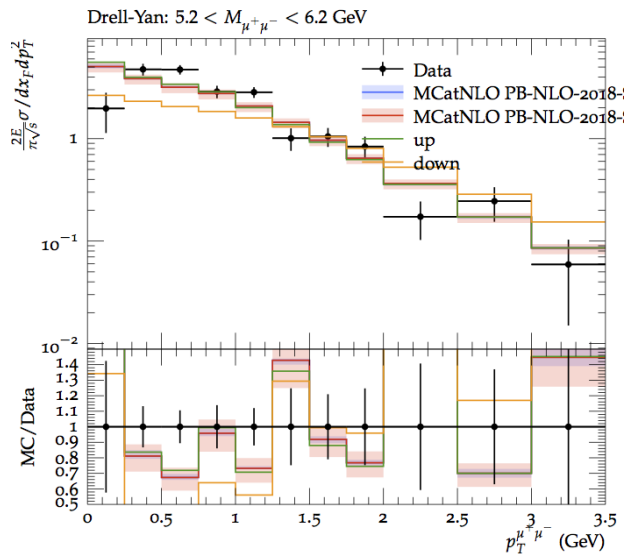
- KMRW (single-emission TMD model) does not describe shape at low pT and high pT

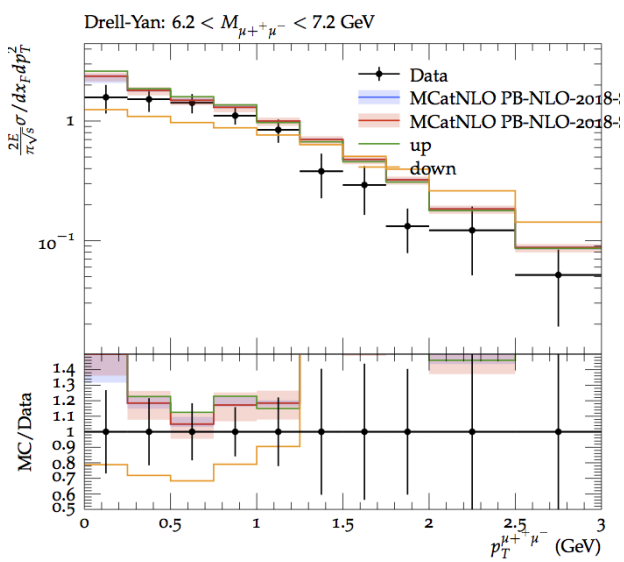


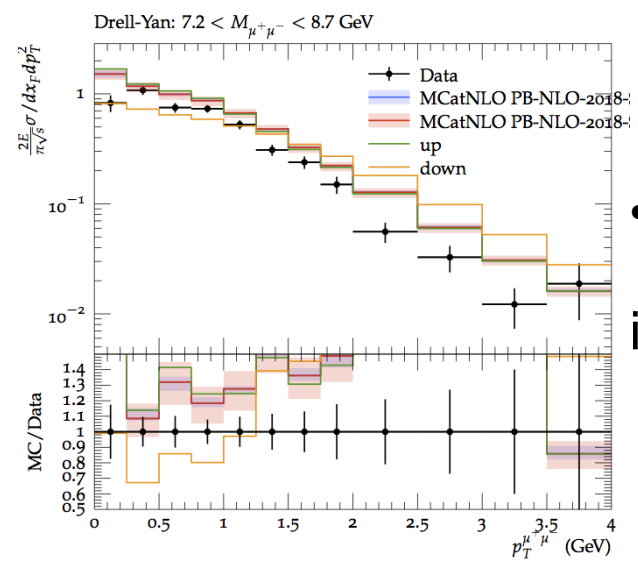
Z-boson DY production at low energy:
E866/NuSea data

Lelek et al., In progress







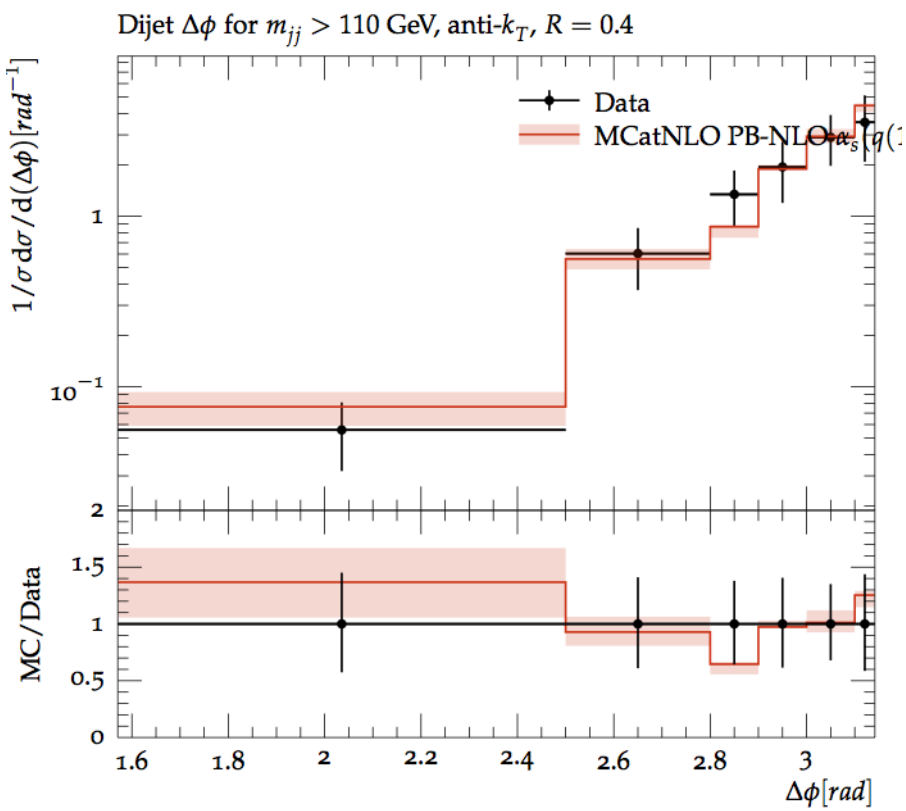


- PB-TMDs + NLO predictions using aMC-at-NLO
- unlike DY at the LHC, large effects from intrinsic kT distribution

Heavy quark hadroproduction:
b-jets at the LHC from PB TMDs + NLO

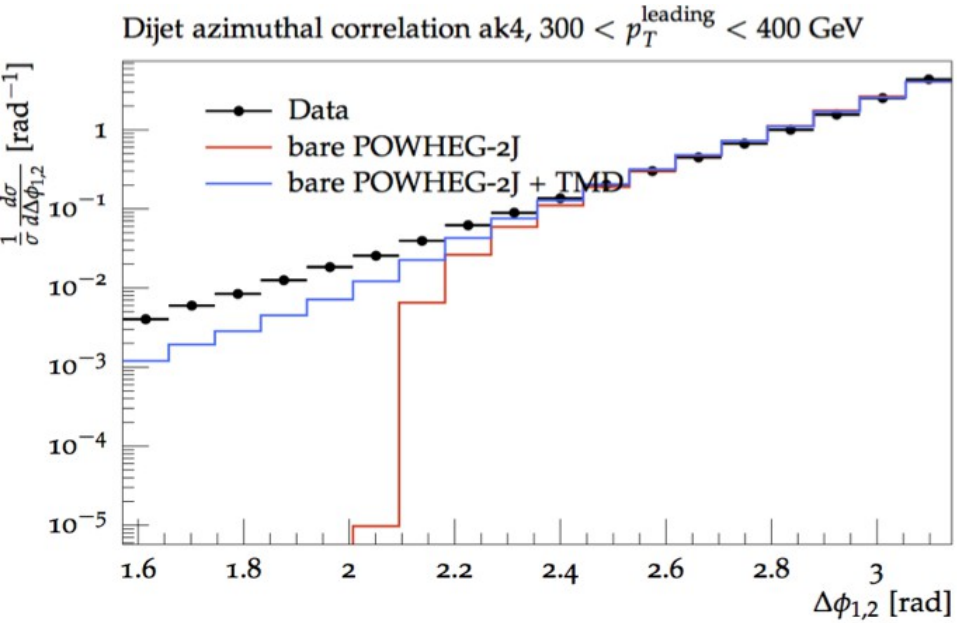
- Use MadGraph5_aMC-at-NLO
- Apply PB-TMD
- Set matching scale mu_m (kT < mu_m)

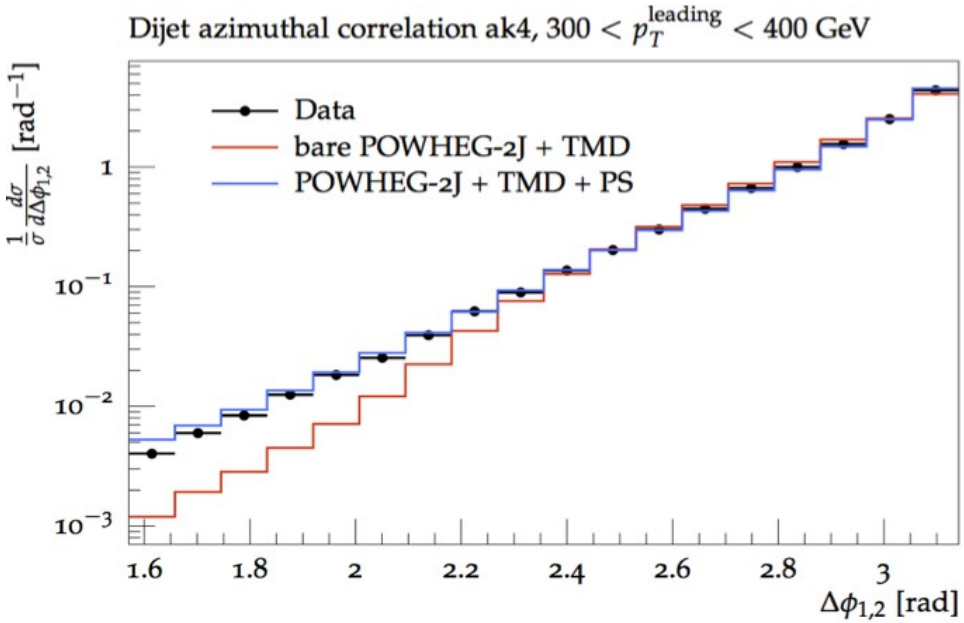
L Estevez et al, in progress



ATLAS 7 TeV data [E. Phys. J. C71 (2011) 1846]

The role of TMD densities and TMD showers: inclusive jets



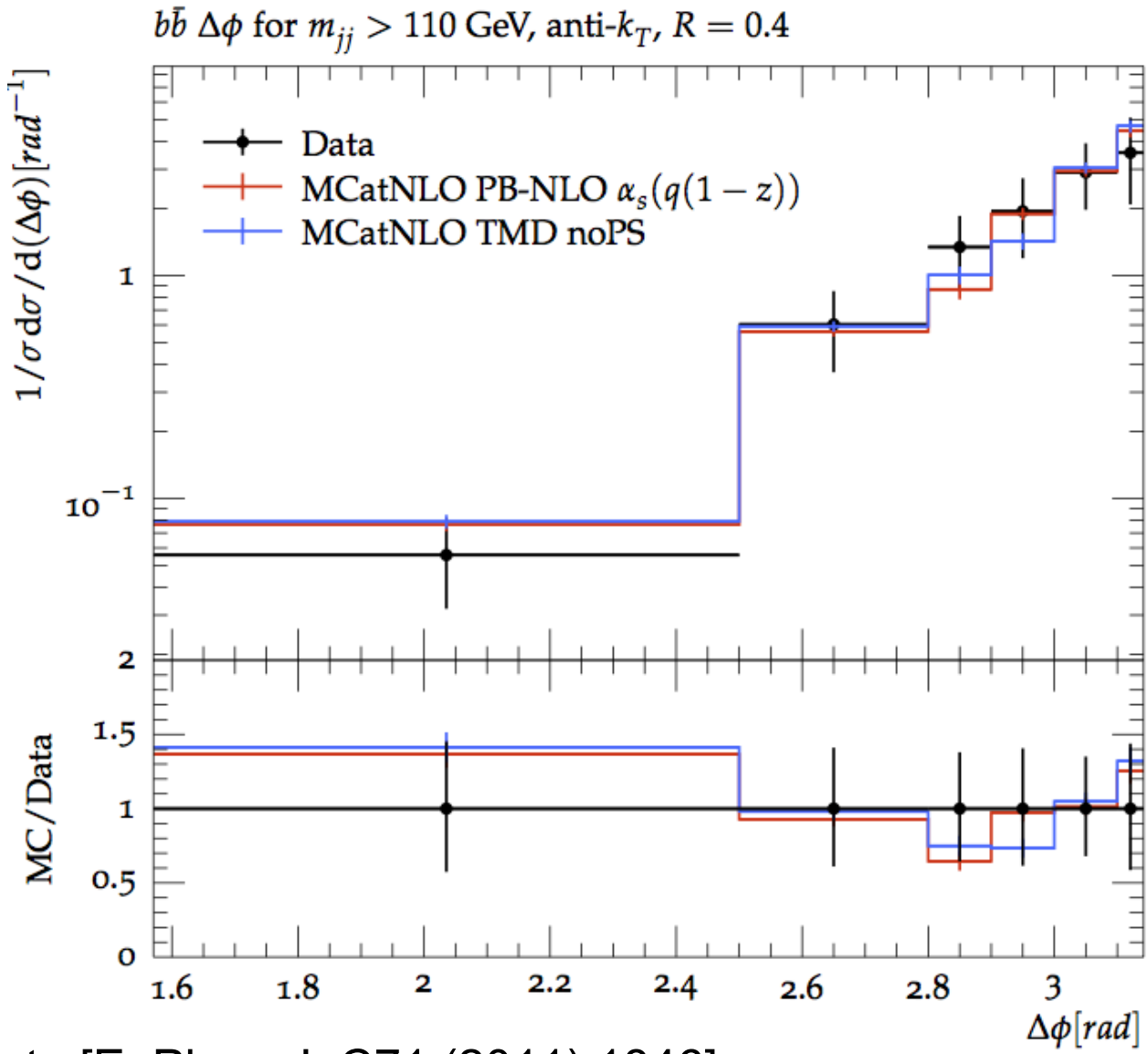


L Estevez et al, in progress

- Events by NLO POWHEG 2 jets
- PB TMD (with angular ordering)
- TMD parton shower

The role of TMD densities and TMD showers: b-jets

L Estevez et al, in progress



ATLAS 7 TeV data [E. Phys. J. C71 (2011) 1846]

Conclusions

- TMD effects control QCD resummations for high energies and for high masses -- > needed for high-precision predictions

- 3D hadron structure impacts LHC and future hadron-hadron experiments

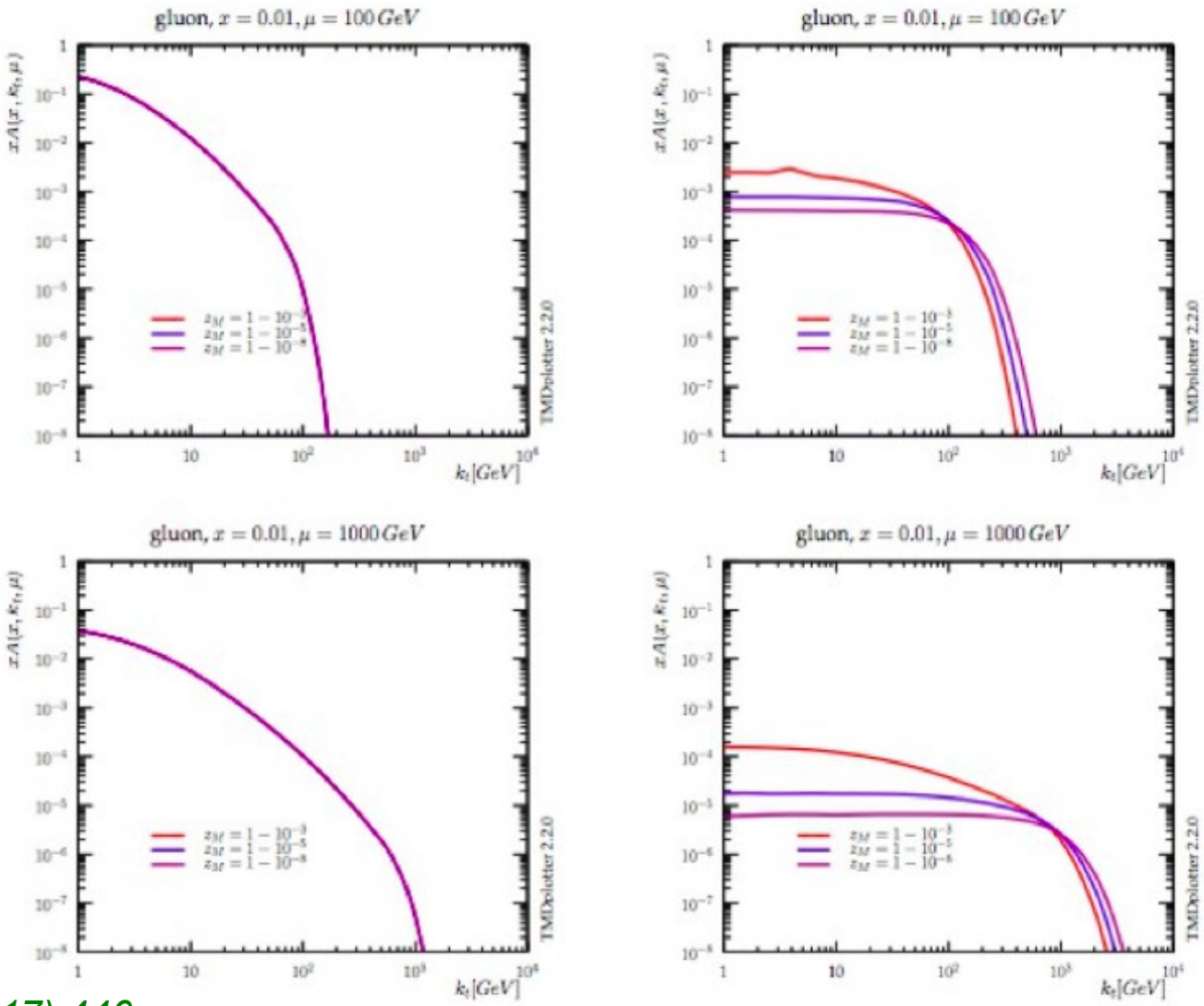
- Can be explored in semi-inclusive DIS processes at future ep/eA colliders

- PB formalism to take into account simultaneously soft-gluon emission at z -> 1 and transverse momentum qT recoils in the parton branchings along the QCD cascade

  - - > first results from Monte Carlo generator with TMDs and TMD shower

EXTRA SLIDES

TMDs and soft-gluon resolution effects



Phys. Lett. B 772 (2017) 446

angular ordering

transverse momentum ordering

Well-defined TMDs require appropriate ordering condition

Mapping branching scales to transverse momenta

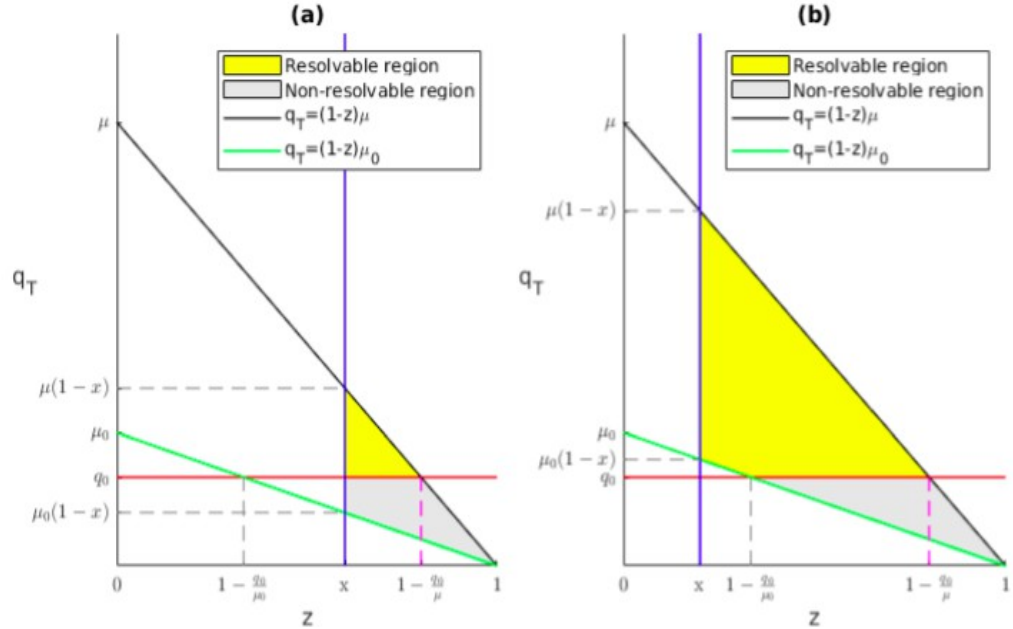


Figure 3: Resolvable and non-resolvable emission regions in the $(z, q_\perp)$ plane for evolution in the cases a) $1 > x \geq 1 - q_0/\mu_0$ and b) $1 - q_0/\mu_0 > x > 0$.

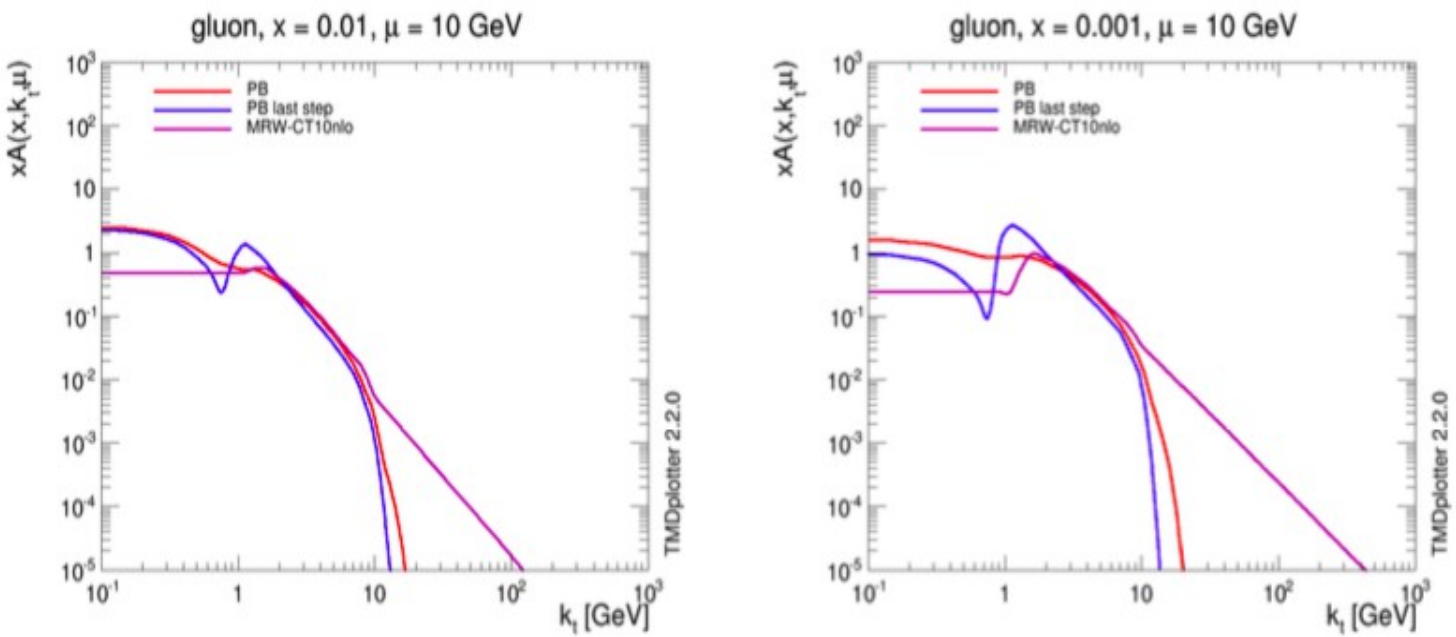
- The evolution in qT goes down to q0. But for x < 1 – q0 / mu0 resolvable emissions can only occur for qT > mu0 (1 – z). Thus a subtraction term arises in the evolution equation for the low-qT region q0 < qT < mu0 (1 – x):

$$\begin{aligned}
\widetilde{f}_a(x,\mu^2) &= \Delta_a(\mu^2,\mu_0^2)\widetilde{f}_a(x,\mu_0^2) + \sum_b \int \frac{\mathrm{d}q_\perp^2}{q_\perp^2} \int_x^1 \mathrm{d}z \left[\Theta(q_\perp^2 - q_0^2)\,\Theta(\mu^2(1-x)^2 - q_\perp^2)\right. \\
&\times \left.\Theta(1 - q_\perp/\mu - z) - \Theta(q_\perp^2 - q_0^2)\,\Theta(\mu_0^2(1-x)^2 - q_\perp^2)\,\Theta(1 - q_\perp/\mu_0 - z)\right] \\
&\times \frac{\Delta_a(\mu^2,\mu_0^2)}{\Delta_a\left(q_\perp^2/(1-z)^2,\mu_0^2\right)}\, P_{ab}^R\left(z,\alpha_s\left(q_\perp^2\right)\right)\widetilde{f}_b\left(\frac{x}{z},\frac{q_\perp^2}{(1-z)^2}\right) .
\end{aligned}$$

Comparison with KMRW unintegrated distributions

(Kimber-Martin-Ryskin-Watt)

KMRW : - transverse momentum generated by last emission
- radiation populates different phase space region
- no rescaling of transverse momenta in Sudakov form factor
- differs in treatment of non-resolvable processes



- low-kT kink from single-emission picture;
- high-kT tail from radiative effects + Sudakov

Comparison with CSS (Collins-Soper-Sterman) resummation

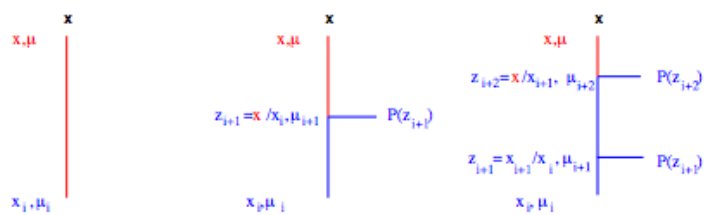
◇ The resummed DY differential cross section is given by

$$\frac{d\sigma}{d^2\mathbf{q}dQ^2dy} = \sum_{q,\bar{q}} \frac{\sigma^{(0)}}{s} H(\alpha_S) \int \frac{d^2\mathbf{b}}{(2\pi)^2}\, e^{i\mathbf{q}\cdot\mathbf{b}} \mathcal{A}_q(x_1,\mathbf{b},Q)\mathcal{A}_{\bar{q}}(x_2,\mathbf{b},Q) + \mathcal{O}\left(\frac{|\mathbf{q}|}{Q}\right) \quad \text{where}$$

$$\begin{aligned}\mathcal{A}_i(x,\mathbf{b},Q) &= \exp\left\{\frac{1}{2}\int_{c_0/b^2}^{Q^2} \frac{d\mu'^2}{\mu'^2}\left[A_i(\alpha_S(\mu'^2))\ln\left(\frac{Q^2}{\mu'^2}\right) + B_i(\alpha_S(\mu'^2))\right]\right\} G_i^{(\mathrm{NP})}(x,\mathbf{b}) \\ &\times \sum_j \int_x^1 \frac{dz}{z} C_{ij}\left(z,\alpha_S\left(\frac{c_0}{\mathbf{b}^2}\right)\right) f_j\left(\frac{x}{z},\frac{c_0}{\mathbf{b}^2}\right)\end{aligned}$$

and the coefficients H, A, B, C have power series expansions in α_S.

◇ The parton branching TMD is expressed in terms of real-emission $P^{(R)}$:



▷ via momentum sum rules, use unitarity to relate $P^{(R)}$ to virtual emission

▷ identify the coefficients in the two formulations, order by order in α_S, at LL, NLL, ...

Comparison with CSS (Collins-Soper-Sterman) resummation

More precisely:

▷ The parton branching TMD contains Sudakov form factor in terms of

$$P_{ab}^{(R)}(\alpha_s, z) = K_{ab}(\alpha_s)\,\frac{1}{1-z} + R_{ab}(\alpha_s, z) \quad \text{where}$$

$$K_{ab}(\alpha_s) = \delta_{ab} k_a(\alpha_s)\,, \quad k_a(\alpha_s) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n k_a^{(n-1)}\,, \quad R_{ab}(\alpha_s, z) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n R_{ab}^{(n-1)}(z)$$

▷ Via momentum sum rules, use unitarity to re-express this in terms of

$$P^{(V)} = P - P^{(R)}\,, \quad \text{where}$$

$$P_{ab}(\alpha_s, z) = D_{ab}(\alpha_s)\delta(1-z) + K_{ab}(\alpha_s)\,\frac{1}{(1-z)_+} + R_{ab}(\alpha_s, z)$$

is full splitting function (at LO, NLO, etc.)

$$\text{with} \quad D_{ab}(\alpha_s) = \delta_{ab} d_a(\alpha_s)\,, \quad d_a(\alpha_s) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n d_a^{(n-1)}$$

▷ Identify $d_a(\alpha_s)$ and $k_a(\alpha_s)$ with resummation formula coefficients (LL, NLL, . .)

Comparison with CSS (Collins-Soper-Sterman) resummation

- $d_a(\alpha_s)$ and $k_a(\alpha_s)$ perturbative coefficients

$$\text{one} - \text{loop} \ :$$

$$d_q^{(0)} = \frac{3}{2} C_F \quad , \quad k_q^{(0)} = 2\, C_F$$

$$\text{two} - \text{loop} \ :$$

$$d_q^{(1)} = C_F^2 \left(\frac{3}{8} - \frac{\pi^2}{2} + 6\, \zeta(3) \right) + C_F C_A \left(\frac{17}{24} + \frac{11\pi^2}{18} - 3\, \zeta(3) \right) - C_F T_R N_f \left(\frac{1}{6} + \frac{2\pi^2}{9} \right) ,$$

$$k_q^{(1)} = 2\, C_F\, \Gamma \, , \quad \text{where} \ \ \Gamma = C_A \left(\frac{67}{18} - \frac{\pi^2}{6} \right) - T_R N_f \frac{10}{9}$$

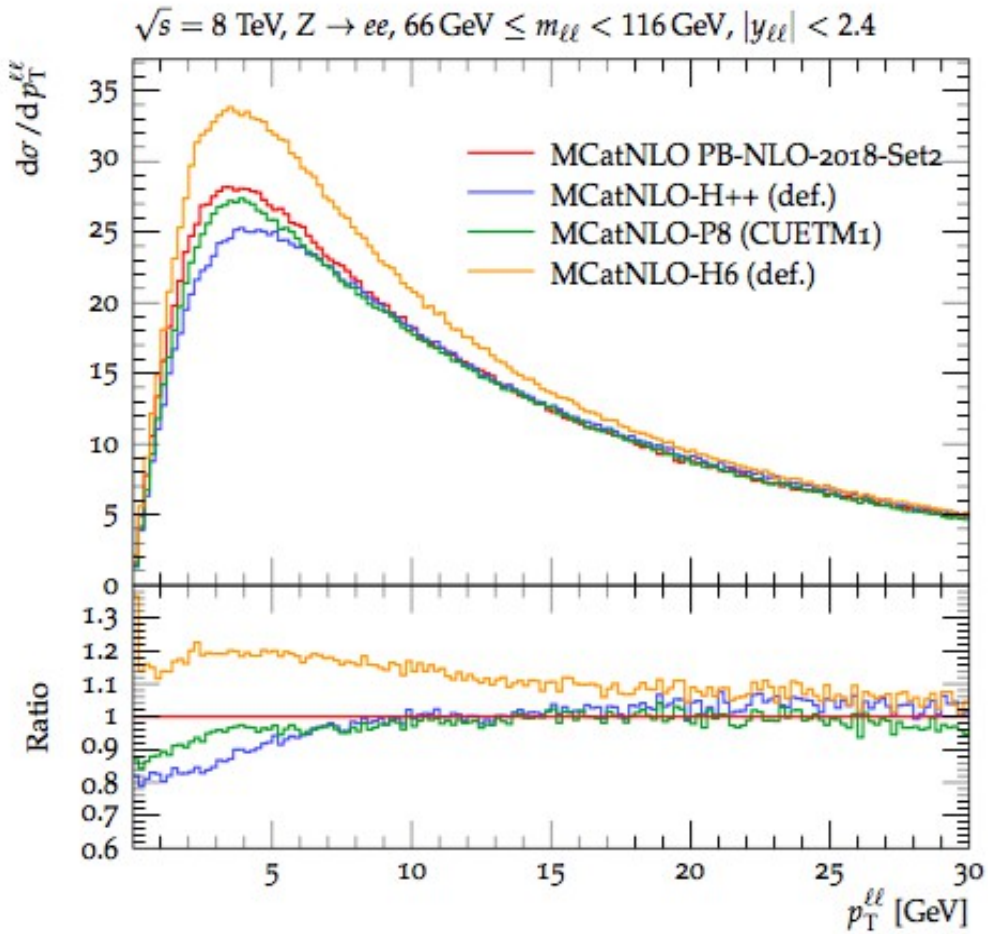
- The k and d coefficients of the PB formalism match, order by order, the A and B coefficients of the CSS formalism:

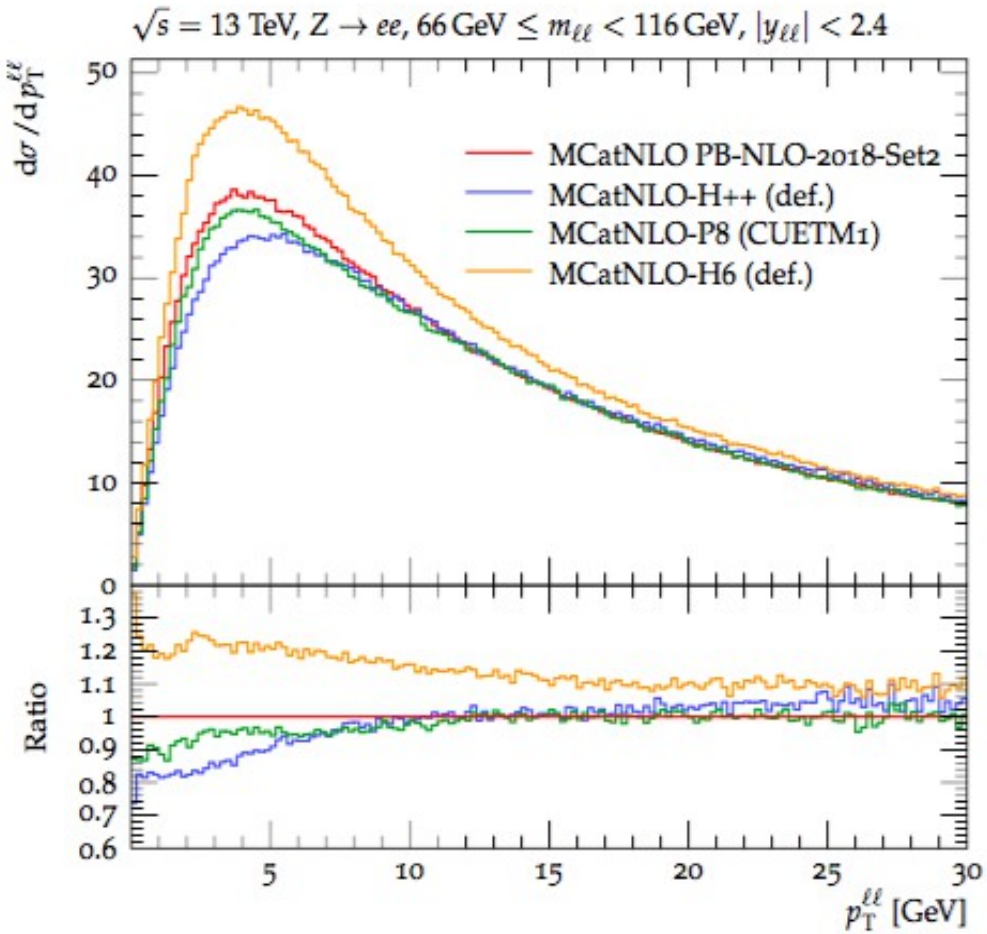
$$\text{LL} \ : \ \ k_q^{(0)} = 2\, C_F = 2\, A_q^{(1)}$$

$$\text{NLL} \ : \ \ k_q^{(1)} = 2\, C_F\, \Gamma = 4\, A_q^{(2)} \ ; \ \ d_q^{(0)} = \frac{3}{2} C_F = -B_q^{(1)}$$

$$\text{NNLL} \ : \ \ \text{analysis in progress}$$

Fine binning at low pT?



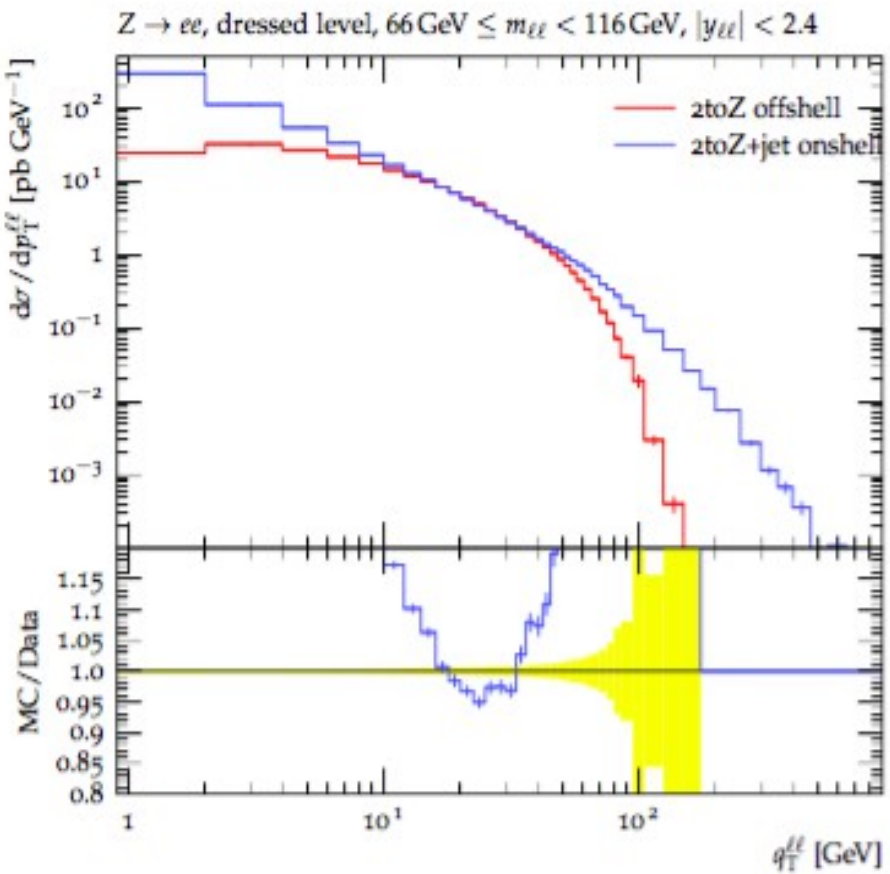


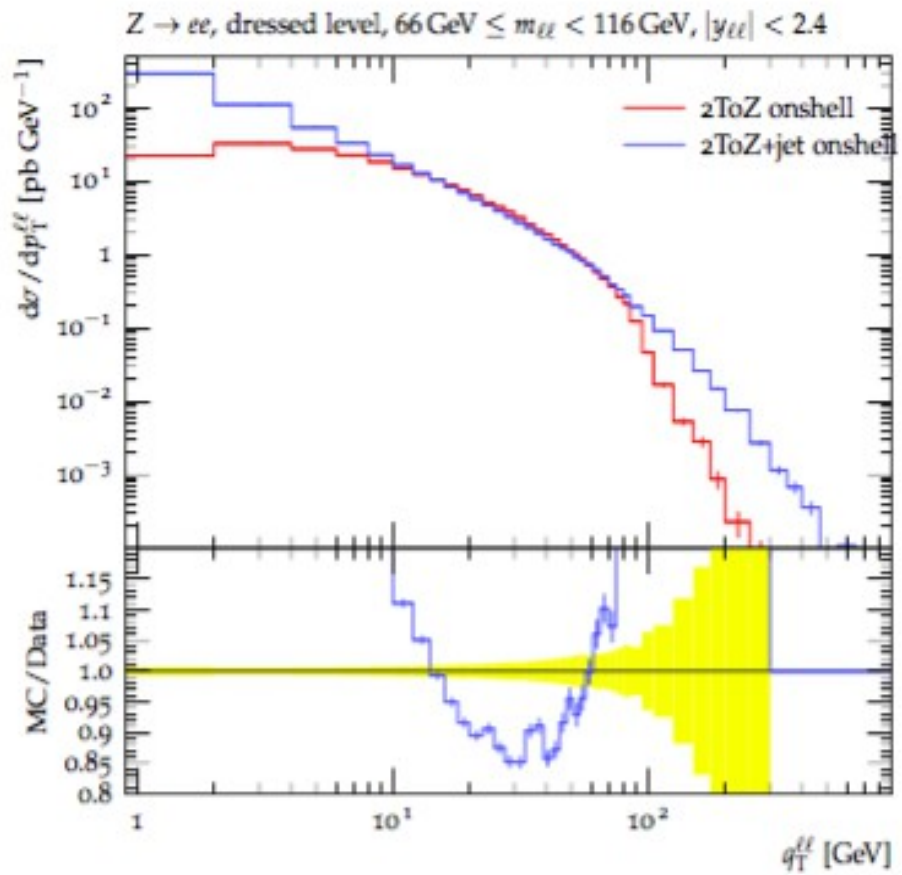
- dedicated measurements in the region of Z-boson pT < 5 -10 GeV?

Toward new approaches to matching/merging, locally in kT

Matching to hard process: off-shell ME with KaTie

van Hameren, A. CPC, 224, 371, 2018, arXiv 1611.00680





KaTie

[A. Van Hameren, talks at DESY MCEG Workshop, February 2019 and DIS2019 Workshop, April 2019]