Wounded quarks in heavy-ion collisions

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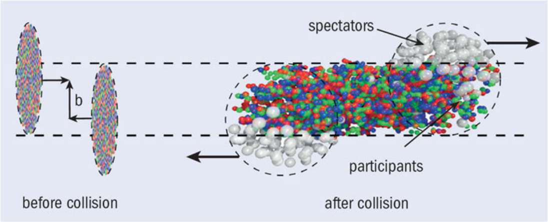
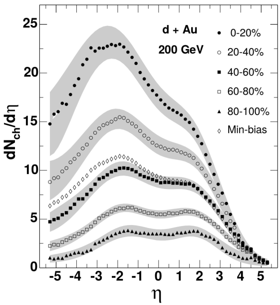
Outline

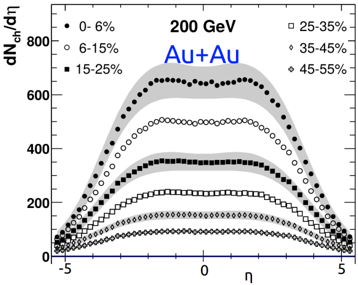
1. Wounded constituents models
2. STAR paper
   - Different geometries of U+U collisions
   - v_2 vs $dN_{ch}/d\eta$
   - Comparison with models
3. Our research
   - Wounded constituent emission function
   - Predictions for $dN_{ch}/d\eta$ compared with data
4. Summary and conclusions

Particle production in relativistic heavy-ion collisions



http://cerncourier.com/cws/article/cern/53089





B. Back *et al.* [PHOBOS], Phys. Rev. Lett. 91, 052303 (2003)

B. Back *et al.* [PHOBOS], Phys. Rev. C 72, 031901 (2005)

Try to describe by wounded nucleon model

- Wounded nucleon model

  A. Bialas, M. Bleszynski and W. Czyz, Nucl. Phys. B **111**, 461 (1976).
- Simple assumptions:
  - Nuclei collision - as a superposition of multiple nucleon-nucleon interactions.
  - Each nucleon which interacts with at least one other - wounded.
  - Each wounded nucleon produces particles independently of how many times it was "wounded".
  - $N_{ch} \sim N_{\text{part}}$

Modification: 2-component model

- Weighted mean of wounded constituents and binary collisions

$$N_{ch} \sim (1 - x_{\text{hard}})\frac{N_{\text{part}}}{2} + x_{\text{hard}} N_{\text{coll}}$$

D. Kharzeev and M. Nardi, Phys. Lett. B **507**, 121 (2001)

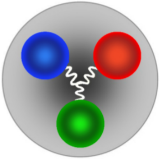
- In all models: each source produces particles independently and according to probability distribution, typically: NBD.

Models similar to wounded nucleon model

- Wounded quark model

  A. Bialas, W. Czyz and W. Furmanski, Acta Phys. Polon. B **8**, 585 (1977).

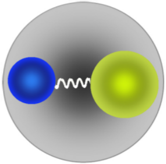
  - analogous
  - valence quarks (nucleon consists of 3)
  - multiple quark-quark interactions
  - $N_{ch} \sim \#$wounded quarks



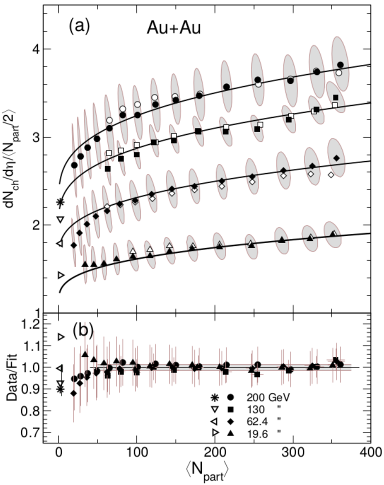
- Wounded quark-diquark model

  A. Bialas and A. Bzdak, Phys. Lett. B **649**, 263 (2007) Erratum: [Phys. Lett. B **773**, 681 (2017)]

  - analogous
  - nucleon consists of a quark and diquark
  - multiple quark-quark, quark-diquark, diquark-diquark interactions
  - $N_{ch} \sim \#$wounded quarks and diquarks



WNM is invalid



B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. C **83**, 024913 (2011)

- WNM:

$$\frac{N_{ch}}{N_{part}} = \text{const}$$

- $\frac{N_{ch}}{N_{part}} \sim \left(1 + cN_{part}^{1/3}\right)$
- Try to introduce:

$$\frac{N_{ch}}{N_{part}} \neq \text{const}$$

  by N_{coll} dependence.
- WQM and WNM + N_{coll} both have the same goal but different underlying physics.
- Models differ at large N_{coll}

STAR research

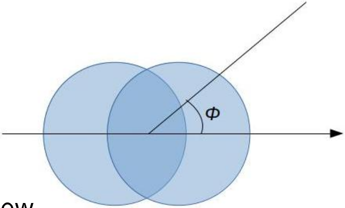
L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

Idea of (elliptic) flow and anisotropies

Anisotropies in the final momentum space distribution

- $\Leftarrow$ anisotropies in the initial stage fireball.
- are studied using harmonics in the Fourier expansion

$$\frac{dN}{d\Phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n\Phi)\right].$$

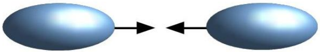


- v_2 describes elliptic flow.

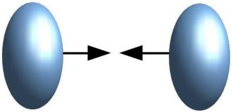
Uranium

U nucleus is prolate.

- U + U collisions having various geometries even in same centrality.
- Let's take central collisions!
- Extreme cases:

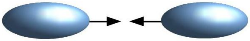
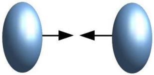


tip-tip



body-body

Idea of study

	tip-tip 	body-body 
N_{coll}	big	small
N_{ch}	**big**	**small**
overlap	circular	elliptic
ε_2	small	big
v_2	**small**	**big**

assuming N_{coll} dependence

ε_2 - measure of eccentricity (deviation from circularity)

$\Rightarrow$ Let's investigate v_2 vs $dN_{ch}/d\eta$!

- Expected: decreasing ($\sim$ anticorrelation).
- Test our qualitative understanding.
- Test models (WNM + N_{coll} and WQM).

Collisions

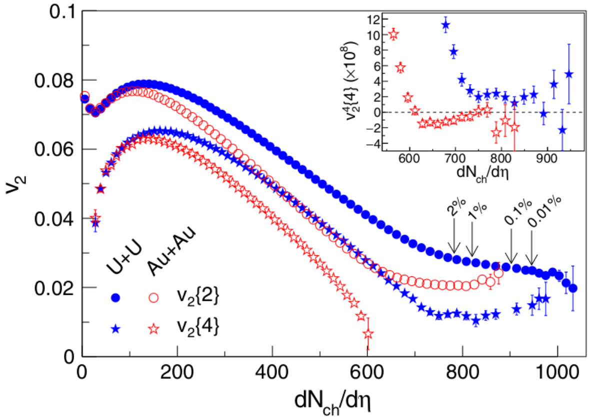
Experiments @BNL RHIC

- **central** collisions selected using ZDCs
- U + U @193 GeV (main sample due to geometry)
- Au + Au @200 GeV (control sample)
- Other cuts for events:
  - $|\eta| < 1$
  - $0.2 < p_T < 2.0$ [GeV/c]

U is prolate

Au is spheric

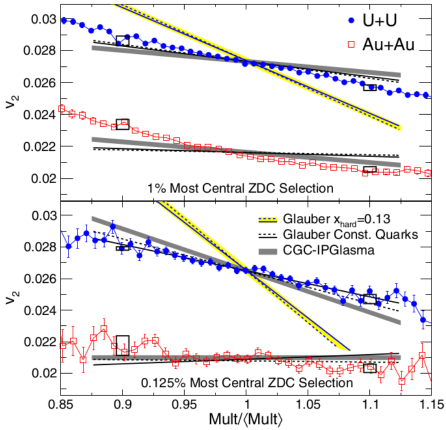
v_2 vs $dN_{ch}/d\eta$



L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

- In general, decreasing ($\sim$ anticorrelation), as expected.
- $v_2^4\{4\} < 0$ for Au+Au $\Leftarrow$ fluctuations in #participants.
- $v_2^4\{4\} > 0$ for U+U $\Rightarrow$ prolate shape increases anisotropy. Shape observable in data.

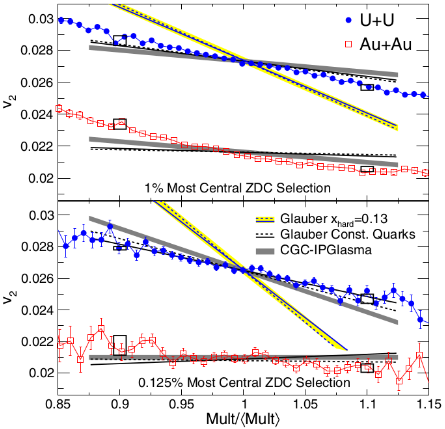
v_2 vs normalized multiplicity



L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

- Used control sample of Au+Au collisions (v_2 should be const at given centrality).
- Normalized multiplicity (different size of Au and U).
- 0-1% centrality: still dependence on centrality (see Au)
- 0-0.125% centrality: dependence mostly on geometry.
  Here multiplicity varies due to tip-tip or body-body etc.

v_2 vs normalized multiplicity



L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

- WNM + N_{coll}: overpredicts the slope assuming big contribution of N_{coll}
- WQM gives good results! (CGC IP-Glasma does too)
- indirect N_{coll} dependence, smaller contribution.

STAR paper summary

- Interesting research.
- Results require models with effects from *subnucleonic* structure and less dependence on N_{coll}.
- Successful central collisions selection.
- U+U data useful to study other effects based on initial geometry (different geometries at same centrality).
- We plan to investigate this.

Our research

MB, A. Bzdak, P. Gutowski, Phys. Rev. C **97**, no. 3, 034901 (2018)

MB, A. Bzdak, P. Gutowski, arXiv:1904.01435 [hep-ph]

Common idea for WNM, WQM and WQDM models

- Each wounded source emits the number of particles according to the same probability distribution *independently of number of collisions*

$$\frac{dN_{ch}}{d\eta}(\eta) = w_L F(\eta) + w_R F(-\eta)$$

$F(\eta)$ - **wounded source emission function**

w_L - mean number of wounded sources in left-going nucleus

w_R - same for right-going one

Common idea for WNM, WQM and WQDM models

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$$N(\eta) := \frac{dN_{ch}}{d\eta}(\eta) = w_L F(\eta) + w_R F(-\eta)$$

$F(\eta)$ - **wounded source emission function**

w_L - mean number of wounded sources in left-going nucleus

w_R - same for right-going one

- Then (if $w_L \neq w_R$):

$$F(\eta) = \frac{1}{2}\left[\frac{N(\eta) + N(-\eta)}{w_L + w_R} + \frac{N(\eta) - N(-\eta)}{w_L - w_R}\right].$$

- Input: known $dN_{ch}/d\eta$ distribution.
- Numbers of wounded sources computed in MC simulation.

First step

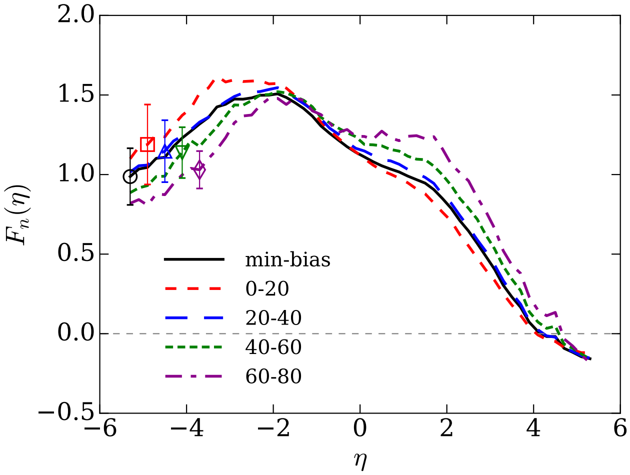
- $F(\eta) = \frac{1}{2}\left[\frac{N(\eta)+N(-\eta)}{w_L+w_R} + \frac{N(\eta)-N(-\eta)}{w_L-w_R}\right]$
- Take distribution $N(\eta) = dN_{ch}/d\eta$ from d+Au @200 GeV @BNL RHIC by PHOBOS.

Simulation algorithm: MC Glauber based.

- For each nucleus-nucleus collision:
  - Draw nucleons positions from density distibutions.
  - [In WQM and WQDM: draw also quarks (and diquarks) positions around the center of nucleon.]
  - Draw impact parameter b.
  - For each pair check whether the collision happened.
  - For each wounded source draw the number of emitted particles according to NBD.
- Divide all events into centrality classes based on the number of produced particles.
- Calculate mean numbers of wounded sources w_L, w_R in centralities.

Emission functions - wounded nucleons

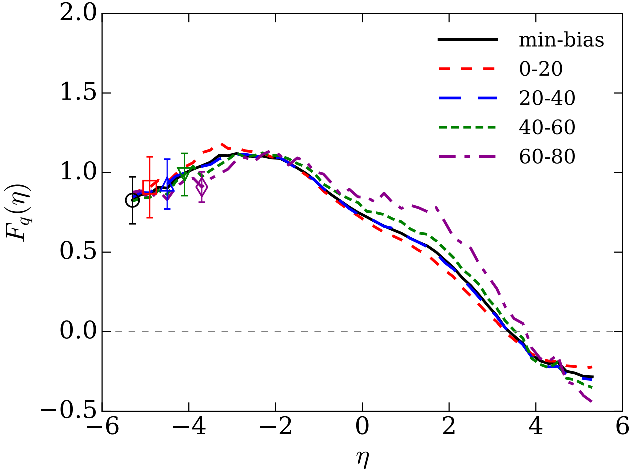
in various centrality classes



MB, A. Bzdak, P. Gutowski, Phys. Rev. C **97**, no. 3, 034901 (2018)

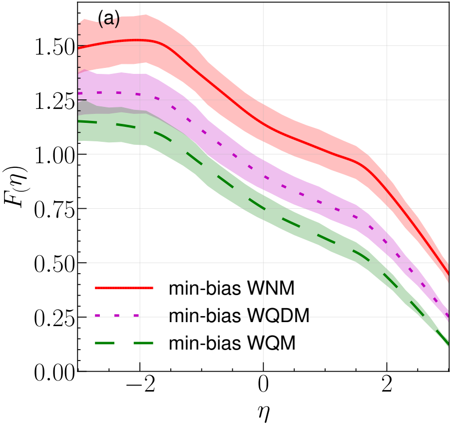
Emission functions - wounded quarks

in various centrality classes



Min-bias wounded constituent emission functions

- Within uncertainties, the emission functions are same in all centralities.
- $\Rightarrow$ Pick min-bias emission functions $F(\eta)$.



MB, A. Bzdak, P. Gutowski, arXiv:1904.01435 [hep-ph]

Next step

- Take extracted min-bias emission functions $F(\eta)$.
- Compute numbers of wounded sources in MC simulation for various systems.
- Predict $dN_{ch}/d\eta$ distributions (assume $F(\eta)$ universal among systems).

$$N(\eta) := \frac{dN_{ch}}{d\eta}(\eta) = w_L F(\eta) + w_R F(-\eta)$$

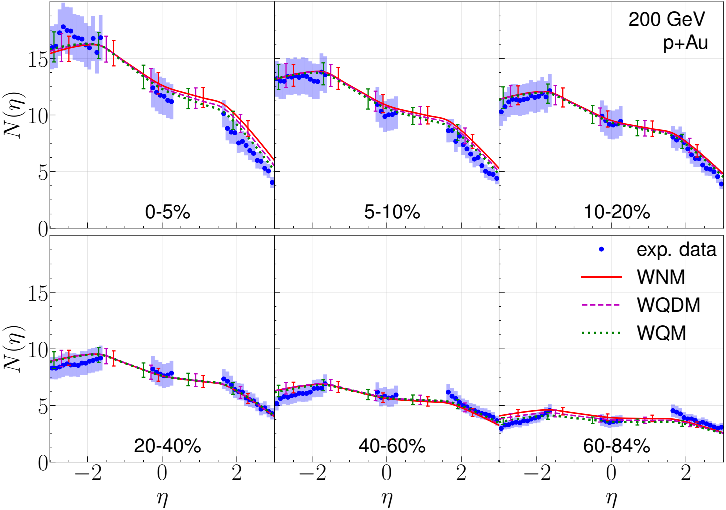
- Compare with experimental data.

PHENIX measurements on asymmetric collisions

- PHENIX collaboration have done dedicated experiments and successfully verified WQM.
- We were asked by PHENIX to make predictions on $dN_{ch}/d\eta$ for asymmetric collisions.
- D. McGlinchey [PHENIX Collaboration], Nucl. Phys. A **982**, 839 (2019)
- A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **121**, no. 22, 222301 (2018)

Asymmetric collisions

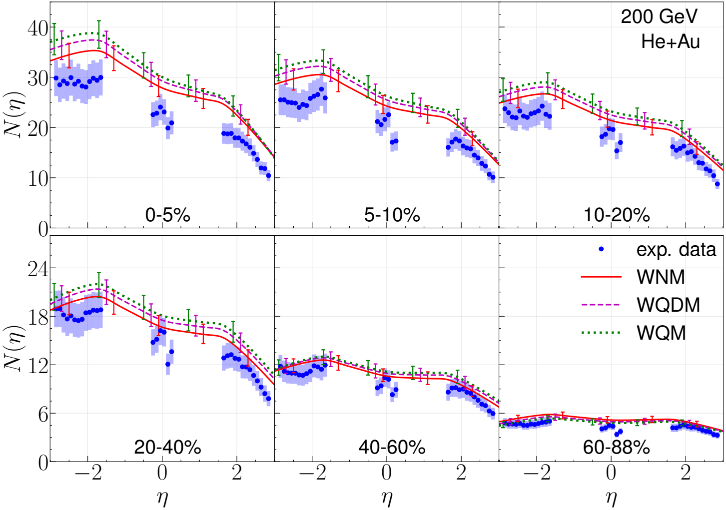
p+Au (small + big)



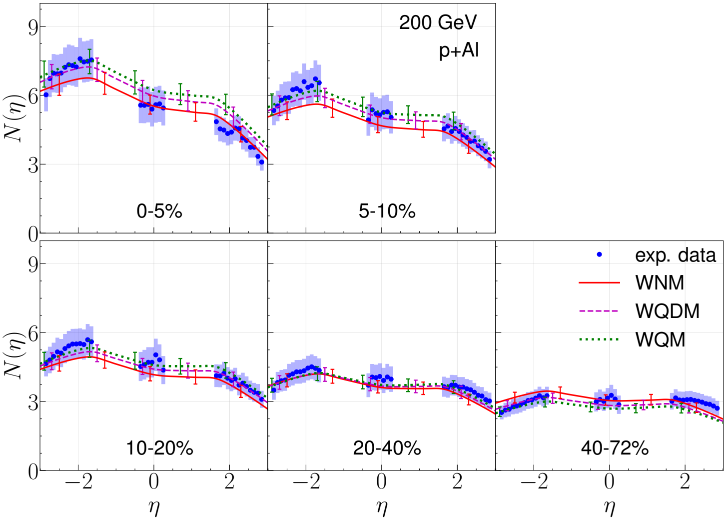
MB, A. Bzdak, P. Gutowski, arXiv:1904.01435 [hep-ph]

Data points: A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **121**, no. 22, 222301 (2018)

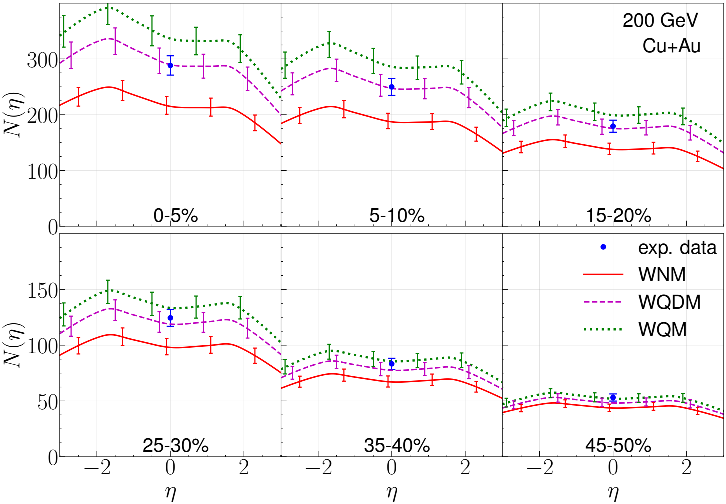
^{3}He+Au (small + big)



p+Al (small + middle)



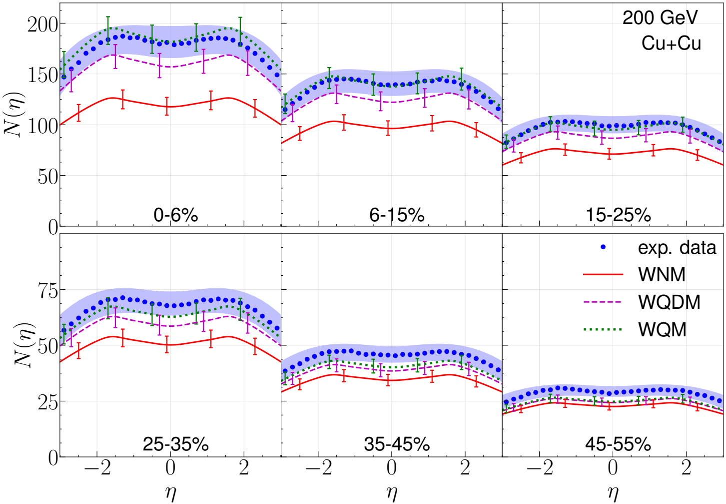
Cu+Au (big + bigger)



Data points: A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **93**, no. 2, 024901 (2016)

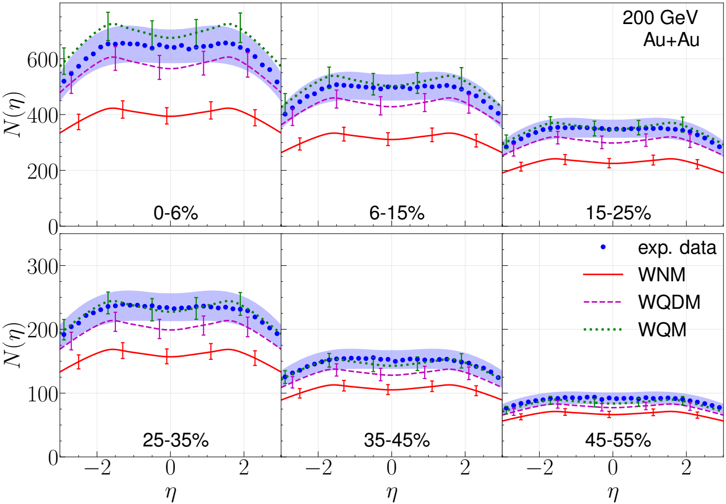
Symmetric collisions

Cu+Cu (big + big)



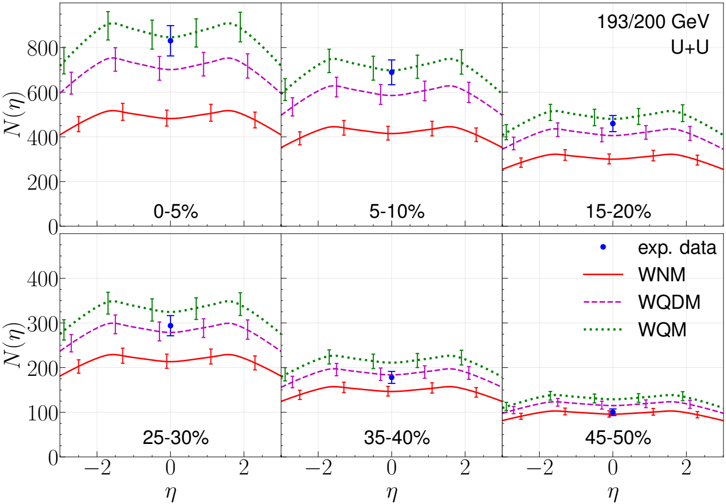
Data points: B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **102**, 142301 (2009)

Au+Au (big + big)



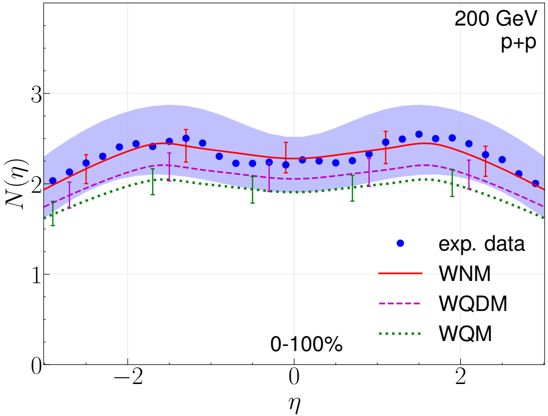
Data points: B. B. Back *et al.*, Phys. Rev. Lett. **91**, 052303 (2003)

U+U (big + big)



Data points: A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **93**, no. 2, 024901 (2016)

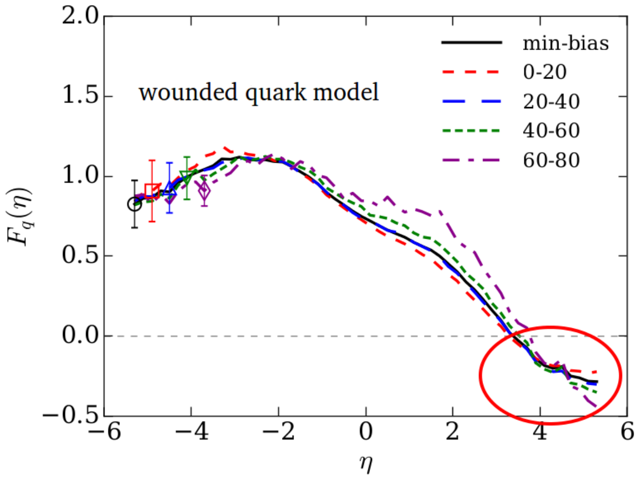
p+p (small + small)



Data points: B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. C **83**, 024913 (2011)

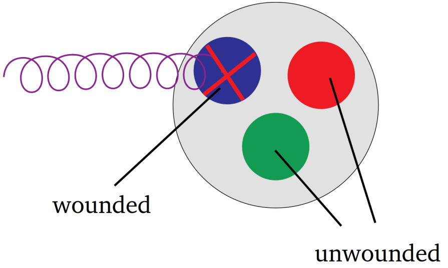
Unwounded quarks

Limited η range of application



Unwounded quarks in wounded nucleons

- Nucleon is wounded if at least one of its quarks is wounded
- If 1 quark is wounded, there are 2 more unwounded quarks remaining!



- A. Białas, A. Bzdak, Phys. Lett. B **649**, 263 (2007) Erratum: [Phys. Lett. B **773**, 681 (2017)]

Unwounded quarks in wounded nucleons

- Add terms in multiplicity equation:

$$N(\eta) = w_L F(\eta) + w_R F(-\eta) + \boldsymbol{\overline{w}_L U(\eta) + \overline{w}_R U(-\eta)}$$

  $\overline{w}_L$, $\overline{w}_R$ - mean numbers of unwounded quarks from wounded nucleons in left- and right-going nucleus, respectively

  $U(\eta)$ - emission function of an unwounded quark from wounded nucleon
- WQM: $w_q + \overline{w}_q = 3w_n$
- $U(\eta)$ not significant as long as $|\eta| < 3$.
- $U(\eta)$ can be extracted:
  $U(\eta) = \frac{\overline{w}_L N(\eta) - \overline{w}_R N(-\eta) - (w_L \overline{w}_L - w_R \overline{w}_R) F(\eta) + (w_R \overline{w}_L - w_L \overline{w}_R) F(-\eta)}{(\overline{w}_L + \overline{w}_R)(\overline{w}_L - \overline{w}_R)}$

Unwounded quarks in wounded nucleons

$$N(\eta) = w_L F(\eta) + w_R F(-\eta) + \boldsymbol{\overline{w}_L U(\eta) + \overline{w}_R U(-\eta)}$$

$$U(\eta) = \frac{\overline{w}_L N(\eta) - \overline{w}_R N(-\eta) - (w_L \overline{w}_L - w_R \overline{w}_R) F(\eta) + (w_R \overline{w}_L - w_L \overline{w}_R) F(-\eta)}{(\overline{w}_L + \overline{w}_R)(\overline{w}_L - \overline{w}_R)}$$

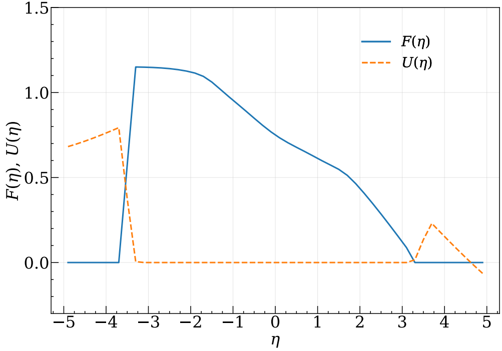
- In order to extract $U(\eta)$ you need:
  - $\overline{w}_L \neq \overline{w}_R$ - asymmetric collision
  - $dN_{ch}/d\eta$ in wide η range
  - to postulate $F(\eta)$ for $|\eta| > 3$, e.g.:

$$\widetilde{F}(\eta) = \begin{cases} 0, & \eta < -\eta_0 - \Delta\eta \\ a\eta + b, & -\eta_0 - \Delta\eta \leq \eta < -\eta_0 \\ F(\eta), & |\eta| \leq \eta_0 \\ 0, & \eta > \eta_0 \end{cases}$$

  - Compare with data and look for good $F(\eta)$ for $|\eta| > 3$ postulate.

Unwounded quarks in wounded nucleons - only trial

$$N(\eta) = w_L F(\eta) + w_R F(-\eta) + \boldsymbol{\overline{w}_L U(\eta) + \overline{w}_R U(-\eta)}$$



$$\widetilde{F}(\eta) = \begin{cases} 0, & \eta < -\eta_0 - \Delta\eta \\ a\eta + b, & -\eta_0 - \Delta\eta \le \eta < -\eta_0 \\ F(\eta), & |\eta| \le \eta_0 \\ 0, & \eta > \eta_0 \end{cases}$$

- $\eta_0 = 3.3$
  $\Delta\eta = 0.4$
- $U(\eta)$ should be 0 for $\eta > 0$
  uncertainties + postulated $F(\eta)$
- Good starting point for further research.

Summary

- U+U study by STAR shows that WQM describes particle production better than WNM + N_{coll}.
- U+U data useful to study effects dependent on initial geometry.
- Using $N(\eta)$ data from d+Au @200 GeV and our MC Glauber simulation, the universal $F(\eta)$ functions were extracted in 3 models.
- WQM and WQDM with $F(\eta)$ work well for all systems (support subnucleonic effects) predicting $dN_{ch}/d\eta$ consistent with data.
- One minimalistic and almost parameter-free model describes all collisions.
- Possible extensions:
  - Different energies
  - Wider η range

Backup

First step

- $F(\eta) = \frac{1}{2}\left[\frac{N(\eta)+N(-\eta)}{w_L+w_R} + \frac{N(\eta)-N(-\eta)}{w_L-w_R}\right]$
- Take distribution $N(\eta) = dN_{ch}/d\eta$ from d+Au @200 GeV @BNL RHIC by PHOBOS.

Simulation algorithm: MC Glauber based.

- For each nucleus-nucleus collision:
  - Draw nucleons positions from density distibutions.
  - [In WQM and WQDM: draw also quarks (and diquarks) positions around the center of nucleon.]
  - Draw impact parameter b.
  - For each pair check whether the collision happened.
  - For each wounded source draw the number of emitted particles according to NBD.
- Divide all events into centrality classes based on the number of produced particles.
- Calculate mean numbers of wounded sources w_L, w_R in centralities.

Simulation details

- Nucleons positions
  - Au, Cu: Woods-Saxon
  - d: Hulthen
  - Deformed nuclei Al, U: generalized W-Sax (no spherical symmetry)
- Quarks positions: $\varrho(\vec{r}) = \varrho_0 \exp\left(-\frac{r}{a}\right)$

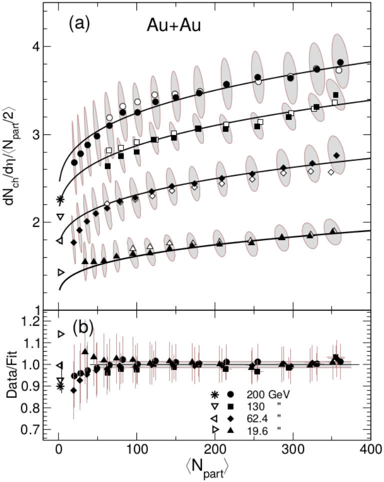
  S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **89**, no. 4, 044905 (2014)
- Impact parameter: b^2 from $[0, b^2_{max}]$
- Check whether it was a collision: $u < \exp\left(-\frac{s^2}{2\gamma^2}\right), \quad \gamma^2 = \sigma/(2\pi)$

  σ - cross section:
  - $\sigma_{nn} = 41$ mb in WNM
  - $\sigma_{qq} = 6.65$ mb in WQM
  - $\sigma_{qq} = 5.75$ mb in WQDM with $\sigma_{\mathrm{qq}} : \sigma_{\mathrm{qd}} : \sigma_{\mathrm{dd}} = 1 : 2 : 4$

Simulation details

- Charged particle production
  - Each wounded nucleon populates number of particles according to NBD with $\langle n \rangle = 5$ oraz $k = 1$
  - In case of WQM and WQDM divide $\langle n \rangle$ and k by 1.27 and 1.14, respectively (mean number of wounded sources per a wounded nucleon).

WNM is invalid



B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. C **83**, 024913 (2011)

- WNM:

$$\frac{N_{ch}}{N_{part}} = \text{const}$$

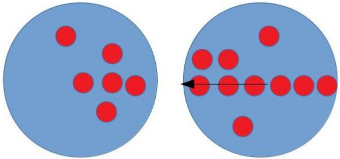
- $\frac{N_{ch}}{N_{part}} \sim \left(1 + cN_{part}^{1/3}\right)$
- Try to introduce:

$$\frac{N_{ch}}{N_{part}} \neq \text{const}$$

  by N_{coll} dependence.
- WQM and WNM + N_{coll} both have the same goal but different physics under it.
- Models differ at large N_{coll}

Explain $N_{part}^{1/3}$ dependence qualitatively

- $V_A \sim N_{part} V_n \sim R^3$
- $R \sim N_{part}^{1/3}$
- $N_{coll} \sim N_{part} \cdot N_{part}^{1/3} = N_{part}^{4/3}$
- $N_{ch} \sim N_{coll}$
- $\frac{N_{ch}}{N_{part}} \sim N_{part}^{1/3}$



Input: d+Au @200 GeV @BNL RHIC by PHOBOS

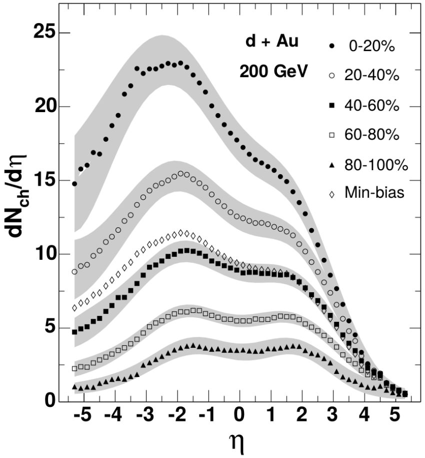
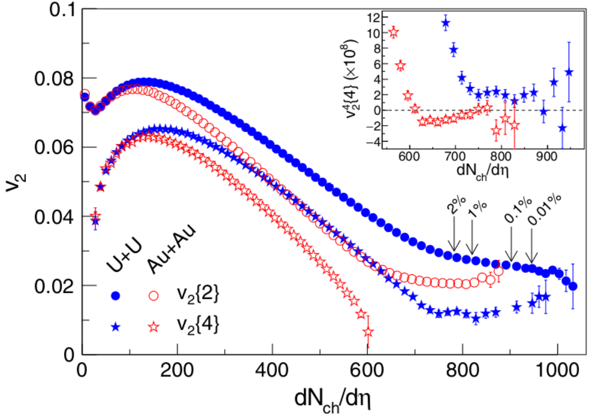


Figure: B. B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. C **72**, 031901 (2005)

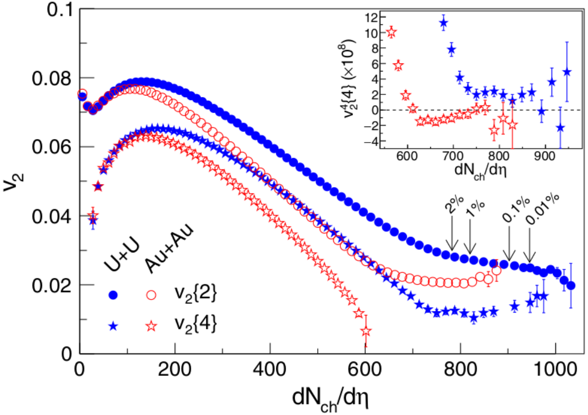
v_2 vs $dN_{ch}/d\eta$



L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

- In general, decreasing ($\sim$ anticorrelation), as expected
- $v_2^4\{4\} < 0$ for Au+Au $\Leftarrow$ fluctuations in #participants.
- $v_2^4\{4\} > 0$ for U+U $\Rightarrow$ prolate shape increases anisotropy. Shape observable in data.

v_2 vs $dN_{ch}/d\eta$



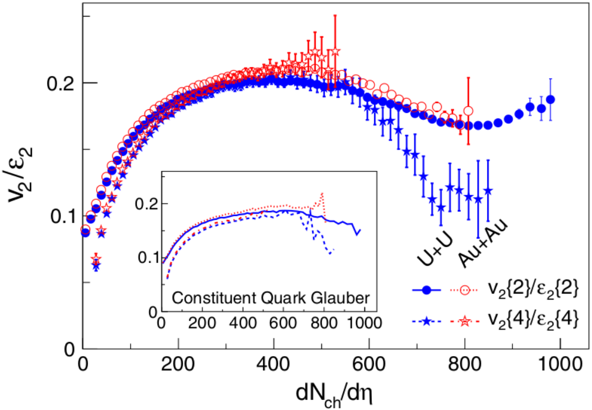
L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

- WNM+N_{coll} $\Rightarrow$ v_2 should decrease in 1% central. "knee" (tip-tip domination).
- Not observed!
- Possible reason: too many fluctuations.

v_2 vs $dN_{ch}/d\eta$

- WNM+N_{coll} $\Rightarrow$ v_2 should decrease in 1% central. "knee" (tip-tip domination).
- Not observed!
- Possible reason: too many fluctuations.
- Add more fluctuations
  - knee should disappear.
  - ε_2 should increase in central collisions.
- Let's take $\frac{v_2}{\varepsilon_2}$ vs $dN_{ch}/d\eta$.

v_2/ε_2 vs $dN_{ch}/d\eta$



L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **115**, no. 22, 222301 (2015)

- General agreement with expectations
- but as fluctuations increased, ε_2 should increase in central collisions.
- Turnover for $v_2\{2\}/\varepsilon_2$ unexpected.
- WQM gives more natural results.

Detailed study of v_2 vs multiplicity

- Lack of knee and presence of turnover ⇒ different explanation required!
- Decrease of v_2 with multiplicity can also be due to less central collisions.
- Use control sample of Au+Au collisions (v_2 should be const at given centrality).
- Normalize multiplicity (different size of Au and U).