Towards a LHC tune: Primordial k_T

LHC EW working group

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Plan for today

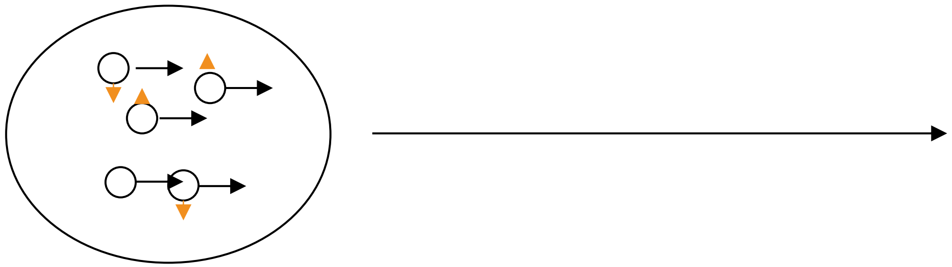
- Introduction
- The intrinsic k_T in Pythia 8
- Conclusions and outlook

Introduction:

1. Definition of intrinsic k_T
2. Motivation

Intrinsic k_T

- Besides longitudinal momenta, partons also have small transverse momentum inside the incoming hadrons



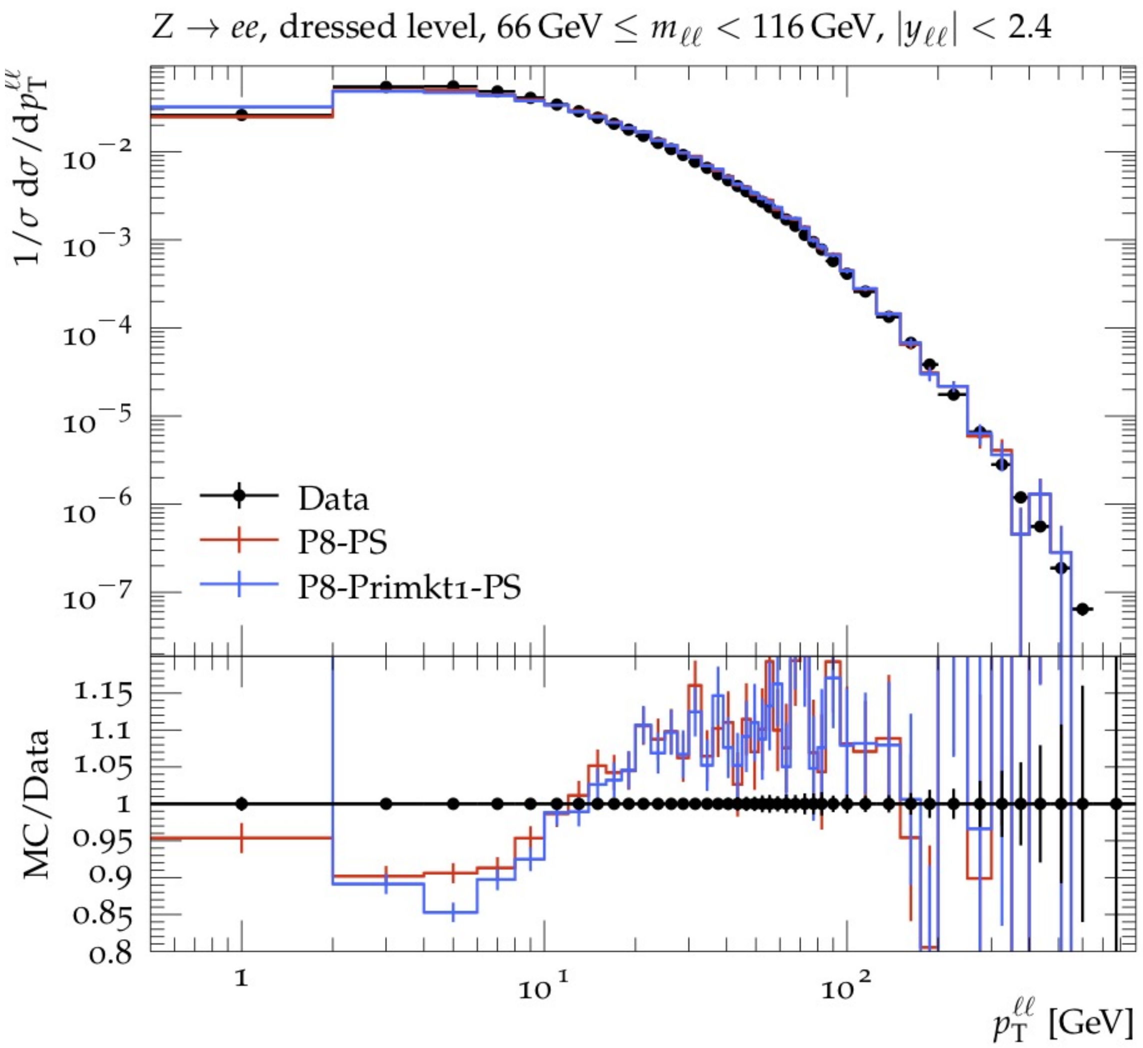
- The intrinsic k_T represents this small transverse momentum, intrinsic k_T ~ 100 MeVs

- It is introduced in the evolution as a non-perturvative parameter, it is generated from a gaussian distribution of width σ

$$e^{-k_T^2/\sigma^2}$$

When is the intrinsic k_T important?

- The contribution of intrinsic k_T is small at LHC energies and at Z peak, only visible at low p_T
- Drell-Yan processes are the cleanest events to study the intrinsic k_T , due to the lack of final state radiation
- The Z transverse momentum is the perfect observable to study the interplay of the initial state radiations and the intrinsic k_T
- Thus, a proper description of the low p_T regions is very important for precision measurements that make use of small p_T regions

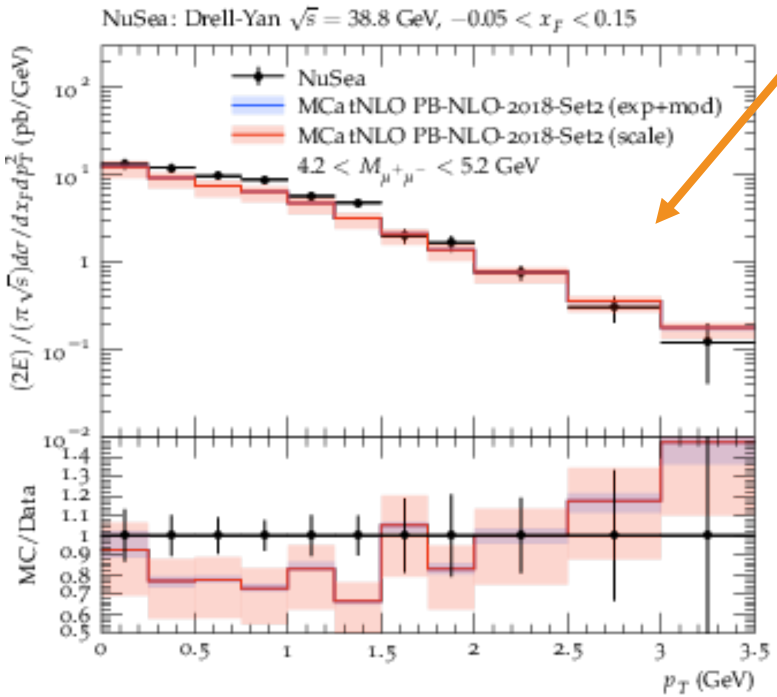


Results from Parton Branching

The p_T spectrum of low mass DY production at NLO in parton branching method (Eur.Phys.J.C 80 (2020) 7, 598)

- These results were shown in REF2020

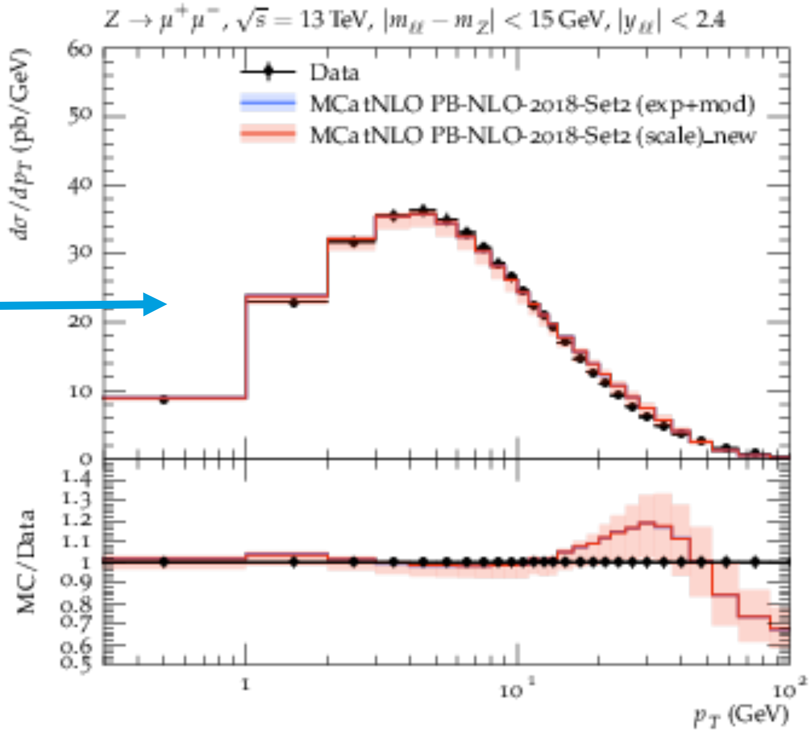
- A good agreement between data and simulation was observed for different DY masses, using the same width $\sigma = \frac{q_s}{\sqrt{2}}$: $q_s = 0.5$ GeV



NuSea($\sqrt{s} = 38.8$ GeV)
$4.2 < m_{\mu^+\mu^-} < 5.2$GeV
$\chi^2/ndf = 1.07$

CMS($\sqrt{s} = 13$ TeV)
$|m_{l^+l^-} - m_Z| < 15$ GeV
$\chi^2/ndf = 0.8$

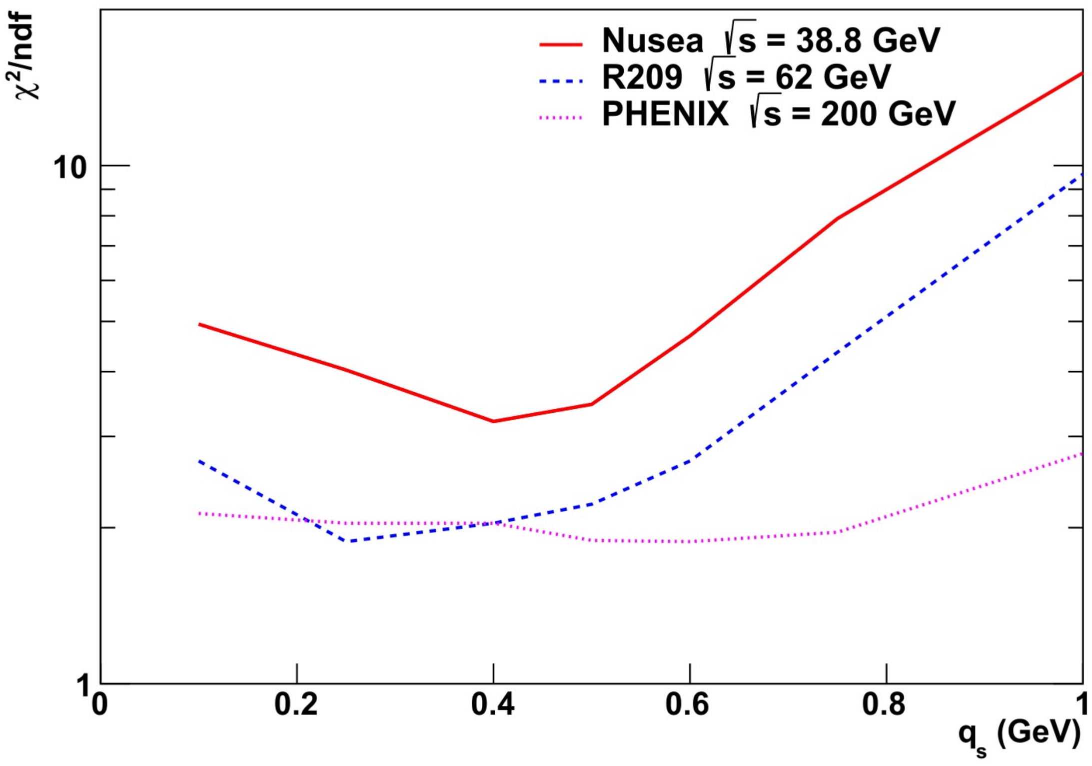
Eur.Phys.J.C 80 (2020) 7, 598



Sensitivity to the intrinsic k_T in Parton Branching

The p_T spectrum of low mass DY production at NLO in parton branching method (Eur.Phys.J.C 80 (2020) 7, 598)

- In PB the width of the gaussian distribution, q_s, is fitted in the TMD
- For different center of mass energies a χ^2 calculation was performed as a function of q_s
- For increasing $\sqrt{s}$ the sensitivity os lower
- A minimum is observed for $q_s \sim 0.3 - 0.4$ GeV for NuSea and R209 measurements



q_s: width of the intrinsic transverse momentum distribution

The intrinsic k_T in Pythia 8

1. Intrinsic k_T parameters
2. Behaviour of intrinsic k_T
3. Modeling the behaviour of the intrinsic k_T

The intrinsic k_T in Pythia 8

- While the intrinsic k_T in Cascade 3 is given by the TMD fit, in Pythia8 a correct traeatment between the interplay of the parton shower and the width of the intrinsic k_T is needed

- For the intrinsic k_T width: BeamRemnants:primordialKThard → σ_{hard}
  - Width of the gaussian distribution where the intrinsic k_T is generated from

$$e^{-k_T^2/\sigma^2} \quad : \quad \sigma \propto \sigma_{hard}$$

- For the initial state shower: SpaceShower:pT0Ref
  - Regularization of the divergence of the QCD emission probability for $p_T \to 0$ $\quad \frac{p_T^2}{(p_{T_0}^2+p_T^2)}$
  - $p_{T_0} = p_{T0Ref}\left(\frac{ecmNow}{ecmRef}\right)^{ecmPow}$ and by default $ecmPow = 0$ → $p_{T_0} = p_{T0Ref}$

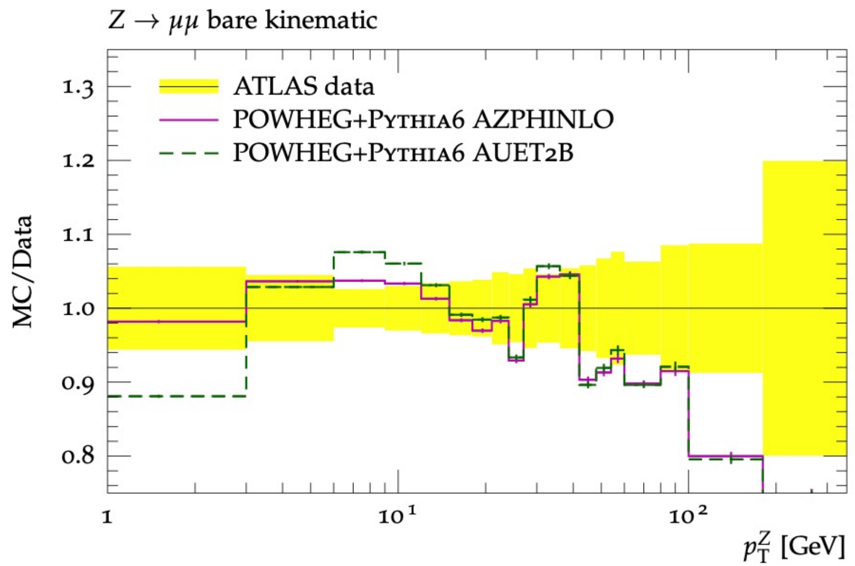
- MC@NLO + Pythia 8

Previous tunings of the intrinsic k_T in Pythia8

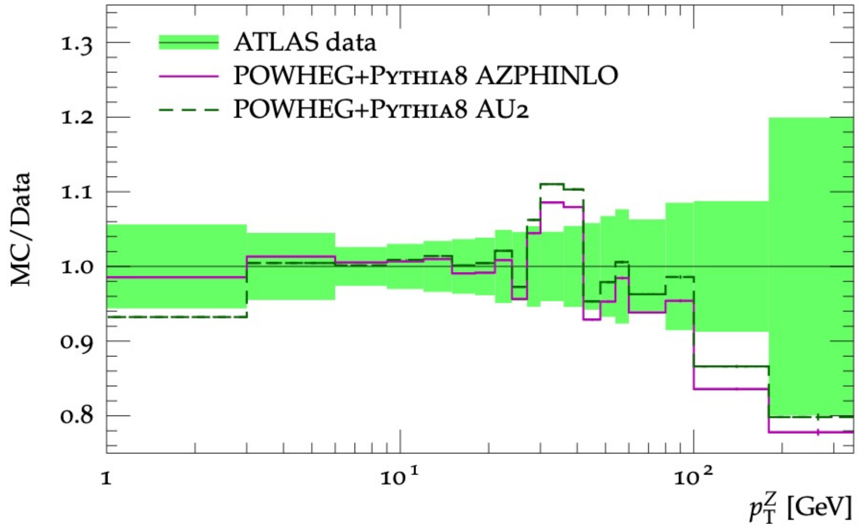
ATL-PHYS-PUB-2013-017

- ATLAS tune of the intrinsic k_T at 7 TeV
  - Pythia6, Pythia8 (AZPHI)
  - Pythia6+POWHEG(NLO), Pythia8+POWHEG(NLO) (AZPHINLO)

Parameter	Pythia6 setting	Variation range	AZPHINLO	AUET2B-CT10
ISR p_T cut-off	PARP(62)	set to `ptsqmin`	2.5	0.312
Scale factor on α_s evaluation scale	PARP(64)	fixed	0.939	0.939
Primordial k_T	PARP(91)	0.1 -1.8	0.8	2.0



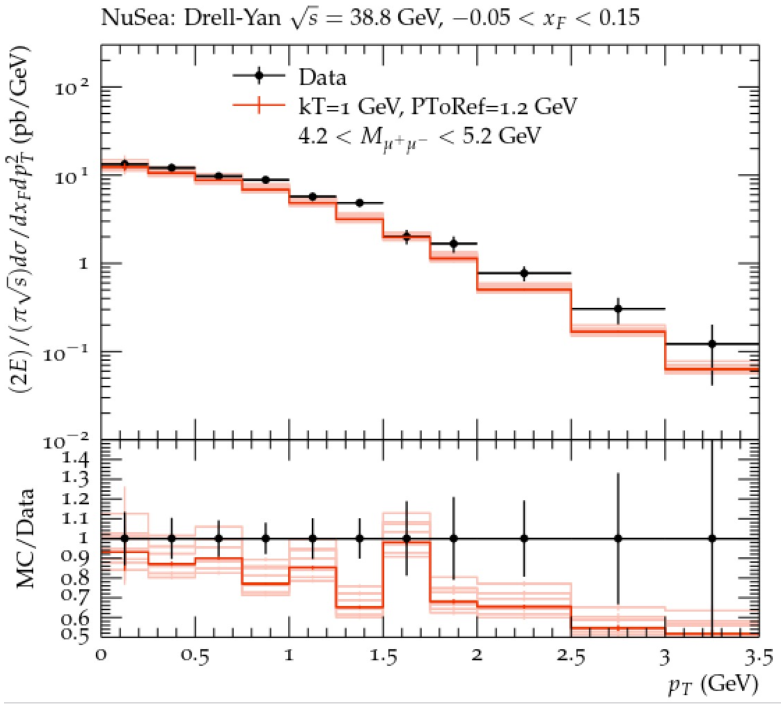
Parameter	Pythia8 setting	Variation range	AZPHINLO	AU2-CT10
Primordial kt	BeamRemnants:primordialKThard	1.0 – 2.5	1.74	2.0
ISR cut-off	SpaceShower:pT0Ref	0.5 – 2.5	1.91	2.0
ISR $\alpha_s(M_Z)$	SpaceShower:alphaSvalue	fixed	0.118	0.137
ISR α_s order	SpaceShower:alphaSorder	fixed	2	1
ISR limit	SpaceShower:pTmaxMatch	fixed	1	0
MPI cut-off	MultipartonInteractions:pT0Ref	1.0 – 2.5	1.57	1.70



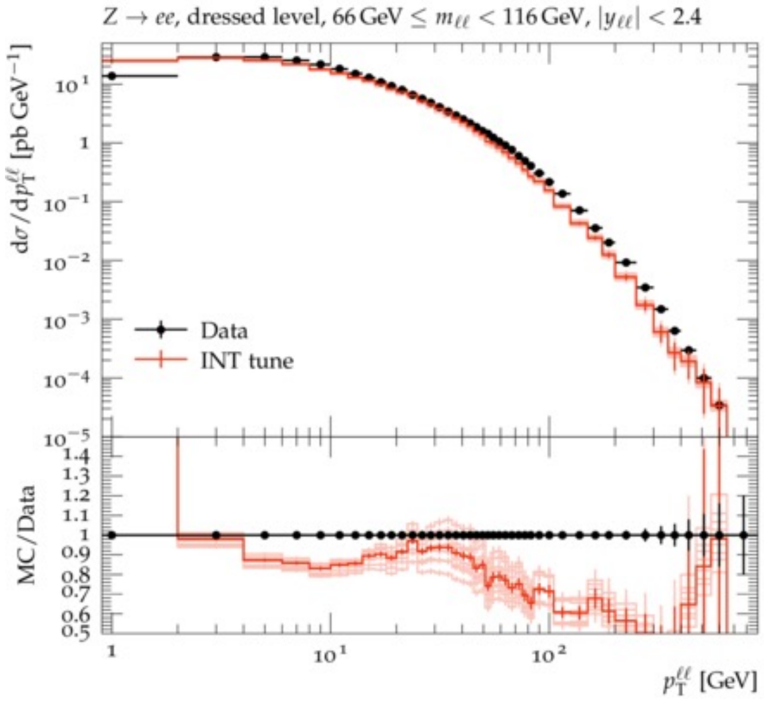
Behaviour of the intrinsic k_T in Pythia 8

- To find a precise value of the intrinsic k_T and the its interplay with the ISR NuSea measurement is used
  - Low DY mass data at $\sqrt{s} = 38.8$ GeV → Little room for QCD evolution
  - $k_T = 1$ GeV, pT0Ref $= 1.2$ GeV, $\alpha_s = 0.118$ (fixed) → INT

NuSea($\sqrt{s} = 38.8$ GeV)
$4.2 < m_{\mu^+\mu^-} < 5.2$GeV



ATLAS($\sqrt{s} = 7$ TeV)
$66 < m_{\mu^+\mu^-} < 116$GeV



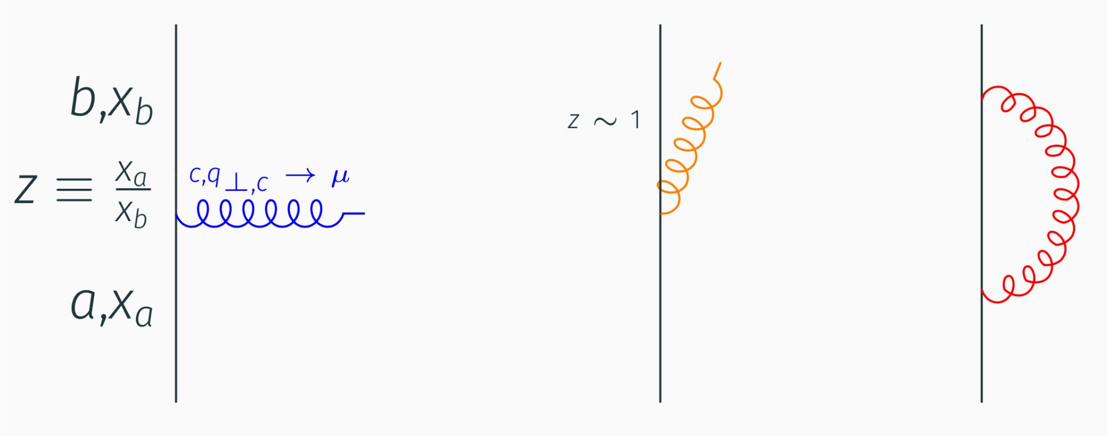
Why hight sensitivity in Pythia 8?

- The treatment of perturvative effects can play a role in the sensitivity of non-perturvative effects

Cascade 3:
- TMD shower
- Angular ordering
- $z_{max} \sim 1$

Pythia 8:
- Collinear shower
- p_T ordering
- $z_{max} < z_{max}^{Cas3}$

- A low z_{max} value would mean that the $1 > z > z_{max}$ region would not contain any radiation/correction and only non-perturvative effects populate it → At higher centre of mass energies soft gluons should play a larger role



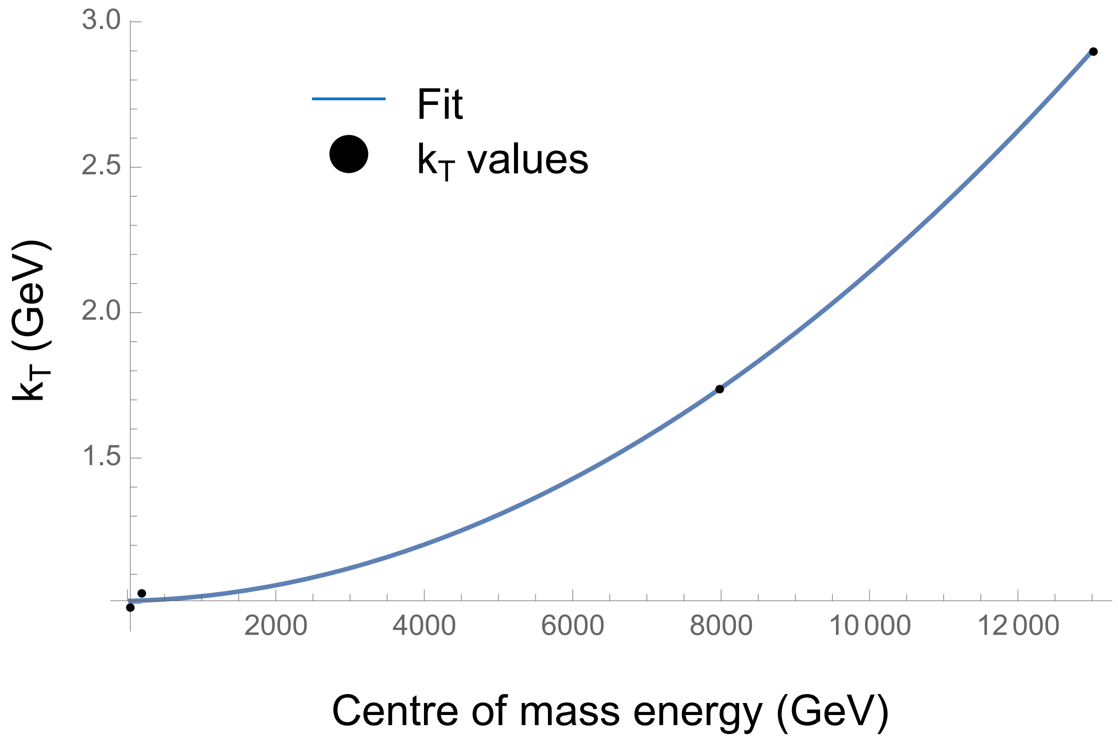
When $z \sim 1$ the emission is not resolvable → z_m is introduced

Model of the intrinsic k_T in Pythia 8

- For increasing centre of mass energies a larger intrinsic k_T is needed to describe the lowest DY p_T spectrum

- We tried different intrinsic k_T values for different centre of mass energies

Experiment	Centre of mass energy (GeV)	Intrinsic k_T (GeV)	Intrinsic k_T from fit (GeV)
NuSea	38.8	1.00	1.019
PHENIX	200	1.05	1.020
ATLAS*	7 000	1.74	1.740
CMS	13 000	2.90	2.899



- A polynomial is used to fit the intrinsic k_T values:

$$k_T(\sqrt{s}) = 1.019 + 3.182 \cdot 10^{-6}\sqrt{s} + 1.086 \cdot 10^{-8}\sqrt{s}^2$$

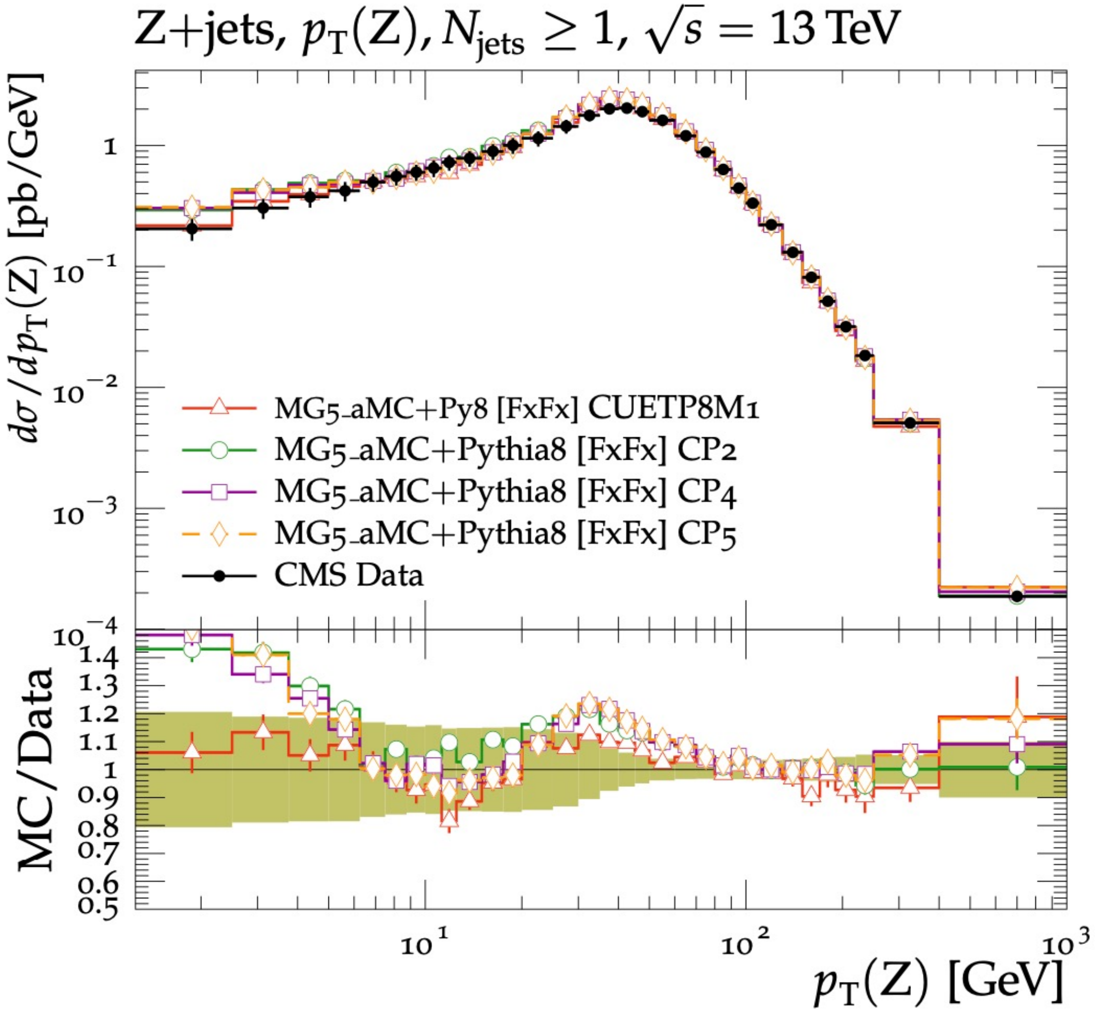
*ATL-PHYS-PUB-2013-017

Conclusions and outlook

CP family tunes *Eur. Phys. J. C* **80**, 4 (2020)

- CP family tunes do not include the tune of the intrinsic k_T
- We can observe that at low Z p_T region CP tunes are not able to describe data
- CUETP8M1, with $\alpha_s = 0.1365$, agrees with data → A larger α_s broadness the effect of intrinsic k_T

PYTHIA8 parameter	CP3	CP4	CP5
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118	0.118	0.118
`SpaceShower:rapidityOrder`	off	off	on
`MultipartonInteractions:EcmRef` [GeV]	7000	7000	7000
$\alpha_S^{ISR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO



Summary

- A good description of the intrinsic k_T is important for precision measurement in the low p_T regions
  - Cascade 3: able to describe low and high DY mass process with the same width of the intrinsic k_T → Fitted from DIS data
  - Pythia 8: for larger CME larger width of intrinsic k_T

- The treatment of perturvative effects in Pythia 8 enhances the contributions of non-perturvative effects

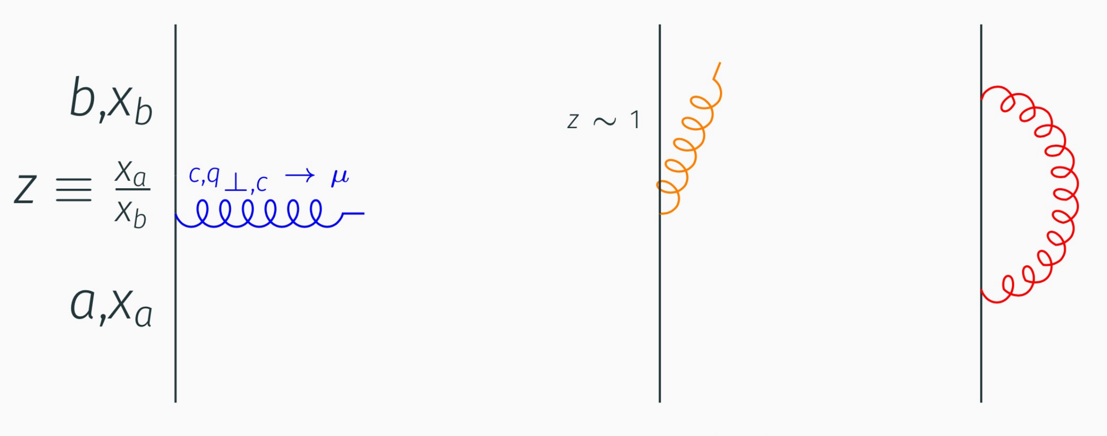
- We modell the behaviour of the width of the intrinsic k_T in Pythia 8 using different DY measurements at different centre of mass energies:
  - NuSea $\sqrt{s} = 38.8\ \mathrm{GeV}$
  - PHENIX $\sqrt{s} = 200\ \mathrm{GeV}$
  - ATLAS $\sqrt{s} = 7\ \mathrm{TeV}$
  - CMS $\sqrt{s} = 13\ \mathrm{TeV}$
  - D0 $\sqrt{s} = 1.9\ \mathrm{TeV}$ (on the way)

$$k_T(\sqrt{s}) = 1.019 + 3.182 \cdot 10^{-6}\sqrt{s} + 1.086 \cdot 10^{-8}\sqrt{s}^2$$

Thank you

PB-TMDs evolution

Cascade 3



$$\text{EVOLUTION} \rightarrow \underbrace{\text{Real resolvable splittings}}_{\text{Splitting functions}} + \underbrace{\text{Non resolvable splittings} + \text{Virtual correction}}_{\text{Sudakov}}$$

$$A_a(x,\mu^2,k_\perp) = A(x,\mu_0^2,k_\perp)\Delta_a(\mu^2) + \int \frac{d^2\mu_1}{\pi\mu_1^2}\Theta(\mu^2-\mu_1^2)\Theta(\mu_1^2-\mu_0^2)\frac{\Delta_a(\mu^2)}{\Delta_a(\mu_1^2)} \times \sum_b \int_x^1 dz_1 \Theta(z_m(\mu_1)-1)P_{ab}^R(\mu_1^2,z_1)A_b\left(\frac{x}{z_1},\mu_0^2,k_\perp\right)\Delta_b(\mu_1^2) + \cdots$$

- The intrinsic k_T of the intial state parton is generated from a gaussian distribution: $A_{0,a}(x,k_{T_0},\mu_0) = f_{0,a}(x,\mu_0)e^{-\frac{k_{T_0}^2}{\sigma^2}}$ $: \sigma = q_s/\sqrt{2}$

- When $z \sim 1$ the emission is not resolvable → z_m is introduced

- The evolution in PB formalism applies angular ordering → $\theta_i < \theta_{i+1}$

Intrinsic k_T of initial state partons

In PB formalism

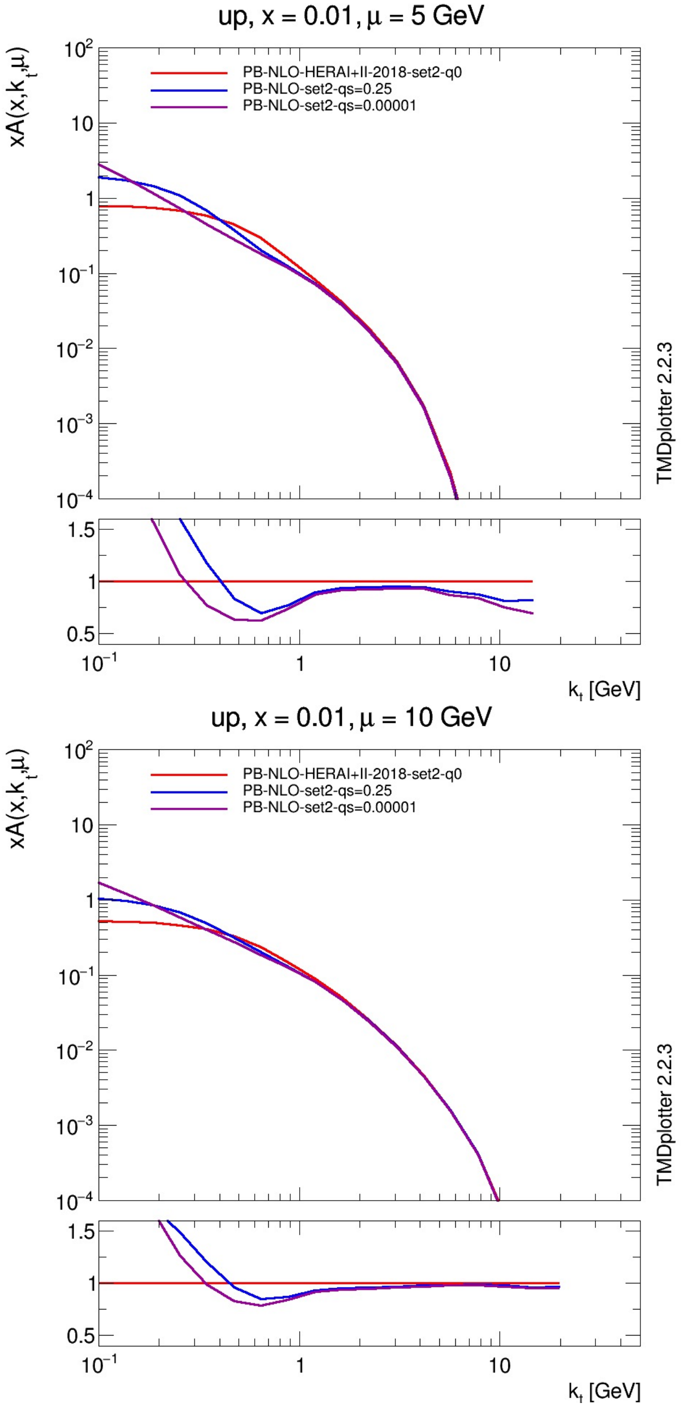
- The intrinsic k_T of the intial state parton is generated from a gaussian distribution

$$A_{0,a}(x, k_{T_0}, \mu_0) = f_{0,a}(x, \mu_0) e^{-\frac{k_{T_0}^2}{\sigma^2}}$$

- The parameter to study is q_s, the width of the distribution:

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

- Small values of q_s makes larger TMDs at low k_T region
  - PB-NLO-HERAI+II-2018-Set2-q0 with $q_s = 0.5$ GeV
  - PB-NLO-2018-Set2 with $q_s = 0.25$ GeV
  - PB-NLO-2018-Set2 with $q_s = 0.00001$ GeV



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