How to simulate heavy ion collisions without a Quark-Gluon Plasma

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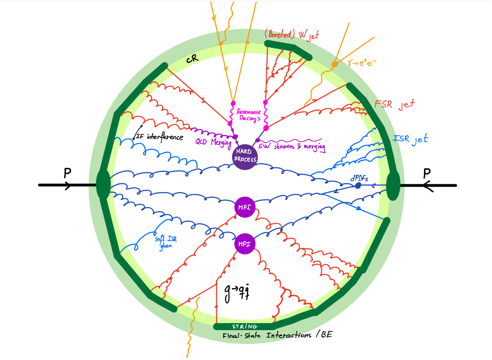
Introduction... to heavy ions vs. proton collisions

- Most are familiar with high energy proton–proton events.

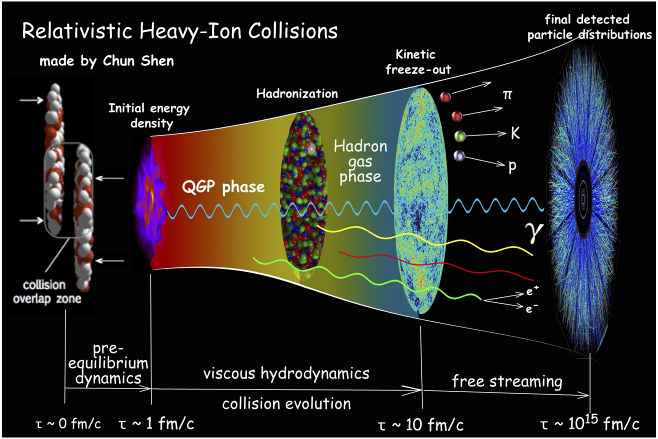


(Figure: Peter Skands)

- Experimentally focused on hard processes (+ jets), QCD resummation by parton showers, MPIs a sideshow, hadronization a necessity.

Standard model of heavy ion physics

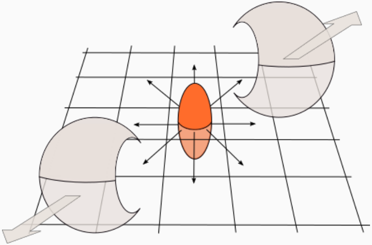
- Heavy ions traditionally viewed very differently.

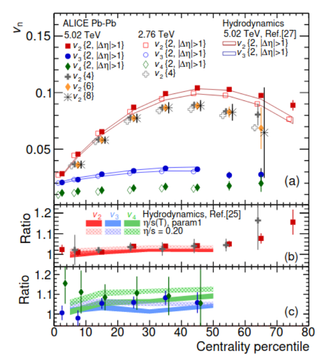


- Experimentally focused on properties of the QGP, viscosity, temperature, mean-free-path.

Flow: the collective behaviour of heavy ions

- Staple measurement: often modeled with hydrodynamics.





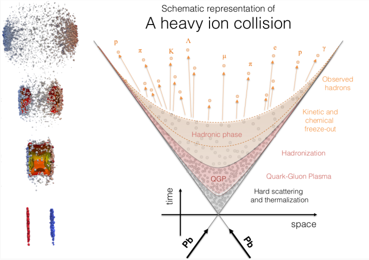
(ALICE: 1602.01119)

Fourier series decomposition of ϕ distribution:

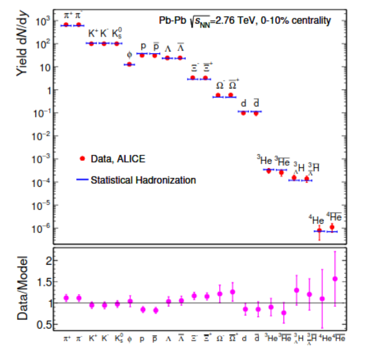
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]$$

Hadron abundances: a QGP thermometer

- The temperature when QGP ends: statistical hadronization.
- Describes yields well with few parameters.



(Figure: D. Chinellato)

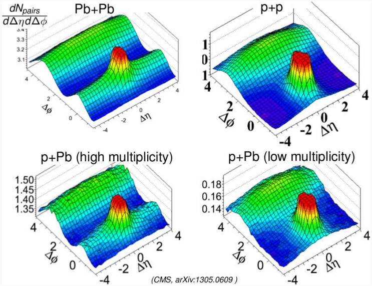


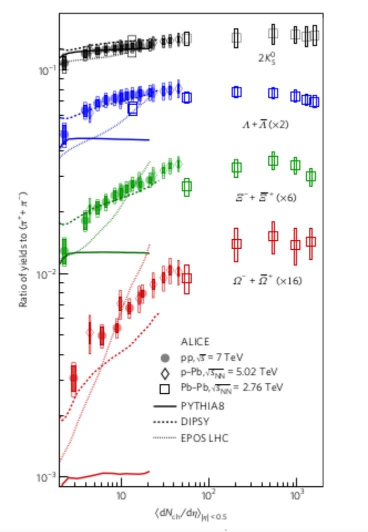
(Andronic et al: 1710.09425)

- There are other types of observables (jet quenching, HBT, quarkonia, ...). But these will be today's focus.

Not so clear division!

- LHC revealed heavy-ion like effects in pp collisions.





(ALICE: Nat. Phys.13 (2017))

- And the transition is smooth!
- Are heavy ion collisions and pp collisions then really that different?

Rest of the seminar

- MPIs and The Lund string model for hadronization.
  - So what is really the big deal about pp collectivity?
- Generalization to heavy ions: The Angantyr model.
- Generating flow: string shoving.
- Rope hadronization and strangeness.
- A further look at geometry.
  - EIC prospects.
- Conclusion and next steps.

MPIs in PYTHIA8 pp (Sjöstrand and Skands: arXiv:hep-ph/0402078)

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

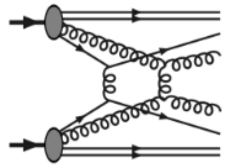


Figure T. Sjöstrand

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

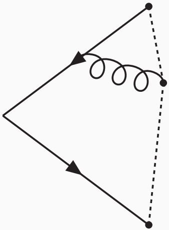
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > ...$ from:

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

- Picture blurred by CR, but holds in general.

The Lund String (80's: Andersson, Bo et al. Z.Phys. C3 (1980) 223, Z.Phys. C20 (1983) 317)

- Non-perturbative phase of final state.
- Confined colour fields ≈ *strings* with tension $\kappa \approx 1$ GeV/fm.



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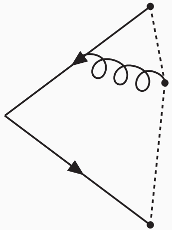

Lund symmetric fragmentation function

$$f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right).$$

a and b related to total multiplicity.

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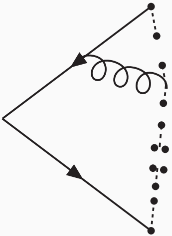

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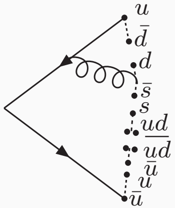

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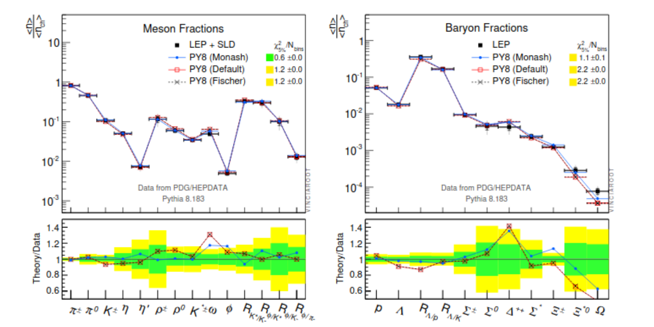
Light flavour determination

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

Related to κ by Schwinger equation.

Flavours constrained by LEP

- Strings make strong predictions about kinematics.
- Quark/di-quark masses unclear – have to rely on data.
- End of the day $\mathcal{O}(10)$ parameters.
- LEP delivers a single string.



(P. Skands: 1404.5630)

- Used for *ep* (HERA) and pp (RHIC/LHC) predictions.

What's the big deal about pp collectivity?!

- Above pp description: Summary of 30 years of successful phenomenology. Cannot describe collective effects.
- The AA models: Vastly different in assumptions – how well can they hold at very low multiplicity?
- Two paradigms at the price of one!

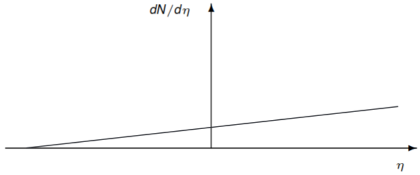
 It might be possible to reconcile!

 One has got to give! Can we even extend pp description to AA?

- Pythia MPI model extended to heavy ions since v. 8.235.
  1. Glauber geometry with Gribov colour fluctuations.
  2. Attention to diffractive excitation & forward production.
  3. Hadronize with Lund strings.

Particle production: Wounded nucleons

- Simple model by Białas and Czyz.
- Wounded nucleons contribute equally to multiplicity in η.
- Originally: Emission function $F(\eta)$ fitted to data.



$$\frac{dN}{d\eta} = \quad F(\eta)$$ (single wounded nucleon

- Angantyr: No fitting to HI data, but include model for emission function.
- Model fitted to reproduce pp case, high $\sqrt{s}$, can be retuned down to 10 GeV.

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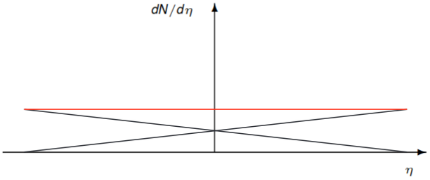

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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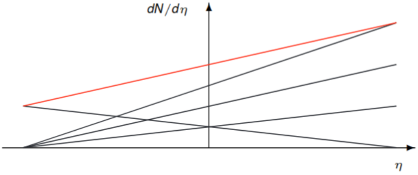

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (pA)$$

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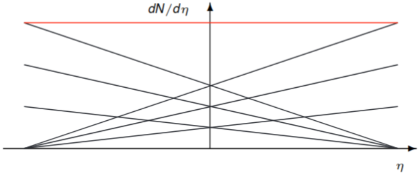

$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

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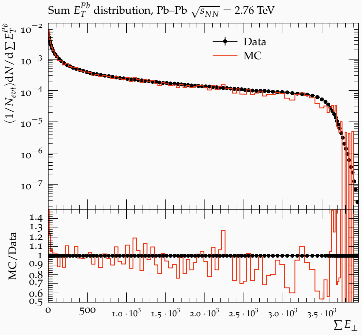
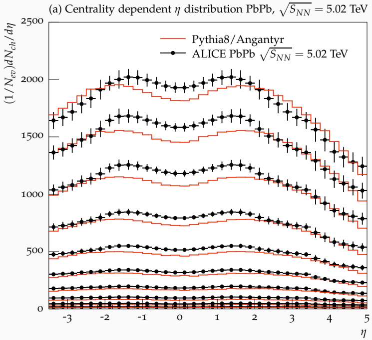
Basic quantities in AA

- Reduces to normal Pythia in pp. In AA:
  1. Good reproduction of centrality measure.
  2. Particle density at mid–rapidity.

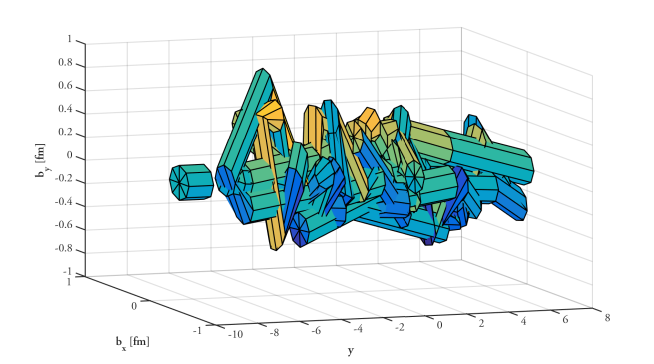




- Clean slate for new models!

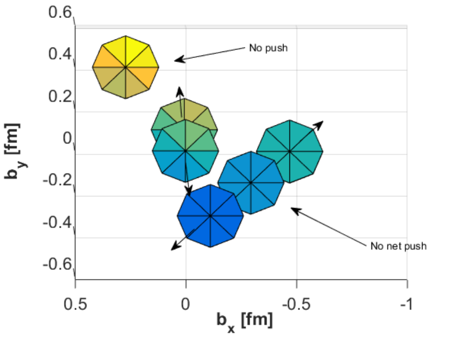
How to add space-time dependence to Lund strings?

- Shopping list:
  1. Space time structure (KISS for now, convolution of 2D Gaussians, Lorentz contracted in z-direction).
  2. What effect could generate flow?
  3. What effect could change the string tension?



Shoving: The cartoon picture (CB, Gustafson, Lönnblad: 1710.09725, +=Chakraborty: 2010.07595)

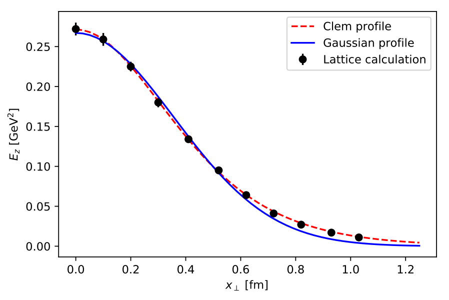
- Strings push each other in transverse space.
- Colour-electric fields → classical force.



👍 Transverse-space geometry.
👍 Particle production mechanism.
?? String radius and shoving force

MIT bag model, dual superconductor or lattice?

- Easier analytic approaches, eg. bag model:
  $\kappa = \pi R^2[(\Phi/\pi R^2)^2/2 + B]$
- Bad R 1.7 and dual sc. 0.95 respectively, shape of field is input.
- Lattice can provide shape, but uncertain R.



- Solution: Keep shape fixed, but R ballpark-free.

The shoving force

- Energy in field, in condensate and in magnetic flux.
- Let g determine fraction in field, and normalization N is given:

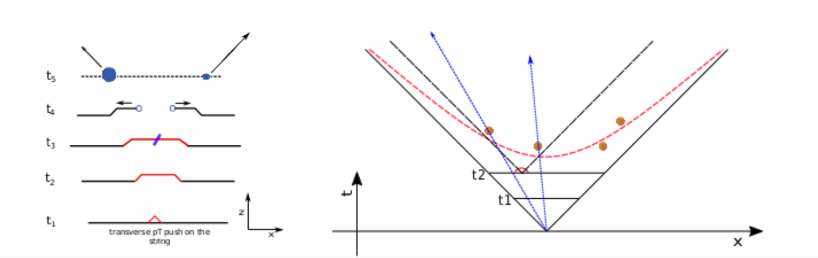
$$E = N \exp(-\rho^2/2R^2)$$

- Interaction energy calculated for transverse separation $d_\perp$, giving a force:

$$f(d_\perp) = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

Monte Carlo details

- Distance $d_\perp$ calculated in a frame where strings lie in parallel planes.
- Everything is two-string interactions.
- The shoving action implemented as a parton shower.
- Push propagated along string, and distributed on final state hadrons.



Rope Hadronization (JHEP 1503 (2015) 148 – explored heavily in 80's and 90's!)

- After shoving, strings (p and q) still overlap.
- Combines into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

$$\kappa \propto C_2 \Rightarrow \frac{\tilde{\kappa}}{\kappa_0} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}.$$

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Easily calculable using SU(3) recursion relations

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

$$\underbrace{\begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \ldots \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix}}_{\text{All anti-triplets}} \underbrace{\otimes \square \otimes \square \otimes \ldots \otimes \square}_{\text{All triplets}}$$

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- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight in the random walk.

Fragmenting the multiplets

- Highest multiplet = highest string tension.
- Intermediate multiplets = string junctions, carry baryon number.
- Rope breaks one string at a time, reducing the *remaining* tension.

Strangeness enhanced by:

$$\rho_{LEP} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho} = \rho_{LEP}^{\kappa_0/\kappa}$$

- QCD + geometry extrapolation from LEP.
- Can *never* do better than LEP description!

Microscopic final state collectivity in summary

- Proposal: Model microscopic dynamics with interacting Lund strings
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$\tau \approx 0$ **fm:** Strings no transverse extension. No interactions, partons may propagate.

$\tau \approx 0.6$ **fm:** Parton shower ends. Depending on "diluteness", strings may shove each other around.

$\tau \approx 1$ **fm:** Strings at full transverse extension. Shoving effect maximal.

$\tau \approx 1.4$ **fm:** Strings will hadronize. Possibly as a colour rope.

$\tau > 1.4$ **fm:** Possibility of hadronic rescatterings.

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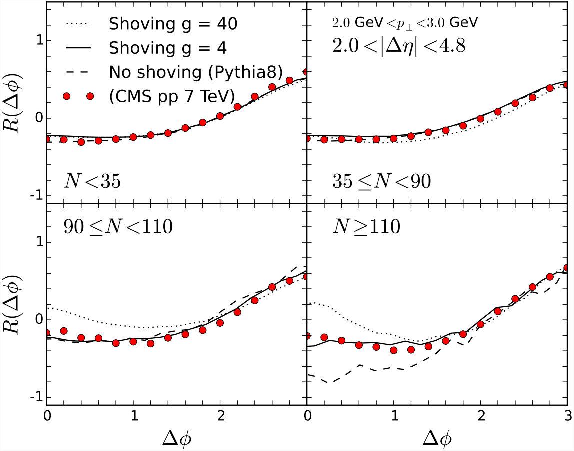
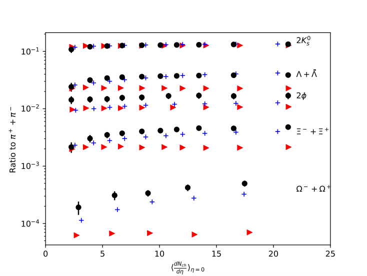
Shoving results

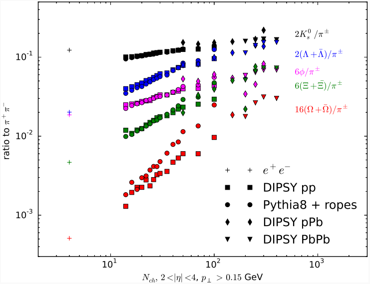
- The pp ridge (and much more, see 2010.07595).



Results: ropes

- Good description of strangeness enhancement.
- Left pp final calculation, right pp-AA preliminary results (WiP).

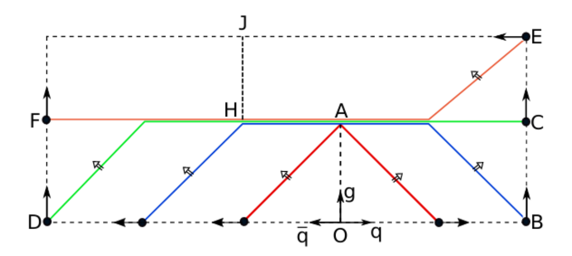




(Data in black (ALICE))

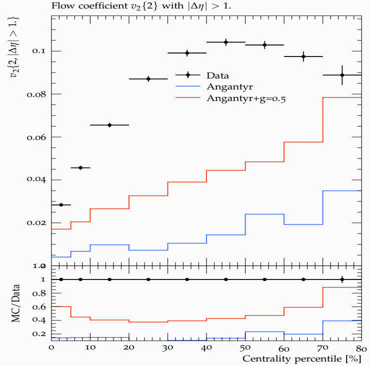
Did you skip shoving for AA?

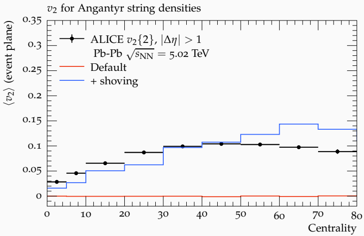
- Adding small pushes propagating along the string is difficult!
- Current problem: "secondary" string pieces arising from origami regions.
- If only there were no soft gluons around...



Shoving results PbPb

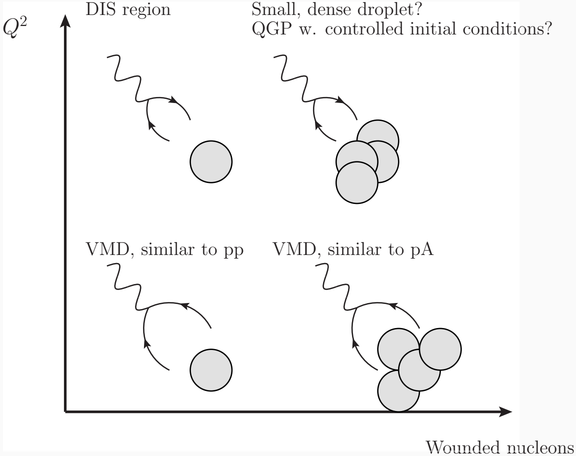
- Missing origami regions, realistic inital states (left).
- Toy model configuration (right)
- Both lacking hadronic rescattering, which also plays a role.





The story so far

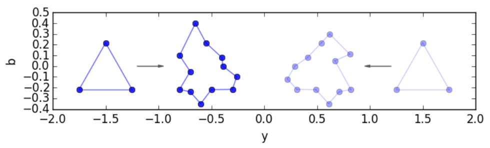
- Extensions of MPI formalism to pA and AA.
- String based models for collectivity.
- Geometry is crucial and surprisingly difficult to get right.
- The future EIC will give new possibilities.



Mueller dipole initial states

The aim and the means

A reasonable calculation of initial state geometry.
Fluctuating γ^*–nucleon cross sections.
MC implementation of Mueller dipoles.

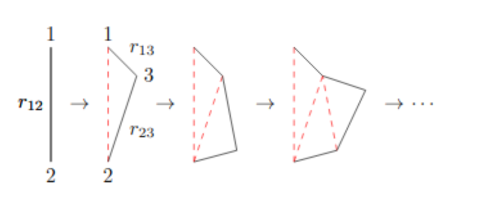


- Projectile and target cascades evolved for each event.
- Formalism in impact parameter and rapidity.
- Single-event spatial structure.

A step back, BFKL, B-JIMWLK and all that...

- Start with Mueller dipole branching probability:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}y} = \mathrm{d}^2\vec{r}_3 \, \frac{N_c \alpha_s}{2\pi^2} \frac{r_{12}^2}{r_{13}^2 r_{23}^2} \equiv \mathrm{d}^2\vec{r}_3 \, \kappa_3 .$$



- Evolve any observable $O(y) \rightarrow O(y + \mathrm{d}y)$ in rapidity:

$$\bar{O}(y+\mathrm{d}y) = \mathrm{d}y \int \mathrm{d}^2\vec{r}_3 \, \kappa_3 \left[O(r_{13}) \otimes O(r_{23})\right] + O(r_{12}) \left[1 - \mathrm{d}y \int \mathrm{d}^2\vec{r}_3 \, \kappa_3\right]$$

$$\rightarrow \frac{\partial \bar{O}}{\partial y} = \int \mathrm{d}^2\vec{r}_3 \, \kappa_3 \left[O(r_{13}) \otimes O(r_{23}) - O(r_{12})\right].$$

Monte Carlo implementation

Drawbacks to analytic approach

Involved observables are hard!
Not obvious how to include sub-leading effects.
Not obvious how to treat exclusive final states.

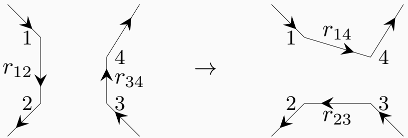
- The MC way is a tradeoff: formal precision vs. pragmatism.
- Get for free: Rest of the MC infrastructure.
- Practically a parton shower-like implementation.
- Step 1: Modify splitting kernel with Sudakov:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}y\ \mathrm{d}^2\vec{r}_3} = \frac{N_c\alpha_s}{2\pi^2}\frac{r_{12}^2}{r_{13}^2 r_{23}^2}\exp\left(-\int_{y_{\min}}^{y}\mathrm{d}y\mathrm{d}^2\vec{r}_3\ \frac{N_c\alpha_s}{2\pi^2}\frac{r_{12}^2}{r_{13}^2 r_{23}^2}\right)$$

- Winner-takes-it-all algorithm generates emission up to maximal rapidity.
- Throws away the non-linear term in the cascade.

Colliding dipole chains & unitarity

- Have: Evolved dipole chain á la BFKL.
- Dipole cross section in large-N_c limit (consistency with evolution):



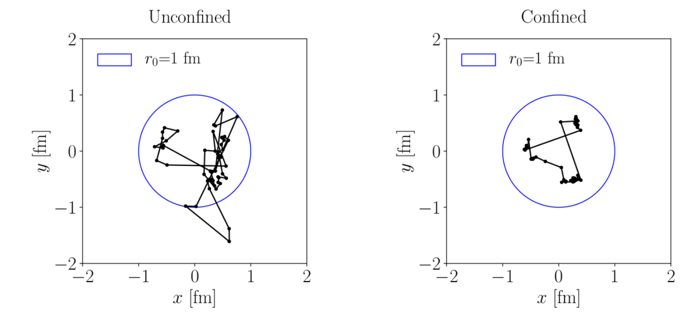
$$\frac{\mathrm{d}\sigma_{\mathrm{dip}}}{\mathrm{d}^2\vec{b}} = \frac{\alpha_s^2 C_F}{N_c} \log^2\left[\frac{r_{13}r_{24}}{r_{14}r_{23}}\right]$$

$$\rightarrow \frac{\alpha_s^2}{2} \log^2\left[\frac{r_{13}r_{24}}{r_{14}r_{23}}\right] \equiv f_{ij}$$

- Unitarized scattering amplitude: $T(\vec{b}) = 1 - \exp\left(-\sum_{ij} f_{ij}\right)$

Example: confinement → hot-spots

- MC makes it easy to switch physics effects on and off.
- More activity around end-points: Hot-spots!
- Initial triangle by hand. Less important at high energies, but deserves more thought.



- Dynamically generated!
- To be added as reasonable proton geometry.

Good–Walker & cross sections

- Cross sections from $T(\vec{b})$ with normalizable particle wave functions:

$$\sigma_{\rm tot} = 2\int \mathrm{d}^2\vec{b}\Gamma(\vec{b}) = 2\int \mathrm{d}^2\vec{b}\ \langle T(\vec{b})\rangle_{p,t}$$

$$\sigma_{\rm el} = \int \mathrm{d}^2\vec{b}|\Gamma(\vec{b})|^2 = \int \mathrm{d}^2\vec{b}\ \langle T(\vec{b})\rangle_{p,t}^2$$

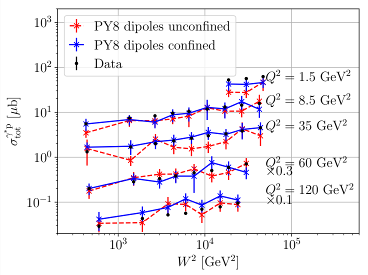
$$B_{\rm el} = \frac{\partial}{\partial t}\log\left(\frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}t}\right)\Big|_{t=0} = \frac{\int \mathrm{d}^2\vec{b}\ b^2/2\ \langle T(\vec{b})\rangle_{p,t}}{\int \mathrm{d}^2\vec{b}\ \langle T(\vec{b})\rangle_{p,t}}$$

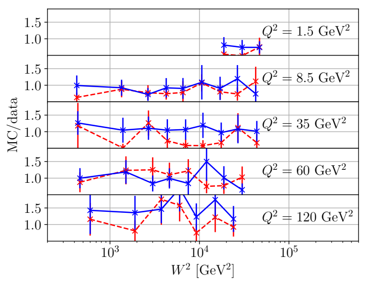
- Or with photon wave function:

$$\sigma^{\gamma^*\mathrm{p}}(s) = \int_0^1 \mathrm{d}z \int_0^{r_{\max}} r\mathrm{d}r \int_0^{2\pi} \mathrm{d}\phi \left(|\psi_L(z,r)|^2 + |\psi_T(z,r)|^2\right) \sigma_{\rm tot}(z,\vec{r})$$

Model parameters

- This means that all parameters (4) can be tuned to cross sections

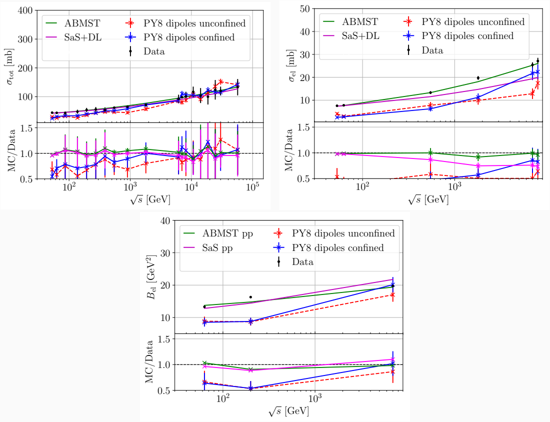




- Could constrain better in *ep* with eg. vector meson production.

Model parameters II

- Same parameters should describe pp, adds more data to the tuning.



- Not as good as dedicated (Regge-based) models.
- Accuracy not the point, control of physics features is!

Cross section colour fluctuations

- Cross section fluctuates event by event: important for pA, $\gamma^* A$ and less AA.
- Projectile remains frozen through the passage of the nucleus.
- Consider fixed state (k) projectile scattered on single target nucleon:

$$\Gamma_k(\vec{b}) = \langle \psi_S | \psi_I \rangle = \langle \psi_k, \psi_t | \hat{T}(\vec{b}) | \psi_k, \psi_t \rangle =$$

$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \langle \psi_k, \psi_t | \psi_k, \psi_t \rangle =$$

$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \equiv \langle T_{tk}(\vec{b}) \rangle_t$$

- And the relevant amplitude becomes $\langle T^{(nN_i)}_{t_i,k}(\vec{b}_{ni}) \rangle_t$

Fluctuating nucleon-nucleon cross sections

- Let nucleons collide with total cross section $2\langle T\rangle_{p,t}$
- Inserting frozen projectile recovers total cross section.
- Consider instead inelastic collisions only (color exchange, particle production):

$$\frac{\mathrm{d}\sigma_{\mathrm{inel}}}{\mathrm{d}^2\vec{b}} = 2\langle T(\vec{b})\rangle_{p,t} - \langle T(\vec{b})\rangle_{p,t}^2.$$

- Frozen projectile will not recover original expression, but requre target average first.

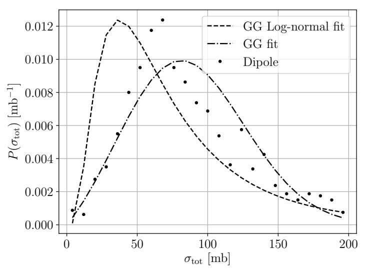
$$\frac{\mathrm{d}\sigma_w}{\mathrm{d}^2\vec{b}} = 2\langle T_k(\vec{b})\rangle_p - \langle T_k^2(\vec{b})\rangle_p = 2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p$$

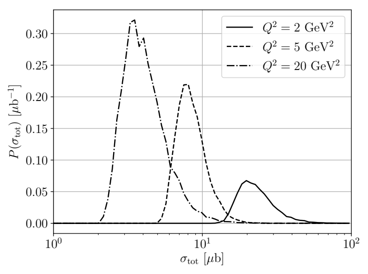
- Increases fluctuations! But pp can be parametrized.

EIC adds more complications

- For $\gamma^* A$ collisions the trick can be repeated.
- But photon wave function collapse to previous result at first hit.

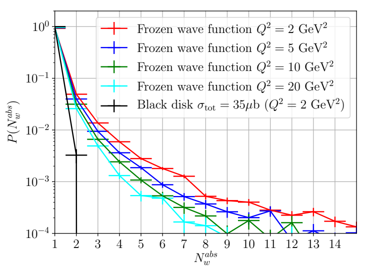
$$\frac{\mathrm{d}\sigma_w}{\mathrm{d}^2\vec{b}} = \int \mathrm{d}z \int \mathrm{d}^2\vec{r}\,(|\psi_L(z,\vec{r})|^2 + |\psi_T(z,\vec{r})|^2)(2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p).$$

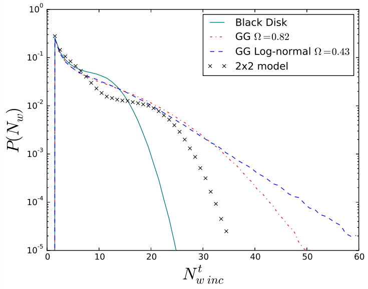




Drastic for number of wounded nucleons

- More multi-hit events, meaning more background.
- Clearly non-negligible, lesson already learned in p-Pb at LHC.





Summary and future

- Heavy ion physics traditionally different from high energy pp.
- Small system collectivity (LHC) blurred the lines.
- Several new/updates models for string interactions.
- Extension of MPI formalism to AA.
- Ongoing efforts to improve geometry modeling.
- EIC provides strong tests of all aspects.

Thank you for the invitation!