Probing baryon stopping and diffusion with rapidity-even directed flow of protons and anti-protons

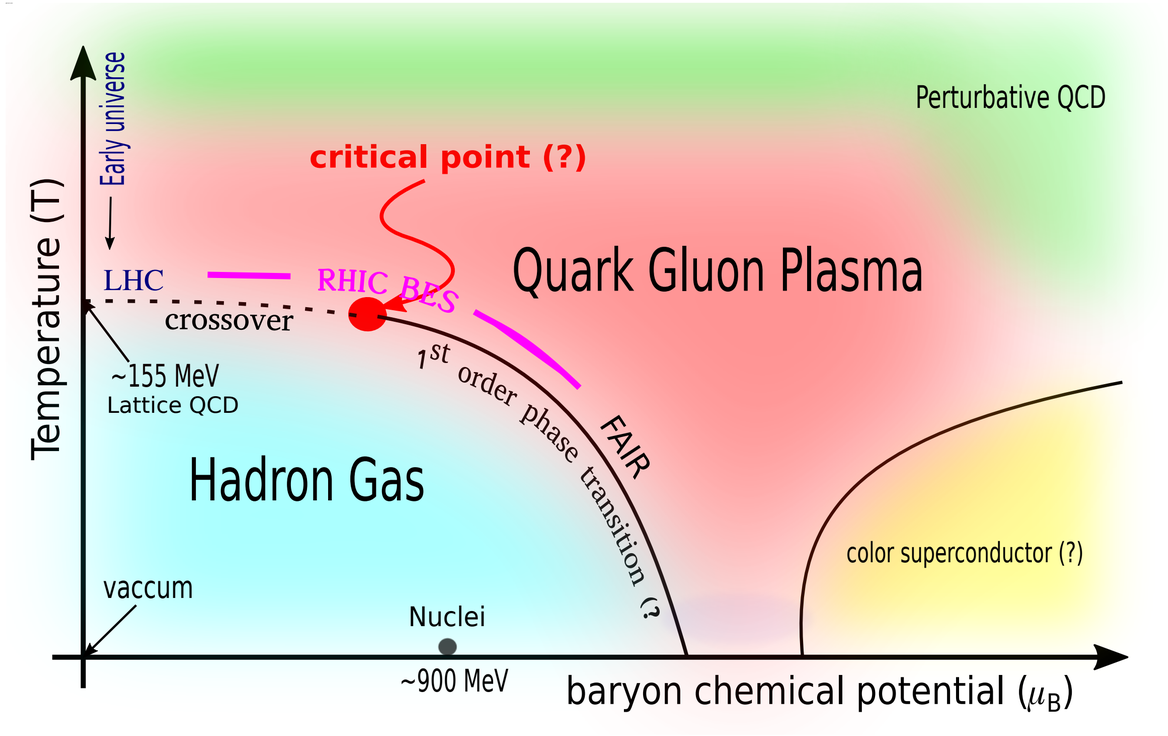
Tribhuban Parida

AGH University of Krakow



30 Oct 2026

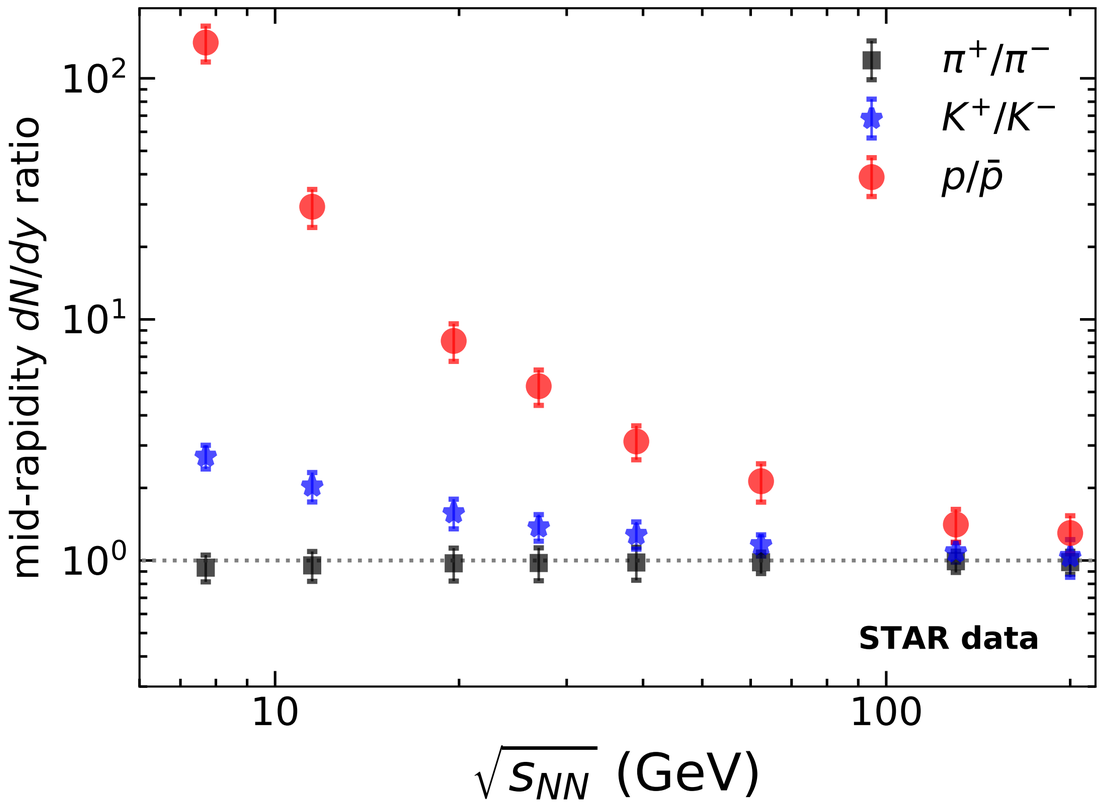
QCD phase diagram : accessing high baryon density region



- **Low μ_B:** Lattice QCD predicts a smooth crossover from the quark–gluon plasma (QGP) to hadronic matter.
- **High μ_B:** The phase structure remains uncertain due to limitations of first-principles lattice QCD calculations.
- **Experimental exploration:** Lowering the collision energy increases baryon stopping and allows experiments to probe regions of higher μ_B, potentially accessing the QCD critical point and a first-order phase transition.

accessing baryon rich QCD matter

Central Au + Au collisions

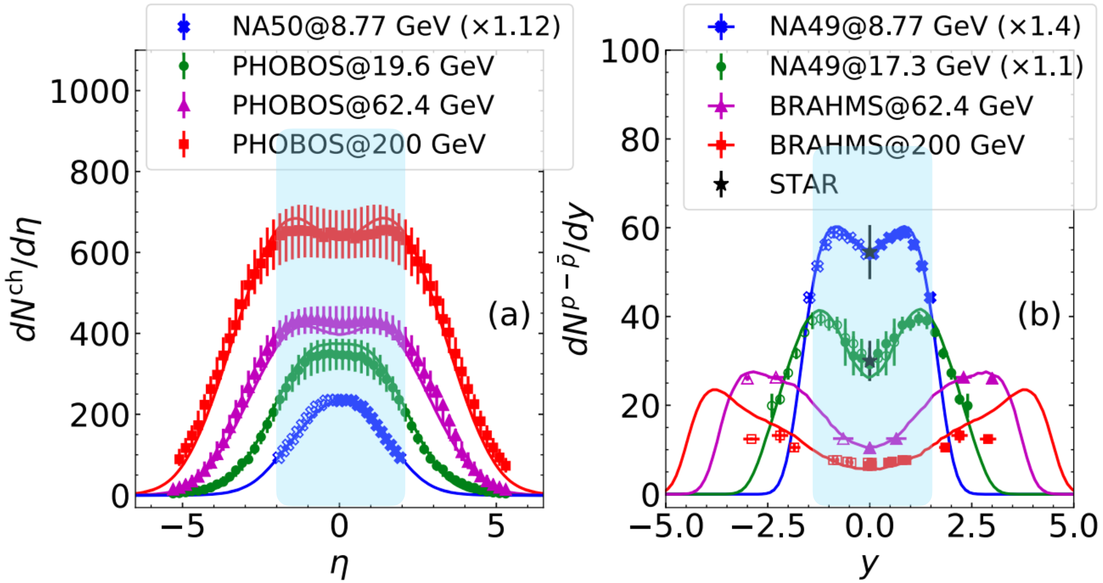


Within the statistical thermal model, assuming chemical equilibrium, the Boltzmann approximation, and negligible μ_Q :

$$\frac{N_p}{N_{\bar{p}}} \approx \frac{\exp\left(\frac{-E+\mu_B}{T}\right)}{\exp\left(\frac{-E-\mu_B}{T}\right)} \approx \exp\left(\frac{2\mu_B}{T}\right)$$

- Lower collision energies lead to increased baryon stopping.
- The increasing $p/\bar{p}$ ratio provides experimental evidence of increasing baryochemical potential with decreasing collision energy.

Baryon stopping : opportunity to study baryon dynamics



L. Du et. al. arXiv : 2211.16408

LHC / high collision energy

- Approximate boost invariance around mid rapidity
- Smaller net proton yield

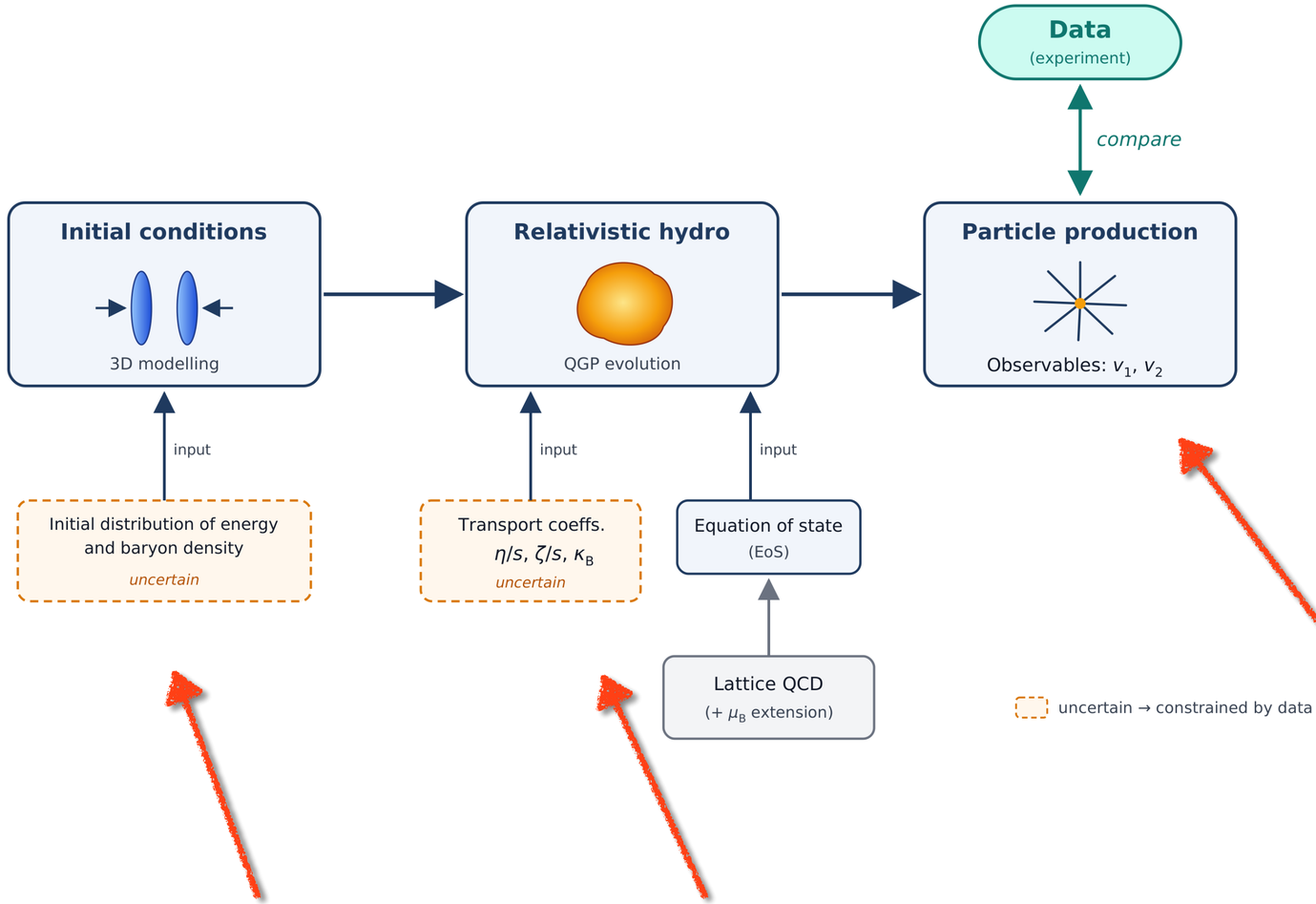
2+1D hydro with $n_B = 0$

Lower collision energy

- Stronger rapidity dependence
- Sizable net proton yield

3+1D hydro with finite baryon density

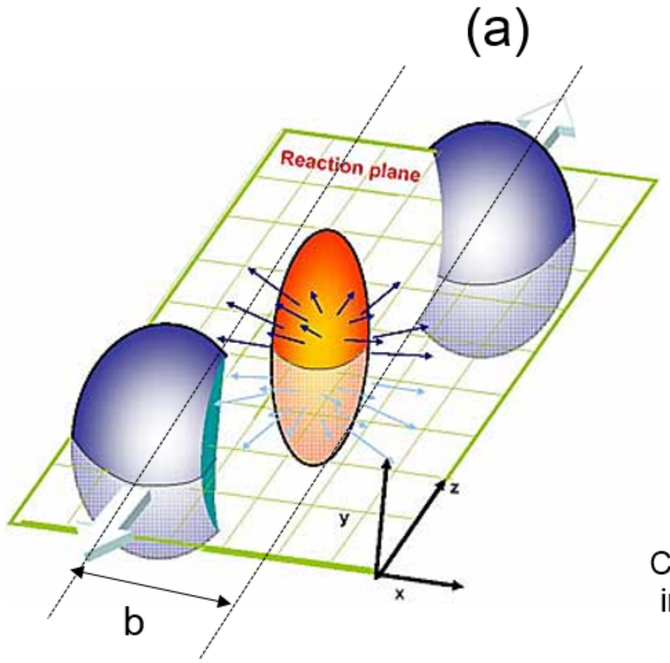
Simulation chain

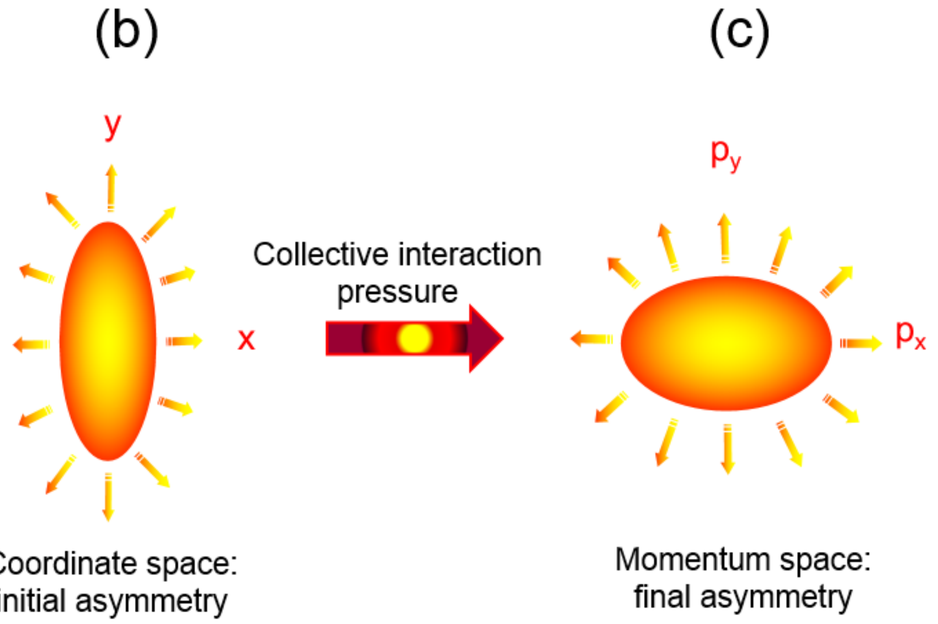


Talk title : Probing **baryon stopping** and **diffusion** with **rapidity-even directed flow** of protons and anti-protons

Elliptic flow : Probably the most famous observable as collectivity probe

$$(\epsilon + P)Du^{\rho} = -\Delta^{\mu\rho}\nabla_{\mu}P$$



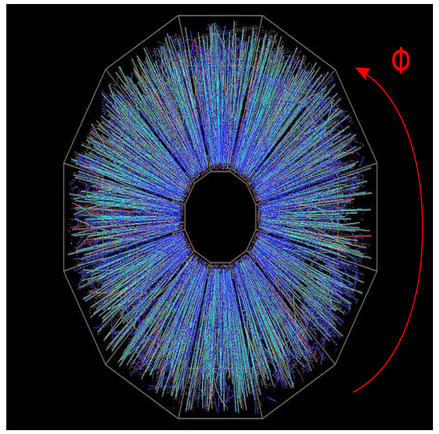


$$\epsilon_2 = \langle \frac{y^2 - x^2}{y^2 + x^2} \rangle \quad \rightarrow \quad v_2 = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle = \langle \cos 2(\phi - \Psi_2) \rangle$$

R. Nouicer. arXiv:1512.08993

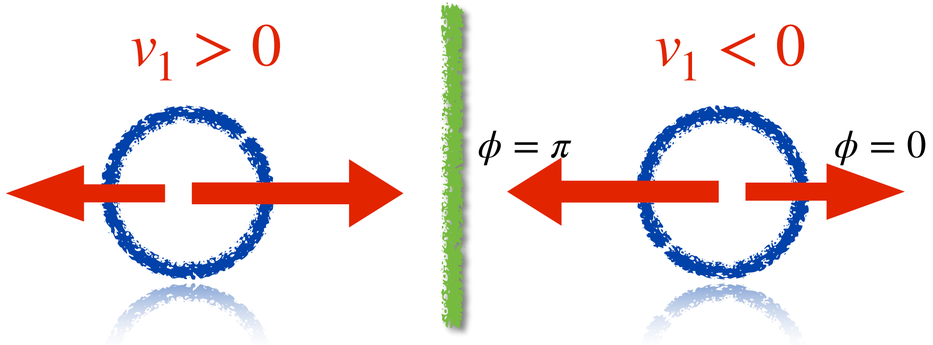
In every event one has to find out the direction along which the smaller axis of the ellipse lies.

Directed flow

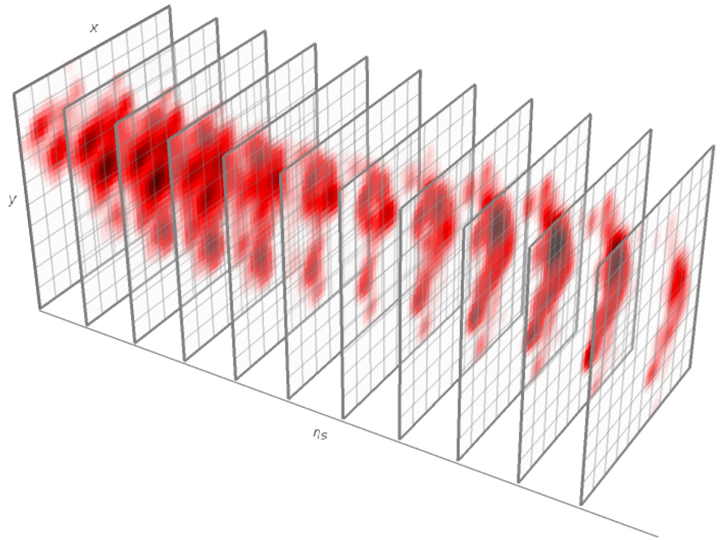


Definition of v_1

$$\frac{dN}{d\phi}(y) = N_0 + v_1(y)\cos\phi + v_2\cos 2\phi + \ldots$$



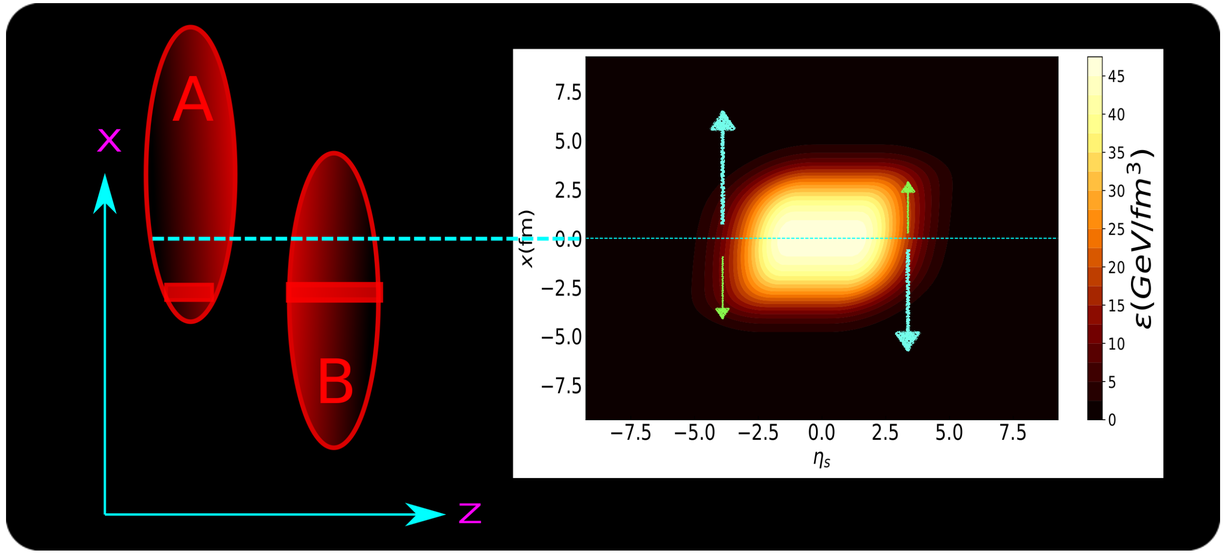
Seeder et. al. 2306.08665



3D energy deposition in a heavy ion collision event

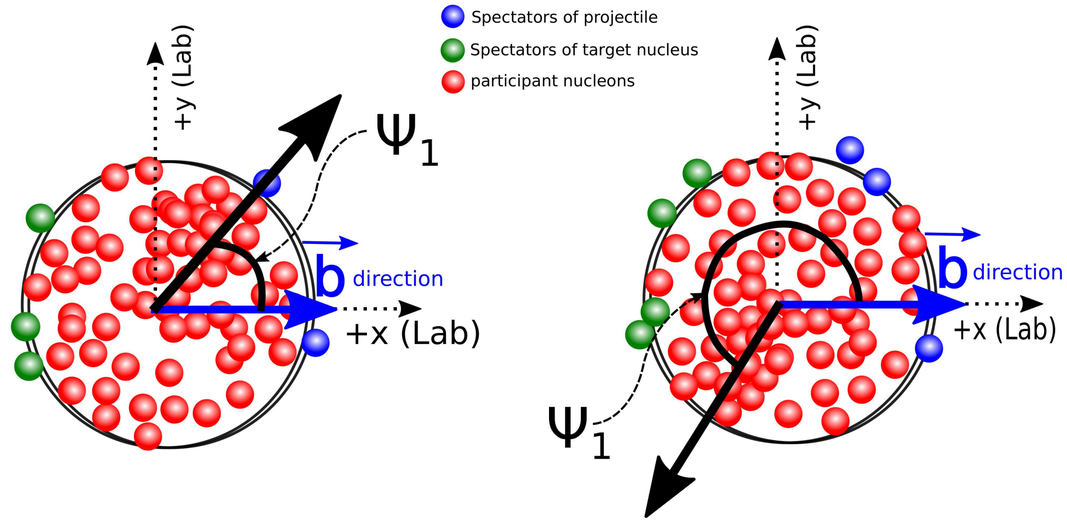
- At each/any rapidity slice if there would be a +x to -x symmetry breaking then in the final state we obtain $v_1 \neq 0$

v_1-odd



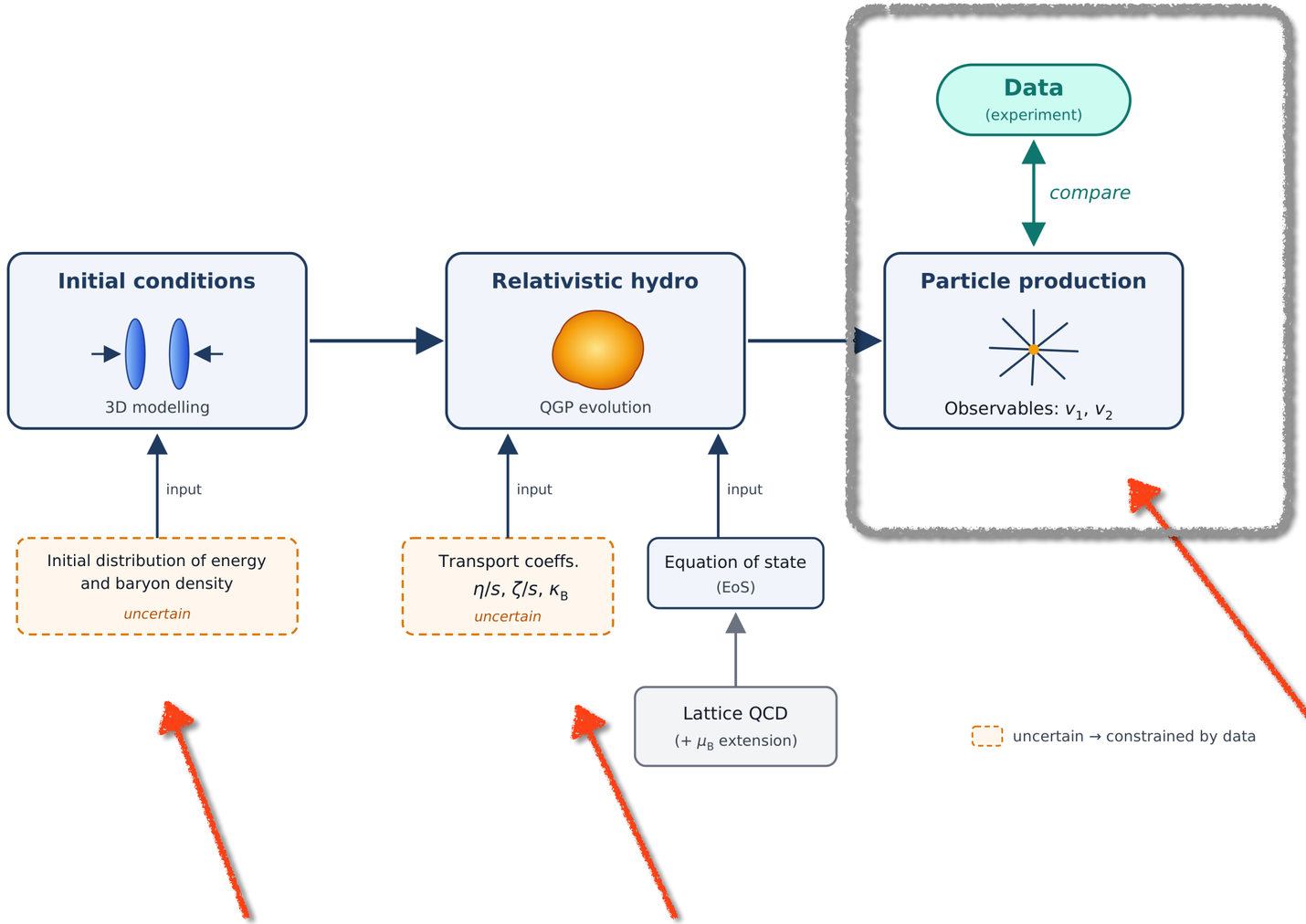
1. Origin - Geometry
2. Correlated with the direction of $\vec{b}$
3. Rapidity odd in nature (zero at mid-rapidity)

v_1-even



1. Origin - Fluctuation
2. Not correlated with the direction of $\vec{b}$
3. Rapidity even in nature (non zero at mid-rapidity)

Simulation chain

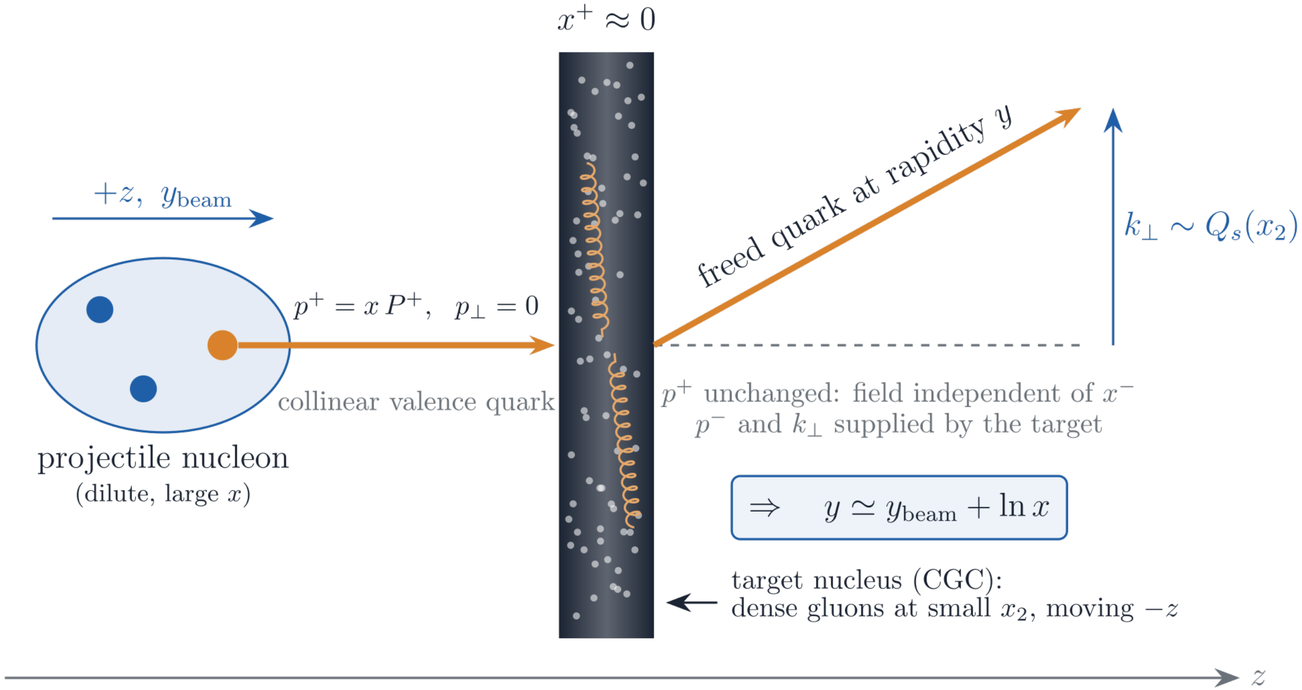


Talk title : Probing **baryon stopping** and **diffusion** with **rapidity-even directed flow** of protons and anti-protons

What I am going to show

1. How different model of Initial baryon distribution, affects the v_1 of protons and anti-protons.
2. Hence by measuring this kind of observable we can probe the initial baryon stopping.

Rapidity structure - first guidance from theory



A collinear valence quark crosses the CGC wall and emerges with (p_T, y)

1. p^+ conservation leads to

$$x\sqrt{s_{NN}} = m_T e^y \implies y \approx y_{beam} + \ln x$$

2. Where does the quark land?

$$\Delta y \equiv y_{beam} - y \implies x = e^{-\Delta y}$$

A quark's rapidity loss is Δy, if it initially carried longitudinal momentum fraction x.

3. How many valence quarks carry x?

$$xq_f(x) = Ax^{0.5} \qquad \text{DIS}$$

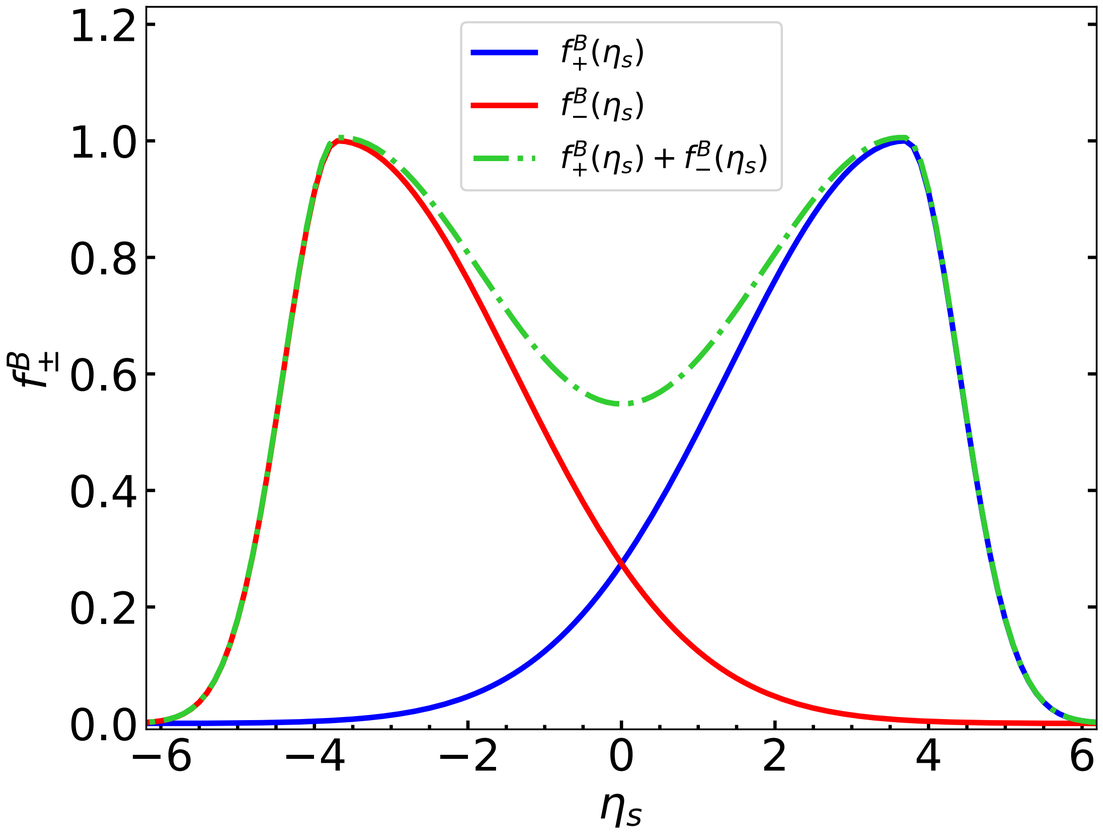
4. Put in $x = e^{-\Delta y}$

$$dN_{B-\bar{B}} / dy \simeq A\, e^{-0.5\,\Delta y}$$

Around mid-rapidity, baryon stopping rises **exponentially** toward beam rapidity.

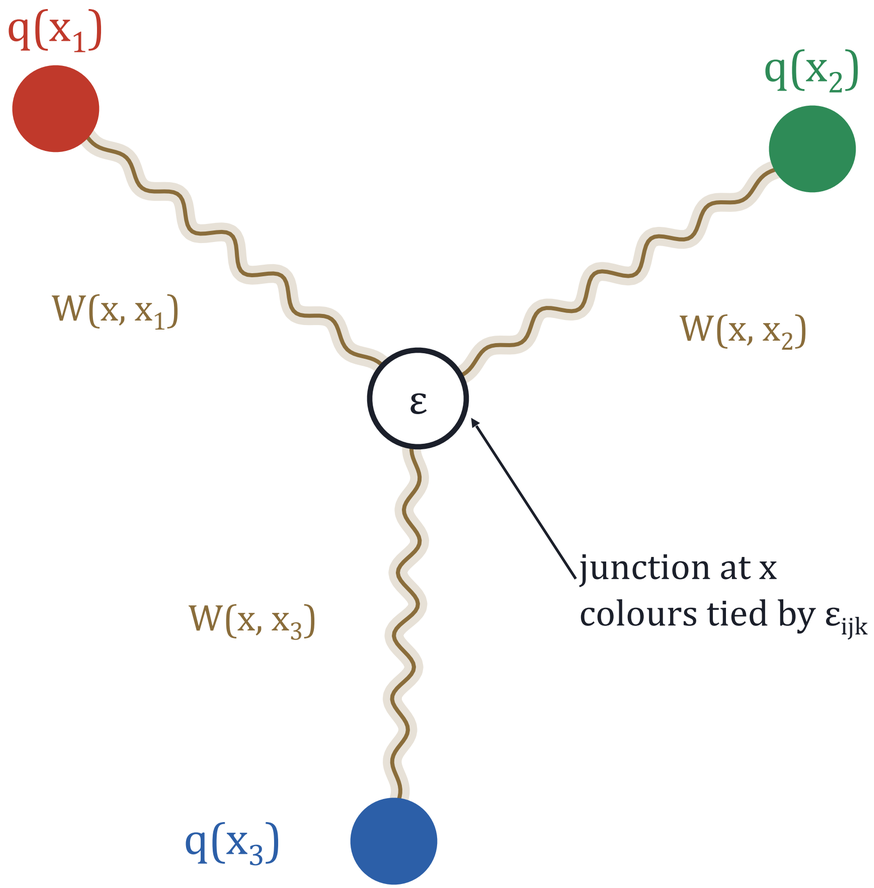
Model of initial net-baryon rapidity distribution

$$n_B(x, y, \eta_s) = N_B \left[(1-\omega)\left(N_+(x,y) f_+^B(\eta_s) + N_-(x,y) f_-^B(\eta_s) \right) + \omega N_{coll}(x,y)\left(F_{coll}(\eta_s) \right) \right]$$



1. Valance quark distribution peaks around x=0.2, which implies that the rapidity distribution must peak somewhere around $y \approx y_{beam} - 1.5$.
2. Here we parametrise that peak and both side falls.
3. We fix the parameters by comparing with rapidity distribution of net-proton yield.

second input from theory



gauge invariance demands the baryon junction

$\varepsilon_{ijk}\, q_i q_j q_k$ is the colour-singlet combination of three quarks, which is how a baryon is built in QCD.

A. All three quarks at one point x

Under a gauge rotation every quark turns with the same matrix:

$$q_i(x) \;\to\; U_{ia}(x)\, q_a(x), \qquad \det U = 1$$

The three U's combine into a determinant, so the state is invariant:

$$\epsilon_{ijk}\, q_i q_j q_k \;\to\; \epsilon_{ijk} U_{ia} U_{jb} U_{kc}\, q_a q_b q_c = (\det U)\, \epsilon_{abc}\, q_a q_b q_c$$

B. Quarks at three different points

Now each quark turns with its own matrix, and no determinant forms:

$$\epsilon_{ijk}\, U_{ia}(x_1)\, U_{jb}(x_2)\, U_{kc}(x_3) \;\neq\; \epsilon_{abc} \quad\Rightarrow\quad \text{not invariant}$$

C. Wilson lines to a common point x

The Wilson line carries colour from x_n to x:

$$W(x, x_n) \;\to\; U(x)\, W(x, x_n)\, U^\dagger(x_n)$$

so the transported quark forgets $U(x_n)$ and turns with U(x):

$$Q_n \equiv W(x, x_n)\, q(x_n) \;\to\; U(x)\, W\, [U^\dagger(x_n) U(x_n)]\, q(x_n) = U(x)\, Q_n$$

All three now share U(x), so tying them with ε_{ijk} at x works again:

$$B = \epsilon_{ijk}\, Q_{1i}\, Q_{2j}\, Q_{3k} \;\to\; \det U(x)\, B = B$$

The common point x, where ε_{ijk} ties the three strings, is the junction: it is demanded by gauge invariance and carries the baryon number.

Model of initial baryon distribution

$$n_B(x,y,\eta_s) = N_B\left[(1-\omega)\left(N_+(x,y)f_+^B(\eta_s)+N_-(x,y)f_-^B(\eta_s)\right)+\omega N_{coll}(x,y)\left(F_{coll}(\eta_s)\right)\right]$$

1. We associate the binary collision with the double junction stopping - since two units of baryons involved.
2. It's rapidity structure is varied (plateau - according to double junction stopping cross-section and Gaussian - a more general form)

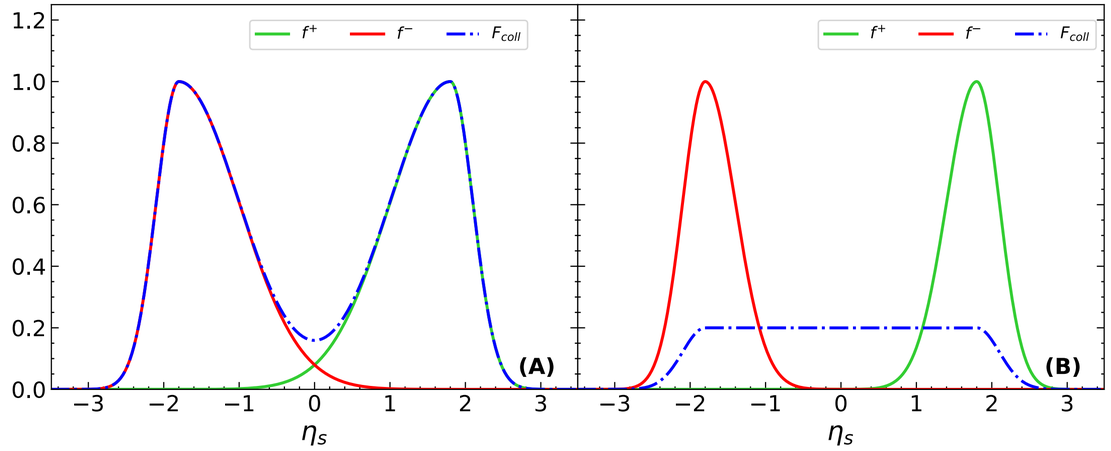
Kharzeev (1996) nucl-th/9602027

- In nucleon-nucleon collision.

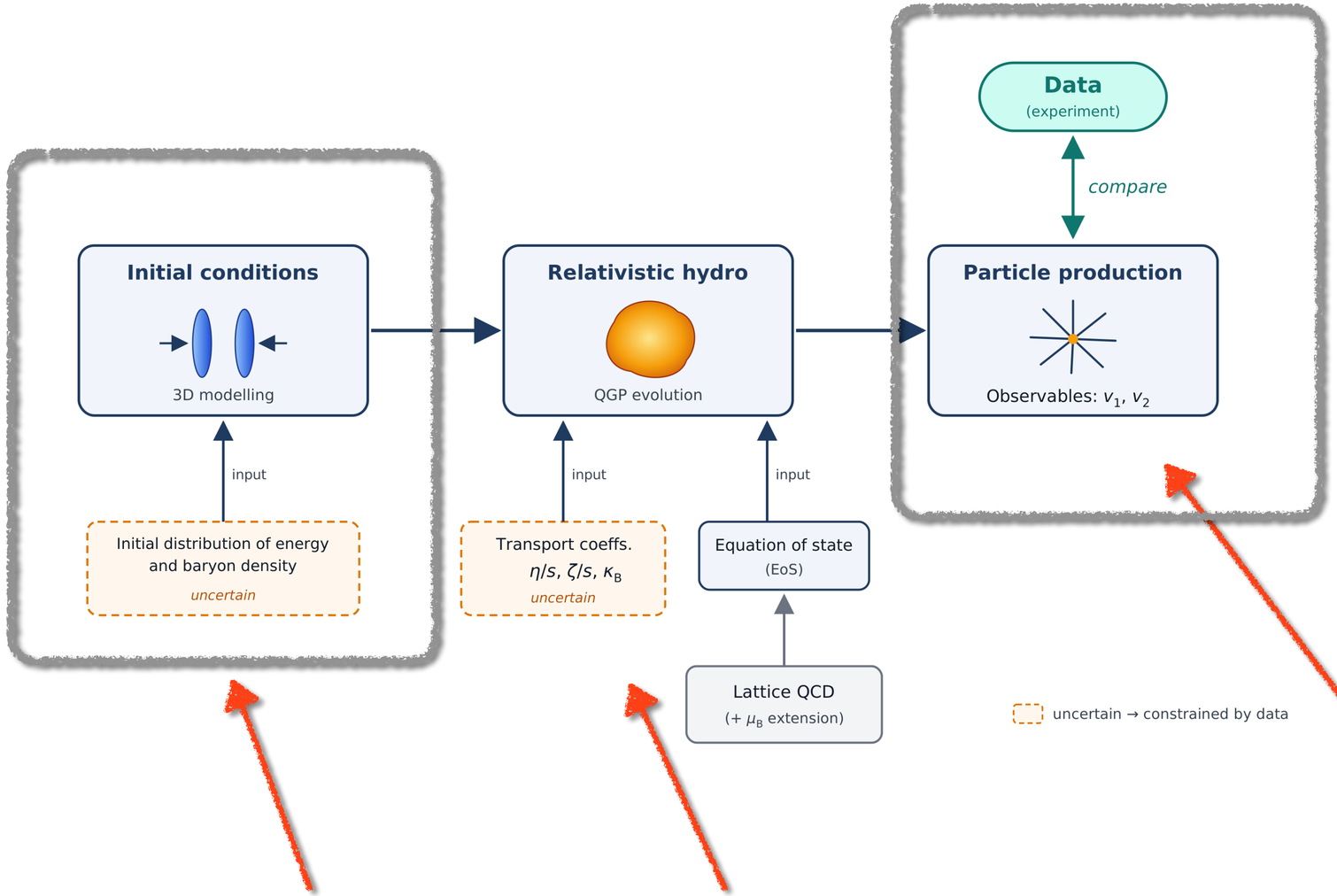
Junction type	Baryon units	Rapidity dependence
Single junction	1	$\sigma^J \sim e^{-\alpha_2 y}$
Double junction	2	No rapidity dependence

Du, Shen, Jeon, Gale (2022)

Gaussian **Plateau**



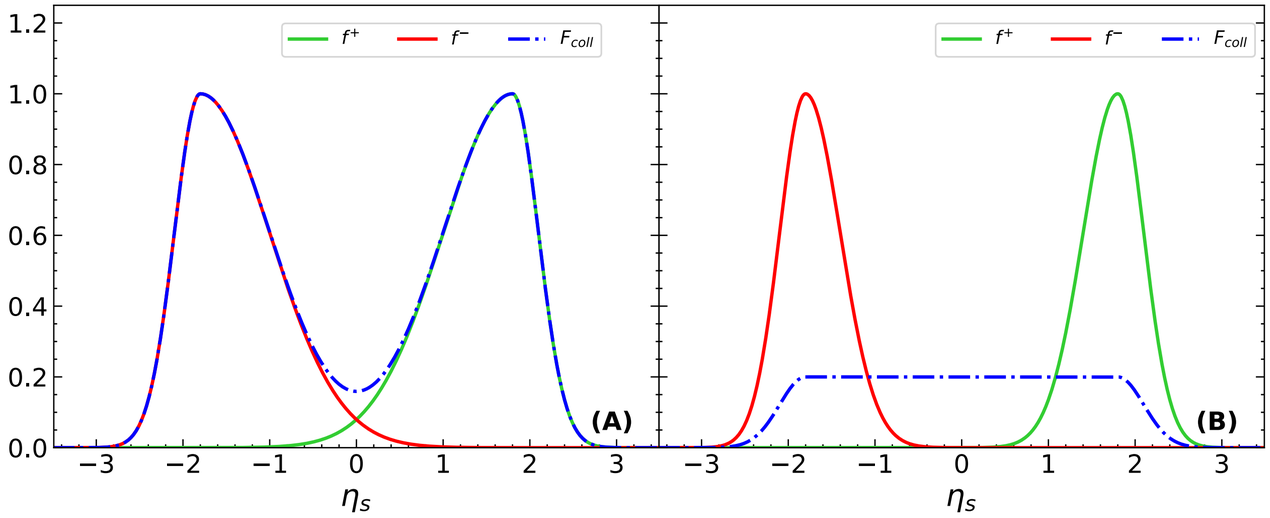
Simulation chain

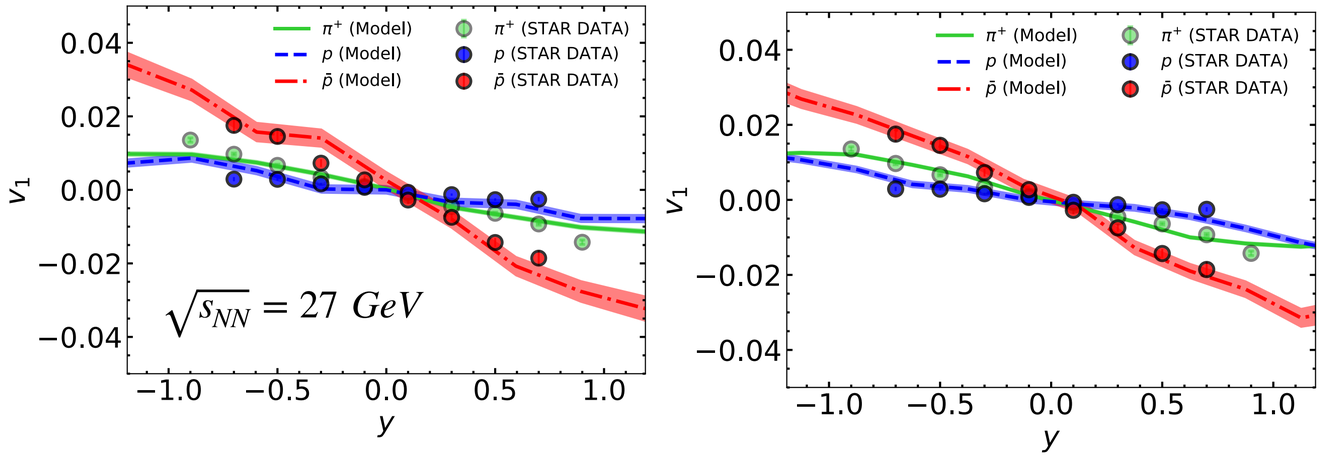


Talk title : Probing **baryon stopping** and **diffusion** with **rapidity-even directed flow** of protons and anti-protons

Results : Hydrodynamic model calculation with finite baryon density and baryon diffusion

Gaussian **Plateau**





Baryon diffusion coefficient

$$\kappa_B = \frac{C_B}{T} n_B \left[\frac{1}{3} \coth\left(\frac{\mu_B}{T} \right) - \frac{n_B T}{\epsilon + p} \right]$$

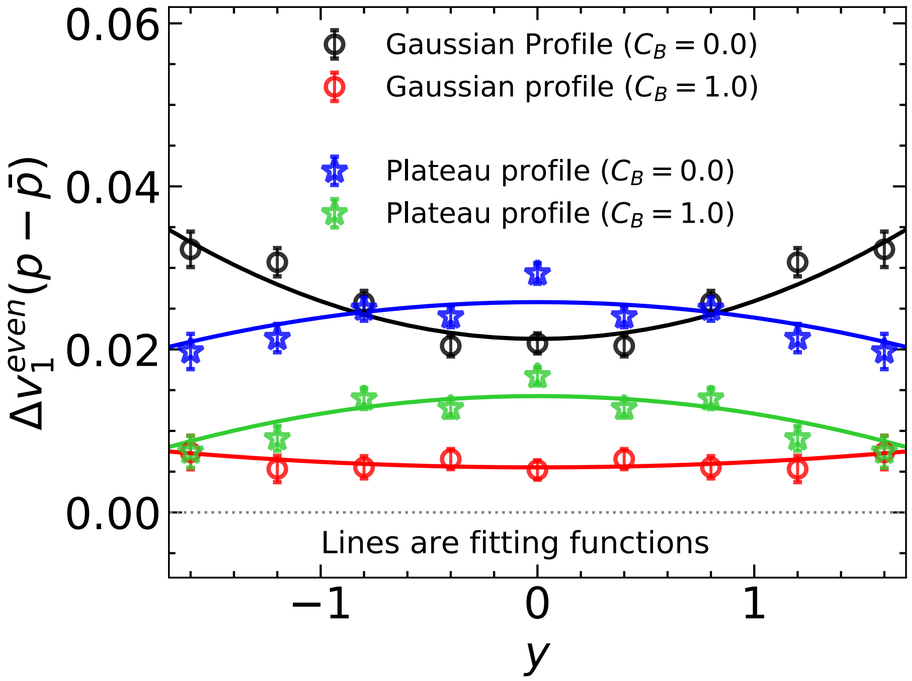
Denicol et . al . , Phys . Rev . C 98, 034916 (2018)

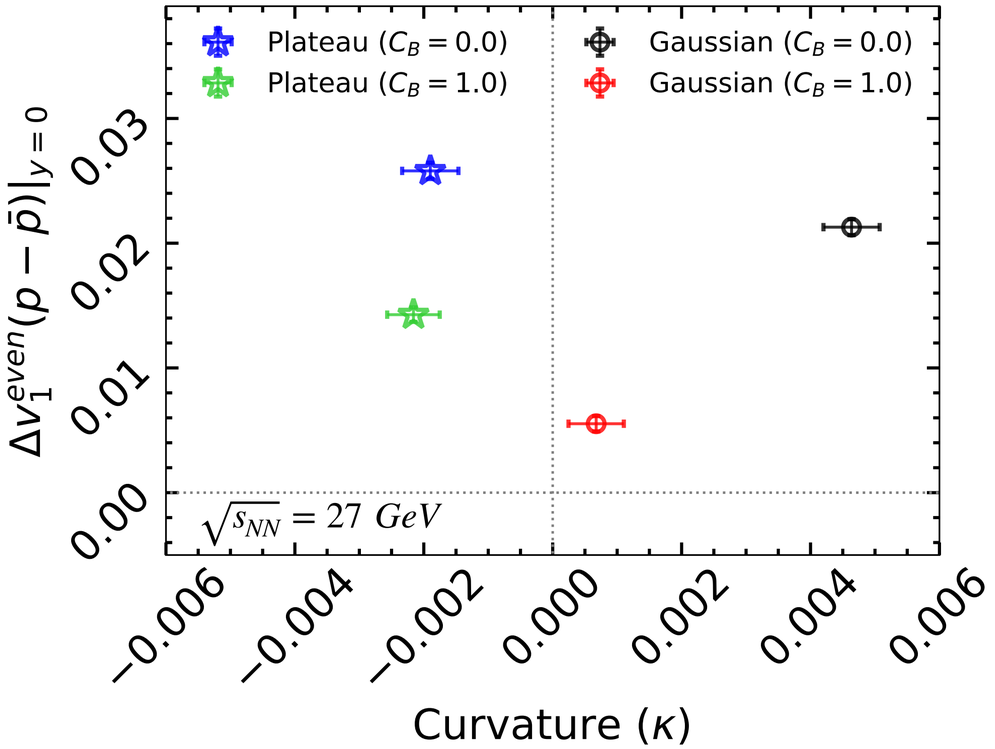
Different form of rapidity even profile - both captures rapidity odd v_1

Rapidity odd v_1 can not discriminate different rapidity even profile.

Rapidity even v_1 could probe the even component of the profile.

Results : Hydrodynamic model





1. Splitting of Rapidity even v_1 between p and $\bar{p}$ probes the rapidity even profile of net baryon deposition.
2. It is also sensitive to baryon diffusion.

Summary

☑ Rapidity even dipolar flow of identified hadrons is useful to be measured.

☑ It can constrain the initial baryon stopping and diffusion.

Thanks

Backup

Simulation framework

Glauber model for initial energy and baryon deposition

MUSIC
Hydrodynamic evolution

iSS
Particlization/ Cooper-Frye Sampling

UrQMD
Late stage hadronic transport

$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu J^\mu_B = 0$$
$$J^\mu_B = n_B u^\mu + q^\mu$$

$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right)$$



Diffusion

NEoS-BQS Constraints

$n_S = 0, \quad n_Q = 0.4 n_B$

$\mu_S \neq 0 \qquad \mu_Q \neq 0$

Baryon diffusion coefficient

$$\kappa_B = \frac{C_B}{T} n_B \left[\frac{1}{3}\coth\left(\frac{\mu_B}{T}\right) - \frac{n_B T}{\epsilon + p}\right]$$

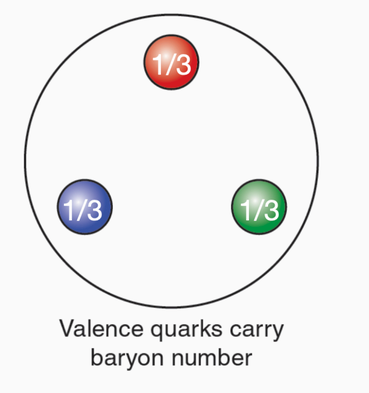
Denicol et. al., Phys. Rev. C 98, 034916 (2018)
A. Monnai, C. Shen and B. Schenke, Phys. Rev. C 100, 024907 (2019)

Model of the initial baryon profile

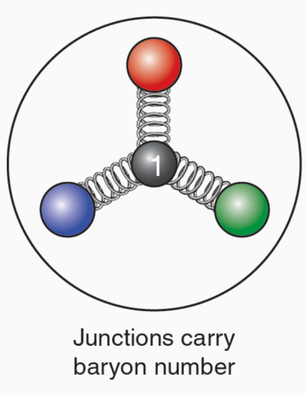
$$n_B(x,y,\eta_s) = N_B\left[(1-\omega)\left(N_+(x,y)f_+^B(\eta_s)+N_-(x,y)f_-^B(\eta_s)\right) + \omega N_{coll}(x,y)\left(f_+^B(\eta_s)+f_-^B(\eta_s)\right)\right]$$

- Baryon junction picture : single junction stopping with forward-backward asymmetric profile (similar to participant deposition in our model), double junction stopping has no rapidity bias (similar to Ncoll deposition)

- In microscopic models rapidity loss depends on number of binary collisions.

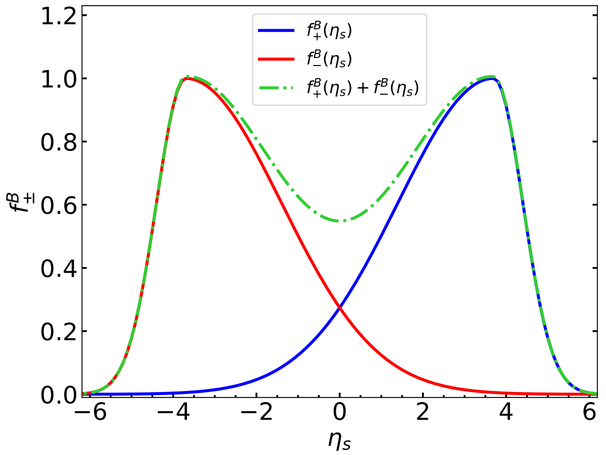


Valence quarks carry baryon number

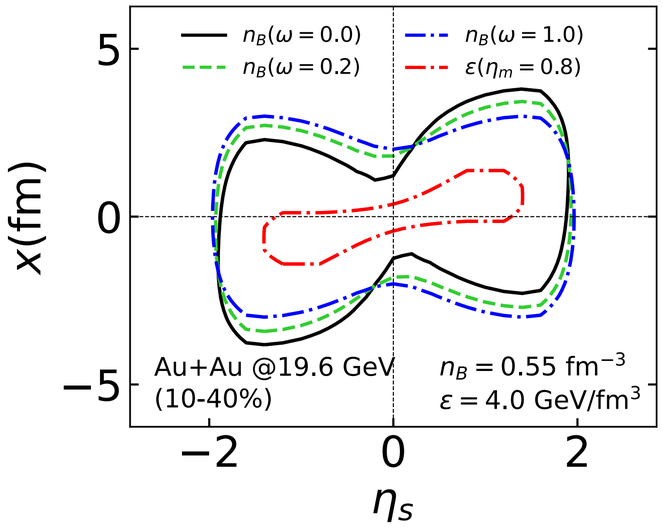


Junctions carry baryon number

Junction type	Baryon units	Rapidity dependence
Single junction	1	$\sigma^J \sim e^{-\alpha_2 y}$
Double junction	2	No rapidity dependence



TP and S. Chatterjee arxiv: 2211.15729

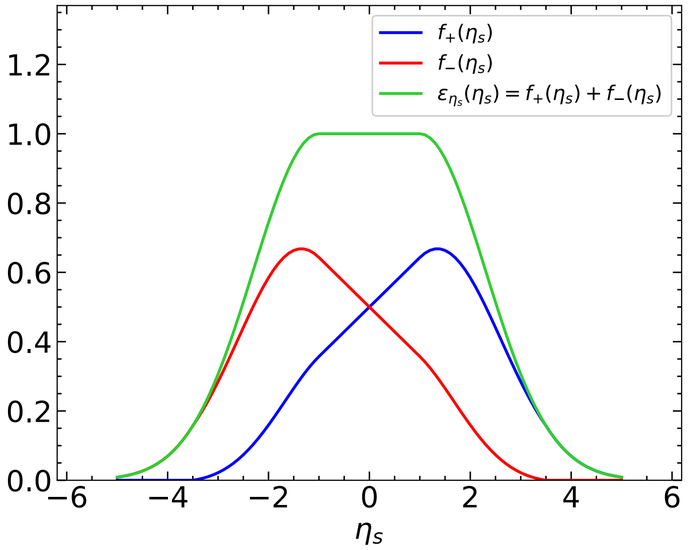


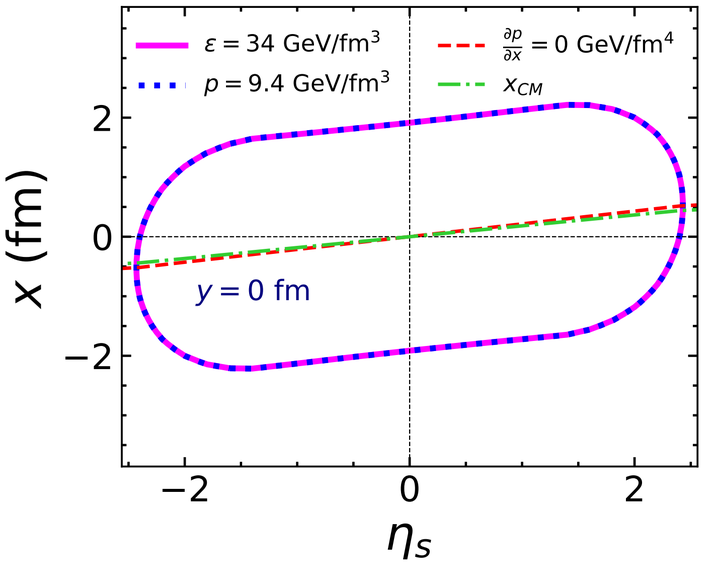
Tilted energy deposition

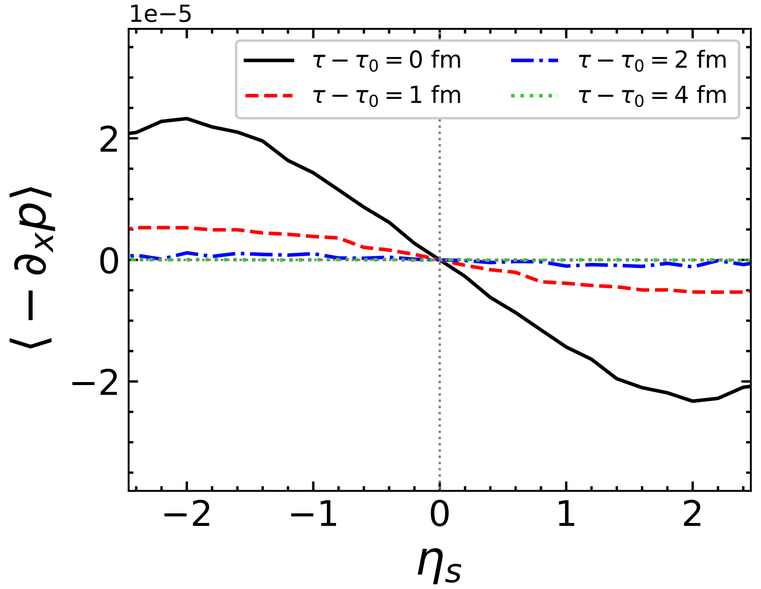
P. Bozek and I. Wyskiel, Phys. Rev. C 81, 054902 (2010)

A participant nucleon deposits more energy along it's direction of motion.

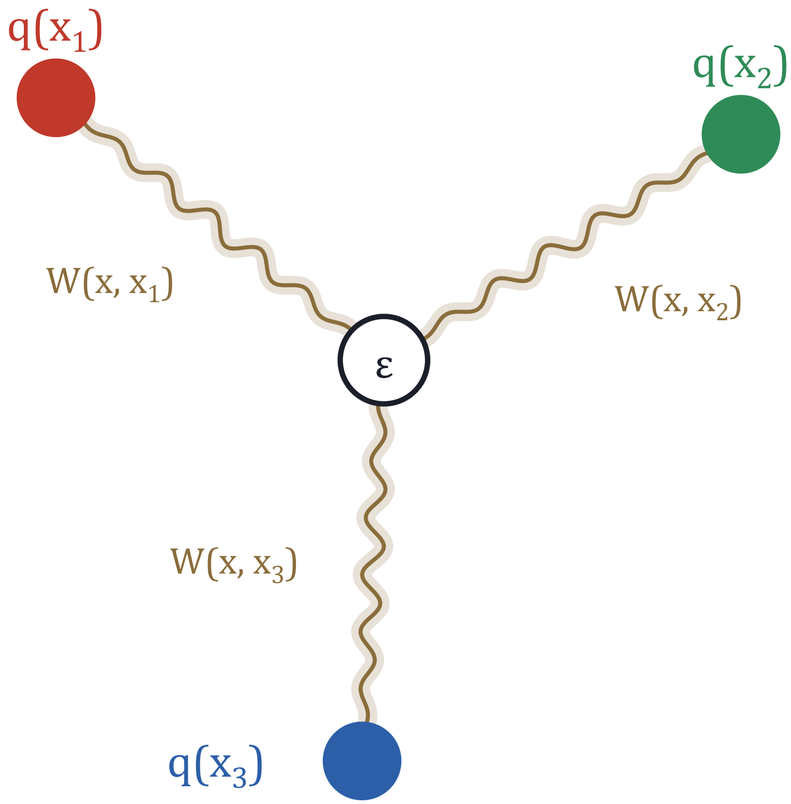
$$\epsilon(x,y,\eta_s) = \epsilon_0 \left[\left(N_+(x,y) f_+(\eta_s) + N_-(x,y) f_-(\eta_s) \right) (1-\alpha) + N_{coll}(x,y) \epsilon_{\eta_s}(\eta_s) \alpha \right]$$







$$\langle (-\partial_x p) \rangle = \frac{\int dx \; (-\partial_x p) \epsilon(x)}{\int dx \; \epsilon(x)}$$


q(x1)
q(x2)
W(x, x1)
W(x, x2)
ε
W(x, x3)
q(x3)