Drell-Yan lepton pair production using TMD distribution functions from parton branching

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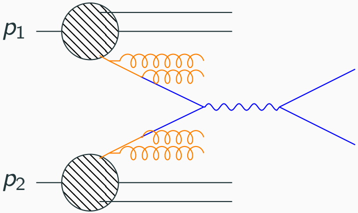
Plan for today

Introduction

Introduction

- In collider physics we need predictions to compare theory with data
- For pp collisions the collinear factorization theorem is commonly used

$$\sigma_h \propto \int \underbrace{f_1 \otimes f_2}_{npQCD+pQCD} \otimes \underbrace{\hat{\sigma}_{parton}}_{pQCD}$$



1. Transverse momentum in the proton is neglected

   Transverse momentum of the partons building the proton

2. Many observables are perfectly described
3. However, there are observables where transverse momentum cannot be neglected $\rightarrow$ Another approach must be used

Introduction

We need to understand where the transverse momentum of the final states comes from

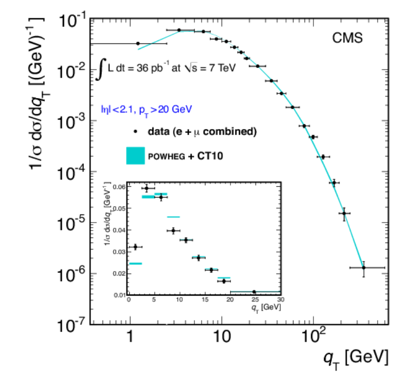
- The initial state partons have some intrinsic transverse momentum
- Later on the transverse momentum is generated via QCD radiations

$$\propto \log \frac{M}{q_T}$$

- These contributions need to be resummed:
  1. Parton showers
  2. TMDs

An example: Z boson q_T

Z boson q_T spectrum in the lepton pair's invariant mass range 60 GeV$< M <$ 120 GeV



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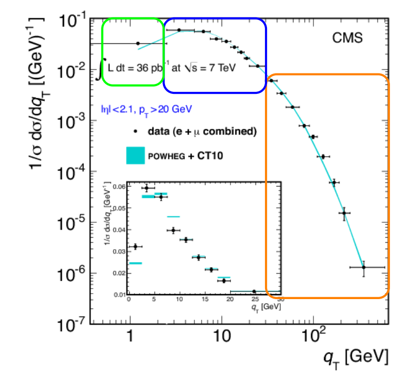

We can distinguish 3 regions

1. High p_T region
2. Peak region
3. Low p_T region

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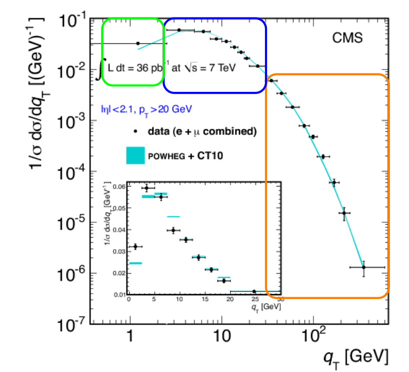


We can distinguish 3 regions

1. High p_T region
2. Peak region
3. Low p_T region

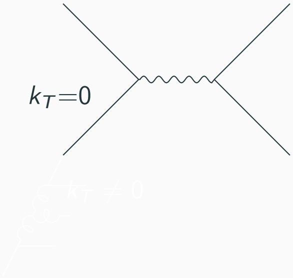
- The high p_T region is described by perturbative QCD
- The peak & low p_T regions can not be described by fixed order QCD $\Rightarrow$ The prediction diverges as q_T decreases
- The Z boson spectrum at the peak and below is dominated by QCD radiation

Why TMDs

- Parton showers:
  1. The partonic CS are computed within perturbation theory
  2. Higher order corrections are obtained via parton showers

PS simulate soft gluon emissions and then resumme them

  3. The PS are applied backwards: Hard process



- ME is generated using collinear PDF in a proton

x is generated according to the PDF

TMDs vs Parton Showers

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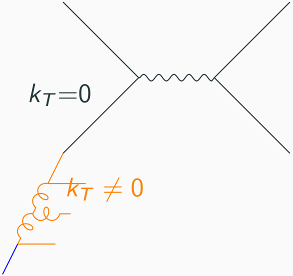

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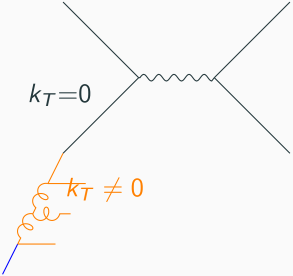


- ME is generated using collinear PDF in a proton

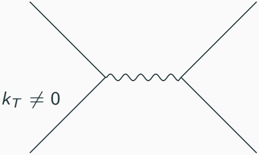
  x is generated according to the PDF

- PS are used to generate QCD radiation → k_T is generated
- The CS is manipulated to add the k_T → Mismatch

  The new kinematics does not correspond to de PDF according to which it was initially generated

- TMDs:
  1. The TMD factorization theorem

$$\sigma = \sum_{q\bar{q}} \int d^2k_{T1} d^2k_{T2} \int d_{x1} d_{x2} A_q(x_1, k_{T1}, \mu^2) A_{\bar{q}}(x_2, k_{T2}, \mu^2) \hat{\sigma}_{q\bar{q}}(x_1, x_2, k_{T1}, k_{T2}, \mu^2)$$



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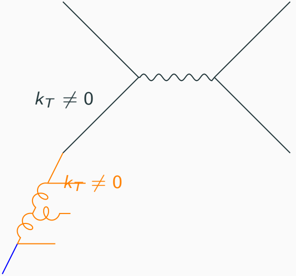

- k_T dependent ME, ME according to TMDs
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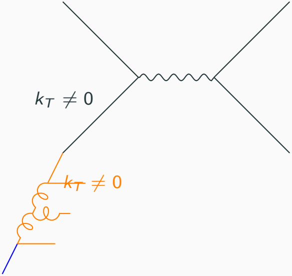

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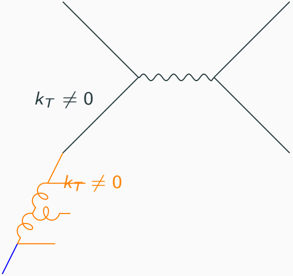

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We need TMDs to make this idea possible

Parton Branching

Parton Branching

- QCD: many splittings occur before parton enters the hard process

$$\underbrace{\text{EVOLUTION}}_{DGLAP}$$

$$\widetilde{f}_a(x,\mu^2) = \widetilde{f}(x,\mu_0^2)\Delta_a(\mu^2) + \int_{\ln\mu_0^2}^{\ln\mu^2} d\ln\mu_1^2 \frac{\Delta_a(\mu^2)}{\Delta_a(\mu_1^2)} \sum_b \int_x^{z_M} dz_1 P_{ab}^R(\mu_1^2, z_1)\widetilde{f}_b\left(\frac{x}{z_1},\mu_0^2\right)\Delta_b(\mu_1^2) + \ldots$$

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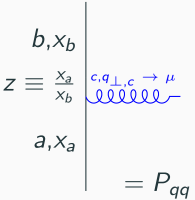

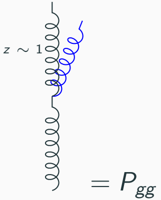

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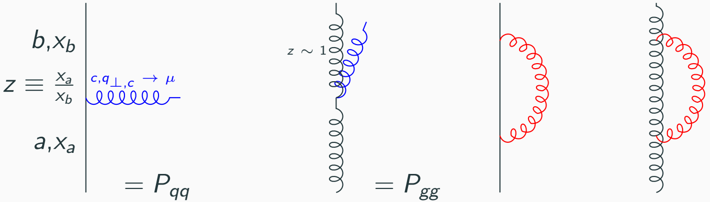

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- The Sudakov represents the probability of no emission between scales μ_0 and μ
- DGLAP limitation: does not have transverse momentum

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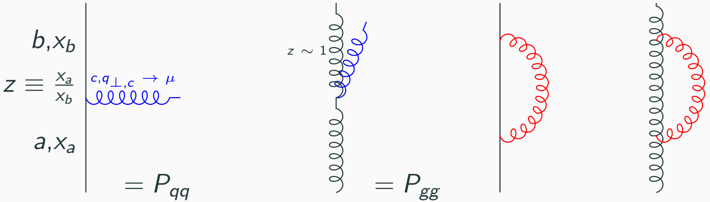

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With PB we go further!

- At every splitting we compute the momentum of the emitted and propagating partons
- The evolution equations that the TMDs follow using PB method

$$\widetilde{A}_a(x, \mu^2, k_\perp) = \widetilde{A}(x, \mu_0^2, k_\perp)\Delta_a(\mu^2)$$

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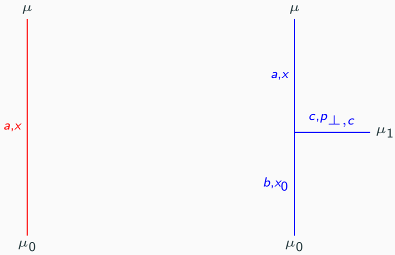

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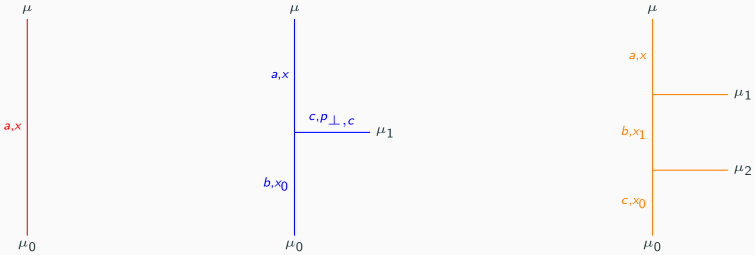
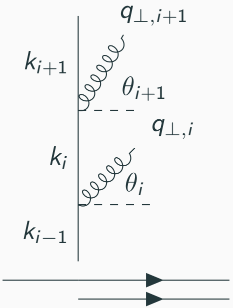


Angular ordering

- The way we choose how to order the evolution in PB incorporates an important physical phenomena

Angular ordering: $\theta_{i+1} > \theta_i$



- Angular ordering enters in the evolution as

$$q^2_{\perp,c} = (1-z)^2 \mu'^2 \quad z_M = 1 - \left(\frac{q_0}{\mu'}\right) \quad \alpha_s((1-z)^2\mu'^2)$$

- The scale is proportional to the angle of the momentum of the radiated particle with respect to the particle beam

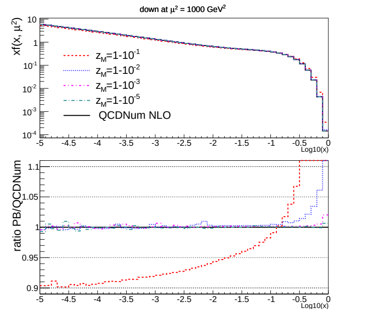
$$\frac{q_{\perp,i}}{1-z_i} = |k_{i-1}| \sin\theta_i = \mu'$$

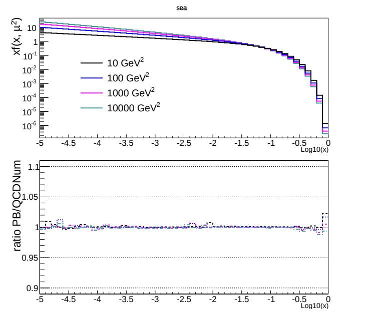
- The first radiation is the one with the smallest angle

Remember: $\Delta_a(z_M, \mu^2, \mu_0^2) = exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} zP^R_{ba}(\mu'^2, z)dz\right)$

Parton Branching validation

- PB is implemented in updfevolv code
- The code is checked using QCDnum package → Solves DGLAP semi-analytically
  1. We take the same starting distribution as in QCDnum
  2. We evolve the PDF up to some scale μ both with QCDnum and updfevolv
- Left figure: different values of z_M, if $z \sim 1$ we are able to reproduce DGLAP, if $z_M = 0.9$ we differ
- Right figure: PB is validated in wide range of scales





Important: In order to reproduce DGLAP we need fixed z_M and $\alpha_s(\mu)$

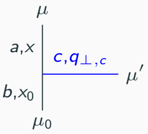
Non-perturbative effects

q_0 dependence

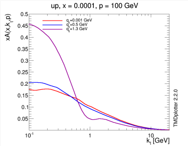
- q_0 is the minimum transverse momentum of the parton emitted in the branching $(q_{\perp,c} > q_0)$
- The choice of q_0 will affect z_M, thus

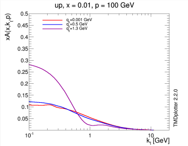
$$\Delta_a(z_M, \mu^2, \mu_0^2) = exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} zP^R_{ba}(\alpha_s(q_\perp), z)dz\right)$$

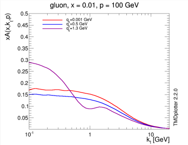
- With small q_0 more branchings
- Large q_0: for up quarks and gluons at higher x intrinsic k_t dominates at low k_t, lower contribution from evolution at higher k_t, compared to small q_0
- Small q_0: intrinsic k_t contribution smeared via the evolution
- For gluons at low x radiation dominates in the whole k_t range

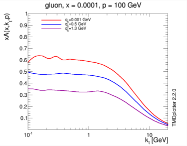


REMEMBER, ANGULAR ORDERING $\Rightarrow z_M = 1 - \left(\frac{q_0}{\mu'}\right)$









q_{cut} dependence

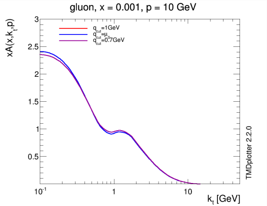
- At small values of $q_\perp$ α_s diverges, we introduce a cut

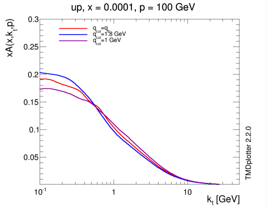
$$\alpha_s(q_\perp) \rightarrow \alpha_s(q_\perp > q_{cut})$$

- This will affect the Sudakov form factor

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

- If q_0 is large the q_{cut} will not affect (upper plot)
- For small q_0 we see an effect from the choice of the cut (lower plot)
- The explanation of the shape of the distribution is analogous to q_0 dependence





Intrinsic k_t dependence

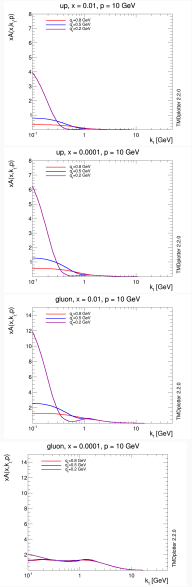
- The intrinsic k_t of the initial parton is generated from a gaussian distribution,

$$\mathcal{A}_{0,a}(x, k_{t_0}, \mu_0) = f_{0,a}(x, \mu_0) e^{-\frac{k_{t_0}^2}{\sigma^2}}.$$

- The parameter we are studying is q_s, the width of the distribution:

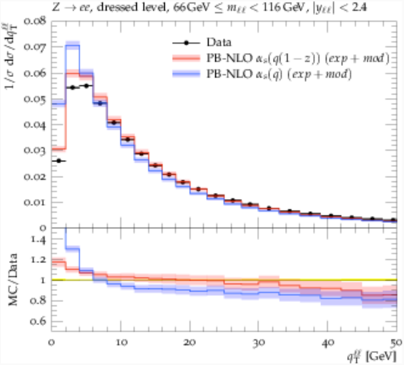
$$\sigma = \frac{q_s}{\sqrt{2}}.$$

- Small values of q_s make larger TMDs at lower k_t
- The effect of q_s not visible for gluon at small x, evolution dominates the contribution



Predictions for ATLAS and NuSea Drell-Yan measurements

Prediction for the Z boson $p_\perp$ spectrum



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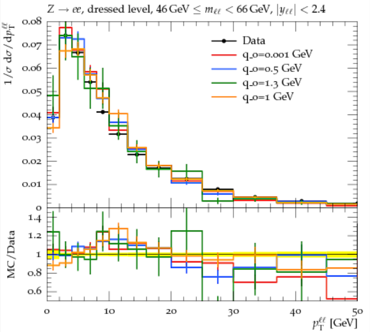
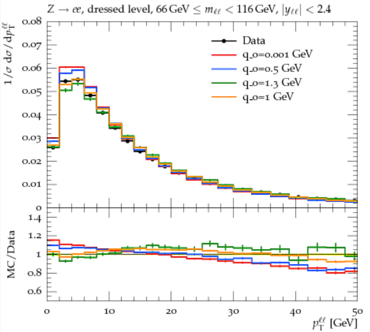
- Predictions obtained with TMDs obtained from the fit of HERA DIS data
- With fixed z_M PBset2, where $\alpha_s(q_\perp)$, better predictions than PBset1, where $\alpha_s(\mu)$
- PBset2 works fine but we can still improve using dynamic z_M
- Dynamic z_M has been deeply studied in arXiv:1908.08524v1, accepted for the publication in Nuclear Physics B

Dependence on q_0



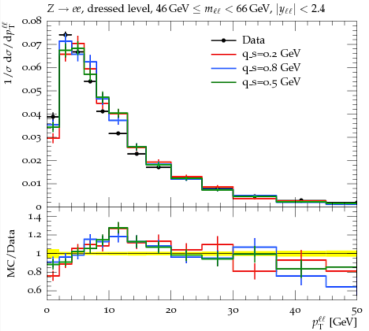


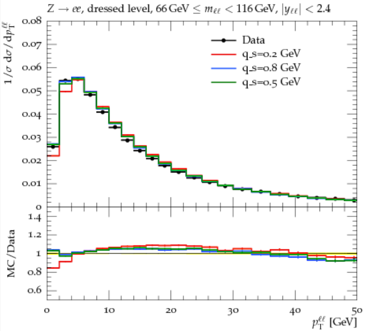
q_0 is the minimum transverse momenta of the parton emitted in the branching

$$z_M = 1 - \frac{q_0}{\mu'}$$

Visible effect in the whole p_t region, $q_0 \sim 1$GeV the best

Dependence on intrinsic k_t



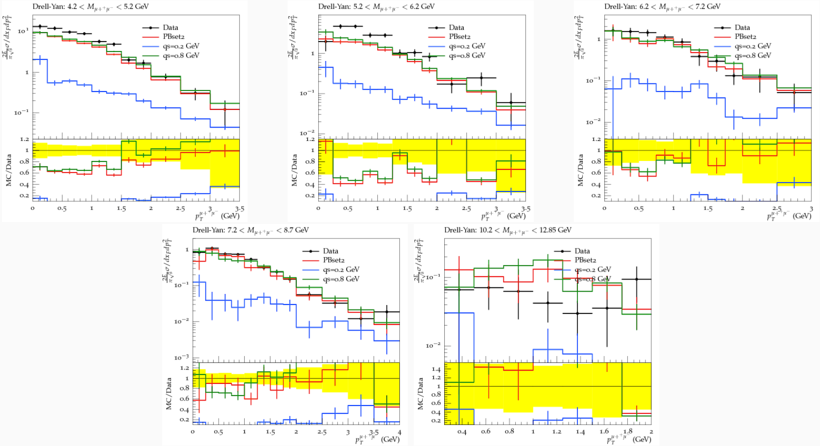


The width of the Gaussian of the k_T distribution affects the low p_T region and should be studied in detail in low energy experiments

ATLAS data is not sensitive enough at low p_T $\rightarrow$ NuSea experiment (Low mass DY)

PB predictions for NuSea

NuSea experiment is a fixed target low energy experiment performed at Fermilab where protons collide with deuterium and hydrogen



At low energy DY there is a big sensitivity to intrinsic k_T

The intrinsic k_T distribution can be fitted from these data (Perform a global fit using HERA and NuSea data)

Conclusions

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- Precise predictions for QCD observables crucial for searches for BSM
- Standard MC generators and PS suffer from inprecise kinematics treatment
- TMD factorization gives a new idea how to obtain predictions with a correct kinematics treatment by using TMDs
- PB method allows us to obtain TMDs and collinenar PDFs
- Non-perturbative effects play an important role in the accuracy of predictions and can be fitted from low energy experiments

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Thank you!