Drell-Yan pT spectra at fixed-target and collider energies

CPHI-2022

- **Ola Lelek** on behalf of the Parton Branching team

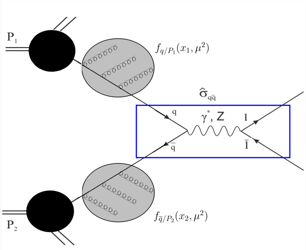
Universiteit Antwerpen

Research Foundation Flanders
Opening new horizons

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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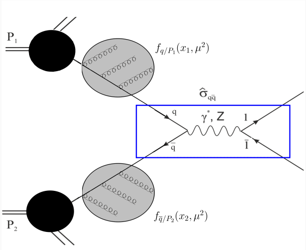

Basis of many QCD calculations BUT

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

$\rightarrow$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

$A\left(x, k_\perp, \mu^2\right)$ - 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
z_M - soft gluon resolution scale, separates resolvable ($z < z_M$) and non-resolvable ($z > z_M$) branchings

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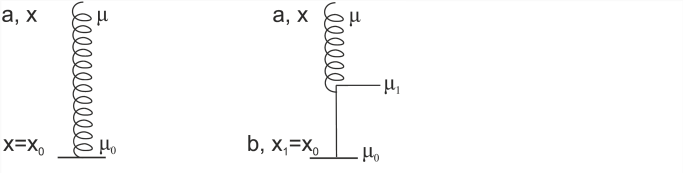

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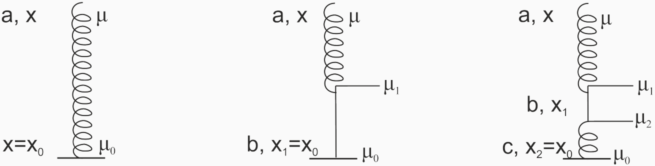

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Transverse momentum in PB

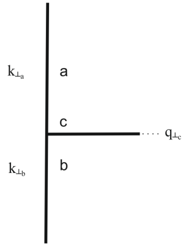
- intrinsic transverse momentum at μ_0^2: $\widetilde{A}_{a,0}(x, k_{\perp 0}^2, \mu_0^2) = \widetilde{f}_{a,0}(x, \mu_0^2) \frac{1}{2\pi\sigma^2} \exp\left(\frac{-k_{\perp 0}^2}{2\sigma^2}\right)$

  $\sigma^2 = q_s^2/2,\ q_s = 0.5\ \mathrm{GeV}$

- 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)

- 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 $\mathbf{k} = \mathbf{k}_0 - \sum_i \mathbf{q}_i$

- 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

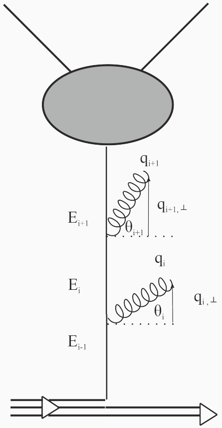


PB TMDs and iTMDs available in TMDlib and TMDPlotter arXiv:2103.09741
iTMDs can be used in LHAPDF

Angular Ordering

PB implements angular ordering (AO) condition Nucl.Phys.B 949 (2019) 114795
similar to Catani-Marchesini-Webber Nucl. Phys. B349, 635 (1991)

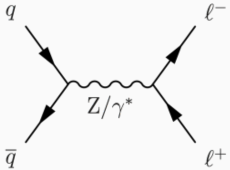
- angles of emitted partons increase from the hadron side towards hard scattering
- relation between μ' and $\mathbf{q}$, scale of α_s, z_M
- with AO soft gluon resummation included
  LL, NLL coefficients in Sudakov the same as in CSS, NNLL-difference from renormalization group (difference proportional to β_0)



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

- ME obtained from standard automated methods used in collinear physics (Pythia, MCatNLO,...) with **k** added according to TMD

- 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

Phys. Rev. D 99, 074008 (2019)

In collinear MC transverse momentum comes from PS$\Leftrightarrow$ in PB method it is included in TMD

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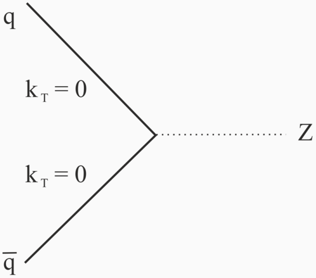

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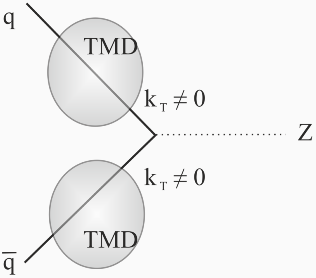

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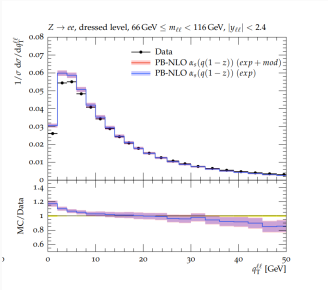

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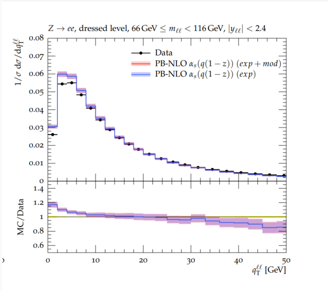

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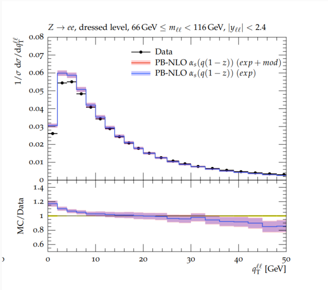

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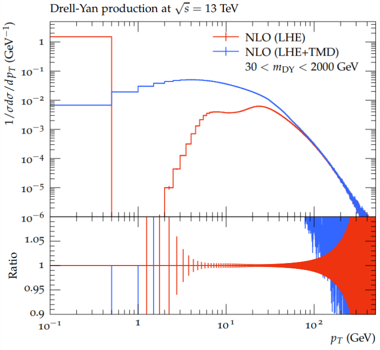
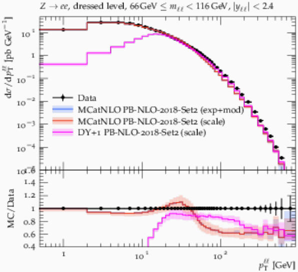
PB TMDs and MCatNLO for DY

- standard MCatNLO: when ME matched with PS, subtraction terms (for soft and collinear contribution) must be used to avoid double counting
- 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

ATLAS 8 TeV



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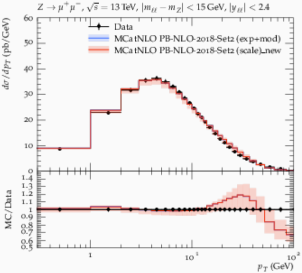
CMS 13 TeV



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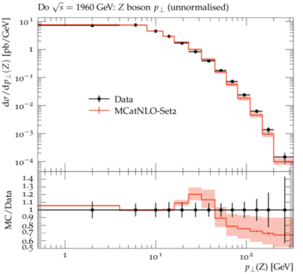
D0 1960 GeV



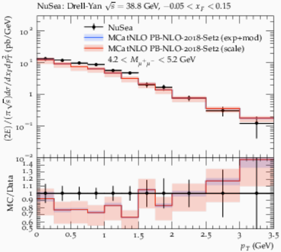
Low and middle $p_\perp$ spectrum well described

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

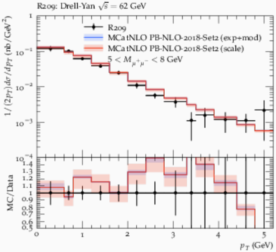
Uncertainty: experimental + model (from the fit procedure) small, scale uncertainties (μ_f and μ_r variation in ME) sizeable

Fixed target and low energy colliders:

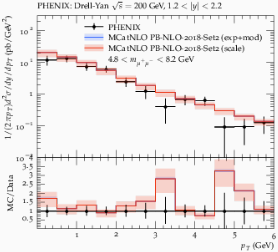
$\sqrt{s} = 38.8$ GeV



$\sqrt{s} = 62$ GeV



$\sqrt{s} = 200$ GeV



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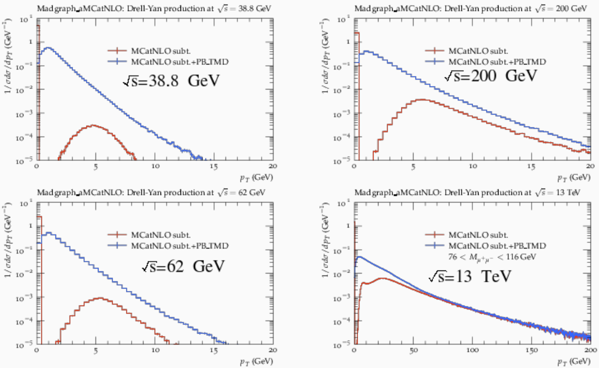
We look at $p_\perp / M_{DY} \sim 1$

$p_\perp$ 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.



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MCatNLO calculation with subtraction.
k included in ME according to PB TMD

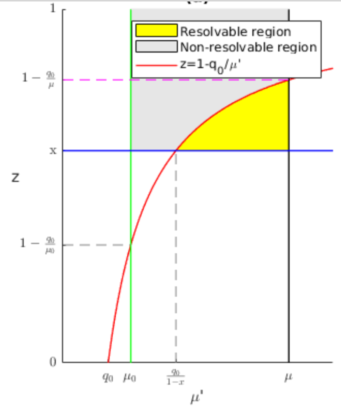
- at low DY mass and low $\sqrt{s}$ even in the region of $p_\perp/m_{DY} \sim 1$ the contribution of soft gluon emissions essential to describe the data
- at larger masses and LHC energies the contribution from soft gluons in the region of $p_\perp/m_{DY} \sim 1$ is small and the spectrum driven by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

WORK IN PROGRESS

Infrared resummation: Angular Ordering needed!
AO: $q_\perp^2 = (1-z)^2 \mu'^2$
if q_0- min resolvable $q_\perp$ $\rightarrow$ condition on z_M: $z_M = 1 - q_0/\mu'$
Phase space for the resolvable branchings reduced

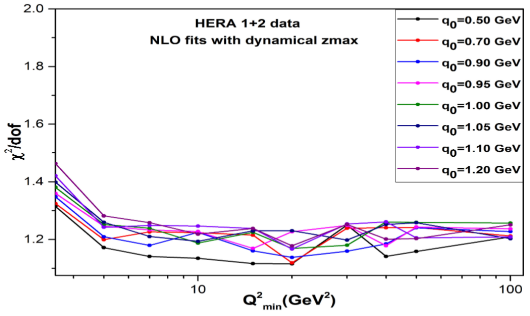
PB developments:

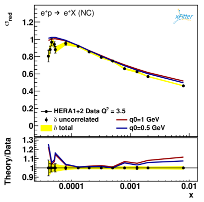
- PB-NLO-HERAI+II-2018-set1 - purely DGLAP-like
- PB-NLO-HERAI+II-2018-set2 AO running coupling ($\alpha_s(q_\perp)$) BUT fixed z_M
- Next step: Full AO

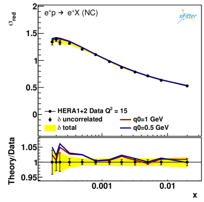


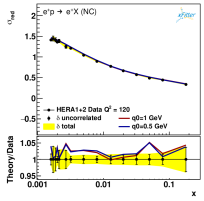
- Is it possible to obtain reasonable fit with dynamical z_M within PB framework?
- Which q_0 value to choose?

Preliminary fits with dynamical z_M





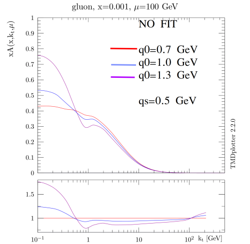




PB-NLO-HERAI+II-2018-set2: $\chi^2/dof = 1.21$
$q0 = 0.5$ GeV: $\chi^2/dof = 1.27$
$q0 = 1$ GeV: $\chi^2/dof = 1.38$

Possible to obtain good fit with dynamical z_M even with low Q^2 data
Good description of HERA 1+2 F2 data but no sensitivity to q_0
Other data need to be included in the fit

Effect of non perturbative parameters on TMDs



Let's look at the toy model- no fit:

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

$z_M = 1 - q_0/\mu'$

smaller q_0 → more branchings

- large q_0: matching of intrinsic distribution with the evolution visible
- with low q_0 intrinsic $k_\perp$ distribution smeared by the evolution

  more branchings which fill matching region of intrinsic $k_\perp$ and evolution ($q_\perp^2 = (1-z)^2\mu'^2$)

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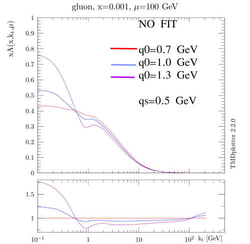

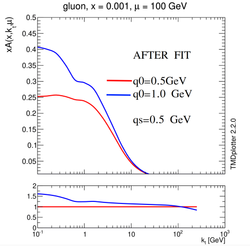

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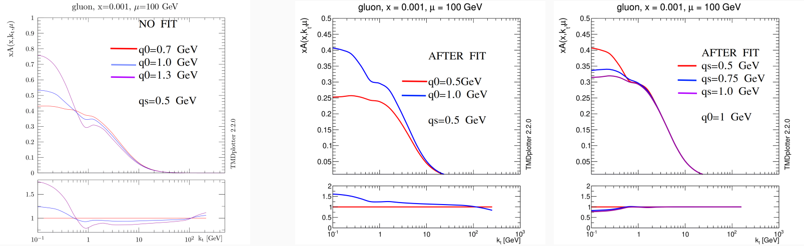

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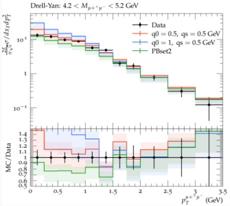
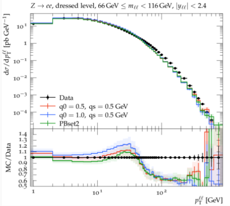
Characteristic features still preserved after the fit
What if we change intrinsic $k_\perp$?

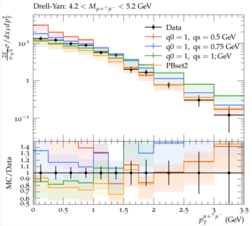
- intrinsic $k_\perp$ affects only the low $k_\perp$ region
- with large q_s smooth matching of intrinsic $k_\perp$ and evolution

Interplay between non-perturbative input parameters
One should perform a simultaneous fit of q_s and q_0!

Preliminary DY predictions with dynamical z_M







DY data from different experiments described reasonably well with predictions with dynamical z_M

Simultaneous fit of q_s and q_0 needed

Outlook:

NUSEA sensitive to q_s and q_0

NUSEA data are at large x but no large x in HERA data → constrain large x (i)TMDs better with more datasets in the fit, to get better view on q_0 and q_s values

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

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

WORK IN PROGRESS: To fully incorporate AO, z_M must be scale dependent

- preliminary fits with dynamical z_M look good
- there is an interplay between q_0 and intrinsic $k_\perp$, simultaneous fit of q_s and q_0 needed

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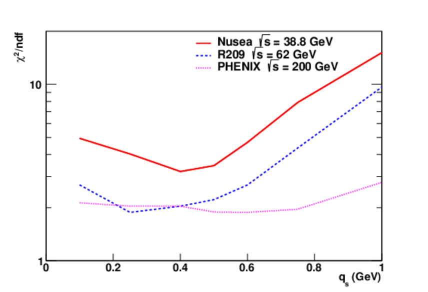
Thank you!

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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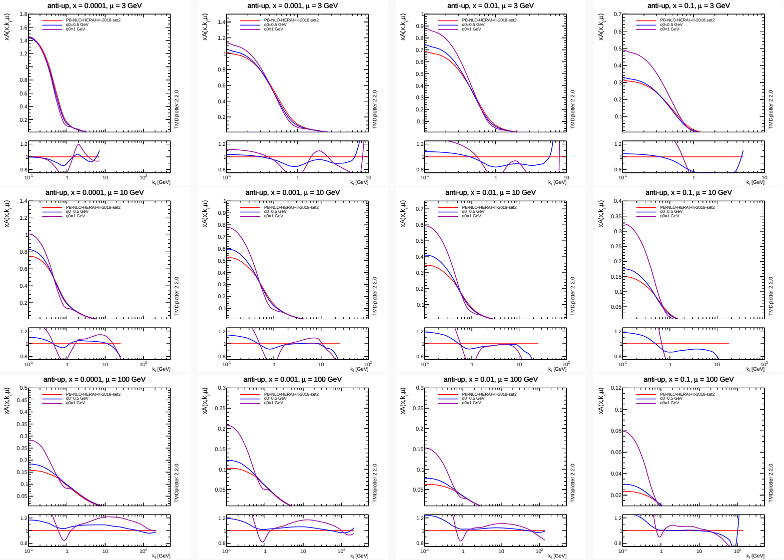
NuSea and R209 show minimum for q_s close to the q_s value used by assumption in PB.
With low mass DY we hoped to constrain better q_s

antiup



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anti-up, x = 0.001, μ = 3 GeV
anti-up, x = 0.01, μ = 3 GeV
anti-up, x = 0.1, μ = 3 GeV
anti-up, x = 0.0001, μ = 10 GeV
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anti-up, x = 0.01, μ = 10 GeV
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anti-up, x = 0.0001, μ = 100 GeV
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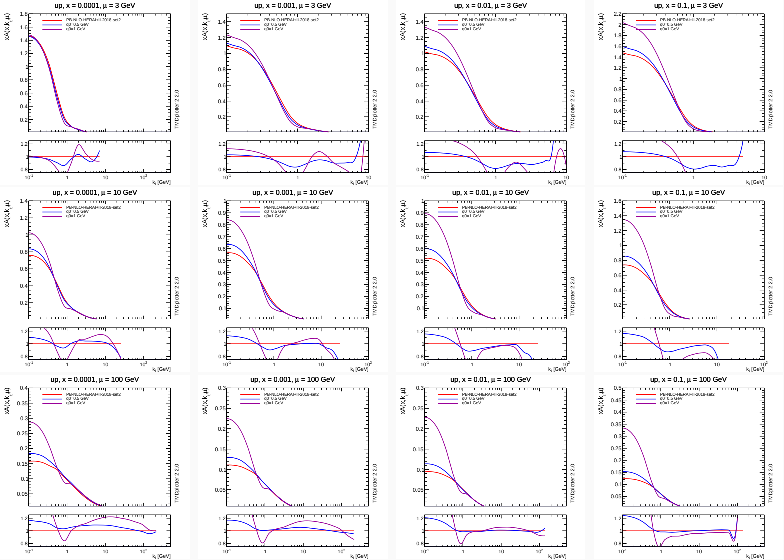
anti-up, x = 0.01, μ = 100 GeV
anti-up, x = 0.1, μ = 100 GeV
PB-NLO-HERAI+II-2018-set2
q0=0.5 GeV
q0=1 GeV
xA(x,k_t,μ)
k_t [GeV]
TMDplotter 2.2.0

up



up, x = 0.0001, μ = 3 GeV
up, x = 0.001, μ = 3 GeV
up, x = 0.01, μ = 3 GeV
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up, x = 0.0001, μ = 10 GeV
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PB-NLO-HERAI+II-2018-set2
q0=0.5 GeV
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xA(x,k_t,μ)
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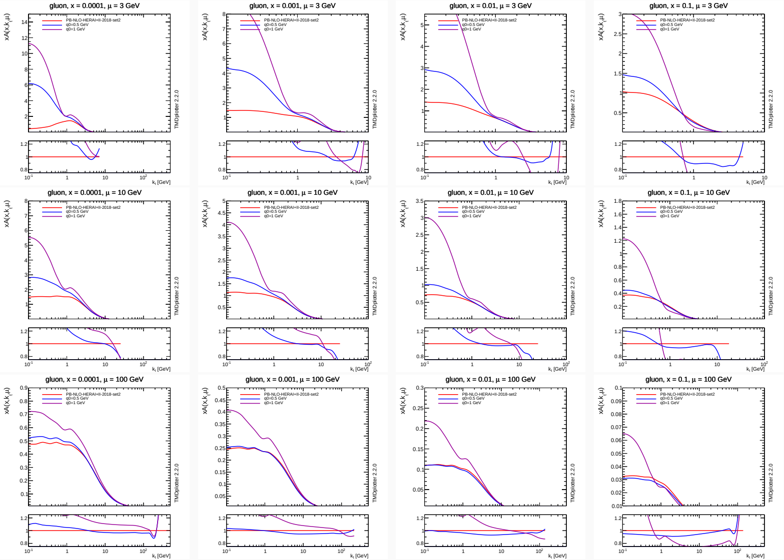
gluon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gluon, x = 0.001, μ = 3 GeV
gluon, x = 0.01, μ = 3 GeV
gluon, x = 0.1, μ = 3 GeV
gluon, x = 0.0001, μ = 10 GeV
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iTMDs full range