Hrátky s Herwigem

Miroslav Myška

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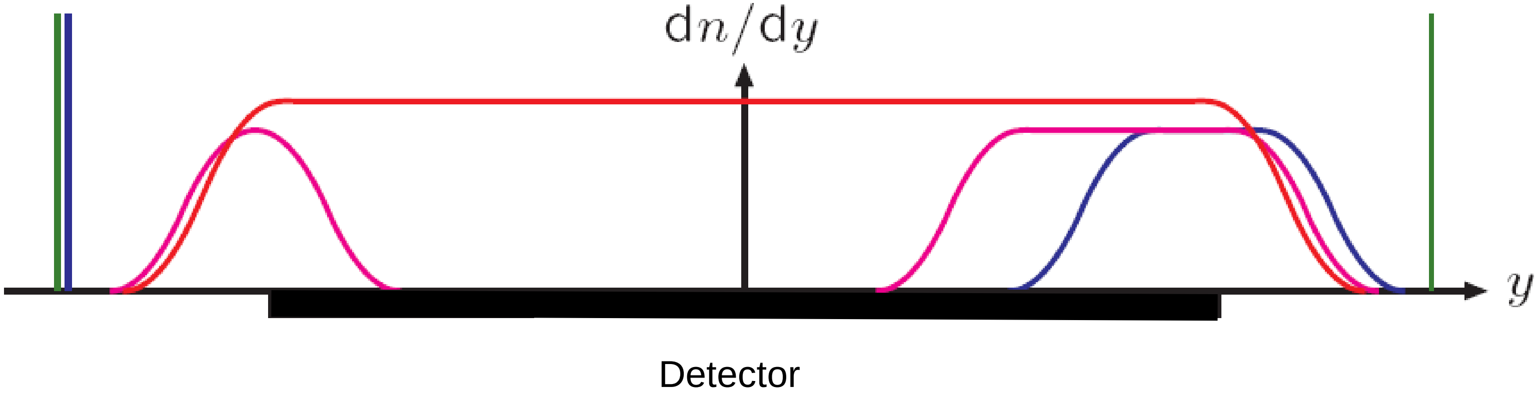
~~Hrátky s Horwigem~~

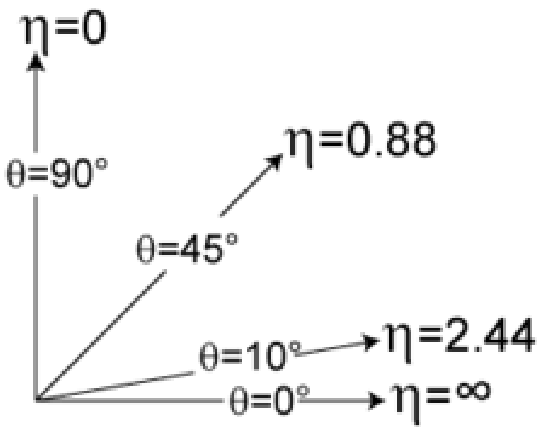
~~Miroslav~~ Myš~~ka~~ Maš

Proton-proton collision

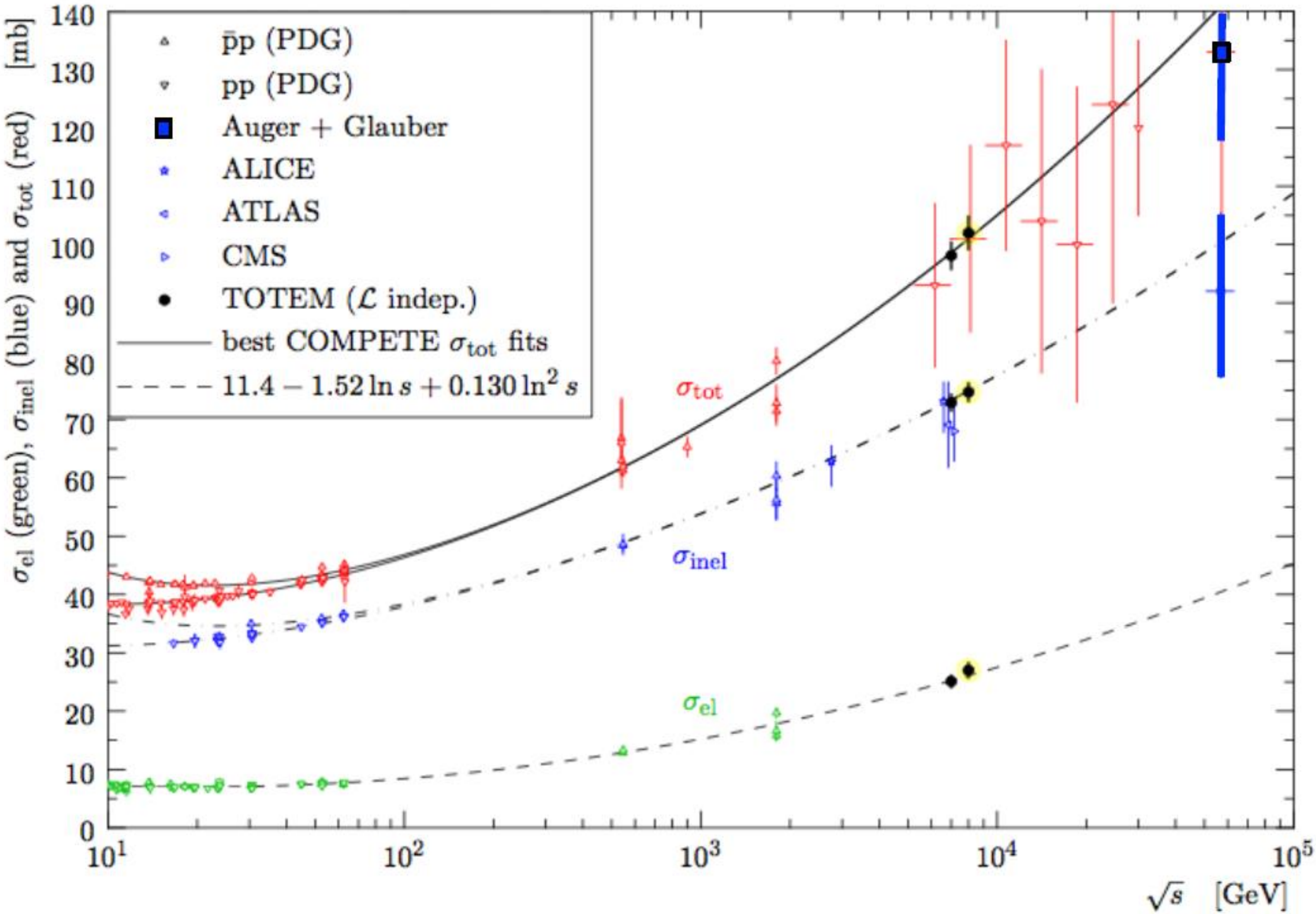
- What everything can happen?

$$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \dots + \sigma_{\text{non-diffractive}}$$



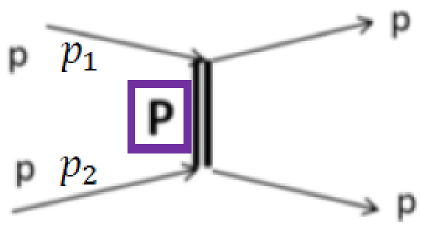


20-25% elastic
25-35% diffractive
40-55% non-diffractive



p̄p (PDG)
pp (PDG)
Auger + Glauber
ALICE
ATLAS
CMS
TOTEM ($\mathcal{L}$ indep.)
best COMPETE σ_{tot} fits
$11.4 - 1.52 \ln s + 0.130 \ln^2 s$
σ_{tot}
σ_{inel}
σ_{el}
σ_{el} (green), σ_{inel} (blue) and σ_{tot} (red) [mb]
$\sqrt{s}$ [GeV]
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
10^1
10^2
10^3
10^4
10^5

using optical theorem and Regge theory we can write for a process



$$\sigma_{\text{tot}} \approx s^{\alpha(0)-1}$$

$$s = (p_1 + p_2)^2$$

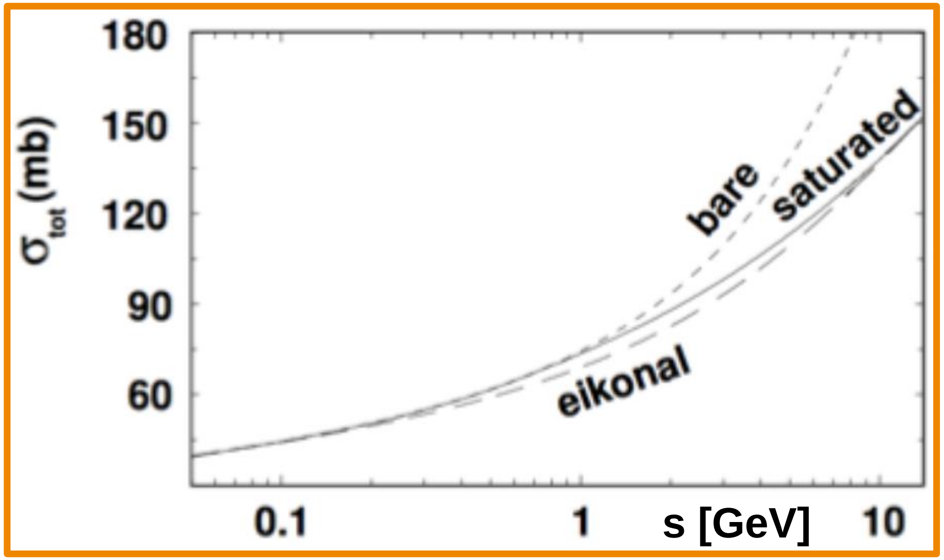
$$\frac{d\sigma_{\text{el}}}{dt} \approx s^{2(\alpha(0)-1)} e^{-B|t|}$$

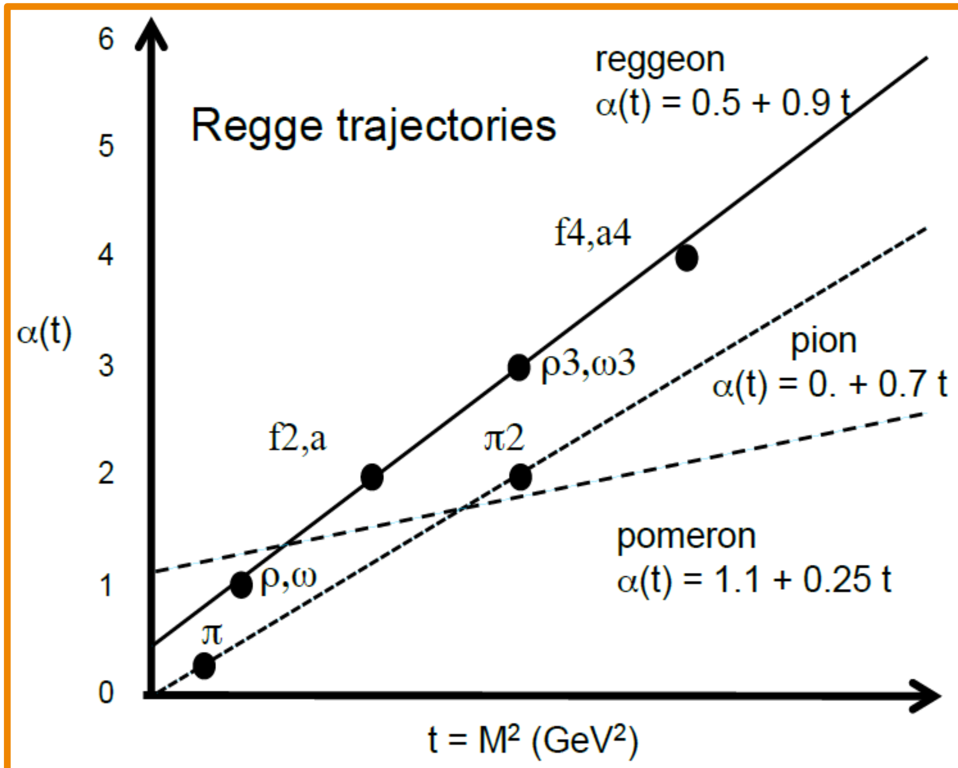
$$B = B_0 + 2\alpha' \ln s$$

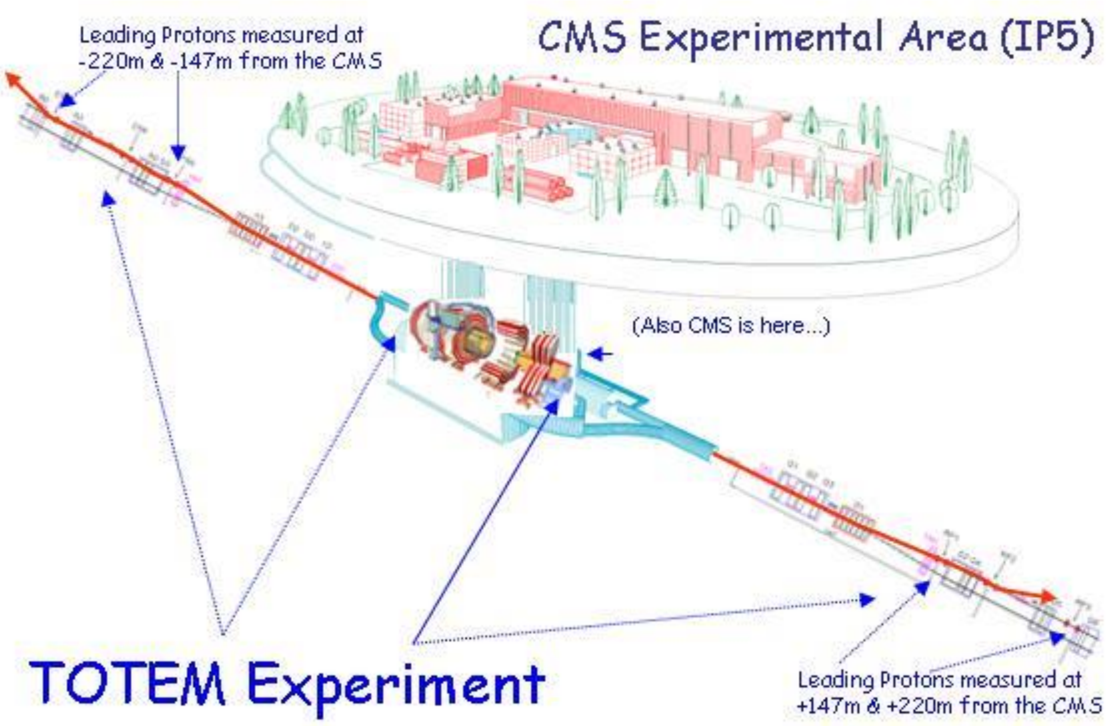
where $\alpha(0)$ is so-called intercept of a Regge trajectory

$$\alpha(t) = \alpha(0) + \alpha' t \qquad t = (p_1 - p_2)^2 \underset{\text{elastic}}{\cong} -(p_0\theta)^2,\ |p_1| = |p_2| = p_0$$

if $\alpha(0) > 1$, σ_{tot} will rise with rise of s



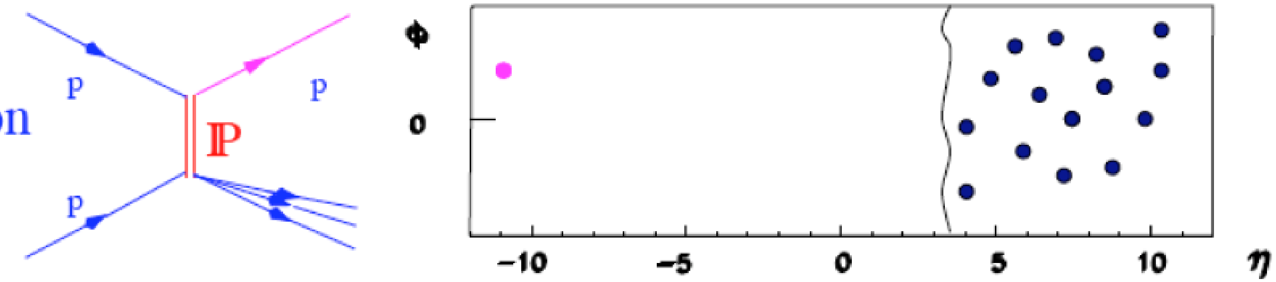




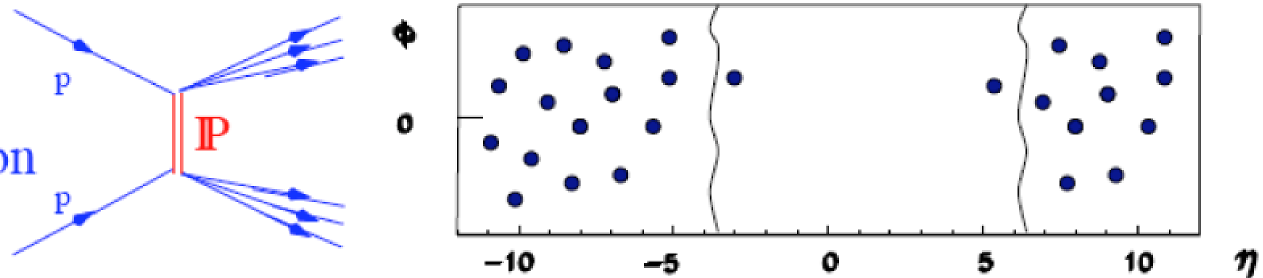
3 detector types:

- Roman Pots with microstrip silicon detectors used to detect protons
- Cathode Strip Chambers and GEM (gas electron multiplier) Detectors that will measure the jets of forward-going particles that emerge from collisions when the protons break apart.

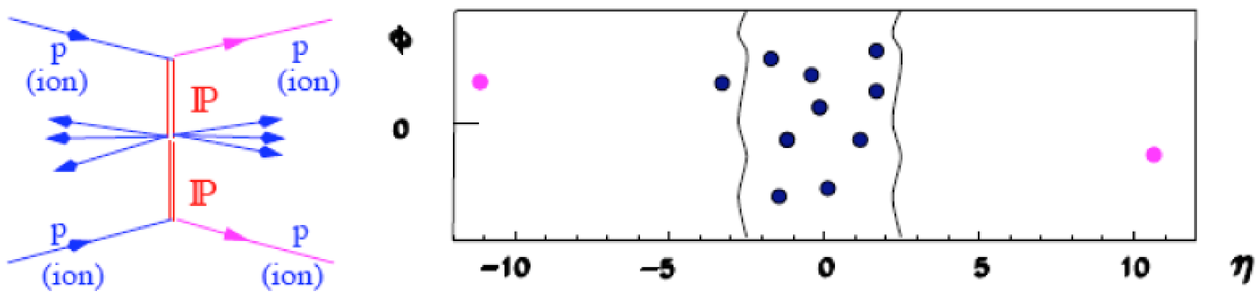
single diffraction



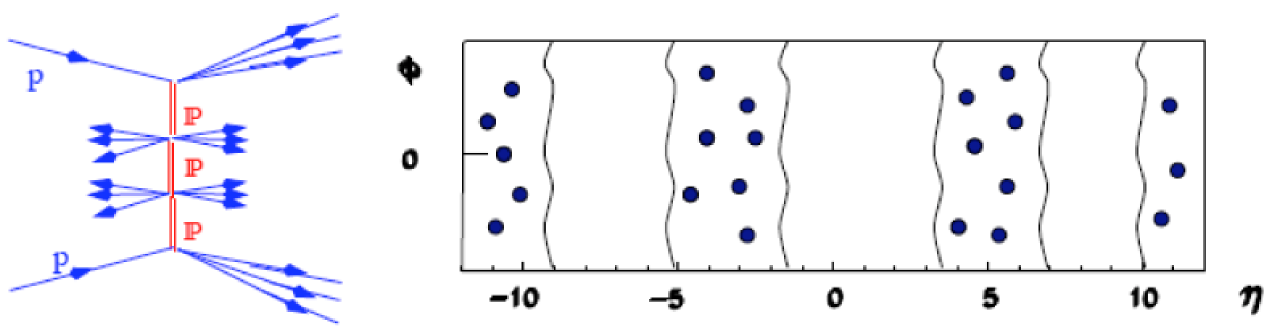
double diffraction



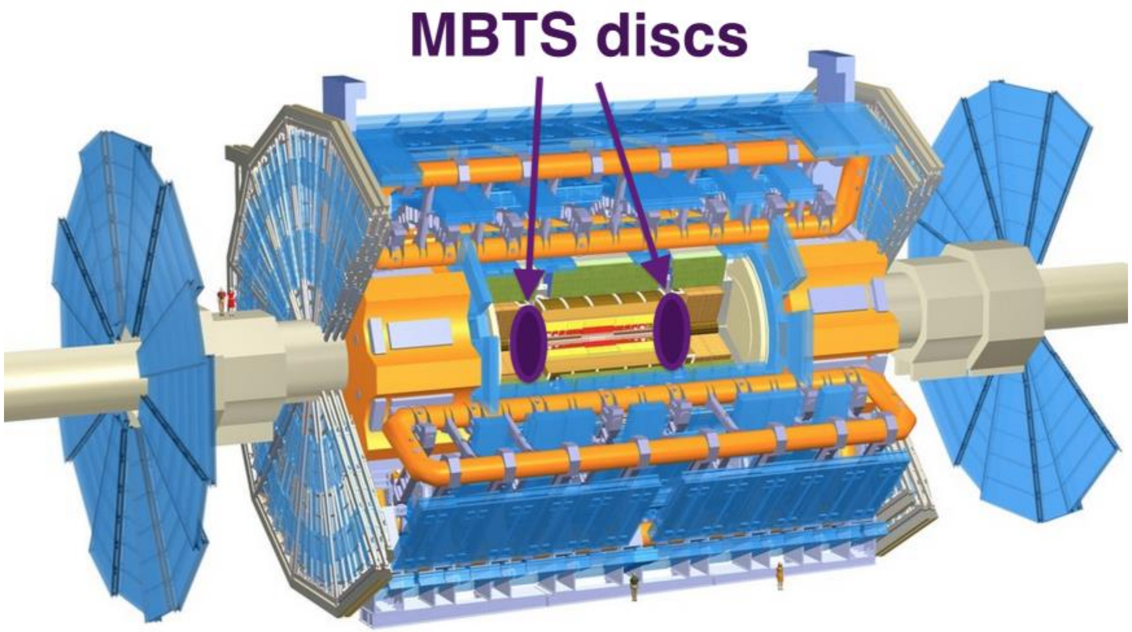
Double
Pomeron
Exchange



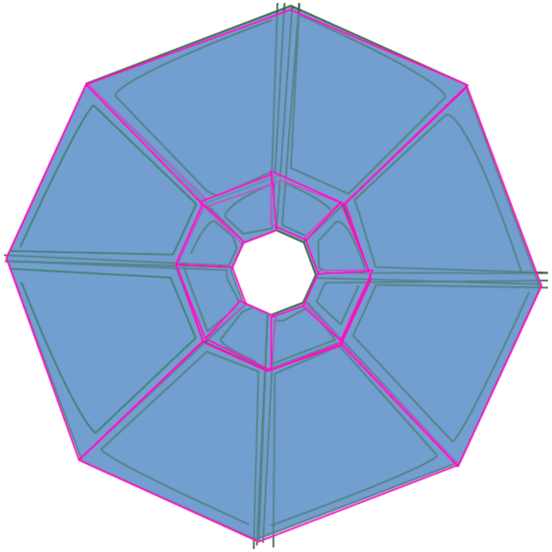
Multi
Pomeron
Exchange

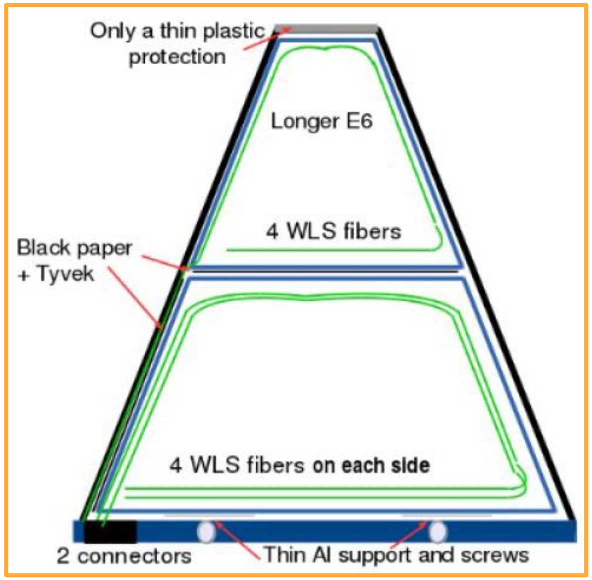


minimum bias



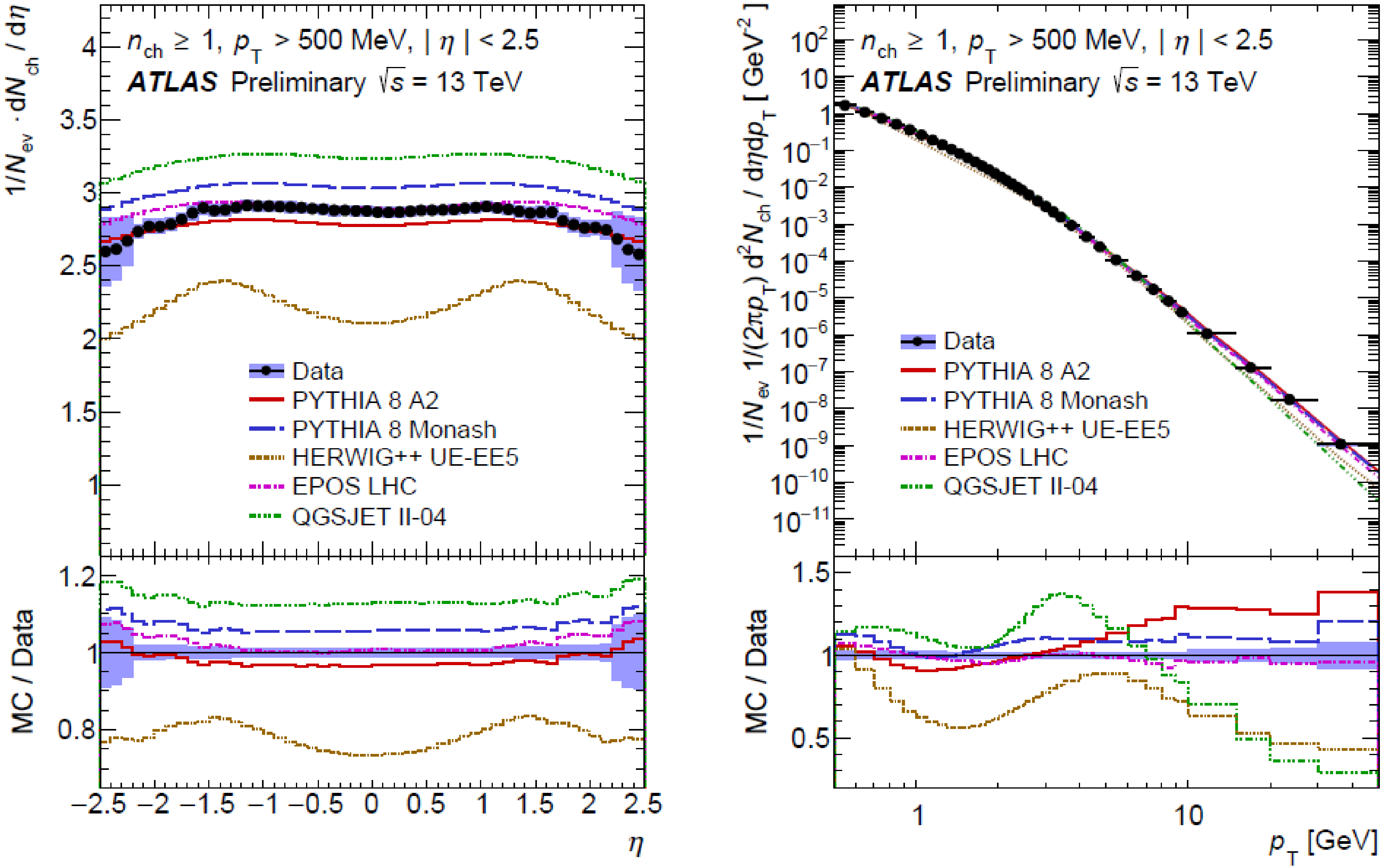
8 segments in the inner octagonal ring, 4 segments in the outer ring



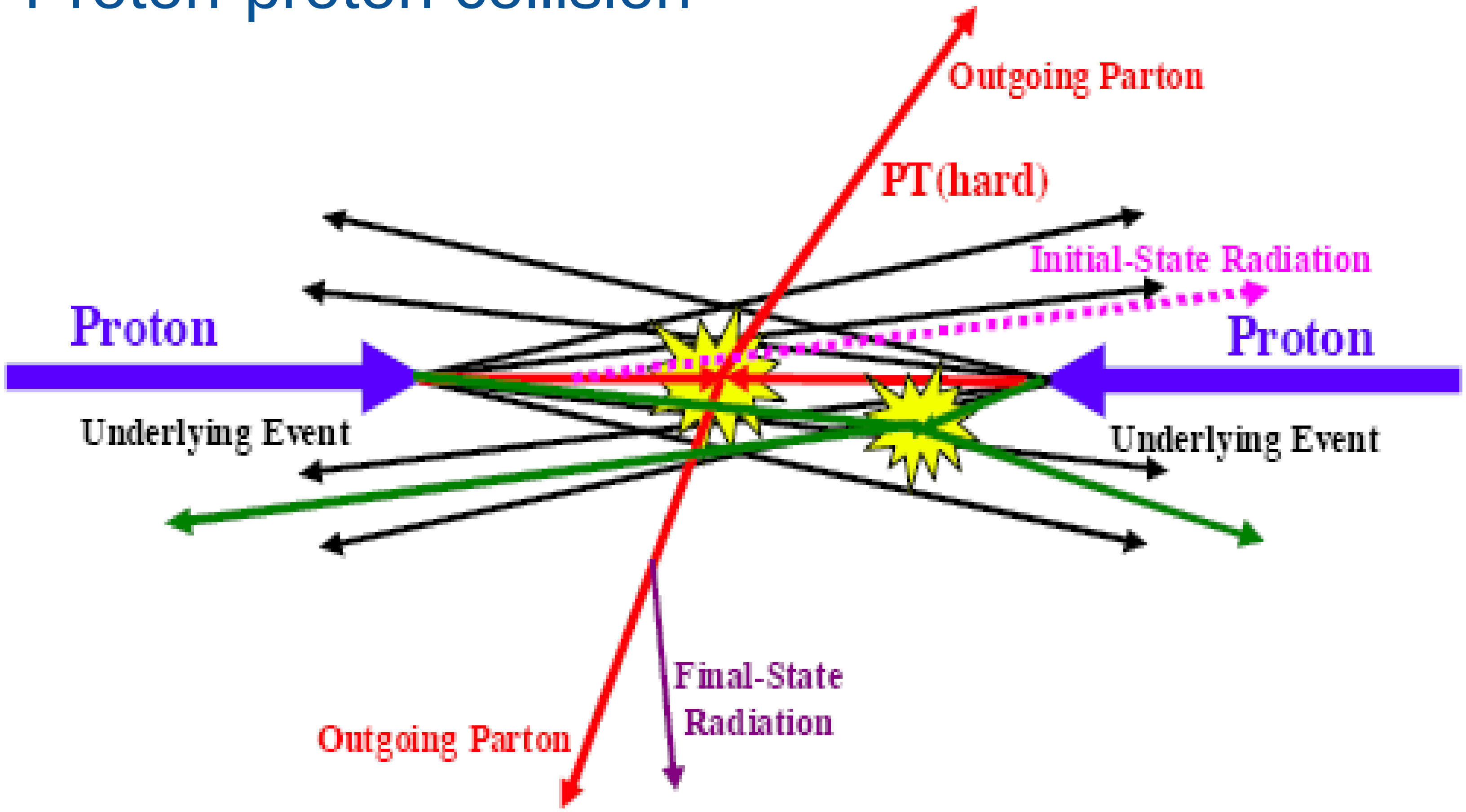


- Thin polystyrene scintillation counters, the total of 24 counter segments
- Located at ± 3.6 meters between inner tracking detector and calorimeter
- Pseudo-rapidity acceptance: $2.07 < |\eta| < 3.86$

minimum bias



Proton-proton collision



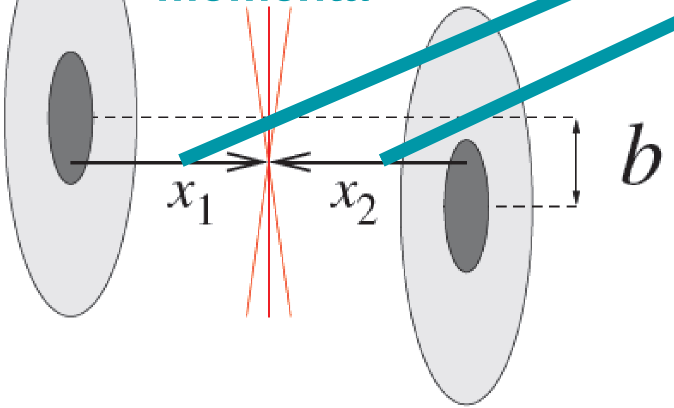
Components: **primary process** and **underlying event**

Primary process – factorization theorem

Inclusive hard jet cross section in pQCD:

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

fractional momenta



Parton Distribution Functions (non-perturbative)

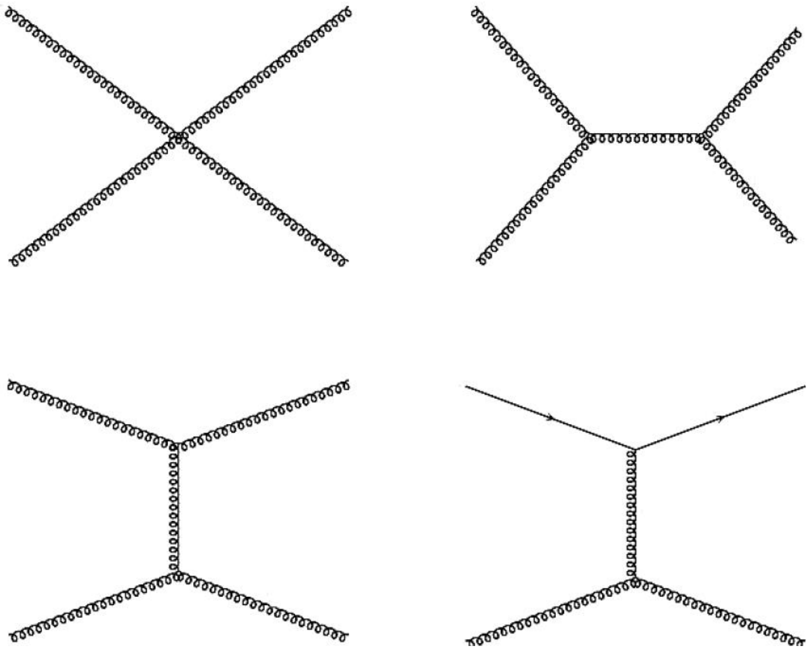
parton interaction (perturbative -> Feynman diagrams)

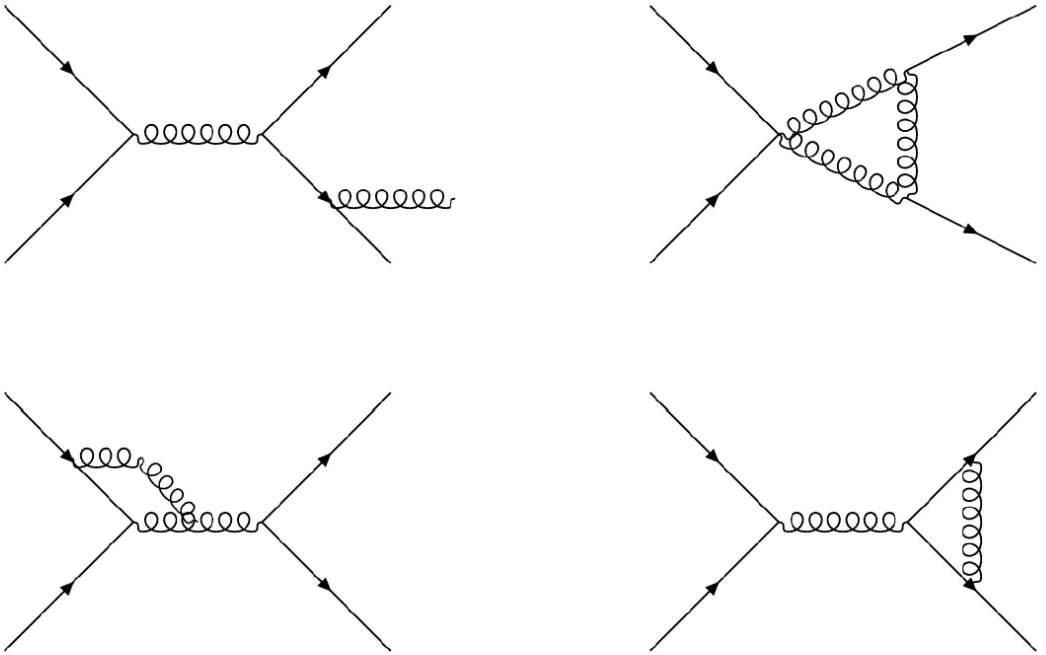
http://hepdata.cedar.ac.uk/pdf/pdf3.html

https://lhapdf.hepforge.org/

http://madgraph.phys.ucl.ac.be/

Higher orders of perturbative expansion





LO: Pythia & Herwig

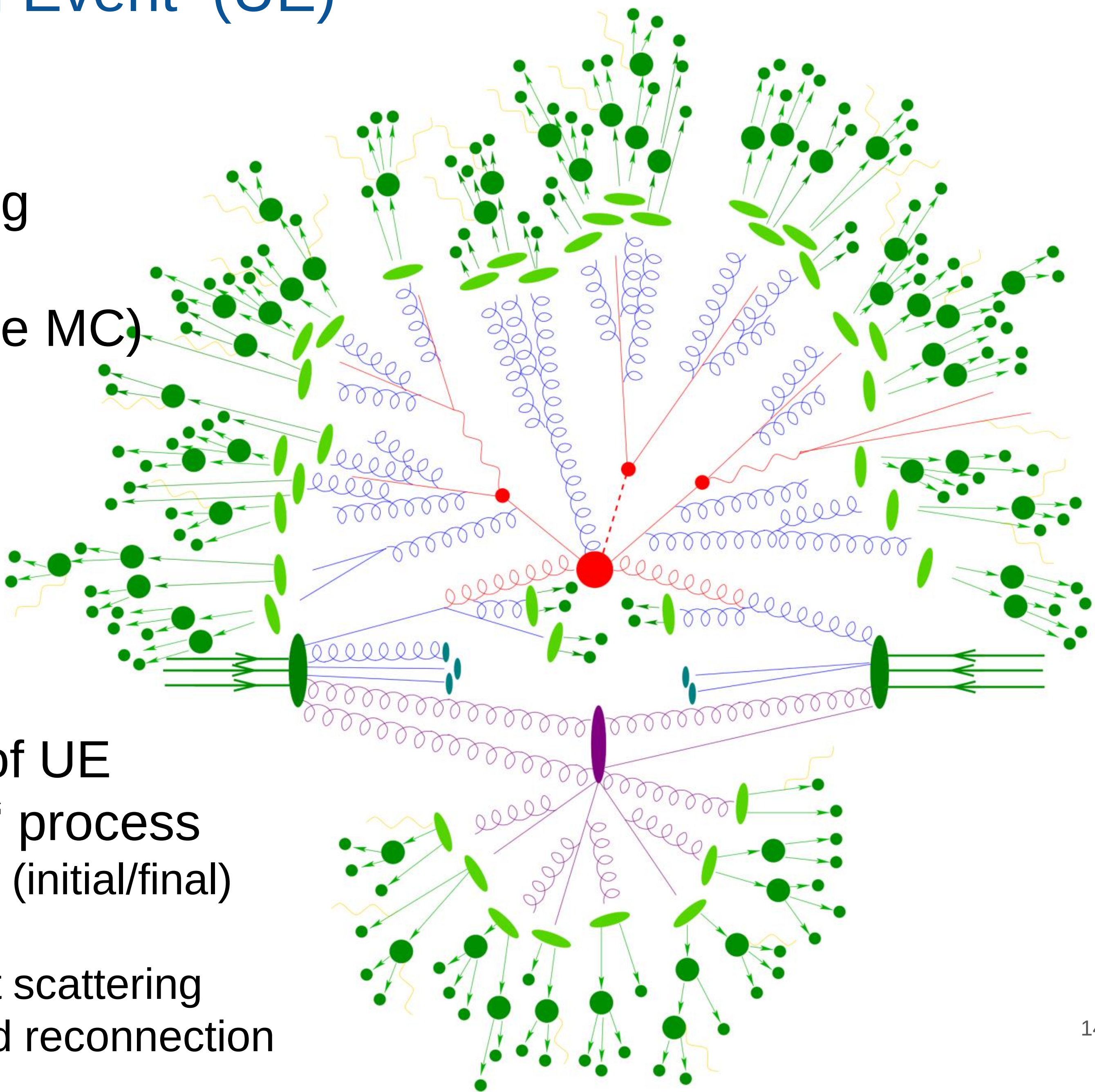
NLO: Powheg, MC@NLO

LO + external legs: HIJING, Alpgen

Underlying Event (UE)

Hadronization
- Cluster: Herwig
- String: Pythia

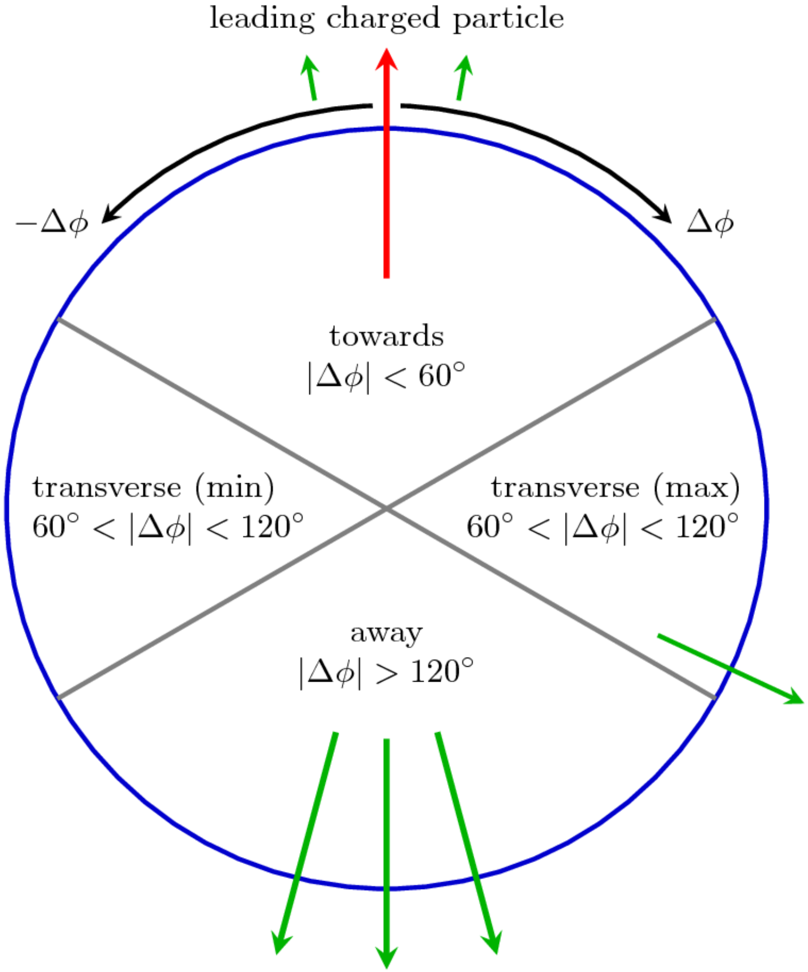
(General-Purpose MC)

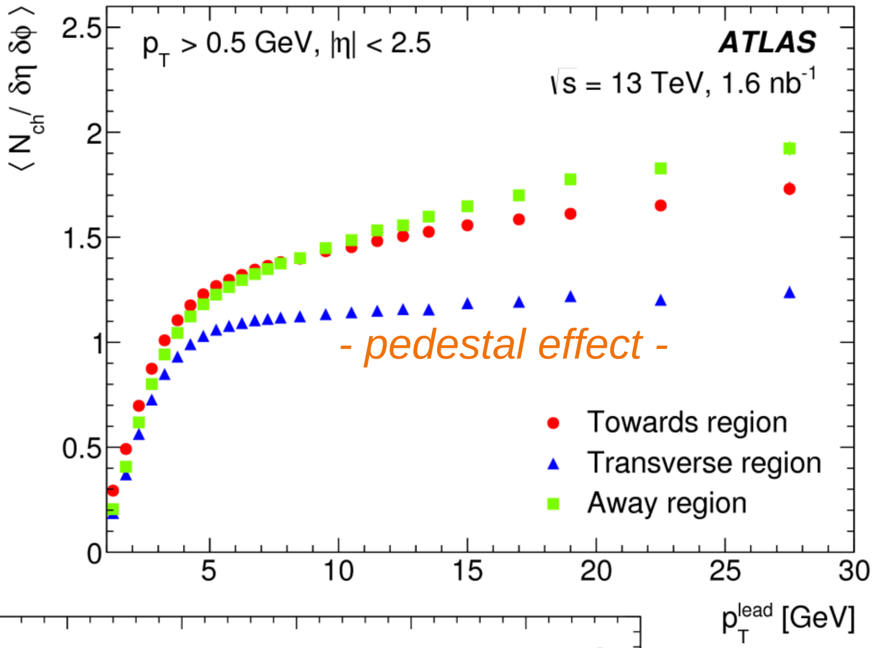


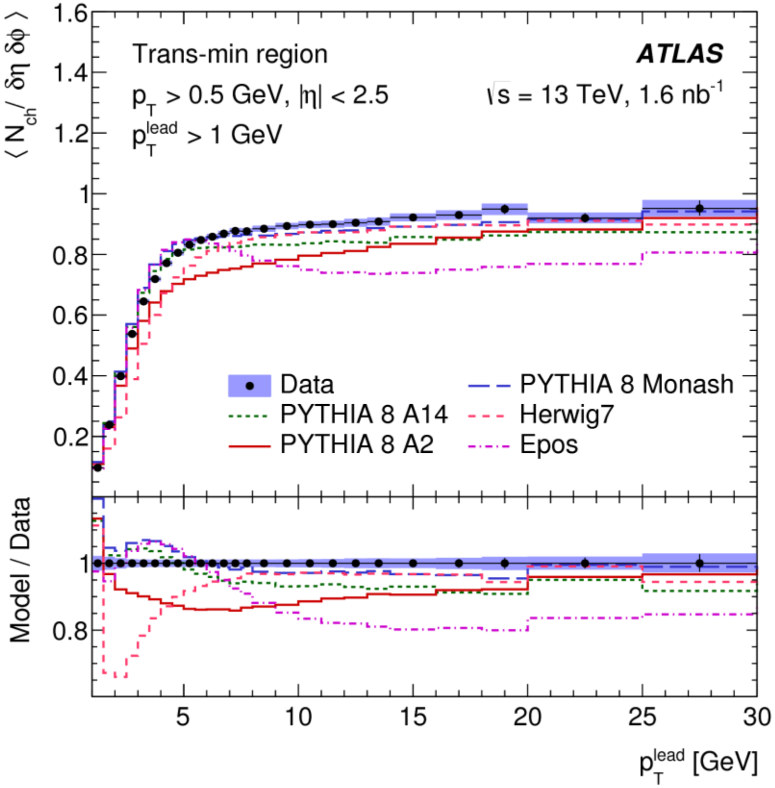
Phenomenology of UE

– on top of “hard“ process
- shower algorithms (initial/final)
- semi-hard MPI
- soft MPI / remnant scattering
- color evolution and reconnection

Underlying Event (UE)

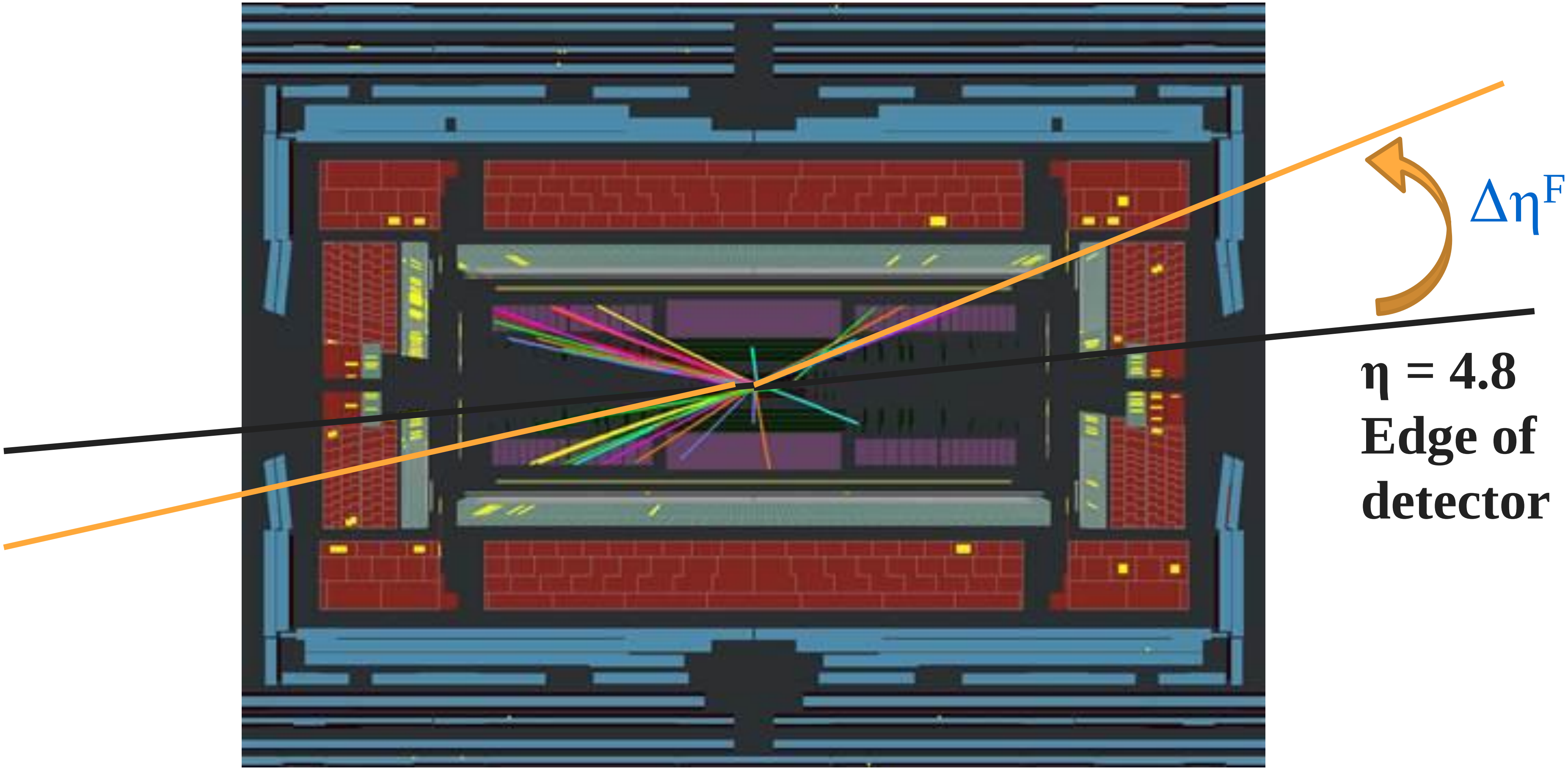






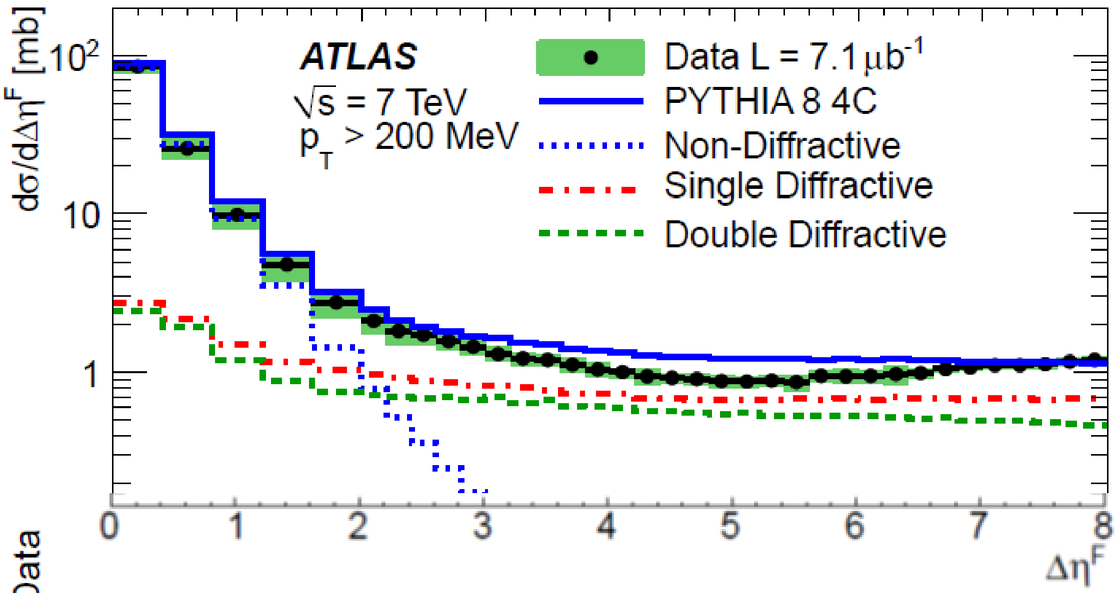
Hrátky s Herwigem

Forward (pseudo)rapidity gap, $\Delta\eta^F$

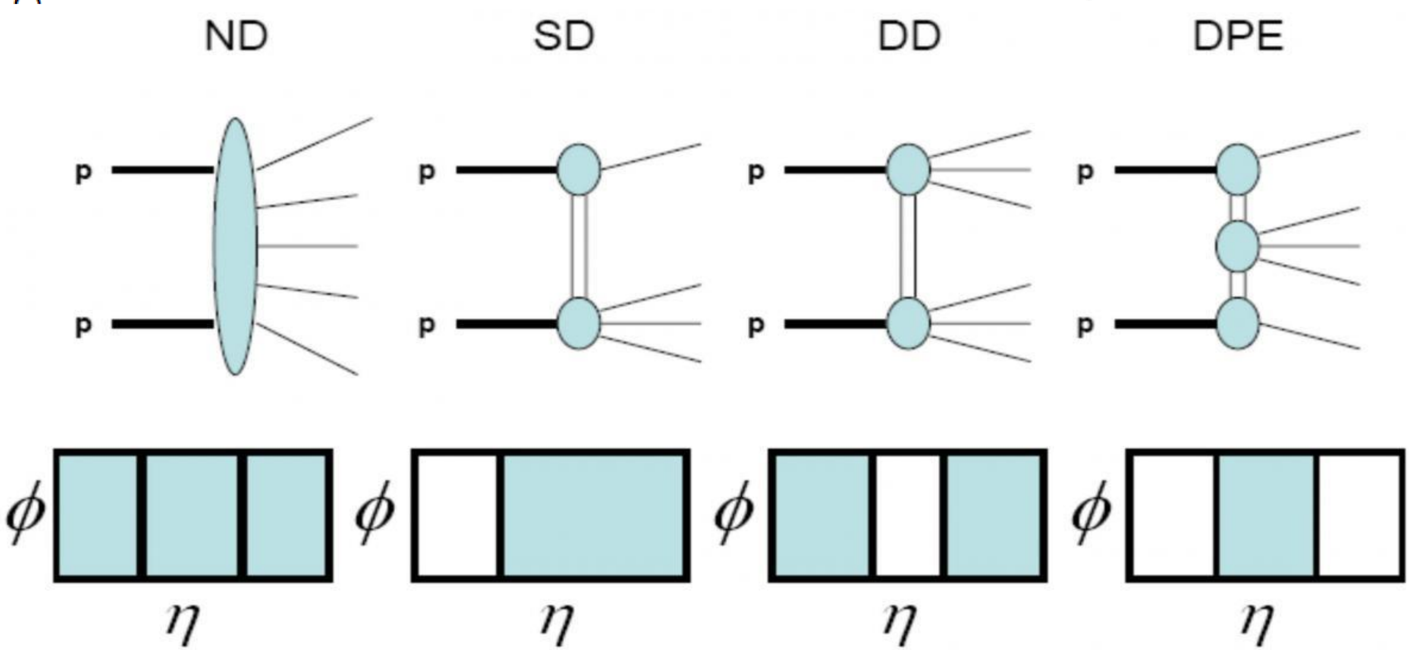


$\Delta\eta^F$ defined as the larger one of two eta-distances from the last particle to the edge of the detector acceptance

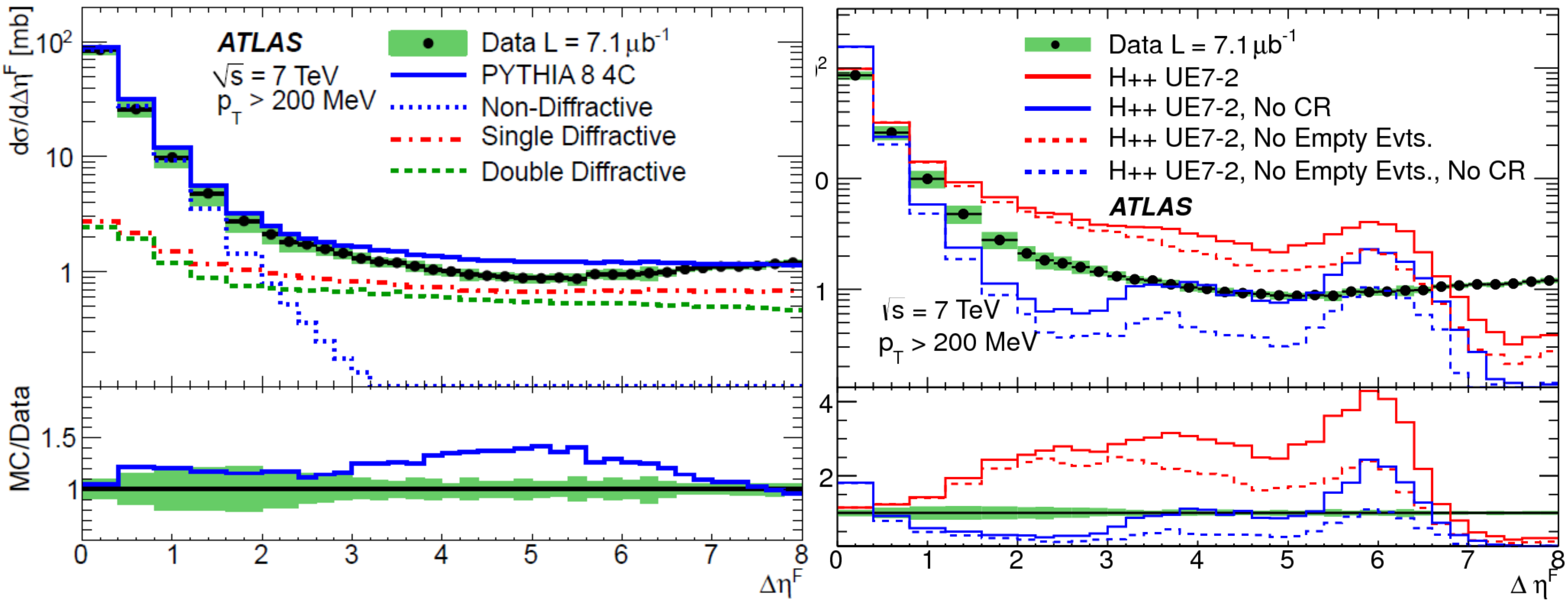
Forward (pseudo)rapidity gap, $\Delta\eta^F$



- Diffraction-sensitive variable
- Non-diffractive (ND) events populate most of the acceptance, $\Delta\eta^F \rightarrow 0$
- Single- (SD) and double- (DD) diffractive events leaves empty regions, not only in the central region, $\Delta\eta^F \sim$ const.



Forward (pseudo)rapidity gap



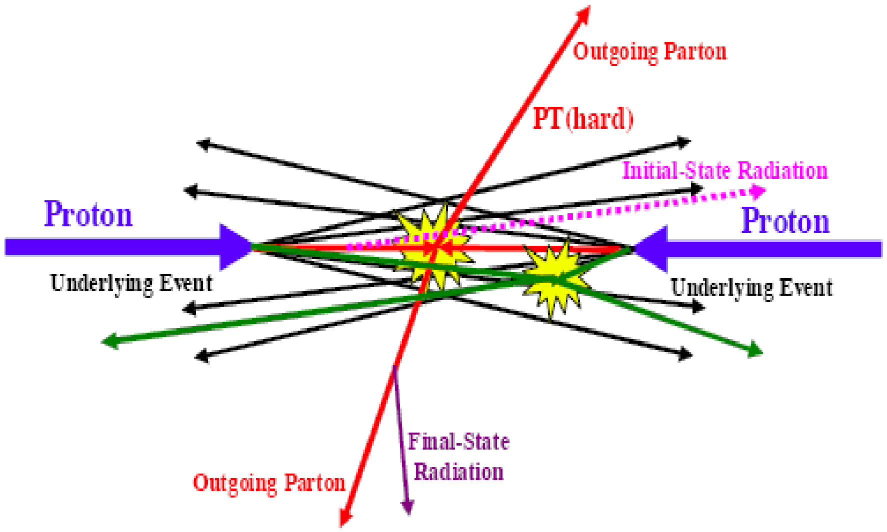
- Herwig++/H7 missmodeling of $\Delta\eta^F$ found – “bumb”

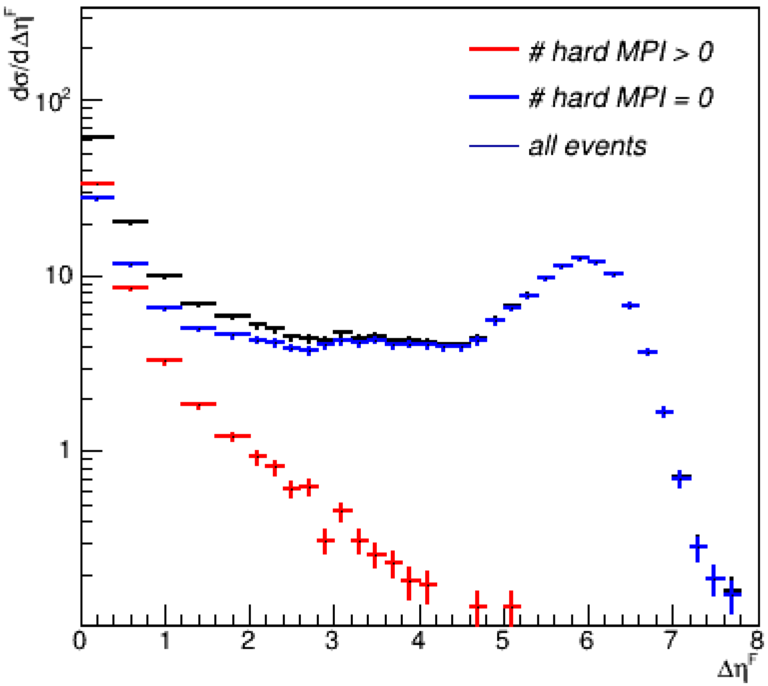
  - no diffractive component of minimum bias model so far

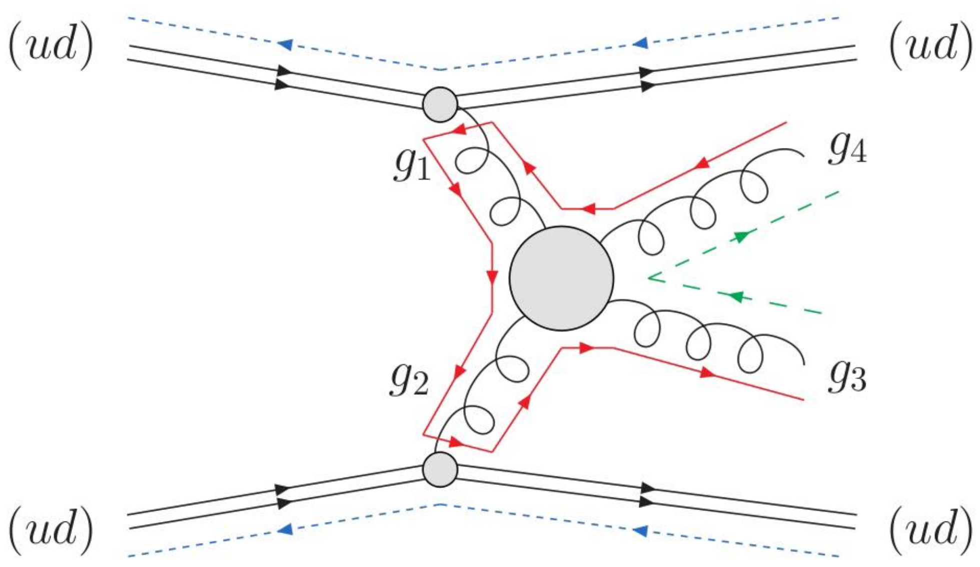
  sharp decrease of $\Delta\eta^F$ expected

  → **improvement under construction**

Multiple-proton interactions (MPI)







Soft MPI
= remnant–remnant scattering

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:

$$\bar{n}(\vec{b},s) = L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$\times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|)$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$\times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|)$$

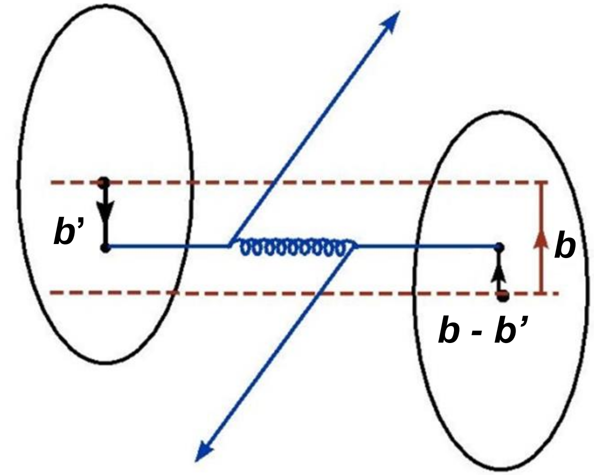
$$= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\text{min}}) \,.$$

- 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

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

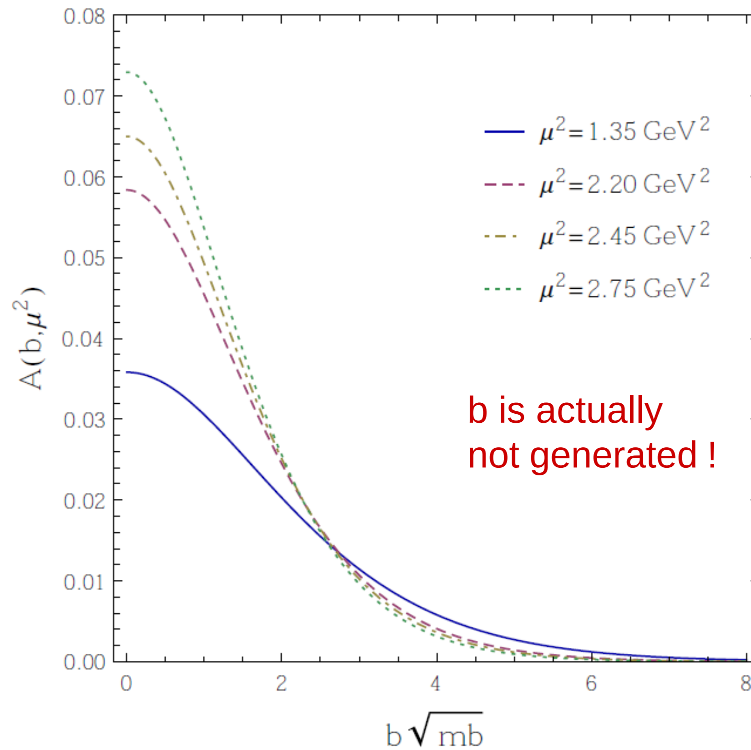
$$A(\vec{b}) = \int d^2\vec{b}' g(\vec{b}')g(\vec{b}-\vec{b}')$$

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

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

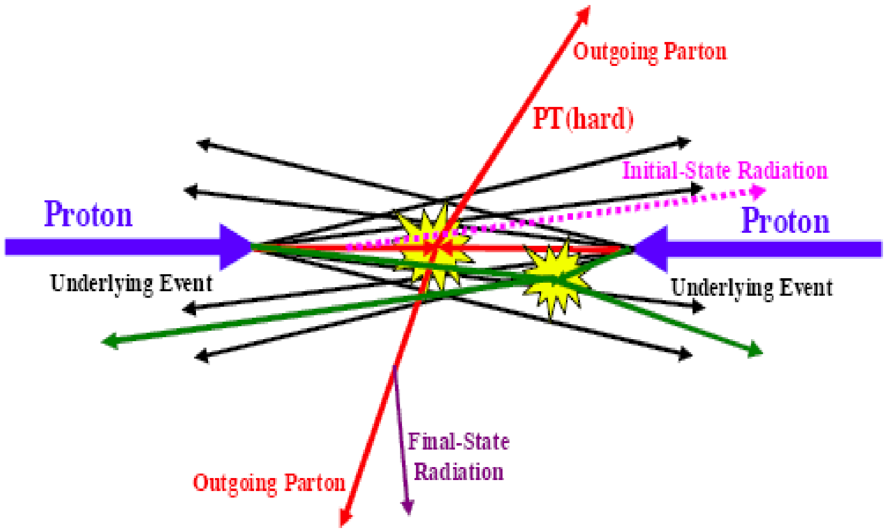
and ***μ*** as a free parameter
(i.e. not fixed at EM value of 0.71 GeV^2)

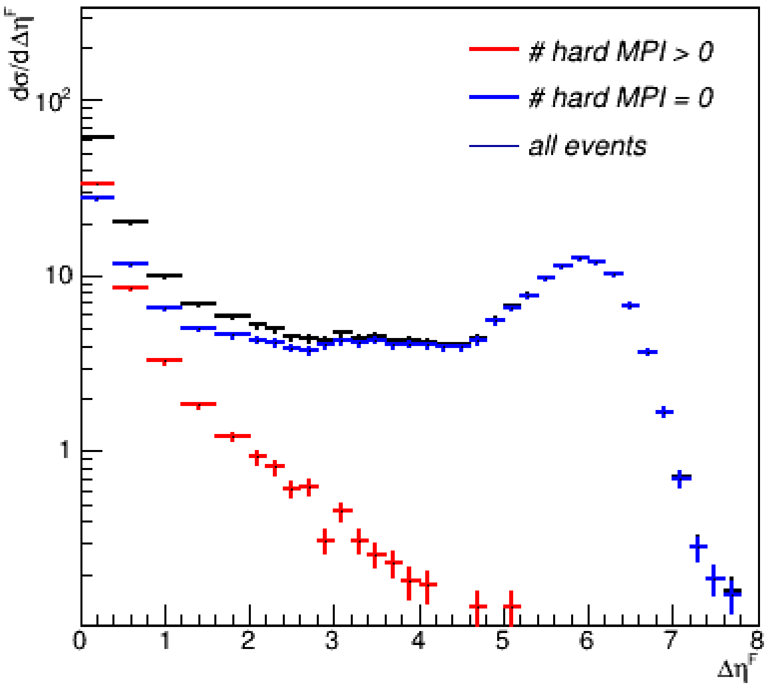
=> two main parameters ***μ***, ***p_t^{min}***

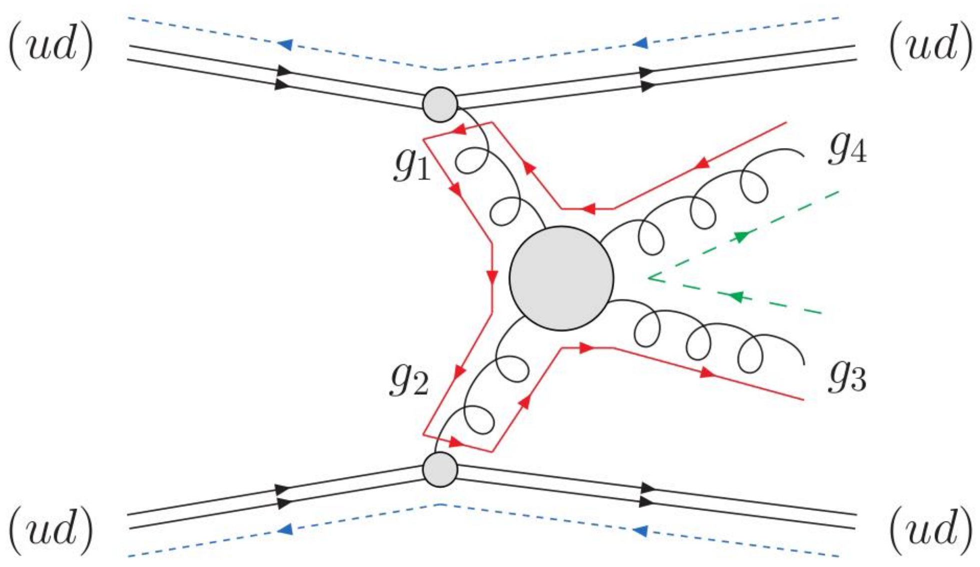


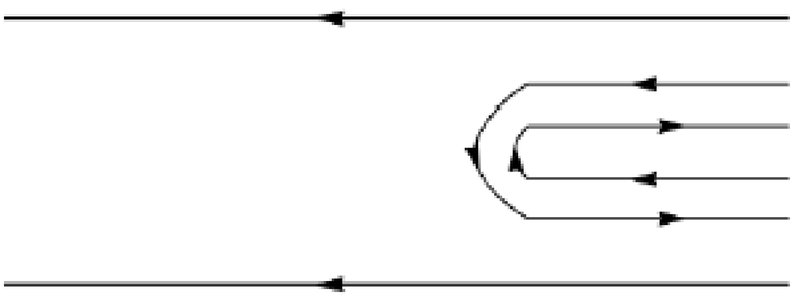
b is actually
not generated !

Multiple-proton interactions (MPI)

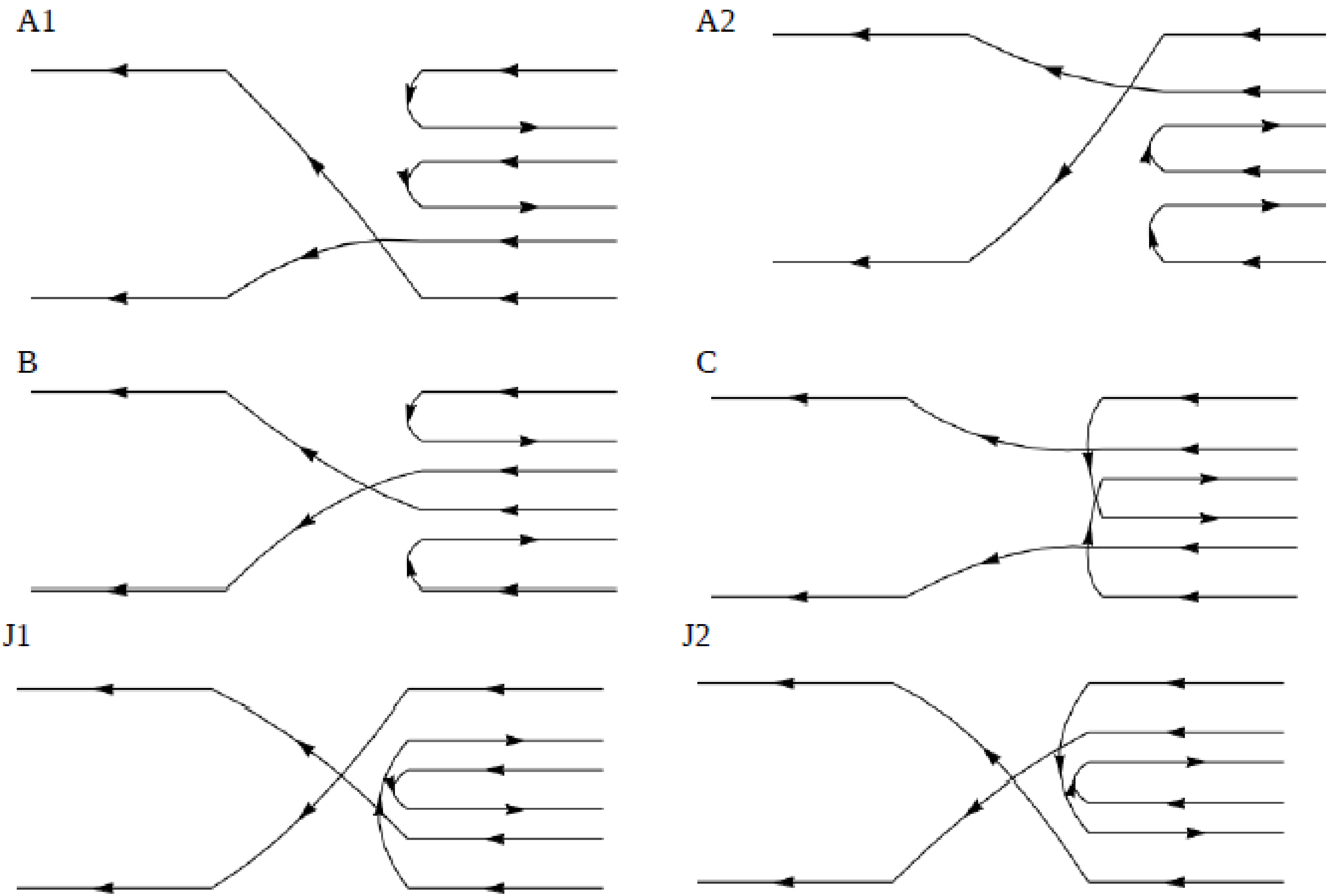




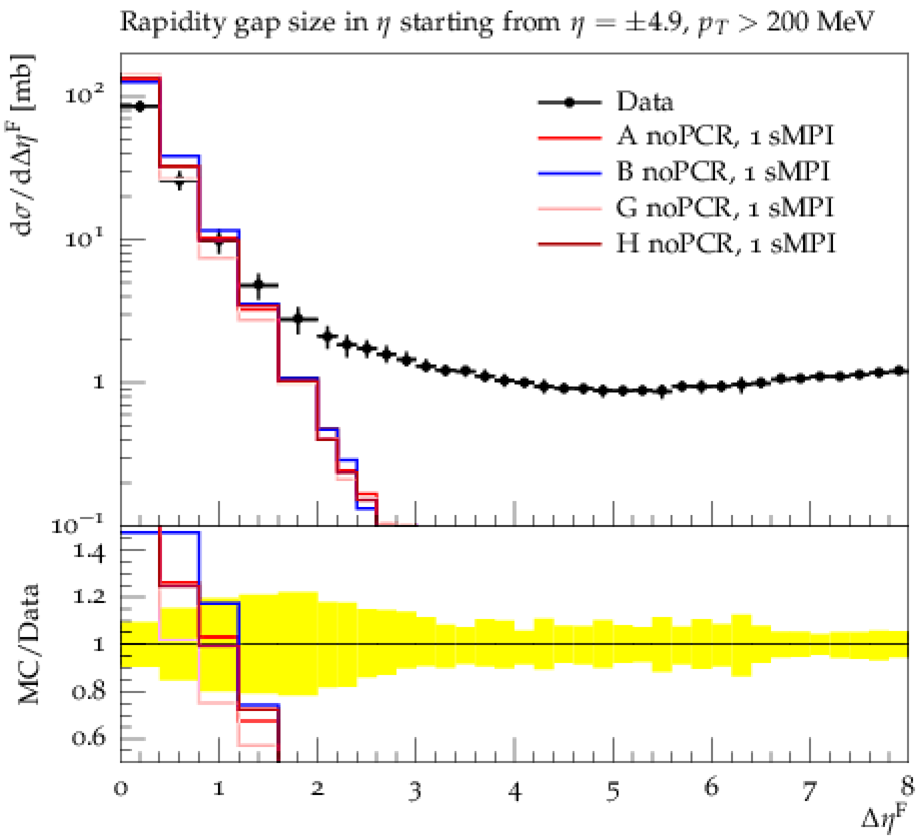


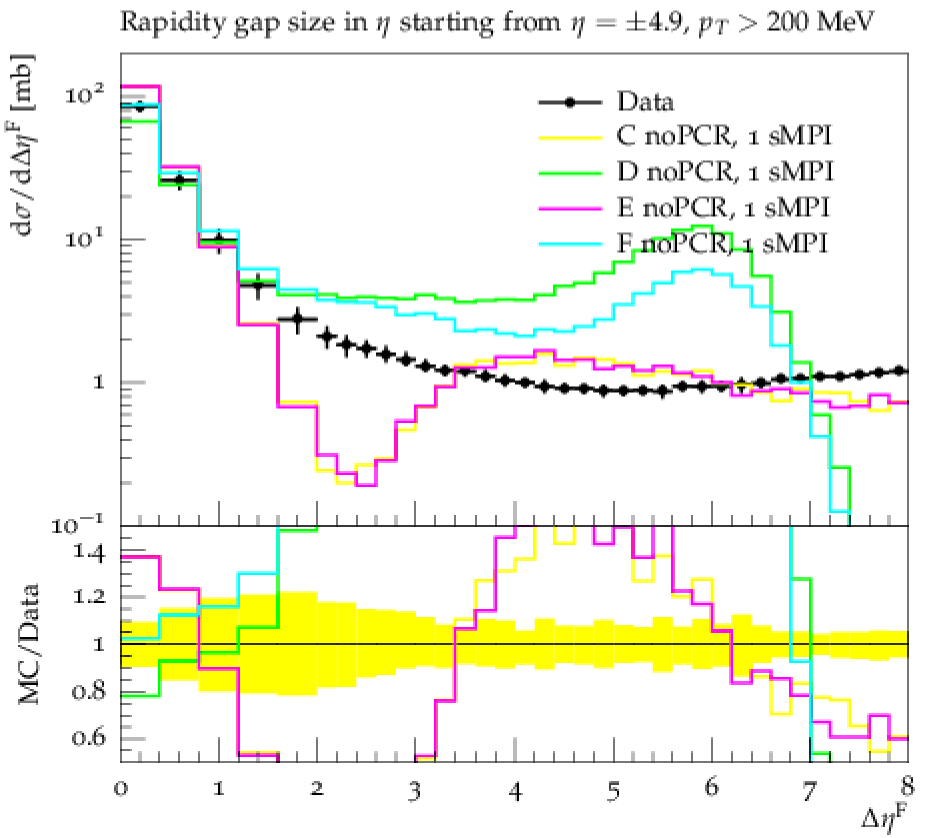


Color flow – NEW model (14 diagrams)



Color flow – NEW model





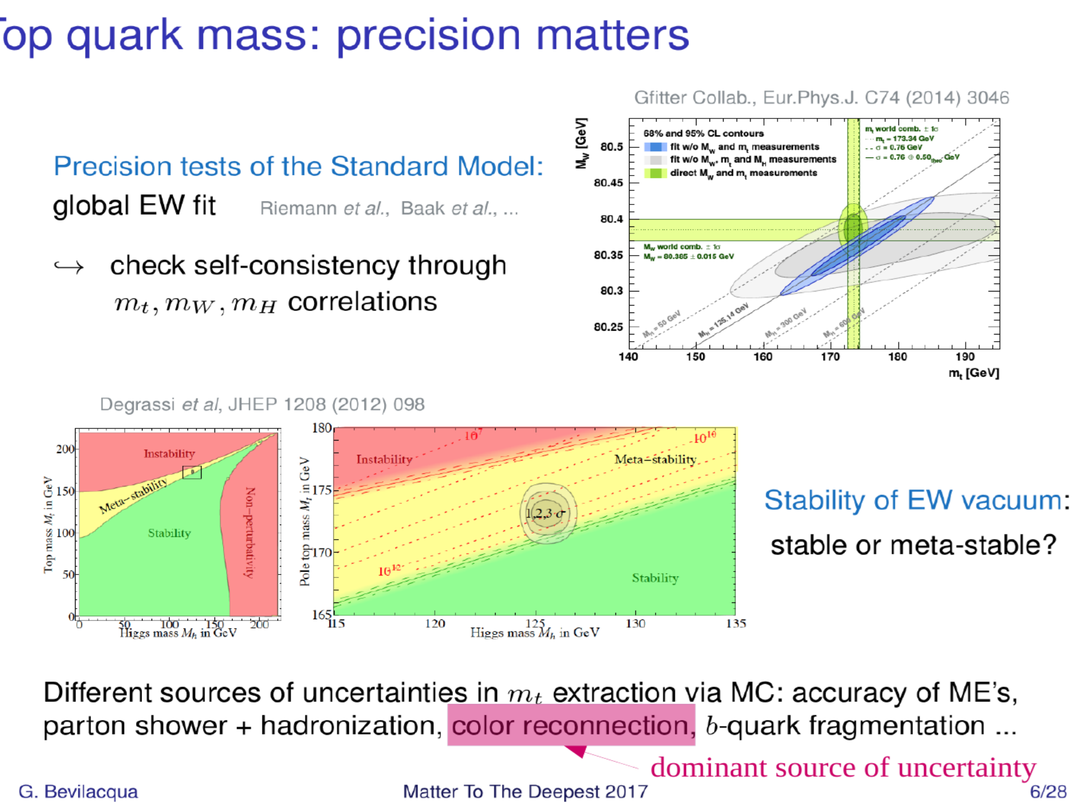
There are good-behaved models.... and bad-behaved models

NO COLOR RECONNECTION

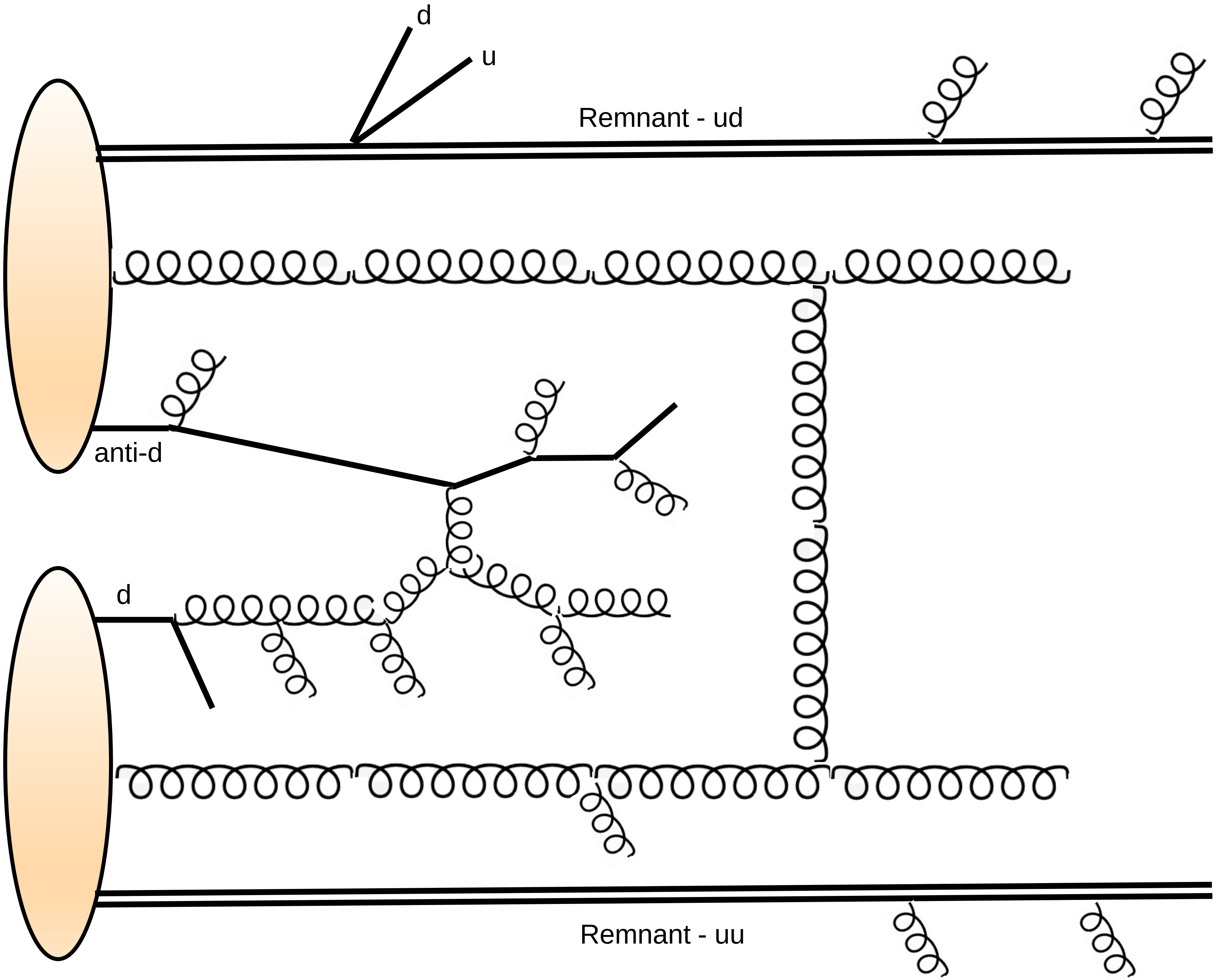
Color Reconnection

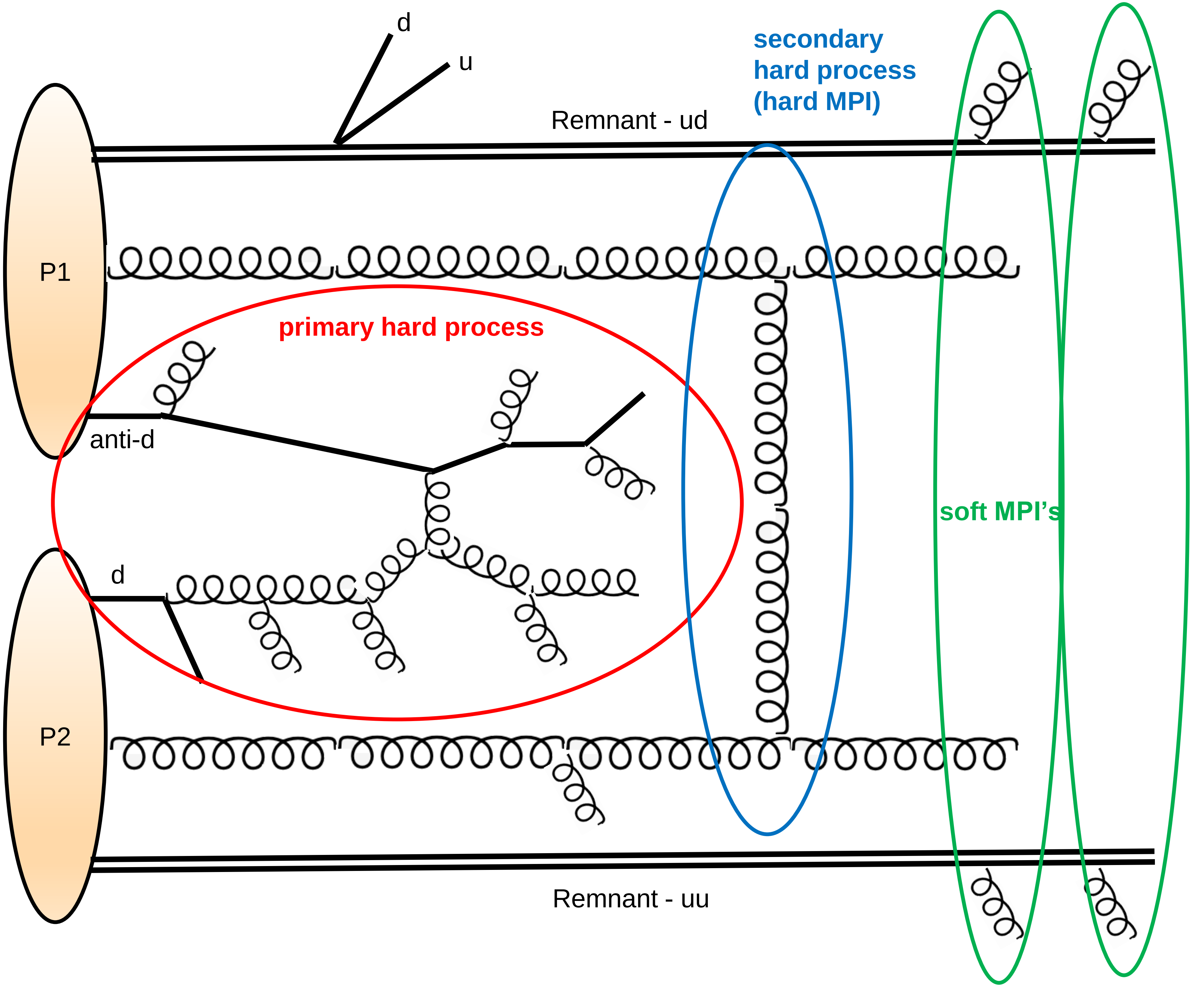
- Non perturbative effects like colour reconnection start to be important source of uncertainties in precise LHC measurements (for example top mass).

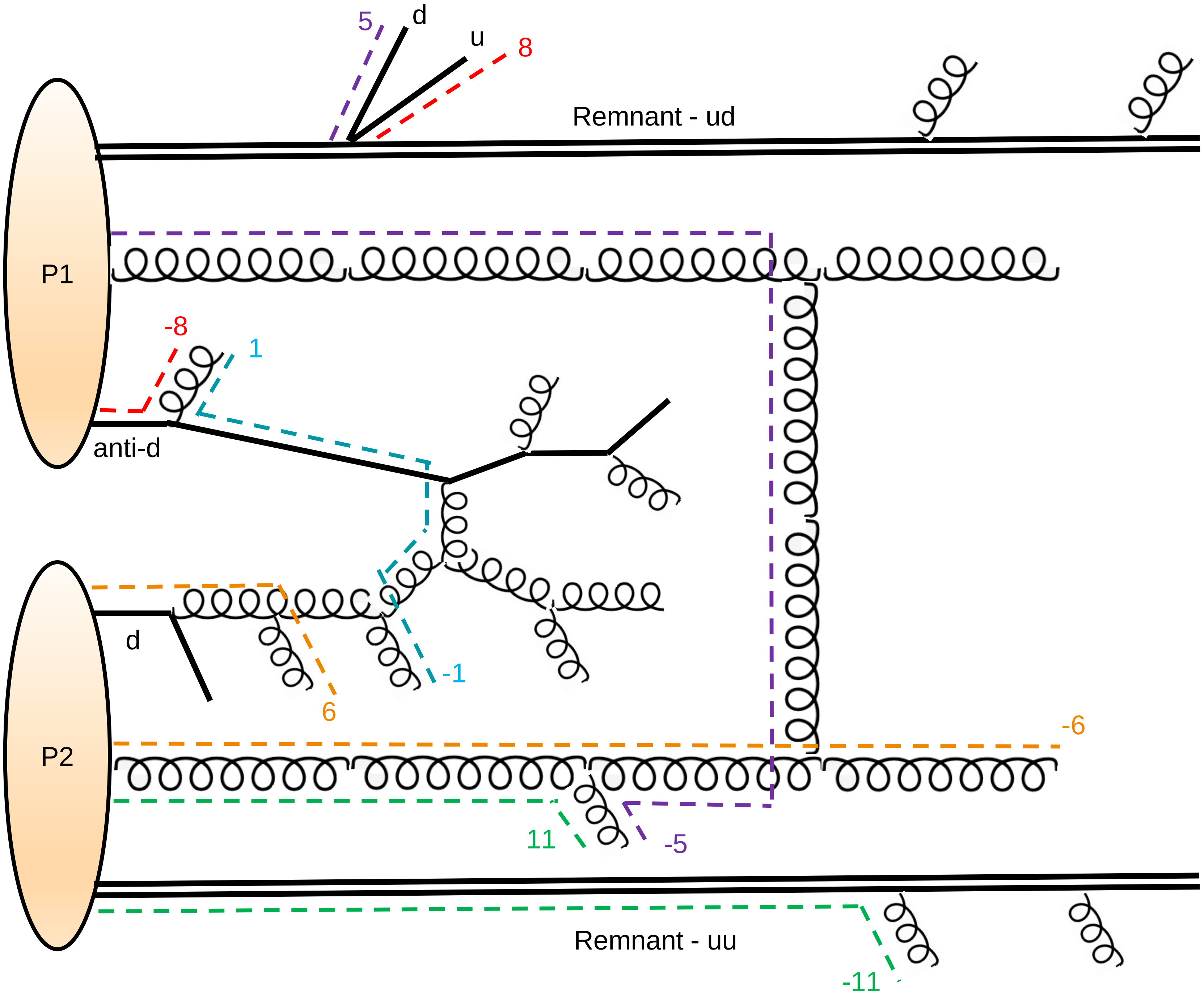
e.g.
S. Argyropoulos , T. Sjöstrand,
Effects of color reconnection on $t\bar{t}$
final states at the LHC
JHEP 1411 (2014) 043



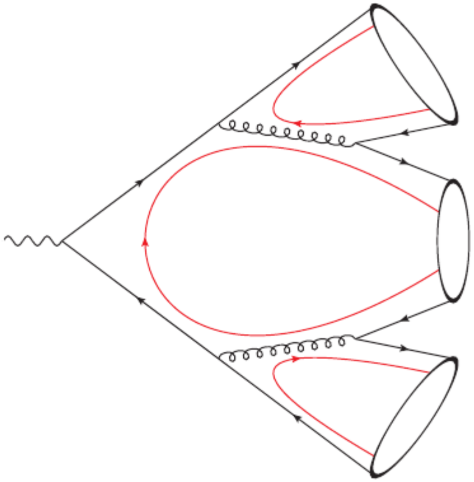
- Our aim is to introduce the space-time picture in Herwig 7
- notice a similar effort in Pythia [S. Ferreres-Solé, T. Sjöstrand, **Eur.Phys.J. C78 (2018) no.11, 983**]


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
d
6
-1
-6
P2
11
-5
Remnant - uu
-11

Basic building blocks of MPI in Herwig - Colour connection



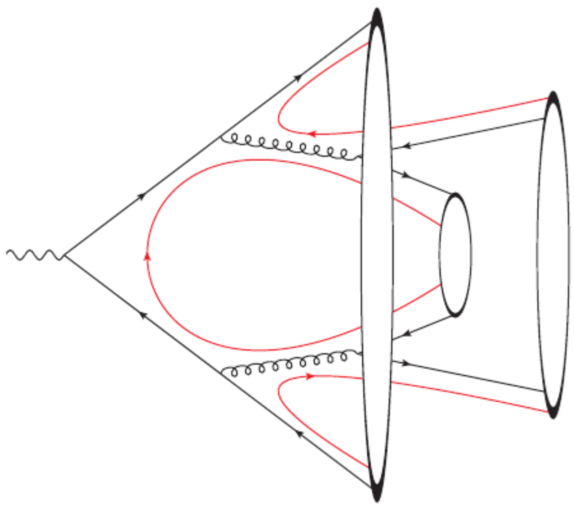
Extending the hadronization model in Herwig(++):

- 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

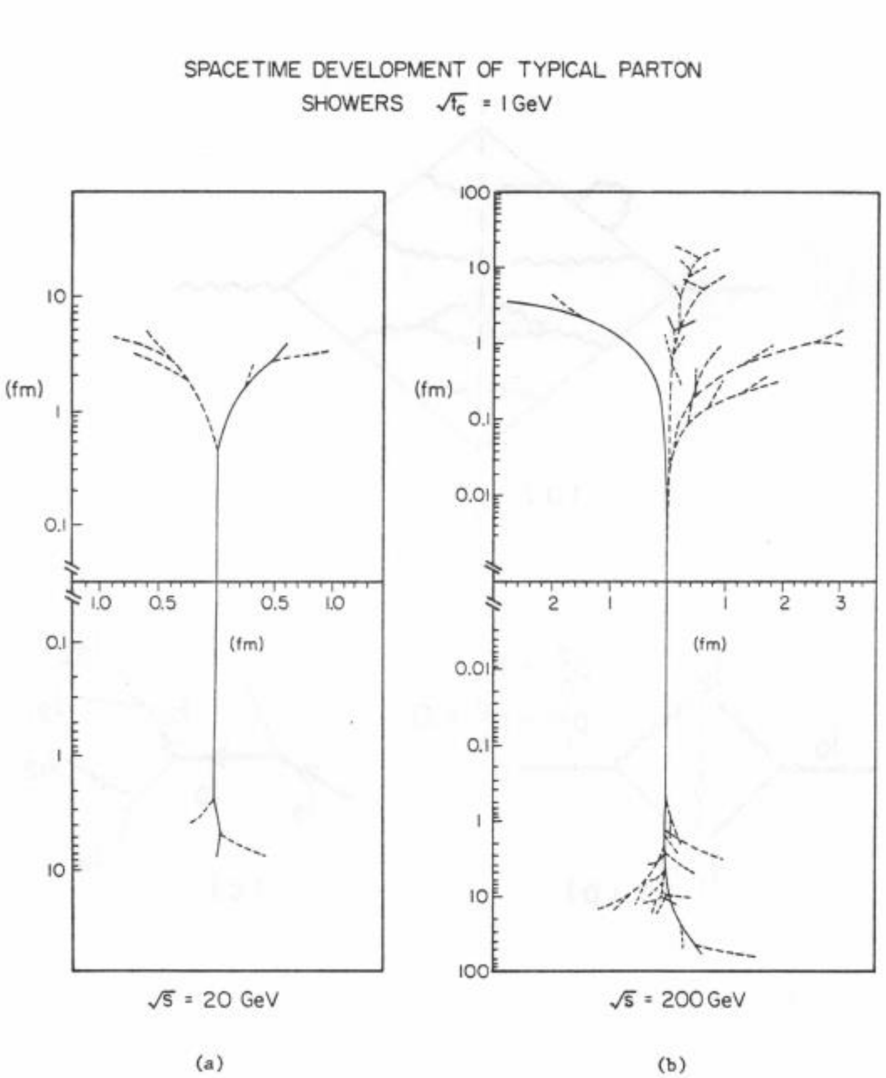
- Allow CR if the cluster mass decreases,

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

  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

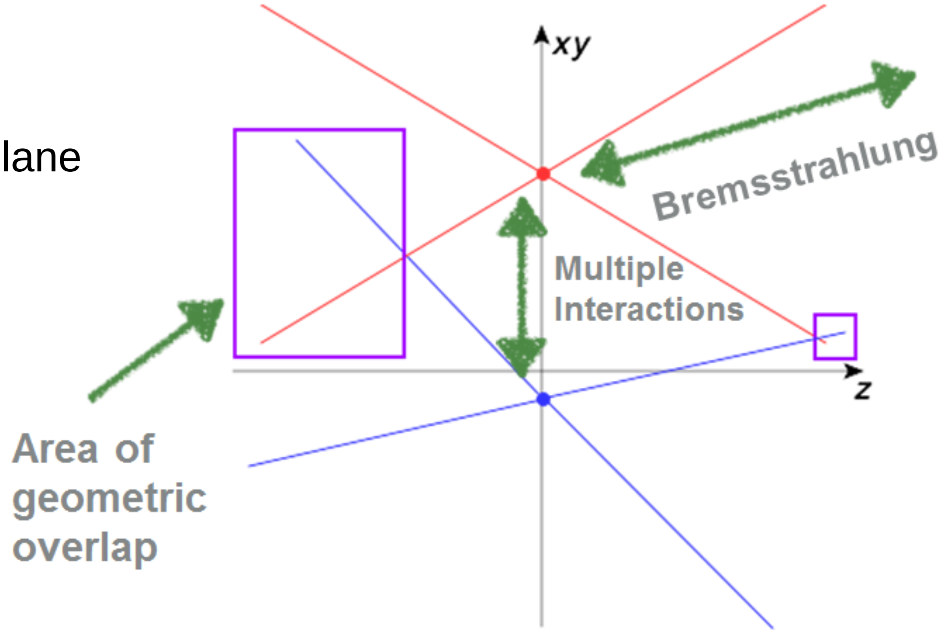
$$\tau(q^2) = \frac{\hbar\sqrt{q^2}}{\sqrt{(q^2 - M^2)^2 + (\Gamma q^2/M)^2}}$$

➢ **Distance travelled for proper lifetime**

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

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

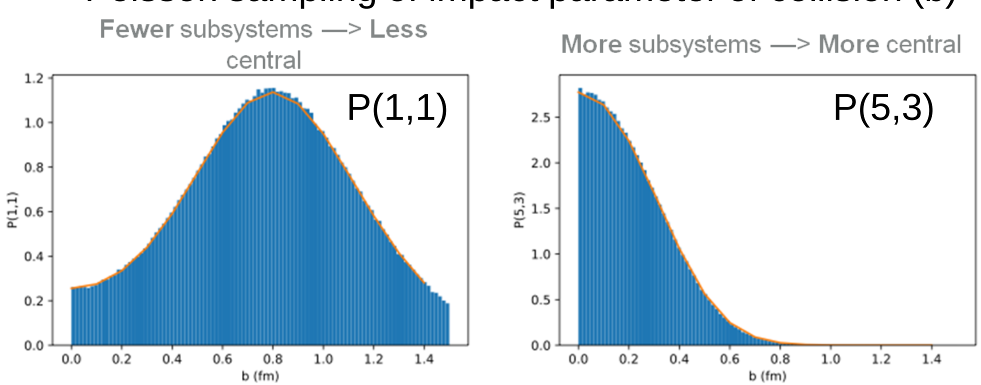
- ➢ Each scatter (MPI) gets its point in xy plane (inspired by heavy ion collision)
- ➢ Shower evolves partons further in xyz
- ➢ Motivation to cluster "close" partons



Issues:

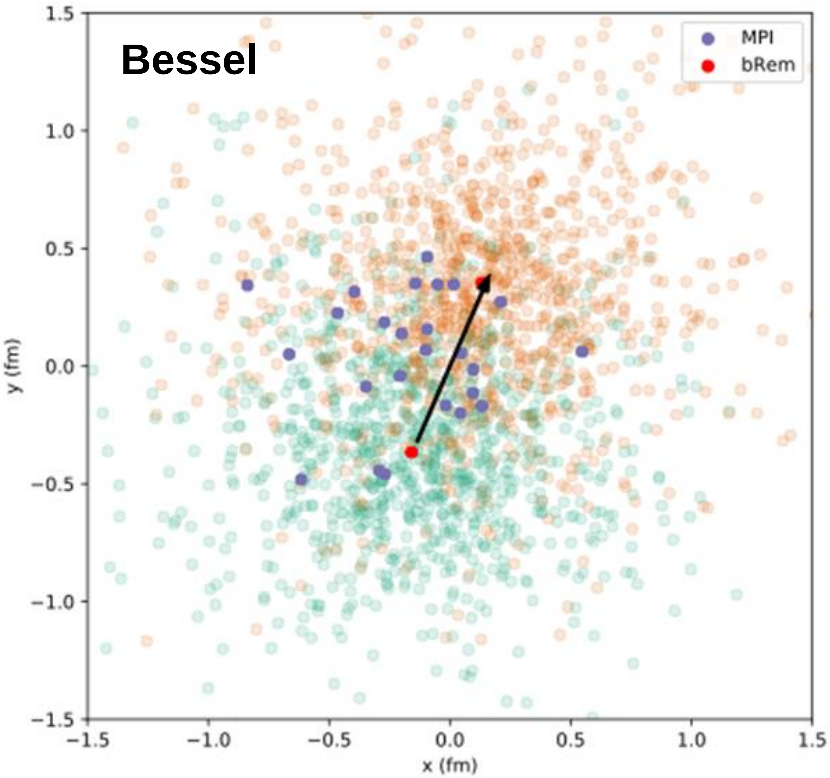
- ➔ Impact parameter
- ➔ Proton profile
  - ◆ Black disk
  - ◆ Gaussian
  - ◆ Overlap function (Bessel)
- ➔ Proton mean radius (r_0)
- ➔ Proton remnants

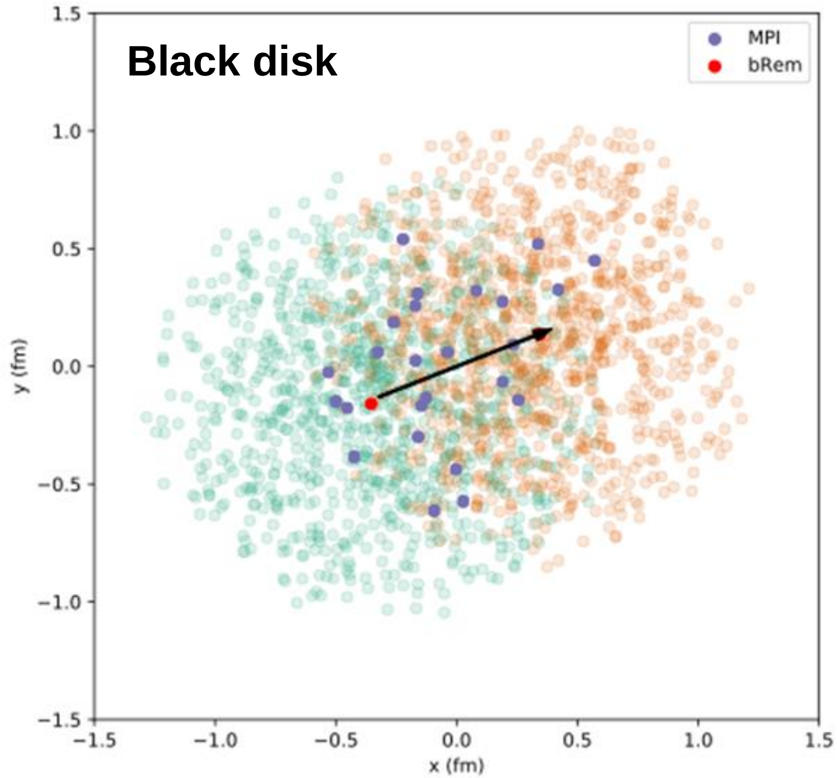
Poisson sampling of impact parameter of collision (b)

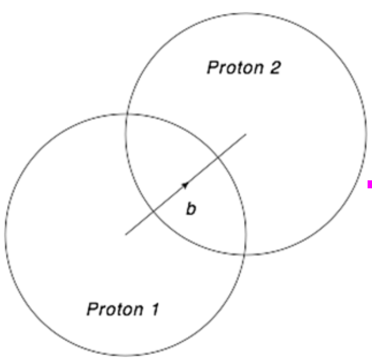


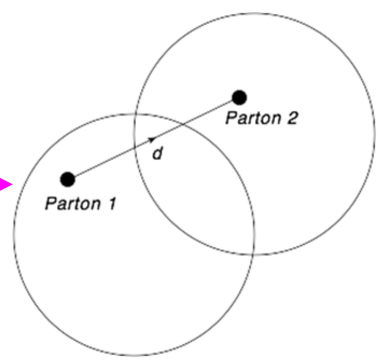
$$\mathcal{P}_{h,k} = \frac{\langle n_h(b)\rangle^h}{h!}\frac{\langle n_k(b)\rangle^k}{k!}\exp[-(\langle n_h(b)\rangle + \langle n_k(b)\rangle)]$$

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



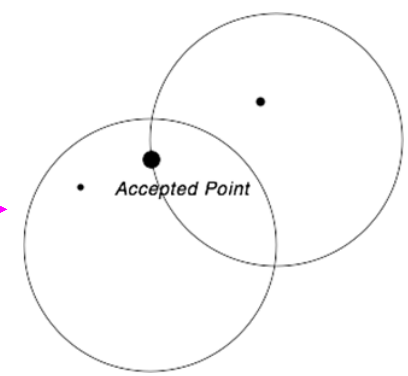






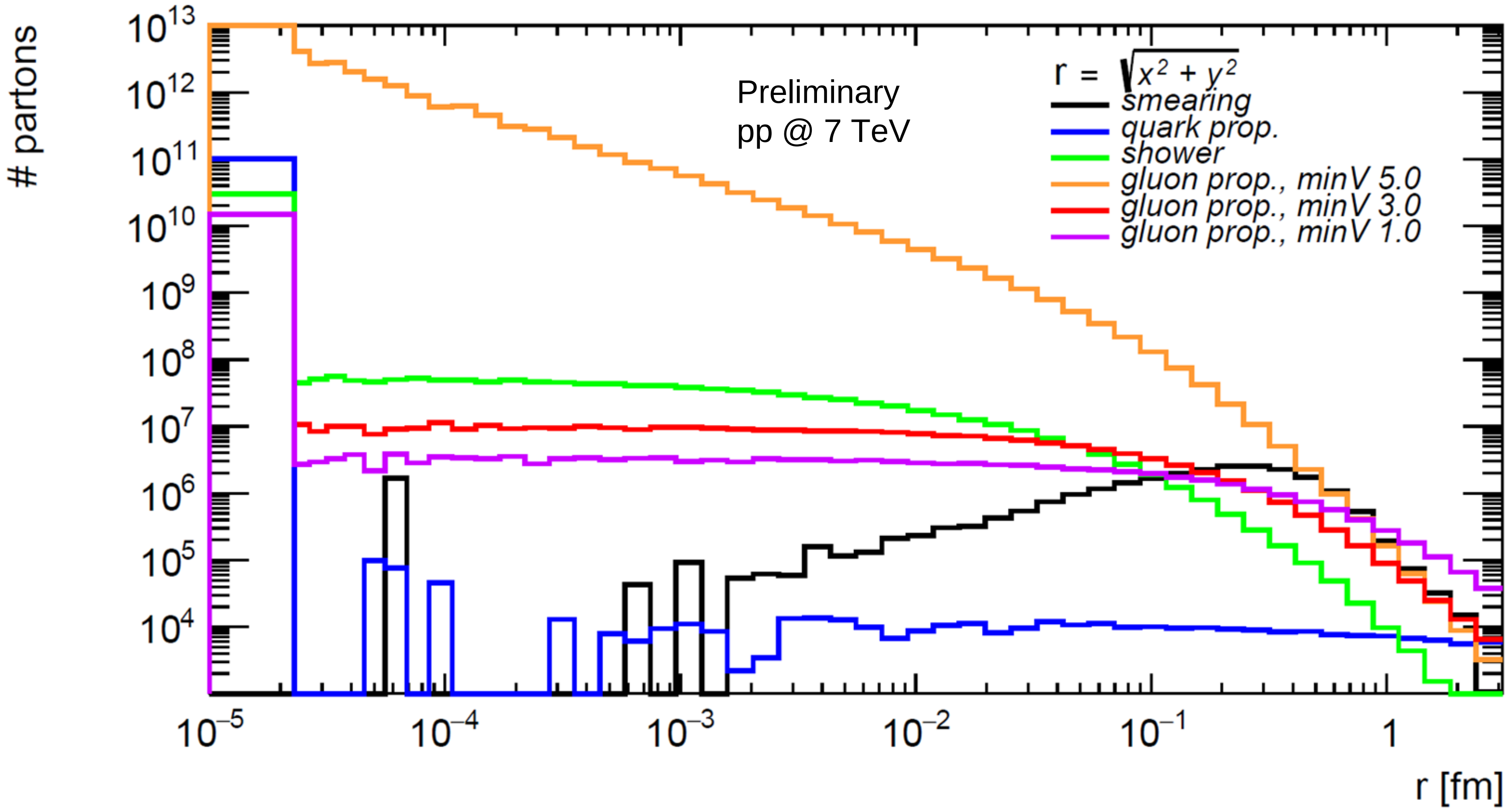
Probability to accept
or reject the points

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



iterated N times; discarded points → remnants

Space-time Model - sources of displacement - summary

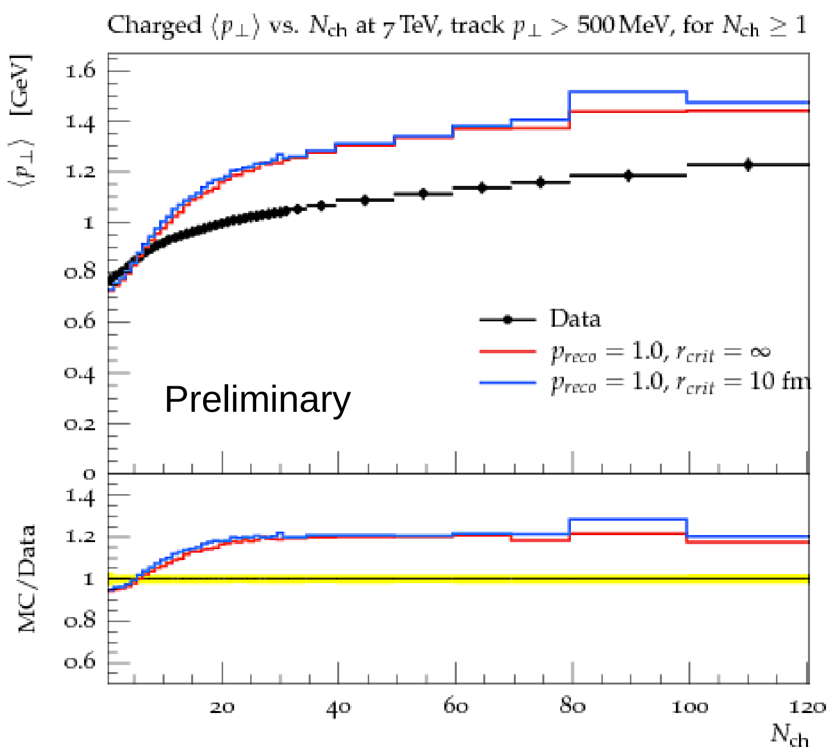


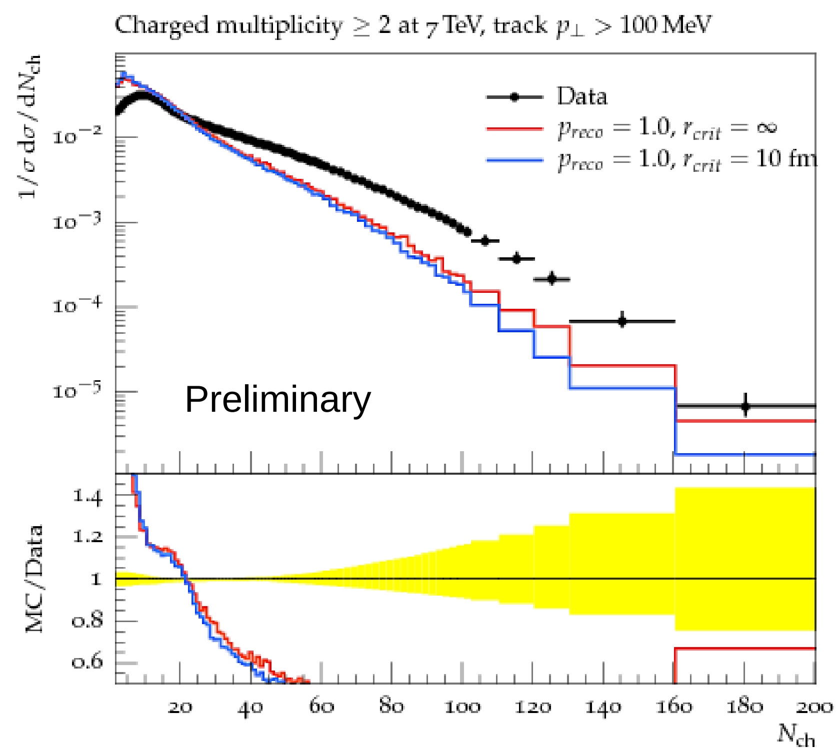
- “final” state partons in shower are further allowed to propagate
- **minV** (minimal virtuality) - so far a free parameter
- gluons are then forced to split to qqbar pair

Space-time Model - preliminary results

First idea: critical radius

→ plain CR + critical radius (new parameter)



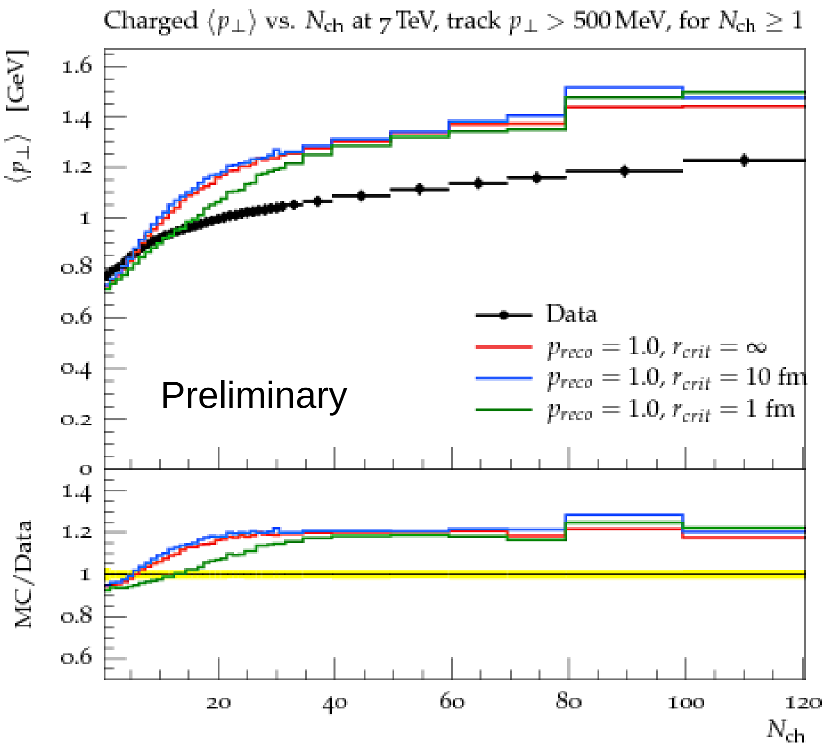


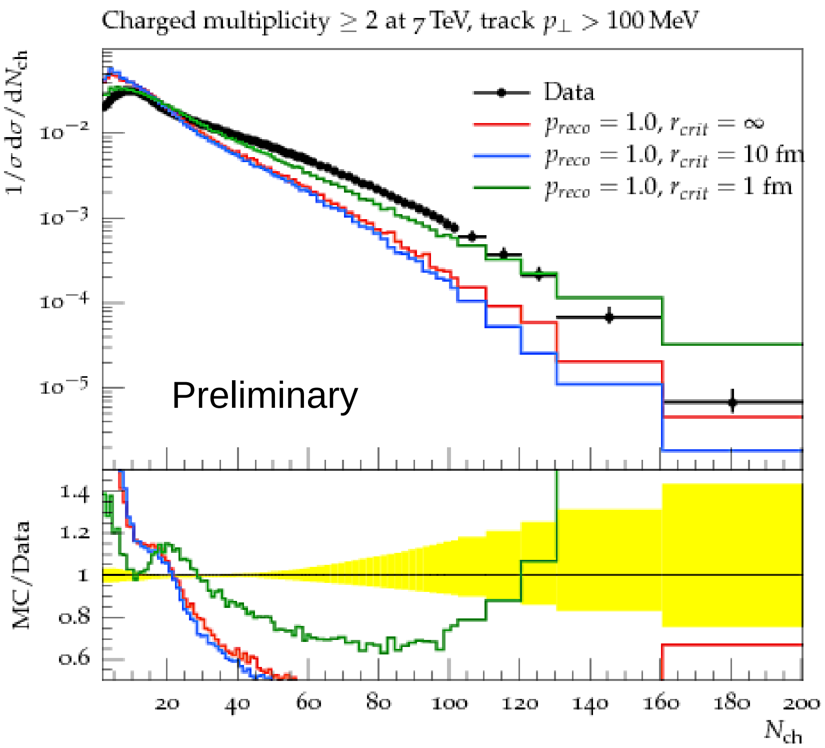
Not tuned (just to see the effect), **MPI smearing only** - no shower ST

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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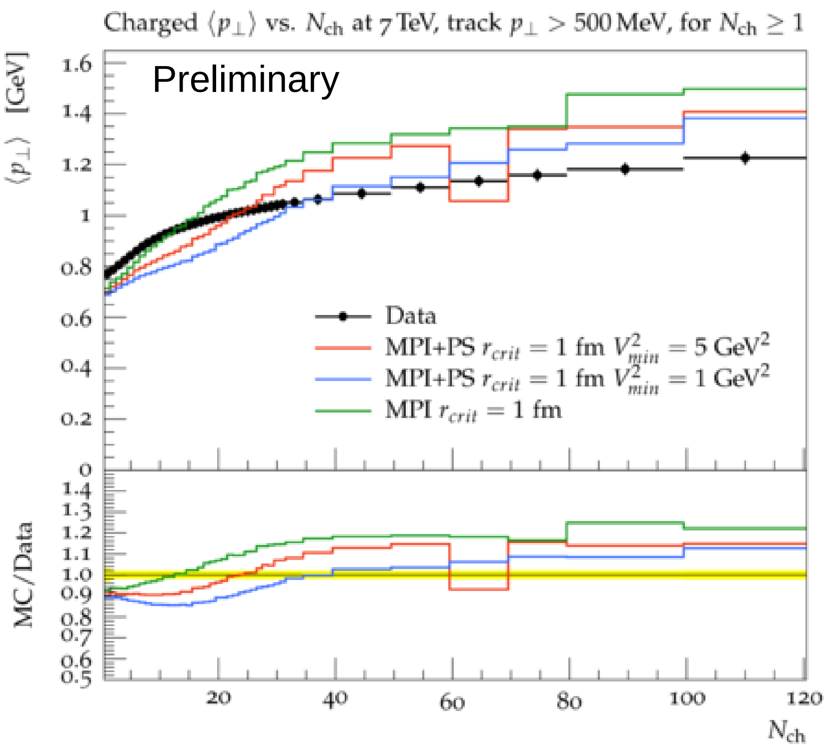

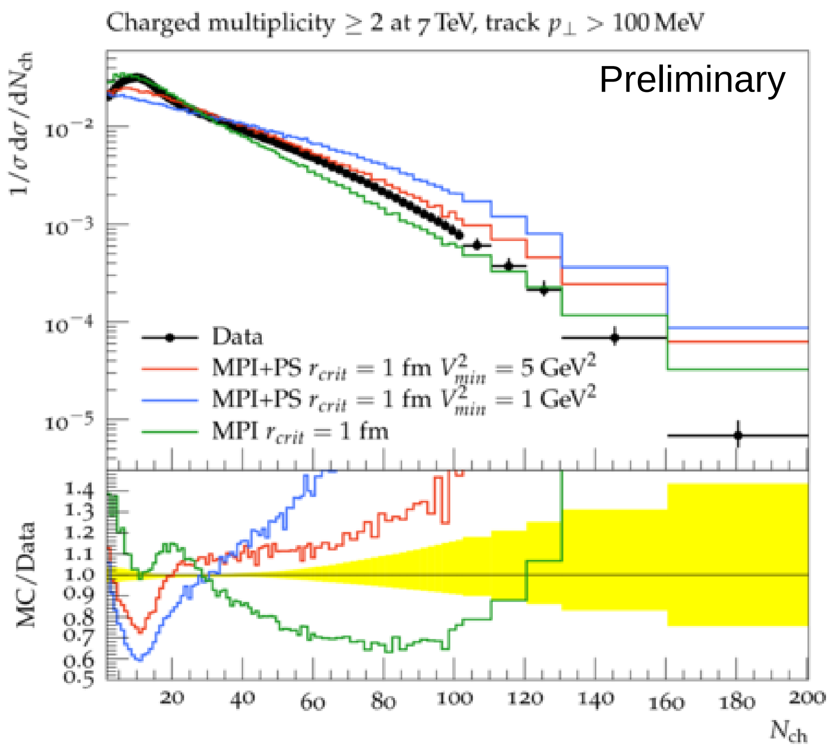

Not tuned (just to see the effect), **MPI + shower ST**, p_{reco} = 1 (same as previous slides)

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 μ_{soft} and $\sigma^{\text{inc}}_{\text{soft}}$ in

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

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

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

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

Sum up:

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