Karlsruhe Institute of Technology

Bundesministerium
für Bildung
und Forschung

Theory and recent developments in MC simulation of soft QCD

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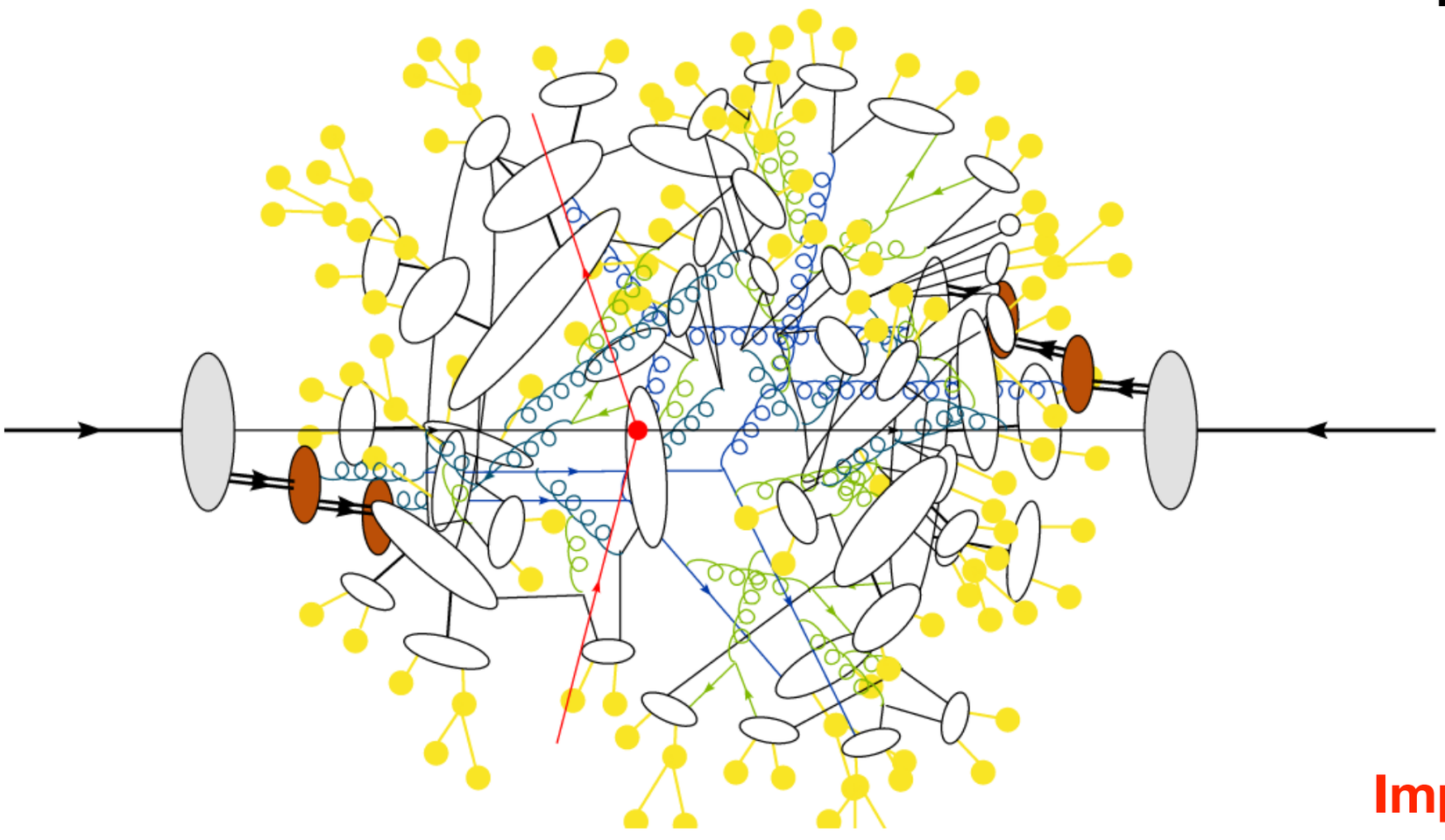
MCnet

Introduction

Pythia

Herwig



Building blocks

- PDF
- Initial State Radiation
- Hard interaction
- **Multi Parton Interactions**
- Final State Radiation
- **Diffraction**
- Parton Shower
- **Hadronization**
- **Colour Reconnection**
- **Decay**

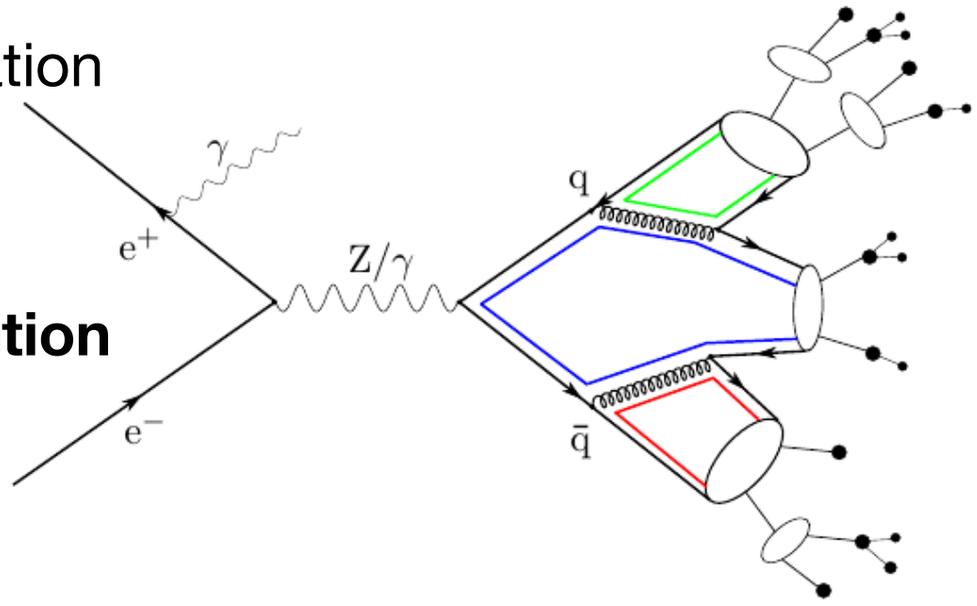
Important for soft QCD modeling

Simulating pp collisions is complicated!

Introduction

The LEP environment

- Hard processes + Parton Shower + Hadronization

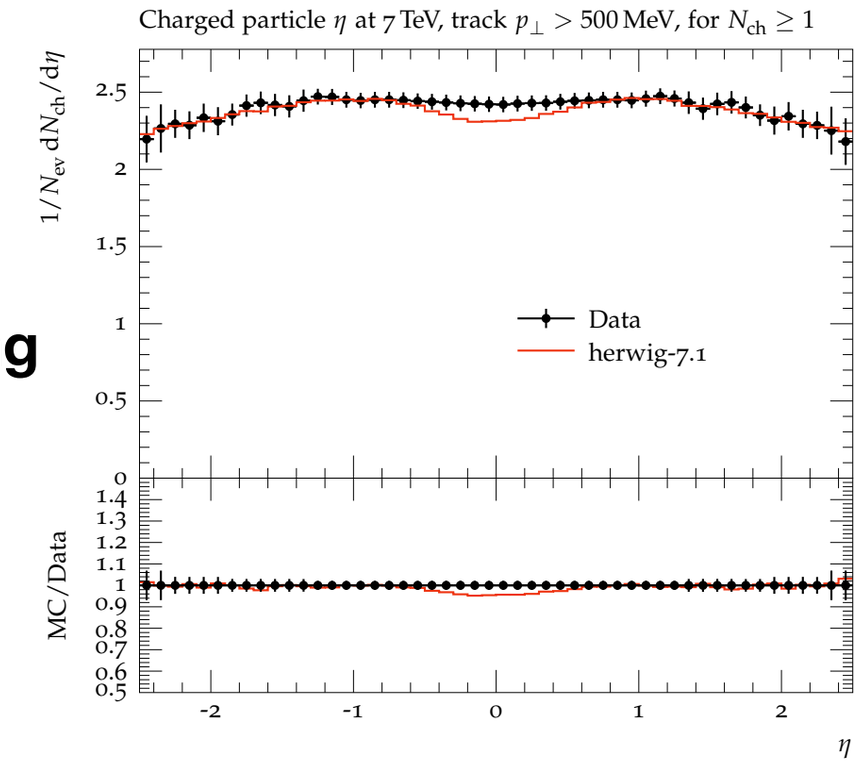


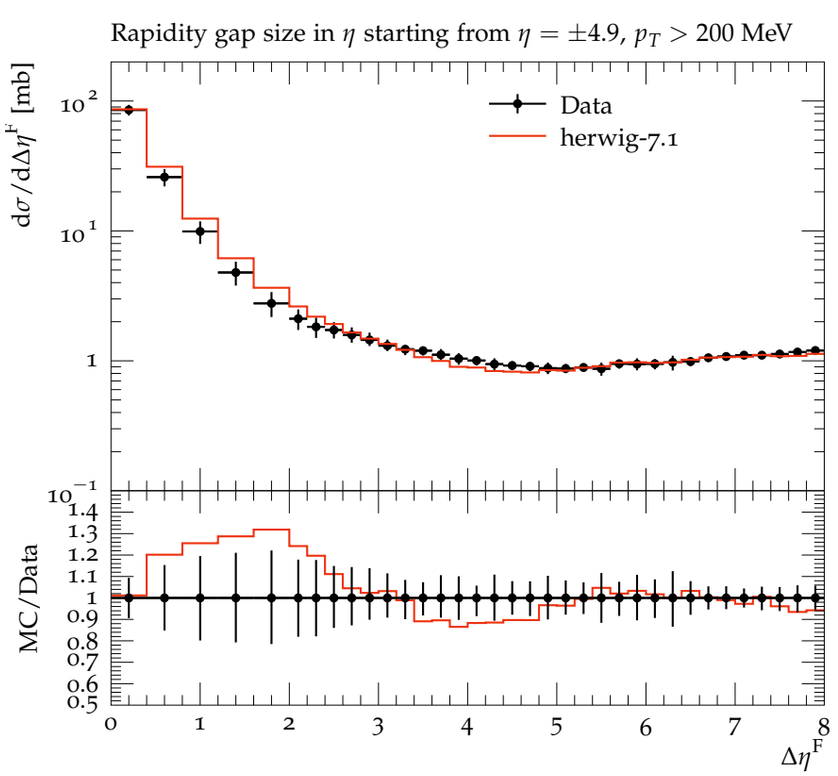
The LHC environment

Guiding principle: Jet universality and factorization

- Tune Hadronization model to LEP data
- Add MPI
- Add Diffraction
- Add Colour Reconnection

Good overall description of MB and UE data aiming for a precision <10%





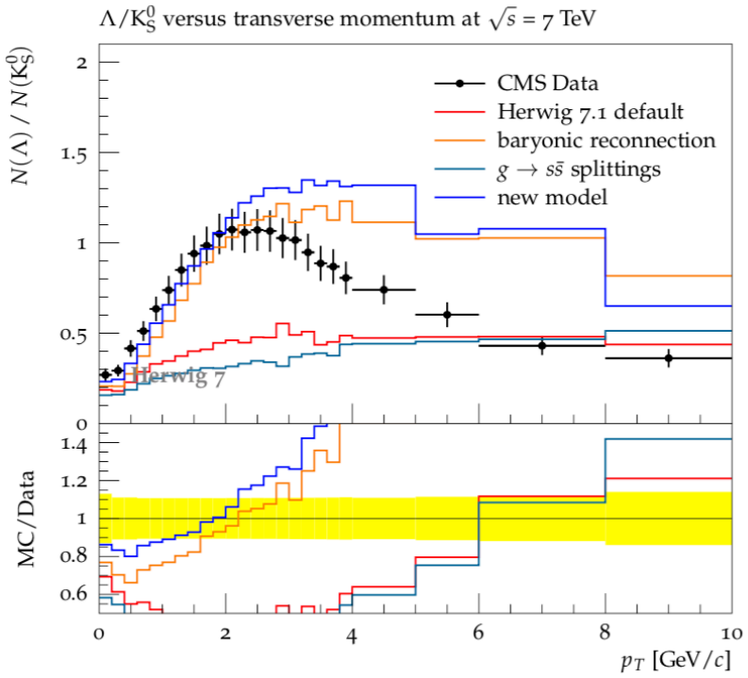
[ATLAS New J.Phys. 13 (2011) 053033] [ATLAS Eur.Phys.J. C72 (2012) 1926]

Introduction

Driving force behind development: Experimental data!

General properties well described but as measurements are getting more and more differential MPMCEG reach their limit of possibilities

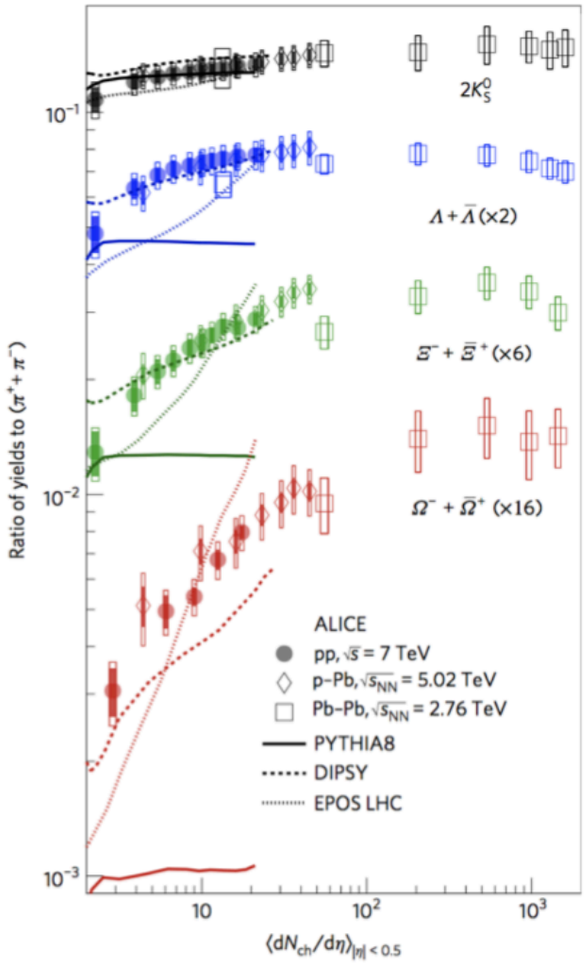
Flavour observables



[CMS, JHEP 05 (2011) 064]

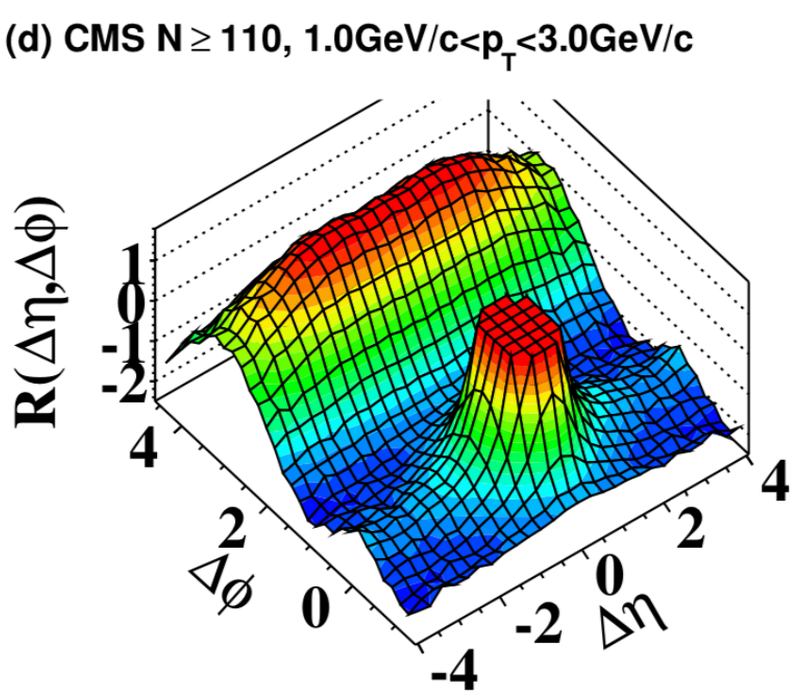
Tunable/tweakable?

Strangeness enhancement



[ALICE, Nature Physics 13, 535–539 (2017)]

Collective effects „ridge“



[CMS, JHEP 1009 (2010) 091]

-> New models and ideas needed for non-flow approaches

Simulation of soft QCD - Model overview

EPOS3

- Core-Corona approach — [K. Werner, B. Guiot, Iu. Karpenkob, T. Pierog, Nucl. Phys. A 931 (2014) 83]

Colour Glass Condensate

- CGC+Lund model — [B. Schenke, S. Schlichting, P. Tribedy, R. Venugopalan Phys. Rev. Lett. 117, 162301 (2016)]

Pythia/Dipsy

- Rope hadronization — [C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov, JHEP 1503, 148]
- String shoving — [C. Bierlich, G. Gustafson, L. Lönnblad, 1612.05132]
- Space-time model — [S. Ferrees-Solé, T. Sjöstrand, 1808.04619]

Herwig

- Soft and diffractive scattering — [S. Gieseke, PK, F. Loshaj, Eur.Phys.J. C77 (2017) no.3, 156]
- Baryonic colour reconnection — [S. Gieseke, PK, S. Plätzer, Eur.Phys.J. C78 (2018) no.2, 99]
- Space-time model — [J. Bellm, C. B. Duncan, S. Gieseke, M. Myska, A. Siodmok, in preparation]
- New theory approach to CR — [S. Gieseke, PK, S. Plätzer, A. Siodmok, JHEP 1811 (2018) 149]

Connection to HI

- Angantyr — [C. Bierlich, G. Gustafson, L. Lönnblad, H. Shah, JHEP 2018,134]
- PISTA — [J. Bellm, C. Bierlich, 1807.01291]

This talk

EPOS 3 - The Core Corona model

[K. Werner, B. Guiot, Iu. Karpenkob, T. Pierog, Nucl. Phys. A 931 (2014) 83]

Motivation

- High mult. pp collisions similar energy density as HI collisions
- Similar behavior of pp pPb and PbPb observed
- Hydrodnamical treatment for pp justified

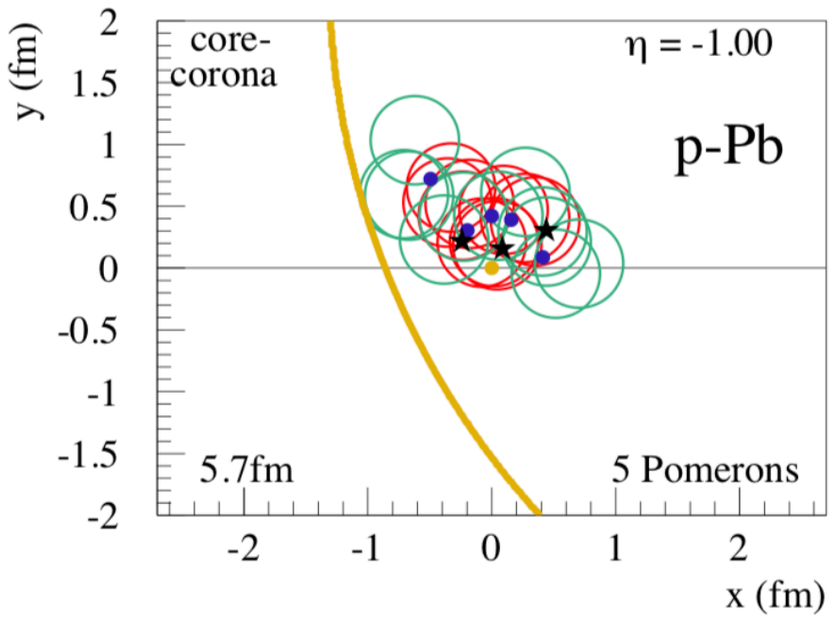
Initial conditions

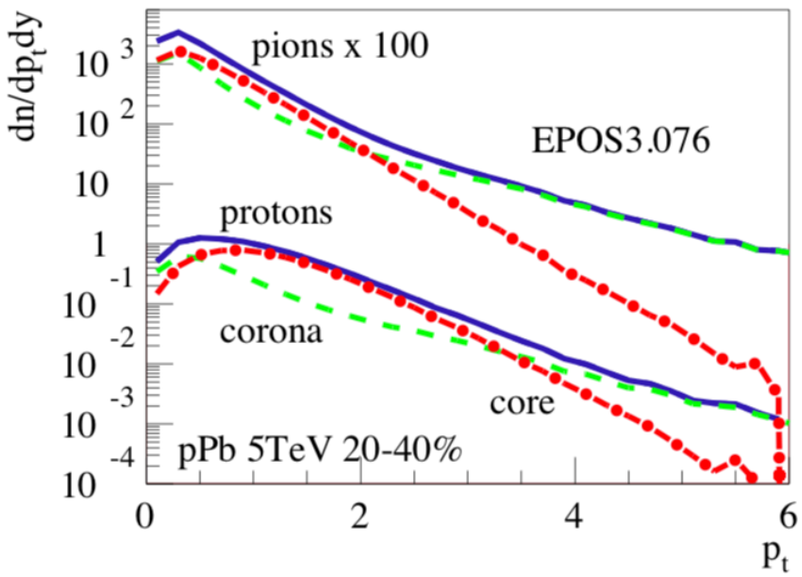
- Gribov-Regge multiple scatterings
- CGC motivated saturation scale
- Parton ladders treated as strings

Core-Corona approach

- High pT strings escape (corona)
- High density region of stings (core)
- Hydrodynamical evolution of core

Allows a smooth transition from pp to PbPb





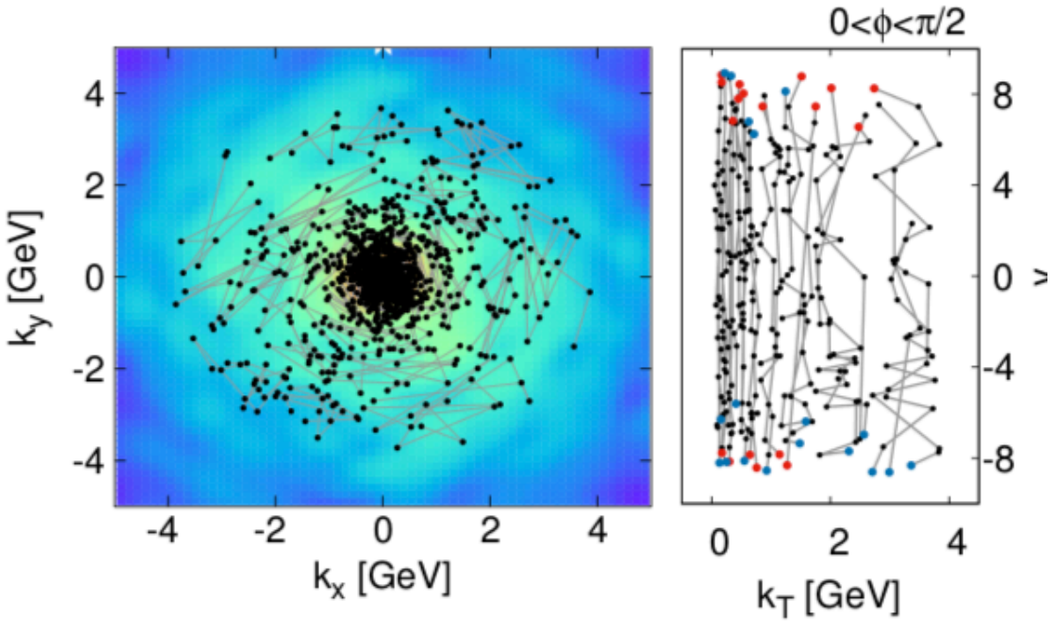
Colour Glass Condensate + Lund Strings

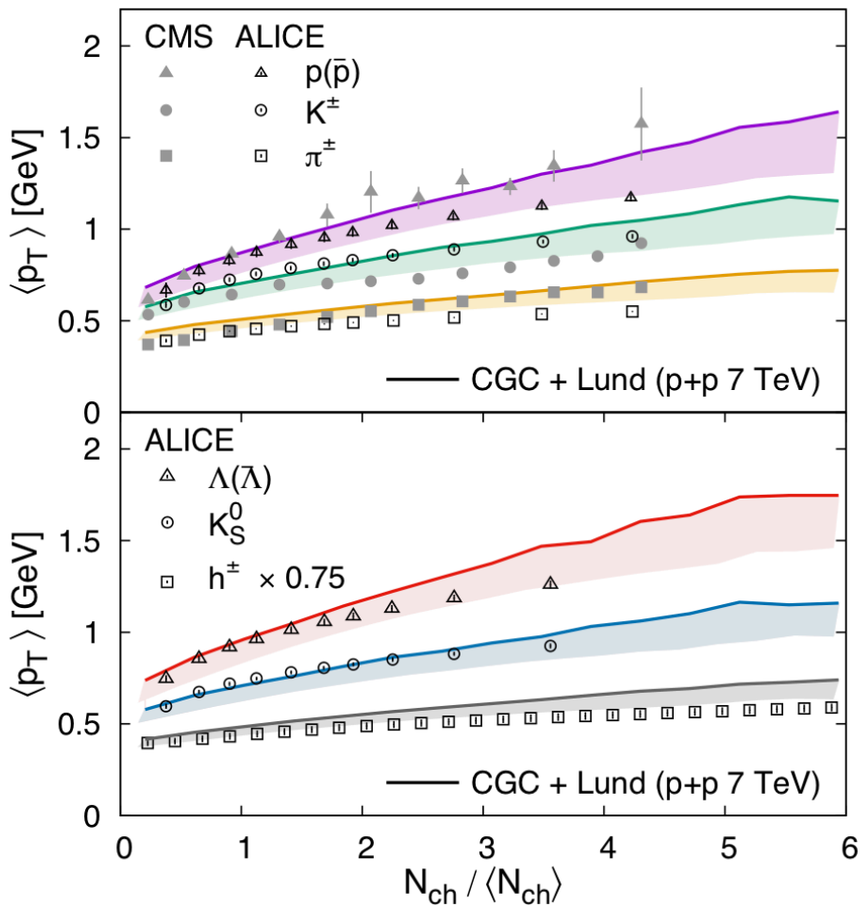
[B. Schenke, S. Schlichting, P. Tribedy, R. Venugopalan Phys. Rev. Lett. 117, 162301 (2016)]
[B. Schenke et. al, Phys. Rev. Lett.108, 252301 (2012)]

CGC+Lund model

- Non-perturbative ansatz
- Initial conditions from IP-Glasma model

  -> Calculate gluon distribution (pT) on an event by event basis from collision geometry
- Sample number of gluons
- Distribute gluons uniform in rapidity
- Feed gluons into Pythia
- Group gluons close in momentum into strings
- Add qqbar to guarantee colour neutrality





Strong growth of avg pT and clear mass ordering from pure initial state correlations

Pythia space-time evolution for hadronization

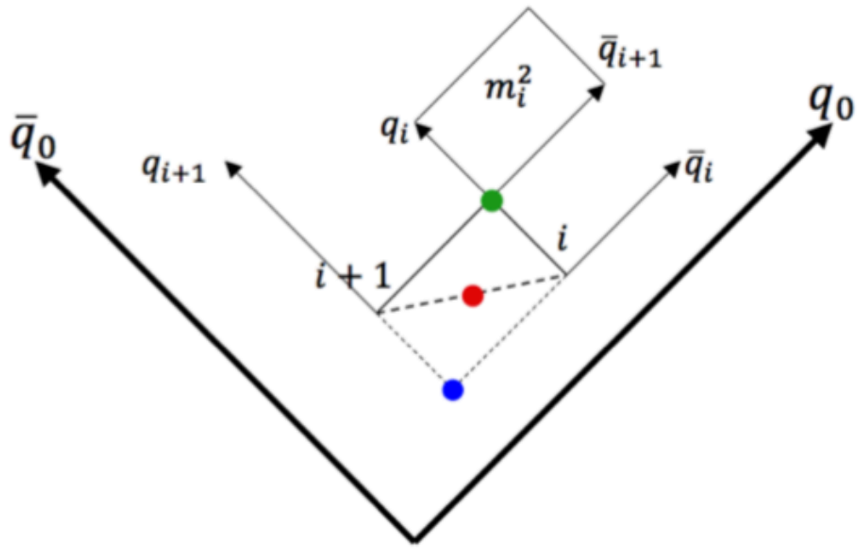
[S. Ferrees-Solé, T. Sjöstrand, 1808.04619]

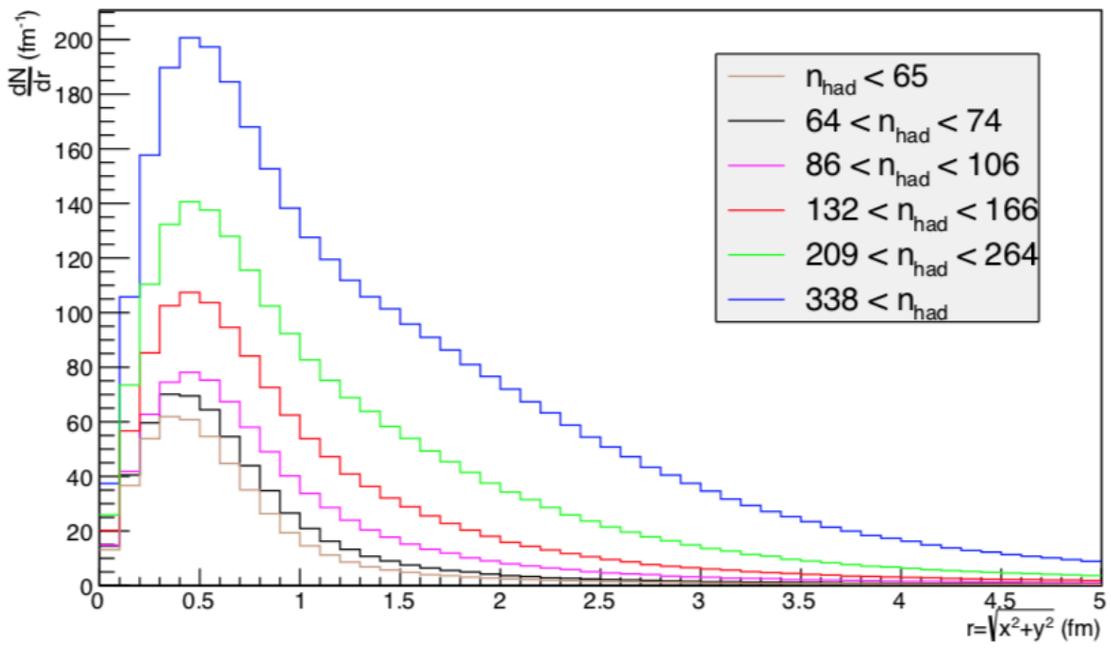
Linear translation from energy-momentum to space-time for massless quarks

$$\left|\frac{\mathrm{d}p_{z,\mathrm{q}/\overline{\mathrm{q}}}}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_{z,\mathrm{q}/\overline{\mathrm{q}}}}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E_{\mathrm{q}/\overline{\mathrm{q}}}}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}E_{\mathrm{q}/\overline{\mathrm{q}}}}{\mathrm{d}z}\right| = \kappa \ .$$

Location of break up point of $q\bar{q}$ string

$$v_i = \frac{\hat{x}_i^+ p^+ + \hat{x}_i^- p^-}{\kappa} \ .$$





Density of hadron production high for high multiplicity pp events

Close packing becomes important ->additional motivation for collective behavior

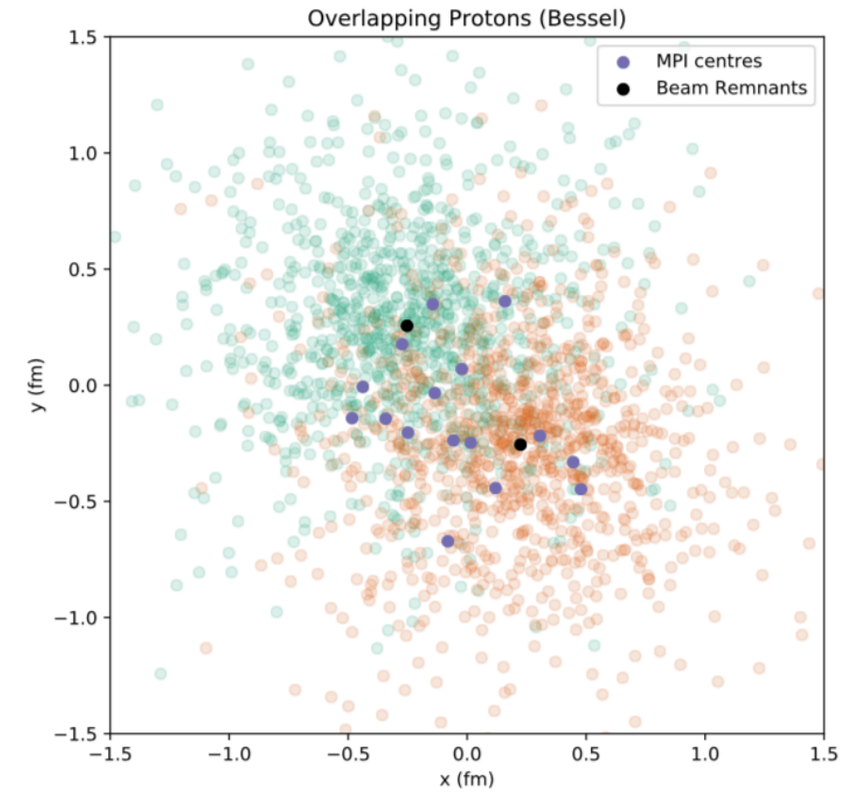
No space-time vertices for individual MPI collisions

Herwig space-time model preview

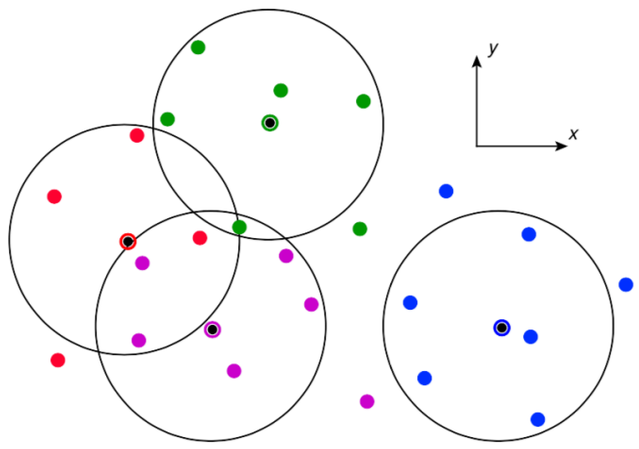
[J. Bellm, C. B. Duncan, S. Gieseke, M. Myska, A. Siodmok in preparation]

Sample MPI scattering centers from overlap function

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



Parton shower: propagation in transverse plane



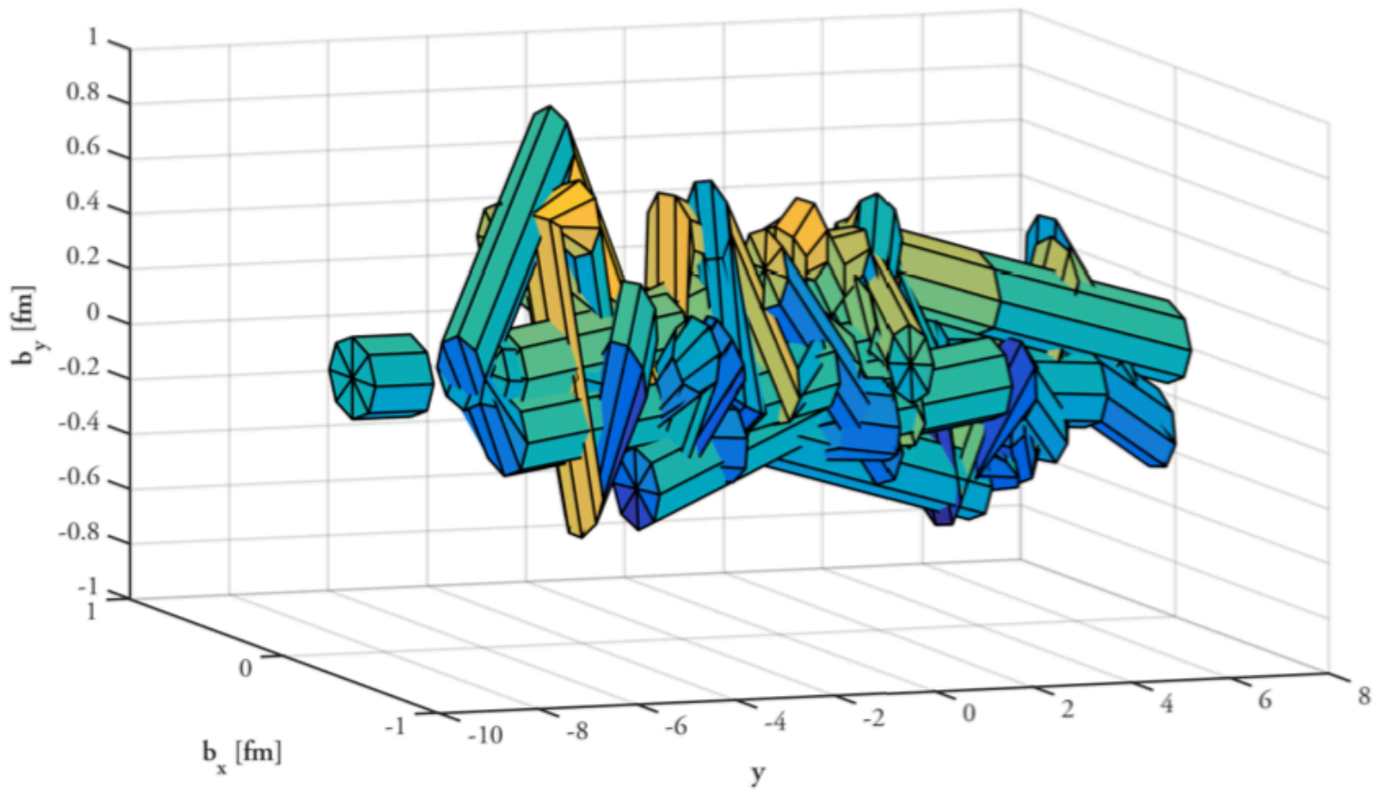
Colour Reconnection based on space-time measure

$$R_{ij}^2 = \frac{\Delta d_{\perp ij}^2}{d_0^2} + \Delta y_{ij}^2, \qquad p_{\mathrm{M,reco}} = \exp\left(-\frac{R_{14} + R_{23}}{R_{12} + R_{34}}\right) = \exp\left(-\frac{\sum R_{\mathrm{new}}}{\sum R_{\mathrm{old}}}\right).$$

->Less parameters and CR depends on event topology

Rope Hadronization Pythia/Dipsy

[C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov, JHEP 1503, 148]



Basic idea

- Dense environment
- Overlapping strings -> ropes
- Higher string tension

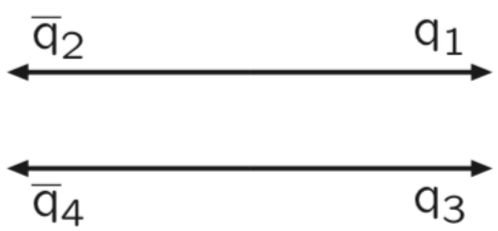
-> more baryons

-> more strangeness

Casimir scaling

- QCD potential in different representations proportional to quadratic Casimir

$$\kappa_{\text{eff}} \propto C_2$$



$$3 \otimes 3 = 6 \oplus \bar{3}$$

$$C_2^{(6)} = \tfrac{5}{2} C_2^{(3)}$$

String breaking

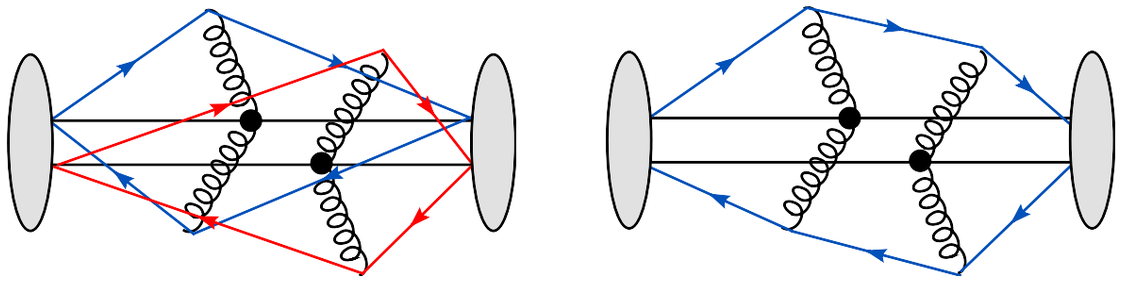
- Tunneling $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$
- Larger string tension
- More heavy hadrons

Colour Reconnection - Herwig

[S.Gieseke, C.Röhr, A.Siodmok, Eur.Phys.J. C72 (2012) 2225]
[S. Gieseke, PK, S. Plätzer – EPJ C78 (2018) 99]

Algorithms

- **Plain** Colour Reconnection
- **Statistical** Colour Reconnection
- **Baryonic** Colour Reconnection



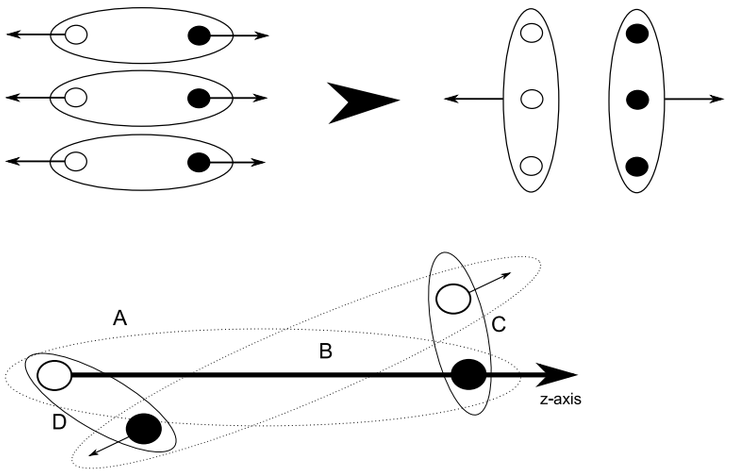
Plain and Stat CR based on reduction of invariant cluster mass

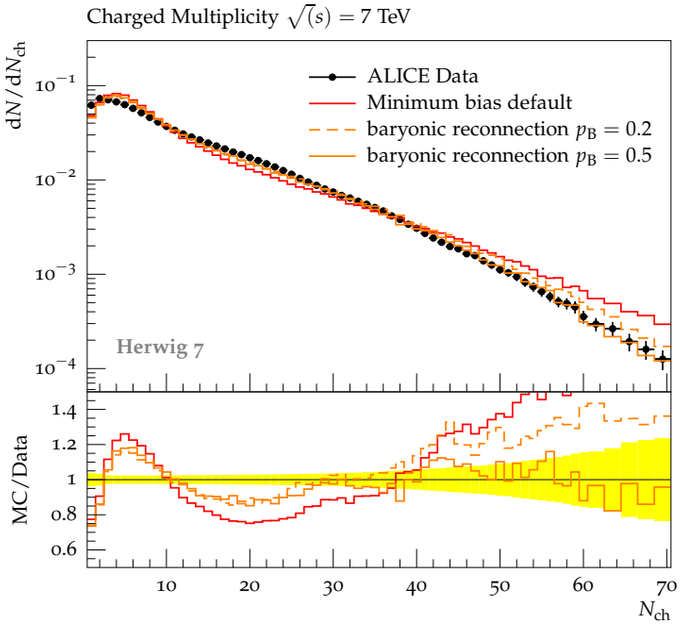
$$\lambda = \sum_{i=1}^{N_{\mathrm{cl}}} M_i^2$$

Important for the description of MB and UE data

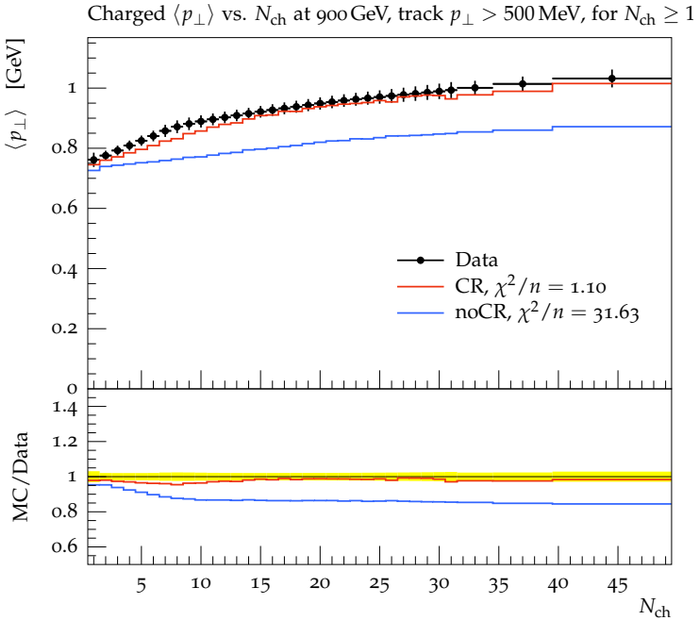
Baryonic CR

- Allow baryonic cluster during CR
- Geometrical model





[Eur.Phys.J. C68 (2010) 345-354]

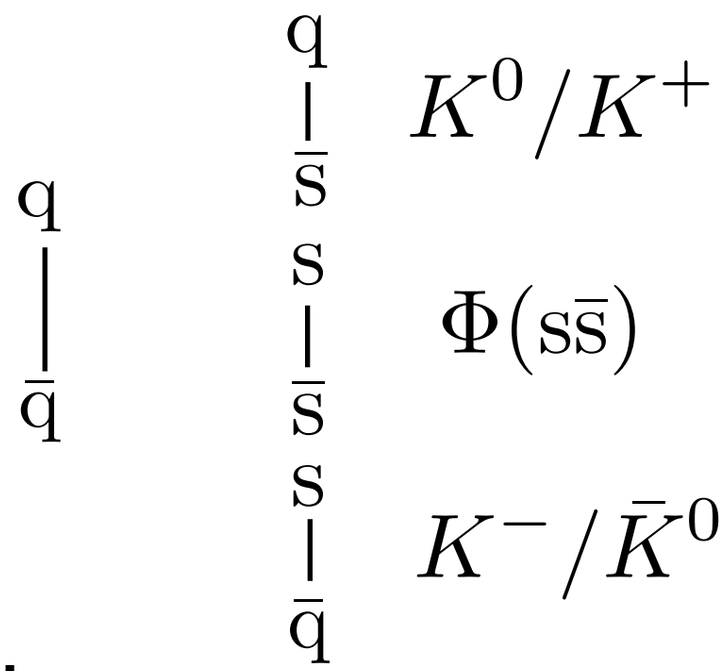


[New J.Phys.13:053033,2011]

Exploring strangeness enhancement with strings and clusters (working title)

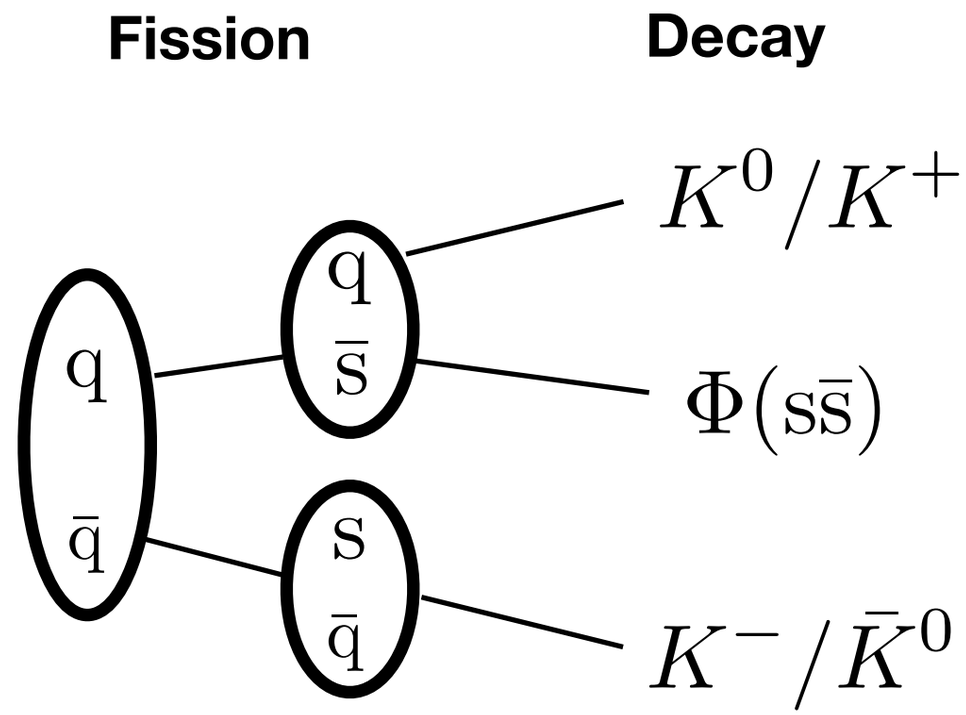
[C. Bierlich, S. Gieseke, PK]

String fragmentation



vs.

Clusters



Idea

- Two adjacent breakings with $s\bar{s}$ necessary to produce $\Phi(s\bar{s})$
- Use $\Phi(s\bar{s})$ as a trigger particle and study number of hadron species for different rapidity intervals in bins of centrality

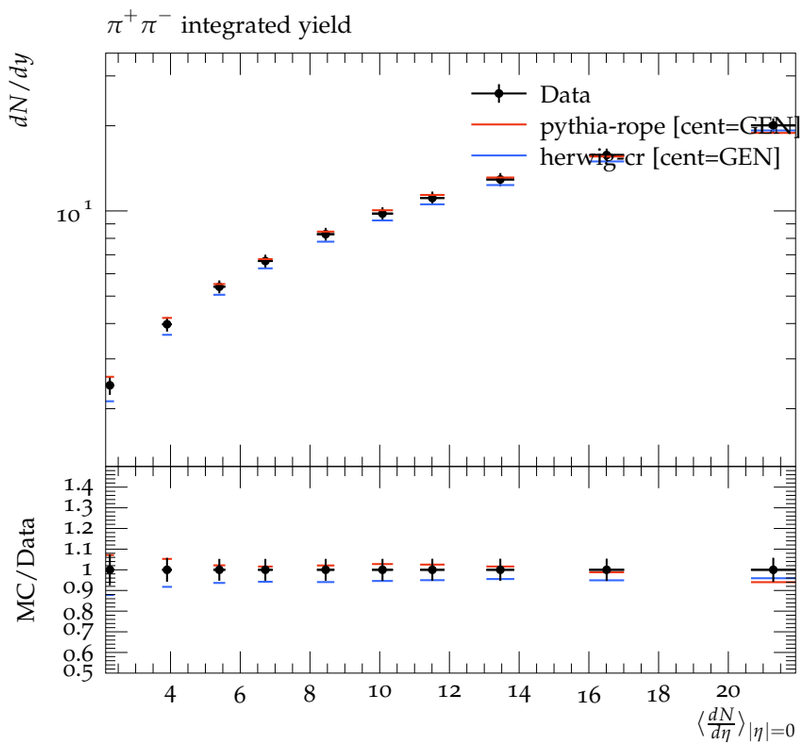
$$\Delta y = \{0.1, 0.5, 1, ...\}$$

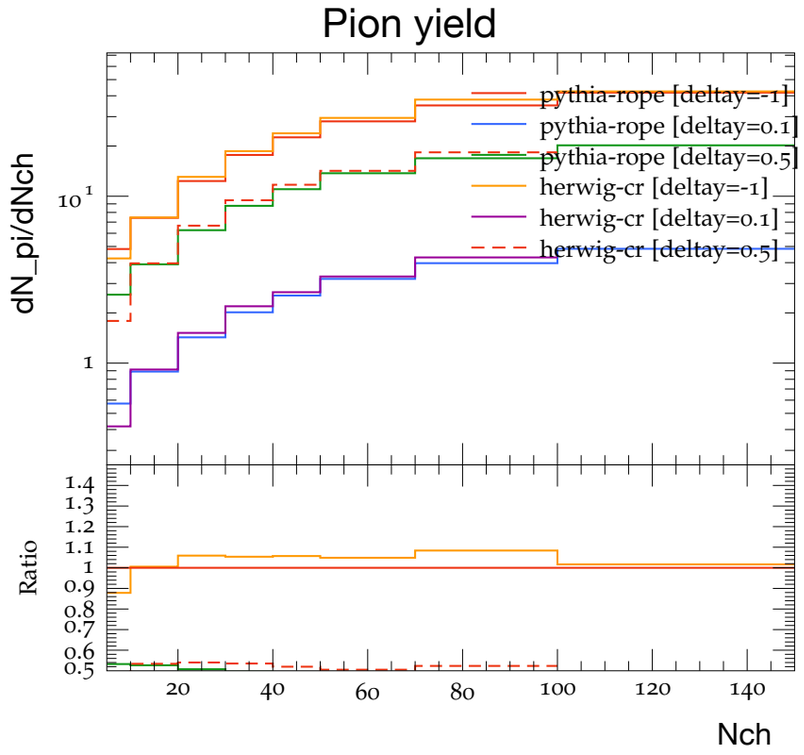
- Look at correlations between different strange hadrons

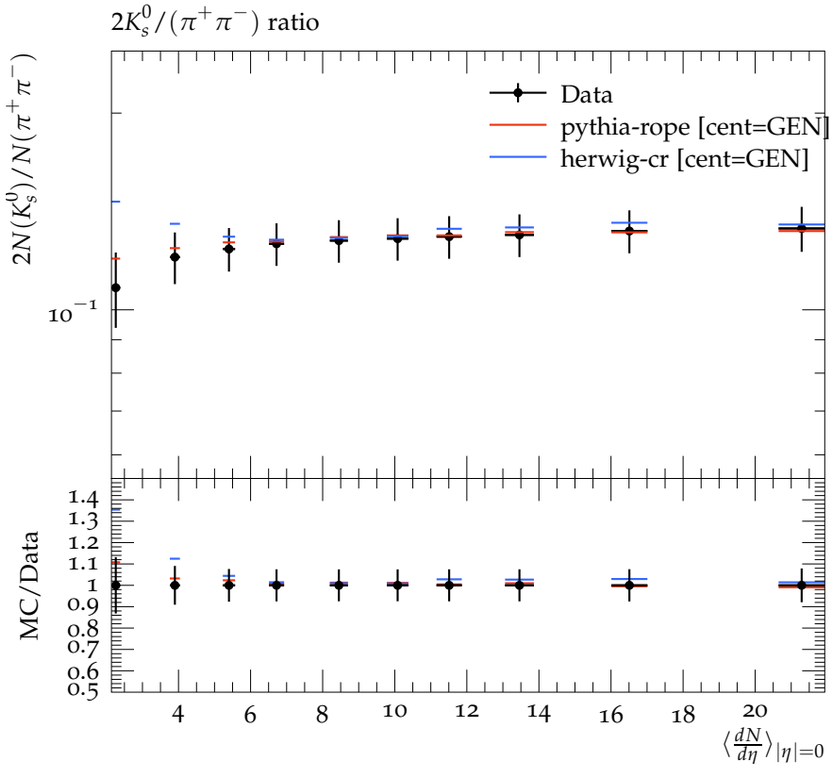
Allows us to study subtle differences in the soft models between Herwig and Pythia

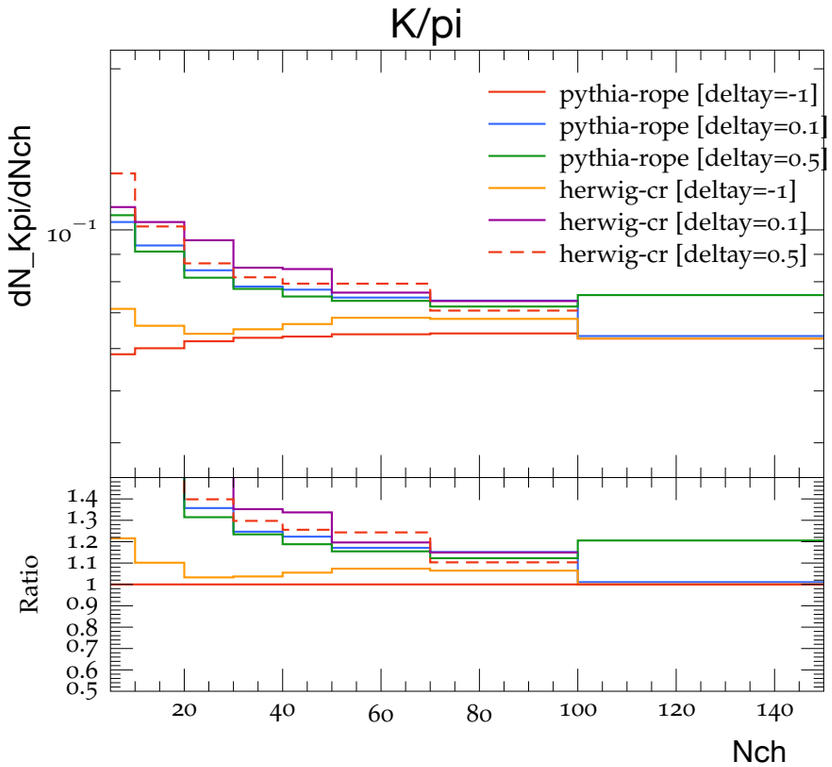
Exploring strangeness enhancement with strings and clusters (working title)

[C. Bierlich, S. Gieseke, PK]





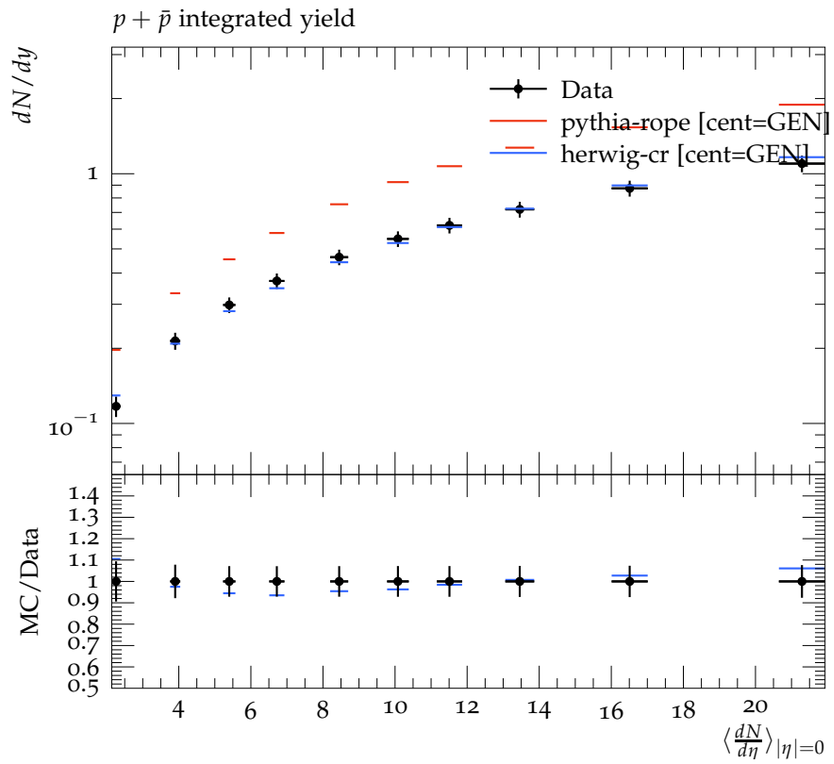


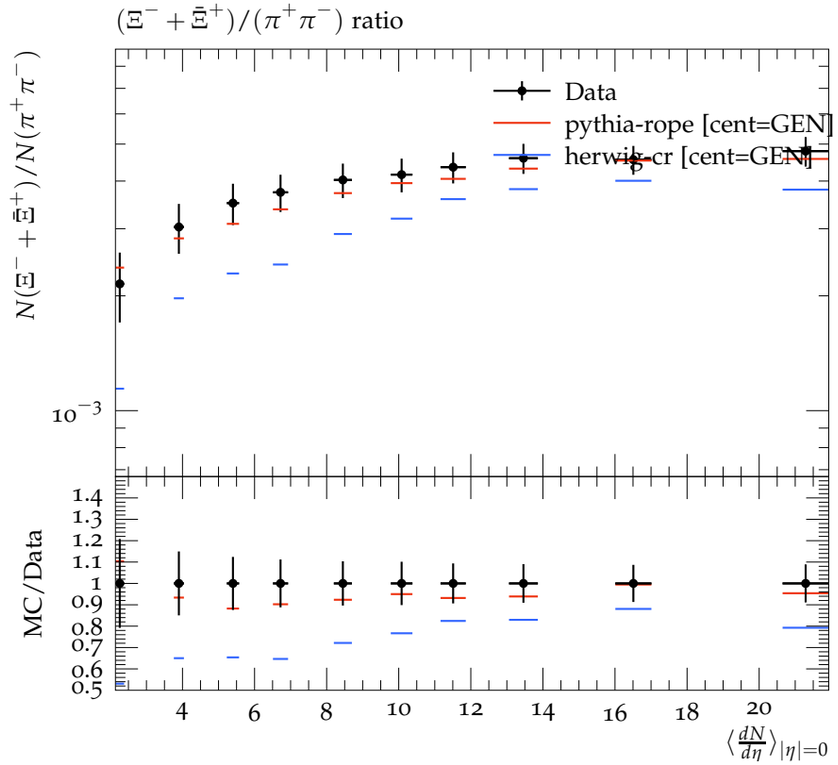


Exploring strangeness enhancement with strings and clusters (working title)

[C. Bierlich, S. Gieseke, PK]

More plots..



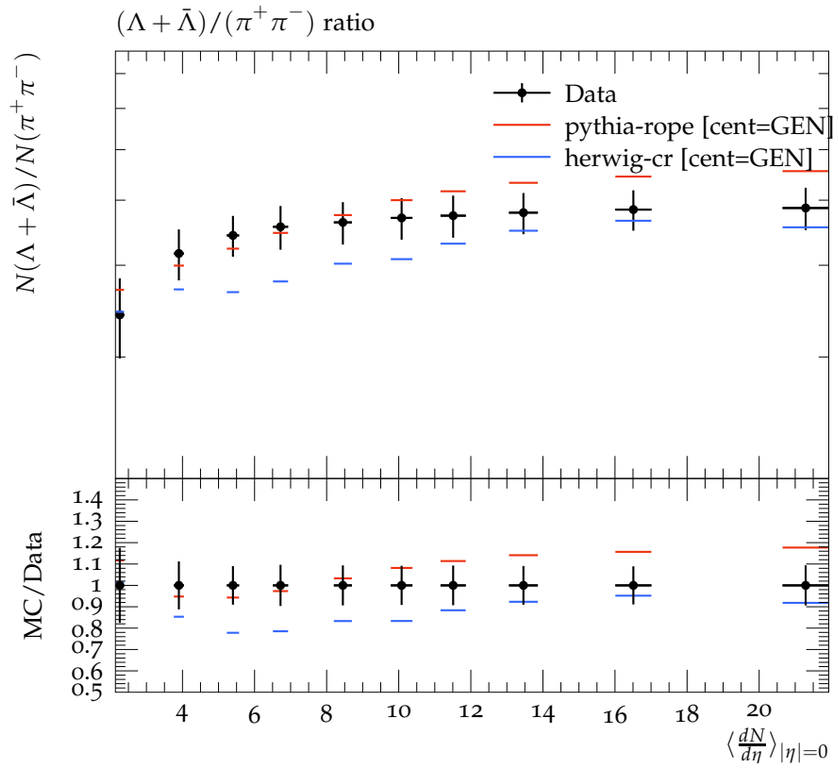


Pythia-Ropes

- More baryons (overestimation of protons)
- More strangeness
- Best current description of „strange“ ratios

Herwig-Baryonic CR

- Describes strangeness enhancement qualitatively
- Protons, pions and kaons on point but…
- Could be „stranger“



Conclusions

Different approaches to simulate collective effects, strangeness enhancement

I showed you

- **EPOS** (flow)
- **CGC+Lund** (perturbative approach)
- **Pythia/Dipsy ropes** (microscopic)
- **Herwig Baryonic Colour Reconnection** (microscopic)

Improvement in sight from different studies (Space-time models, Pythia vs. Herwig)

-> Microscopic ansätze important to study QGP from different directions

Backup

Backup

Backup

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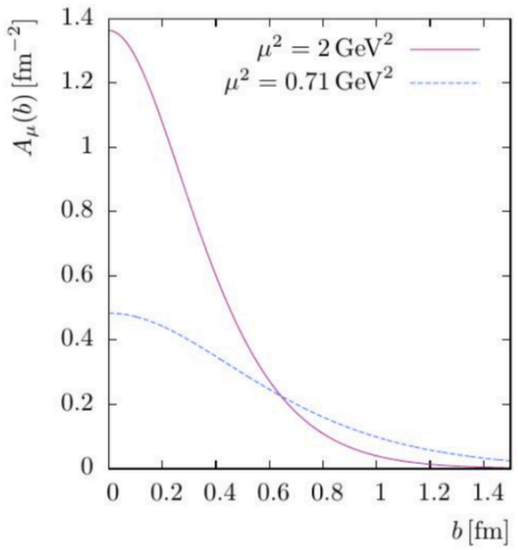
The MPI model - basics

Matter distribution

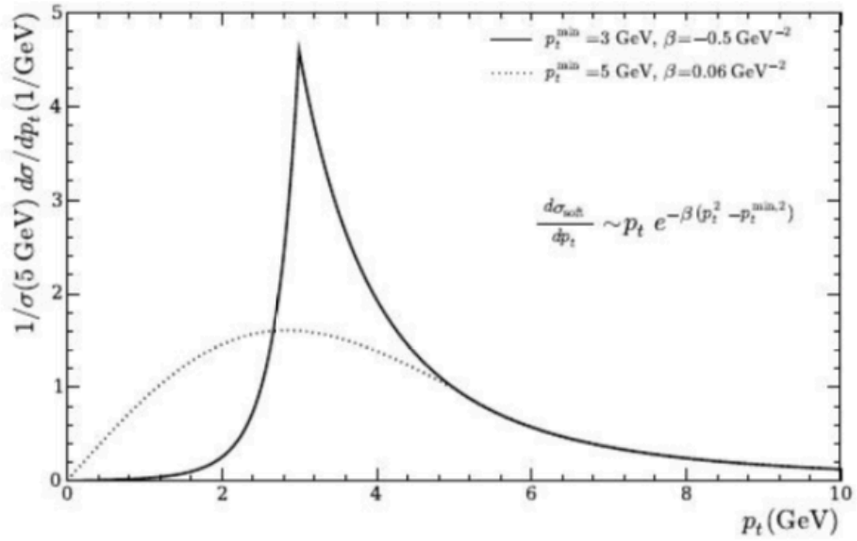


- Based on the Eikonal model
- Parameters fixed to describe σ_{tot}

$$\mathcal{P}_{h,s} = \frac{2\chi_{\mathrm{hard}}(b,s)^h}{h!}\frac{2\chi_{\mathrm{soft}}(b,s)^n}{n!}e^{-2\chi_{\mathrm{tot}}(b,s)}$$

$$\chi_{\mathrm{tot}}(b,s) = \frac{1}{2}(A(b,\mu)\sigma_{\mathrm{hard}}(s,p_\perp^{\mathrm{min}}) + A(b,\mu_{\mathrm{soft}})\sigma_{\mathrm{soft}})$$

Extension to soft region



- Interactions above $p_\perp^{\mathrm{min}}$ simulated as QCD 2 to 2 processes (semi-hard interactions)
- Interactions below $p_\perp^{\mathrm{min}}$ simulated as soft gluon ladders with *multiperipheral* kinematics (soft interactions)

Different matter distribution for soft interactions

$$p_{\mathrm{T}}^{\mathrm{min}}(s) = p_{\mathrm{T},0}^{\mathrm{min}}\left(\frac{\sqrt{s}}{E_0}\right)^b$$

Main parameters

- set /Herwig/UnderlyingEvent/MPIHandler:pTmin0 3.5
- set /Herwig/UnderlyingEvent/MPIHandler:InvRadius 1.4
- set /Herwig/UnderlyingEvent/MPIHandler:Power 0.4
- set /Herwig/Hadronization/ColourReconnector:ReconnectionProbability 0.5

MPI - soft interactions

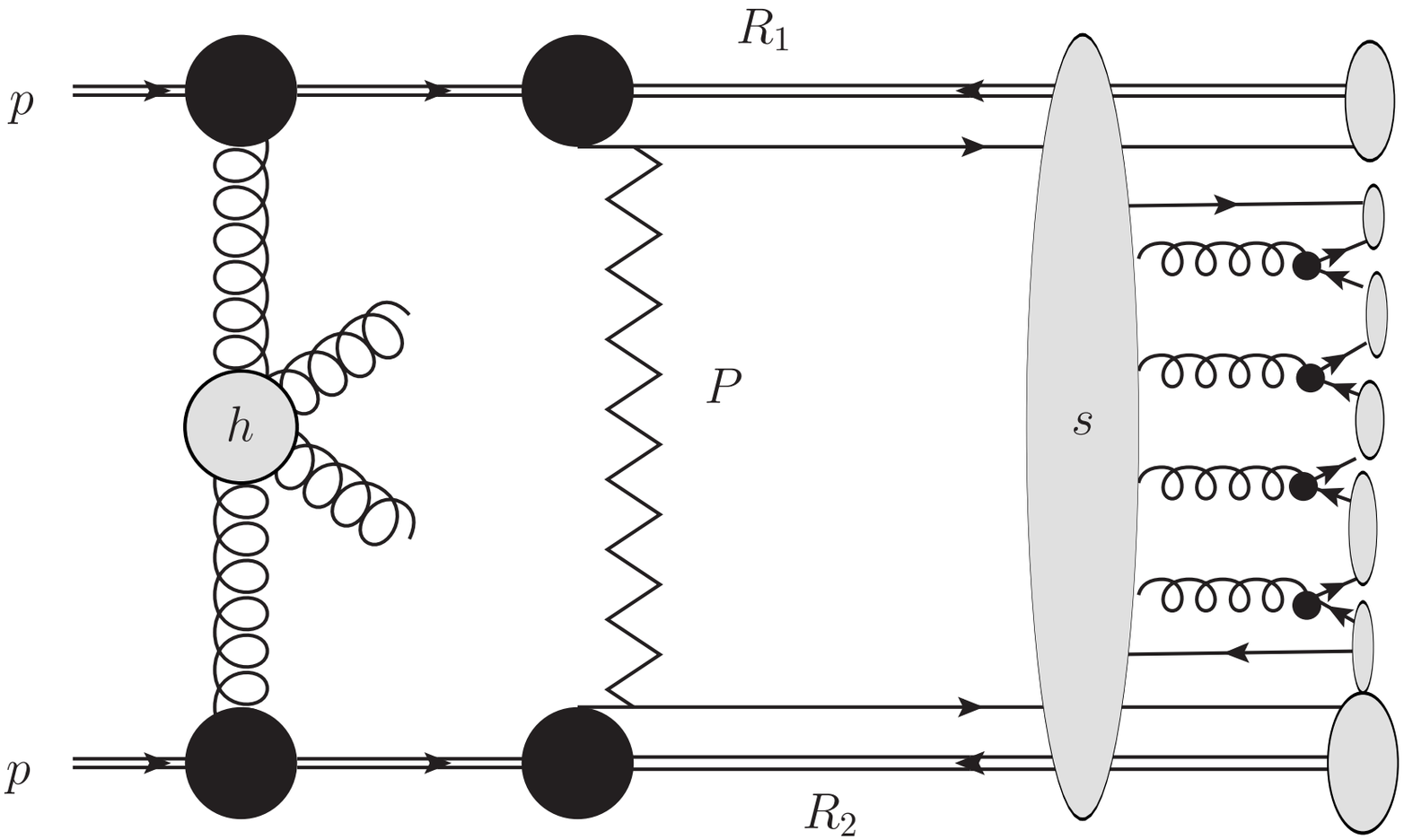
New model for soft interactions

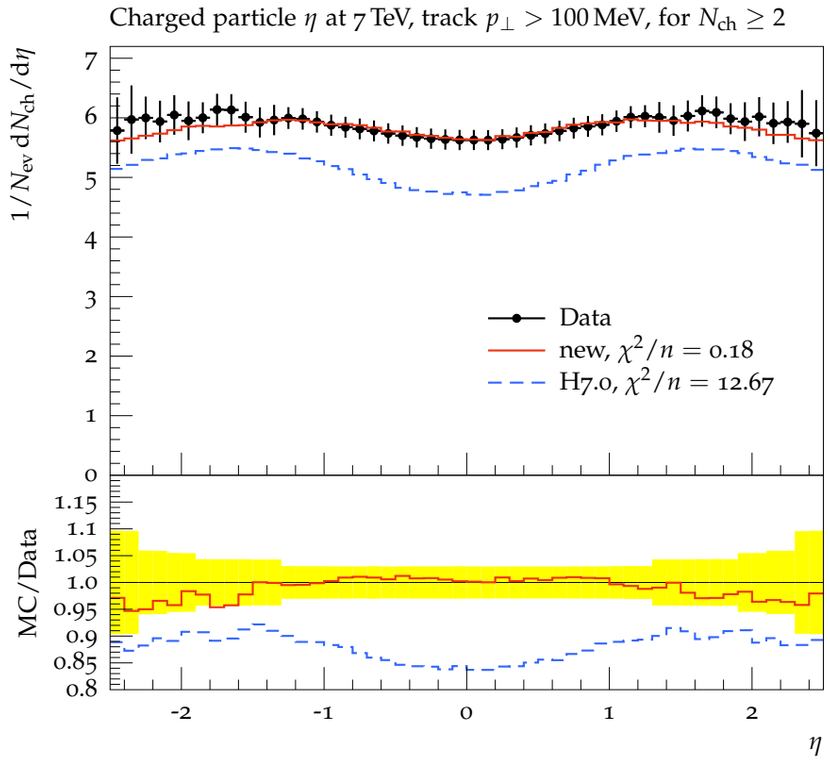
[Gieseke, Loshaj, Kirchgaesser – EPJ C77 (2017) 156]

- Multiperipheral gluon ladder
- Gluons treated non-perturbatively
- Paramaters of the model parametrized to describe 0.9, 7 and 13 TeV MB data

$$\langle N \rangle \approx N_{\text{ladder}} \times \ln \frac{s}{m^2}$$

$$N_{\text{ladder}} = N_0 \left(\frac{s}{\text{TeV}^2} \right)^{-0.08}$$





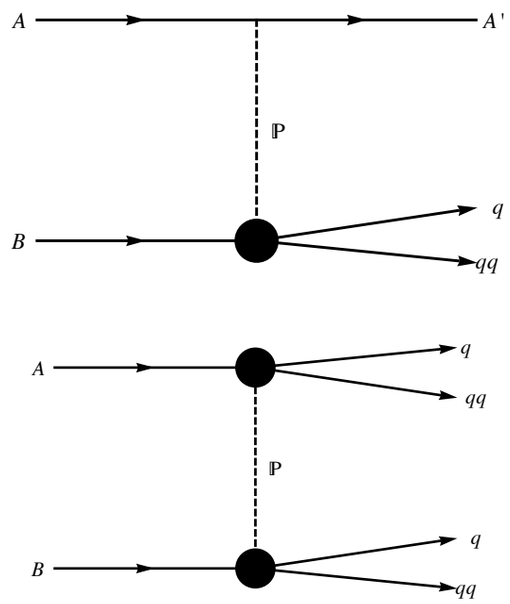
ATLAS [New J.Phys.13:053033,2011]

Diffraction

[Gieseke, Loshaj, Kirchgaesser – EPJ C77 (2017) 156]

Inclusion of diffractive topologies

- Single and double diffraction
- Final state treated fully non-perturbatively
- Small pT but tail towards high diffractive masses
- Characterized through large rapidity gaps



Combination with UE model

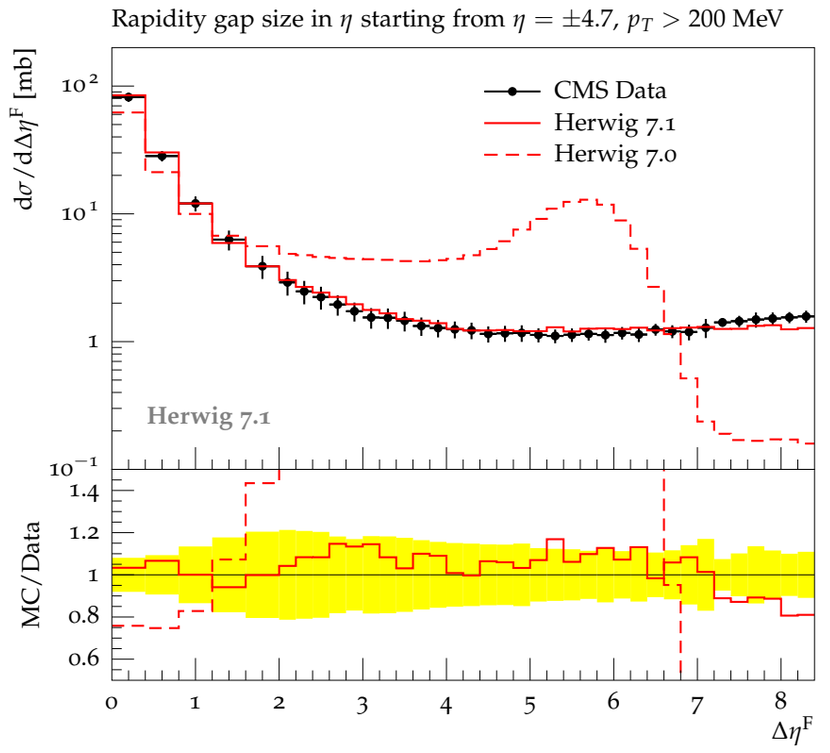
- Either diffractive or MPI event
- Cross sections tuned to data
- H7->H7.1: The bump problem disappears

New versions come with improved physics capabilities!

```
# Needed to get the correct fraction of diffractive events
set /Herwig/MatrixElements/MEMinBias:csNorm 4.5584


# Set weight for Diffraction
set MEDiffractionLeft:DiffractionAmplitude 12
set MEDiffractionRight:DiffractionAmplitude 12
set MEDiffractionDouble:DiffractionAmplitude 8

set MEDiffractionDeltaLeft:DiffractionAmplitude 4
set MEDiffractionDeltaRight:DiffractionAmplitude 4
set MEDiffractionDeltaDouble:DiffractionAmplitude 2
```



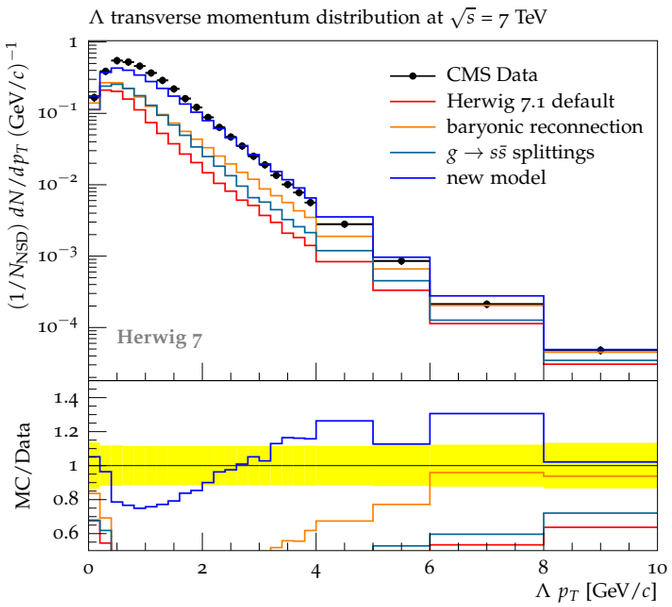
CMS [Phys.Rev. D92 (2015) no.1, 012003]

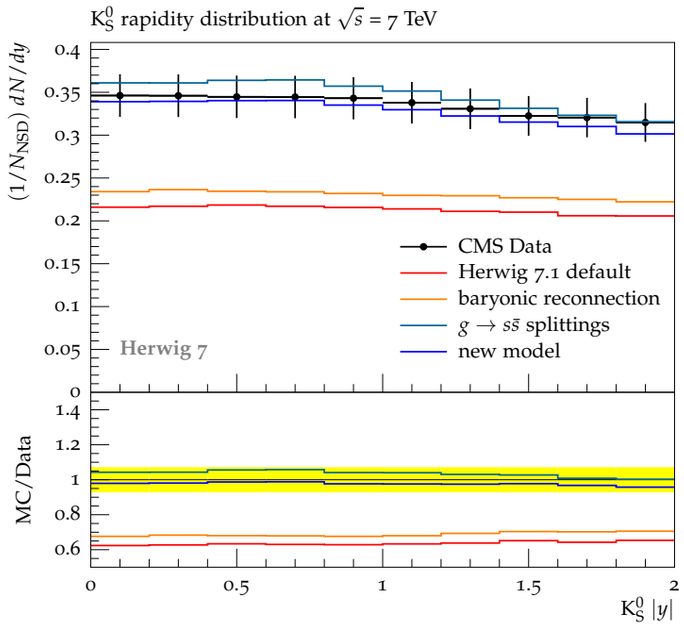
Herwig 7.1.4

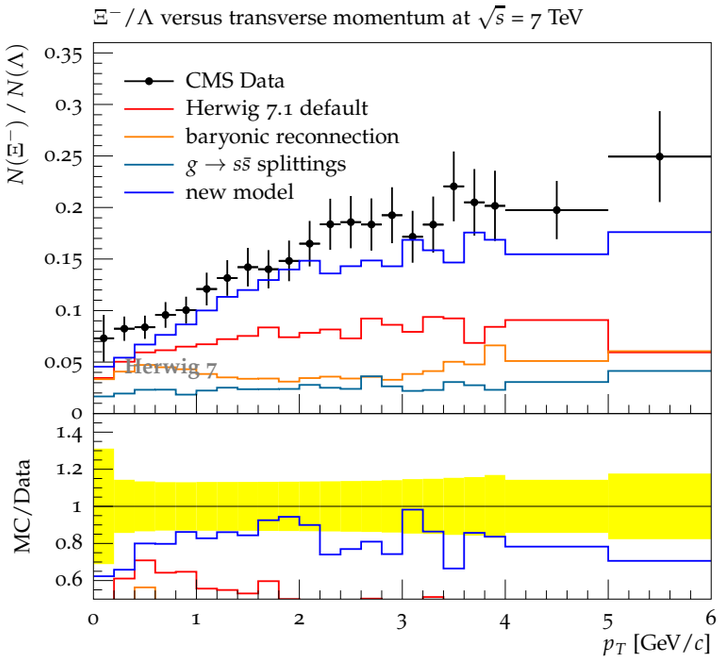
Allow additional source of strangeness during non-perturbative gluon splitting

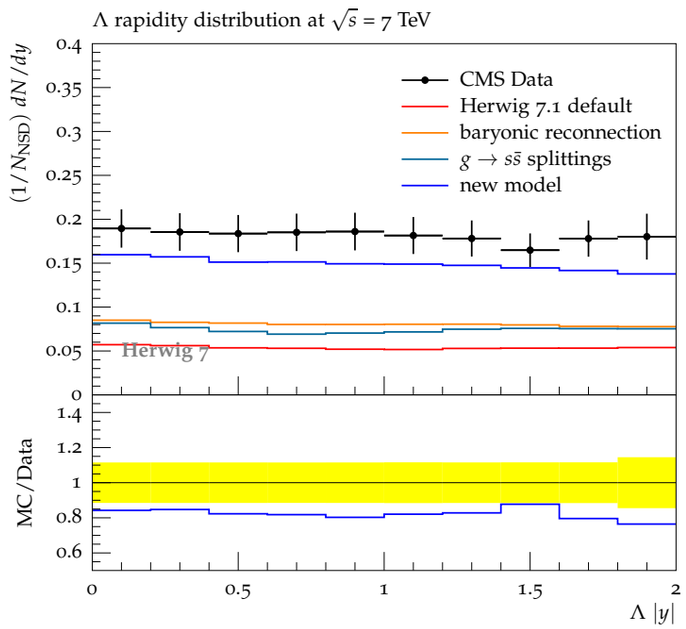
$$g \to s\bar{s}$$

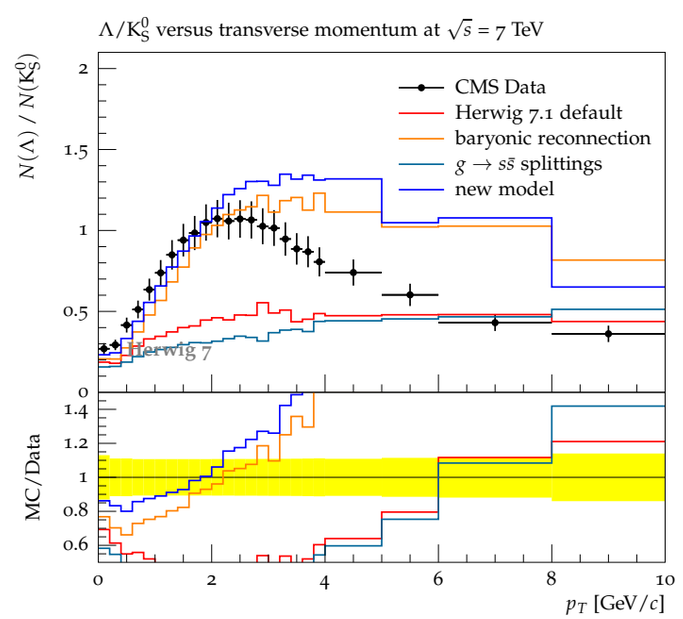
Combination with Baryonic reconnection -> improvements in more differential observables [new model in plots]

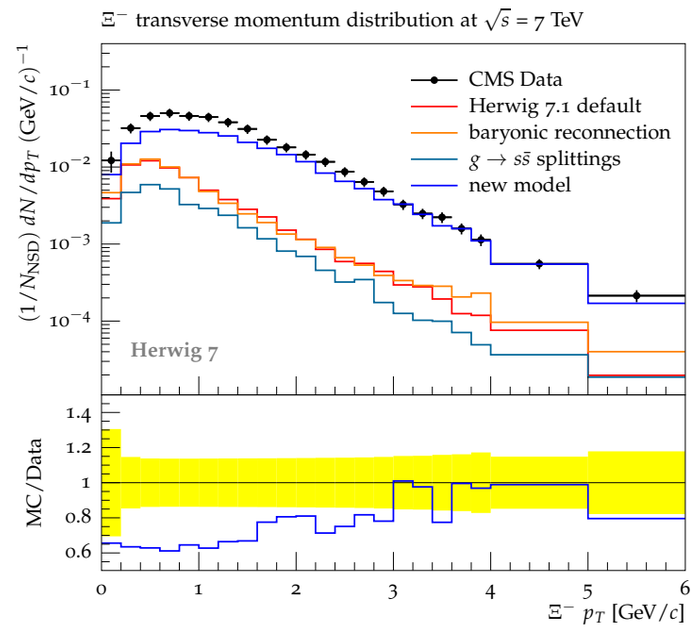












[C. B. Duncan, PK, Eur. Phys. J. C79 no. 1 (2019) 61]

More developments on the soft front

Kinematic strangeness production

- **Motivation**: Strangeness enhancement not well described across all MC event generators
- Different Ansätze: **Flow** vs. **QGP** vs. **Modeling**
- How far can one push existing models?
- Review of existing production mechanism and new mechanisms necessary

Introduce scaling s.t. probability to produce strange quarks depends on immediate environment

Parton Splitter

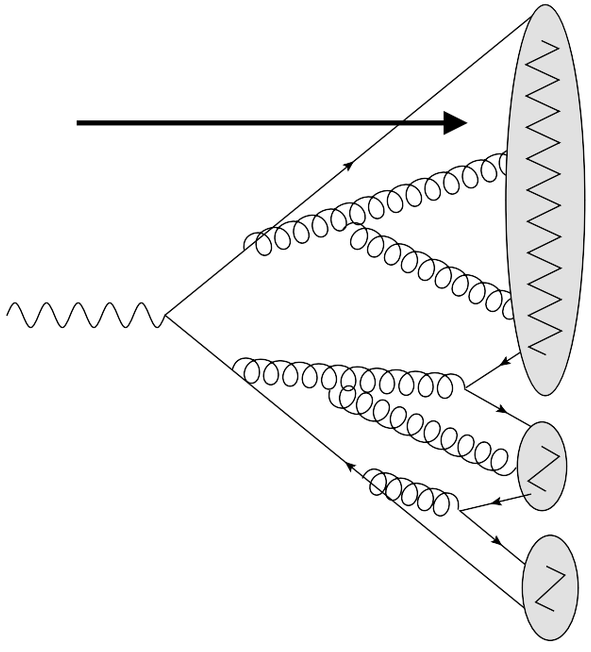
- Mass of colour singlet

Cluster Fissioner

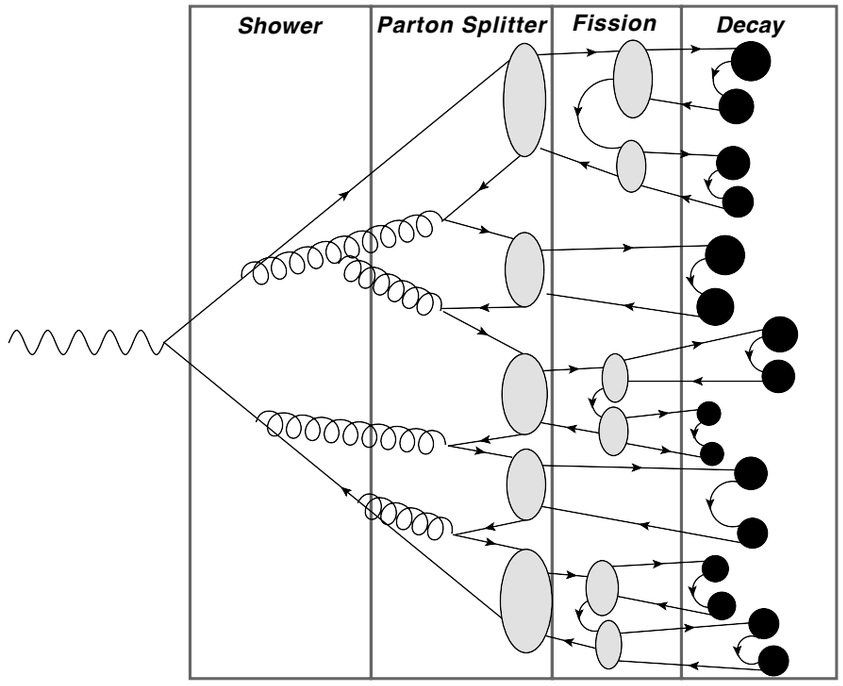
- Inv cluster mass

Cluster Decayer

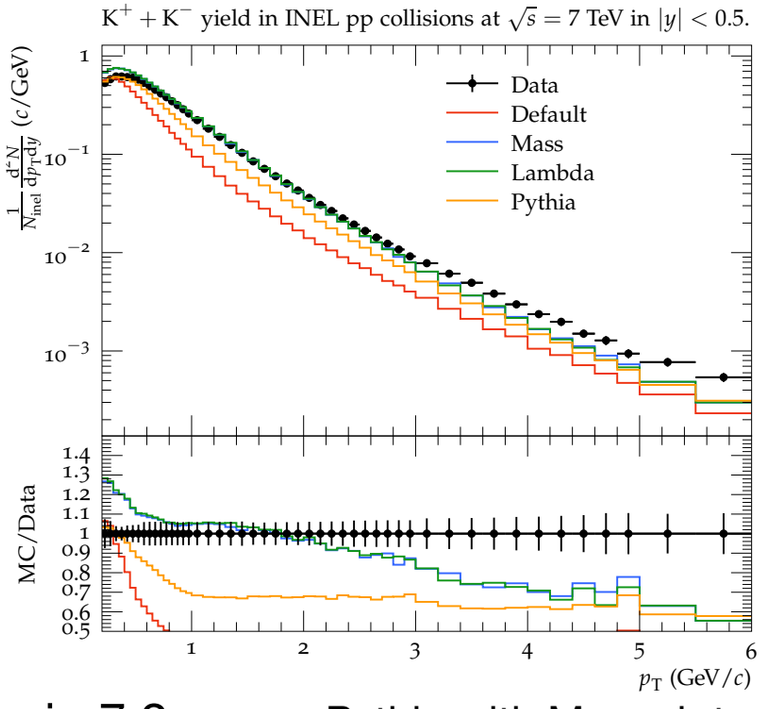
- Inv cluster mass



Stages of Hadronization (+Shower)



[ALICE - Eur.Phys.J. C75 (2015) no.5, 226]



More dynamic and collective model for strange flavour production ->Herwig 7.2

Pythia with Monash tune

Current Version Herwig 7.1.5

Since 7.0 several improvements on the soft front

- New soft model (7.1)
- Baryonic Colour Reconnection (7.1.4)
- In general good agreement with MB and UE data
- Most differential observables reasonably well described

Works out of the box

- LHC-MB.in
- read LHC-MB.in
- run LHC-MB.run -N 10000x

```
11
12 read snippets/PPCollider.in
13
14 ##################################################
15 # Technical parameters for this run
16 ##################################################
17 cd /Herwig/Generators
18 ##################################################
19 # LHC physics parameters (override defaults here)
20 ##################################################
21 set EventGenerator:EventHandler:LuminosityFunction:Energy 7000.0
22
23
24 # Minimum Bias
25 read snippets/MB.in
26
27 # Read in parameters of the soft model recommended for MB/UE simulations
28 read snippets/SoftTune.in
29
30 # Diffraction model
31 read snippets/Diffraction.in
32
33 # Read in snippet in order to use baryonic reconnection model with modified gluon splitting
    (uds)
34 # For more details see [S. Gieseke, P. Kirchgaeßer, S. Plätzer. arXiv:1710.10906]]
35 ##################################################################################################
   ###
36
37 read snippets/BaryonicReconnection.in
38
```

Tuned parameters and settings for Baryonic CR

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+Contur+hepforge+…

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