Space-time model for colour reconnection

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in collaboration with
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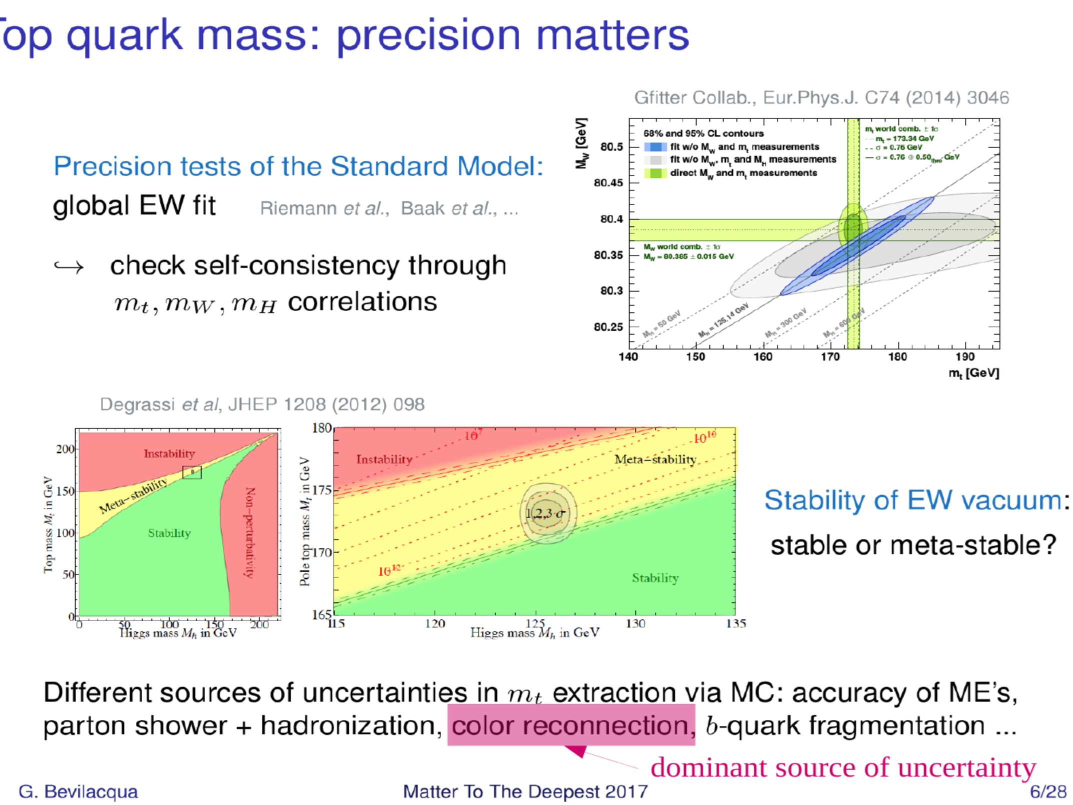
Outline

1. Introduction and motivation
2. Basic building blocks of MPI in Herwig
3. MPI and Parton Shower space-time models
4. Preliminary results
5. Summary and outlook

Motivation

- Non perturbative effects like colour reconnection start to be important source of uncertainties in precise LHC measurements (for example top mass).

e.g.
S. Argyropoulos , T. Sjöstrand,
Effects of color reconnection on $t\bar{t}$
final states at the LHC
JHEP 1411 (2014) 043



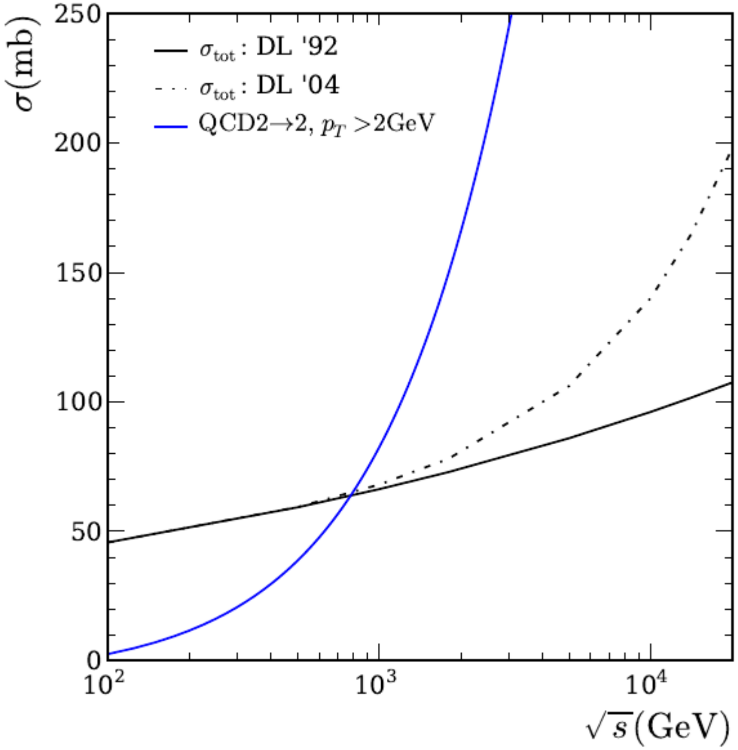
- Our aim is to introduce the space-time picture in Herwig 7

- notice a similar effort in Pythia [S. Ferreres-Solé, T. Sjöstrand, **Eur.Phys.J. C78 (2018) no.11, 983**]

Basic building blocks of MPI in Herwig

Inclusive hard jet cross section in pQCD:

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



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

Interpretation:

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

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

Basic building blocks of MPI in Herwig

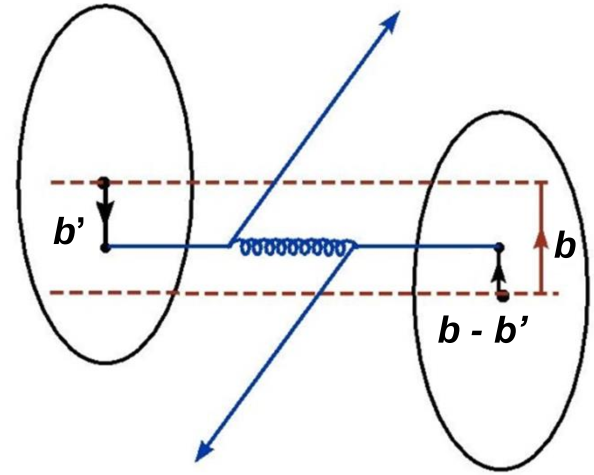
Assumptions:

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

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

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

Basic building blocks of MPI in Herwig



From assumptions:

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

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

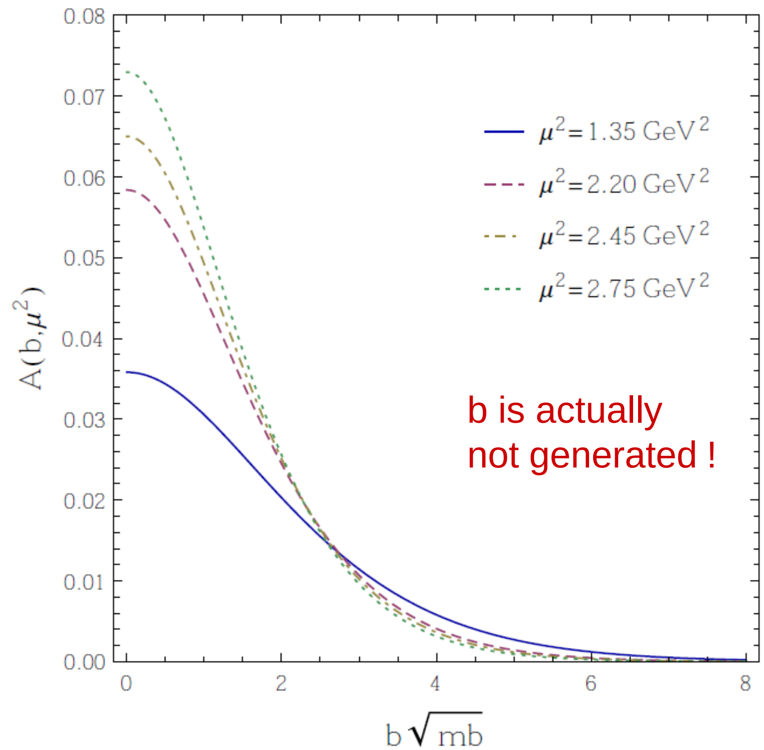
where ***A(b)*** is partonic **overlap function** of the colliding hadrons

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

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

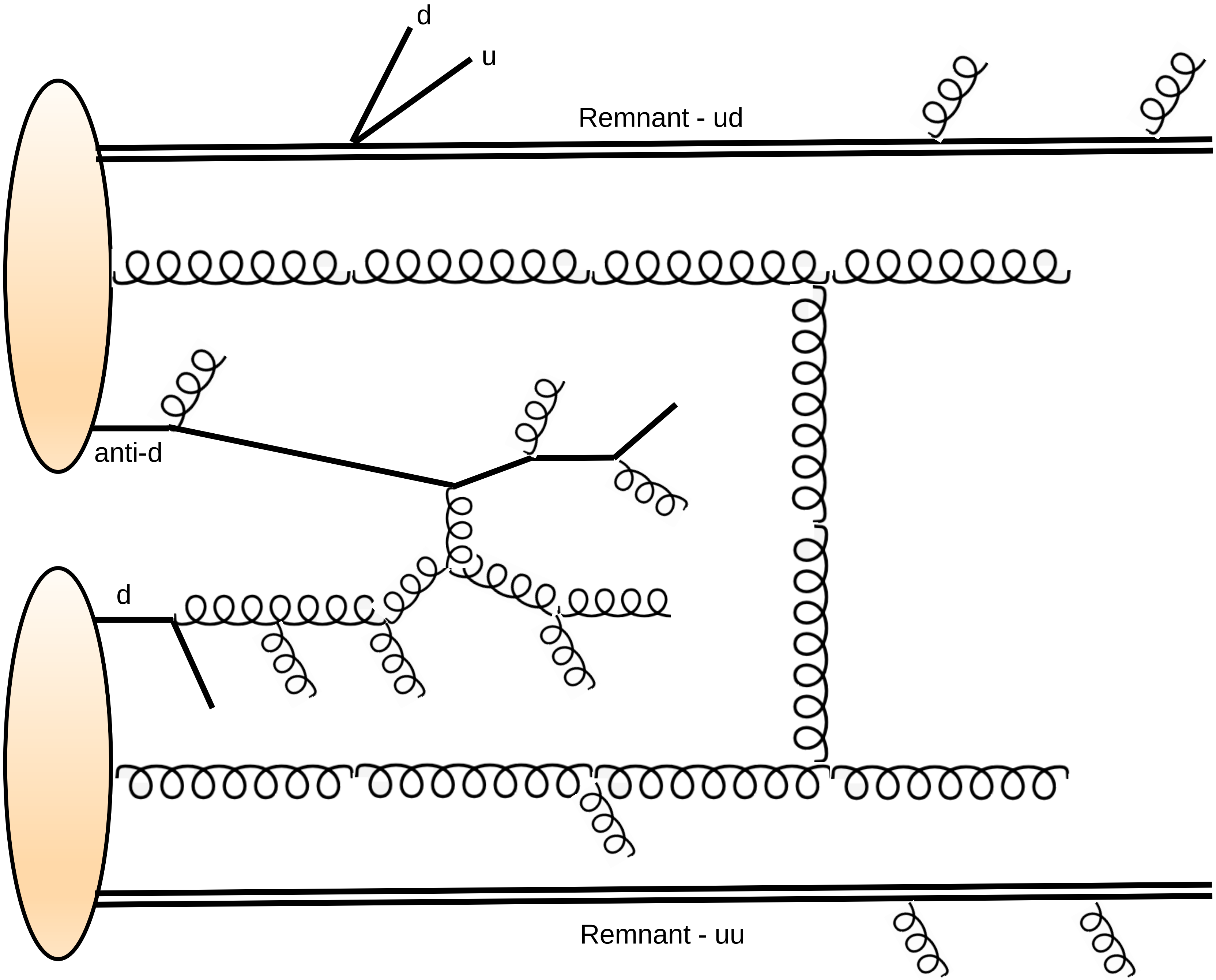
with ***g(b')*** being EM FF

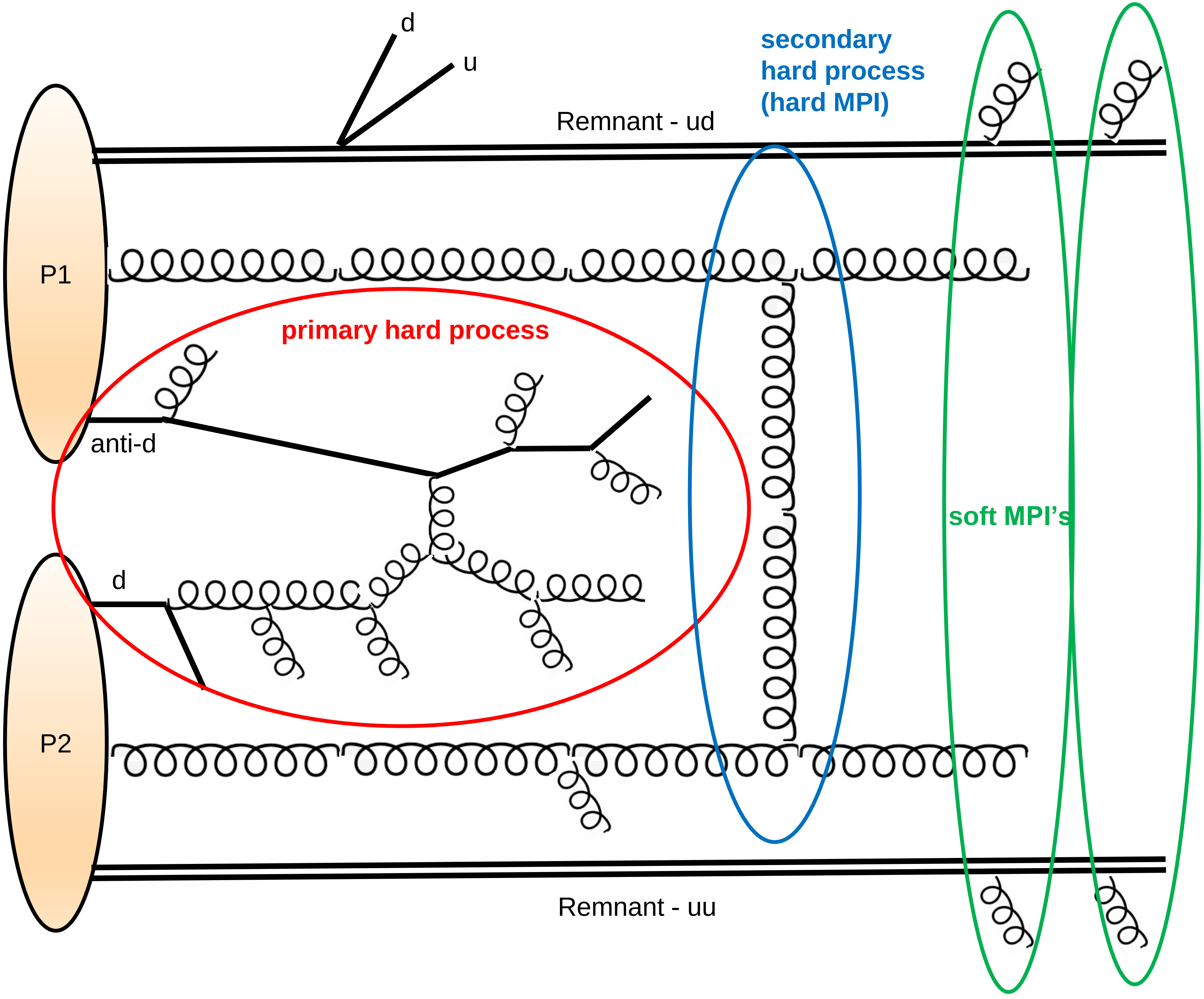
$$g(\vec{b'}) = \frac{1}{(2\pi)^2}\int d^2\vec{k}\frac{e^{i\vec{k}\vec{b'}}}{\left(1+\frac{|\vec{k}|^2}{\mu^2}\right)^2}$$

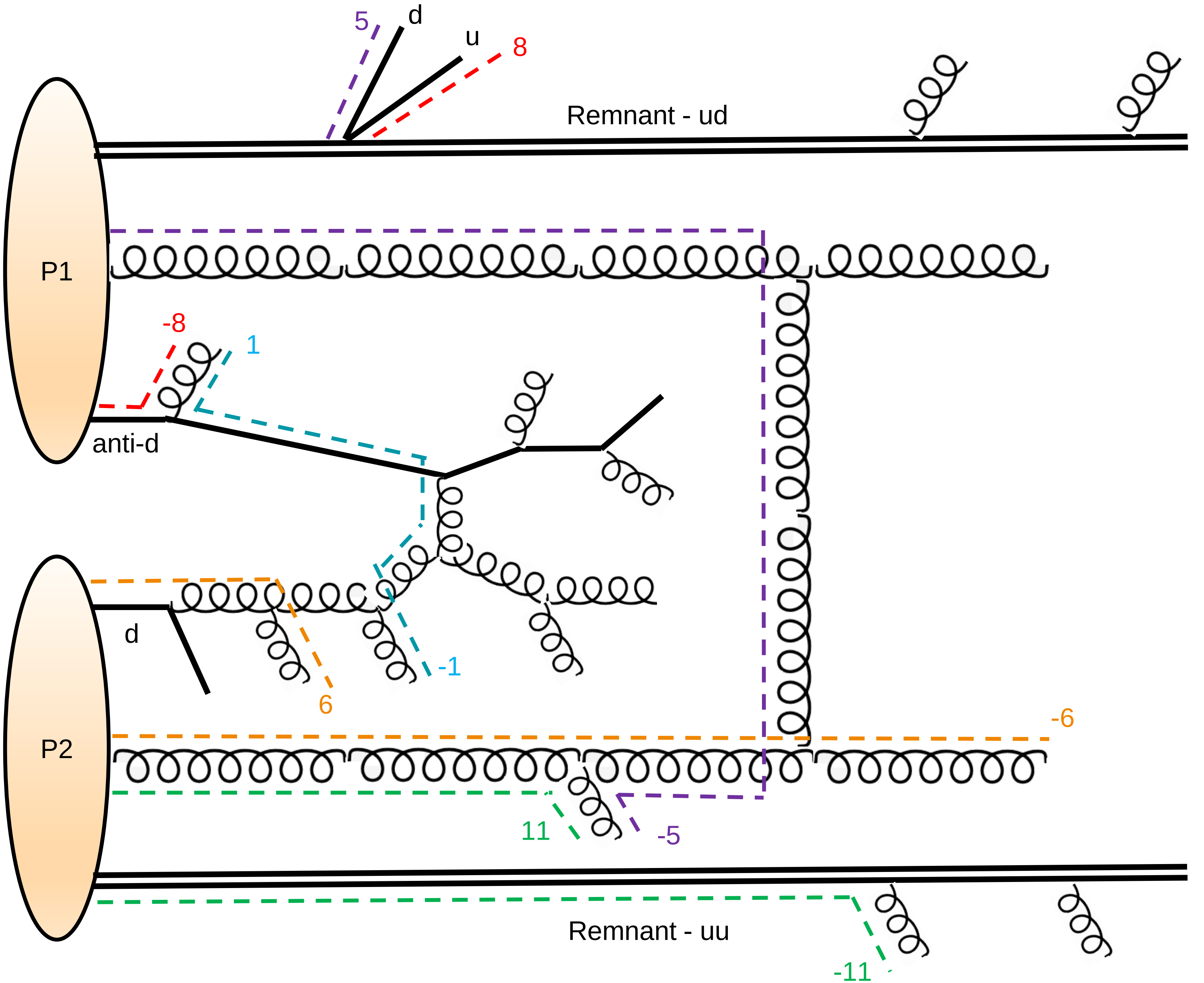


and ***μ*** as a free parameter
(i.e. not fixed at EM value of 0.71 GeV^2)

=> two main parameters ***μ***, p_t^{min}

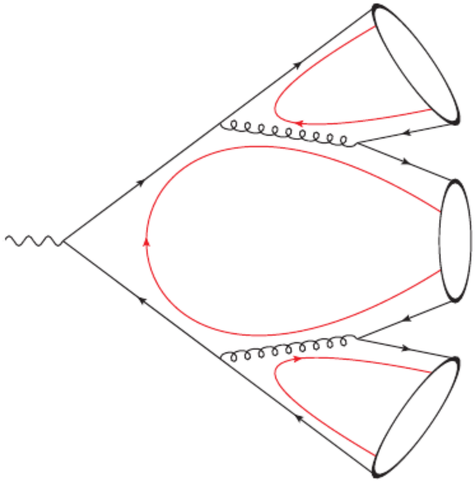

d
u
Remnant - ud
anti-d
d
Remnant - uu


d
u
Remnant - ud
secondary
hard process
(hard MPI)
P1
primary hard process
anti-d
soft MPI's
d
P2
Remnant - uu



5
d
u
8
Remnant - ud
P1
-8
1
anti-d
P2
d
6
-1
-6
11
-5
Remnant - uu
-11

Basic building blocks of MPI in Herwig - Colour connection



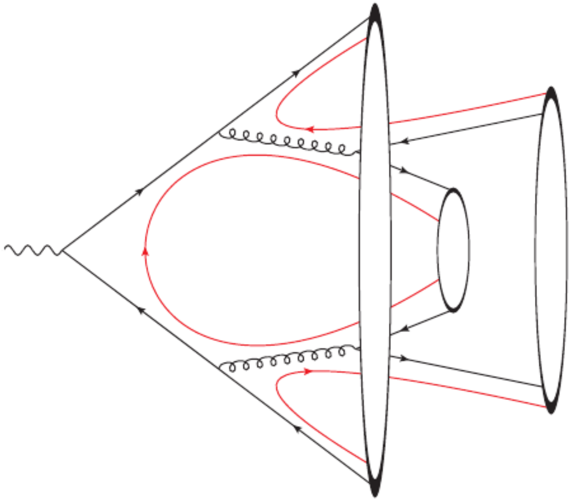
Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement*
  $\Rightarrow$ colour-anticolour pairs form highly excited hadronic states, the *clusters*

Basic building blocks of MPI in Herwig - Plain colour reconnection

More CR ideas in H7 for example: Colour Reconnection from Soft Gluon Evolution, S. Gieseke, P. Kirchgaeßer, S. Plätzer, A. Siodmok, **JHEP 1811 (2018) 149**

→ **see Patrick's talk**



Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

Implementation

- Allow CR if the cluster mass decreases,

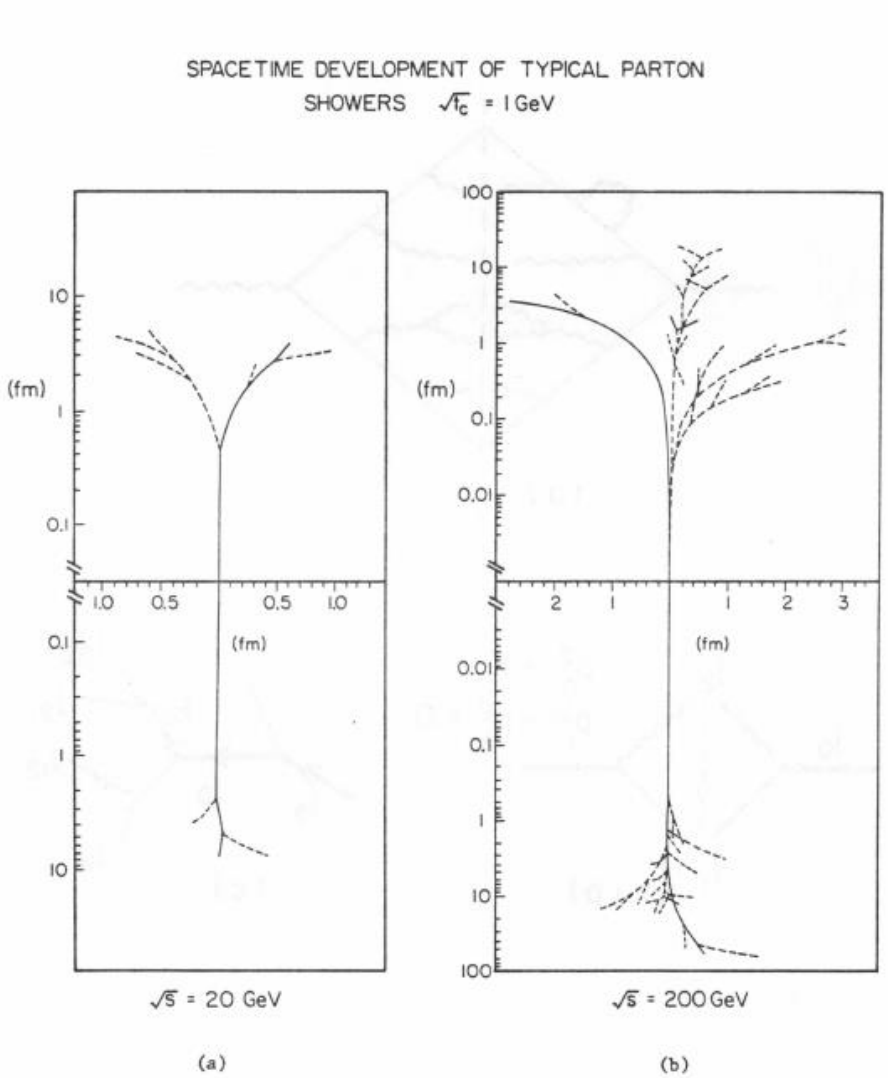
$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

where $M_{ab}^2 = (p_a + p_b)^2$ is the (squared) cluster mass

- Accept alternative clustering with probability p_{reco} (model parameter) ⇒ this allows to switch on CR smoothly

No information about space-time used → potential problems with products of long lived particles

Space-time Model - shower



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

Herwig7:

- fortranHerwig-like algorithm

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

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

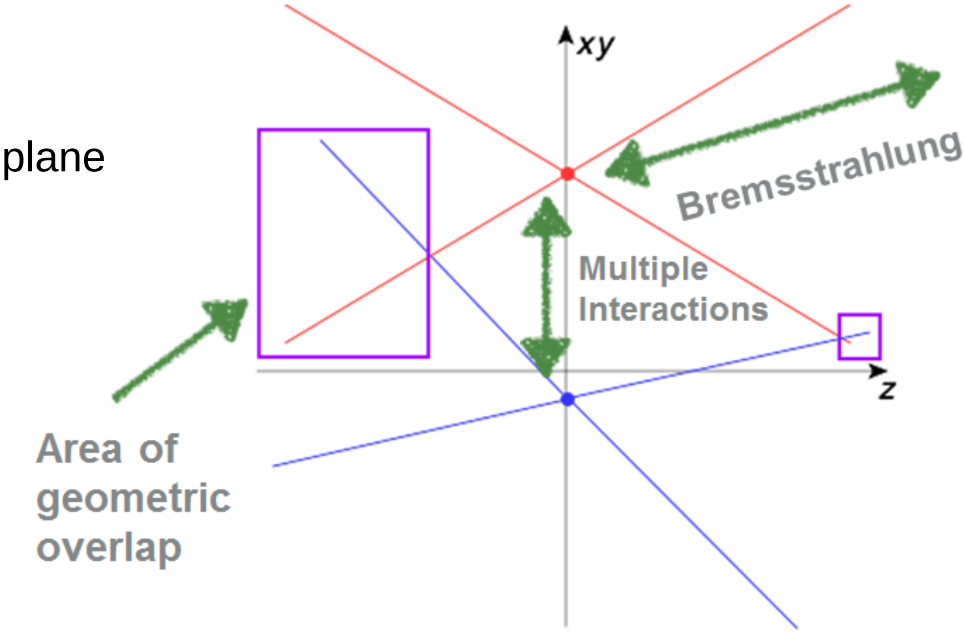
$$\tau(q^2) = \frac{\hbar\sqrt{q^2}}{\sqrt{(q^2 - M^2)^2 + (\Gamma q^2/M)^2}}$$

- **Distance travelled for proper lifetime**

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

Space-time Model - smearing of scatter points in *b* space

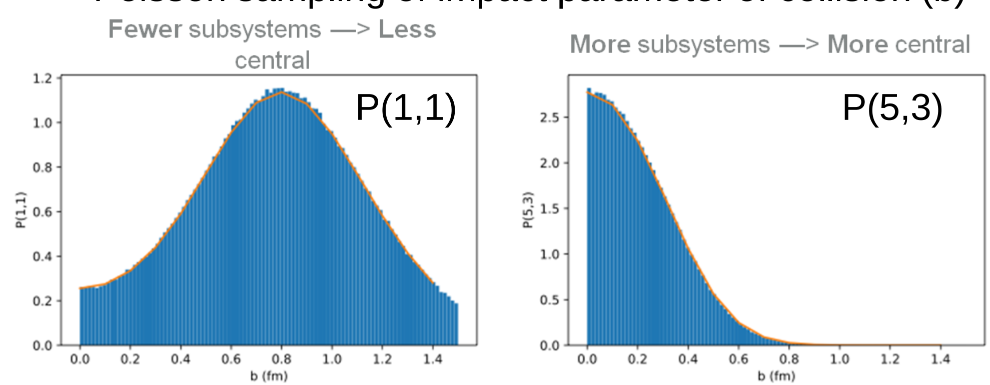
- ➢ Each scatter (MPI) gets its point in xy plane (inspired by heavy ion collision)
- ➢ Shower evolves partons further in xyz
- ➢ Motivation to cluster “close” partons



Issues:

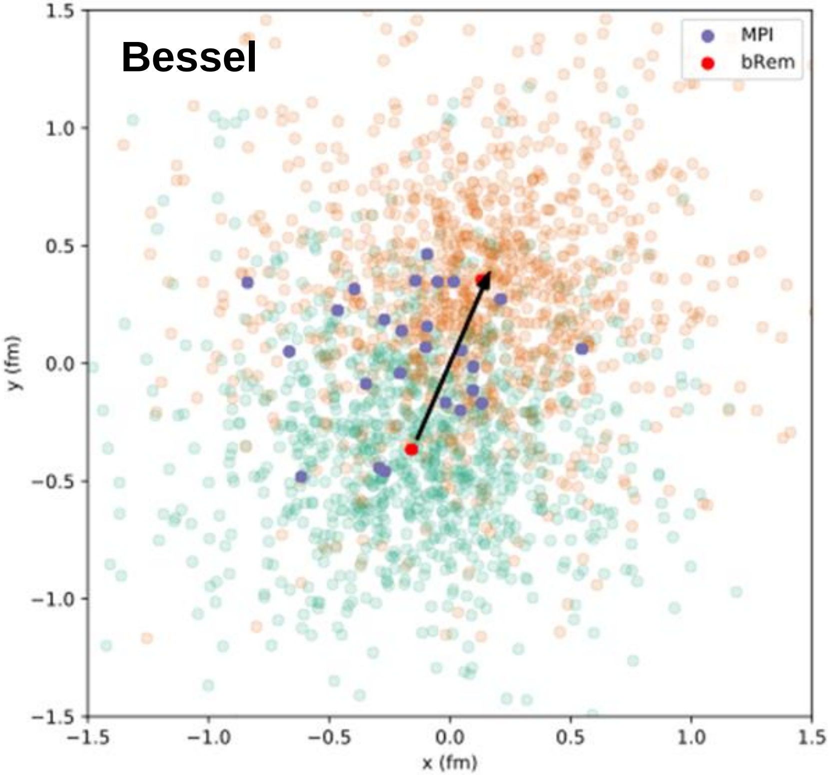
- ➔ Impact parameter
- ➔ Proton profile
  - ◆ Black disk
  - ◆ Gaussian
  - ◆ Overlap function (Bessel)
- ➔ Proton mean radius (r_0)
- ➔ Proton remnants

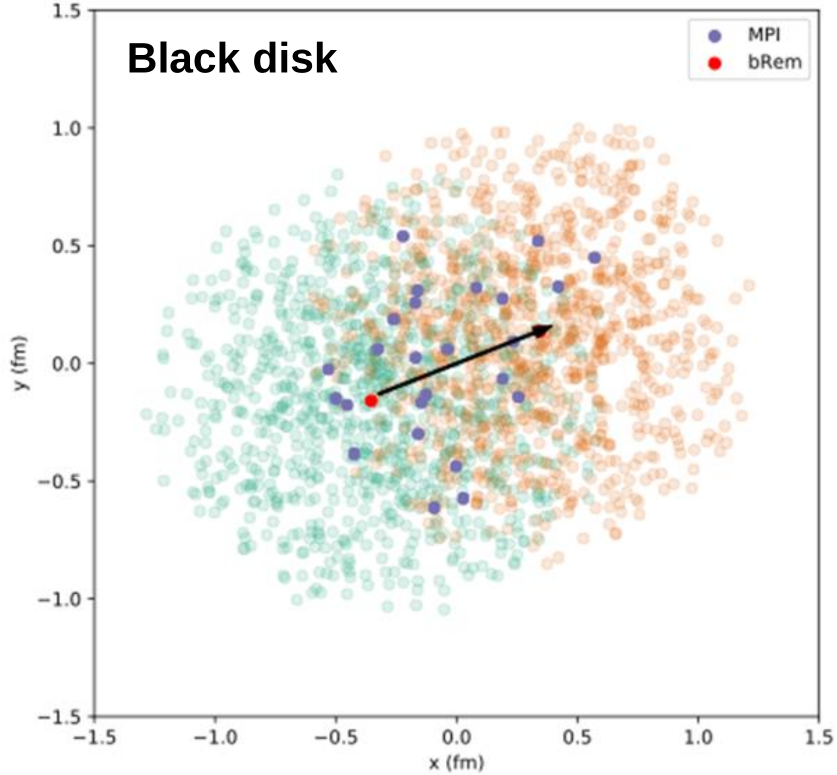
Poisson sampling of impact parameter of collision (b)

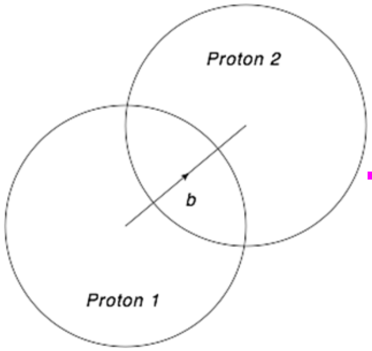


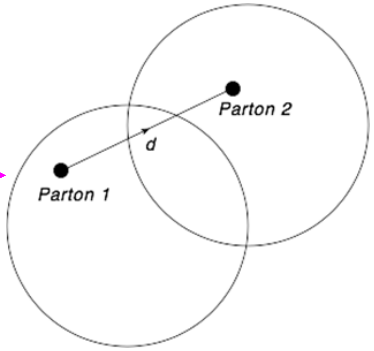
$$\mathcal{P}_{h,k} = \frac{\langle n_h(b)\rangle^h}{h!}\frac{\langle n_k(b)\rangle^k}{k!}\exp[-(\langle n_h(b)\rangle + \langle n_k(b)\rangle)]$$

Space-time Model - smearing of scatter points in *b* space



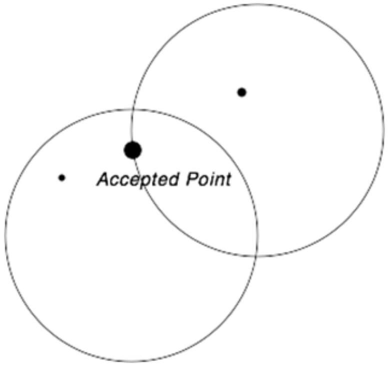






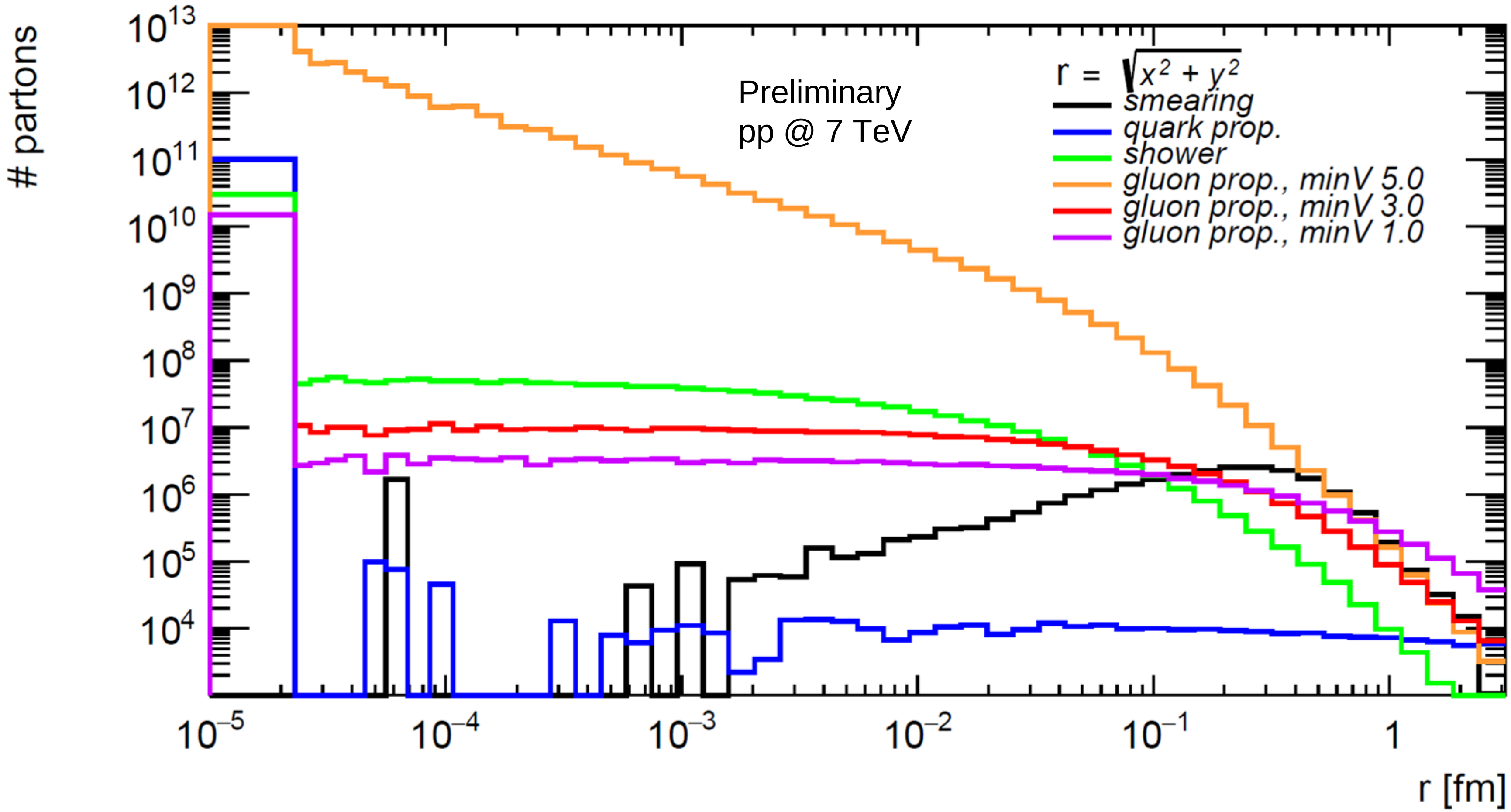
Probability to accept
or reject the points

$$P = \exp\left(\frac{-d}{r_0}\right)$$



iterated N times; discarded points → remnants

Space-time Model - sources of displacement - summary

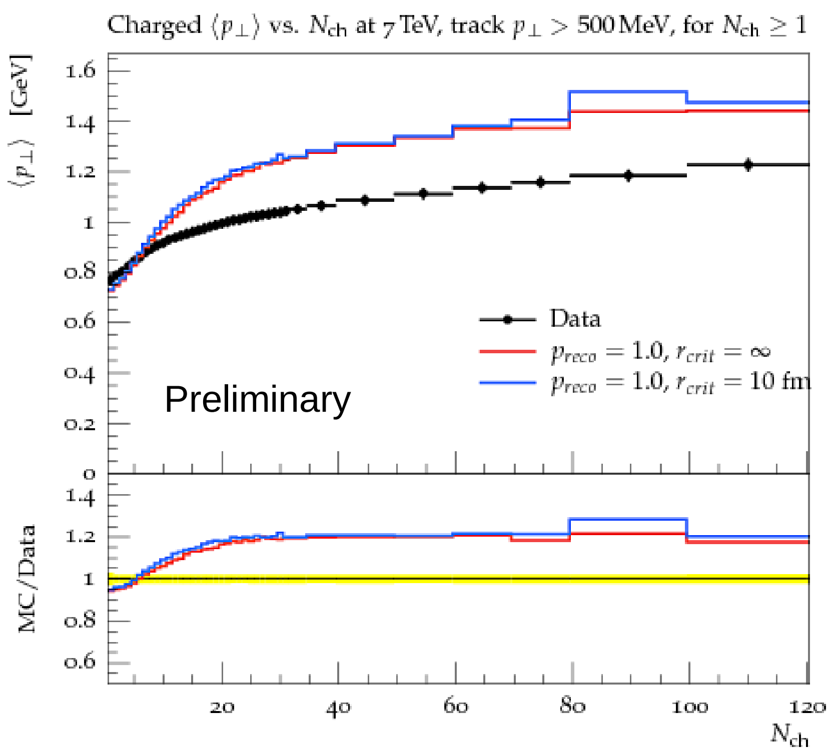


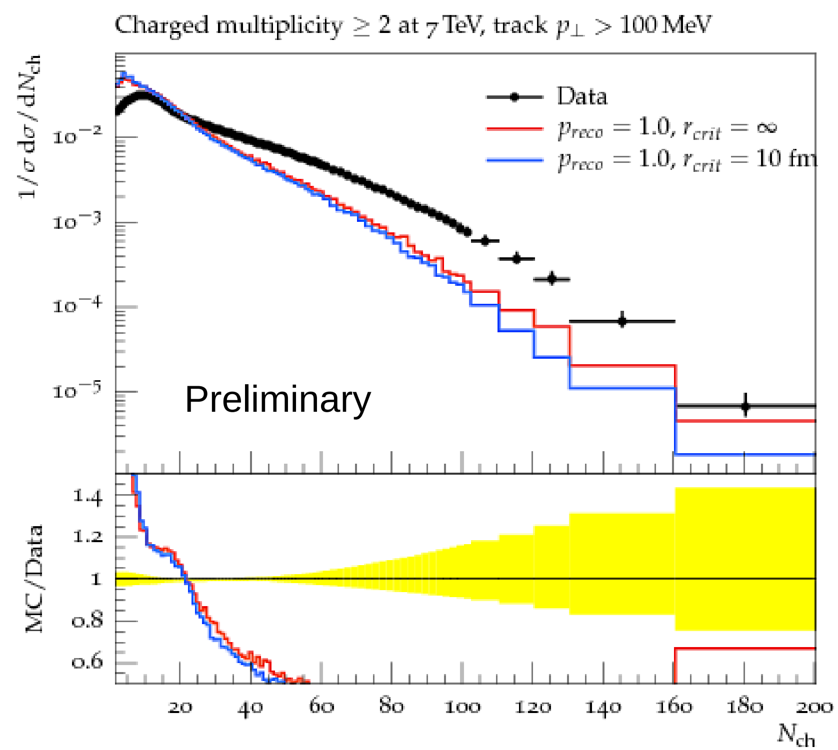
- “final” state partons in shower are further allowed to propagate
- **minV** (minimal virtuality) - so far a free parameter
- gluons are then forced to split to qqbar pair

Space-time Model - preliminary results

First idea: critical radius

→ plain CR + critical radius (new parameter)





Not tuned (just to see the effect), **MPI smearing only** - no shower ST

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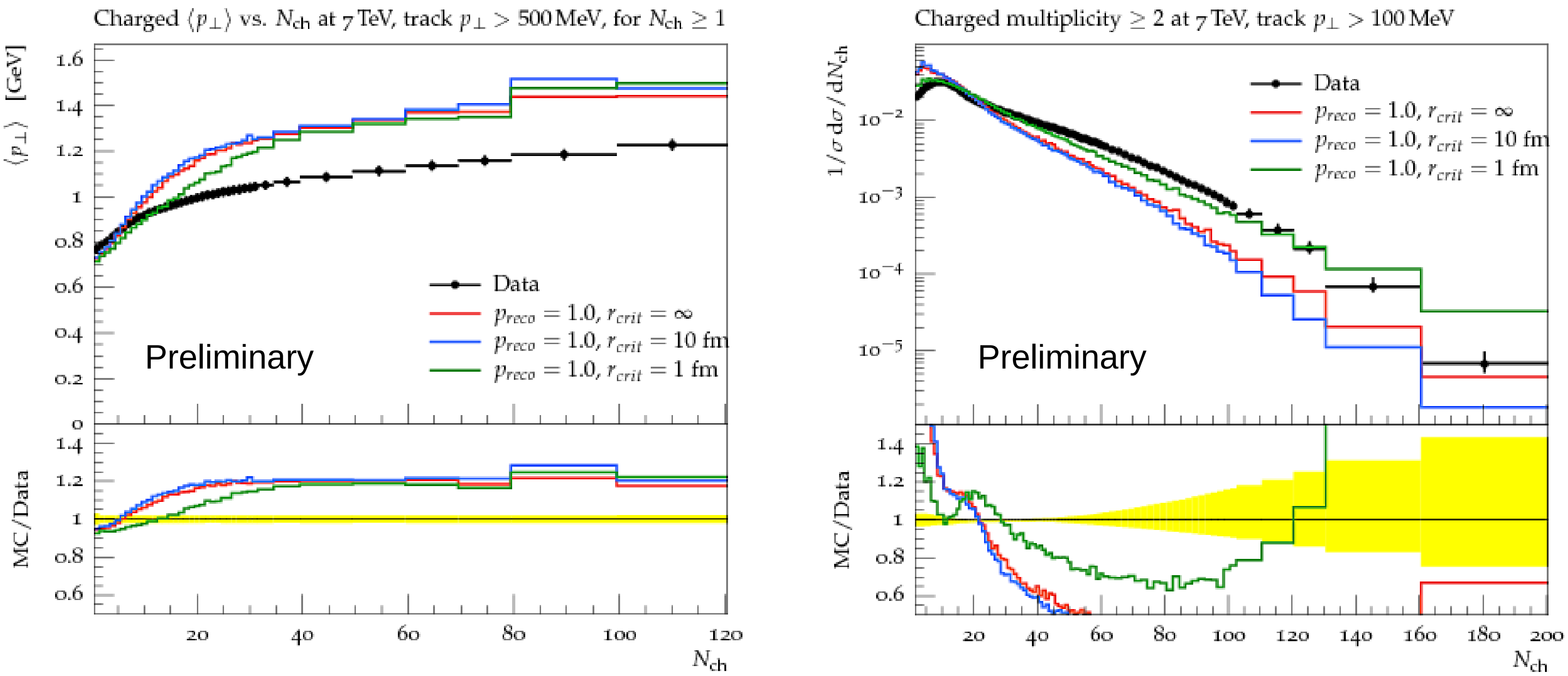

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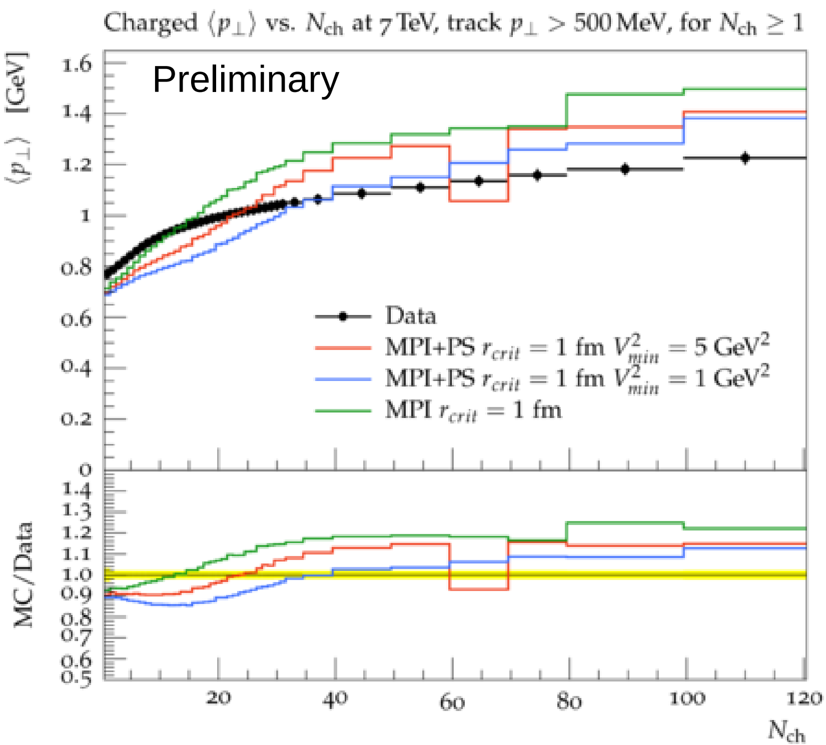

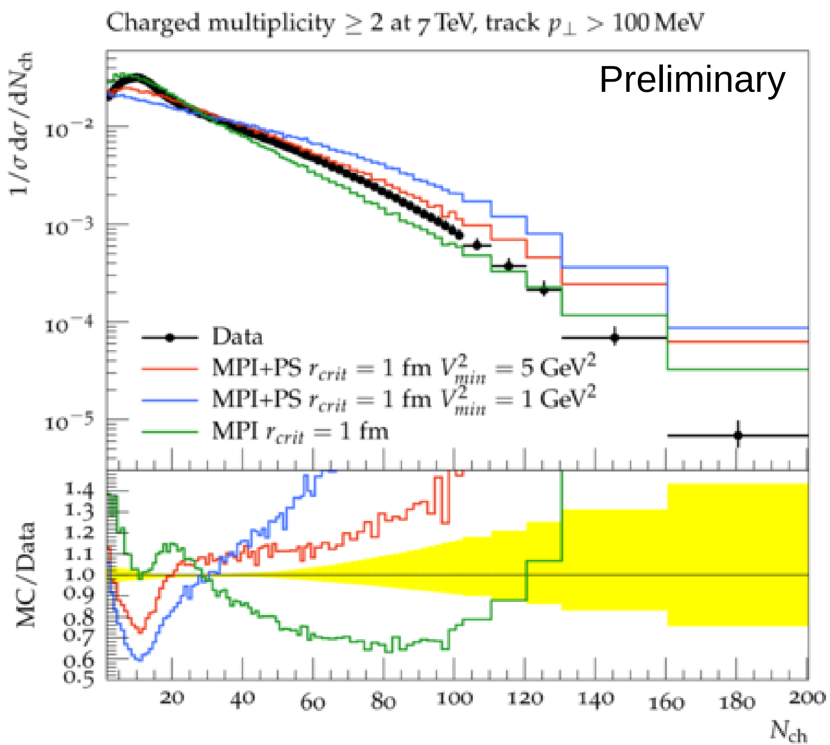

Not tuned (just to see the effect), **MPI + shower ST**, p_{reco} = 1 (same as previous slides)

Summary and outlook

- We introduced space-time picture to MPI (probe b from the overlap function) and to the Parton Shower (based on mean life-time)
- We study sources of displacement and its dependence on the main parameters
- We introduced space-time information to the simplest CR model in Herwig and studied its influence on MB and UE event data (without any tuning).
- We plan to implement more CR models based on space-time picture
- Space-time picture could serve us as a starting point to study collective effects in p-p collisions

Backup slides

Soft MPI

So far only hard MPI.
Now extend to soft interactions with

$$\chi_{\text{tot}} = \chi_{QCD} + \chi_{\text{soft}}.$$

Similar structures of eikonal functions:

$$\chi_{\text{soft}} = \frac{1}{2} A_{\text{soft}}(\vec{b}) \sigma_{\text{soft}}^{\text{inc}}$$

Simplest possible choice: $A_{\text{soft}}(\vec{b};\mu) = A_{\text{hard}}(\vec{b};\mu) = A(\vec{b};\mu)$.
Then

$$\chi_{\text{tot}} = \frac{A(\vec{b};\mu)}{2} \left(\sigma_{\text{hard}}^{\text{inc}} + \sigma_{\text{soft}}^{\text{inc}}\right) .$$

One new parameter $\sigma_{\text{soft}}^{\text{inc}}$.

Taking the Tevatron data together with the wide range of possible values of σ_{tot} considered at LHC, we see that this model is to simple.

Soft MPI

Extension: Relax the constraint of identical overlap functions:

$$A_{soft}(b) = A(b, \mu_{soft})$$

Fix the two parameters $\mu_{\rm soft}$ and $\sigma^{\rm inc}_{\rm soft}$ in

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

from two constraints. Require simultaneous description of $\sigma_{\rm tot}$ and $b_{\rm el}$ (measured / well predicted),

$$\sigma_{\rm tot}(s) \stackrel{!}{=} 2\int {\rm d}^2\vec{b}\left(1 - {\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) ,$$

$$b_{\rm el}(s) \stackrel{!}{=} \int {\rm d}^2\vec{b}\,\frac{b^2}{\sigma_{\rm tot}}\left(1 - {\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) .$$

Sum up:

$\Rightarrow$at the end of the day we have two main parameters: μ^2, p_t^{min}.