Wounded quarks, diquarks and nucleons in heavy-ion collisions

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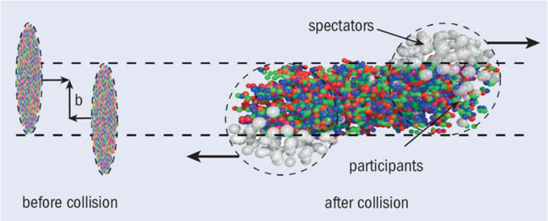
In collaboration with Adam Bzdak and Paweł Gutowski

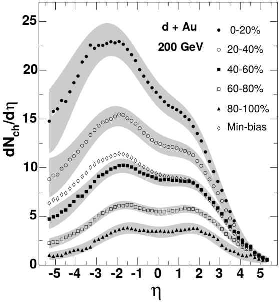
Outline

1. Wounded constituent models
2. Wounded constituent emission function
3. Predictions for $dN_{ch}/d\eta$ compared with PHENIX and PHOBOS data
4. Summary

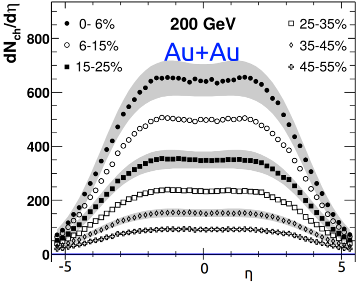
Particle production in relativistic heavy-ion collisions



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



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



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

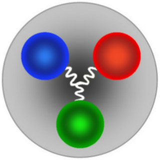
Try to describe by wounded nucleon model

- 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.
  - For each nucleon from one nucleus check whether it interacts with each nucleon from another nucleus.
  - Each nucleon which interacts with at least one other - wounded.
  - Each wounded nucleon produces particles independently of how many times it was "wounded".
  - $N_{ch} \sim N_{\text{part}}$

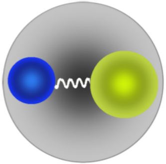
Wounded quark model

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



- WQDM not only works for particle production but also successfully describes the differential elastic pp cross-section $\frac{d\sigma}{dt}$.

  A. Bialas and A. Bzdak, Acta Phys. Polon. B **38**, 159 (2007)

  and extended model, e.g.

  F. Nemes, T. Csörgő and M. Csanád, Int. J. Mod. Phys. A **30**, no. 14, 1550076 (2015)

Common idea for WNM, WQM and WQDM models

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

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

A. Bialas and W. Czyz, Acta Phys. Polon. B **36**, 905 (2005)

$F(\eta)$ - **wounded constituent emission function**
w_L - mean number of wounded constituents 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 constituents computed in MC simulation.

First step

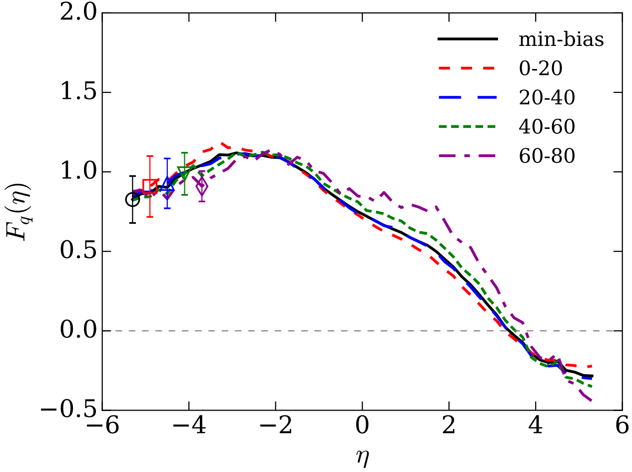
- $F(\eta) = \frac{1}{2}\left[\frac{N(\eta)+N(-\eta)}{w_L+w_R} + \frac{N(\eta)-N(-\eta)}{w_L-w_R}\right]$
- Take distribution $N(\eta) = dN_{ch}/d\eta$ from d+Au @200 GeV @BNL RHIC by PHOBOS.

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 constituent 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 constituents w_L, w_R in centralities.

Emission functions - wounded quarks

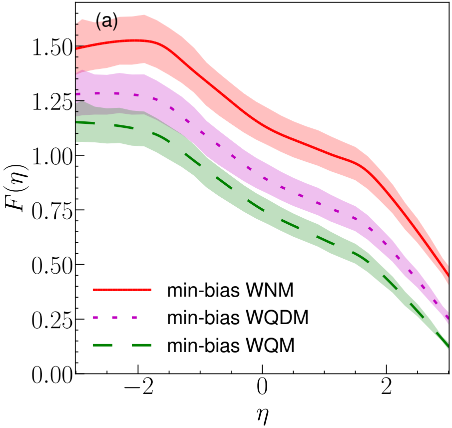
in various centrality classes



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

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, Phys. Rev. C **100**, no. 6, 064902 (2019)

Next step

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

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

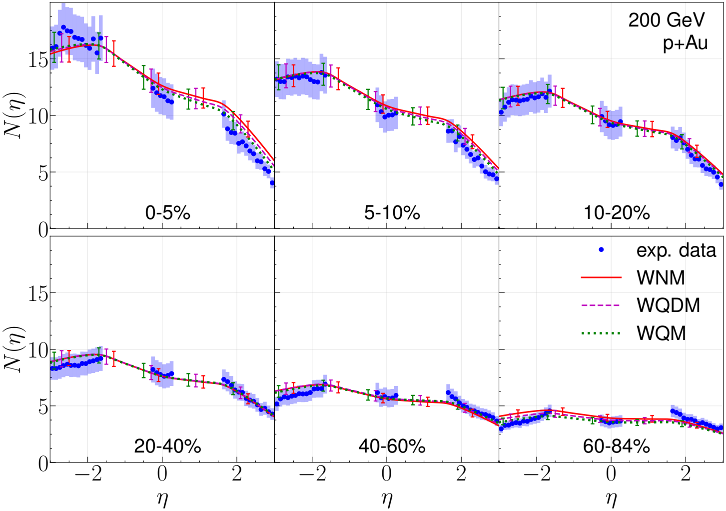
- Compare with experimental data.

PHENIX measurements on asymmetric collisions

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

Asymmetric collisions

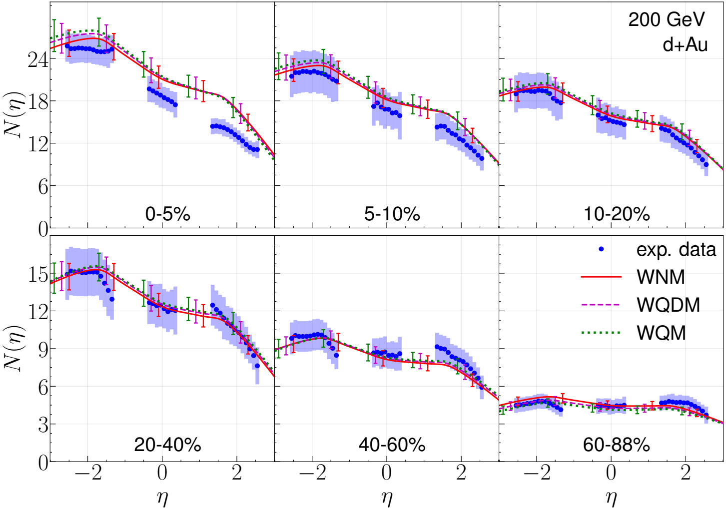
p+Au (small + big)



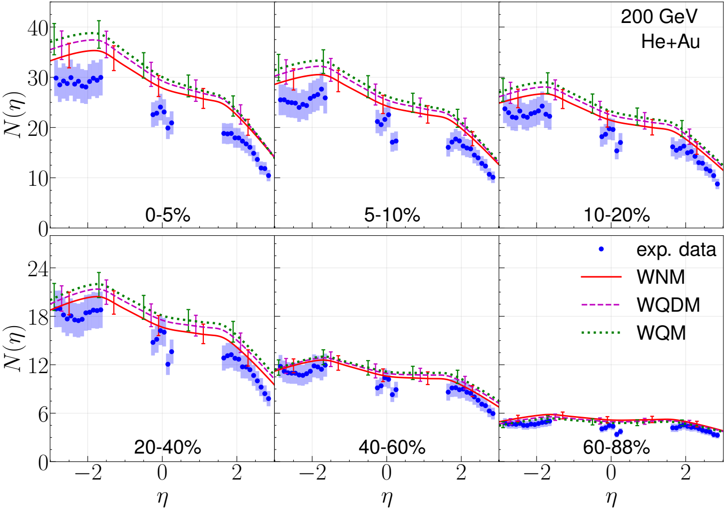
MB, A. Bzdak, P. Gutowski, Phys. Rev. C **100**, no. 6, 064902 (2019)

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

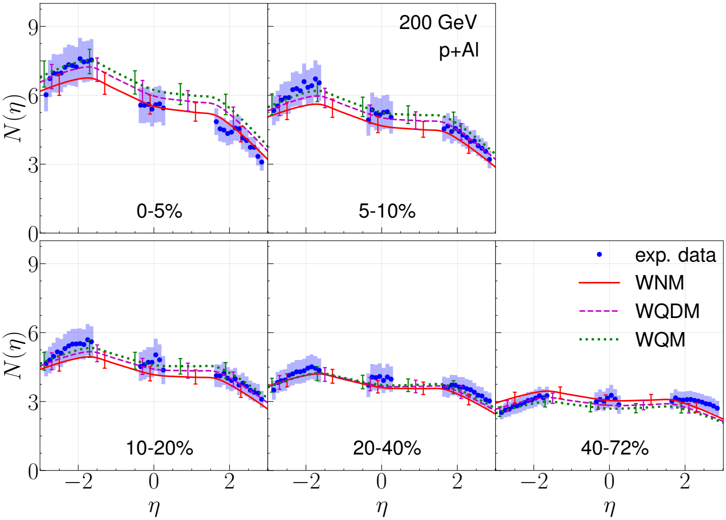
d+Au (small + big)



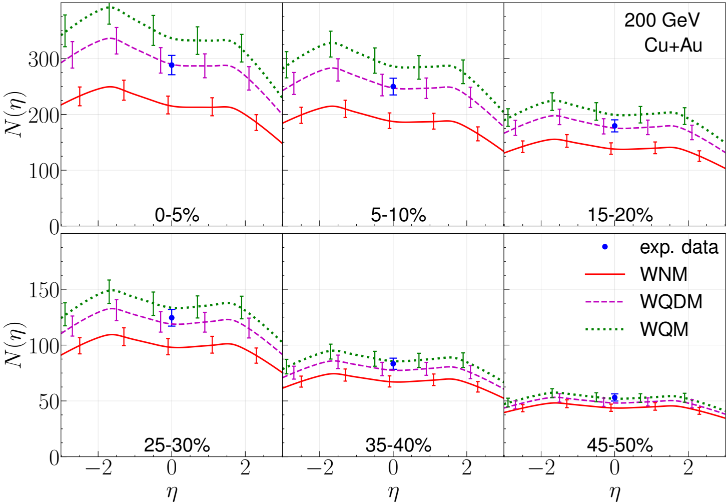
^{3}He+Au (small + big)



p+Al (small + middle)



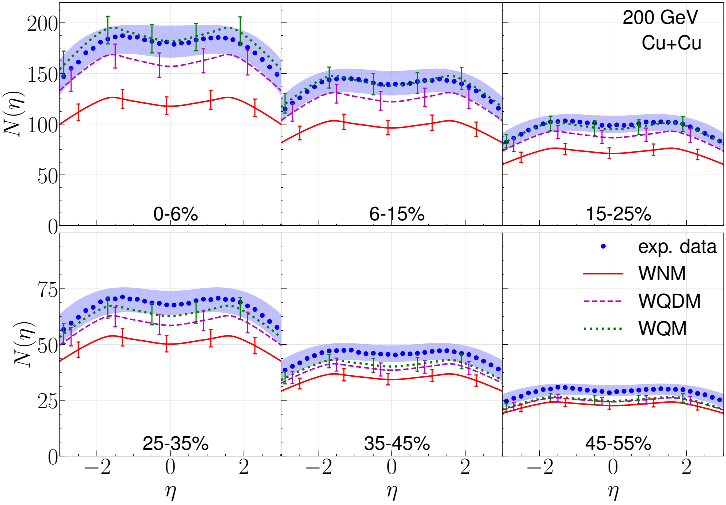
Cu+Au (big + bigger)



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

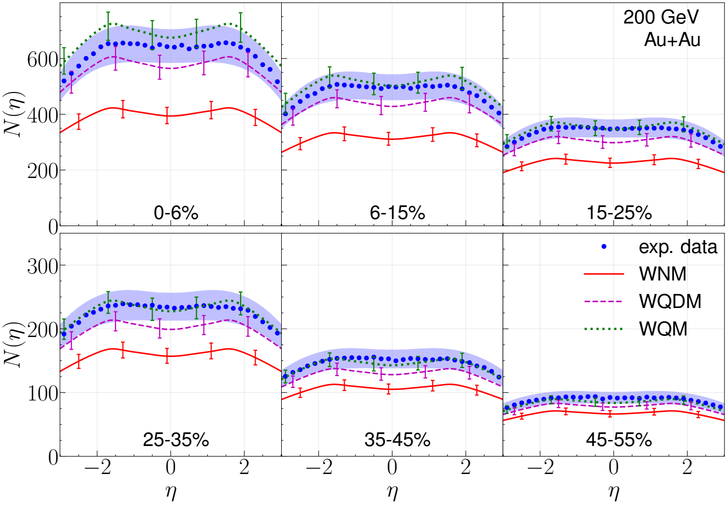
Symmetric collisions

Cu+Cu (big + big)



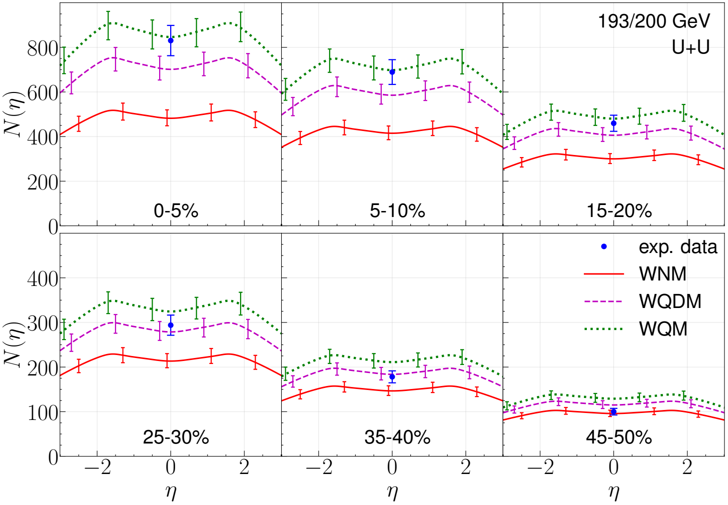
Data points: B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **102**, 142301 (2009)

Au+Au (big + big)



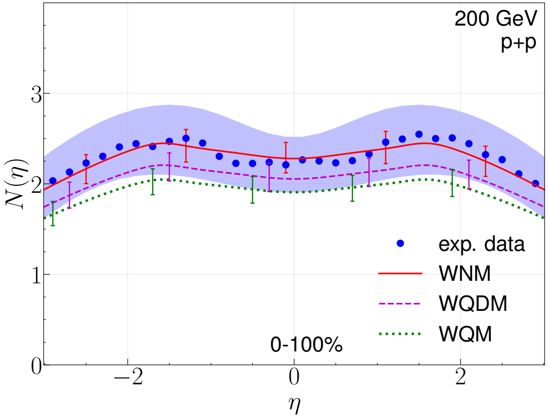
Data points: B. B. Back *et al.*, Phys. Rev. Lett. **91**, 052303 (2003)

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)

Summary

- Using $dN_{ch}/d\eta$ data from d+Au @200 GeV by PHOBOS and our MC Glauber simulation, the universal $F(\eta)$ wounded-constituent emission functions were extracted in 3 models.
- WQM and WQDM with $F(\eta)$ work well for all systems predicting $dN_{ch}/d\eta$ consistent with data.
- A minimalistic and almost parameter-free model describes all collisions.
- Possible extensions:
  - Different energies
  - Wider η range (by taking unwounded quarks into account)

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 constituent 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 constituents 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 uniform on $[0, b^2_{max}]$
- Check whether it was a collision: $u < \exp\left(-\frac{s^2}{2\gamma^2}\right), \quad \gamma^2 = \sigma/(2\pi)$

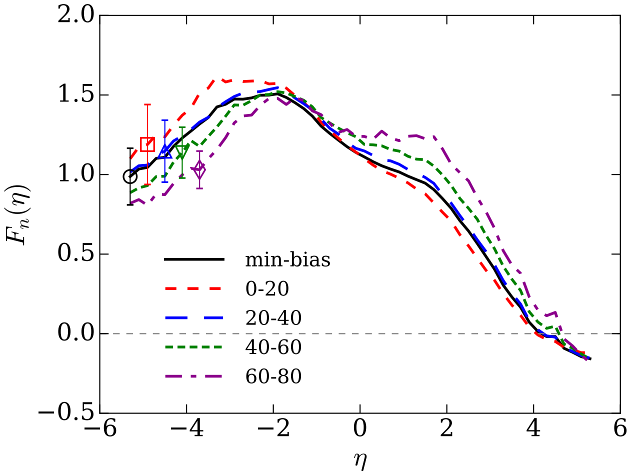
  σ - cross section:
  - $\sigma_{nn} = 41$ mb in WNM
  - $\sigma_{qq} = 6.65$ mb in WQM
  - $\sigma_{qq} = 5.75$ mb in WQDM with $\sigma_{\mathrm{qq}} : \sigma_{\mathrm{qd}} : \sigma_{\mathrm{dd}} = 1 : 2 : 4$

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 constituents per a wounded nucleon).

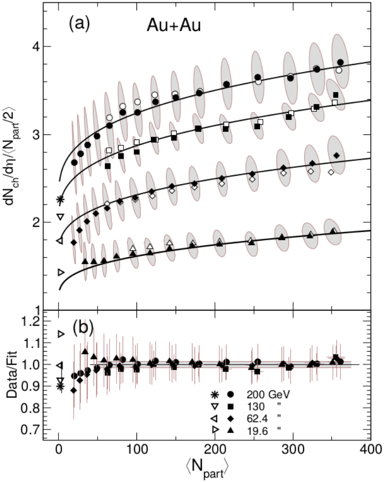
Emission functions - wounded nucleons

in various centrality classes



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

WNM is invalid



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

- WNM:

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

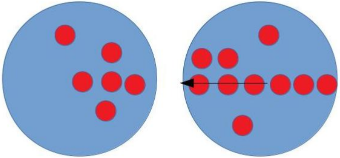
- Data: $\frac{N_{ch}}{N_{part}} \sim \left(1 + cN_{part}^{1/3}\right)$
- Try to introduce:

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

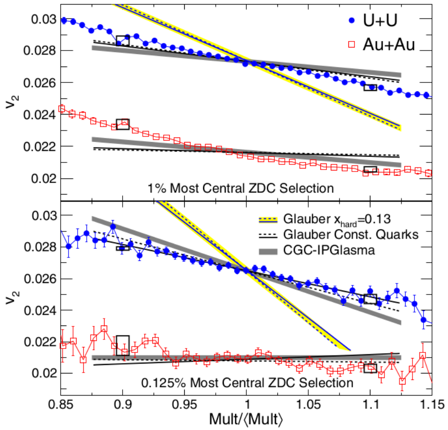
  by N_{coll} dependence.
- WQ(D)M and WNM + N_{coll} both have the same goal but different physics under it.
- Models differ at large N_{coll}

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

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



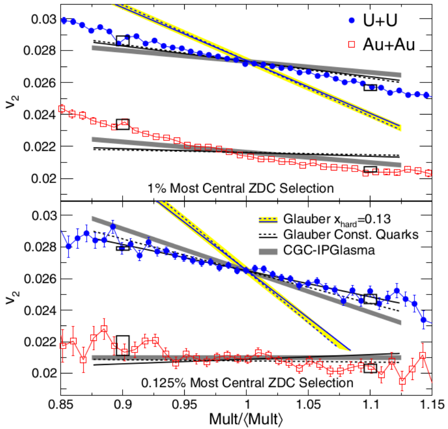
v_2 vs normalized multiplicity



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}:

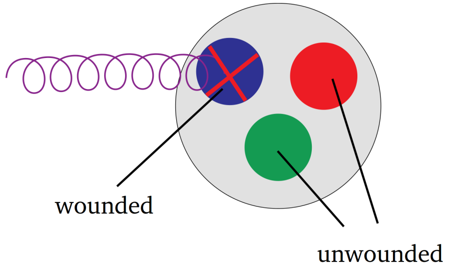
  $N_{ch} \sim (1 - x_{hard})\frac{N_{part}}{2} + x_{hard} N_{coll}$

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

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

Unwounded quarks in wounded nucleons

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



- A. Białas, A. Bzdak, Phys. Lett. B **649**, 263 (2007)

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

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

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

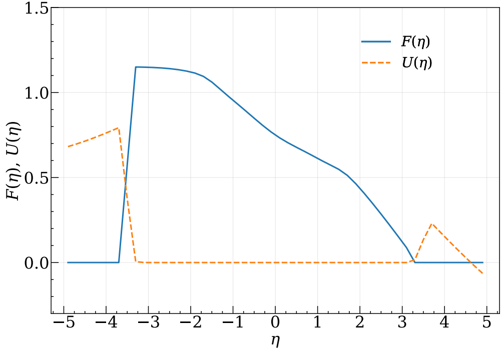
- In order to extract $U(\eta)$ you need:
  - $\overline{w}_L \neq \overline{w}_R$ - asymmetric collision
  - $dN_{ch}/d\eta$ in wide η range
  - to postulate $F(\eta)$ for $|\eta| > 3$, e.g.:

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

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

Unwounded quarks in wounded nucleons - only trial

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

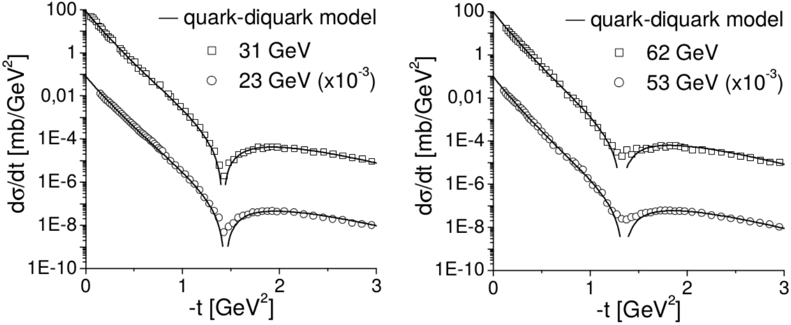


$$\widetilde{F}(\eta) = \begin{cases} 0, & \eta < -\eta_0 - \Delta\eta \\ a\eta + b, & -\eta_0 - \Delta\eta \le \eta < -\eta_0 \\ F(\eta), & |\eta| \le \eta_0 \\ 0, & \eta > \eta_0 \end{cases}$$

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

WQDM for the elastic pp $\frac{d\sigma}{dt}$

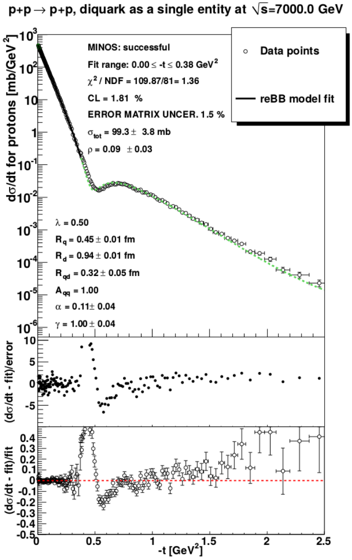
Original model introduced for 23-62 GeV energies

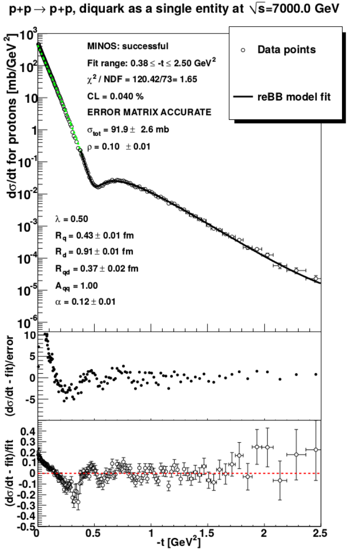


A. Bialas and A. Bzdak, Acta Phys. Polon. B **38**, 159 (2007) [hep-ph/0612038]

WQDM for the elastic pp $\frac{d\sigma}{dt}$

Extended model for TeV energies





F. Nemes, T. Csörgő and M. Csanád, Int. J. Mod. Phys. A **30**, no. 14, 1550076 (2015)