$^{96}_{44}\mathrm{Ru}$ $^{96}_{40}\mathrm{Zr}$

Physics of the Isobar Comparison Run

Yuji Hirono

Brookhaven National Laboratory

Outline

- **Anomalous chiral effects in heavy-ion collisions**
- **Difficulties in separating signal from background**
- **What can we learn from isobar collisions?**
- **Prospects on theoretical developments**

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Anomalous chiral effects

$$\boldsymbol{j}_{\mathrm{anom}} = \kappa_B \boldsymbol{B} + \kappa_\omega \boldsymbol{\omega}$$

$$\boldsymbol{j}_{5,\mathrm{anom}} = \xi_B \boldsymbol{B} + \xi_\omega \boldsymbol{\omega}$$

Anomalous chiral effects

- Macroscopic manifestation of chiral anomaly
  - Dissipationless
  - Many theoretical derivations
    - Perturbation theory, lattice QCD, real-time lattice…
    - Required piece of hydrodynamics **[Son-Surówka PRL'09]**
  - Transport coefficients are fixed by anomaly itself
  - Experimentally found in Dirac semimetals

[Li et. al. Nature Phys.'16]

Chiral magnetic effect requires chirality imbalance

- Axial charge generation from color fields

$$\partial_\mu j_5^\mu = \frac{g^2}{16\pi^2} \boldsymbol{E}^a \cdot \boldsymbol{B}^a$$

- Signature of chiral symmetry restoration
  - In the presence of chiral condensate, the chirality imbalance dissipates at the time scale (1 / the constituent quark mass) $< 1\,\mathrm{fm}$
  - If the chiral symmetry is restored, the chirality dissipation occurs with $(2\ \mathrm{MeV})^{-1} \simeq 100\ \mathrm{fm}$

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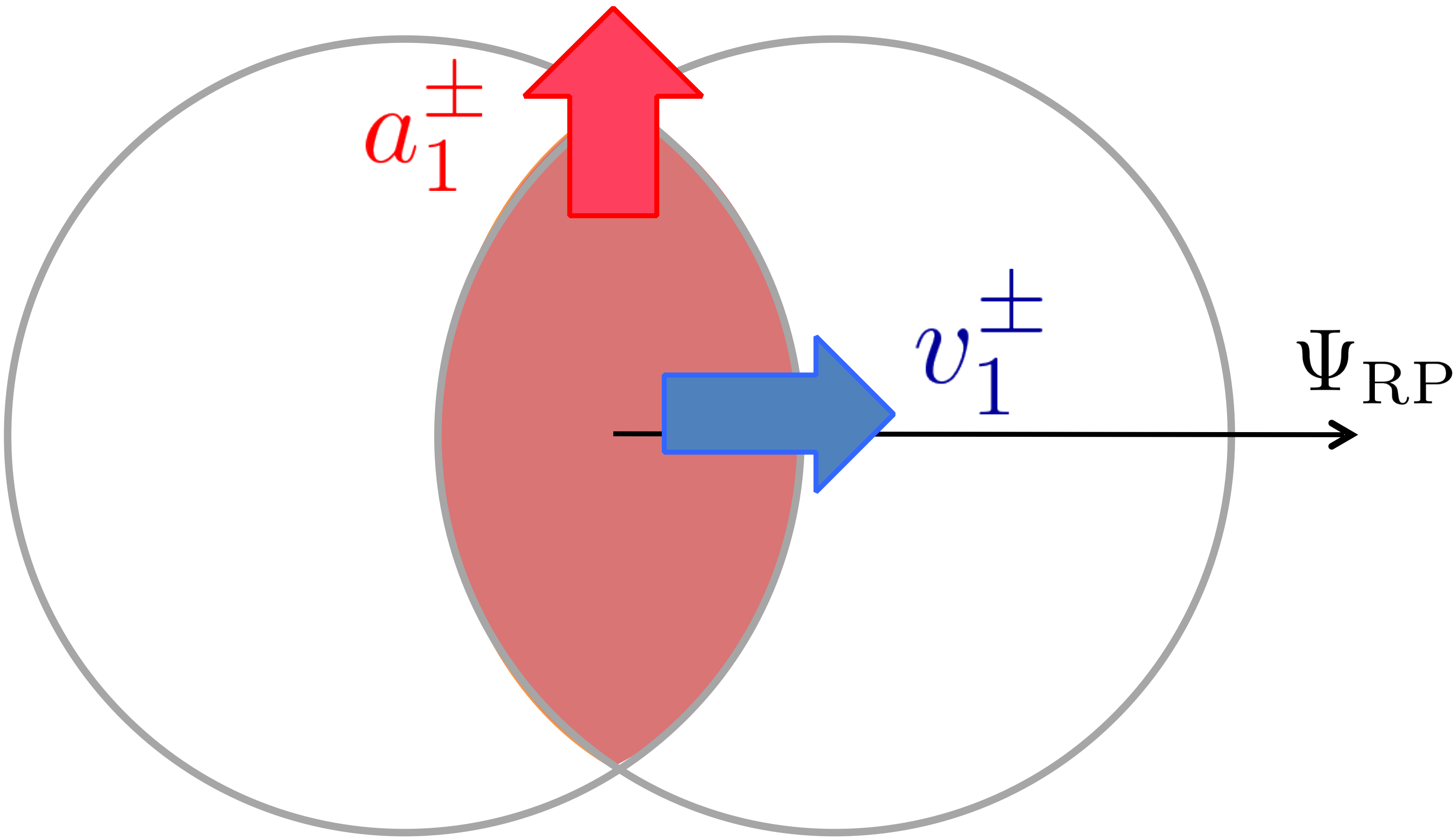
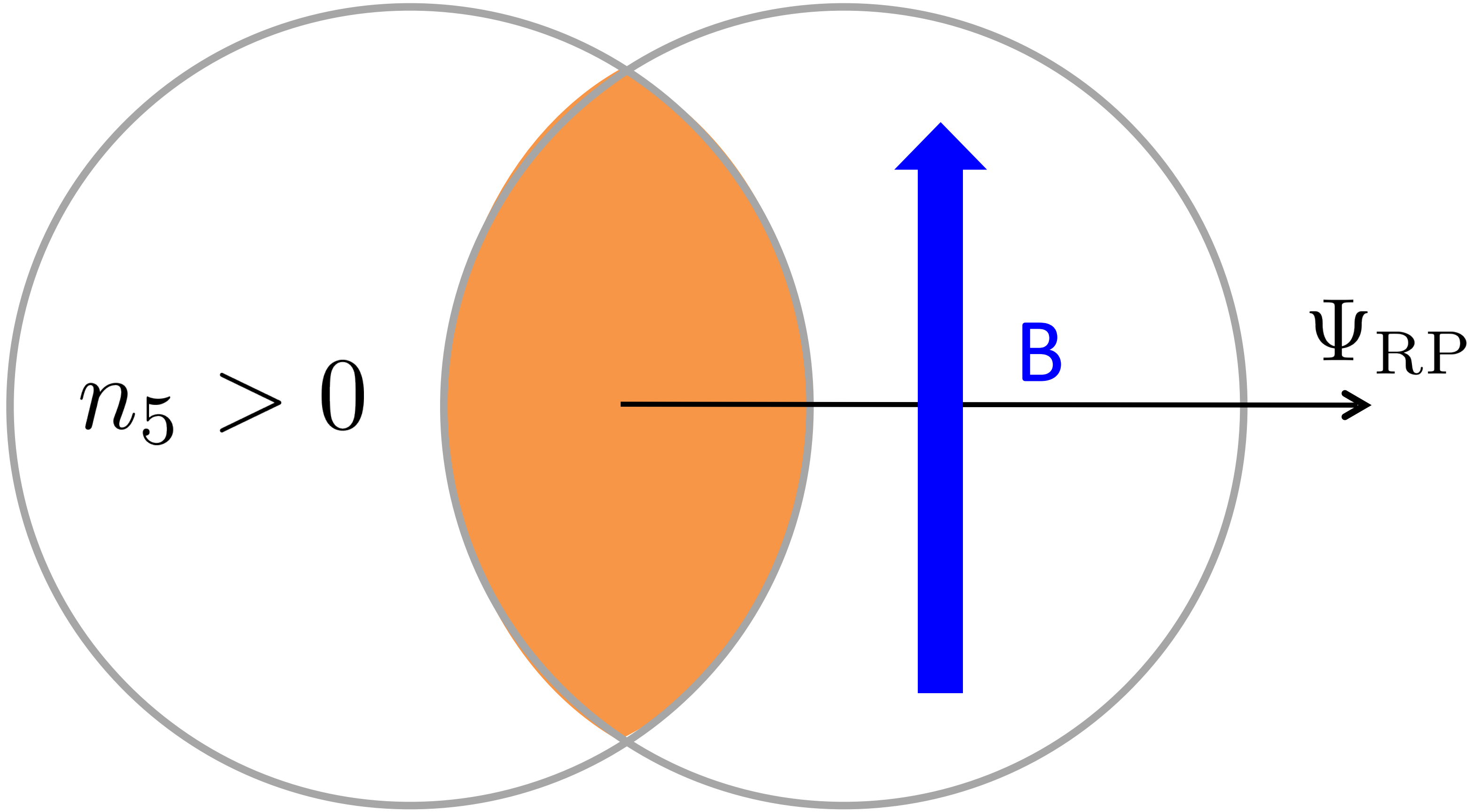
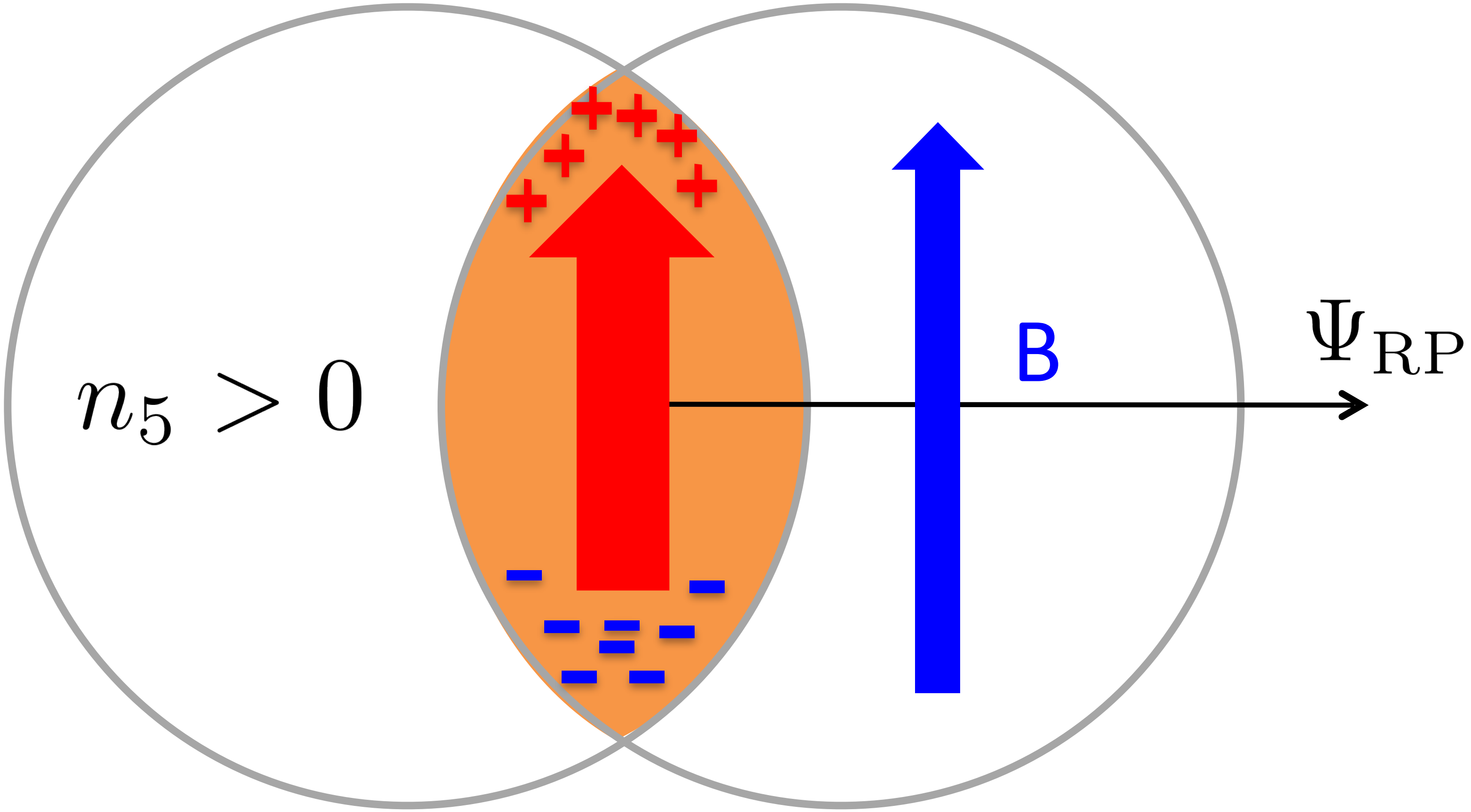
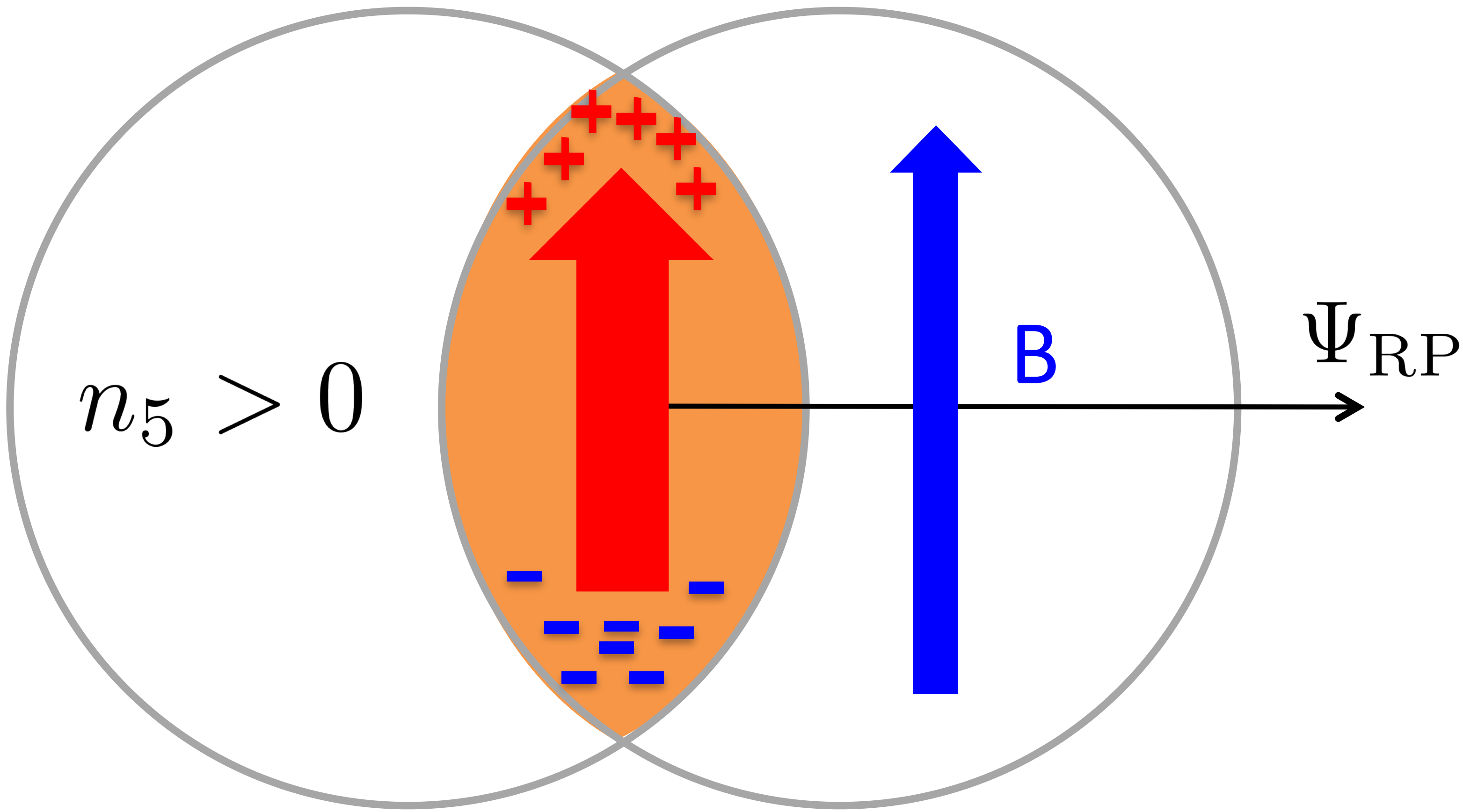
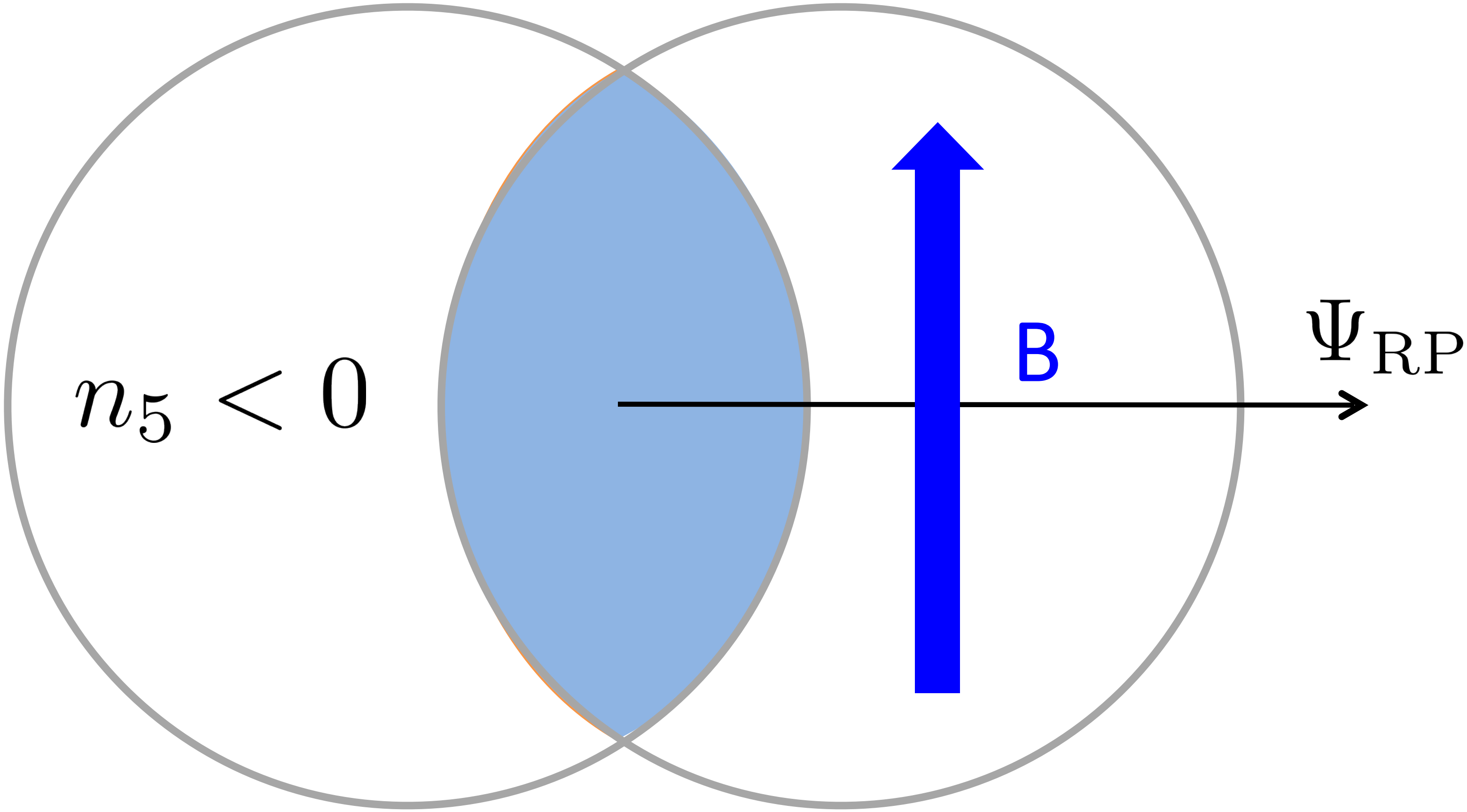

$a_1^{\pm}$
$v_1^{\pm}$
$\Psi_{\rm RP}$


$n_5 > 0$
B
Ψ_{RP}

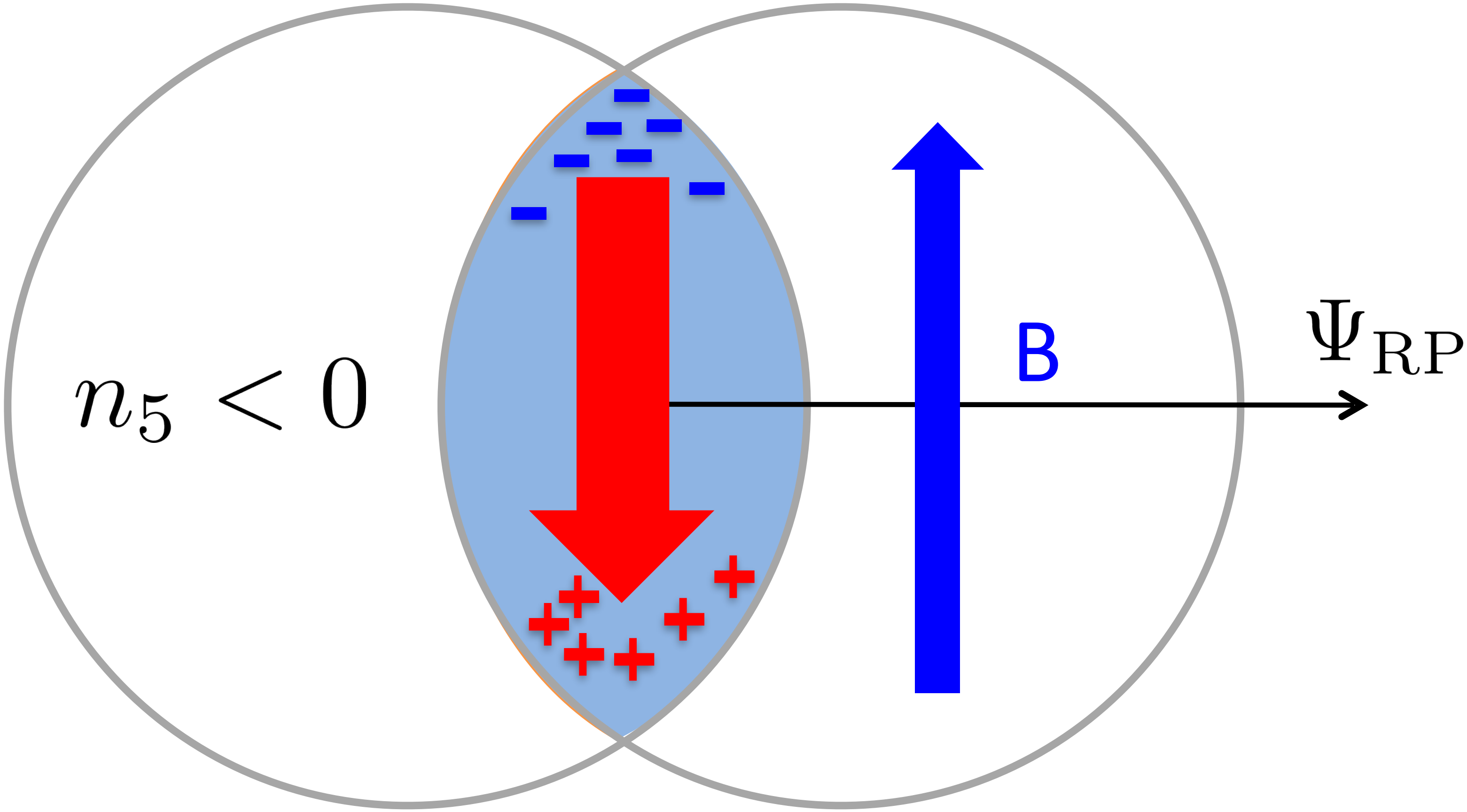

$n_5 > 0$
B
$\Psi_{\rm RP}$

$$a_1^+ > 0 \quad a_1^- < 0$$





$n_5 < 0$
B
Ψ_{RP}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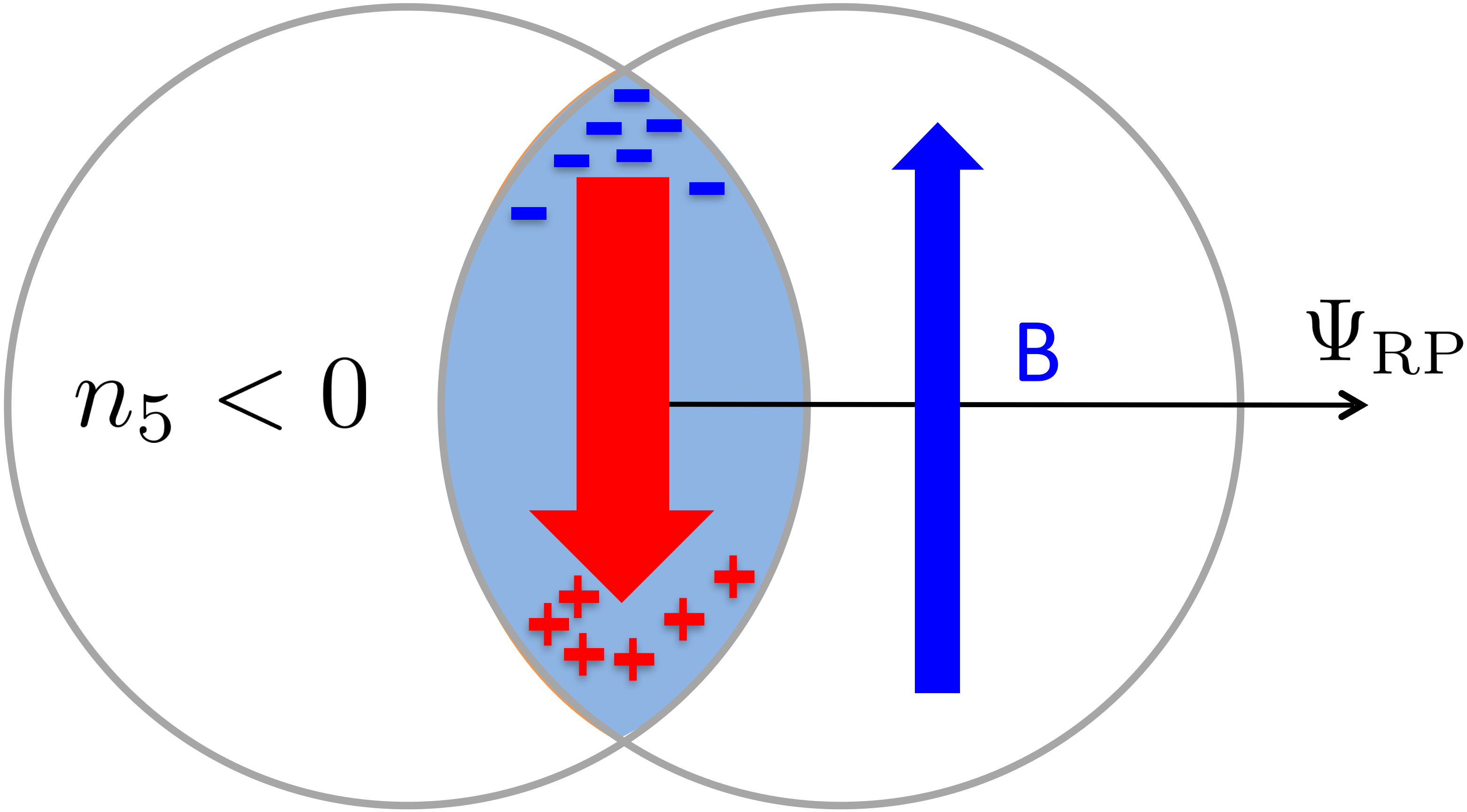


Charged single-particle distribution

$$\frac{dN^\alpha}{d\phi} = \frac{\bar{N}^\alpha}{2\pi}\left[1 + 2a_1^\alpha \sin(\phi - \Psi_{\rm RP}) + 2v_1^\alpha \cos(\phi - \Psi_{\rm RP}) + 2v_2^\alpha \cos 2(\phi - \Psi_2) + \cdots\right]$$

$$a_1^+ = -a_1^-$$

$$\langle a_1^+ \rangle = \langle a_1^- \rangle = 0$$

Observables

- gamma correlation $\gamma_{\alpha\beta} = \left\langle \cos(\phi_1^\alpha + \phi_2^\beta - 2\Psi_{\mathrm{RP}}) \right\rangle$

- Can pick up two-particle correlations unrelated to charge separation ("non-flow")

$$f_{\alpha\beta}(\boldsymbol{p}_1, \boldsymbol{p}_2) = f_\alpha(\boldsymbol{p}_1) f_\beta(\boldsymbol{p}_2) + \underline{f^c_{\alpha\beta}(\boldsymbol{p}_1, \boldsymbol{p}_2)}$$

$$\sim \frac{1}{N}$$

- Reaction-plane independent background cancels out

$$\gamma_{\alpha\beta} = \left[\left\langle v_1^\alpha v_1^\beta \right\rangle + B_{\mathrm{in}} \right] - \left[\left\langle a_1^\alpha a_1^\beta \right\rangle + B_{\mathrm{out}} \right]$$

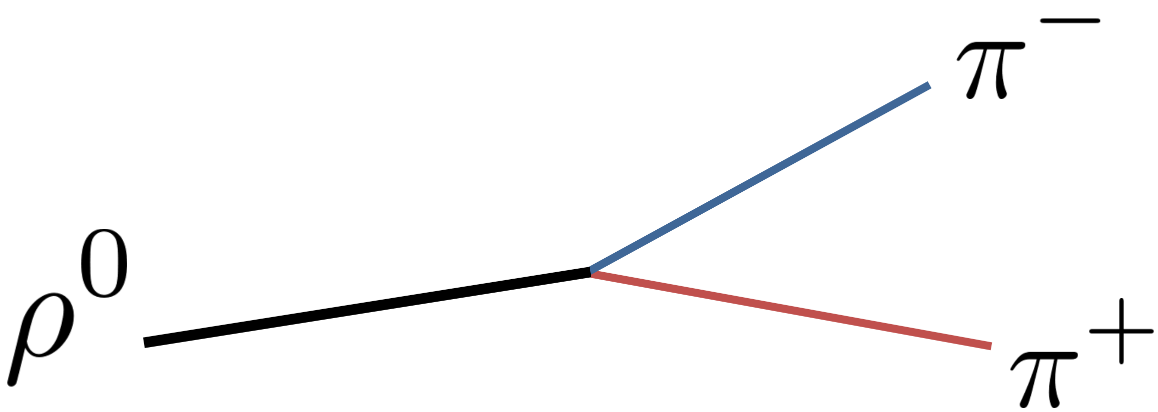
Backgrounds

- Flowing resonances [Voloshin PRC'04] [F. Wang PRC'10]
- Local charge conservation + flow [Schlichting-Pratt, PRC'11] [Pratt-Schlichting-Gavin PRC'11]
- Transverse momentum conservation [Bzdak-Koch-Liao PRC'10, PRC'11] [Pratt-Schlichting-Gavin PRC'11]

Those all contribute as $\sim \dfrac{v_2}{N}$

Flowing resonances

$$B_{\text{in}} - B_{\text{out}} \propto v_{2,\text{clust}} \cos(\phi_1^\alpha + \phi_2^\beta - 2\phi_{\text{clust}})$$



Local charge conservation + flow
gives similar correlations

Transverse momentum conservation

[Bzdak-Koch-Liao PRC (2011)]

$$\gamma_{\mathrm{SS}} = \left\langle \frac{\sum_{<i,j>} \cos(\phi_i + \phi_j)}{\sum_{<i,j>} 1} \right\rangle$$

Transverse momentum conservation

[Bzdak-Koch-Liao PRC (2011)]

$$\gamma_{\rm SS} = \left\langle \frac{\sum_{<i,j>} \cos(\phi_i + \phi_j)}{\sum_{<i,j>} 1} \right\rangle$$

$$= \left\langle \frac{\sum_i \sum_j (1 - \delta_{ij}) \cos(\phi_i + \phi_j)}{\sum_{<i,j>} 1} \right\rangle$$

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$$= \left\langle \frac{(\sum_i \cos\phi_i)^2 - (\sum_i \sin\phi_i)^2 - \sum_i \cos 2\phi_i}{\sum_{<i,j>} 1} \right\rangle$$

Transverse momentum conservation

[Bzdak-Koch-Liao PRC (2011)]

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$$= \left\langle \frac{(\sum_i \cos \phi_i)^2 - (\sum_i \sin \phi_i)^2 - \sum_i \cos 2\phi_i}{\sum_{<i,j>} 1} \right\rangle$$

$$\simeq -\frac{v_2}{N}$$

Backgrounds

- Flowing resonances **[Voloshin PRC'04]** **[F. Wang PRC'10]**
- Local charge conservation + flow **[Schlichting-Pratt, PRC'11]** **[Pratt-Schlichting-Gavin PRC'11]**
- Transverse momentum conservation **[Bzdak-Koch-Liao PRC'10, PRC'11]** **[Pratt-Schlichting-Gavin PRC'11]**
- Charge-independent background removed by

$$\Delta\gamma = \gamma_{\rm OS} - \gamma_{\rm SS}$$

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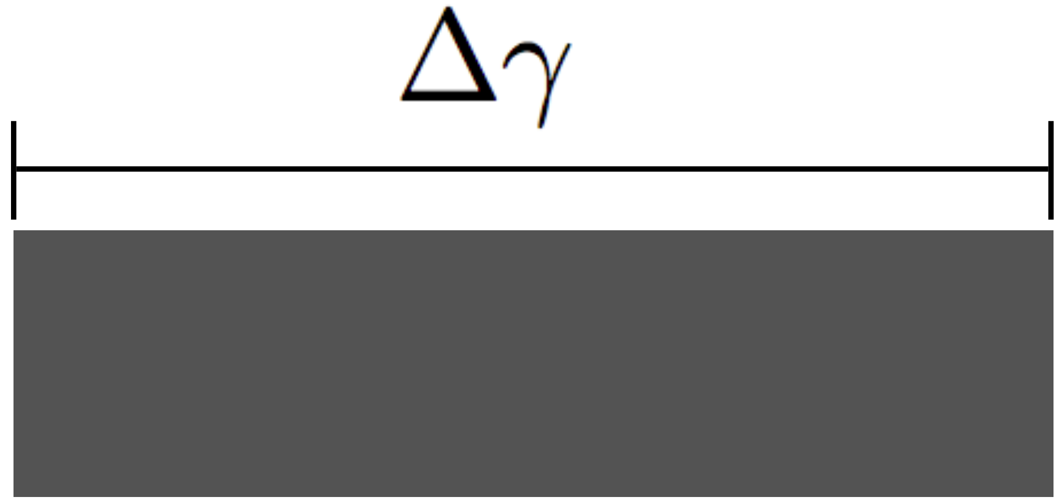
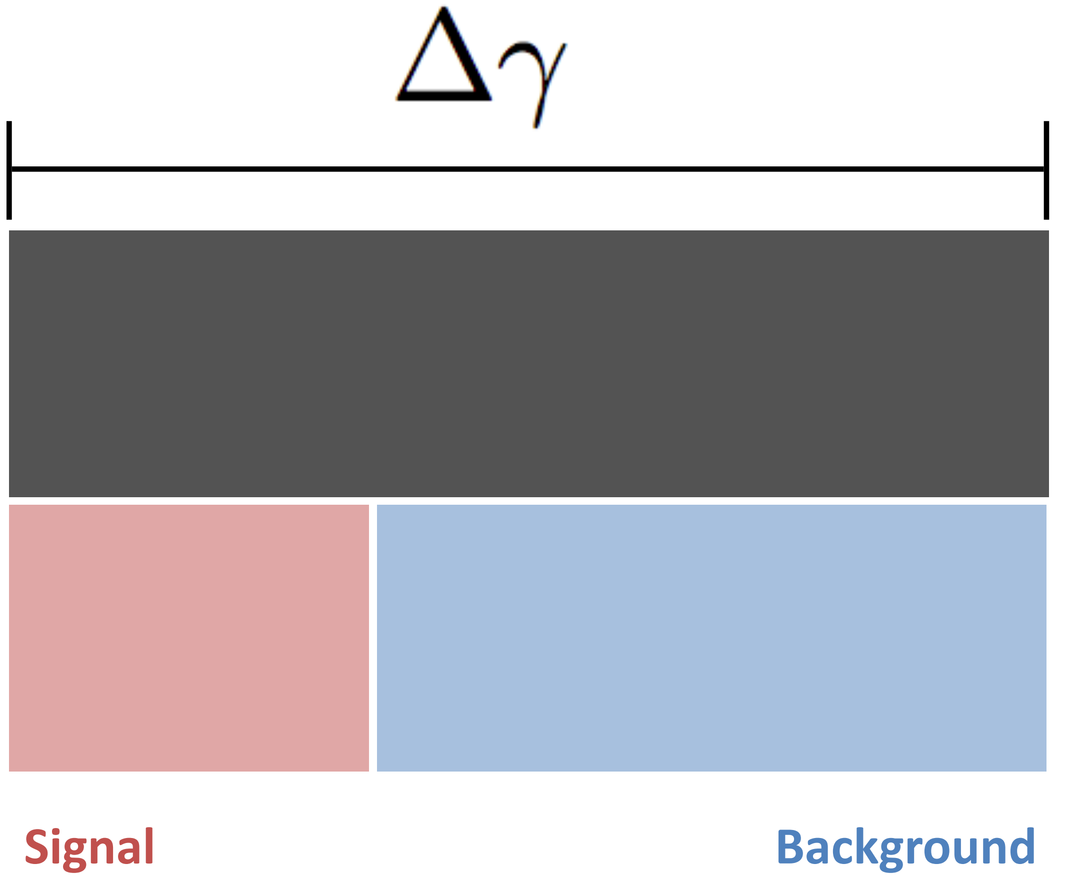
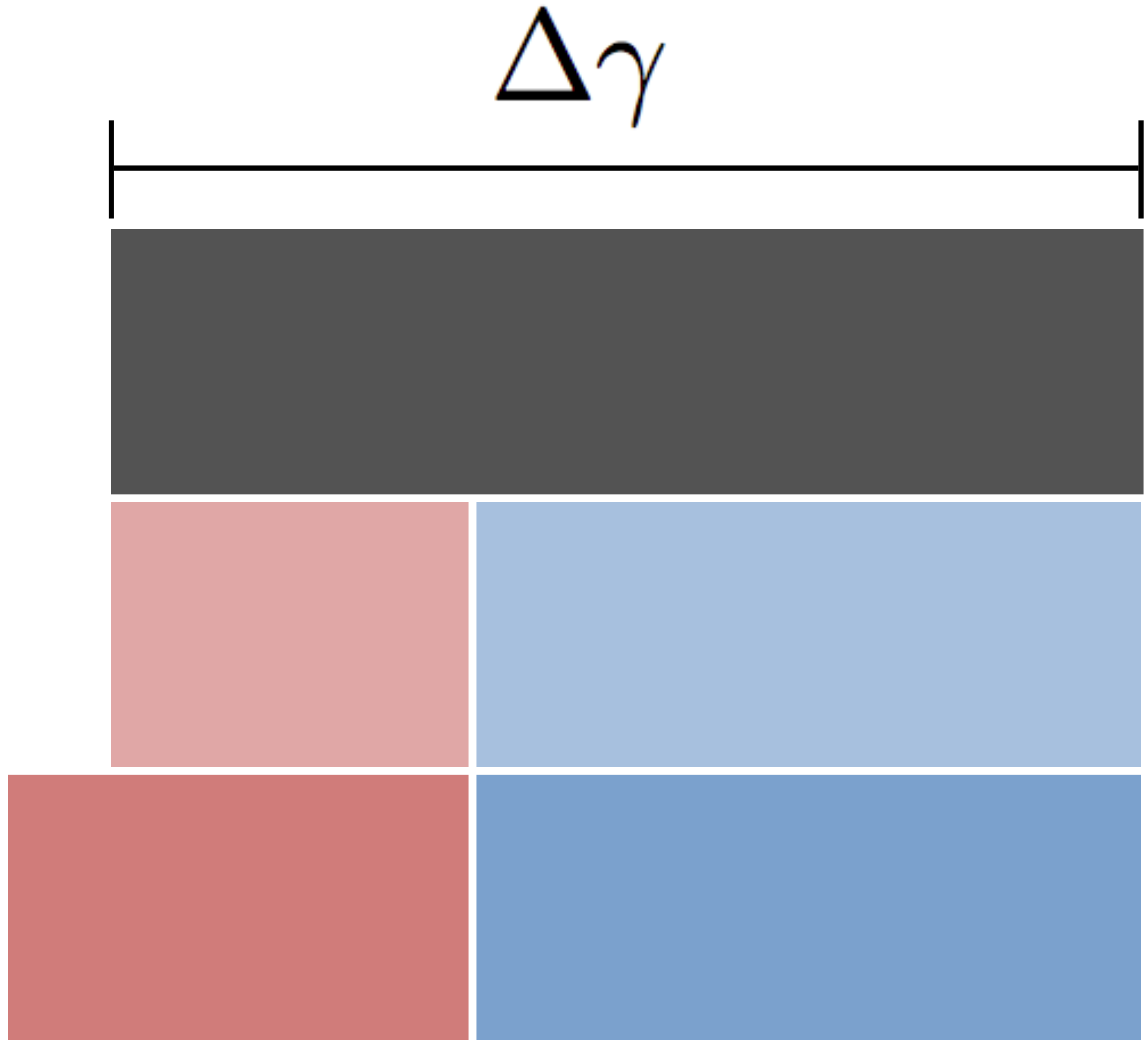
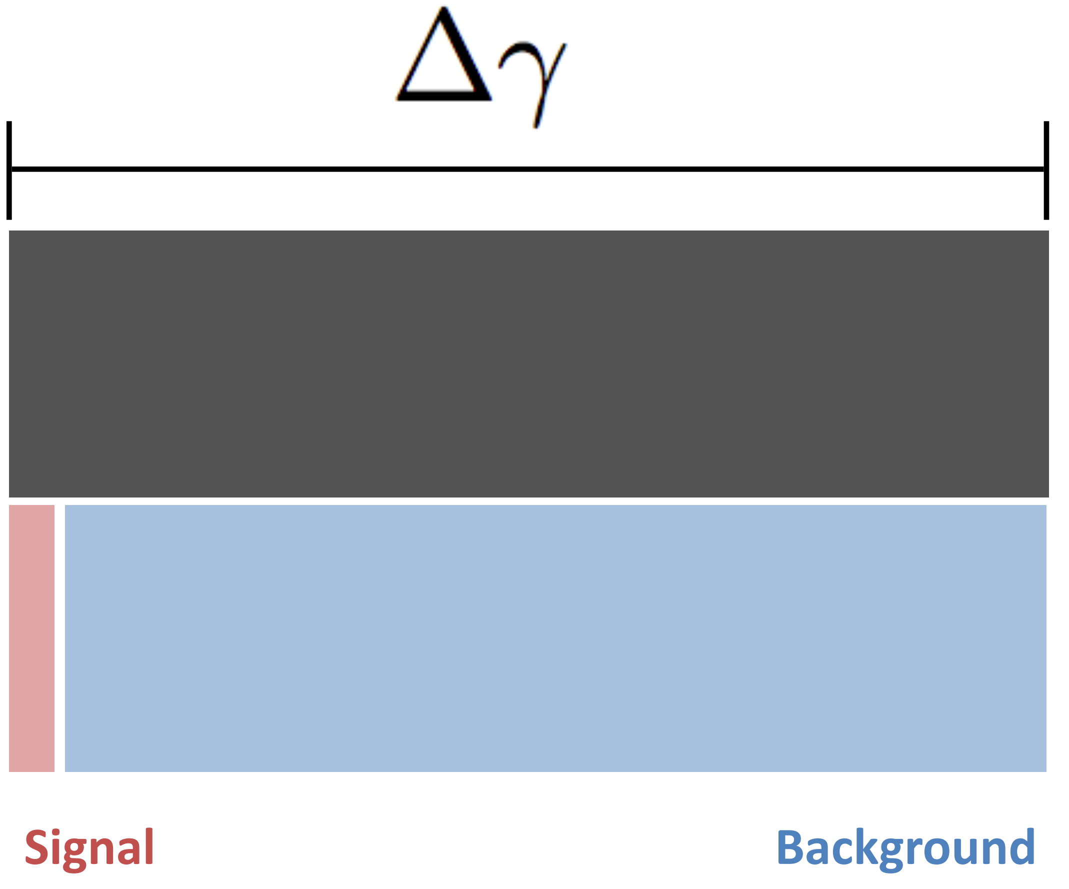

Δγ



$\Delta\gamma$
Signal
Background


$\Delta\gamma$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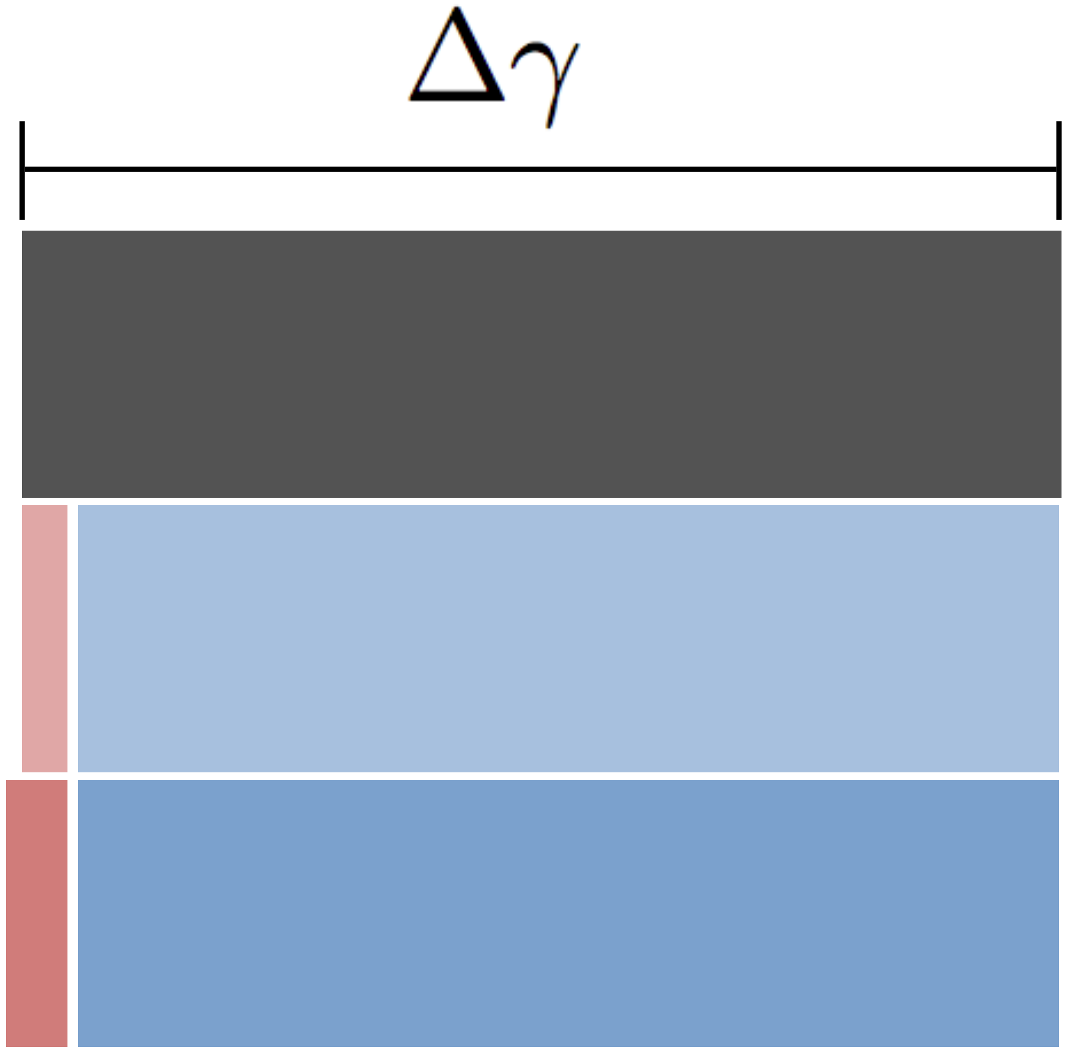
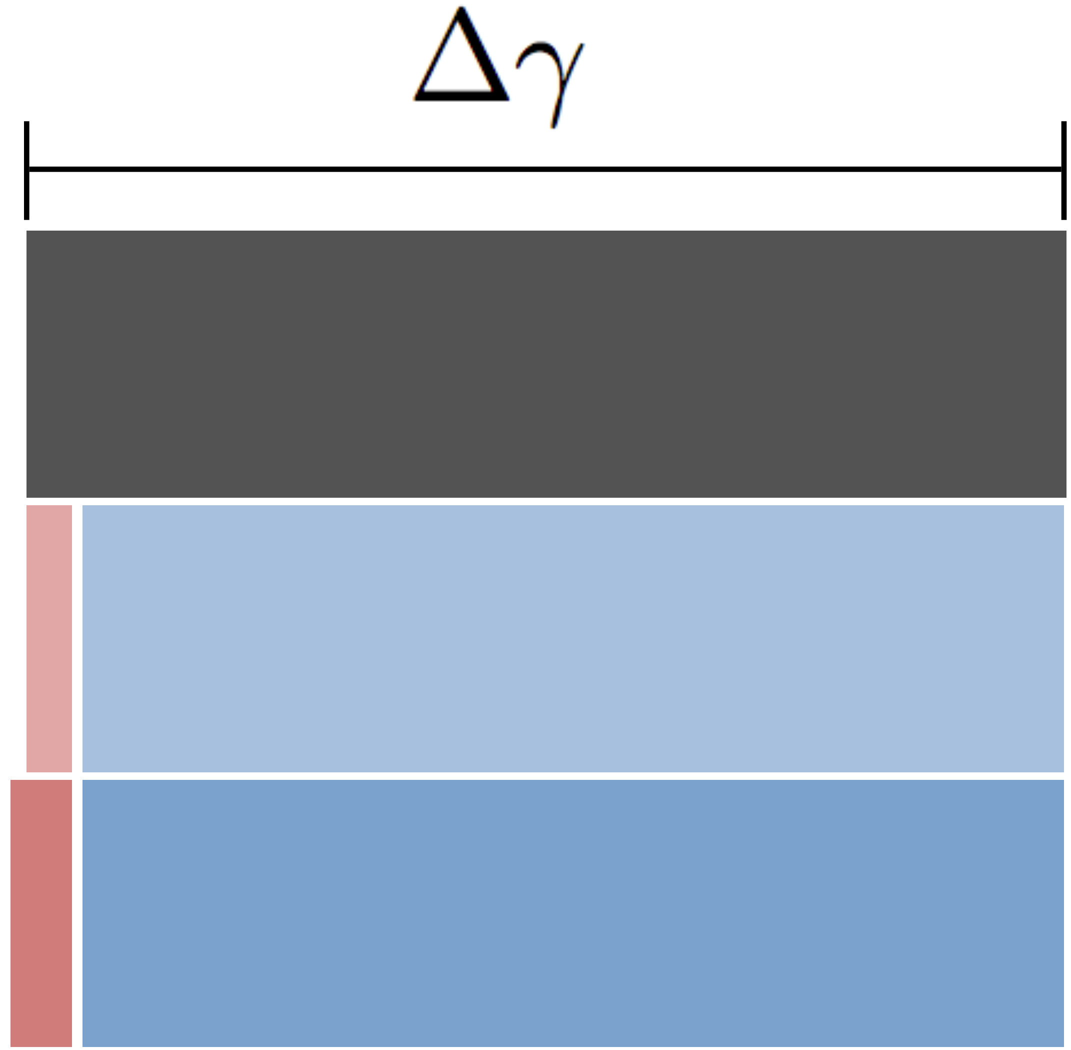

$\Delta\gamma$



$^{96}_{44}\mathrm{Ru}$ $^{96}_{40}\mathrm{Zr}$

Varying signal with fixed background

- CME-driven part is proportional to

$$B_{\rm sq} = \left\langle \frac{(eB)^2}{m_\pi^4} \cos 2(\Psi_B - \Psi_{\rm RP}) \right\rangle$$

[Bloczynski-Huang-Zhang-Liao PLB'13]

$$a_1 \propto \mu_5 \boldsymbol{B} \qquad \Delta\gamma \sim \left\langle a_1^\alpha a_1^\beta \right\rangle \sim \left\langle B^2 \cos 2(\Psi_B - \Psi_{\rm RP}) \right\rangle$$

Varying signal with fixed background

$$S = aB_{\mathrm{sq}} + b\,v_2$$

$$\begin{aligned} S &\equiv N_{\mathrm{part}}\Delta\gamma \\ &= N_{\mathrm{part}}(\gamma_{\mathrm{OS}} - \gamma_{\mathrm{SS}}) \end{aligned}$$

Varying signal with fixed background

$$S = a B_{\mathrm{sq}} + b\, v_2$$

$$S \equiv N_{\mathrm{part}} \Delta\gamma = N_{\mathrm{part}}(\gamma_{\mathrm{OS}} - \gamma_{\mathrm{SS}})$$

$$1 = \frac{a B_{\mathrm{sq}}}{S} + \frac{b\, v_2}{S} = f_s + f_{bg}$$:Signal & background fractions

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δ : Difference between Ru+Ru & Zr+Zr collisions

$$\delta S = a\delta B_{\mathrm{sq}} + b\delta v_2$$

Varying signal with fixed background

$$\boxed{S = aB_{\rm sq} + b\,v_2}$$

$$S \equiv N_{\rm part}\Delta\gamma = N_{\rm part}(\gamma_{\rm OS} - \gamma_{\rm SS})$$

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δ : Difference between Ru+Ru & Zr+Zr collisions

$$\delta S = a\delta B_{\rm sq} + b\delta v_2$$

$$\frac{\delta S}{S} = \delta \ln S = \frac{aB_{\rm sq}\delta \ln B_{\rm sq}}{S} + \frac{bv_2\delta \ln v_2}{S}$$

$$= f_s\delta \ln B_{\rm sq} + f_{bg}\delta \ln v_2$$

Varying signal with fixed background

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Flow is unchanged

Varying signal with fixed background

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$$\delta \ln S = f_s \delta \ln B_{\rm sq} + f_{bg} \delta \ln v_2$$

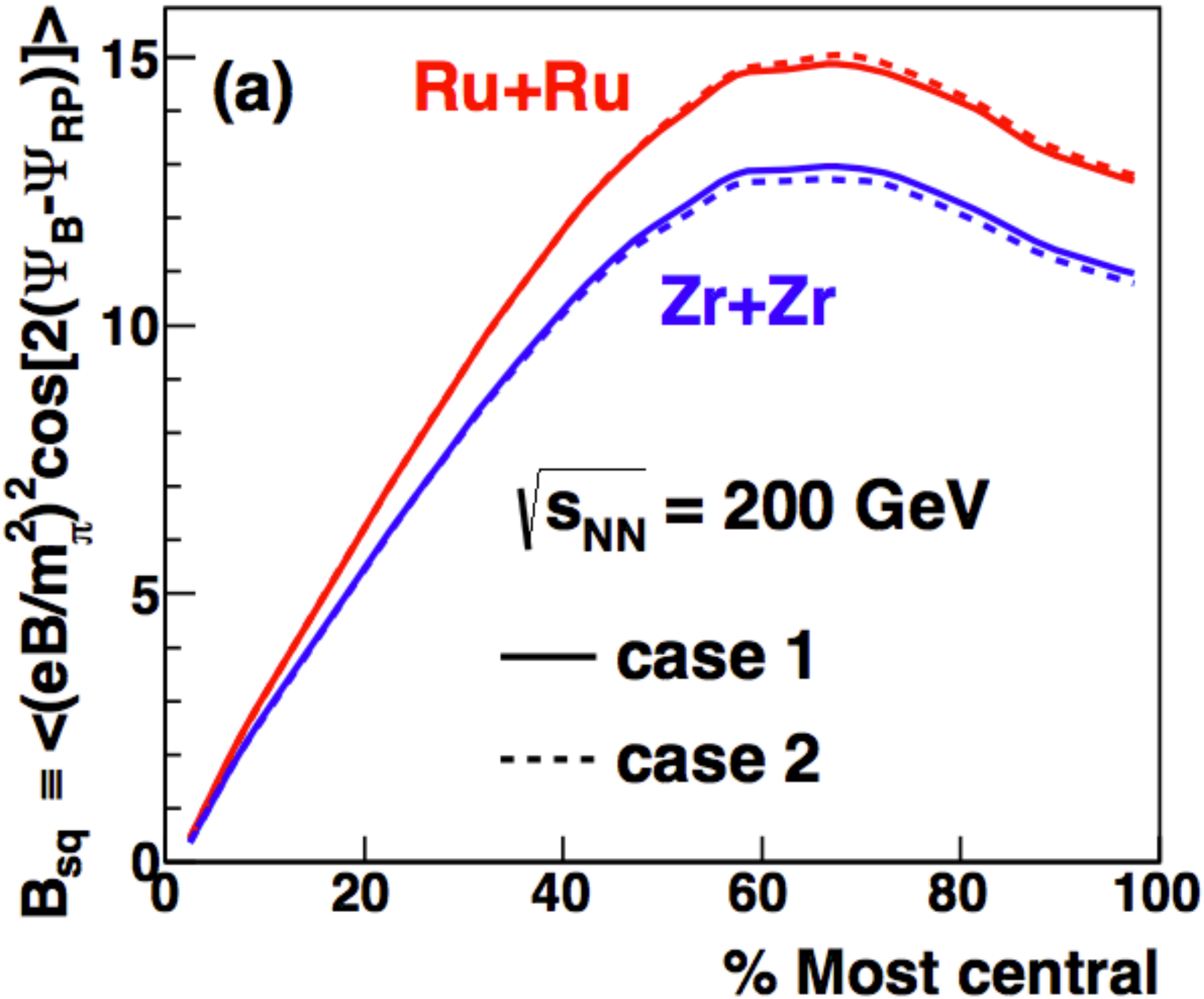
Flow is unchanged

$$\Rightarrow f_s = \frac{\delta \ln S}{\delta \ln B_{\rm sq}}$$

← **Theoretically calculable**

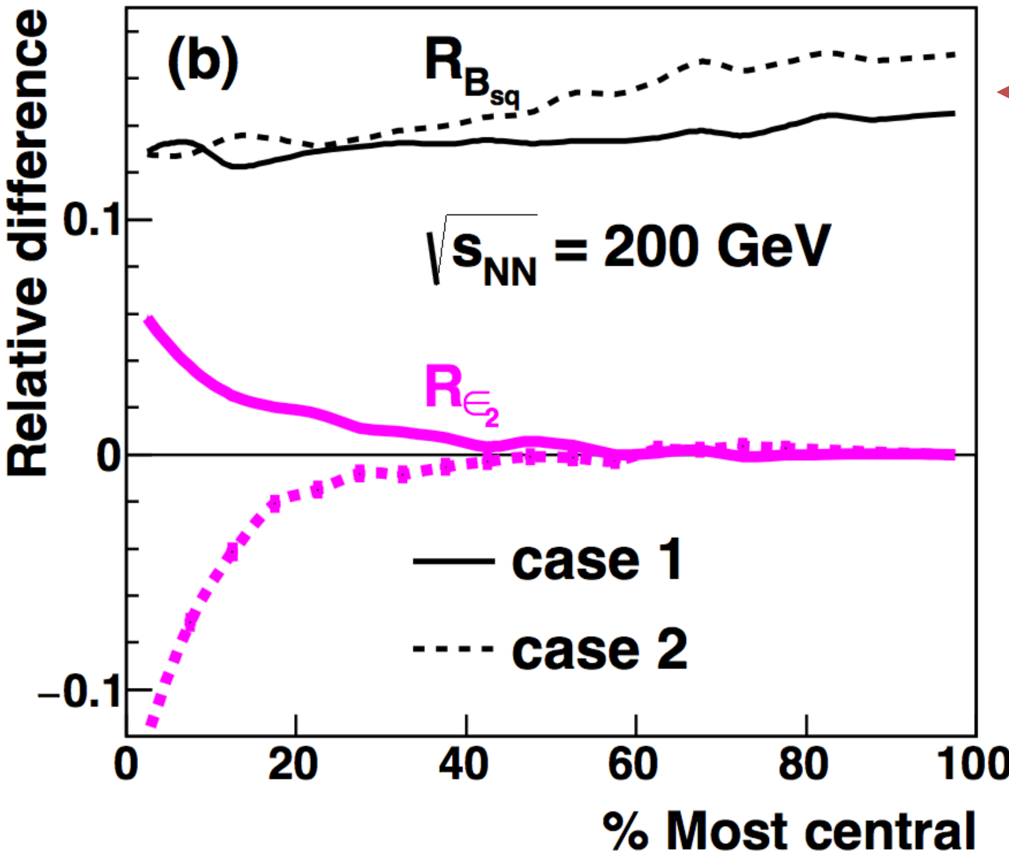
B_sq is varied 10-20%

[Deng-Huang-Ma-Wang PRC’16]



Flow remains the same

[Deng-Huang-Ma-Wang PRC'16]



Difference in Bsq (10-20%)

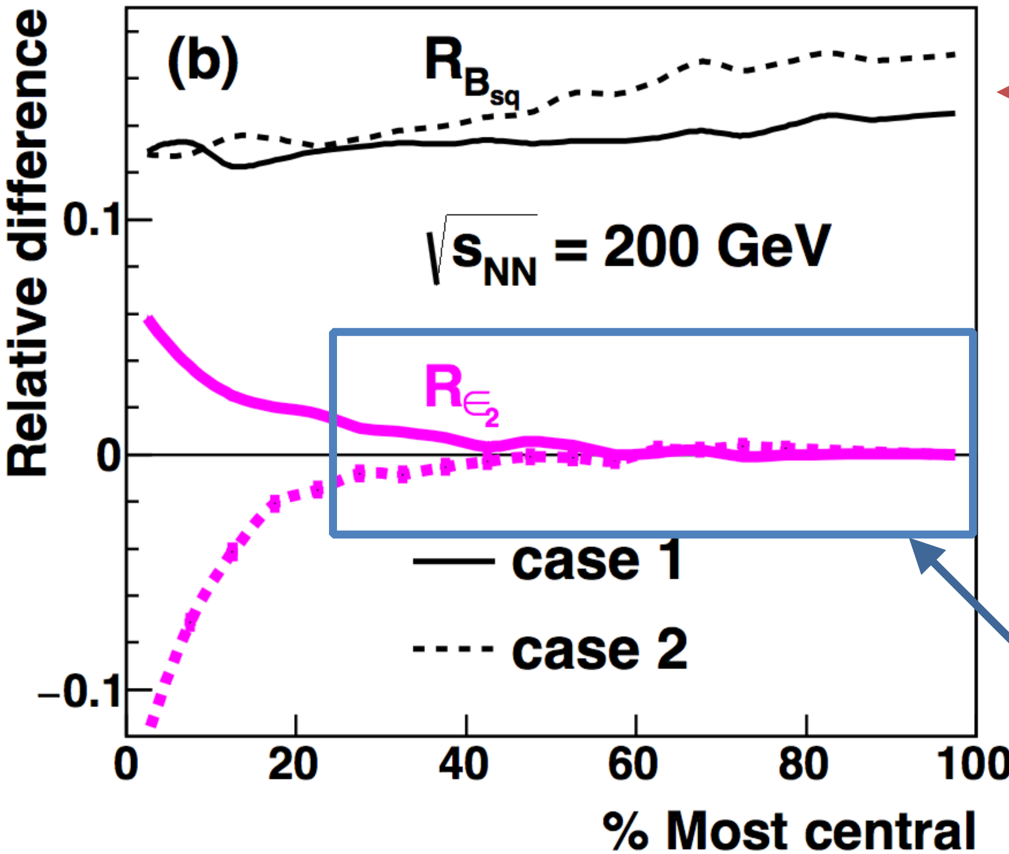
$$R_{B_{\rm sq}} = \delta \ln B_{\rm sq}$$

$$R_{\epsilon_2} = \delta \ln \epsilon_2 \simeq \delta \ln v_2$$

$$R_F \equiv \frac{F^{\rm Ru+Ru} - F^{\rm Zr+Zr}}{(F^{\rm Ru+Ru} + F^{\rm Zr+Zr})/2}$$

Flow remains the same

[Deng-Huang-Ma-Wang PRC'16]



Difference in Bsq (10-20%)

$$R_{B_{\rm sq}} = \delta \ln B_{\rm sq}$$

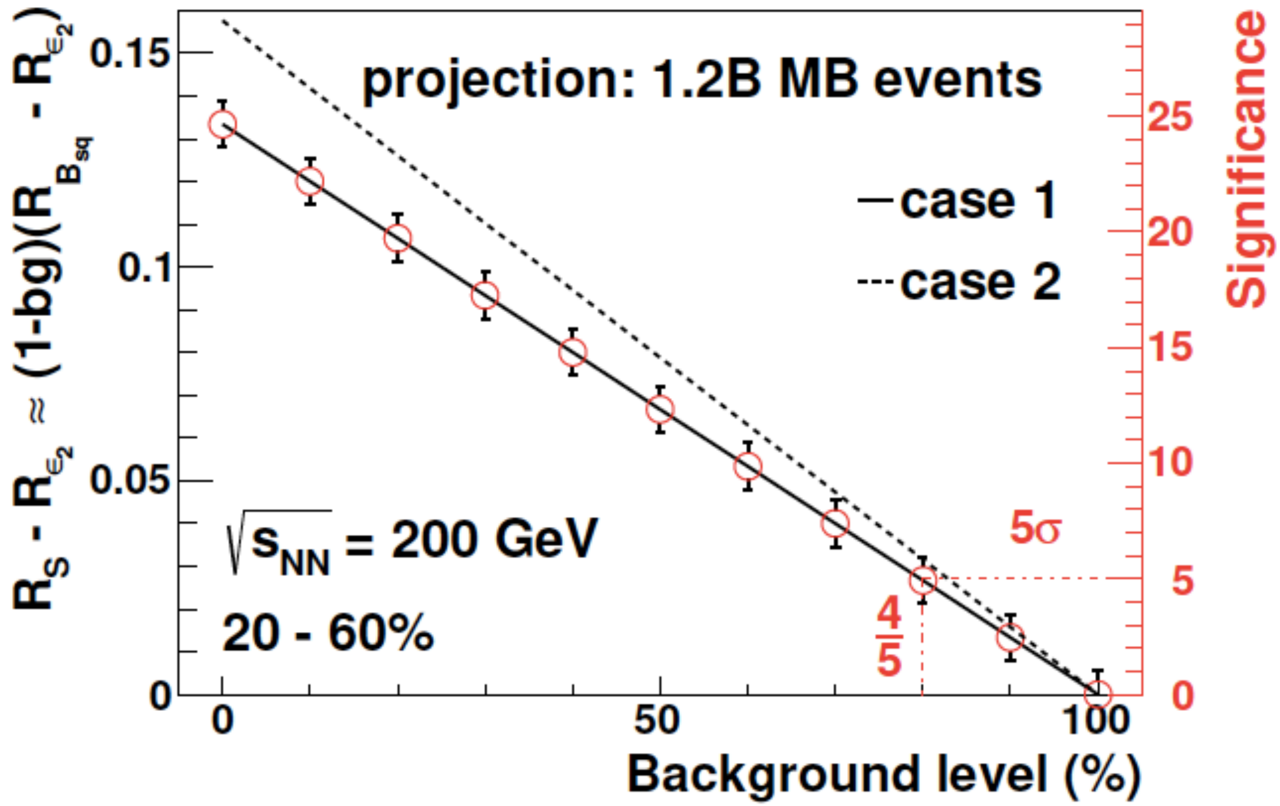
$$R_{\epsilon_2} = \delta \ln \epsilon_2 \simeq \delta \ln v_2$$

Little difference in eccentricity, hence flow

$$R_F \equiv \frac{F^{\rm Ru+Ru} - F^{\rm Zr+Zr}}{(F^{\rm Ru+Ru} + F^{\rm Zr+Zr})/2}$$

Significance vs background level

[Deng-Huang-Ma-Wang PRC'16]



$$\delta \ln S = f_s \delta \ln B_{\rm sq}$$

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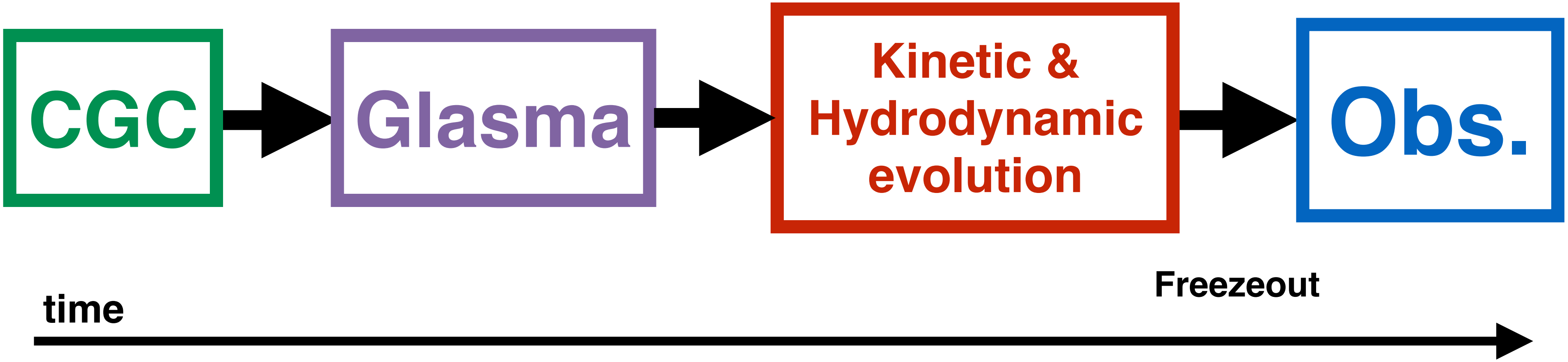
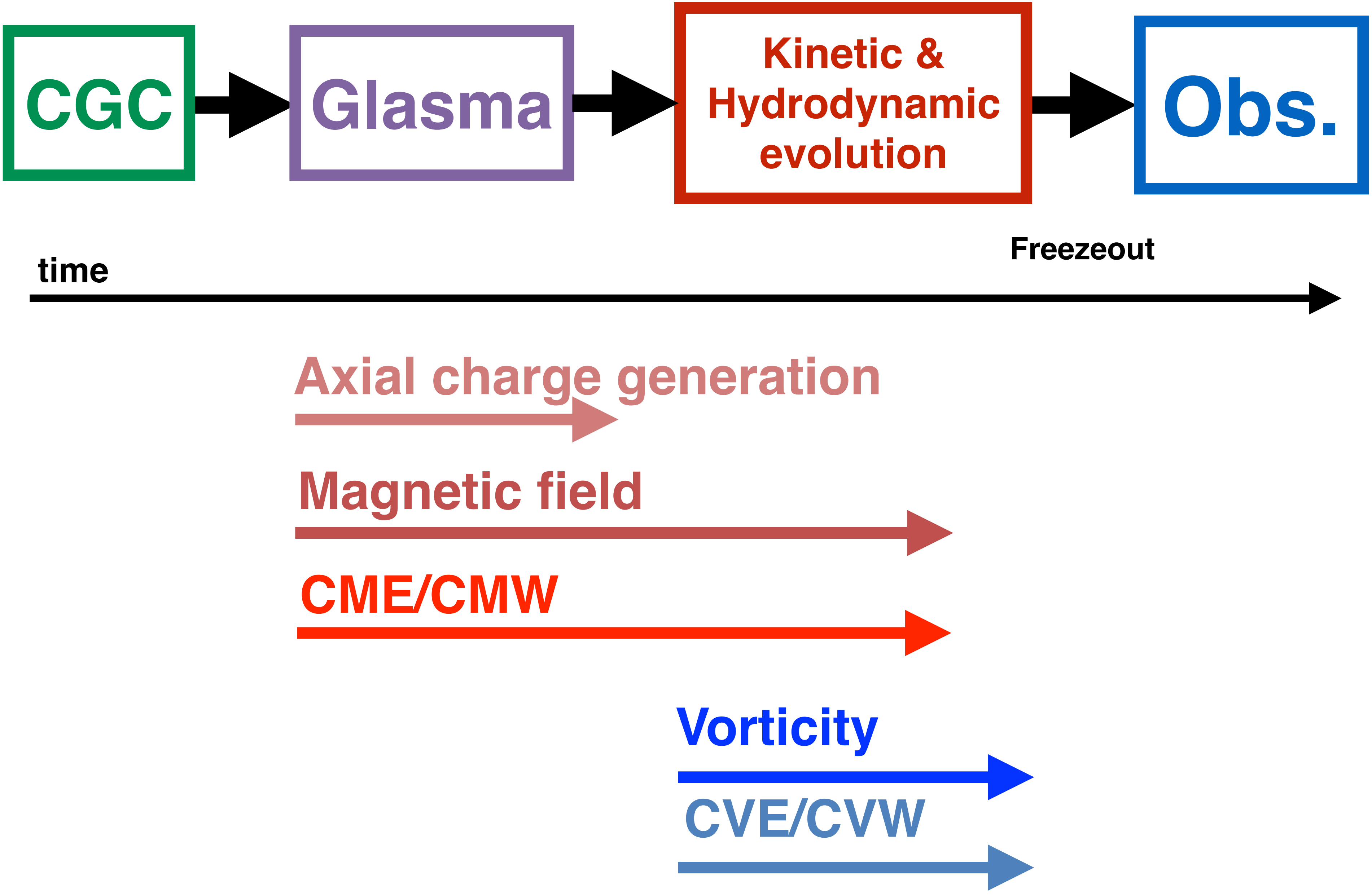

CGC
Glasma
Kinetic & Hydrodynamic evolution
Obs.
Freezeout
time


CGC
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Kinetic & Hydrodynamic evolution
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time
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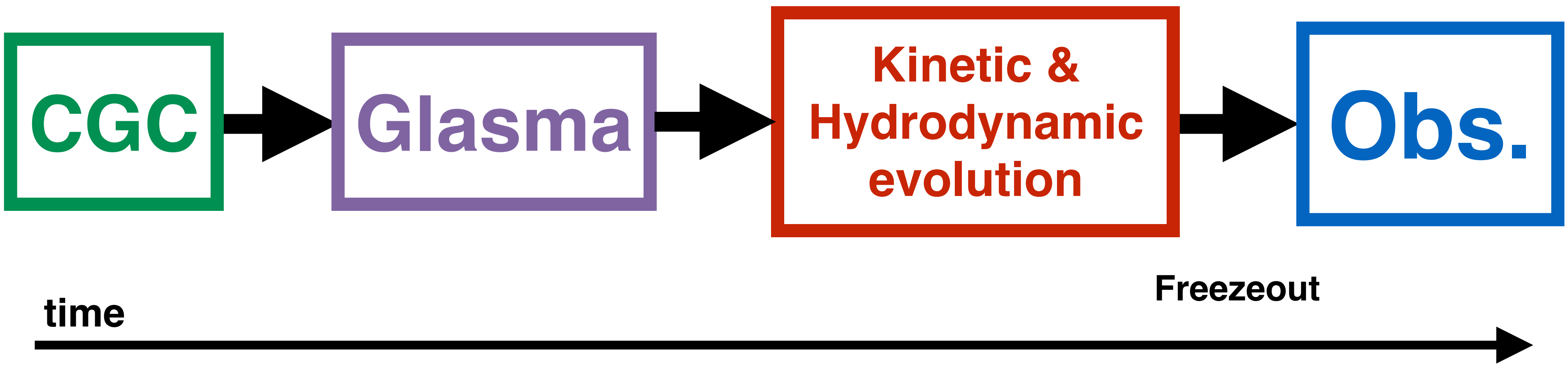
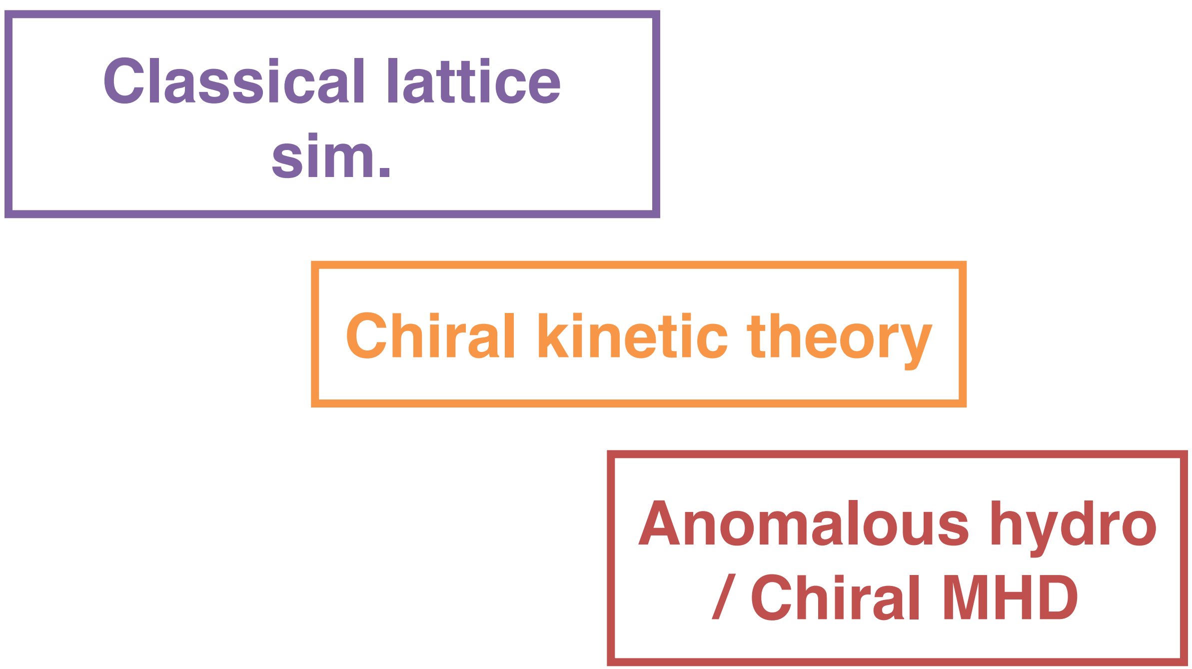
Axial charge generation
Magnetic field
CME/CMW
Vorticity
CVE/CVW

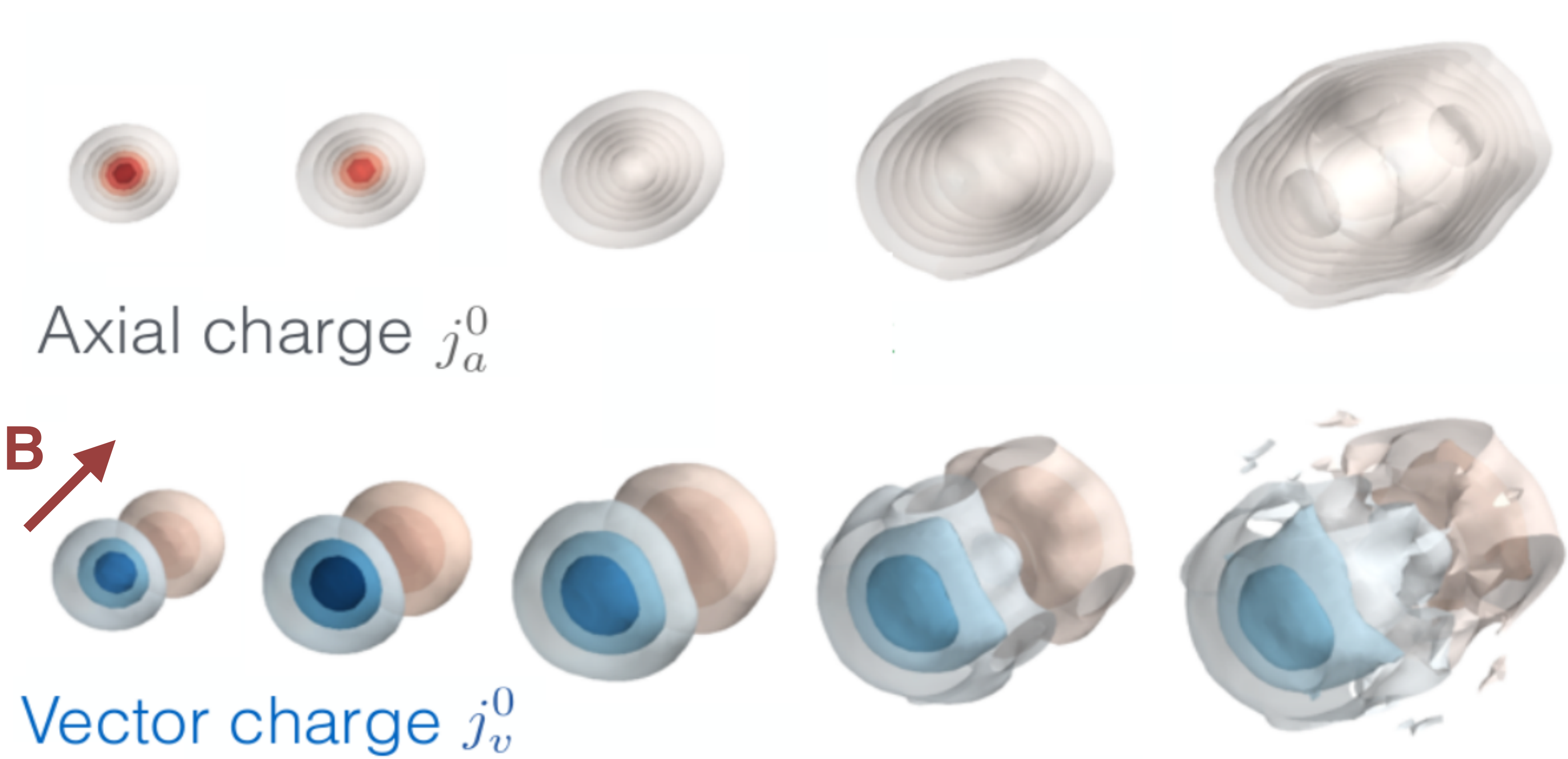


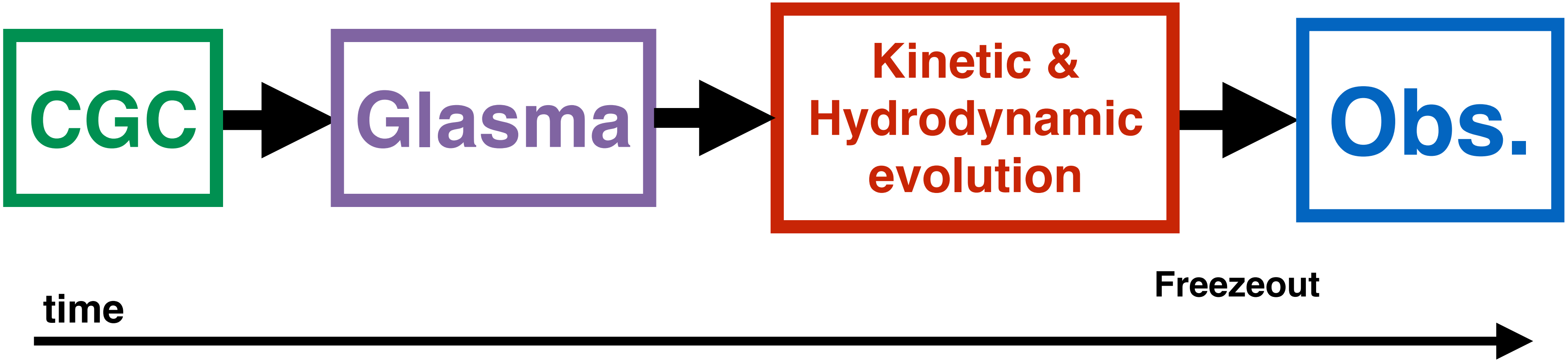
Theoretical descriptions:



CME in real-time lattice sim.

[Mueller-Schlichting-Sharma PRL'16]
[Mace-Mueller-Schlichting-Sharma PRD'17]





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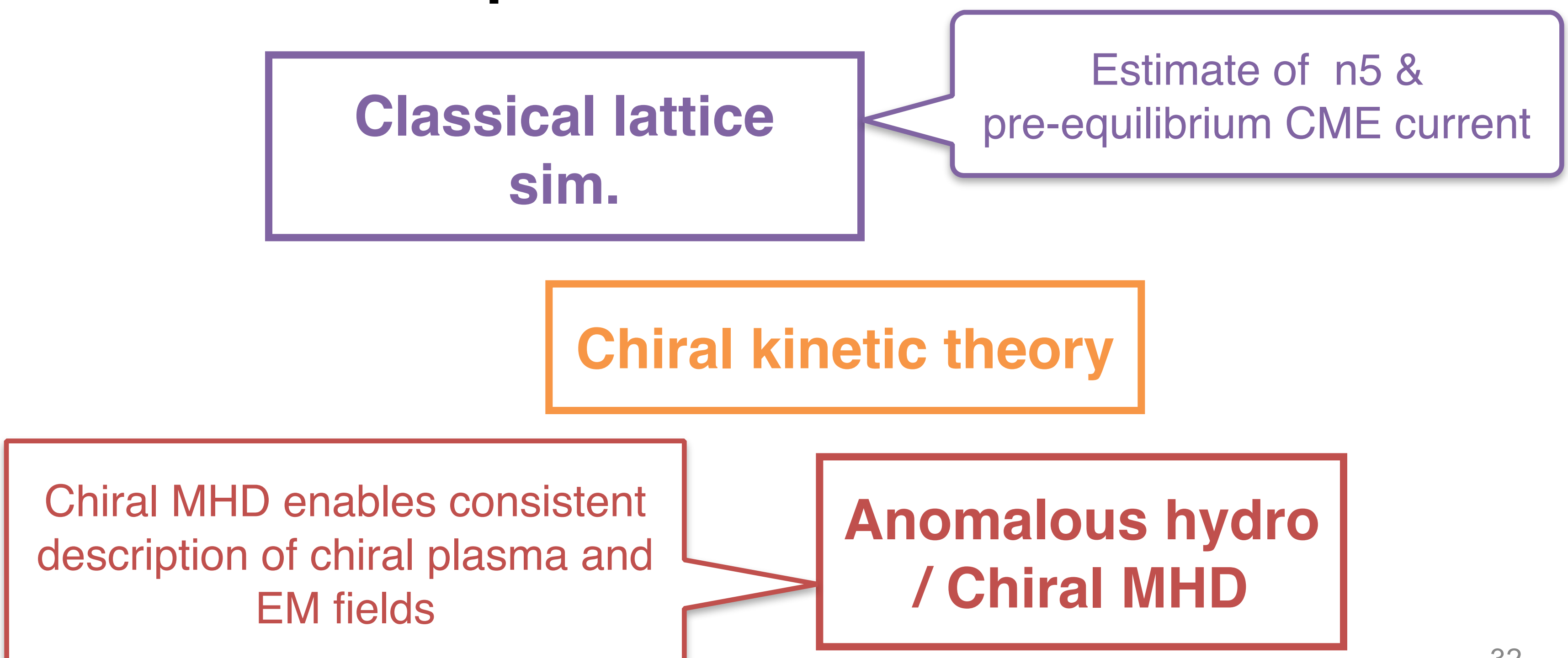
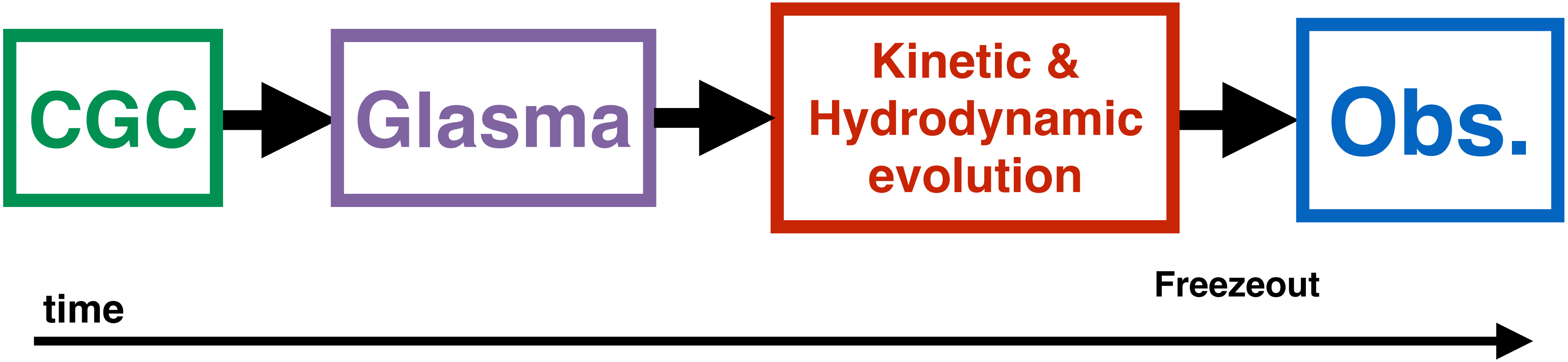




Theoretical descriptions:

Classical lattice sim.

Estimate of n5 & pre-equilibrium CME current

Bayesian estimate of parameters
[Bernhard-Moreland-Bass-Liu-Heinz PRC'19]

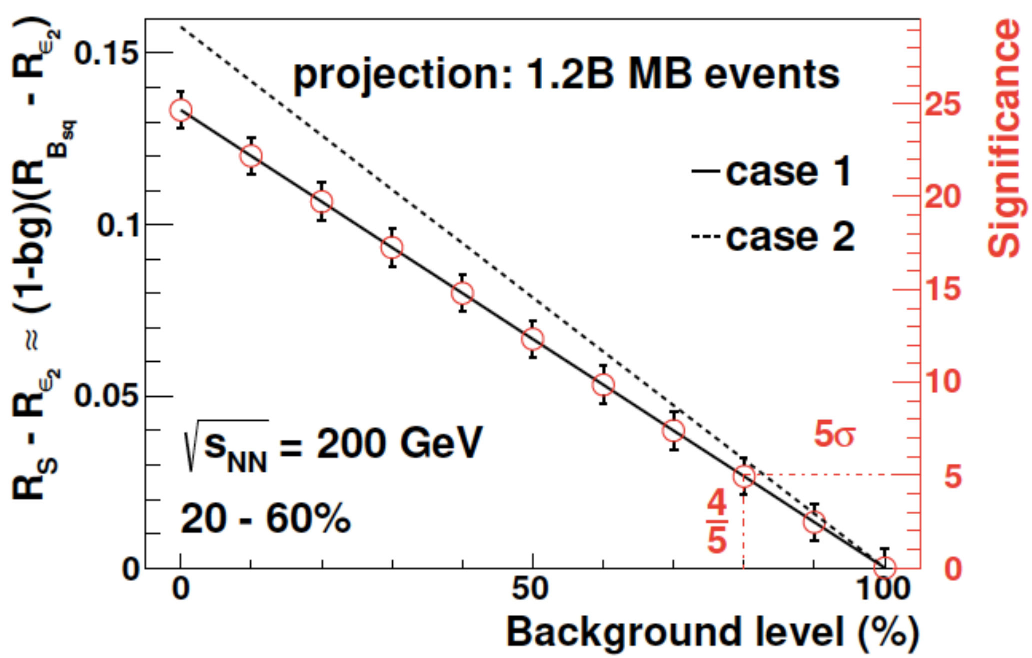
Chiral kinetic theory

Chiral MHD enables consistent description of chiral plasma and EM fields

Anomalous hydro / Chiral MHD

Summary

- Study of anomaly-induced transport in HIC
  - Existence of CME
  - Chirality generation from color fields
  - Chiral symmetry restoration
- Multi-particle correlations contaminate the obs.
  - contribute as v2 / N
- Isobar collisions
  - Vary the signal with backgrounds fixed



Back up slides

Toward quantitative description

- Pre-hydro CME current
- Pre-hydro n5 generation
- Lifetime of B
- Vortical contribution
- Background/dilution
  - TMC/LCC
  - Resonance decays

Real-time lattice simulations of glasma

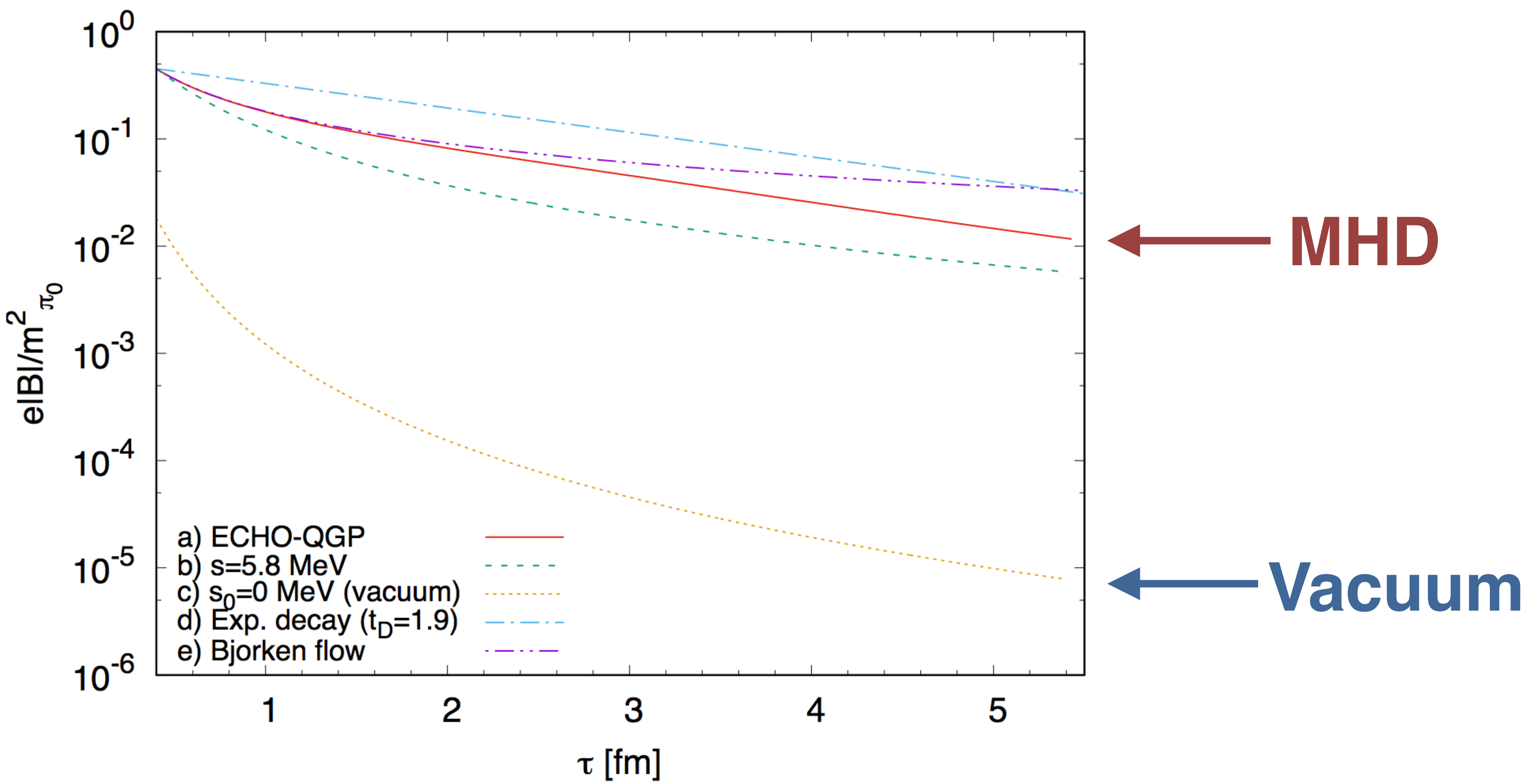
Hydro (CMHD)

Chiral kinetic th.

MHD evolution of B field

- MHD

  "ECHO-QGP" **[Inghirami et. al. EPJC'16]**



Recent calculation from hydro/kinetic theory

[Yin-Liao PLB'16]

- Anomalous charge transport on 2+1D viscous fluid (VISH)
- Quantify the effects of transverse momentum conservation (TMC)

[Jiang-Shi-Yin-Liao 1611.04586]

- Anomalous charge transport on 2nd order viscous fluid in 2+1D (VISHNew)
- Smooth profile
- Include background from resonance decay
- Event-by-event

[Sun-Ko 1612.02408]

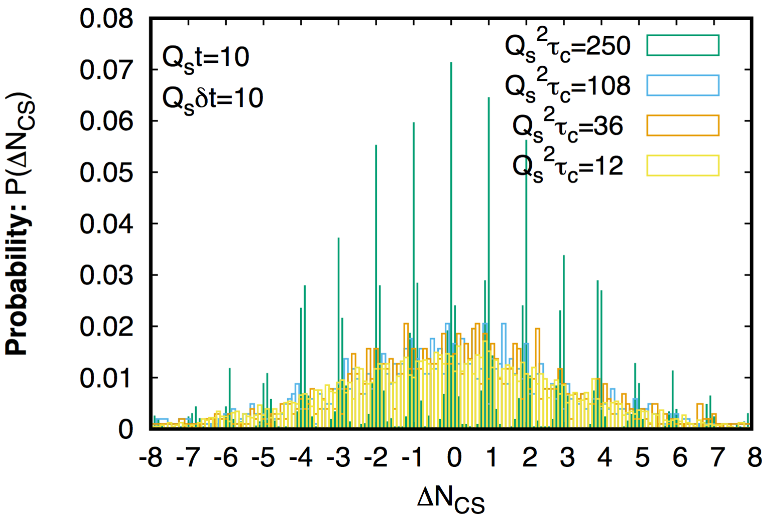
- Kinetic theory with CME/CVE

[Huang-Jiang-Shi-Liao-Zhuang in progress] **[poster by Huang]**

- Kinetic theory with CME
- Pre-hydro contribution

Enhanced sphaleron rate in glasma

[Mace-Schlichting-Venugopalan PRD'16]



Probability dist. of ΔN_{CS}

Glasma evolution in classical YM equations

Enhanced sphaleron rate in non-eq