Particle production and QGP effects in pp and pA with the DIPSY generator

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QCD Challenges in pp pA and AA Collisions at High Energies

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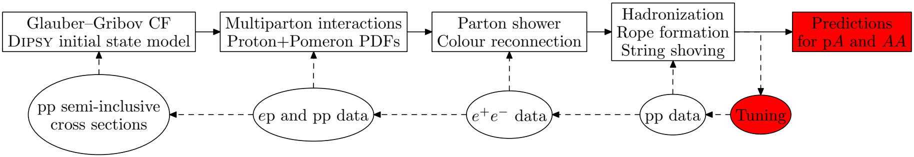
Universal event generator for pA and AA – why and how?

- Universal models for e^+e^-, ep and pp, such as PYTHIA8 .
  - Unfeasible for pA and AA because of QGP $=$ non-universality.
- LHC has revealed QGP-like 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?
- Put data and theory on the same footing for comparison.
- 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

- DIPSY and pp extrapolations (CB, Gustafson, Lönnblad: arXiV:1607.04434 [hep-ph]).
  1. Geometry of a pA collision.
  2. The "wounded" cross section.
  3. Glauber–Gribov colour fluctuations.
  4. Particle production with FritiofP8.
- Microscopic collectivity in pp and e^+e^-.
  1. Rope Hadronization (CB, Gustafson, Lönnblad, Tarasov: arXiv:1412.6259 [hep-ph]).
  2. Effects on strangeness in pp (CB, Christiansen: arXiv:1507.02091 [hep-ph]).
  3. "The ridge" in pp (CB, Gustafson, Lönnblad: arXiv:1612.05132 [hep-ph]).
  4. Prospects at an FCC-ee (CB: arXiv:1702.01329 [hep-ph]).
- Outlook and wish list for experimentalists.

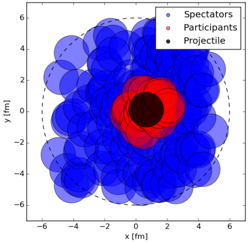
Extrapolating from pp: Glauber model + partonic picture from DIPSY

- Will introduce corrections to Glauber-Gribov based on DIPSY partonic picture.
- 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:

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

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

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



The wounded cross section

- Fluctuations related to diffractive excitations: Good-Walker.

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

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

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

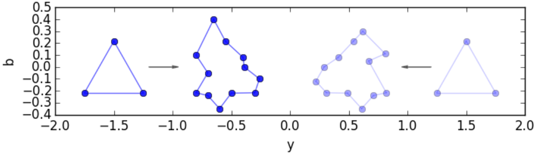
$$\frac{d\sigma_{w}}{d^2b} = \frac{d\sigma_{abs}}{d^2b} + \frac{d\sigma_{SD,t}}{d^2b} + \frac{d\sigma_{DD}}{d^2b} = 2\langle T\rangle_{p,t} - \left\langle \langle T\rangle^2_{t} \right\rangle_{p}.$$

- 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:

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

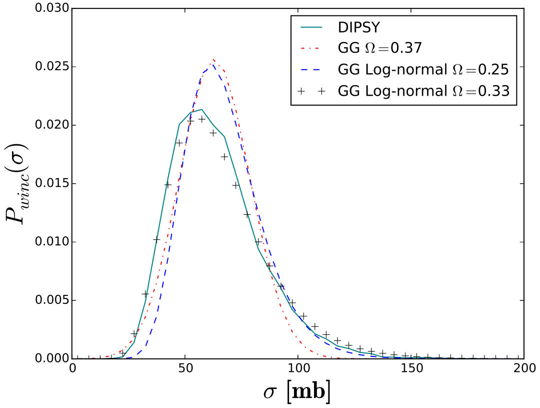
- Normal usage: With black disk, scale to total inelastic $\sigma_{in} = \lambda \sigma_{tot}$.
- From arguments above, should be σ_w
- BUT! $\sigma_{Glauber} = \sigma_w$ in GG/GGCF is not enough.
- Lack of information wrt. DIPSY calculates full $T(b)$.
- Assume semi-transparent disk:

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

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

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

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

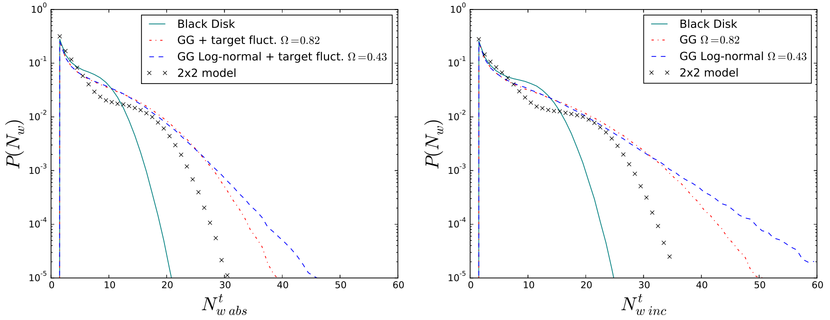


Types of wounded nucleons

- 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 $\rightarrow$ which are which!

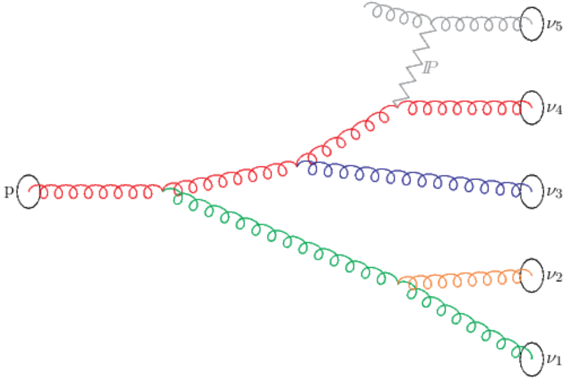
$$P(\text{diff}|w_{incl}) = \Theta\left(\sqrt{\sigma_{GG}/\pi} - (r_1 - r_2) - b\right)\frac{2-\alpha}{2-\alpha c}.$$

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



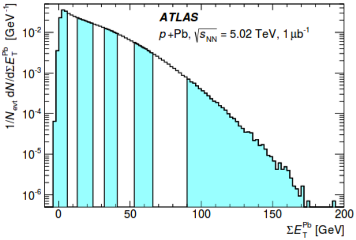
Full final states: Revival of Fritiof

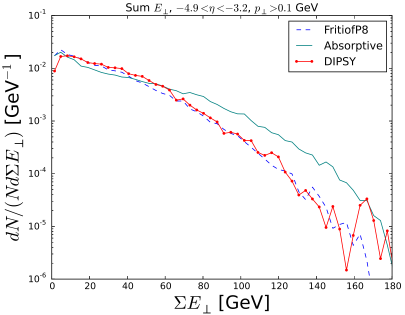
- One absorptive collision contributes to full rapidity span.
- The rest contributes similarly to diffractive excitation (plus a colour exchange).
- Implementation in PYTHIA8 (FritiofP8), but idea is general.



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

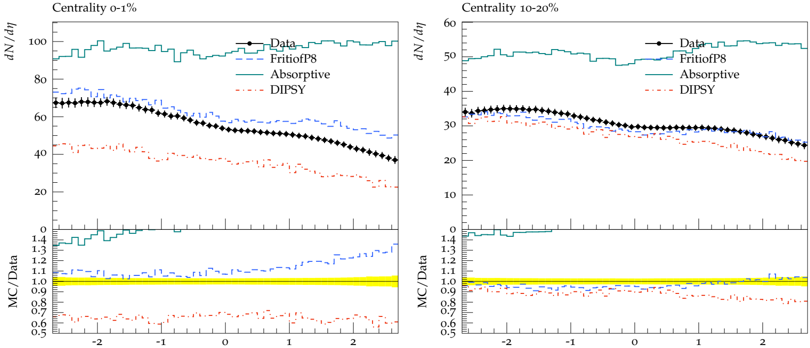
- Very good agreement with centrality observable.
- "Absorptive" overshoots.
- Measuring the exact region where diffractive excitation is important.





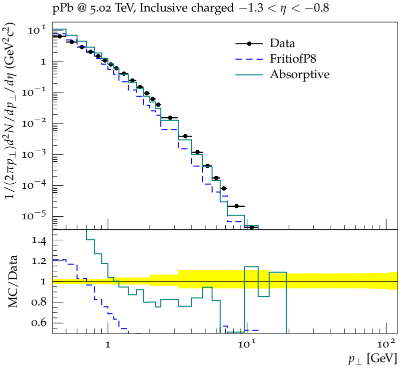
Multiplicity

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



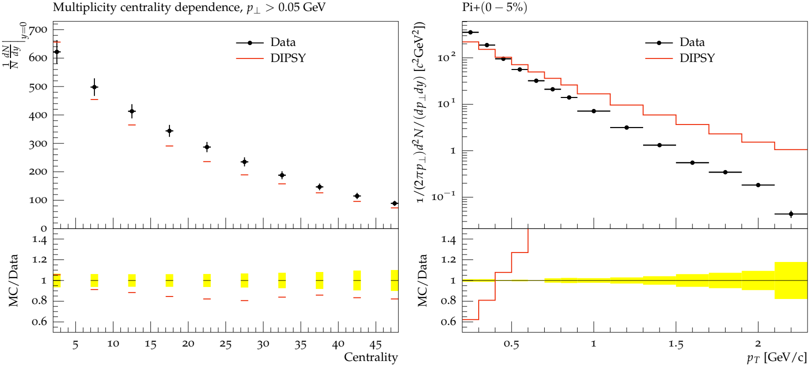
Transverse momentum (Data: CMS: 1502.05287 [nucl-ex])

- 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 ?

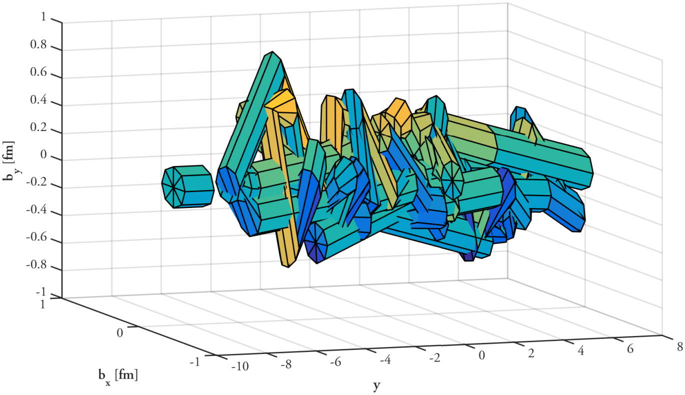
- DIPSY is implemented as a full event generator.
- Can produce exclusive final states for pp pA and AA.



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

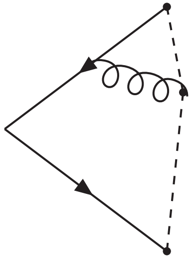
Partial summary

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



String Hadronization [See *e.g.* hep-ph/0603175]

- Lund Strings = Non-perturbative phase of final state.
- Confined colour fields ≈ *strings* with tension $\kappa \approx 1$ GeV/fm.
- *Breaking*/tunneling with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.



- Flavours determined by relative probabilities:

$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

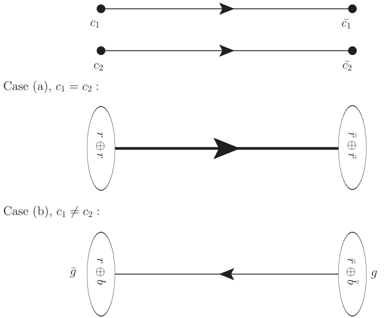
- Probabilities are related to κ via tunneling equation.
- Changing $\kappa \rightarrow \tilde{\kappa}$ changes s/u ratio:

$$\tilde{\rho} = \rho^{\kappa/\tilde{\kappa}} \Rightarrow \lim_{\tilde{\kappa}\rightarrow\infty} (\tilde{\rho}) = 1$$

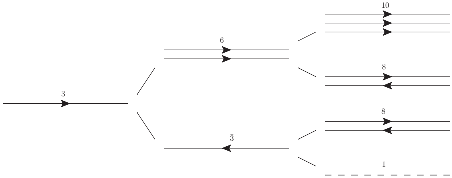
.

String overlaps in a Random Walk

- Two $q\bar{q}$ pairs act coherently:



- All possibilities handled in random walk procedure.
- Highest multiplets, singlets and junctions.



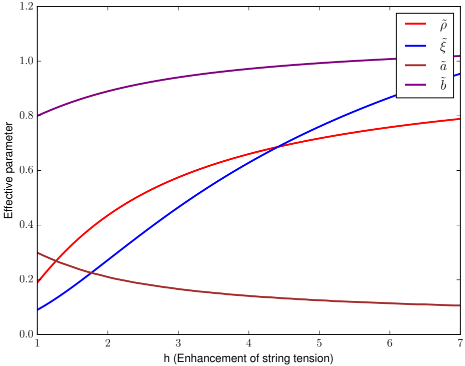
String tension from lattice calculations.

$$\kappa \propto C_2 \Rightarrow \tilde{\kappa}/\kappa = \frac{C_2(\text{multiplet})}{1\ \text{GeV/fm}}$$

Effect on hadronization parameters

- Strange quark breakup suppression:

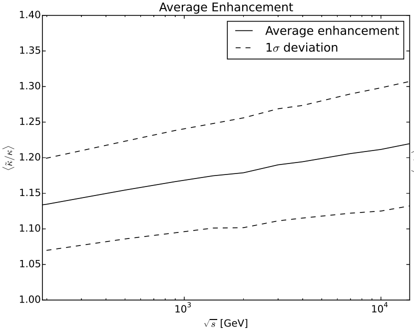
$$\rho = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right).$$

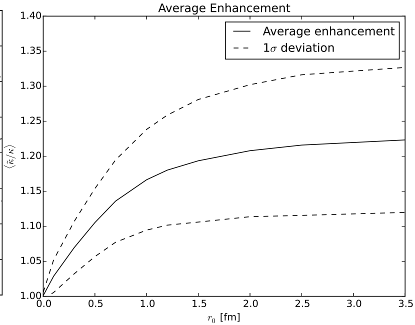


- Large effect on hadronic flavours.
- Smaller effect on hadron $p_\perp$ and multiplicity (tunable).

Sensitivity

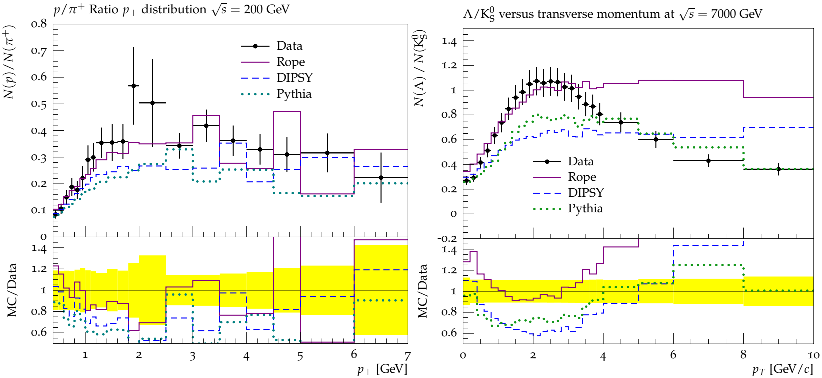
- On average noticeable effect in pp.
- Primary physical parameter is string radius, cylindrical $r_0 \approx 0.8$ fm.





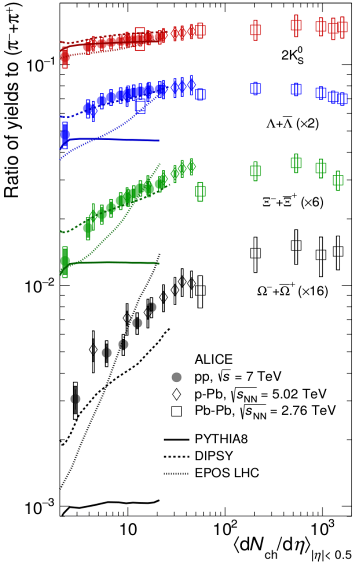
Effect in pp Data: STAR and CMS

- Improvement inclusively.
- Tail of $p_\perp$ spectrum not fully understood.
- Need better observables isolating strangeness and baryons.



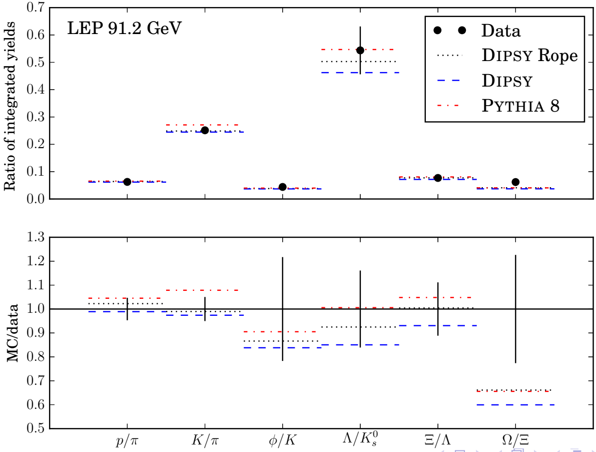
Effect in pp II (ALICE: arXiv:1606.07424 [nucl-ex])

- Description of strangeness enhancement for central events.
- Signal linked to Quark Gluon Plasma in Heavy Ion Physics.
- Not shown: (lack of) baryon enhancement in data.



The Ω-issue

- The Ω shape fits, but normalization is off.
- Not surprising, problem already in LEP.
- Junction/popcorn production is possible, needs further studies.
- Experimental study of Ω-correlations could cast light.



Prospects for FCC-ee

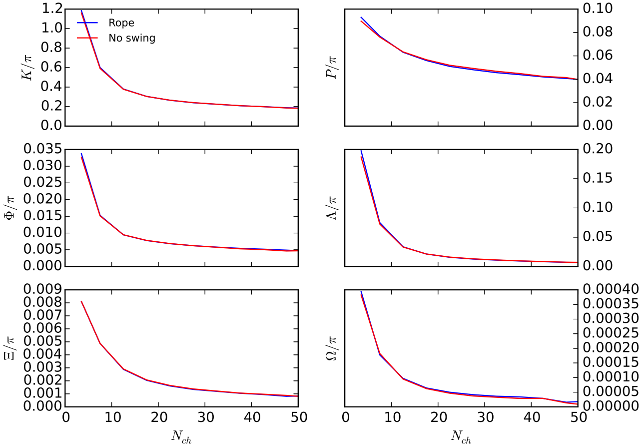
- $e^+e^- \to Z \to q\bar{q}$ constitutes a good lab for probing universal effects.
- Multiplicity is no longer a good centrality measure (no MPIs!).
- Toy study for FCC-ee physics concept input: Use Event Shapes instead.
- Simulated 10^9 Z events, Ideal detector with $-2 < y < 2$, $p_\perp > 0.5$ GeV coverage.
- Reminder: Sphericity tensor, a, b spatial components of momentum, ordered eigenvalues λ_i:

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

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

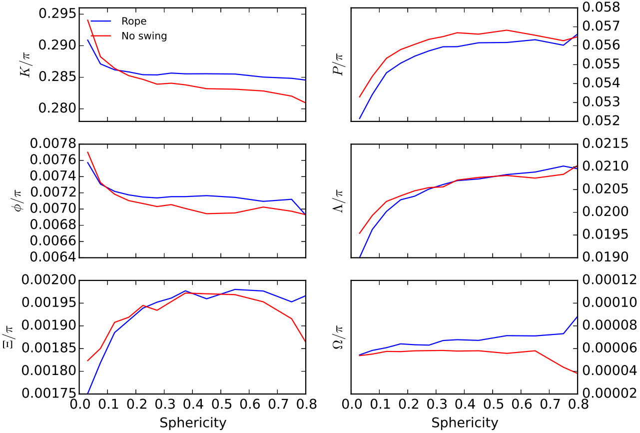
Multiplicity dependence

- Flavour observables: No difference for high multiplicity.



Sphericity dependence

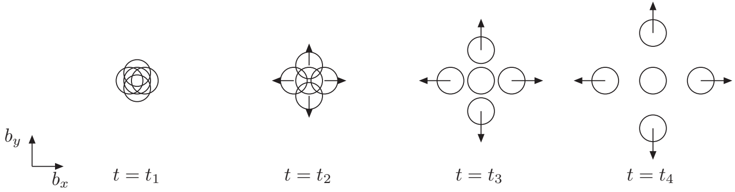
- Flavour observables: Potential observable effect at FCC-ee.
- Suggests a QGP program at FCC-ee is potential path.



Shoving: A microscopic model for hydrodynamic expansion

(CB, Gustafson and Lönnblad, arXiv:1612.05132 [hep-ph]).

- Idea: The overlapping regions will generate a transverse pressure.
- First suggested by Abramovsky et al. in Pisma Zh. Eksp. Teor. Fiz. 47, 281 (1988).
- This will "shove" the strings apart.



- Hydrodynamics from event-by-event fluctuations and microscopic QCD pheno. No thermalization.

The kick

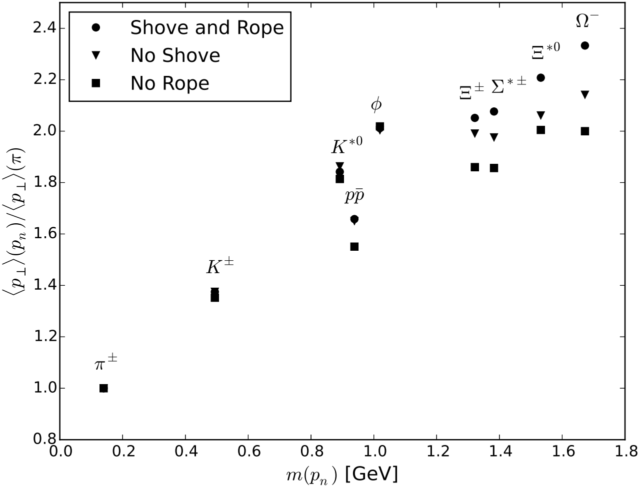
- All strings are sliced into dy slices.
- In each time–step dt, each string will get a kick from other strings:

$$\frac{dp_\perp}{dydt} = \frac{C_0 td}{R^2} \exp\left(-\frac{d^2}{2R^2}\right).$$

- Momentum conservation is observed.
- Transverse kicks resolved pairwise.
- Longitudinal recoil absorbed by kicking dipole.

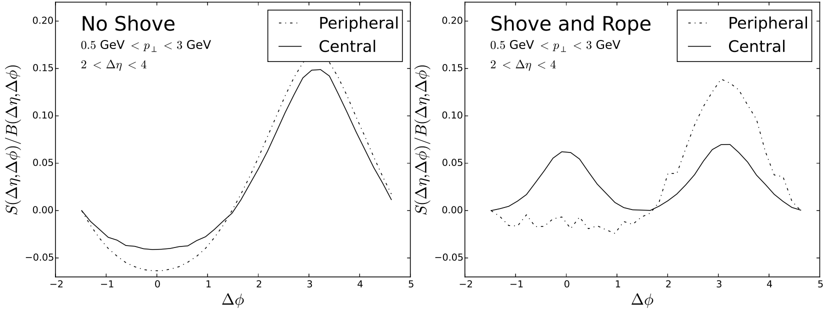
Average $p_\perp$

- 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.
- Possible contamination from overestimation of minijets.
- Working towards a complete description.



Conclusions and Outlook

- New general purpose event generator for HI built on:
  1. Extrapolation model currently implemented for pA.
  2. Microscopic collectivity, rope hadronization and shoving.
- Extrapolation reproduces pA "underlying event".
- Rope hadronization: good results for strangeness in pp.
- Shoving: Promising preliminary results.
- My very biased wish list for experimentalists
- Overall: Data accessible in a format where direct comparison is possible – Rivet.
  1. Exclusive production pA, smaller nuclei. SMOG or older RHIC data.
  2. Flavour ratios(y) in pA allows for test of Fritiof picture.
  3. Jet escape: ratios inside and outside jets in pp.
  4. ϕ/π vs. p/π vs. multiplicity and $p_\perp$.
  5. The Ω-puzzle – quite rare, correlations can point to production mech.

Thank you for your attention!

Bonus slides

Color reconnection

- Many partonic subcollisions $\Rightarrow$ Many hadronizing strings.
- But! $N_c = 3$, not $N_c = \infty$ gives interactions.
- Easy to merge low-$p_\perp$ systems, hard to merge two hard-$p_\perp$.

$$\mathcal{P}_{merge} = \frac{(\gamma p_{\perp 0})^2}{(\gamma p_{\perp 0})^2 + p_\perp^2}$$

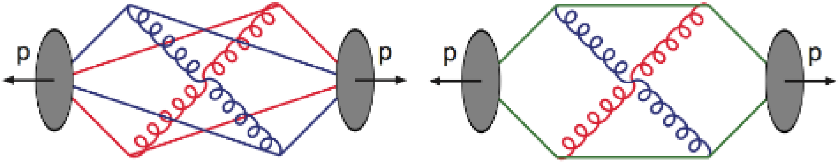


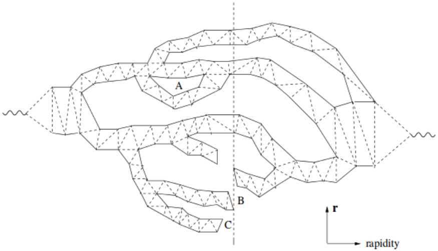
Figure T. Sjöstrand

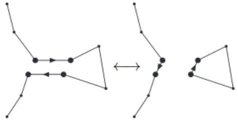
- Actual merging is decided by minimization of "potential energy":

$$\lambda = \sum_{dipoles} \log(1 + \sqrt{2}E/m_0)$$

Saturation and swings

- In DIPSY MPIs are fluctuations going on shell in interactions.
- Similar to saturation in another frame: Initial state swing.
- Multiple scatterings of a single dipole ⇔ Several swings (Avsar, E.: arXiv:0709.1371 [hep-ph])
- Re-absorption of non-interacting branches.



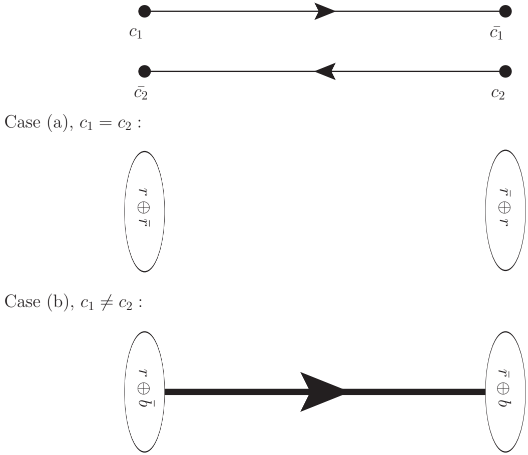


- Initial state swing competes with emission.
- All gluons get index from 1 to N_c^2, reconnect if compatible with:

$$\frac{\mathcal{P}_{(12)(34)}}{\mathcal{P}_{(14)(32)}} = \frac{(\vec{x}_1 - \vec{x}_4)^2(\vec{x}_3 - \vec{x}_2)^2}{(\vec{x}_1 - \vec{x}_2)^2(\vec{x}_3 - \vec{x}_4)^2}.$$

Rope model – example 2

- Next-to-simplest: Two $q\bar{q}$ pairs act coherently, having oppositely directed colour flow:



Particle production: MPIs Sjöstrand and Skands: arXiv:hep-ph/0402078

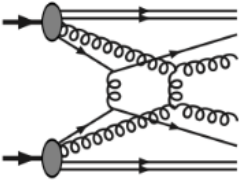


Figure T. Sjöstrand

- Several partons taken from the PDF.
- Hard sub-collisions with $2 \to 2$ ME:

$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

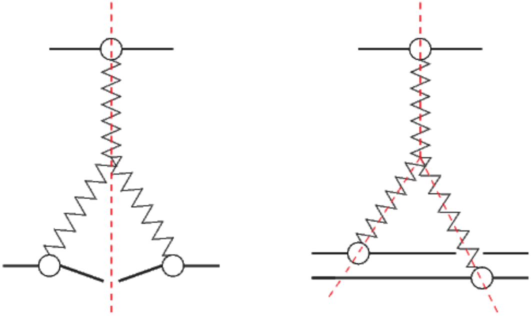
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \ldots$ from:

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{nd}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp \right]$$

- Number distribution narrower than Poissonian (momentum and flavour rescaling).

Similar to diffractive excitation? Really?

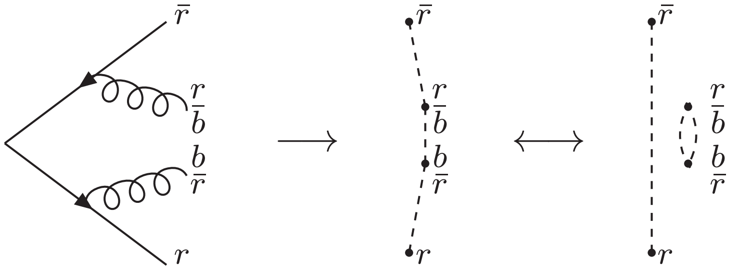
- Secondary absorptive interactions are similar to single diffractive ones.
- Consider cut Pomeron diagrams for:
  - (a) Single diffractive proton–proton.
  - (b) Double diffractive proton–deuteron.
- Not far fetched to assume that interactions are similarly distributed in rapidity.



(a) (b)

Retuning: Singlet swing and LEP

- Example: $Z \to q\bar{q} + 2$ emissions.
- No swing effect before 2 emissions (α_s^2 suppressed).
- First configuration is leading N_c approximation result always.
- Second configuration is $\frac{1}{N_c^2 - 1}$ colour surpressed.



Singlet swing and LEP cont'd Data: DELPHI, Z.Phys. C73 (1996) 11-60

- Hence we need a two-emission observable.
- No large difference, $p_\perp^{out}$ somewhat improved.
- Future perspective: Effects at FCC-ee.