Constraining Initial Condition from Hard Probes

Yen-Jie Lee

Collaborators: Wilke van der Schee and Yi Chen

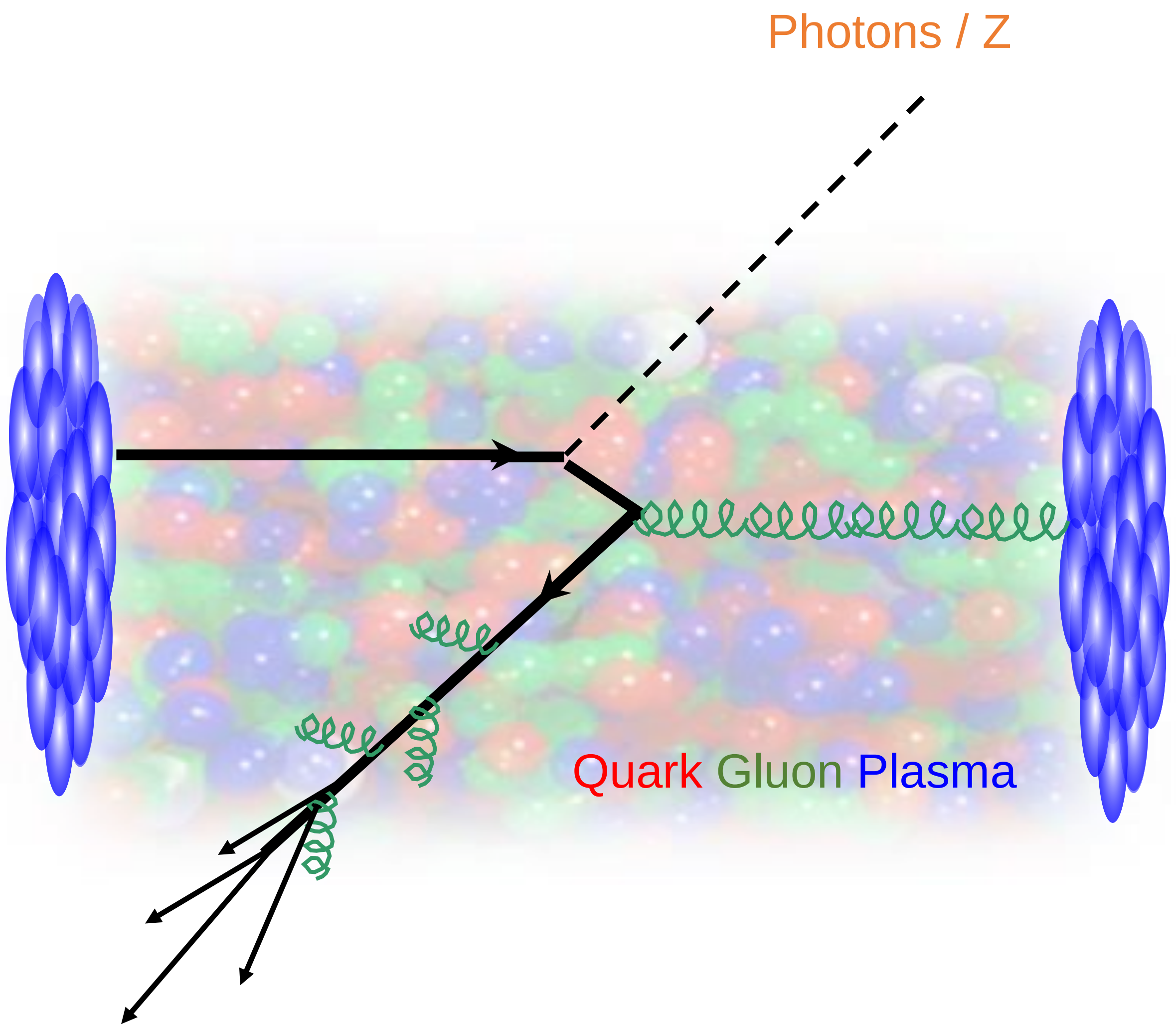
Intersection of nuclear structure and high-energy nuclear collisions

INT, Seattle, WA

9 February, 2023

MIT HIG group's work was supported by US DOE-NP

Colorless and Colored Hard Probes



Colorless Probes

Photons, electroweak bosons

Validation

Tag the initial state

Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…

Colored Probes:

Fast-moving high energy quarks and gluons,
Heavy quarks

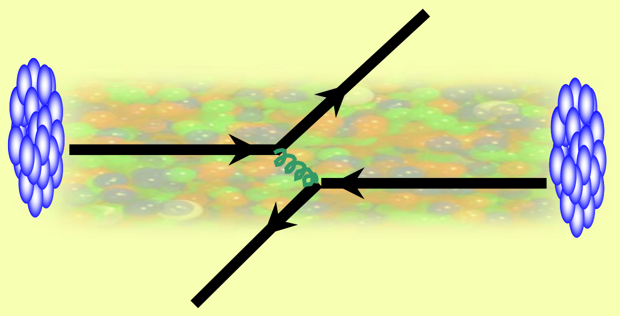
Medium properties

Extract the Medium Effect in A+A collisions

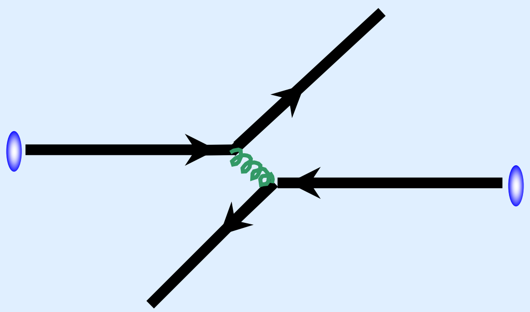
One typical way is to compare A+A data to pp reference measurement

See for instance review form
D. d'Enterria and C. Loizides
Ann.Rev.Nucl.Part.Sci. 71 (2021) 315-44

A+A measurements



pp reference



'Nuclear modification factors'

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{"QCD Medium"}}{\text{"QCD Vacuum"}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

$N_{coll} \rightarrow$ Averaged number of binary scattering

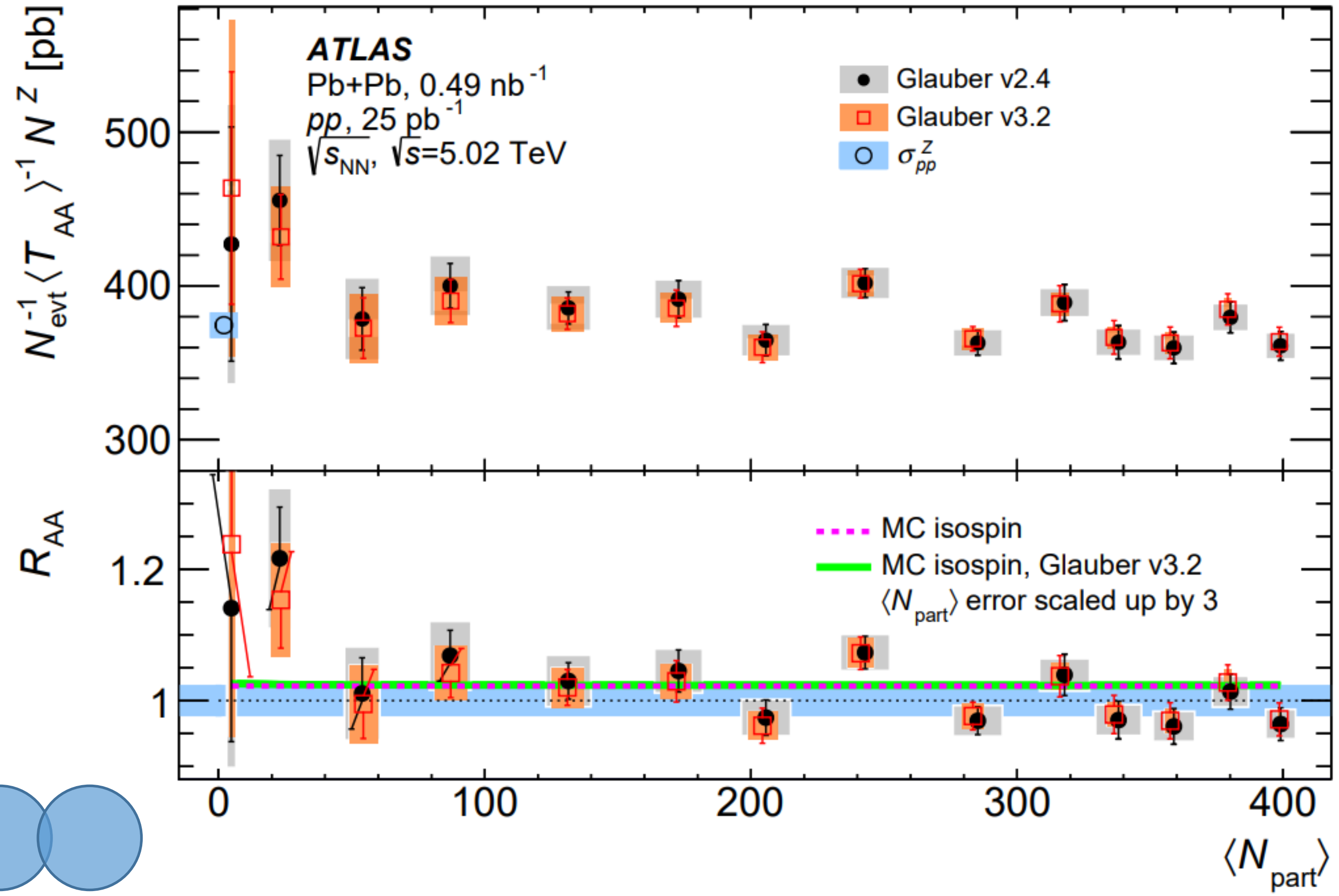
Can also be written as $1/T_{AA}$

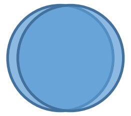
$$T_{AA} = \frac{N_{coll}}{\sigma_{pp}^{inel}}$$

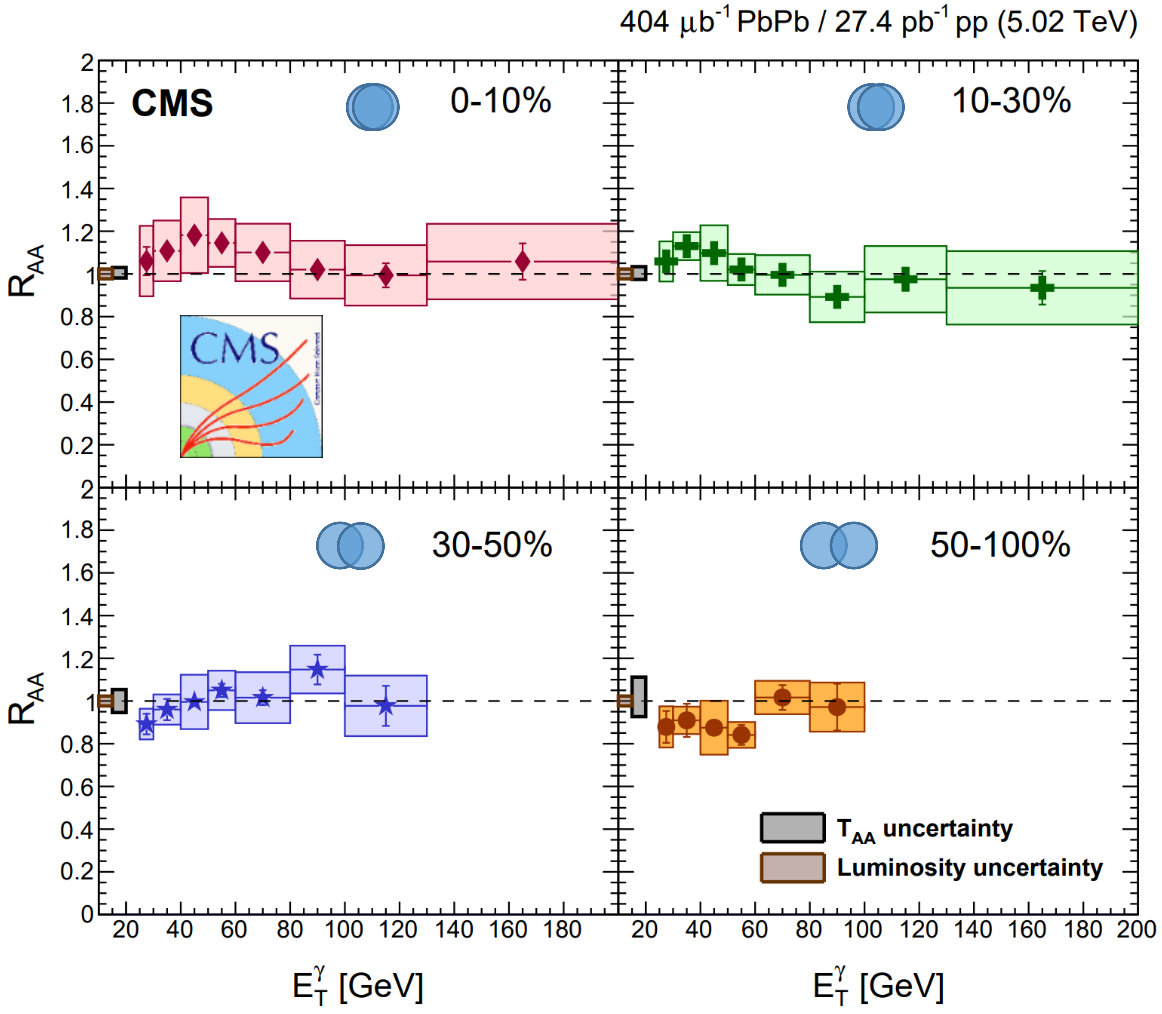
"NN equivalent integrated luminosity per A+A collision"

Reduces the uncertainty from pp inclusive cross-section

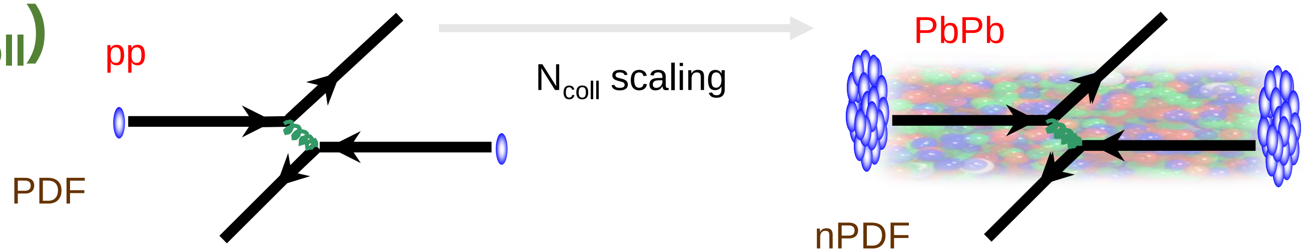
Colorless Probes: Z and Isolate Photon R_{AA}



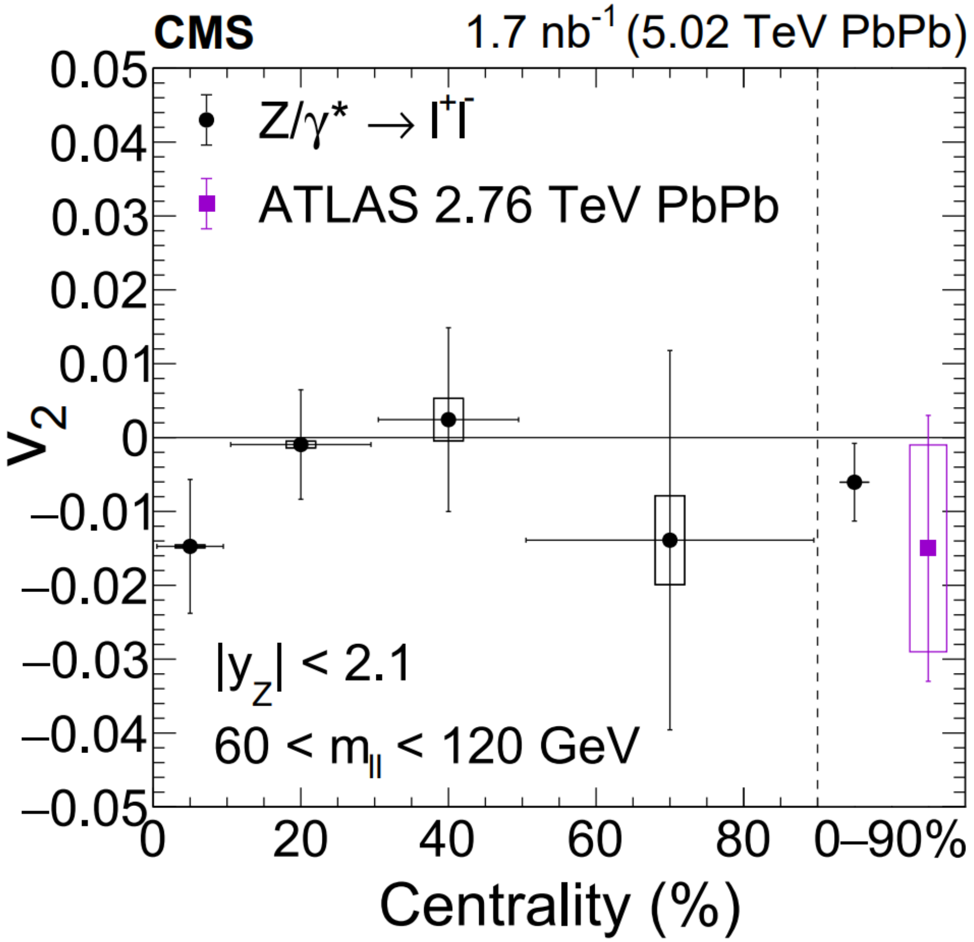


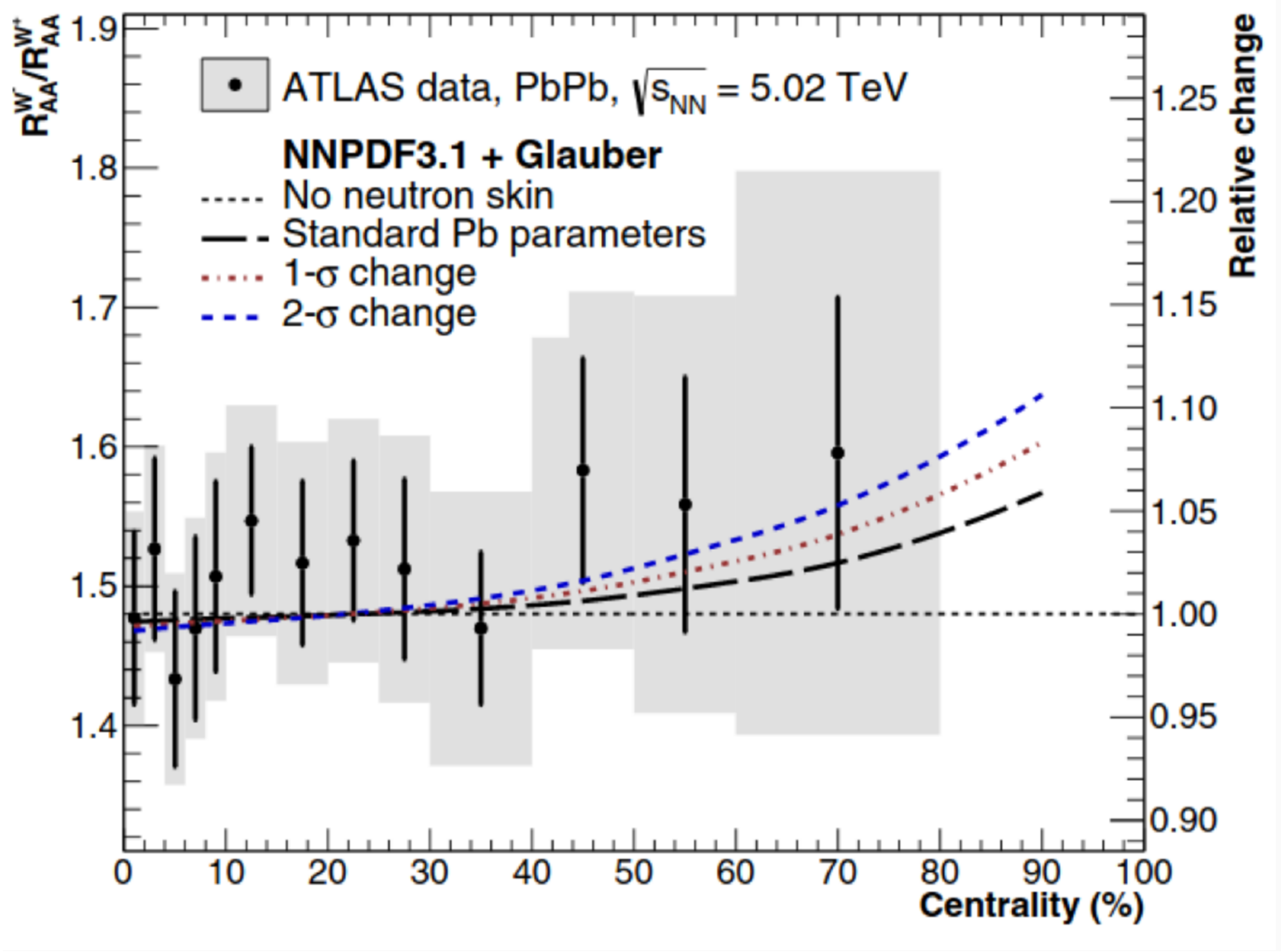


- Electroweak probes are unmodified (R_{AA}~1)
- EWK probe yields: **probe the system size (N_{coll})**
- High precision W, Z and isolated photon measurements: **constraint nPDF**



Colorless Probes: Z v_2 and W^- / W^+ R_{AA} Ratios



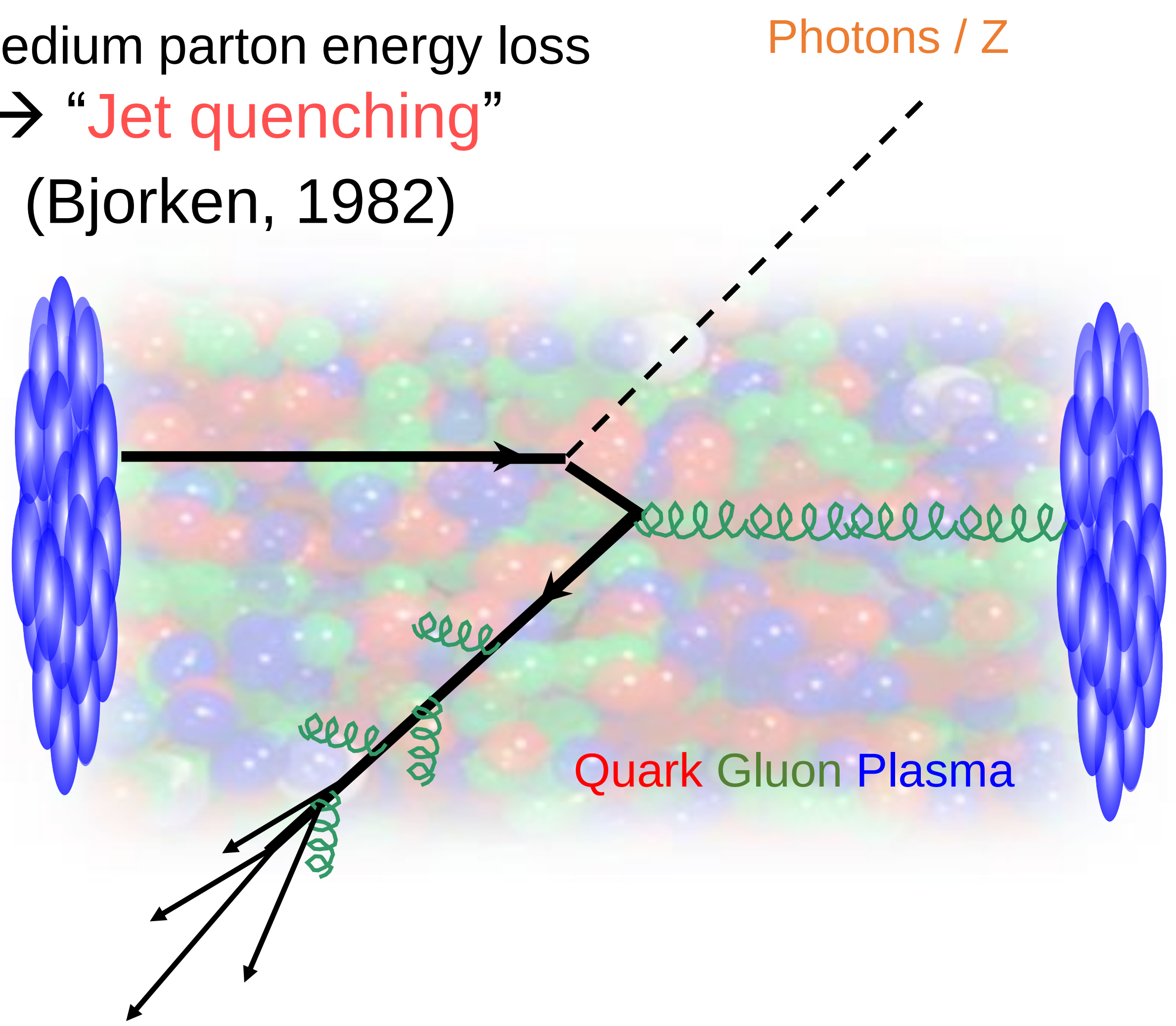


PRC 104 (2021) 044905

- No significant Z boson v_2
- W^-/W^+ ratio as a tool for the extraction n/p ratio in centrality classes

Colorless and Colored Hard Probes

In medium parton energy loss
→ "Jet quenching"
(Bjorken, 1982)



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Colored Probes:

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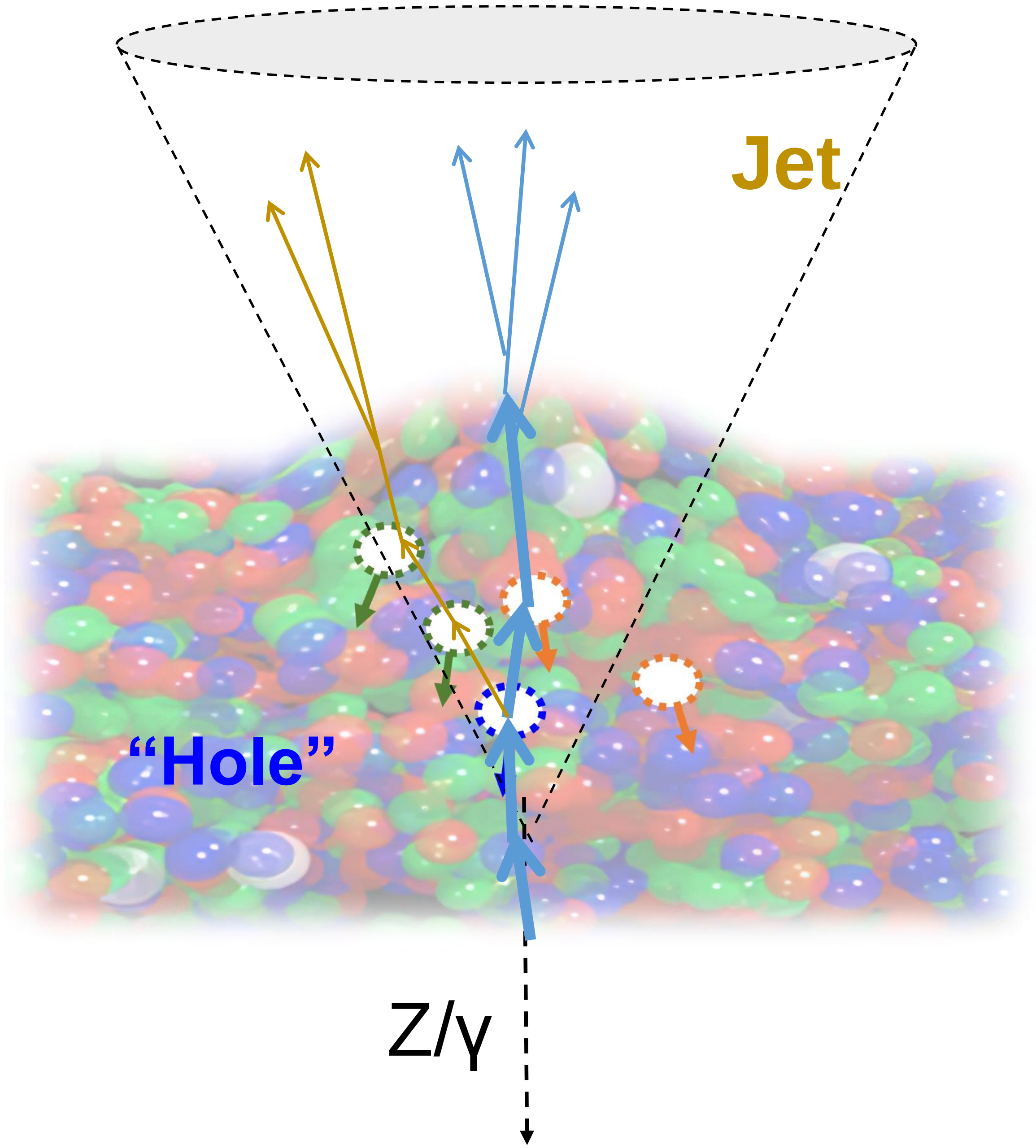
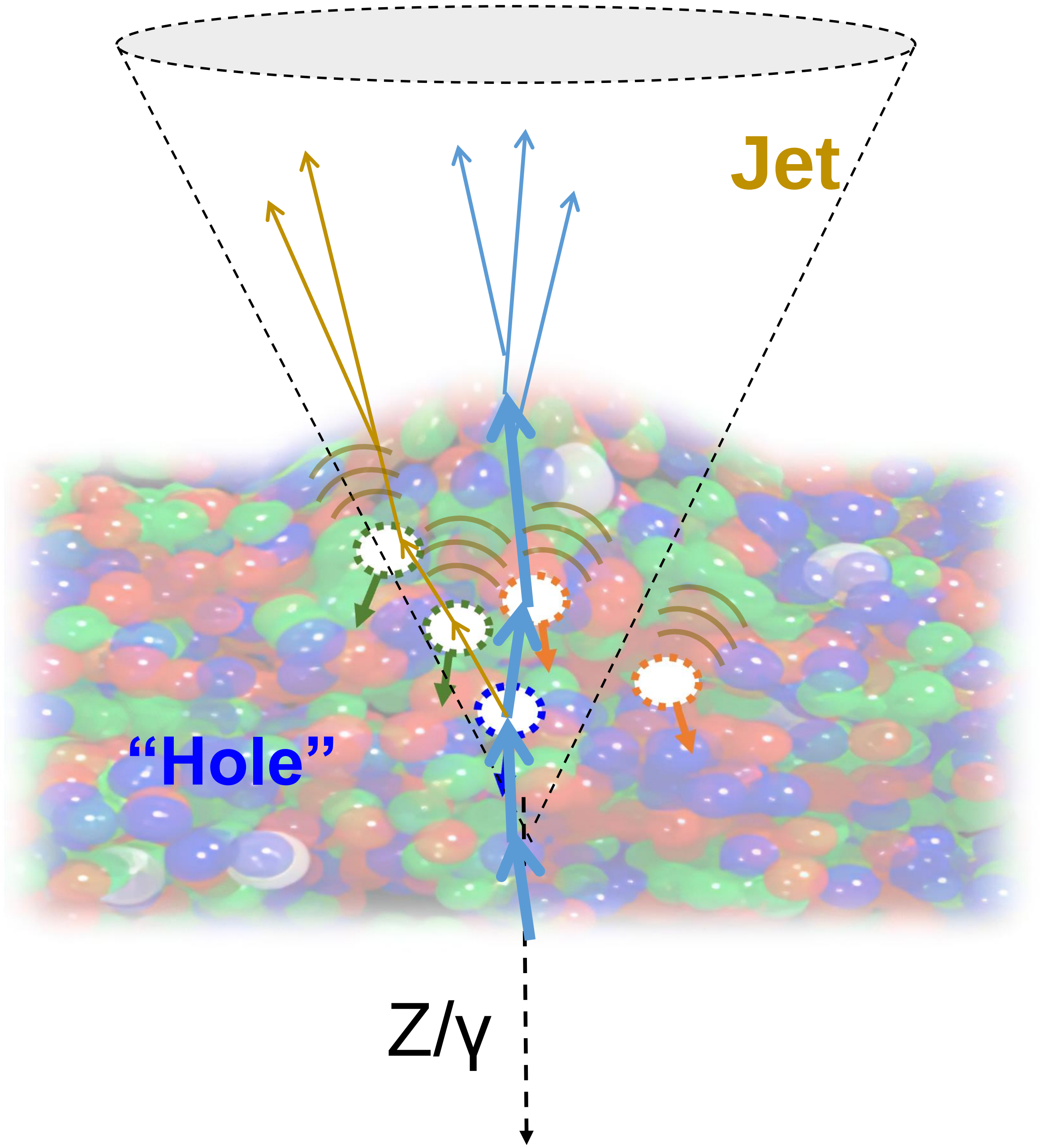
Medium properties

QGP Transport Properties and Structure with Jets



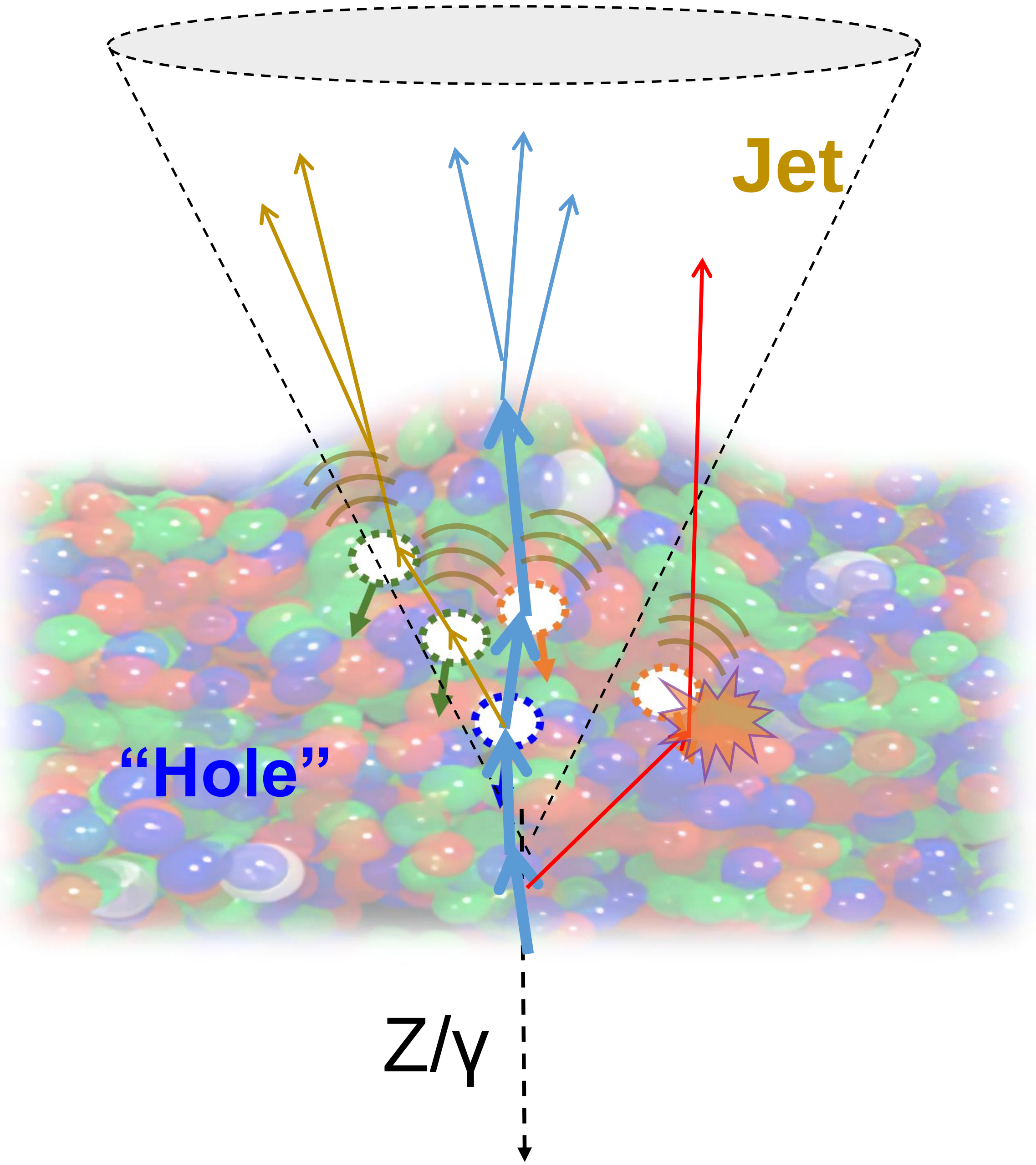
- Jet broadening effects from multiple soft scattering ($\hat{q}$)

QGP Transport Properties and Structure with Jets



- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)

QGP Transport Properties and Structure with Jets



- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes) 
- With the precise understanding of the phenomena above, one could study the QGP structure with Moliere scattering

Jet Quenching without Jet: Charged Particle R_{AA}

'Nuclear modification factors'

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{"QCD Medium"}}{\text{"QCD Vacuum"}}$$

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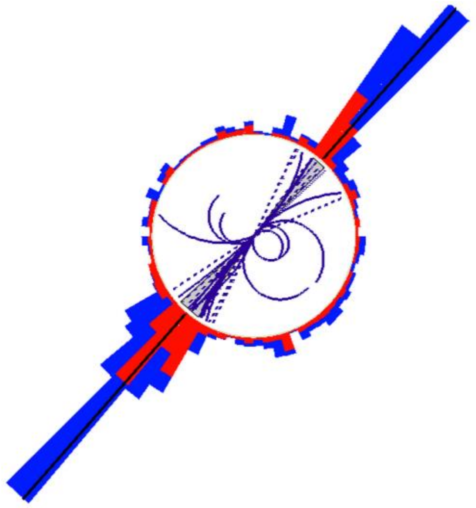
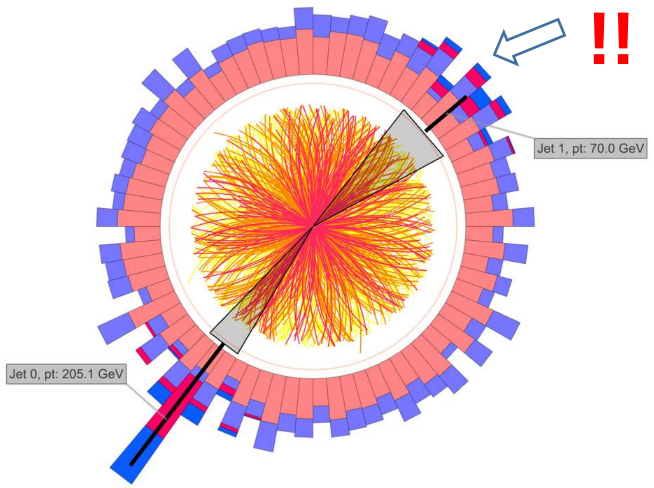
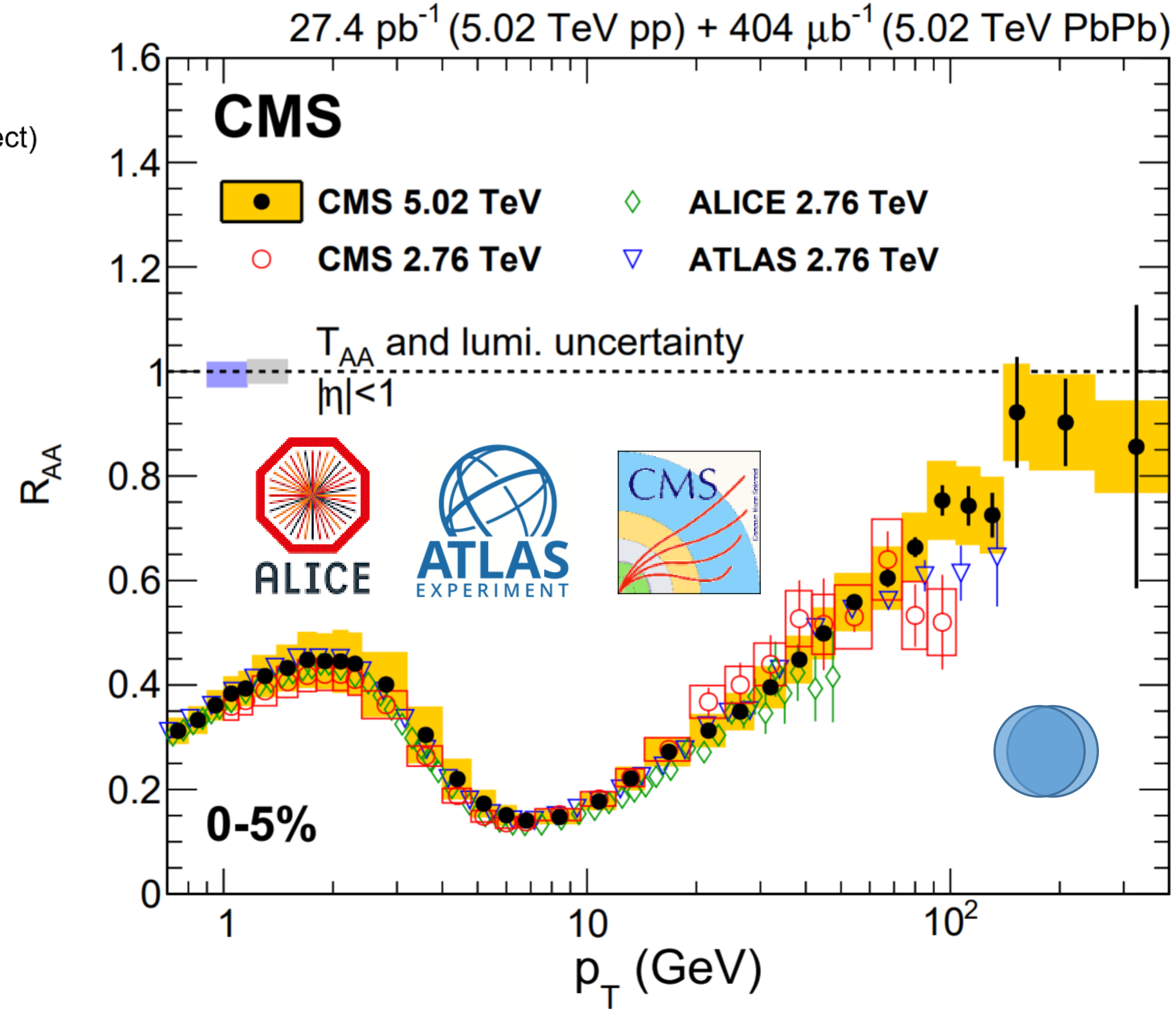


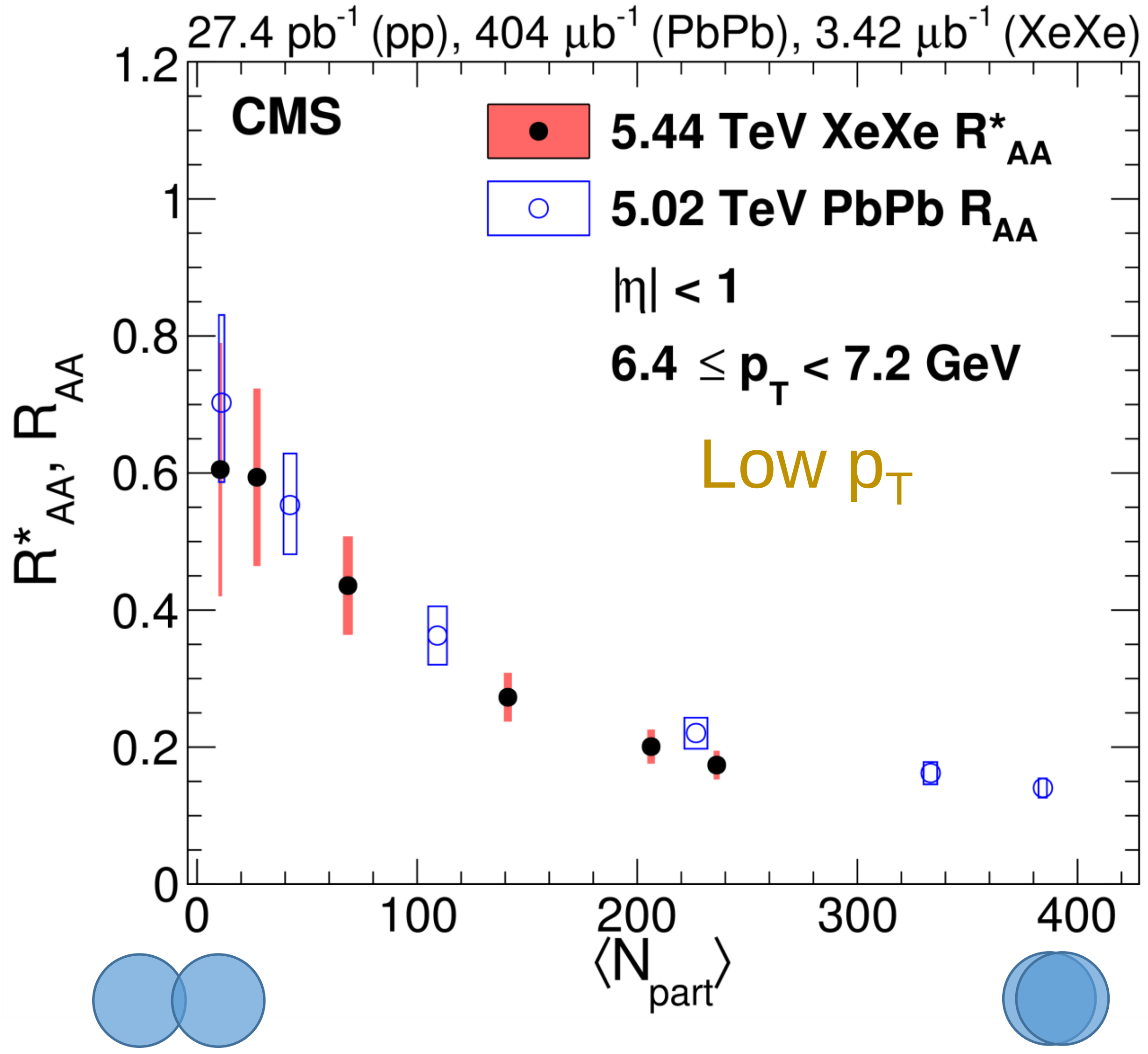


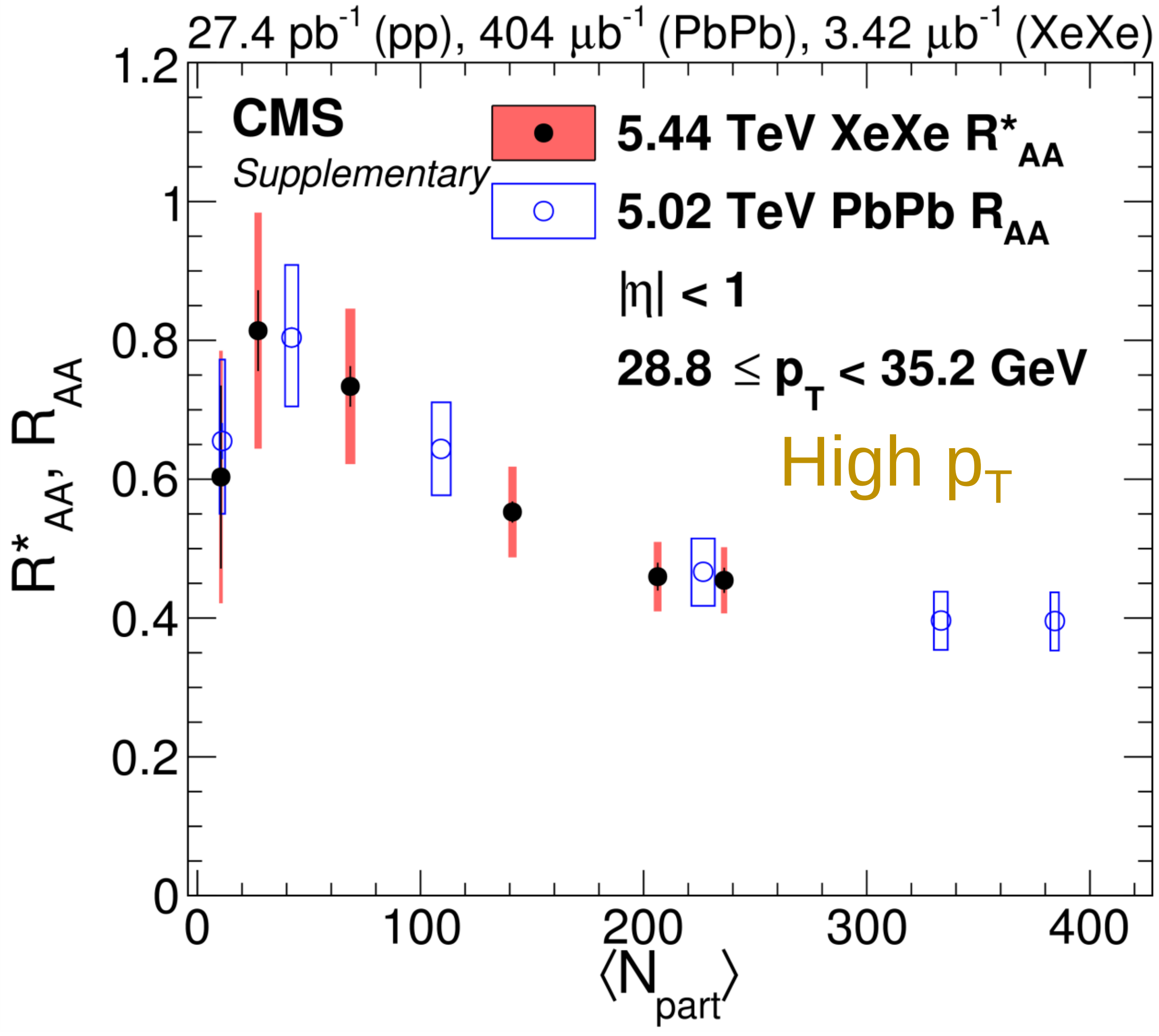
Proton+Proton **Lead+Lead**



- A prominent "S shape" in charged particle R_{AA}
- Good agreement between experiments at the LHC

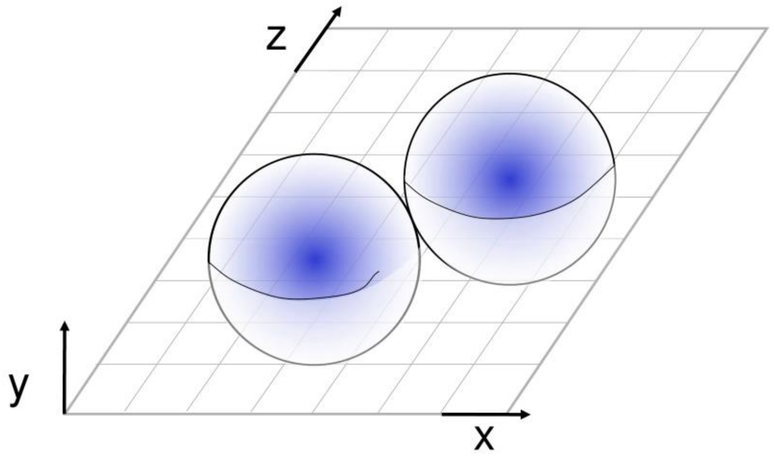
Charged Particle R_{AA} vs. N_{part}





- R_{AA} decreases as we go to large system size / small impact parameter
- Scaling behavior: XeXe vs. PbPb R_{AA}

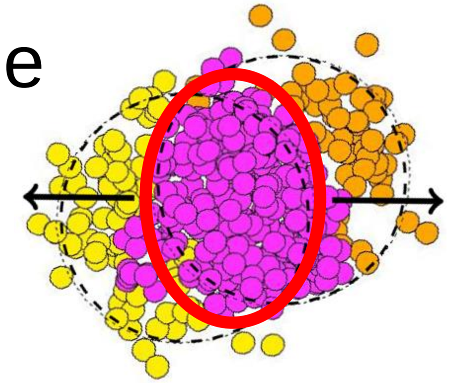
Azimuthal Anisotropy of Charged Particles



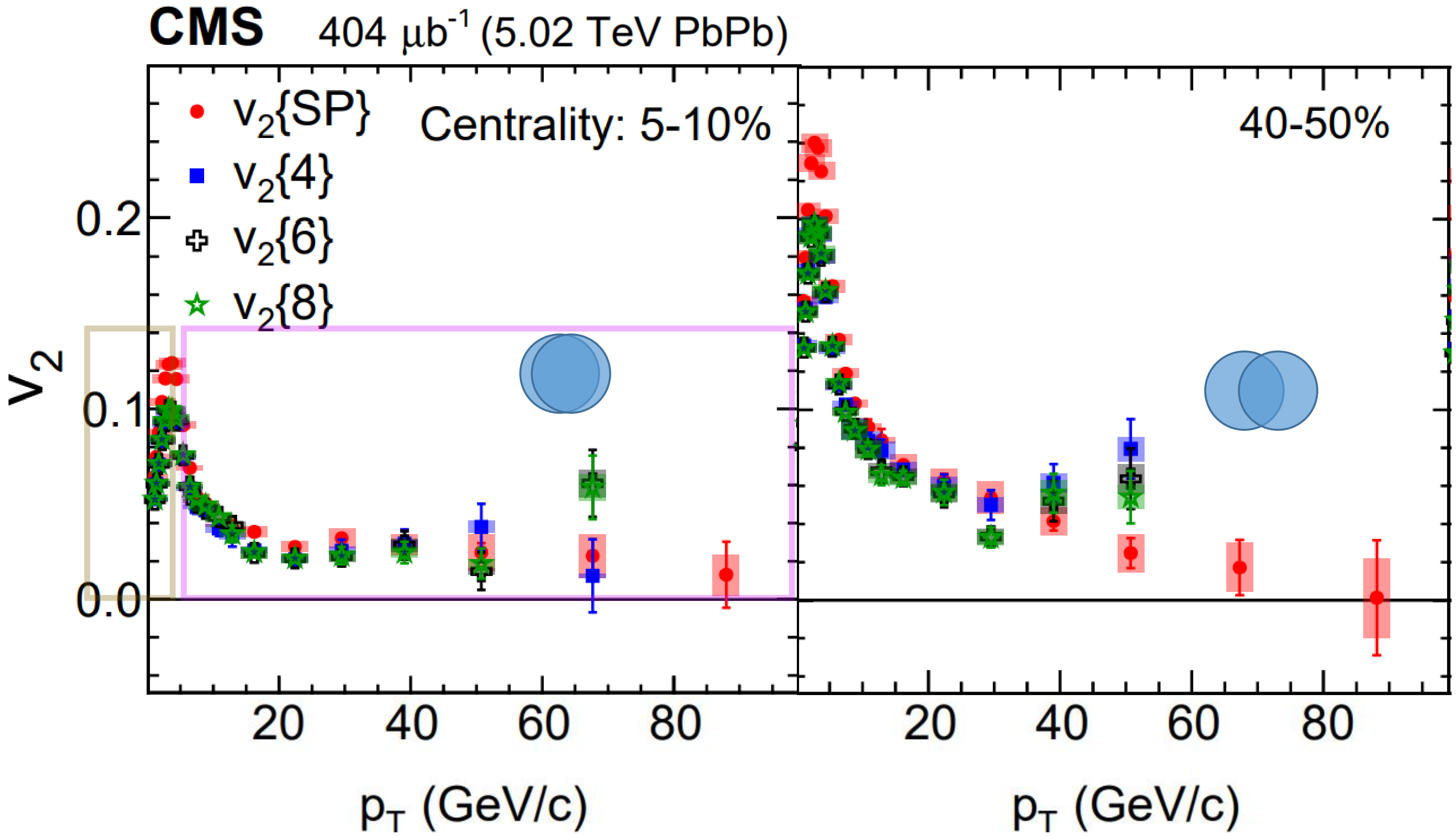
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

Magnitude

V_2

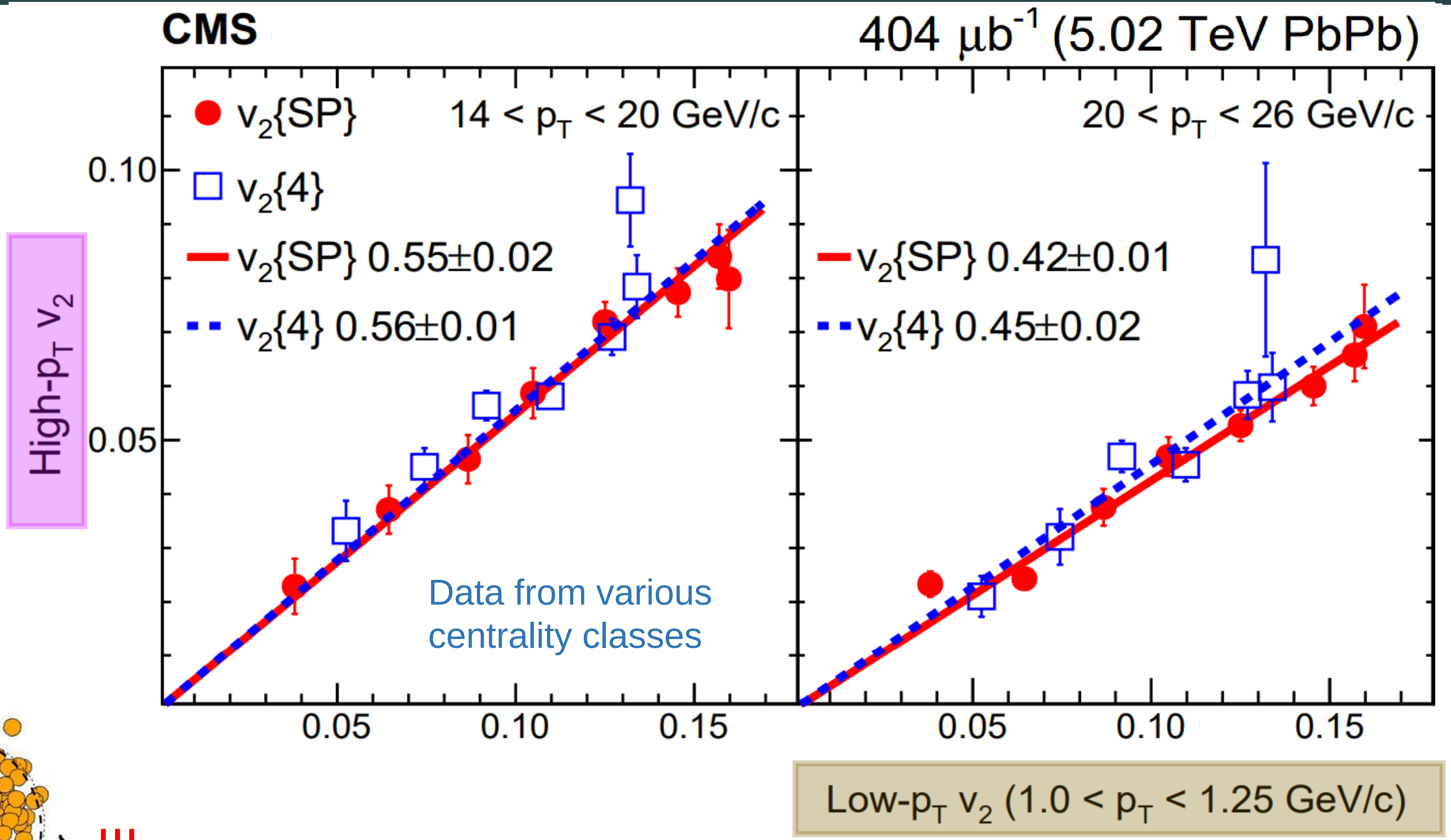


Ψ_2



- **Low p_T** v_2 : pressure-driven expansion of QGP
- **High p_T** v_2 : jet quenching

Azimuthal Anisotropy of High p_T Particles



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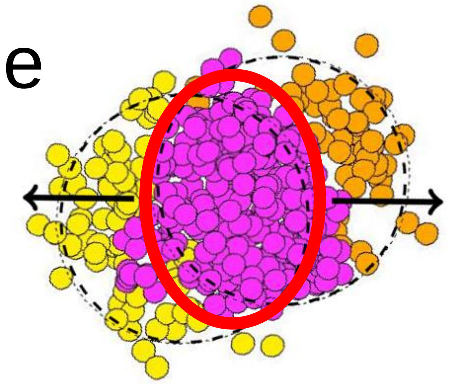
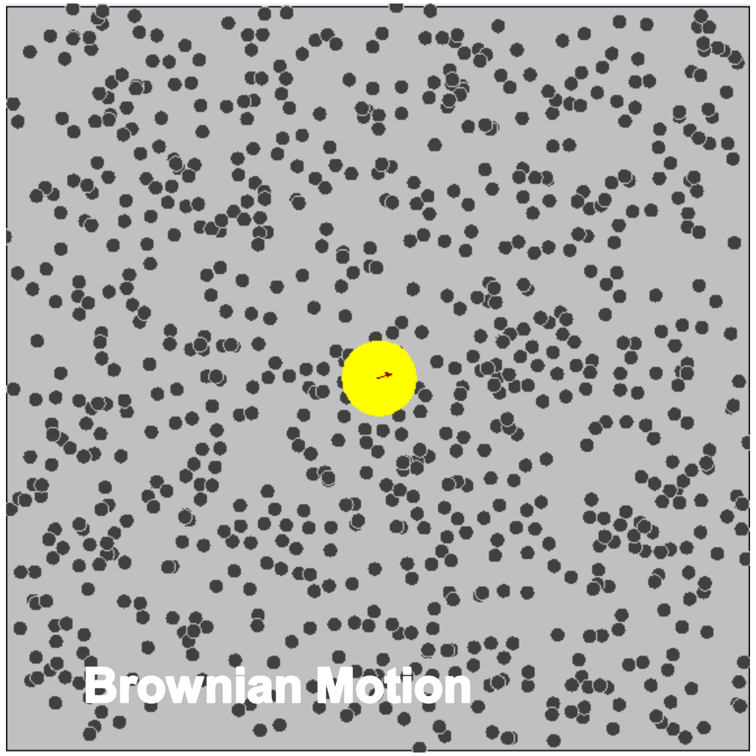


Ψ_2

- **Low p_T** v_2 : pressure-driven expansion of QGP
- **High p_T** v_2 : jet quenching
- **Linear Correlation!** Hard probes could **“see” the QGP shape**

Heavy Quarks as Probes of Quark Gluon Plasma

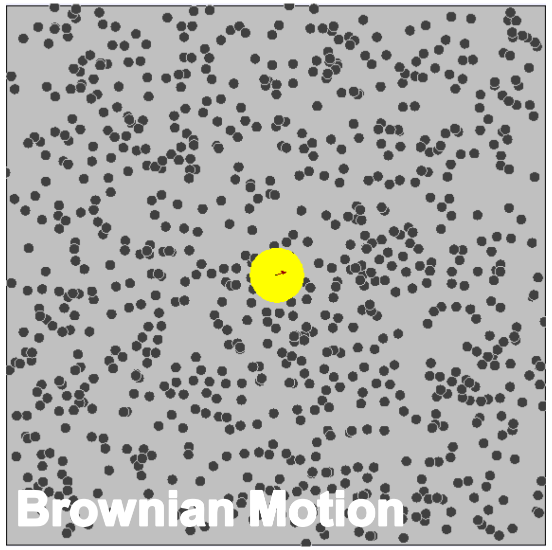
- **Charm** and **beauty** quarks (heavy quarks) are produced before QGP formation (<0.2 fm/c)
- Once produced, they **can not be destroyed by strong interaction** (in particular, for beauty)
- An opportunity to study QGP with a "**slow-moving hard probe**"



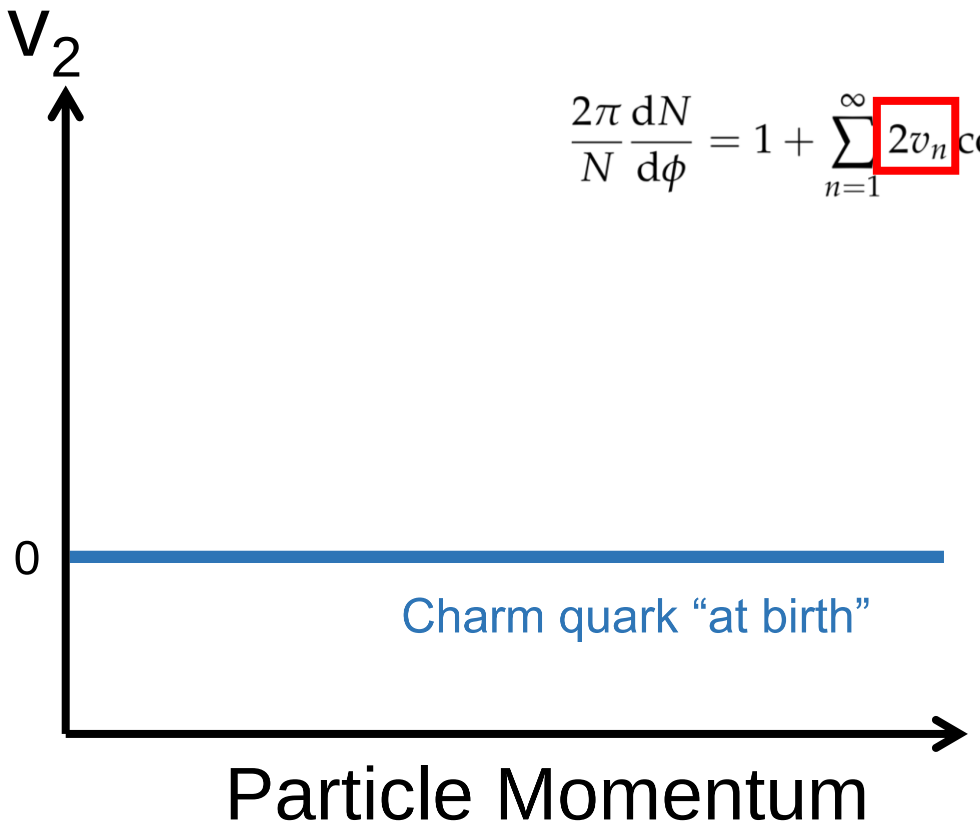
- Low momentum heavy quarks are then "kicked around" by quasi-particles (Brownian Motion) before they hadronized: A direct window to in-medium color force
- Heavy quark diffusion constant can be calculated in phenomenological models or Lattice based calculations

Heavy Quark (Charm and Beauty) Diffusion

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

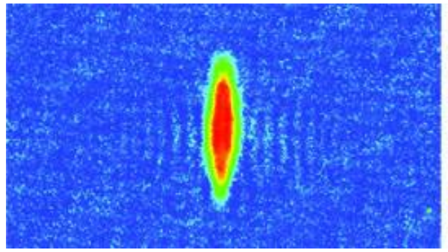


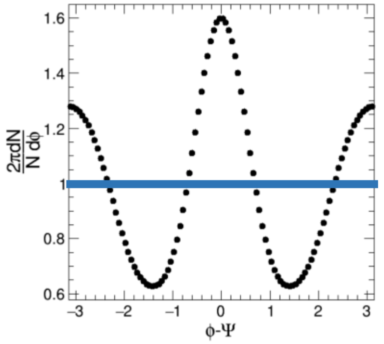
Artist's impression



- No azimuthal anisotropy "at birth"

Heavy Quark (Charm and Beauty) Diffusion





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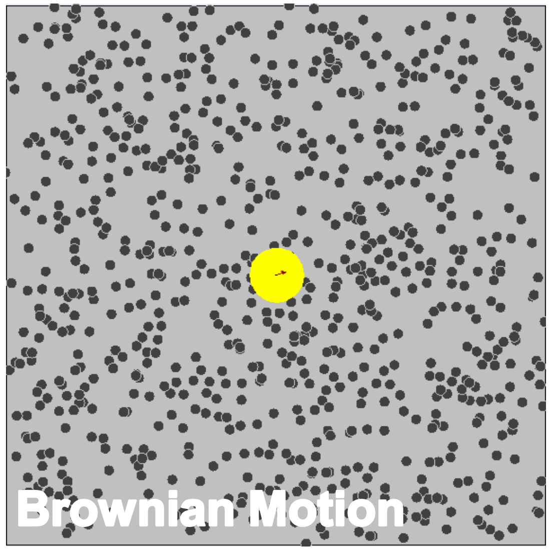

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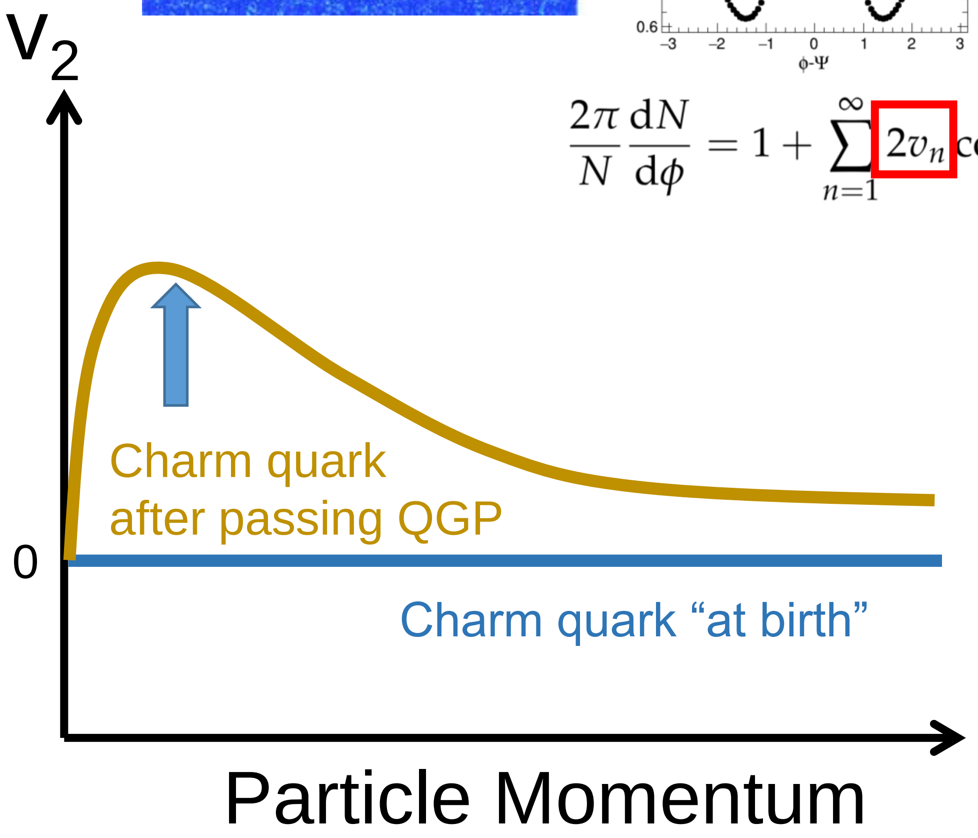


Fokker-Planck equation

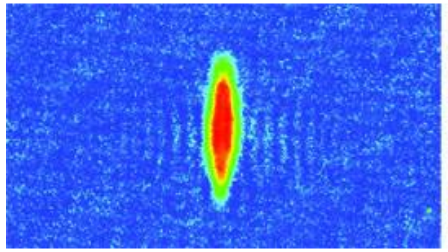
$$\frac{\partial}{\partial t} f_Q(t,p) = \frac{\partial}{\partial p} pA(p) f_Q(t,p) + \frac{\partial^2}{\partial^2 \vec{p}} B(p) f_Q(t,p)$$

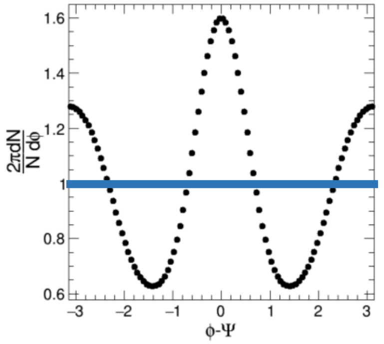
A and B are transport coefficients

$$\mathcal{D}_s = \frac{T}{m_Q A(p=0)}$$

- Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the v_2 of the charm quarks in the QGP bath!!

Heavy Quark (Charm and Beauty) Diffusion





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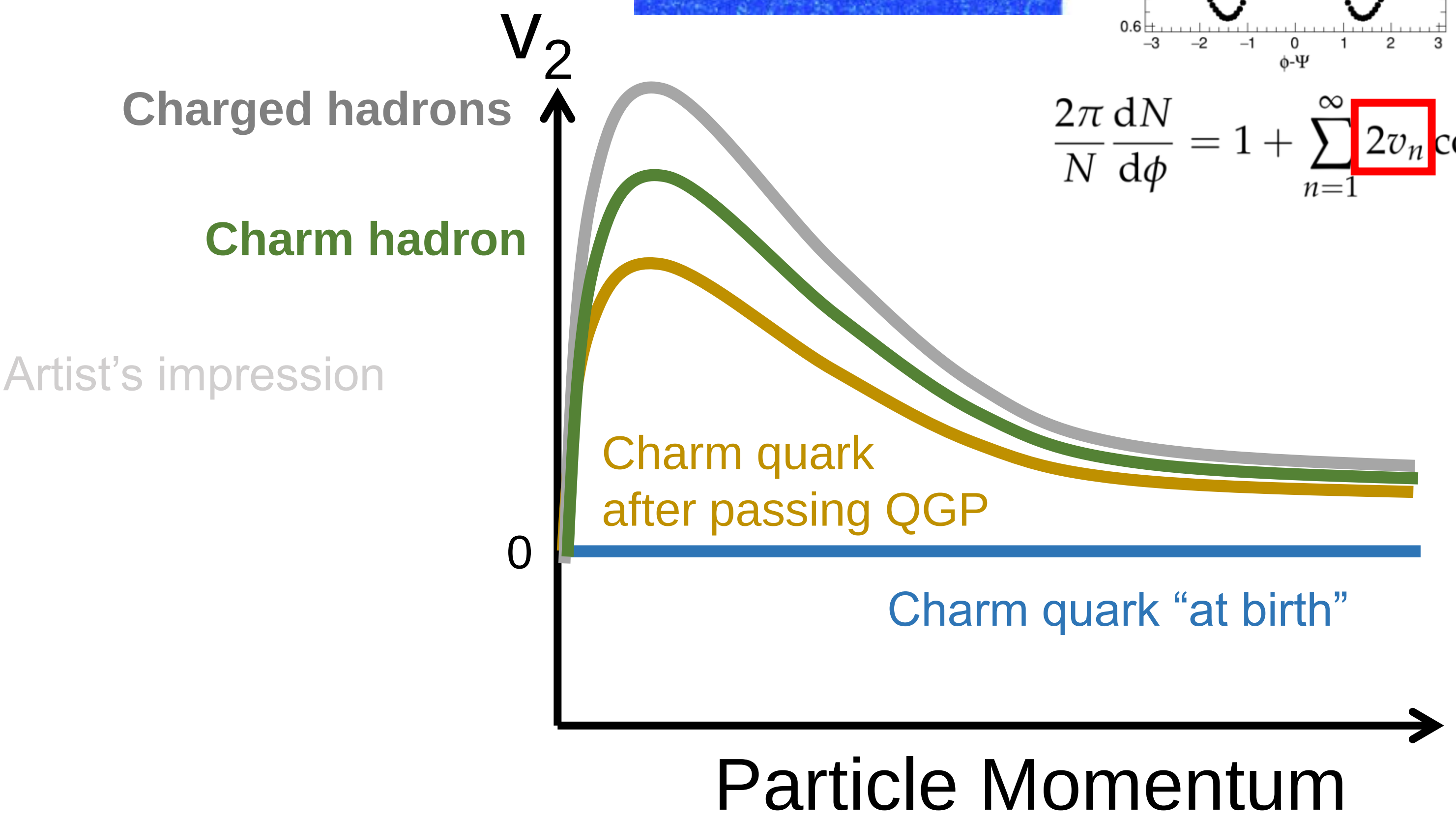
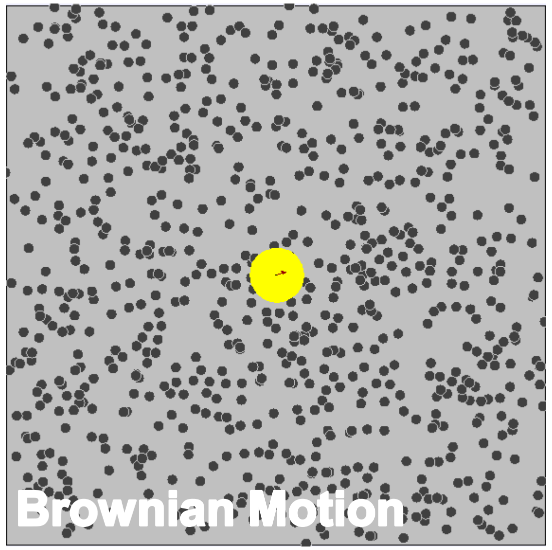
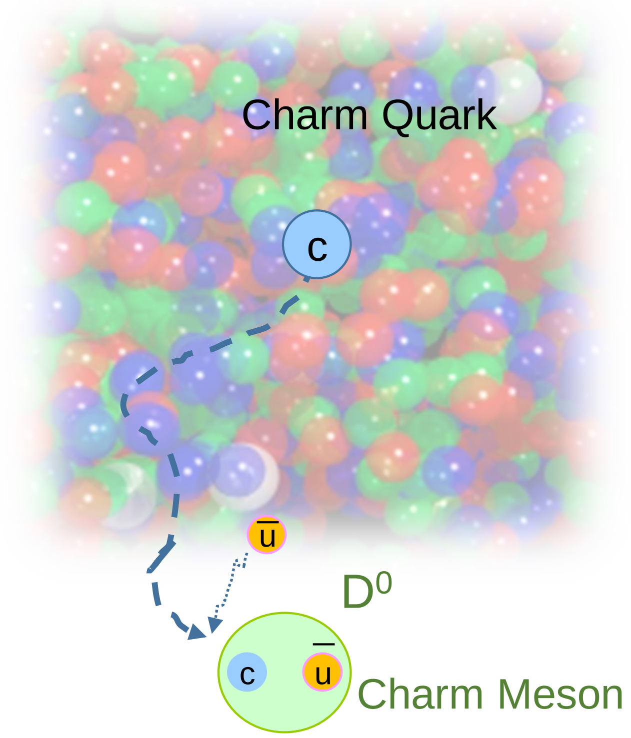
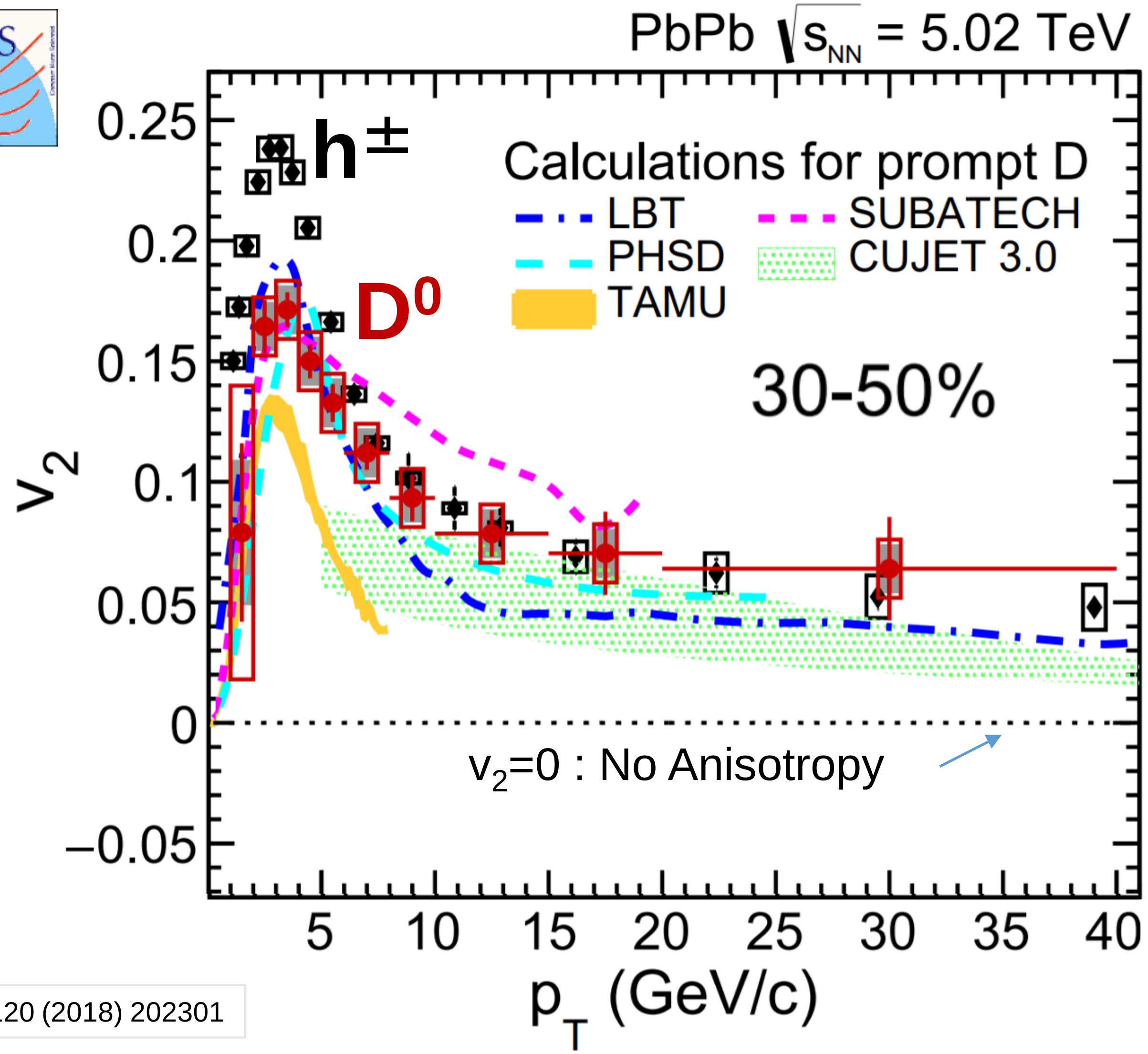






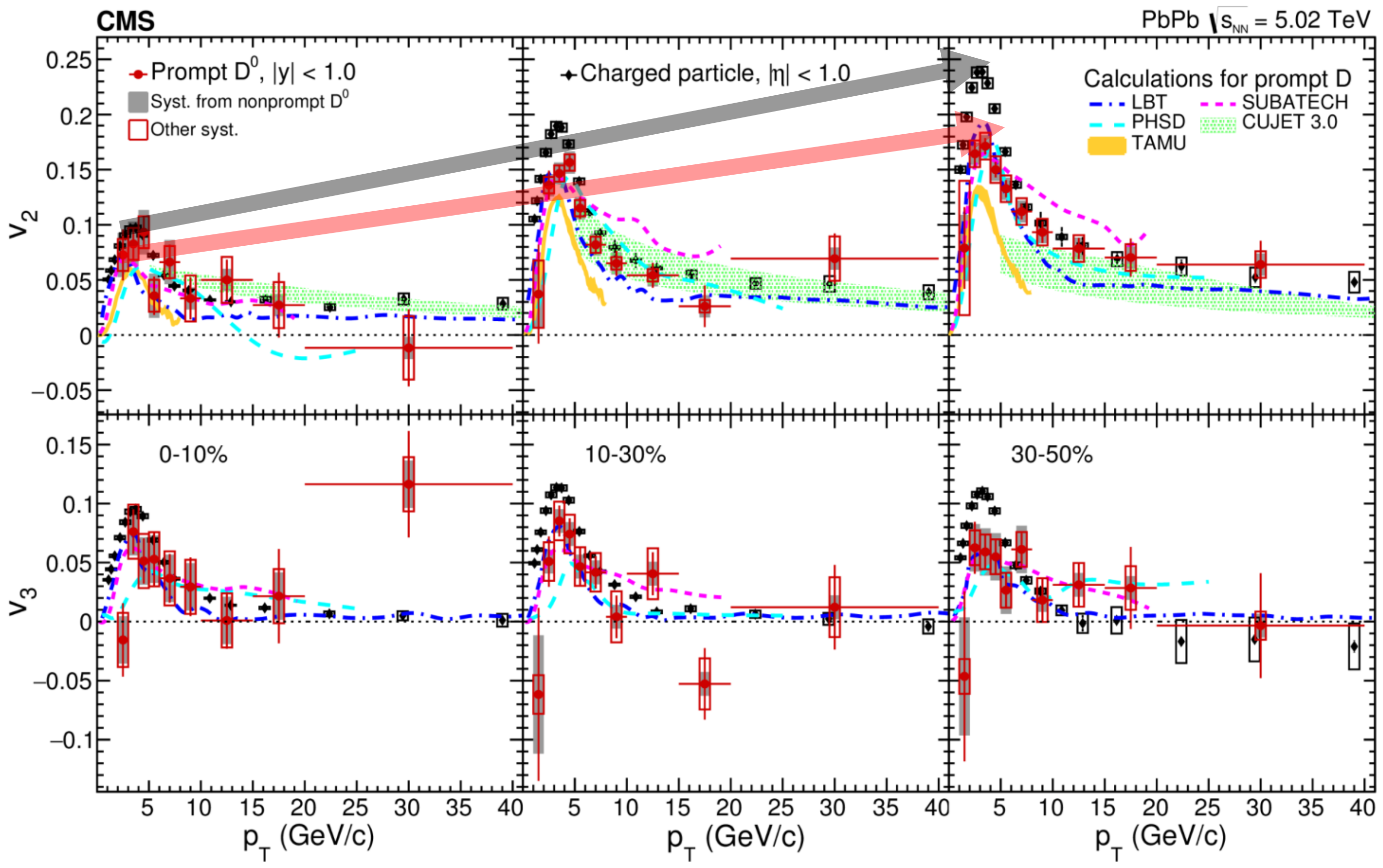
- Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the v_2 of the charm quarks in the QGP bath!!
- **Hadronization effect** could change the v_2 of the heavy flavor hadron further

Charm Diffusion Signal



PRL 120 (2018) 202301

Different centrality classes

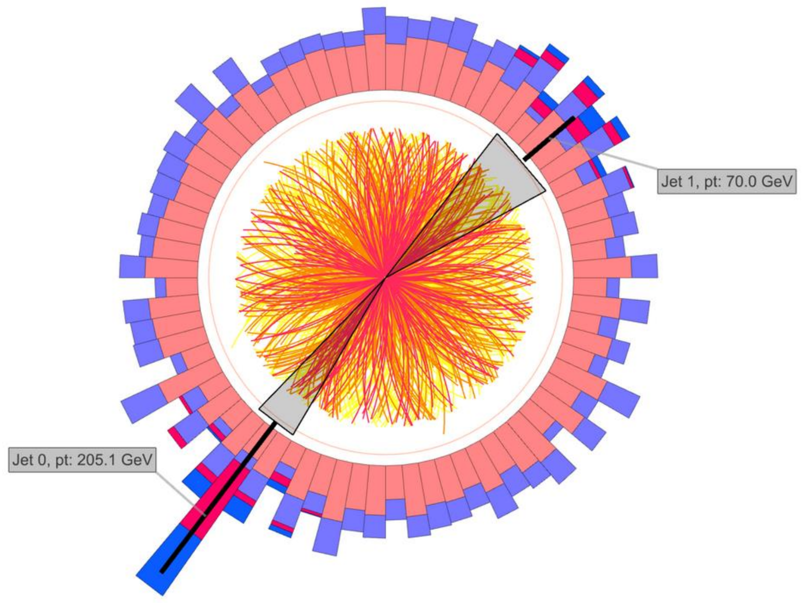


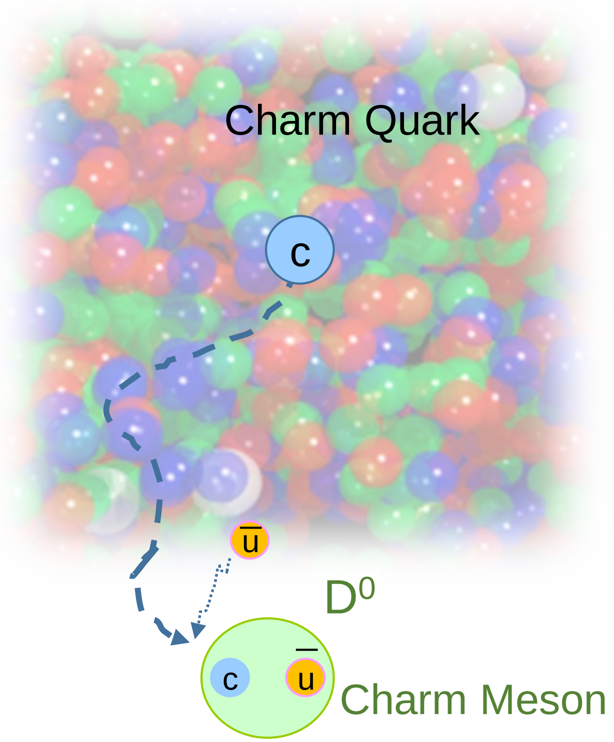
- Observation of charm meson elliptic flow (v_2)
- **Charm v_2 < hadron v_2**
- **Charm v_2** values are correlated with **hadron v_2** !
  → **reflect the initial condition**

Take Away

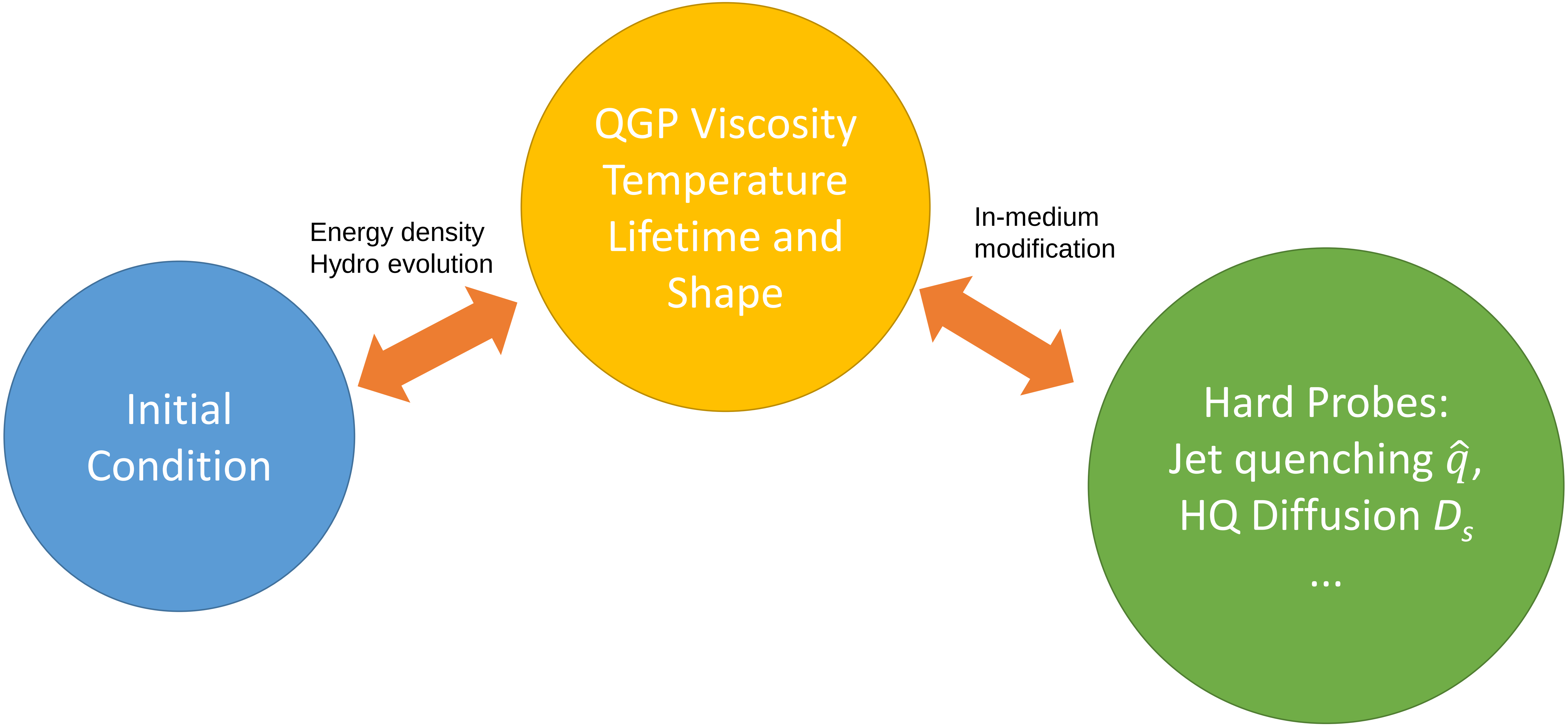
- Colorless probes: unmodified, sensitive to N_{coll} and nPDF

- **Colored Probes**: modified. Size of the effect correlated with soft particle observables

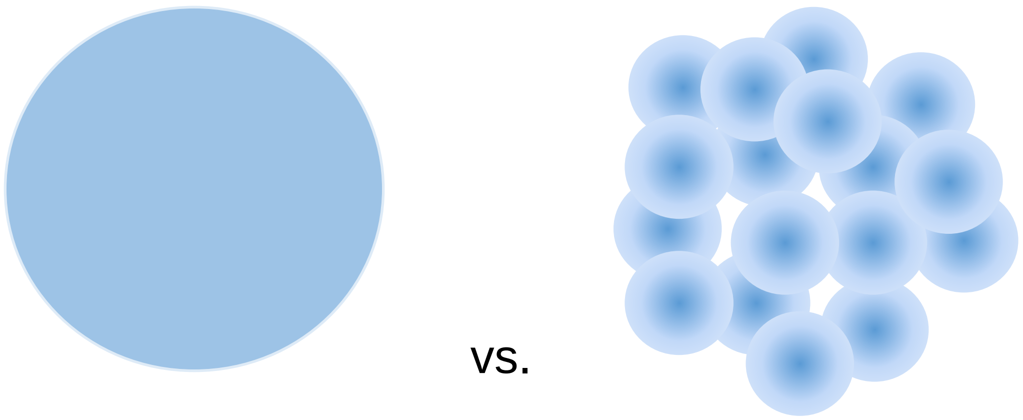




Hard Probes and Initial Condition

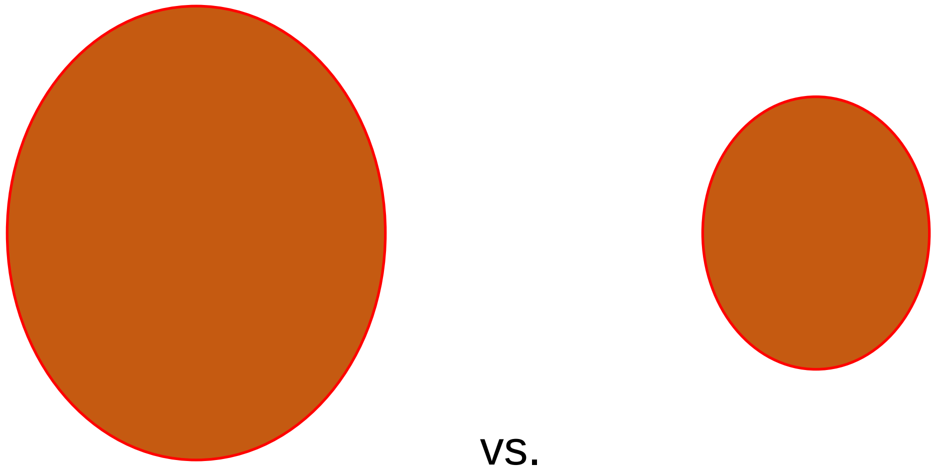


Medium Property: Major Issues Related to Hard Probes



Initial energy density fluctuation:

Uncertainty associated with QGP medium



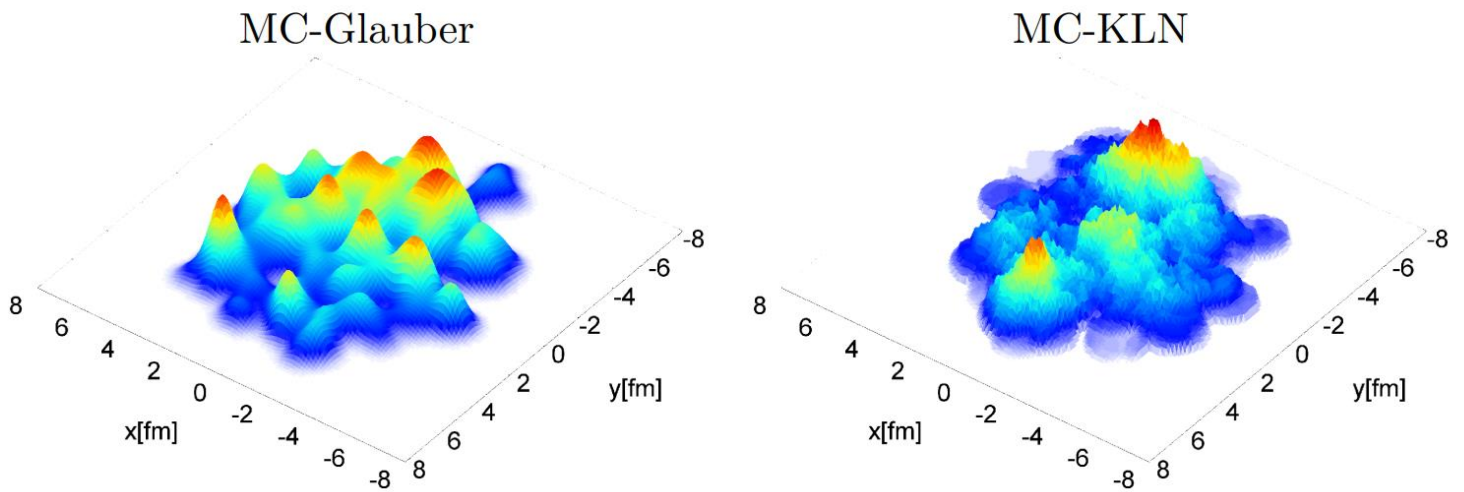
Path length dependence of the in-medium modification:

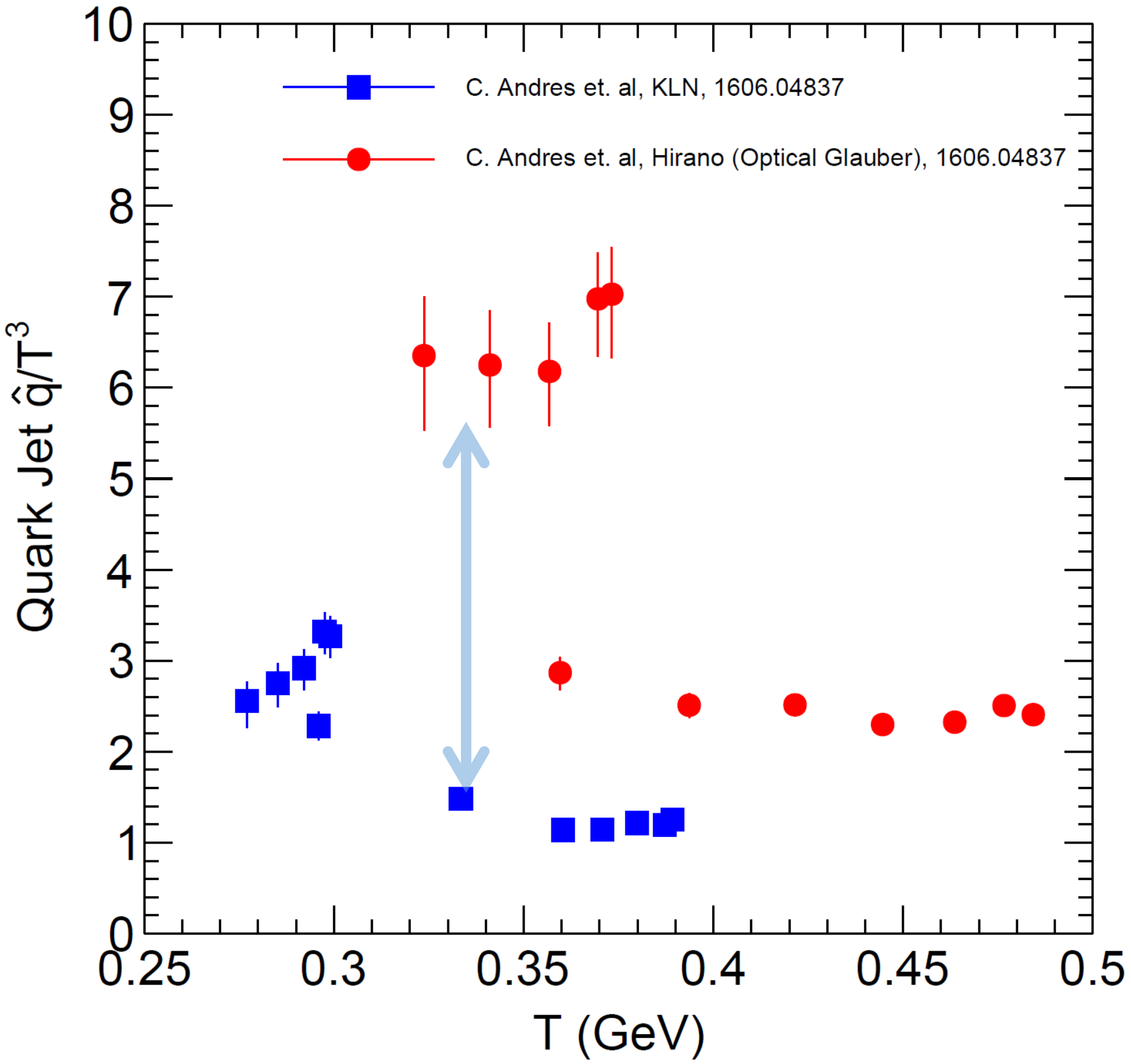
Quenching and HQ diffusion mechanism

Impact to Jet Quenching Parameter

- The extracted quark jet quenching parameter depends highly on the **initial state** and the **start time** of QGP.

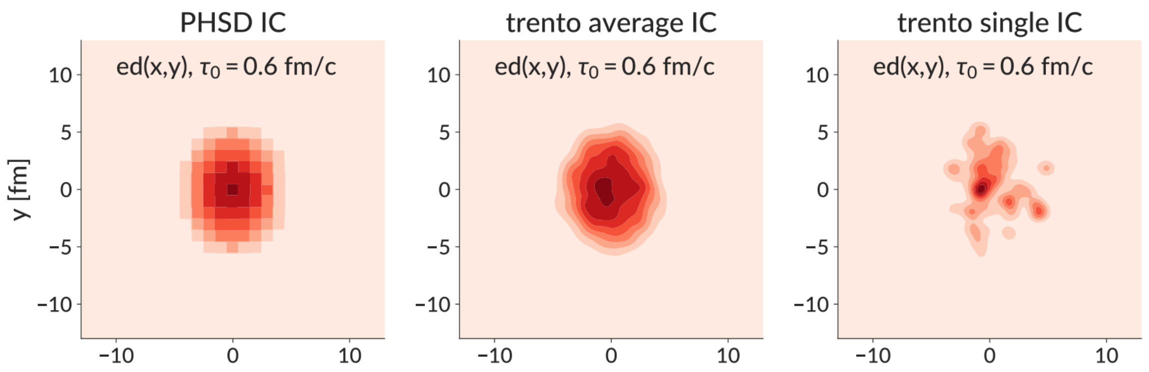
- This means that in the case of Optical Glauber, the color charge density is lower than KLN and has to be compensated by a **larger** $\hat{q}$

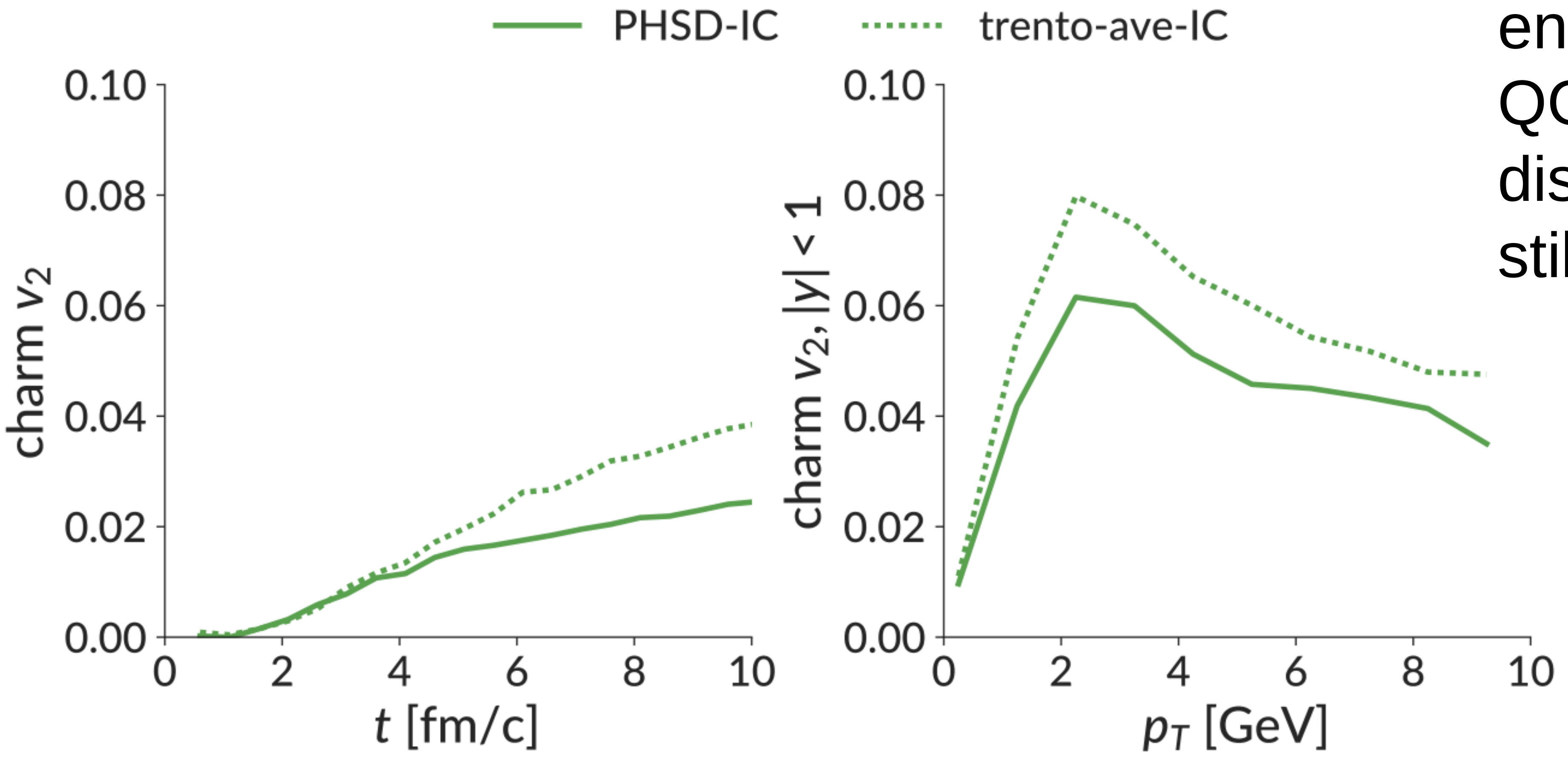




Carlota Andrés et. al EPJC 76 (2016) 9, 475

Influence of Initial Condition to HQ Diffusion Calculation

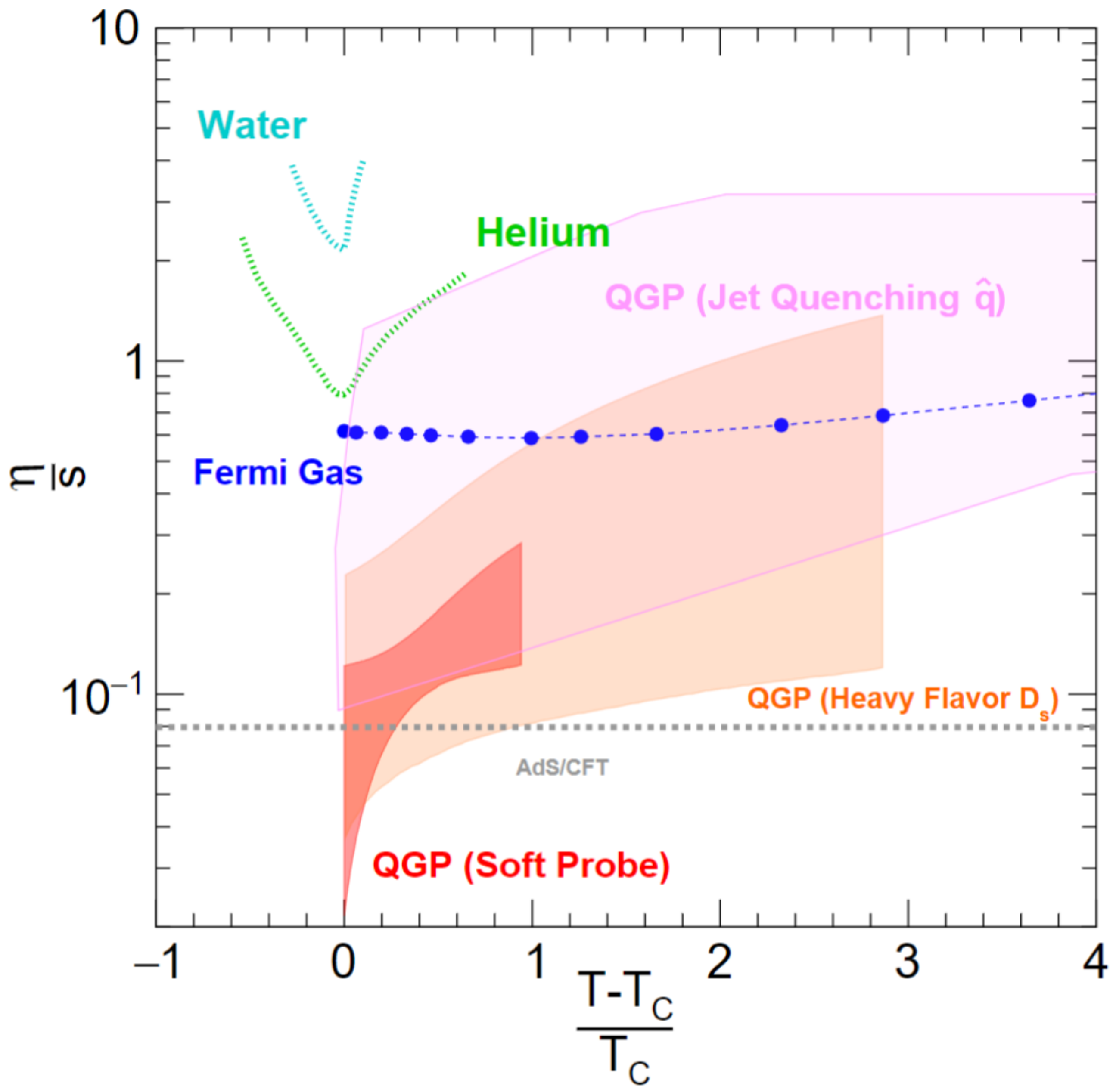




- Initial conditions significantly change the calculated charm v_2
- Correlation between the initial energy/entropy density of the QGP and the initial position distribution of heavy quarks is still a matter of active research.

Y. Xu et. al.
PRC 99 (2019) 1, 014902

Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** are consistent with the results from **Soft Probes**

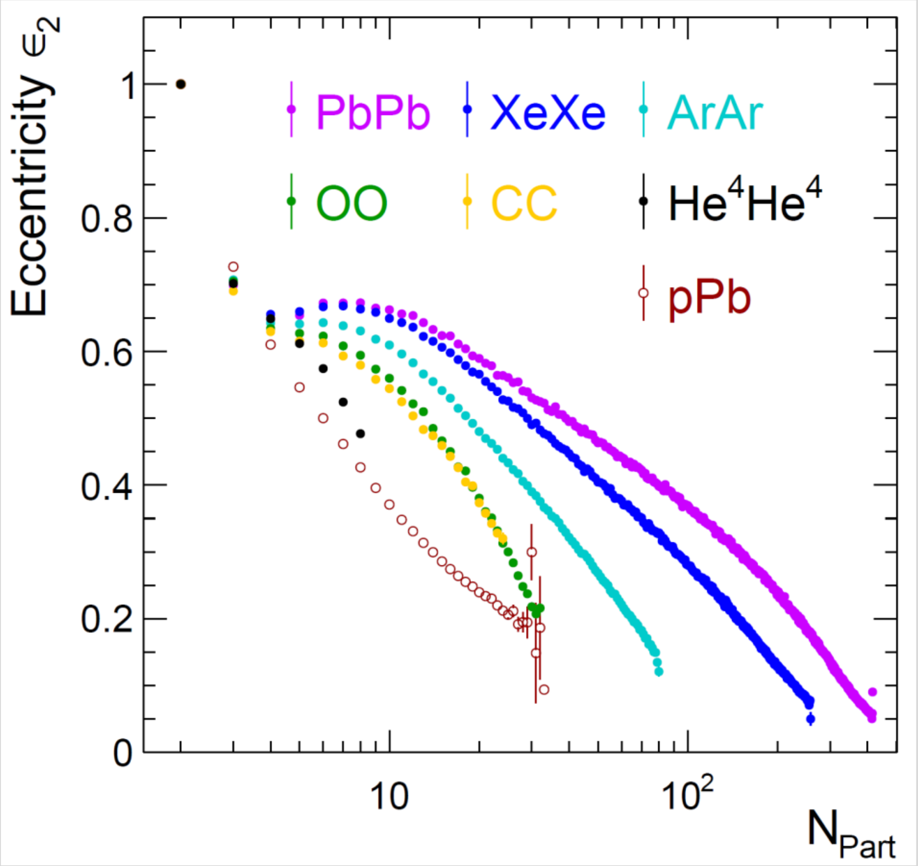
However, the large uncertainties prevent firm conclusion

Major items contributed to the uncertainties:

(1) Initial conditions and QGP medium
(2) Jet quenching and HQ diffusion mechanisms
(3) Hadronization effects
(4) Accuracy of experimental data

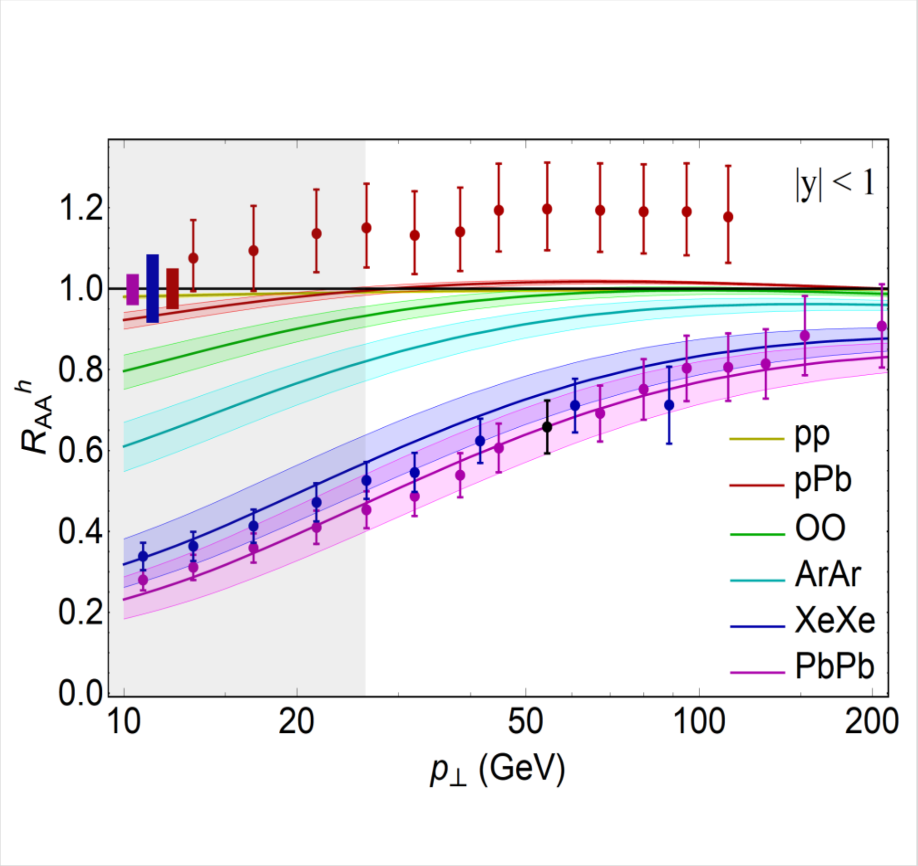
Stress Test with System Size Scan

Flow



New opportunity to sample QGP droplets on the eccentricity ϵ_2 and N_{part} phase space

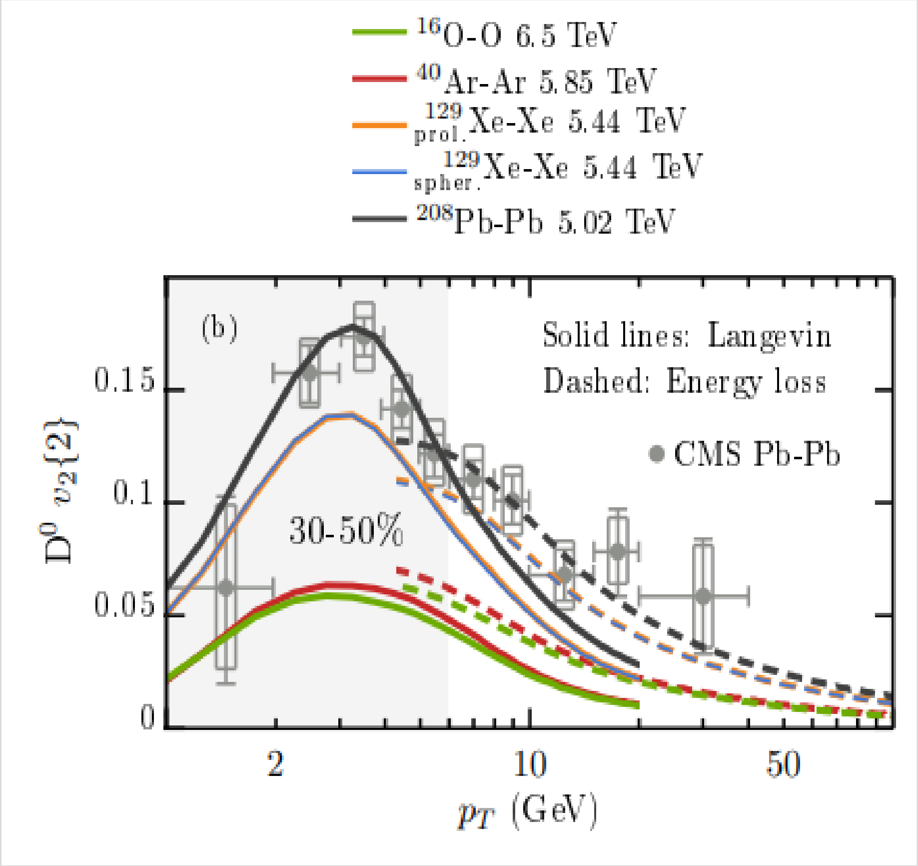
Jet Quenching



- Significant jet quenching effect predicted in **OO** and **ArAr**

A. Huss+
PRC 103 (2021) 5, 054903

Charm Diffusion



- Different D^0 v_2 in various systems in 30-50% centrality

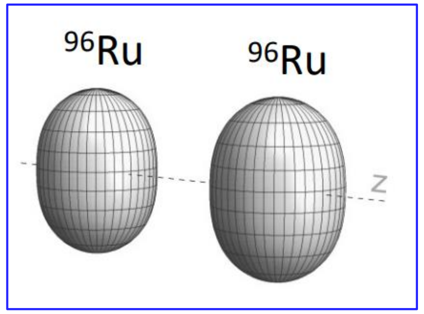
R. Katz, C. A. G. Prado, J. Noronha-Hostler, and A. A. P. Suaide
PRC 102 (2020) 4, 041901

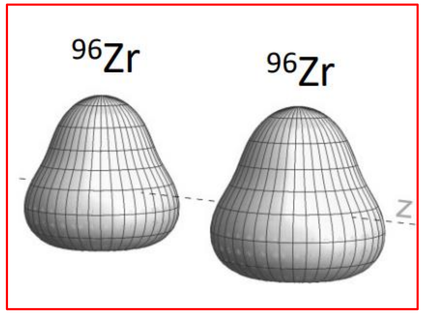
Hard Probes in RuRu and ZrZr Collisions

Preliminary Results

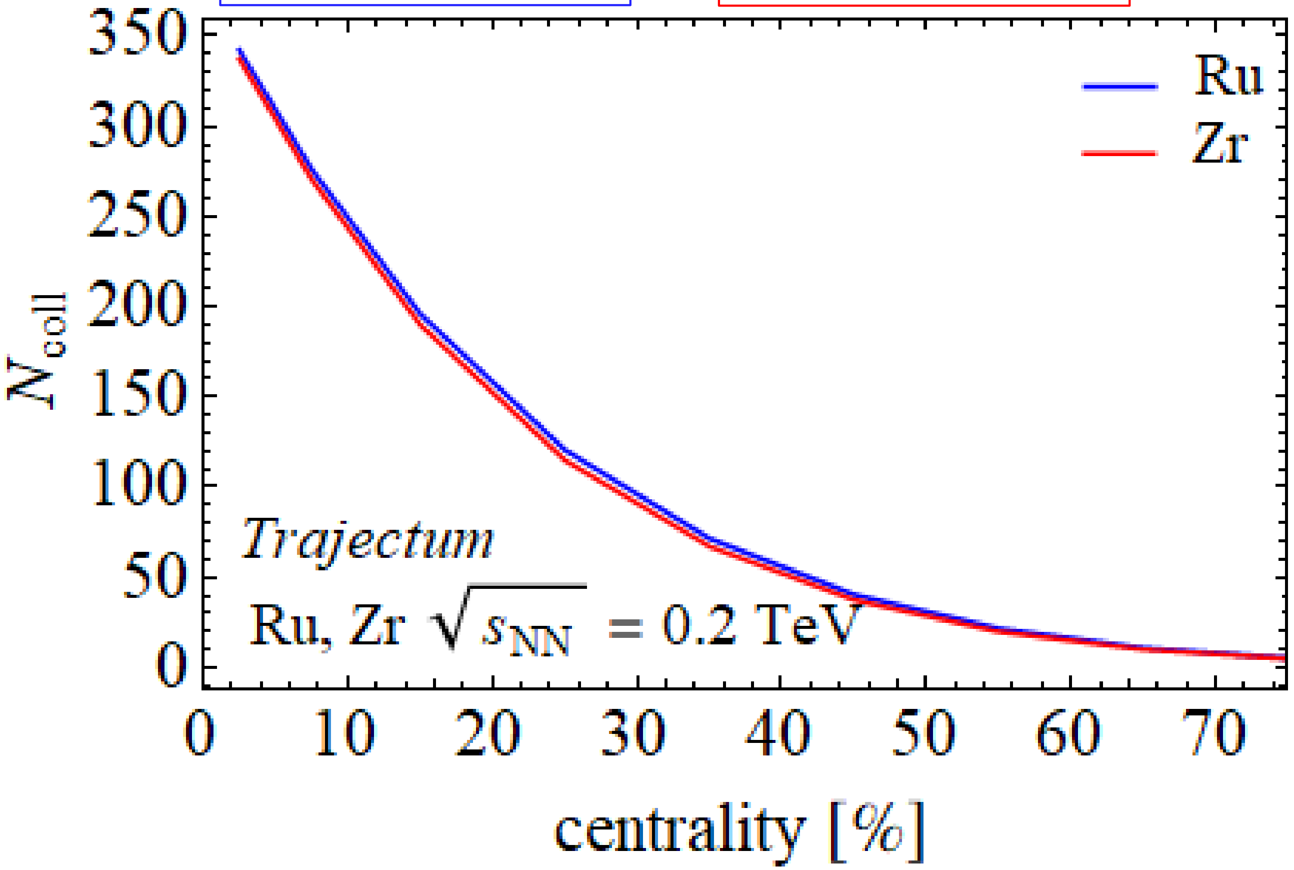
Results are 1-2 days old

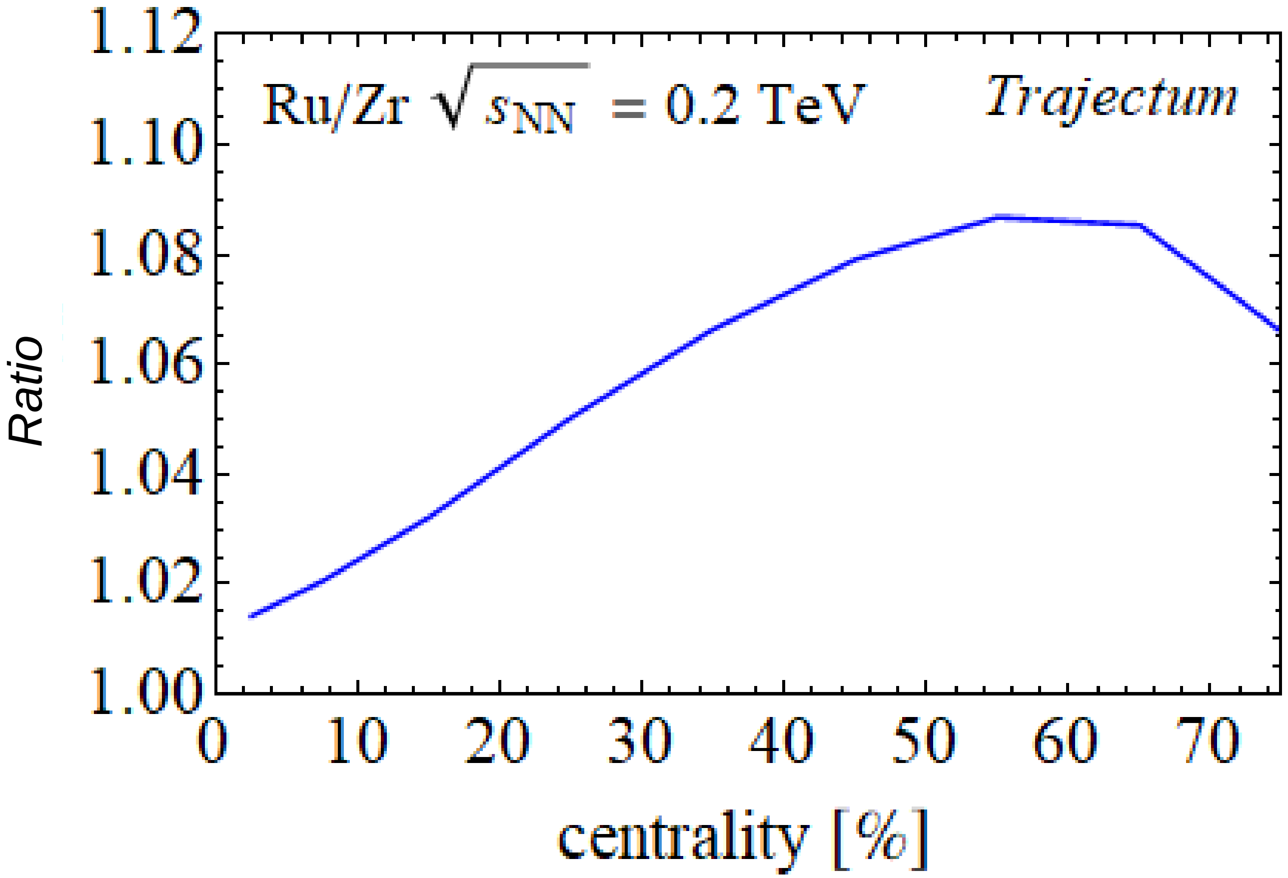
N_{coll} in Ru+Ru and Zr+Zr





$$\text{Ratio} = \frac{\text{RuRu}}{\text{ZrZr}}$$

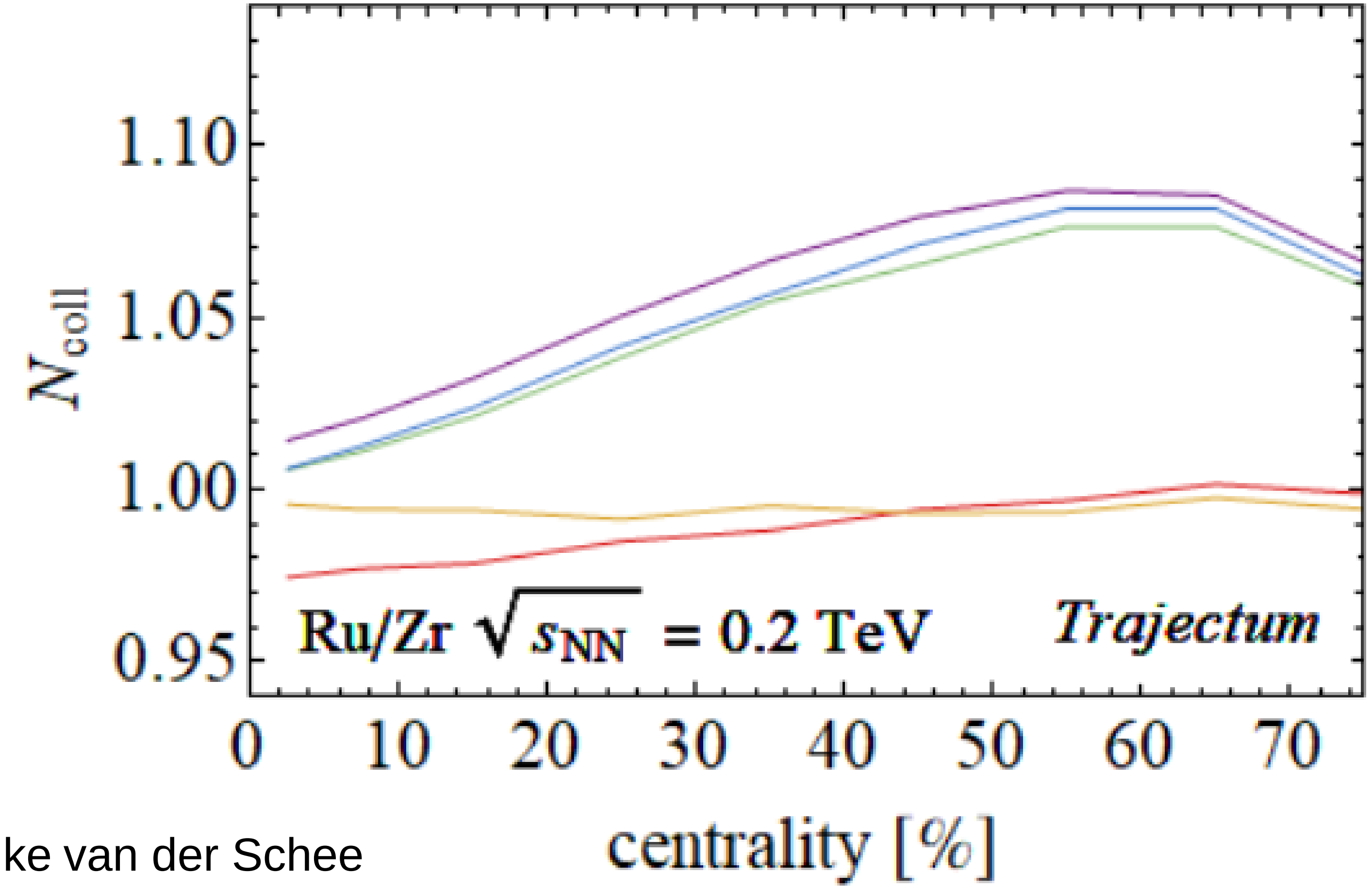




Difference between Ruthenium and Zirconium: N_{part} ~ 6%, N_{coll} ~ 9%

Wilke van der Schee

Sensitivity of Electroweak Probes



Wilke van der Schee

nucleus	R_p [fm]	σ_p [fm]	R_n [fm]	σ_n [fm]	β_2	β_3	σ_{AA} [b]
$^{96}_{44}$Ru(1)	5.085	0.46	5.085	0.46	0.158	0	4.628
$^{96}_{40}$Zr(1)	5.02	0.46	5.02	0.46	0.08	0	4.540
$^{96}_{44}$Ru(2)	5.085	0.46	5.085	0.46	0.053	0	4.605
$^{96}_{40}$Zr(2)	5.02	0.46	5.02	0.46	0.217	0	4.579
$^{96}_{44}$Ru(3)	5.06	0.493	5.075	0.505	0	0	4.734
$^{96}_{40}$Zr(3)	4.915	0.521	5.015	0.574	0	0	4.860
$^{96}_{44}$Ru(4)	5.053	0.48	5.073	0.49	0.16	0	4.701
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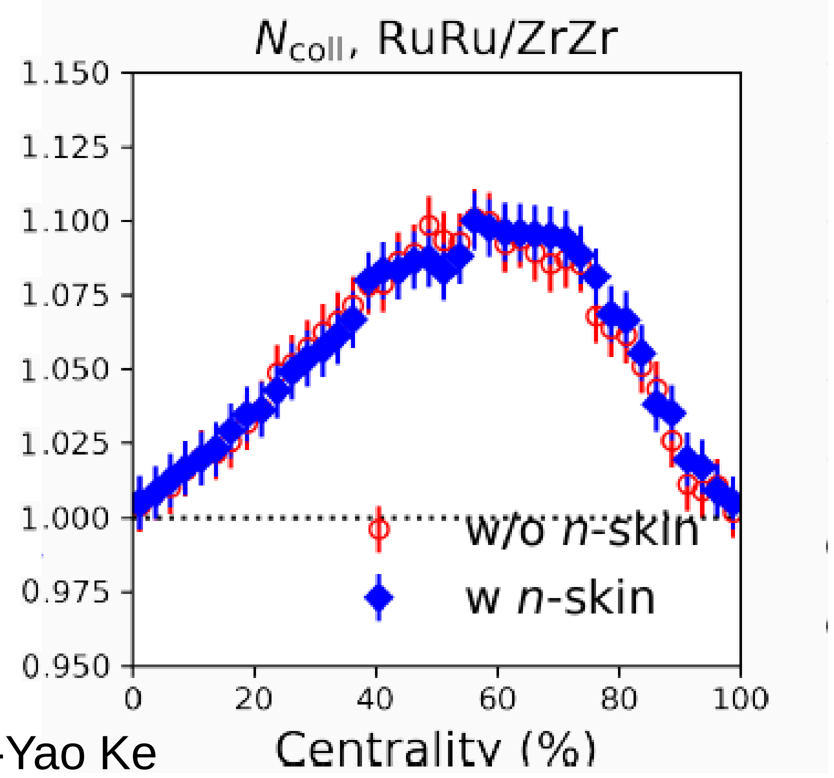
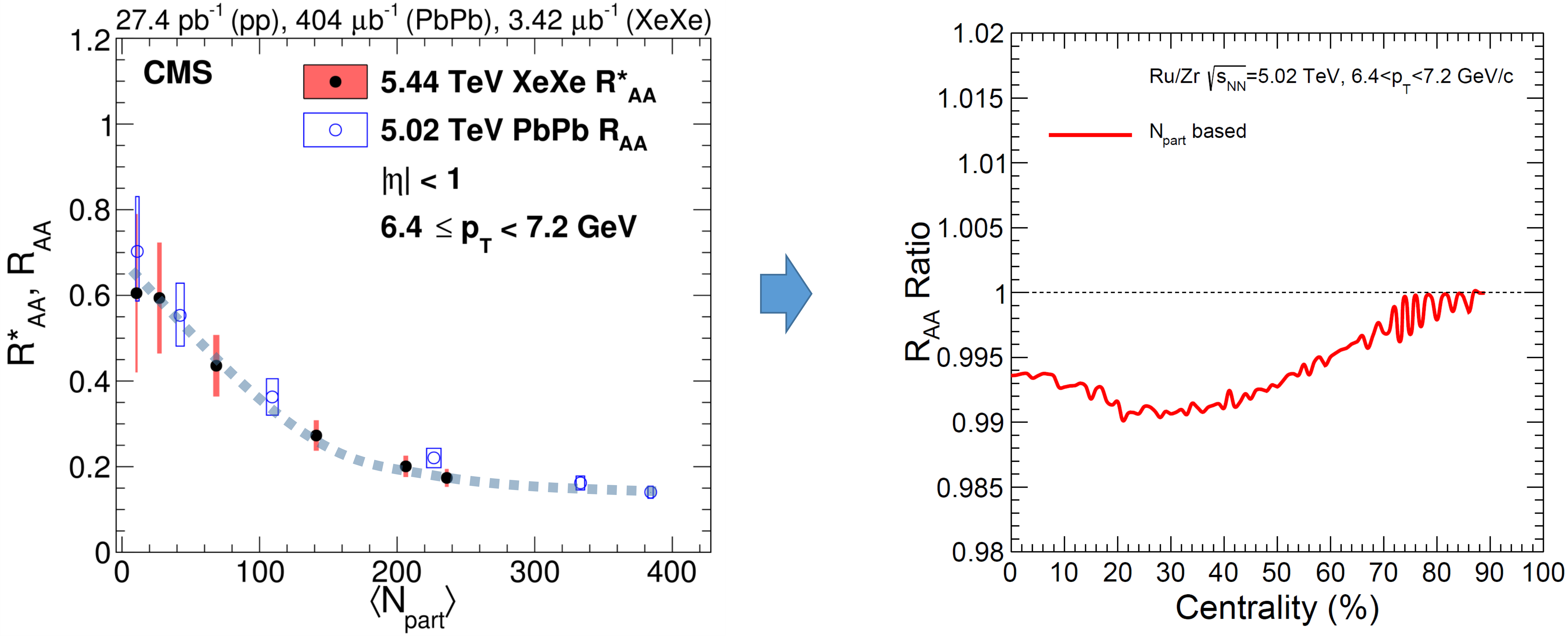


Talk by Wei-Yao Ke

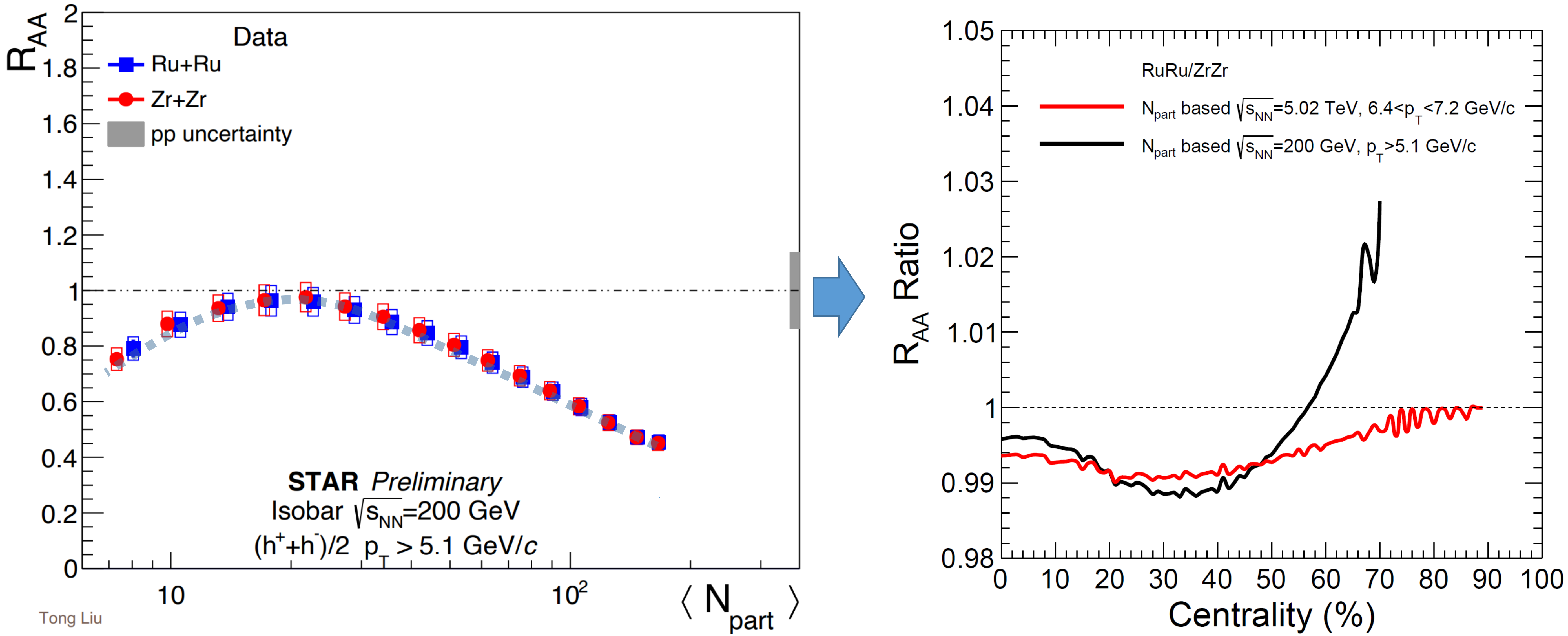
- Colorless probes: W, Z and γ yield ratios (RuRu/ZrZr) are sensitive to σ_n and σ_p
- Size of the effect: up to 8-10%

N_{part} Based Estimation of Charged Particle R_{AA} at LHC



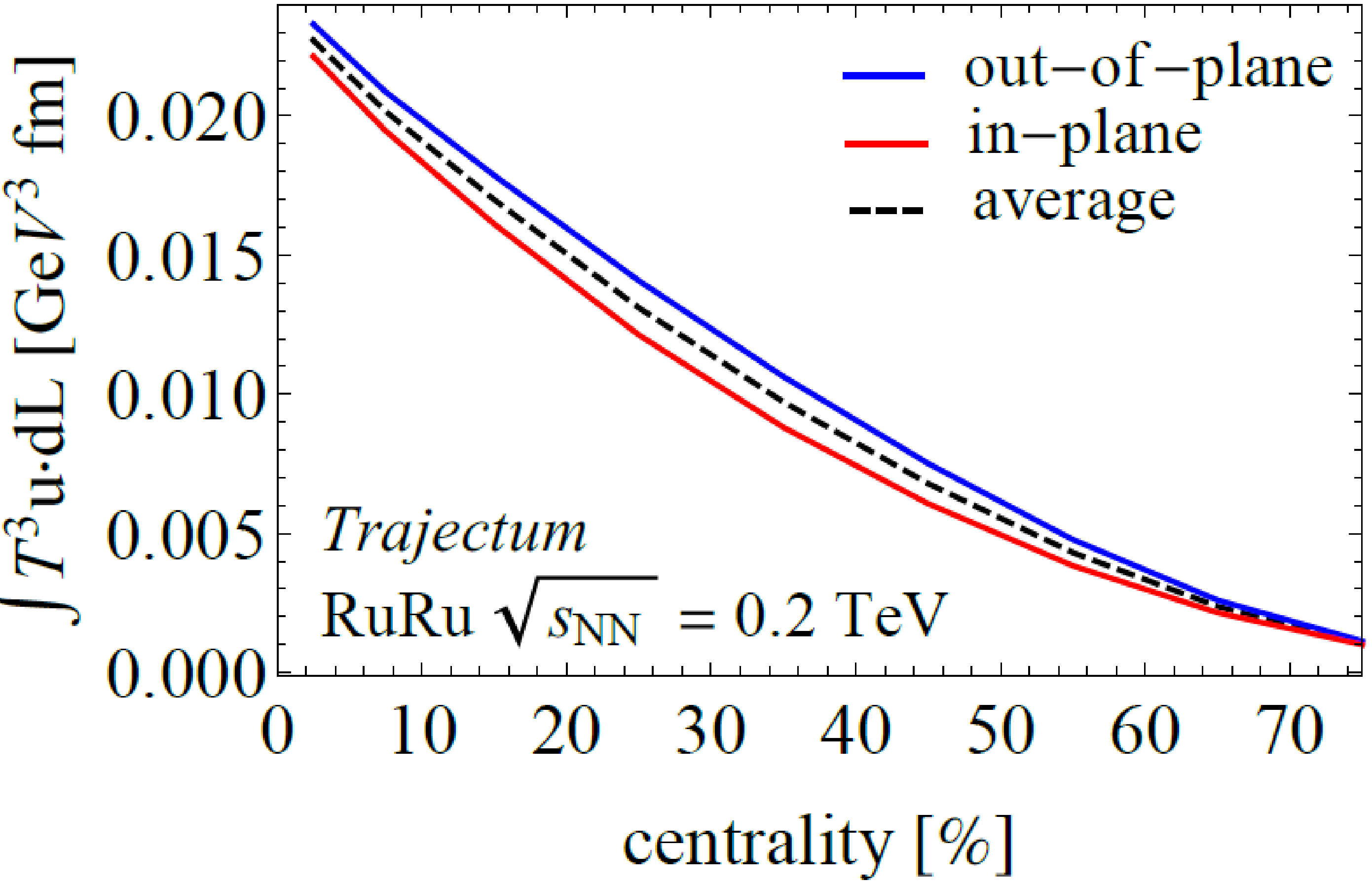
- Scaling behavior in XeXe and PbPb R_{AA}: use it as **a lookup table**
- **Larger N_{part}** in RuRu translate to a **smaller R_{AA}** compared to ZrZr
- Effect is at the level of **1%**

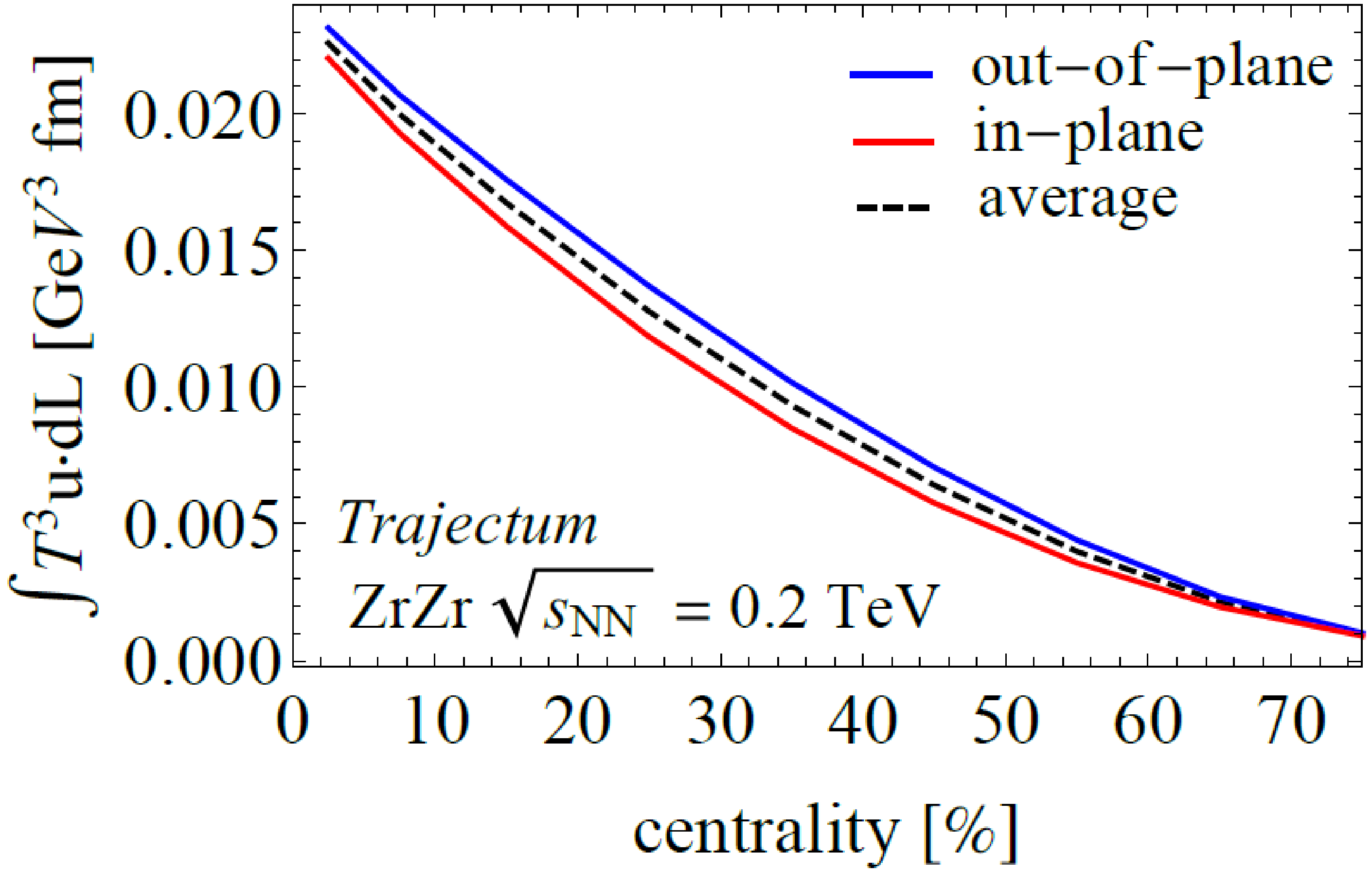
N_{part} Based Estimation of Charged Particle R_{AA} at RHIC

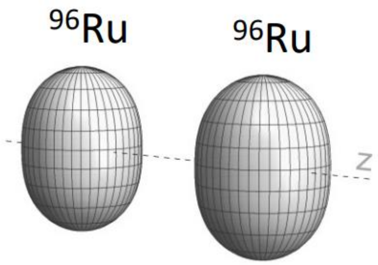


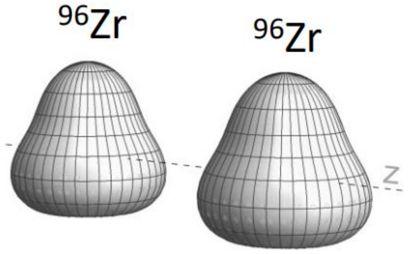
- Similar exercise with STAR data at RHIC, assuming R_{AA} scale with N_{part}
- Effect is at the level of 1-2% at 200 GeV, higher ratio due to selection bias in data

Trajectum: Path Length in RuRu and ZrZr





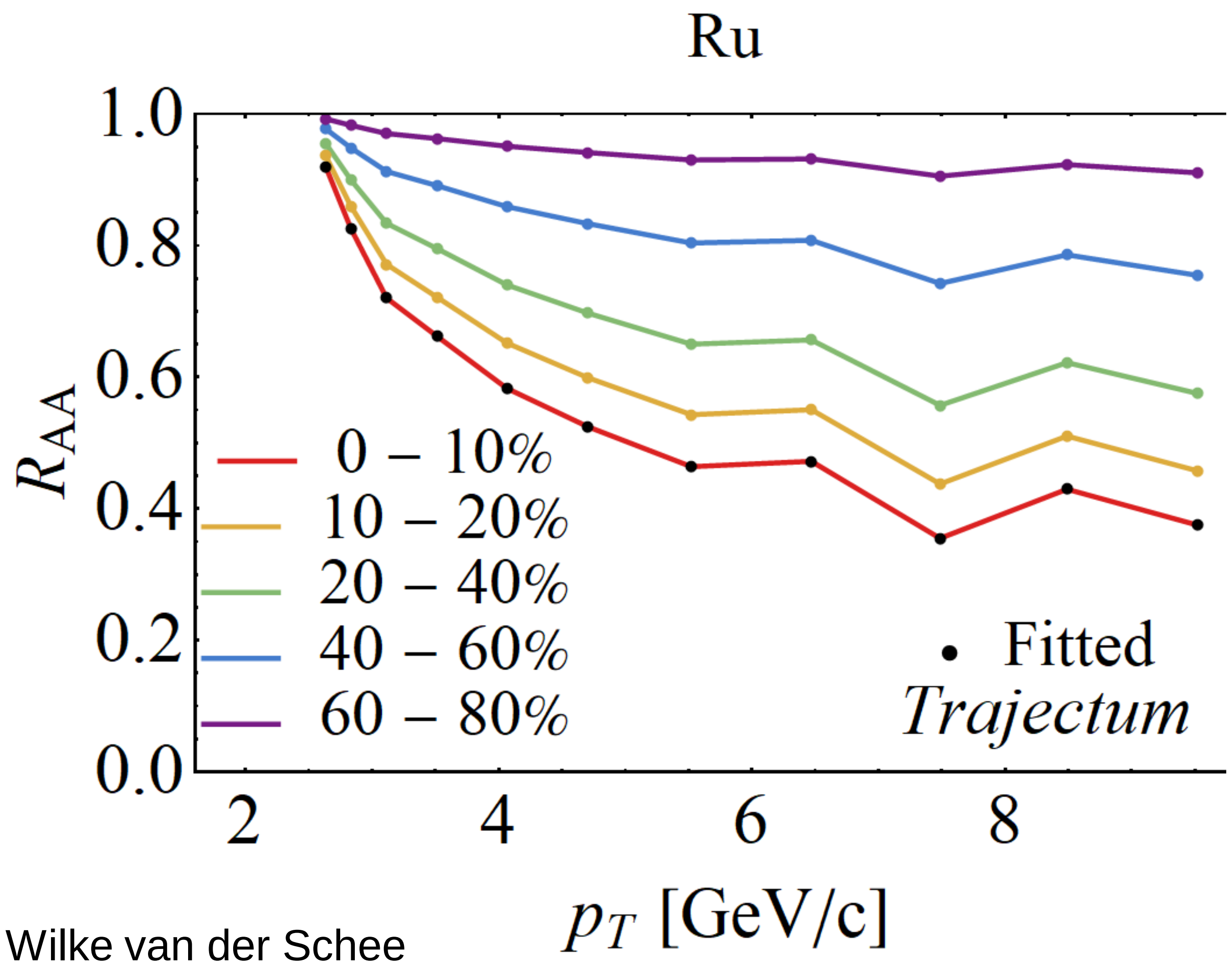




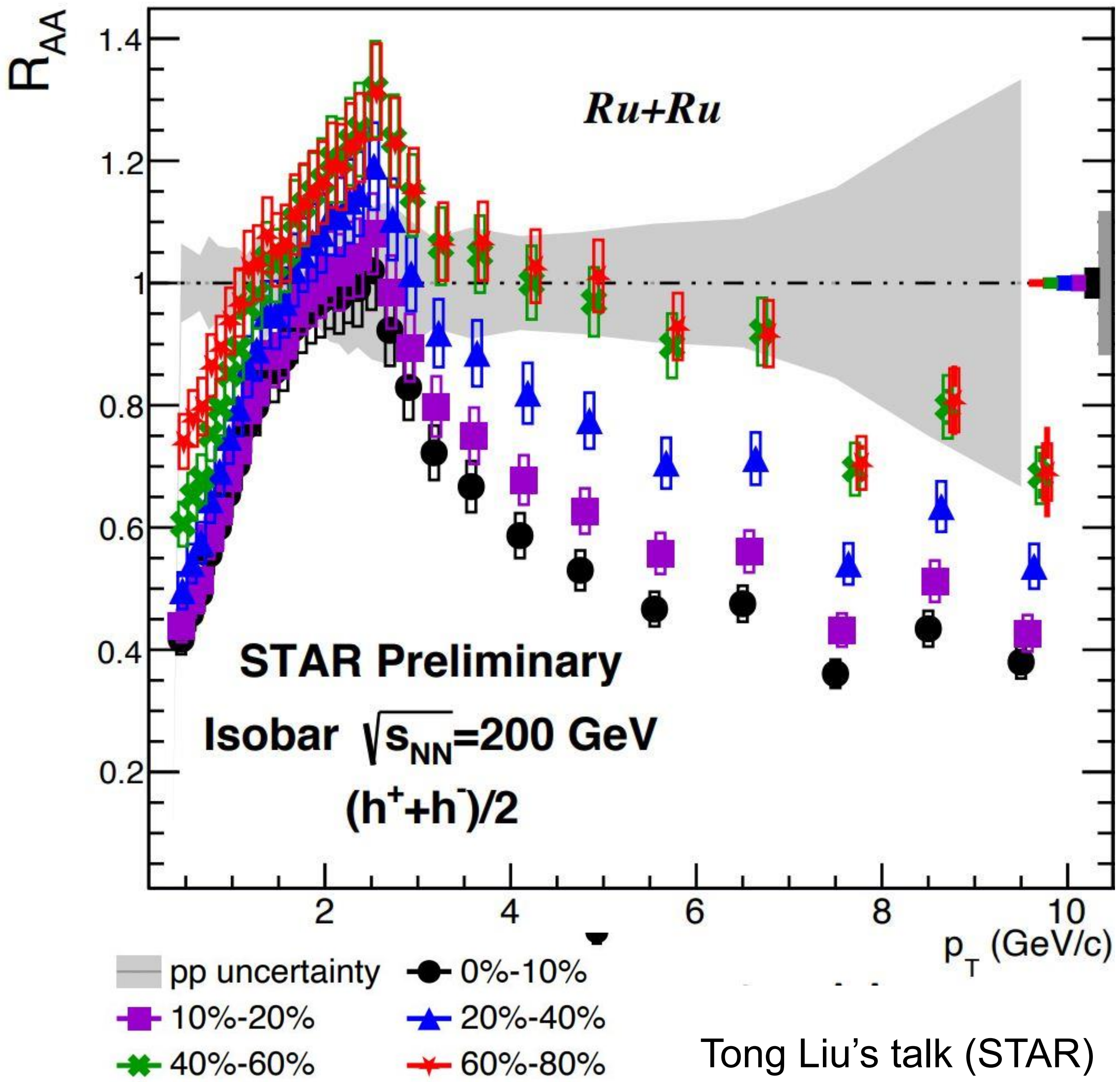
Wilke van der Schee

Trajectum: Ru+Ru R_{AA}

- **0-10% STAR data used for calibration**
- Reasonable agreement with STAR data

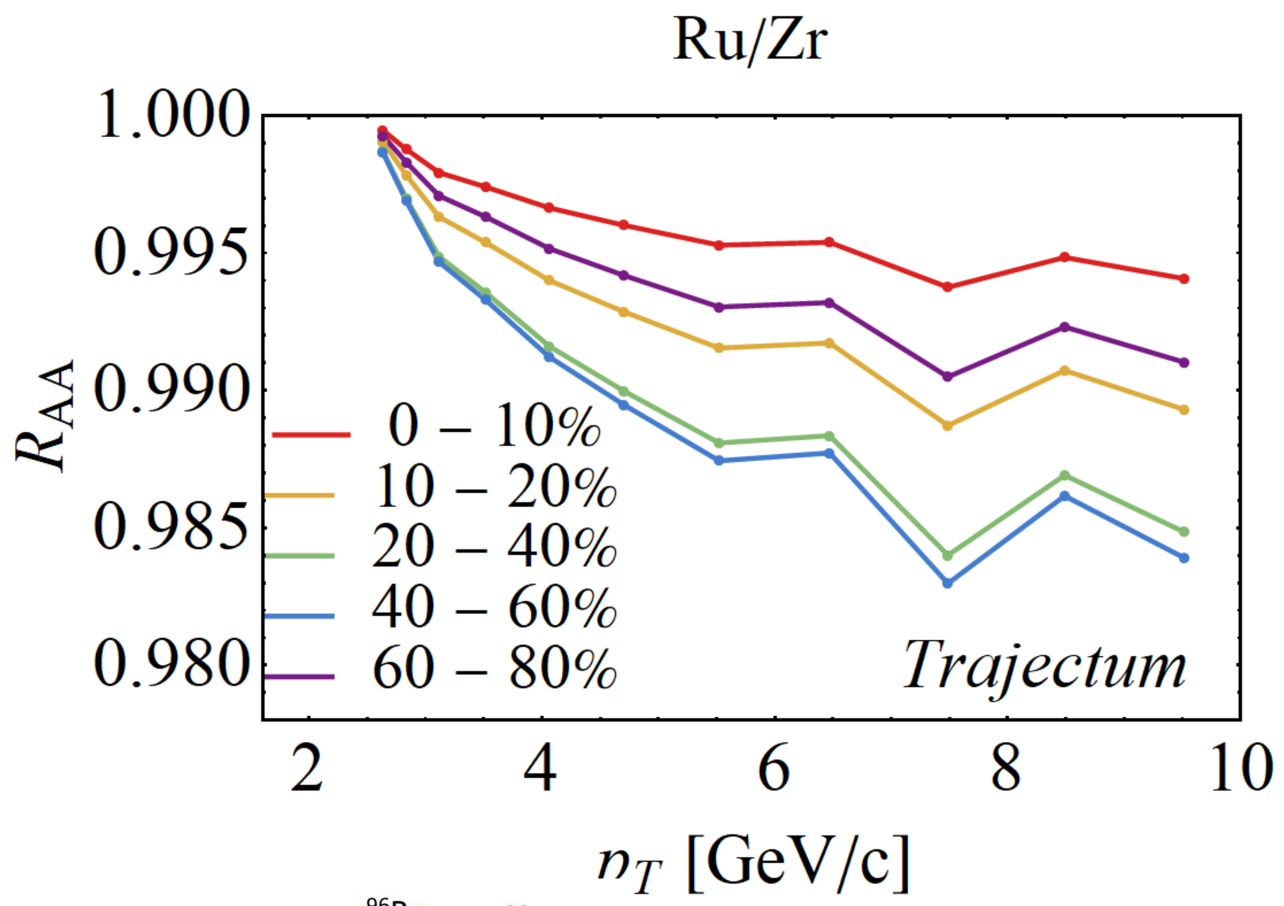


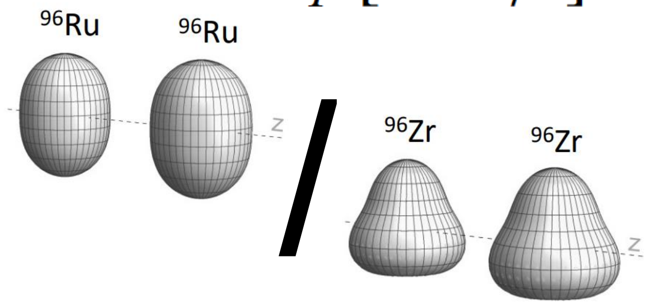
Wilke van der Schee

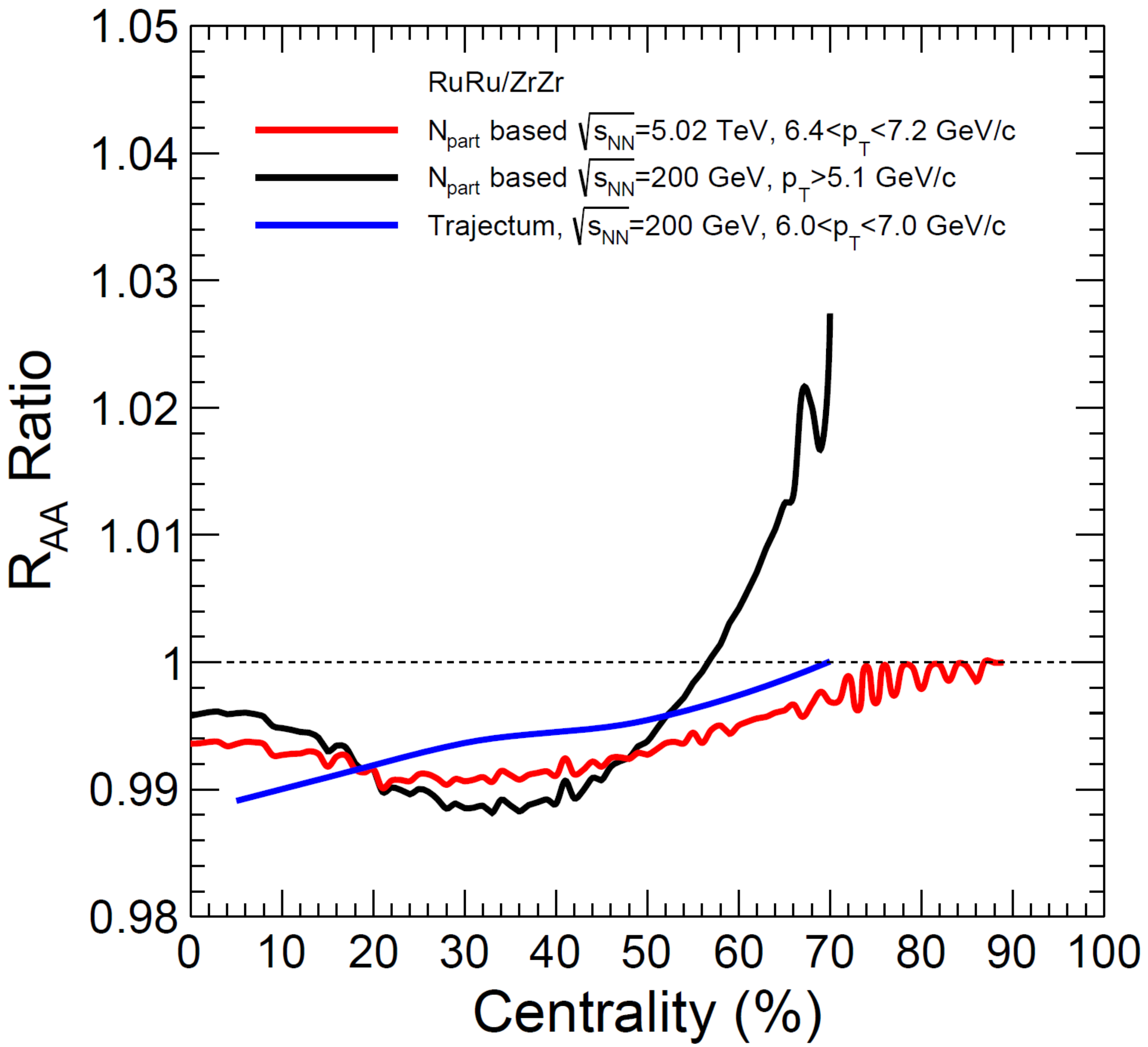


Tong Liu's talk (STAR)

Trajectrum: R_{AA} ratios



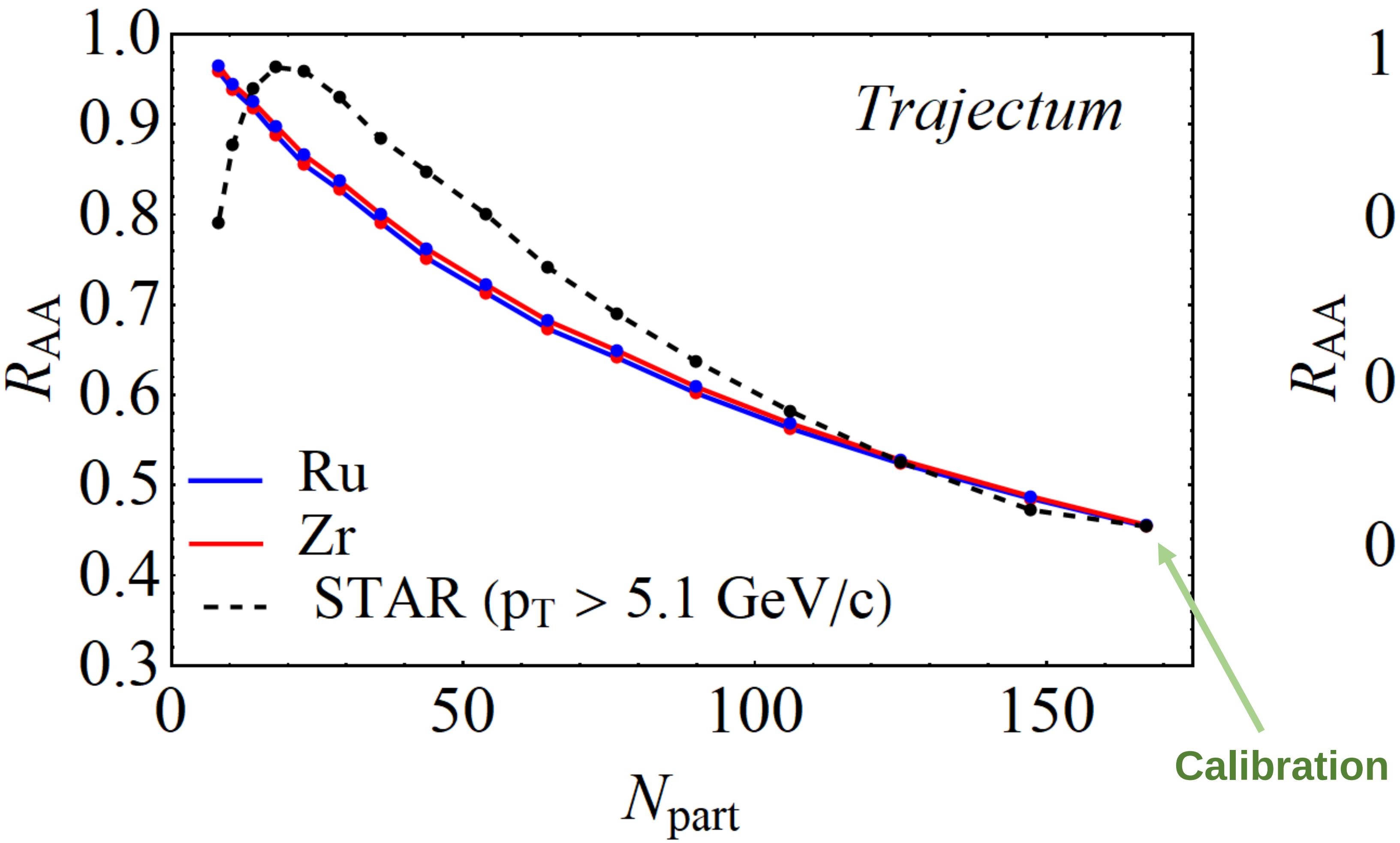


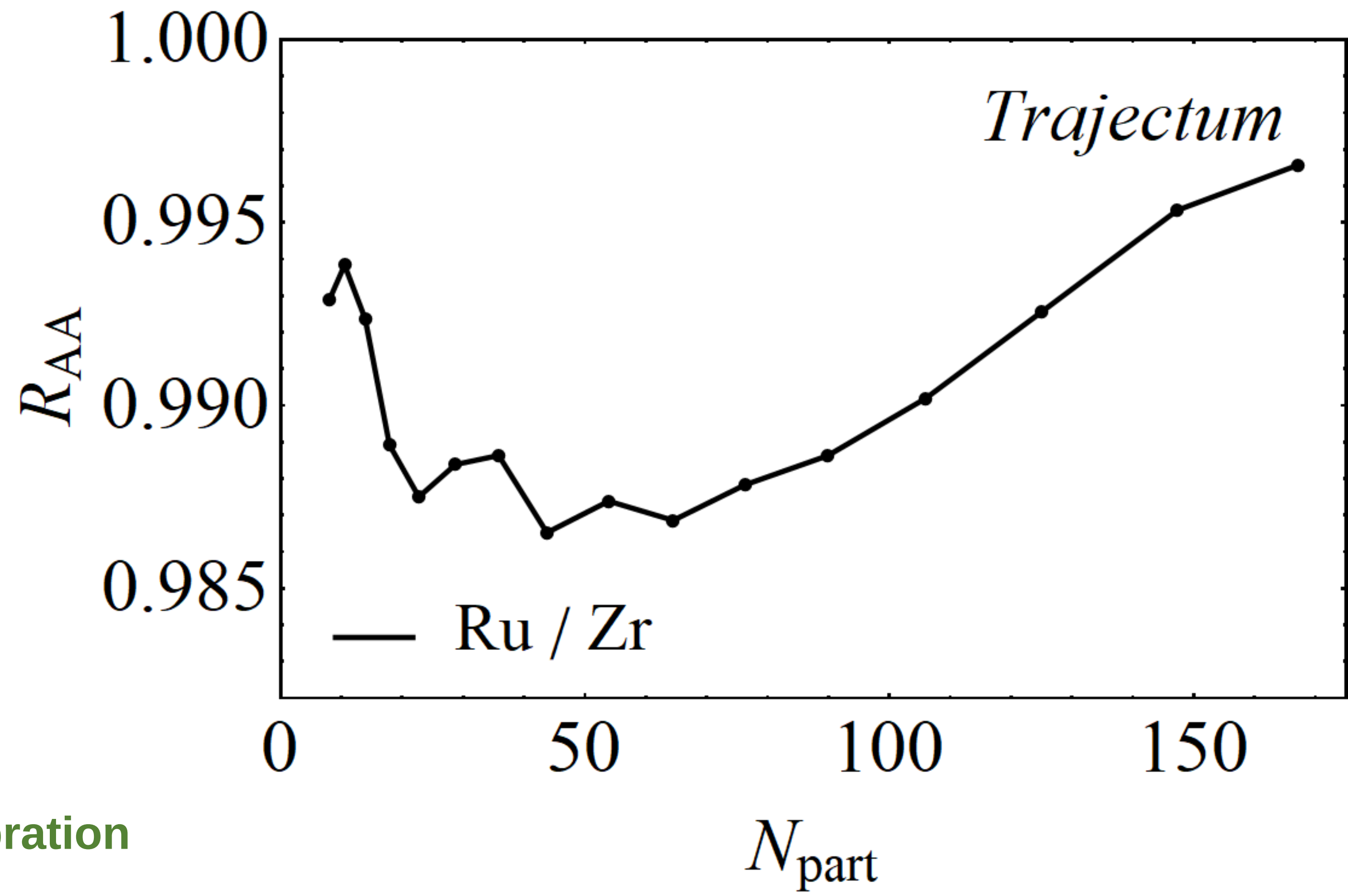


Overall, we see a similar picture between data-driven and Trajectrum results

Wilke van der Schee

R_{AA} vs. N_{part}

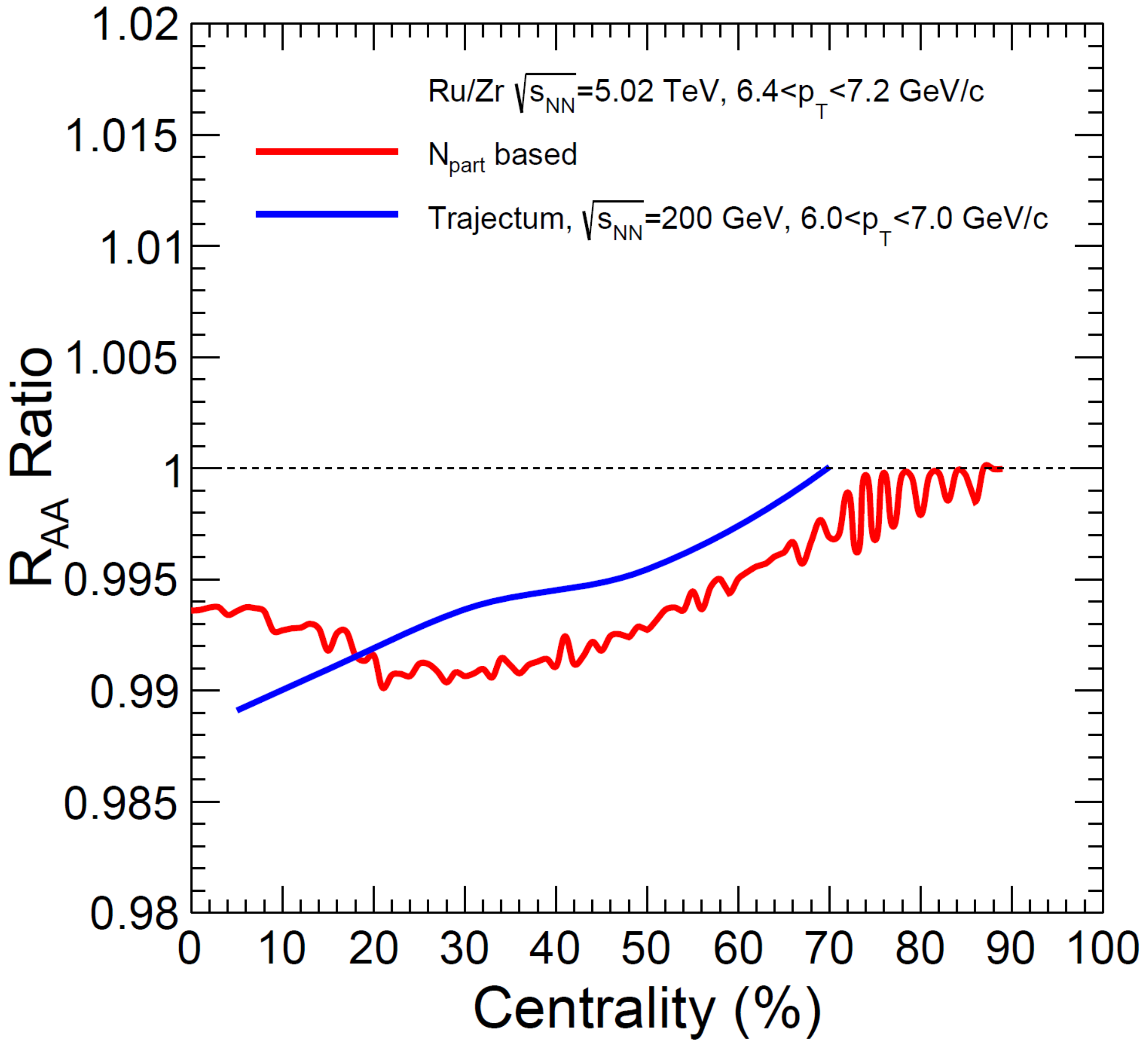


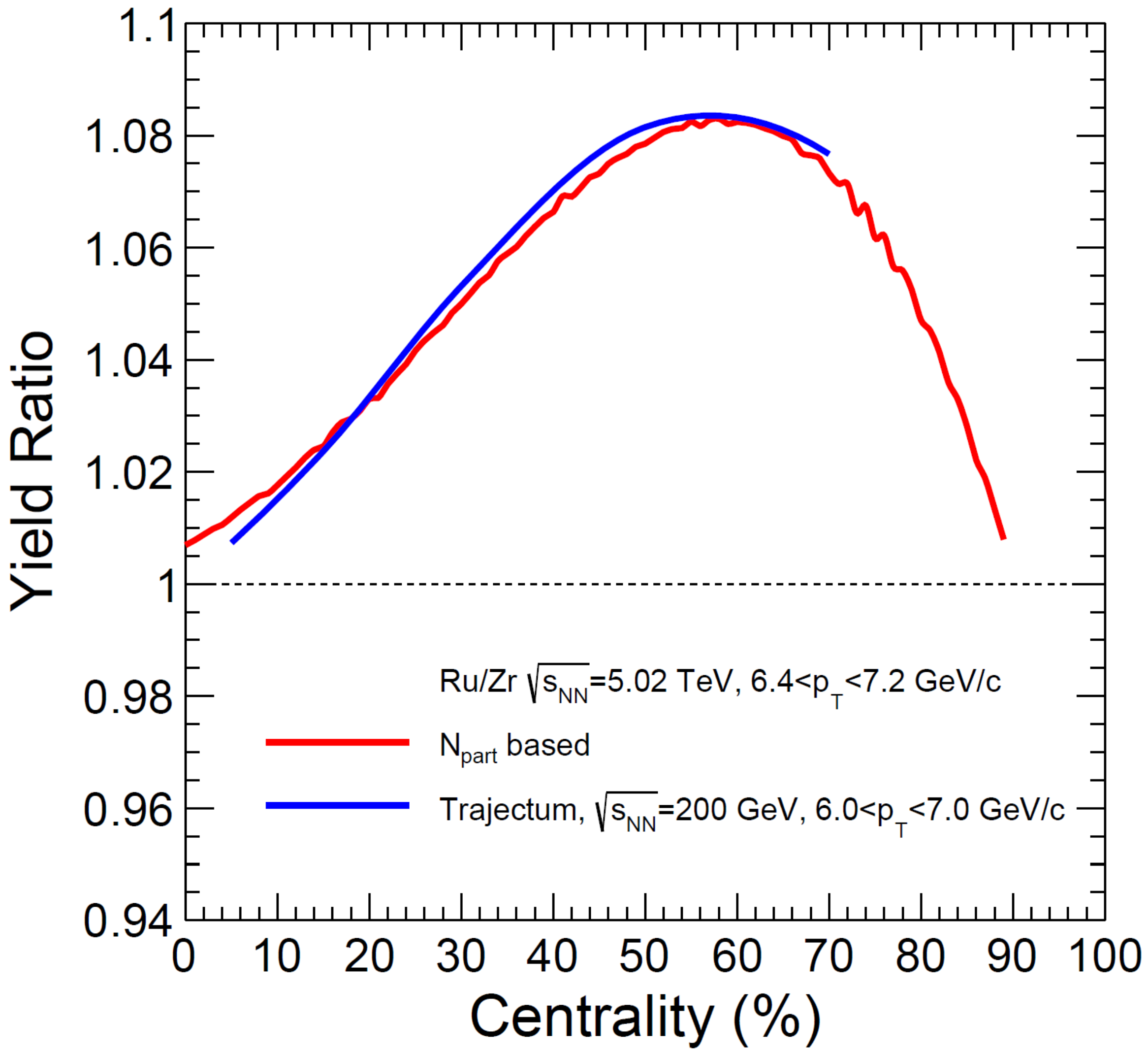


- Reproduce the trend of STAR data
- **Selection bias effect** in peripheral events can not described by Trajectum

Wilke van der Schee

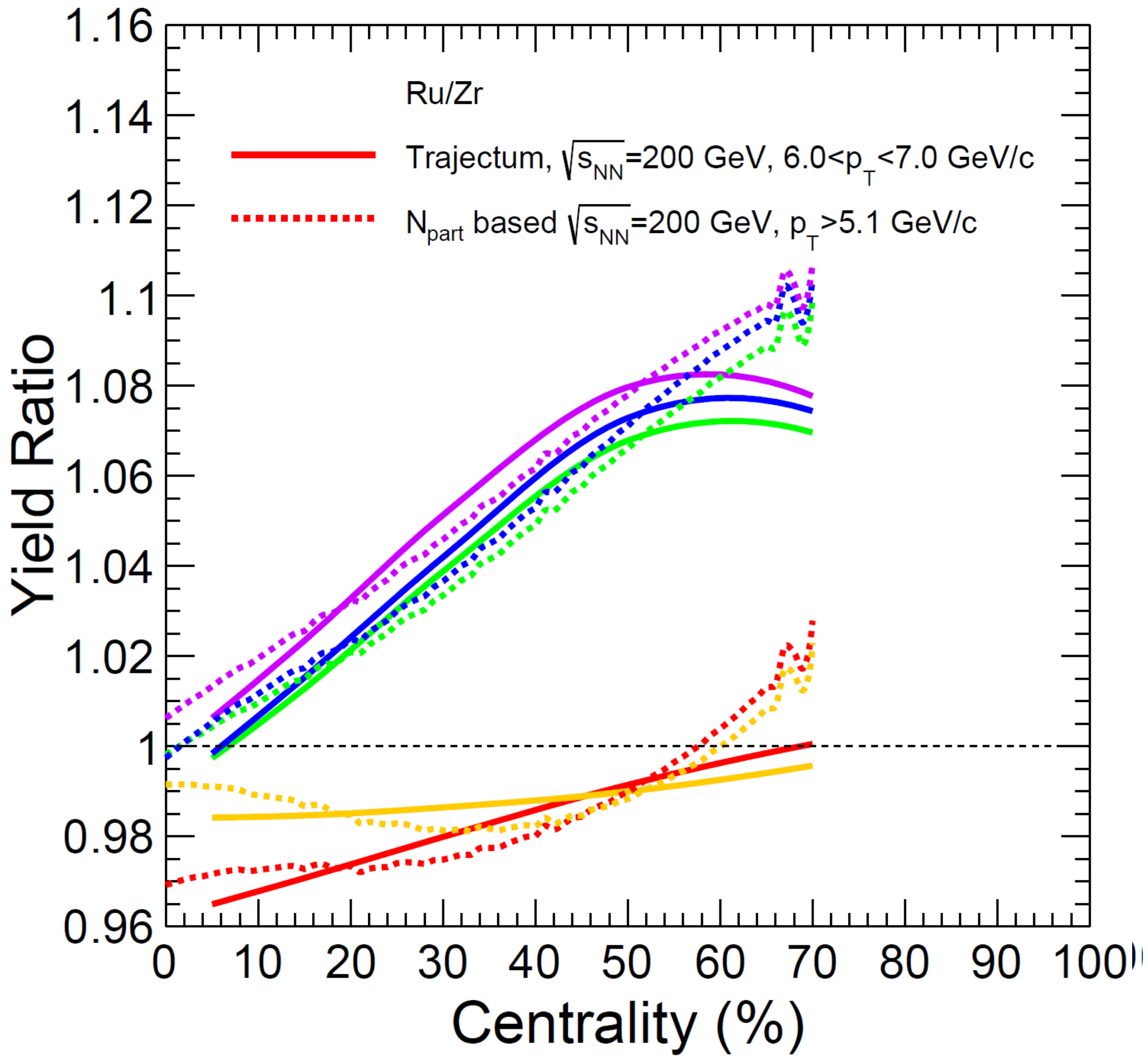
High p_T Charged Particle Yield Ratio





- **R_{AA}: mix theory uncertainty and pp reference uncertainties in!**
- Instead of the R_{AA} ratios, yield ratios are more sensitive to initial conditions (via N_{coll})

Sensitivity to Different Parameter Sets



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- Similar to Electroweak bosons, we could use high p_T hadrons to infer nuclear structure
- **Require much smaller statistics** than Z and W bosons; **higher accuracy** than isolated photonsS

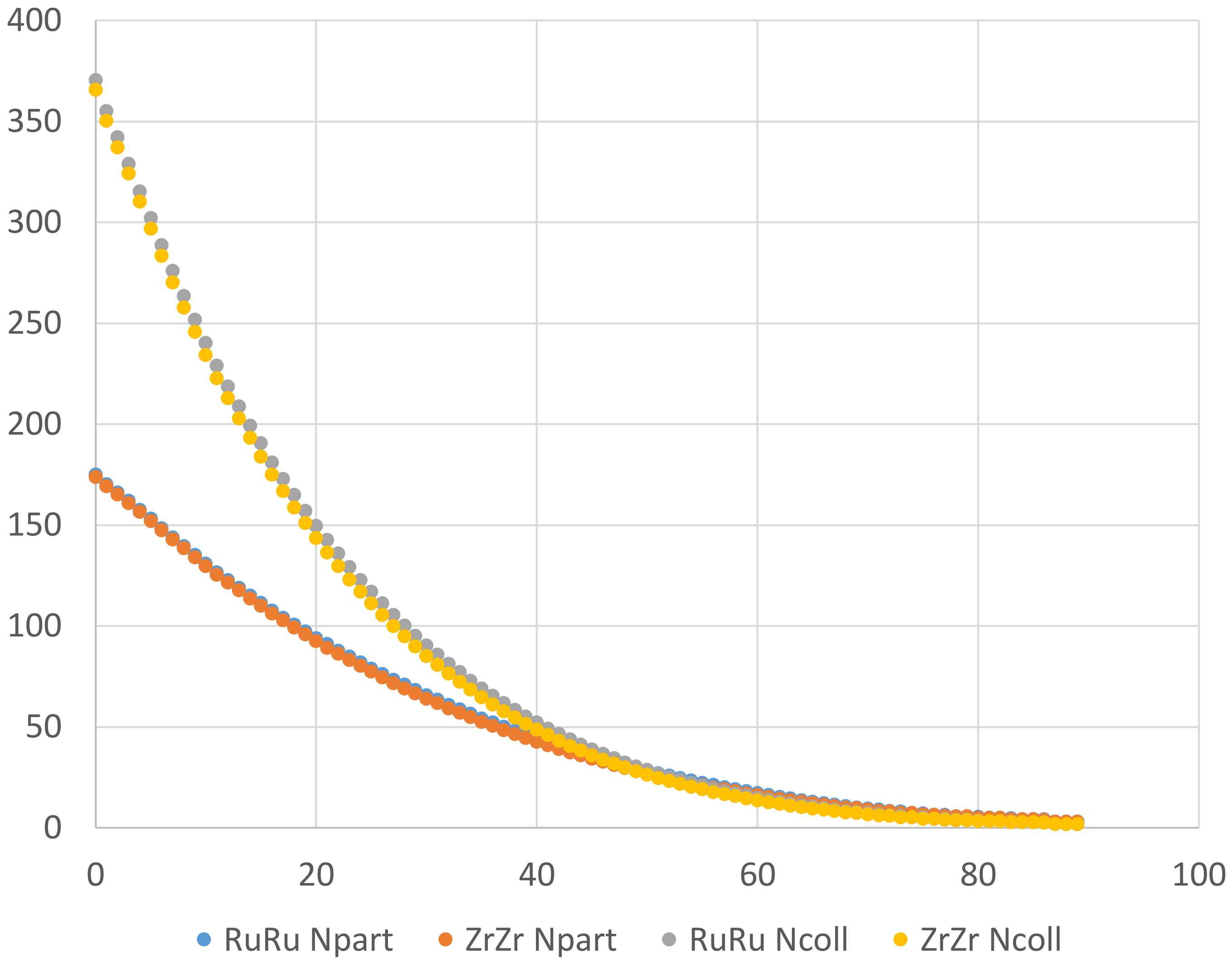
Summary

- Colorless probes: unmodified, sensitive to N_{coll} and nPDF

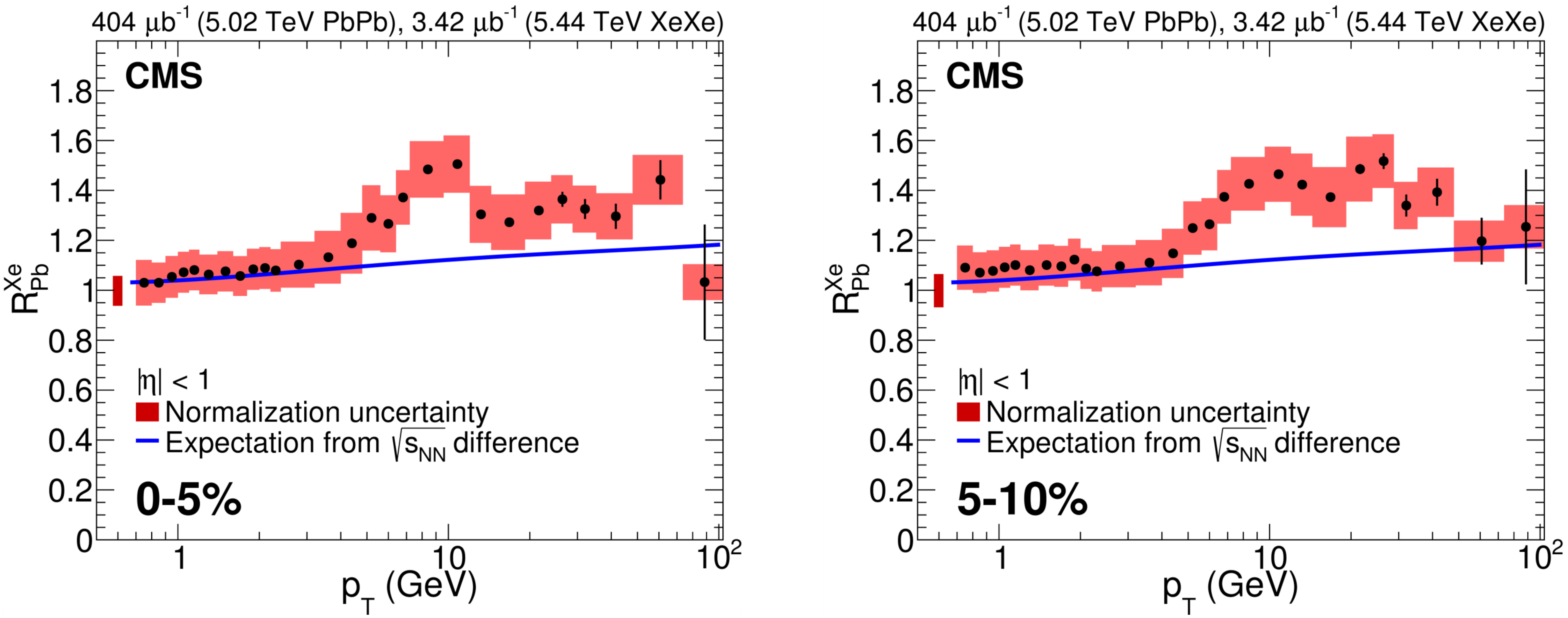
- **Colored Probes**: modified, size of the modification reflect the initial conditions of the collisions

- Work during the workshop on RuRu and ZrZr:
  - **W/Z/γ and DY yield ratios**: directly window to the N_{coll} ratios
    - Sensitive to σ_p and σ_n
  - Difference in jet quenching effect is at the level of 0-2%
    - Can be extracted by hadron to EWK boson yield ratios at the LHC
    - Quenching effect largely cancel in yield ratios
    - High p_T hadrons (jets) could be used to infer nuclear structure

Backup Slides


400
350
300
250
200
150
100
50
0
0
20
40
60
80
100
RuRu Npart
ZrZr Npart
RuRu Ncoll
ZrZr Ncoll

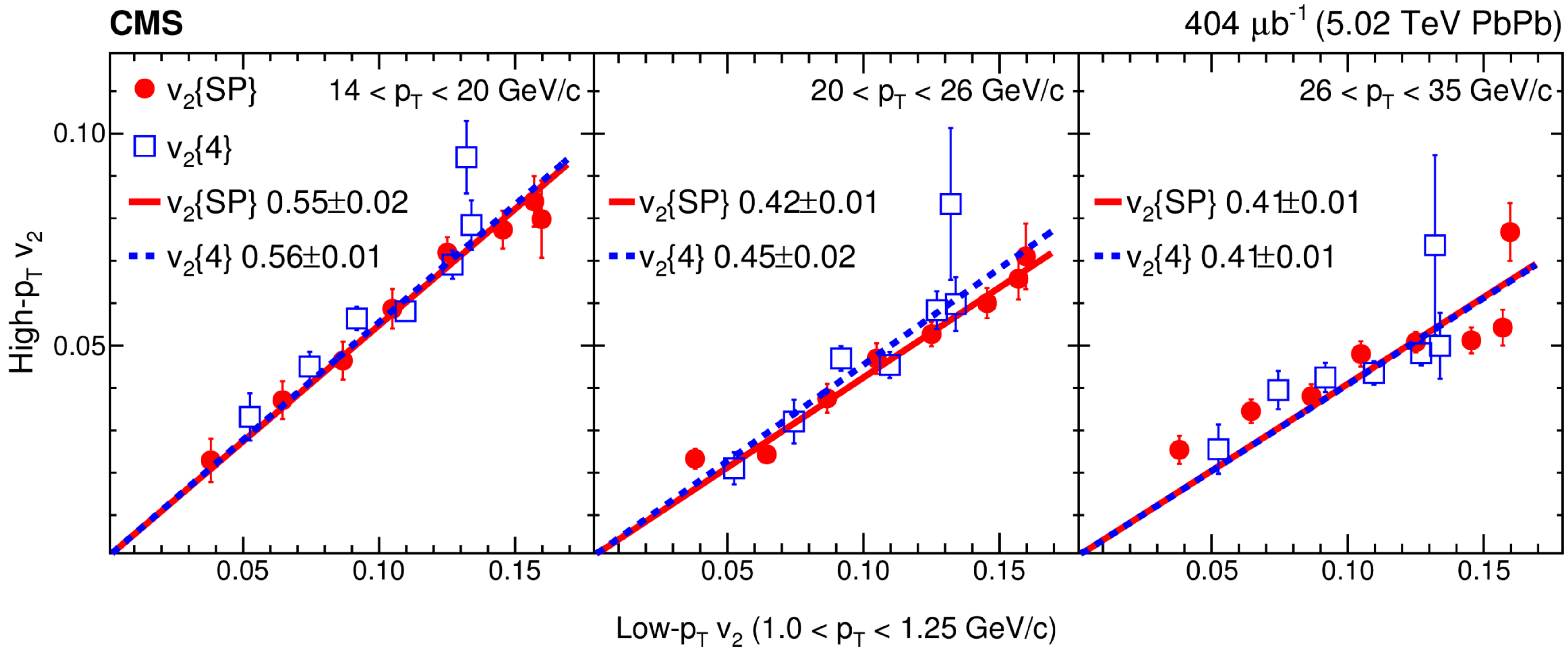
Ratio of Charged Particle p_T spectra in XeXe and PbPb



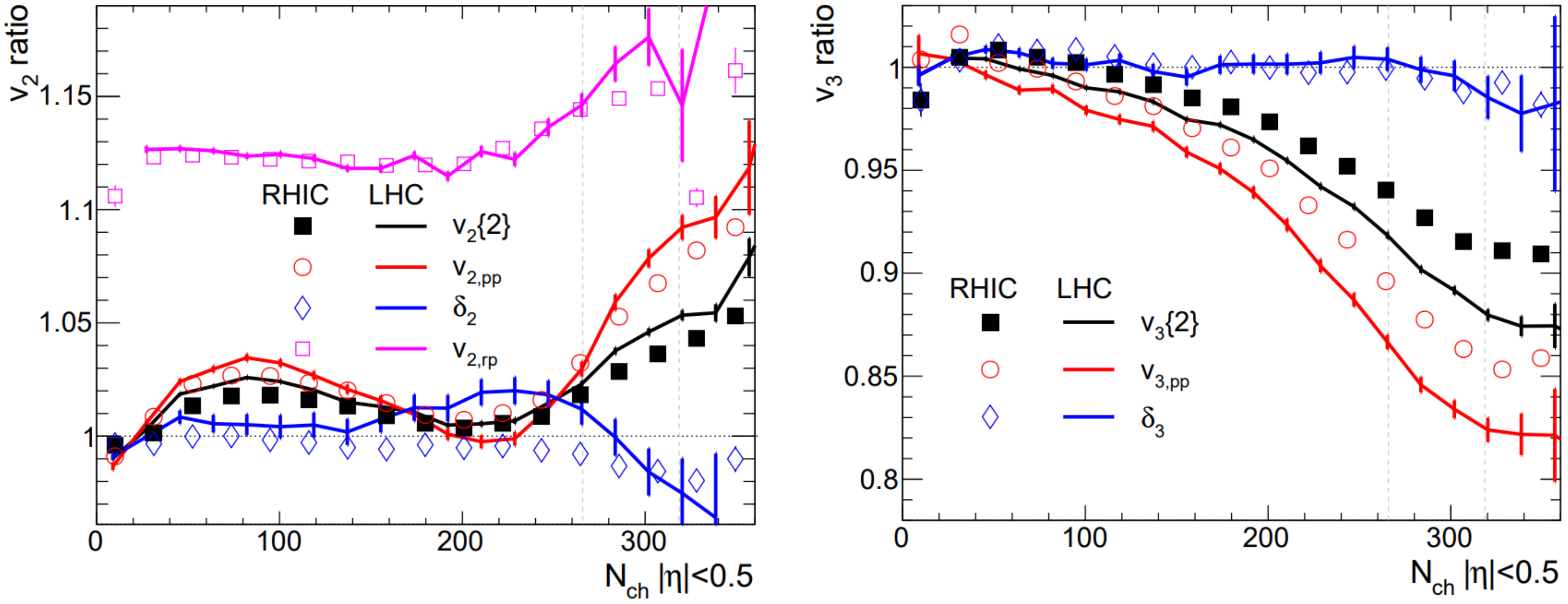
$$R^{\mathrm{Xe}}_{\mathrm{Pb}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N^{\mathrm{XeXe}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N^{\mathrm{PbPb}}/\mathrm{d}p_{\mathrm{T}}} \frac{T_{\mathrm{PbPb}}}{T_{\mathrm{XeXe}}}$$

- Below p_T~5 GeV: $R^{Xe}{}_{Pb}$~ ratio of pp in different CM energies
- At high p_T, the deviation from pp is up to 30%

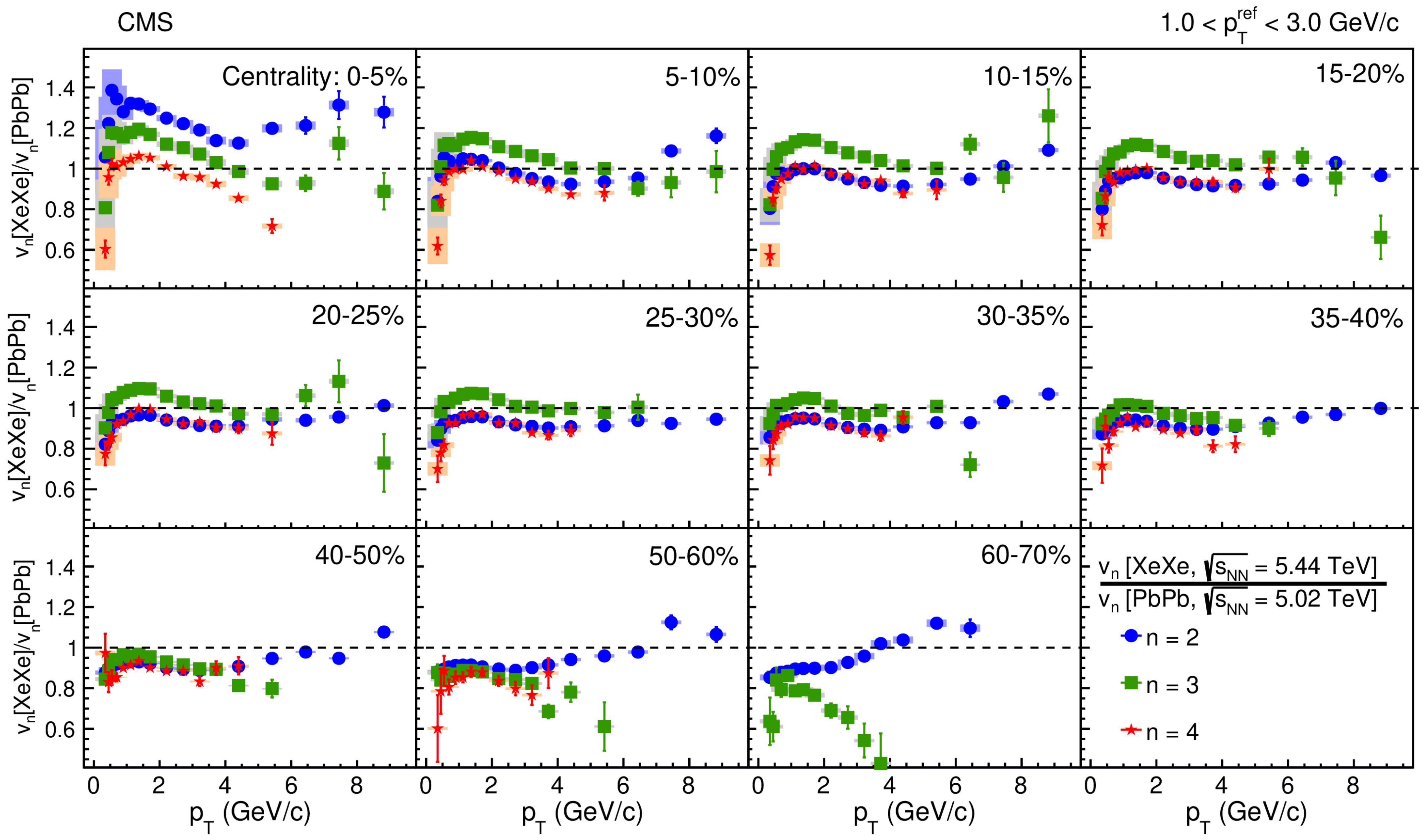
Correlation between high p_T and low p_T v_2



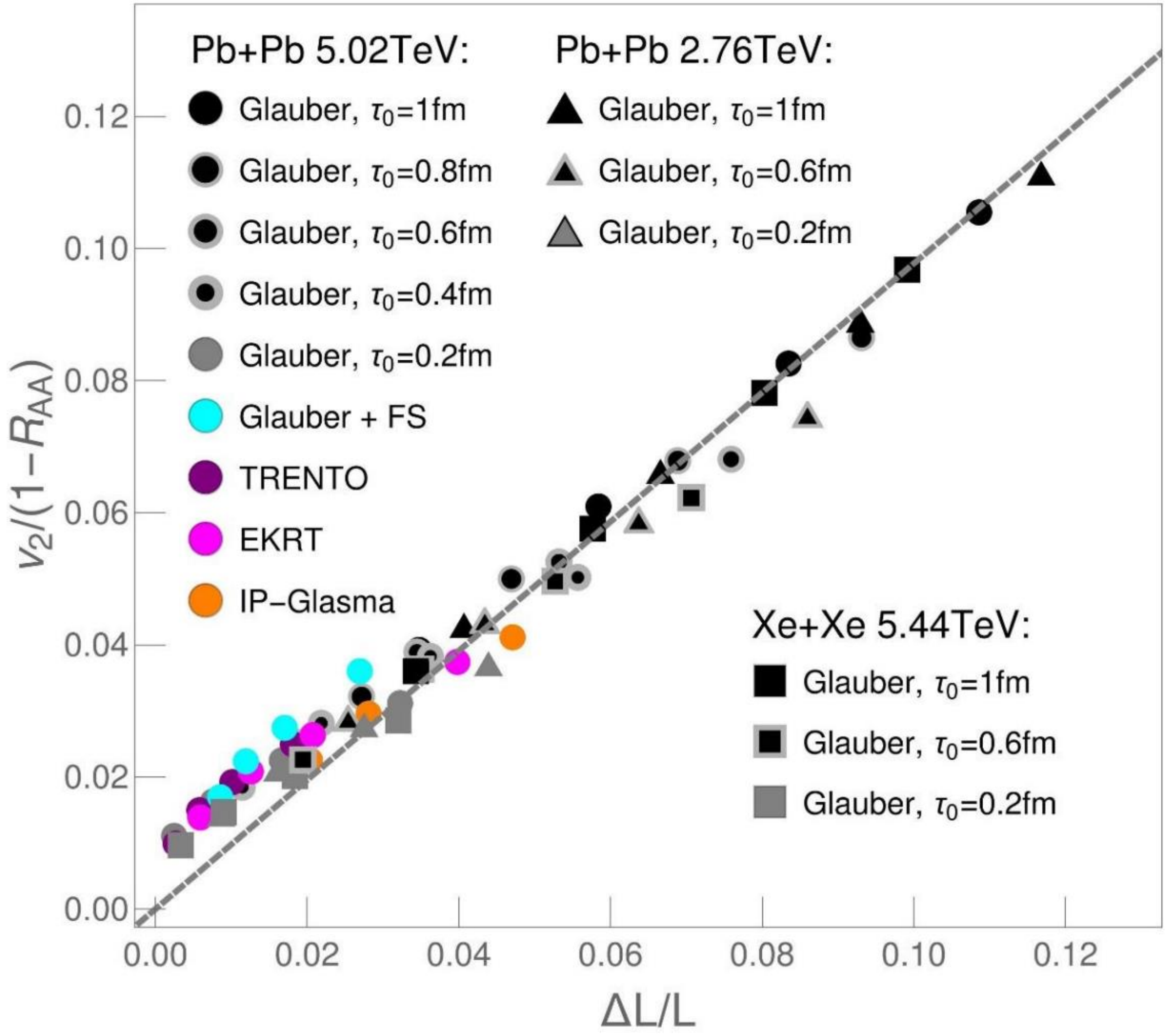
- Linear correlation between high and low p_T v_2
- The points represent the centrality bins 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50, and 50–60%.


v2 ratio
1.15
1.1
1.05
1
0
100
200
300
Nch |η|<0.5
RHIC
LHC
v2{2}
v2,pp
δ2
v2,rp
v3 ratio
1
0.95
0.9
0.85
0.8
0
100
200
300
Nch |η|<0.5
RHIC
LHC
v3{2}
v3,pp
δ3

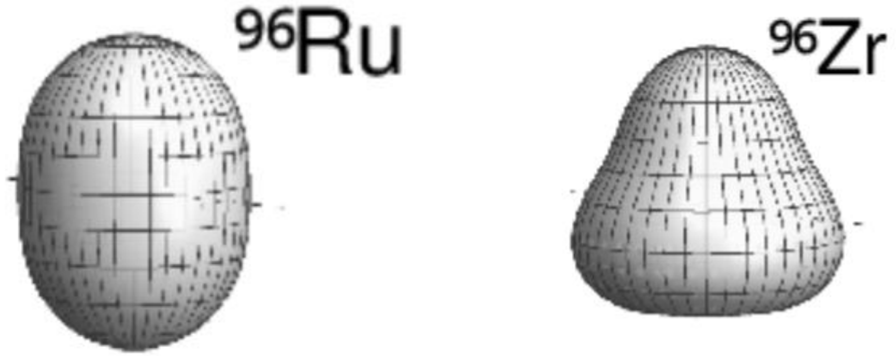
High p_T v_2

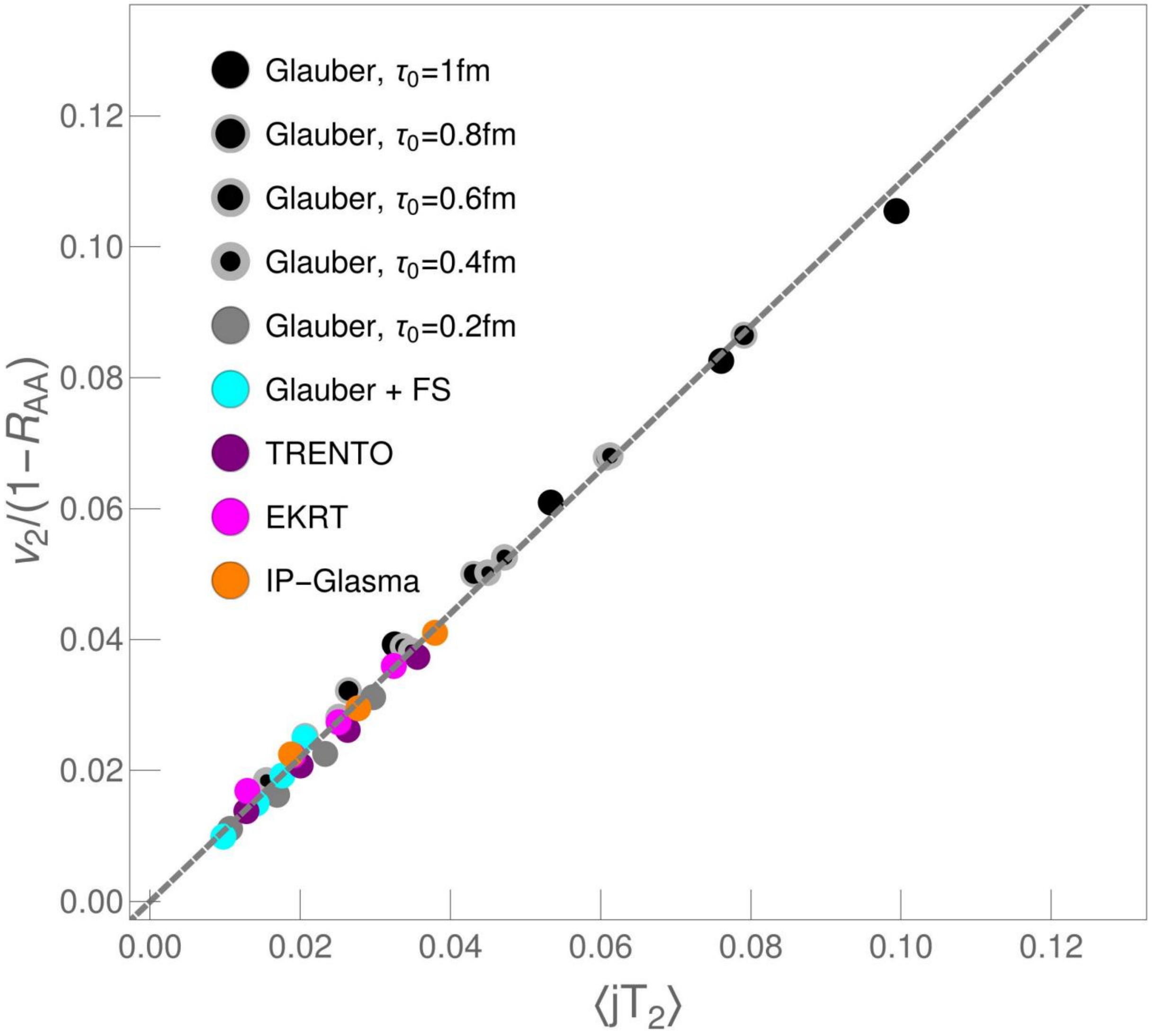


CMS
$1.0 < p_T^{ref} < 3.0$ GeV/c
Centrality: 0-5%
5-10%
10-15%
15-20%
20-25%
25-30%
30-35%
35-40%
40-50%
50-60%
60-70%
v_n[XeXe]/v_n[PbPb]
p_T (GeV/c)
v_n [XeXe, $\sqrt{s_{NN}}$ = 5.44 TeV] / v_n [PbPb, $\sqrt{s_{NN}}$ = 5.02 TeV]
n = 2
n = 3
n = 4



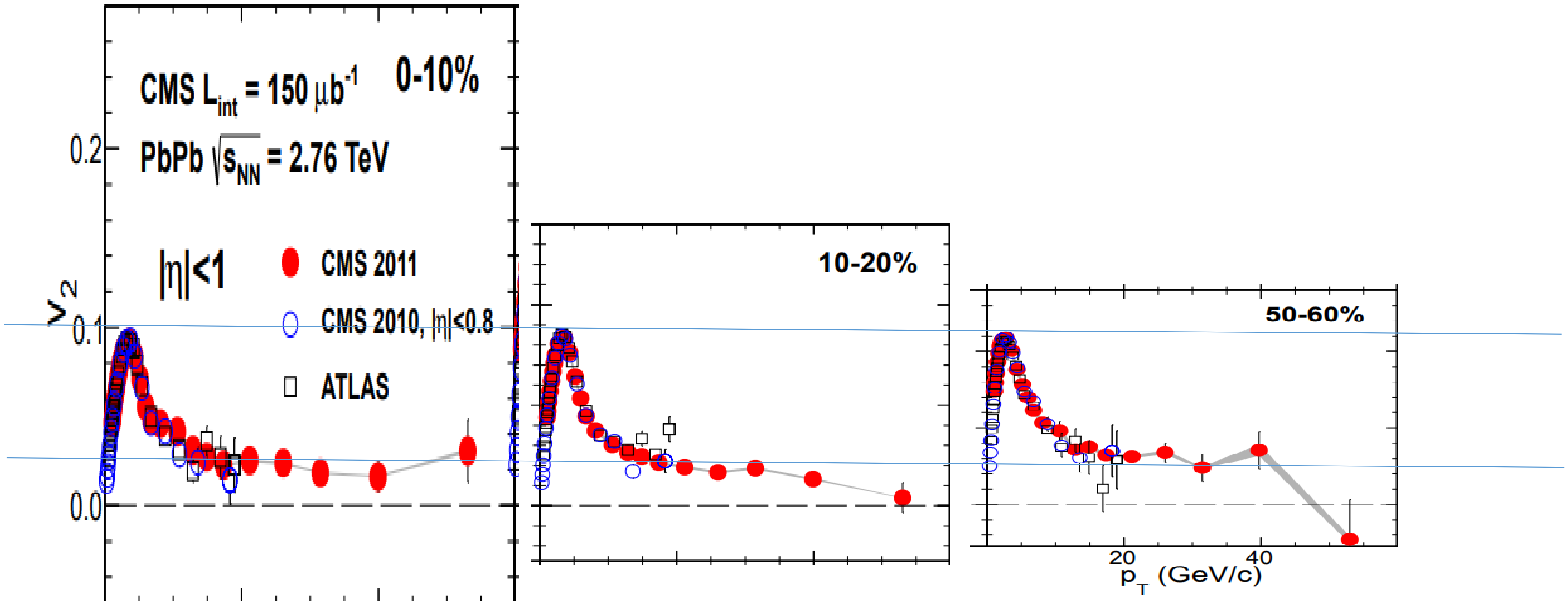
$$\frac{\Delta L}{\langle L\rangle} = \frac{\langle L_{out}\rangle - \langle L_{in}\rangle}{\langle L_{out}\rangle + \langle L_{in}\rangle}$$



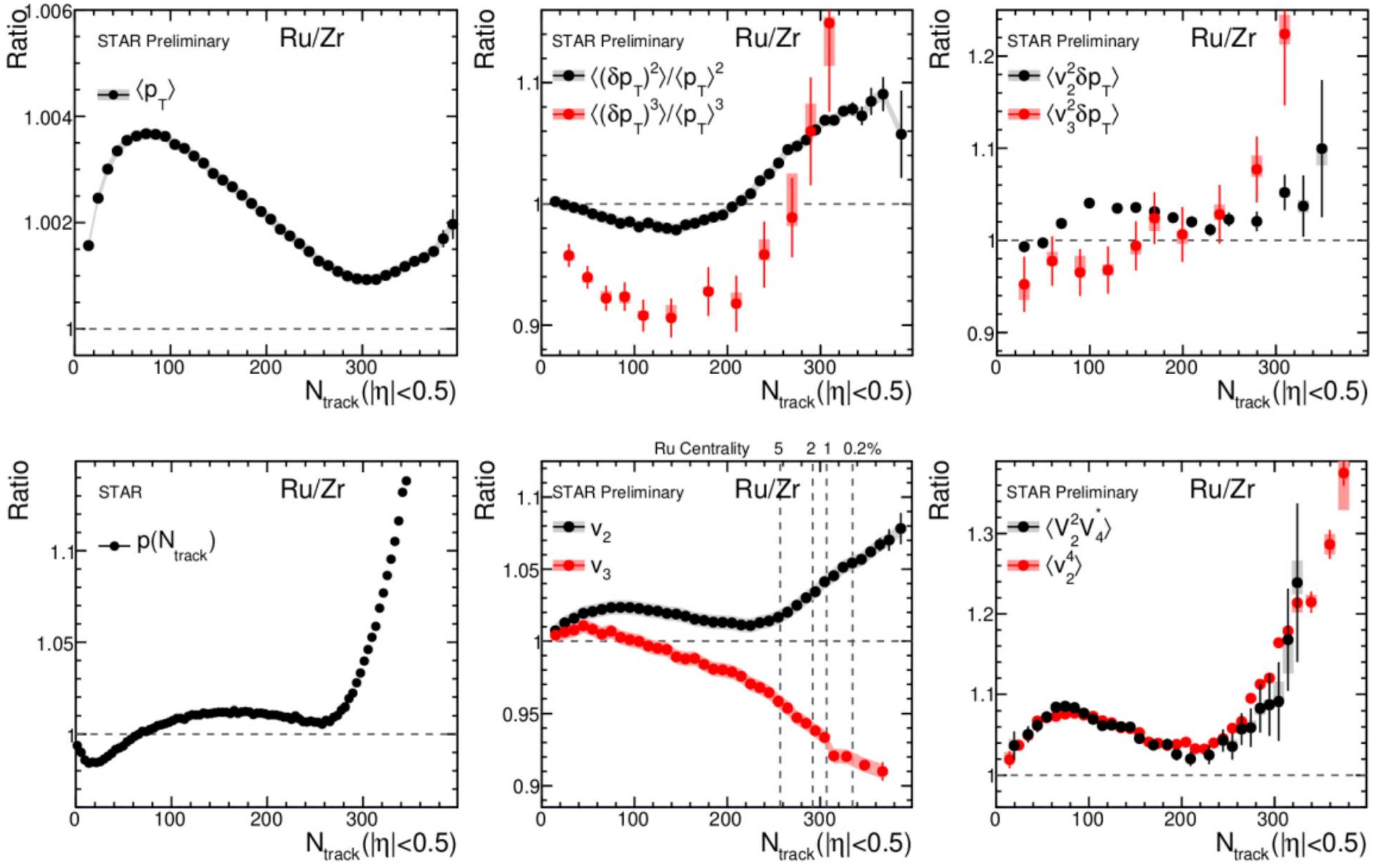


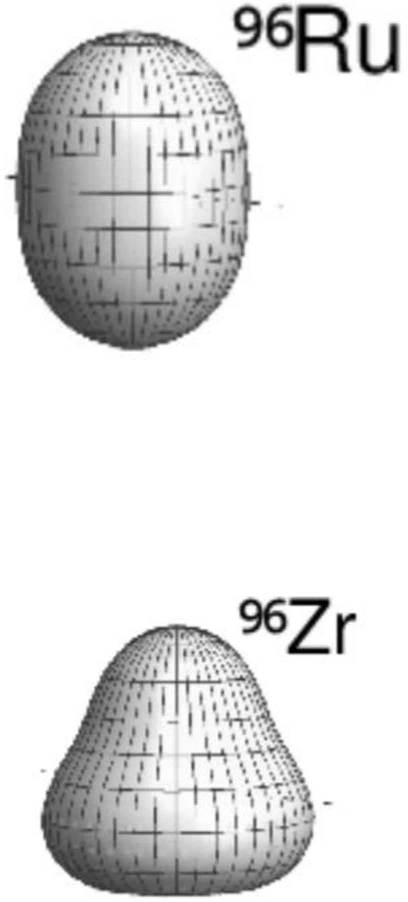
$$jT(\tau,\phi) \equiv \frac{\int \mathrm{d}x\mathrm{d}y\, T^3(x+\tau\cos\phi, y+\tau\sin\phi,\tau)\, n_0(x,y)}{\int \mathrm{d}x\mathrm{d}y\, n_0(x,y)}$$

$$jT_2(\tau) = \frac{\int \mathrm{d}x\mathrm{d}y\, n_0(x,y) \int \mathrm{d}\phi \cos 2\phi\, T^3(x+\tau\cos\phi, y+\tau\sin\phi,\tau)}{\int \mathrm{d}x\mathrm{d}y\, n_0(x,y) \int \mathrm{d}\phi\, T^3(x+\tau\cos\phi, y+\tau\sin\phi,\tau)}.$$

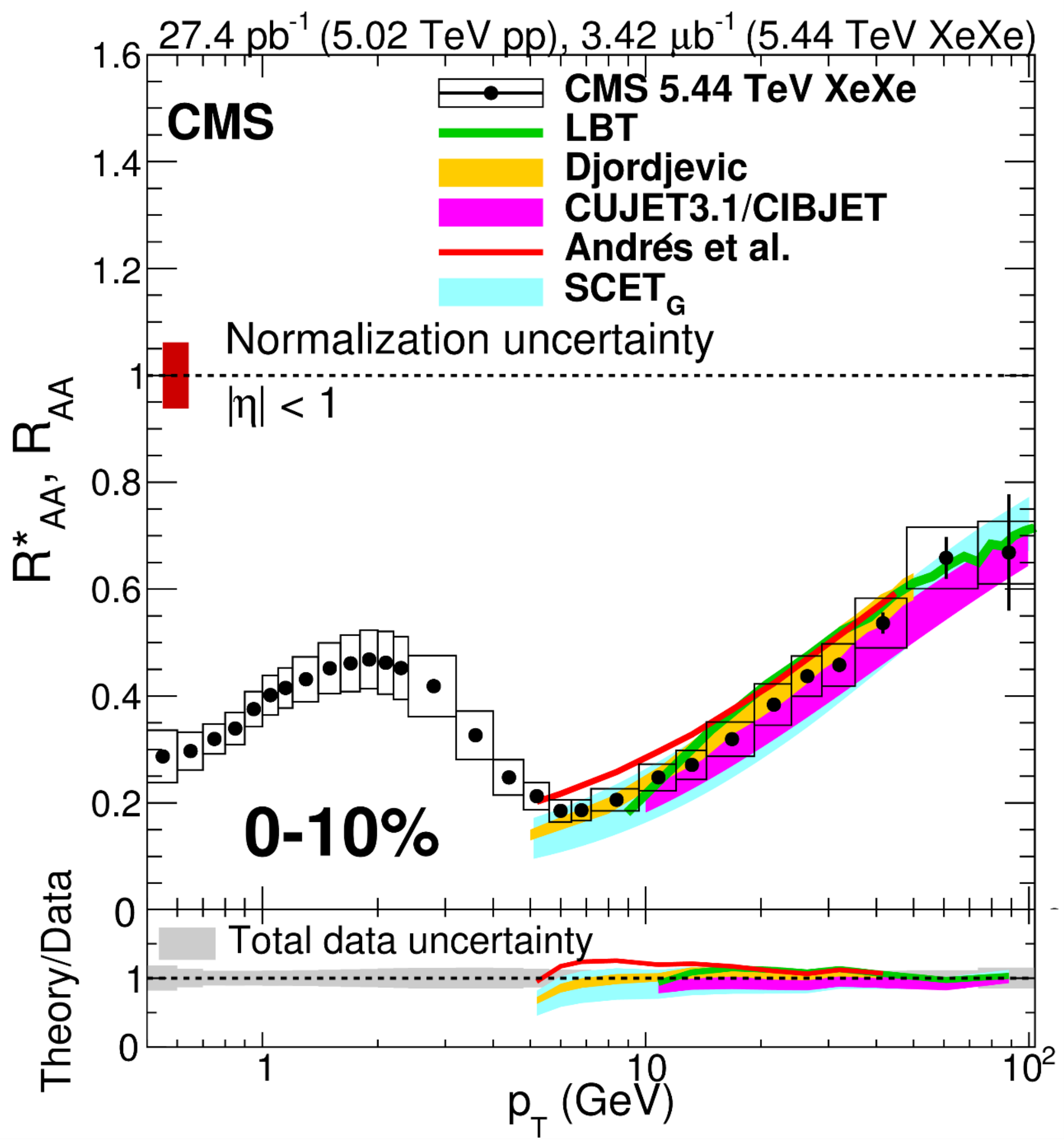


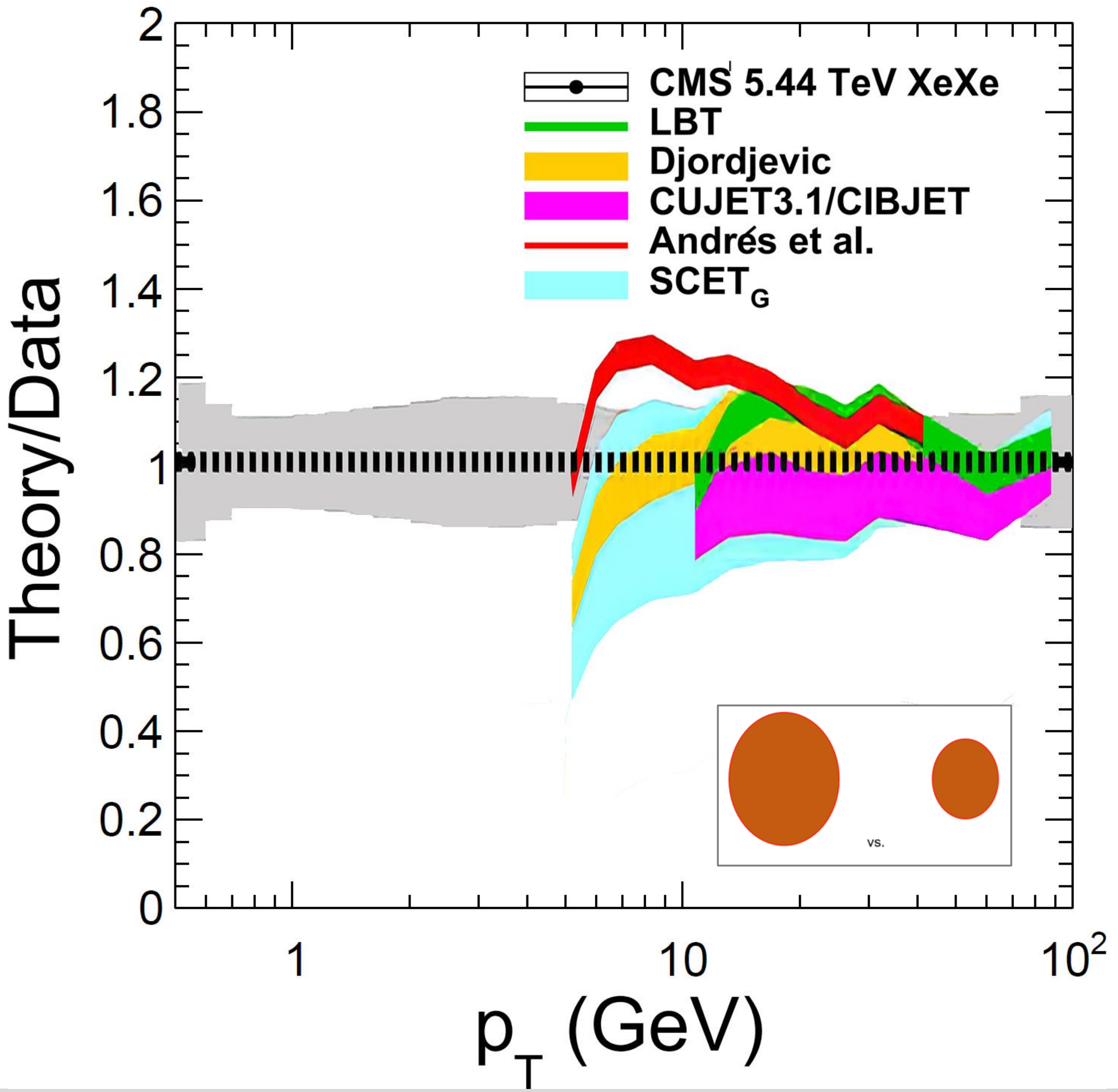
CMS L_int = 150 μb^-1
0-10%
PbPb √s_NN = 2.76 TeV
0.2
v_2
0.1
0.0
|η|<1
CMS 2011
CMS 2010, |η|<0.8
ATLAS
10-20%
50-60%
20
40
p_T (GeV/c)


STAR Preliminary
Ru/Zr
$\langle p_T \rangle$
STAR Preliminary
Ru/Zr
$\langle (\delta p_T)^2 \rangle / \langle p_T \rangle^2$
$\langle (\delta p_T)^3 \rangle / \langle p_T \rangle^3$
STAR Preliminary
Ru/Zr
$\langle v_2^2 \delta p_T \rangle$
$\langle v_3^2 \delta p_T \rangle$
STAR
Ru/Zr
$p(N_{track})$
Ru Centrality 5 2 1 0.2%
STAR Preliminary
Ru/Zr
v_2
v_3
STAR Preliminary
Ru/Zr
$\langle V_2^2 V_4^* \rangle$
$\langle v_2^4 \rangle$
Ratio
$N_{track}(|\eta|<0.5)$

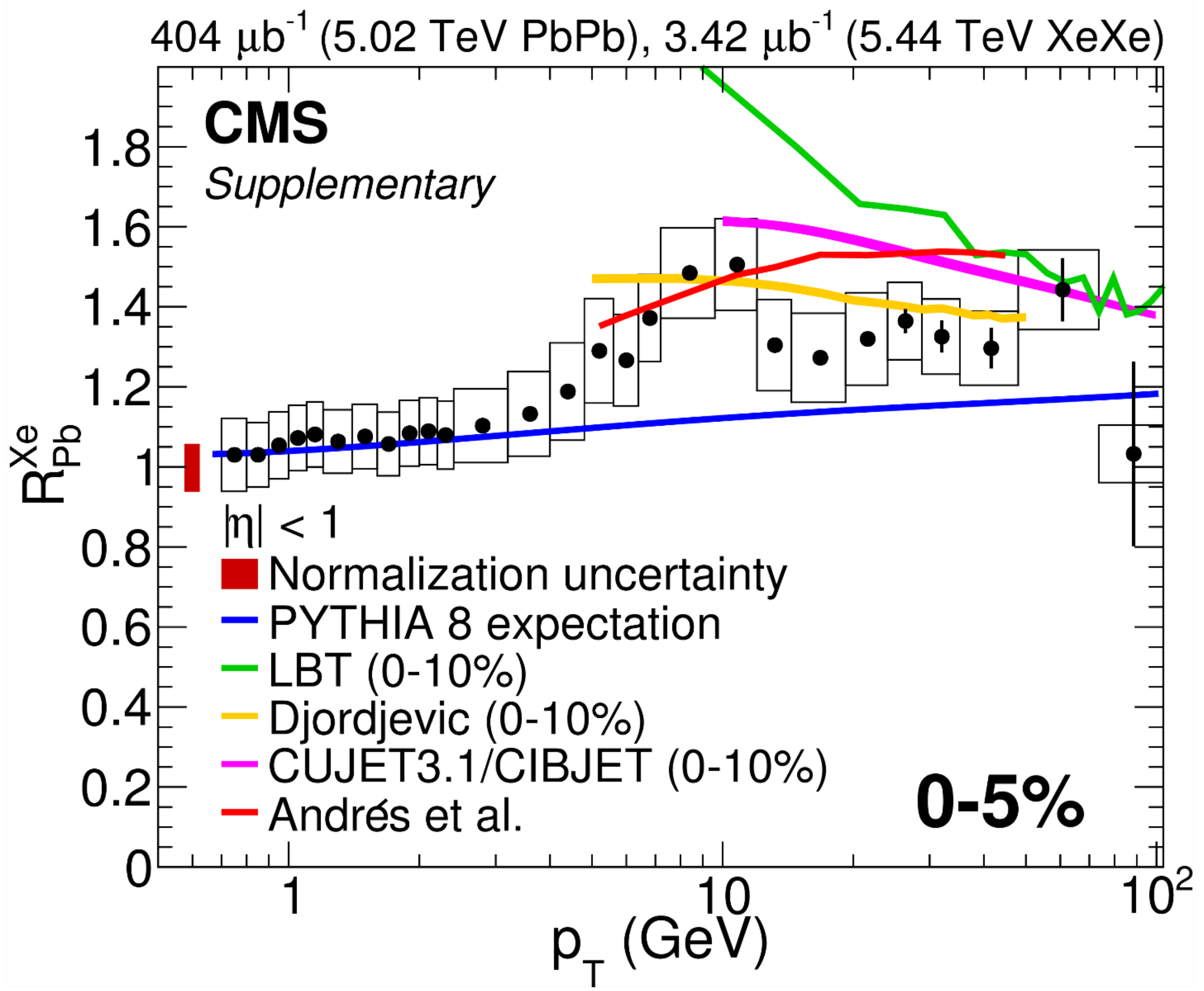

^{96}Ru
^{96}Zr

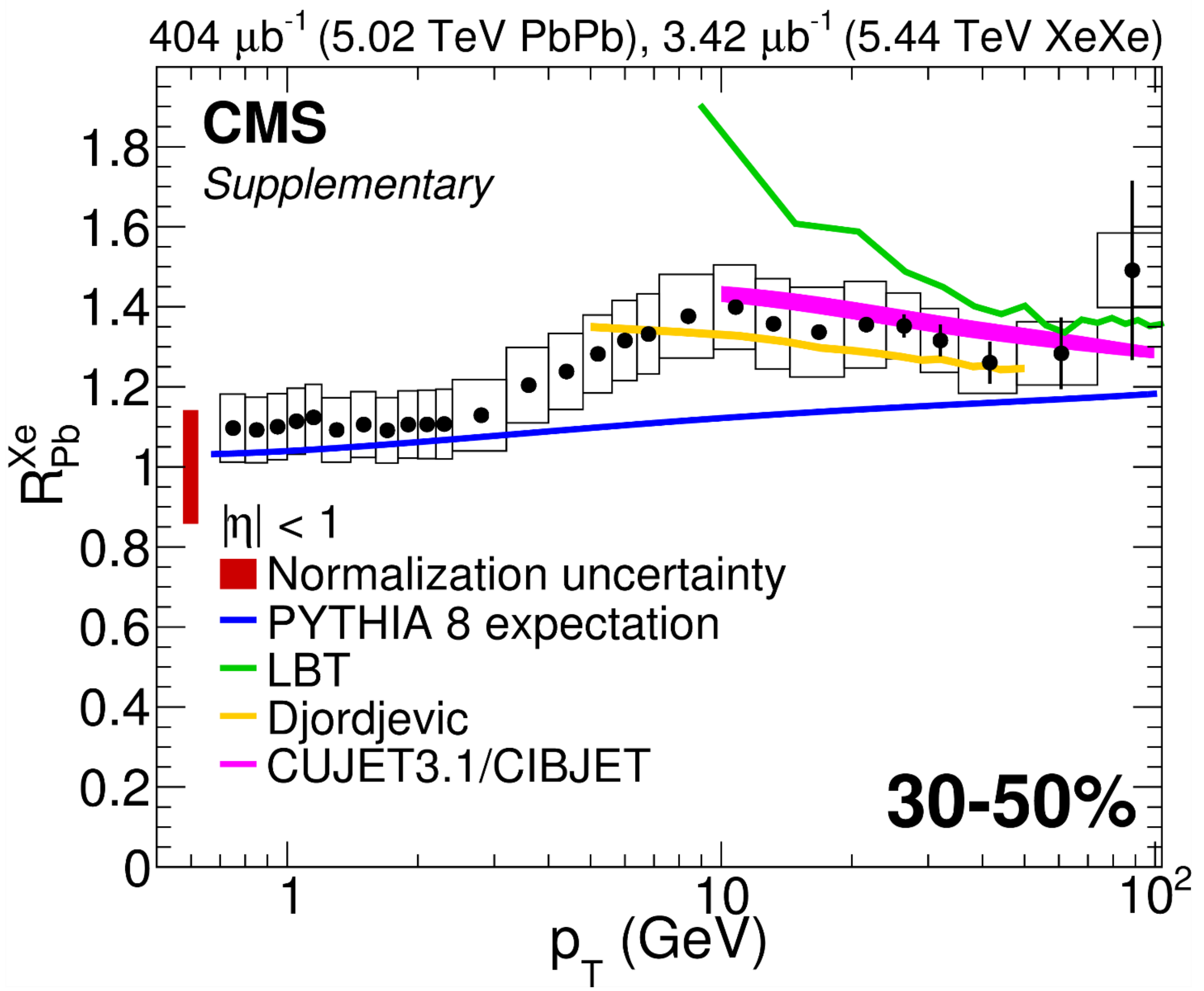
Charged Particle R_{AA} in XeXe collisions

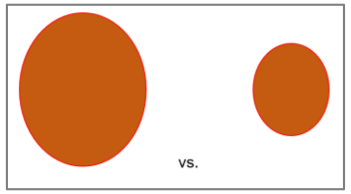




XeXe and PbPb Charged Particle p_T Spectra Ratio







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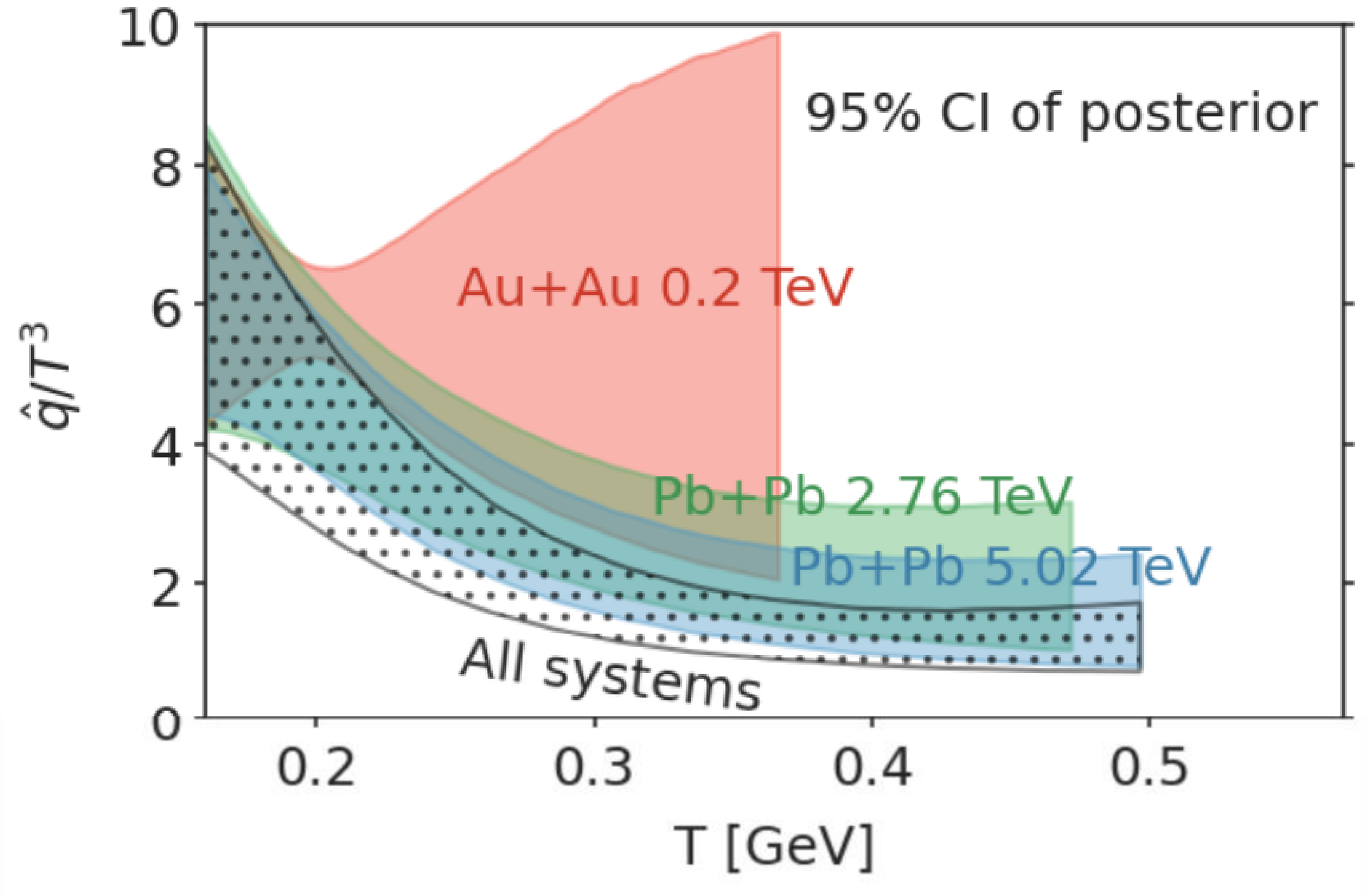
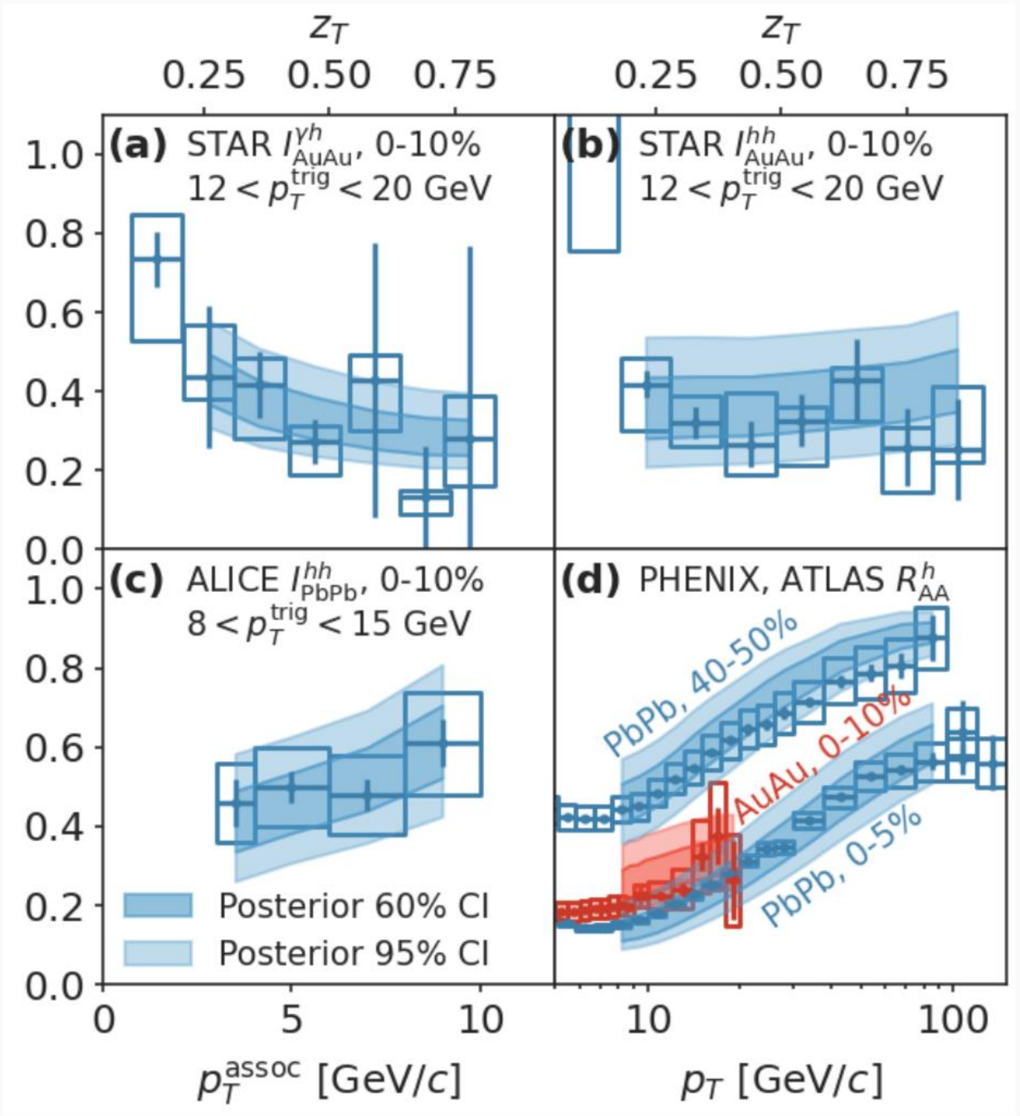
Consistency between RHIC and LHC Results

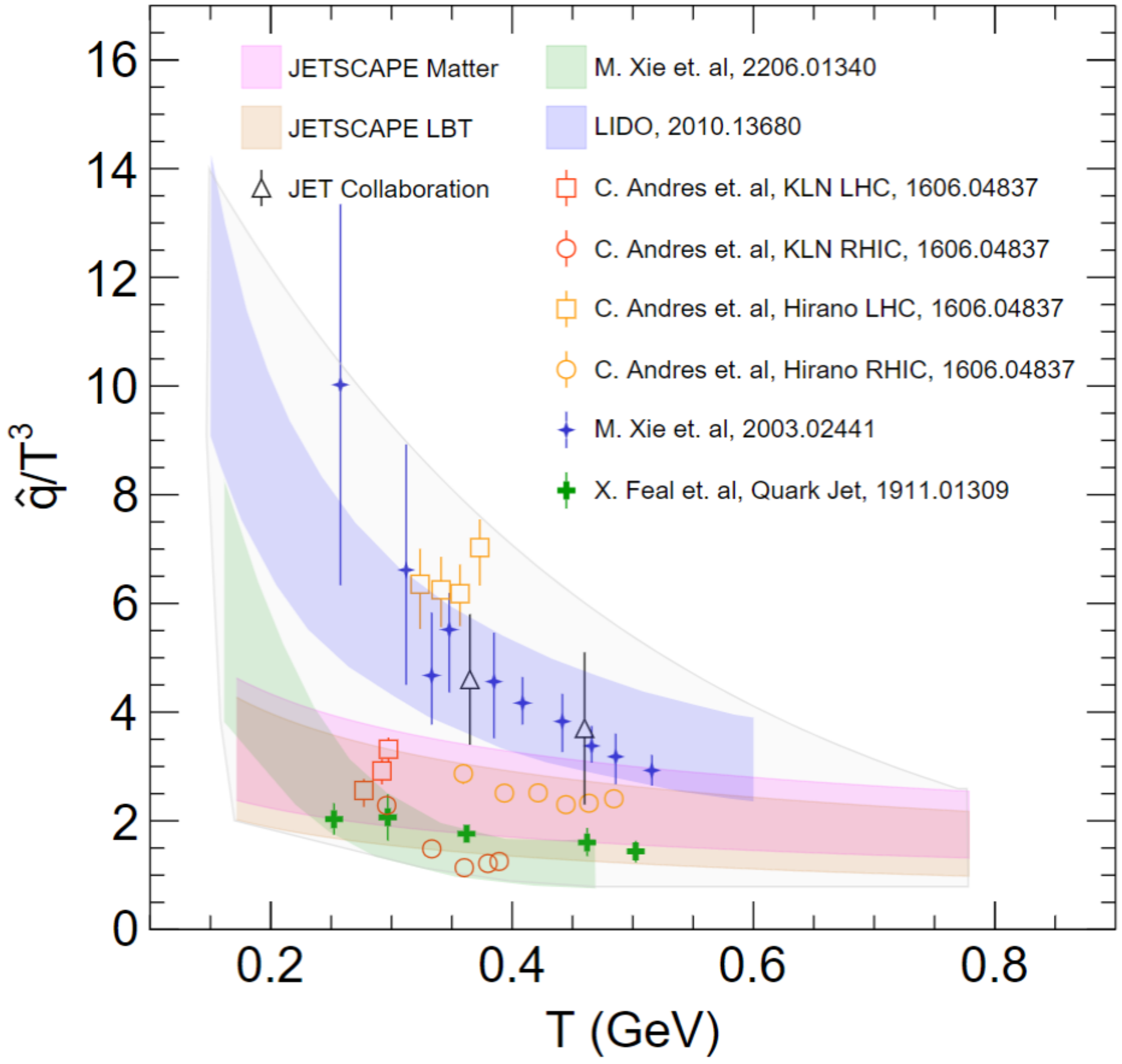




- Don't have enough accuracy
- Expect high precision data from sPHENIX should provide important constraints at low T
- Consistency checks between RHIC and LHC data

Wei-Yao Ke

QGP Transport Properties with RHIC and LHC Run 2 Data



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

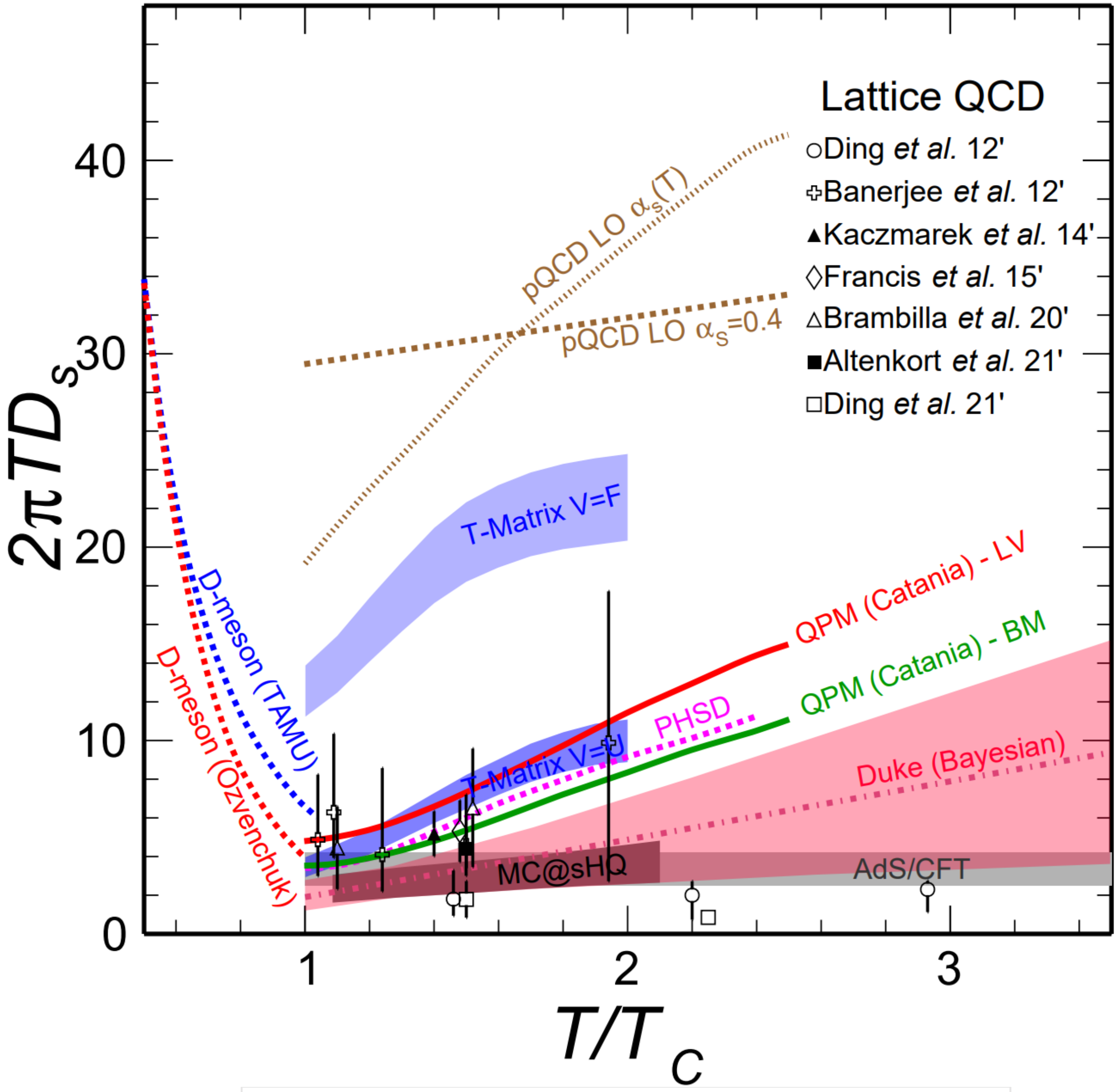
Jet Quenching Parameter $\hat{q}$

- Extracted mainly from charged hadron spectra R_{AA} data
  - Some analyses included γ-hadron and di-hadron data
- $\hat{q}/T^3$: decreasing trend vs. T
- Extracted values differ by up to a factor of 7

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- **Different QGP media used in calculations**
- Hadron re-scattering in the hadron gas phase
- Hadronization of fast moving partons

QGP Transport Properties with RHIC and LHC Run 2 Data



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

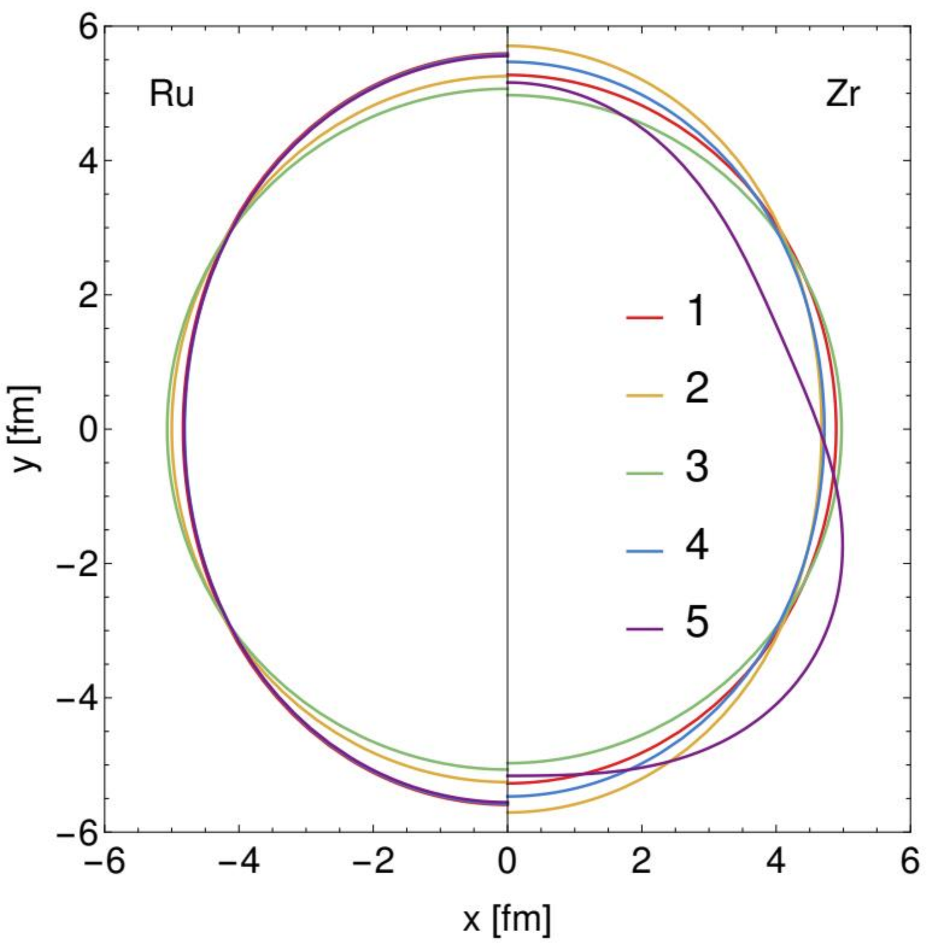
Charm diffusion coefficient D_s

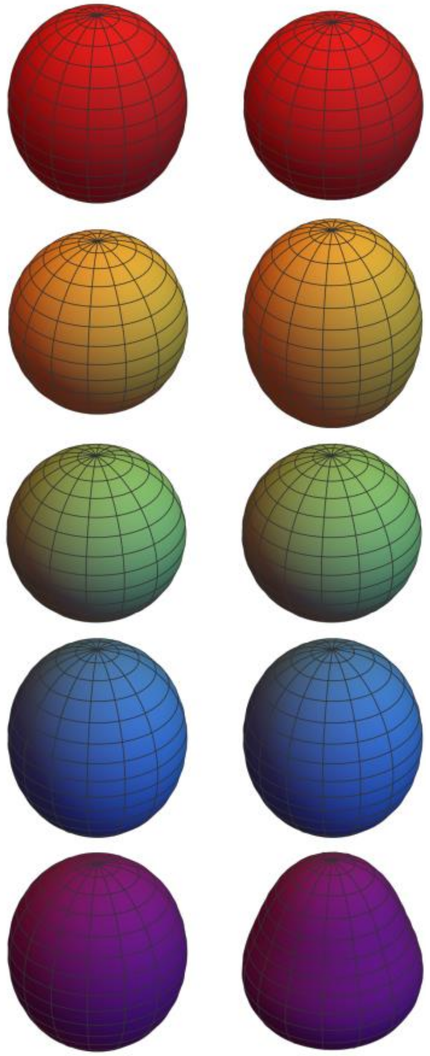
- Bayesian analysis from D meson R_{AA} and v_2
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of $2\pi TD_s$ vs. T in various models

Remaining Issues:

- Hadronization of charm quarks
- Charm diffusion mechanism
- **Different QGP media used in various calculations**
- Precision of the experimental data

Parameter Sets





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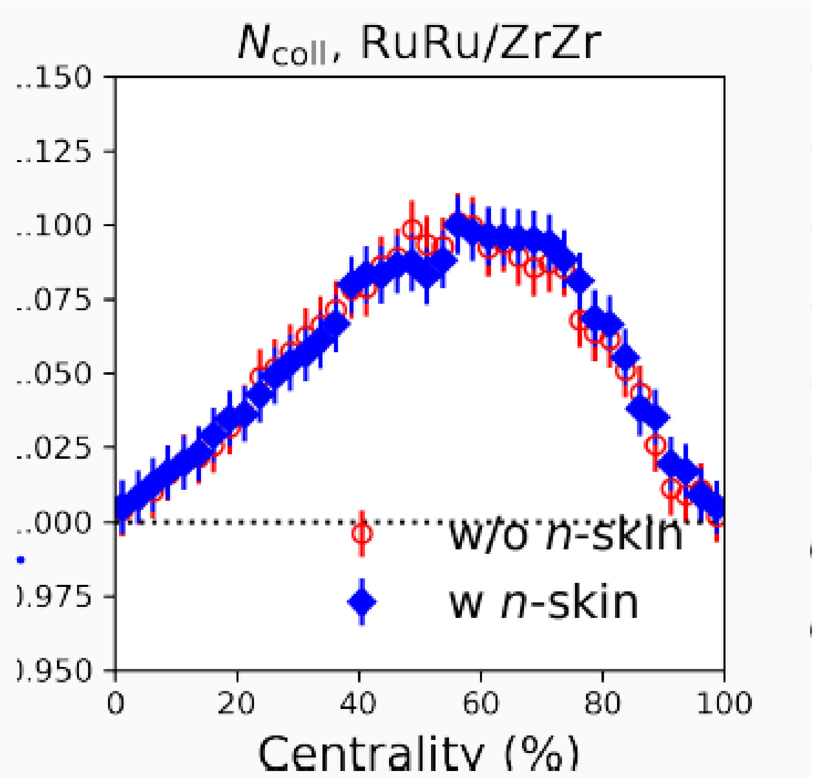
Wilke van der Schee

Parameter Sets

Table 2: The WS parameterizations (radius parameter R and diffuseness parameter a) of proton and neutron (and nucleon) density distributions for ^{96}Ru and ^{96}Zr, matching to the corresponding $\langle r \rangle$ and $\langle r^2 \rangle$ from the DFT-calculated spherical densities with SLy4 skyrme parameter set [1, 25]. The WS parameterization of nucleon density assuming a quadrupole deformity parameter $\beta_2 = 0.16$ and matching to the spherical DFT density is also listed. All quoted numbers are in fm.

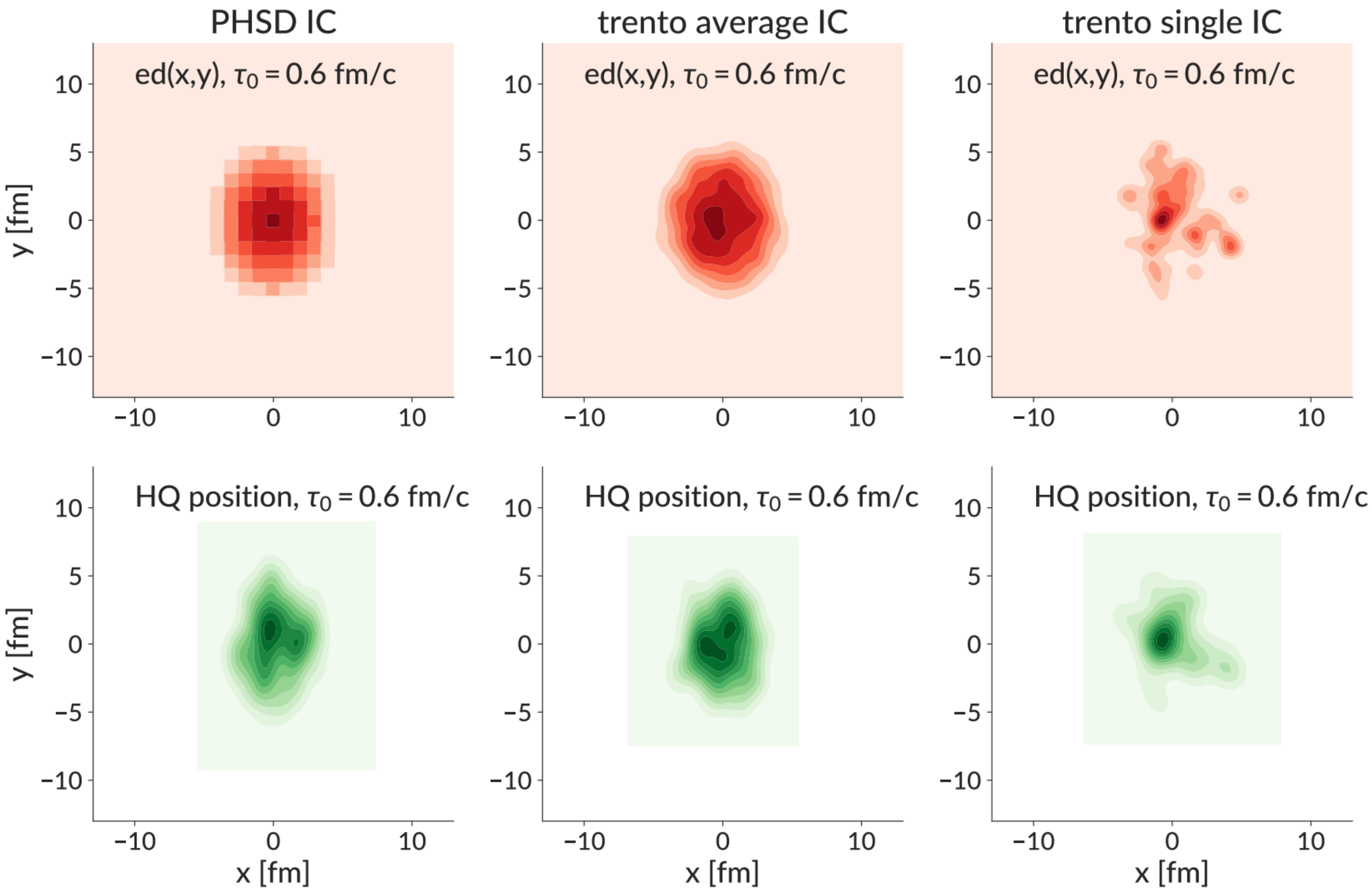
		^{96}Ru		^{96}Zr	
		R	a	R	a
$\beta_2 = 0$	p	5.060	0.493	4.915	0.521
	n	5.075	0.505	5.015	0.574
	p+n	5.067	0.500	4.965	0.556
$\beta_2 = 0.16$	p	5.053	0.480	4.912	0.508
	n	5.073	0.490	5.007	0.564
	p+n	5.065	0.485	4.961	0.544

Z



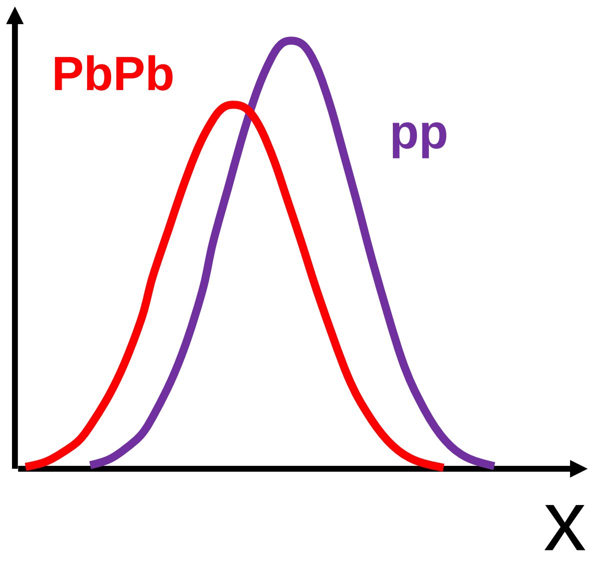
Wei-Yao Ke

Initial Condition Used in HQ Diffusion Models



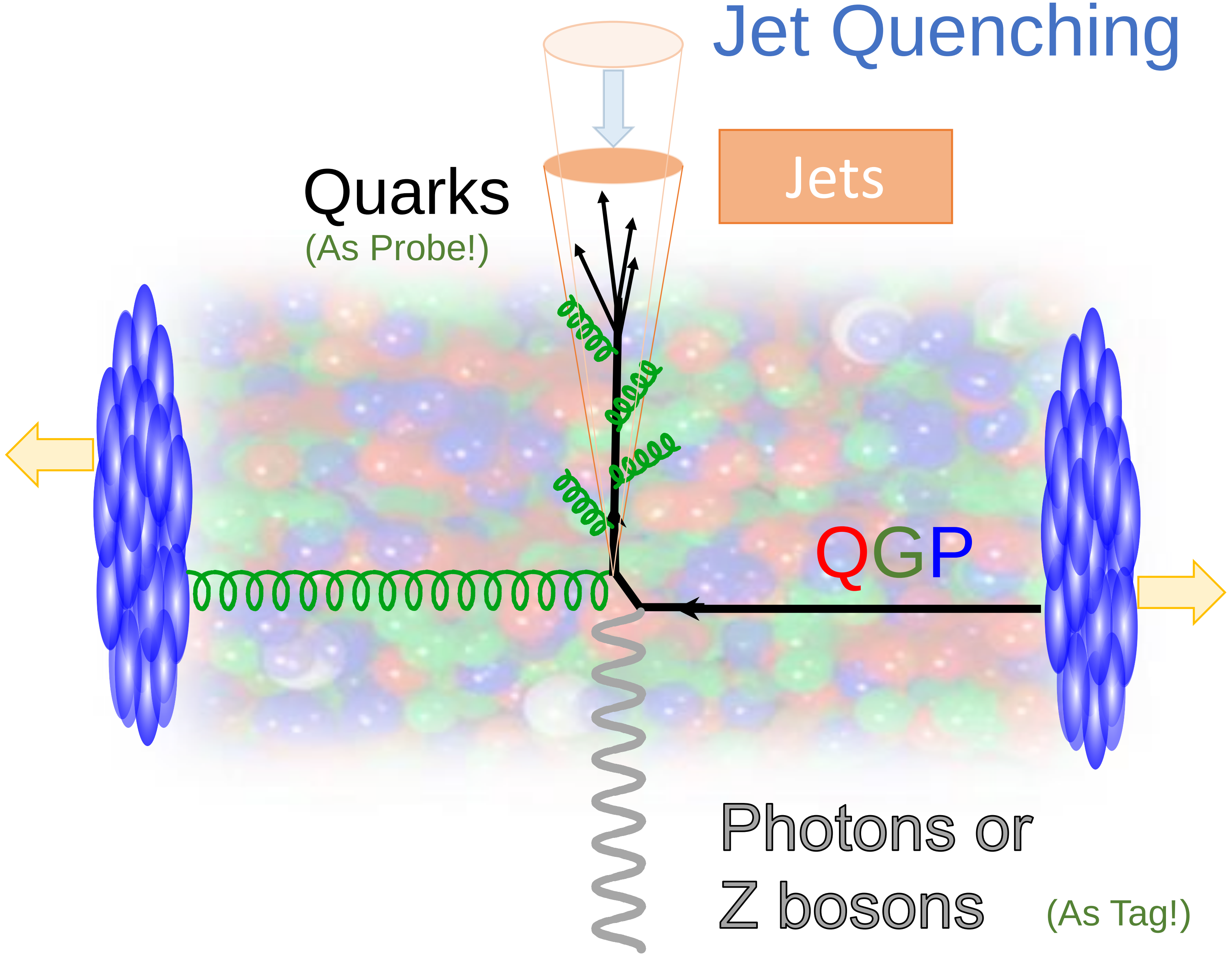
PRC 99 (2019) 1, 014902

Probes Produced with the QGP



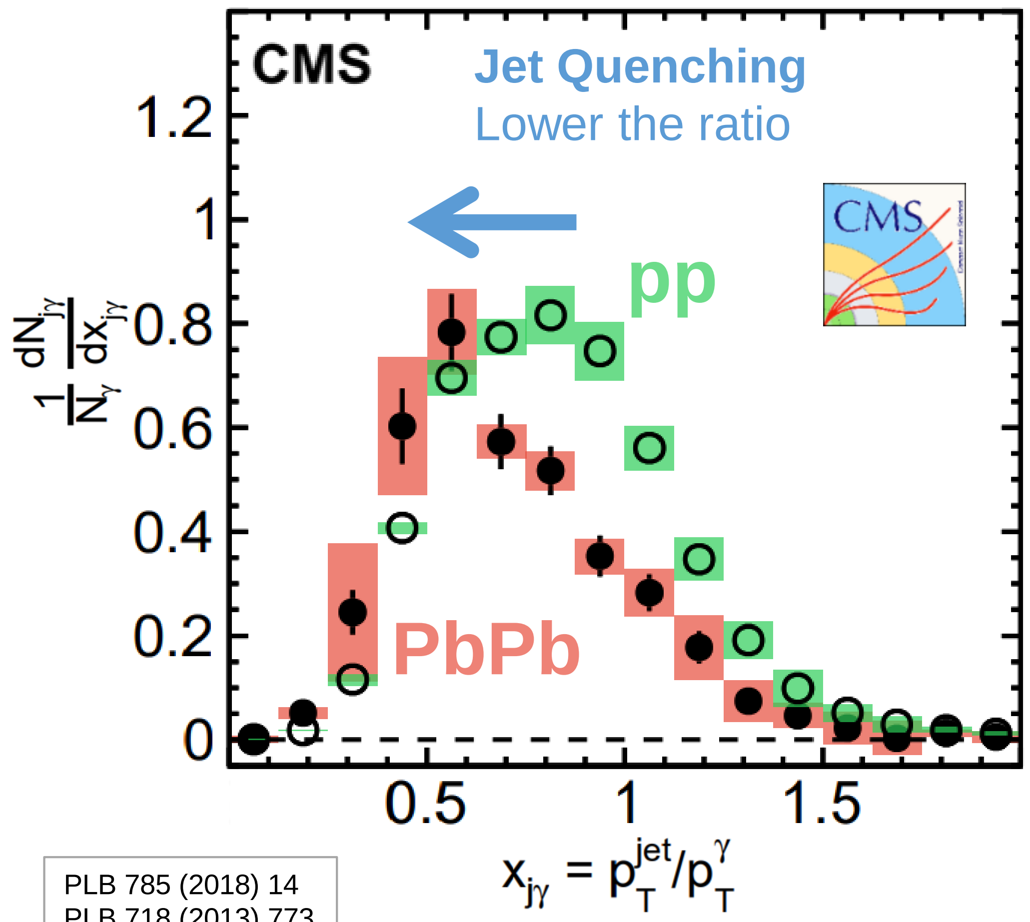
$$x = p_T^{Jet} / p_T^{\gamma}$$

LBT-CCNU Model

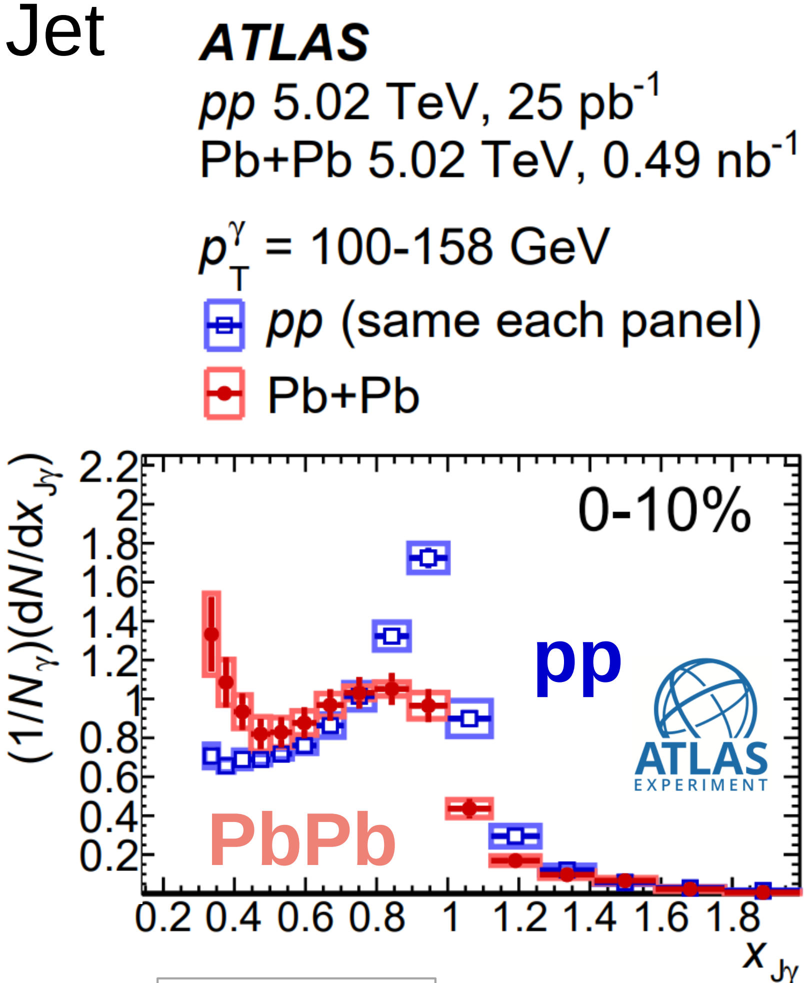


Transverse Momentum Ratio of Quark-enriched Jet and Boson

Photon + Jet

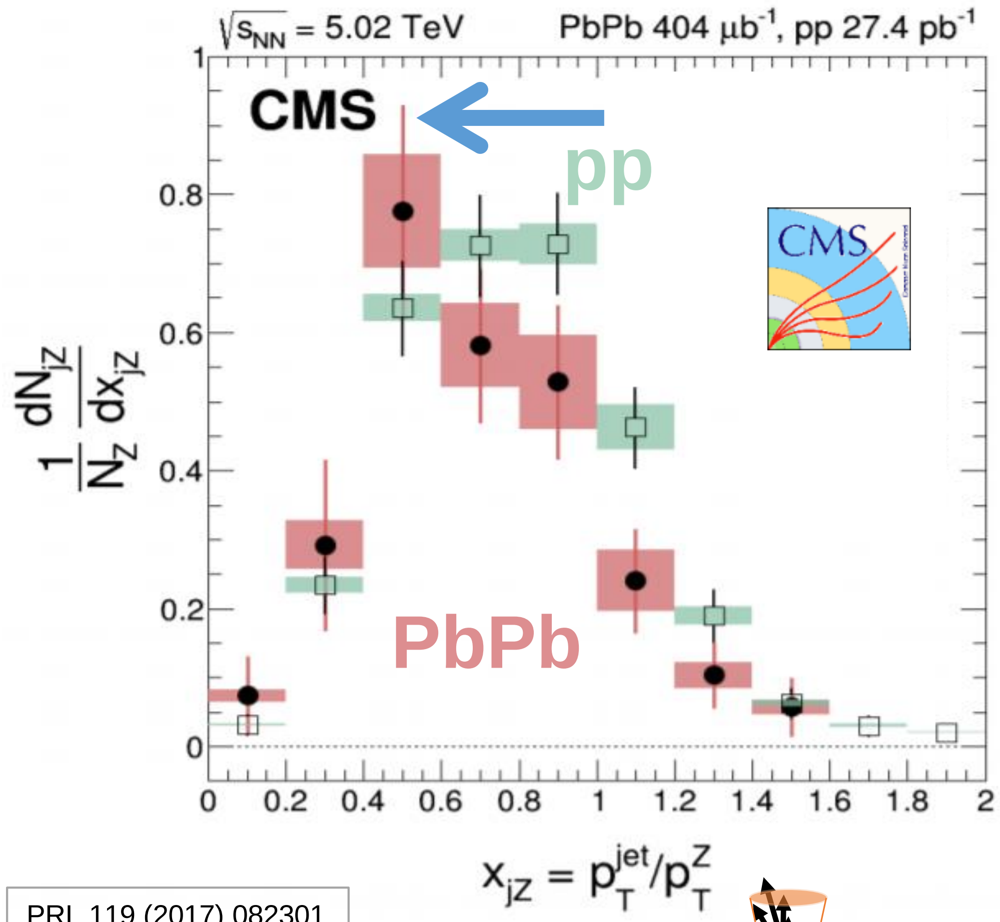


PLB 785 (2018) 14
PLB 718 (2013) 773

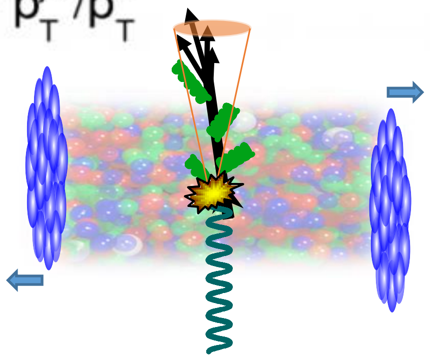


PLB 789 (2019) 167

Z^0 boson + Jet

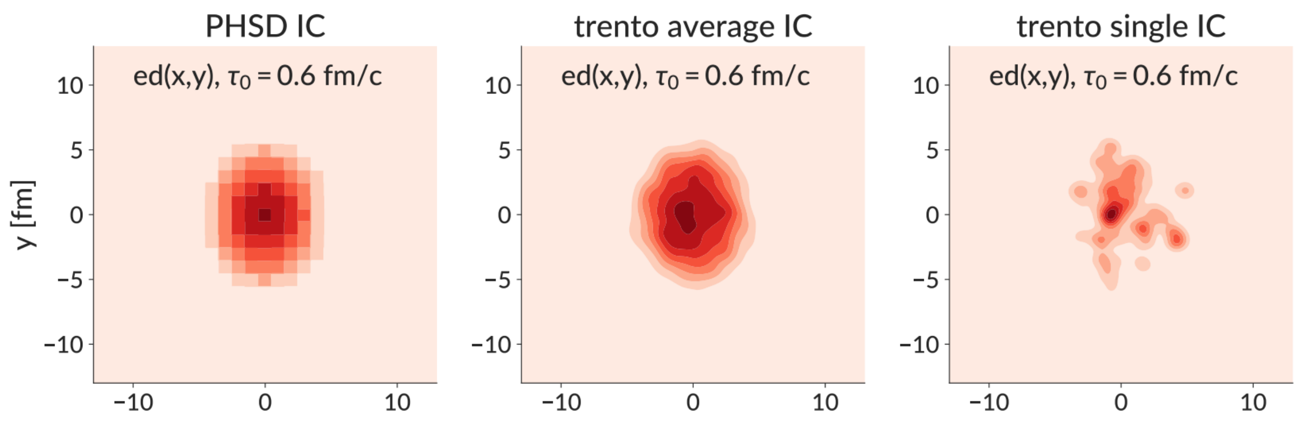


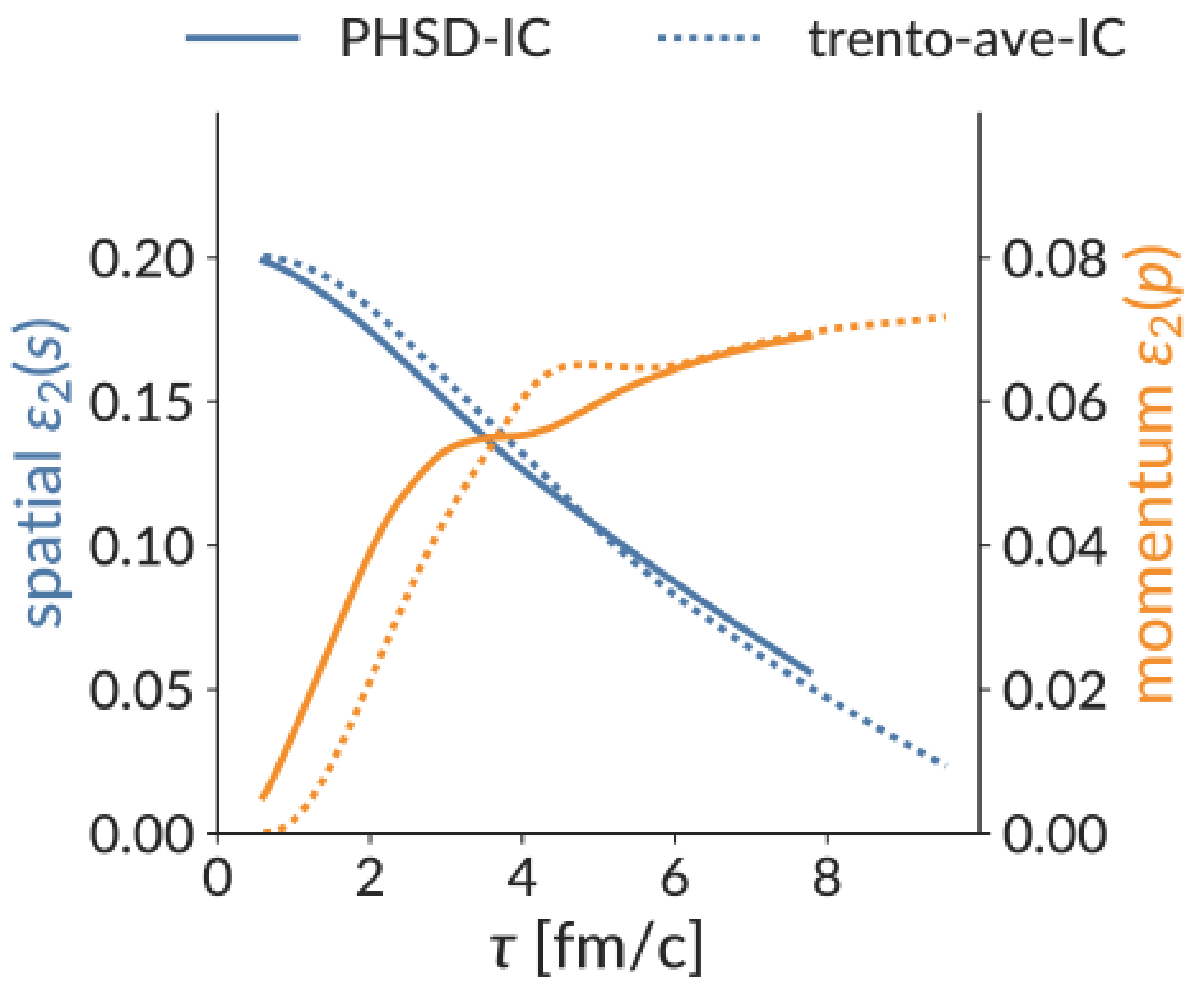
PRL 119 (2017) 082301



- Initial transverse momentum ~ 0
- Photons and Z bosons are not affected by QGP
  → **Quark-enriched jet (70% quark) to boson momentum ratio lowered**

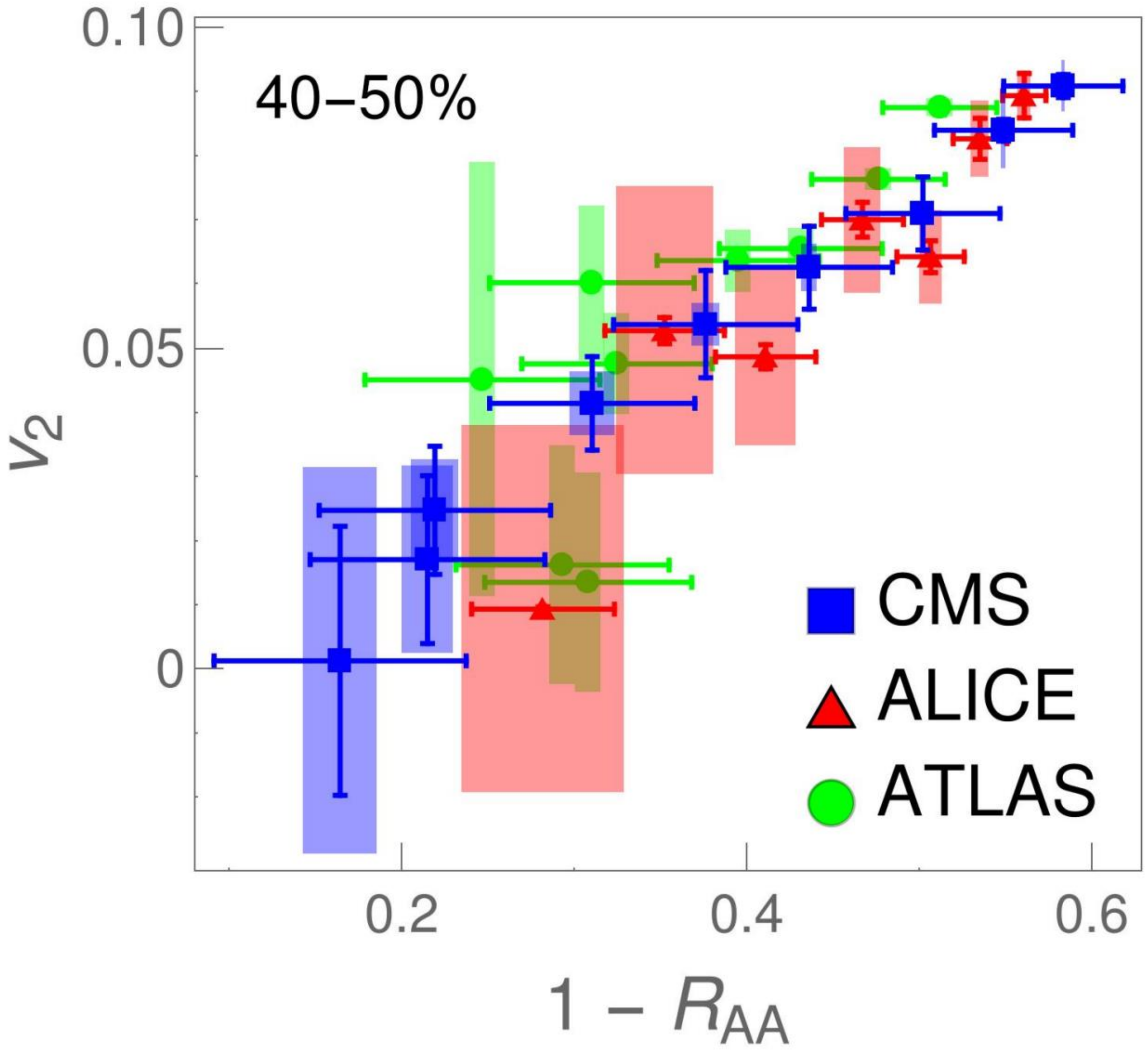
Evolution of spatial and momentum eccentricity





v_2 based method: Correlation between v_2 and $(1-R_{AA})$

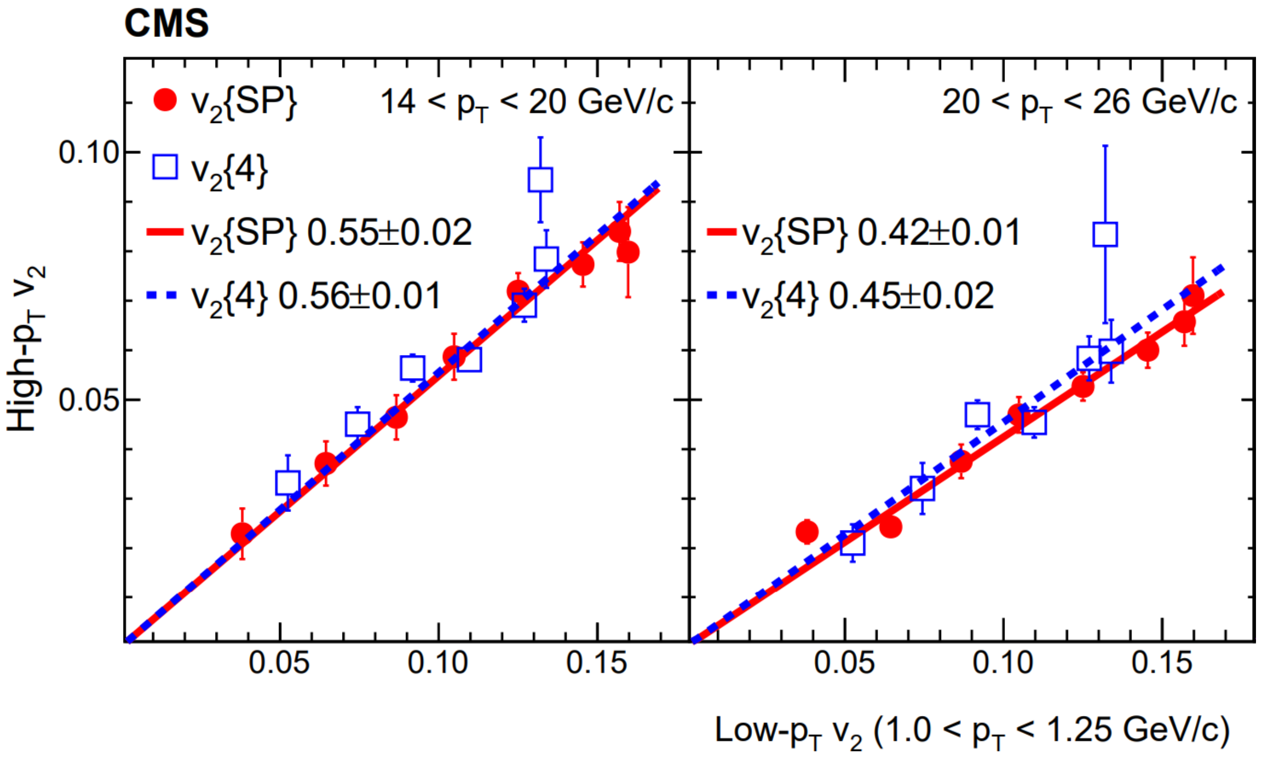
- Experimentally in PbPb collision at 5.02 TeV
- Linear correlation between v_2 and $(1-R_{AA})$:
  - **$v_2 / (1-R_{AA})$ ~ constant**



PLB 835 (2022) 137501

v_2 based method: Correlation between low and high p_T v_2

- Experimentally in PbPb collision at 5.02 TeV
- Linear correlation between v_2 and $(1-R_{AA})$:
  - $v_2 / (1-R_{AA}) \sim$ constant
- STAR has measured low p_T particle v_2
  - **Assume low p_T v_2 ratio = high p_T v_2 ratio are the same (like in PbPb)**
  - → $(1-R_{AA})$ ratio = high p_T v_2 ratio
    = low p_T v_2 ratio



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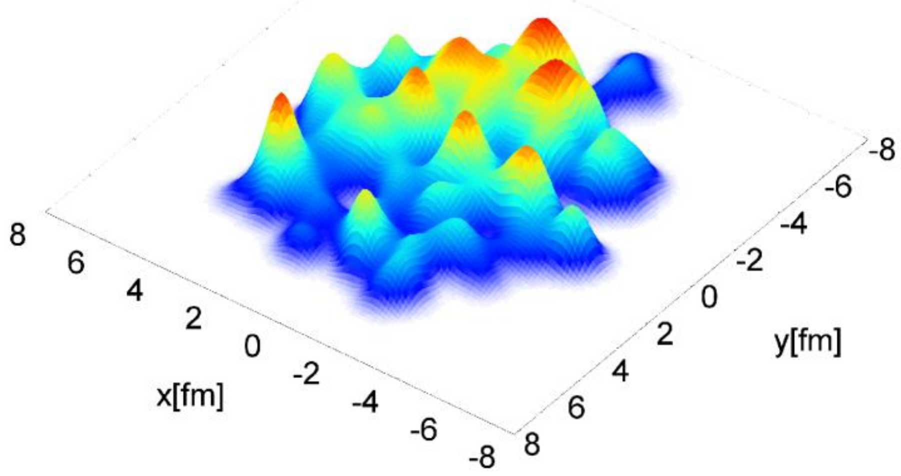
Intuition

Smoother initial condition



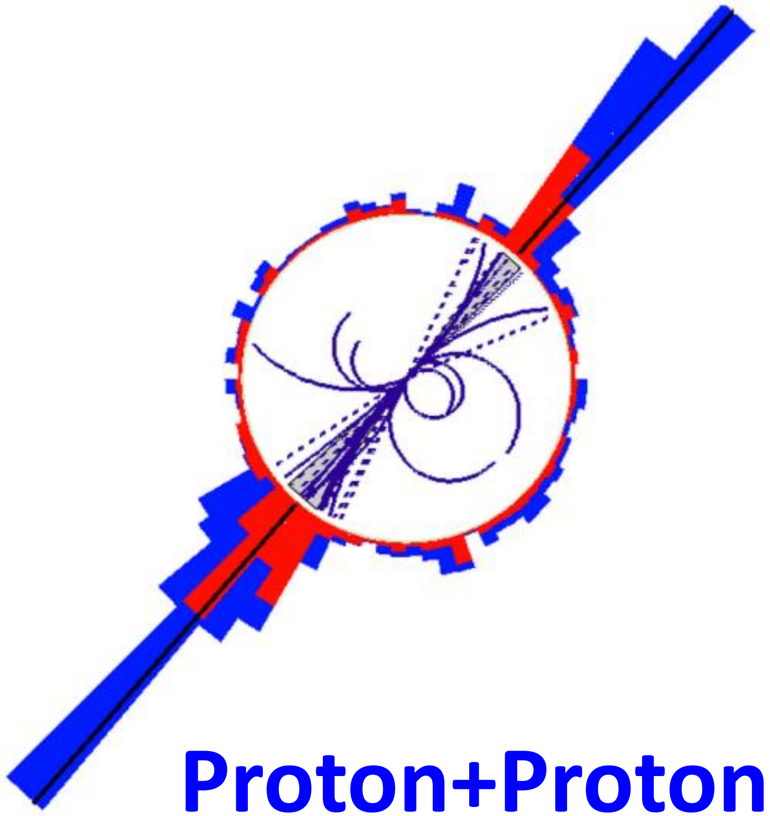
Need to have smaller η/s to reproduce v_n data

(smaller smearing effect)

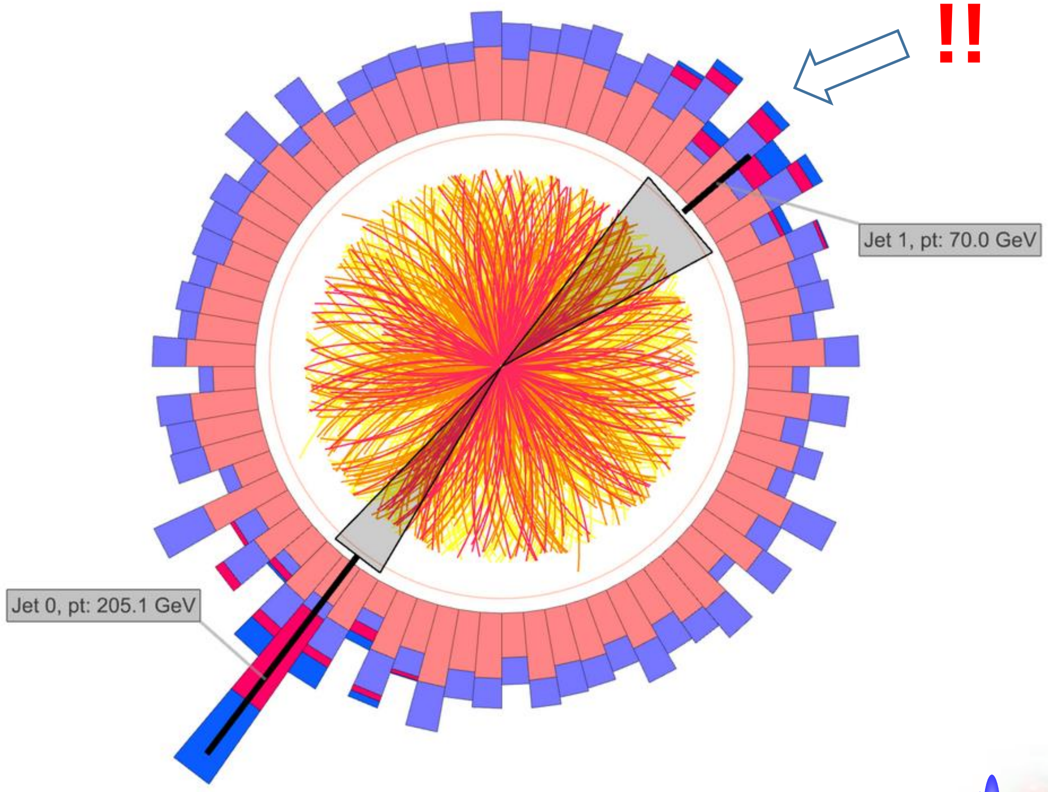
Lead to small D_s

And larger $\hat{q}$

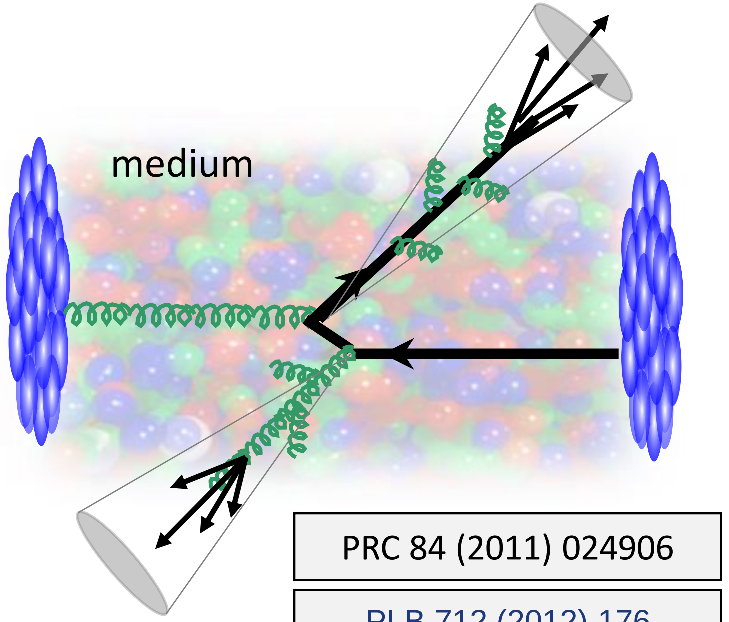
Probe the QGP with High Energy Quarks and Gluons



Proton+Proton



Lead+Lead

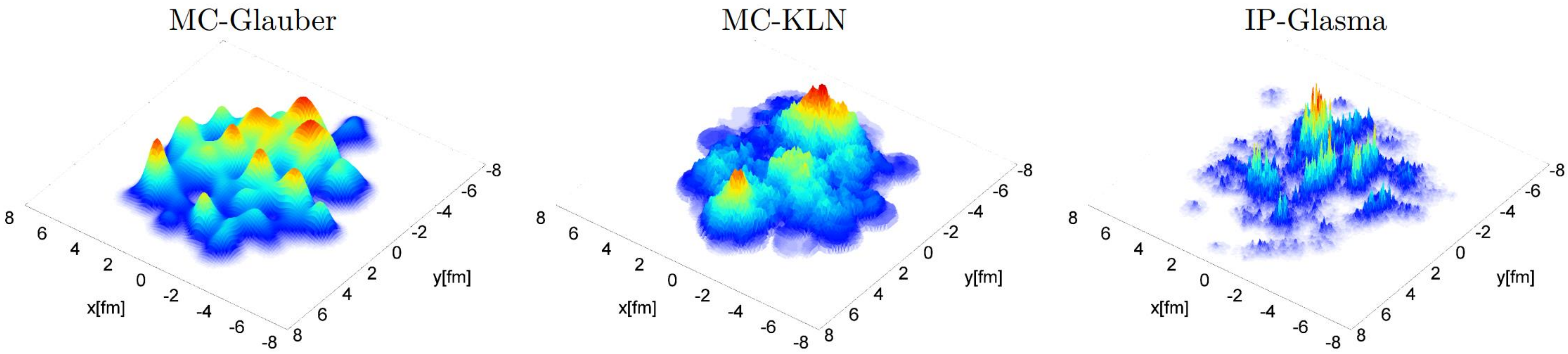


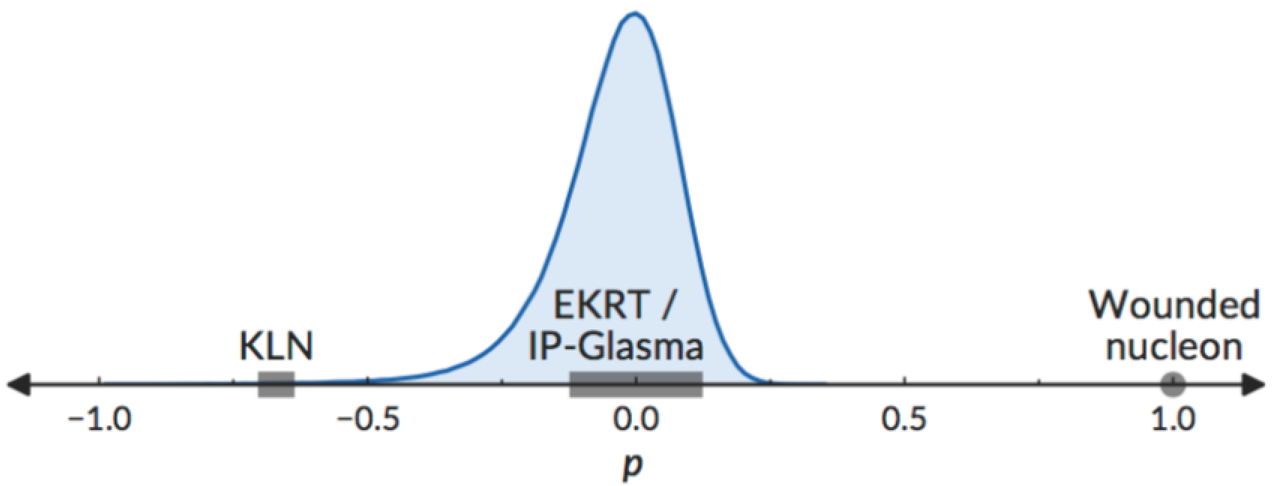
Asymmetric dijets in Lead+Lead collisions!

PRC 84 (2011) 024906

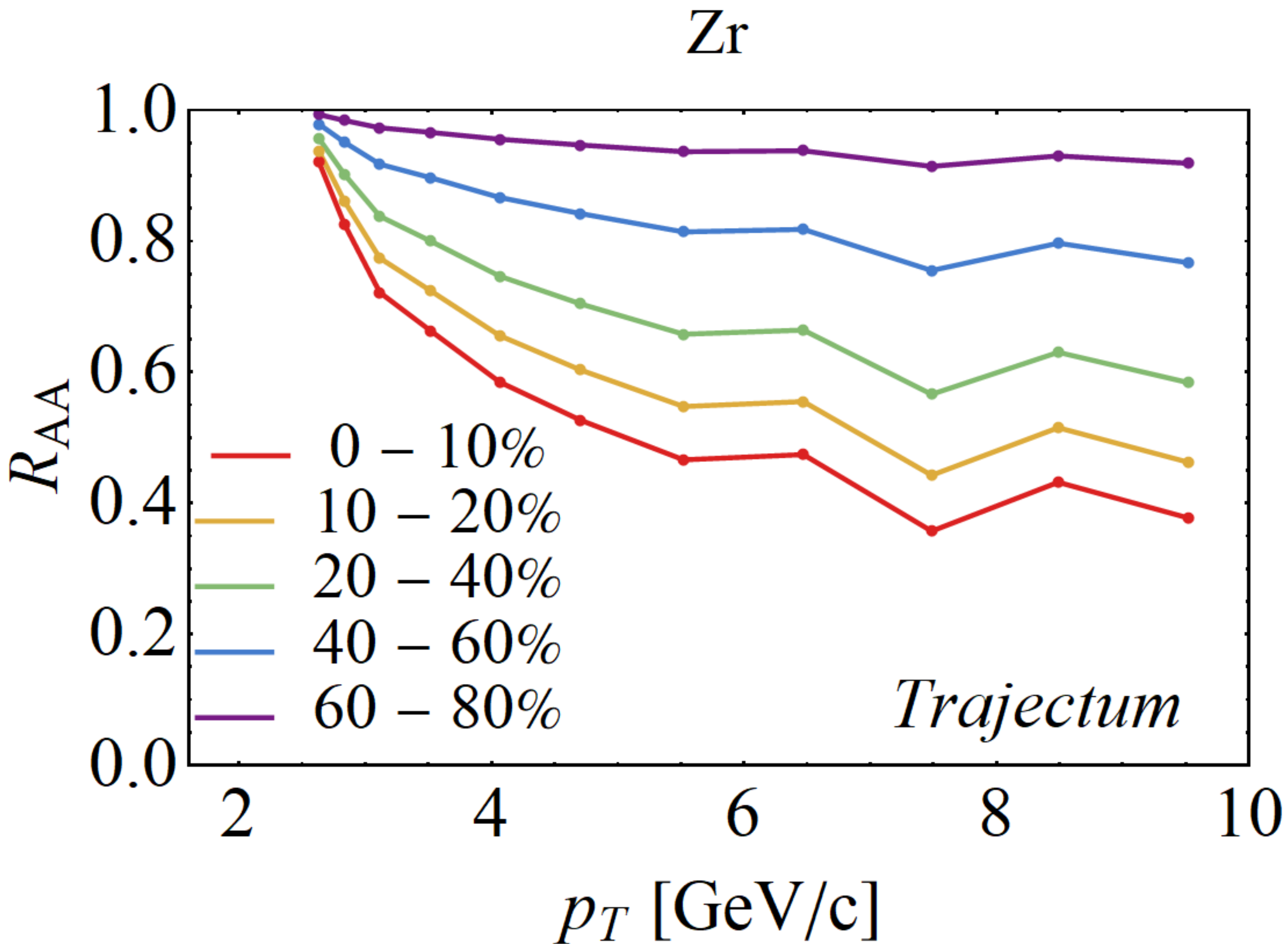
PLB 712 (2012) 176

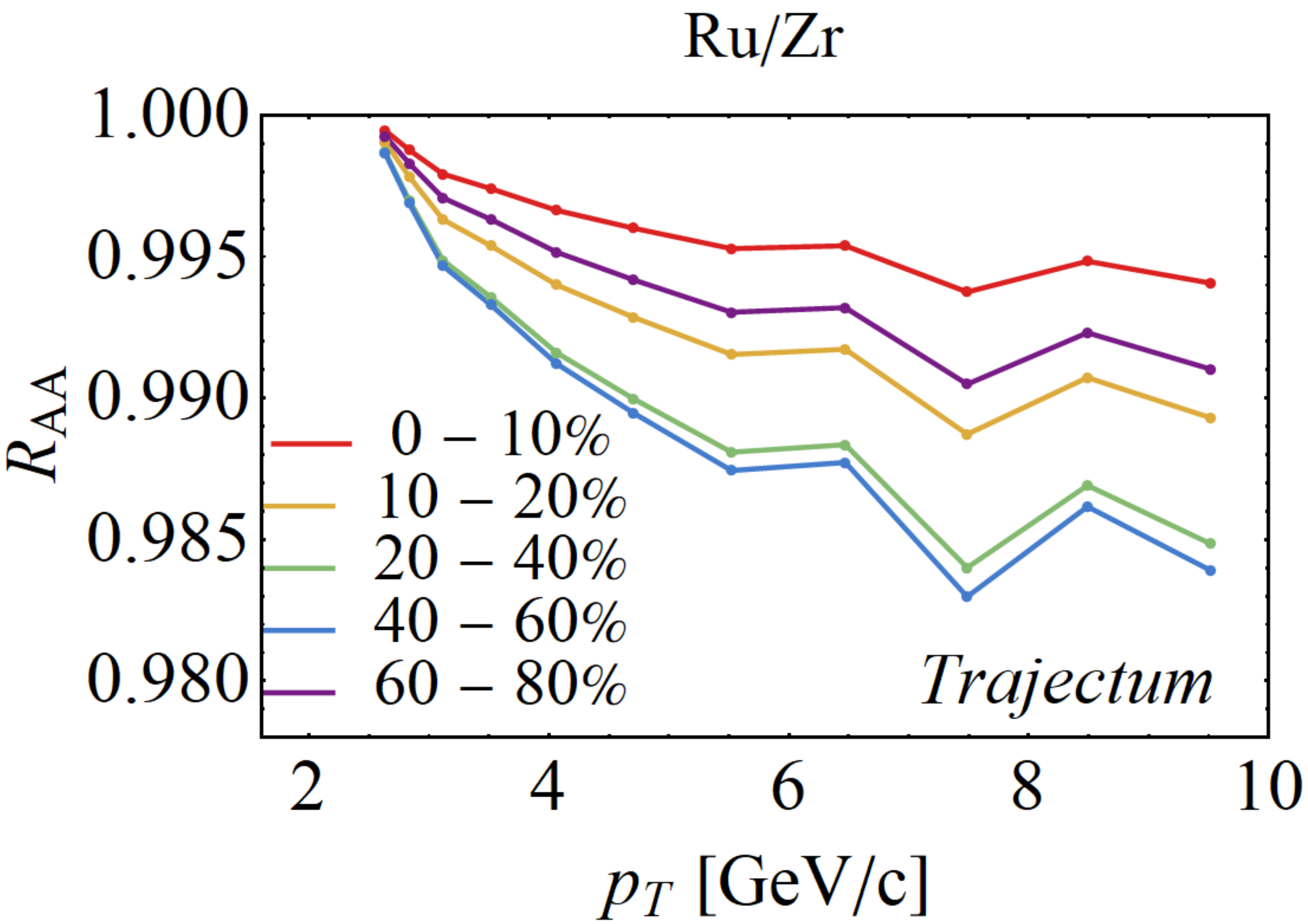
Transverse Energy Density in Different Models

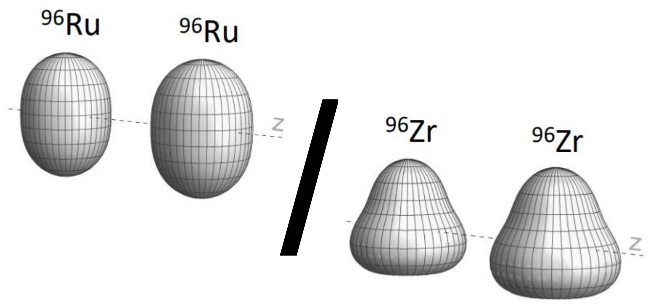




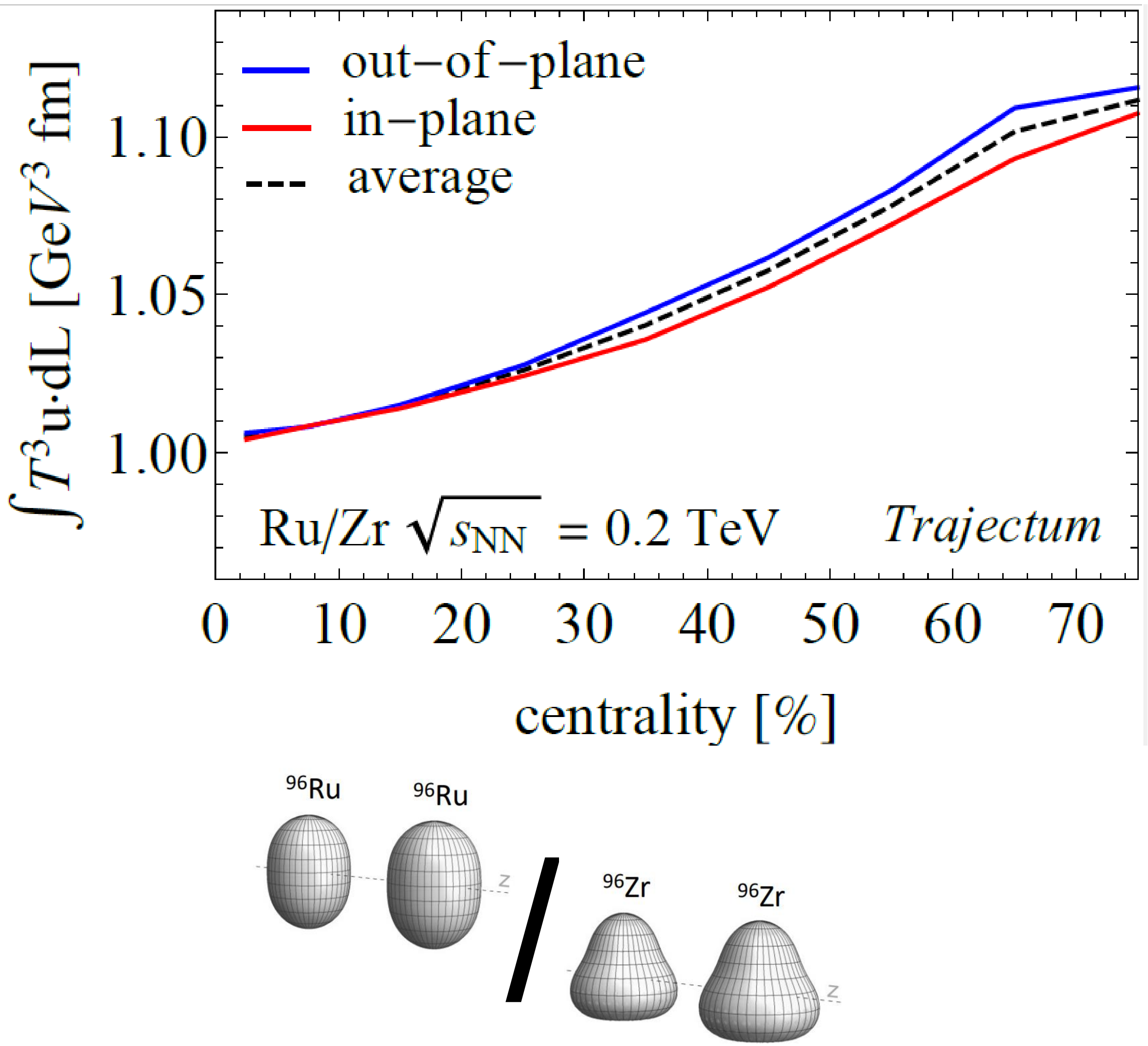
Trajectum: Zr+Zr R_{AA} and Ru/Zr R_{AA} Ratios

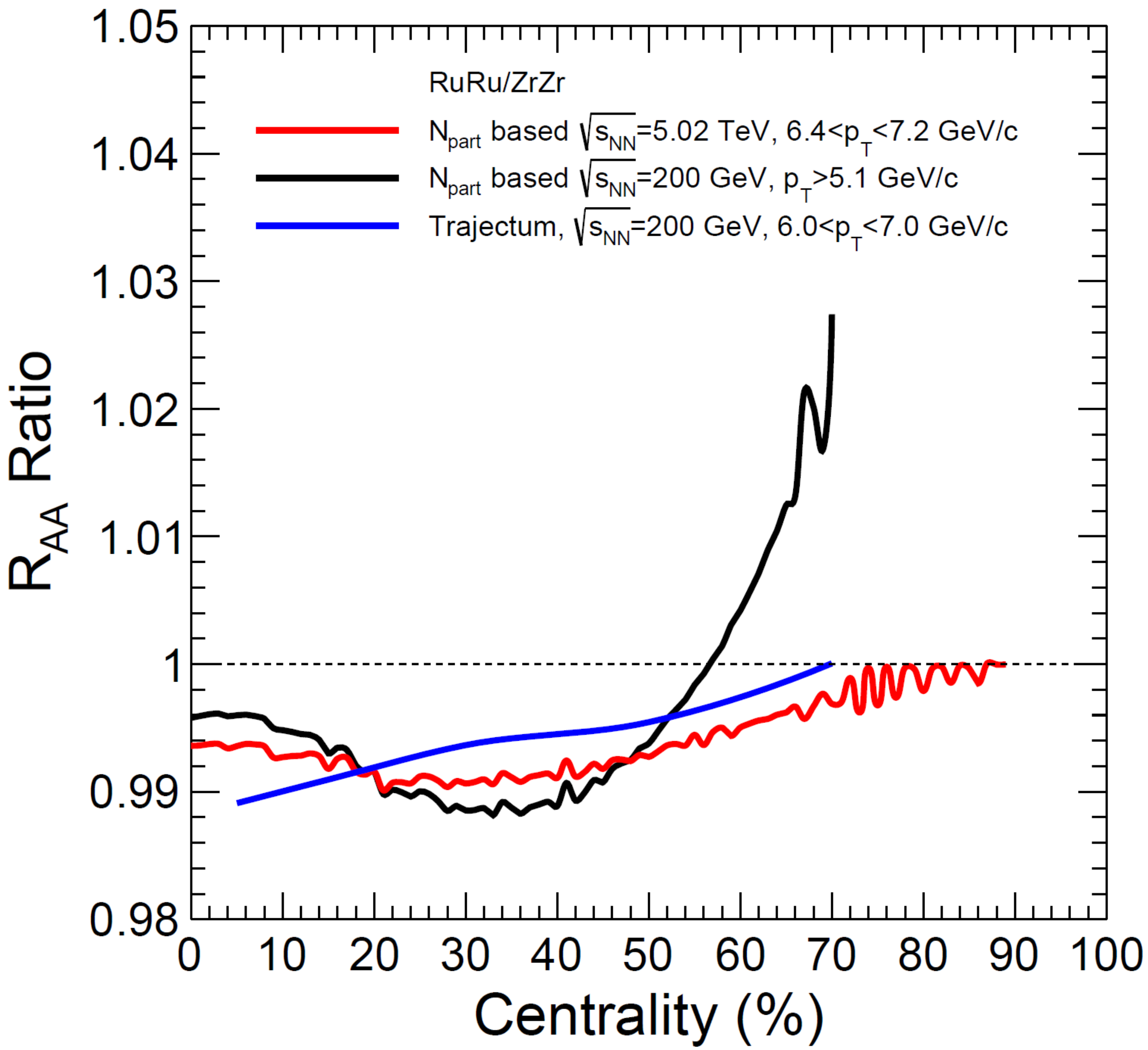






Trajectrum: R_{AA} ratios





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