Soft QCD in Monte Carlo Event generators

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QCD@LHC 2024, Freiburg, 11/10/24

DISCLAIMER

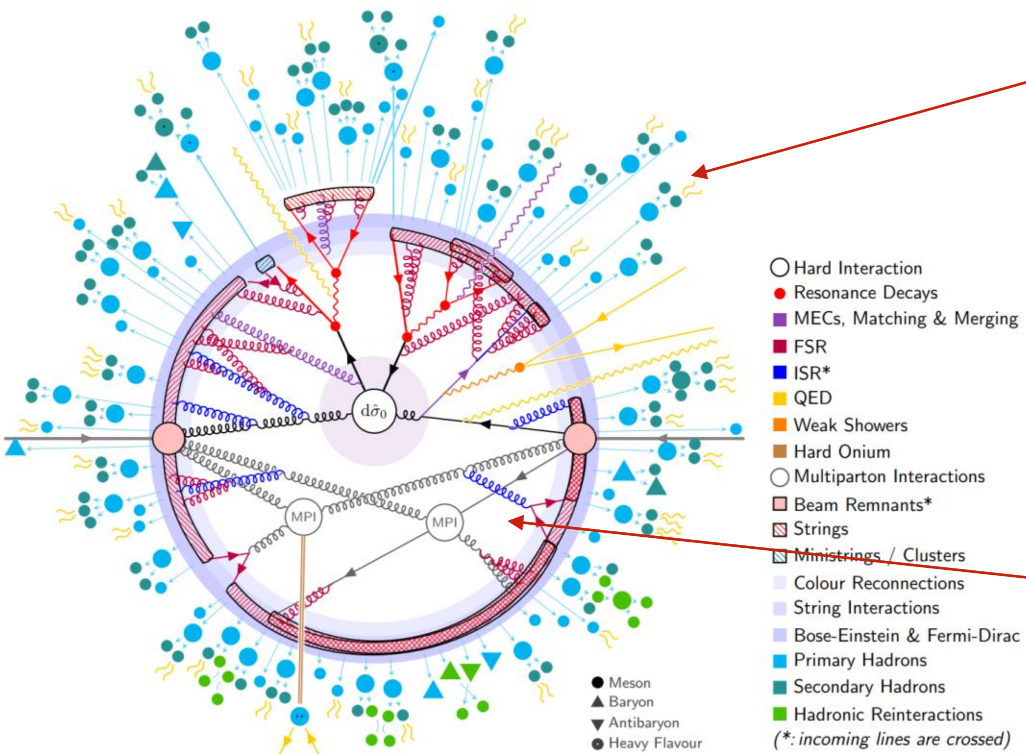
Will mainly focus on Pythia and Herwig.

EPOS → talk by T. Pierog on Tuesday
More Pythia+Angantyr → talk by L. Lönnblad on Thursday

Apologies in advance for any inaccuracies or omissions!

SOFT QCD IN MC GENERATORS

‘Soft’ aspects of Monte Carlo event generators:



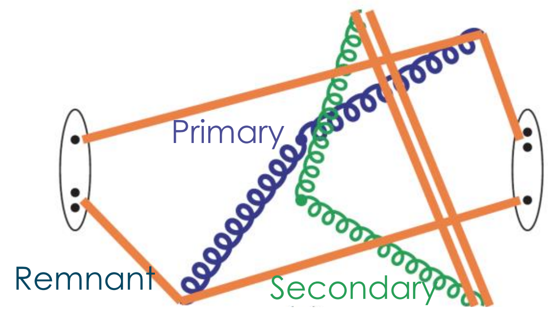
Hadronisation: conversion of partons to hadrons

Multiple parton interactions: additional parton scatters (can also be hard!)

From Bierlich et al., 2203.11601

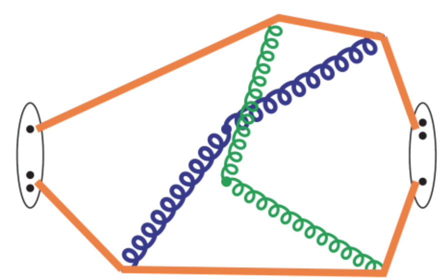
SOFT QCD IN MC GENERATORS

‘**Colour reconnection**’:
LC configuration from PS can lead to multiple colour strings spanning across event, particularly with MPI:



Sjöstrand, arXiv:1706.02166

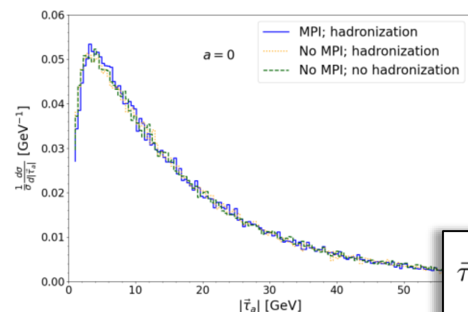
At finite N_c possibility for colour connections to ‘rewire’ to yield lower energy configuration

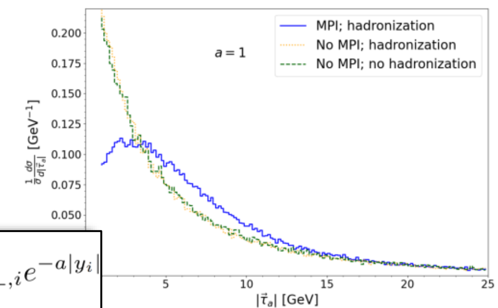


EFFECTS OF SOFT QCD

Strong effect on hadronic event shapes (particularly from MPI)

Bijl, Niedenzu, Waalewijn, 2307.02521





$$\vec{\tau}_a = \sum_i \vec{k}_{\perp,i} e^{-a|y_i|}$$

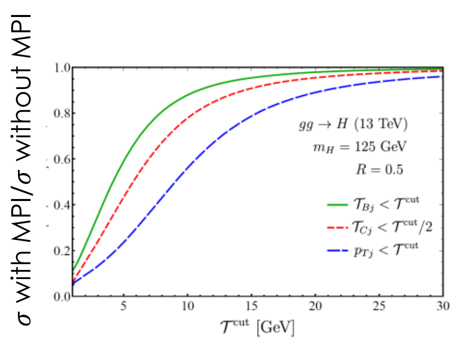
$Z/\gamma^* \, p_t$ distribution

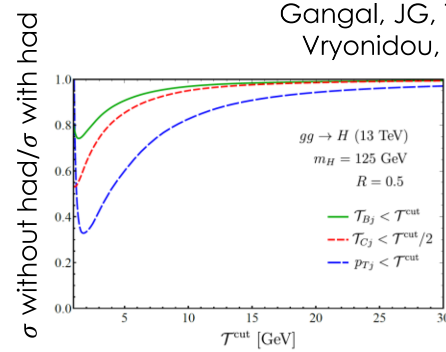
(but sensitive to intrinsic k_t - see talk by W Jin on Tuedsay)

Hadronic event shape

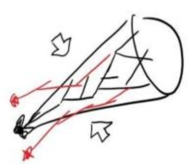
Affects jet measurements – MPI feeds particles into jets (effect increases as R ↑), and hadronisation smears particles out of jets (effect increases as R ↓)

Gangal, JG, Tackmann, Vryonidou, 2003.04323

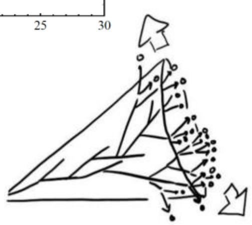




Scale of jet veto



Underlying Event



Hadronisation

Dasgupta, Magnea, Salam, 0712.3014

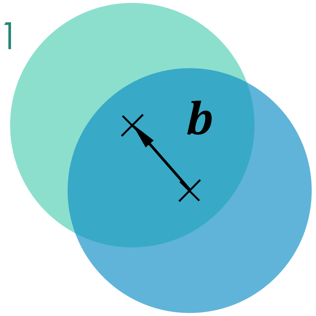
“there is soft QCD everywhere at the LHC” (talk of L. Lönnblad)

MPI MODELS IN MONTE CARLO GENERATORS

MPI MODELS IN MC GENERATORS

Starting point of Monte Carlo models of MPI in MC generators: **uncorrelated** scatters

➔ Poisson distribution of scatters



$$\sigma_n = \int d^2b\, P_n(b,s) = \int d^2b \frac{\bar{n}(b,s)^k}{k!} \exp\big(-\bar{n}(b,s)\big)$$

Cross section for exactly n scatters

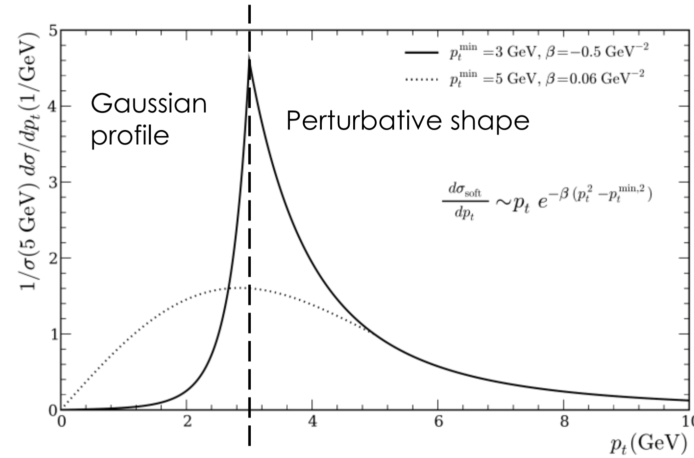
Prob of *n* scatters at impact parameter *b*

Average number of scatters

Borozan, Seymour, arXiv:hep-ph/0207283
Bahr, Gieseke, Seymour, arXiv:0803.3633

HERWIG MPI MODEL

Herwig MPI model: Two components, "hard" and "soft", applicable above and below some p_t^{min}:

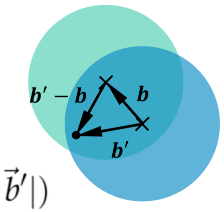


Then:

1 2 3 4 ← Model params

$$\bar{n}(b,s) = A(b,\mu)\sigma_{hard}^{inc}\left(s,p_t^{min}\right) + A\left(b,\mu_{soft}\right)\sigma_{soft}^{inc}$$

Width parameters



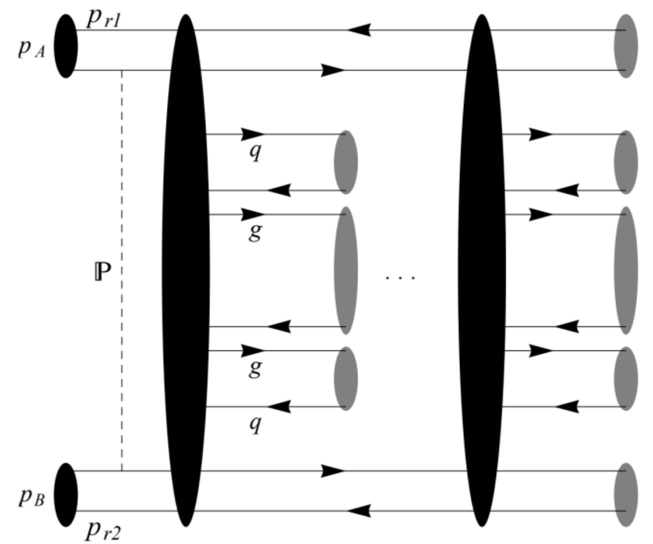
$$A(b) = \int \mathrm{d}^2\vec{b}'\, G_A(|\vec{b}'|)G_B(|\vec{b}-\vec{b}'|)$$

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

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

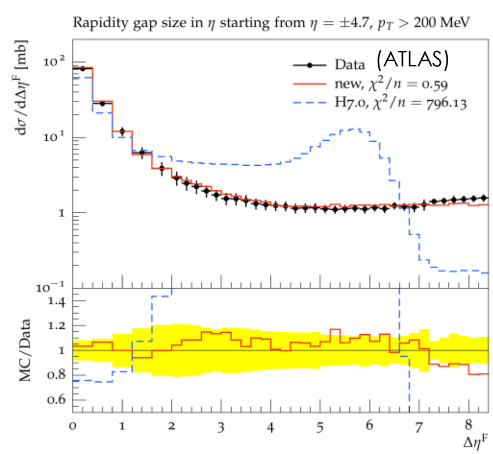
Use σ_{tot} and $\frac{d}{dt}\left(\ln\frac{d\sigma_{el}}{dt}\right)_{t=0}$ to fix 3, 4 ➔ 2 parameter model

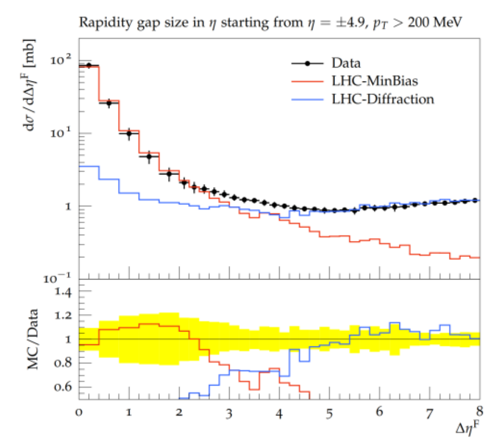
IMPROVEMENTS IN SOFT MPI MODEL



Previously: soft MPI modelled by 2→2 QCD scatters.

More realistic picture from low x physics/multiperipheral model – spray of particles evenly distributed in Y





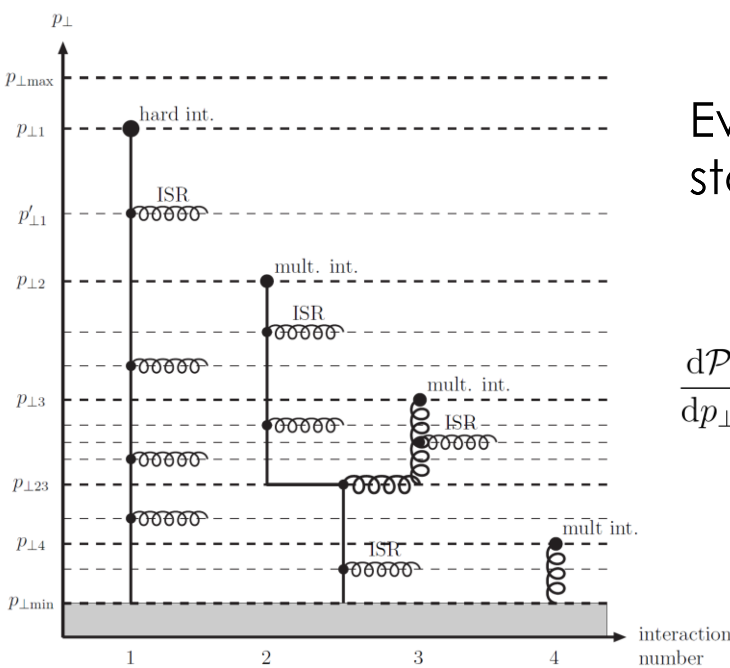
Implemented in Herwig, alongside a model of diffraction. Fixes predictions for events with large rapidity gap in minbias.

Gieseke, Loshaj, Kirchgaeßer, arXiv:1612.04701

PYTHIA MPI MODEL

Pythia MPI model: model additional scatters as 2→2 scatters, use perturbative cross section regularised at small p_t

$$\frac{d\hat{\sigma}}{dp_\perp^2} = \frac{8\pi\alpha_s^2(p_\perp^2)}{9p_\perp^4} \to \frac{8\pi\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{9(p_\perp^2 + p_{\perp 0}^2)^2}$$



Evolution of MPI interleaved with initial-state radiation:

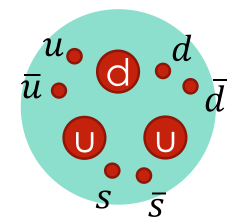
$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp}\right) \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)$$

Sjöstrand, van Zijl, Phys.Rev. D36 (1987) 2019,
Sjöstrand, Skands, hep-ph/0402078
hep-ph/0408302

MULTIPLE SCATTERING IN PYTHIA

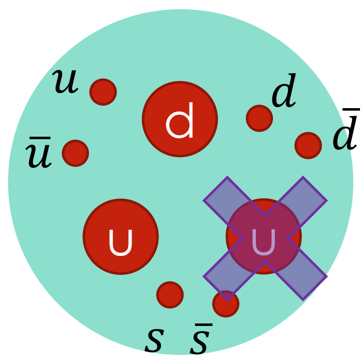
Parton densities adjusted to take into account removal of flavour/momentum.

Sjöstrand, van Zijl, Phys.Rev. D36 (1987) 2019,
Sjöstrand, Skands, arXiv:hep-ph/0402078
hep-ph/0408302



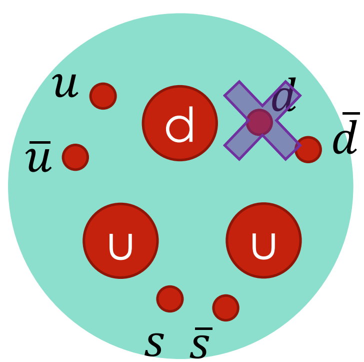
Start at hardest interaction and work 'backwards'. Start with normal PDFs: $\int f^{u_v}(x)\mathrm{d}x = 2\,, \int f^{d_v}(x)\mathrm{d}x = 1, \sum_i \int f^{i}(x)\, x\, \mathrm{d}x = 1$

Interaction 1 involves valence u parton with momentum z



Adjust PDFs for remaining interactions: Total momentum $1 - z$, number of u valence = 1.

Interaction 1 involves sea d parton with momentum z



Adjust PDFs for remaining interactions: Total momentum $1 - z$, add to $\bar{d}$ distribution 'companion quark distribution'

PYTHIA MPDFS: SUM RULES

Are these modifications consistent with QCD? For case of 2,3 scatters all at the same scale, can test Pythia's model mPDFs against sum rule constraints from QCD:

E.g. momentum sum rule for double PDFs:

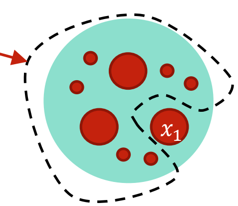
JG, Stirling, arXiv:0910.4347
Blok et al., arXiv:1306.3763
Diehl, Plößl, Schäfer, arXiv:1811.00289

$$\sum_j \int dx_2\, x_2\, F^{ij}(x_1, x_2) = (1 - x_1)\, f^i(x_1)$$

dPDF

PDF

$$\sum_i x_i = 1 - x_1$$



True equal-scale dPDFs symmetric under $x_1 \leftrightarrow x_2$, $i \leftrightarrow j$, & sum rules should hold integrating over x_1 or x_2.

Pythia dPDFs are ordered – sum rule perfectly satisfied integrating over mtm of second parton, but not the first.

PYTHIA MPDFS: SUM RULES

When scales equal, hardness ordering is ambiguous, and half the time process 1 is first, and half the time process 2 is first.

dPDFs used for equal scale processes are then effectively:

$$D^{\text{sym}}_{j_1 j_2}(x_1, x_2, Q) \equiv \frac{\overset{\text{1 first}}{D_{j_1 j_2}(x_1, x_2, Q)} + \overset{\text{2 first}}{D_{j_2 j_1}(x_2, x_1, Q)}}{2}$$

(n.b. this is not quite true, since Pythia actually symmetrises at the level of the scatterings rather than the dPDFs)

Symmetrised DPDs satisfy sum rules reasonably, though large deviations in places

Fedkevych, JG, arXiv:2208.08197

x_1	Momentum sum rule ($j_1 = u$). Should = 1.	$\bar{u}u$ number sum rule. Should = 3.
10^{-6}	0.979	2.961
10^{-3}	0.980	3.351
10^{-1}	1.014	3.491
0.2	1.047	3.580
0.4	1.133	3.858
0.8	1.679	7.048

Naively symmetrised Pythia DPDs

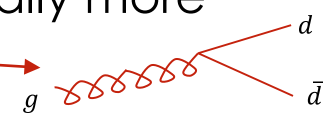
AN IMPROVED MODEL FOR MPDFS

Can one design a model of equal-scale multi-parton PDFs that is symmetric and satisfies sum rules better?

Ongoing work with Oleh Fedkevych, Seonagh Smith

"Minimal" adjustments to Pythia picture:

- Order scatters in x rather than Q + smooth transitions
- Improve "companion quark mechanism" so that it is naturally more symmetric & follows expectations from QCD splitting
- Add a (weak) damping factor at small x fractions



Resultant dPDFs satisfy sum rules well!

Procedure also seems to work well with tPDFs (WIP).

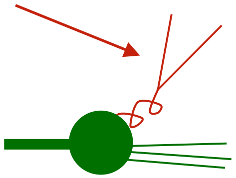
x_1	$j_1 = u$ MSR. Should = 1.	$\bar{u}u$ NSR. Should = 3.
10^{-6}	0.965	3.072
10^{-3}	0.960	3.035
0.1	1.019	2.902
0.2	1.020	2.904
0.4	1.006	2.953
0.8	1.001	2.995

PRELIMINARY

PERTURBATIVE SPLITTING IN MPI

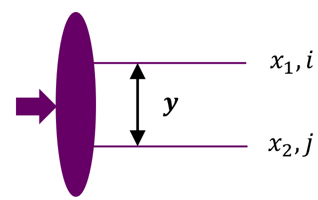
In full QCD, perturbative source of correlations between partons taking part in different scatters is '1→2 splitting' mechanism

Diehl, Ostermeier, Schafer; JG, Stirling; Manohar, Waalewijn; Blok, Dokshitzer, Frankfurt, Strikman; Snigirev, Ryskin,…



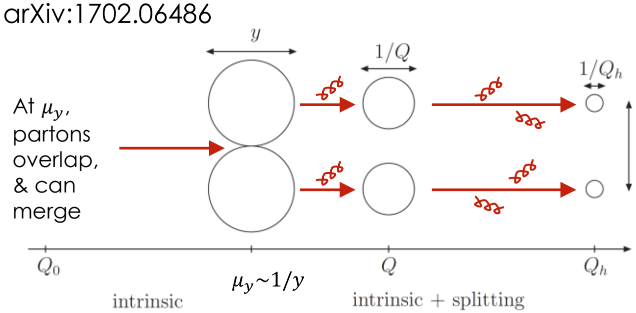
Mechanism investigated in Sjöstrand, Skands, hep-ph/0408302 (referred to as "joined interactions"): claimed impact was small.

However this work ignored strong y dependence of this mechanism ($\propto 1/y^2$)– accounting properly for this increases impact.



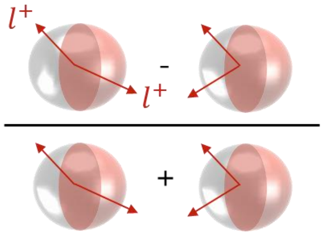
Diehl, Ostermeier, Schafer, arXiv:1111.0910
Diehl, Gaunt, Schönwald, arXiv:1702.06486

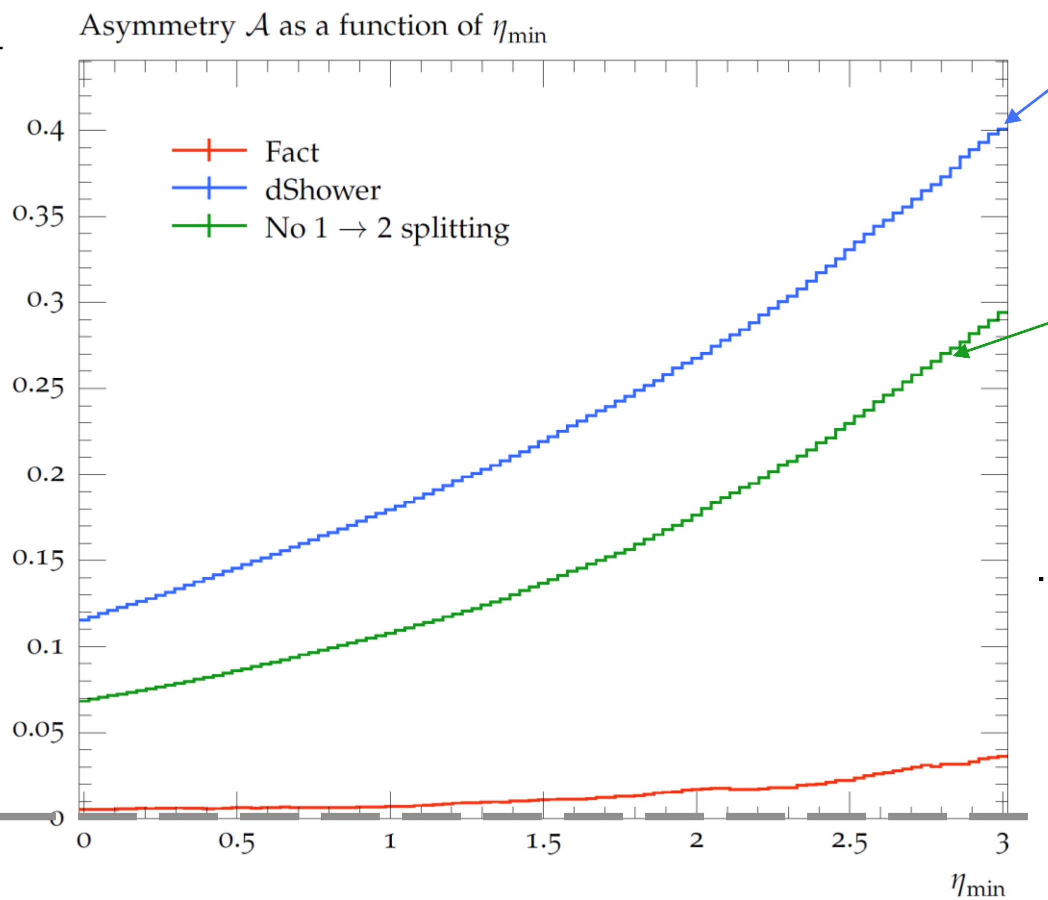
'1→2 splitting' mechanism incorporated with correct y dependence in dedicated double parton scattering simulation dShower



Cabouat, JG, Ostrolenk, 1906.04669, 2008.01442

WW ASYMMETRY

$\mathcal{A} =$ 



Includes 1→2 splittings + valence number effects

Simple valence number effects

No parton-parton correlations

Cabouat, JG, Ostrolenk, 1906.04669

Z + JETS

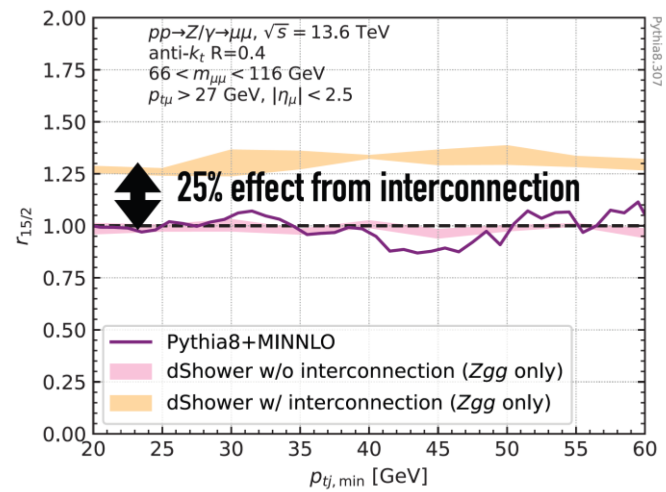
Study of Andersen et al. looking at Z+jets. Phase space where Z has very small p_t (~ few GeV) and jets have some intermediate p_t (~10 GeV) is dominated by multiple scattering.

Can consider change in jet rate when Z p_T cut is changed:

$$r_{15/2} = \frac{\langle n(p_{tj,\min}) \rangle_{15}^{\text{pure-MPI}}}{\langle n(p_{tj,\min}) \rangle_{2}^{\text{pure-MPI}}}$$

$p_{TZ} < 15$ GeV

$p_{TZ} < 2$ GeV



If two scatters are uncorrelated, $r_{15/2}$~1. 1→2 splittings induce $r_{15/2}$~1.25!

Andersen, Monni, Rottoli, Salam, Soto-Ontoso, arXiv:2307.05693

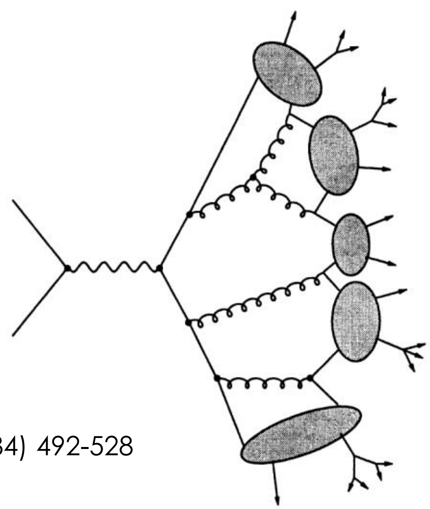
(DPS in Z+jets also discussed in the talk of W Jin on Tuesday)

HADRONISATION AND COLOUR RECONNECTION

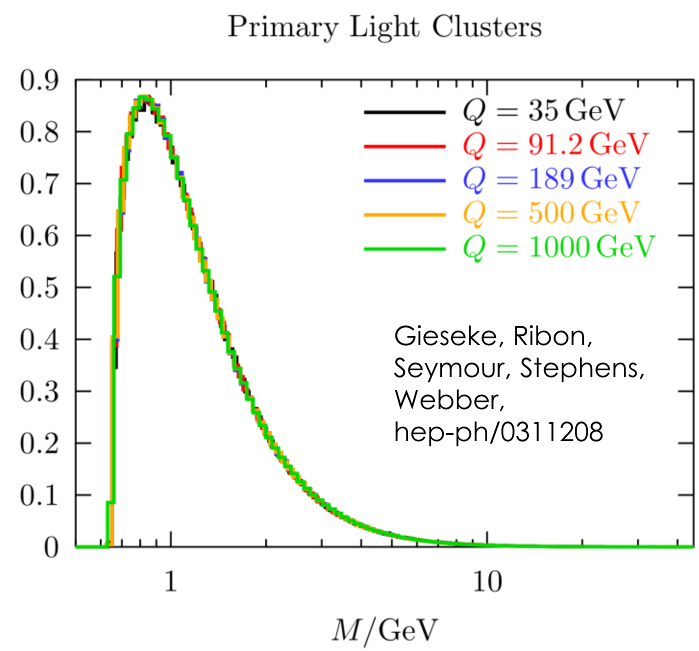
CLUSTER HADRONISATION

Two main hadronisation models: CLUSTER and STRING.

Cluster model (Herwig):



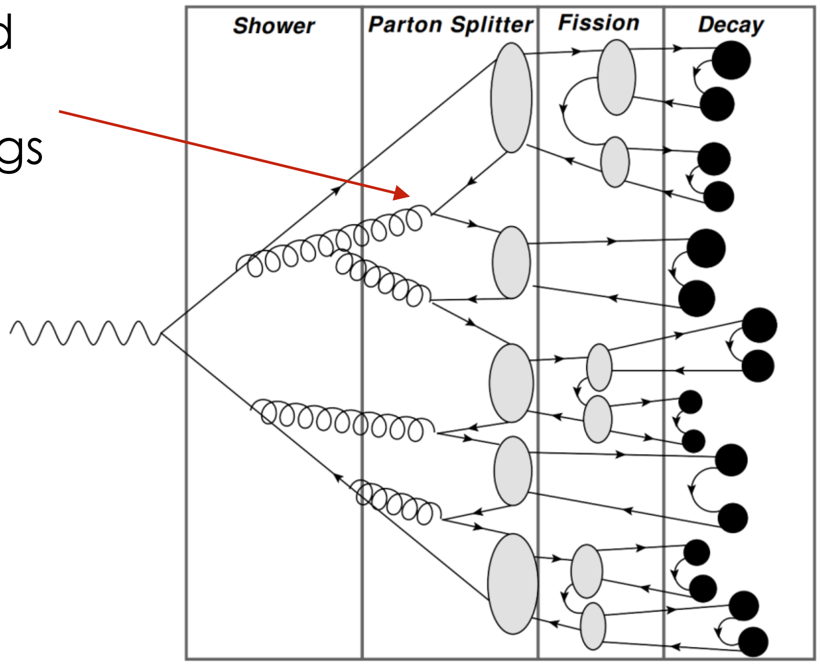
Webber, Nucl.Phys.B 238 (1984) 492-528



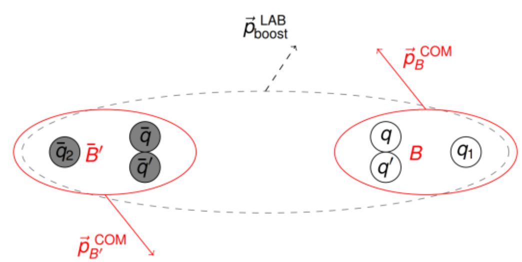
In shower with coherence, colour connected partons at end of shower end up close in phase space ('preconfinement'). Starting point of cluster hadronization model.

CLUSTER HADRONISATION

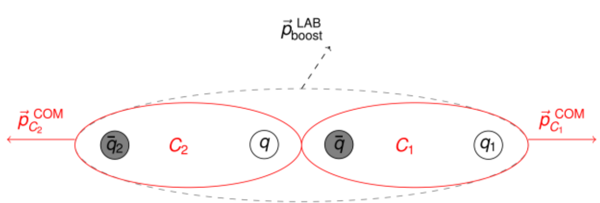
Forced gluon splittings



Cluster decay: Clusters decay isotropically into a pair of hadrons, either baryons or mesons



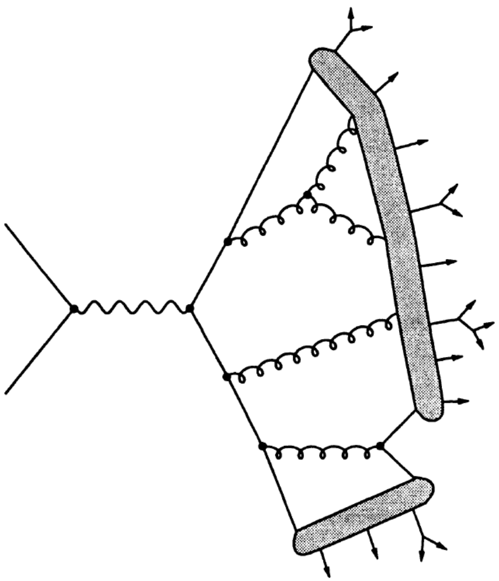
Cluster fission: split clusters above some mass threshold (only mesonic)



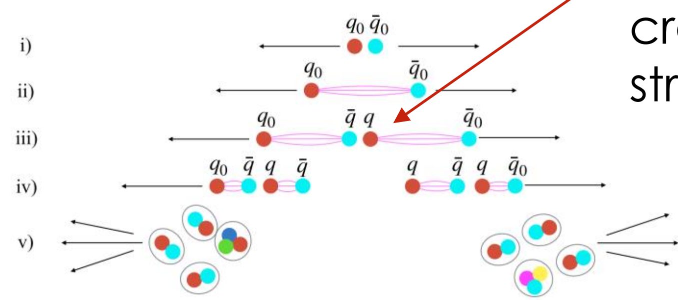
(Cluster model also used in Sherpa: see Chahal, Krauss, arXiv:2203.11385 for recent work)

STRING HADRONISATION

String model (Pythia):



Colour strings form between colour connected partons. String breaking via Schwinger mechanism:



$q\bar{q}$ pair creation in string field

Longitudinal distribution:

$$f(z) = N\frac{1}{z}(1-z)^{a}\exp\left(\frac{-bm_\perp^2}{z}\right)$$

Tunable parameters

Transverse + mass distribution:

$$\exp\left(\frac{-\pi m_\perp^2}{\kappa}\right) = \exp\left(\frac{-\pi p_\perp^2}{\kappa}\right)\exp\left(\frac{-\pi m^2}{\kappa}\right)$$

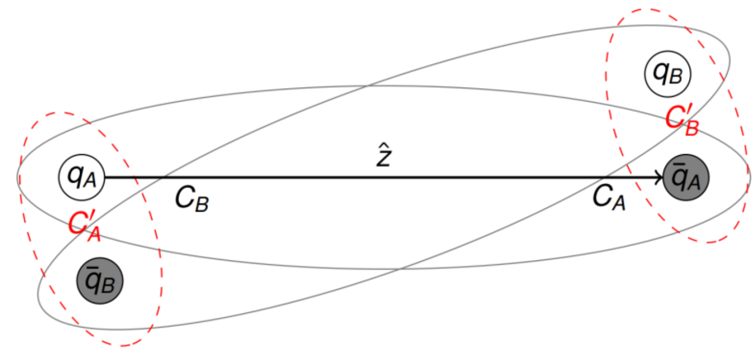
κ~1 GeV/fm

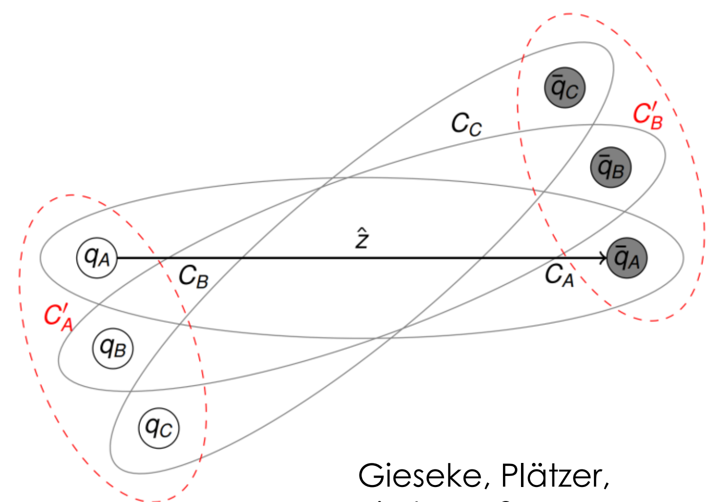
String breaking cannot produce heavy quarks

Andersson, Gustafson, Ingelman , Sjostrand, Phys.Rept. 97 (1983) 31-145

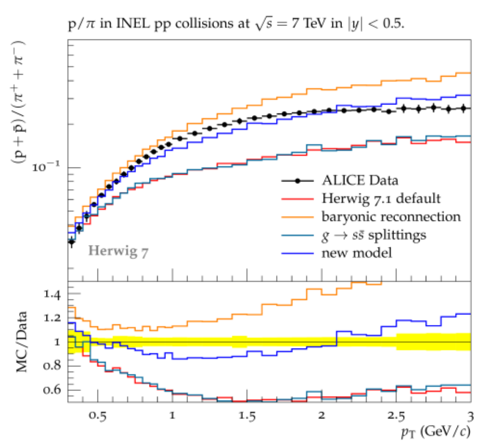
HERWIG COLOUR RECONNECTION

Herwig: Geometric picture for colour reconnection, including both mesonic and baryonic reconnection





Baryonic reconnection improves e.g. p/π ratio



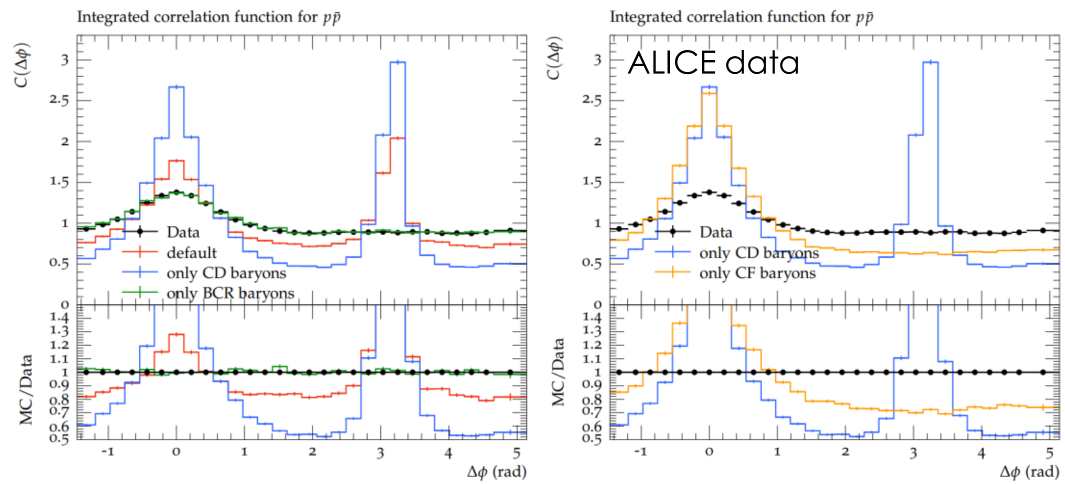
Gieseke, Plätzer, Kirchgaeßer, arXiv:1710.10906

BARYON CORRELATIONS

Study of baryonic correlations by Gieseke, Kiebacher, Plätzer:

See Kiebacher, talk at PSR24 conference

Cluster decay (CD) mechanism → unphysical far side peak.



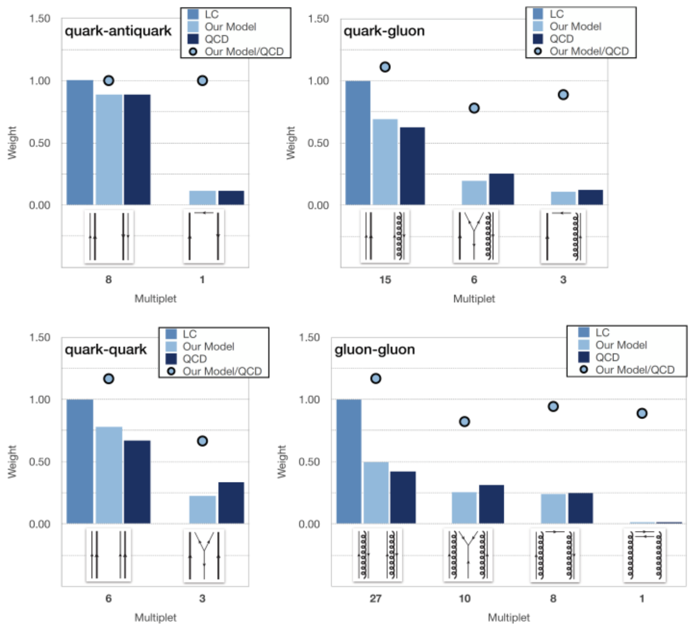
Baryonic reconnection (BCR) reproduces data well. Turn off CD? But then how can Herwig produce baryons at LEP?

Baryon production in cluster fission (CF) doesn't have unphysical far side peak. Switch off CD and turn on CF? Still problems…

(see backup slides of Lönnblad's talk for situation in Pythia)

PYTHIA QCD-BASED RECONNECTION

Pythia colour reconnection model: choose reconnections according to a model approximating QCD colour structure



Christiansen, Skands, arXiv:1505.01681

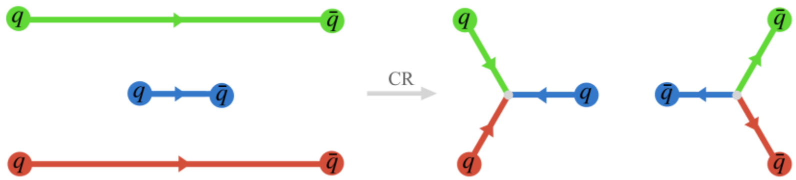
Pick reconnections to minimise string length:

$$\lambda^{q\bar{q}} = \max\left[\ln\left(\frac{E_1 + |\vec{p}|}{m_1 + m_0}\right), 0\right] + \max\left[\ln\left(\frac{E_2 + |\vec{p}|}{m_2 + m_0}\right), 0\right]$$

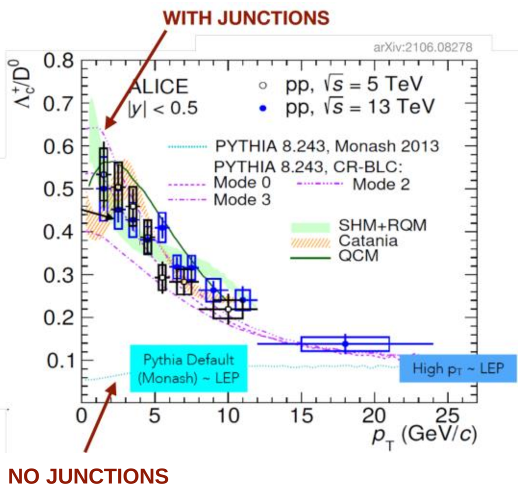
Altmann, Skands, arXiv:2404.12040

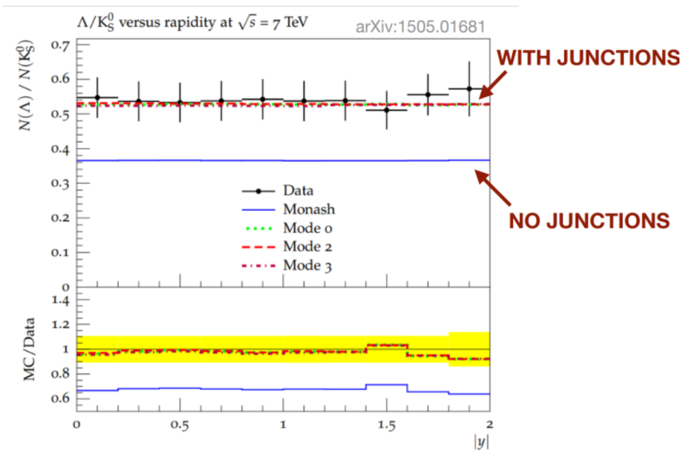
JUNCTIONS AND BARYONS

New configuration possible beyond LC: junctions!



Junctions play a crucial role in baryon production: ~40% of baryons from junctions in Pythia, ~70% of heavy flavour baryon production!

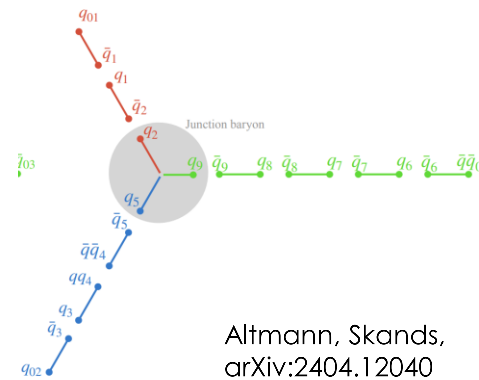




NEW TREATMENT OF JUNCTIONS

Improved treatment of junctions in recent work.

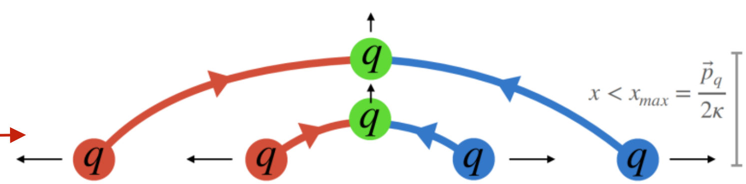
Old treatment relied on finding 'Mercedes frame'. Cases where this frame doesn't exist (heavy quarks), procedure fails 10% of the time.

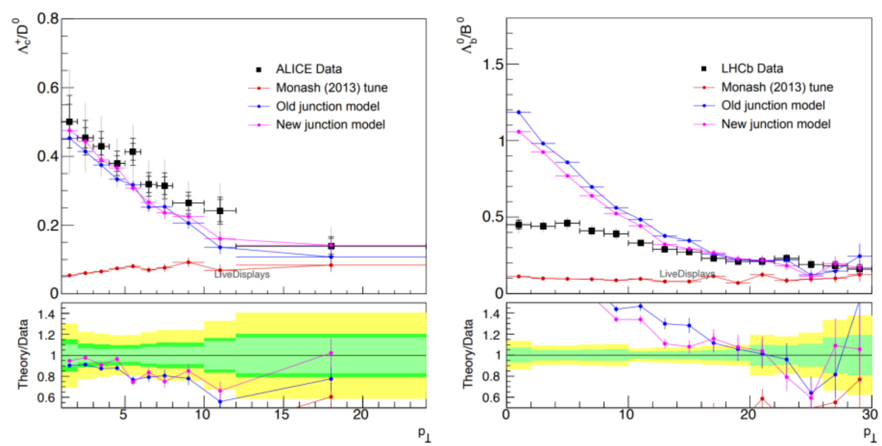


Altmann, Skands, arXiv:2404.12040

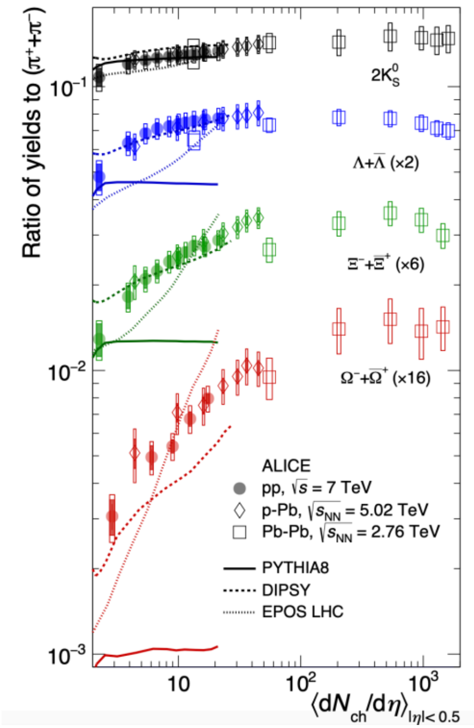
New procedure:

- treatment of heavy quarks ('pearl on a string')
- soft endpoints (endpoint oscillations)
- average junction rest frame established by considering pull on junction over time (more stable).

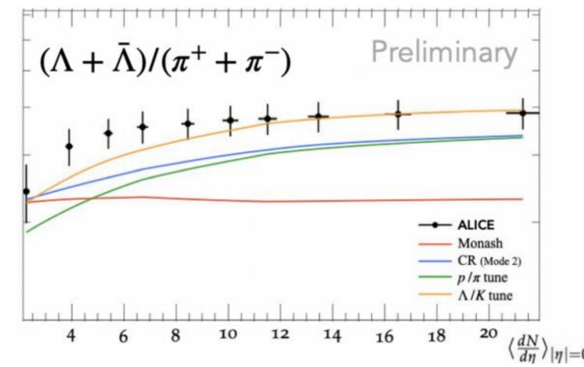


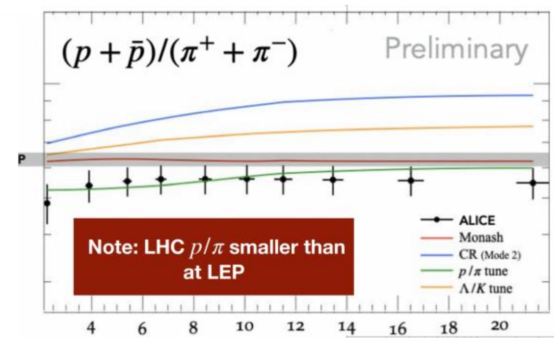


FURTHER ISSUES



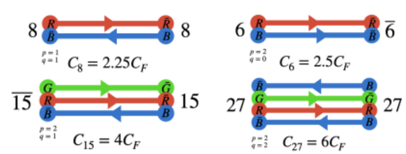
Talk by J. Altmann at MPI@LHC 2023





"Proton problem"

Colour ropes



Biro, Nielsen, Knoll, Nucl.Phys. B245 (1984) 449-468
Bierlich, Gustafson, Lönnblad, Tarasov, arXiv:1412.6259

Different string tension near a junction?

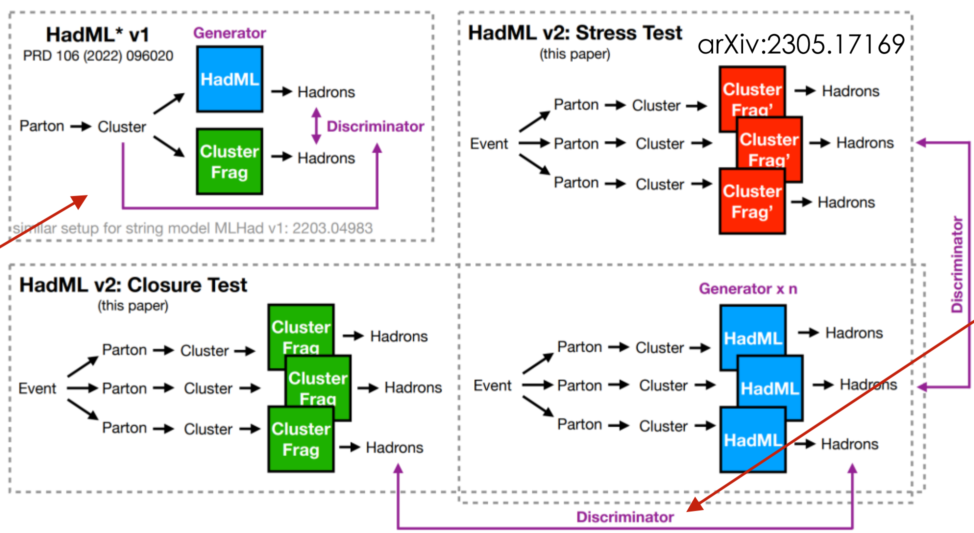
Issues with strange hadrons

Talk by J. Altmann at LHCP 2024

ML FOR HADRONISATION

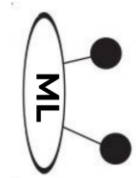
One approach: ‘fit’ hadronisation using neural networks.
E.g. HadML, uses Generative Adversarial Network (GAN)

Chan, Ghosh, Ju, Kania, Nachman, Sangli, Siodmok



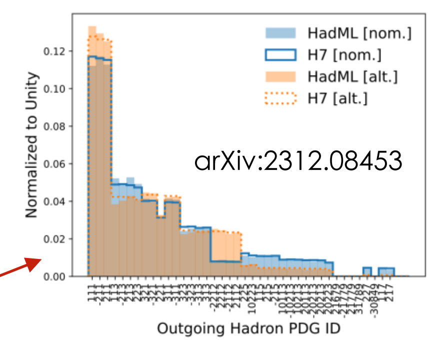
Discriminator compared HadML output to data at level of clusters (not possible for actual exp data)

arXiv:2203.12660

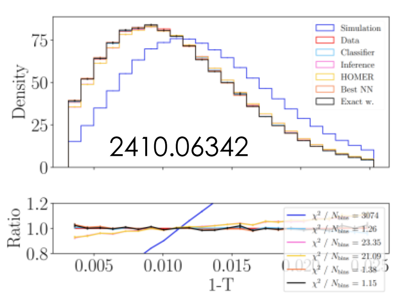


NN describes cluster decay to 2 hadrons

Now discriminator compares at level of events



Now fitting both kinematics and particle flavour

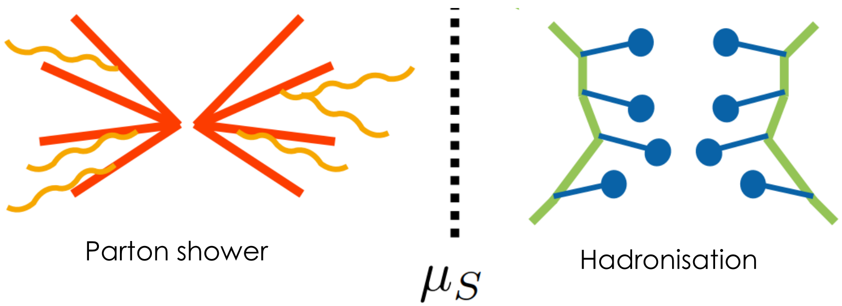


Alternative approach: MLHad. “HOMER” training method that can use binned distributions or event-by-event data.

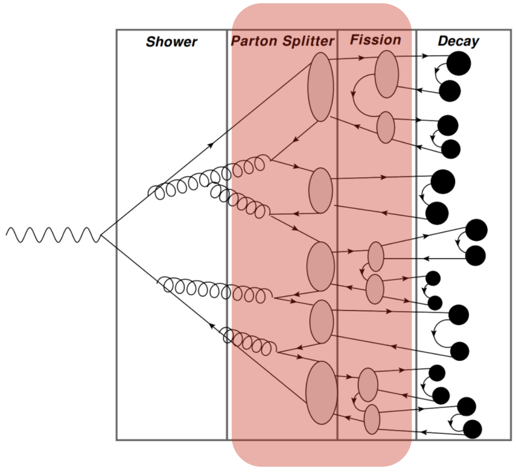
Bierlich, Ilten, Menzo, Mrenna, Szewc, Wilkinson, Youssef, Zupan

A FACTORISATION COMPATIBLE HADRONISATION MODEL

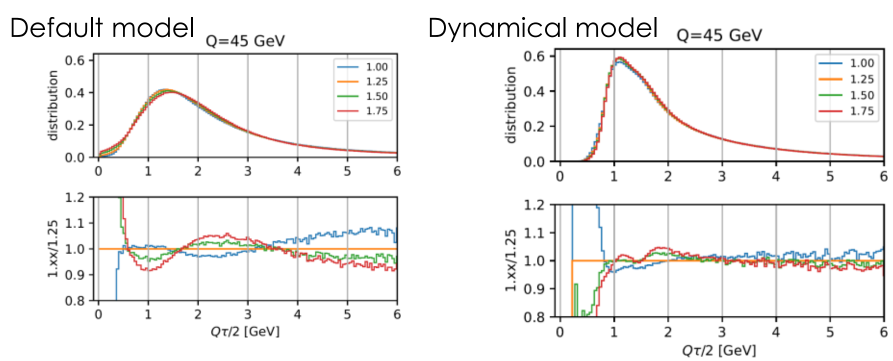
Approach by Plätzer et al. where shower cutoff = IR factorisation scale. Combination of PS + hadronisation should be independent of cut-off.



See talk of S. Plätzer on Monday



New "dynamical" model where forced gluon splitting + cluster fission dynamics adjusted to better mesh with PS.



Hoang, Jin, Plätzer, Samitz, arXiv:2404.09856

See also Plätzer, arXiv:2204.06956
& ongoing work by Gieseke, Kiebacher, Plätzer (e.g. talk by Kiebacher at PSR24).

A FACTORISATION COMPATIBLE HADRONISATION MODEL

Prediction from QCD for hadronic thrust:

Abbate, Fickinger, Hoang, Mateu, Stewart, arXiv:1006.3080

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau, Q) = \int_0^{Q\tau} \mathrm{d}\ell \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\tau}\left(\tau - \frac{\ell}{Q}, Q\right) \, S_{\mathrm{had}}(\ell)$$

$$= \int_0^{\tau} \mathrm{d}\hat{\tau} \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{\tau}}(\hat{\tau}, Q) \, Q \, S_{\mathrm{had}}(Q(\tau - \hat{\tau}))$$

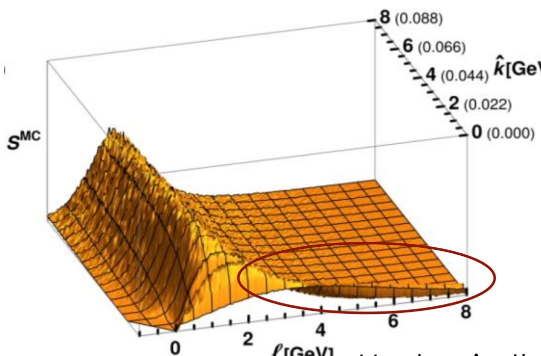
Partonic thrust

Shower

'Shape function' describing leading hadronisation effects

Hadronisation

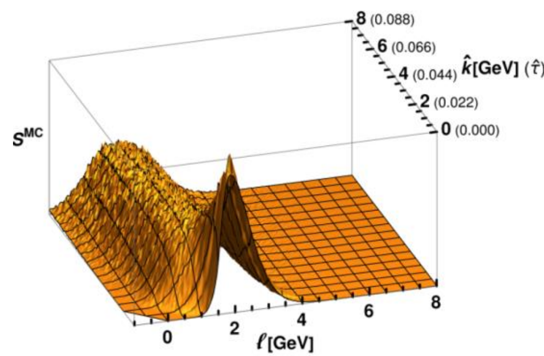
Default model

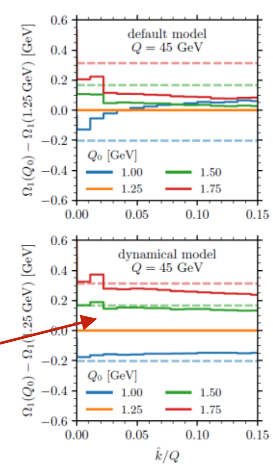


Partonic thrust

Hadronic thrust – partonic thrust

Dynamical model





Dashed line = QCD prediction

SUMMARY

Lots of progress on soft physics modelling in Monte Carlo event generators

Multiple Parton Interactions:
- Incorporating **number and momentum sum rule constraints**. Pythia model not perfect (in equal scale case) – work on improved model.
- Correct treatment of **perturbative 1→2 splitting** (dShower). Appreciable effects on same-sign WW and Z+jets DPS processes.

Hadronisation and colour reconnection
- Getting **baryon production** right. Herwig: **geometric colour reconnection** model. Issues with baryon correlations.
- Pythia: QCD-based colour reconnection model with **junctions**. Strange hadron production: **ropes**, **strange junctions**. "Proton problem."
- **ML models** of hadronisation.
- **Shower cut-off as a factorisation scale** (shower ↔ hadronisation).