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CZECH TECHNICAL UNIVERSITY IN PRAGUE

Space-time Colour Reconnection in Herwig 7

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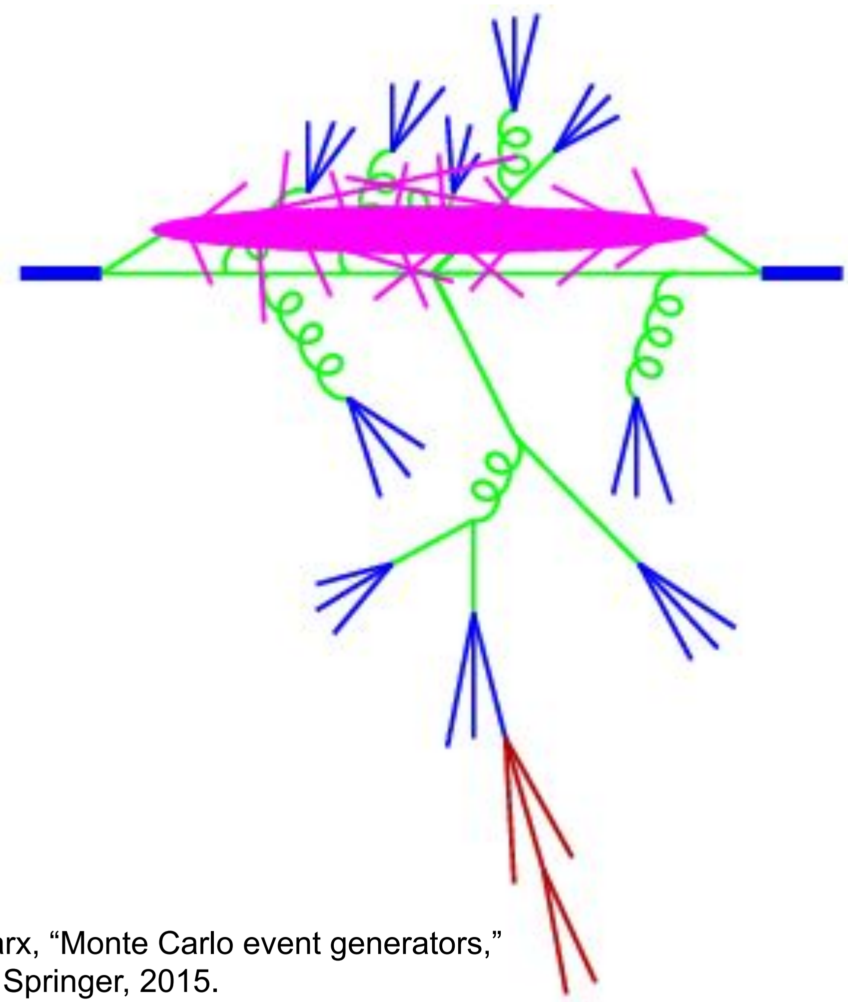
in collaboration with

J. Bellm, C.B. Duncan, S. Gieseke, A. Siodmok

based on arXiv:1909.08850, EPJ C79 (2019) 12

General-purpose Monte Carlo generators

- Hard Process, ISR, FSR, PDF’s, Hadronization, MPI, Beam Remnants, Decays, … Colour Flow model and Colour Reconnection



picture from M. H. Seymour and M. Marx, “Monte Carlo event generators,” in LHC Phenomenology, pp. 287–319, Springer, 2015.

Motivation

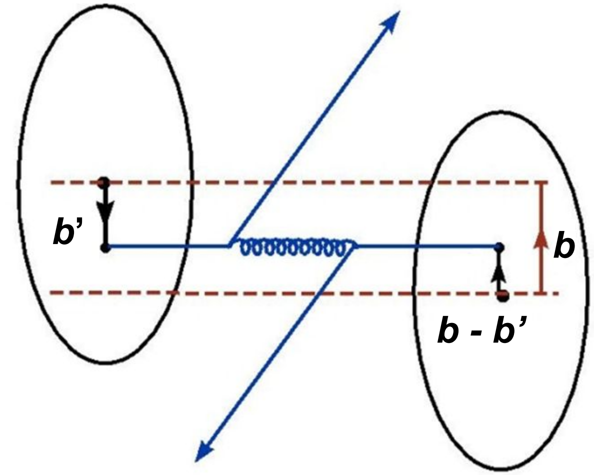
- ❑ Very successful energy-momentum framework for MC
- ❑ So far very little of any notion of spacetime separation

- ❑ e.g. non perturbative effects like colour reconnection start to be important source of uncertainties in precise LHC measurements (for example top mass).
- ❑ Heavy ion collision effects like propagation through the hadron medium

- ❑ Our aim is to introduce the space-time picture in Herwig 7
  - notice a similar effort in Pythia

[S. Ferreres-Sole, T. Sjöstrand, EPJ C78 (2018) no.11, 983]
[T. Sjöstrand, M. Utheim, arxiv:2005.05658 (2020)]

Basic building blocks of MPI in Herwig



From assumptions:

- independent scatters at fixed impact parameter ***b***
- factorization of ***b*** and ***x*** dependence

$$\boxed{\langle n(b,s)\rangle = A(b)\sigma^{inc}(s)}$$

where ***A(b)*** is partonic **overlap function** of the colliding hadrons

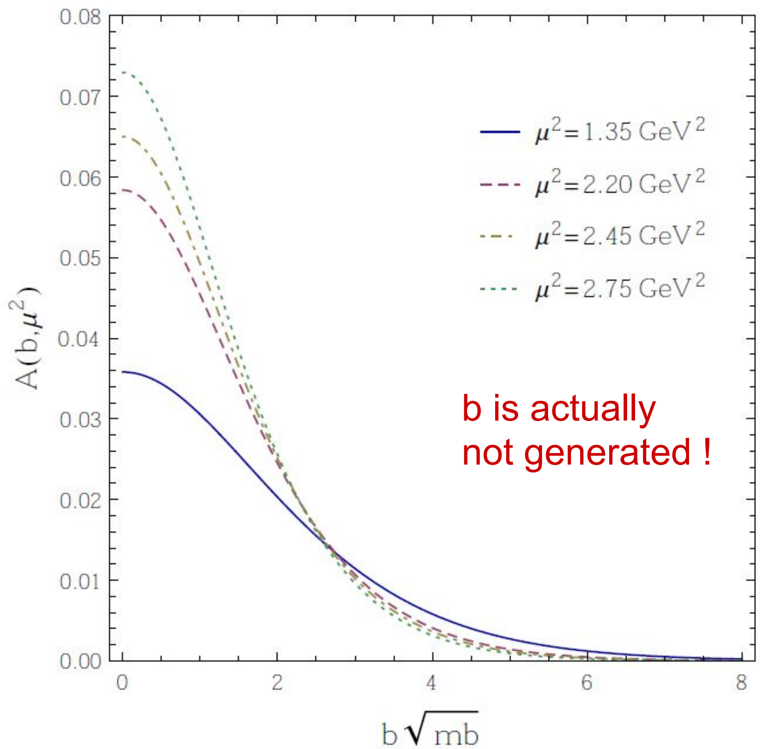
$$\sigma_{\text{eff}} = \frac{28\pi}{\mu^2}$$

$$A(\vec{b}) = \int d^2\vec{b}' g(\vec{b}') g(\vec{b}-\vec{b}')$$

with ***g(b')*** being EM FF

$$g(\vec{b}') = \frac{1}{(2\pi)^2}\int d^2\vec{k}\frac{e^{i\vec{k}\vec{b}'}}{\left(1+\frac{|\vec{k}|^2}{\mu^2}\right)^2}$$

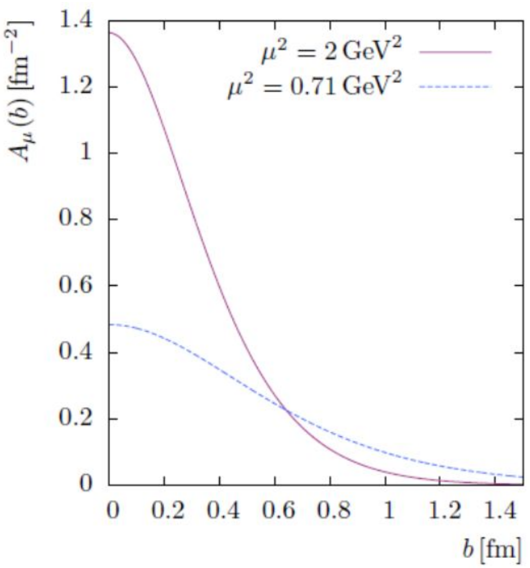
and ***μ*** as a free parameter
(i.e. not fixed at EM value of 0.71 GeV^2)



Basic building blocks of MPI in Herwig - summary

Matter distribution

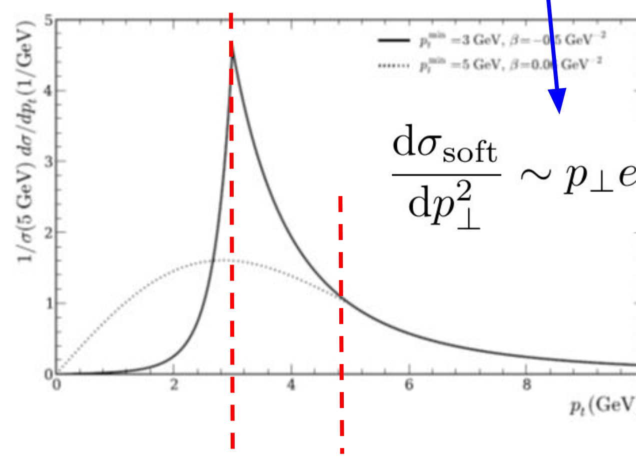
EM FF -> Bessel
(μ - inverse proton radius)



$$A(b;\mu) = \frac{\mu^2}{96\pi}(\mu b)^3 K_3(\mu b)$$

Extended to soft MPI

$p_t < p_t^{min}$
Gaussian extension to zero
Long. momentum ~ 1/x
Energy dependent p_t^{min}



$$\frac{\mathrm{d}\sigma_{\mathrm{soft}}}{\mathrm{d}p_\perp^2} \sim p_\perp e^{-\beta(p_\perp^2 - p_\perp^{\mathrm{min},2})}$$

$$p_\perp^{\mathrm{min}}(s) = p_{\perp,0}^{\mathrm{min}} \left(\frac{\sqrt{s}}{7\,\mathrm{TeV}}\right)^b$$

Two main parameters of the model

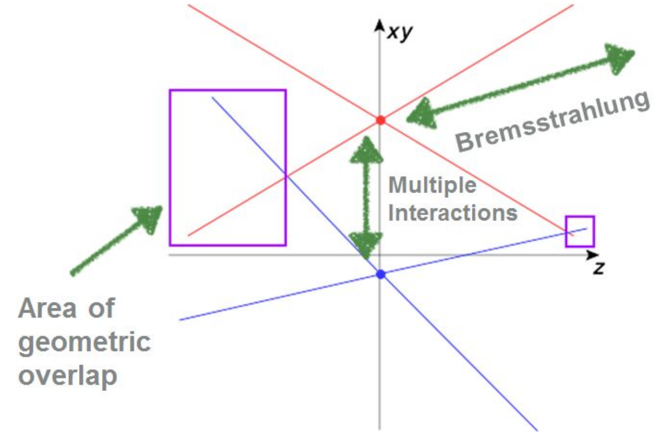
μ_{hard} , $p_{T,0}^{min}$

Further development of MPI:
[J. Bellm, S. Gieseke, P. Kirchgaesser,Eur. Phys. J. C 80 (2020) 469]

e.g. $$p_\perp^{\mathrm{min}}(s) = p_{\perp,0}^{\mathrm{min}} \left(\frac{b + \sqrt{s}}{E_0}\right)^c$$

Spacetime Model - MPI

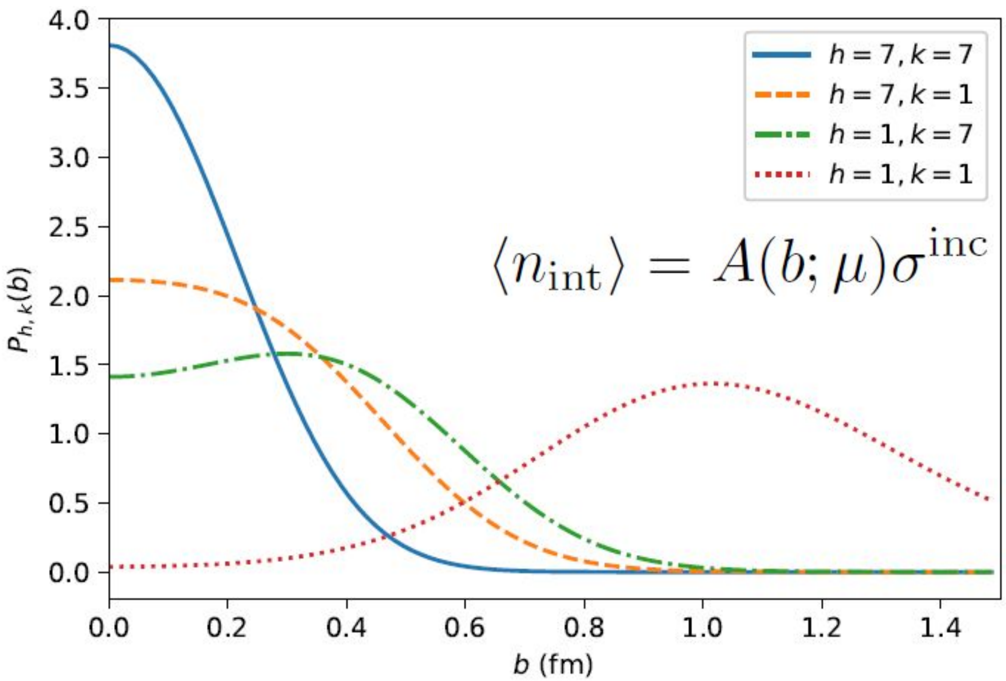
- ❑ Each scatter (MPI) gets its point in **xy plane**
- ❑ (inspired by heavy ion collision)
- ❑ Shower evolves partons further in xyz
- ❑ Motivation to cluster “close” partons



Sub-steps:

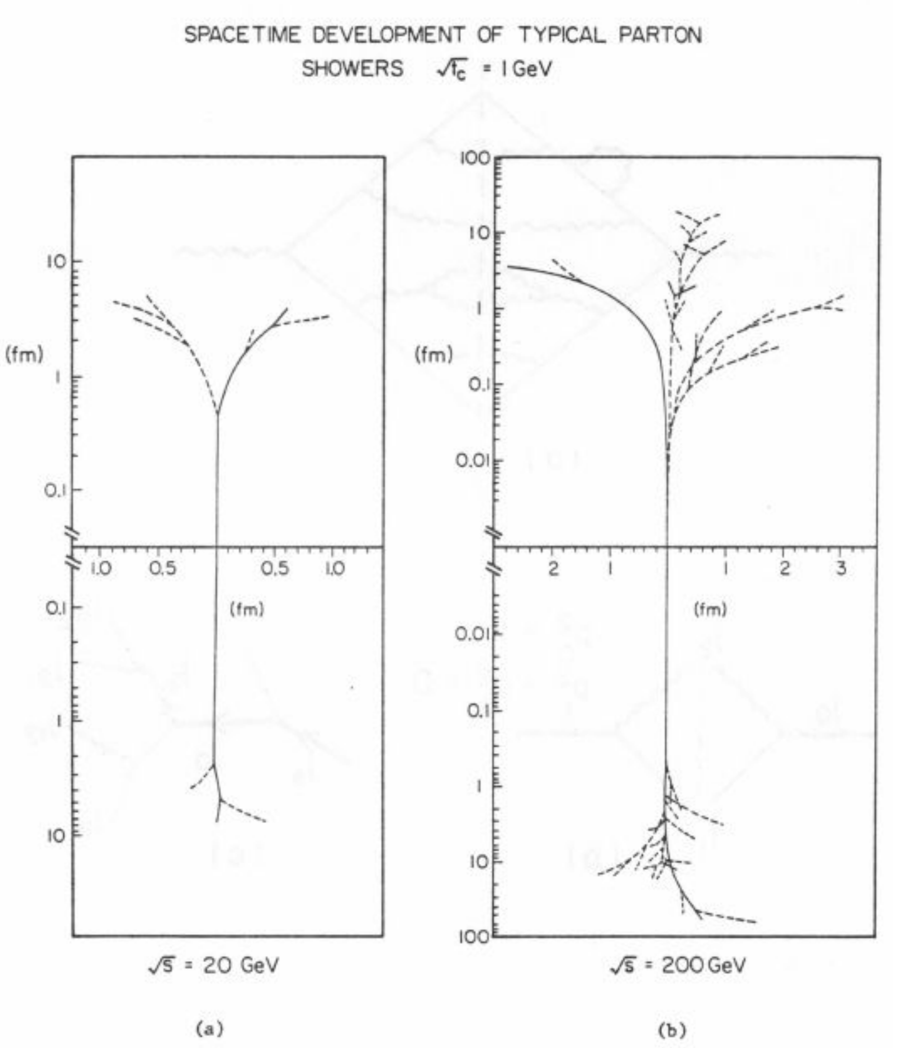
- ➔ Impact parameter
- ➔ Proton profile
  - ◆ Black disk
  - ◆ Gaussian
  - ◆ Overlap function (Bessel)
- ➔ Proton finite radius
- ➔ Proton remnants

Poisson sampling of impact parameter of collision (b)



$$\mathcal{P}_{h,k} = \frac{\langle n_h(b)\rangle^h}{h!}\frac{\langle n_k(b)\rangle^k}{k!}\exp[-(\langle n_h(b)\rangle + \langle n_k(b)\rangle)]$$

Spacetime Model - shower (angular-ordered)



[G. C. Fox, S. Wolfram,
A Model for Parton Showers in QCD
Nucl. Phys. B168 (1980) 285]

Herwig7:

- ❑ fortran Herwig-like algorithm

- ❑ **Mean lifetime**
  virtuality dependence - interpolation between on-shell and high virtuality

$$\tau(q^2) = \frac{\hbar\sqrt{q^2}}{\sqrt{(q^2 - M^2)^2 + (\Gamma q^2/M)^2}}$$

- ❑ **Distance travelled for proper lifetime**

$$\mathrm{Prob}(\text{proper time} > t^*) = \exp(-t^*/\tau)$$

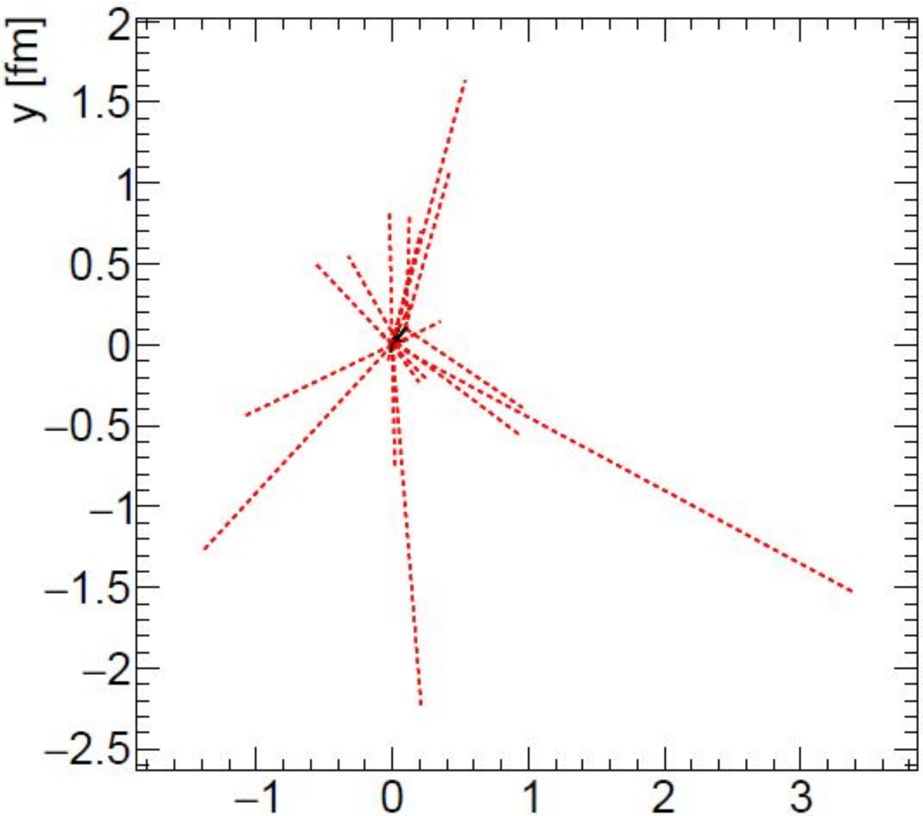
- ❑ **Lab frame distance**

$$\boldsymbol{d = \beta\gamma t^*}$$

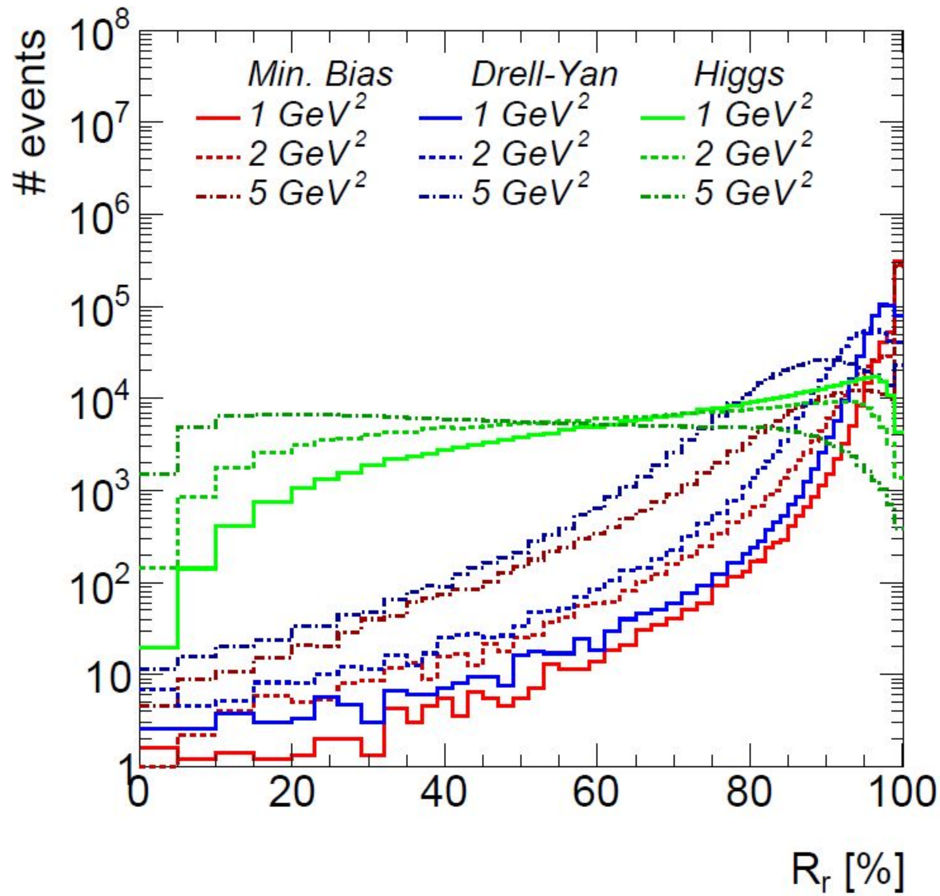
Space-time Model - shower (angular-ordered)

$$\tau(q^2) = \frac{\hbar\sqrt{q^2}}{\sqrt{(q^2 - M^2)^2 + (\Gamma q^2/M)^2}} \quad \rightarrow \quad \hbar/\sqrt{q^2}$$

- low virtuality allows large distances



Example event



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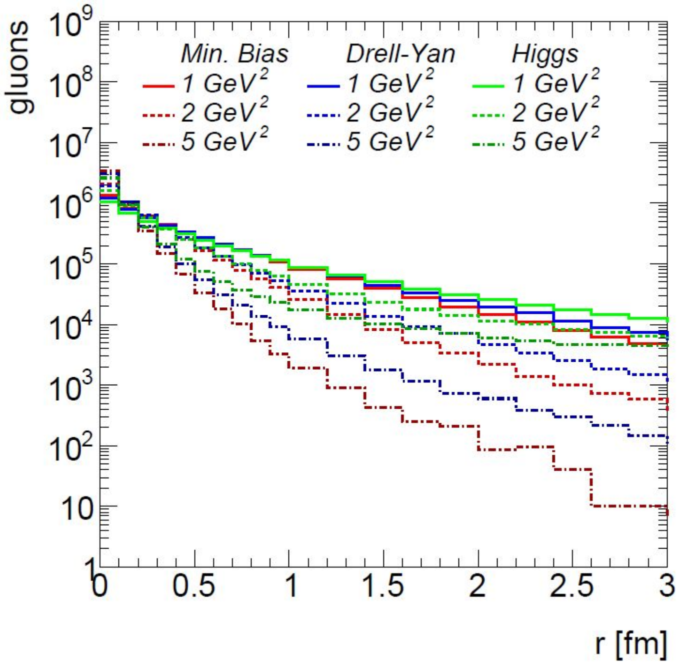

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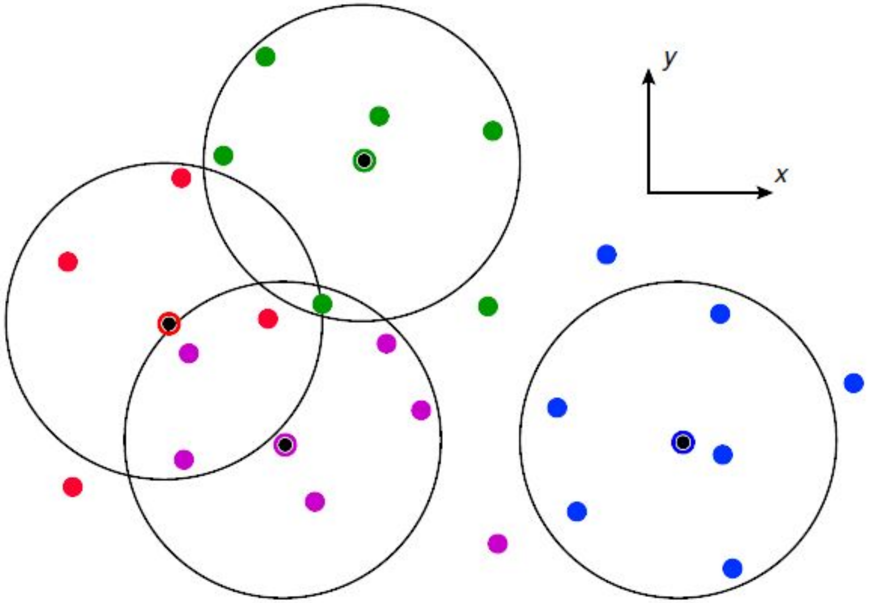
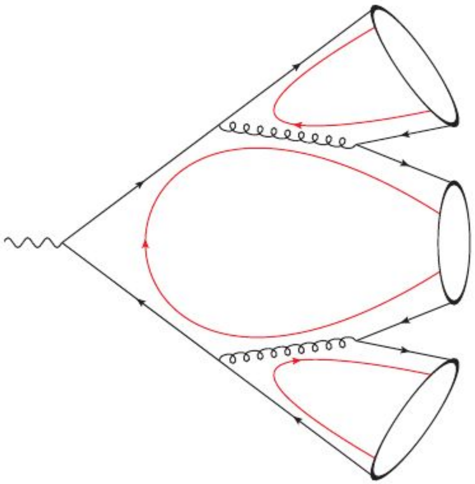


- all "final" partons are set to the same "minimal virtuality" ν
  - a tunable parameter

$$\tau_{0,p} = \frac{\hbar m_p}{\nu^2}$$

- such a smearing might be viewed as a result of uncertainty principle

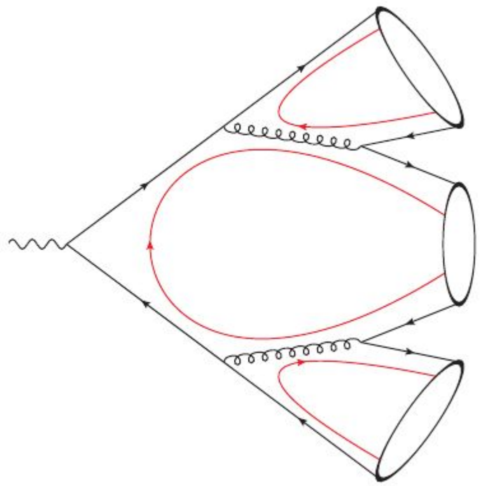
Colour Reconnection



- **cluster hadronization**
  [Webber, Nucl. Phys. B238 (1984) 492]

- perturbative QCD provides *preconfinement*
  - colour-anticolour pairs form higly excited hadronic states = clusters
  [Amati, Veneziano, Phys.Lett. B83(1979)87]

Colour Reconnection



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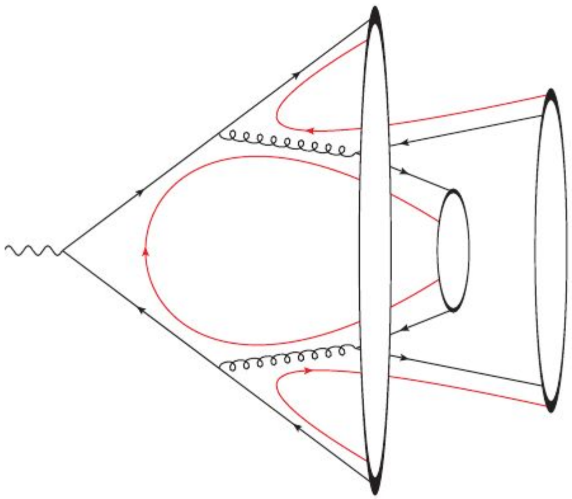


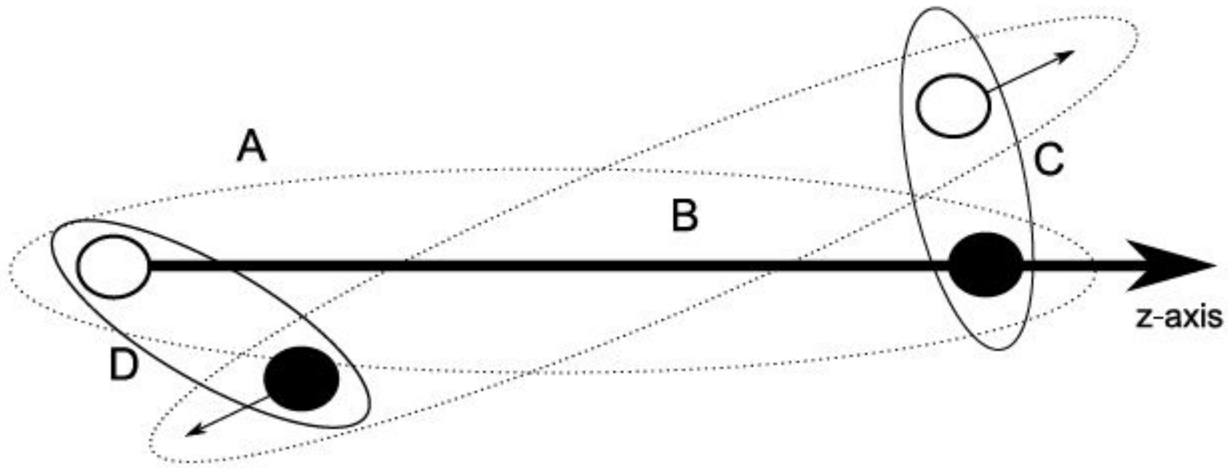
- ❑ **Colour Reconnection**
  - partons before hadronizing may be modelled as they exchange gluons - an extra step to swap the colours

- ❑ improve description of soft MB events and UE

- ❑ effectively reduces cluster masses and thus the number of particles produced in the final state (with higher momentum)

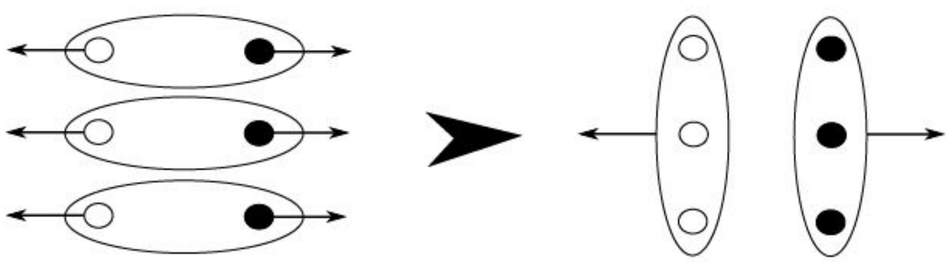
[S. Gieseke, C. Rohr, A. Siodmok, Eur. Phys. J C72 (2012) 2225]
[S. Gieseke, P. Kirchgasser, S. Platzer, A. Siodmok, JHEP 1811 (2018) 149]
[S. Gieseke, P. Kirchgasser, S. Platzer, Eur. Phys. J C78 (2018) no.2, 99]
[S. Gieseke, P. Kirchgasser, S. Platzer, A. Siodmok, Acta Phys. Polon. B50 (2019) 1871]

Baryonic Colour Reconnection



- pick a random cluster (mesonic)
- make an axis ("z-axis") - back-to-back in the rest frame
- take all other clusters - boost them and get rapidity wrt original cluster
- if quarks fly in the opposite direction → make mesonic cluster
- if quarks fly in the same direction → barionic cluster candidate

- barion cluster formation: measure & probability
  - measure: rapidity span OR **spacetime measure** !

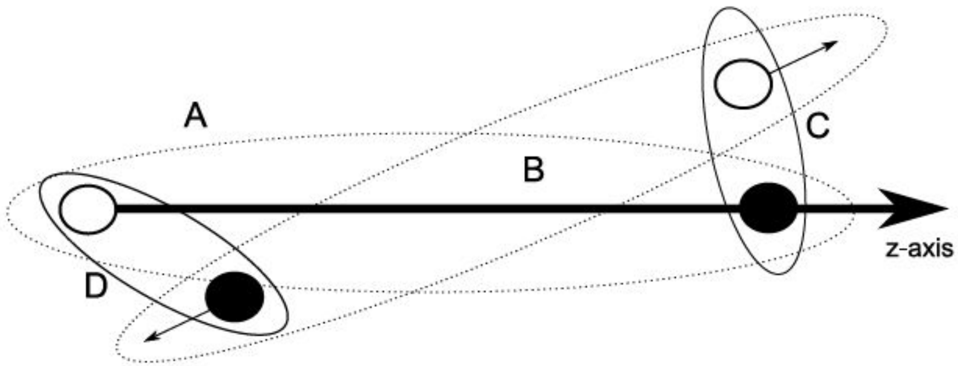


Baryonic Colour Reconnection - spacetime measure

- this time combine rapidity (i.e. momentum) & position info
  (similarly to $\sqrt{(\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2}$)

$$R_{ij}^2 = \frac{\Delta r_{ij}^2}{d_0^2} + \Delta y_{ij}^2$$

characteristic length scale d_0 regulates the ratio: transverse distance vs rapidity



mesonic clusters $$R_{q\bar{q}'} + R_{q'\bar{q}} < R_{q\bar{q}} + R_{q'\bar{q}'}$$

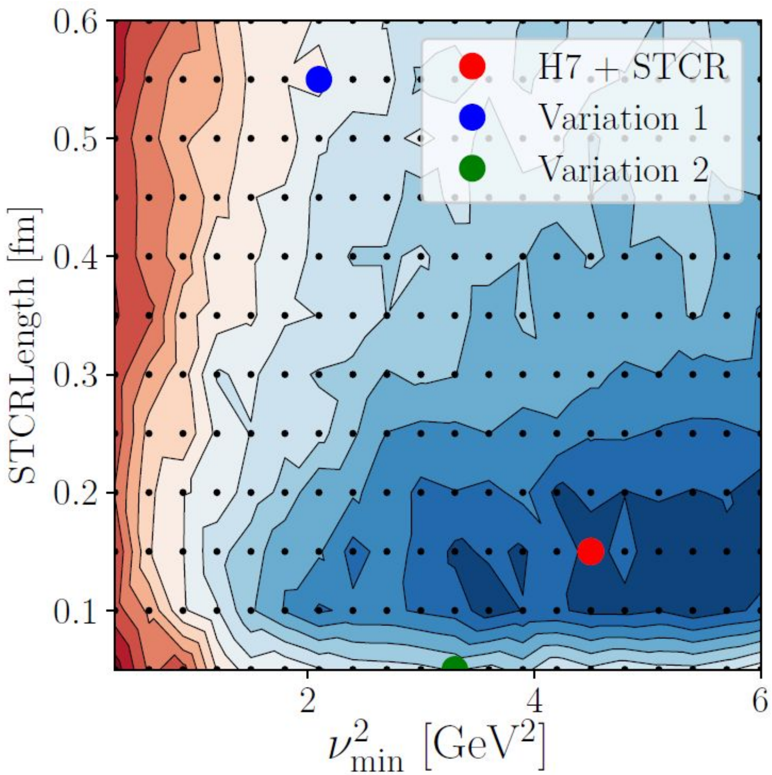
baryonic clusters $$R_{q,qq} + R_{\bar{q},\bar{q}\bar{q}} < R_{q,\bar{q}} + R_{qq,\bar{q}\bar{q}}$$

Baryonic Colour Reconnection - tuning of parameters

σ_{tot} [mb]	R_{Diff}	$p_{\perp}^{\mathrm{min}}$ [GeV]	μ_{hard}^2 [GeV^2]
96.0	0.2	3.0	1.5

ν^2 [GeV^2]	d_0 [fm]	w_b	(μ_{soft}^2 [GeV^2])
4.5	0.15	0.98	0.254

$1/d_0^2 \sim 44$



Variation 1:

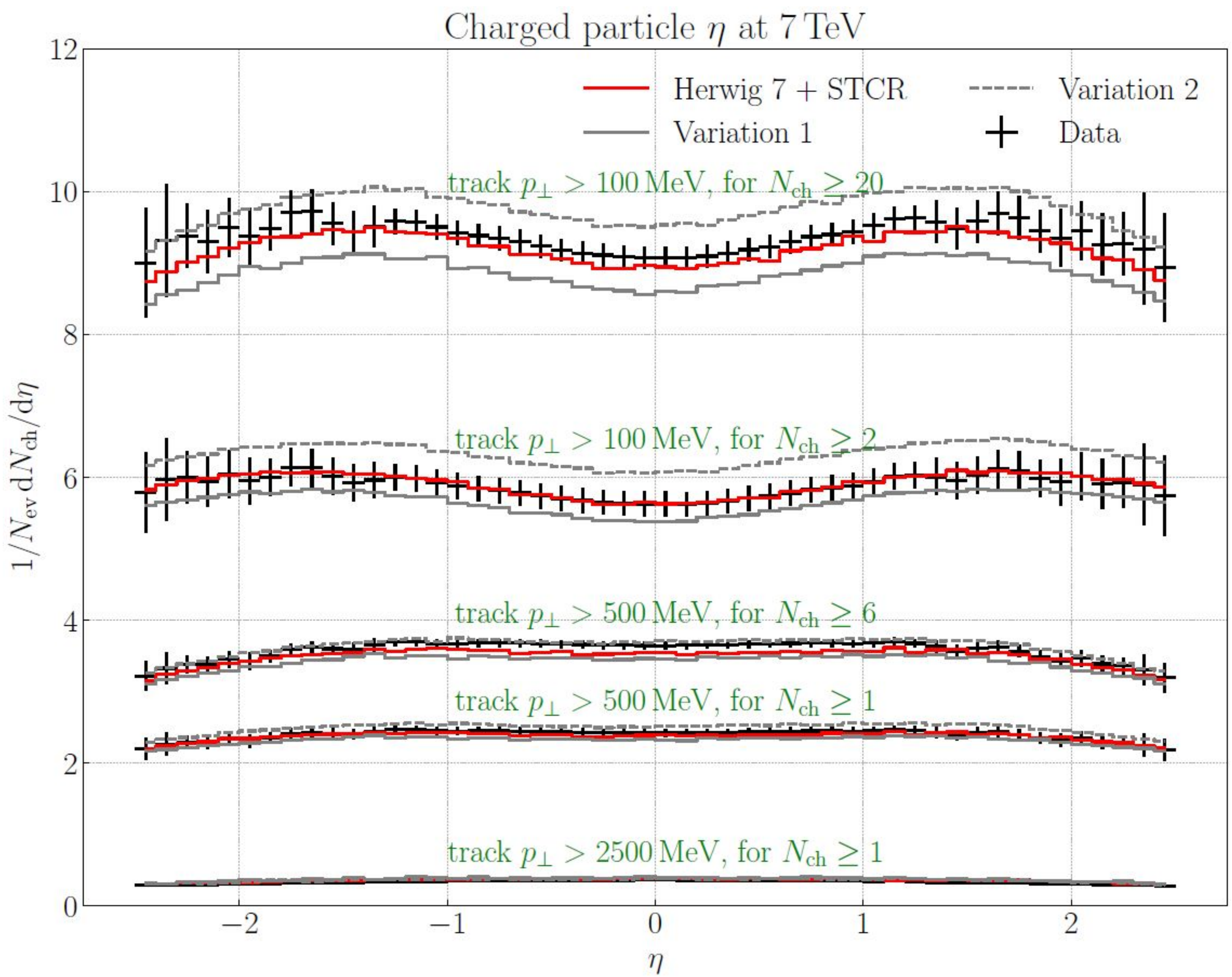
$$\nu^2 = 2.1\ \mathrm{GeV}^2,\ d_0 = 0.55\ \mathrm{fm}$$

Variation 2:

$$\nu^2 = 3.3\ \mathrm{GeV}^2,\ d_0 = 0.05\ \mathrm{fm}$$

Baryonic Colour Reconnection - results

- good agreement with Minimum Bias data (ATLAS)



Baryonic Colour Reconnection - results

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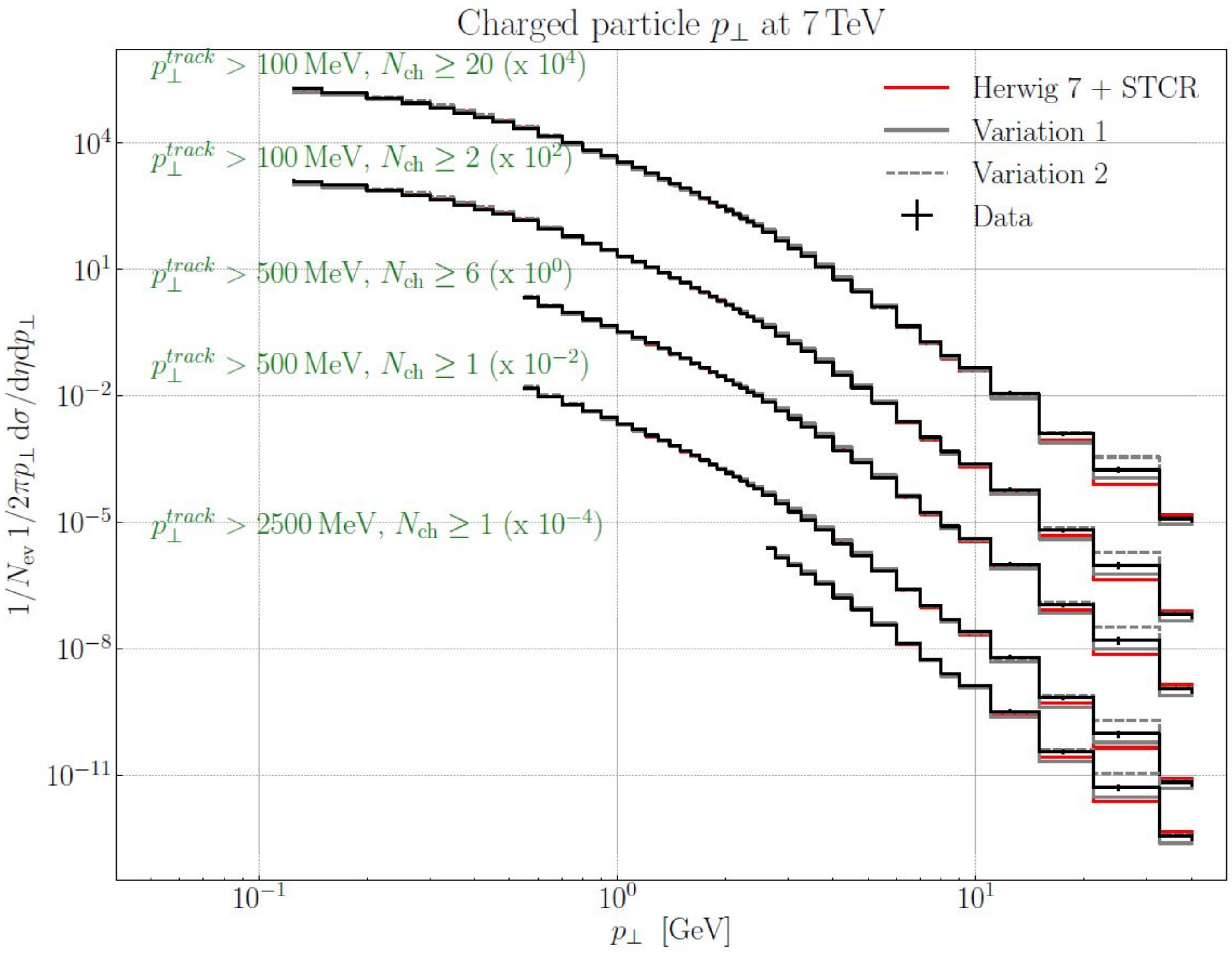
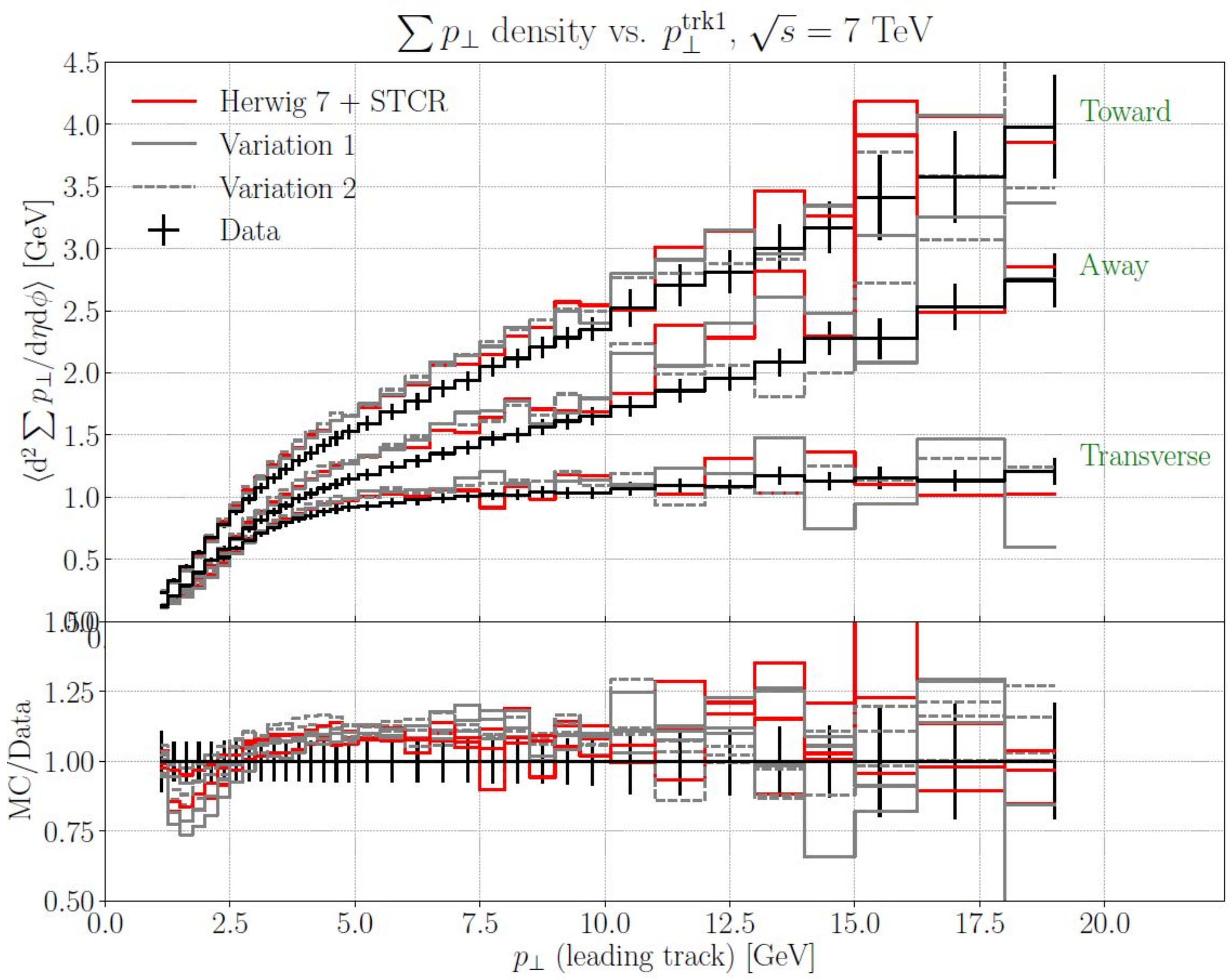


Baryonic Colour Reconnection - results

- good agreement with Underlying Event data (ATLAS)



Summary and outlook

- We introduce spacetime picture to MPI (transverse space)
- Modify spacetime in Parton Shower
- Use spacetime information to Colour Reconnection and study its influence on MB and UE event data
- Space-time picture could serve us as a starting point to study collective effects in p-p collisions
- Opens a field of many possibilities: reconnect only close MPI’s, soft-gluon-evolution in local systems, Bose-Einstein correlations, ...

Thank you for your attention!