Open Issues in Soft Physics

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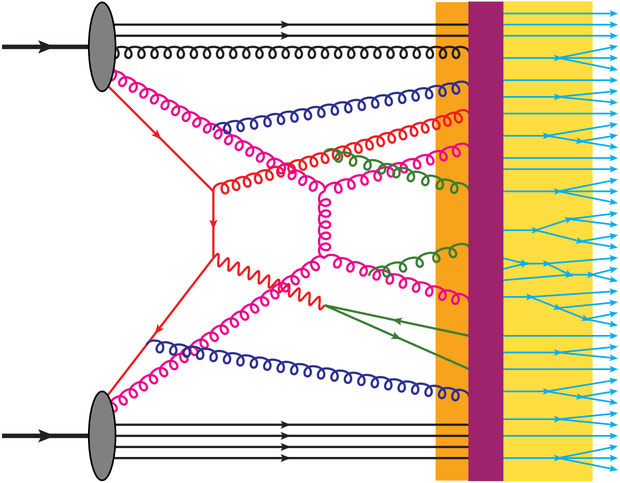
The structure of an event

An event consists of many different physics steps to be modelled:



PDF
ME
ISR
FSR
M&M
MPI
BBR
CR
Fragmentation
Decays
Rescattering
BE
$\sigma_{\text{tot}} = \cdots$
Unknown?

Fragmentation can include clusters, strings, ropes, QGP, shove, . . .

Agenda

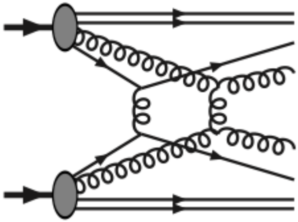
- Multiparton Interactions
- Colour Reconnection
- Collective effects
- Total cross sections and diffraction
- Beam remnants and forward physics
- Heavy Ions
- $\mathrm{e}^+\mathrm{e}^-$/DIS/photoproduction/$\gamma\gamma$
- Various and sundry
- Conclusions

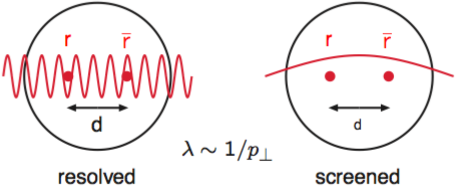
Warning 1: Expect no answers, simple or otherwise.

Warning 2: PYTHIA-centric outlook, by personal knowledge, but also biggest selection of **soft-physics** models and options

MultiParton Interactions (MPIs)

Hadrons are composite $\Rightarrow$ many partons can interact:





Divergence for $p_\perp \to 0$ in perturbative $2 \to 2$ scatterings;
tamed by unknown colour screening length d in hadron

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

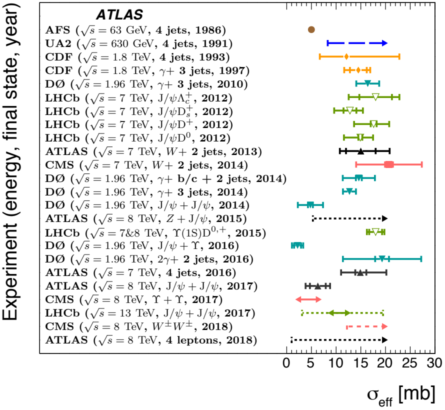
with $p_{\perp 0} \approx$ 2–3 GeV $\simeq 1/d$.
MPIs now baseline for minbias and underlying event
Variants in Herwig and in Shrimps/Sherpa models

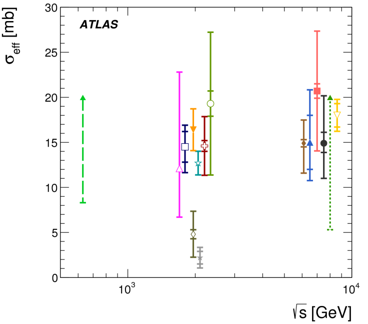
Double Parton Scattering

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \qquad \sigma_{AA} = \frac{\sigma_A^2}{2\sigma_{\text{eff}}}$$

State-of-the-art measurements

JHEP 11 (2016) 110





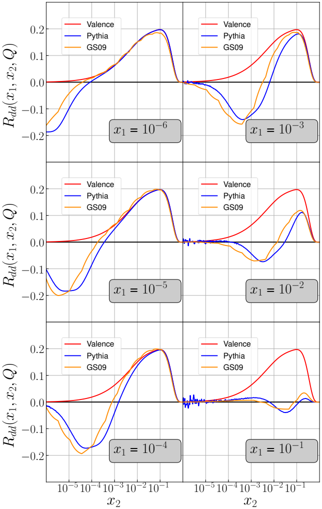
(D. Kar, MPI@LHC 2018)

arXiv:1811.11094

Dependance on c.m energy[19]

Double Parton Scattering Parton Distributions

Time to go beyond simple one-number characterization.



σ_{eff} assumes PDF factorization

$$f_{ab}(x_1, x_2, Q) = f_a(x_1, Q)\, f_b(x_2, Q)$$

but PYTHIA has sophisticated procedure to modify PDFs step-by-step based on already extracted partons.
Comparable with Gaunt–Stirling 09, but allows more partons.

Plot:

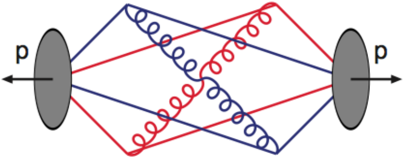
$$R_{\mathrm{dd}}(x_1, x_2, Q) = x_2 \frac{(f_{\mathrm{dd}} - f_{\mathrm{d\bar{d}}})(x_1, x_2, Q)}{f_d(x_1, Q)}$$

(O. Fedkevych et al, in prep)

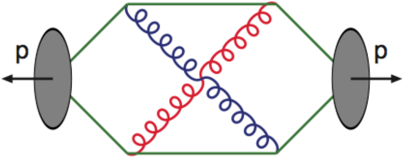
Also study underlying event!

Colour Reconnections and $\langle p_\perp \rangle(n_{\mathrm{ch}})$

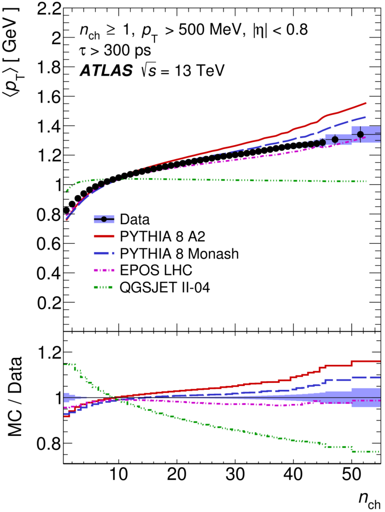
$\langle p_\perp \rangle(n_{\mathrm{ch}})$ is very sensitive to colour flow



long strings to remnants $\Rightarrow$ much n_{ch}/interaction $\Rightarrow$ $\langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ flat



short strings (more central) $\Rightarrow$ less n_{ch}/interaction $\Rightarrow$ $\langle p_\perp \rangle(n_{\mathrm{ch}})$ rising



Colour Reconnection and baryon production

One PYTHIA model relies on two main principles

⋆ **SU(3)** colour rules give allowed reconnections

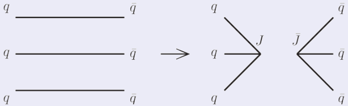
Ordinary string reconnection

(q$\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

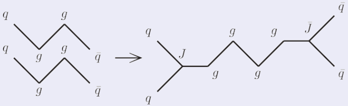
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



(q$\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



(Depends on number of gluons)

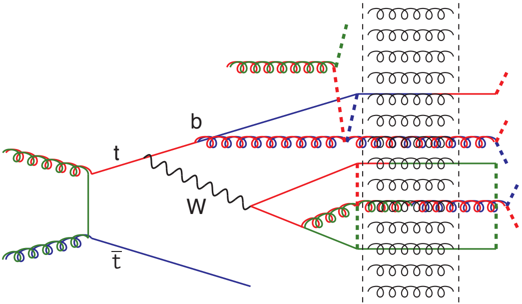
⋆ minimal string length gives preferred reconnections

J.R. Christiansen & P.Z. Skands, JHEP 1508, 003

Triple junction equivalent also introduced in Herwig cluster.

Colour Reconnection and the top mass

$$\Gamma_t \approx 1.5 \text{ GeV}$$
$$\Gamma_W \approx 2 \text{ GeV}$$
$$\Gamma_Z \approx 2.5 \text{ GeV}$$
$$\Rightarrow$$
$$c\tau \approx 0.1 \text{ fm}$$



Decays occur when p "pancakes" have passed, after MPI/ISR/FSR with $p_\perp \geq 2$ GeV, but inside hadronization colour fields.

Experimentalists achieve impressive m_t precision,
e.g. CMS $m_t = 172.35 \pm 0.16 \pm 0.48$ GeV (PRD93 (2016) 072004),
whereof CR ± 0.10 GeV
from PYTHIA 6.4 Perugia 2011 |CR - noCR|
Is this realistic? (see also S. Bhattacharya, EF05 2020-07-17)

Colour Reconnection effects on top mass

No publicly available measurements of UE in top events (then).

- Afterburner models tuned to ATLAS jet shapes in $\mathrm{t\bar{t}}$ events
  $\Rightarrow$ high CR strengths disfavoured.
- Early-decay models tuned to ATLAS minimum bias data
  $\Rightarrow$ maximal CR strengths required to (almost) match $\langle p_{\perp} \rangle (n_{\mathrm{ch}})$.

model	Δm_{top} rescaled
default (late)	$+0.239$
forced random	-0.524
swap	$+0.273$

Δm_{top} relative to no CR

Excluding most extreme (unrealistic) models

$\boldsymbol{m_{\mathrm{top}}^{\mathrm{max}} - m_{\mathrm{top}}^{\mathrm{min}} \approx 0.50}$ GeV

(in line with Sandhoff, Skands & Wicke)

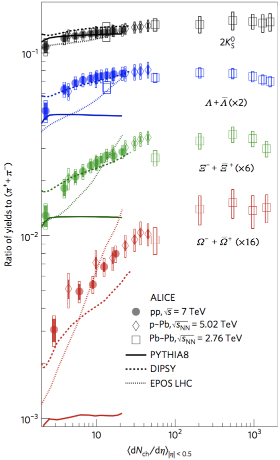
But $\Delta m_{\mathrm{top}} \approx 0$ in QCD-based model

Studies of top events could help constrain models:

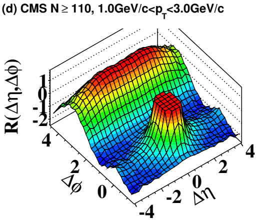
- jet profiles and jet pull (skewness)
- underlying event

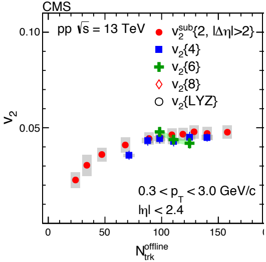
Collective Effects

I: Flavour composition



II: Flow





Signs of QGP-like collective behaviour in pp actively studied, but beyond default behaviour of standard pp generators

A tale of two communities

pp paradigm: **Jet Universality**
- hadronization determined from $\mathrm{e}^+\mathrm{e}^-$ data (LEP)
- hard processes and parton showers from perturbative QCD
- add multiparton interactions (MPI) for activity
- and colour reconnection (CR) for collectivity

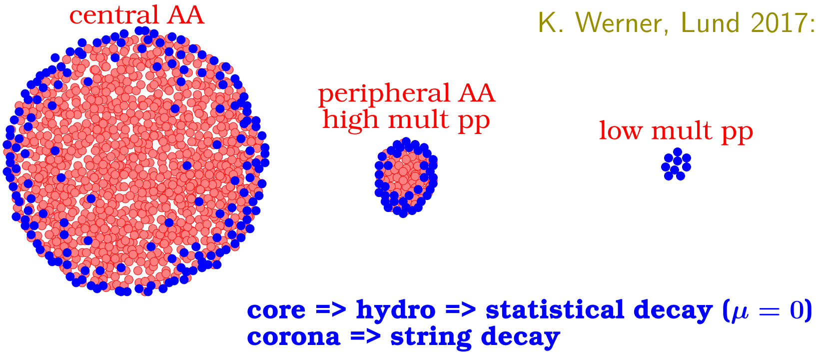
AA paradigm: **Quark-Gluon Plasma**
- deconfinement, hydrodynamics, perfect liquid, flow, ...
- pp (and pA): not enough time or volume for QGP

Time to rethink relationship:
- QGP formed in high-multiplicity pp?
- (some) signals for QGP red herring?

The Core–Corona solution

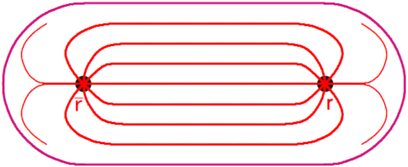
Currently most realistic "complete" approach

K. Werner, Lund 2017:



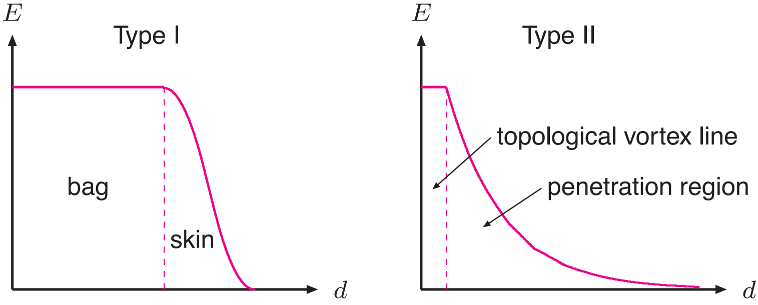
allows smooth transition. Implemented in **EPOS** MC
(Werner, Guiot, Pierog, Karpenko, Nucl.Phys.A931 (2014) 83)

Can conventional pp MCs be adjusted to cope?



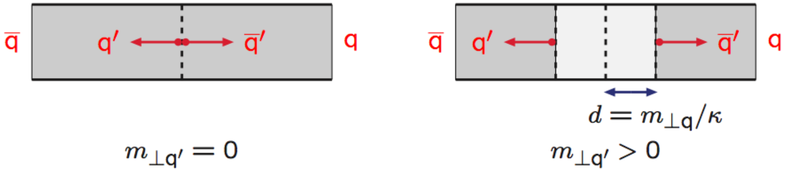
QCD field lines compressed to tubelike region $\Rightarrow$ **string**.
Gives linear confinement $V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm.
Confirmed e.g. on the lattice.

Nature of the string viewed in analogy with superconductors:



but QCD could be intermediate, or different.

How does the string break?



String breaking modelled by tunneling:

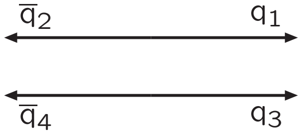
$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_{q}^2}{\kappa}\right)$$

- Common Gaussian $p_\perp$ spectrum, $\langle p_\perp \rangle \approx 0.4$ GeV.
- Suppression of heavy quarks,
  $\mathrm{u\overline{u} : d\overline{d} : s\overline{s} : c\overline{c}} \approx 1 : 1 : 0.3 : 10^{-11}$.
- Diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production.
  Extended by popcorn model: consecutive $\mathrm{q\overline{q}}$ pair production

Rope hadronization (Dipsy model)

Dense environment $\Rightarrow$ several intertwined strings $\Rightarrow$ **rope**.

Sextet example:



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

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

At first string break $\kappa_{\mathrm{eff}} \propto C_2^{(6)} - C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$.

At second string break $\kappa_{\mathrm{eff}} \propto C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \kappa$.

Multiple $\sim$parallel strings $\Rightarrow$ random walk in colour space.

Larger $\kappa_{\mathrm{eff}} \Rightarrow$ larger $\exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa_{\mathrm{eff}}}\right)$

- more strangeness ($\tilde{\rho}$)
- more baryons ($\tilde{\xi}$)
- mainly agrees with ALICE (but p/π overestimated)

Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503, 148;
from Biro, Nielsen, Knoll (1984), Białas, Czyz (1985), . . .

Quantized or continuous rescaling?

Close-packing of strings $\Rightarrow$ smaller area A for each?

$$\begin{aligned}
\kappa &= E^2 A + B' A = \left(\frac{\Phi}{A}\right)^2 A + B' A = \frac{\Phi^2}{A} + B' A \\
\kappa_{\mathrm{opt}} &= 2\Phi\sqrt{B'} \text{ for } A_{\mathrm{opt}} = \Phi/\sqrt{B'} \\
A &= k A_{\mathrm{opt}} \Rightarrow \kappa = \frac{1+k^2}{2k}\kappa_{\mathrm{opt}} \\
\kappa &\to \left(n_{\mathrm{string}}^{\mathrm{eff}}\right)^{2r} \kappa \\
n_{\mathrm{string}}^{\mathrm{eff}} &= 1 + \frac{n_{\mathrm{string}} - 1}{1 + p_{\perp\mathrm{had}}^2 / p_{\perp 0}^2}
\end{aligned}$$

where n_{string} is number of strings crossing rapidity of hadron.
Results comparable with rope picture (but not quite as good).
N. Fischer, TS, JHEP 1701, 140

Thermodynamical string model

Old lesson from fixed target and ISR (pp at $\sqrt{s} = 62$ GeV):

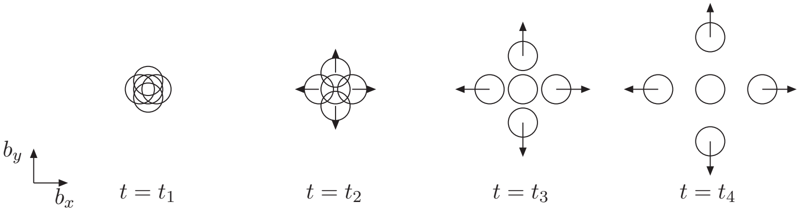
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_\perp} = N \exp\left(-\frac{m_{\perp\mathrm{had}}}{T}\right) \quad , \quad m_{\perp\mathrm{had}} = \sqrt{m_{\mathrm{had}}^2 + p_\perp^2}$$

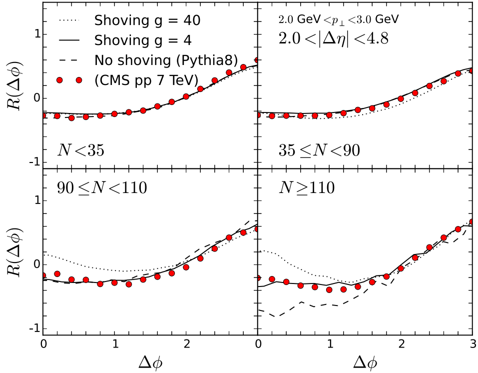
provides reasonable description, for $p_\perp$ not too large,
with $\sim$ same N and T for all hadron species.
But inclusive description: no flavour, **p** or E conservation!

Now: combine with basic string framework for local flavour and $p_\perp$ compensation. (With some approximations.)
Exponential gives overall decent rates compared with LEP, but with too many multistrange baryons, opposite to tunneling.
N. Fischer, TS, JHEP 1701, 140

Can be understood as fluctuating string width/tension, already for single isolated string.
A. Białas, PLB 466, 301

Shove (Dipsy model)





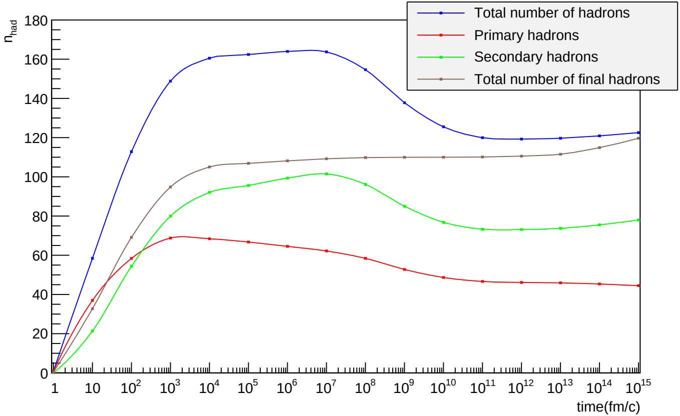
Overlapping string at early times can give repulsive push, so strings get transverse motion, imparted to hadrons produced from them.

Can give ridge and flow, in azimuth and $p_\perp$.

Bierlich, Gustafson, Lönnblad, PLB 779, 58

Spacetime evolution

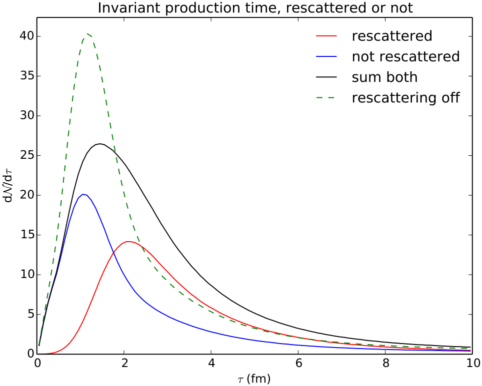
PYTHIA can calculate production vertex of each particle,
e.g. number of hadrons as a function of time for pp at 13 TeV:



S. Ferreres-Solé, TS, EPJC 78, 983

Hadronic rescattering

13 TeV nondiffractive pp events:



PYTHIA now contains framework for hadronic rescattering:

1) Space–time motion and scattering opportunities

2) Cross section for low-energy hadron–hadron collisions

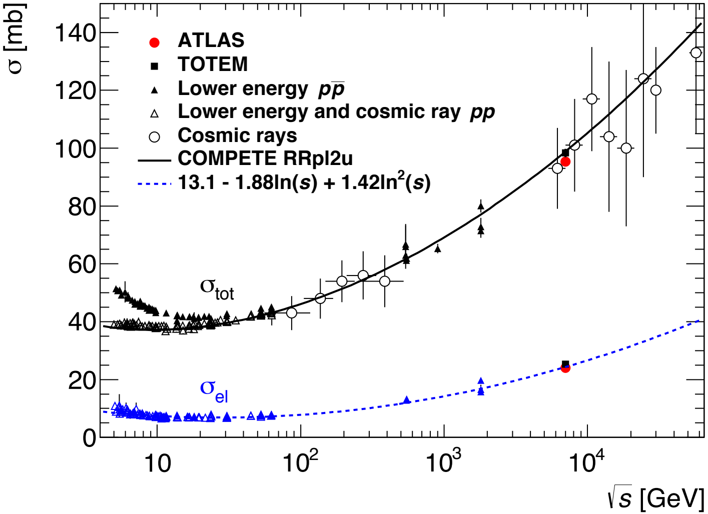
3) Final-stater topology in such collisions

M. Utheim, TS, arXiv:2005:05658

Observable consequences in pp minor, but:

- important for AA modelling
- pp collisions from $\sim$threshold to FCC energies

Total cross section



Several options for total and partial pp & $\mathrm{p\overline{p}}$ cross sections: DL/SaS, MBR, ABMST, RPP2016.

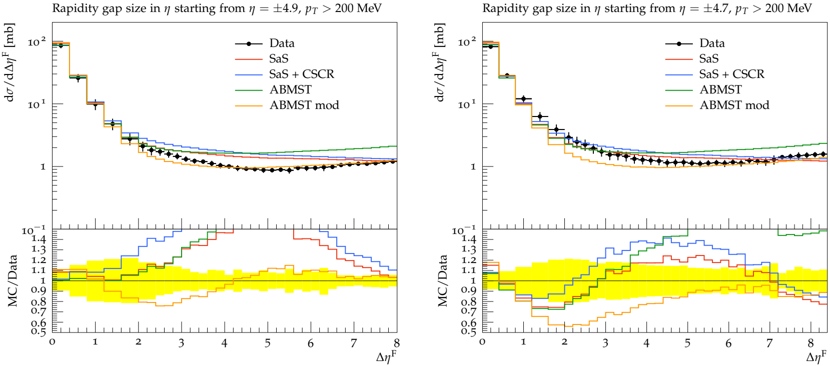
Partial cross sections

$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{SD},XB} + \sigma_{\mathrm{SD},AX} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{CD}} + \ldots (+\sigma_{\mathrm{Coulomb}} + \sigma_{\mathrm{int}})$

Warning: theoretical classification $\neq$ experimental one.

Complicated modelling of components and conflicting data

ATLAS: CMS:

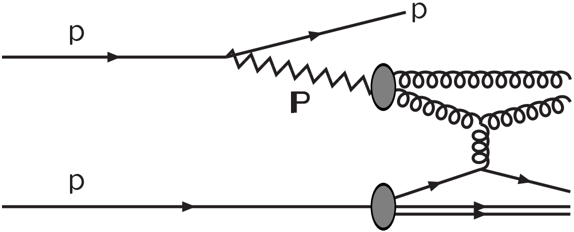


Appleby, Barlow, Molson, Serluca, Toader, EPJC 76, 520

C.O. Rasmussen, TS, EPJC 78, 461

Diffraction

Ingelman-Schlein: Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) × ($\mathbb{P}$p collision)



Used e.g. in
POMPYT
POMWIG
PHOJET

1) σ_{SD}, σ_{DD} and σ_{CD} set by Reggeon theory.

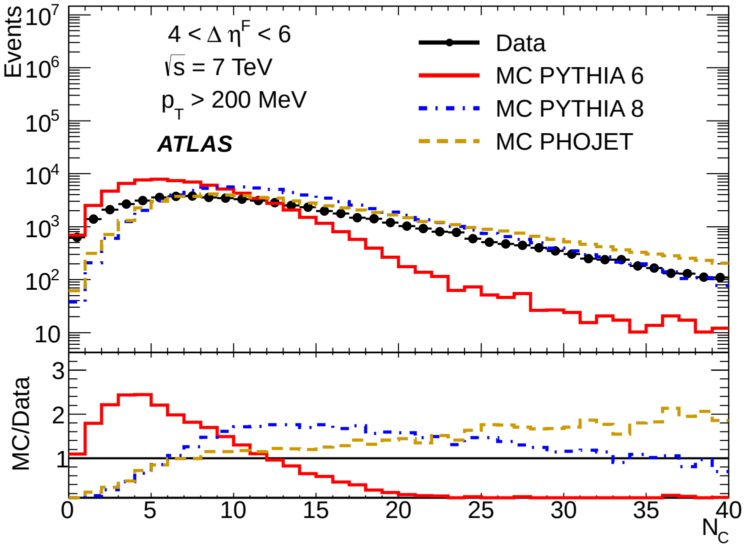
2) $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \Rightarrow$ diffractive mass spectrum, $p_{\perp}$ of proton out.

3) Smooth transition from simple model at low masses to $\mathbb{P}$p with full pp machinery: multiparton interactions, parton showers, etc.

4) Choice between different Pomeron PDFs.

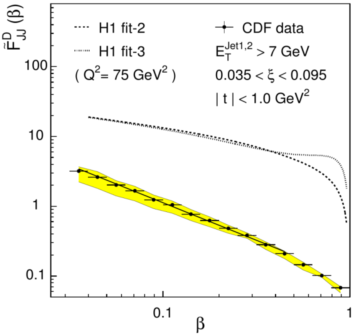
5) Free parameter $\sigma_{\mathbb{P}\mathrm{p}}$ needed to fix $\langle n_{\mathrm{interactions}} \rangle = \sigma_{\mathrm{jet}} / \sigma_{\mathbb{P}\mathrm{p}}$.

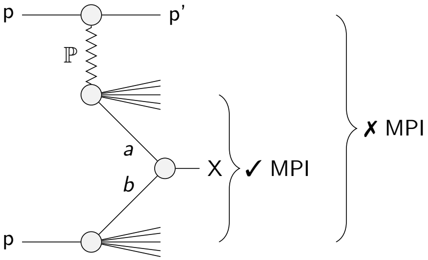
Multiplicity in diffractive events



PYTHIA 6 lacks MPI, ISR, FSR in diffraction, so undershoots.

Hard processes in diffractive events





C.O. Rasmussen, TS, JHEP 1602, 1421
CDF, PRL 84, 5043

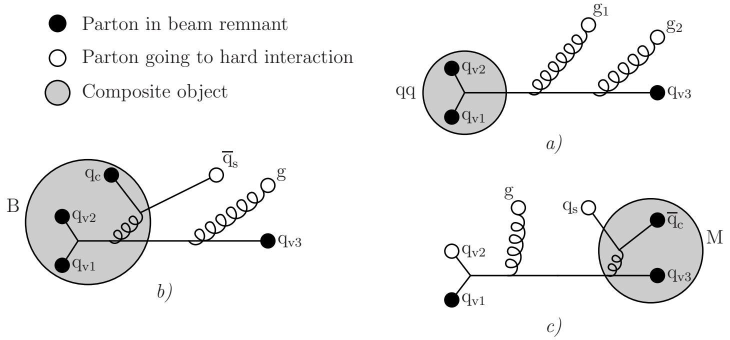
Many modelling details and uncertainties, not perfect description.

Qualitative understanding:

Parameter	$(p\overline{p} \to \overline{p}' + W) \times 2$	$(p\overline{p} \to \overline{p}' + Z) \times 2$
CDF	(1.0 ± 0.11) %	(0.88 ± 0.22) %
$p_{\perp 0}^{\mathrm{ref}} = 2.78$ GeV	(0.59 ± 0.06) %	(0.49 ± 0.05) %
Exponential overlap	(0.25 ± 0.04) %	(0.24 ± 0.04) %

whereas $\sim 10\%$ without gap suppression

Beam remnants

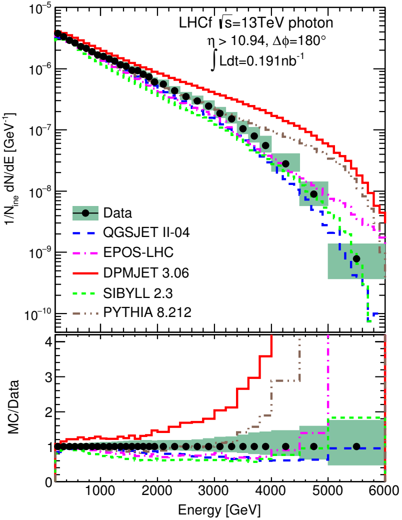


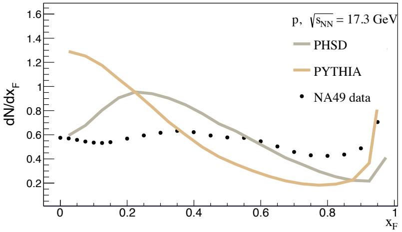
Need to model:

- Flavour content of remnant; also valence vs. sea/companion
- Colour structure of partons; including junctions and CR
- Longitudinal sharing of momenta
- Transverse sharing of momenta — primordial $k_\perp$ (nontrivially relates to low-$p_\perp$ ISR handling)

Forward physics

Forward region especially important for cosmic-ray physics.





V. Kireyeu et al., arXiv:2006.14739
LHCf, PLB 78, 233

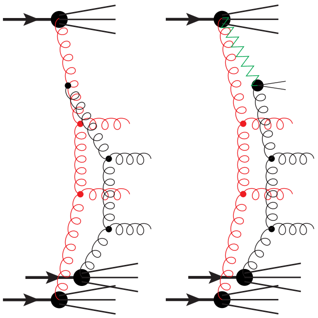
Need mechanism for protons to take more energy (from pions). Diffractive-related or not?

Heavy-ion physics and Angantyr

Quark–Gluon Plasma (QGP) well established. Typical modelling:

- Initial conditions by Color Glass Condensate and MPIs.
- Energy–momentum flow in QGP phase by hydrodynamics.
- Local phase transition (freezeout) to hadrons.

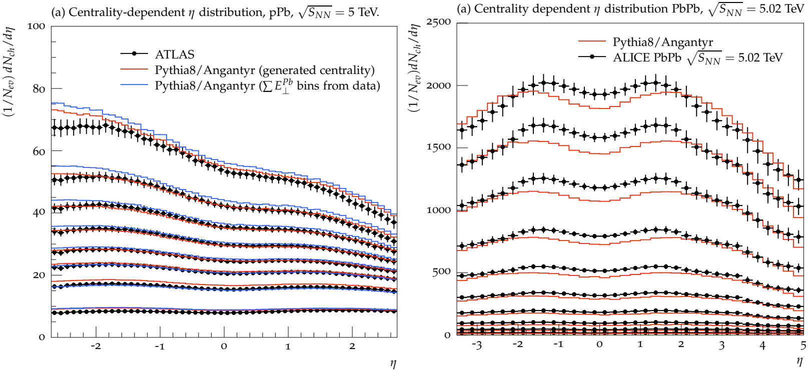
Is it possible to construct a model without QGP
that still reproduces many/most experimental phenomena?



Angantyr/PYTHIA:

- Glauber–Gribov nucleon distributions and cross section fluctuations.
- MPI-style colour connections, and diffractive topologies.
- Standard PYTHIA machinery: showers, MPIs, strings, . . .

Examples of Angantyr results



Bierlich, Gustafson, Lönnblad, Shah, JHEP 1810, 134

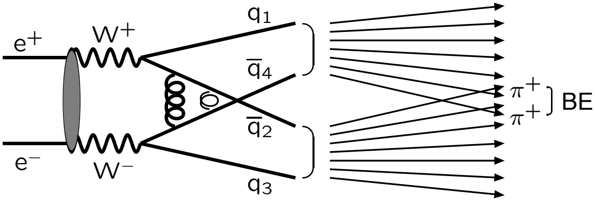
Angantyr under continued development.

To come: shoving, ropes, hadronic rescattering, . . .

e^+e^- annihilation

- $e^+e^- \to \gamma^*/Z^0 \to q\overline{q}$ is starting point for our understanding of hadronization (and FSR).
- Old data+analyses, especially LEP, reconstructed in **Rivet**, but mainly global event properties (n_{charged}, Thrust, ...) or single-particle spectra
- Correlations needed, but require expertise to encode, e.g.
  – flavour chains for baryon production,
  – decay distributions of higher resonances, $f_2 \to \pi^+\pi^-$
- **Belle** in unique position to contribute to common effort, in continuum and for B decay tables

Colour Reconnection and the W mass in e^+e^-



At LEP 2 search for effects in $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q_1\overline{q}_2\, q_3\overline{q}_4}$:

- perturbative $\langle \delta M_{\mathrm{W}} \rangle \lesssim 5$ MeV : negligible!
- nonperturbative $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV :

  favoured; no-effect option ruled out at 99.5% CL.

  Best description for reconnection in $\approx 50\%$ of the events.
- Bose-Einstein $\langle \delta M_{\mathrm{W}} \rangle \lesssim 100$ MeV : full effect ruled out (while models with ~ 20 MeV barely acceptable).

New: hadronic rescattering and shove!

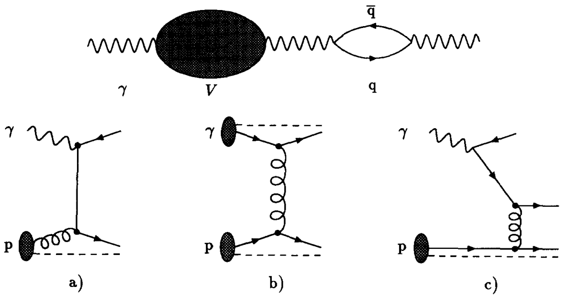
Deeply Inelastic Scattering and Photoproduction

- DIS starting point for all PDF studies
- . . . but also key for ISR and beam remnant hadronization
- H1 and ZEUS analyses in **HZTool**, but Fortran and next-to-nothing ported to Rivet
- HERA-era generators also Fortran, and only little ported

Given EIC, new/extended code needed for

- DIS split by diffractive or not
- photoproduction split by direct or resolved
- transition region between photoproduction and DIS
- extensions to eA, $\gamma\mathrm{A}$, $\gamma^*\mathrm{A}$
- polarization effects

The nature of the real photon



Photon fluctuations lead to three classes:

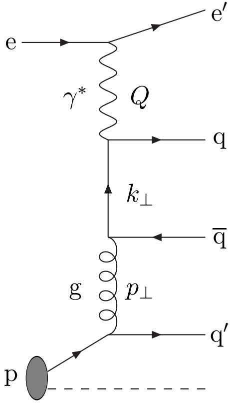
a) direct: pointlike coupling

b) VMD: photon fluctuates to vector meson $(\rho^0, \omega, \phi, \ldots)$ and interacts as such, including MPIs, elastic, diffraction

c) anomalous/GVMD: photon fluctuates to perturbative $\mathrm{q}\overline{\mathrm{q}}$ pair, similar to VMD but no MPIs

Unclear borders, even more so in higher orders.

Event classes for a virtual photon



In general three scales characterizing process

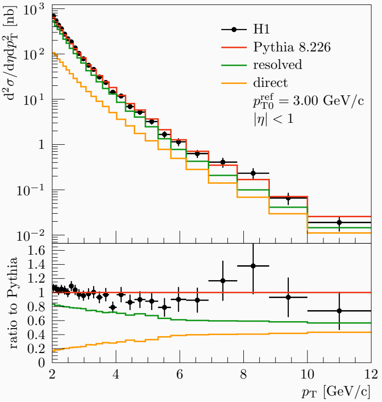
- Q, the photon virtuality
- $k_\perp$, the scale at which the photon couples to a quark line
- $p_\perp$, the hardest scale in the parton ladder, excluding $k_\perp$

Ordering of $Q, k_\perp, p_\perp$ decides classification and simulation of collision.

In PYTHIA 6 (Fortran) implemented as 4 event classes for $\gamma^*\mathrm{p}$ (smoothly combined), and 13 for $\gamma^*\gamma^*$ (using $Q_1, Q_2, k_{\perp 1}, k_{\perp 2}, p_\perp$).

Cumbersome, not ported to PYTHIA 8. Currently DIS and photoproduction separate, and latter only direct + resolved. $\gamma\gamma$ only real, as useful e.g. for AA grazing collision studies.

Photoproduction at HERA



[H1: Eur.Phys.J. C10 (1999) 363-372]

H1 measurement

- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q^2_\gamma < 0.01$ GeV^2

Comparison to PYTHIA 8

- Resolved contribution dominates
- Good agreement with the data using $p_{T0}^{ref} = 3.00$ GeV/c

$\Rightarrow$ MPI probability between pp and $\gamma\gamma$

(from Ilkka Helenius presentation at POETIC8, 20 March 2018)

Also diffractive dijet production studied.

I. Helenius, C.O. Rasmussen, EPJC 79, 413

Possible contributions from Lattice QCD

- PDFs, especially at low Q^2
- Characterize vortex line (string) properties; type I, type II, ...
- Interaction between two parallel nearby strings
- Sort out multiplet structure, especially lowest $L = 1$ mesons
- Identify glueball state and mixing with other mesons
- Explain exotic states, e.g. $\mathrm{f}_0(500)$
- Calculate partial widths (and thereby BRs) for two-body states
- ...

Tuning

1000 Many physics mechanisms with hundereds of model choices or parameters in description of pp physics.

950 Most parameters set by prejudice + hints from some data.

50 Global tunes, like Monash (P. Skands et al., EPJC 74, 3024), but split in subgroups, and much informed prejudice.

5 Typical experimental tunes improve a handful of these, e.g. with automated tools such as Professor.

1 For quick-and-dirty actions one change may be good enough, e.g. compensate change of PDFs by a new MPI $p_{\perp 0}$ to maintain same $\langle n_{\mathrm{charged}} \rangle$.

Modelling of each aspect may have significant inherent uncertainty, but tuning to data introduces nontrivial anticorrelations. Reasonable set and range of variations will depend on task.

No simple answer.

Some topics not discussed

- Improved partons showers and matching+merging
- Consequences of NLO (negative) PDFs in shower context
- Initial-state impact-parameter picture, e.g. Dipsy dipoles
- Differences between quark and gluon jets
- Heavy-flavour production and hadronization
- Jet quenching in high-multiplicity pp systems (?)
- Partonic rescattering ($3 \to 3$ etc. in MPIs)
- Transition from showers to hadronization
- Deuteron, tritium, helium, tetraquark, pentaquark coalescence (within space–time picture)
- . . .

Summary and outlook

- Deceptively good agreement with much LHC/LEP data.
- Collective effects in high-multiplicity pp game-changer.
- Reinvigorated study of soft physics; many "new" ideas: CR, rope, shove, thermodynamic, rescattering, ...
- More correct physics should mean better tunes
- Much experimental work needed to sort out what is going on; **requires further low-luminosity running**
- Challenges await EIC, ILC, FCC, ν beams, cosmic rays
- **Rivet should be extended** to include more data, old as new

You sought an answer
and found a question
– you are disappointed.

inspired by
Edith Södergran
(1916)

Thank You!

Snowmass 1984, Wu-Ki Tung (picture by speaker)

Backup: Interleaved evolution in PYTHIA

- Transverse-momentum-ordered parton showers for ISR and FSR
- MPI also ordered in $p_\perp$

$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right)$$
$$\times \exp\left(- \int_{p_\perp}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

Ordered in decreasing $p_\perp$ using "Sudakov" trick.
Corresponds to increasing "resolution":
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

- Start from fixed hard interaction $\Rightarrow$ underlying event
- No separate hard interaction $\Rightarrow$ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

Backup: MPIs in PYTHIA

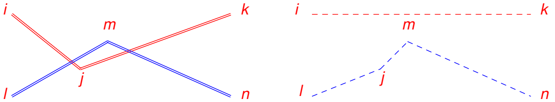
- MPIs are gererated in a falling sequence of $p_\perp$ values; recall Sudakov factor approach to parton showers.
- Core process QCD $2 \to 2$, but also onia, γ's, $\mathrm{Z}^0, \mathrm{W}^\pm$.
- Energy, momentum and flavour conserved step by step: subtracted from proton by all "previous" collisions.
- Protons modelled as extended objects, allowing both central and peripheral collisions, with more or less activity.
- Colour screening increases with energy, i.e. $p_{\perp 0} = p_{\perp 0}(E_{\mathrm{cm}})$, as more and more partons can interact.
- Colour connections: each interaction hooks up with colours from beam remnants, but also correlations inside remnants.
- Colour *re*connections: many interaction "on top of" each other $\Rightarrow$ tightly packed partons $\Rightarrow$ colour memory loss?

Backup: Colour Reconnection models for top studies

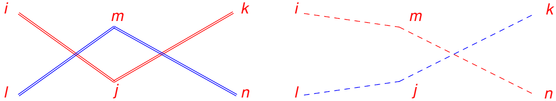
Late t decay: first ordinary CR (existing model) as if t stable, then CR between g's from $\mathrm{t}\&\mathrm{W}$ decays and g's from rest of event, in 5 variants, some "straw-man", e.g. random ($\Rightarrow \langle\lambda\rangle$ increases)

Early t decay: new "gluon-move" model for whole event

1) move: remove gluon and insert on other string if reduces λ



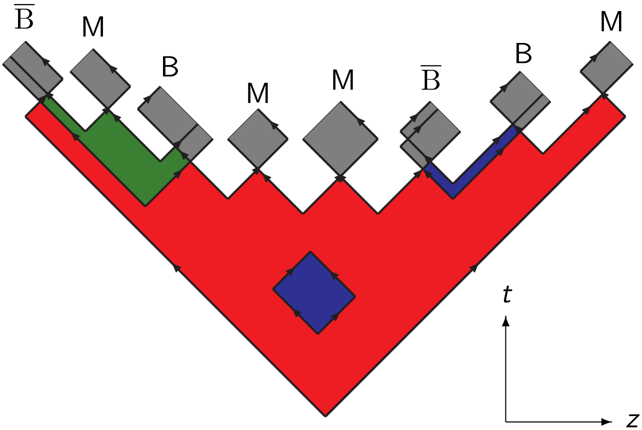
2) flip: cross two chains if reduces λ ($\sim$ swing)



3) (swap: interchange two gluons if reduces λ)

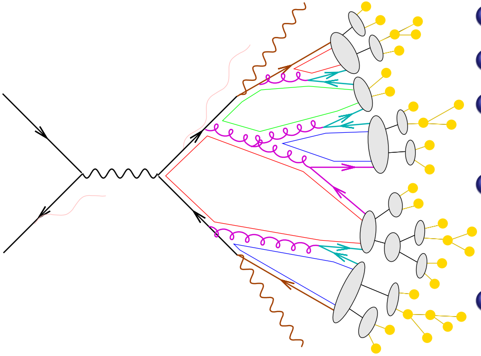
S. Argyropoulos & TS, JHEP 1411, 043; P. Skands et al. earlier

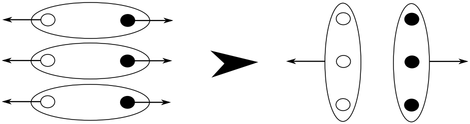
Backup: The popcorn model for baryon production



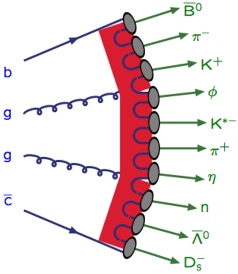
- SU(6) (flavour×spin) Clebsch-Gordans needed.
- Quadratic diquark mass dependence
  ⇒ strong suppression of multistrange and spin 3/2 baryons.
  ⇒ effective parameters with less strangeness suppression.

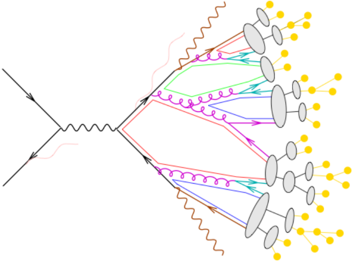
Backup: The Herwig cluster model





1. Force $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ branchings.
2. Form colour singlet clusters.
3. Decay high-mass clusters to smaller clusters.
4. Decay clusters to 2 hadrons according to phase space times spin weight.
5. New: allow three aligned $\mathrm{q}\overline{\mathrm{q}}$ clusters to reconnect to two clusters $\mathrm{q}_1\mathrm{q}_2\mathrm{q}_3$ and $\overline{\mathrm{q}}_1\overline{\mathrm{q}}_2\overline{\mathrm{q}}_3$.
6. New: allow nonperturbative $\mathrm{g} \to \mathrm{s}\overline{\mathrm{s}}$ in addition to $\mathrm{g} \to \mathrm{u}\overline{\mathrm{u}}$ and $\mathrm{g} \to \mathrm{d}\overline{\mathrm{d}}$.



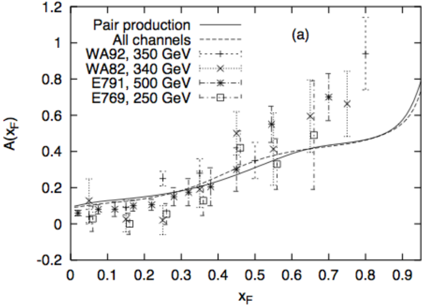


program	PYTHIA	Herwig
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

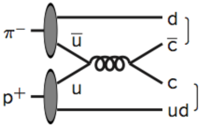
Backup: Beam remnant physics

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- p$

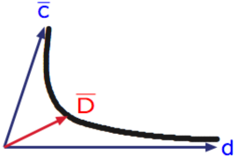
$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$



(also B asymmetries at LHC, but small)



If low-mass string e.g.:
$\bar{c}d$: D^-, D^{*-}
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}
$\Rightarrow$ flavour asymmetries



Can give D 'drag' to larger x_F than c quark for any string mass