Influence of the neutron skin effect in heavy-ion collisions

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Based on:
arXiv:1908.10231

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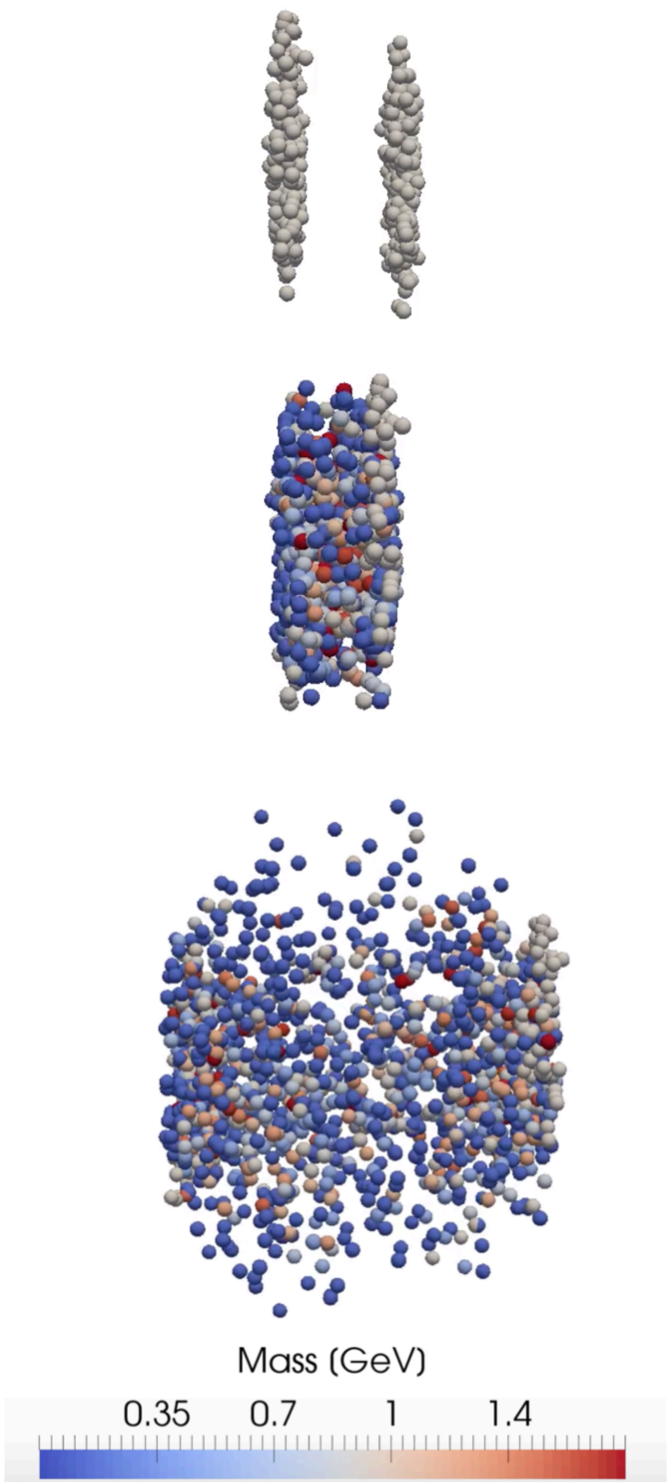
Introduction

Study properties of QCD matter and phase diagram

Performing heavy ion collisions at different energy regimes to produce QCD matter at different temperatures and baryochemical potential

Due to non-perturbative regime of QCD it is challenging to compute observable quantities from first principles

Transport models give unique insights on the dynamical evolution of heavy ion collisions



Pb-Pb collision with 17.3 GeV center-of-mass energy
(by J. Mohs)

Nucleon distribution

How are protons and neutrons distributed in the nucleus in the initial state?

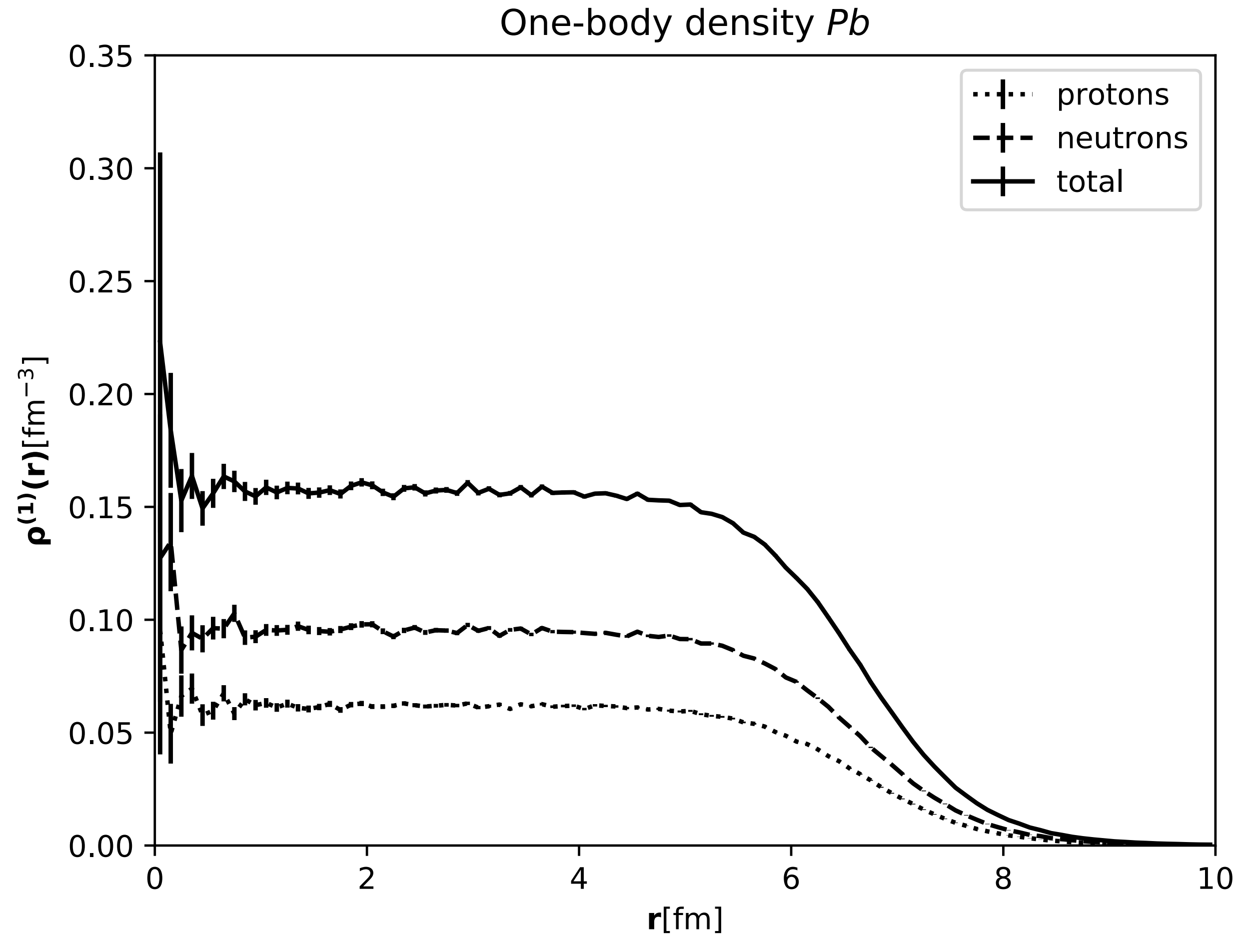
Traditional Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{e^{(r - R(\theta,\phi)/d)} + 1},$$

with $R(\theta, \phi) = R_0 \left(1 + \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \beta_{lm} Y_l^m \right)$

Proton and neutron distribution:

$$\rho(r) = \frac{Z}{A}\rho_p(r) + \frac{N}{A}\rho_n(r)$$



Neutron skin effect

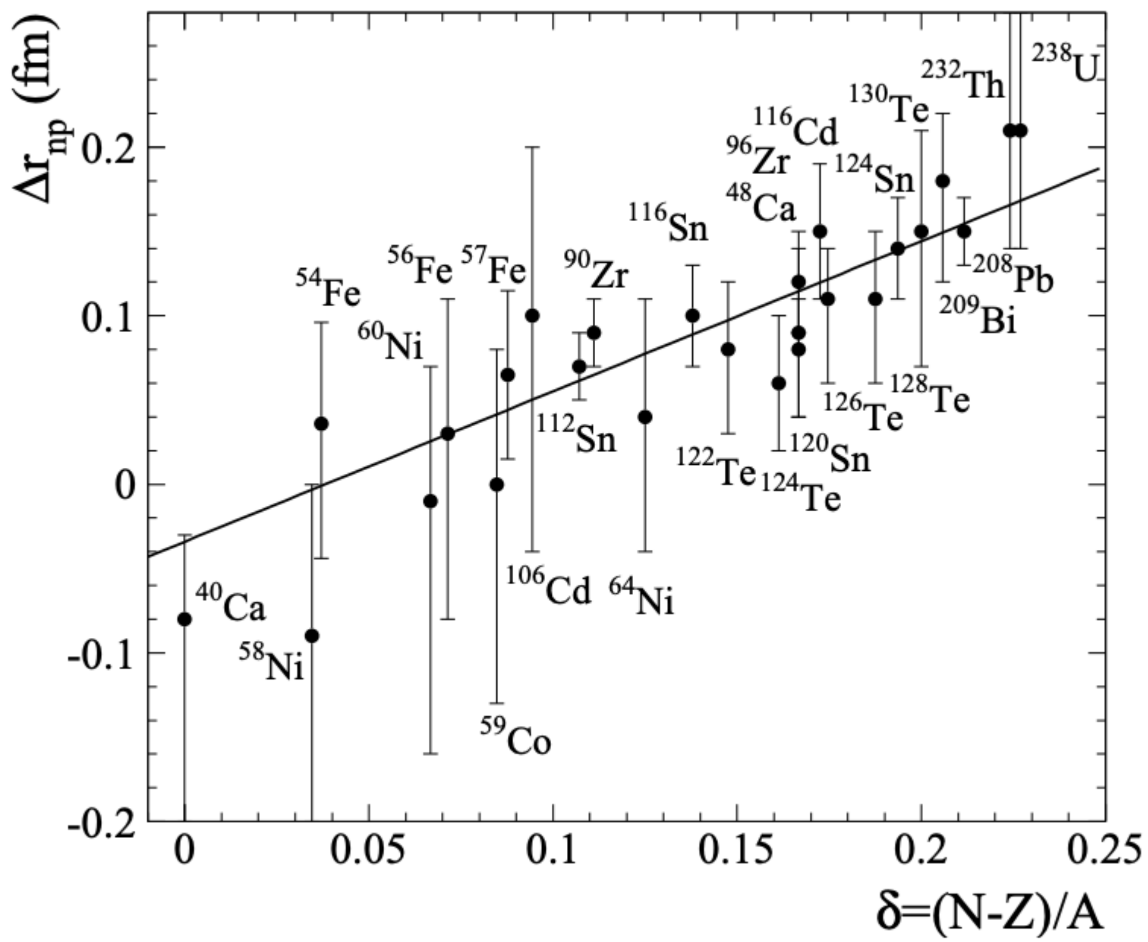
Experimental measurement of

$$\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$

→ Different Woods-Saxon parameter for protons and neutrons

Nuclei of interest in this work:
^{208}Pb($\delta \approx 0.21$), ^{96}Zr($\delta \approx 0.17$), ^{96}Ru($\delta \approx 0.08$), ^{197}Au($\delta \approx 0.2$)

→ Neutron skin emerges in neutron rich nuclei



LEAR Collab. Int Jour of Mod Phys E 13 (2004) 343

Neutron skin effect

Phenomenological formula for binding energy per nucleon

$$B(Z,N) = \underbrace{a_V A}_{\text{volume}} - \underbrace{a_S A^{2/3}}_{\text{surface}} - \underbrace{a_C Z^2/A^{1/3}}_{\text{Coulomb}} - \underbrace{a_A (N-Z)^2/A}_{\text{asymmetry}} + \dots$$

Nucleus is in favor to populate more neutrons in the outer region

$$e_{sym} = J + Lx + \frac{1}{2}Kx^2 + \dots \ , \qquad x = (\rho - \rho_0)/3\rho_0$$

Neutron skin emerges from a competition between surface and stiffness of the symmetry energy

$$\Delta r_{np}^{\mathrm{Pb}} \sim L$$

C.J. Horowitz et al. arXiv:1401.5839

Neutron skin effect

Experimentally confirmed:

$\Delta r_{np}^{\mathrm{Pb}} = 0.15 \pm 0.03^{+0.16}_{-0.18}\,\mathrm{fm}$ → $\Delta r_{np}^{\mathrm{Pb}} = 0.15\,\mathrm{fm}$

$\Delta r_{np}^{\mathrm{Zr}} = 0.12 \pm 0.03$ → Largest value of neutron skin within the uncertainty → $\Delta r_{np}^{\mathrm{Zr}} = 0.15\,\mathrm{fm}$

Assumed:

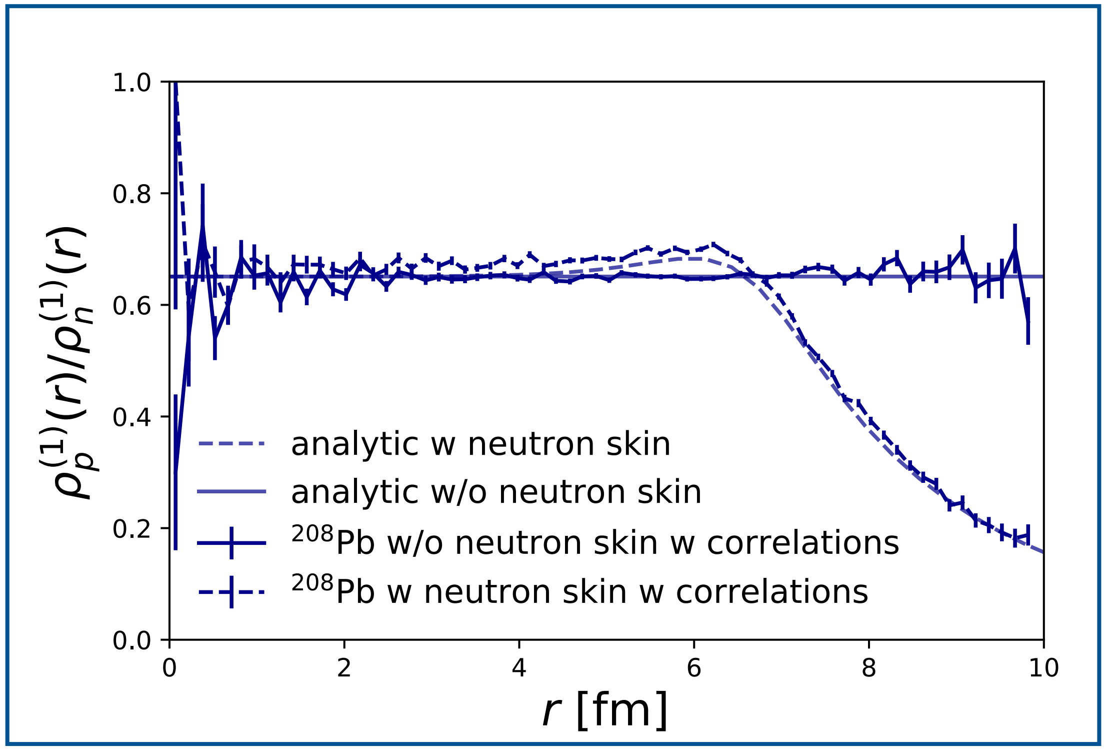
$\Delta r_{np}^{\mathrm{Au}} = 0.15\,\mathrm{fm}$

$\Delta r_{np}^{\mathrm{Ru}} = 0$

C. M. Tarbert, et al Phys. Rev. Lett. 112 (24) (2014) 242502
A. Trzcinska, et al Phys. Rev. Lett. 87 (2001) 082501

Implementation of neutron skin in SMASH via different Woods-Saxon parameters for protons and neutrons respectively

We use a halo type neutron skin $d_p < d_n$



Nucleon-nucleon short range correlations

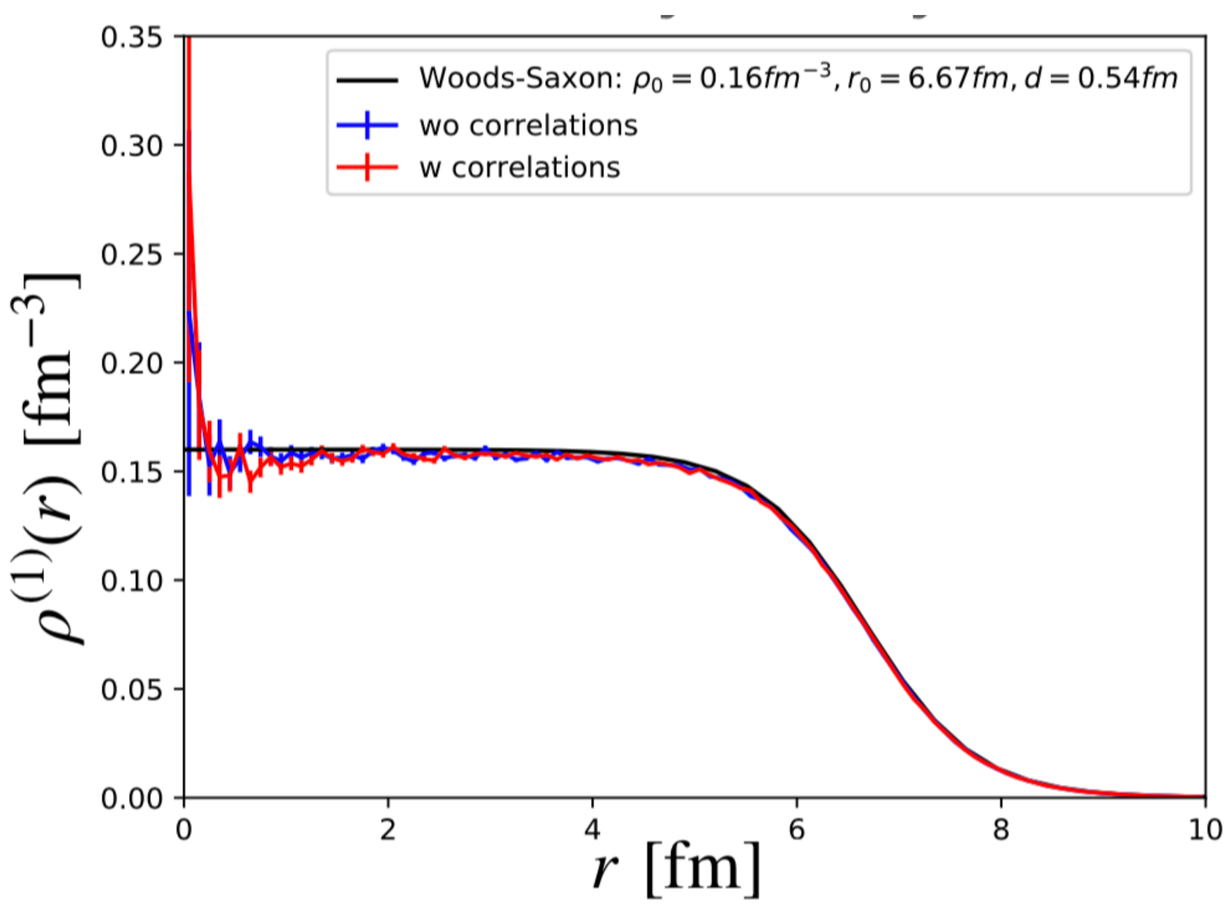
Ensure realistic spatial nucleon distribution by introducing correlation

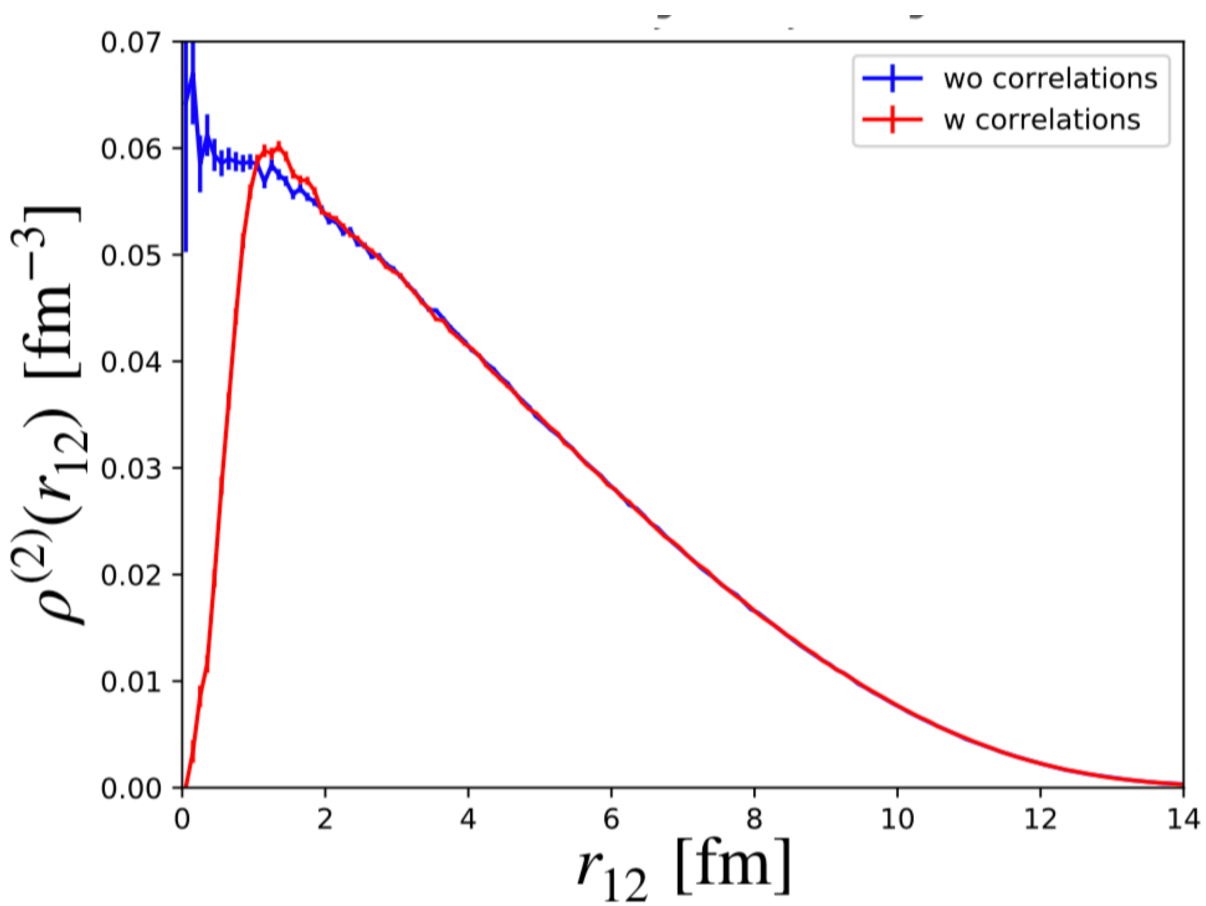
$$\psi(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N) = \hat{F}(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N)\, \phi_0(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N)$$

ϕ_0 : Uncorrelated wavefunction

$\hat{F}$: Correlation operator

Alvioli et al. Phys.Rev. C87 (2013) no.3, 034603





Other studies in heavy-ion collisions: inspirehep.net/author/profile/M.Alvioli.1

Model: SMASH

Simulating Many Accelerated Strongly-interacting Hadrons

Hadronic transport approach, effectively solving Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{coll}$$

Uses a geometric collision criterion

$$\pi d_\perp^2 < \sigma_{\mathrm{tot}}$$

Good description of low energy heavy ion collisions and of late stages of high energy heavy ion collisions

https://smash-transport.github.io

Weil et al PRC.94.054905 [2016]

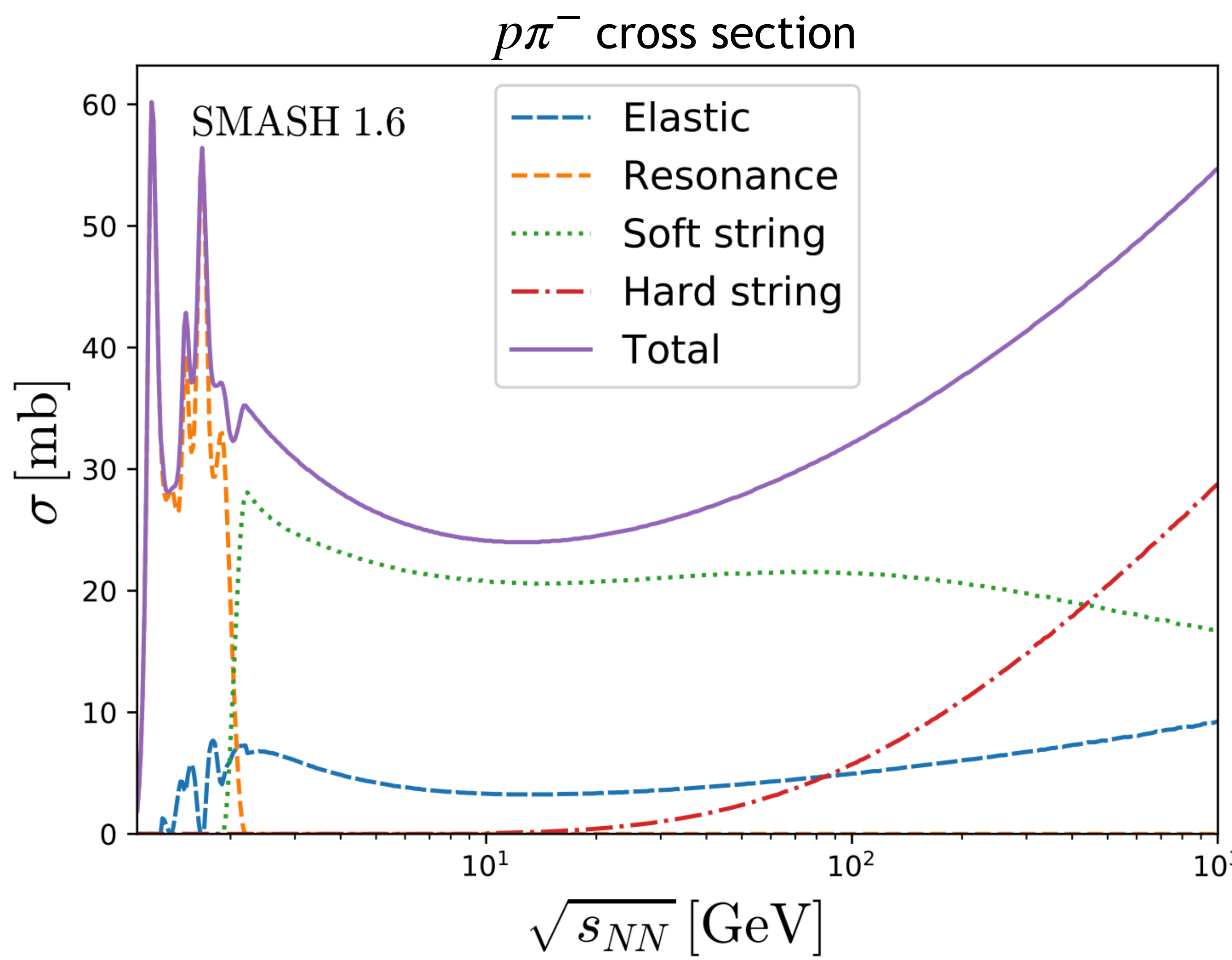
Model: SMASH

SMASH contains all baryons and mesons with masses up to $\sim 2\,\mathrm{GeV}$

$2 \leftrightarrow 1$ and $2 \leftrightarrow 1$ collision modeled through resonance formation and decay

Resonances are modeled via Breit Wigner spectral functions to reproduce experimental measurements

String excitation in high energy regime by PYTHIA for interactions with large $\sqrt{s}$



J. Mohs et al arXiv:1909.05586v1

Model: SMASH

Particles contained in the latest version SMASH 1.7

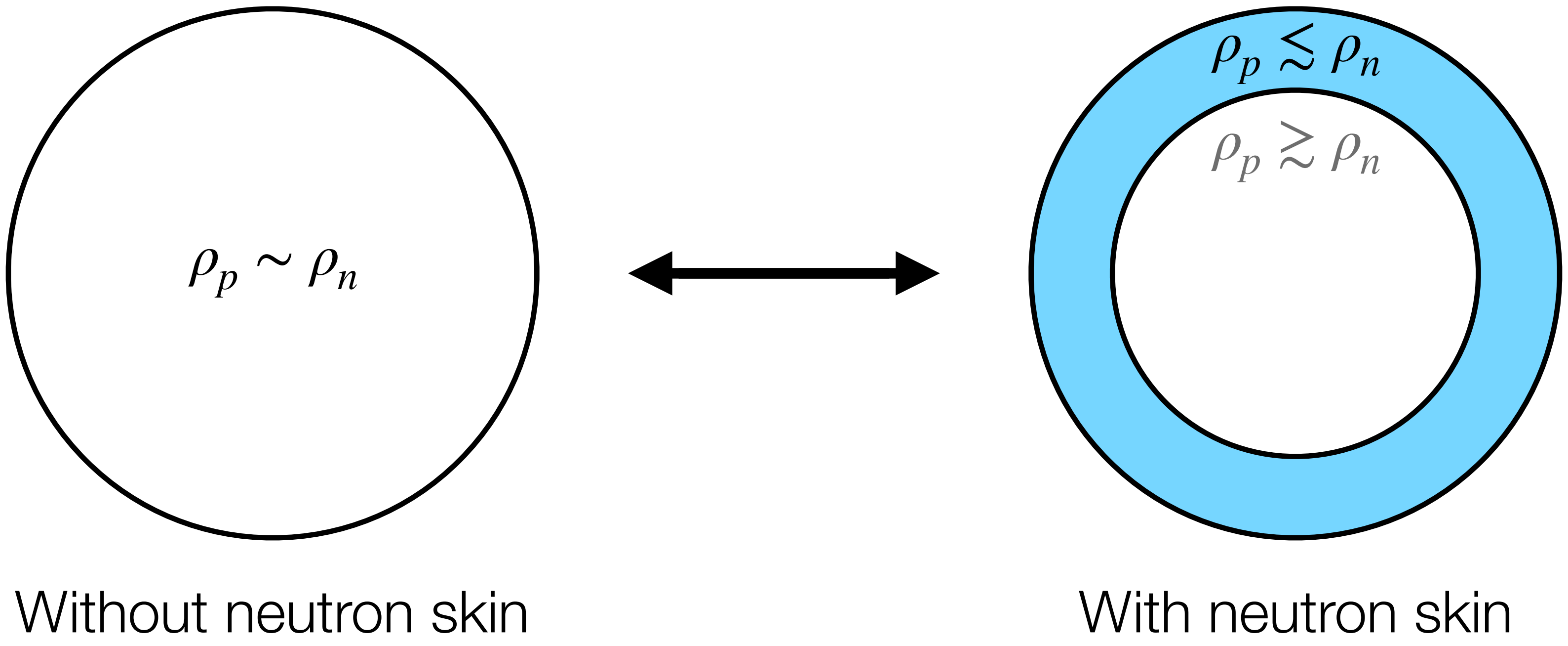
N	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω_{1672}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω_{2250}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}	
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}	
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}		
N_{1720}		Λ_{1830}	Σ_{2250}		
N_{1875}		Λ_{1890}			
N_{1900}		Λ_{2100}			
N_{1990}		Λ_{2110}			
N_{2060}		Λ_{2350}			
N_{2080}					
N_{2100}					
N_{2120}					
N_{2190}					
N_{2220}					
N_{2250}					

Unflavored				Strange
π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
π_{1300}	$f_{0\ 1370}$	$f_2'{}_{1525}$		K^*_{892}
π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
	$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^*_{1410}
η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_0^*{}_{1430}$
η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_2^*{}_{1430}$
η_{1405}		$f_{1\ 1285}$		K^*_{1680}
η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
	ϕ_{1680}			$K_3^*{}_{1780}$
σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
	$h_{1\ 1170}$			$K_4^*{}_{2045}$
ρ_{776}		$\pi_{1\ 1400}$		
ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
ρ_{1700}				
	$a_{1\ 1260}$	$\eta_{2\ 1645}$		
ω_{783}				
ω_{1420}		$\omega_{3\ 1670}$		
ω_{1650}				

Weil et al PRC.94.054905 [2016]

Starting position

Different charge distribution in the initial state of the heavy-ion collision



Which electric charge dependent reactions are influenced?
How is the electric charge density in the collision affected?
What about the magnetic fields?

Outline

Implement the neutron skin in the initial state of SMASH

Present different calculations:

1. Dilepton production in different centrality classes
2. Electric charge density in the collision
3. Magnetic fields and its impact on the isobar run at RHIC

Other calculations so far on this topic:

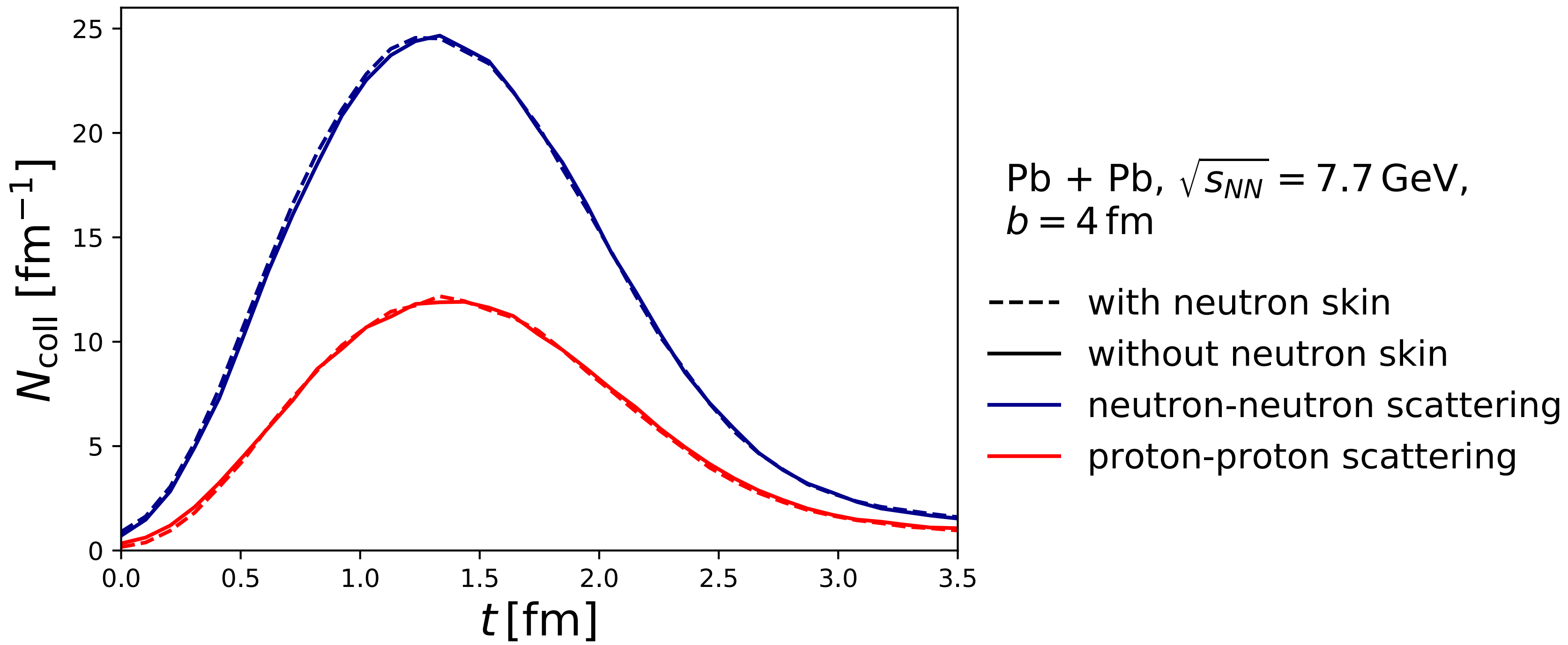
π^-/π^+ - ratio at beam energies of $400\ \mathrm{AMeV}$ C. Hartnack et al. arXiv:1808.09868

Dependence of charged hadron multiplicity on the neutron skin thickness Hanlin Li et al arXiv:1910.06170

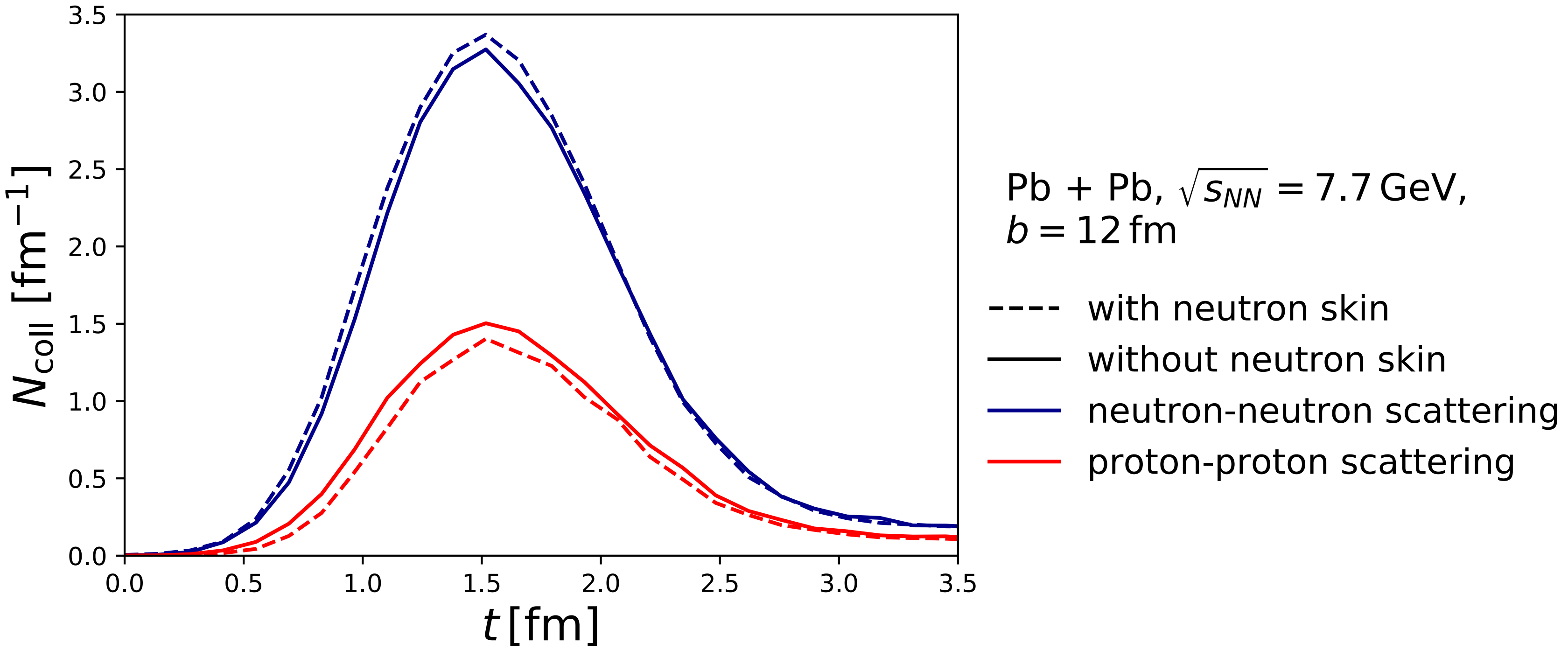
Impact of neutron skin on $W^{\pm}$ production at LHC M. Alvioli et al. Phys. Rev. C 100, 024912

Number of NN scatterings

No large difference in central collisions



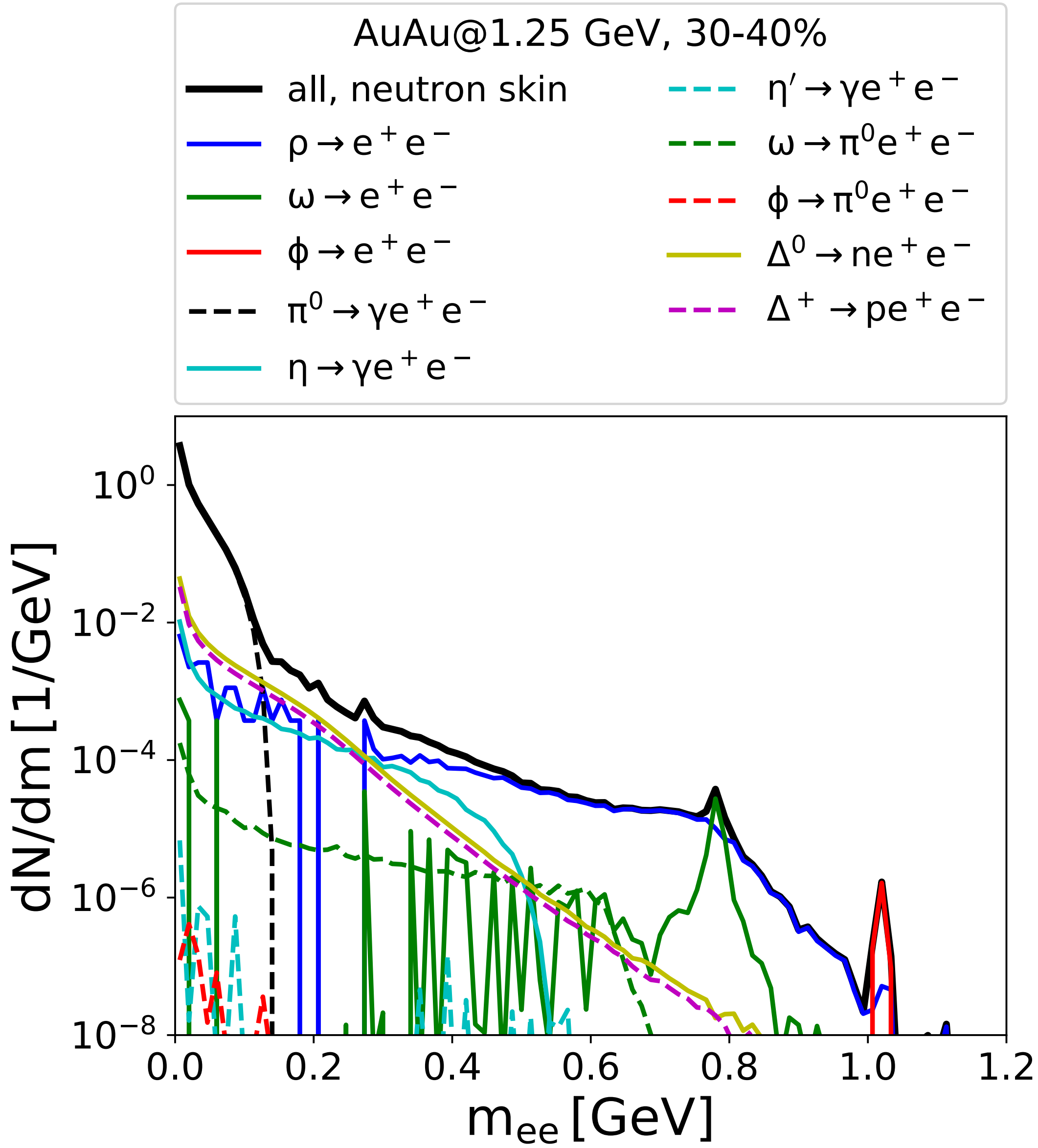
Increased *nn* and decreased *pp* collisions in peripheral collisions



Dilepton production

Study influence of the neutron skin at HADES energies Au+Au@E_{kin}=1.25GeV

Invariant mass spectrum



$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\phi \to e^+e^-$
$\pi^0 \to \gamma e^+e^-$
$\eta \to \gamma e^+e^-$
$\eta' \to \gamma e^+e^-$
$\omega \to \pi^0 e^+e^-$
$\phi \to \pi^0 e^+e^-$
$\Delta^0 \to n e^+e^-$
$\Delta^+ \to p e^+e^-$

Dilepton production channels in SMASH

Differences may arise from:

Isospin dependent cross section

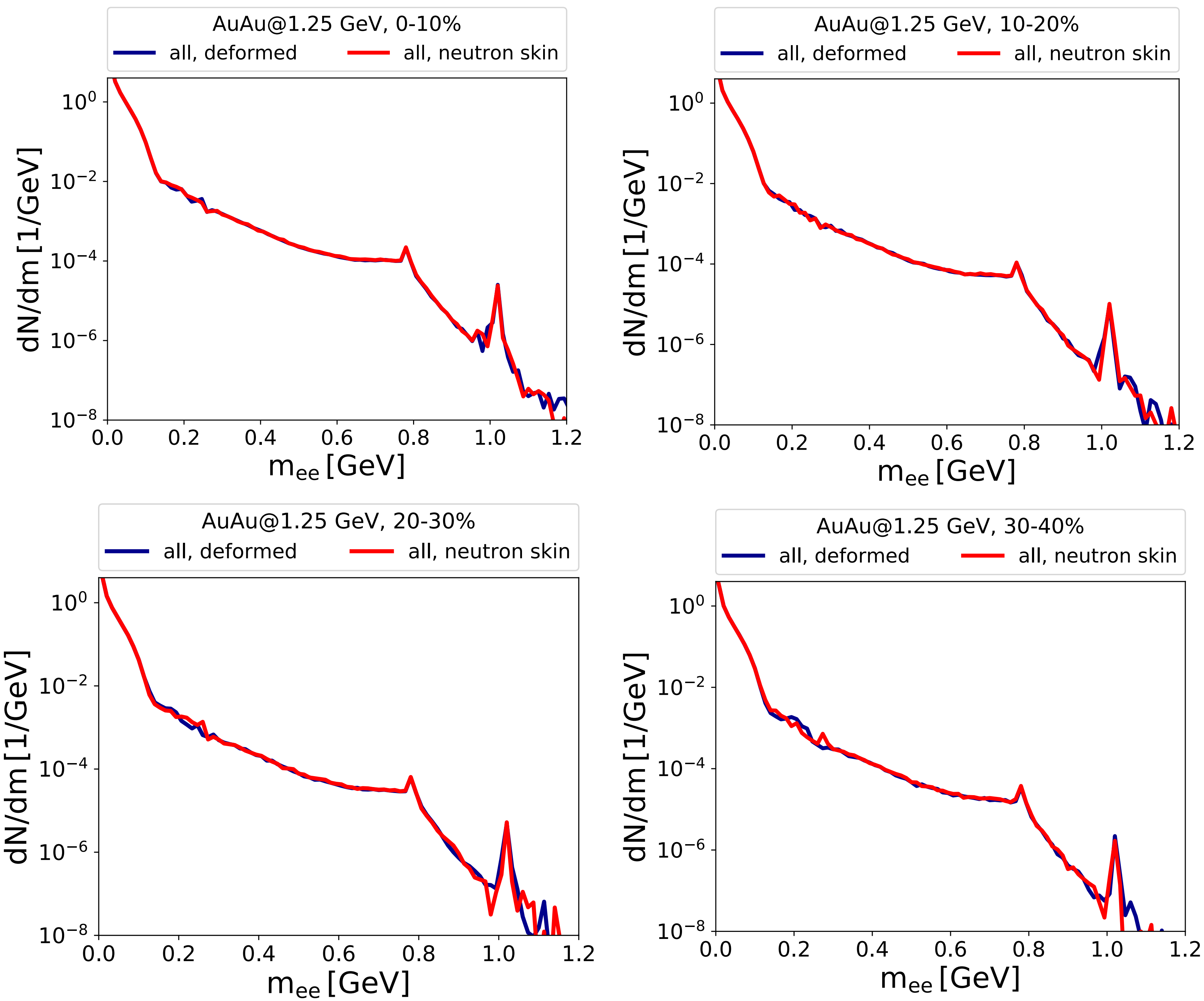
$$|\mathcal{M}_{pn\to NN^\star_{(1535)}}|^2 = 6.5 \times |\mathcal{M}_{pp\to NN^\star_{(1535)}}|^2$$

Electric charge dependent production channels

$$NN \to \Delta N$$

J. Staudenmaier et al Phys. Rev. C98 (5) (2018) 054908

Dilepton production



Au+Au@E_{kin}=1.25GeV

Deformation w neutron skin
vs.
deformation w/o neutron skin

Result:

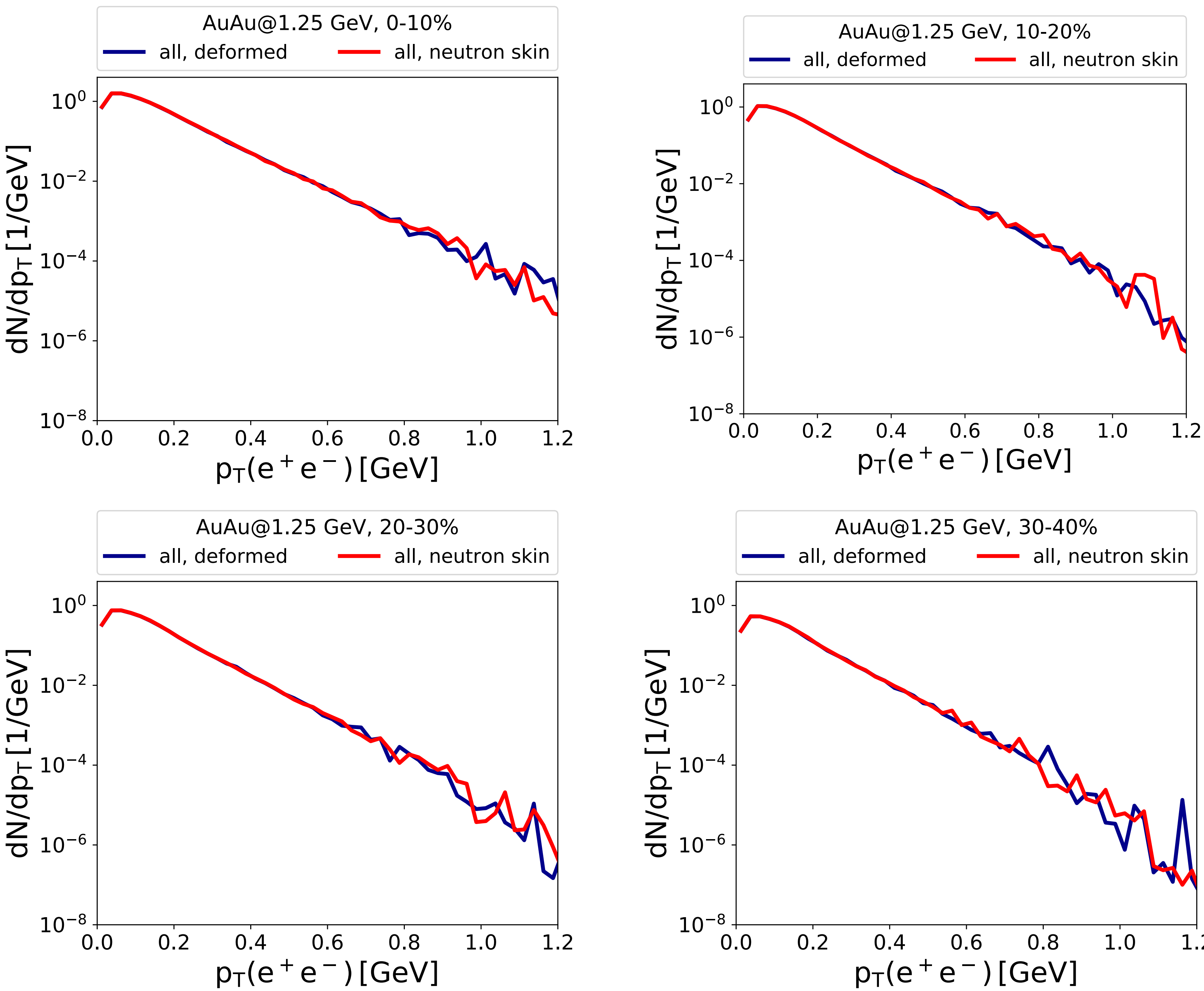
Invariant mass spectra show no influence due to different charge distribution in the nucleus

Individual channels are unaffected as well

p_T spectra also show no visible difference

Adamczewski-Musch, J. et al, Eur. Phys. J. A (2018) 54: 85

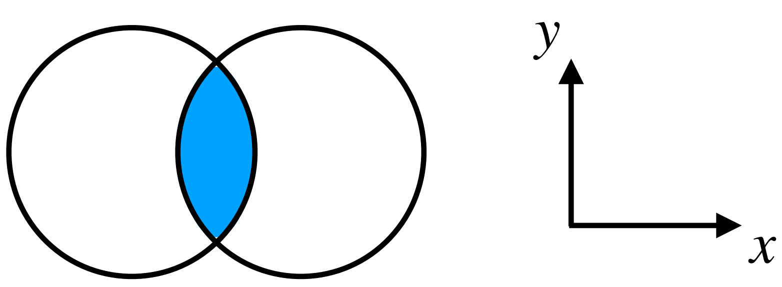
Dilepton p_T spectra



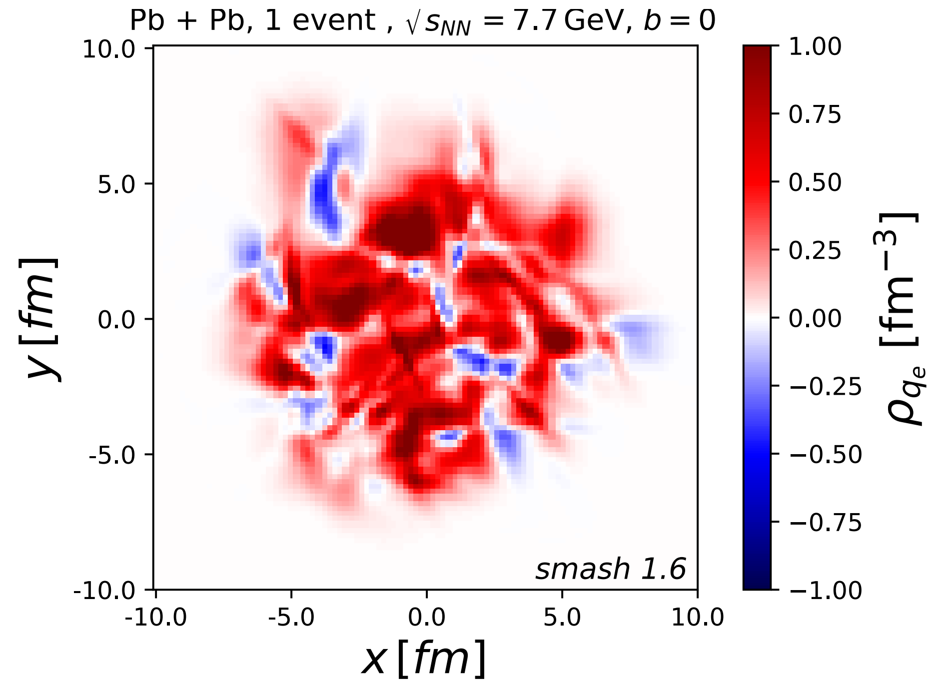
Density dependence

Construct four current of a given density type I, assume Wigner density

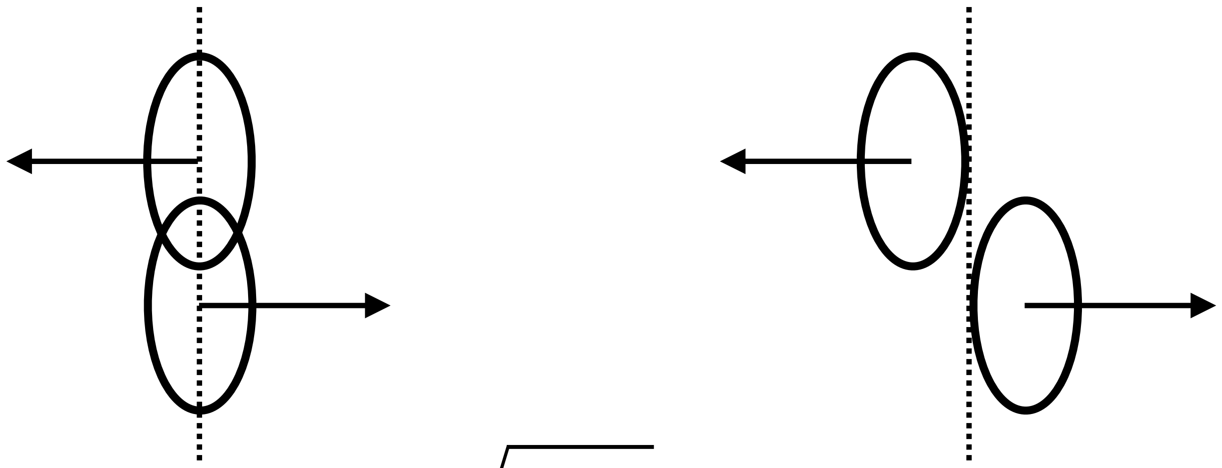
$$j^\mu(r,t) = \int \frac{d^3p}{(2\pi)^3} D \frac{p^\mu}{p^0} f(r,p,t)$$



Density in the Eckart frame is defined as $\rho = \sqrt{j^\mu j_\mu} = \rho_+ - \rho_-$



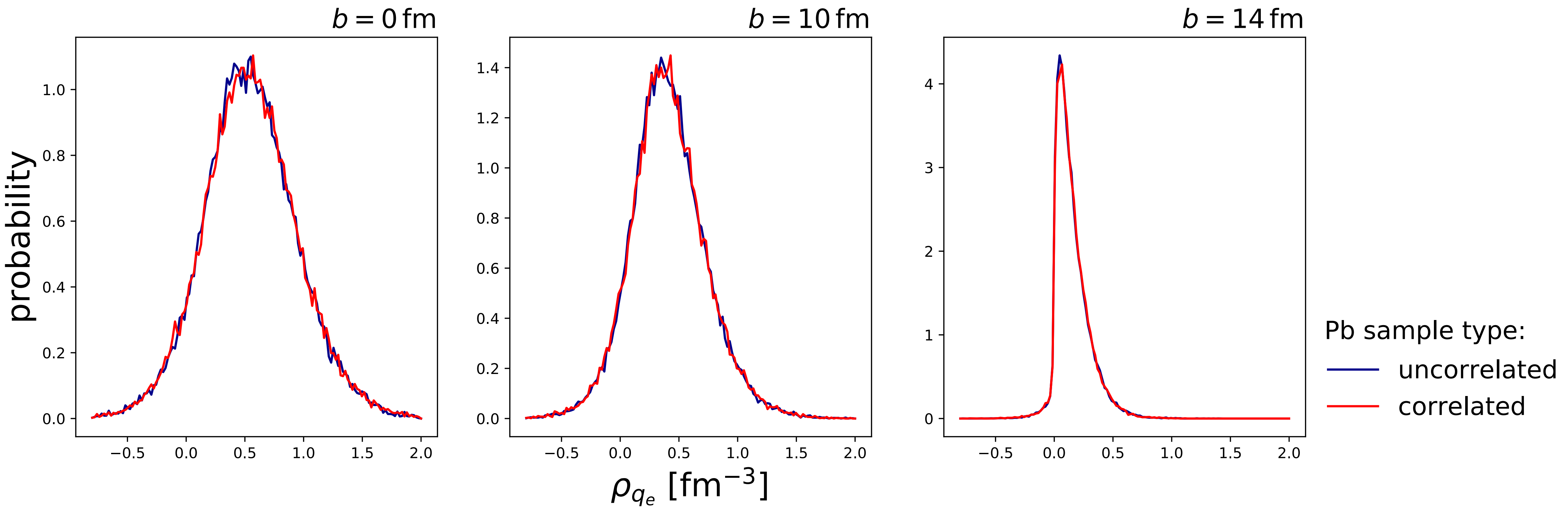
Look at two different times



$t_1 = 1R/\sqrt{\gamma^2 - 1}$ $t_2 = 2R/\sqrt{\gamma^2 - 1}$

Impact of correlations

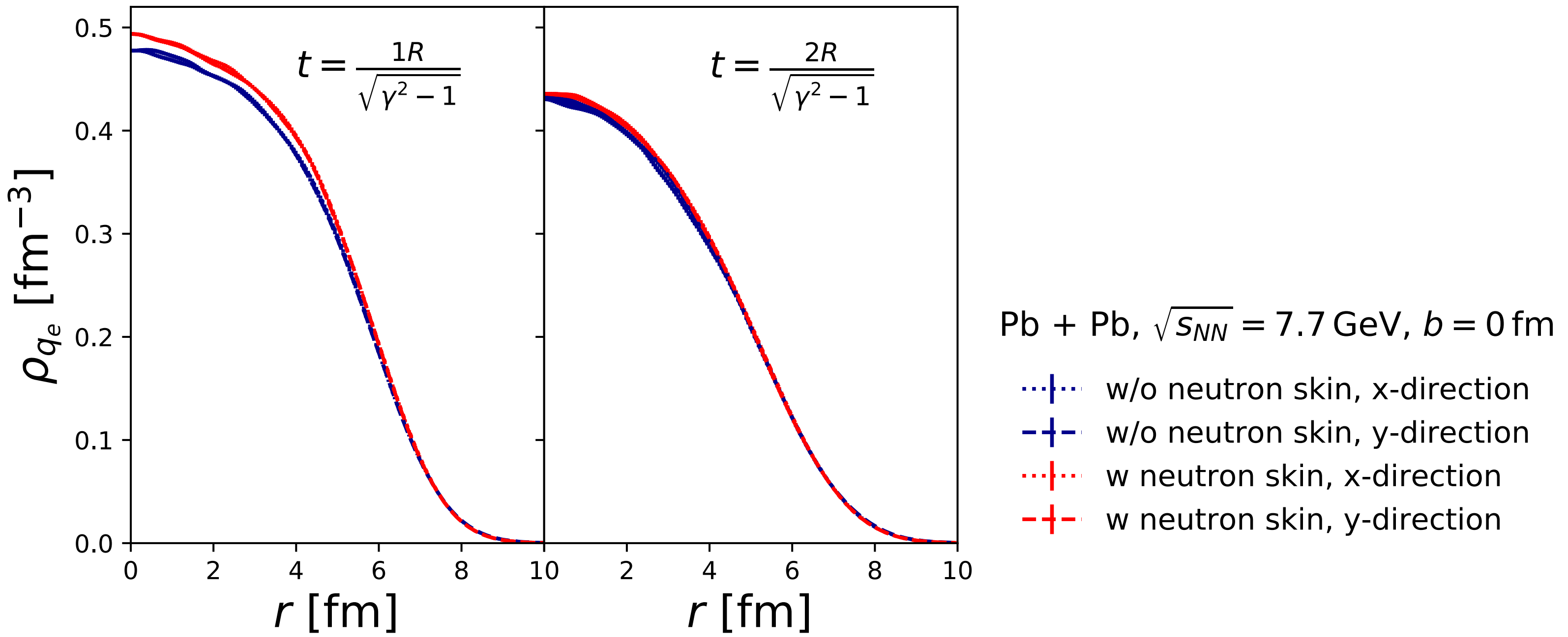
Impact of nucleon-nucleon correlations on the electric charge density in the most central point $\vec{r} = 0,\ t = 1R/\sqrt{\gamma^2 - 1}$

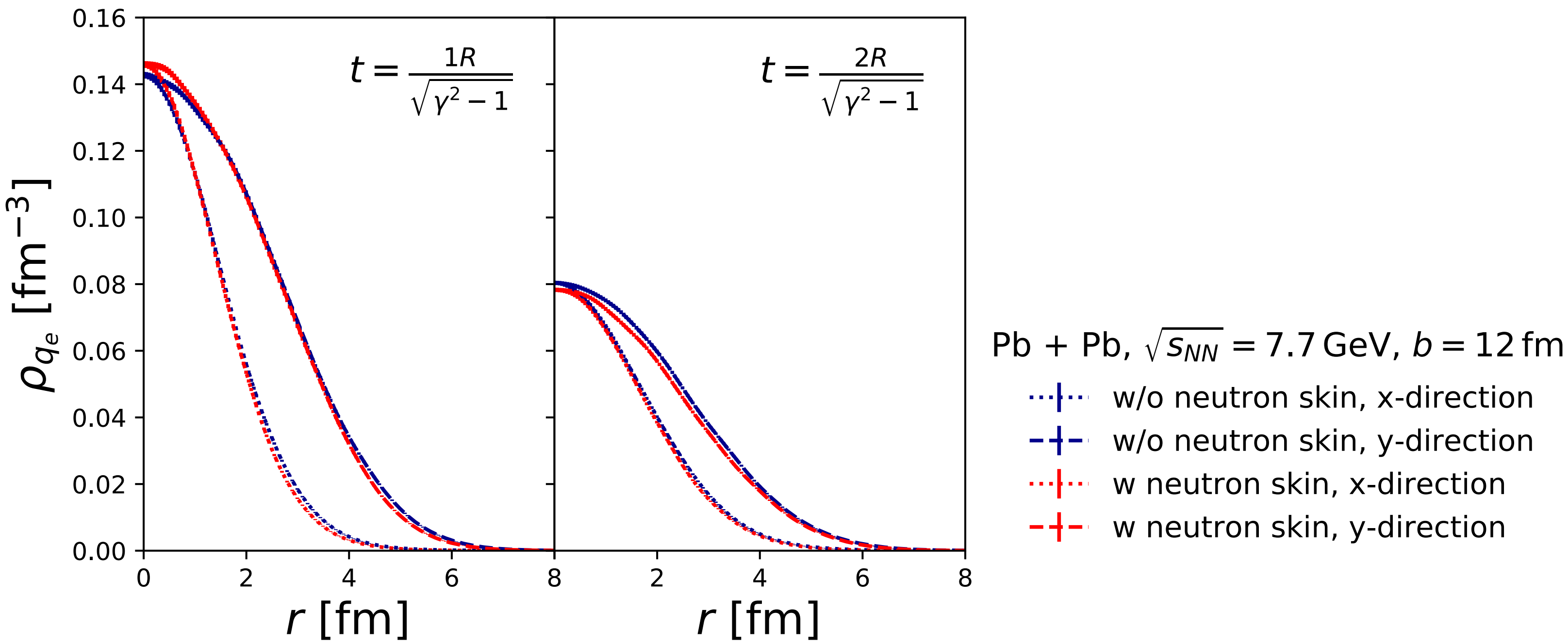


→ correlations have no visible impact on the probability distribution

Radial density dependence

Pb+Pb@7.7 GeV





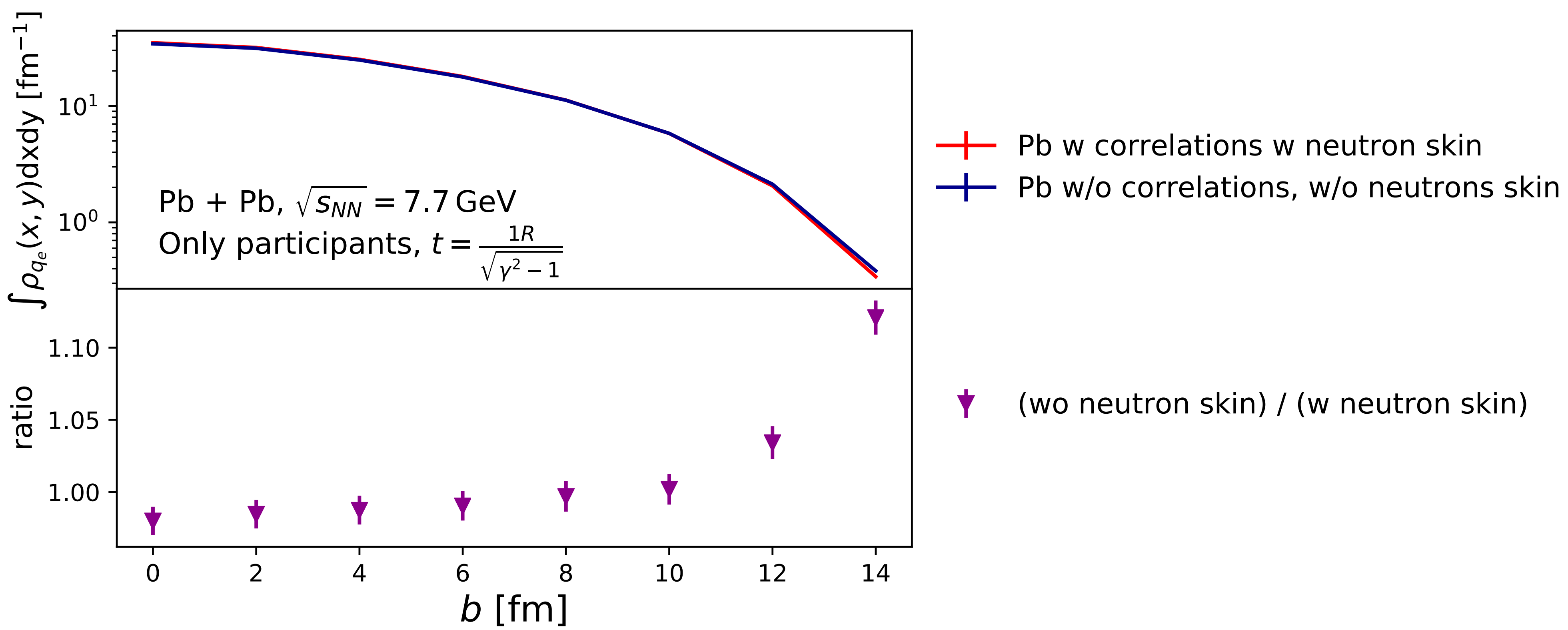
Neutron skin increases the electric charge density in the center of the collision up to b~8fm

Even at large impact parameters the neutron skin increases electric charge density in the center of the collision

Integrated electric charge density

Pb+Pb@7.7 GeV

Integrate participant density in the transverse plane



Non-trivial behavior of the ratio
Neutron skin increases the electric charge density in central collisions
Neutron skin decreases the electric charge density in peripheral collisions

Magnetic fields

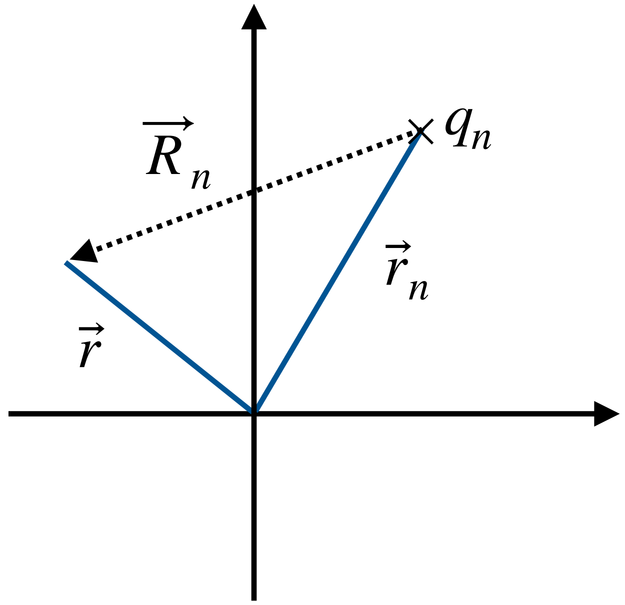
Calculation via Lienard-Wichert potentials

$$e\overrightarrow{B}(\vec{r},t) = \alpha \sum_{i=1}^{N_{ch}} Z_n \frac{1-\overrightarrow{v}_n}{R_n^3\left(1-[\overrightarrow{R}_n \times \overrightarrow{v}_n]^2/R_n^2\right)^{3/2}} \overrightarrow{v}_n \times \overrightarrow{R}_n$$

Point of observation $\overrightarrow{R}_n(t) = \vec{r} - \vec{r}_n(t)$

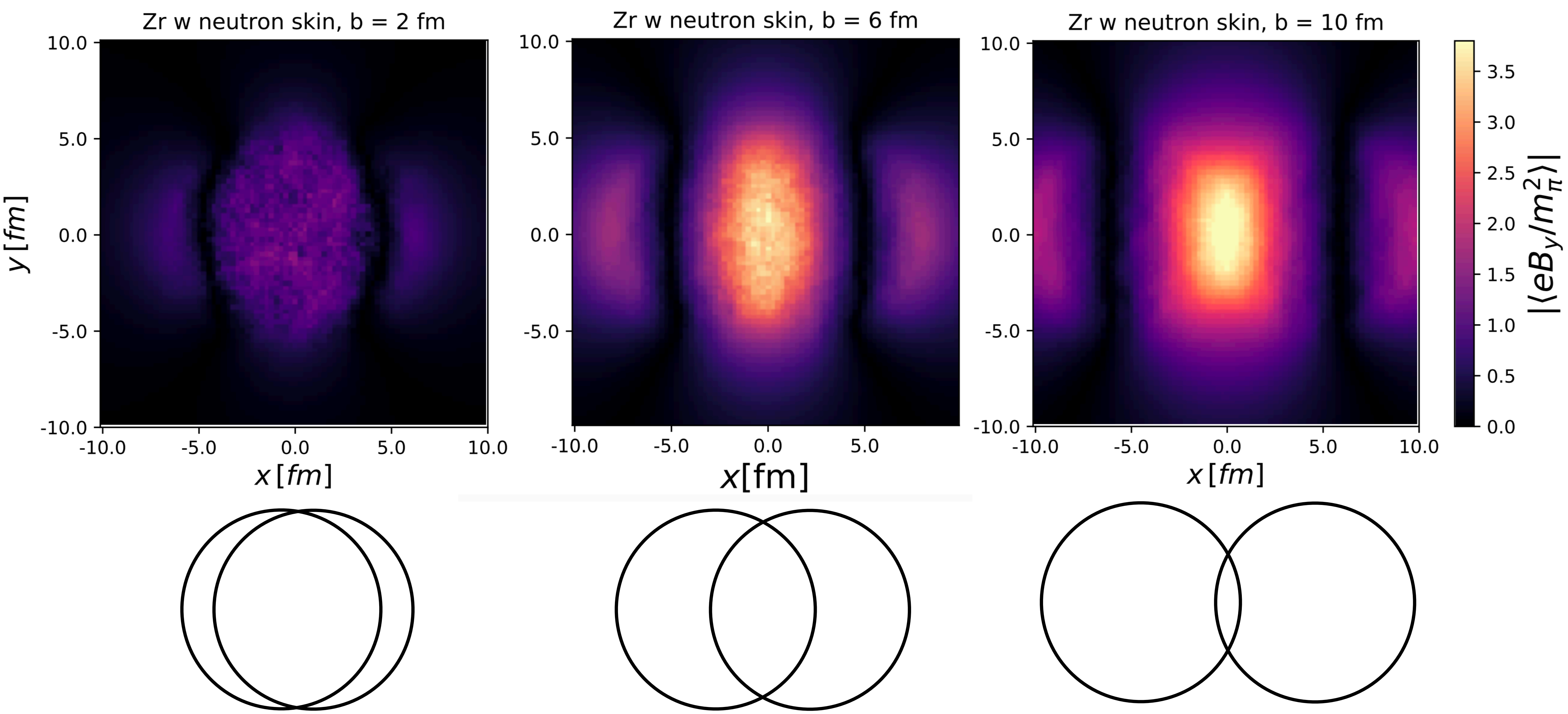
Sum $\sum_n$ runs over all charged particles

Velocity of charged particle $\overrightarrow{v}_n$



Wiechert, Annalen der Physik, vol. 309, 4, pp.667-68 (1901)
Lienard, L'éclairage électrique 16, 5-14 (1898)

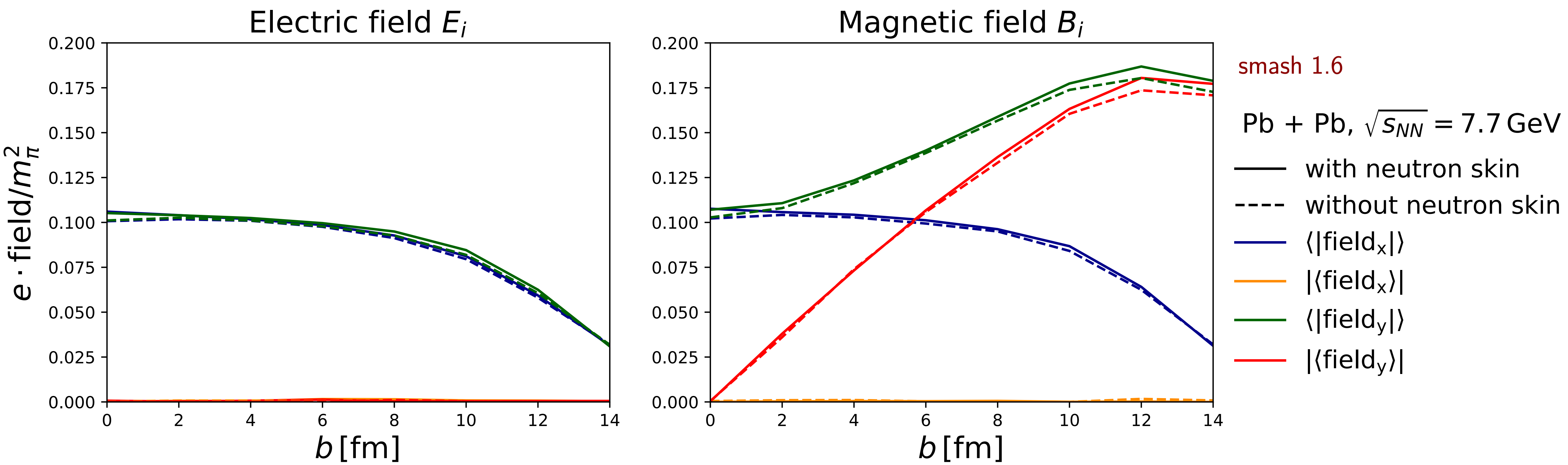
Spatial magnetic field profile



Magnetic fields

Pb+Pb@7.7 GeV

Value of the magnetic field at the most central point $\vec{r} = 0$, when the nuclei overlap $t_1 = 1R/\sqrt{\gamma^2 - 1}$



Neutron skin increases B_y at peripheral collisions due to concentrated proton density in the center of the nuclei

The other components B_x, E_x, E_y show no strong impact due to the neutron skin

In agreement with other calculations

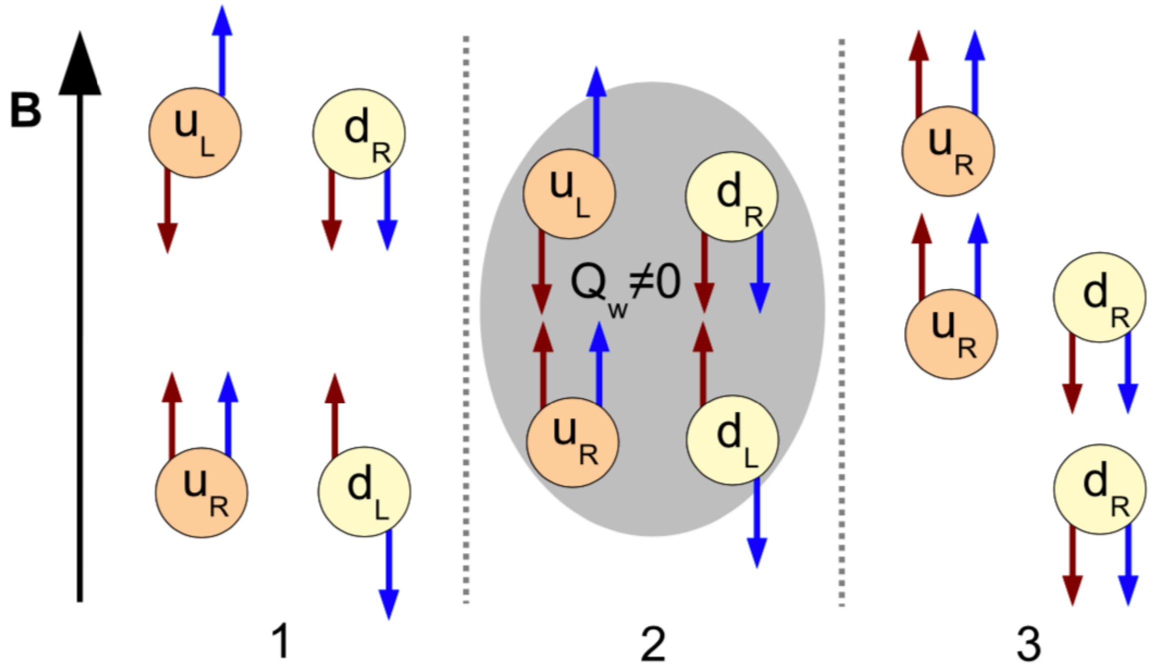
Chiral magnetic effect

Axial anomaly in the massless limit

$$\partial_\mu j_5^\mu = -\frac{g^2 N_f}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}$$

Topological sphaleron transition induces additional axial charge imbalance

Axial charge imbalance + large magnetic field result in an effective charge separation $\vec{j}_5 \sim \sigma_5 \vec{B}$



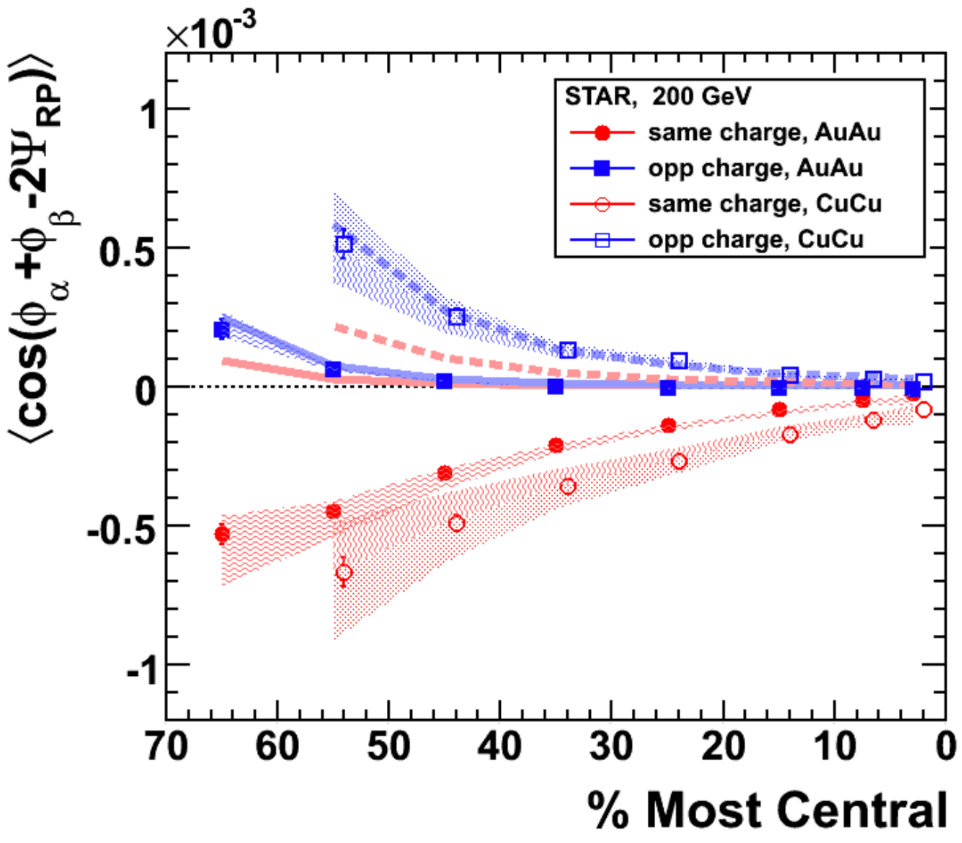
D. E. Kharzeev Nucl. Phys. A803 (2008) 227–253

Chiral magnetic effect

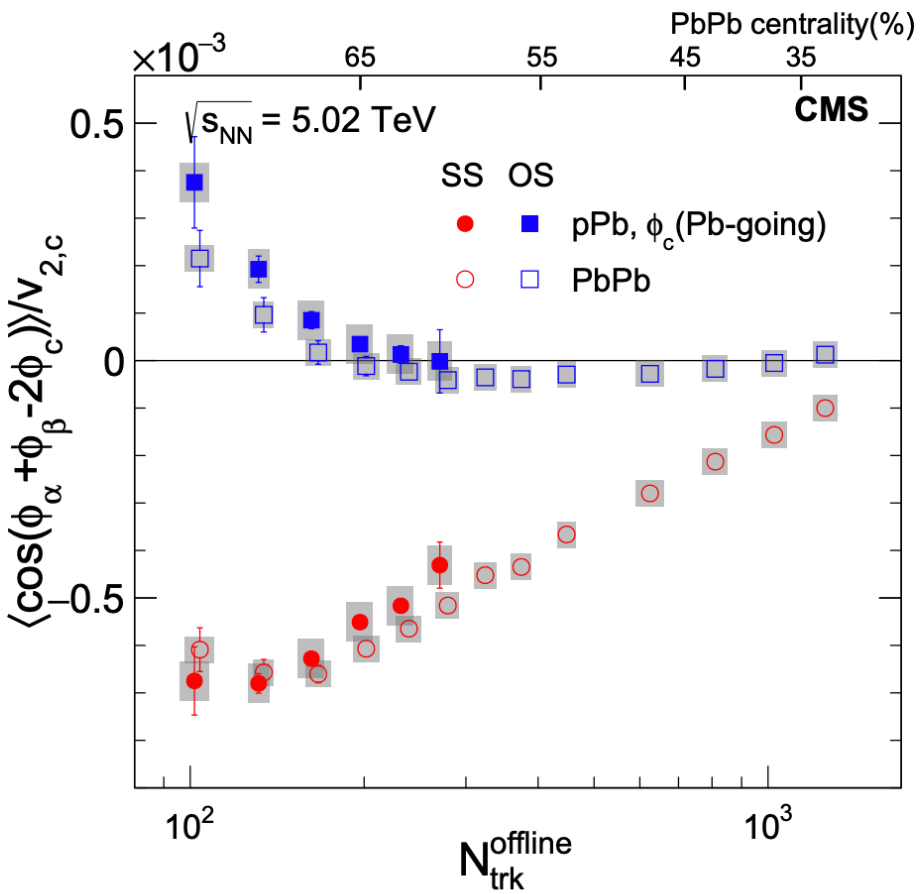
Experimental status

Measure two particle correlations $\gamma_{\alpha\beta} = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$

S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)



[STAR Collab. PRL 103, 251601 (2009)]



[CMS Collab. PRL.118, 122301 (2017)]

Same results for PbPb and pPb

→What is the background component?

Chiral magnetic effect

Idea of isobar run at RHIC Zr+Zr/Ru+Ru@200GeV:

➡ Keep the background in RuRu and ZrZr collisions the same by same number of nucleons

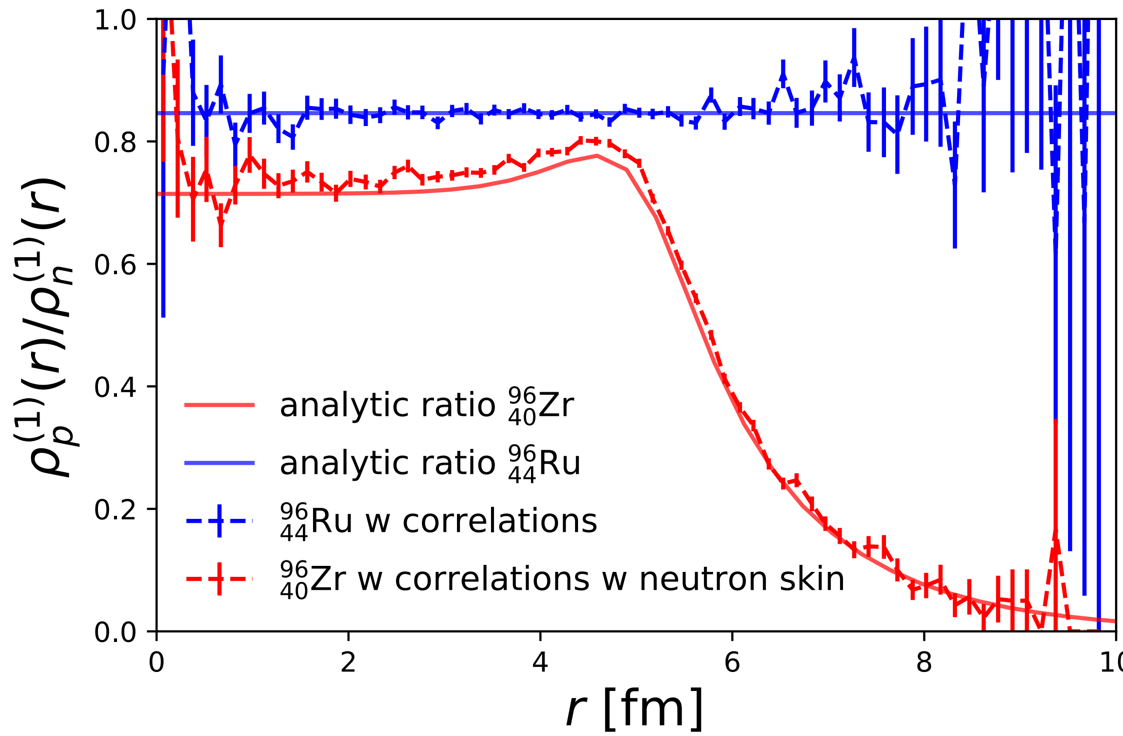
➡ Increase the magnetic field in RuRu due to different charge number

Uncertainty due to nuclear structure of nuclei:

Ru with deformation vs. Ru without deformation

Zr with neutron skin vs. Zr without neutron skin

Woods-Saxon parameters for the isobar system

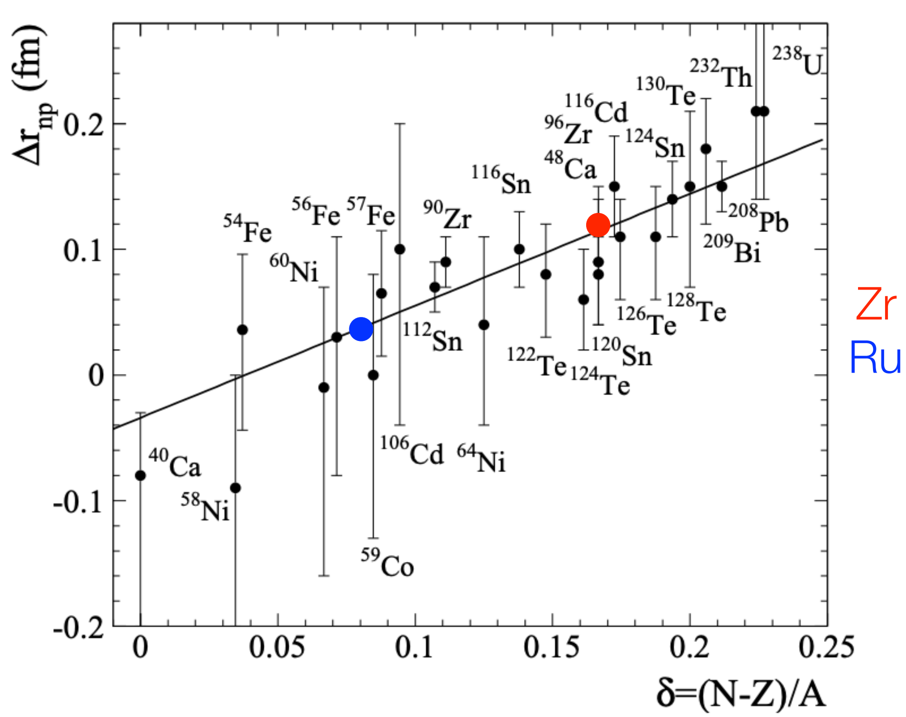


$$_{40}\mathrm{Zr}^{96},\ \Delta r_{np} = 0.15\ \mathrm{fm}$$

$$R_p = 5.08\ \mathrm{fm} \quad R_n = 5.08\ \mathrm{fm}$$

$$d_p = 0.34\ \mathrm{fm} \quad d_n = 0.46\ \mathrm{fm}$$

$$\beta_2 = 0$$



LEAR Collab. Int Jour of Mod Phys E 13 (2004) 343

$$_{44}\mathrm{Ru}^{96},\ \Delta r_{np} = 0$$

$$R_0 = R_p = R_n = 5.08\ \mathrm{fm}$$

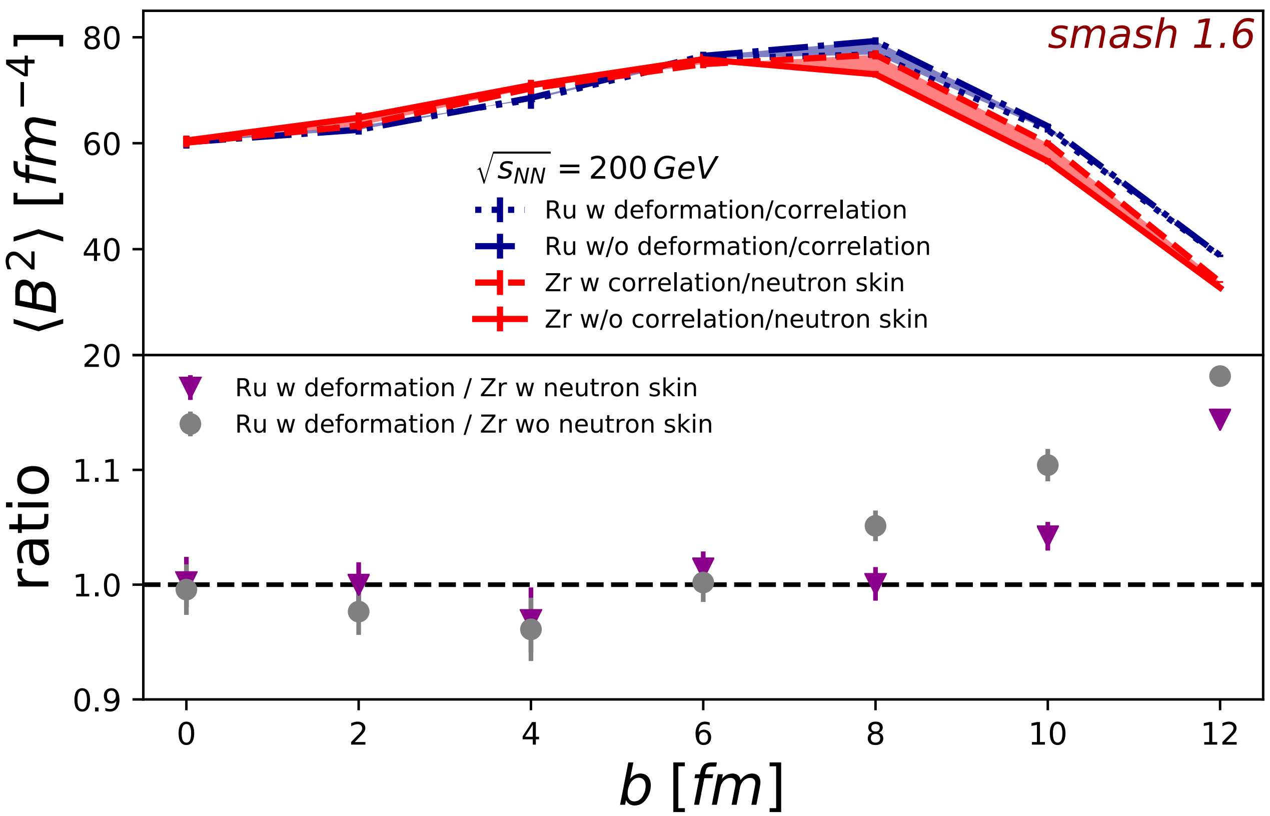
$$d = d_p = d_n = 0.46\ \mathrm{fm}$$

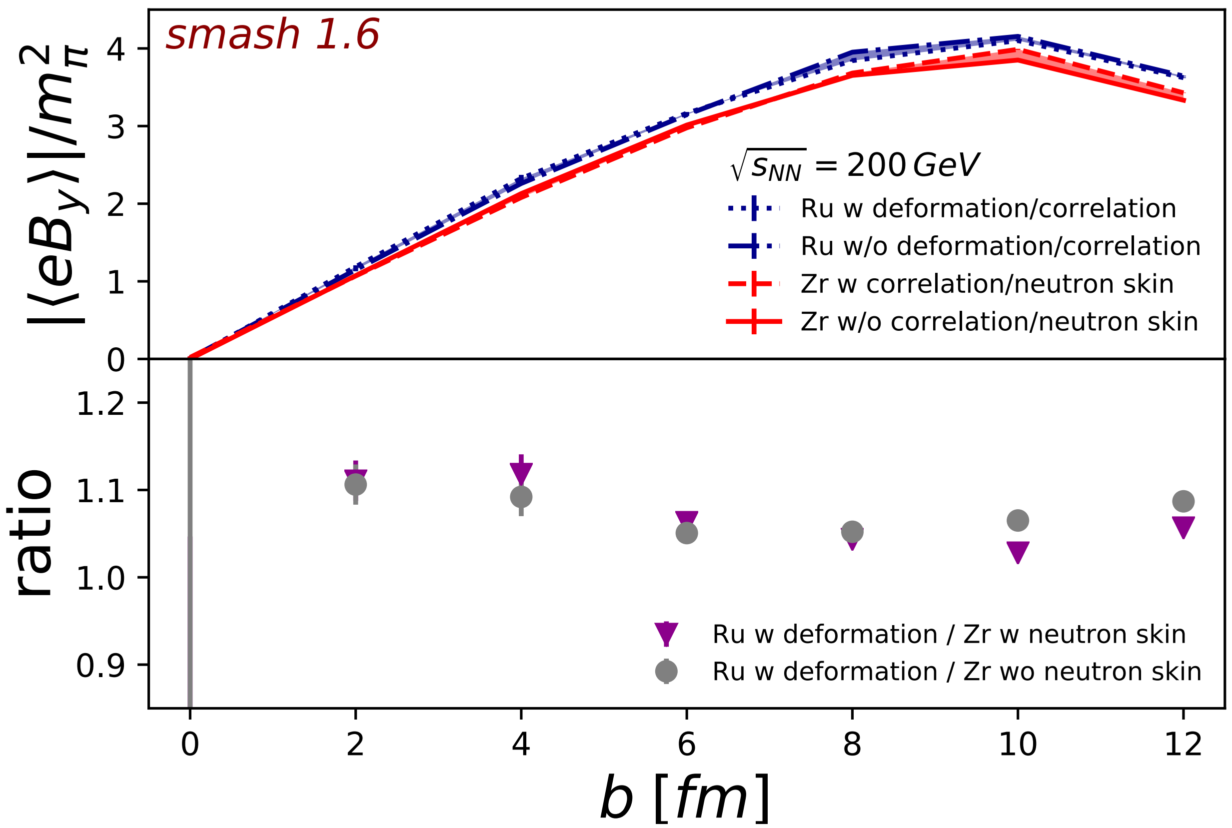
$$\beta_2 = 0.158$$

Deformation according to:
Prytichenko et al. Atom Data Nucl. Data Tabl. 107 1, (2016)

Magnetic fields

Value of the magnetic field at the most central point $\vec{r} = 0$, when the nuclei overlap $t_1 = 1R/\sqrt{\gamma^2 - 1}$





Same argument:

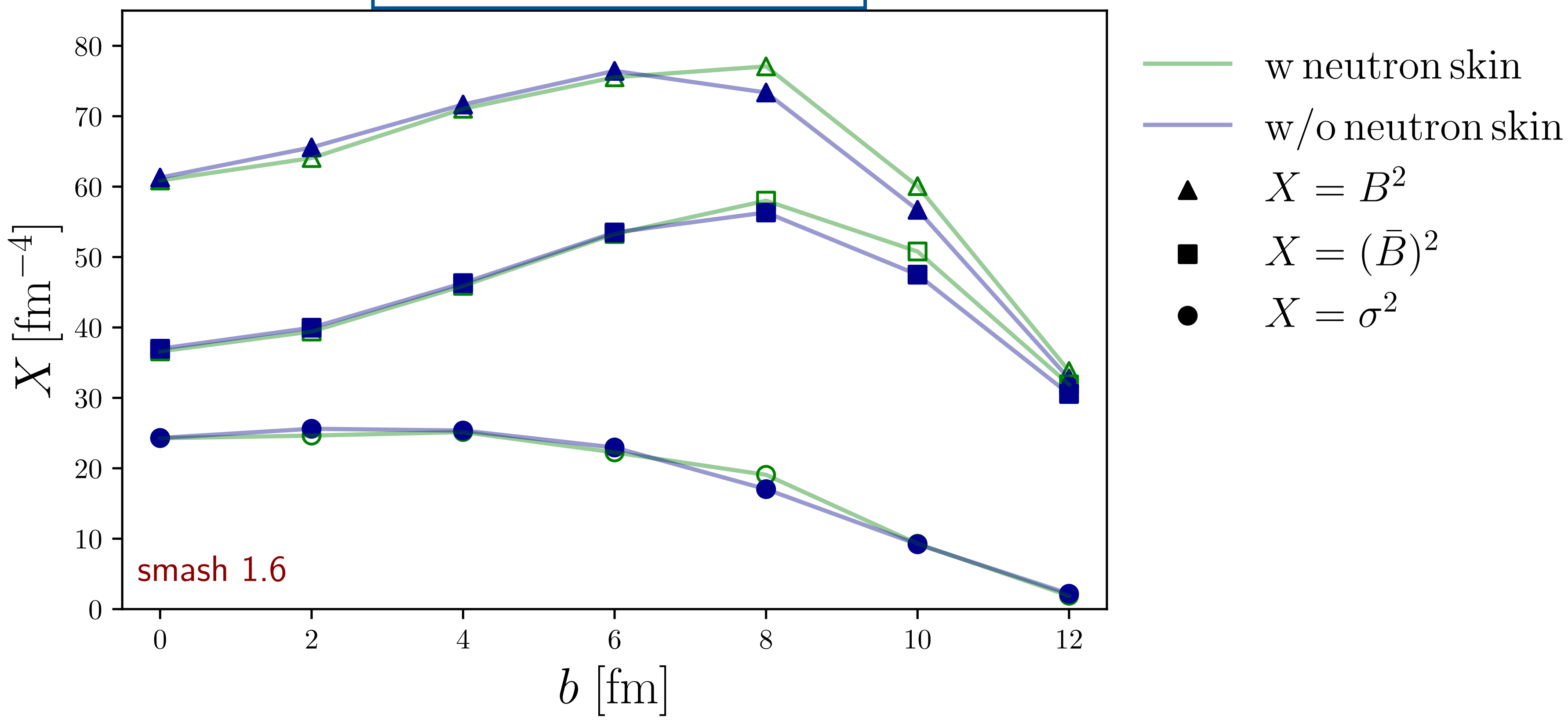
Neutron skin increases B at large impact parameter due to enhanced proton density in the center

Fluctuation vs mean

Where is the increase in B^2 coming from ?

$$B^2 = (\bar{B})^2 + \sigma_{\bar{B}}^2$$

Zr+Zr@200 GeV



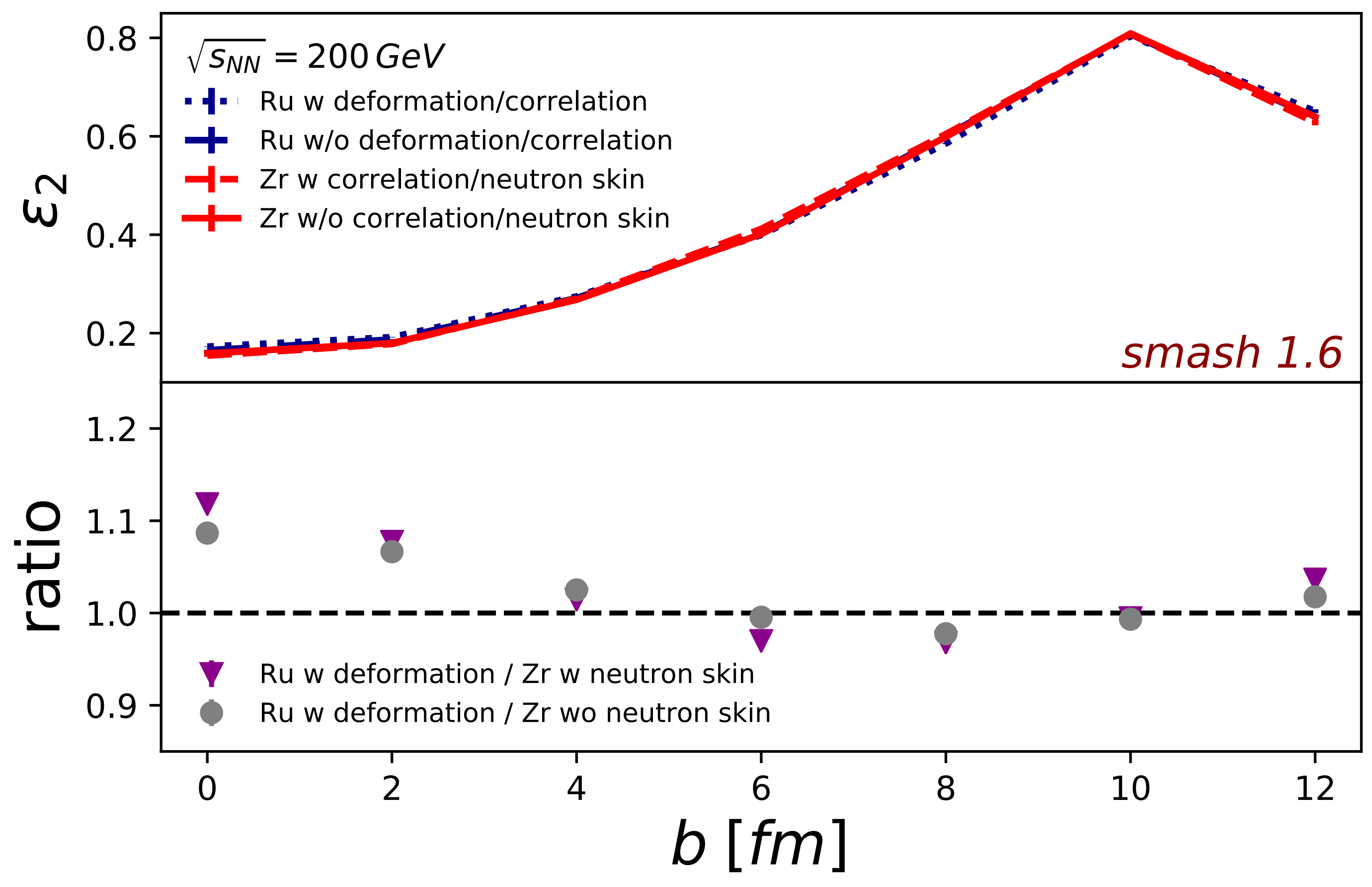
→ The mean increases, whereas the variance is the same in both cases

Eccentricity

Estimate the total background v_2 by computing the eccentricity $v_n \sim \kappa_n \epsilon_n$ at the maximum overlap time

Participant eccentricity:

$$\epsilon_2 = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_x^2 + \sigma_y^2}$$



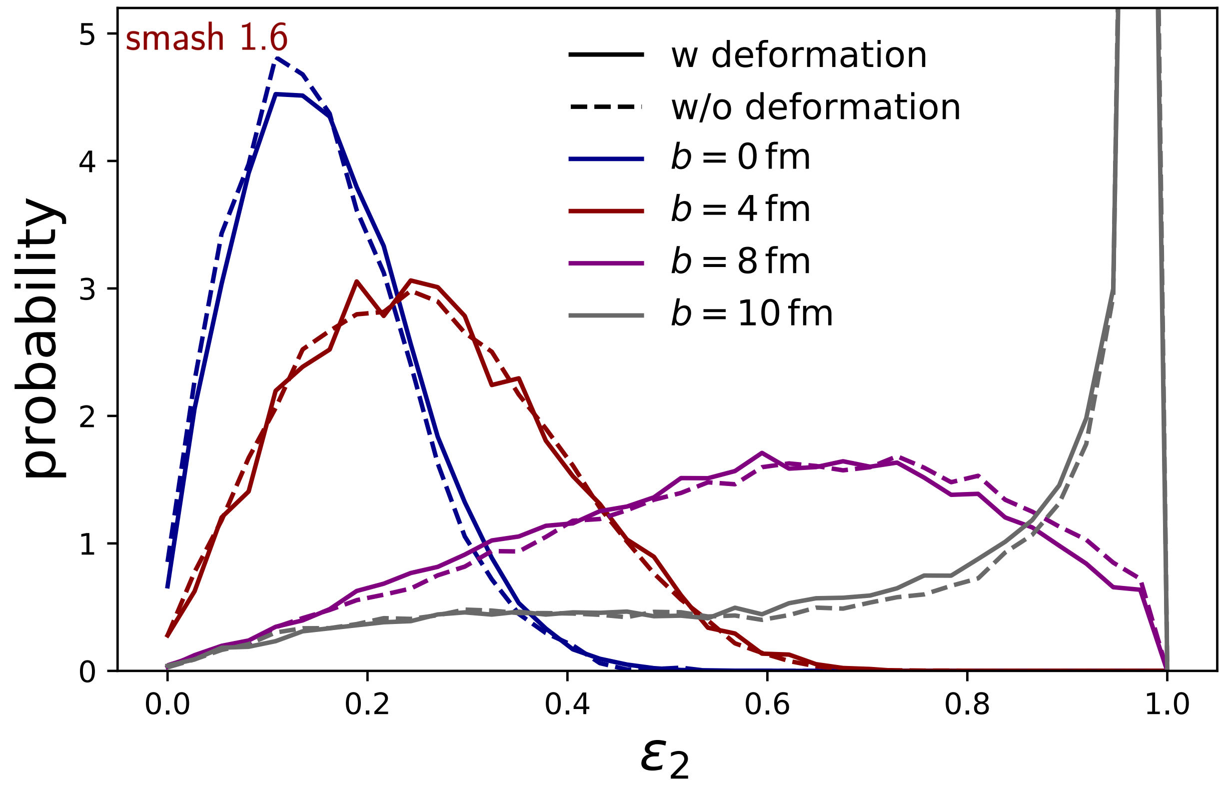
Our result is in good agreement with
[Deng et al. PRC, 041901 (2016)]
[Schenke, Shen, Tribedy PRC 99, 044908 (2019)]

Complete background evaluation by AMPT, see arXiv:1909.04083v1

Eccentricity

How is the eccentricity affected by the deformation?

Probability distribution



→ No large impact due to deformation

$\Psi_B \Psi_2^{SP}$- Correlation

Neutron spectator plane:

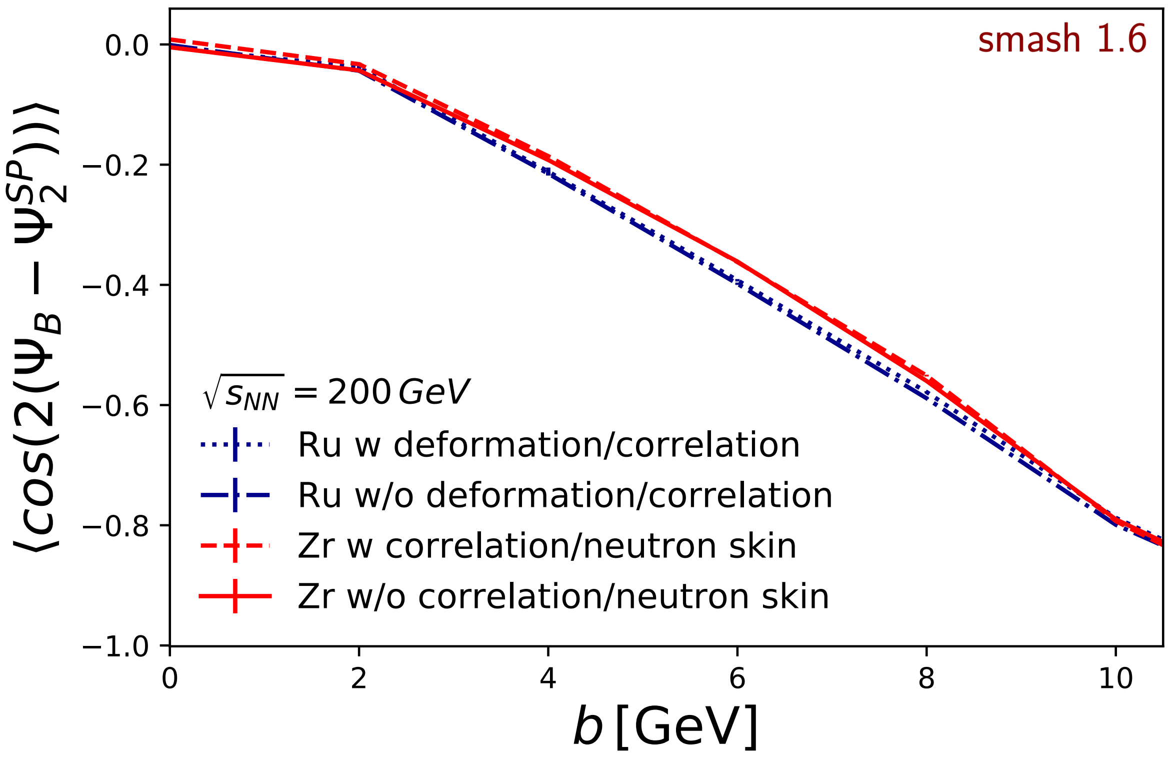
$$\Psi_2^{SP} = \frac{1}{2}\left(\arctan\frac{\sum_i r_i^2 \sin 2\phi_i}{\sum_i r_i^2 \cos 2\phi_i}\right)$$

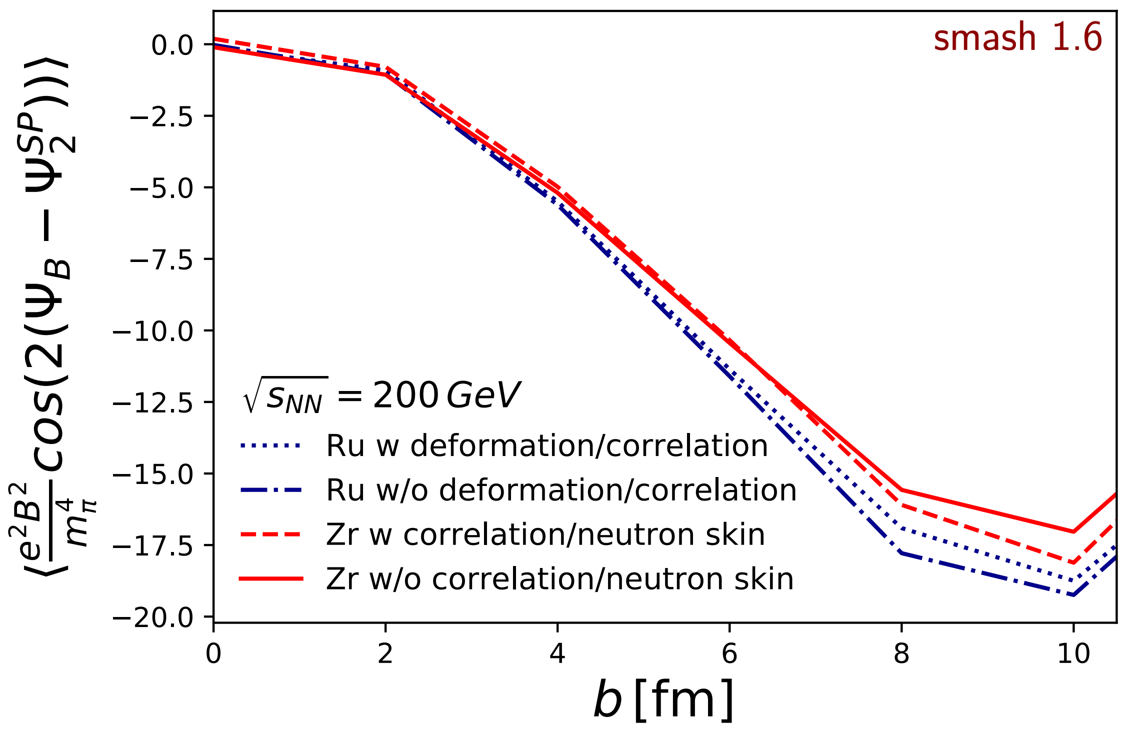
Proxy for the measured two particle correlator

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS} \sim \langle \frac{e^2 B^2}{m_\pi^4} \cos 2(\Psi_B - \Psi_2) \rangle$$

Magnetic field:

$$\Psi_B = \arctan^{-1}\left(B_y / B_x\right)$$





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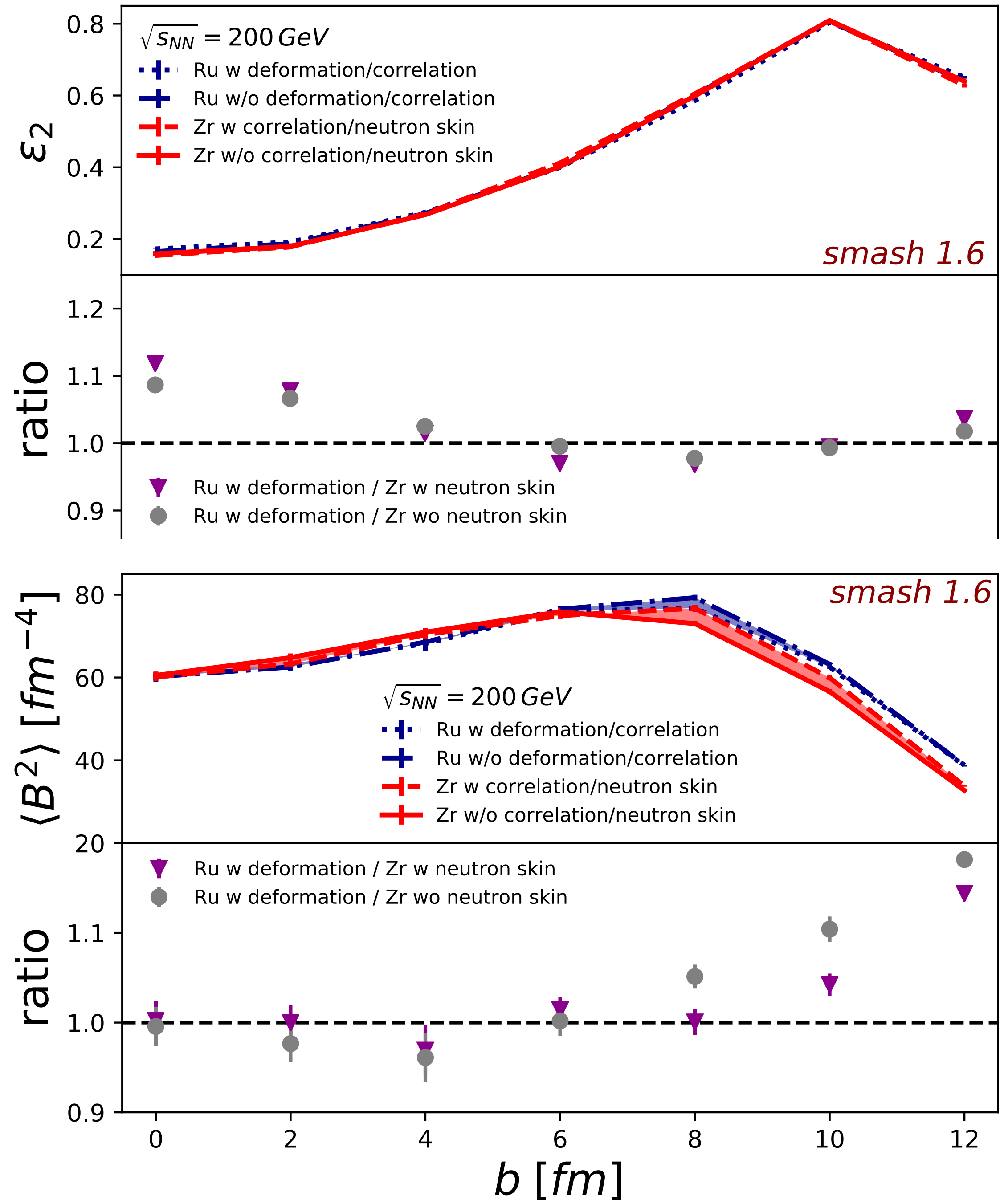
Background/signal ratio



Conclusion

- No visible impact on the dilepton production at HADES energies
- Neutron skin affects the density distribution in the created medium
- The magnetic field strength in peripheral collisions of Pb+Pb and Zr+Zr collisions is influenced, deformation has no large impact
- CME signal to background ratio is decreased

Outlook

- Extend CME related calculations to HADES energies
- Search for measurable observable to determine properties of the symmetry energy parameter L

Backup slides

Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r - R(\theta,\phi)}{d}}}\,, \qquad R(\theta,\phi) = R_0\left(1 + \sum_{l=1}^{\infty}\sum_{m=-l}^{l}\beta_{lm}Y_l^m\right)$$

$$Y_{2,0}(\theta,\phi) = \frac{1}{4}\sqrt{\frac{5}{\pi}}(3\,cos^2\theta - 1)$$

$$Y_{4,0}(\theta,\phi) = \frac{3}{16}\sqrt{\frac{1}{\pi}}(35\,cos^4\theta - 30\,cos^2\theta + 3)$$

Used Woods-Saxon parameters in this work:

Type	r_0 / fm	d / fm	β_2	β_4	$r_{0,p}$ / fm	$r_{0,n}$ / fm	d_p / fm	d_n / fm
^{208}Pb	6.67	0.54	0	0	6.680	6.7	0.447	0.55
^{197}Au	6.37	0.546	−0.13	−0.03	6.42	6.42	0.45	0.57
^{96}Zr	5.02	0.46	0	0	5.08	5.08	0.34	0.46
^{96}Ru	5.085	0.46	0.158	0	0	0	0	0

Nucleon-nucleon short range correlations

Ensure correct spatial nucleon distribution by introducing short range correlations

$$\left[\sum_{i=1}^{A}\frac{\vec{p}_i^{\,2}}{2M_N}+\hat{V}_{eff}(1,2,\ldots A)\right]\psi_n(1,2,\ldots A)=E_n\psi_n(1,2,\ldots A)$$

ψ_n : Nucleonic wavefunction

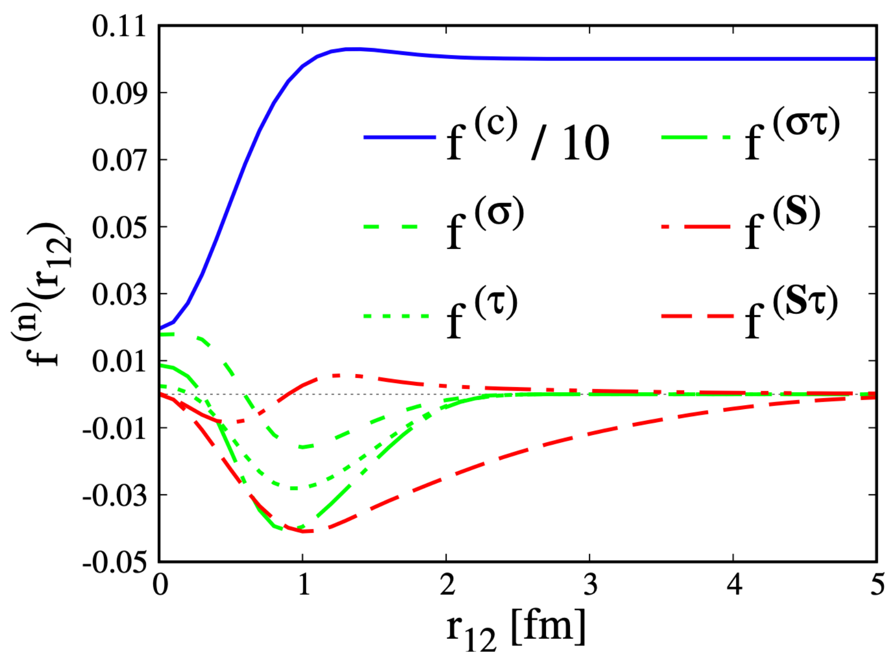
Potential would include 2-body interactions

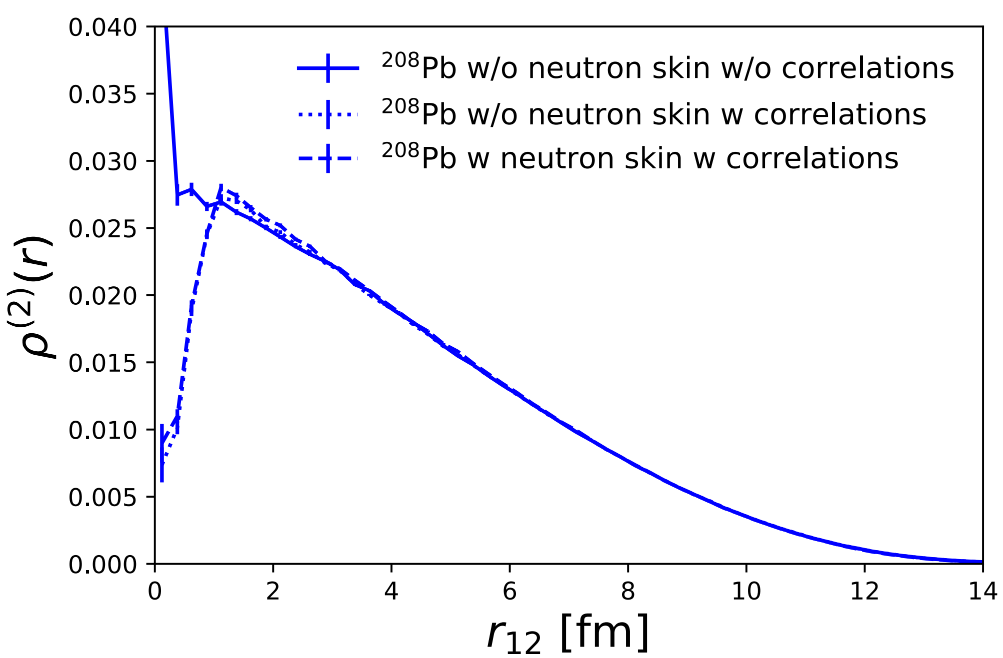
$$\hat{V}_{eff}(1,2,\ldots A)=\sum_{i<j}\hat{v}_2(i,j)$$

$$\psi(\vec{x}_1,\vec{x}_2,\ldots,\vec{x}_N)=\prod_{i<j}^{A}\hat{f}_{i,j}\,\phi(\vec{x}_1,\vec{x}_2,\ldots,\vec{x}_N)$$

ϕ_n : Uncorrelated wavefunction

$\hat{f}_{ij}$: Correlation operator





Alvioli et al. Phys.Rev. C87 (2013) no.3, 034603

Density in SMASH

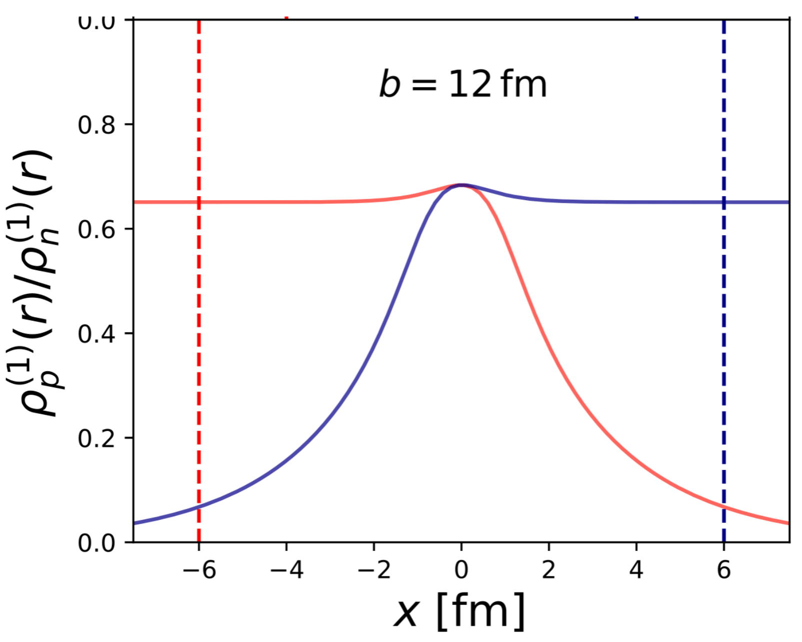
Four vector:

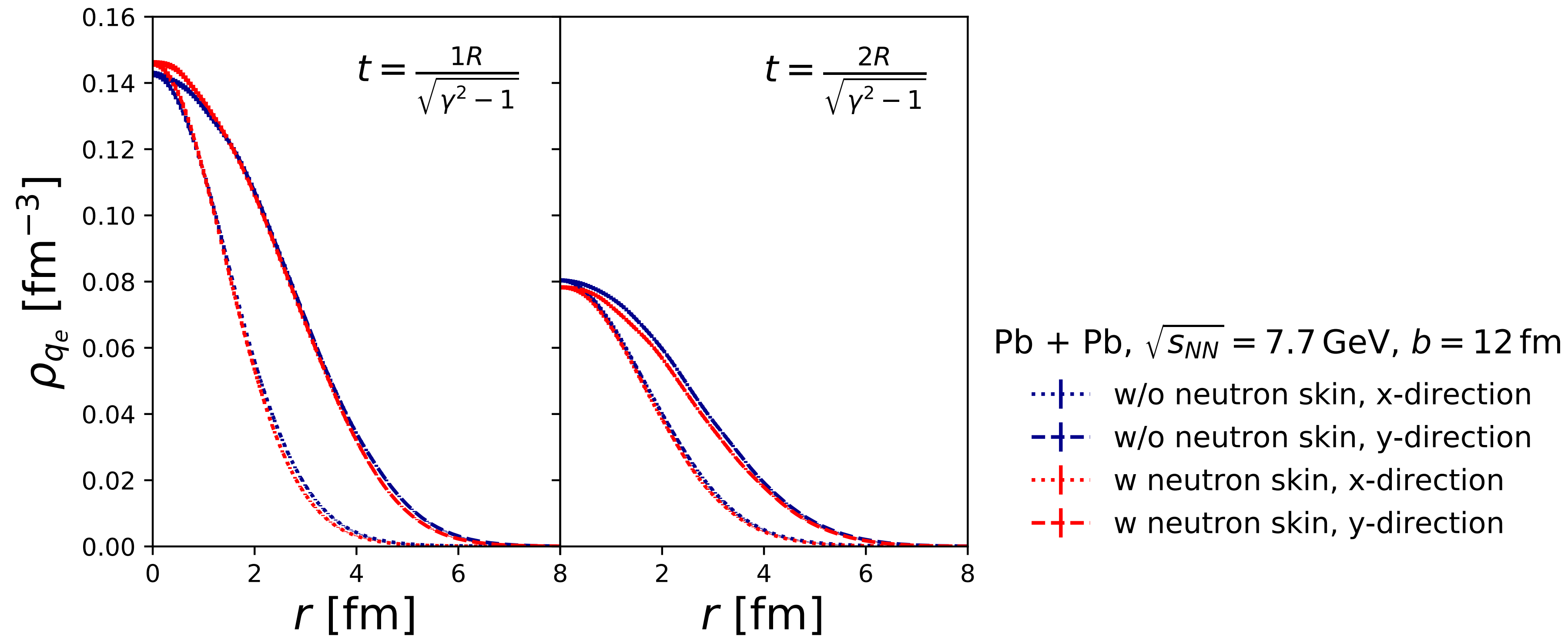
$$j^\mu = D\frac{p^\mu}{p^0}\left(2\pi\sigma^2\right)^{-3/2}\exp\left(-\frac{(\mathrm{r}-\mathrm{r}_0(\mathrm{t}))^2}{2\sigma^2}\right)$$

After boosting:

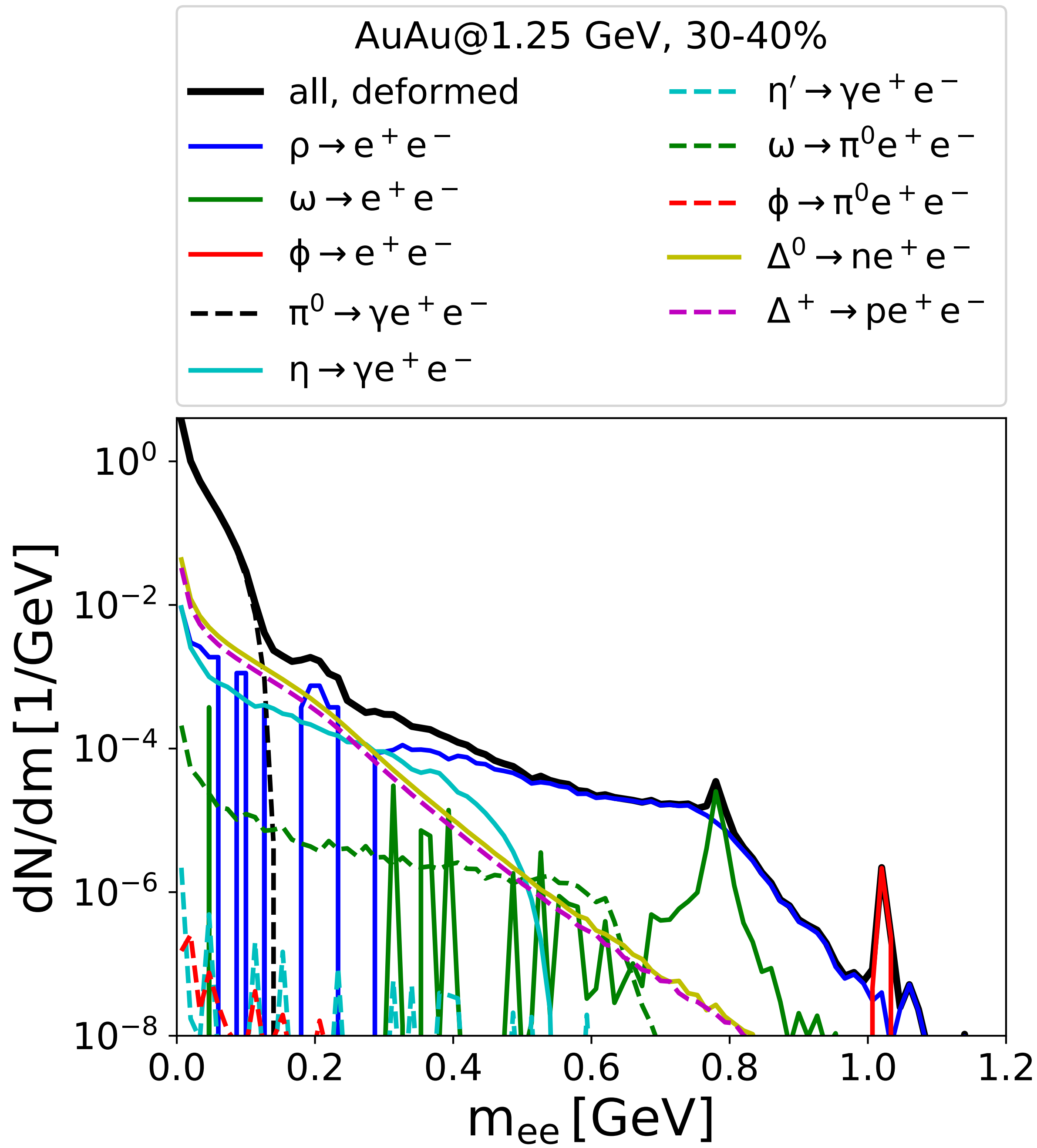
$$j^\mu_{comp}(\vec{r}) = (2\pi\sigma)^{3/2}\sum_{i=1}^{N} D_i u_i^\mu \exp\left(-\frac{\left(\vec{\mathrm{r}}-\vec{\mathrm{r}}_\mathrm{i}+(\gamma_\mathrm{i}-1)\frac{\vec{\beta}_\mathrm{i}(\vec{\beta}_\mathrm{i}\cdot(\vec{\mathrm{r}}-\vec{\mathrm{r}}_\mathrm{i}))}{\vec{\beta}^2_\mathrm{i}}\right)^2}{2\sigma^2}\right)$$

Radial density dependence

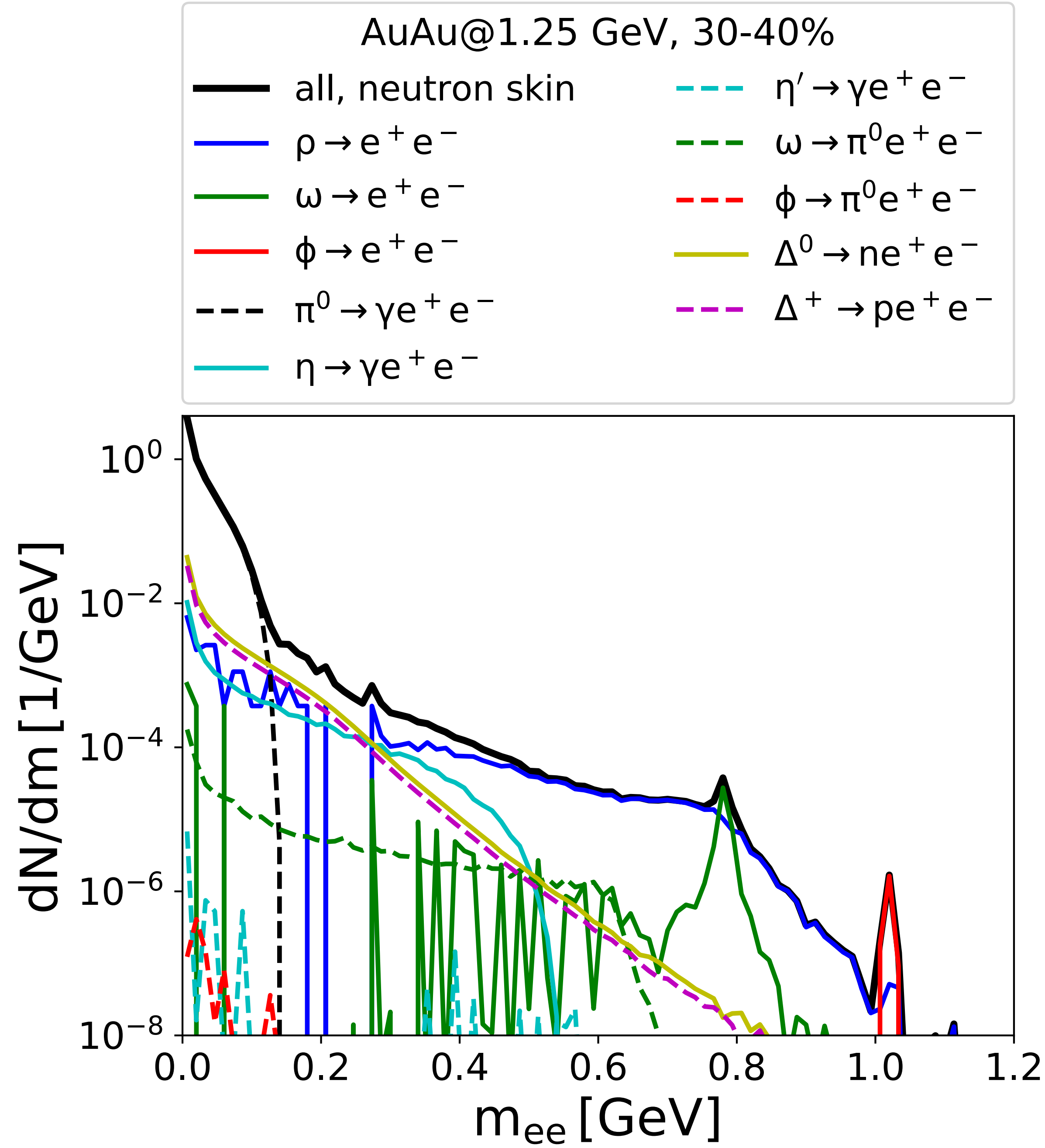




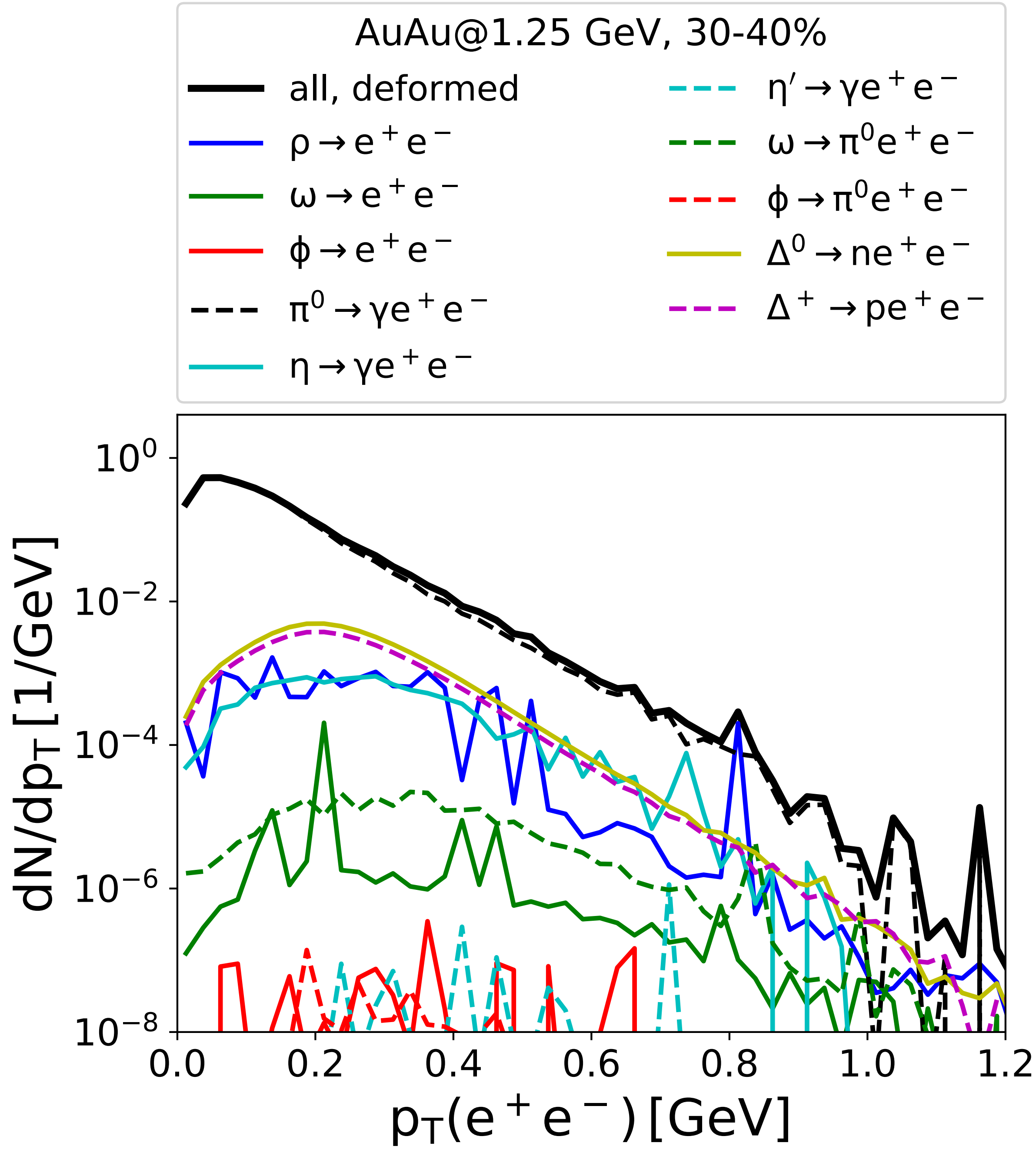
Invariant mass spectrum



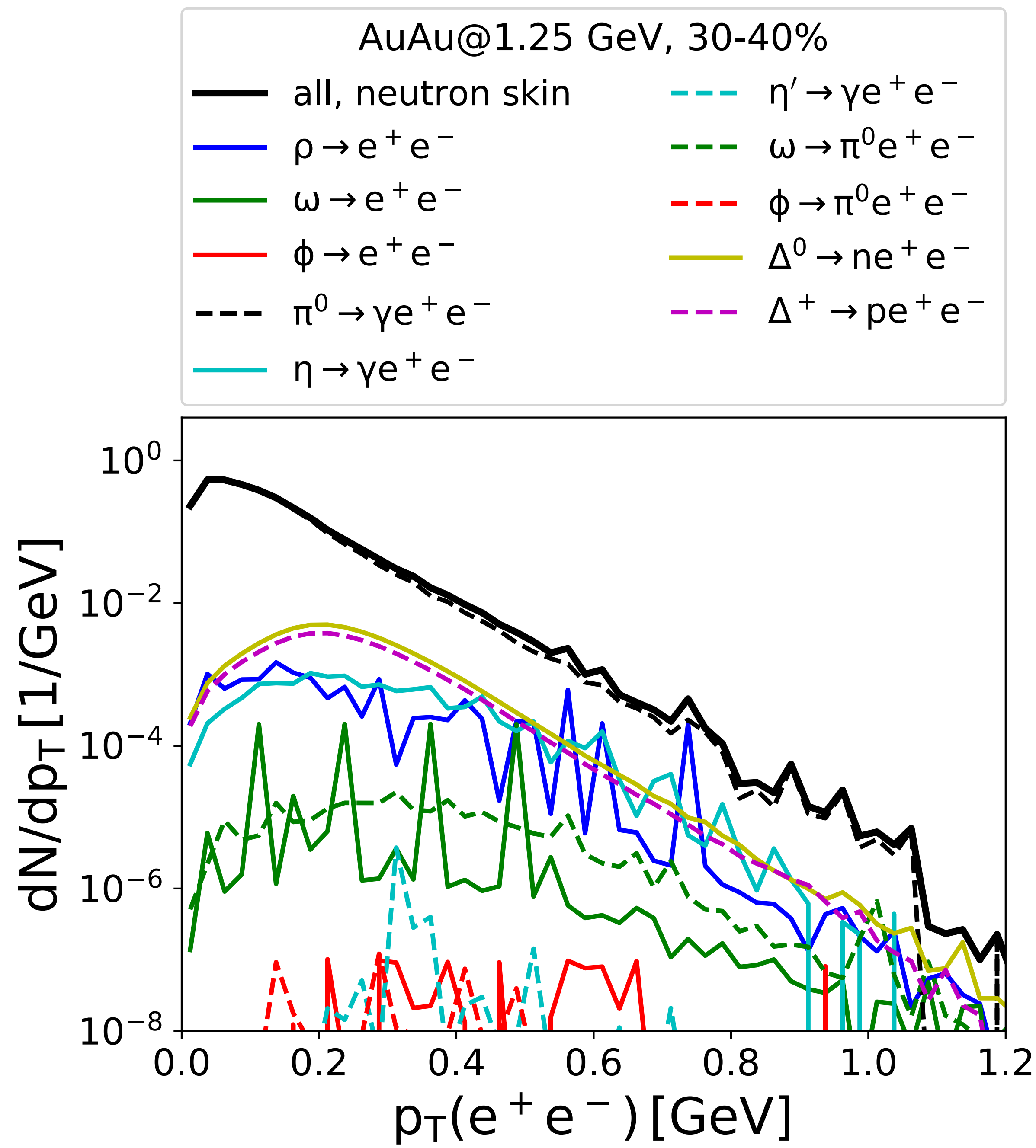
Invariant mass spectrum



p_T-spectrum


AuAu@1.25 GeV, 30-40%
all, deformed
ρ→e⁺e⁻
ω→e⁺e⁻
ϕ→e⁺e⁻
π⁰→γe⁺e⁻
η→γe⁺e⁻
η′→γe⁺e⁻
ω→π⁰e⁺e⁻
ϕ→π⁰e⁺e⁻
Δ⁰→ne⁺e⁻
Δ⁺→pe⁺e⁻
dN/dp_T [1/GeV]
p_T(e⁺e⁻) [GeV]

p_T-spectrum



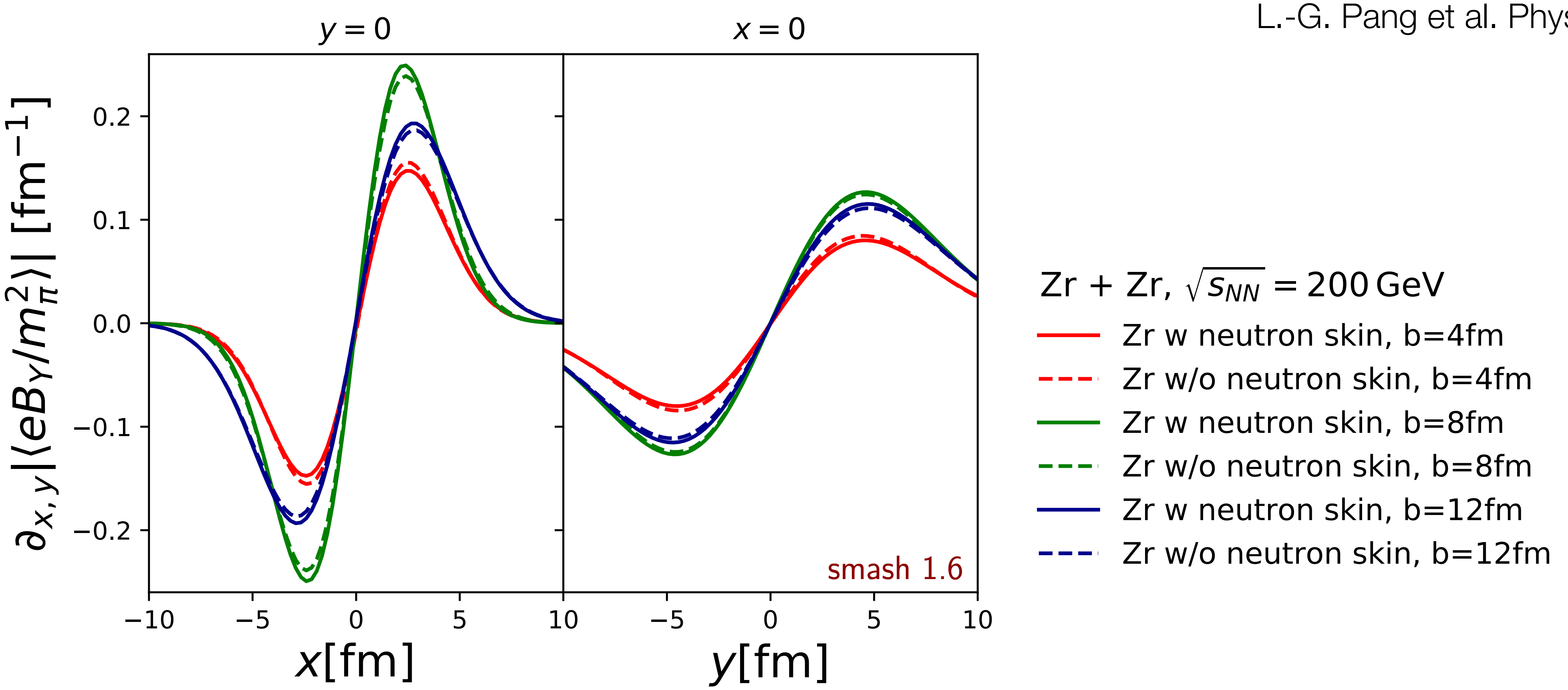
AuAu@1.25 GeV, 30-40%
all, neutron skin
ρ→e⁺e⁻
ω→e⁺e⁻
ϕ→e⁺e⁻
π⁰→γe⁺e⁻
η→γe⁺e⁻
η′→γe⁺e⁻
ω→π⁰e⁺e⁻
ϕ→π⁰e⁺e⁻
Δ⁰→ne⁺e⁻
Δ⁺→pe⁺e⁻
10⁰
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
dN/dp_T [1/GeV]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
p_T(e⁺e⁻) [GeV]

Spatial magnetic field profile

Impact on the magnetic squeezing force $F_{x,y} = \frac{\chi}{2}\partial_{x,y}|\vec{B}|^2$

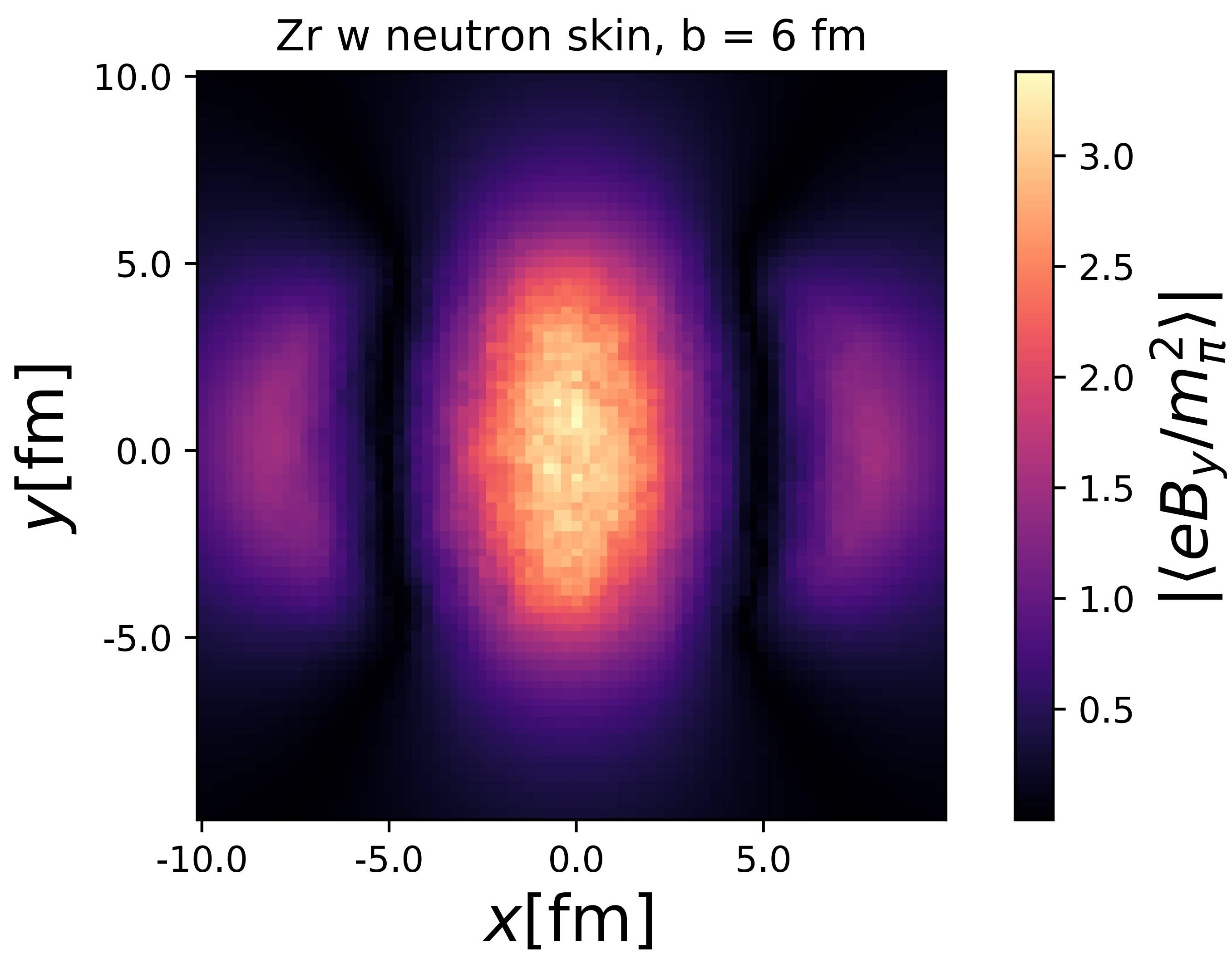
See also:

L.-G. Pang et al. Phys Rev C.93.044919



Neutron skin slightly varies the magnetic field profile in x and y slices

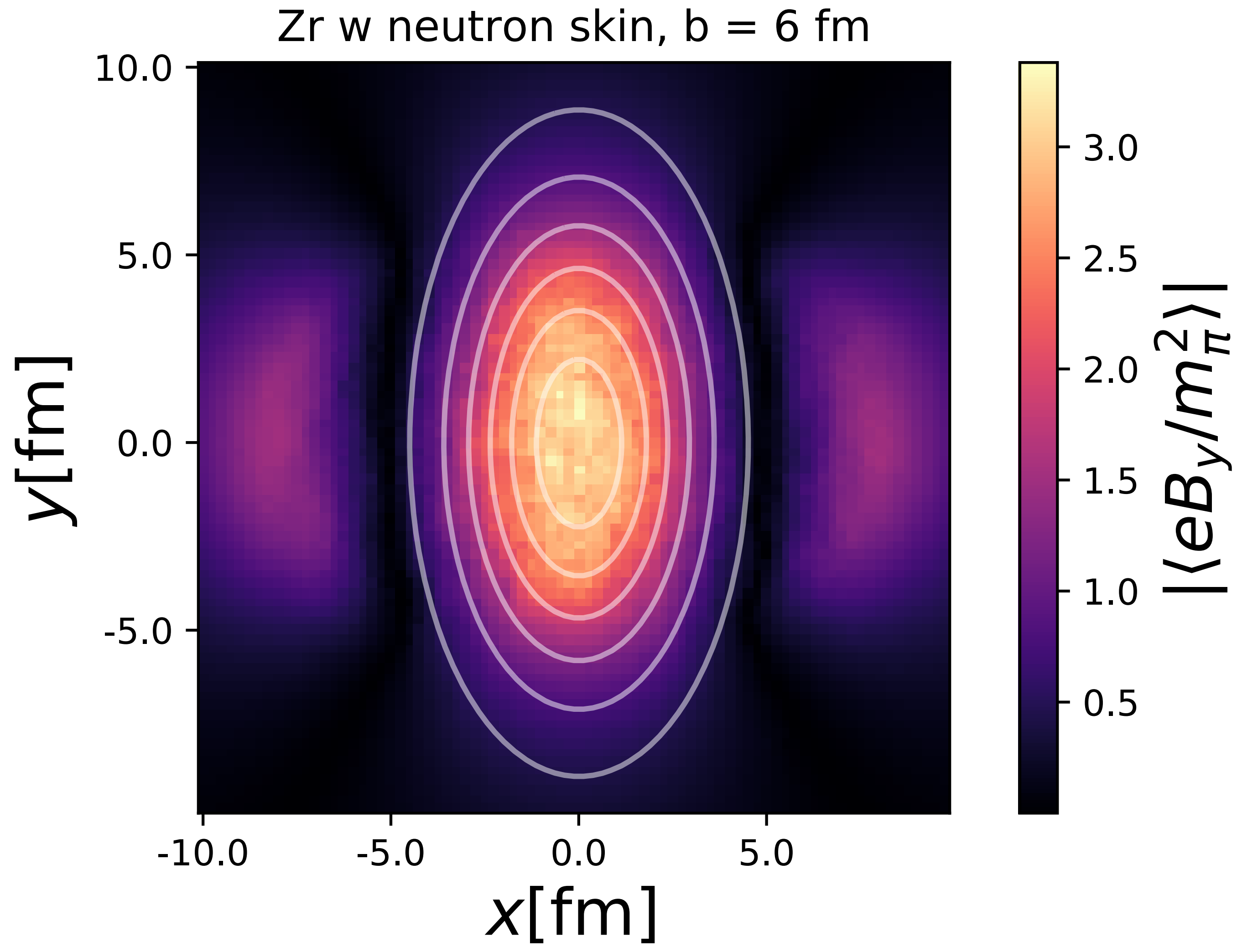
Spatial magnetic field profile



Fit the magnetic field a 2d Gaussian function of the following form

$$eB_y/m_\pi^2\,(x,y) = A\,exp\left\{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}\right)\right\}$$

Spatial magnetic field profile



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$$eB_y/m_\pi^2\,(x,y) = A\,exp\left\{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}\right)\right\}$$