Rope hadronization in the DIPSY event generator

arXiv:1412.6259 [hep-ph] and arXiv:1507.02091 [hep-ph]

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Jan 20, 2016
QCD Challenges at the LHC: from *pp* to *AA*

Introduction

- Focus of my work: Hadronization.
- This talk:
  1. String Model for Hadronization.
  2. Rope model corrections.
  3. Models for space-time configurations.
  4. Heavy Ion – why are we not done yet?
- Goals:
  1. Understand QGP effects from microscopic model.
  2. Universality for e^+e^-, pp, pA, AA.

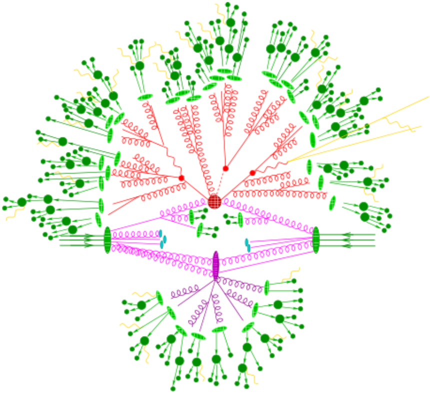


Figure credit: Frank Krauss

A simple model for mesons

- String models predates QCD, leading Regge trajectories, $\alpha \approx 0.9$ GeV^{-2}:

$$J(s) = J(0) + \alpha s$$

- What kind of force law could reproduce this? Revolving string (circular directrix).
- Consider string of length l, massless ends moving with c (so $v_\perp(x) = 2cx/r$), string tension in rest is κ.

$$E = \int_{-l/2}^{l/2} \frac{\kappa}{\sqrt{1 - v_\perp^2}} dx = \frac{l\kappa}{2} \int_{-1}^{1} \frac{dy}{\sqrt{1 - y^2}} = \frac{\pi l \kappa}{2}$$

$$J = \int_{-l/2}^{l/2} \frac{\kappa v_\perp x}{\sqrt{1 - v_\perp^2}} dx = \frac{l^2 \pi \kappa}{8}$$

$$\Rightarrow \kappa = \frac{1}{2\pi\alpha} \approx 0.180\text{GeV}^2 = 0.91\text{GeV/fm}.$$

Concepts of String Hadronization hep-ph/0603175

- Linear confinement potential $V(r) \approx \kappa r$, confirmed on the lattice.
- Valid for large distances – for small distances perturbation theory should be valid.

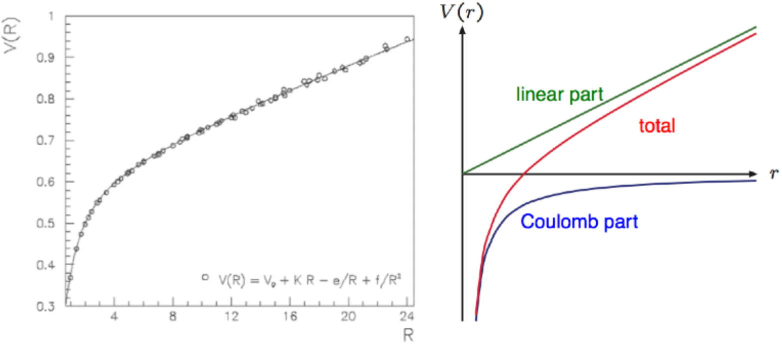


Figure credit: Torbjörn Sjöstrand

- Very simple, but powerful, picture of $e^+e^- \to q\bar{q}$.

The yo-yo directrix

- The yo-yo directrix makes for a nicer description of mesons.
- Collinear boosts simpler in lightcone coordinates, area as mass:

$$p_+ = E + p = \sqrt{2}|AD|, p_- = E - p = \sqrt{2}|AC|$$

$$m^2 = p_+ p_- = 2A$$

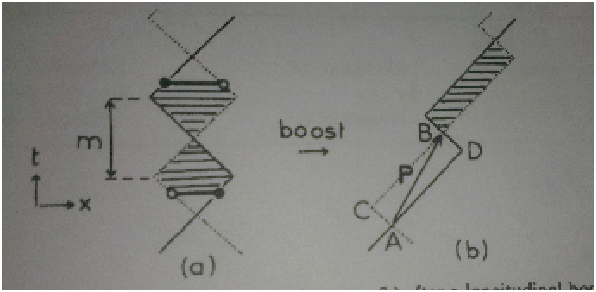


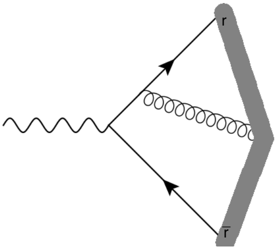
Figure credit Xavier Artru

- Transverse boosts also affects string tension:

$$\kappa(v_\perp) = \kappa_0\sqrt{1 - v_\perp^2}.$$

String Hadronisation

- Repeated *breaking* with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.
- Left-right symmetry in the breaking gives $f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right)$.



- a and b related to total multiplicity.
- Flavours determined by relative probabilities:

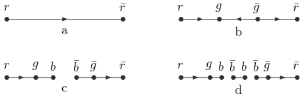
$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

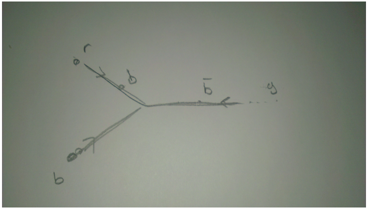
$$x = \frac{\mathcal{P}_{\text{strange diquark}}}{\mathcal{P}_{\text{diquark}}}, y = \frac{\mathcal{P}_{\text{spin 1 diquark}}}{\mathcal{P}_{\text{spin 0 diquark}}}$$

- Notice that probabilities are related to κ via tunneling equation.

Baryons, popcorn and junctions

- Behind diquark splits lies the popcorn model.
- Here colour fluctuations gives extra quarks, which are "caught" in another breakup.
- Introduces explanation, but no direct prediction.
- Naively one could factorize ξ in a popcorn fluctuation part and a mass-difference part.
- Junction configurations are usually associated with baryon production.
- Popcorn fluctuations could eliminate this effect.





Recap: String Hadronization

- So far: Pythia 8 string hadronization.
- Simple, but powerful, model for mesons.
- String breaking gives hadrons.
- Baryons produced by popcorn and junctions.
- Kinematics: Predictive, few parameters.
- Flavours: Tunable, many parameters.

Change of string tension

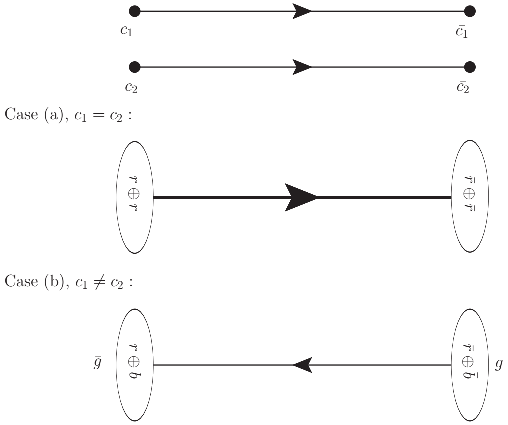
- Field changes when strings overlap - remember the simple picture: $2E/l = \pi\kappa$.
- Estimate $\kappa \mapsto \tilde{\kappa} = h\kappa$ from number of overlapping strings.
- Electrodynamics: Principle of superposition, simple.
- QCD: Not so simple. Secondary Casimir operator of multiplet.

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

- Confirmed on the lattice.

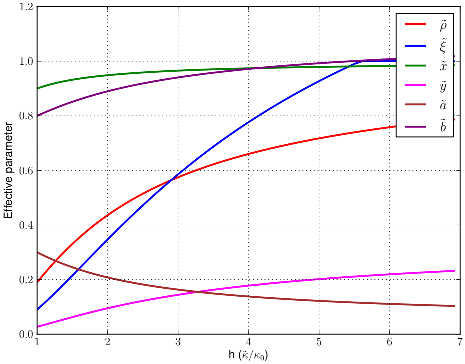
Example arXiv:1412.6259 [hep-ph]

- The simplest example: Two $q\bar{q}$ pairs act coherently.
- Two distinct possibilities:



Effect on hadronization parameters

- All parameters related through string tension.
- Parameters ρ and ξ are very sensitive to change in κ.



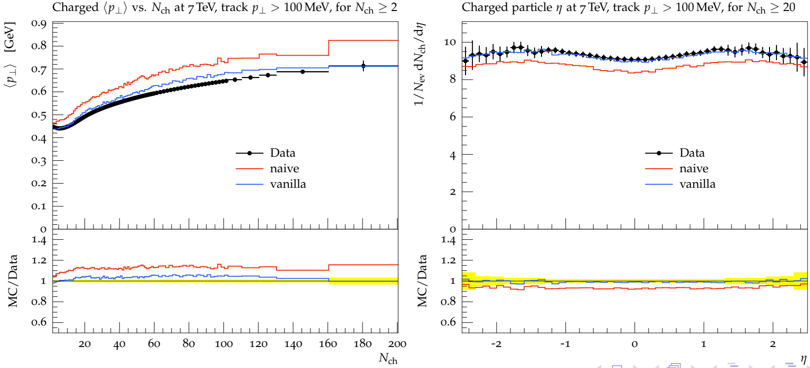
- Large effect on hadronic content.
- Smaller effect on hadron $p_\perp$ and multiplicity (tunable).

Space-time picture

- We must now estimate the amount of overlap.
- Handling of junctions is also of importance.
- Will show three levels of sofistication.
  1. Simplest possible model - higher κ overall.
  2. Toy model for randomized segment overlap.
  3. The full DIPSY model.
- More sophisticated models needs more parameters.
- Not a problem *if* parameters are sensible.

Higher overall κ Unpublished Pythia plugin – ask me.

- Use higher κ for pp and AA than e^+e^-.
- We limit ourselves to typical UE observables.
- Easily implemented in Pythia 8.
- Destroys jet universality!
- Should be tuned if taken seriously.



Randomized segment overlap Unpublished Pythia plugin – ask me.

- Parton Showers normally has no space-time information.
- Randomize $\vec{b}$-space overlap, track rapidity overlap.
- Whenever a string breaks, let two conditions decide wheter another string overlaps.
  1. Does another string exist at same rapidity?
  2. Place two strings randomly within a typical proton radius, check for overlap.
  3. Only one parameter, α, dertermining ratio of string to proton radius.

$$4\alpha^2 > (\sqrt{r_1}\cos\theta_1 - \sqrt{r_2}\cos\theta_2)^2 + (\sqrt{r_1}\sin\theta_1 - \sqrt{r_2}\sin\theta_2)^2)$$

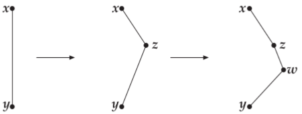
- With r_1, θ_1 and r_2, θ_2 being random points on the unit circle.

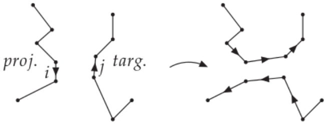
The DIPSY model [Flensburg et al. arXiv:1103.4321 [hep-ph], 2011]

- Full $\vec{b}$-space information: the Mueller formulation of BFKL (with corrections).
- Builds up virtual Fock states of proton, colliding dipoles interact via gluon exchange.
- A dipole $(\vec{x}, \vec{y})$ can emit a gluon at position $\vec{z}$ with probability (P) per unit rapidity (Y); dipoles i and j interacts with probability $2f_{ij}$:

$$\frac{dP}{dY} = \frac{3\alpha_s}{2\pi^2} d^2\vec{z} \frac{(\vec{x}-\vec{y})^2}{(\vec{x}-\vec{z})^2(\vec{z}-\vec{y})^2}$$

$$f_{ij} = \frac{\alpha_s^2}{8}\left[\log\left(\frac{(\vec{x}_i-\vec{y}_j)^2(\vec{y}_i-\vec{x}_j)^2}{(\vec{x}_i-\vec{x}_j)^2(\vec{y}_i-\vec{y}_j)^2}\right)\right]^2$$





DIPSY cont'd

- Assume uncorrelated subcollisions and eikonal approximation.
- Integrated probability for inelastic interaction:

$$P = 1 - \exp(-2F) \text{ with: } F = \sum f_{ij}$$

- MPIs ⇔ Dipole chain loops ⇔ Pomeron loops.
- Elastic scattering amplitude from optical theorem

$$T = 1 - \exp(-F)$$

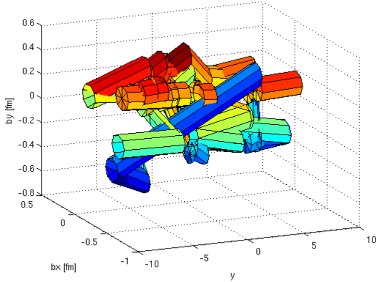
- And we get diffractive cross section and diffractive excitation cross section as by-product.

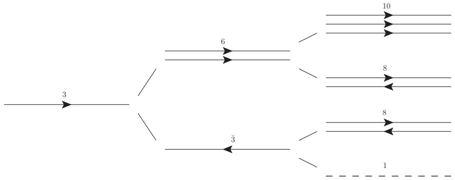
Event generation

- Many corrections beyond Mueller's model – see reference on previous page.
  1. Generate projectile and target cascades
  2. Determine which dipoles interact
  3. Reabsorption of non-interacting chains (dipole loops)
  4. Final state radiation (ARIADNE 5)
- DIPSY generates full, exclusive events, does *not* describe all the physics!
- Generally *worse* data description than Pythia 8, but also quite different.
- Features: No pdfs, no separate MPI/UE, *full Space/Time information*, HI "trivial".
- Pending issues: No quarks and no Matrix Elements, Final state swings, frame independence.

Deciding the rope

- Overlaps are calculated for each individual dipole in impact parameter space and rapidity.
- We then have m, n at the point of the string breakup.





- Three options (random walk)
  1. Highest multiplet.
  2. Junction structure.
  3. Singlet.

Highest multiplet

- Here p and q is the number of triplet and anti-triplet strings.
- Addition takes place with recursion relations.

$$\{p,q\} \otimes \vec{3} = \{p+1,q\} \oplus \{p,q+1\} \oplus \{p,q-1\}$$

$$\underbrace{\begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \ldots \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix}}_{\text{All antitriplets}} \underbrace{\otimes \square \otimes \square \otimes \ldots \otimes \square}_{\text{All antitriplets}}$$

- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight, low weight states is handled by special procedures in the implementation.

Junction handling

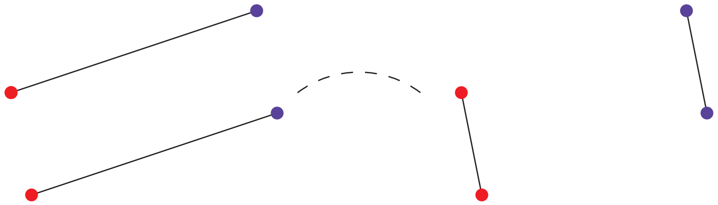
- Extra junctions handled through simplistic, popcorn-based approach.
- Extra parameter controls colour fluctuations.
- No handle on this from data.

The singlet swing

- Singlets are handled already in the FS shower.
- Allow matching colours two *swing* with one another, competing w. emission.

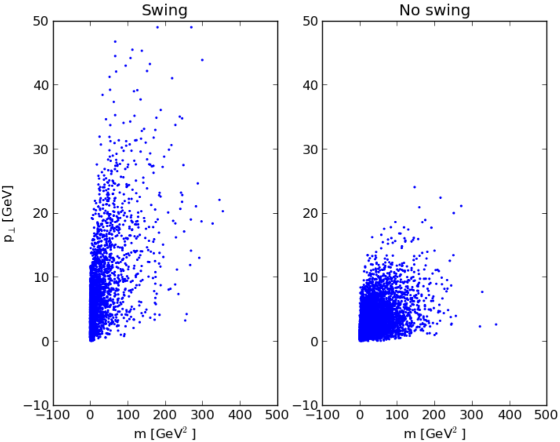
$$\frac{dP_e}{d\ln(p_\perp^2)} \approx dy\frac{C_F\alpha_s}{2\pi}$$

$$\frac{dP_r}{d\ln(p_\perp^2)} = \lambda\frac{(\vec{p_1}+\vec{p_2})^2(\vec{p_3}+\vec{p_4})^2}{(\vec{p_1}+\vec{p_4})^2(\vec{p_2}+\vec{p_3})^2}$$



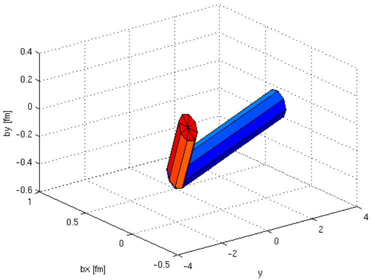
Effect of swing

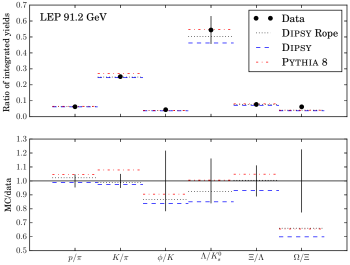
- Swing transforms low $p_\perp$ particles to high $p_\perp$ particles.
- Seems to be right for pp, but overshooting the effect in HI collisions.



Results - LEP Data: SLD, LEP and PDG Avg.

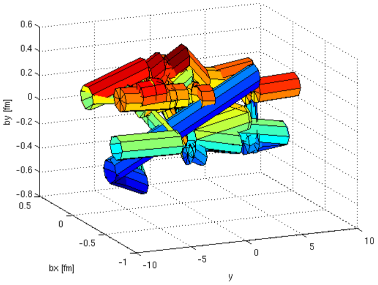
- String at LEPs. Agreement with data (ALEPH, SLD, PDG).
- Notice structure of string: $qg\bar{q}$ event; two dipoles.
- Jet universality: Gain predictive power in pp by fixing parameters here.

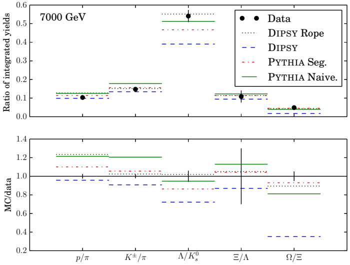




Results - LHC Data: CMS and ALICE

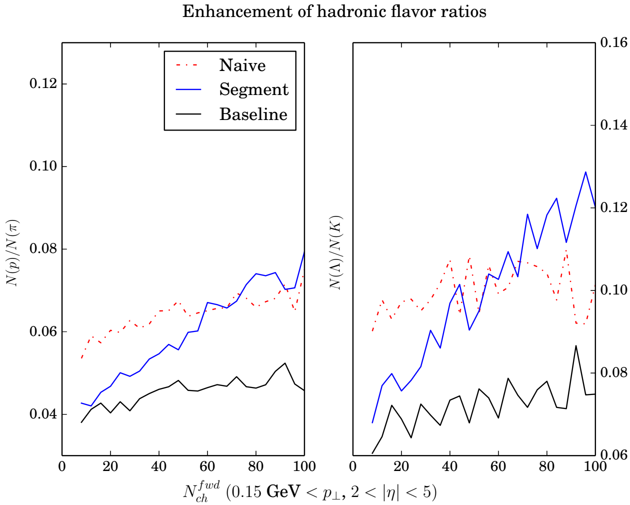
- String at LHC. Agreement with data when correcting for overlap.
- Model for space-time structure is not that important.
- Integrated quantities, need per event quantities as function of activity.





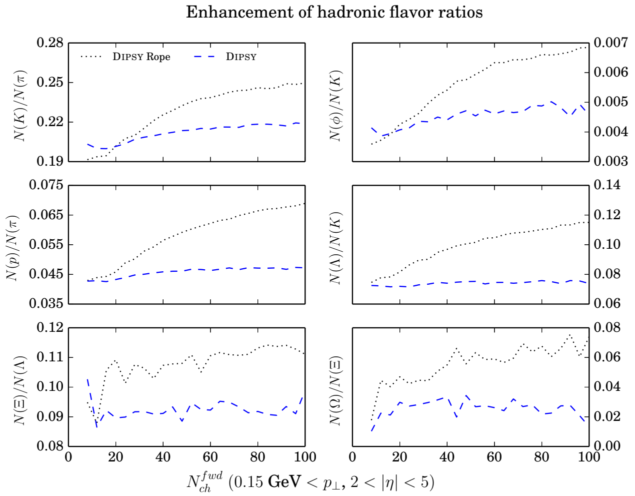
Multiplicity dep. I

- The Pythia toy models.
- Simplest one not adequate at all.
- How far do we need to go before the segment model fails?



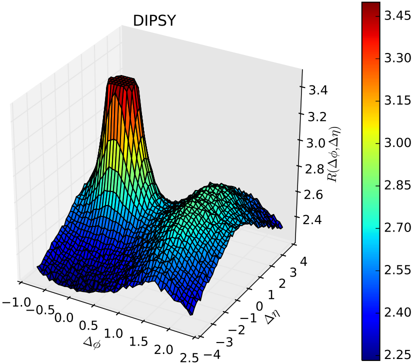
Multiplicity dep. II

- The DIPSY model.
- High hopes for ratios(mult) in jets vs. bulk.



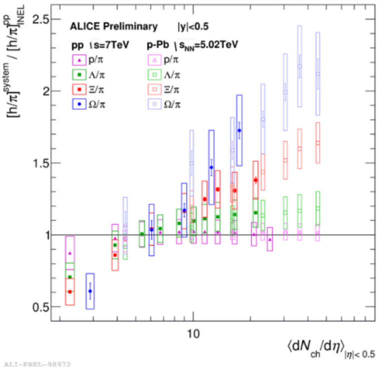
Correlations – the ridge

- The ridge is not reproduced, which is not surprising!
- No long range correlations are introduced anywhere.
- Is String Repulsion a viable candidate?
- Other observables linked to same type of correlation?



Results from ALICE

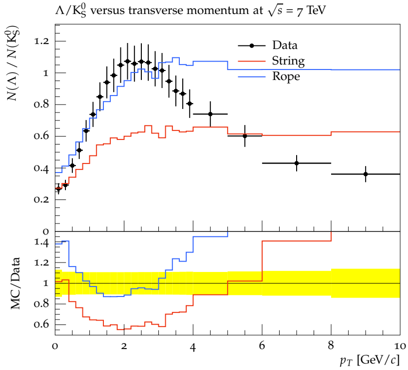
- Strange enhancement seems to be confirmed, baryonic is not.
- Baryon enhancement and popcorn model – further work.
- Interesting, but not shown, is ϕ/π vs. p/π.



- In string models ϕ is ρ^2-surpressed because of 2 strange quarks.
- In (some) statistical models ϕ is not surpressed wrt. p because equal mass and total strangeness equals 0.
- Ratio easy handle to discriminate.

Extensions to AA

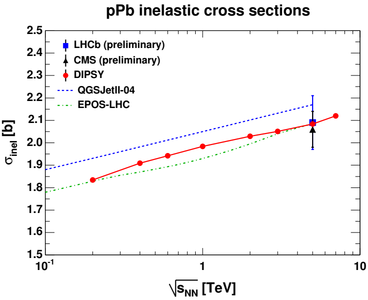
- For AA better control of overlap calculation is needed.
- Case in point: Overlaps with $\tilde{\kappa} = \kappa\sqrt{1 - v_\perp^2}$.

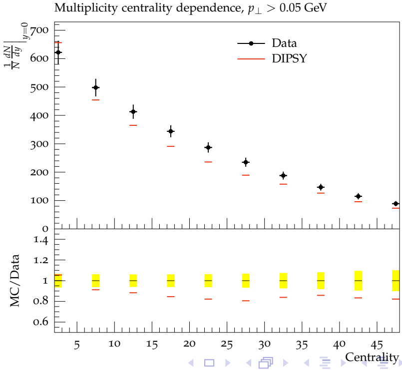


- Also focus on observables: Nuclear modification is of interest.
- How to understand N_{part} in a non-Glauber model?
- Is the Glauber model dependence the best choice?

Wounded nucleons

- All final state effects stand on top of an initial state model.
- Glauber is often used, but maybe too simple?
- Testing in *pA* collisions, DIPSY agrees with inel. x-sec.
- For simple applications DIPSY (almost) reproduces AuAu at 200 GeV centrality dependance.
- We want to increase understanding!





Wounded nucleons II

- Glauber models only distinguish between hit or no-hit.
- But a projectile could interact with nucleons both diffractively and non-diffractively.
- Gribov corrections: Freeze projectile in state k and let target nucleons be in different, uncorrelated states l_ν.
- *Elastic amplitude*:

$$\text{Glauber: } T^{(pA)}(\vec{b}) = 1 - \Pi_\nu 1 - T^{(pp,\nu)}(\vec{b} - \vec{b}_\nu)$$

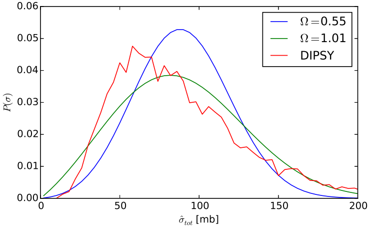
$$\text{Gribov: } \left\langle T^{(pA)(\vec{b})} \right\rangle = 1 - \left\langle \left\langle \Pi_\nu \left\langle 1 - T^{(pp,\nu)}_{k,l\nu}(\vec{b} - \vec{b}_\nu) \right\rangle_{l_\nu} \right\rangle_{\vec{b}_\nu} \right\rangle_k$$

Wounded nucleons III

- Often implemented as fluctuating *pp* cross section, (Strikman ref):

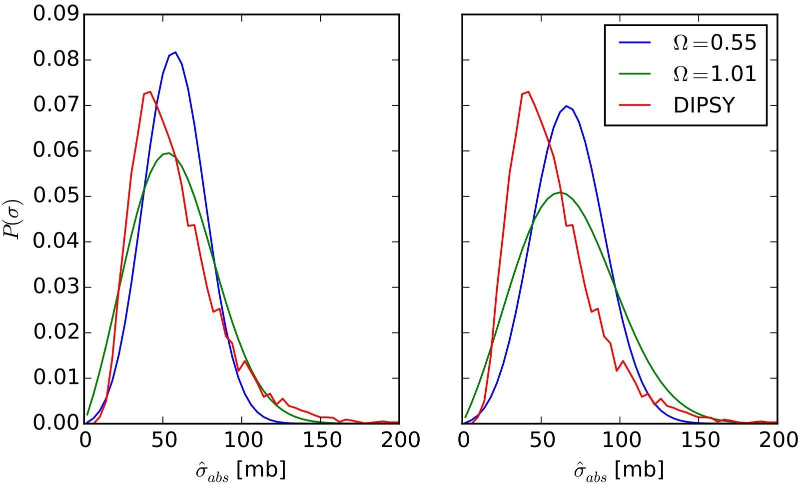
$$\frac{dP}{d\sigma_{tot}} \propto \frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0} \exp\left(-\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2}\right)$$

- Cannot account for frozen projectile and fluctuating target simultaneously.
- Average behaviour agrees with DIPSY, $\sigma_{tot} = 89.6$ mb:

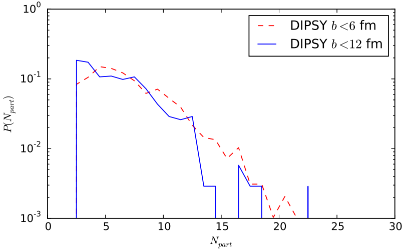


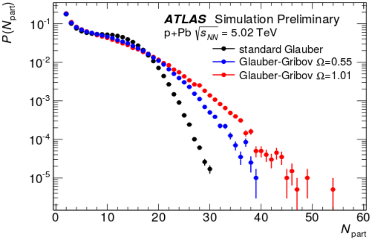
Wounded nucleons IV

- Nucleon-nucleon cross section $\propto \sigma_{tot}$ assumed .
- Using σ_{inel} when σ_{abs} is ment.
- (a) normalized to σ_{abs} (b) normalized to σ_{inel}



- Will change amount of wounded nucleons
- ...but say nothing about how wounded they are!
- Comments, suggestions?





Conclusions

- String hadronization model is:
  1. Firmly rooted in QCD.
  2. Not a black box.
  3. Still ongoing research.
- Rope effects, based on lQCD, get strange enhancement correct.
- Baryon/meson ratios needs further studies.
- Focus right now is:
  1. Understanding of $p_\perp$ spectra/ratios.
  2. Hadrons escaping the rope.
  3. Extending to pPb and PbPb.
- Extension to pPb and PbPb needs futher thought: How to treat subcollisions and centrality?