Microscopic collectivity with the DIPSY event generator

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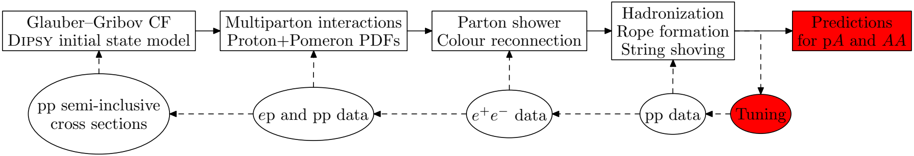
Collectivity in small systems – hairs in the soup or new opportunities?

- Collective behaviour in small systems, pp and pA.
  - Is a plasma in thermal equilibrium formed in pp collisions?
  - Could the QGP features be explained by modified models for pp?
  - What happens when we extrapolate the modified models to heavy ions?
- Microscopic models for QGP.
  - No assumptions of a thermalized plasma.
  - Extensions of Lund string/Colour reconnection in high density environments.
  - Lattice QCD based corrections to non-pert. models.
  - Phenomenological corrections to (perturbative) parton shower.
- Don't think about going from large to small systems...
- ...but rather from small to large!

Universal event generator for $e^+e^- \rightarrow AA$ – why and how?

- Universal models exist for e^+e^-, ep and pp.
  - Unfeasible for pA and AA because QGP = non-universality.
  - What if small systems can restore universality?
- Put data and theory on the same footing for comparison.
  - The most important definition of collectivity is the experimental one!
  - Universal physics model $\rightarrow$ full final states.
  - Universal models should be tuned only once (tune $\neq$ fit)!
  - Rivet is popular in e^+e^- and pp, still missing in ep and HI.
- Microscopic models for collectivity can challenge hydro–picture.
  - Or provide confirmation if unsuccessful.
- Benefit from existing infrastructure for *e.g.* hard processes.
- Tuned to small systems only – built from several elements.



Overview and nomenclature

1. Extrapolation from pp to pA – how? results?
   - *FritiofP8* extrapolation.
   - Based on DIPSY initial state model.
2. Microscopic collectivity – pp ridge, flavour ratios.
   - Rope hadronization – corrections to Lund strings.
   - Final state swings – corrections to Ariadne FS shower.
   - String shoving – dynamical FS interactions between strings.
3. Even smaller systems – e^+e^-, pp CD, UPC.

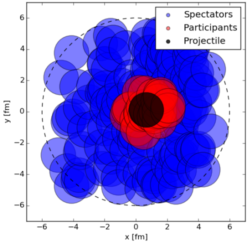
Extrapolate: Glauber + DIPSY (CB et al: arXiv:1607.04434 [hep-ph])

- Q: How can we extrapolate "minimum bias pp" to "minimum bias pA and AA".
- Q: What do we need to reproduce "centrality" $\propto$ forward particle production?
- Wounded nucleons updated to include fluctuations in target and projectile (SD + DD).
- Notation: optical theorem in impact parameter space, fluct's $\rightarrow$ diffractions in Good–Walker:

$$\Im(A_{el}) = \frac{1}{2}(|A_{el}|^2 + P_{abs}); T \equiv -iA_{el} \Rightarrow$$

$$\frac{d\sigma_{el}}{d^2b} = \langle T(b)\rangle^2, \frac{d\sigma_{tot}}{d^2b} = 2\langle T(b)\rangle$$

$$\frac{d\sigma_{abs}}{d^2b} = 2\langle T(b)\rangle - \langle T(b)\rangle^2$$



- No fluctuations! $T(b) = \Theta\left(\sqrt{\sigma_{abs}/\pi} - b\right)$

The wounded cross section

- Fluctuations related to diffractive excitations: Good-Walker.

$$\frac{d\sigma_{tot}}{d^2b} = 2\left\langle T\right\rangle_{t,p}, \ \frac{d\sigma_{el}}{d^2b} = \left\langle T\right\rangle_{t,p}^2, \ \frac{d\sigma_{SD,(p|t)}}{d^2b} = \left\langle \left\langle T\right\rangle_{(t|p)}^2 \right\rangle_{(p|t)} - \left\langle T\right\rangle_{p,t}^2$$

$$\frac{d\sigma_{DD}}{d^2b} = \left\langle T^2\right\rangle_{p,t} - \left\langle \left\langle T\right\rangle_t^2 \right\rangle_p - \left\langle \left\langle T\right\rangle_p^2 \right\rangle_t + \left\langle T\right\rangle_{p,t}^2$$

- The *wounded* cross section is the sum of:

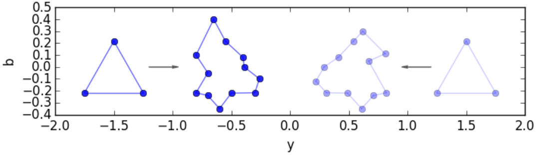
$$\frac{d\sigma_w}{d^2b} = \frac{d\sigma_{abs}}{d^2b} + \frac{d\sigma_{SD,t}}{d^2b} + \frac{d\sigma_{DD}}{d^2b} = 2\left\langle T\right\rangle_{p,t} - \left\langle \left\langle T\right\rangle_t^2 \right\rangle_p.$$

- Contributions to "centrality" observable: absorptively wounded, diffractively wounded, NOT elastically scattered.
- We need now to calculate $T(b)$.

The DIPSY model (Flensburg et al. arXiv:1103.4321 [hep-ph])

- Partonic model in impact parameter space:
  Dipole evolution in **I**mpact **P**arameter **S**pace and rapidit**Y**.
- LL-BFKL with some corrections built on Mueller dipole model (Mueller and Patel arXiv:hep-ph/9403256).
- Proton/Nucleus structure built up dynamically from dipole splittings:

$$\frac{dP}{dY} = \frac{3\alpha_s}{2\pi^2} d^2\vec{z} \frac{(\vec{x}-\vec{y})^2}{(\vec{x}-\vec{z})^2(\vec{z}-\vec{y})^2}, \; f_{ij} = \frac{\alpha_s^2}{8}\left[\log\left(\frac{(\vec{x}_i-\vec{y}_j)^2(\vec{y}_i-\vec{x}_j)^2}{(\vec{x}_i-\vec{x}_j)^2(\vec{y}_i-\vec{y}_j)^2}\right)\right]^2$$



- Optical theorem gives: $T(b) = 1 - \exp\left(-\sum_{ij} f_{ij}\right)$
- Will serve as an initial state "truth" for parametrization development.

Glauber-Gribov fluctuations (GG or GGCF)

- Parametrization of cross section fluctuations in Glauber-Gribov formalism (Alvioli and Strikman: arXiv:1301.0728 [hep-ph]):
- Parametrization of total cross section distribution:

$$\sigma_{tot} = \int d\sigma \sigma P_{tot}(\sigma) = \int d\sigma \rho \frac{\sigma^2}{\sigma + \sigma_0} \exp\left[-\frac{(\sigma/\sigma_0 - 1)^2}{\Omega^2}\right]$$

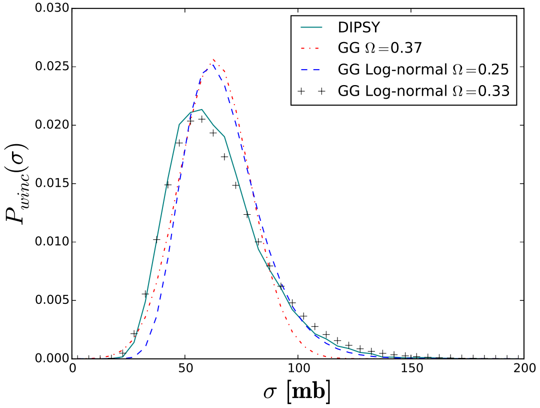
- Normal usage: With black disk, scale to total inelastic $\sigma_{in} = \lambda \sigma_{tot}$.
- From arguments above, should be σ_w
- BUT! $\sigma_{Glauber} = \sigma_w$ in GG/GGCF is not enough.
- Lack of information wrt. DIPSY calculates full $T(b)$.
- Assume semi-transparent disk:

$$T^{(pp)}(b, \sigma) = T_0 \Theta\left(\sqrt{\frac{\sigma}{2\pi T_0}} - b\right)$$

- Fit to semi-inclusive cross sections.
- Log-normal distribution fits DIPSY better.

$$\sigma_{tot} = \int d^2b \int d\sigma P_{tot}(\sigma) 2T^{(pp)}(b,\sigma),\ \sigma_{el} = \int d^2b \left| \int d\sigma P_{tot} T^{(pp)}(b,\sigma) \right|^2,$$

$$\sigma_{w_{inc}} = \int d^2b \int d\sigma P_{tot}(\sigma) \left[2T^{(pp)}(b,\sigma) - T^{(pp)}(b,\sigma) \right],\ P_{tot}(\sigma, b) = \frac{1}{\Omega\sqrt{2\pi}} \exp\left(-\frac{\log^2(\sigma/\sigma_0)}{2\Omega^2} \right)$$

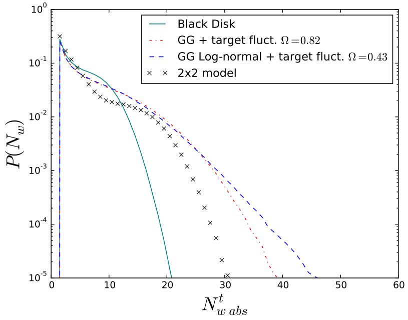


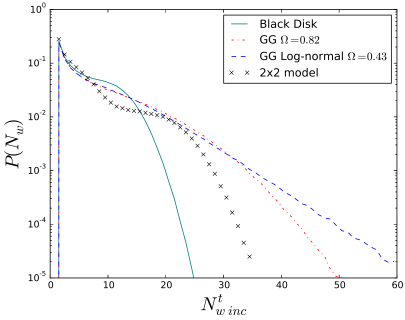
Types of wounded nucleons

- We can now fit to pp cross sections and obtain:
  1. The number of wounded nucleons inc. diffractive excitation.
  2. $T(b)$ assumption+Good–Walker → which are which!

$$P(\text{diff}|w_{incl}) = \Theta\left(\sqrt{\sigma_{GG}/\pi} - (r_1 - r_2) - b\right)\frac{2-\alpha}{2-\alpha c}.$$

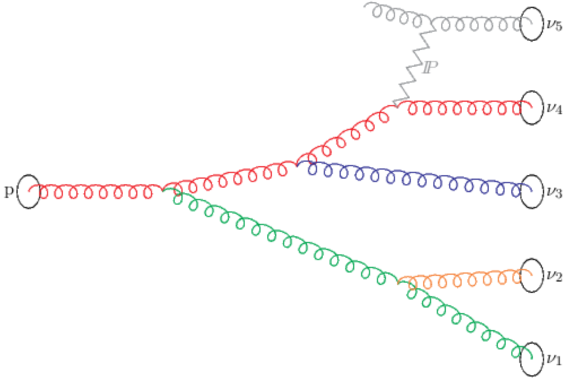
- We now have input for a model for particle production.





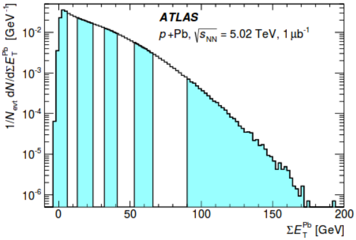
Full final states: Revival of Fritiof

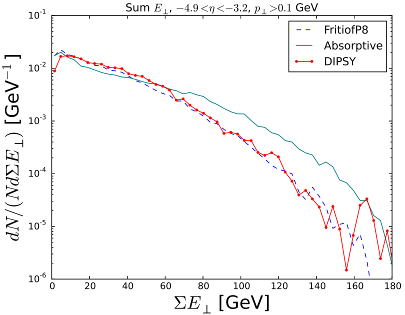
- One absorptive collision contributes to full rapidity span.
- The rest contributes similarly to diffractive excitation (plus a colour exchange).
- Implementation in PYTHIA8 (FritiofP8), but idea is general.



Results (Data: ATLAS: 1508.00848 [hep-ex])

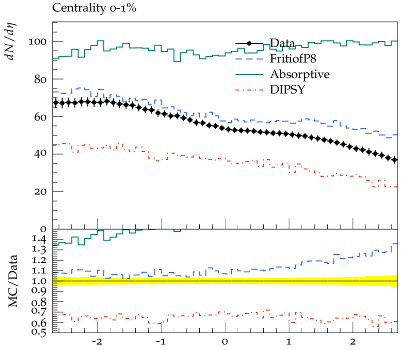
- Very good agreement with centrality observable.
- "Absorptive" overshoots.
- Measuring the exact region where diffractive excitation is important.

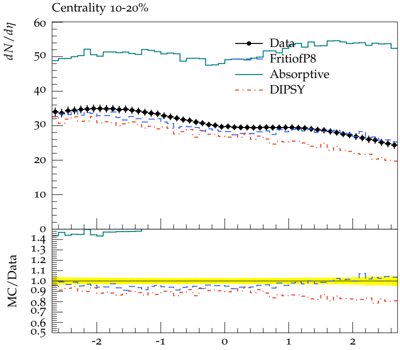




Multiplicity

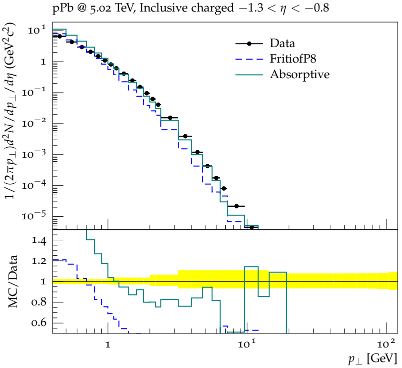
- Reproducing central collisions well.
- Does better than DIPSY in central collision.
- Comparison by own Rivet routine – implementation by exp. would be better.





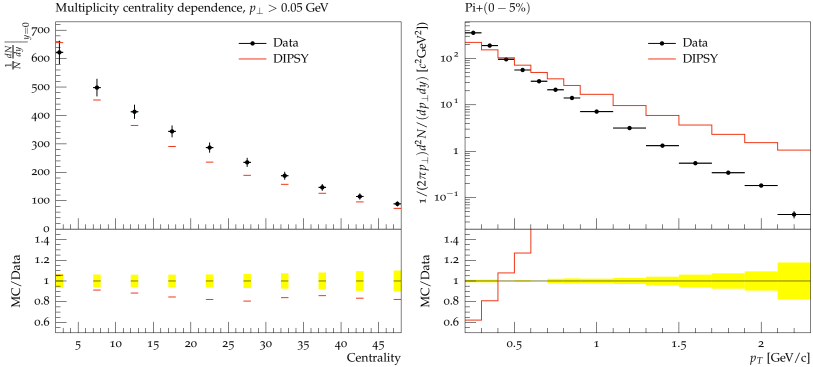
Transverse momentum (Data: CMS: 1502.05287 [nucl-ex])

- Low-$p_\perp$ region improved from Absorptive model.
- Large uncertainties from pdf in this observable.
- (DIPSY – not in figure – does poorly for high $p_\perp$).



Why not just use DIPSY ?

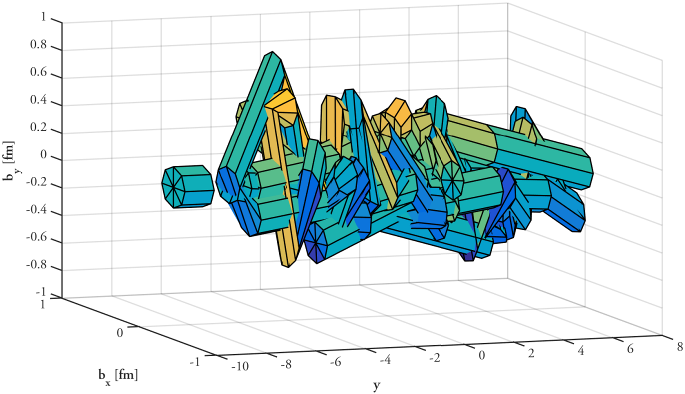
- DIPSY is implemented as a full event generator.
- Can produce exclusive final states for pp pA and AA.



- Limited model, low-$p_\perp$ only, no ME, no quarks, quite untested.
- Also very time consuming.

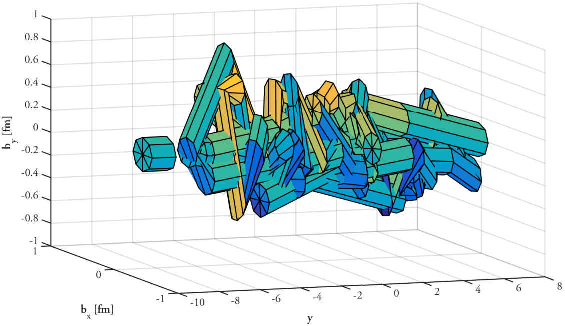
Partial summary

- Including diffractive excitation is important for centrality observables.
- Reproducing charged particle spectra well.
- Now needed: Microscopic model for collective effects.
- What about all the hadronizing strings? Interference?



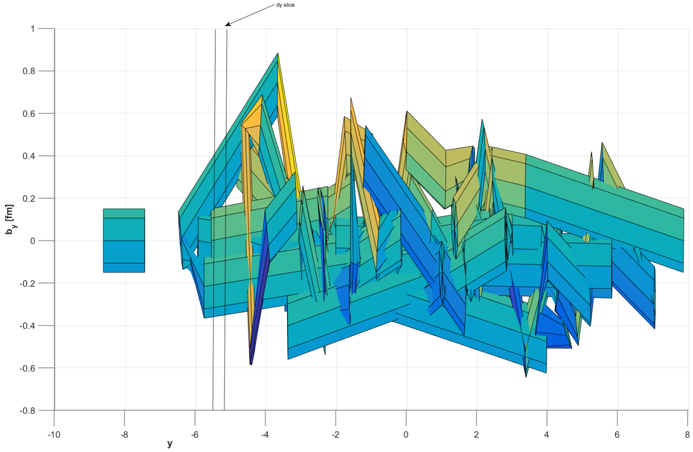
Ropes: Microscopic model for collective effects

- Observations:
  1. Hadrons with strange quarks enhanced in pp, pA and AA wrt. e^+e^-.
  2. The "ridge" effect and flow ($v_{2,3,...}$ coefficients).
- Physics:
  1. Overlapping strings in final state → excess energy in overlapping region.
  2. Dynamical creation of transverse "pressure".
  3. Enhanced string tension produces heavier (s) quarks in string breaking.
- Inspiration from lattice calculations.



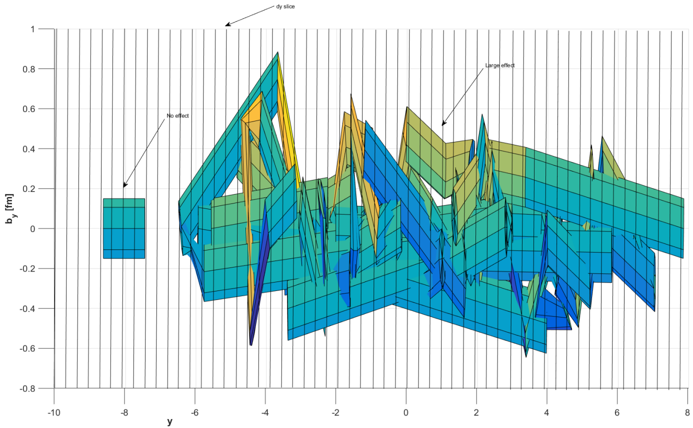
Transverse pressure

- Consider picture from before, rotate and slice in rapidity.
- A slice should be thin enough that we can consider pieces parallel.



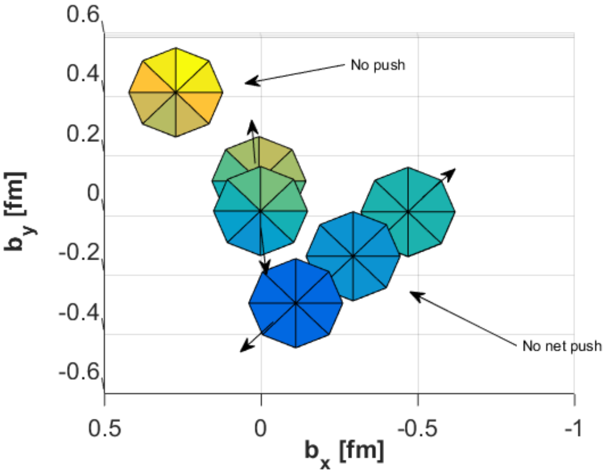
Local pressure, dynamically generated

- Pressure will vary from string to string, slice to slice.
- Slices treated independently during shoving.
- Greatly affected by event-by-event fluctuations.



In the transverse plane

- Shoving resolved pair-wise, $p_\perp$ conservation.
- Practically done by adding a small excitation (gluon) to the string in each slice.



The shoving pressure

- $p_\perp$ push on string segment, length δl, time interval δt.
- If everything starts in a point at $t = 0$ then $\delta l = t\delta y$.

$$\delta p_{\perp 12} = f_{12} \cdot \delta l \delta t = f_{12} \cdot t \delta y \delta t$$

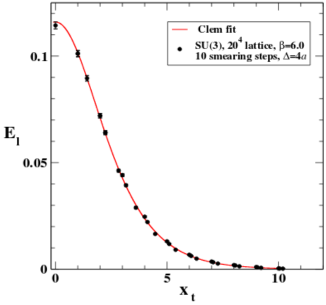
- The force is f; chromoelectric field of effective dual s.c. (lattice).
- Approximate with Gaussian:

$$E_l = C_0 \exp\left(-\frac{x_\perp^2}{2R^2}\right)$$

- Interaction energy between two vortex lines:

$$U_{12} \propto E_l \Rightarrow f_{12} = -\frac{\partial U_{12}}{\partial x_{\perp 12}}$$

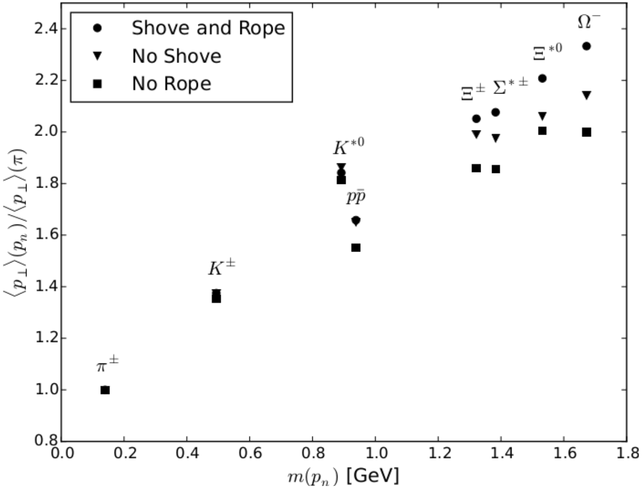
$$= C x_{\perp 12} \exp\left(-\frac{x_{\perp 12}^2}{2R^2}\right)$$



(Cea et al. arXiv:1404.1172 [hep-lat])

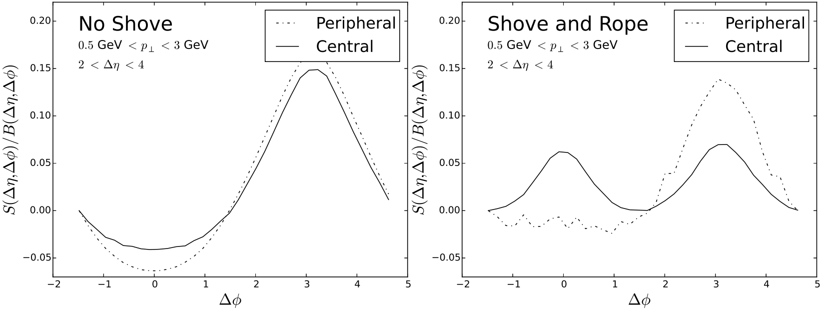
Average $p_\perp$

- Larger effect for heavy hadrons.
- Similar effect as hydrodynamic expansion.



Two–particle correlations

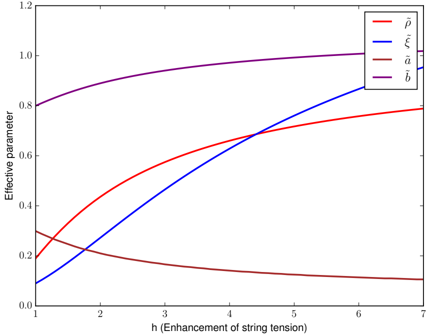
- Shoving produces a "ridge".
- Currently for events consisting of long, soft strings only.
- Working towards a complete description.



String tension and flavour (CB et al: arXiv:1412.6259 [hep-ph])

- String tension enhanced in overlapping regions.
- Strange suppression is detemined by:

$$\rho = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right).$$



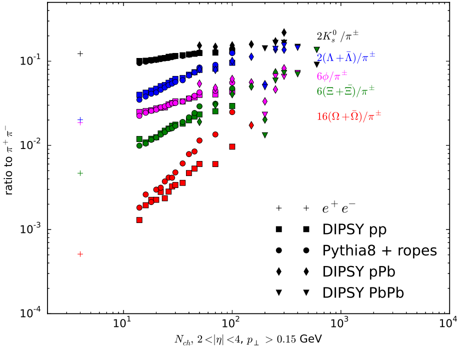
- Enhancement from SU(3) multiplet structure.

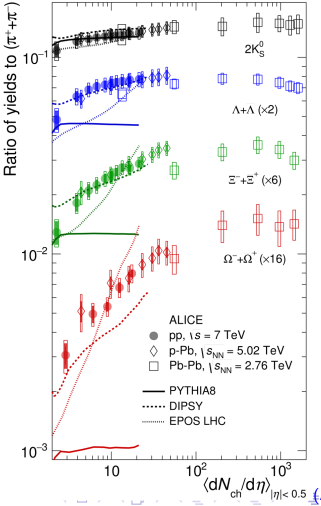
$$h = \frac{\tilde{\kappa}}{\kappa} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}$$

- Also in accordance with lattice QCD.

Flavour composition – more strange quarks

- Result from lattice QCD: Sting tension scales with C_2(multiplet).
- Strange quarks suppressed by: $\exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right)$





Implemented in DIPSY;

(CB and Christiansen: arXiv:1507.02091 [hep-ph])

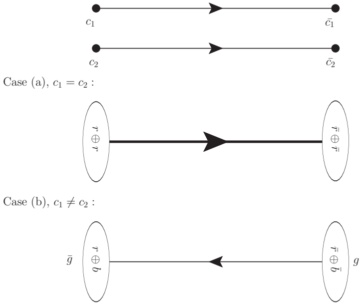
Pythia8 by plugin: `http://home.thep.lu.se/DIPSY#ropes`;

(CB: arXiv:1606.09456 [hep-ph])

(ALICE:

Lower multiplets

- Above description handles highest multiplet only.
- Lower multiplets are notoriously difficult:
  1. Attractive force in shoving.
  2. Junction formation.
  3. Colour reconnection schemes.
- Handle lower multiplets first with through swings and junctions.
- Only the highest multiplet is left.



The swing

- Singlets are handled already in the FS shower (Ariadne 5-beta).
- Matching colours *swing* with each other, competing w. emission.

$$\frac{dP_e}{d\ln(p_\perp^2)} \approx dy\frac{C_F\alpha_s}{2\pi} \text{ and } \frac{dP_r}{d\ln(p_\perp^2)} = \lambda\frac{(\vec{p_1}+\vec{p_2})^2(\vec{p_3}+\vec{p_4})^2}{(\vec{p_1}+\vec{p_4})^2(\vec{p_2}+\vec{p_3})^2}$$

Moving to smaller systems – why?

- Larger systems, pA and AA ongoing (FritiofP8).
- Schukraft: *Small systems important to learn about dynamics.*
  1. Better control of geometry.
  2. Baryon production mechanisms (the Ω issue).
  3. Junctions, popcorn etc.
- Unique opportunity for microscopic models.
- Prospects: QCD physics case for FCC-ee – a QGP program?.
- Could the LHC prepare us better for FCC-ee QGP?
- Need to act soon if special triggers are needed!

The case for e^+e^-

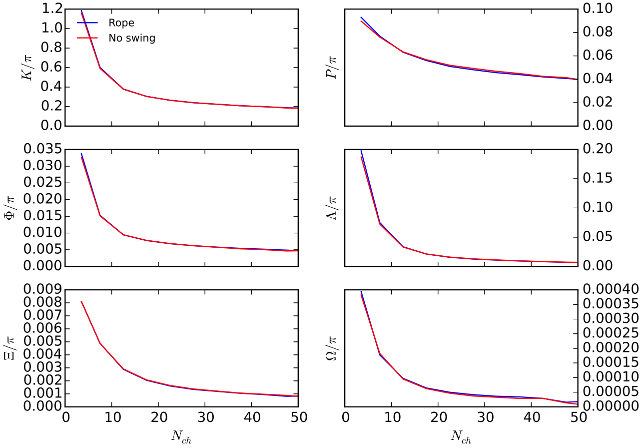
- Can't copy measurements directly – no MPIs!
- Multiplicity not good for "system size"/"Temperature"/"centrality".
- Instead: Look at $Z \to q\bar{q}$, event shapes.
- Toy study for FCC-ee physics concept input.
- Simulated 10^9 Z events, Ideal detector with $-2 < y < 2$, $p_\perp > 0.5$ GeV coverage.
- Reminder: Sphericity tensor, a, b spatial components of momentum, ordered eigenvalues λ_i:

$$S^{ab} = \frac{\sum_i p_i^a p_i^b}{\sum_i |p_i|^2}$$

$$s = \frac{3}{2}(\lambda_2 + \lambda_3)$$

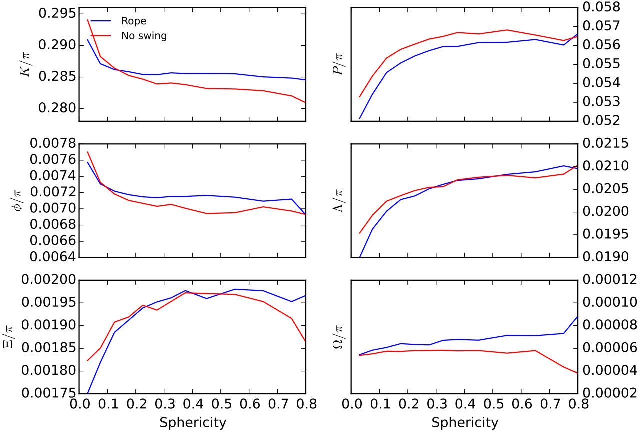
Multiplicity dependence

- Flavour observables: No difference for high multiplicity.



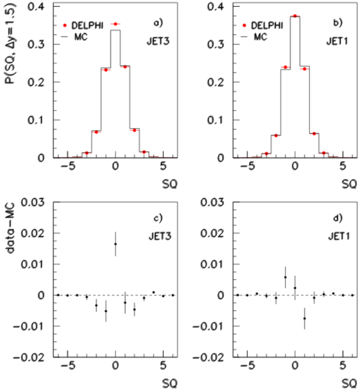
Sphericity dependence

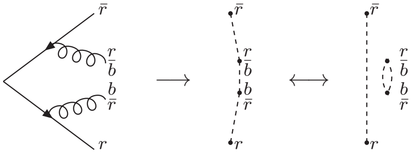
- Flavour observables: Potential observable effect at FCC-ee.
- Suggests a QGP program at FCC-ee is potential path.



Octet neutralization

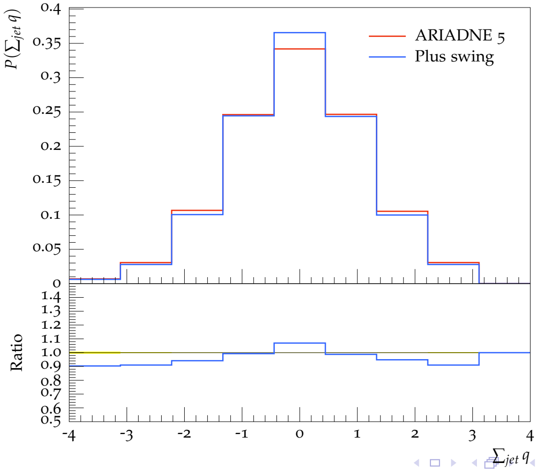
- Separate gluon fragmentation gives enhancement of 0 charge jets.
- Result from DELPHI (Phys.Lett. B643 (2006) 147-157).
- Result from gluon vs. quark enhanced jets in 3-jet events w. rapidity gap between jets.
- Same principle as final state swing.





Result ARIADNE+FS Swing

- Re-use sphericity (sph > 0.8) as centrality measure in 3-jet events.
- Swing qualitatively reproduces effect.
- Analysis could benefit from proper "rivetization".



Using central diffraction as proxy

- Long wait before FCC-ee – what can we do in the mean time?
- Idea: pp central diffraction as proxy for $e^+e^- \to Z$.
- Need rap. gap + forward activity trigger.
- Also: Better insight into CD processes.
- Here: DIPSY "toy" CD ($\mathbb{P}$ is $q\bar{q}$ dipole) and sph $\to$ sph$_\perp$.

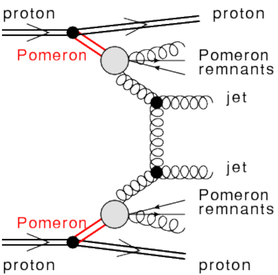
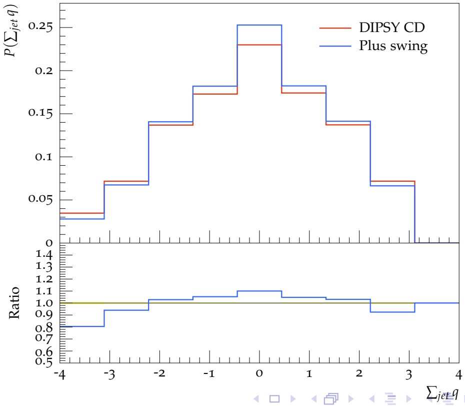


Figure from Akiba *et al.*: J. Phys. G 43 (2016) 110201



Summary

- Study of small systems enables dynamical understanding of collectivity.
  - Dynamical models of non-equilibrium system.
  - Rope hadronization – flavours.
  - Shoving – ridges.
  - Extrapolated from pp using FritiofP8.
- Ropes still not well tested – only implemented fully in DIPSY.
- Plugin for Pythia8 available and developing.
- Future plans include lots of validation – must compare apples to apples!
- Smallest systems provides detailed insight to hadronization.
- FCC-ee will be nice, when and if it comes.
- Possible proxy: pp CD (good experimental student project? anyone?)