Towards precise collider predictions: the Parton Branching method

Hadron21

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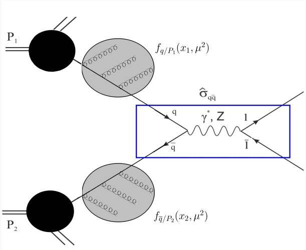
Factorization

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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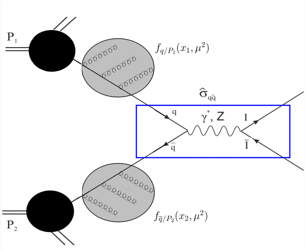

Basis of many QCD calculations BUT

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

→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

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

Components of the Parton Branching Method

Parton Branching (PB) method:

- delivers TMDs (in a wide kinematic range of x, $k_\perp$ and μ^2) from PB TMD evolution equation

$$\widetilde{A}_a\left(x, k_\perp, \mu^2\right) = \Delta_a\left(\mu^2, \mu_0^2\right)\widetilde{A}_a\left(x, k_\perp, \mu_0^2\right) + \sum_b \int \frac{\mathrm{d}\mu_1^2}{\mu_1^2}\int_0^{2\pi}\frac{d\phi}{2\pi}\Theta\left(\mu^2-\mu_1^2\right)\Theta\left(\mu_1^2-\mu_0^2\right)$$
$$\times \quad \Delta_a\left(\mu^2, \mu_1^2\right)\int_x^{z_M}\mathrm{d}z P_{ab}^R\left(z, \mu_1^2, \alpha_s((1-z)^2\mu_1^2)\right)\widetilde{A}_b\left(\frac{x}{z}, |\boldsymbol{k}+(1-z)\boldsymbol{\mu}_1|, \mu_0^2\right)\Delta_b(\mu_1^2, \mu_0^2) + \ldots$$

  initial parameters of the TMDs fitted to HERA DIS data

- uses TMDs as an input to TMD MC generator to obtain predictions for QCD collider observables

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Plan for today:

- How do we obtain PB TMDs?
- How do we use PB TMDs to obtain predictions?
- Example of application: PB results for DY p_T

How do we obtain PB TMDs?

PB TMD evolution equation:

JHEP 1801 (2018) 070

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

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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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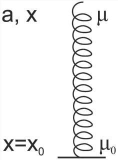

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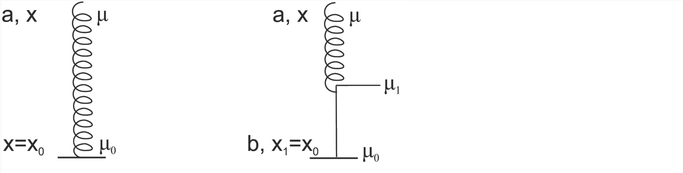

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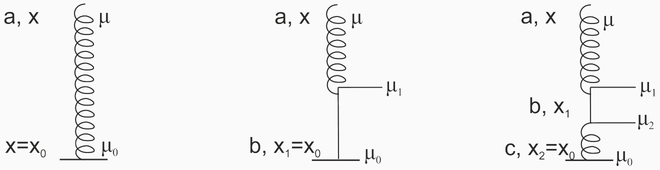

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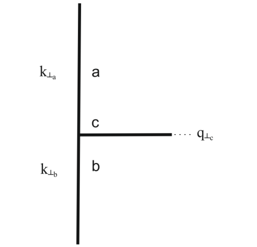
Transverse momentum in PB

- intrinsic transverse momentum at μ_0^2: $\widetilde{A}_{a,0}(x, k_{\perp 0}^2, \mu_0^2) = \widetilde{f}_{a,0}(x, \mu_0^2) \frac{1}{2\pi\sigma^2} \exp\left(\frac{-k_{\perp 0}^2}{2\sigma^2}\right)$

  $\sigma^2 = q_s^2/2, \; q_s = 0.5 \text{ GeV}$
- transverse momentum **k** calculated at each branching

  $\mathbf{k}_a = \mathbf{k}_b - \mathbf{q}_c,$

  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 Nucl.Phys.B 949 (2019) 114795

  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 **q**, scale of α_s, z_M
  - with AO 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 (=PDFs) obtained from integration of PB TMD: $\widetilde{f}_a(x, \mu^2) = \int \mathrm{d}k_\perp^2 \, \widetilde{A}_a(x, k_\perp, \mu^2)$

  can be used in collinear physics applications
- Initial distribution $\widetilde{f}_{a,0}(x, \mu_0^2)$ obtained from fits to HERA DIS data using `xFitter`

  Phys. Rev. D 99, 074008 (2019)

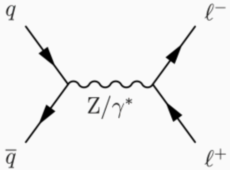
  PB TMDs and iTMDs available in TMDlib and TMDPlotter arXiv:2103.09741

  iTMDs can be used in LHAPDF

Predictions for DY

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:
Literature: perturbative fixed order calculations in collinear factorization not able to describe DY p_T spectra at fixed target experiments for $p_T/m_{DY} \sim 1$

DY predictions with PB TMDs and Cascade in low and middle $p_\perp$ range

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

Z. Phys. C32, 67 (1986)

- DY collinear ME from Pythia (LO)
- Generate $k_\perp$ of $q\bar{q}$ according to TMDs (m_{DY} fixed, x_1, x_2 change)
- compare with the 8 TeV ATLAS measurement

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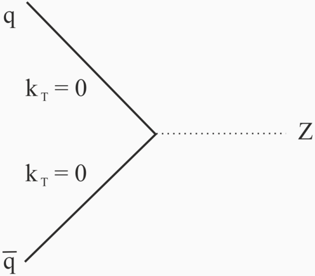

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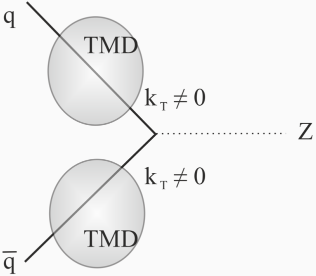

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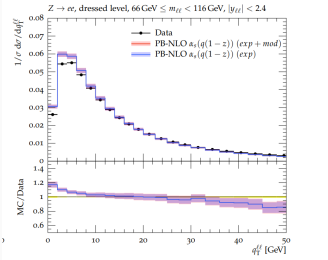

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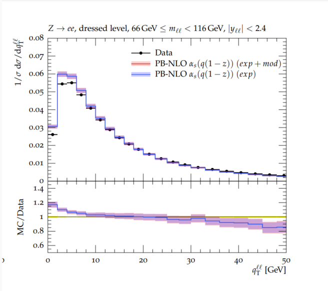

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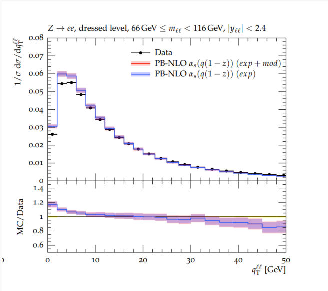

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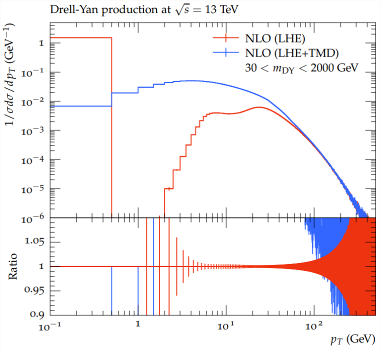
PB TMDs and MCatNLO for DY

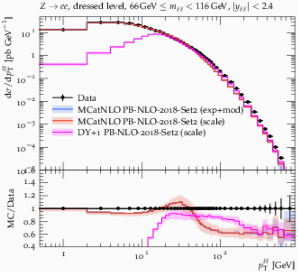
- standard MCatNLO: when ME matched with PS, subtraction terms (for soft and collinear contribution) must be used to avoid double counting JHEP 06 (2002) 029
- Subtraction term depends on the PS to be used
- PB TMDs have similar role to PS
  $\rightarrow$ subtraction term has to be used to combine PB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

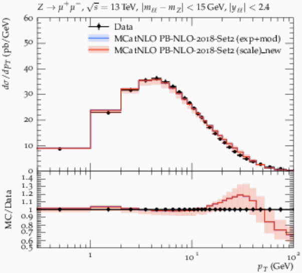
Comparison with data

ATLAS 8 TeV



Phys.Rev.D 100 (2019) 7

CMS 13 TeV



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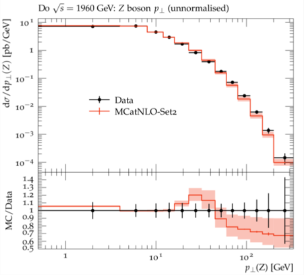
D0 1960 GeV



Low and middle $p_\perp$ spectrum well described

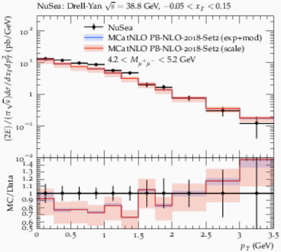
At higher $p_\perp$ contribution from Z+1 jet important

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

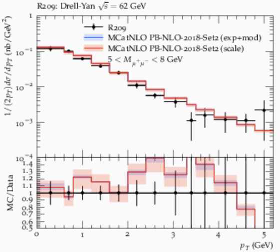
Comparison with data

Fixed target and low energy colliders:

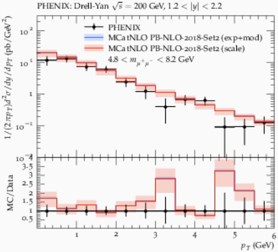
$\sqrt{s} = 38.8$ GeV



$\sqrt{s} = 62$ GeV



$\sqrt{s} = 200$ GeV



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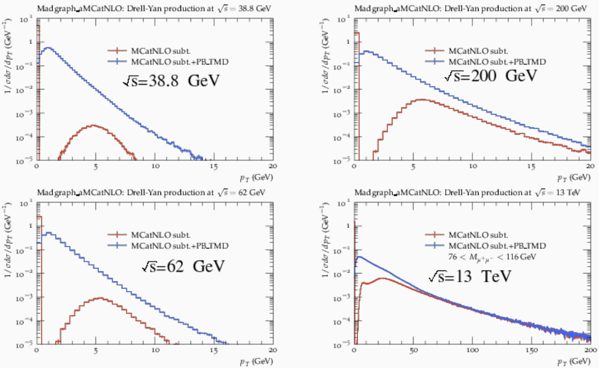
We look at $p_\perp / M_{DY} \sim 1$

$p_\perp$ 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 $\sqrt{s}$



MCatNLO calculation with subtraction.

k included in ME according to PB TMD

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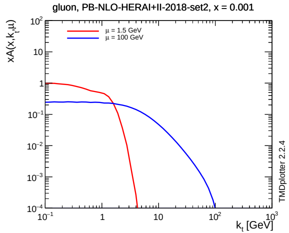
- at low DY mass and low $\sqrt{s}$ even in the region of $p_\perp/m_{DY} \sim 1$ the contribution of soft gluon emissions essential to describe the data
- at larger masses and LHC energies the contribution from soft gluons in the region of $p_\perp/m_{DY} \sim 1$ is small and the spectrum driven by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

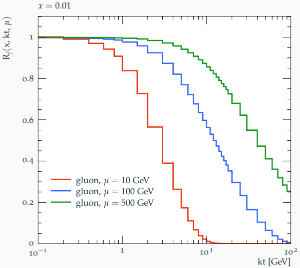
TMD effects at high $p_\perp$

It is commonly known that TMD effects play a role at scales $\mathcal{O}(\text{few GeV})$
Can TMDs also play a role at higher scales?



PB TMD: at $\mu \sim \mathcal{O}(1\ \text{GeV})$ TMD is a gaussian with $\Lambda_{QCD} < \sigma < \mathcal{O}(1\ \text{GeV})$. Effect of the evolution: $k_\perp$ accumulated in each step $\rightarrow$ TMD broadening

in PB: iTMDs (=PDFs) from TMD: $\widetilde{f}_a(x, \mu^2) = \int \mathrm{d}k_\perp^2 \widetilde{A}_a(x, k_\perp, \mu^2)$



What is the contribution to the emission of an extra jet of $p_\perp < \mu$ from the $k_\perp$-broadening of the TMD?

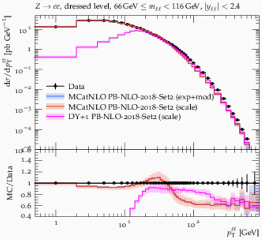
$$R_j(x, k_\perp, \mu^2) = \frac{\int_{k_\perp^2}^{\infty} \mathrm{d}k_\perp'^2 \widetilde{A}_j(x, k_\perp', \mu^2)}{\int \mathrm{d}k_\perp'^2 \widetilde{A}_j(x, k_\perp', \mu^2)}$$

at LHC the contribution from high $k_\perp$ tail to jet emission comparable to perturbative emissions via hard ME!

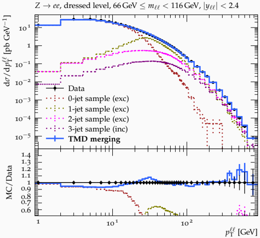
arXiv:2107.01224

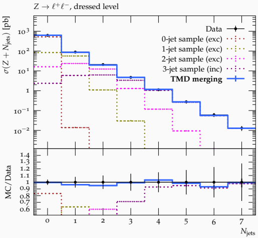
New development: TMDs and MLM Multi-Jet Merging

Recall: At high $p_\perp$ large corrections from higher orders



TMD merging procedure developed (at LO)! arXiv:2107.01224
extension of MLM method NPB 632 (2002) 343–362 to the TMD case





- The merged prediction provides good description of the data in the whole DY $p_\perp$ spectrum
- jet multiplicity in $Z+$ jets production well described, also for multiplicities larger than the maximum nb of jets in MEs

Summary & Conclusions

- Parton Branching: a MC method to obtain QCD collider predictions based on TMDs
- PB: TMD evolution equation to obtain TMDs; TMDs can be used in TMD MC generators to obtain predictions
- As the example of the application DY process discussed, in low and middle and high $p_\perp$ range

NLO PB DY predictions in the low and middle $p_\perp$ range:

- fixed order calculations in collinear factorization not enough to describe DY p_T spectra at fixed target experiments for $p_T/m_{DY} \sim 1$, contribution from soft gluon radiation included in PB TMDs essential to describe the data;
  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
  $PB \otimes \left[H^{(LO)} + \alpha_s \left(H^{(NLO)} - PB(1) \otimes H^{(LO)}\right)\right]$
- Situation different at LHC: in region $p_T/M_Z \sim 1$ purely collinear NLO calculation gives good result

LO PB DY predictions in the high $p_\perp$ range:

- TMD MLM merging procedure developed
- merged predictions describe well the DY $p_\perp$ in the whole $p_\perp$ range and jet multiplicity

Summary & Conclusions

Things I didn't have time to discuss today:

- Photon PB TMD Phys. Lett. B 817 (2021), 136299
- 4FLVN and 5FLVN PB TMDs arXiv:2106.09791
- PB method with TMD splitting functions Presented at Moriond21, DIS21 and EPS21 by L.Keersmaekers
- PB TMD fits with dynamical z_M (at LO and NLO)
- ...

PB method is widely applicable, to many QCD observables, in a wide kinematic range.

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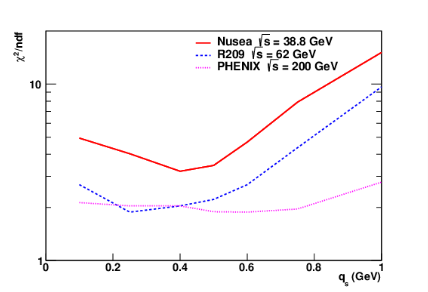
Thank you!

Backup

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.
With low mass DY we hope to constrain better q_s

New development: TMDs and Multi-Jet Merging

MLM merging: NPB 632 (2002) 343–362
TMD merging: arXiv:2107.01224

TMD merging method extends the MLM merging to the TMD case

- MEs generated at LO with MadGraph5_@NLO for Z+0, Z+1, Z+2, Z+3 jets
- PB TMDs used to add $k_\perp$ to the event record
  if $k_\perp$ of any initial parton $>$ min $p_\perp$ of any final state parton $\rightarrow$ event rejected: Sudakov reweighting to avoid double counting between ME and PS
- TMD initial state PS applied with CASCADE an final state PS with Pythia6
- MLM merging method is applied: μ_m to guaranty that the total nb of reconstructed jets equals the nb of final partons in ME ("exclusive"), except the highest multiplicity ("inclusive")