Probing the neutron skin and nuclear symmetry energy with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR

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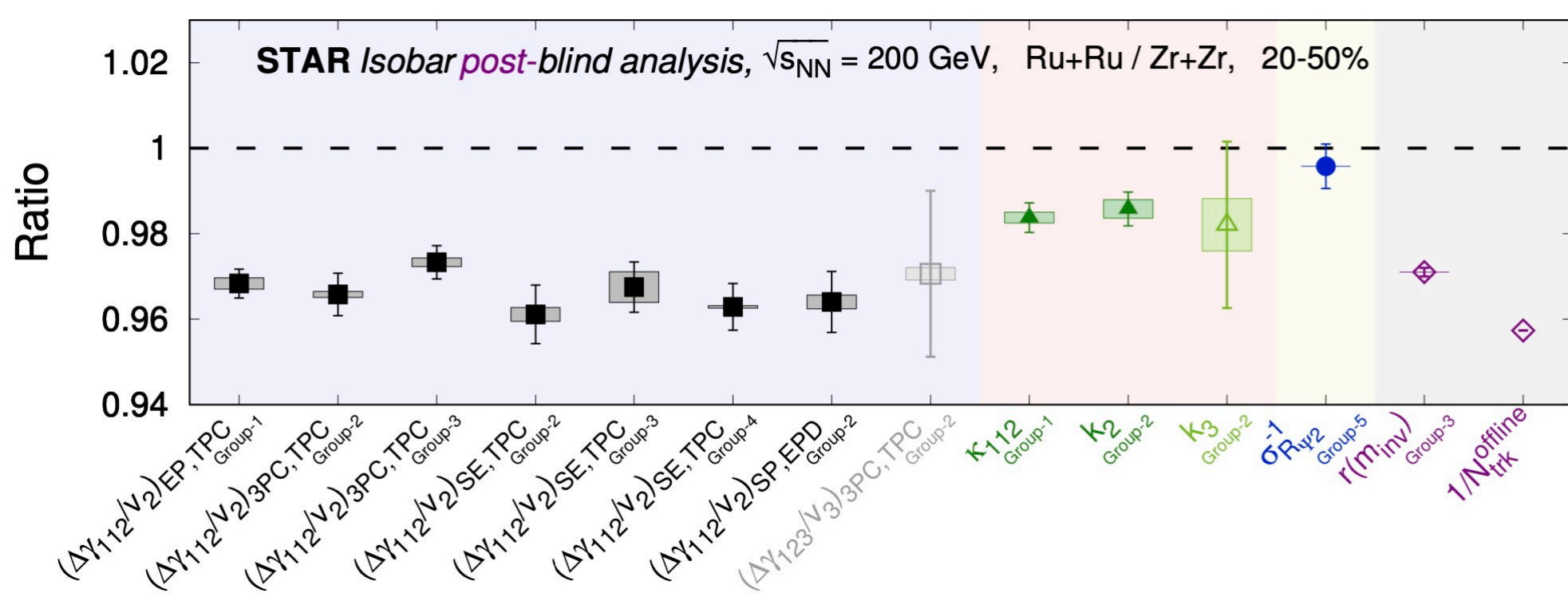
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Abstract:
The neutron skin thickness, Δr_{np}, has traditionally been measured by low-energy hadron-nucleus and nucleus-nucleus scatterings over decades. Recent studies indicate that the neutron skin can also be measured, unconventionally and possibly with better precisions than traditional methods, by colliding isobar nuclei at relativistic energies. The idea is to compare the produced hadron multiplicities (N_{ch}), the mean transverse momenta ($\langle p_T \rangle$), and the net charge multiplicities (ΔQ) to trace back the nuclear structure differences between the isobar nuclei. In this poster, we will present results on the N_{ch}, $\langle p_T \rangle$, and ΔQ ratios between $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR. We extract the neutron skin thickness and the symmetry energy slope parameter from these data. We compare our results to the global data on symmetry energy and discuss their implications in the context of equation-of-state of dense matter and neutron stars.

Relativistic isobar collisions:
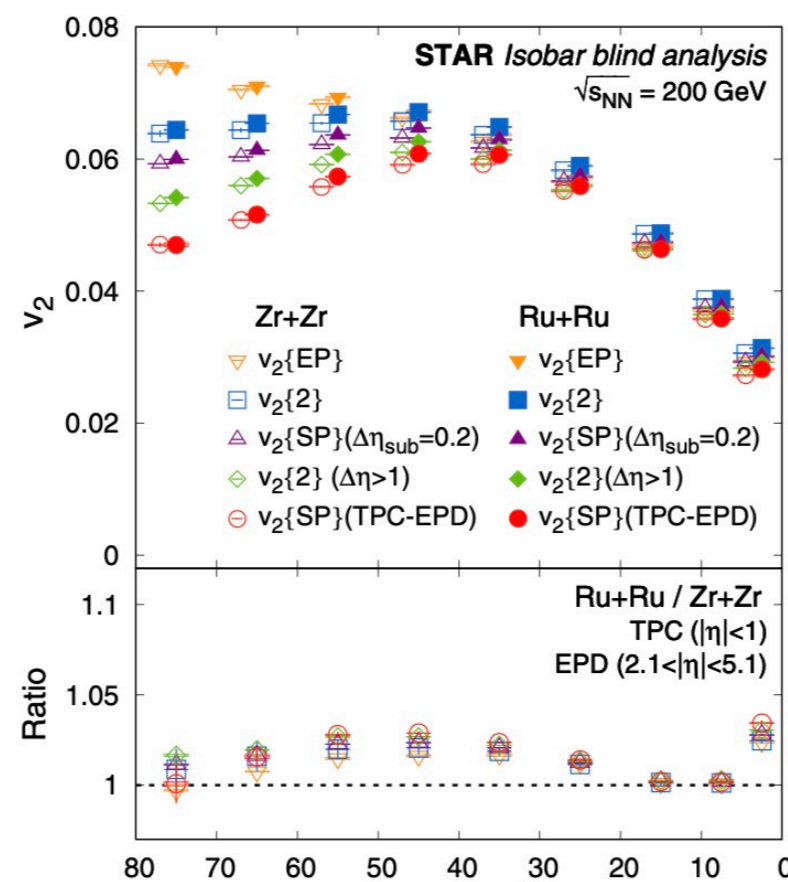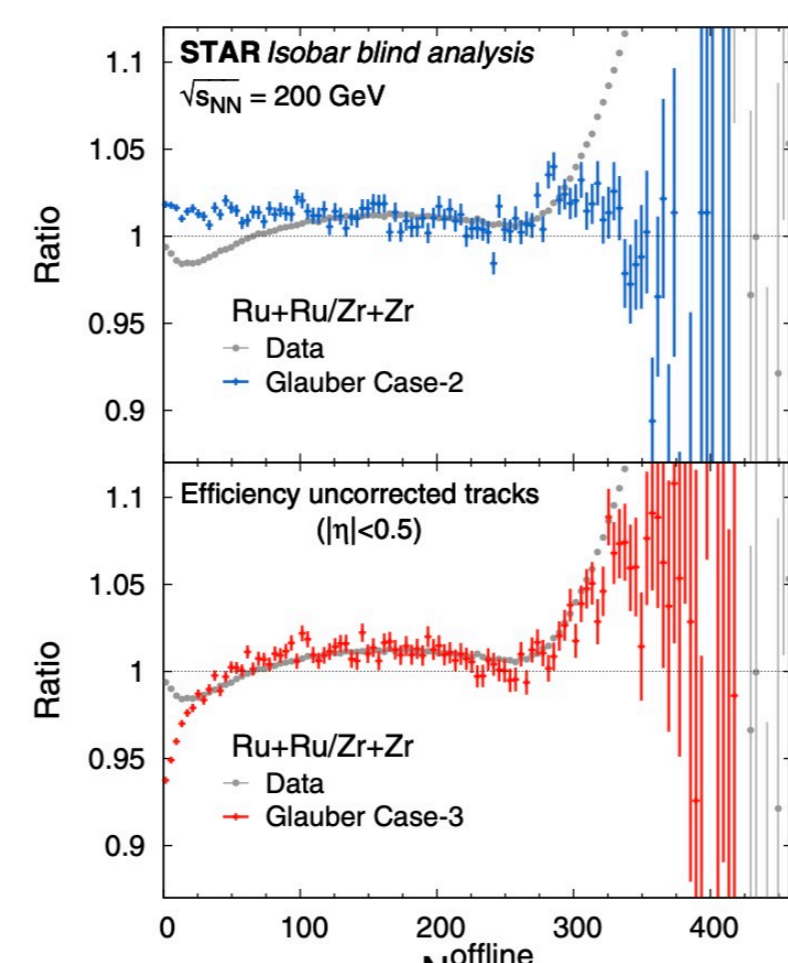
STAR Collaborations, Phys.Rev. C105, 014901 (2022)

➤ Clear differences in multiplicity and elliptic flow, indicating isobar structure difference, moving the baseline from the original expectations of CME search in isobar collisions.
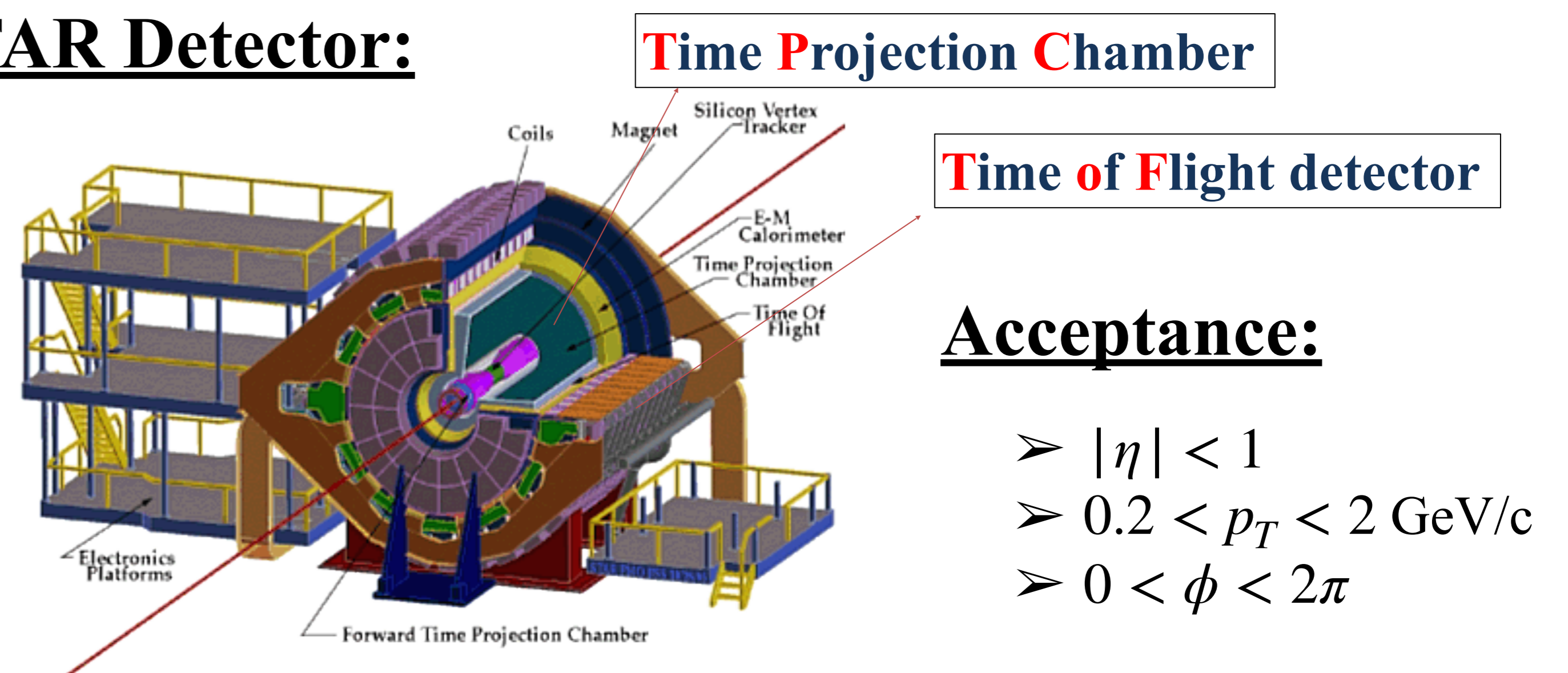
HJX, et.al, Phys.Rev.Lett. 121, 022301 (2018)

➤ The STAR isobar data demonstrate thick halo-type neutron skin in Zr, consistent with energy density functional theory calculations.
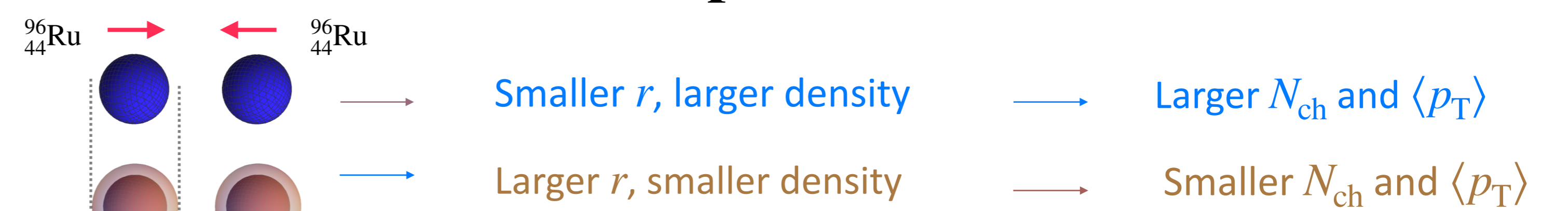
HJX, et.al, Phys.Lett. B819, 136453 (2021)

STAR Detector:

Time Projection Chamber
Time of Flight detector

Acceptance:
➤ $|\eta| < 1$
➤ $0.2 < p_T < 2$ GeV/c
➤ $0 < \phi < 2\pi$

Sensitive observables to probe the neutron skin

$^{96}_{44}$Ru $^{96}_{44}$Ru

Smaller r, larger density → Larger N_{ch} and $\langle p_T \rangle$

Larger r, smaller density → Smaller N_{ch} and $\langle p_T \rangle$

$^{96}_{40}$Zr $^{96}_{40}$Zr

➤ Multiplicity distributions   H. Li, HJX, et.al, Phys.Rev.Lett., 125, 222301 (2020)
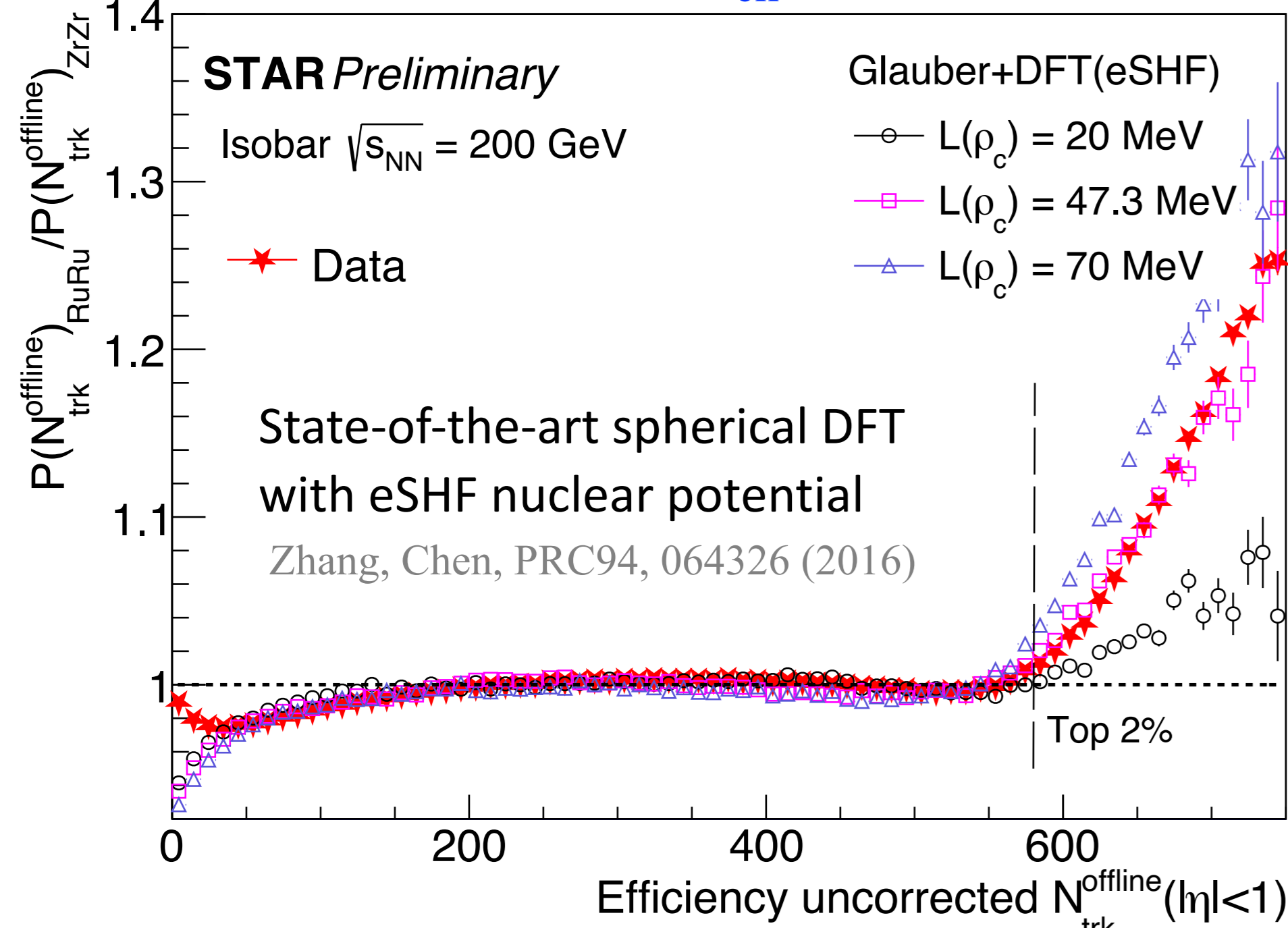➤ Mean transverse momentum   HJX, et.al, arXiv:2111.14812
➤ Net charges (isospin sensitive)   HJX, et.al, Phys.Rev. C105, L011901 (2022)

Results:

Multiplicity (N_{ch}) distributions

STAR Preliminary
Isobar $\sqrt{s_{NN}} = 200$ GeV

Glauber+DFT(eSHF)
- $L(\rho_c) = 20$ MeV
- $L(\rho_c) = 47.3$ MeV
- $L(\rho_c) = 70$ MeV
- Data

State-of-the-art spherical DFT with eSHF nuclear potential
Zhang, Chen, PRC94, 064326 (2016)

Top 2%

Mean transverse momentum ($\langle p_T \rangle$)

STAR Preliminary
Isobar $\sqrt{s_{NN}} = 200$ GeV
$0.2 < p_T < 2$ GeV/c
$|\eta| < 1$

iEBE-VISHNU + DFT(eSHF)
- $L(\rho_c) = 20$ MeV
- $L(\rho_c) = 47.3$ MeV
- $L(\rho_c) = 70$ MeV
- Deformed
- Data

Deformed: Ru($\beta_2 = 0.16$), Zr ($\beta_3 = 0.20$)

Net charges (ΔQ)

STAR Preliminary
Isobar $\sqrt{s_{NN}} = 200$ GeV
$0.2 < p_T < 2$ GeV/c

TRENTo+DFT(eSHF)
- $L(\rho_c) = 20$ MeV
- $L(\rho_c) = 47.3$ MeV
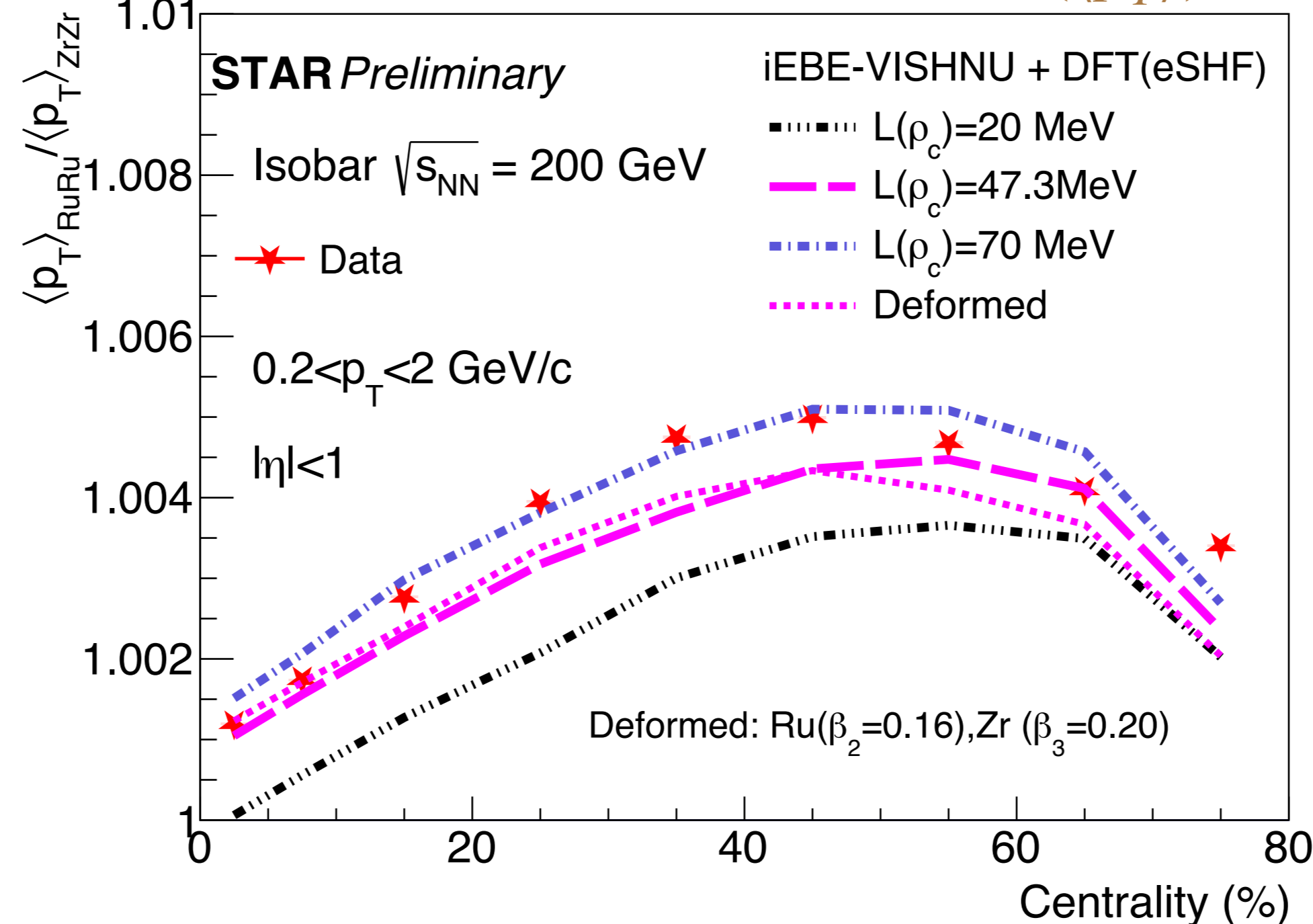- $L(\rho_c) = 70$ MeV
- $\alpha = 0$
- Data

➤ $\langle N_{ch} \rangle$ ratios in central collisions to extract Δr_{np} with linear interpolation
➤ $\Delta r_{np,Zr} = 0.195 \pm 0.019$ fm
  $\Delta r_{np,Ru} = 0.051 \pm 0.009$ fm
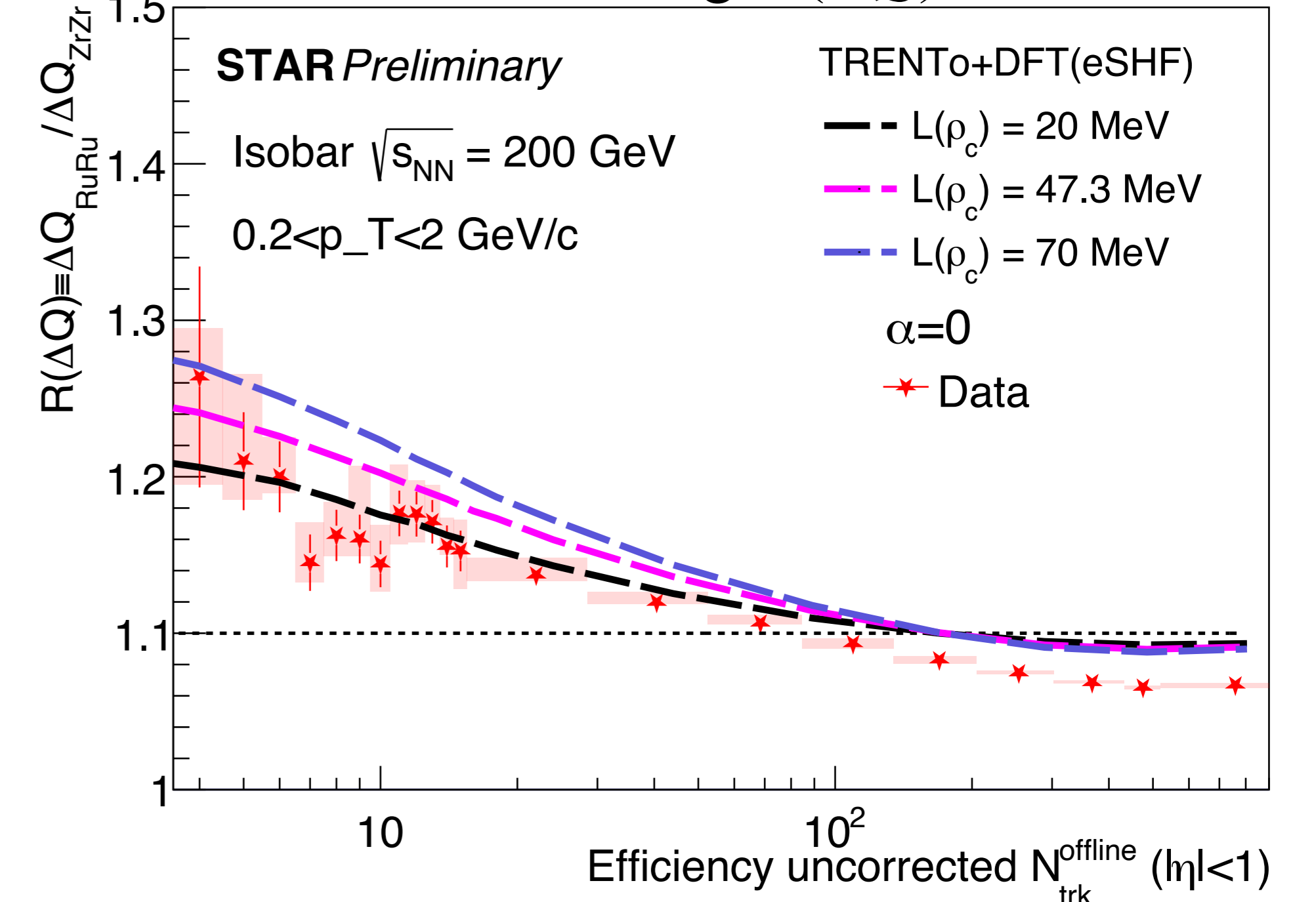➤ Uncertainties dominated by nuclear deformation

➤ $\langle p_T \rangle$ ratios in top 5% centrality to extract Δr_{np} with linear interpolation
➤ $\Delta r_{np,Zr} = 0.202 \pm 0.024$ fm
  $\Delta r_{np,Ru} = 0.052 \pm 0.012$ fm
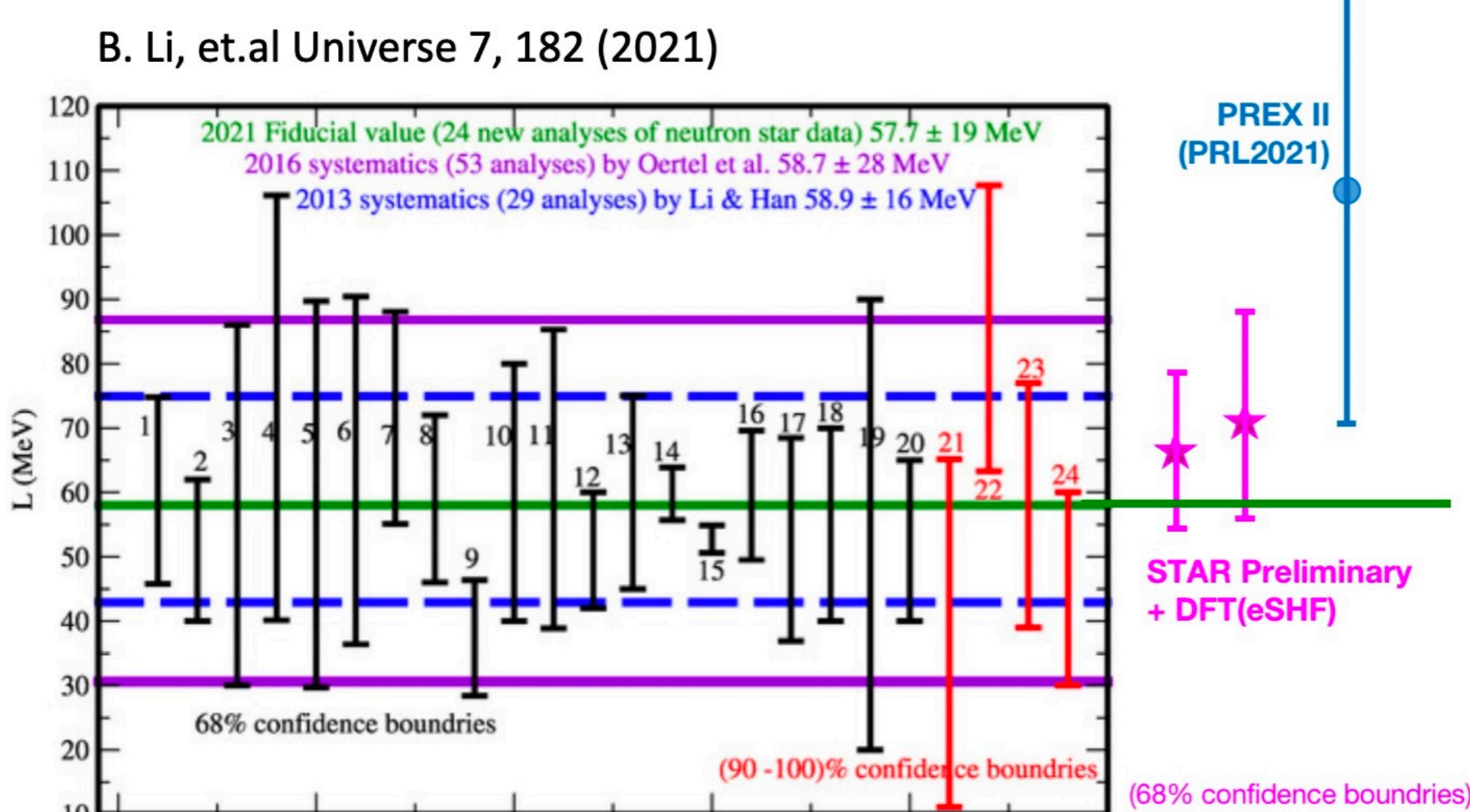➤ Uncertainties dominated by nuclear deformation

➤ ΔQ ratios in very peripheral collisions are directly related to Δr_{np} and $\alpha \equiv \Delta Q_{nn}/\Delta Q_{pp}$
➤ Data imply $\alpha \sim 0$, contrast to model studies $\alpha_{model} \sim -0.3$
HJX, et.al, Phys.Rev. C105, L011901 (2022)

Compare to world wide data:

B. Li, et.al Universe 7, 182 (2021)

2021 Fiducial value (24 new analyses of neutron star data) 57.7 ± 19 MeV
2016 systematics (53 analyses) by Oertel et al. 58.7 ± 28 MeV
2013 systematics (29 analyses) by Li & Han 58.9 ± 16 MeV

68% confidence boundries
(90 -100%) confidence boundries
PREX II (PRL2021)
STAR Preliminary + DFT(eSHF)
(68% confidence boundries)

Summary:

➤ The multiplicity and elliptic flow differences are crucial for the CME search in isobar collisions
➤ $\langle N_{ch} \rangle$ and $\langle p_T \rangle$ ratios in isobar collisions to probe neutron skin and symmetry energy
  ◦ $L(\rho_c) = 53.8 \pm 1.7 \pm 7.8$ MeV from $\langle N_{ch} \rangle$ ratio
  ◦ $L(\rho_c) = 56.8 \pm 0.4 \pm 10.4$ MeV from $\langle p_T \rangle$ ratio
  ◦ Consistent with world wide data with good precision
➤ Net charge ratios in isobar collisions imply the $\alpha \equiv \Delta Q_{nn}/\Delta Q_{pp} \sim 0$, contrast to model studies $\alpha_{model} \sim -0.3$, need further investigation.