THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

Alternate mechanisms of charge separation in heavy-ion collisions

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outline

- What we think the experiment is measuring
- Exotic & non-exotic sources for planar charge separation
- Some semi-exotic sources of planar charge separation
- Effective interactions
- Timeline of origins
- Survival probabilities
- Making simple parameter free estimates

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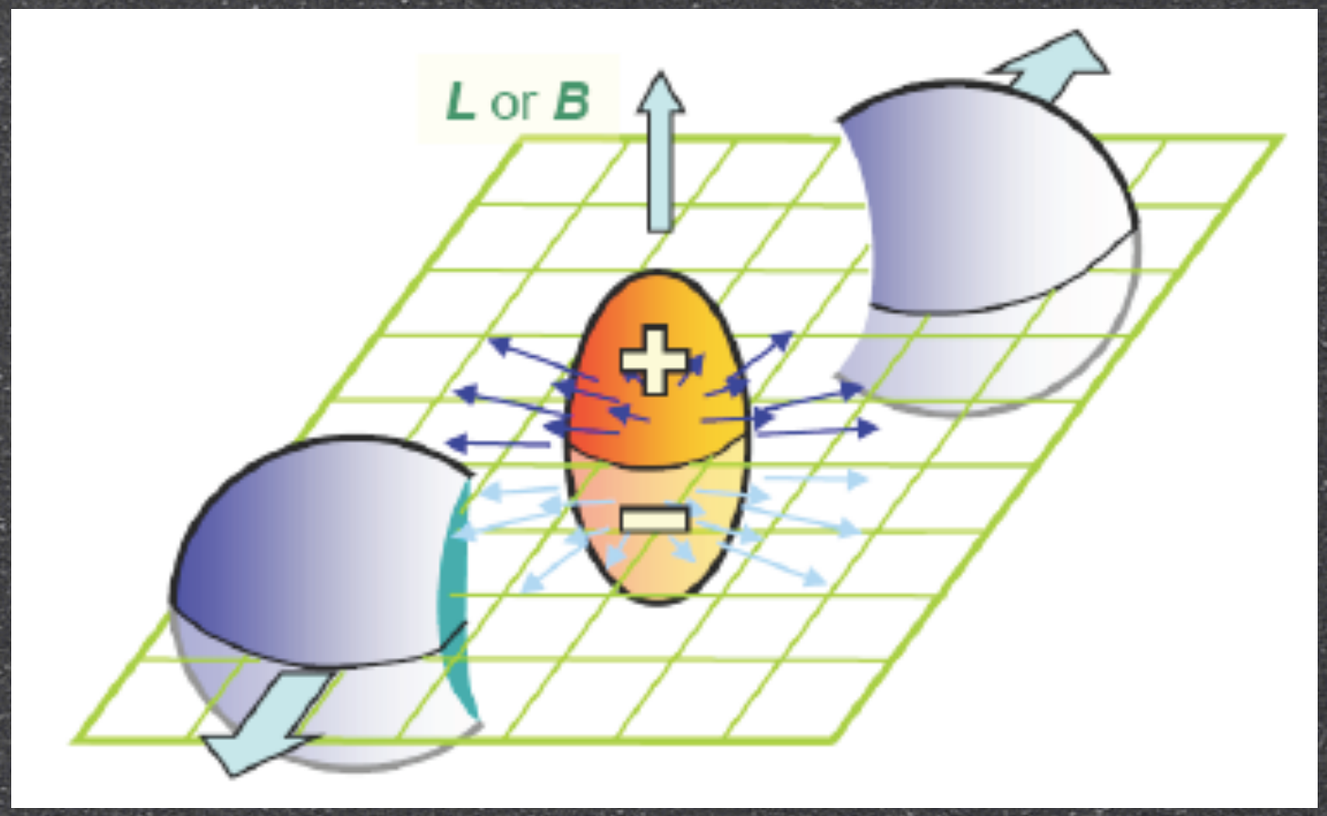
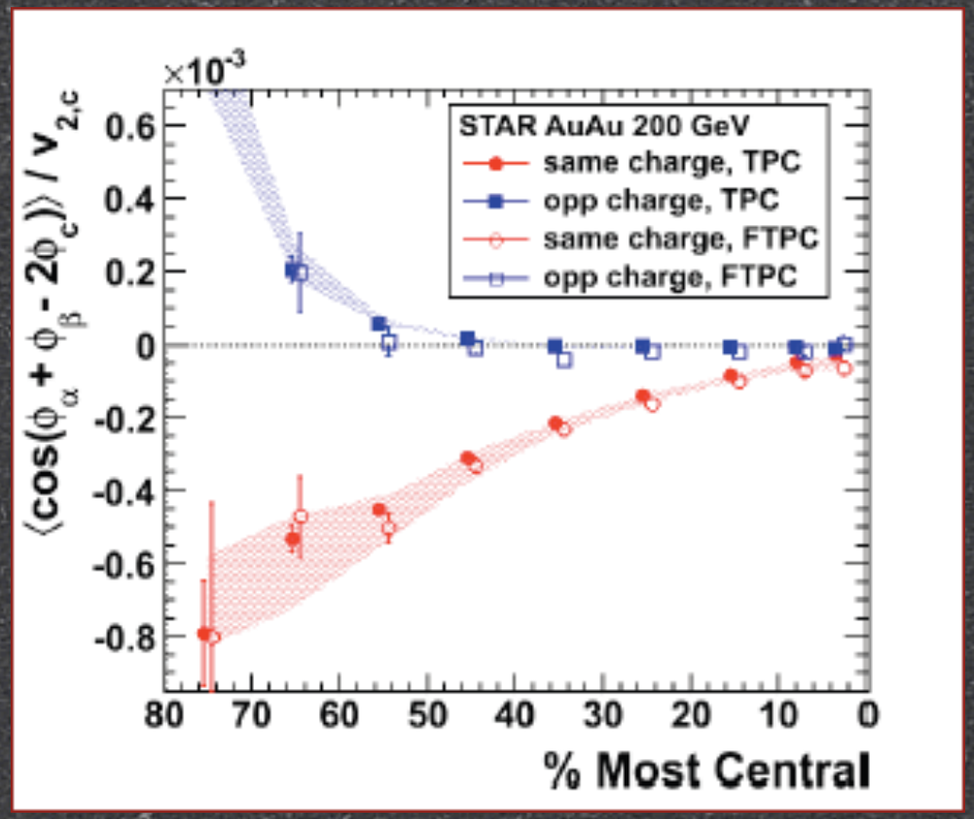
What we think is going on in the experiment





In semi-central collisions
net charge separation (fluctuation)
perp. to RP along L or B direction.

Exotic and Non-Exotic scenarios

Non-exotic, e.g.
explanations based on conservation laws, random charge fluctuations and flow.

Exotic, e.g.
Explanations based on the production of regions of non-zero color $E^a.B^a$ coupling with deconfined quarks to couple electric E and B

Semi-exotic scenarios

Use interactions based on the axial anomaly

Can be partonic or hadronic in nature

Hadronic interaction terms well measured in vacuum experiments

Semi-exotic scenarios

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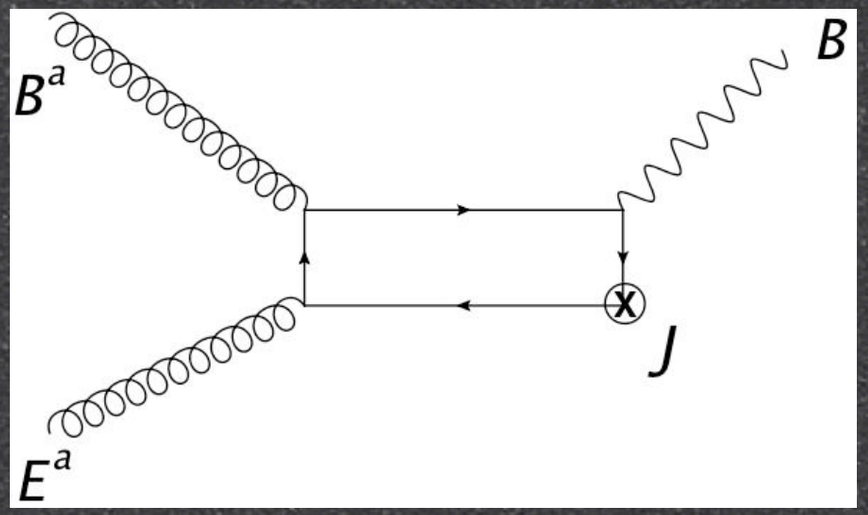
Note: every partonic interaction has some hadronic equivalent.

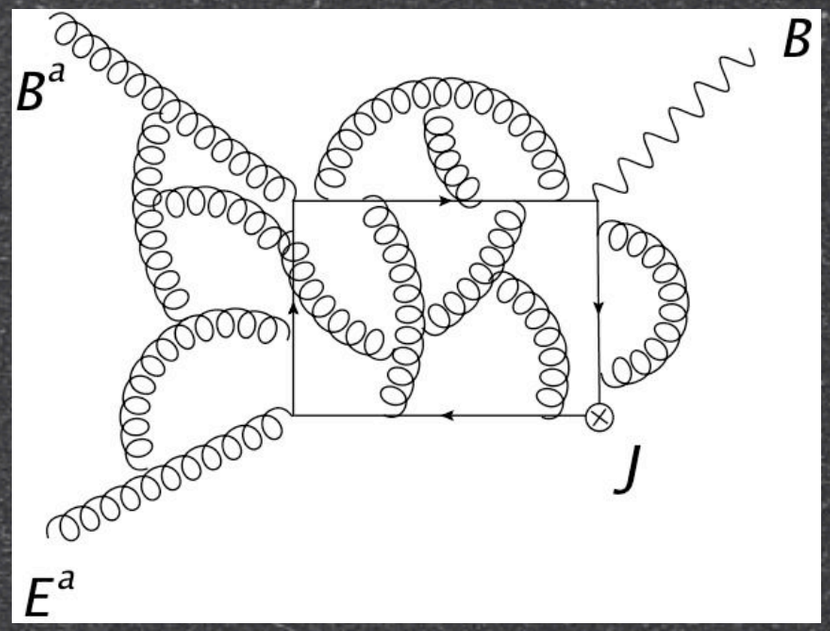
With both a partonic and hadronic part all sectors of HIC contribute to the signal

Case 1: Partonic interaction

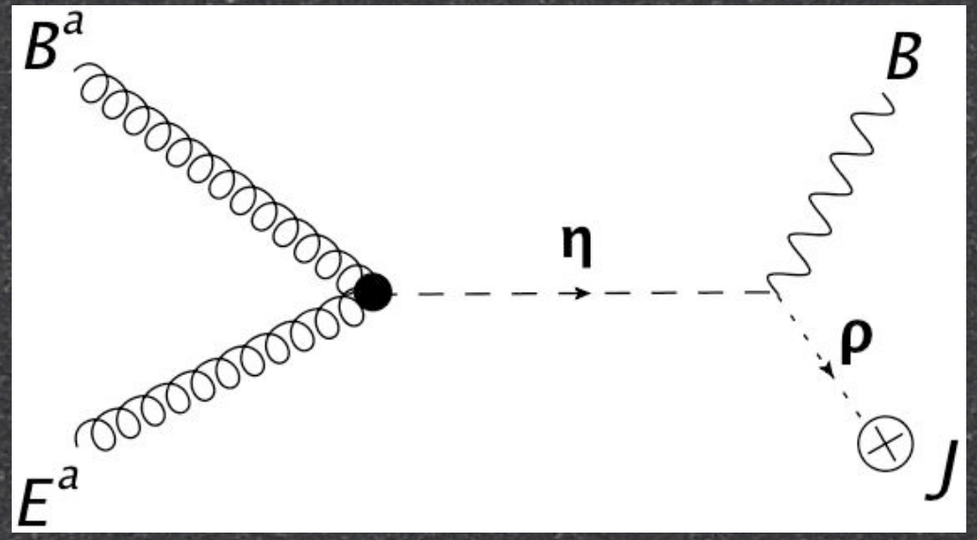
In an ideal world:
weak α_S, and weak fields!



In the real world



LPHD



$$j^\mu = -\frac{e m_\rho^2}{g_{\rho\pi\pi}} \rho^\mu$$

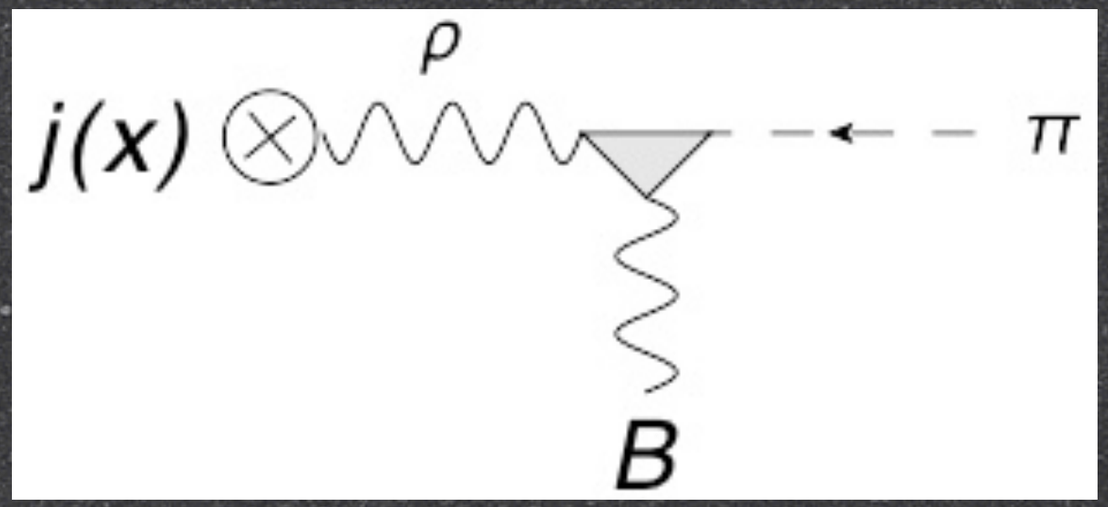
Vector meson dominance (VMD) relates the electromagnetic hadronic current to the neutral rho-meson field:

Case 2: Hadronic interaction

Given that a ρ has an e.m. decay into a π

The reverse process must also exist!
Imagine a π interacting with the B field and excited to a ρ .

$$j^\mu = -\frac{em_\rho^2}{g_{\rho\pi\pi}}\rho^\mu$$



A π in the corona gets excited to a ρ
The ρ decays to a charge pair along the B field

Different sources

1) Gluons in the initial state from two nuclei overlap with an E.B

2) Glasma gluons generate winding number fluctuations (Talk by R. Venugopalan)

3) Winding number fluctuations (sphaleron) in the thermal plasma (Talk by E. Shuryak)

4) π's in the corona convert to ρ's in large initial B fields

4b) π's in the hot hadronic gas convert to ρ's in the remnant weak B field

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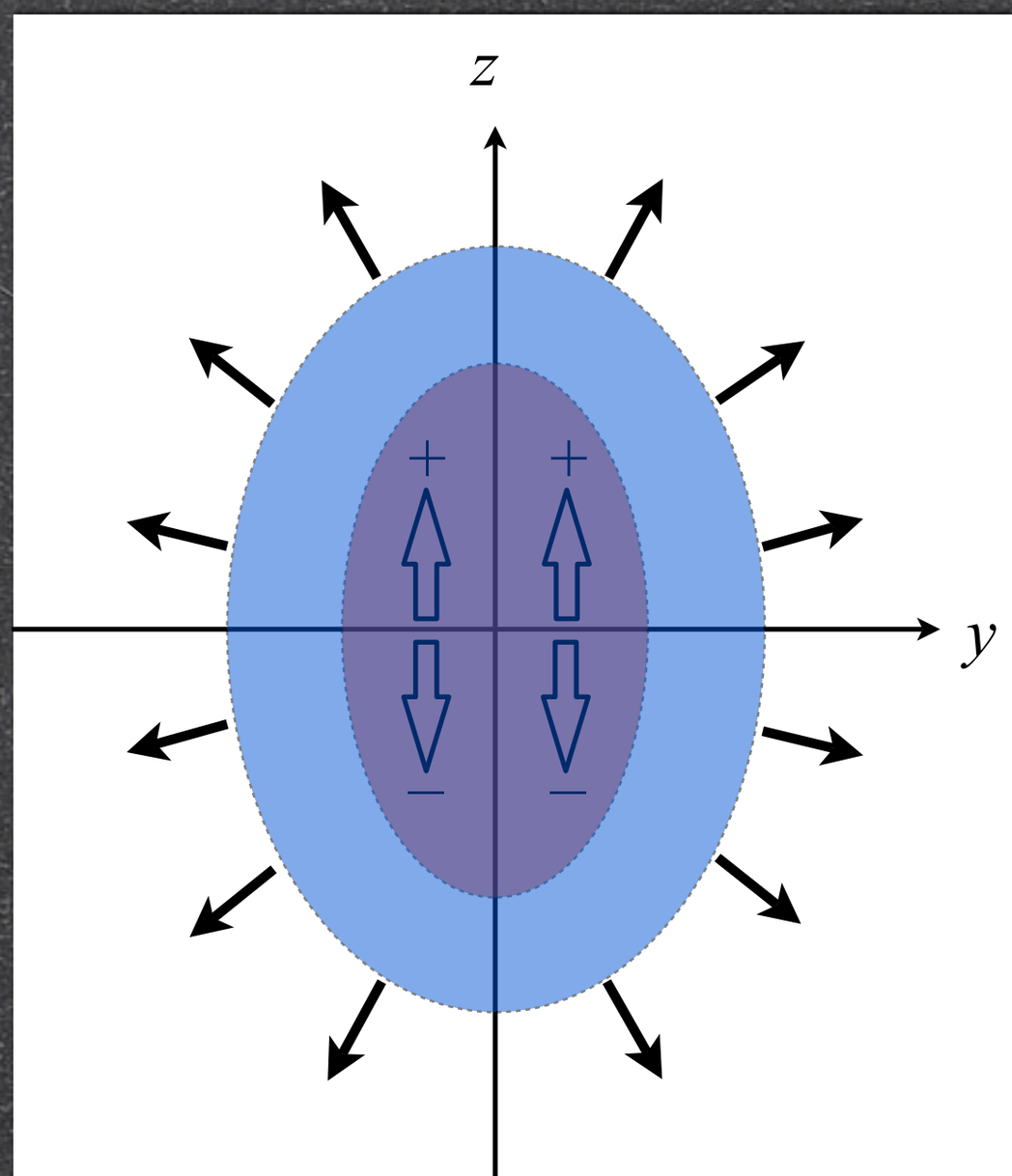
Converting the ρ current into charge separation

simple geometric approximation:

all charges in a hemisphere emitted in the same direction



$$\Delta Q_u = \int d^3x dt \frac{\partial \rho}{\partial t} = \int dt d^3x \nabla \cdot j$$

$$= \int dt d^2\vec{S} \cdot \vec{j} \simeq \int dt d^2 S_{RP} j_\perp$$

$$\therefore \Delta Q_d \simeq -\int dt d^2 S_{RP} j_\perp$$

$$\therefore \quad \Delta Q_u \Delta Q_d \simeq -\int dT d^2 S_{RP} \int dt d^2 s_{RP}$$

$$\times \quad j_\perp(\vec{X} + \vec{x}, 0, T + t) j_\perp(\vec{X}, 0, T)$$

Surf. int. of current-current correlator

Note: this is an over-extimate

Calculational details

From the study of radiative decays of the ρ

$$\mathcal{L}_{eff.} = e\frac{g_{\rho\pi\gamma}}{m_\rho}\varepsilon_{\mu\nu\lambda\delta}\partial^\nu A^\mu \rho^\lambda \partial^\delta \pi$$

Pick RP as the (1,2) plane, B in the 3-dirn

(μ,ν)=(1,2)/(2,1) , thus (λ,δ)=(3,0)/(0,3)

As long as the π^0 has energy there is a ρ^3.

$$\Gamma_{\rho^0\to\pi^0\gamma} = 3\alpha\, g^2_{\rho\pi\gamma}\,\frac{p^3_{\rm cm}}{m^2_\rho} \approx 90 \pm 12 \text{ keV}$$

$$g_{\rho\pi\gamma} = 0.58$$

$$\Gamma_{\eta'\to\rho\gamma} = \alpha\, g^2_{\rho\eta'\gamma}\,\frac{p^3_{\rm cm}}{m^2_{\eta'}} \approx 60 \pm 5 \text{ keV}$$

$$g_{\rho\eta'\gamma} = 1.31$$

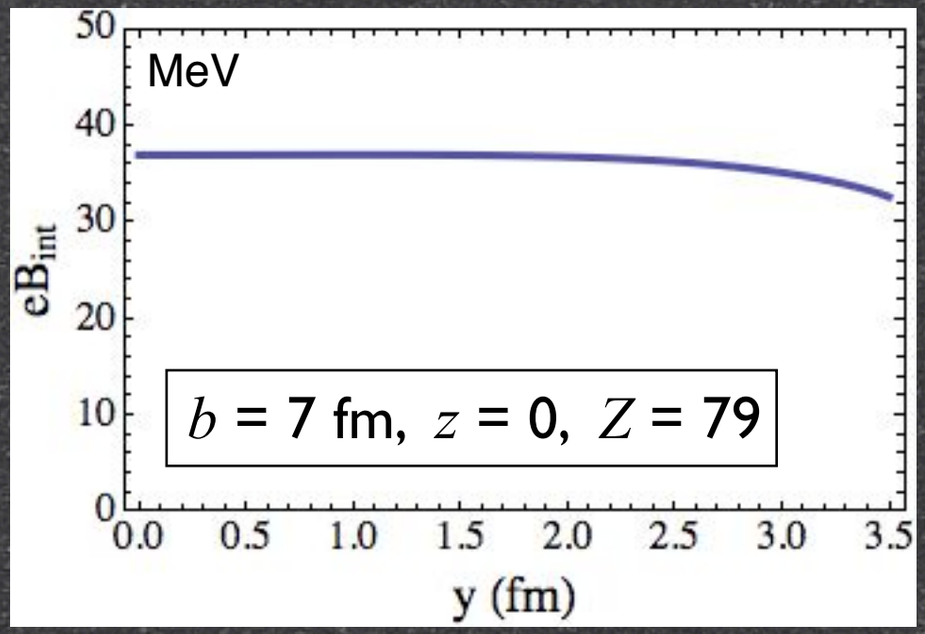
The Magnetic field and nuclear overlap

Assuming the charge is uniformly distributed

(Hard sphere distribution)

$$eB_z^{(\pm)} = \begin{cases} Z\alpha v\gamma\left(\frac{b}{2} \mp y\right)\frac{\bar{r}_\pm}{R^4} & (\bar{r}_\pm \leq R), \\ Z\alpha v\gamma\left(\frac{b}{2} \mp y\right)\frac{1}{\bar{r}_\pm^3} & (\bar{r}_\pm > R), \end{cases}$$

$$\bar{r}_\pm = \left[\left(y \mp \frac{b}{2}\right)^2 + z^2 + v^2\gamma^2 t^2\right]^{1/2}$$

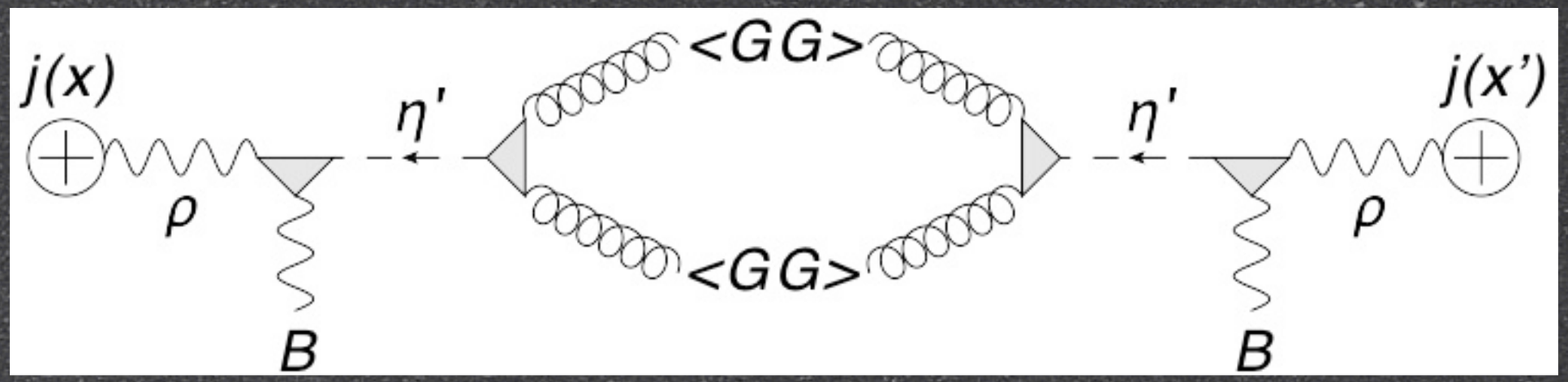


Integrating over the nuclear overlap function

$$\int d\bar{y}\, T_{AA}(\bar{y}; b) = \frac{3A^2}{\pi^2 R^3} f(b)$$

$$f(b) \approx 1 - \frac{b^2}{R^2}\left(1 - \frac{b}{4R}\right)^2$$

Initial state calculation



$$\langle j^3(x) j^3(x') \rangle \approx e^2\, C \langle (\mathbf{E}^a \cdot \mathbf{B}^a)(x)(\mathbf{E}^b \cdot \mathbf{B}^b)(x') \rangle$$

$$C = \frac{g^2_{\rho\eta'\gamma}}{g^2_{\rho\pi\pi}} \frac{3(Z\alpha)^2 \alpha_s^2 \cos^2\theta}{(2\pi f_\eta)^2 m^2_{\eta'} m^2_\rho} \frac{b^2\gamma^2}{R^6}$$

As the E^a and B^a fields in a nucleus are transverse, the E comes form one nucleus and the B from the other

Can relate this to the gluon PDF and the nuclear overlap func.

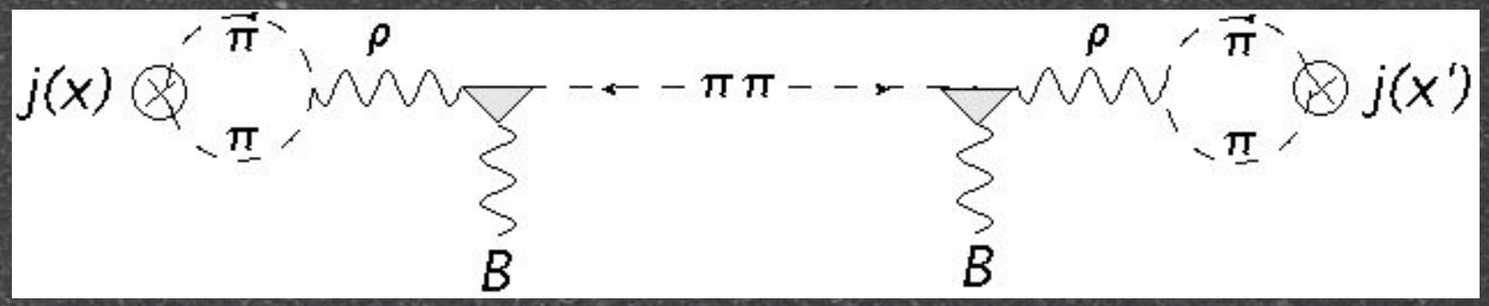
$$\left\langle (\mathbf{E}^a \cdot \mathbf{B}^a)(\mathbf{E}^b \cdot \mathbf{B}^b) \right\rangle \propto [x_0 G(x_0)]^2\, T_{AA}(\bar{\mathbf{x}}_\perp; \mathbf{b})$$

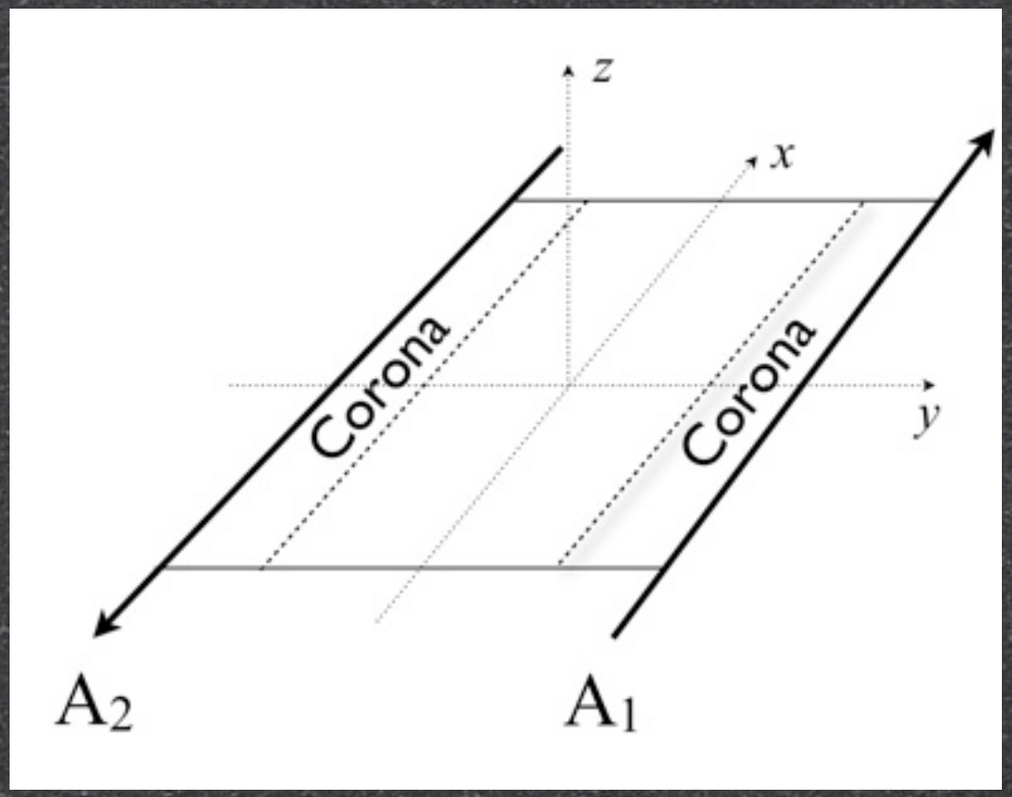
Can get the gluon PDF from CTEQ or from saturation

$$A\,[\xi_0 G(\xi_0)] = \frac{(N_c^2 - 1)\, R^2 Q_s^2}{8\pi^2 \alpha_s}$$

$$\langle N^2_{ch} \rangle = 1.7 \times 10^{-3} \frac{b^2}{R^2} f(b)$$

The corona mechanism





Assume a thermal pion gas with a mean temperature of T=150 MeV
Approximate corona width form hydro simulations of Heinz et al.

$$\langle(\Delta N_{\rm ch})^2\rangle \approx \frac{(\pi Z\alpha g_{\rho\pi\gamma} g_{\rho\pi\pi})^2}{768\, e^2}\left(\frac{T}{m_\rho}\right)^6 \frac{b^2}{R^2} f(b) \approx 3\times 10^{-5}\,\frac{b^2}{R^2} f(b)$$

Note: either result is too small to explain STAR data, requires $\Delta N_{ch}^2 \sim 0.1 - 1$

What else could we have done?

We assumed vacuum properties for the mesons in both the LPHD and the hadronic calc

In a medium there will be a lot of scatt. leading to a change of mass and spectral wt.

We did not attempt this, unclear how to get η mass shift in a non-equilibrium medium

Can we expect a factor of 10 drop in effective mass !!!

Conclusions

Planar charge fluctuation asymmetry does not seem to require local parity violation (Qualitatively!)

PCFA does not seem to be a purely partonic effect (Qualitatively!)

We have presented a parameter free calculation,
If we varied the masses and couplings we could have explained the observed signal

There is now a much narrower, quantitative window for the CME to explain the data