Recent Progress in TMD Parton Densities and Corresponding Parton Showers

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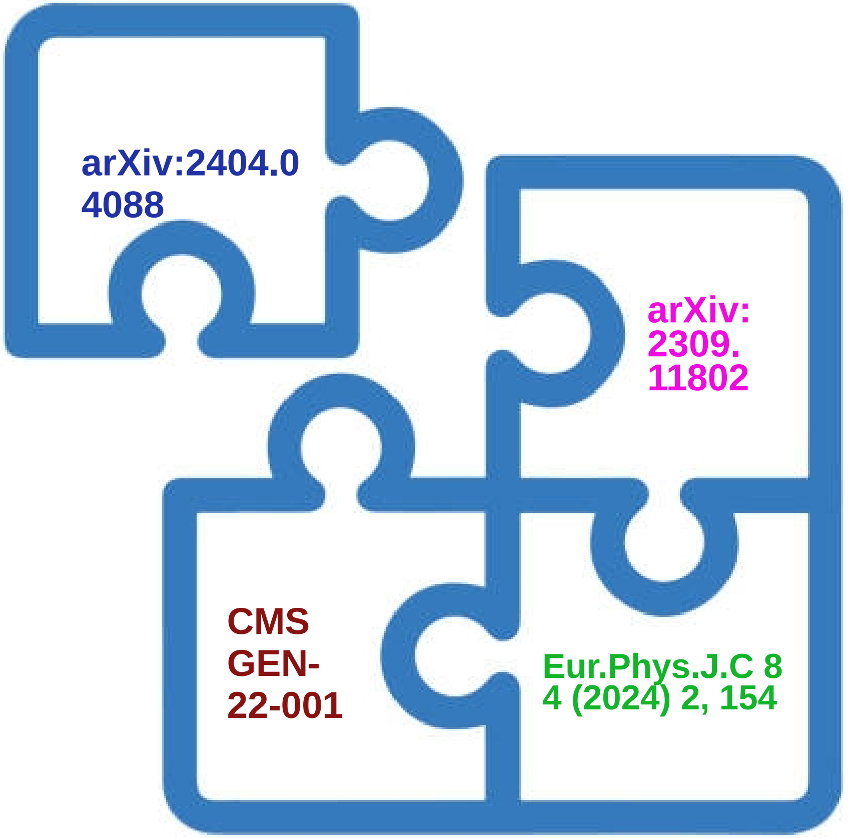
On behalf of CASCADE group

German Research Foundation (DFG) under grant number 467467041

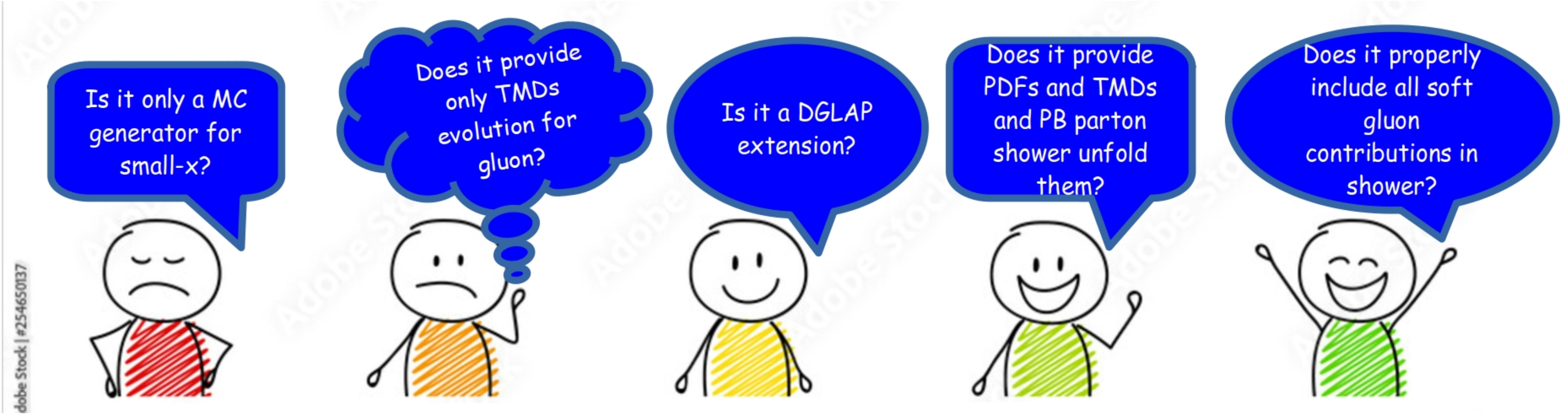


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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)]



No! No! Yes! Yes! Yes!

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 ($\alpha_s(p_T{}^2=\mu^2(1-z)^2)$):

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

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 **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

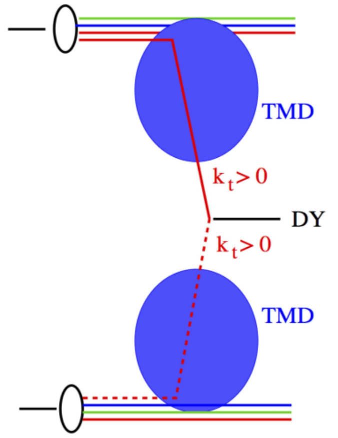
Required settings to calculate the transverse momentum spectrum of DY lepton pairs

- Parameterize collinear PDF at μ_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



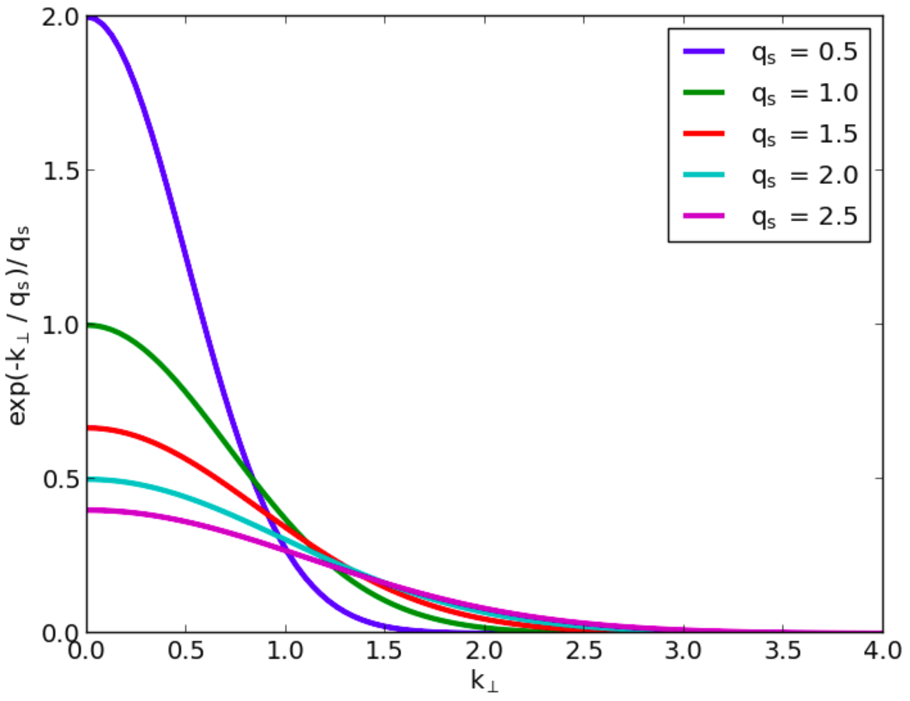
Hard process:
NLO hard-scattering ME are generated by the MADGRAPH_AMC@NLO based on collinear PB-set2
HERWIG6 subtraction terms are used since they are based on the same angular ordering conditions

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



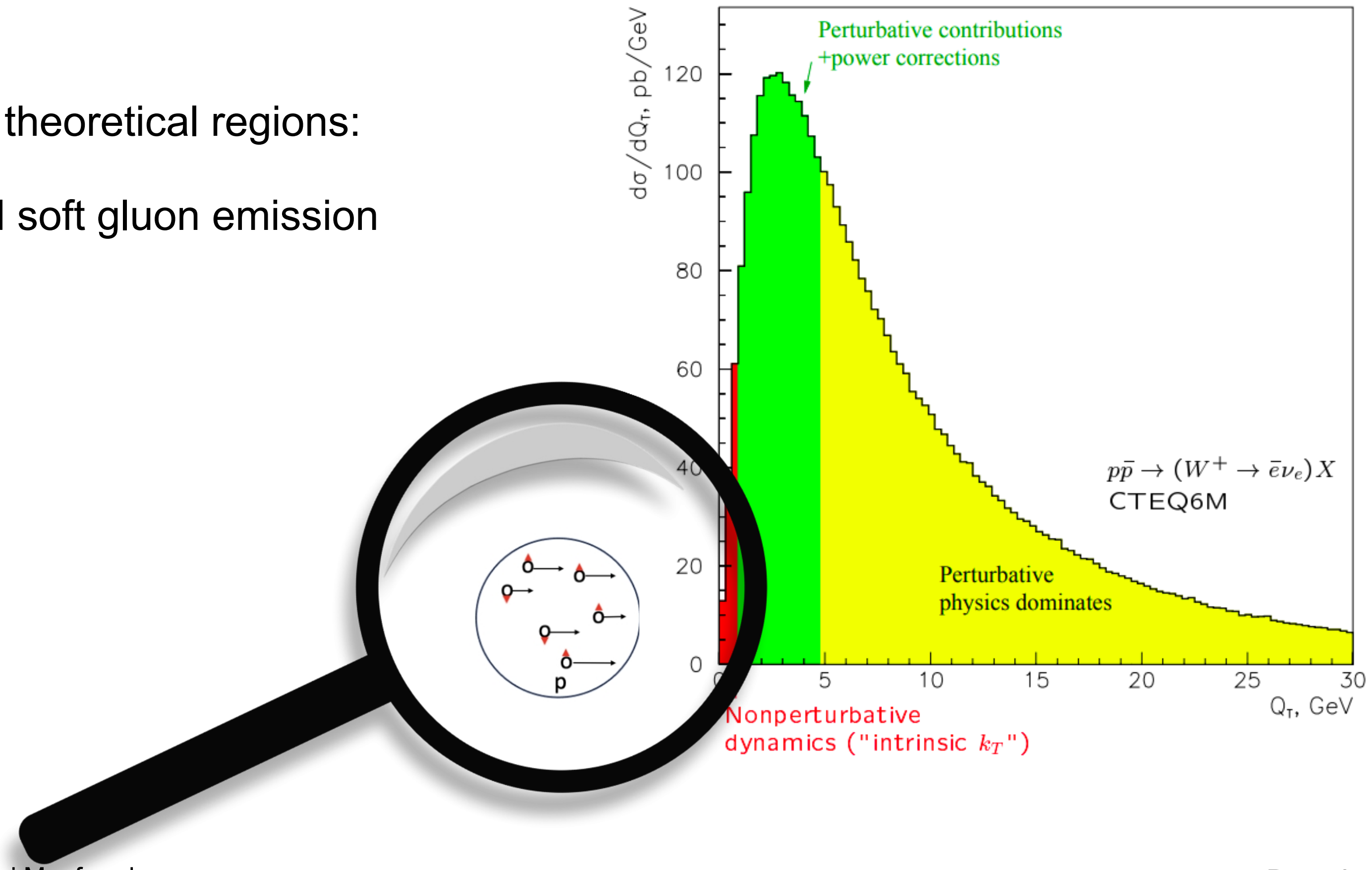
How can one specify intrinsic k_T width?

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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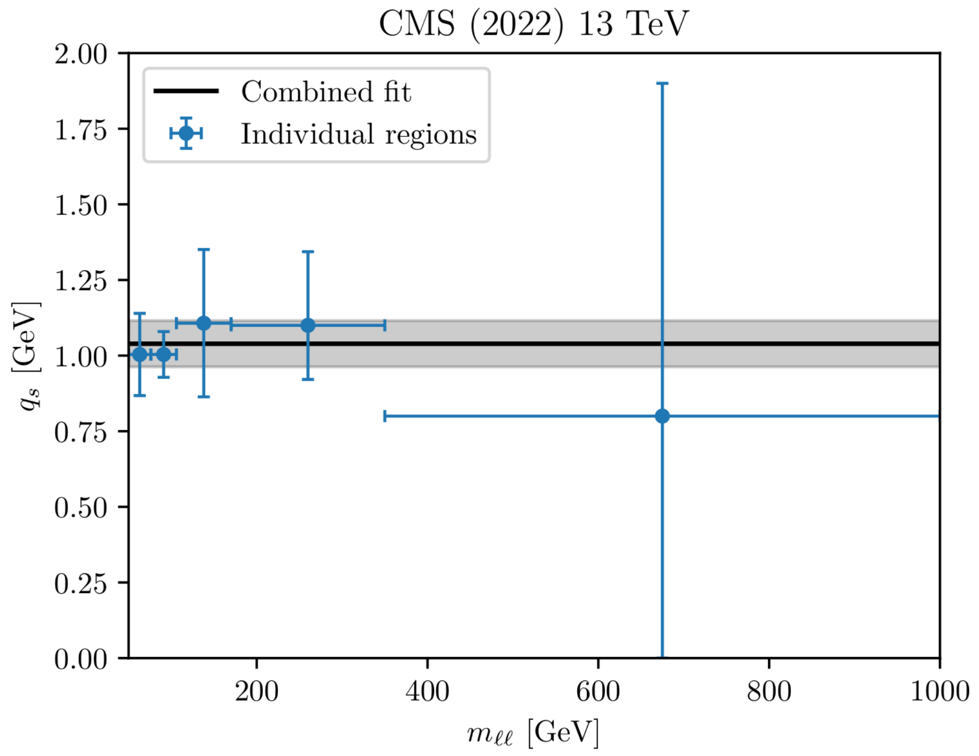

Final q_s extracted from combined covariance matrix analysis across 5 mass bins

- 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

$q_s = 1.04 \pm 0.08$ 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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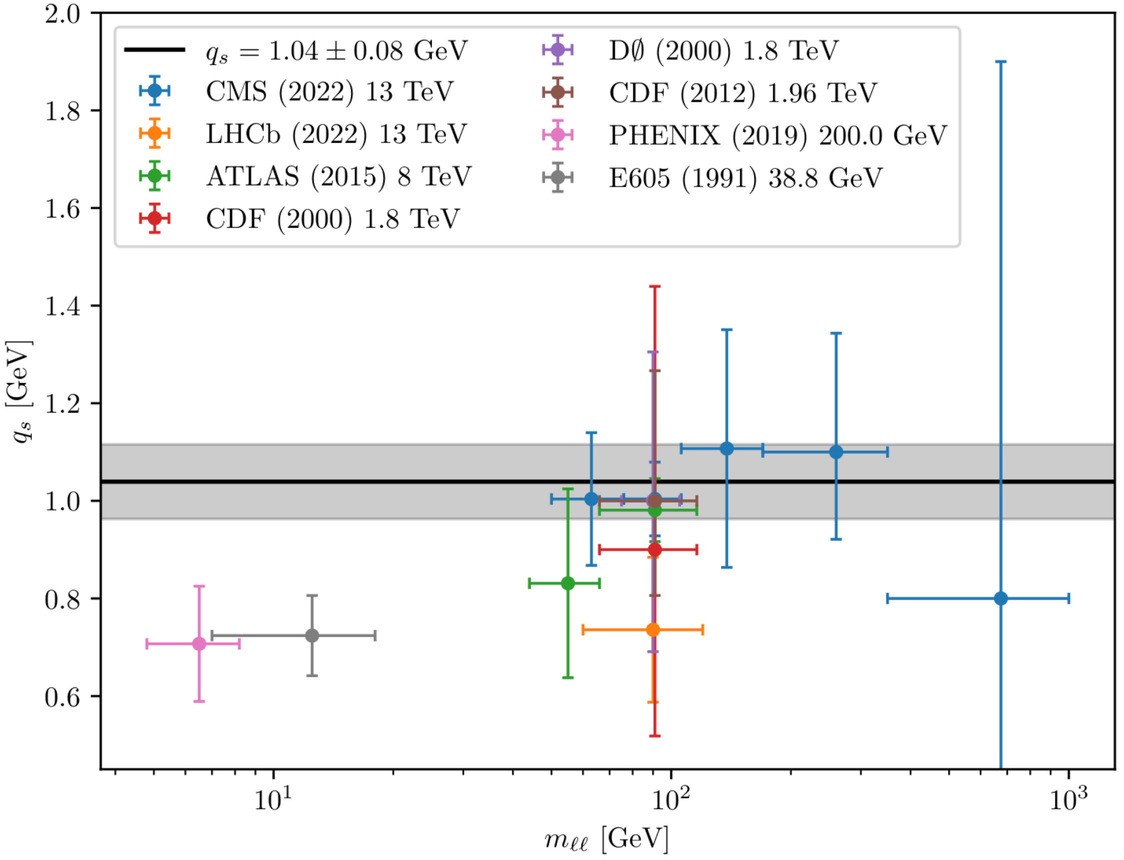
$M(l^+l^-)$ in DY events ~ hard scattering scale



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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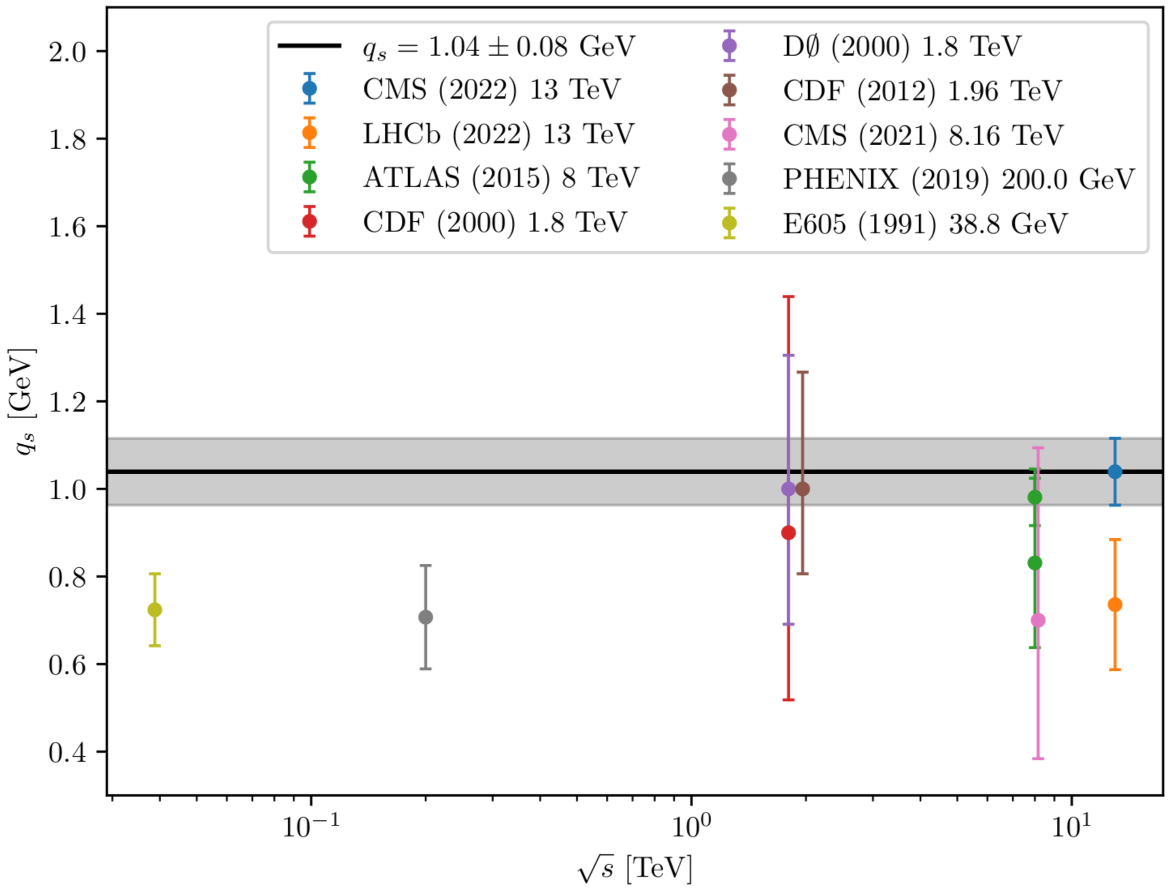
Energy scaling behavior of intrinsic k_T width



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

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

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

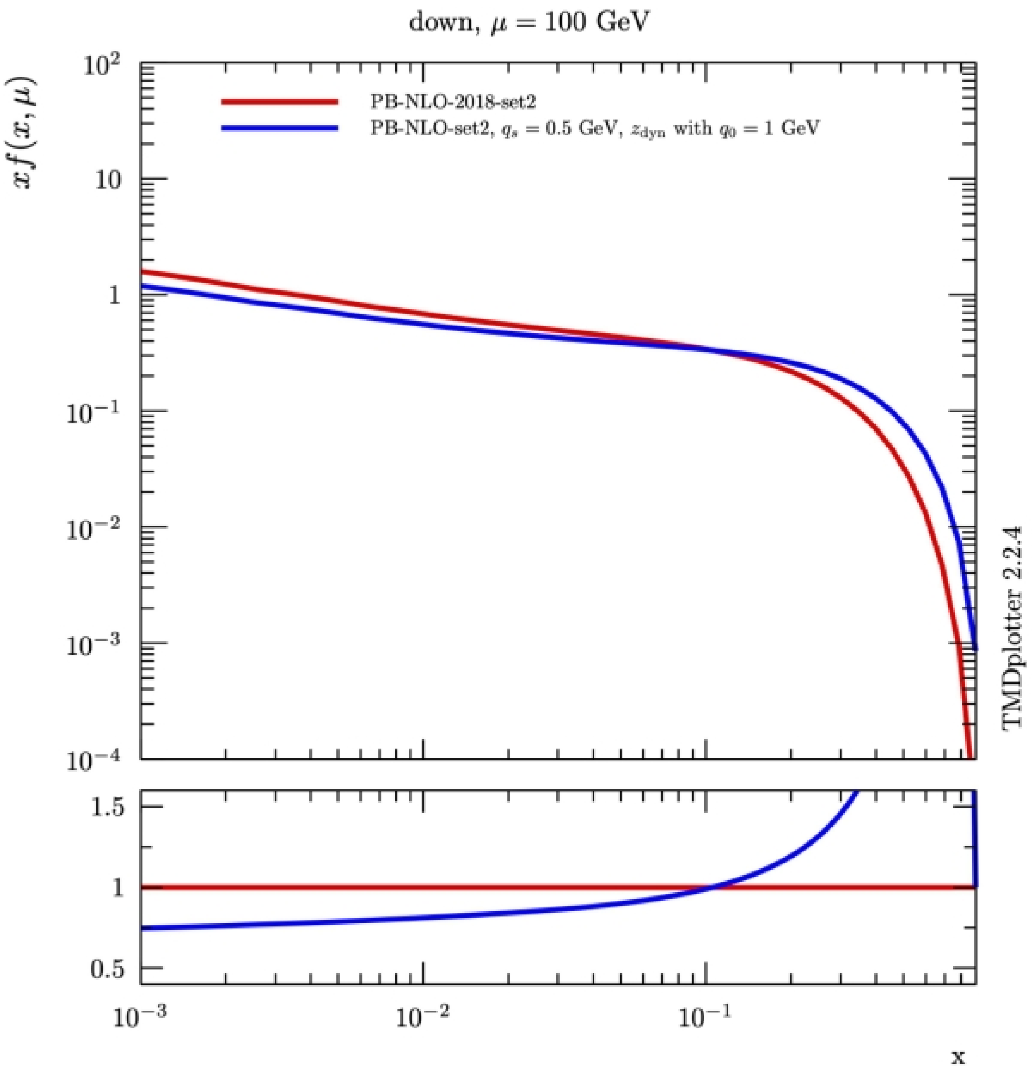
- In PB-approach the nonperturbative sudakov form factor is naturally included ($q_0 \to 0$), while in collinear parton-shower the transverse momentum of emissions is restricted (in PY8 via $z_{max}(Q^2)$ and in H7 by Q_g)
- **With different cut-off values, we can control the amount of soft radiations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

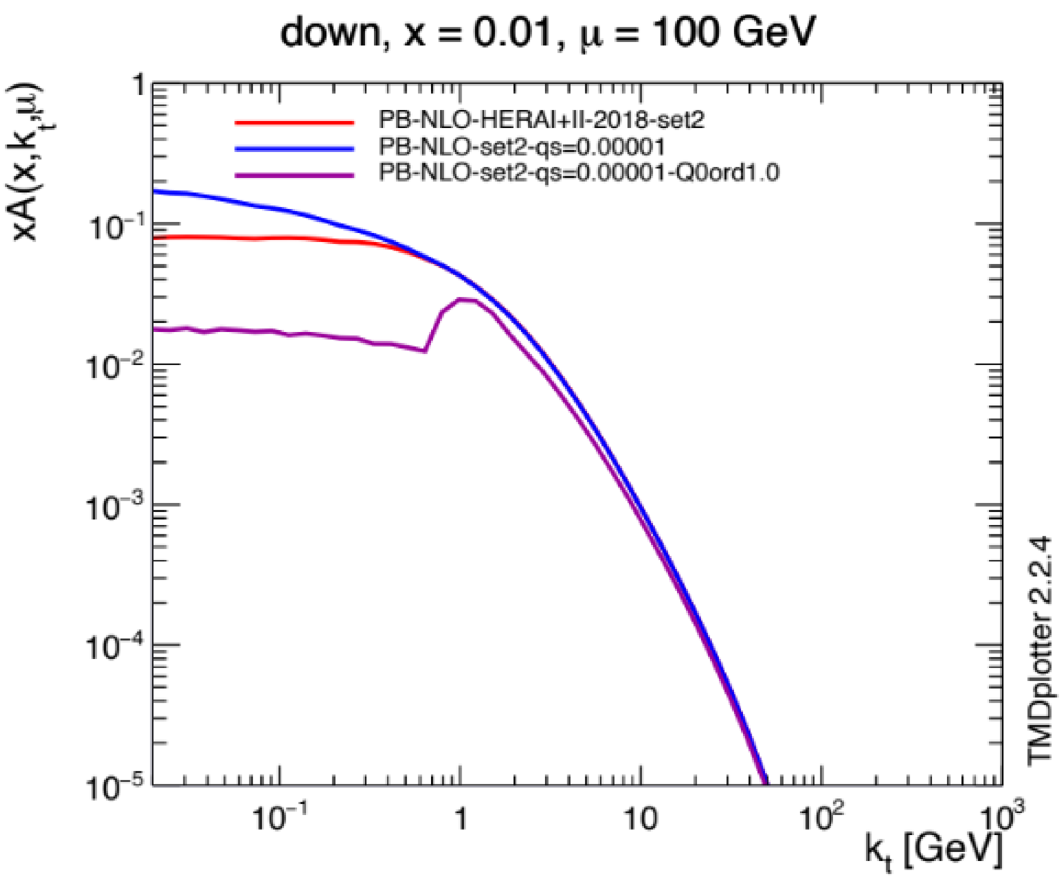
Blue: PB-TMD with q_0=1.0 GeV (z_M <1: leads distributions which are not consistent with the collinear MS factorization scheme)

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)

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

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)

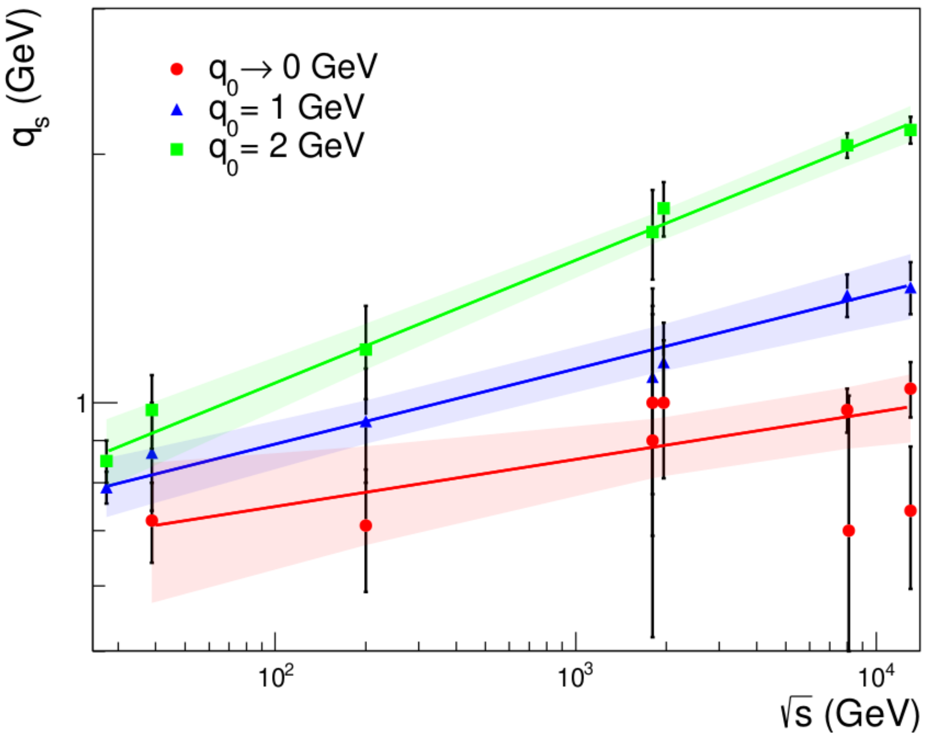
arXiv:2404.04088

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:

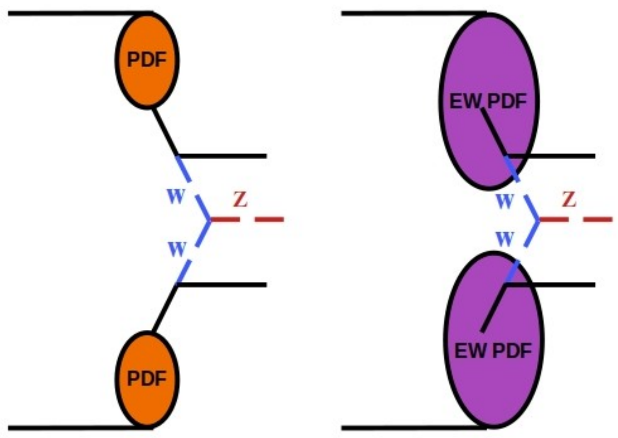
- essential for consistency of NLO matrix elements and PDFs,
- essential for inclusive parton densities (DGLAP required z_M -1), and for TMDs (e.g. q_T spectra)

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.

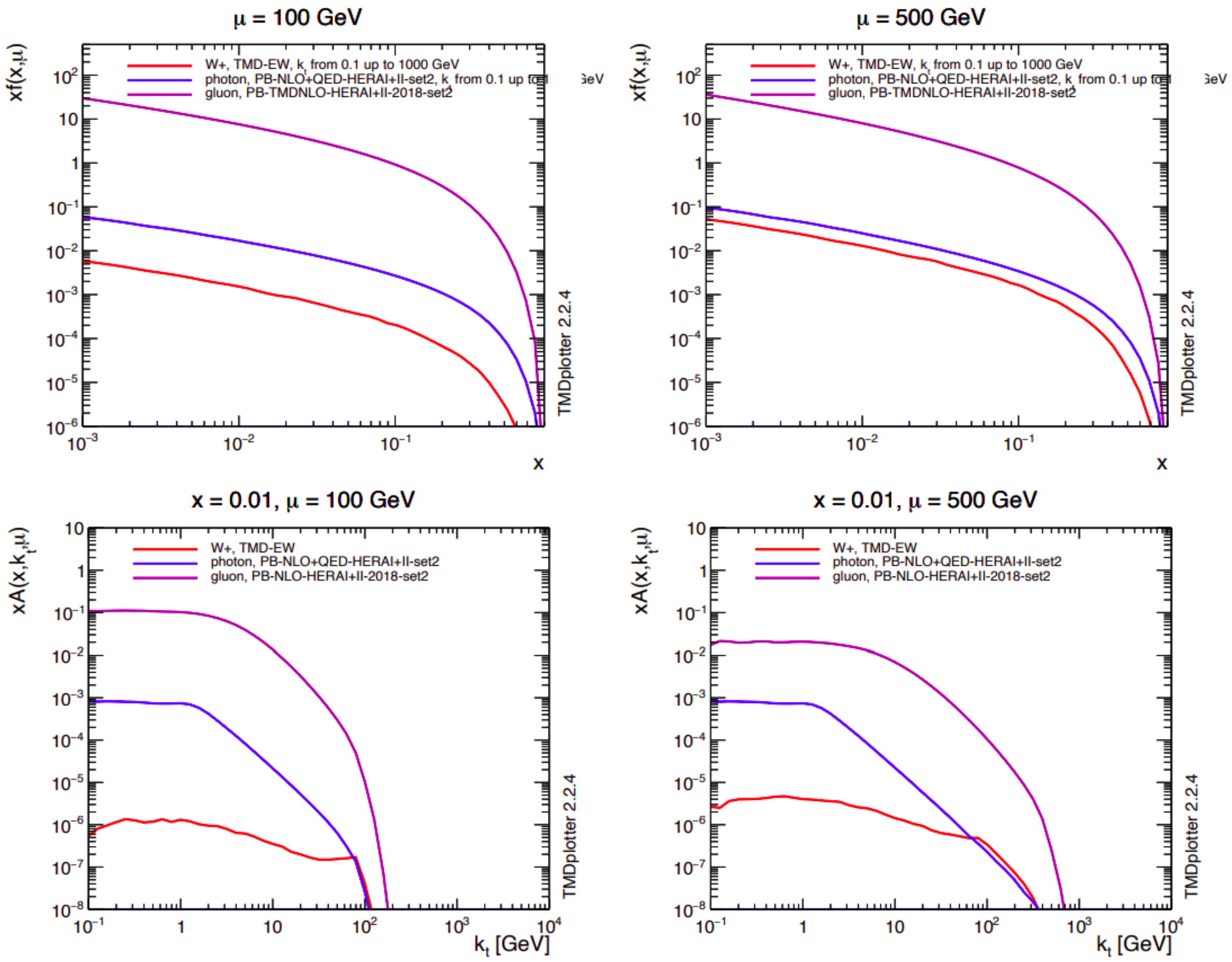
Outlook

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 !

BACK UP SLIDES

DY mass and p_T from fixed-target up to LHC

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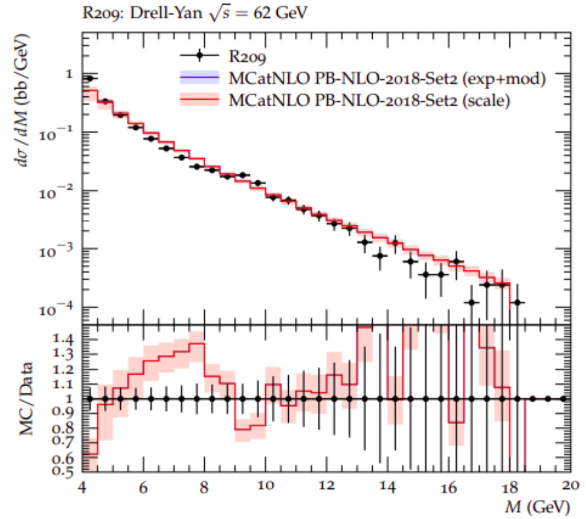
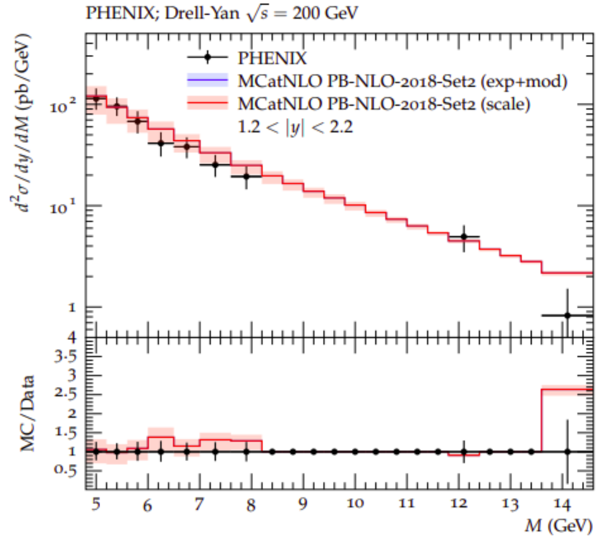
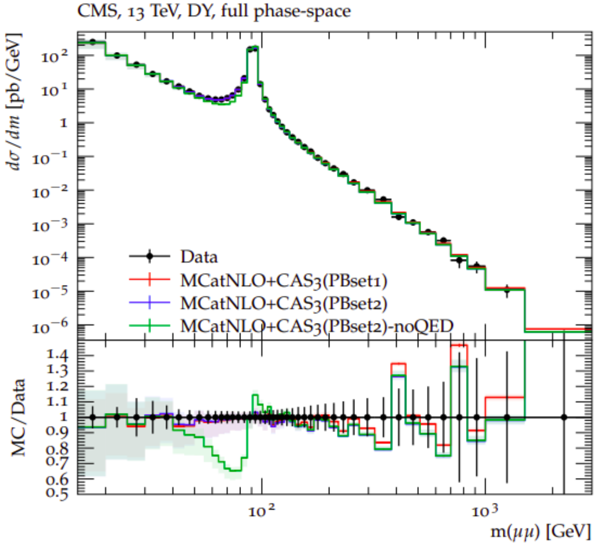
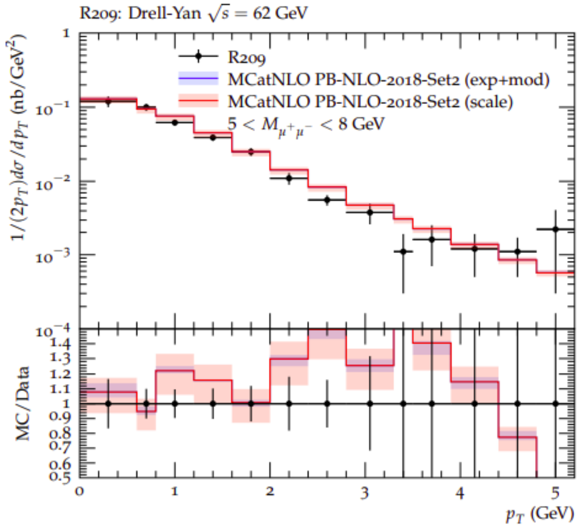
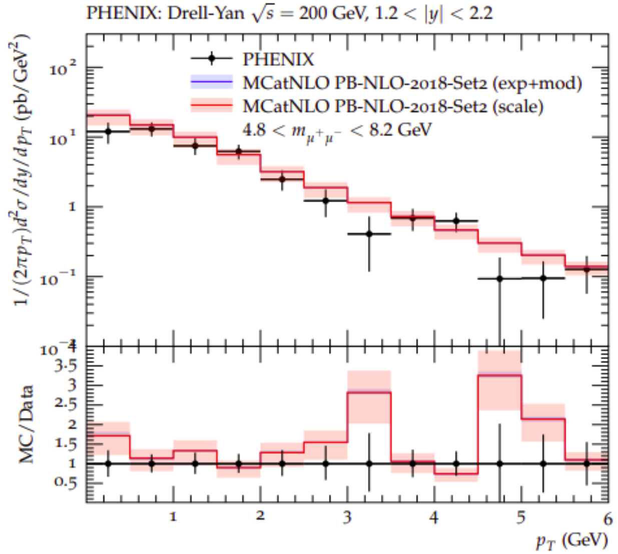
Well description at low and middle p_T, at high p_T large corrections from higher orders required

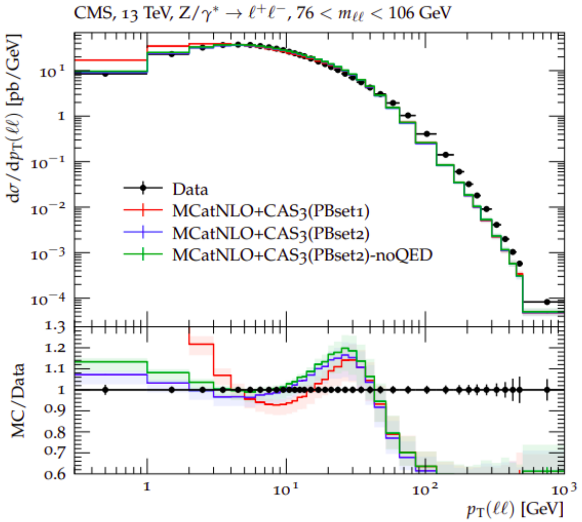








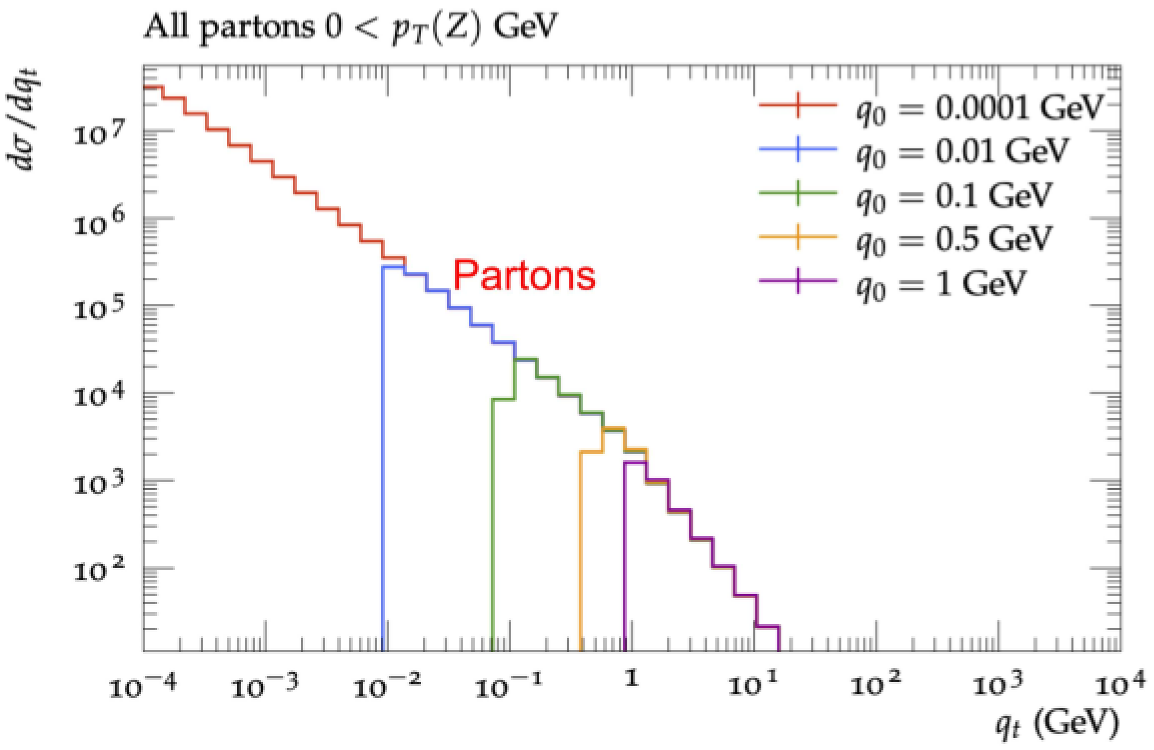




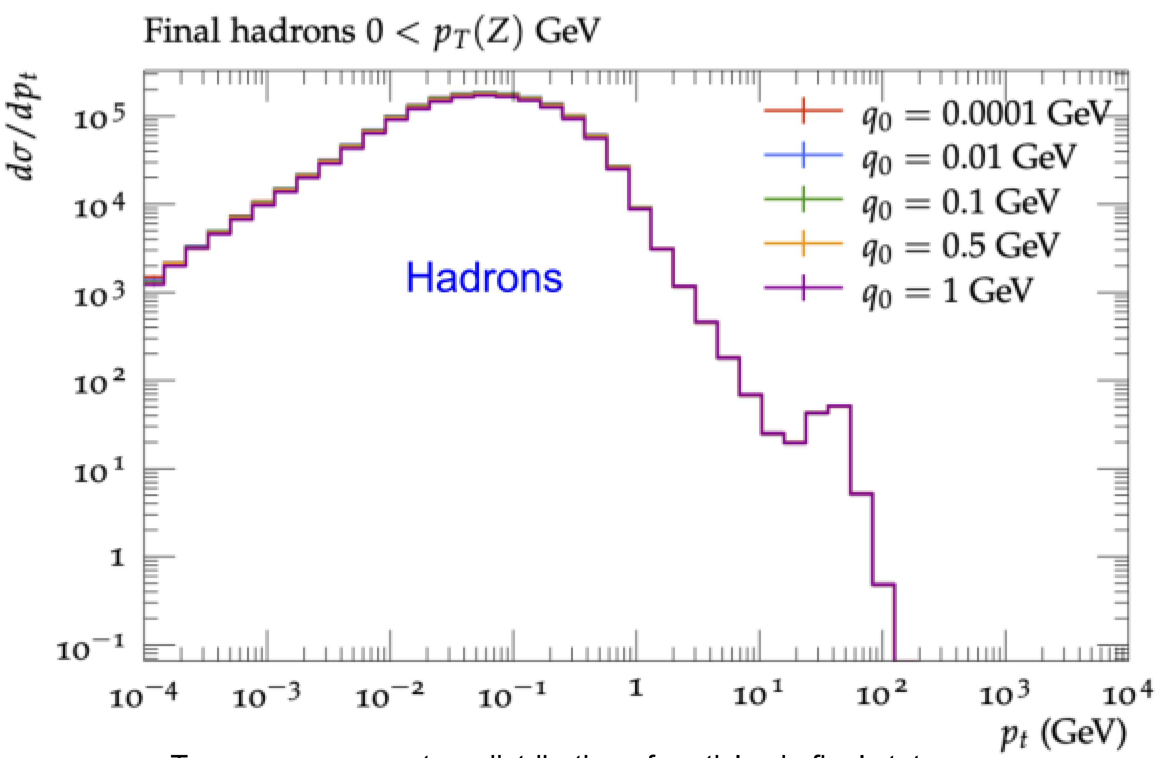
Role of soft contributions in Parton Showers

arXiv:2309.11802

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



Transverse momentum distribution of emitted partons in initial state



Transverse momentum distribution of particles in final state

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

Role of soft parton contributions:

Significant Impact on Inclusive Distributions: Soft partons play a crucial role in shaping inclusive distributions, especially in complete PDFs and TMDs at low p_T → particularly evident in the DY p_T spectrum.

Negligible Effect on Final State Hadron Spectra: In the context of Lund string fragmentation, soft partons have minimal influence on final state hadron spectra→ no issue for the spectra of produced particles (including jets)

Non-perturbative contribution (I): Non-pert. Sudakov form factor

Factorizing to small and large z region: Perturbative and Non-perturbative sudakov form factor

Sudakov form factors: the probability to evolve from one scale to another scale without resolvable branching
z_{dyn}: an intermadiate scale introduced to divide the two regions with different treatments of the strong coupling

$$\Delta_a(\mu^2, \mu_0^2) \approx \exp\left(-\int_{\mu_0^2}^{\mu^2} \frac{\mathrm{d}\mu'^2}{\mu'^2}\left(\int_0^{z_M} k_a(\alpha_s)\frac{1}{1-z}\mathrm{d}z - d_a(\alpha_s)\right)\right)$$

$$\boxed{z_{\text{dyn}}(\mu') = 1 - q_0/\mu'}$$

$$\Delta_a(\mu^2, \mu_0^2) = \exp\left(-\int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2}\left[\int_0^{z_{\text{dyn}}(\mu')} dz \frac{k_a(\alpha_s)}{1-z} - d_a(\alpha_s)\right]\right) \times \exp\left(-\int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2}\int_{z_{\text{dyn}}(\mu')}^{z_M} dz \frac{k_a(\alpha_s)}{1-z}\right).$$

$$\Delta_a(\mu^2, \mu_0^2) = \Delta_a^{(\mathrm{P})}\left(\mu^2, \mu_0^2, q_0\right) \cdot \Delta_a^{(\mathrm{NP})}\left(\mu^2, \mu_0^2, \epsilon, q_0^2\right)$$

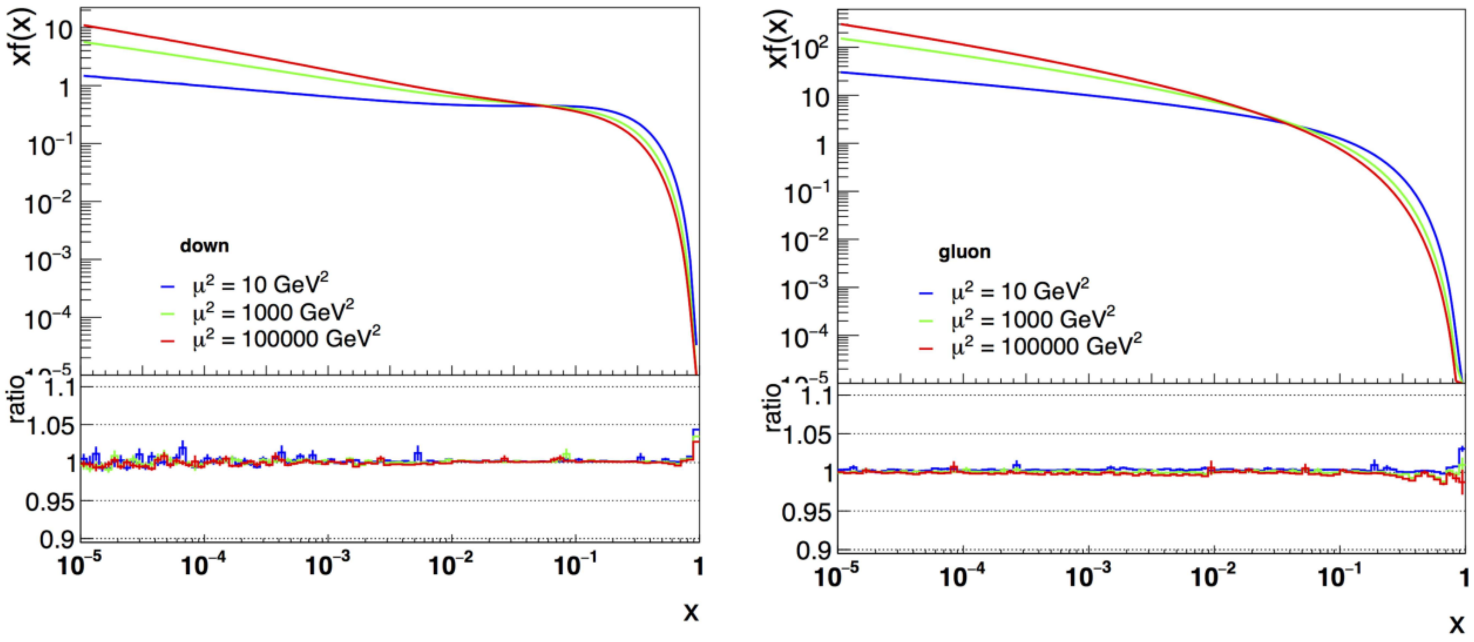
Perturbative: $z < z_{dyn} \Leftrightarrow q_\perp > q_0$

Non-Perturbative: $z_{dyn} < z < z_M$ ($z_M = 1-\varepsilon$) $\Leftrightarrow q_\perp < q_0$
α_s will become large: we freeze α_s at q_{cut}=1 GeV

Motivation for the use of the dynamical resolution scale:
1) To reach the same sudakov form factor of the CSS formalism.
2) To show how the non-perturbative Sudakov affects both the PDF and the TMDs by allowing really soft emissions

Validation of method with QCDnum at NLO

Is it the same as DGLAP? Yes!

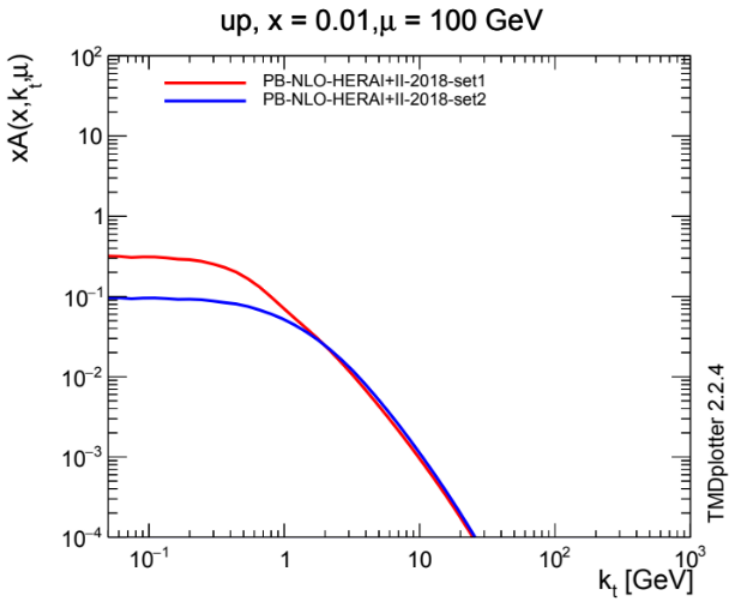


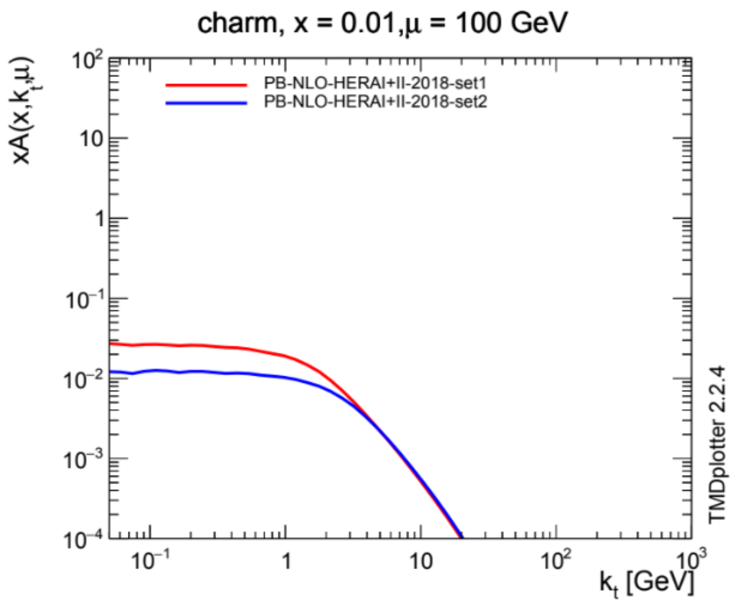
Very good agreement with NLO-QCDnum over all x and Q2.
The same approach works at NNLO

α_s scale

PB-Set1 (with DGLAP-type $\alpha_s(\mu^2)$) and PB-Set2 (with angular-ordered scale $\alpha_s(p_T^2=\mu^2(1-z)^2)$)

PB-Sets are fitted to precision DIS HERA measurements using the xFitter platform (χ^2/dof=1.21)
Accessible in TMDlib and TMDplotter
Both having q_s=0.5 GeV





- Significant difference at low transverasal momenta of partons
- For heavy flavors the difference much smaller since they are only generated dynamically
- **PB-Set2** provides a much better description of measured Z/γ p_T at LHC, in low-energy experiments, and of di-jet Δφ near the back-to-back region. This underlines the relevance of the angular-ordered coupling in regions dominated by soft emissions.

Data used to test the Gauss width at various energies

Global fit of q_s by calculating χ^2 from different measurements

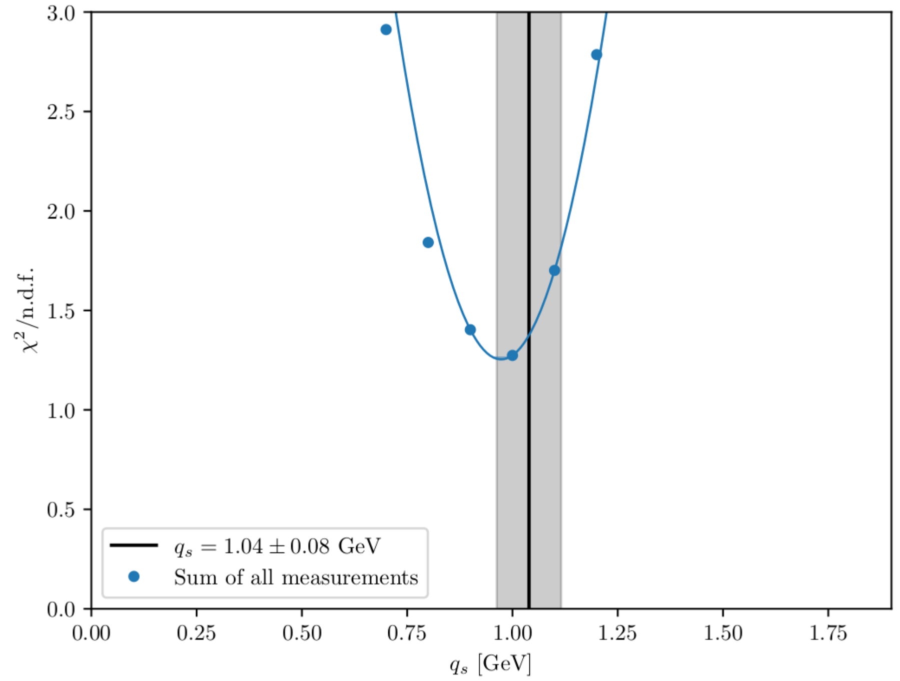
No full error breakdown is available for the other measurements

All uncertainties treated as being uncorrelated and no systematic uncertainty from scale variation in the theoretical calculation

p_T cut:

- **Lower CM energies:** limited $p_T(\ell\ell)$ range → Analyzing intrinsic-k_T impact across entire $p_T(\ell\ell)$ range.
- **Higher CM energies:** Investigating up to peak region

Analysis	$\sqrt{s}$	Collision types	ndf
CMS (2022)	13 TeV	pp	25
LHCb (2022)	13 TeV	pp	5
CMS (2021)	8.1 TeV	pPb	5
ATLAS (2015)	8 TeV	pp	8
CDF (2012)	1.96 TeV	$p\bar{p}$	6
CDF (2000)	1.8 TeV	$p\bar{p}$	5
D0 (2000)	1.8 TeV	$p\bar{p}$	4
PHENIX (2019)	200 GeV	$p\bar{p}$	12
E605 (1991)	38.8 GeV	pp	11
Total			81



The global χ2 distribution exhibits a minimum at around q_s = 1.0 GeV, which is consistent with the value obtained from the measurement over a wide m_{DY} that includes a detailed uncertainty breakdown, with correlated experimental uncertainties.

Fit of the Gauss width in pp at 13 TeV

How to find the best q_s?

Results obtained from public Eur. Phys. J. C 83 (2023) 628 analysis

- m_{DY}= [50,76], [76,106], [106-170], [170-350], [350-1000] GeV
- Detailed uncertainty breakdown: complete treatement of experimental uncertainties + correlations between bins of the measurement
- Variable: p_T(ll) – analysing up to the peak in the p_T range to maximize the sensitivity to intrinsic k_T distribution
- At higher DY transverse momenta, higher order contributions in the matrix element have to be taken into account
- We vary the q_s parameter and calculate a χ^2 to quantify the model agreement to the measurement.

$$\chi^2 = \sum_{i,k} (m_i - \mu_i) C_{ik}^{-1} (m_k - \mu_k),$$

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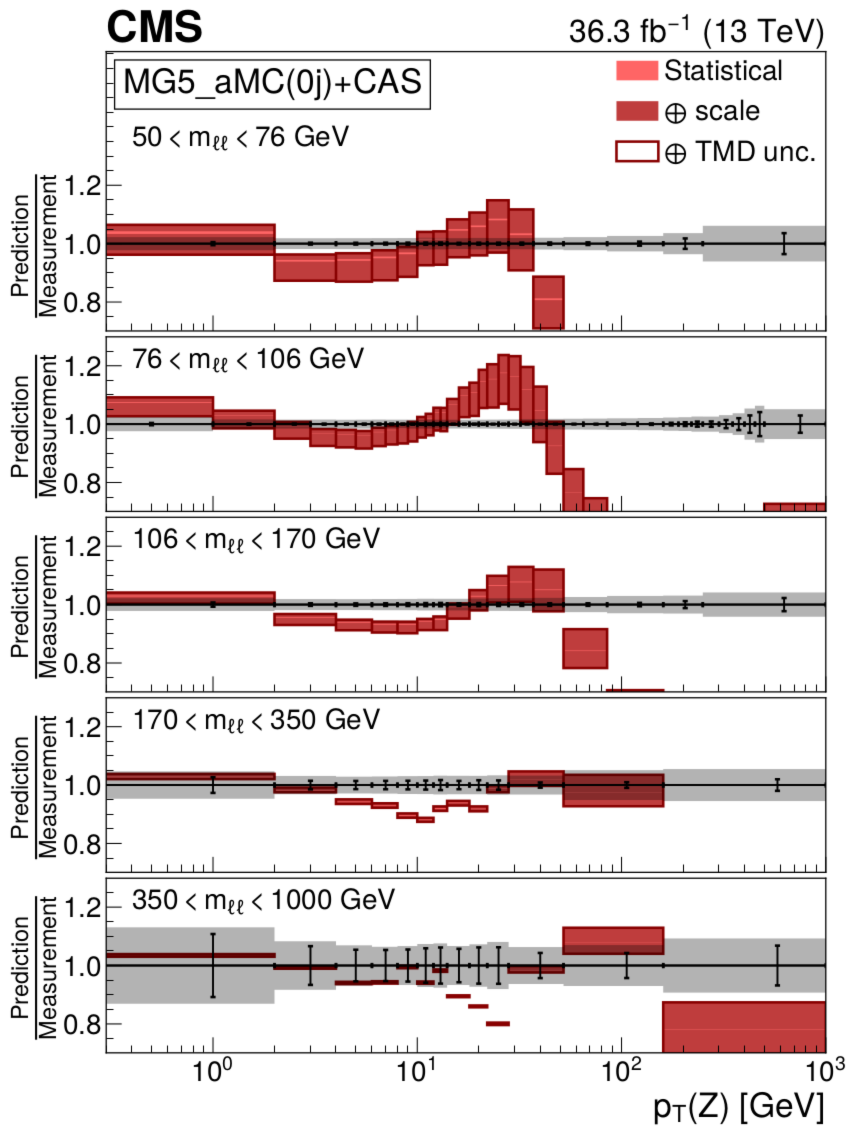
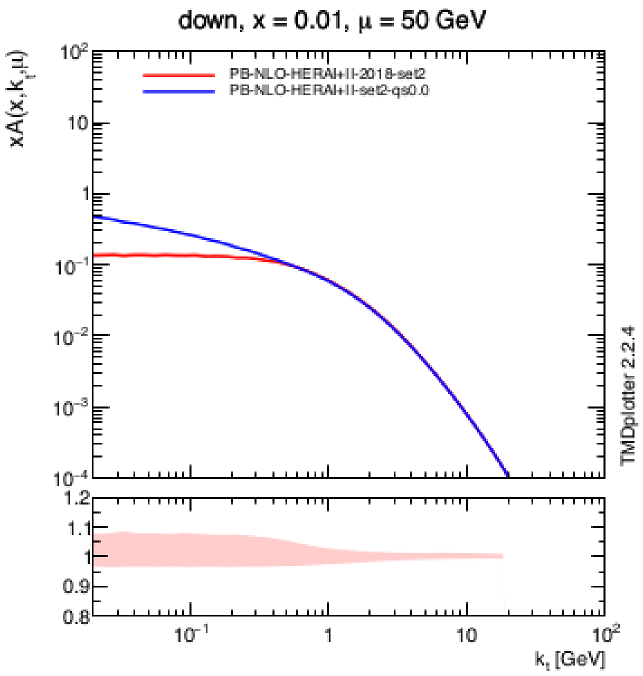
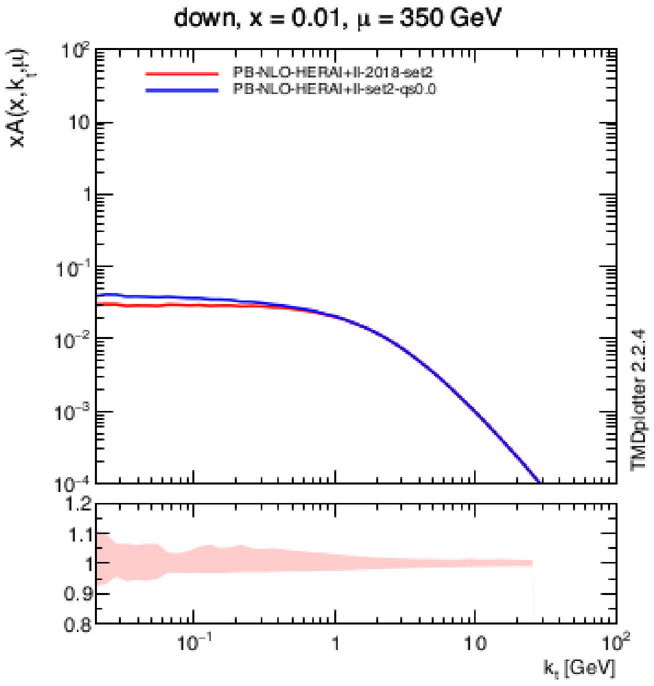
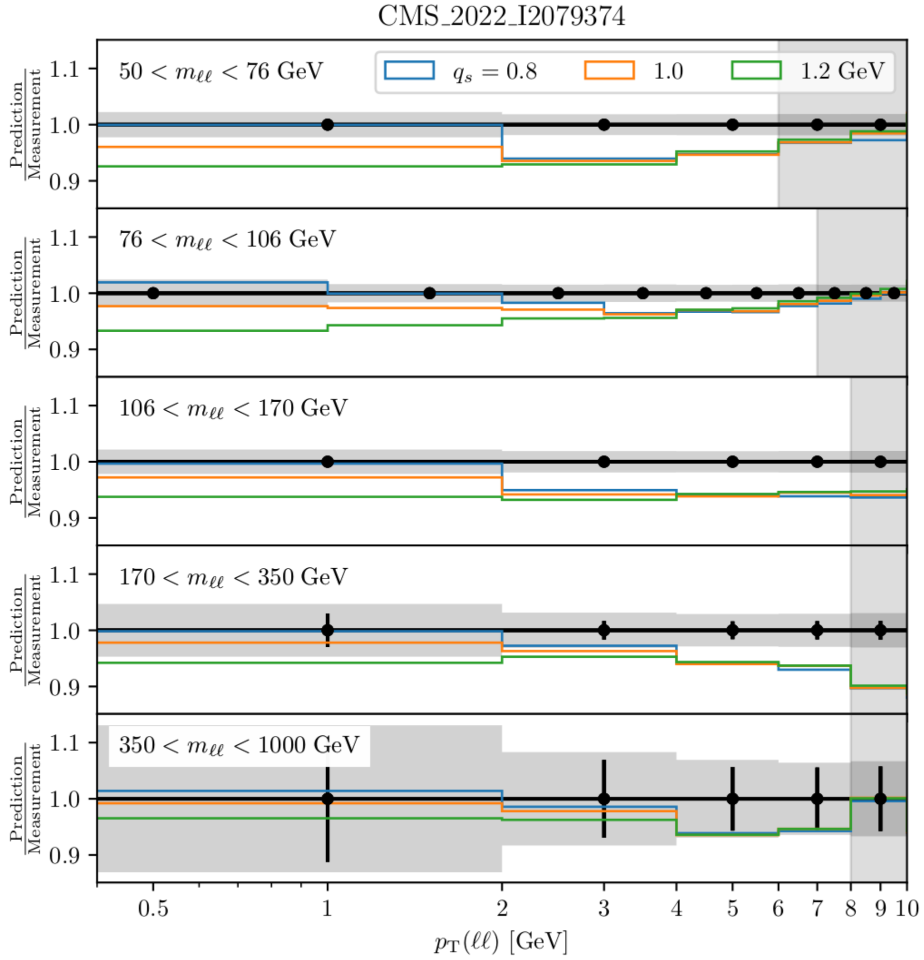


Scale Dependence of Intrinsic k_T Sensitivity in TMD and DY p_T

Why lowest DY mass region is the most sensitive one?







In TMD perspective: as the scale increases, sensitivity to intrinsic k_T decreases.

In DY p_T perspective: higher DY masses show reduced sensitivity to intrinsic k_T.

CSS formalism

Collins, Rogers arXiv 1705.07167

- Collins Soper Sterman (CSS) formalism for pt spectrum of DY production

$$
\begin{aligned}
\frac{d\sigma}{dQ^2\,dy\,dq_T^2} = {} & \frac{4\pi^2\alpha^2}{9Q^2 s} \sum_{j,j_A,j_B} e_j^2 \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2} e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T} \\
& \times \int_{x_A}^{1} \frac{d\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*})\, \tilde{C}^{\text{CSS1, DY}}_{j/j_A}\left(\frac{x_A}{\xi_A}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \int_{x_B}^{1} \frac{d\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*})\, \tilde{C}^{\text{CSS1, DY}}_{\bar{\jmath}/j_B}\left(\frac{x_B}{\xi_B}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \exp\left\{ - \int_{\mu_{b_*}^2}^{\mu_Q^2} \frac{d\mu'^2}{\mu'^2} \left[A_{\text{CSS1}}(a_s(\mu'); C_1) \ln\left(\frac{\mu_Q^2}{\mu'^2}\right) + B_{\text{CSS1, DY}}(a_s(\mu'); C_1, C_2) \right] \right\} \\
& \times \exp\left[-g_{j/A}^{\text{CSS1}}(x_A, b_T; b_{\max}) - g_{\bar{\jmath}/B}^{\text{CSS1}}(x_B, b_T; b_{\max}) - g_K^{\text{CSS1}}(b_T; b_{\max}) \ln(Q^2/Q_0^2) \right] \\
& + \text{suppressed corrections.}
\end{aligned}
$$

intrinsic k_T distribution

non-perturbative Sudakov form factor

intrinsic k_T and non-pert Sudakov must be determined by measurements

Correspondence of PB – TMDs with CSS

- Check correspondence of PB Sudakov form factor with CSS
- use only $P_{qq}(z)$ in large z limit: $P_{qq}(z) \sim \frac{1+z^2}{1-z} + \frac{3}{2}\delta(1-z) \rightarrow \frac{2}{1-z} + \frac{3}{2}\delta(1-z)$
- apply angular ordering constraint for z_M $\quad z_{\mathrm{dyn}} = 1 - q_0/q$

$$\begin{aligned} \Delta_s^{(\mathrm{P})}(\mu) &= \exp\left(-\frac{\alpha_s}{2\pi}\left[\int_{\mu_0^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\int_0^{z_{\mathrm{dyn}}} dz P(z) + \frac{3}{2}\right]\right) \\ &= \exp\left(-\frac{\alpha_s}{2\pi}\left[\int_{\mu_0^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2} 2\log\frac{\mu^2}{\mu'^2} + \frac{3}{2}\right]\right) \end{aligned}$$

- perturbativeSudakov from PB is Sudakov from CSS
- PB give also prediction on non-pert Sudakov:

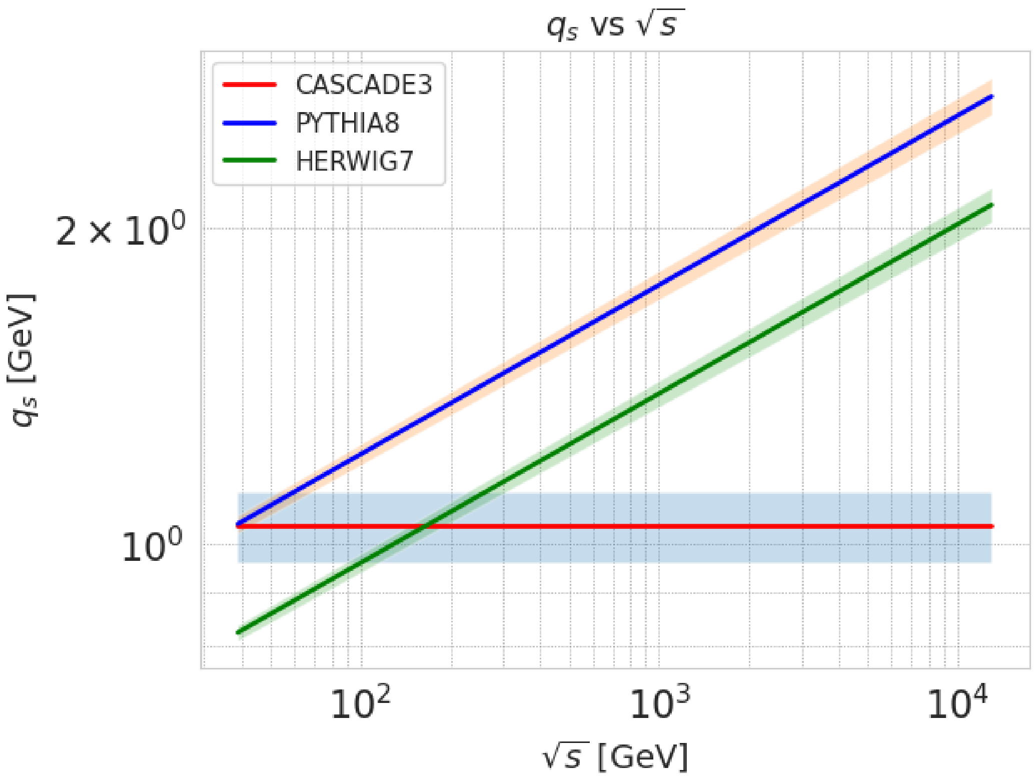
$$\Delta_s^{(\mathrm{NP})}(\mu^2) = \times \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2}\frac{d\mathbf{q}'^2}{\mathbf{q}'^2}\int_{z_{\mathrm{dyn}}}^{z_{\mathrm{M}}} dz\ z\ P_{ba}^{(R)}(\alpha_s, z)\right)$$

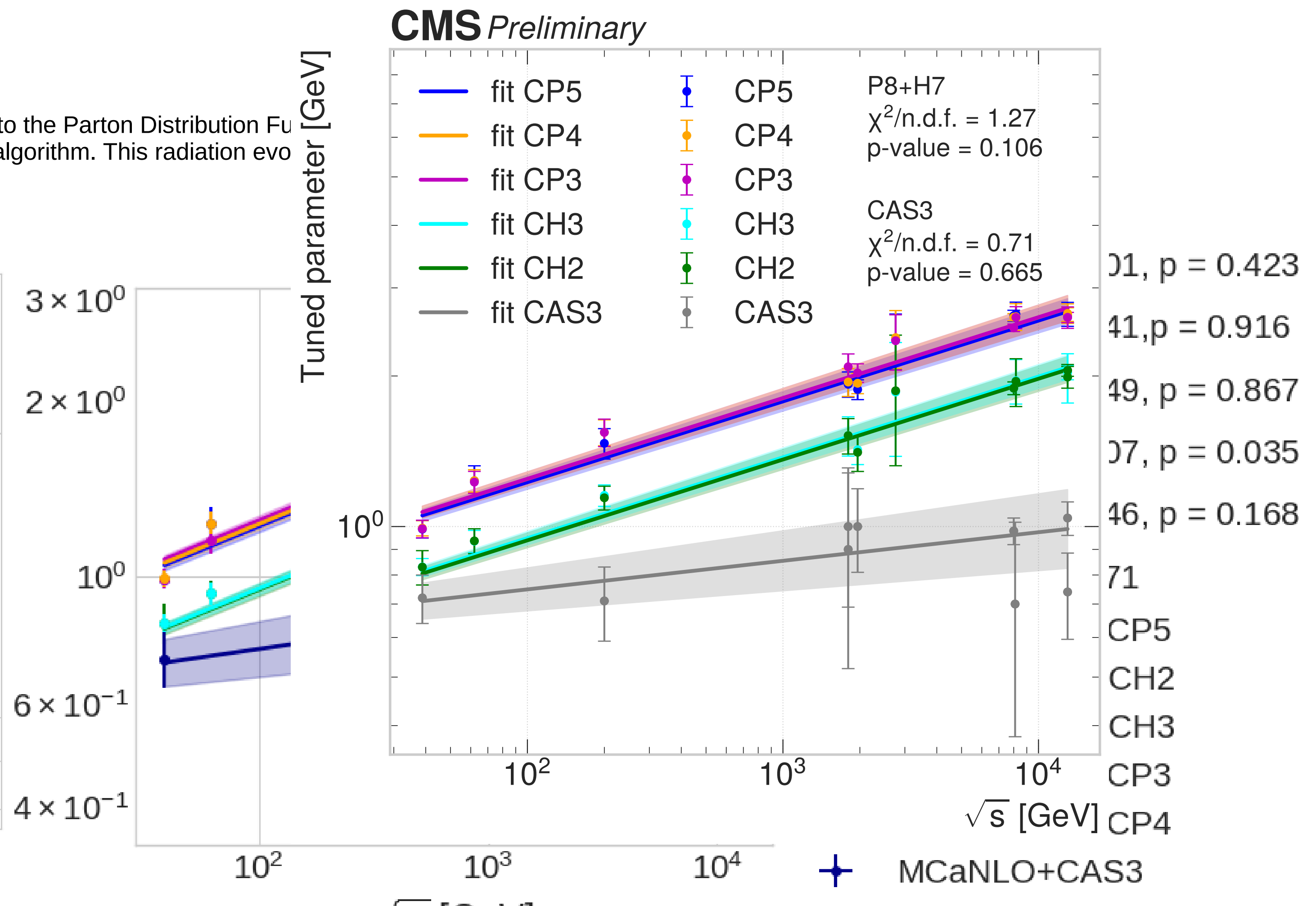
additional

Energy dependence of the intrinsic k_T

Energy scaling behavior of intrinsic k_T width

Event generation in MCs typically proceeds in several steps.
Firstly, the partonic process is simulated, where the kinematics are sampled according to the Parton Distribution Fu
additional radiation, including soft gluon emissions, is generated by the parton shower algorithm. This radiation evo
process to the initial scale μ0.





l soft gluon radiation, CASCADE has less sensitivity to qs value.

Angular-ordered shower in Herwig -> more ISR contribution to DY pT -> lower int-kT value -> smaller intercept

Energy scaling behavior of intrinsic kT width in DY events, GEN-22-001

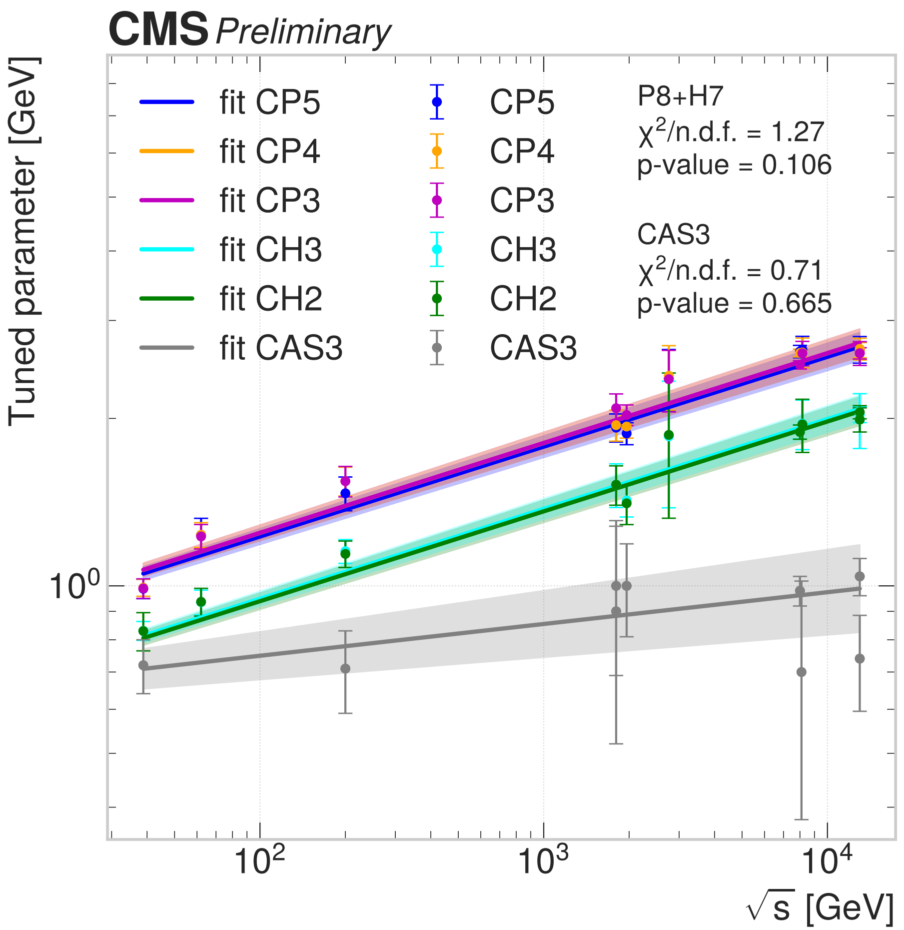
Goal: Tuning intrinsic k_T width with different Monte Carlo Event Generators (Pythia (P8) and Herwig (H7))

Motivation:
- Decreasing model uncertainty (e.g. in W mass measurements)
- Improving predictions on tuning side

Method:
- Data used: low pT Drell–Yan spectrum at various CM energies
- Tuned Parameter: Modeling Intrinsic kT with a Gaussian distribution, where the width parameter is optimized.

Conclusion:
- log(intrinsic kT parameter) scales linearly with log($\sqrt{s}$)
- No sensitivity to the P8 and H7 UE tunes observed
- Identical slope for P8 and H7
  - non-perturbative origin
- Different intercepts for P8 and H7
  - lower intercept for H7 due to angular-ordered shower giving more soft ISR emissions

Talk by Daniel Savoiu at Moriond Conference



Collinear MC generators needs q_s dependent on $\sqrt{s}$ (exceeding the Fermi motion kinematics**) to describe the measurements.**
PB TMDs work with rather constant q_s
Why?

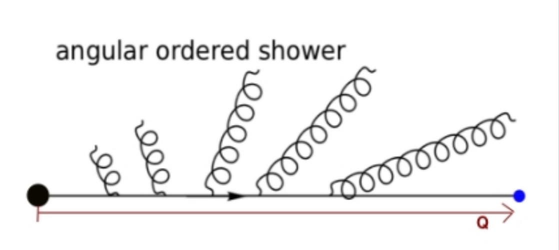
PDFs and TMDs fit in a nutshell

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

- Two angular ordered sets with different choice of scale in α_s:
  - set1: α_s(evolution scale)
  - **set2**: α_s(transverse momentum): similar quality as the NLO + NNLL prediction in $p_t(z)$ description
- TMD parametrization:

$$f_{0,b}(x, \mathbf{k}_{\mathbf{t},0}^2, \mu_0^2) = f_{0,b}(x, \mu_0^2) \cdot \exp(-|k_{\mathrm{T},0}^2|/2\sigma^2) \quad \sigma^2 = q_s^2/2 \ \ \& \ q_s = 0.5 \ GeV$$

Introducing "transverse momentum" instead of "evolution scale" suppresses further soft gluons at low kt.

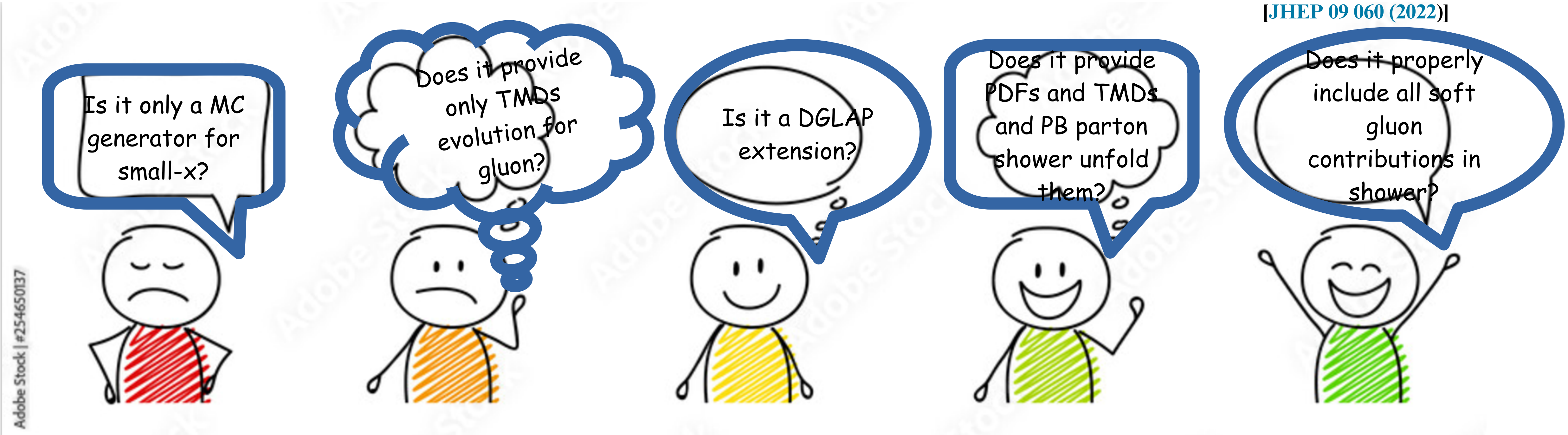


Fitting procedure in a nutshell:

- parameterize collinear PDF at μ_0^2
- produce PB kernels for collinear & TMD distributions to evolve them to $\mu^2 > \mu_0^2$ [Eur. Phys. J. C **74**, 3082 (2014)]
- perform fits to measurements using xFitter frame to extract the initial parametrization (with collinear coefficient functions at NLO)
- store the TMDs in a grid for later use in CASCADE3 [Eur. Phys. J. C **81**, no.5, 425 (2021)]
- plot collinear and TMD pdfs within TMDPLOTTER [arXiv:2103.09741]

What is the Parton Branching method?

[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)]
[JHEP 09 060 (2022)]



No!

No!

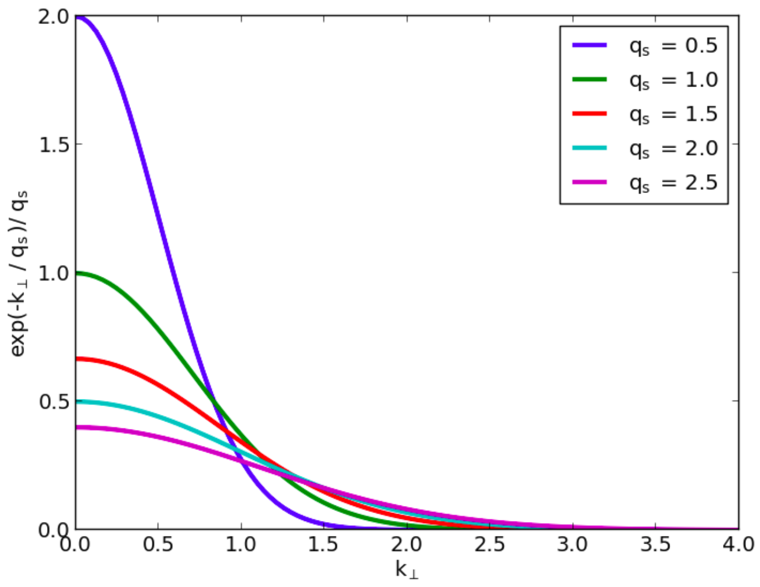
Yes!

Yes!

Yes!

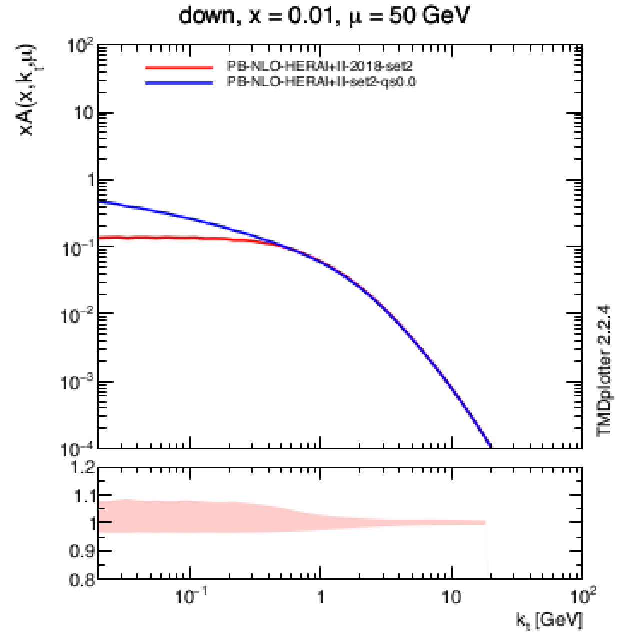
Intrinsic k_T

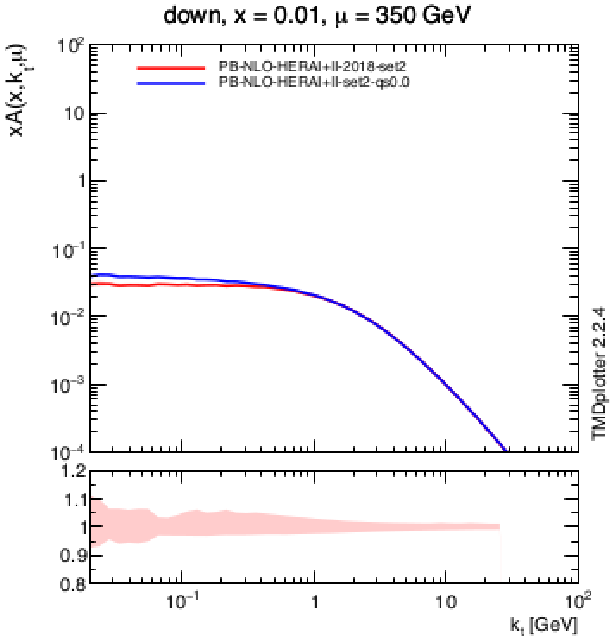
Gaussian distribution



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

Significant effect of the intrinsic-k_T at low scales



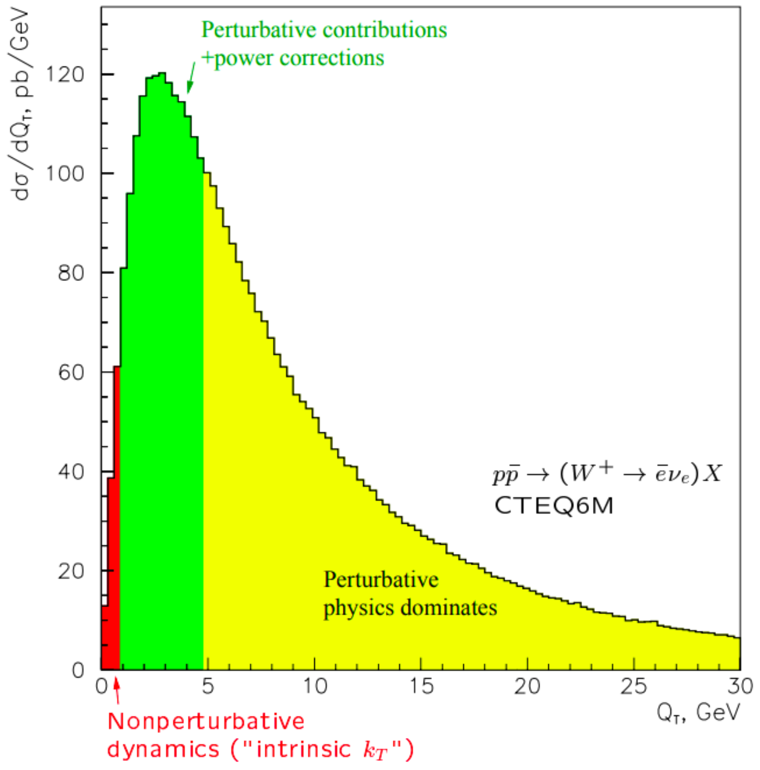


Introduction: DY p_T spectrum

Why small p_T region in DY?

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

Fred Olness, CTEQ summerschool 2003



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

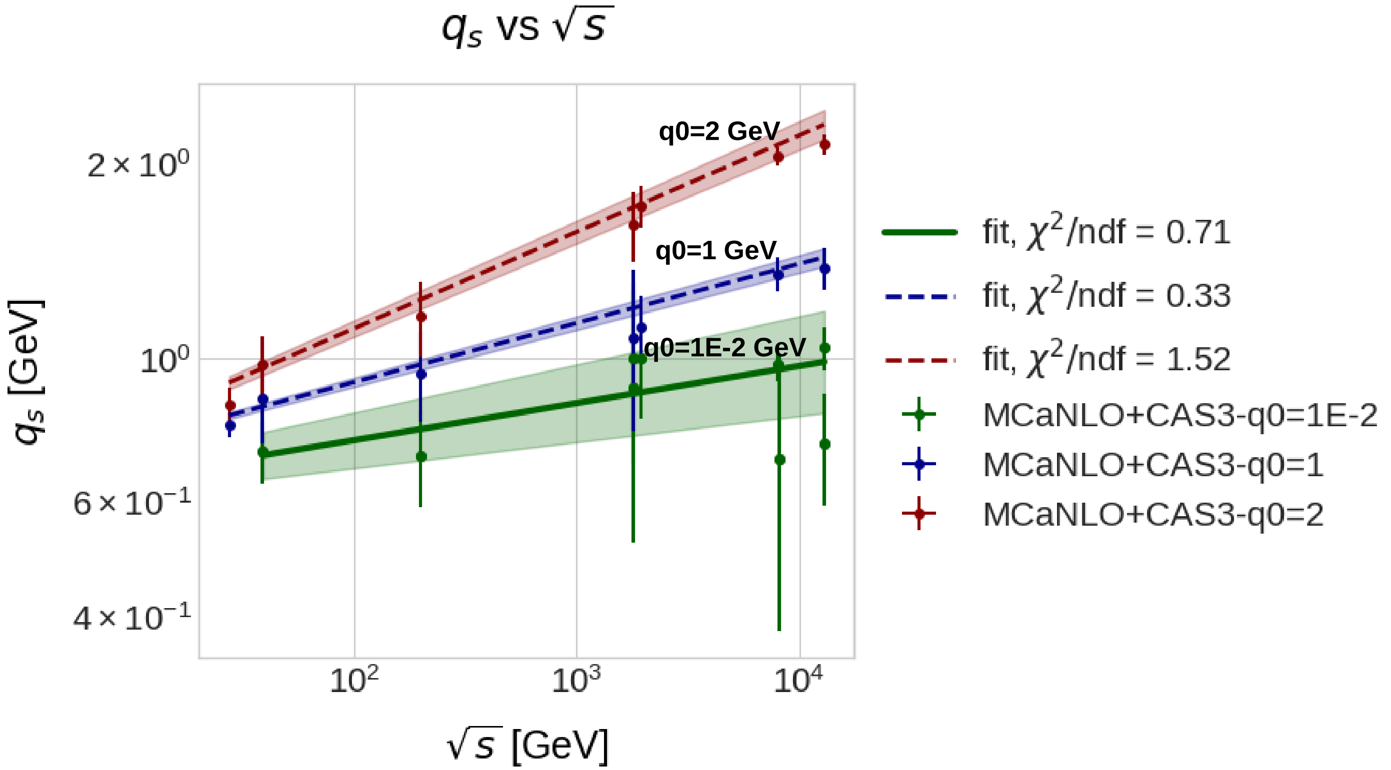
- **Perturbative region:** Collinear factrorization theorem suffices to describe the hard real emissions, perturbative higher-order contributions dominant
- **Transition region:** Soft emissions important, no clear separation between perturbative and non-perturbative effects!
- **Non-perturbative region:** Predominantly sensitive to intrinsic k_T and very soft gluon emission

Today's Focus: Exploring intrinsic k_T contribution in PB-set2 via low p_T DY data tuning.
As a first step, we'll explore the potential contributions from various processes in this specific region.

Understanding the impact of soft gluon emissions on q_s in relation to $\sqrt{s}$

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

Center-of-mass energy dependence of intrinsic-kT distributions obtained from Drell-Yan production I. Bubanja, H. Jung,



Take home message:

The treatment of most small k_T contributions in the PB method already handled within the Non-perturbative Sudakov form factor → only a small contribution of pure intrinsic k_T is needed.

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

Effect of q_0 on dependence:

The slope of this dependence increases and becomes steeper with an increase in q_0.

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_0 value → Smaller uncertainty band

Summary

Parton Branching method solve DGLAP equaiation 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:

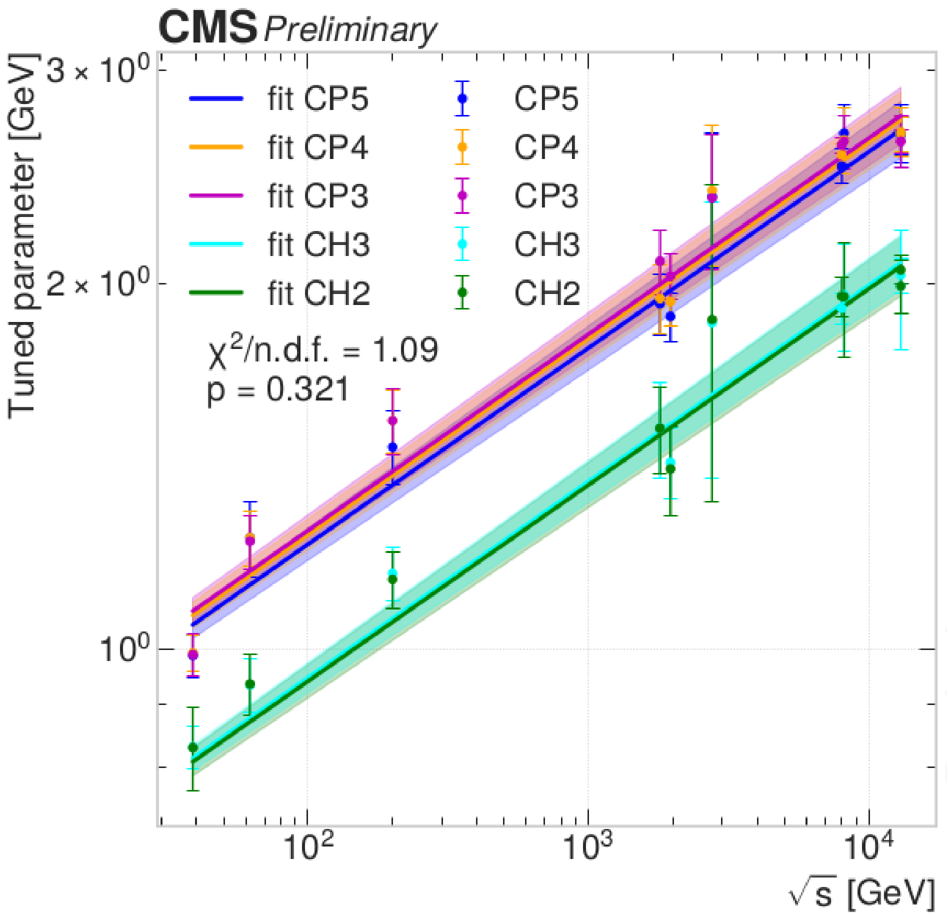
- essential for consistency of NLO matrix elements and PDFs,
- essential for inclusive parton densities (DGLAP required z_M -1), and for TMDs (e.g. q_T spectra)
- soft gluons are not important for final state jets or hadrons from parton shower

Center of mass dependency 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.

PB (CASCADE3), PYTHIA8, HERWIG6

Energy scaling behavior of intrinsic k_T width

Energy Scaling Behaviour of Intrinsic k_T in DY events, GEN-22-001, 2024
Talk by Daniel Savoiu at Moriond Conference



Comparing three different Monte Carlo Event Generators:

- DY ME produced with MadGraph5MC@NLO at NLO
  - proper subtraction term is applied
  - Intrinsic k_T is modeled by Gaussian distribution

- No sensitivity to the PY8 UE tunes observed

- Identical slope for PY8 and H7

- Different intercepts for PY8 and H7
  - AO shower in H7→ more ISR→ lower Intrinsic k_T

Collinear MC generators needs q_s dependent on √s (exceeding the Fermi motion kinematics**)** to describe the measurements.
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