Space-time Colour Reconnection in Herwig 7

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in collaboration with J. Bellm, C. Duncan, S. Gieseke, M. Myska
based on EPJC 79 (2019) no.12, 1003.

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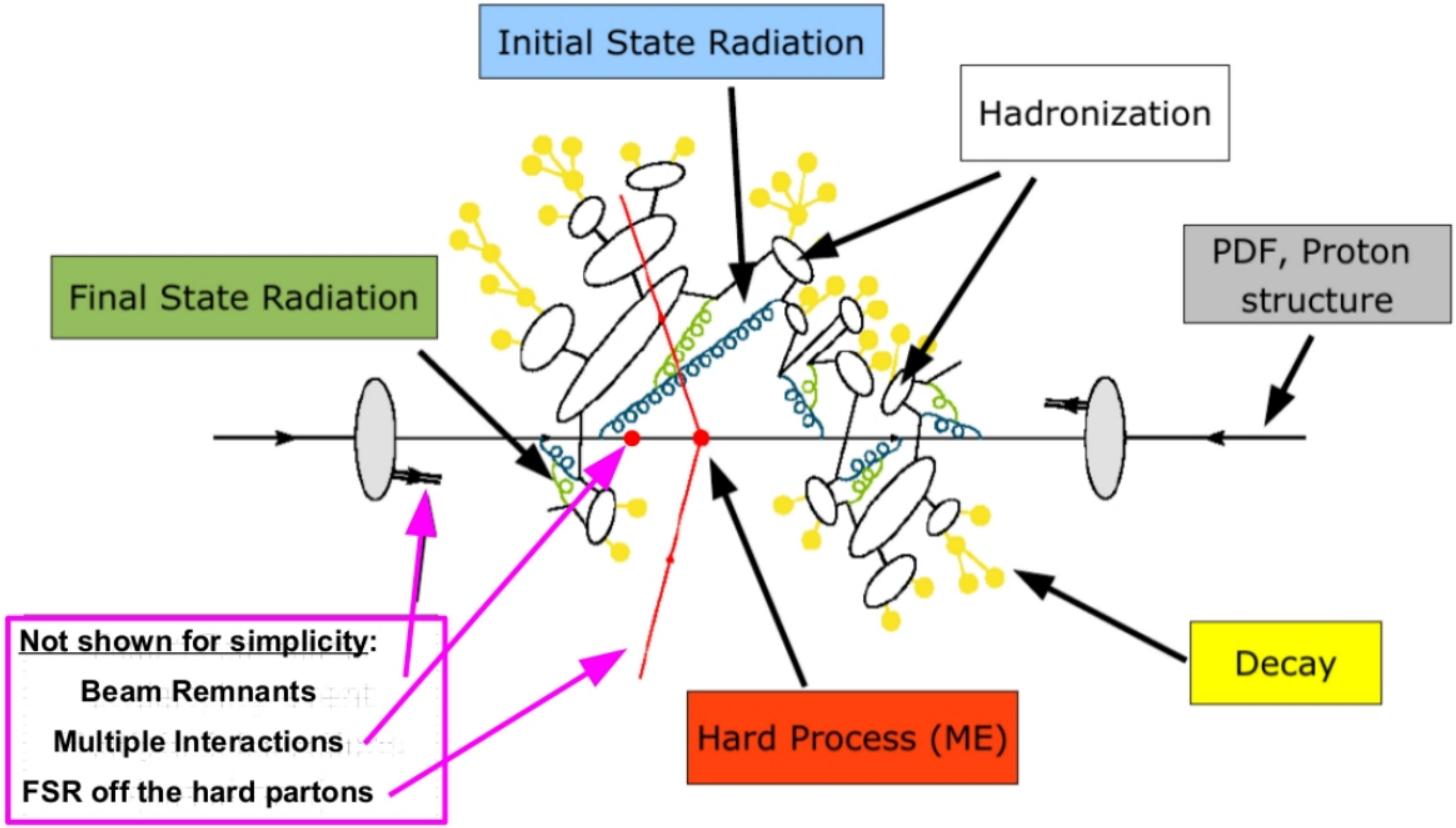
Outline

1. Motivation and introduction
2. Space time position of Multi-Parton Interactions (MPI)
3. Space time position from Parton Shower evolution
4. Colour reconnection based on space-time information
5. Numerical results
6. Summary and outlook

Motivation - Monte Carlo Event Generators



taken from Stefan Gieseke©

The general approach is the same in different programs but the models and approximations used are different.

Motivation. How do we know MPI exists?

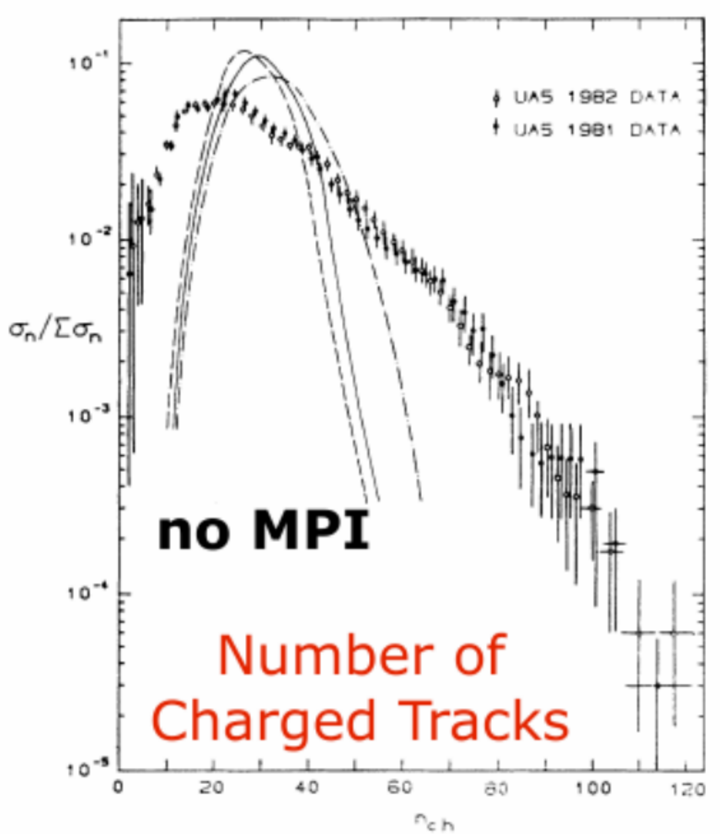


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

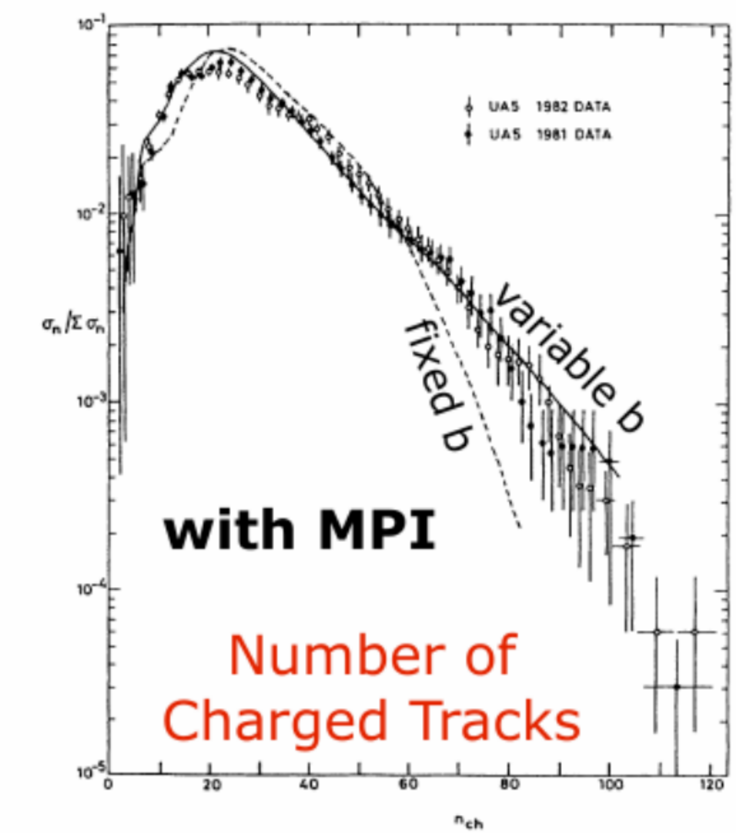


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\bar{O}_0(b)$].

Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

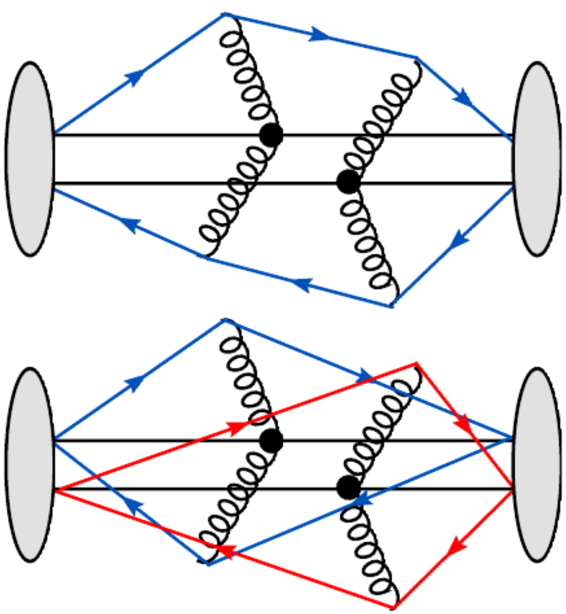
Motivation. Is it really important?

- Better control of perturbative corrections (**“NLO revolution”**) → more often LHC measurements are limited by non-perturbative components (hadronization or multiparton interactions):

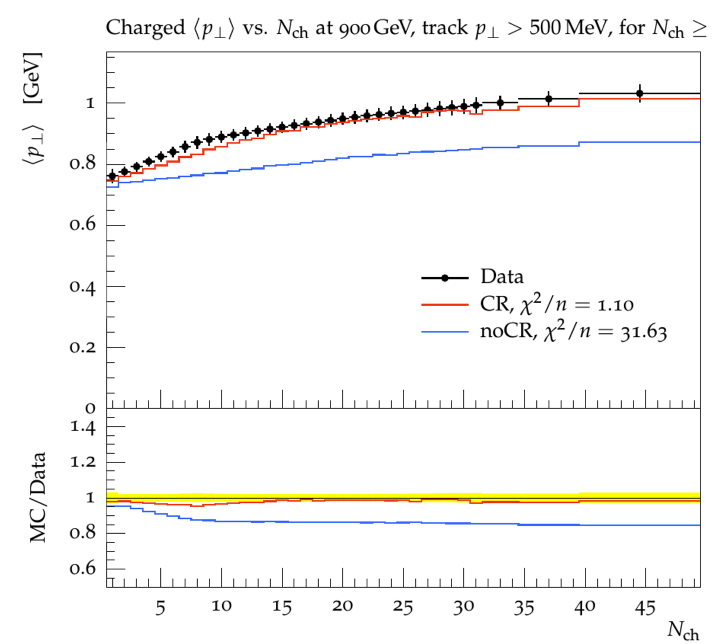
  - W mass measurement using a new method [Freytsis at al. JHEP 1902 (2019) 003]
  - extraction of the strong coupling in [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5, 054013].
  - the top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]

  precision dominated by so called **colour reconnection**.

- **Colour reconnection** – the least understood component of MPI models

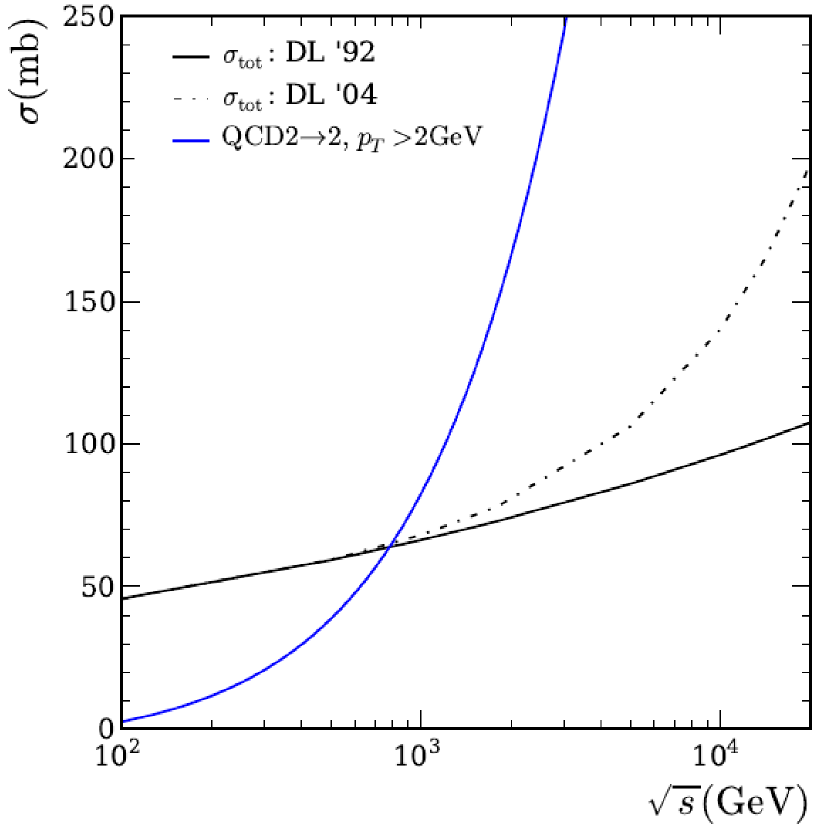


required by data



Inclusive hard jet cross section in pQCD:

$$\sigma^{\mathrm{inc}}(s, p_t^{\mathrm{min}}) = \sum_{i,j} \int_{p_t^{\mathrm{min}\,2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2)\, f_j(x_2, Q^2) \; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$



$\sigma^{\mathrm{inc}} > \sigma_{\mathrm{tot}}$ eventually

Interpretation:

- σ^{inc} counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\mathrm{inc}} = \langle n_{\mathrm{dijets}} \rangle \sigma_{\mathrm{inel}}$$

MPI Eikonal model basics – Overlap function

Assumptions:

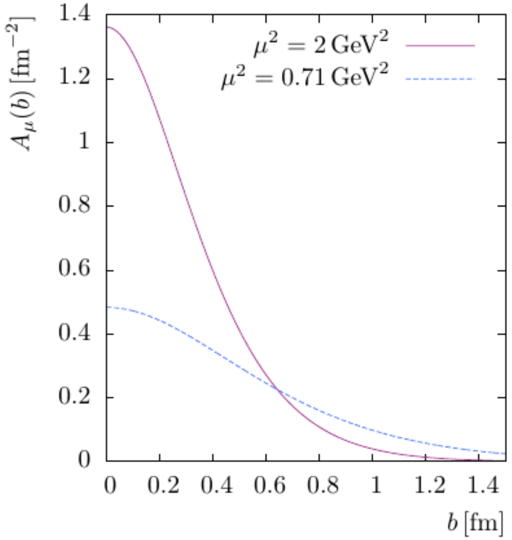
- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$
\begin{aligned}
\bar{n}(\vec{b},s) &= L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|) \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\min}) \; .
\end{aligned}
$$

- at fixed impact parameter b, individual scatterings are independent (leads to the Poisson distribution)

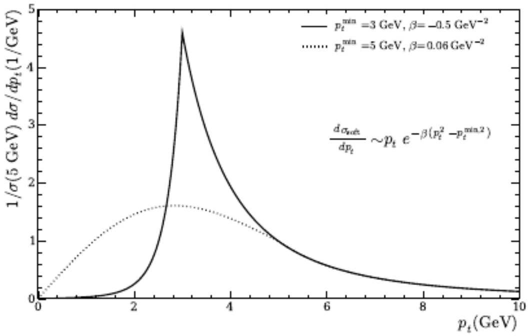
MPI model in Herwig 7 – key components

Matter distribution (μ^2)



Based on electromagnetic form factor (radius of the proton free parameter)

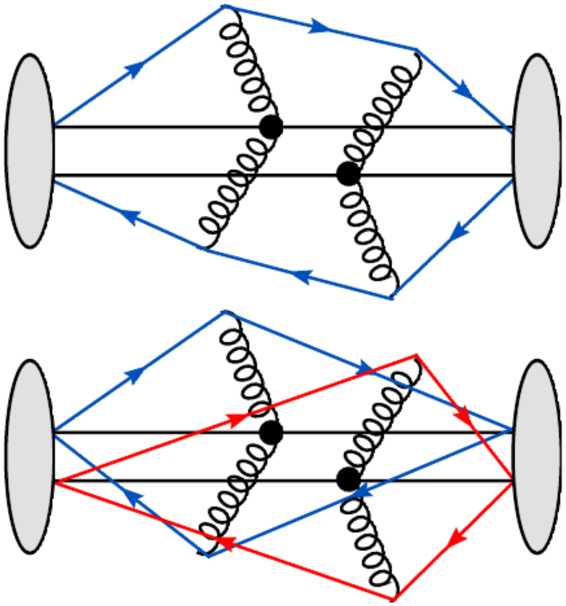
Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

Energy dependent $p_t^{\min}$

Colour structure



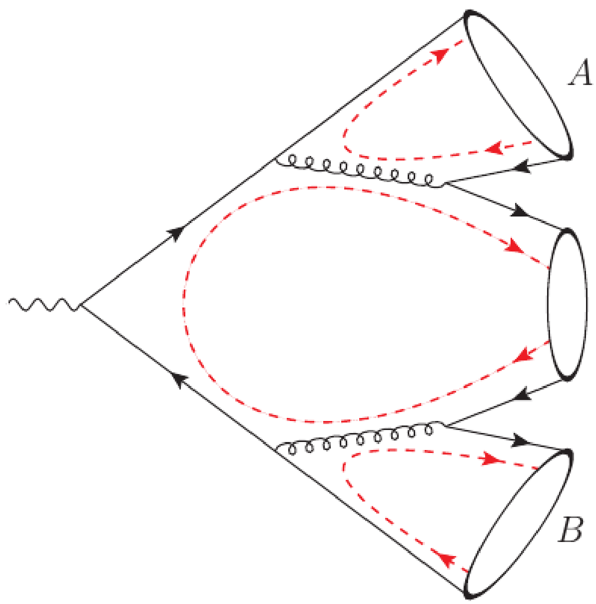
Possibility of change of color structure (color reconnection)

Main parameters:

- μ^2 - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components $\Rightarrow p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- p_{reco} - colour reconnection

Simplest Colour reconnection in Herwig

Cluster hadronization [Webber, Nucl. Phys. B238 (1984) 492]



- perturbative QCD provides *preconfinement* [Amati, Veneziano, Phys. Lett. B83 (1979) 87]
- colour-singlet pairs end up close in phase space and form highly excited hadronic states, the *clusters*

Simplest Colour reconnection in Herwig

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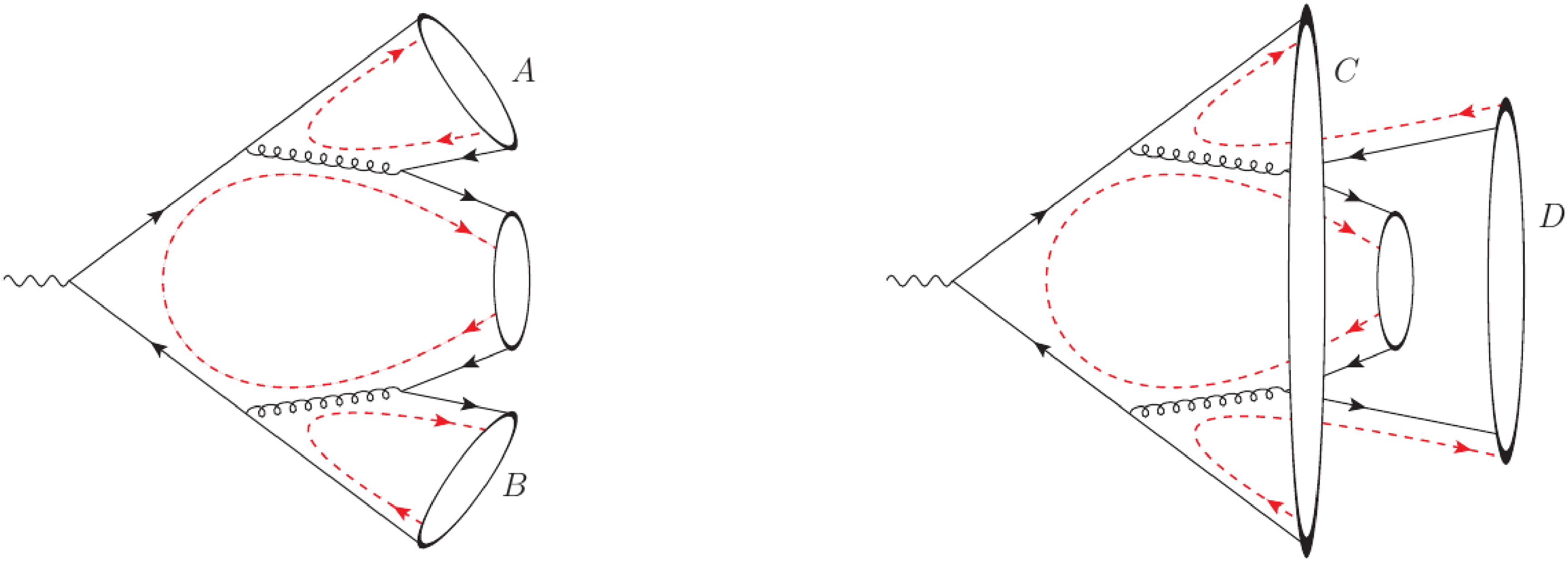
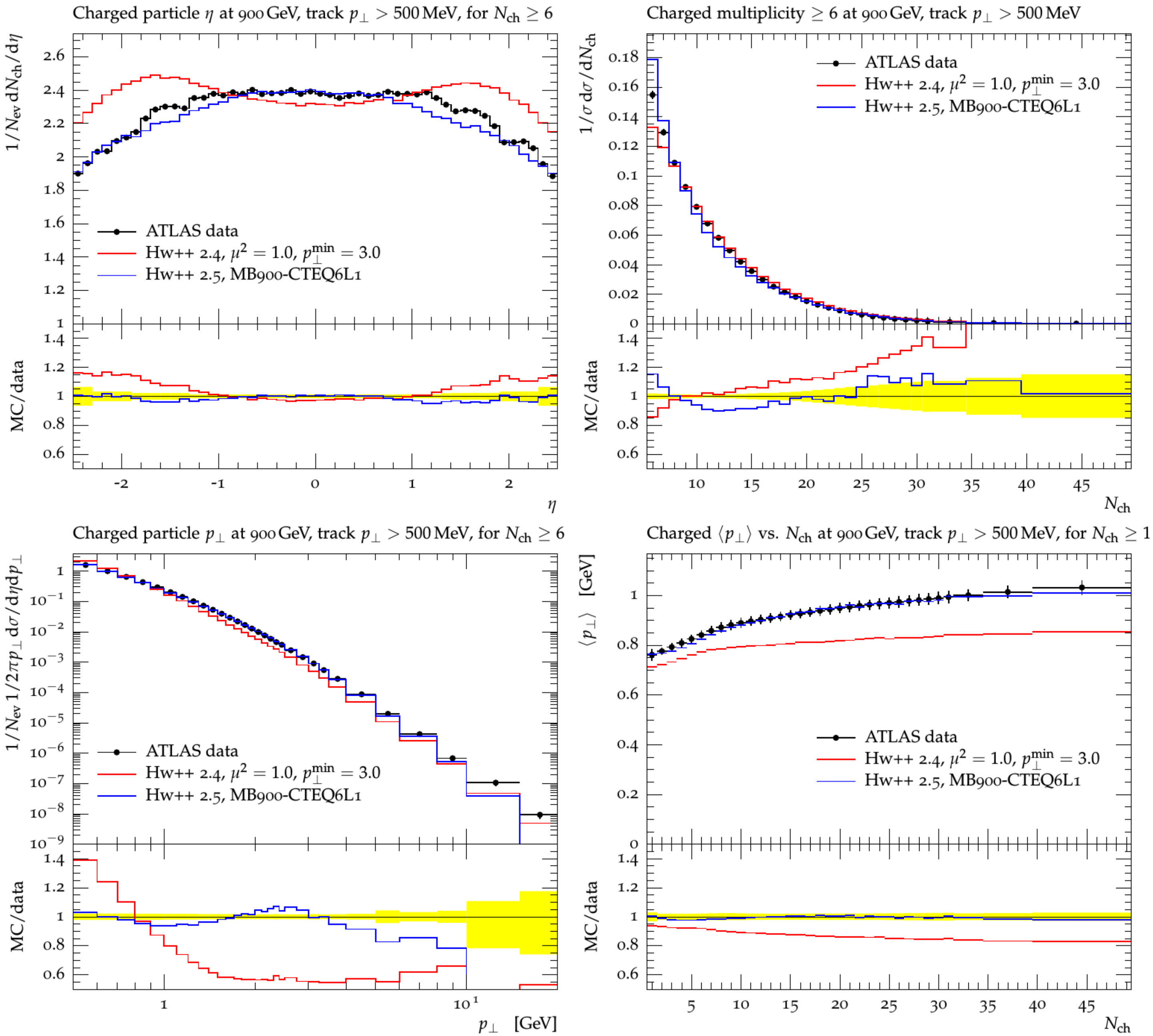
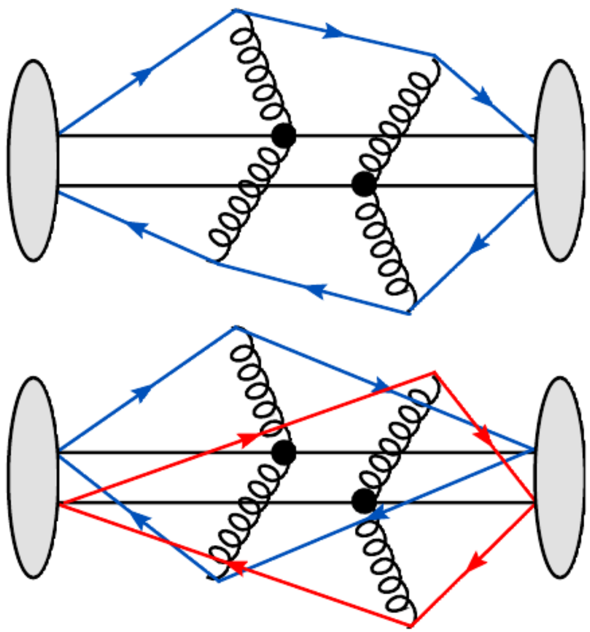


- perturbative QCD provides *preconfinement* [Amati, Veneziano, Phys. Lett. B83 (1979) 87]
- colour-singlet pairs end up close in phase space and form highly excited hadronic states, the *clusters*
- improved description of soft events/UE at hadron colliders: manually reduce cluster masses
- if $M_C + M_D < M_A + M_B$ accept alternative clustering with probability p_{reco} (model parameter)

[Gieseke, Rohr,AS, EPJC 72, 2012]

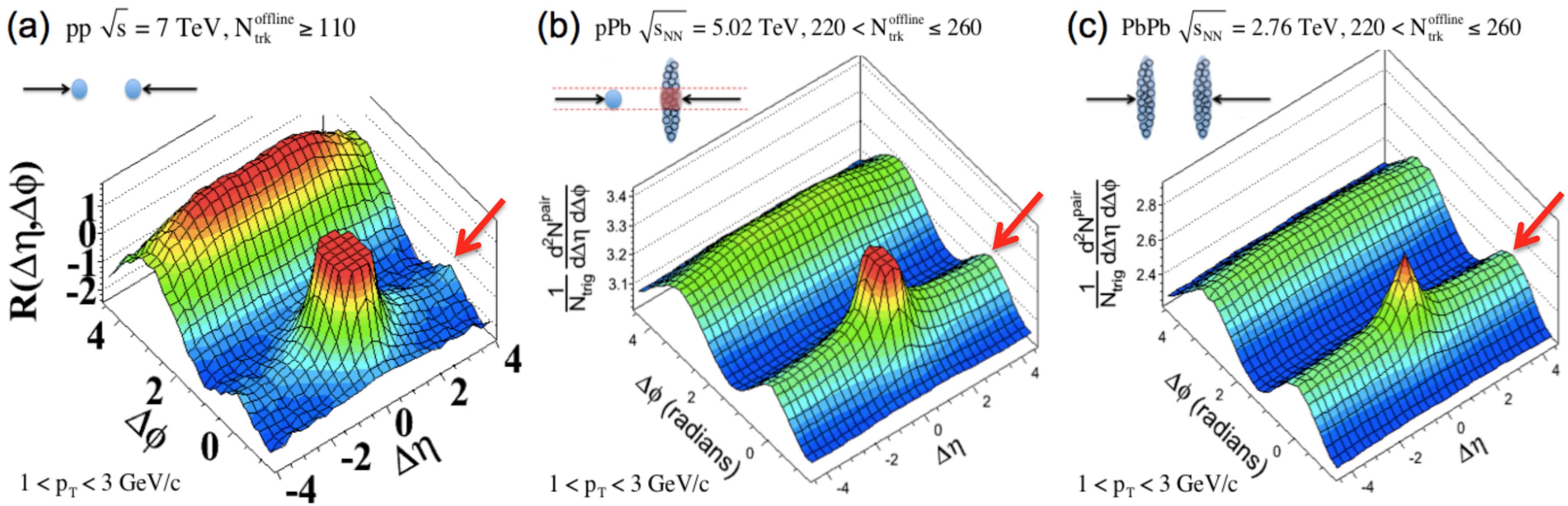
Colour Reconnection fitting to LHC data





Still many open questions

- Hadronization of very dense systems shows unexpected correlations

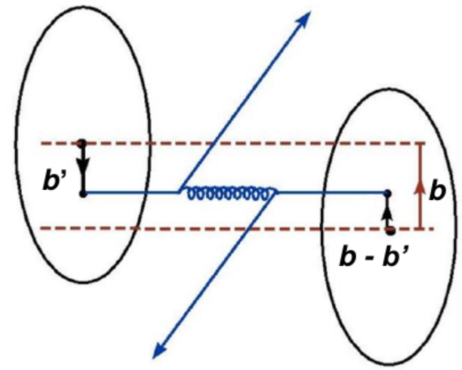


- Can we improve the colour reconnection in Herwig by including space-time information?

Space-time Coordinate of MPI - the impact parameter b

The average number of interactions

$$\bar{n}(b,s) = A(b)\sigma^{inc}(s;p_t^{\min}) = 2\chi(b,s)$$



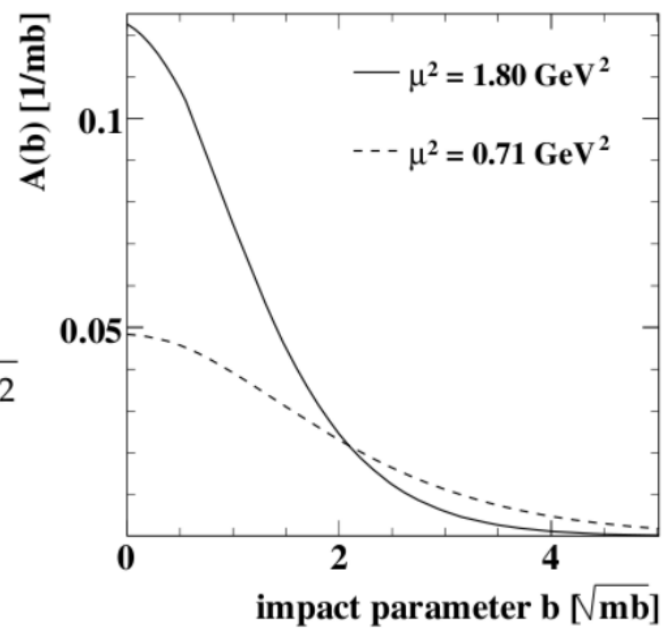
$A(b)$ is the partonic overlap function of the colliding hadrons

$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b}-\vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

But μ^2 *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.
Free for colour charges.



Extension to soft MPI:

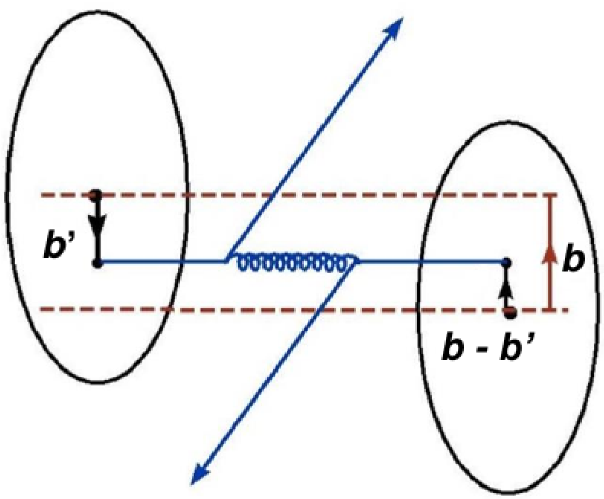
$$\chi_{\mathrm{tot}}(\vec{b},s) = \frac{1}{2}\left(A(\vec{b};\mu_{\mathrm{hard}})\sigma^{\mathrm{inc}}(s;p_t^{\min}) + A(\vec{b};\mu_{\mathrm{soft}})\sigma^{\mathrm{inc}}_{\mathrm{soft}}\right) = \chi_h + \chi_k$$

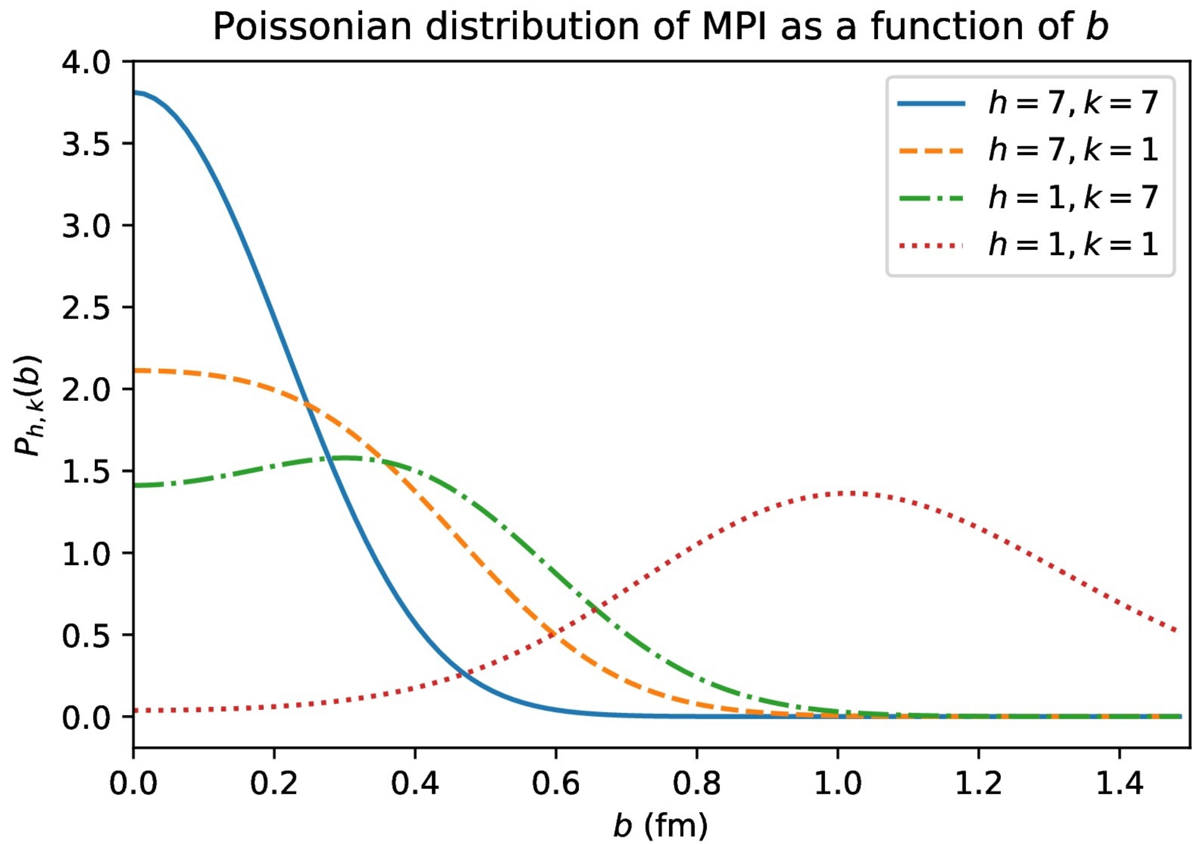
Space-time Coordinate of MPI

Main assumptions of eikonal MPI model:

- Independent scatter at fix **b**

$$\mathcal{P}_{h,k}(b) = \frac{(2\chi_h)^h}{h!}\frac{(2\chi_k)^k}{k!}e^{-2(\chi_h+\chi_k)}$$





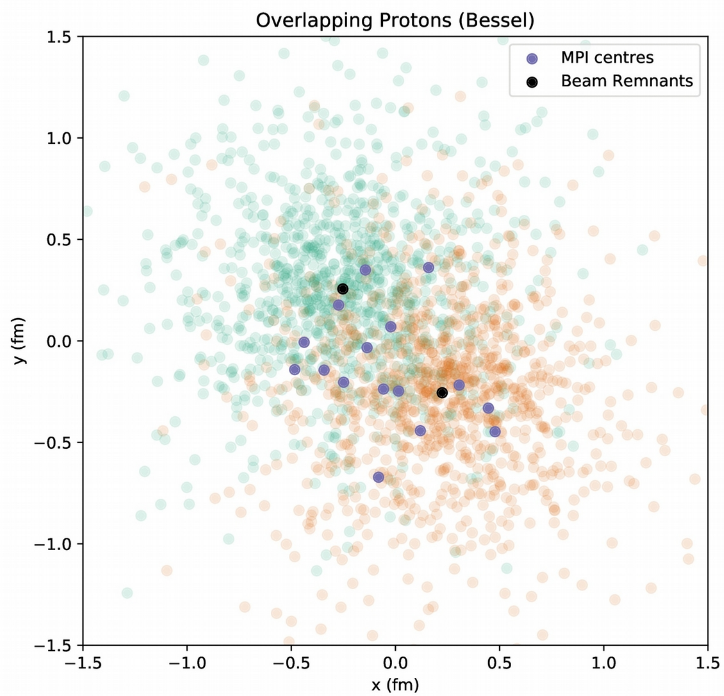
- The more interactions that occur, the more likely the collision is to be central.
- Keeping the number of interactions fixed (h) but having more soft interactions (k) makes the distribution have a broader tail.

Space-time Coordinate of MPI centres

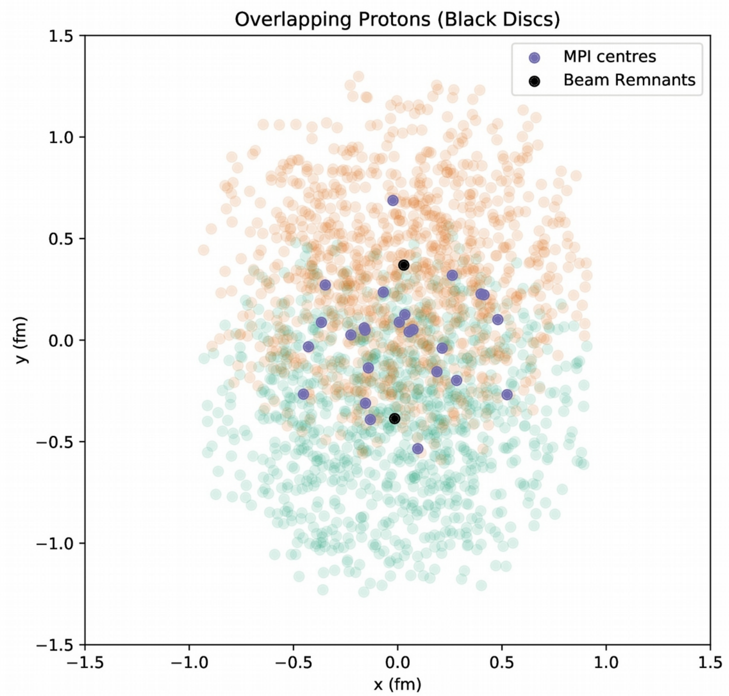
- After b is determined the overlap function governs the density of MPI scattering centres in the transverse plane.

$$A(b) = \int \mathrm{d}^2 b' G(b') G(b - b')$$

Electromagnetic Form Factor

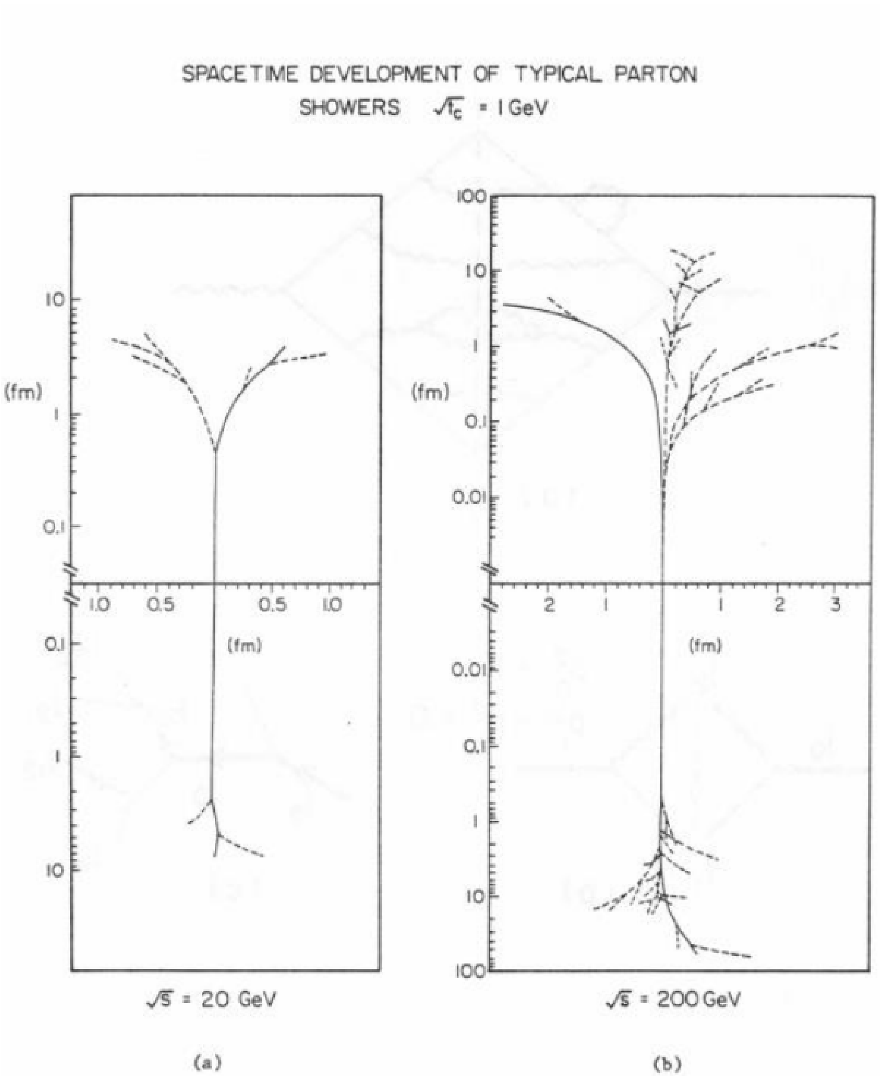


Black Disk



- Soft and hard interactions have different A(b) hard scatters are slightly more concentrated in the centre, while soft scatters have a longer tail.
- The beam remnants receive the proton positions.
- Once these points have been generated, all coordinates get the same random global rotation in the transverse plane.

Space-time Coordinate of Parton Shower in Herwig 7



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

Herwig 7

- FortranHerwig-like algorithm

G. Corcella et al., JHEP 0101 (2001) 010, chapter 3.8

- The mean lifetime τ of a parton in its own rest frame (similar as for particles decays)

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

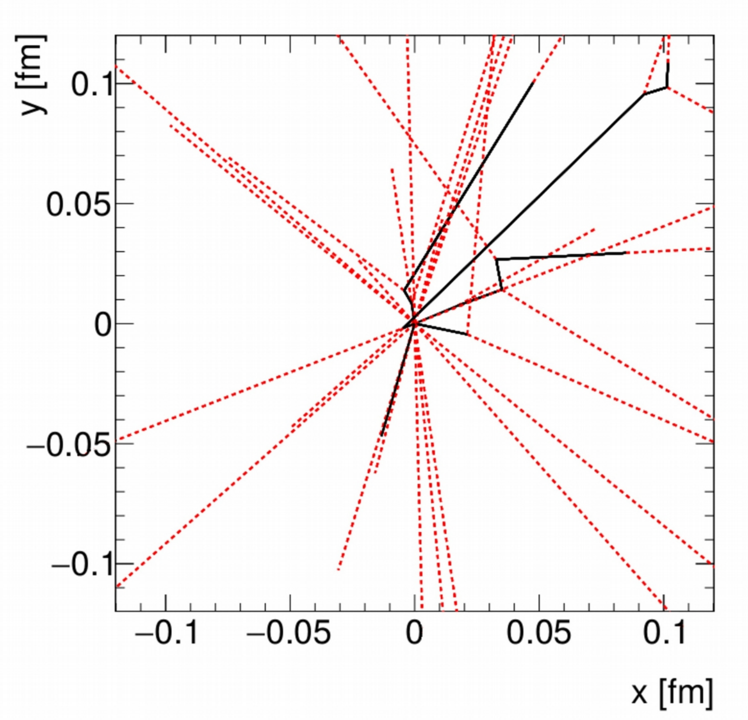
- rest-frame decay time t*

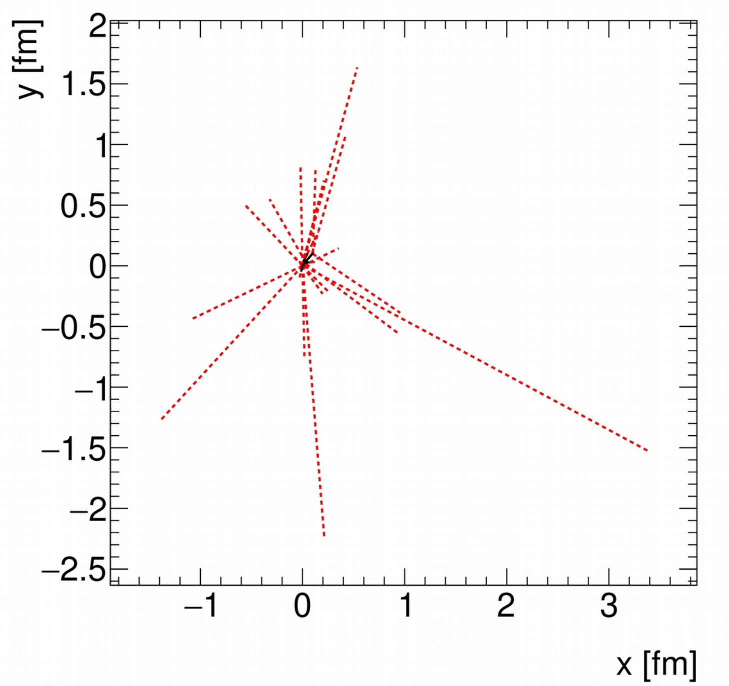
$$P_{\rm decay} = 1 - \exp\left(-\frac{t^*}{\tau}\right).$$

- Distance travelled in the lab-frame

$$t = \gamma t^*, \vec{d} = \vec{\beta}\gamma t^*$$

Space-time Coordinate of Parton Shower





- Fermi-scale parton shower effects
- Most distance traveled by the last step of the parton shower evolution (red lines)
- We will only give coordinates to the partons that remain at the end of the shower
- To avoid unphysically large distances traveled by partons with very small virtualities we introduce a minimum virtuality ν^2 (free parameter of the model), so the mean lifetime:

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

- We do not consider z, t directions

Spacetime Colour Reconnection

- With the transverse coordinates in place, we use this information to perform and inform CR
- We introduce a boost-invariant distance measure:

$$R_{ij}^2 = \frac{\Delta r_{ij}^2}{d_0^2} + \Delta y_{ij}^2, \text{where } \Delta r_{ij}^2 = (\vec{x}_{\perp,i} - \vec{x}_{\perp,j})^2$$

d_0 is the characteristic length scale for CR, a tunable parameter

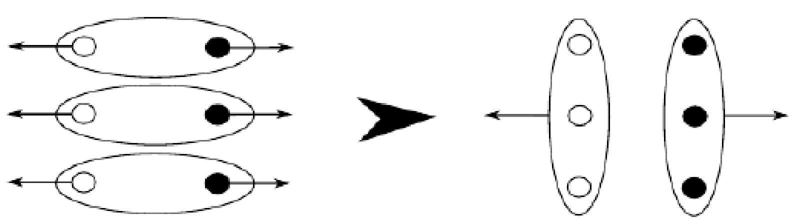
- This is inspired by conventional jet algorithms, where we replace the azimuthal separation with transverse separation.
- We use similar strategy as in the simple plain CR base on the cluster mass measure.
- If the sum of the cluster separations is smaller after a possible reconnection:

$$R_{q'} + R_{q'} < R_q + R_{q''}$$

then we accept the reconnection with a probability p_{reco}

- Baryonic spacetime colour reconnection uses the algorithm from

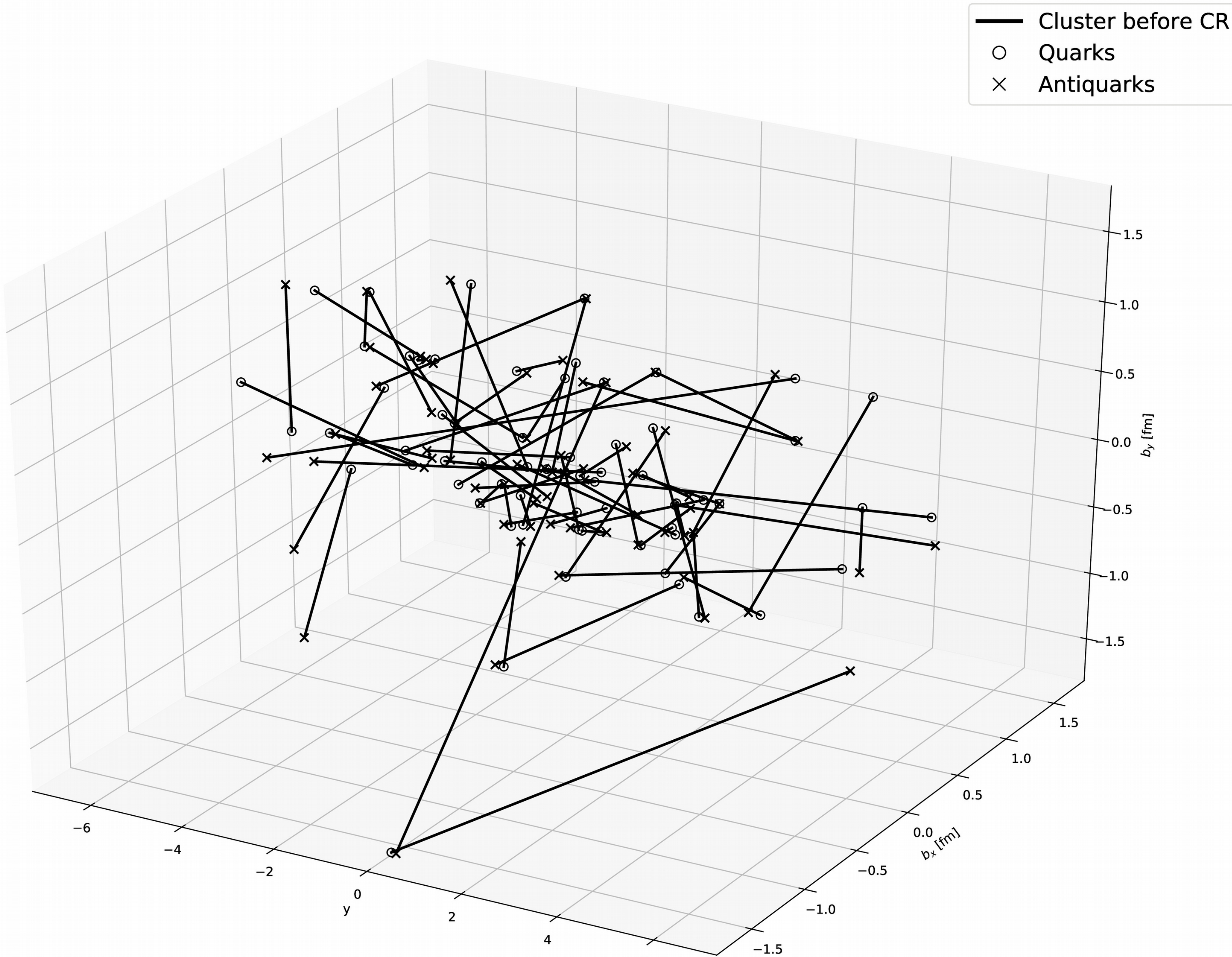
[S. Gieseke, P. Kirchgaeßer, S. Plätzer Eur.Phys.J. C78 (2018)]



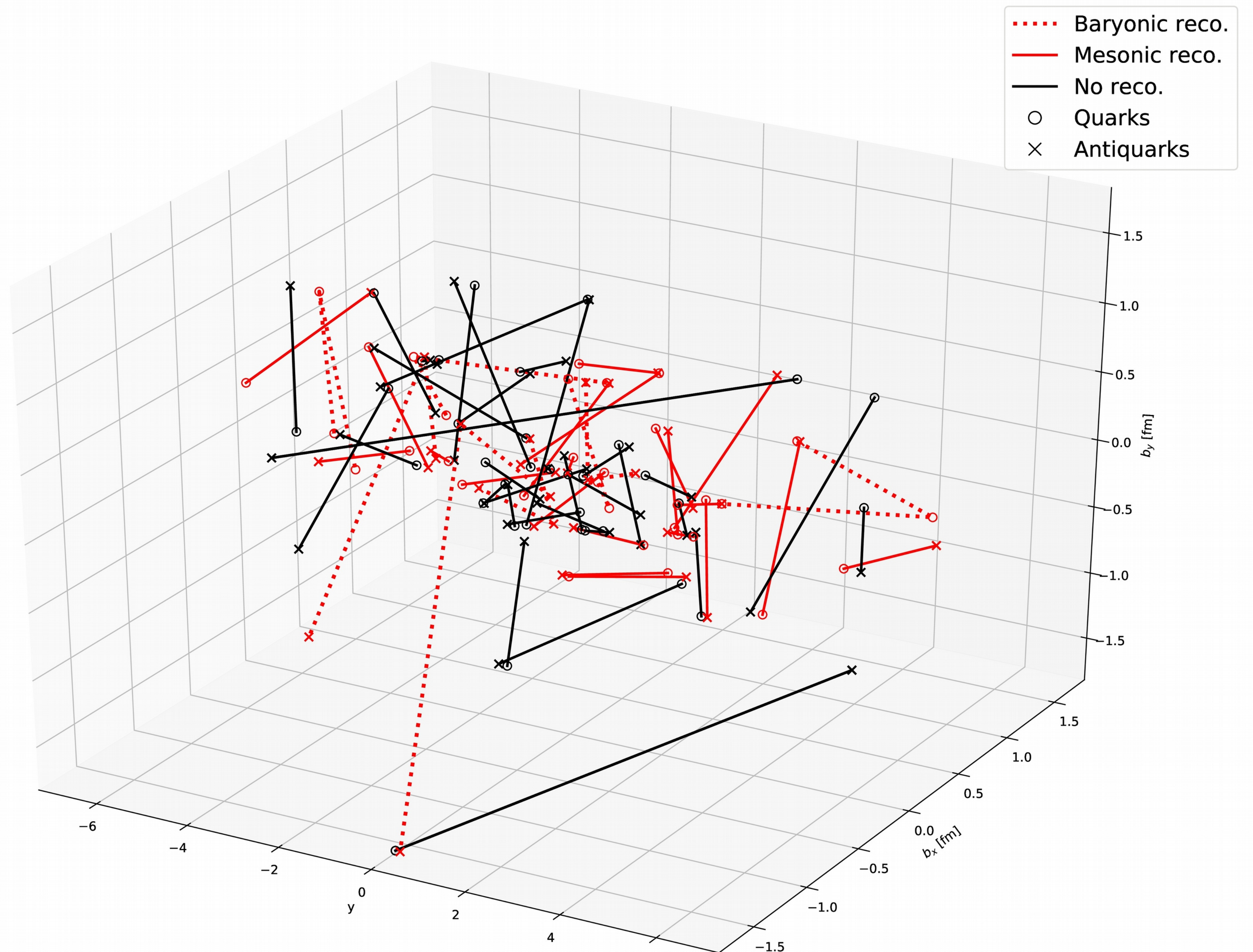
$$R_{q,qq} + R_{\bar{q},\bar{q}\bar{q}} < R_{q,\bar{q}} + R_{qq,\bar{q}\bar{q}}$$

[See Stefan's talk for more models and details]

Spacetime Colour Reconnection – Numerical results



Spacetime Colour Reconnection – Numerical results



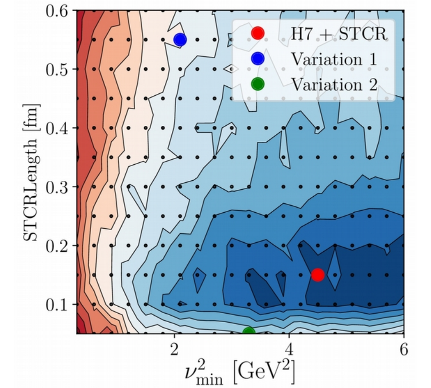
Good agreement with Minimum Bias data

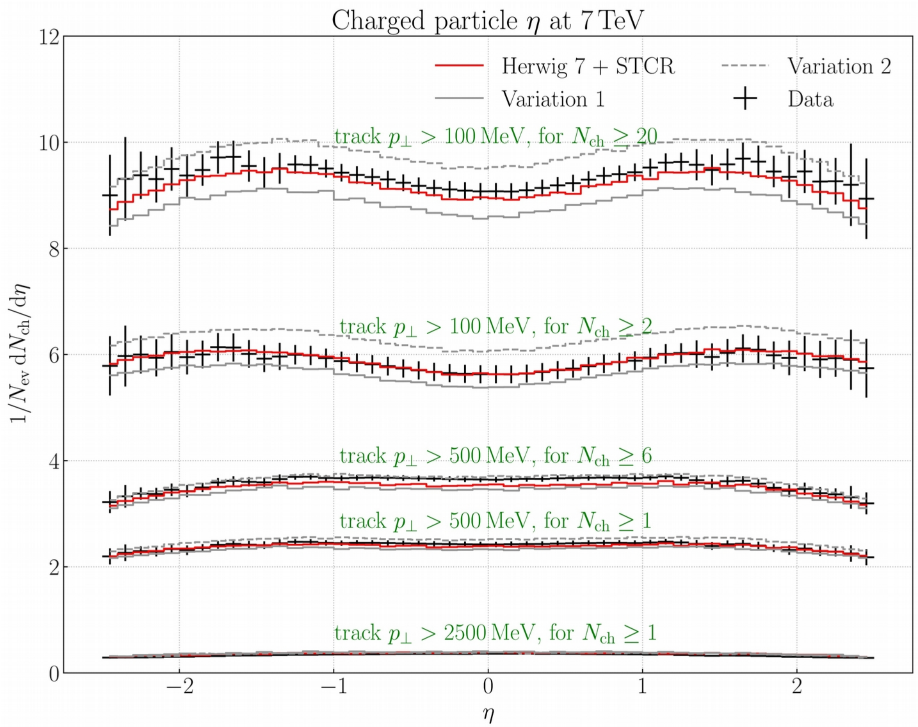
Tuning using autotunes [J. Bellm and L. Gellersen arXiv:1908.10811]

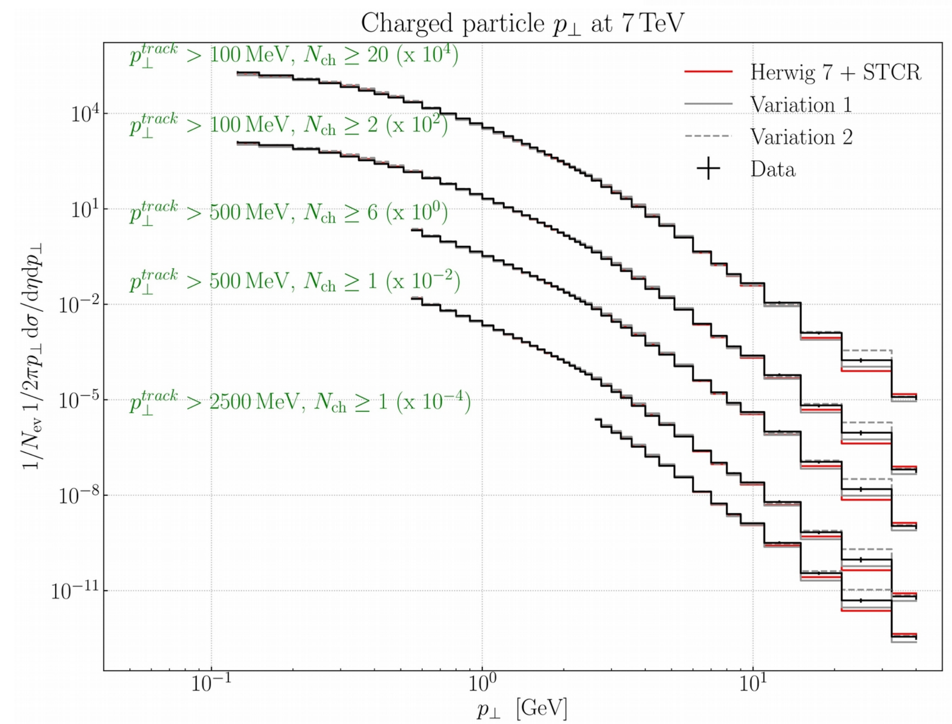
Best tune: $\nu^2 = 4.5\ \mathrm{GeV}^2,\ d_0 = 0.15\ \mathrm{fm}$

Variation 1: $\nu^2 = 3.3\ \mathrm{GeV}^2,\ d_0 = 0.05\ \mathrm{fm}$

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







Good agreement with Underlaying Event data

Tuning using autotunes [J. Bellm and L. Gellersen arXiv:1908.10811]

Best tune: $\nu^2 = 4.5\ \mathrm{GeV}^2,\ d_0 = 0.15\ \mathrm{fm}$

Variation 1: $\nu^2 = 3.3\ \mathrm{GeV}^2,\ d_0 = 0.05\ \mathrm{fm}$

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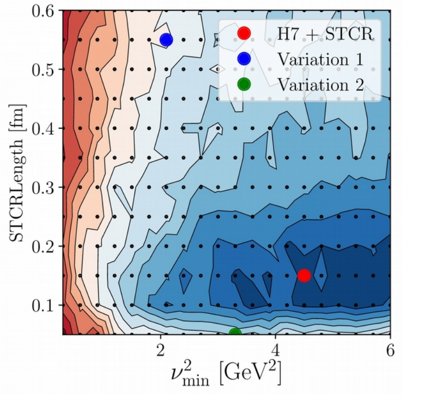

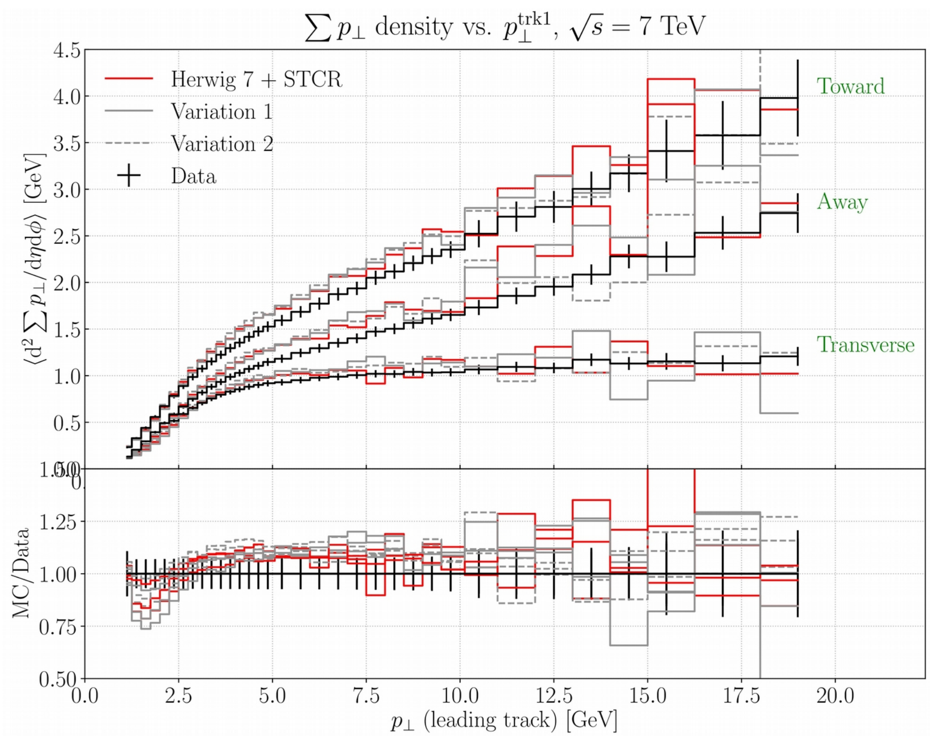

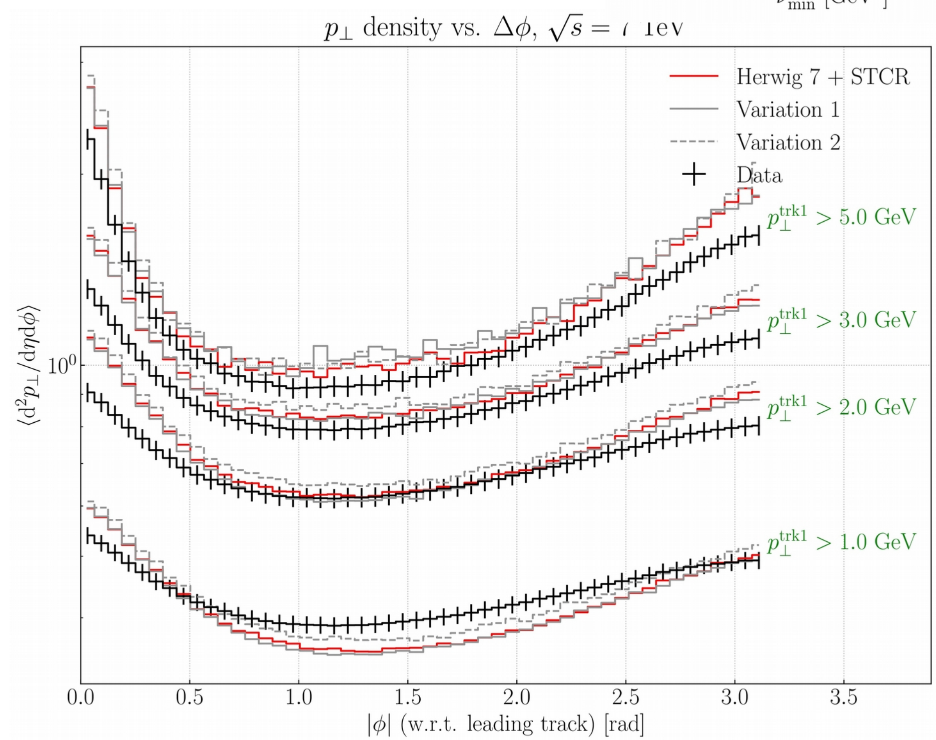

Summary and Outlook

- We present a model for generating spacetime coordinates in the Monte Carlo Herwig 7
- Then we introduced a colour reconnection model by minimizing a boost-invariant distance measure of the system.
- We compare the model to a series of soft physics observables. We find reasonable agreement with the data.
- This suggests that pp-collider colour reconnection may be able to be applied in larger systems.

More information about Monte Carlo Event Generators

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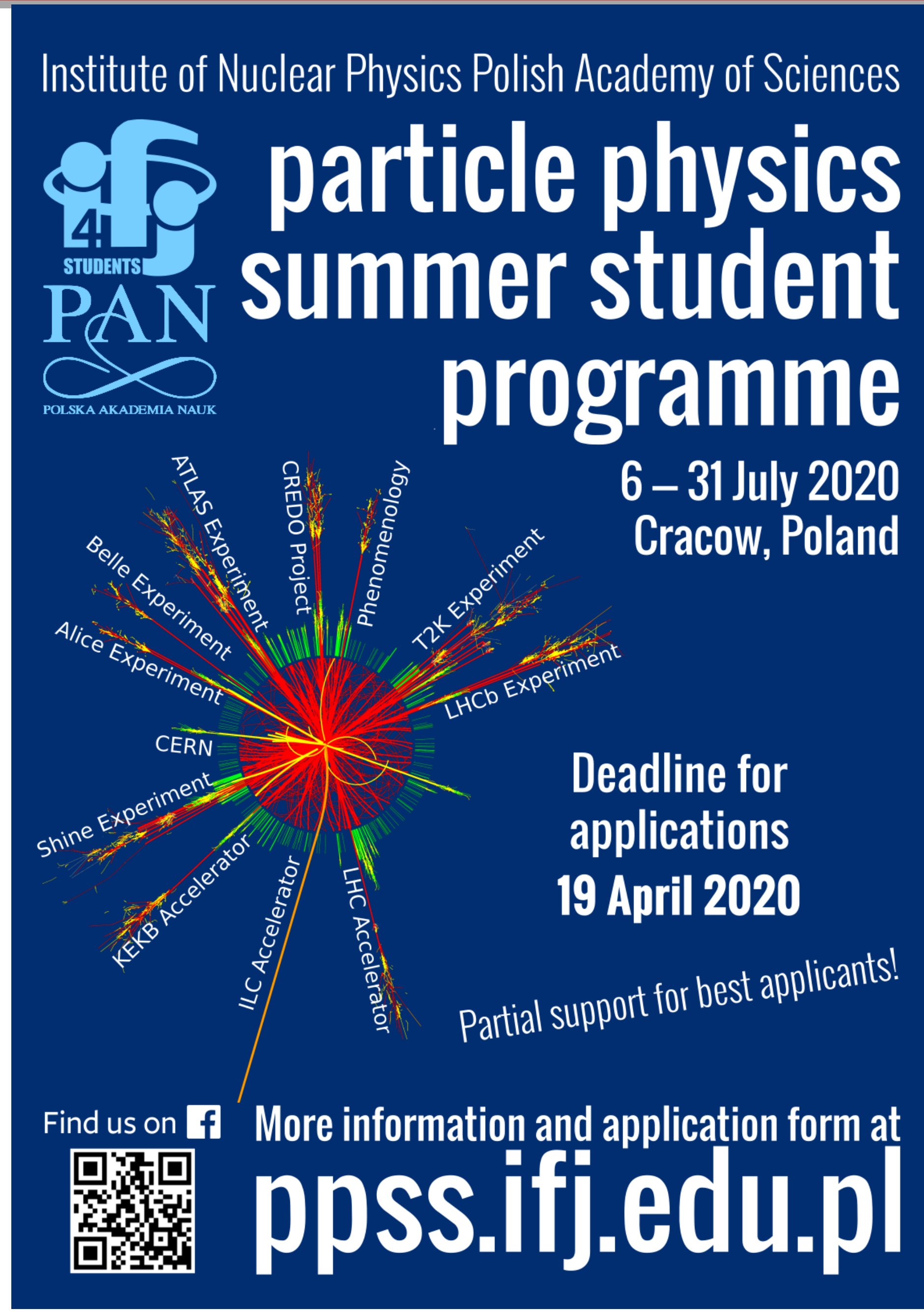
+Contur+hepforge+…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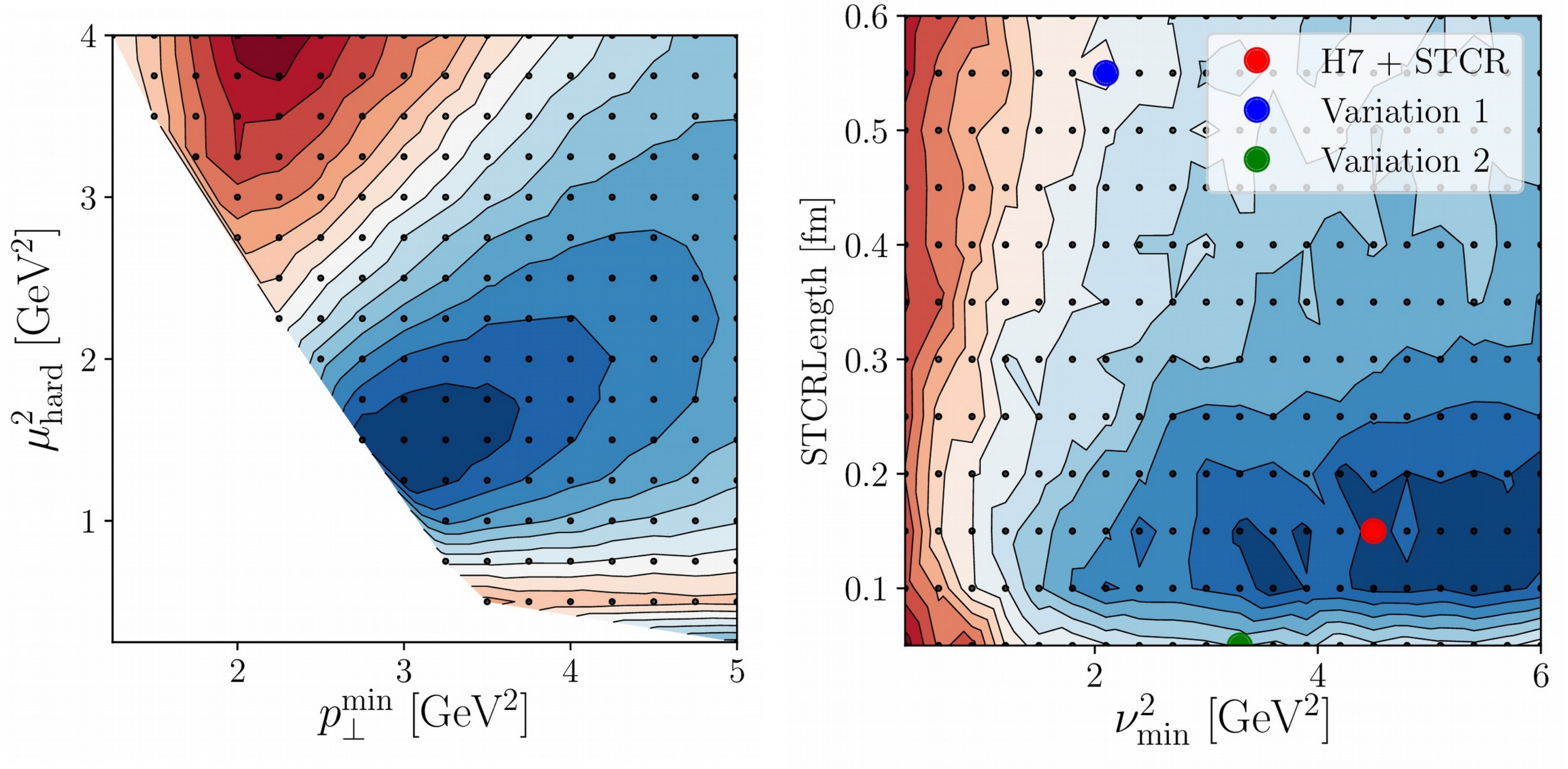
Thank you for your attention!

Tune



$\sigma_{\rm tot}$ [mb]	$R_{\rm Diff}$	$p_\perp^{\rm min}$ [GeV]	$\mu^2_{\rm hard}$ [GeV^2]
96.0	0.2	3.0	1.5

ν^2 [GeV^2]	d_0 [fm]	w_b	($\mu^2_{\rm soft}$ [GeV^2])
4.5	0.15	0.98	0.254