Collective Effects:

the viewpoint of HEP MC codes

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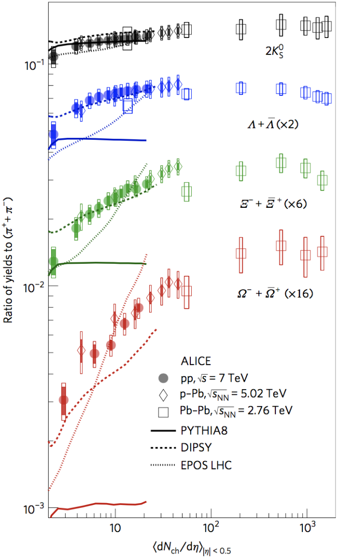
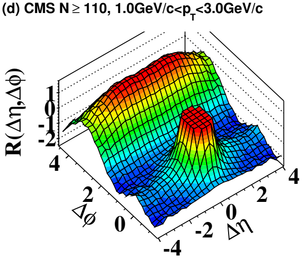
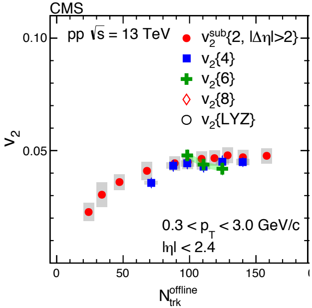
Why this presentation?

I: Flavour composition



II: Flow





A tale of two communities

pp paradigm: **Jet Universality**

- hadronization determined from e^+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

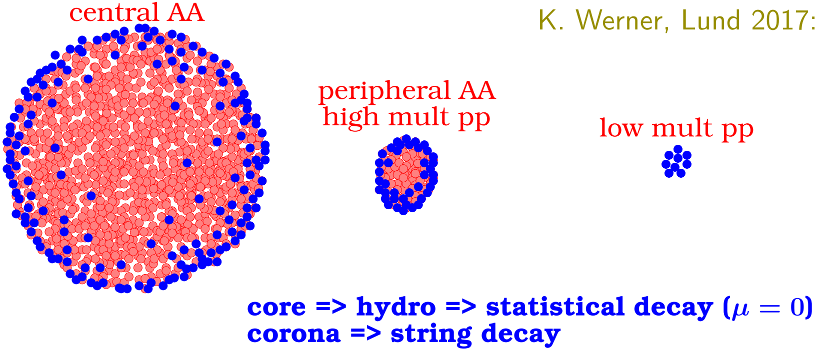
Time to rethink relationship:

- 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)

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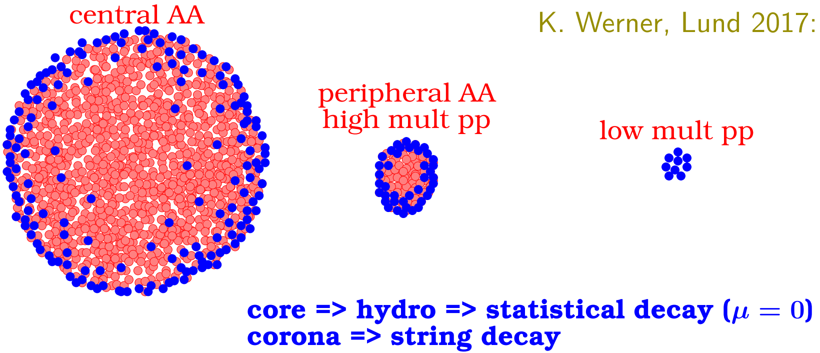

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(Werner, Guiot, Pierog, Karpenko, Nucl.Phys.A931 (2014) 83)

Can conventional pp MCs be adjusted to cope?

The pp workhorses

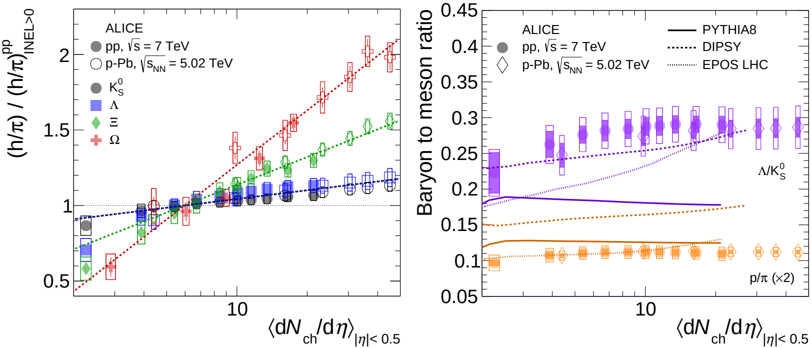
PYTHIA originated in string hadronization studies.
Historically strong interest in soft physics: MPI, CR.
Several ongoing projects for high-multiplicity pp.
Angantyr model for pA and AA (cf. Fritiof).

Herwig originated with coherent showers.
MPI, CR and cluster hadronization added.
Some ongoing hadronization studies.

Sherpa originated with matrix elements/match/merge.
Soft physics, like MPI and CR, PYTHIA-inspired.
KMR model coming as alternative (Shrimps).
Either cluster or string hadronization.

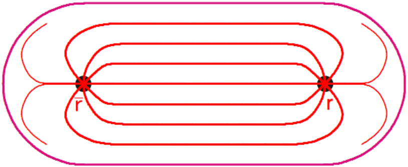
Also external add-ons like JEWEL (Zapp) for jet quenching,
or spin-offs like HIJING (Gyulassy, Wang) for heavy ions.

Part I: Flavour composition



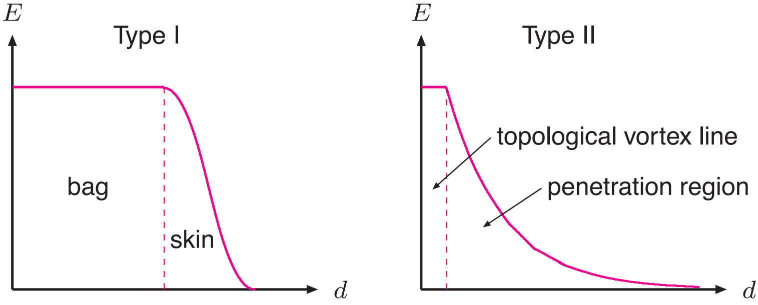
- **Significant strangeness enhancement; the more the merrier.**
- **Minimal baryon enhancement.**
- Not described by the Lund string fragmentation model.

The QCD string



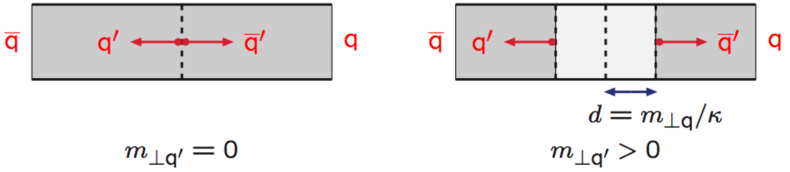
QCD field lines compressed to tubelike region ⇒ **string**.
Gives linear confinement $V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm.
Confirmed e.g. on the lattice.

Nature of the string viewed in analogy with superconductors:



but QCD could be intermediate, or different.

The tunneling mechanism in string fragmentation



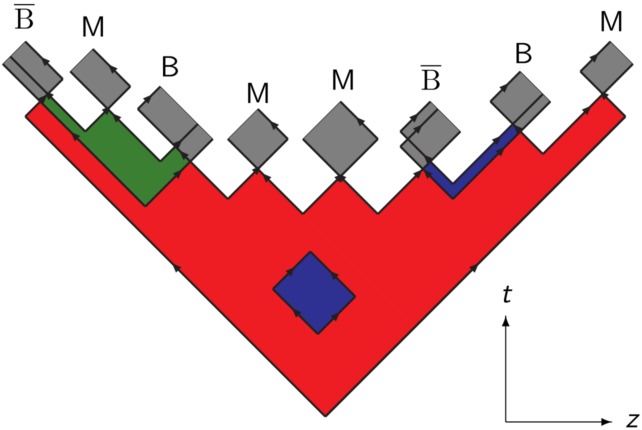
String breaking modelled by tunneling:

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

with string tension $\kappa \approx 1$ GeV/fm ≈ 0.2 GeV^2

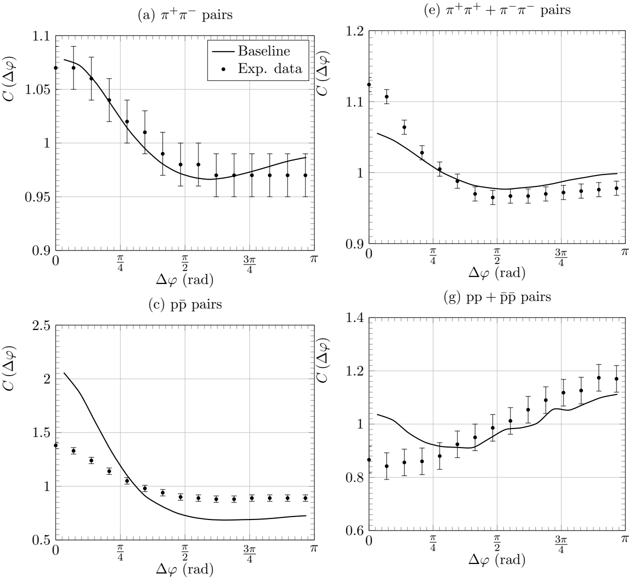
- common Gaussian $p_\perp$ spectrum
- suppression of heavy quarks
  $\mathrm{u\bar{u}} : \mathrm{d\bar{d}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1 : 1 : 0.3 : 10^{-11}$
- diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

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.

Azimuthal pair correlations



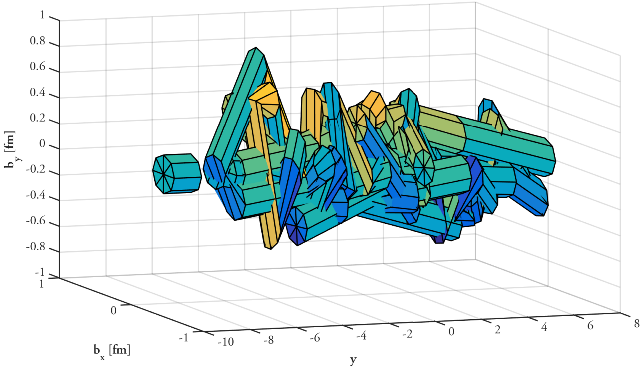
7 TeV ALICE:
EPJ C77, 567

PYTHIA:
baryons
too strongly
correlated
in minijets!

J. Alnefjord
LU TP 17-13
(bachelor study)

Rope hadronization (Dipsy/PYTHIA) (1)

Best current description offered by Dipsy rope hadronization.



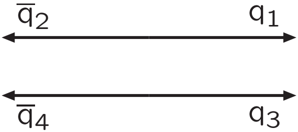
Dense environment ⇒ several intertwined strings ⇒ rope.

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

Sextet example:

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

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



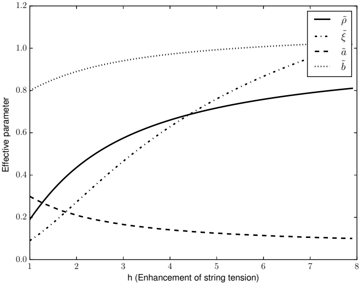
At first string break $\kappa_{\mathrm{eff}} \propto C_2^{(6)} - C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$.

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

Multiple ~parallel strings ⇒ 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 (p/π overestimated)



A QCD-based Colour Reconnection model

Model by Christiansen & Skands relies on two main principles

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

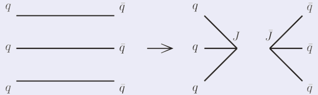
Ordinary string reconnection

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

Double junction reconnection

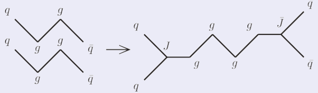
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



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

Zipping reconnection



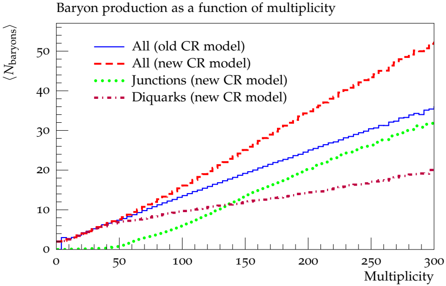
(Depends on number of gluons)

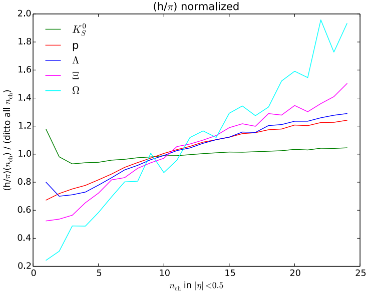
⋆ minimal λ measure gives preferred reconnections

$\lambda \approx \sum_{\mathrm{dipoles}} \ln(1 + m_{ij}^2/m_0^2)$ measure of string length, $\propto n_{\mathrm{hadronic}}$

Christiansen, Skands, JHEP 1508, 003

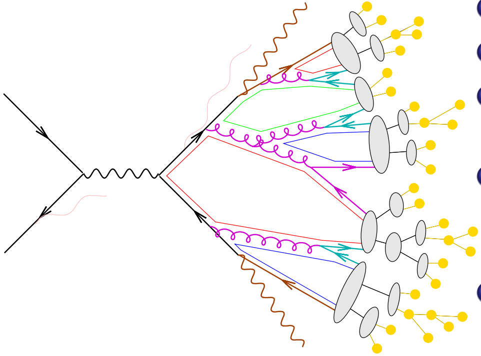
Results for QCD-based Colour Reconnection model

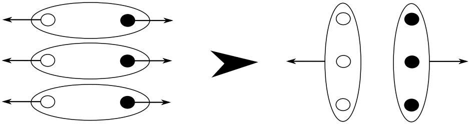




- Many small strings ⇒ fewer regular baryons.
- Junction baryons rise faster than multiplicity.
- Net effect clear relative rise of baryon production.
- Λ similar to p since mainly light diquarks ($\Lambda \approx \mathrm{ud}_0 + s$).
- Steeper multistrange baryon rise,
  since no diquark m^2 suppression for junction.

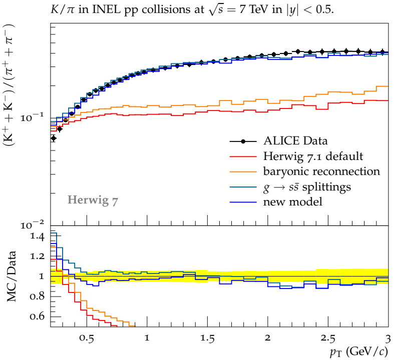
Herwig cluster news





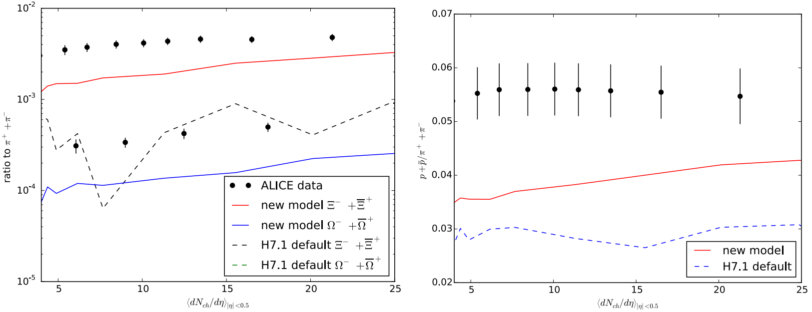
1. Force $g \rightarrow q\overline{q}$ branchings.
2. Form colour singlet clusters.
3. Decay high-mass clusters to smaller clusters.
4. Decay clusters to 2 hadrons according to phase space times spin weight.
5. New: allow three aligned $q\overline{q}$ clusters to reconnect to two clusters $q_1q_2q_3$ and $\overline{q}_1\overline{q}_2\overline{q}_3$.
6. New: allow nonperturbative $g \rightarrow s\overline{s}$ in addition to $g \rightarrow u\overline{u}$ and $g \rightarrow d\overline{d}$.

Herwig cluster good news



Gieseke, Kirchgaeßer, Plätzer, EPJ C78 (2018) 99

Herwig cluster bad news



- Significantly enhanced strangeness production, especially multistrange baryons.
- Some rise of (multi)strange baryon production with increasing event multiplicity . . .
- . . . but comes from increased baryon production in general.

High multiplicity ⇒ more reconnection possibilities to baryons.

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.

Significant reduction from ~ 20 parameters to 3:
$T \approx 0.20$ GeV, $\mathrm{s/u} \approx 0.5$, $\mathrm{qq/q} \approx 0.5$.

Fischer, TS, JHEP 1701, 140

Quantized or continuous rescaling?

$$V = E^2 A + B'A = \left(\frac{\Phi}{A}\right)^2 A + B'A = \frac{\Phi^2}{A} + B'A$$

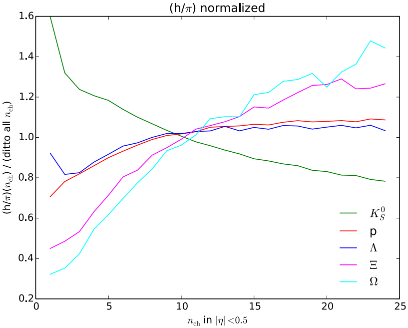
$$V_{\mathrm{opt}} = 2\Phi\sqrt{B'} \text{ for } A_{\mathrm{opt}} = \Phi/\sqrt{B'}$$

$$A = kA_{\mathrm{opt}} \Rightarrow V = \frac{1+k^2}{2k} V_{\mathrm{opt}} \Rightarrow T = \frac{1+k^2}{2k} T_{\mathrm{opt}}$$

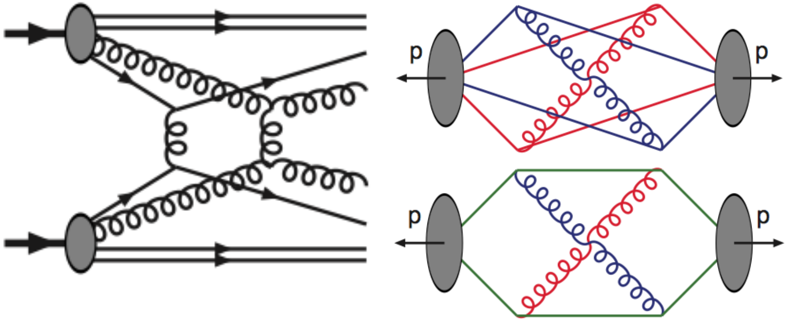
$$T \rightarrow \left(n_{\mathrm{string}}^{\mathrm{eff}}\right)^r T$$

$$n_{\mathrm{string}}^{\mathrm{eff}} = 1 + \frac{n_{\mathrm{string}} - 1}{1 + p_{\perp\mathrm{had}}^2 / p_{\perp 0}^2}$$

with tuned $r \approx 0.13$;
similar to rope,
but continuous effect.



Part II: Collectivity and flow



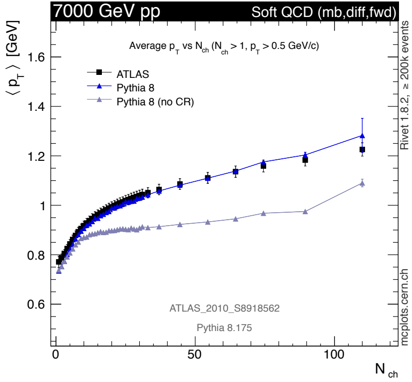
If MultiParton Interactions (MPIs) occur independently
then many MPIs is more of the same.

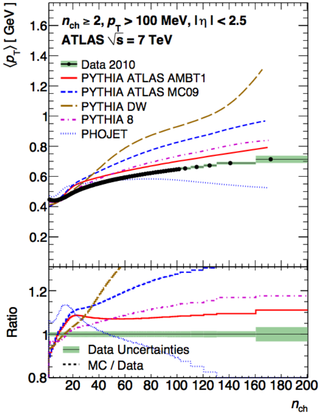
Colour Reconnections (CR) introduce some kind of collectivity.
Important in all pp generators.

Typically: reduce total string length,
$\lambda \approx \sum_{\mathrm{dipoles}} \ln(1 + m_{ij}^2/m_0^2) \propto n_{\mathrm{ch}}$

The rise of transverse momentum

$\langle p_\perp \rangle(n_{\mathrm{ch}})$ increasing from ISR energies upwards.



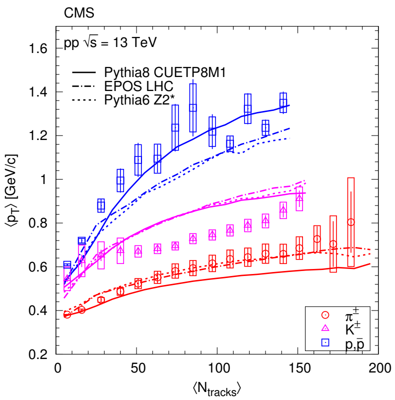


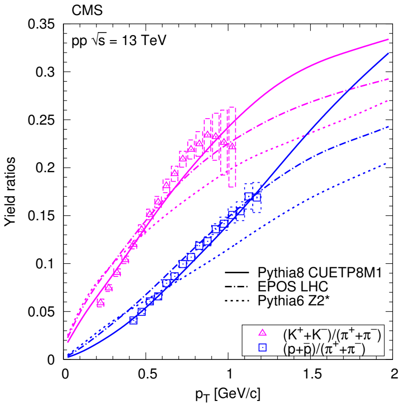
$\langle p_\perp \rangle(n_{\mathrm{ch}})$ is sensitive to colour flow:

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

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

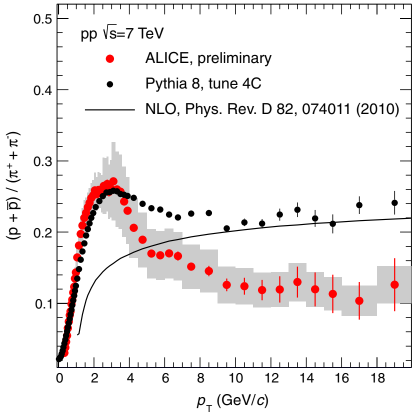
Hadron transverse momentum spectra (1)

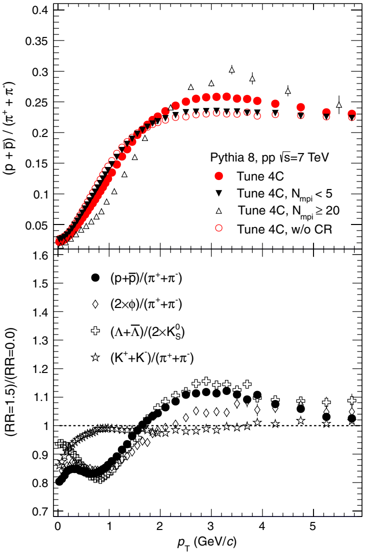




- All hadron kinds participate in rise.
- Heavy particles have significant depletion at low $p_{\perp}$.

Hadron transverse momentum spectra (2)



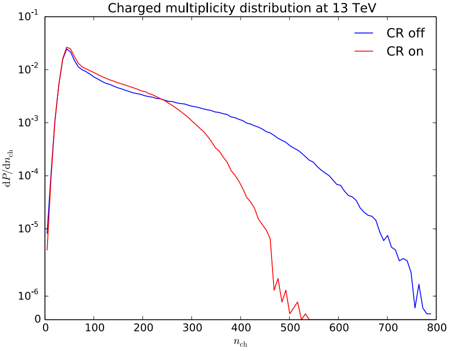


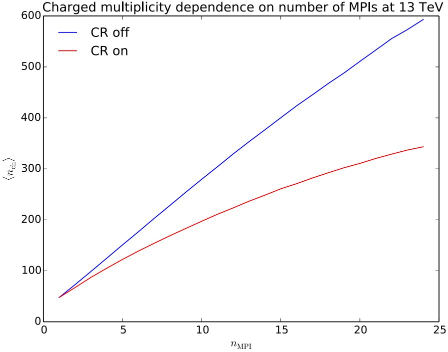
CR can give flowlike effects!

Ortiz Velasquez et al.,

PRL 111 (2013) 042001

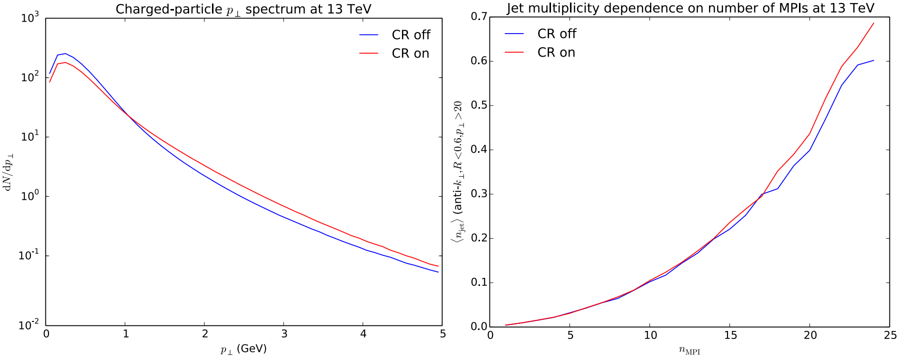
Charged multiplicity dependence on CR





CR $\Rightarrow$ fewer hadrons, fewer more per extra MPI.

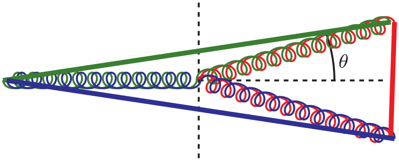
Transverse momentum dependence on CR

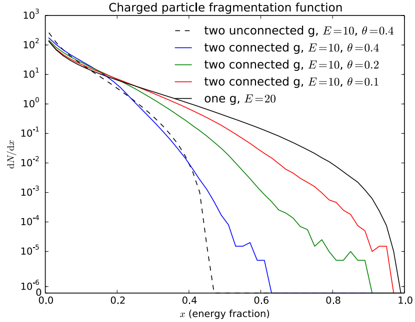


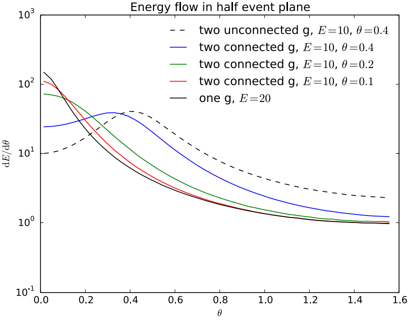
CR $\Rightarrow$ fewer particles at low $p_\perp$, more for $p_\perp > 1$ GeV.

Anti-$k_\perp$ jets with $p_{\perp\mathrm{jet}} > 20$ GeV and $R = 0.6$, no UE subtraction: rate comparable for fixed n_{MPI}, in spite of lower multiplicity.

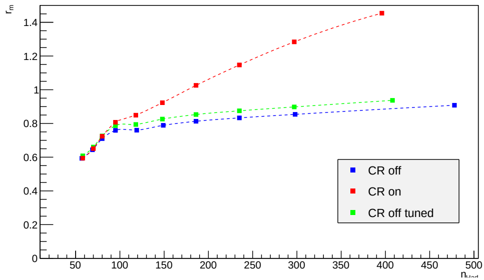
Merging of two nearby colour-connected partons

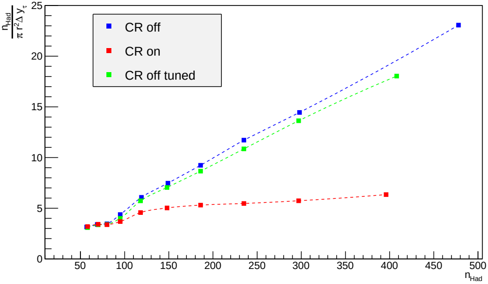






Collinear safety of string fragmentation!





r_m = median radius (fm)

$$\text{density} = \frac{n_{\text{hadrons}}}{\pi r_m^2 \, \Delta y_\tau}$$

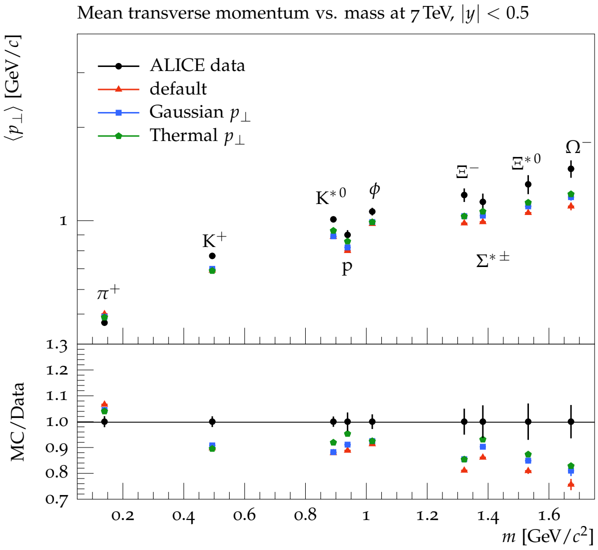
$$y_\tau = \frac{1}{2} \ln \left(\frac{t+z}{t-z} \right)$$

no CR:
r_m rather flat,
steep increase of density.

with CR:
r_m increases with n_{hadrons},
density reasonably flat
but still large.

Ferreres-Solé, TS, in prep.

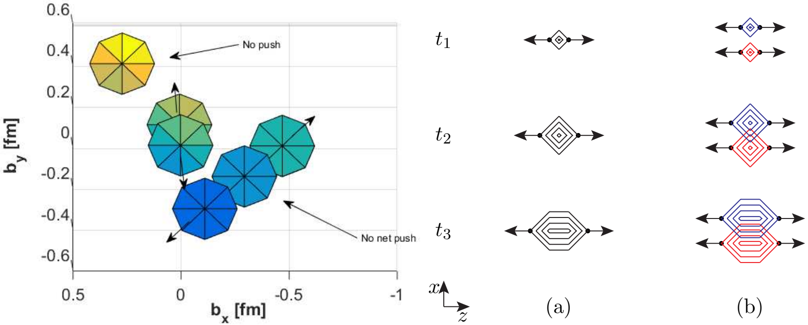
Hadron mean transverse momenta



Qualitatively OK, quantitatively not: resonance decays.

Will need hadronic rescattering, also after ρ decays (?).

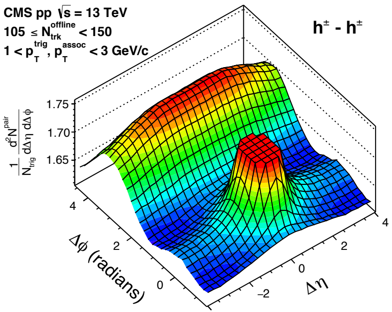
String shoving (1)

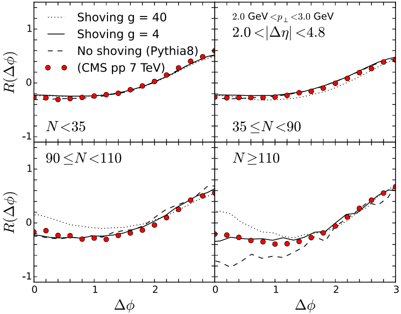


- Shoving begins in the middle of local longitudinal rest frame.
- Strings sliced in rapidity and time.
- Pairwise transverse kicks with $p_\perp$ conservation.
- Represented by adding a gluon.

Bierlich, Gustafson, Lönnblad, PLB779 (2018) 58,
from Abramovsky, Gedalin, Gurvich, Kancheli, JETP Lett 47 (1988) 337

String shoving (2)

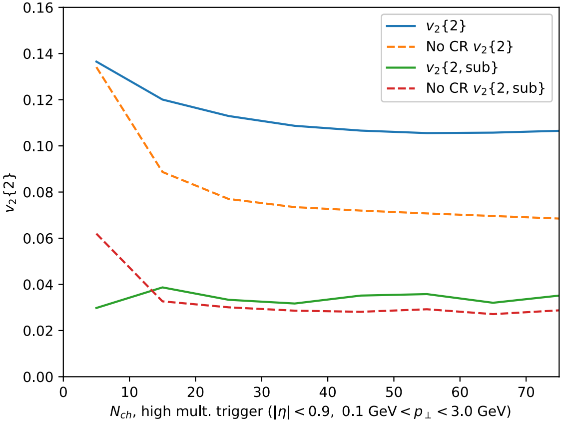




Future:

- Continuous hadron-centered effect rather than slices.
- Go beyond long, soft strings.
- Combine with rope.
- Flow v_2 coefficients etc?

Flow coefficients



(preliminary)

Approximate ALICE high-forward-energy trigger.

With or without CR.

"sub" $=$ central $\eta = 1.4$ gap.

More details on ropes, shove, flow, etc. in Dipsy/PYTHIA context:
C. Bierlich, in Small Systems session, tomorrow Tuesday 16.00

What next?

Further studies needed for high-multiplicity events:

- Jet quenching.
- Υ (1s,2s,3s) phenomenology.
- Prompt photons.
- Other supposed QGP signals.
- Flavour composition in jets vs. in UE
  (less overlap in jets, so expect less effect).
- Flavour correlations, e.g. baryon-antibaryon.

Is new data already explained by core-corona models?
Can conventional pp models explain observations?

`Angantyr`: modern-day version of the `Fritiof` model
for pp, pA and AA, with shoving and ropes,
being developed by Bierlich, Gustafson and Lönnblad.
H. Shah: poster.

Summary and outlook

- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.
- String close-packing likely to influence hadronization, before (shoving), during (ropes) and after (rescattering).
- Currently no known unique solution, so free to explore.
- Several recent & ongoing studies look promising, but much work and few active with pp generator outlook.
- Further experimental input crucial!

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- String close-packing likely to influence hadronization, before (shoving), during (ropes) and after (rescattering).
- Currently no known unique solution, so free to explore.
- Several recent & ongoing studies look promising, but much work and few active with pp generator outlook.
- Further experimental input crucial!

Whole new field of study opening up!