Drell-Yan $p_\perp$ with NLO-matched Parton Branching TMDs at energies from fixed-target to LHC

DIS 2021

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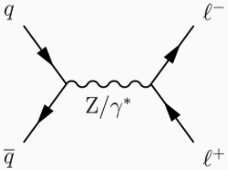
Motivation

Drell-Yan process:

- is a "standard candle" for electroweak precision measurements at LHC
- helps to understand the QCD evolution, resummation, factorization (collinear, transverse momentum dependent (TMD))
- used for extraction of the PDFs
- at low mass and low energy gives access to partons' intrinsic $k_\perp$
- ...

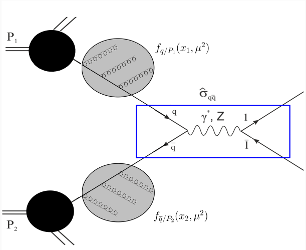


The description of the DY data in a wide kinematic regime is problematic

Factorization

Collinear factorization theorem

$$\sigma = \sum_{q\bar{q}} \int \mathrm{d}x_1 \mathrm{d}x_2 f_q(x_1, \mu^2) f_{\bar{q}}(x_2, \mu^2) \hat{\sigma}_{q\bar{q}}(x_1, x_2, \mu^2, Q^2)$$



Basis of many QCD calculations BUT

- proton structure in longitudinal direction only
- for some observables also the transverse degrees of freedom have to be taken into account
  $\rightarrow$ soft gluons need to be resummed

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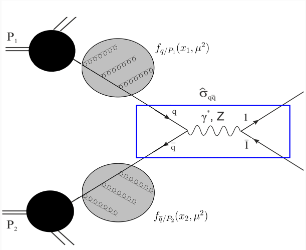

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$\rightarrow$Transverse Momentum Dependent (TMD) factorization theorems
low $q_\perp$ (Collins-Soper-Sterman CSS) or High energy ($k_\perp$-) factorization
For practical applications Monte Carlo approach needed: Parton Branching (PB) method:

$$\sigma = \sum_{q\bar{q}} \int \mathrm{d}^2 k_{\perp 1} \mathrm{d}^2 k_{\perp 2} \int \mathrm{d}x_1 \mathrm{d}x_2 A_q(x_1, k_{\perp 1}, \mu^2) A_{\bar{q}}(x_2, k_{\perp 2}, \mu^2) \hat{\sigma}_{q\bar{q}}(x_1, x_2, k_{\perp 1}, k_{\perp 2}, \mu^2, Q^2)$$

- applicable in a wide kinematic range, for multiple processes and observables
- crucial for consistent treatment of parton shower's transverse momentum kinematics

$A\left(x, k_\perp, \mu^2\right)$ - TMD PDFs (TMDs)

Components of the Parton Branching Method

Parton Branching (PB) method:

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- delivers TMDs (in a wide kinematic range of x, $k_\perp$ and μ^2) from PB TMD evolution equation
  initial parameters of the TMDs fitted to HERA DIS data
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Plan for today:

- How do we obtain PB TMDs?
- How do we use PB TMDs to obtain predictions?
- PB results for DY p_T

How do we obtain PB TMDs?

PB TMD evolution equation:

JHEP 1801 (2018) 070

$$\widetilde{A}_a\left(x,k_\perp,\mu^2\right)=\Delta_a\left(\mu^2,\mu_0^2\right)\widetilde{A}_a\left(x,k_\perp,\mu_0^2\right)+\sum_b\int\frac{\mathrm{d}\mu_1^2}{\mu_1^2}\int_0^{2\pi}\frac{d\phi}{2\pi}\Theta\left(\mu^2-\mu_1^2\right)\Theta\left(\mu_1^2-\mu_0^2\right)$$

$$\times\quad\Delta_a\left(\mu^2,\mu_1^2\right)\int_x^{z_M}\mathrm{d}zP_{ab}^R\left(z,\mu_1^2,\alpha_s((1-z)^2\mu_1^2)\right)\widetilde{A}_b\left(\frac{x}{z},|\boldsymbol{k}+(1-z)\boldsymbol{\mu}_1|,\mu_0^2\right)\Delta_b(\mu_1^2,\mu_0^2)+\ldots$$

Sudakov form factor: probability of an evolution between μ_0 and μ without any resolvable branching:

$$\Delta_a\left(\mu^2,\mu_0^2\right)=\exp\left(-\sum_b\int_{\mu_0^2}^{\mu^2}\frac{\mathrm{d}\mu'^2}{\mu'^2}\int_0^{z_M}\mathrm{d}z\;zP_{ba}^R(z,\mu^2,\alpha_s\left((1-z)^2\mu'^2\right)\right)$$

$\widetilde{A}=xA$, $x=zx_1$,
P_{ab}^R- real part of DGLAP splitting function for parton $b\to a$, at LO probability that branching happens
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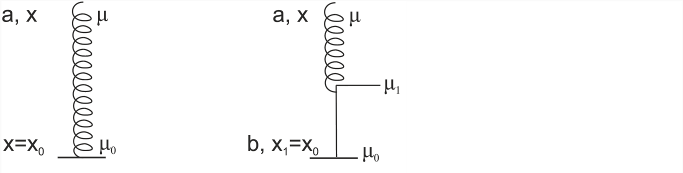

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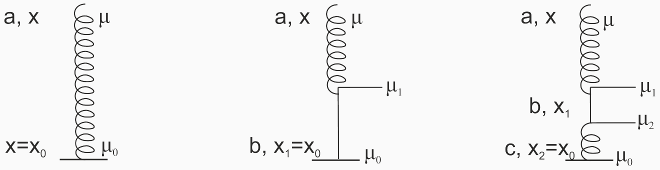

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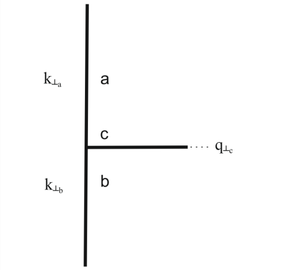
Features of PB

- uses intrinsic transverse momentum:
  $\widetilde{A}_{a,0}(x, k^2_{\perp 0}, \mu^2_0) = \widetilde{f}_{a,0}(x, \mu^2_0) \frac{1}{2\pi\sigma^2} \exp\left(\frac{-k^2_{\perp 0}}{2\sigma^2}\right)$ $\sigma^2 = q^2_s/2$,
  $q_s = 0.5\ \mathrm{GeV}$
- calculates $\mathbf{k}$ at each branching $\mathbf{k}_a = \mathbf{k}_b - \mathbf{q}_c$,
  $\mathbf{k}$ of the propagating parton is a sum of intrinsic transverse momentum and all emitted transverse momenta
  $\mathbf{k} = \mathbf{k}_0 - \sum_i \mathbf{q}_i$
- implements angular ordering (AO) condition similar to Catani-Marchesini-Webber Nucl. Phys. B349, 635 (1991):
  - angles of emitted partons increase from the hadron side towards hard scattering
  - relation between μ' and $\mathbf{q}$, scale of α_s, z_M
  Nucl.Phys.B 949 (2019) 114795



$\rightarrow$ soft gluon resummation included
LL, NLL coefficients in Sudakov the same as in CSS, NNLL-difference from renormalization group (difference proportional to β_0) thesis of M. van Kampen (UAntwerp 2019), M. Pavlov (UAntwerp2020)

- iTMDs obtained from integration of TMD: $\widetilde{f}_a(x, \mu^2) = \int \mathrm{d}k^2_\perp \widetilde{A}_a(x, k_\perp, \mu^2)$
- Initial distribution $\widetilde{f}_{a,0}(x, \mu^2_0)$ obtained from fits to HERA DIS data using `xFitter`
  Phys. Rev. D 99, 074008 (2019)

Predictions with PB TMDs

PB TMDs are used by TMD MC generator CASCADE to obtain predictions arXiv:2101.10221

CASCADE:

- ME: off-shell **k**-dep ME or ME obtained from standard automated methods used in collinear physics (Pythia, MCatNLO,...) with **k** added according to TMD
- For exclusive observables: TMD Parton Shower
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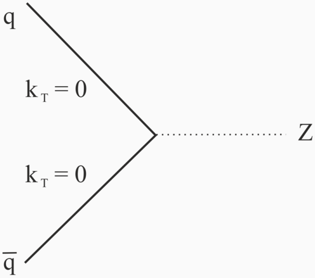

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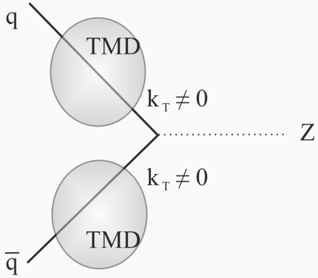
• compare with the 8 TeV ATLAS measurement

• For NLO: double counting → some extra effort needed



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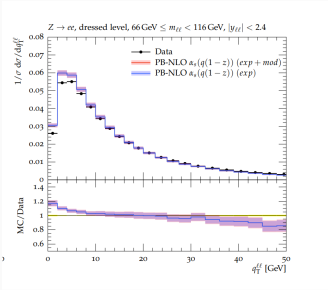

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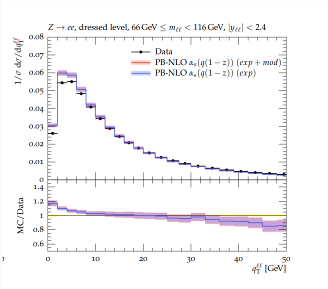

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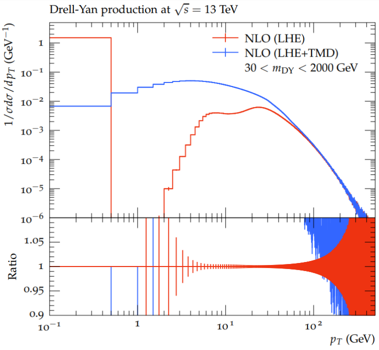
PB TMDs and MCatNLO for DY

- standard MCatNLO: when ME matched with PS, subtraction terms (for soft and collinear contribution) must be used to avoid double counting JHEP 06 (2002) 029
- Subtraction term depends on the PS to be used
- PB TMDs have similar role to PS
  $\rightarrow$ subtraction term has to be used to combine PB TMDs with NLO cross section
- PB uses AO, similar to Herwig6
  $\rightarrow$ MCatNLO + Herwig6 subtraction used by PB TMD + MCatNLO calculation



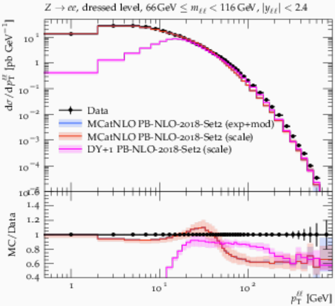
MCatNLO calculation with subtraction

k included in ME according to PB TMD

Comparison with data

LHC:

ATLAS 8 TeV



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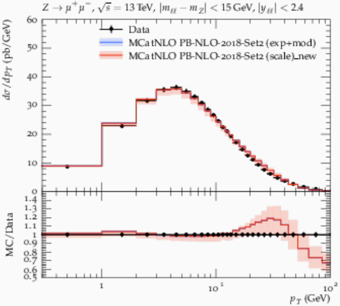
CMS 13 TeV



Eur.Phys.J.C 80 (2020) 7, 598

Low and middle p_T spectrum well described

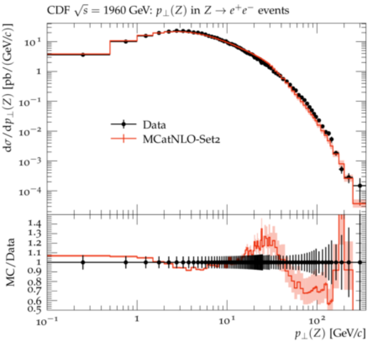
At higher p_T contribution from Z+1 jet important

Uncertainty: experimental + model (from the fit procedure) small, scale uncertainties (μ_f and μ_r variation in ME) sizeable

Comparison with data

Tevatron:

CDF 1960 GeV



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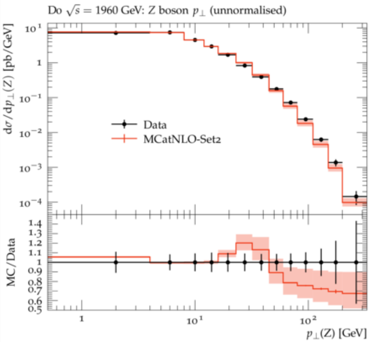
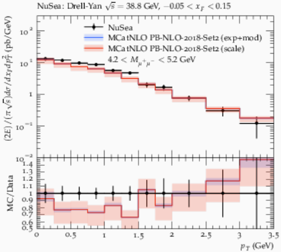


Low and middle p_T spectrum well described by MCatNLO + PB TMD

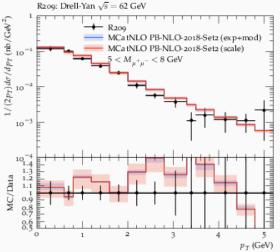
Comparison with data

Fixed target and low energy colliders:

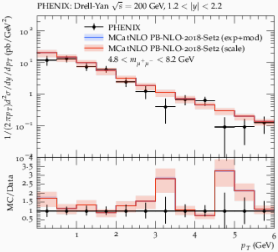
$\sqrt{s} = 38.8$ GeV



$\sqrt{s} = 62$ GeV



$\sqrt{s} = 200$ GeV



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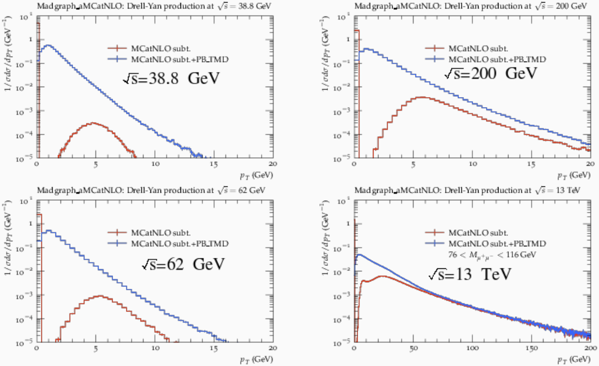
We look at $p_T/M_{DY} \sim 1$

p_T spectrum well described by MCatNLO+ PB TMD

No additional tuning, adjusting of the method compared to the procedure applied to LHC and Tevatron data

Good theoretical description of the DY data coming from experiments in very different kinematic ranges: NuSea, R209, Phenix, Tevatron and LHC (8 TeV and 13 TeV) obtained with PB TMDs + MCatNLO.

Subtraction at different energies s



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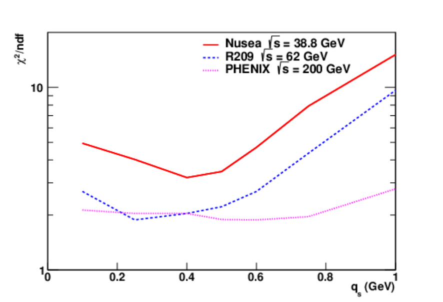
MCatNLO calculation with subtraction.

k included in ME according to PB TMD

- at low DY mass and low $\sqrt{s}$ even in the region of $p_t/m_{DY} \sim 1$ the contribution of soft gluon emissions essential to describe the data
- at larger masses and LHC energies the contribution from soft gluons in the region of $p_t/m_{DY} \sim 1$ is small and the spectrum driven by hard real emission.

Intrinsic k_T

- Initial distribution in PB:
  $\widetilde{A}_{a,0}(x, k_{\perp 0}^2, \mu_0^2) = \widetilde{f}_{a,0}(x, \mu_0^2) \frac{1}{2\pi\sigma^2} \exp\left(\frac{-k_{\perp 0}^2}{2\sigma^2}\right)$
  $\sigma^2 = q_s^2/2$
- $\widetilde{f}_{a,0}(x, \mu_0^2)$ - fitted to HERA DIS data
- q_s - not constrained by current fit procedure (HERA DIS not sensitive to intrinsic k_T)
  $q_s = 0.5\ \mathrm{GeV}$ assumed in PB
- Low mass DY data can be used to constrain intrinsic transverse momentum distribution



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NuSea and R209 show minimum for q_s close to the q_s value used by assumption in PB.

Discussion

- Literature: perturbative fixed order calculations in collinear factorization not able to describe DY p_T spectra at fixed target experiments for $p_T/m_{DY} \sim 1$ - our observation consistent with this remark (contribution from soft gluon radiation included in PB TMDs essential to describe the data)
- Situation different at LHC: in region $p_T/M_Z \sim 1$ purely collinear NLO calculation gives good result
- DY p_T spectrum in low mass region sensitive to both fixed order QCD and all order soft gluon radiation; theoretical predictions depend on matching between those two
- In PB: matching of PB TMDs and MCatNLO
  not additive matching (as in CSS) but operatorial matching
  $PB \otimes \left[H^{(LO)} + \alpha_s \left(H^{(NLO)} - PB(1) \otimes H^{(LO)}\right)\right]$
- PB method:
  1. contains intrinsic kt + well defined perturbative branching evolution
  2. contains angular ordered soft gluon radiation
  3. is matched through MCatNLO to NLO hard scattering
- This method works in wide kinematic range

Discussion

- Literature: perturbative fixed order calculations in collinear factorization not able to describe DY p_T spectra at fixed target experiments for $p_T/m_{DY} \sim 1$ - our observation consistent with this remark (contribution from soft gluon radiation included in PB TMDs essential to describe the data)
- Situation different at LHC: in region $p_T/M_Z \sim 1$ purely collinear NLO calculation gives good result
- DY p_T spectrum in low mass region sensitive to both fixed order QCD and all order soft gluon radiation; theoretical predictions depend on matching between those two
- In PB: matching of PB TMDs and MCatNLO
  not additive matching (as in CSS) but operatorial matching
  $PB \otimes \left[H^{(LO)} + \alpha_s \left(H^{(NLO)} - PB(1) \otimes H^{(LO)}\right)\right]$
- PB method:
  1. contains intrinsic kt + well defined perturbative branching evolution
  2. contains angular ordered soft gluon radiation
  3. is matched through MCatNLO to NLO hard scattering
- This method works in wide kinematic range

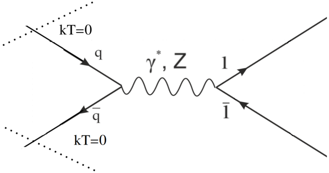
Thank you!

Backup

Monte Carlo (MC) generators and Parton Showers (PS)

Collinear factorization: base assumption for MC generators

$$\sigma = \sum_{q\bar{q}} \int \mathrm{d}x_1 \mathrm{d}x_2 f_q(x_1, \mu^2) f_{\bar{q}}(x_2, \mu^2) \hat{\sigma}_{q\bar{q}}(x_1, x_2, \mu^2)$$



- kinematics of fixed order ME generated according to PDFs → incoming partons do not have transverse momenta
- PS applied backwards from ME towards beam. Transverse momentum generated → mismatch between kinematics after PS and ME
- 4-momenta of incoming partons adjusted to compensate for k_T

this affects predictions for many observables!

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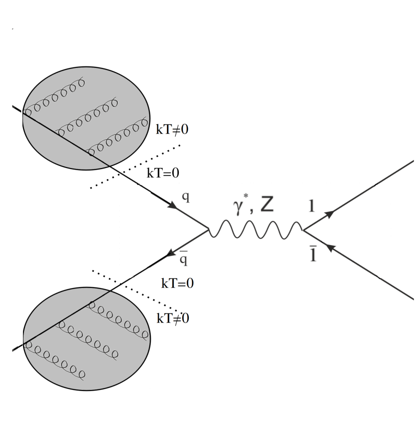

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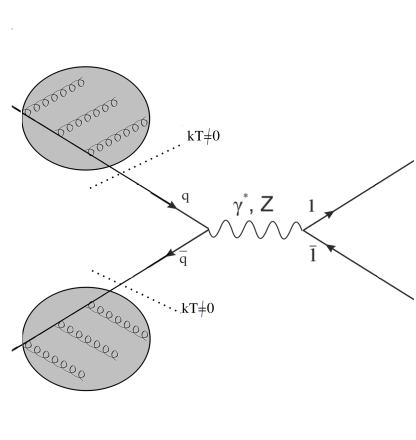

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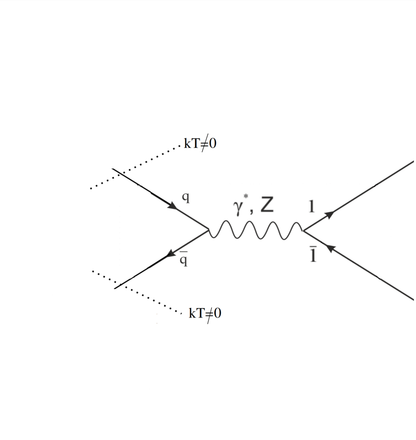
Parton Branching Method: Idea

Develop a MC approach in which ME kinematics will not be affected by Parton Shower (PS) $\rightarrow$ Transverse Momentum Dependent (TMD) factorization & TMD PDFs (TMDs)

$$\sigma = \sum_{q\bar{q}} \int \mathrm{d}^2 k_{\perp 1} \mathrm{d}^2 k_{\perp 2} \int \mathrm{d}x_1 \mathrm{d}x_2 A_q(x_1, k_{\perp 1}, \mu^2) A_{\bar{q}}(x_2, k_{\perp 2}, \mu^2) \hat{\sigma}_{q\bar{q}}(x_1, x_2, k_{\perp 1}, k_{\perp 2}, \mu^2)$$



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- Exclusive observables: TMD PS applied backwards from ME towards beam. k_T at each branching fixed by TMD $\rightarrow$ PS does not change kinematics of the ME

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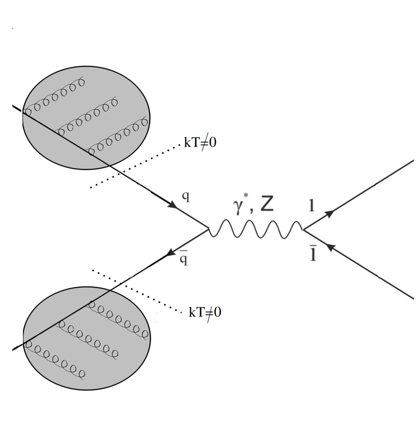

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