# Recent Progress in TMD Parton Densities and Corresponding Parton Showers

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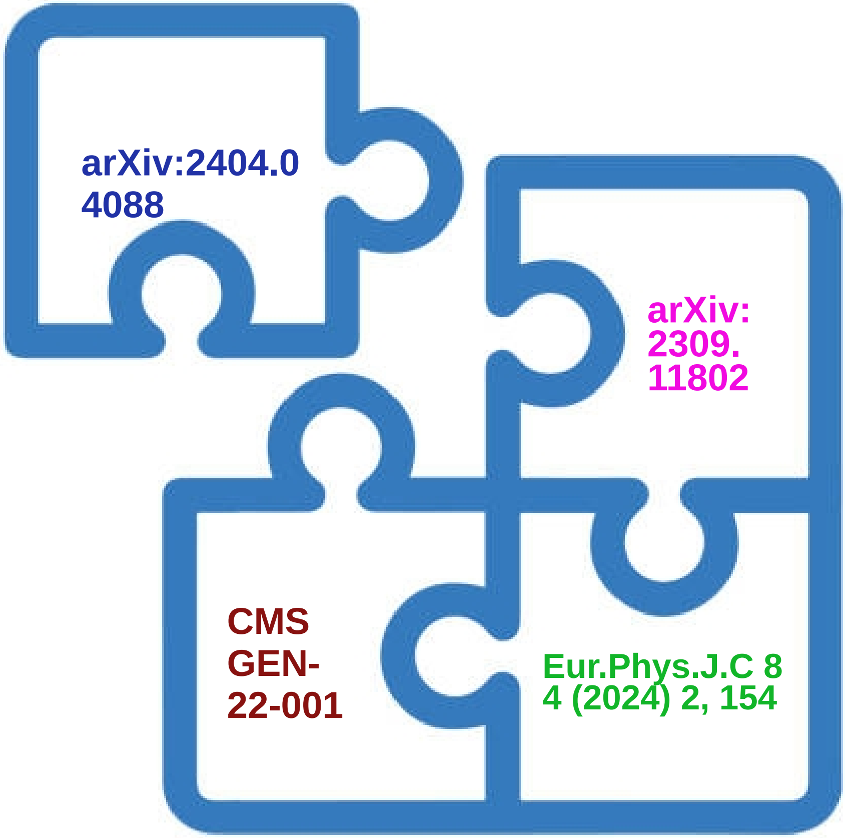
**On behalf of CASCADE group**

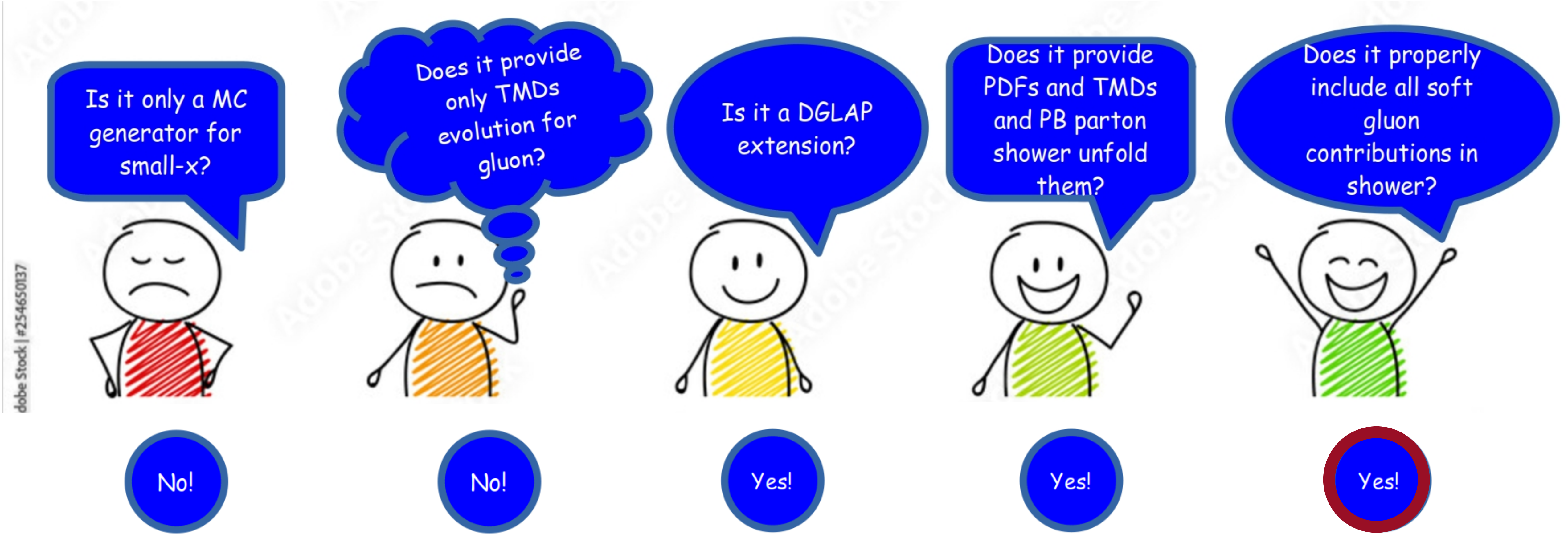




HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

# What is the Parton Branching method?

[JHEP 09 060 (2022)]
[Phys. Rev. D 100 (2019) no.7, 074027]
[Eur.Phys.J.C 82 (2022) 8, 755]
[Eur.Phys.J.C 82 (2022) 1, 36]
[Phys. Lett. B 822 136700 (2021)]



# The Parton Branching (PB) method

## Evolution for both collinear and TMD PDFs

Parton BR approach provides angular ordered evolution for TMD parton densities
PB-Set1 ($\alpha_s(\mu^2)$) and PB-Set2 ($\alpha_s(p_T^2=\mu^2(1-z)^2)$):

$$\widetilde{\mathcal{A}}_a(x,k_\perp^2,\mu^2) = \widetilde{\mathcal{A}}_a(x,k_\perp^2,\mu_0^2)\Delta_a(\mu^2,\mu_0^2) + \int \frac{\mathrm{d}^2\mu'_\perp}{\mu'^2_\perp}\Delta_a(\mu^2,\mu'^2_\perp)\Theta(\mu^2-\mu'^2_\perp)\Theta(\mu'^2_\perp-\mu_0^2) \times \sum_b \int_x^{z_M} \mathrm{d}z P_{ab}^R(z,\alpha_s)\widetilde{\mathcal{A}}_b\left(\frac{x}{z},(k_\perp+(1-z)\mu'_\perp)^2,\mu'^2_\perp\right) ,$$

$z_M$ : soft gluon resolution parameter
For $z_M \sim 1$ : we recover DGLAP

and collinear parton densities:

$$\widetilde{f}_a(x,\mu^2) = \widetilde{f}_a(x,\mu_0^2)\Delta_a(\mu^2,\mu_0^2) + \int_{\mu_0^2}^{\mu^2} \frac{\mathrm{d}\mu'^2}{\mu'^2}\Delta_a(\mu^2,\mu'^2)\sum_b \int_x^{z_M} \mathrm{d}z P_{ab}^R(z,\alpha_s)\widetilde{f}_b\left(\frac{x}{z},\mu'^2\right)$$

initial distribution is factorized in a collinear part and a normalized Gaussian factor with the width defined by the $\mathbf{q_s}$ parameter

$$\tilde{\mathcal{A}}_a(x,k_{\perp,0}^2,\mu_0^2) = x f_a(x,\mu_0^2)\cdot\frac{1}{q_s^2}\exp\left(-\frac{k_{\perp,0}^2}{q_s^2}\right)$$

# PDFs and TMDs fit in a nutshell

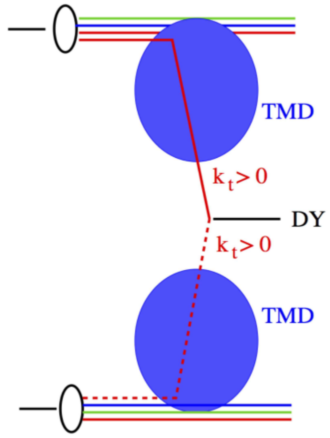
## Required settings to calculate the transverse momentum spectrum of DY lepton pairs

- Parameterize collinear PDF at $\mu_0^2$
- Produce PB kernels individually for collinear and TMD densities for quarks and gluons with uPDFevolv2 package
- Perform fit to measurements using xFitter package to extract the initial parametrization (with collinear coefficient functions at NLO)
- Store the TMDs in grid for later use in CASCADE3 — Eur. Phys. J. C 81 (2021) 425
- Plot both collinear and TMD pdfs within TMDplotter — Eur. Phys. J. C 81 (2021) no.8, 752

# Application of PB TMDs

## PDFs & TMDs fitted to HERA data applied to different measurements, e.g. DY

**Our setting:**
Introducing “transverse momentum” instead of “evolution scale” in strong coupling suppresses further soft gluons at low $k_T$.
We use PB-set2 [$\alpha_s(p_T)$] with $q_{cut}$=1 GeV and $\alpha_s(M_z)$=0.118



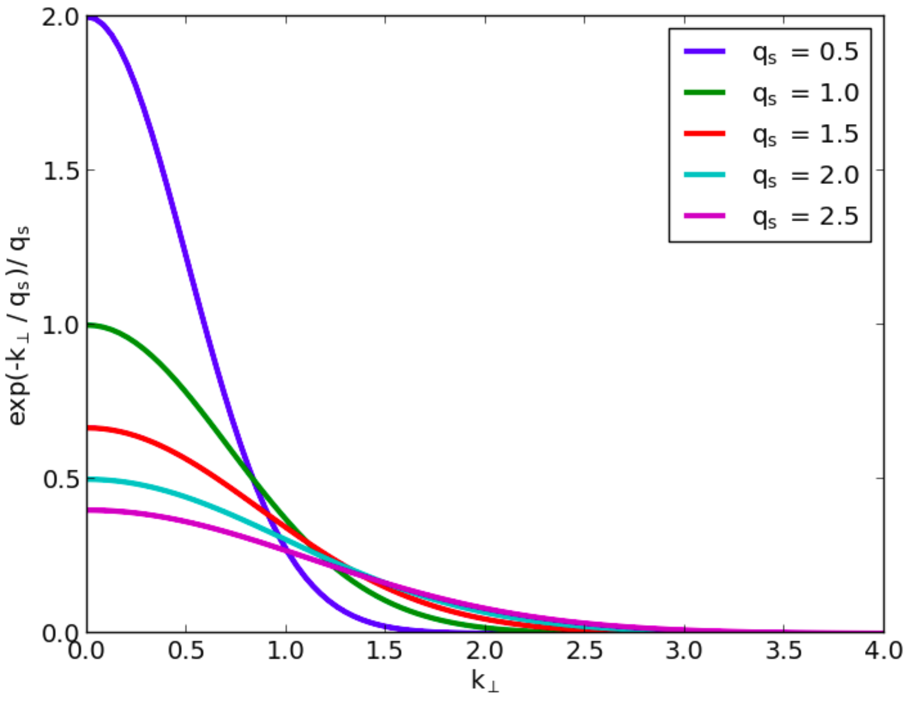

**Hard process:**
NLO hard-scattering ME are generated by the MADGRAPH_AMC@NLO based on collinear PB-set2
HERWIG6 subtraction terms are used since they are based on the same angular ordering conditions

**Soft process:**
$k_T$ is added to ME by an algorithm in CASCADE3 using the subtractive matching procedure

# Intrinsic $k_T$

## Gaussian distribution

Transverse momenta of partons in incoming colliding hadrons due to Fermi motion.
**Not calculable** in perturbative QCD.
Described by phenomenological models
**Modelled using a tunable parameter, $q_s$, through a Gaussian distribution**
First assuption was $q_s$=0.5 GeV



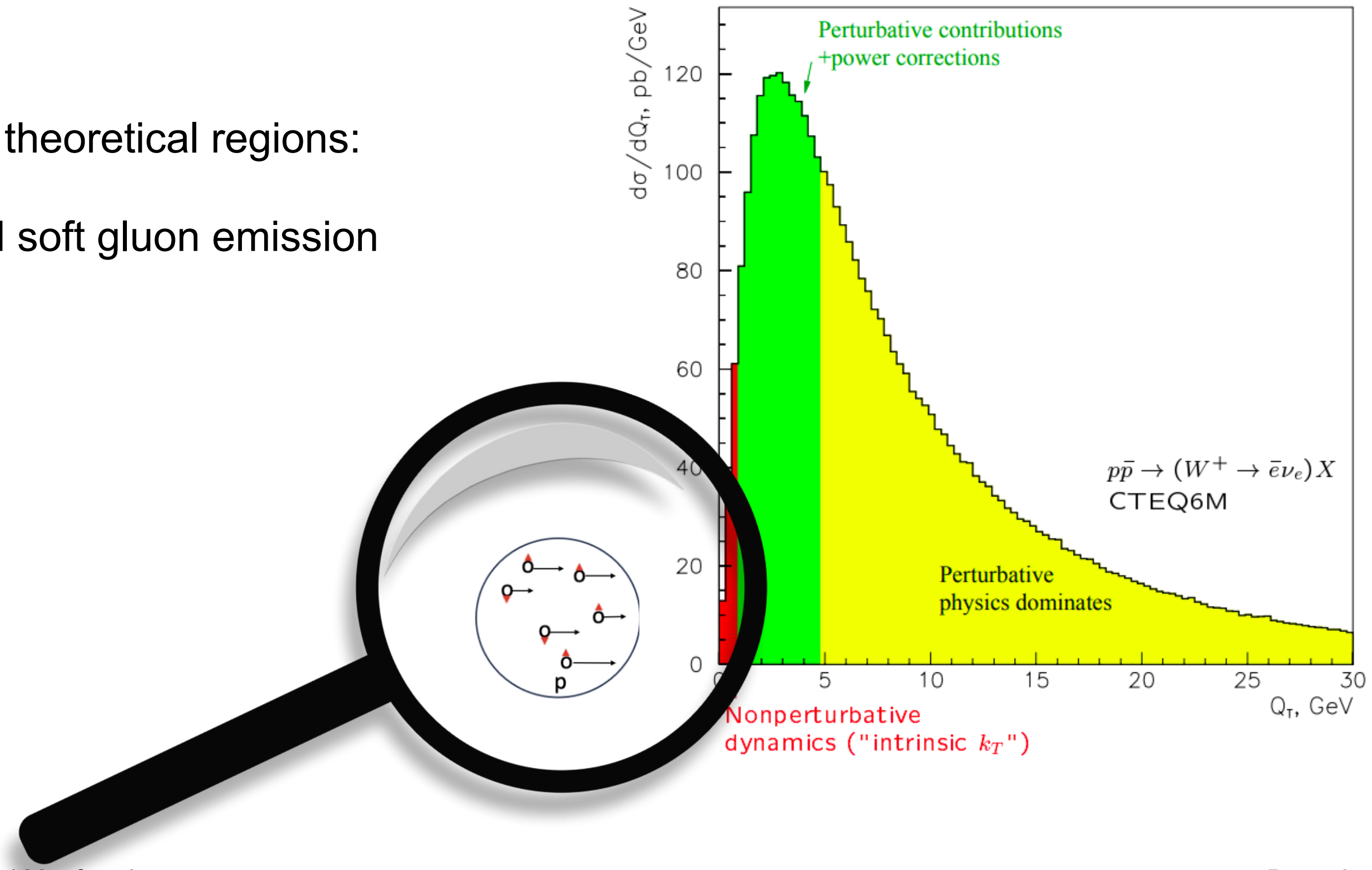
# How can one specify intrinsic $k_T$ width?

DY provides a clean, high-resolution final state for better understanding of various QCD effects.

Description of DY $p_T$ spectrum can be divided into three theoretical regions:

- **Non-perturbative region:** sensitive to intrinsic $k_T$ and soft gluon emission
- **Transition region**
- **Perturbative region**

Fred Olness, CTEQ summerschool 2003



# Gauss width tuned to 13 TeV pp data across various $m_{DY}$ bins

## The region sensetive to $q_s$, $p_T(ll)$ < 8 GeV is considered

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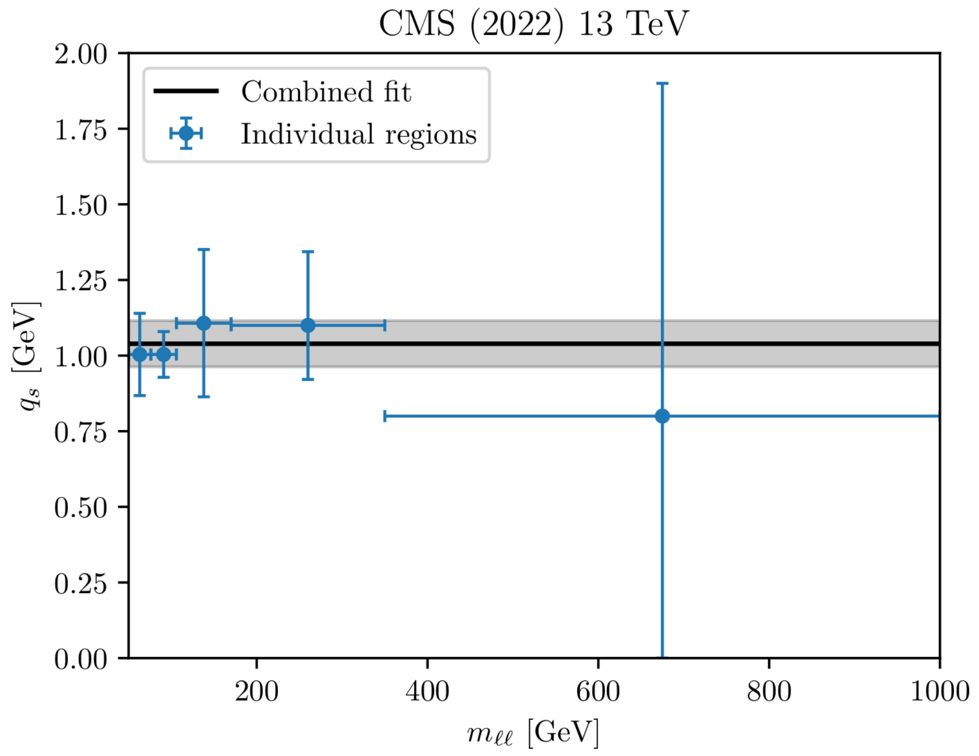


Final $q_s$ extracted from combined covariance matrix analysis across 5 mass bins

- One-sigma confidence obtained as the region of all $q_s$ values for which $\chi^2(q_s) < \chi_{min}^2 + 1$
- Scan resolution and bin uncertainties are taken into account

**$q_s$=1.04 ± 0.08 GeV**

The values extracted from all $m_{DY}$ interval are compatible with each other.

# Mass dependence of the intrinsic $k_T$

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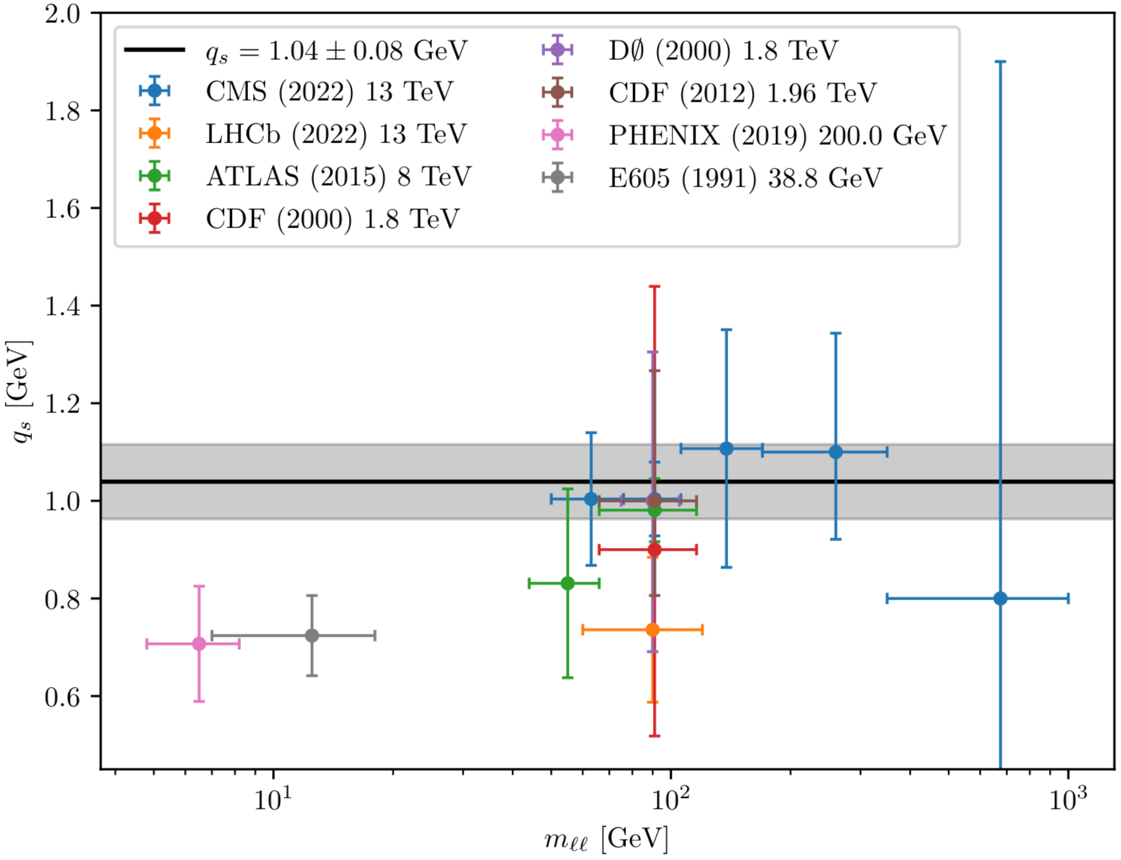
## $M(l^+l^-)$ in DY events ~ hard scattering scale




The value of **$q_s$=1.04 ± 0.08 GeV**, as derived from the CMS pp DY measurements, is compatible for all ranges of $m_{ll}$.

# Energy dependence of the intrinsic $k_T$

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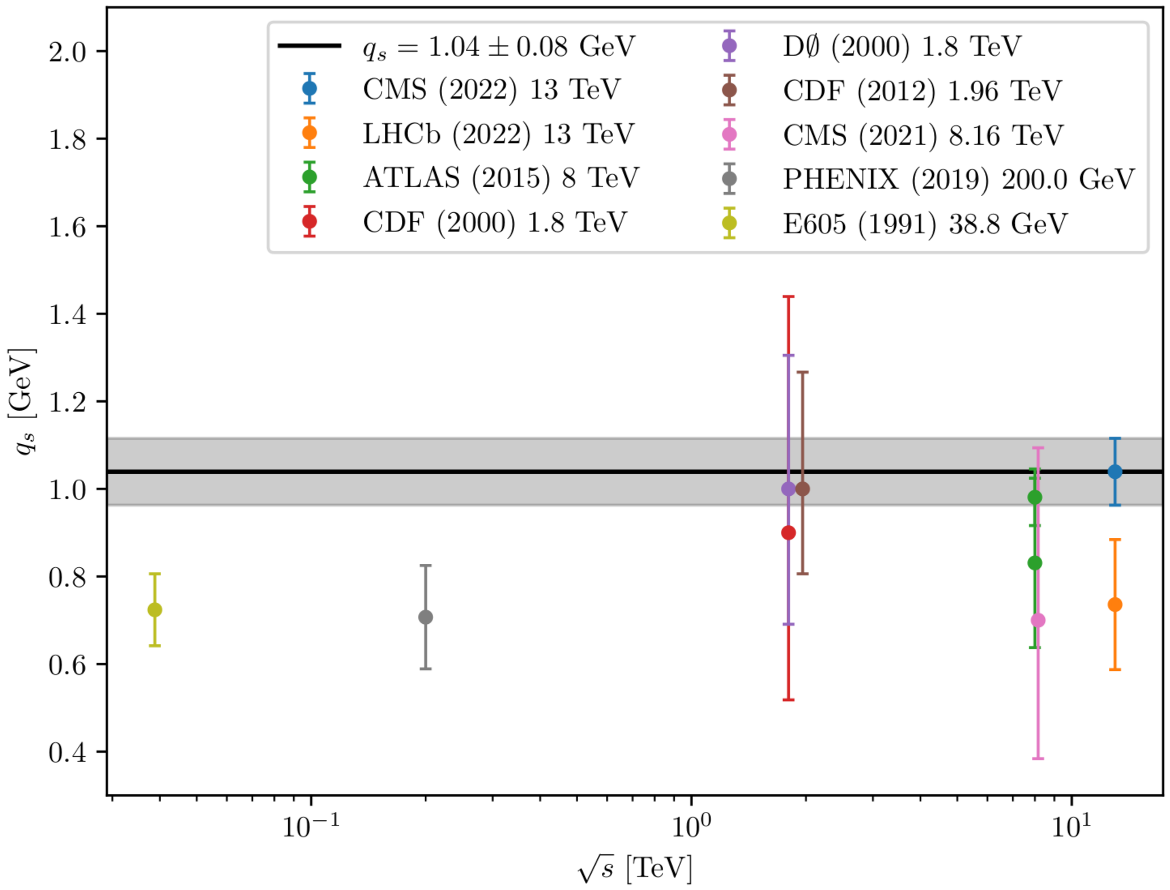
## Energy scaling behavior of intrinsic $k_T$ width




$q_s$=1.04 ± 0.08 GeV

**PB TMDs (applying CASCADE3):** very mild dependence of $q_s$ on various center of mass energies from 32 GeV to 13 TeV.

# Is it the same for collinear MC parton shower?

# Parton shower Monte Carlo event generator

## $q_0$ : minimum value of transverse momentum of emitted parton to be resolvable.

**Parton shower follows backward evolution for efficiency** (not known at which parton it will end up at interesting scale)**:**

Sudakov Form Factor for the backward evolution: the probability of evolution without resolvable branching between two scales

$$\Pi = \exp\left[ - \int_{\mu_l^2}^{\mu_h^2} \frac{d\mu'^2}{\mu'^2} \int^{z_{\rm dyn}} \frac{dz}{z} \hat{P}(z) \frac{f(x/z,\mu^2)}{f(x,\mu^2)} \right]$$

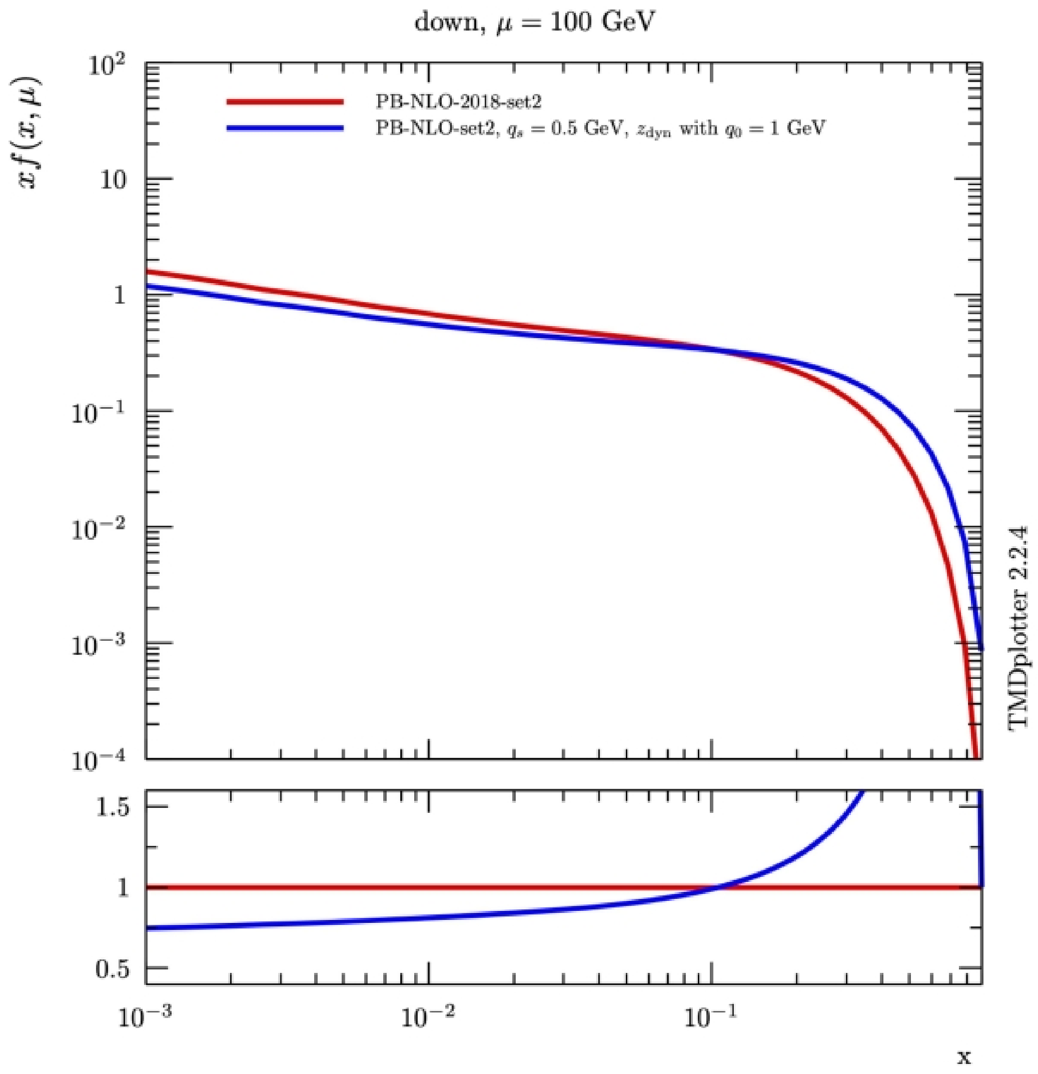
$$z_{\rm dyn} = 1 - q_0/\mu'$$

- In PB-approach the nonperturbative sudakov form factor is naturally included ($q_0 \rightarrow 0$), while in collinear parton-shower the transverse momentum of emissions is restricted (in PY8 via $z_{max}(Q^2)$ and in H7 by $Q_g$)
- **With different cut-off values, we can control the amount of soft radiations contributing in evolution**
- What is the role of these soft gluons in collinear PDF, TMD PDF, parton shower?

# Role of soft contributions in inclusive distributions arXiv:2309.11802

## Performing evolution with PB method with and without $q_0$ cut

$$
\begin{aligned}
\Delta_s(\mu^2) &= \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_0^{z_M} dz\ z\ P_{ba}^{(R)}(\alpha_s, z)\right) \\
&= \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_0^{z_{\rm dyn}} dz\ z\ P_{ba}^{(R)}(\alpha_s, z)\right) \\
&\quad \times \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_{z_{\rm dyn}}^{z_M} dz\ z\ P_{ba}^{(R)}(\alpha_s, z)\right) \\
&= \Delta_s^{(\rm P)}\left(\mu^2, \mu_0^2, q_0^2\right) \cdot \Delta_s^{(\rm NP)}\left(\mu^2, \mu_0^2, q_0^2\right)
\end{aligned}
$$




**Red: PB-TMD** ($z_M$~1)

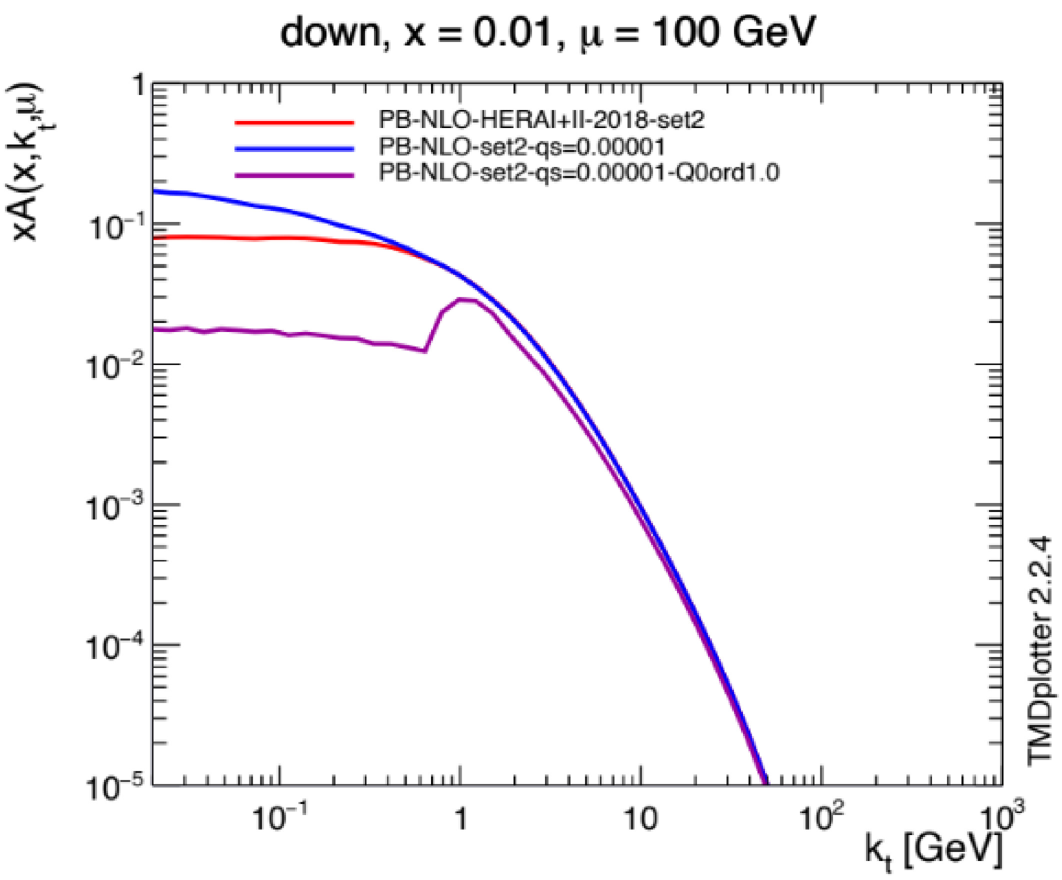
**Blue: PB-TMD with $q_0$=1.0 GeV** ($z_M$ <1: leads distributions which are not consistent with the collinear MS factorization scheme)

Difference between curves illustrates the importance of soft contributions even for collinear distributions (to have proper cancellation of virtual and real emissions)

# Role of soft contributions in TMD distributions

arXiv:2309.11802

**The effect of the $z_M$ cutoff is even more visible in TMDs!**




**Red: PB-TMD, $q_s$=0.5** ($z_M$~1)

**Blue: PB-TMD, $q_s$=0.0** ($z_M$~1: full Sudakov form factor + No intrinsic $k_t$)

$$z_M = z_{\rm dyn} = 1 - q_0/\mu'$$

**Purple: PB-TMD with $q_0$=1 GeV, $q_s$=0** (Z<1 + No intrinsic $k_t$)

- $k_T > q_0$ is not affected by the choice of $z_M$ , while the soft region is significantly affected
- Emissions below $q_0$=1 GeV are not allowed: There are contributions coming from adding vectorially all intermediate emissions

# Role of soft contributions in PB (CASCADE3)

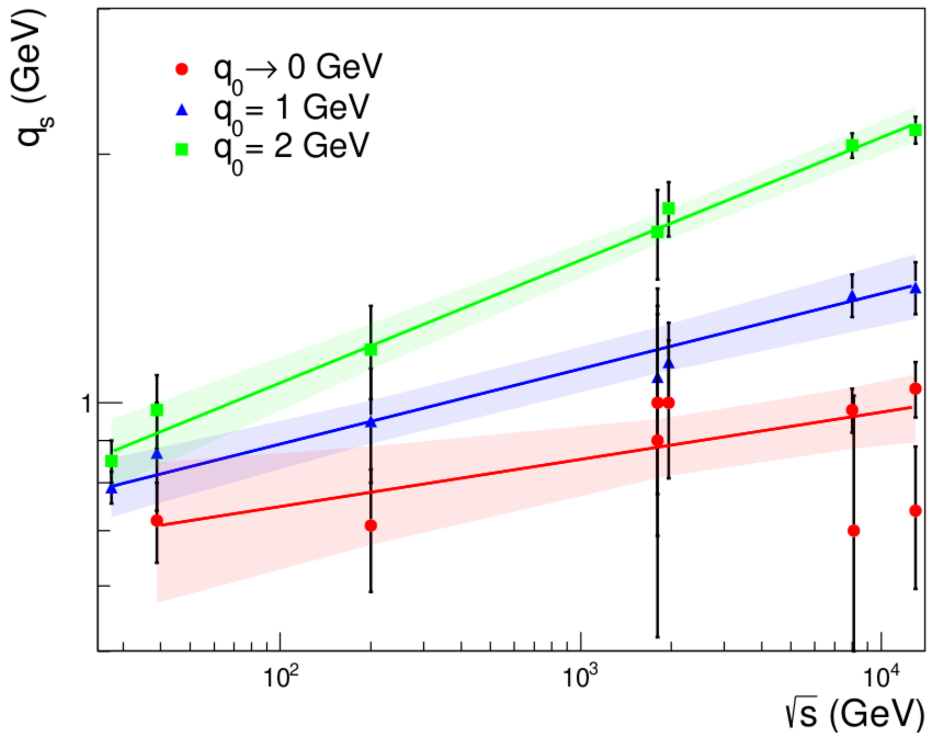
arXiv:2404.04088

**By limiting $q_0$ (minimum value of transverse momentum of emitted parton) at branchings**

We try to mimic directly what is happening in a collinear parton shower approach.
TMDs recalculated by imposing different $q_0$ using the starting PB-set2

**Take home message:**

**The slope of this dependence increases with an increase in $q_0$ (exclusion of more soft parton emissions)**




Linear dependence of $\log(q_s)$ on $\log(\sqrt{s})$ is confirmed

Higher $q_0$ → Less contribution from soft gluons → More contribution from intrinsic $k_T$ is needed to compensate and describe DY $p_T$ spectrum → More sensitivity to $q_s$ value → Smaller uncertainty band

# Summary

Parton Branching method solves DGLAP equation at different orders, method directly applicable to determine $k_T$ distribution

Application to inclusive DY processes in pp at different energies and masses:

- Intrinsic $k_T$ distribution determined over various mass ranges (~10-1000 GeV) and CM energies (32 GeV to 13 TeV)- consistent from $q_s$ = 1.04 ± 0.08 GeV extracted from CMS_2022
- No significant dependence observed

Importance of soft gluons established:

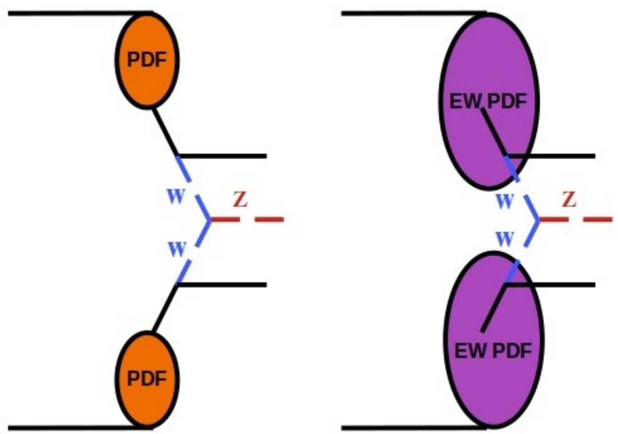
- essential for consistency of NLO matrix elements and PDFs,
- essential for inclusive parton densities (DGLAP required $z_M$ -1), and for TMDs (e.g. $q_T$ spectra)

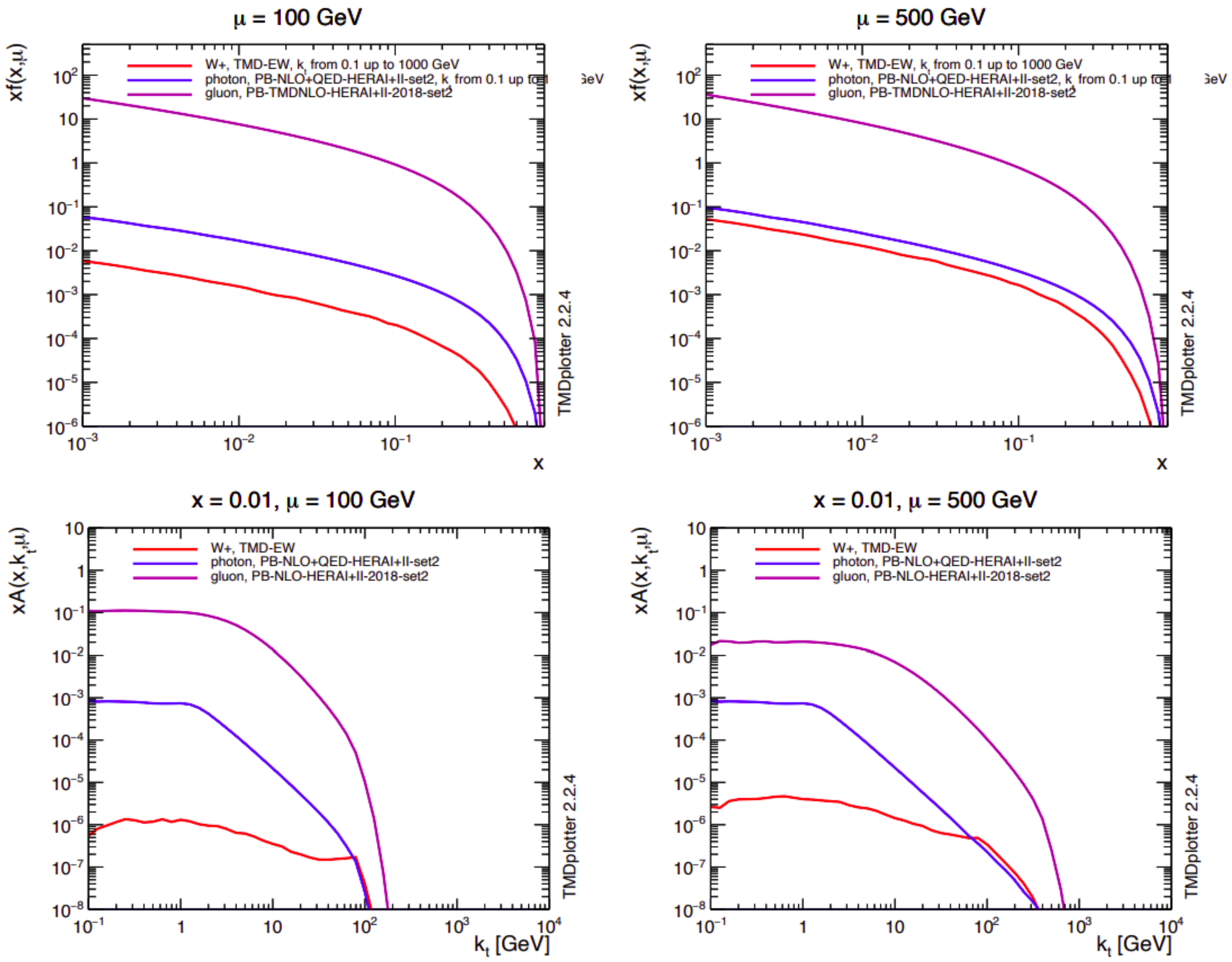
Center of mass dependency of $q_s$ observed in collinear Monte Carlo Generators at different center of mass energies can be produced with PB method (CASCADE3), if we exclude a part of soft gluon emissions.

# Outlook

Heavy bosons PDFs and TMDs are coming

**Sketch of VBF process:** what if heavy bosons were considered to be inside proton?




Left: calculation with standard QCD PDFs.
Right: calculation with EW PDFs.

# Thank you for your attention !