Pion interferometry with Lévy-stable sources in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at STAR

Partly supported by: ELTE Eötvös Loránd University; Brookhaven National Laboratory; U.S. Department of Energy

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International Symposium on Multiparticle Dynamics, August 21-26, 2023

Introduction to femtoscopy and the appearance of Lévy-type sources

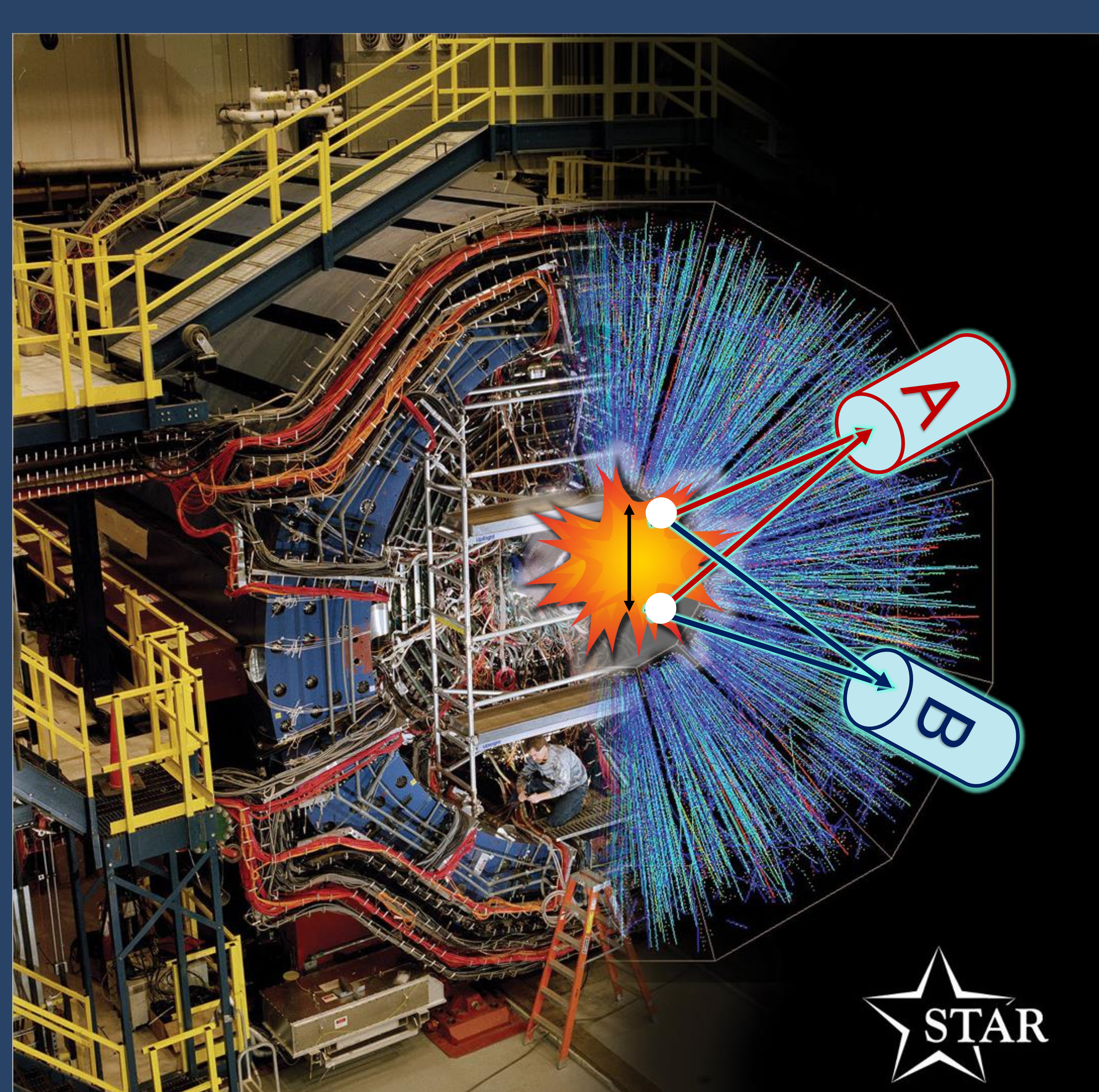
1) Femtoscopy for identical particles

- Pair momentum correlation (relative momentum Q):

$$C_2(Q) = \int D(r)\left|\psi_Q(r)\right|^2 dr$$

- Pair source function (pair separation r, avgerage mom. K):

$$D(r,K) = \int d^4\rho S\left(\rho + \frac{r}{2}, K\right) S\left(\rho - \frac{r}{2}, K\right)$$



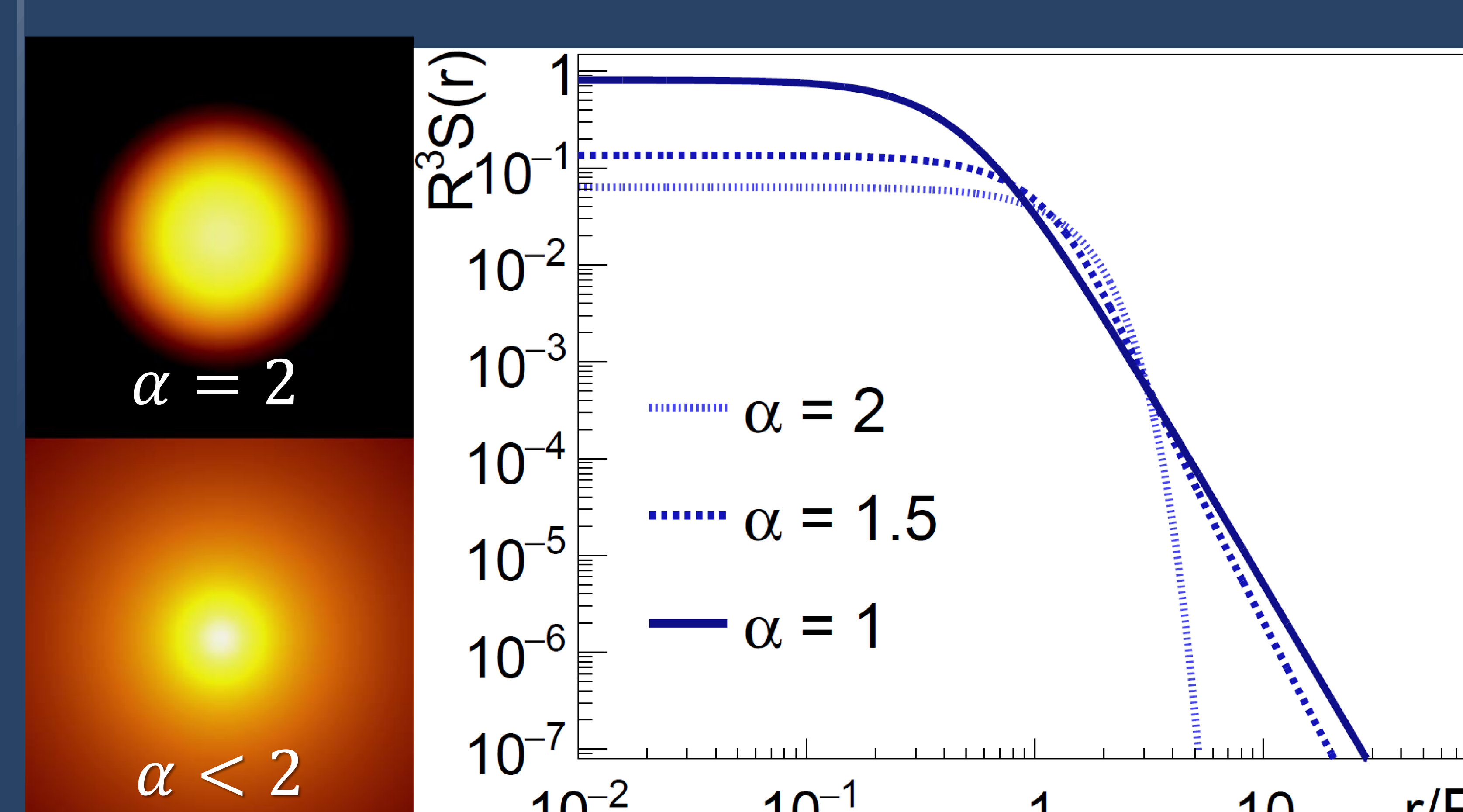
2) Lévy-type source functions

- Appearance of such sources [1-6]: anom. diff., crit. behavior, jets, decays

$$\mathcal{L}(\alpha, R; \boldsymbol{r}) = \frac{1}{(2\pi)^3}\int d^3\boldsymbol{q} e^{i\boldsymbol{q}\boldsymbol{r}} e^{-\frac{1}{2}|\boldsymbol{q}R\boldsymbol{q}|^{\alpha/2}}$$

$$S(r) = \mathcal{L}(\alpha, R; r)$$
$$\Downarrow$$
$$D(r) = \mathcal{L}\left(\alpha, 2^{1/\alpha}R; r\right)$$

- Lévy exponent: $\alpha = 2$ Gaussian, $\alpha < 2$ power-law
- Lévy-scale parameter R: connection to geometry



3) Final-State Interactions (FSI)

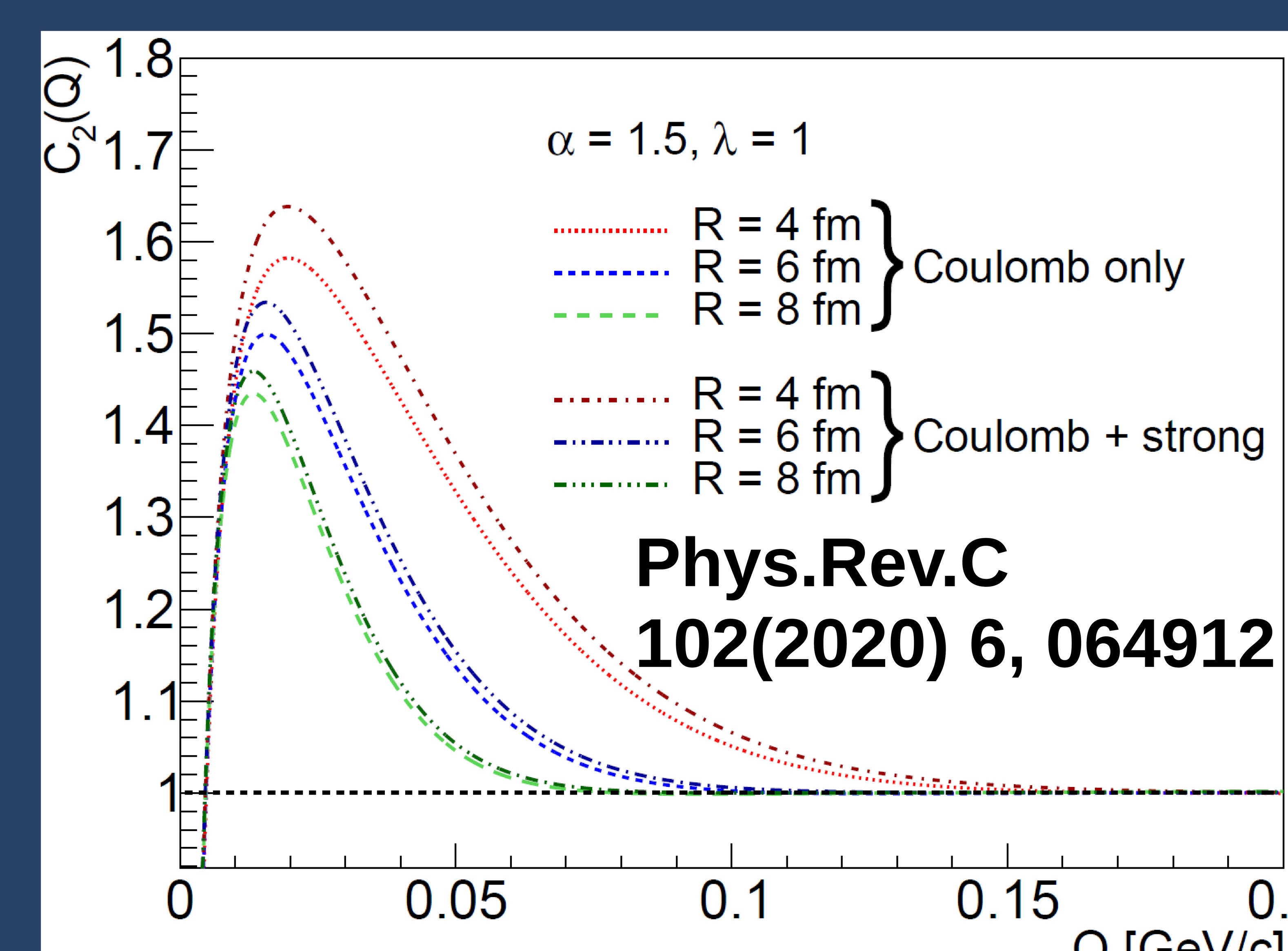
- Correlation function (w/o FSI, w strength param. λ):

$$C_0(Q) = 1 + \lambda \cdot e^{-(RQ)^\alpha}$$

- Correlation function with Coulomb correction $\mathcal{K}$ [6]:

$$C_2(Q) = 1 - \lambda + \lambda \cdot \mathcal{K} \cdot \left(1 + e^{-(RQ)^\alpha}\right)$$

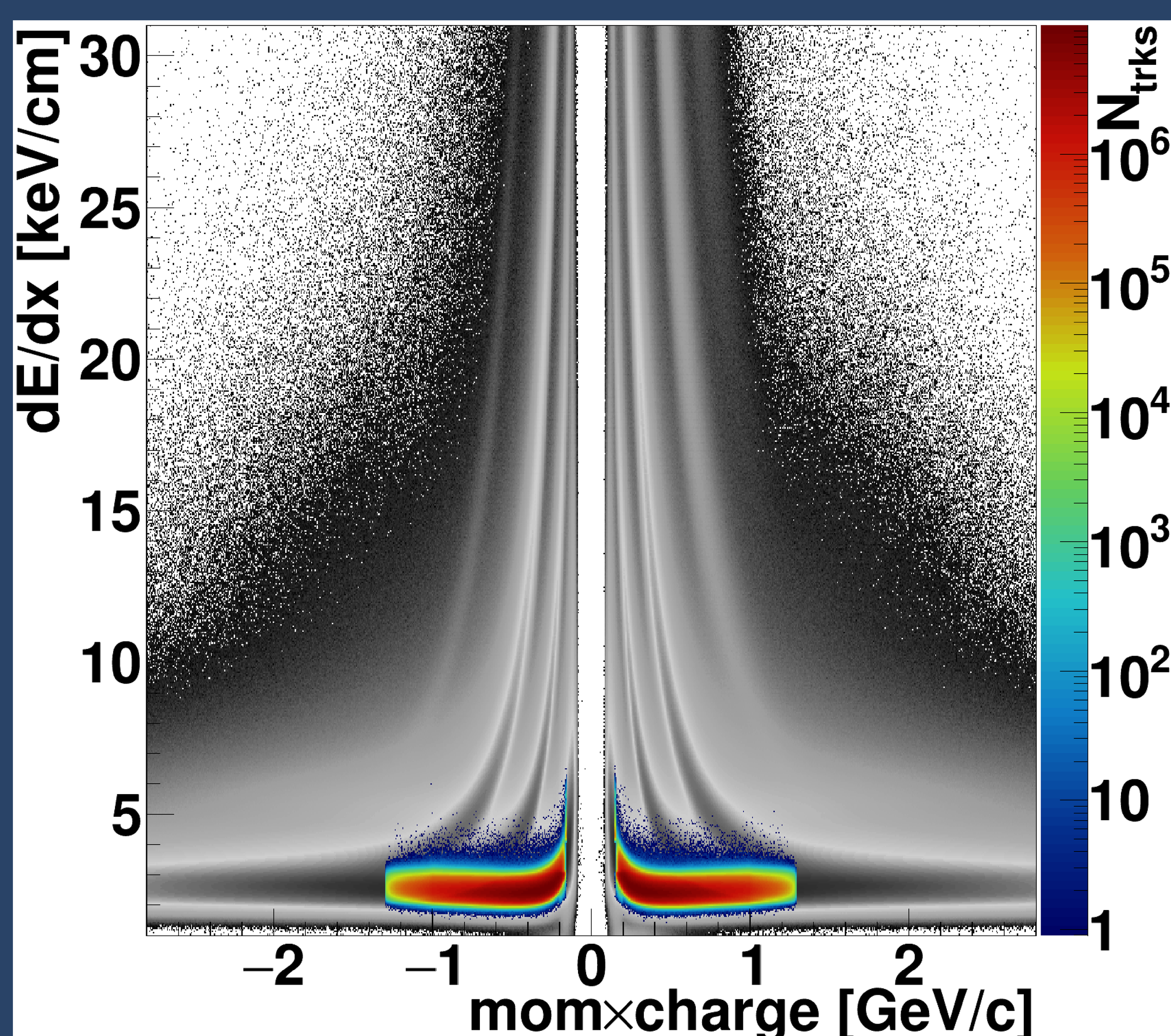
- $\mathcal{K} = \left(\int D(r)\left|\psi_Q(r)\right|^2 dr\right) / \left(1 + e^{-(RQ)^\alpha}\right)$
- Strong interaction - small effect [7]

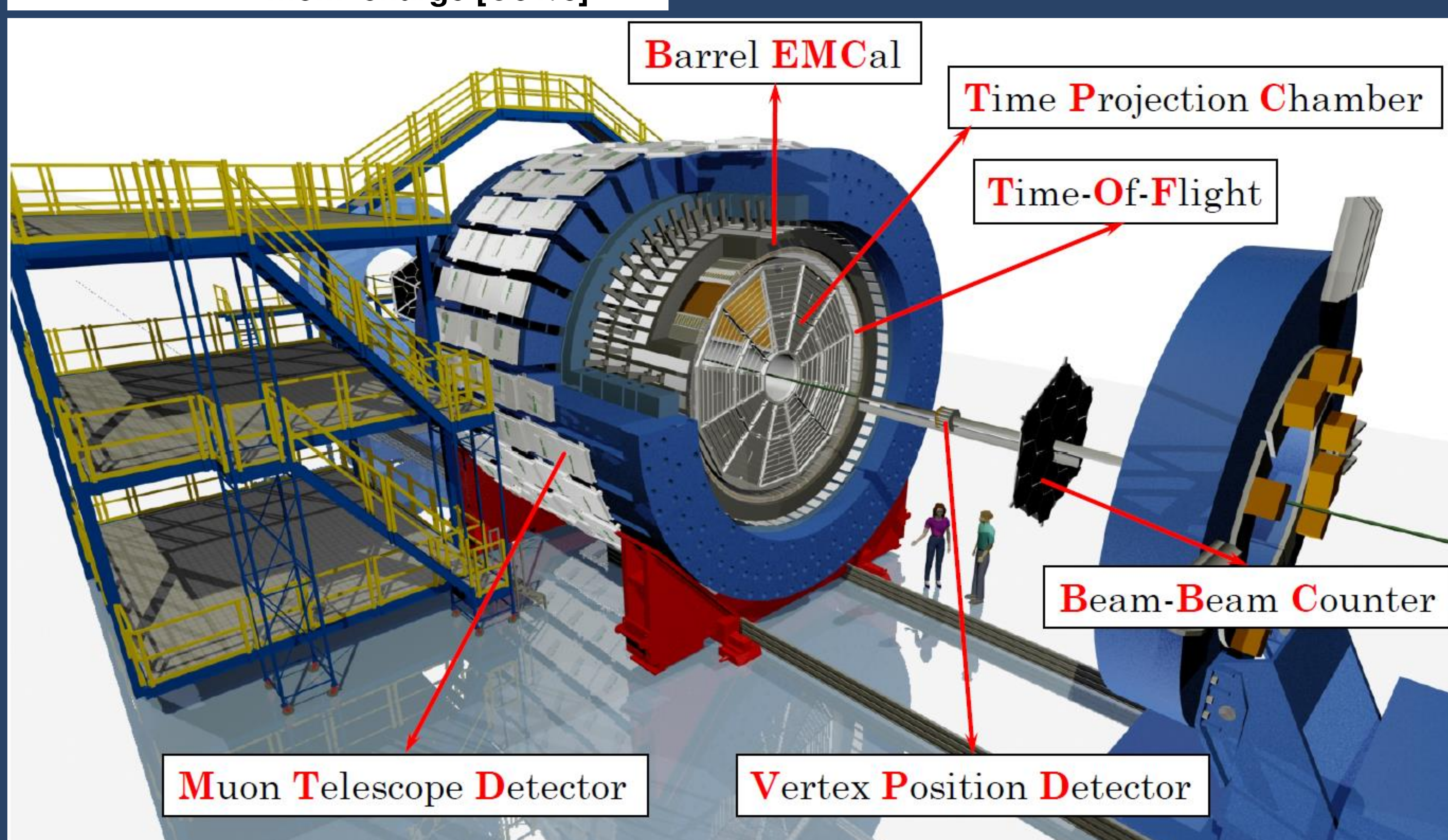


Measurement and fitting of two-pion correlation functions

4) The STAR experimental setup

- Vertex position, centrality: **BBC, VPD, TPC**
- Tracking and momentum reconstruction: **TPC**
- Particle ID: **TPC (dE/dx), TOF**



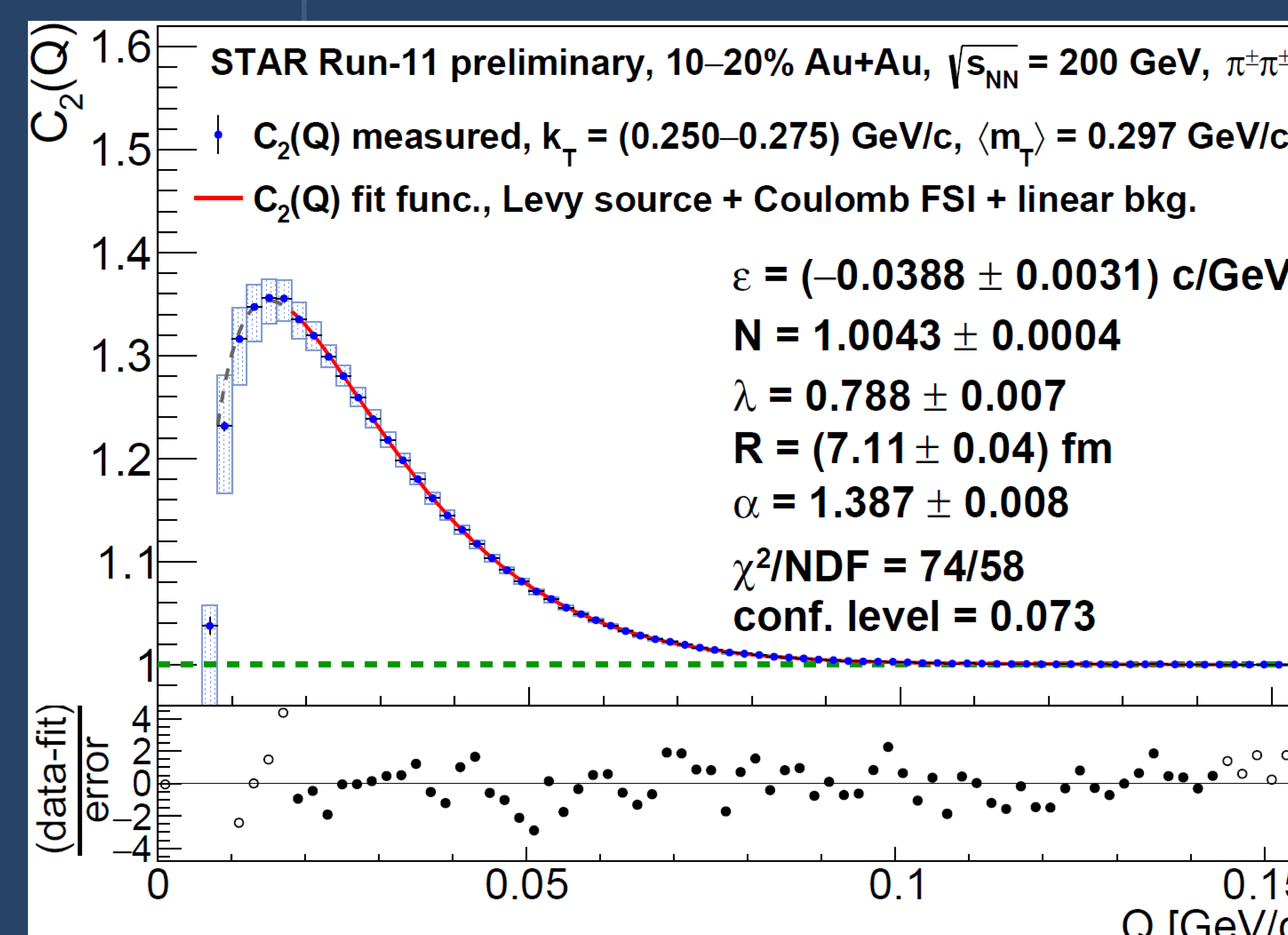


5) Measurement of the corr. func.

- Run-11 Au+Au, $\sqrt{s_{NN}} = 200$ GeV, ~550 M evts.
- Event-mixing: C(Q) = A(Q)/B(Q)
  - A(Q): pairs w members from same evt.
  - B(Q): pairs w members from diff. evt.
- C(Q) measurements:
  - Avg. tr. mom.: $k_T = 0.5\sqrt{K_x^2 + K_y^2}$ 21 bins, (0.175-0.750) GeV/c
  - Centrality: 0-10%,10-20%, 20-30%, 30-40%

6) Example fit to a measured C(Q)

- Iterative fitting method, Coulomb FSI & Lévy source
- Track and pair systematic uncert. illustrated with boxes
- Fit range study included in total systematic uncertainty
- Fits converged with conf.level > 0.001 in all cases



m_T and centrality dependence of the source parameters

7) Correlation strength λ

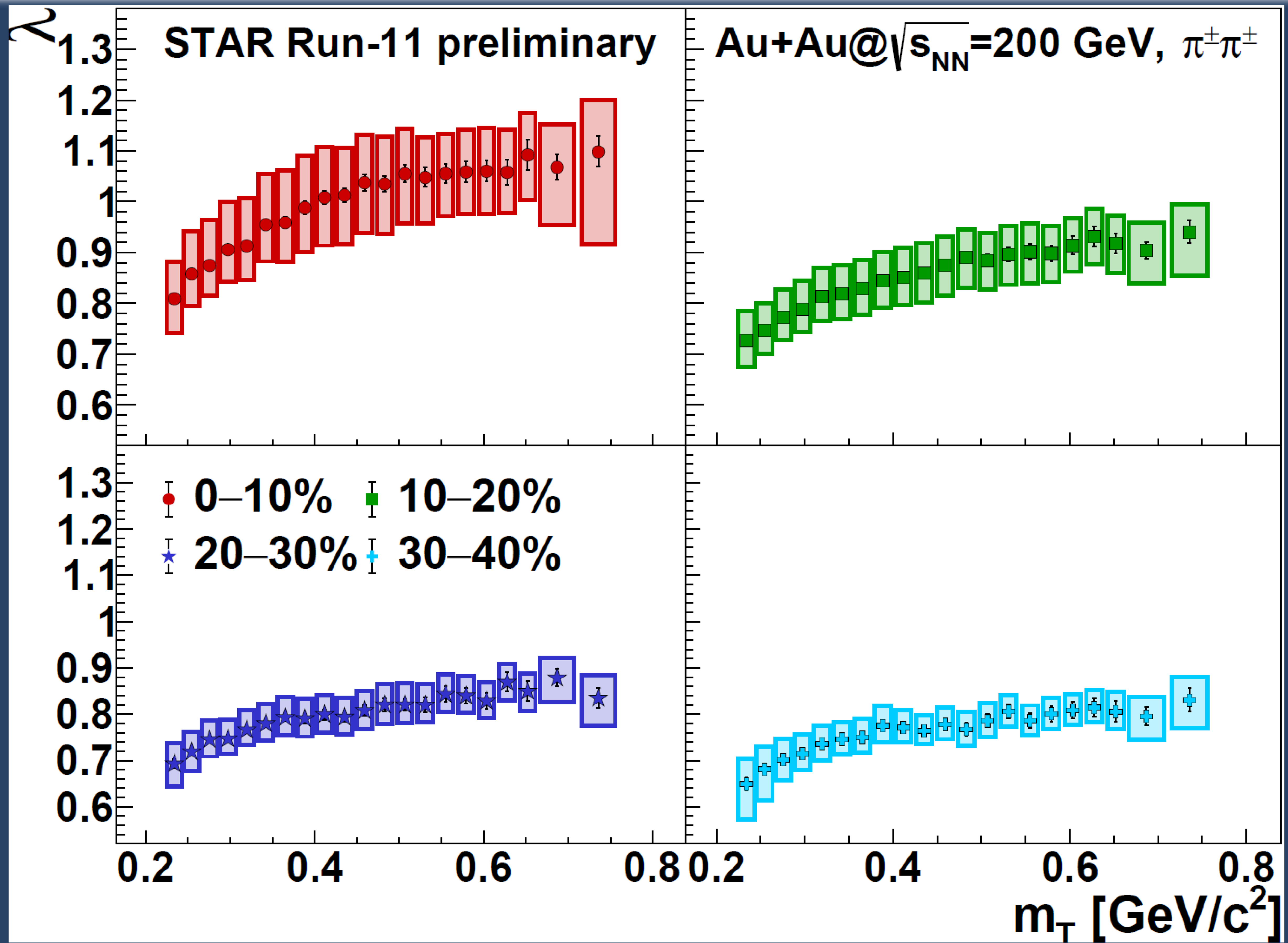
- Increase from low to high $m_T = \sqrt{m_\pi^2 + k_T^2}$
- Decrease from central to peripheral

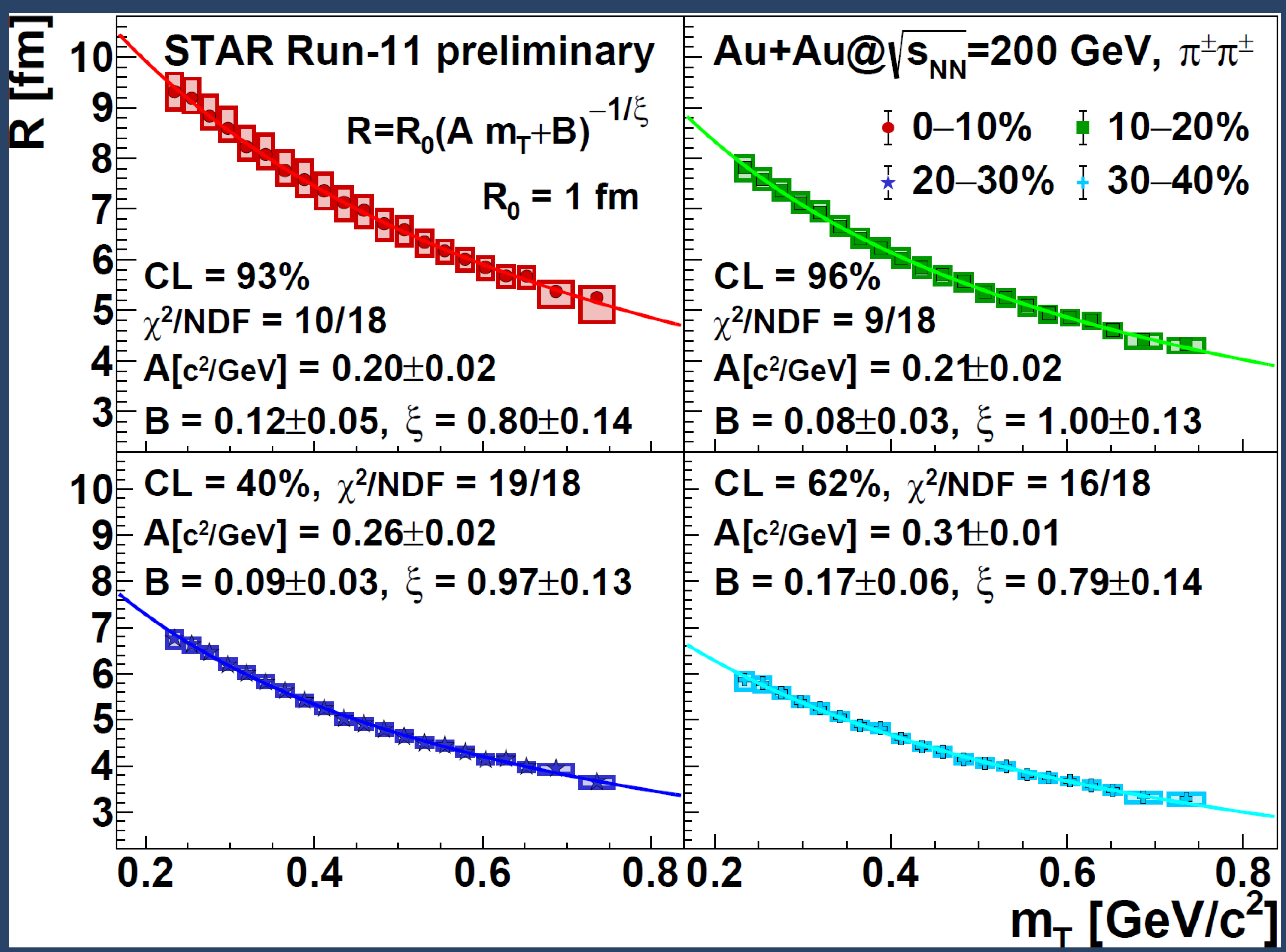
8) Lévy scale R

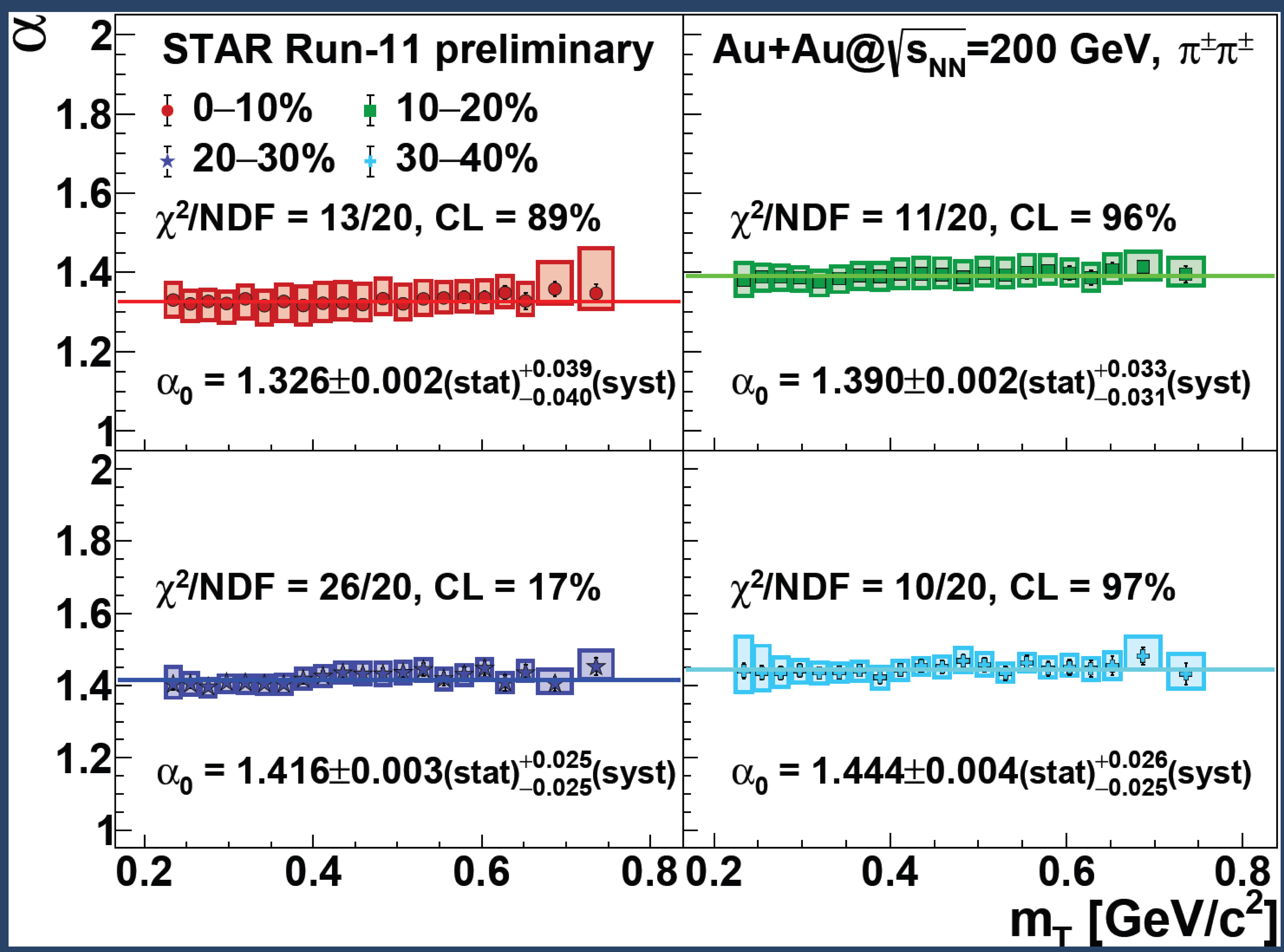
- $R = R_0(Am_T + B)^{-1/\xi}$
  good description for m_T dep.
- Decreases with centrality (connection to geometry)

9) Lévy exponent α

- $\alpha = \alpha_0$ constant fit,
  good description for m_T dep.
- Slight increase from central to peripheral



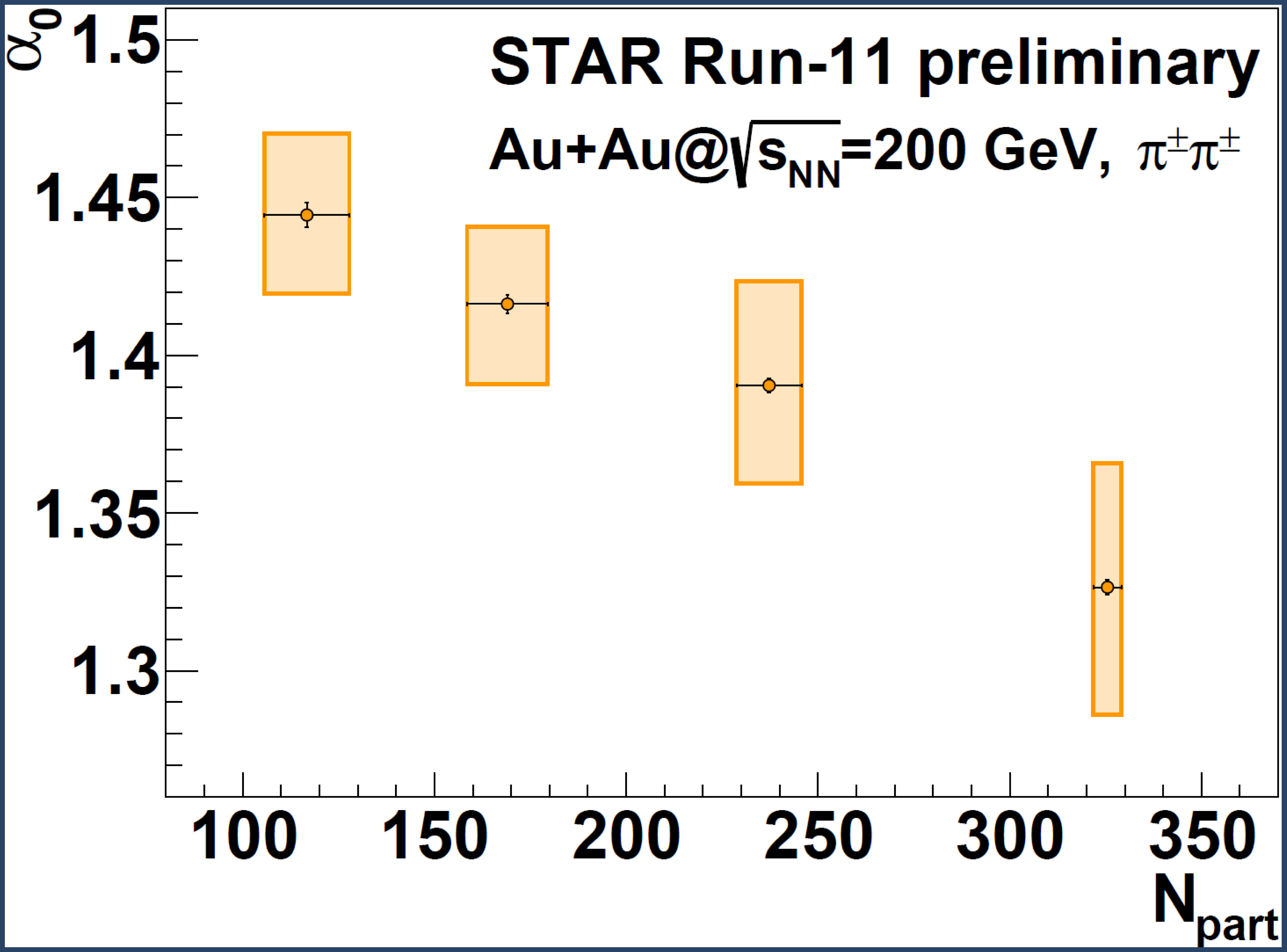




Conclusions

10) Summary, outlook

- Pion pair source described by Lévy distribution
- m_T and centrality dependence investigated
- Lévy-exponent $\alpha \approx 1.3 - 1.5$, not Gaussian ($\alpha \neq 2$)
- α independent of m_T, slightly decreasing with N_{part}
- Next steps:
  similar analysis in 3D,
  similar analysis for kaons,
  similar analysis at lower energies
- **For more discussion, come and check out the poster!**



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[5] Kincses, Stefaniak, Csanád, Entropy 2022, 24(3), 308
[6] Kurgyis, Kincses, Nagy, Csanád, Universe 9(2023) 328
[7] Kincses, Nagy, Csanád, Phys.Rev.C102(2020)6,064912

A game for which a deck of elementary particles can be used:

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INTERACTIONS OF ELEMENTARY PARTICLES

Introduction

- Games that use a deck of cards with elementary particles
- Proposition for a **new game**

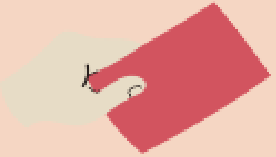
Rules correlate with the elementary particle interactions for each of the four fundamental forces

Players must take turns placing one card of their choice (from the cards they hold in their hands) on the central card, while naming the interaction according to the following rules!

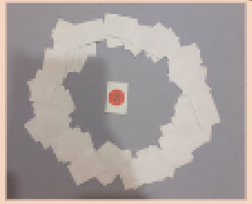
GAME BEGINS

Let's Play!

- The game is intended for **2 to 4 players**
- Firstly, players need to choose **one card**
- That card must represent **a particle**
- The remaining 65 cards should be thoroughly **shuffled** and then placed **in a circle** around the central card facing downwards



EXAMPLE



- Then, each player draws **4 cards** from the circle.
- **After that, the game begins!**

PLACING PARTICLES ON THE CENTRAL CARD

Strong interaction

- Due to the short range of this force, it is assumed that only quarks **within the same baryon** can interact strongly

EXAMPLE

- During this interaction, there is an **exchange of color** between them, while maintaining the overall color neutrality of the baryon.

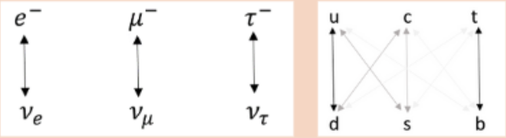
As a result, the following moves are allowed:

*On each quark (u,c, or d) it is possible to put any other quark (u,c or d) provided that they **differ in color**.*

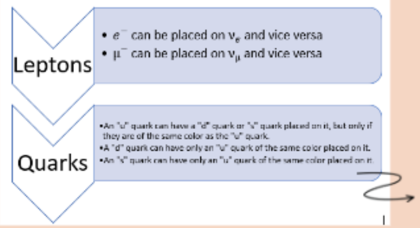
(The fact that quarks placed on the given quark must be different color reflects color exchange in a baryon!)

Weak interaction

- Particles that can interact:



- As a result, the following moves are allowed:



(The fact that quarks must be the **same color** reflects the observation that the weak force can change the flavor but not the color of the quark!)

Electromagnetic interaction

- The fundamental property of this force is that only two **electrically charged** particles can interact with it.
- As a result, the following moves are allowed:

*Any electrically charged particle (u, s, or d quark of any color, electron or muon) can be placed on **any other** electrically charged particle!*

Gravitational interaction

- Through this interaction, all massive particles can interact with each other.
- However, this interaction between elementary particles is **extremely weak** (due to their small masses)

*__Only once__ during the game (but not when the player has only one card left, and all the cards from the central circle have been taken), the player can take advantage of the opportunity for "gravitational interaction" and place **any particle card** on the central one.*

- This situation can be **very intriguing** as it may change the course of the game and give a **significant advantage** to the player who utilizes it at the right moment.

REMEMBER

Rules correlate with the elementary particle interactions for each of the four fundamental forces

PLACING ANTIPARTICLES ON THE CENTRAL CARD

*Cards representing antiparticles can be placed on the central card only if they truly represent the **antiparticle** of the central card!*

- In that situation, the player must say **"Annihilation"**!
- By doing that, the player can (in the same move) place **any other** card on the table
- That intentionally changes the course of the game

useful & strategic move

ADDITIONAL RULES AND GAME ENDING

- In order to make the game even more **interesting** and **dynamic**, additional rules have been designed.
- This way, players can gain an **extra advantage**, but also deepen their knowledge of interactions of elementary particles, and even learn about **neutrino oscillations**!

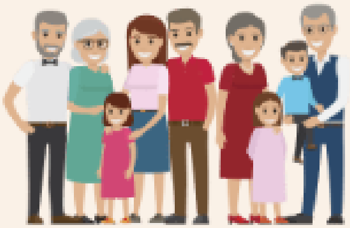
SCAN ME

- *Game is over when all cards from the central pile have been taken, and one of the players has **run out of all cards** representing particles*
- *That player is **the winner**, and the other players are ranked according to the number of cards representing particles they have left*

Conclusion

For whom is the game intended?

SCAN ME



What to do after playing?

Questions and topics for further discussions and learning

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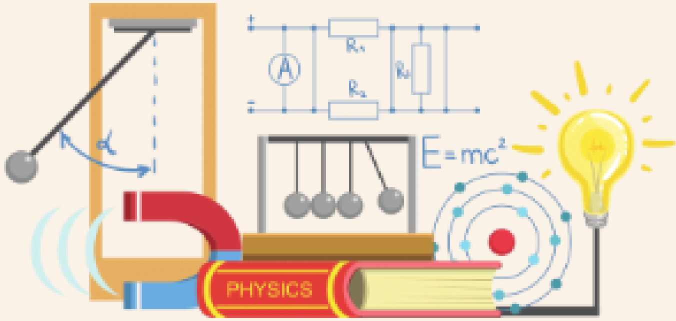

A game for which a deck of elementary particles can be used:

THE EIGHTFOLD PATH

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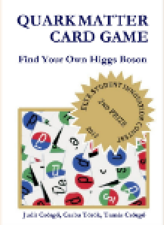
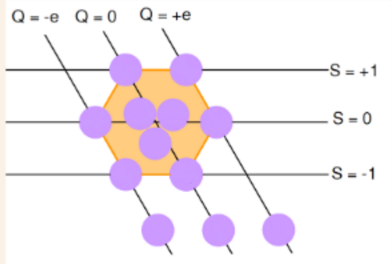
Introduction

- Games that use a deck of cards with elementary particles



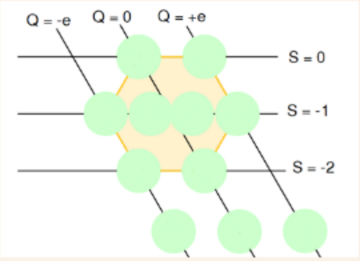
- Proposition for a new game which utilises the concept of **The eightfold path**

This is a board (card) game!



First board - Meson hexagon

- For the three mesons located in the center of the hexagon, their properties of total strangeness (S) and total electric charge (Q) are such as if they were at the very center of the hexagon, where S = 0 and Q=0.



Second board - Baryon hexagon

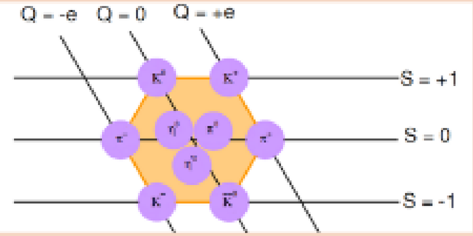
- For the two baryons located in the center of the hexagon, their properties of S and Q are such as if they were at the very center of the hexagon, where S = -1 and Q = 0

- Boards correspond to the baryon and meson hexagons according to the eightfold path with **three additional circles** at the bottom.

What is the eightfold path in physics?

- **Property of symmetry** in the representation of baryons and mesons
- It was independently observed by **Murray Gell-Mann** and **Yu'val Ne'eman** in 1961**
- Such grouping often results in **sets of eight** (or more) hadrons

EXAMPLE



Hadrons can be represented in suitable symmetric groups according to their charge (Q) and strangeness (S) properties

LEARN MORE

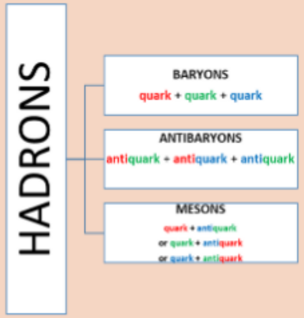
SCAN ME

RULES AND COURSE OF THE GAME

What is the main goal?

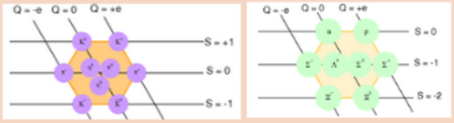
To fill the designated circles in hexagons with the corresponding cards, so that within each circle, the total strangeness (S) and electrical charge (Q) are equal to the markings

- Players are arranging hadrons
- The 3 lower circles (located outside the hexagon) must be filled with 4 lepton/anti-lepton cards so that the total Q and S also correspond to the markings



Level 1 : Beginner ★★★☆☆

- Names of baryons and mesons can be written on the boards



- Players can use following tables:

Level 2: Intermediate ★★★★★

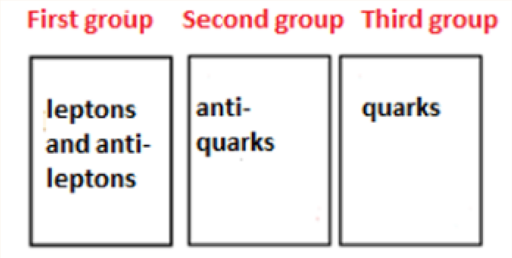
- Players do not have pre-written hadrons on the board
- Instead, they must place them on the board themselves based on their Q and S.
- It is impornant to be fast and skilled at recognizing potential opportunities to assemble the appropriate hadron that is left unfilled on the board.

Players need to be familiar with the individual S and Q of each elementary particle in the deck, as the total strangeness and electric charge of each hadron (or group of leptons) is equal to the sum of S and Q of all individual particles that make it up.

RULES AND COURSE OF THE GAME

Rules and course of the game

- The game is intended for **2 to 4 players**
- At the beginning, it is necessary to divide the cards from the deck into **three piles**
- Then, each player must take **two cards** from each pile
- Players hold their cards in their hands so that only they can see them.
- After that, the first part of the game begins!



The cards are shuffled and arranged according to the type of elementary particles, but they are faced down, so the players **cannot** see them

Part 1 - Assembling leptons, antileptons and mesons

- The game is played **in rounds** (for example, in clockwise order)
- In each round, each player has **two possible choices**:
  - To discard one of their own cards and draw a new card from one of the piles
  - OR
  - To place cards (correctly) in an empty circle within the hexagon!
- For a correctly filled circle, **1 point** is awarded...and there are also penalties!

Detailed explanations of the rules for the first part of the game can be found here

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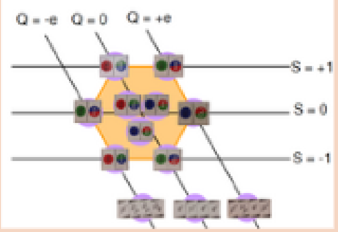
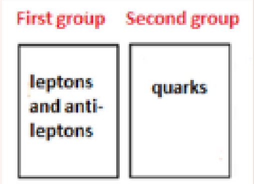


EXAMPLE

Correctly filled board at the end

Part 2- Assembling leptons, antileptons and baryons

- After the first part is finished, players must **return** all the cards and make **two piles:**

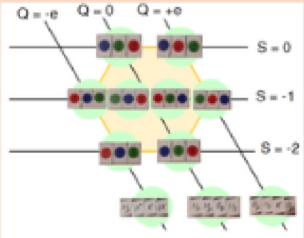


The cards are shuffled and arranged according to the type of elementary particles, face down. However, in this part of the game, the pile with antiquarks is **not** used

- Rules, choices and scoring are **very similar** to the first part of the game!

Detailed explanations of the rules for the second part of the game can be found here

SCAN ME



EXAMPLE

Correctly filled board at the end

Conclusion

For whom is the game intended, and what can we learn from it?

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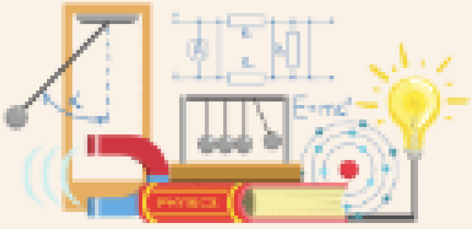


- Various ideas and concepts of particle physics (which may seem very **complicated** at first), can be brought closer to players of different ages and backgrounds through **fun** and **social interactions**

- In addition to existing games, there is a particularly interesting and significant possibility of creating **new** and **diverse** games centered around the existing deck of cards
- As a result, these games can continue to be developed **in parallel with new physical discoveries** and theories

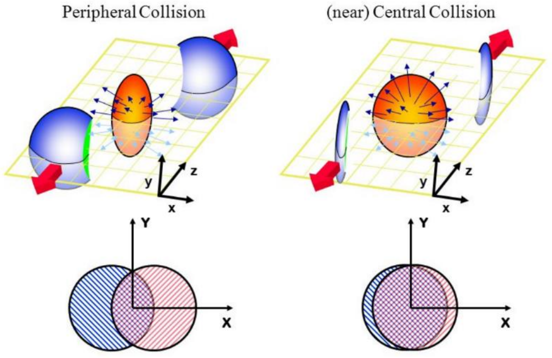
Estimating elliptic flow coefficient in heavy-ion collisions using deep learning

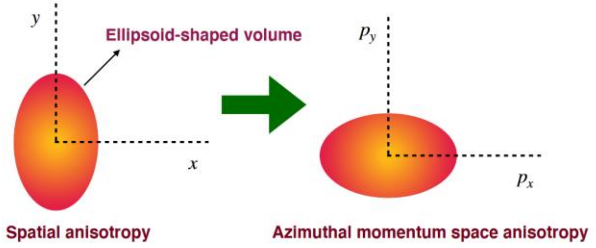
N. Mallick*, S. Prasad, A. N. Mishra, R. Sahoo, and G. G. Barnaföldi

52nd International Symposium on Multiparticle Dynamics
21-26 Aug, 2023
Károly Róbert Campus of MATE in Gyöngyös, Hungary

1. Introduction

- Transverse collective flow is a crucial observable in studying the properties of quark-gluon plasma (QGP)
- Collective flow is anisotropic and depends on the equation of state and transport coefficients of the system
- Hydrodynamic response to the initial eccentricity of the system
- Anisotropic flow appears to be developed in the early partonic phase, evolves through relativistic hydrodynamics, and later gets influenced by hadronic rescatterings
- **First deep learning-based estimator for elliptic flow (v_2)**
- Machine learning model to learn from multiparticle production dynamics and its correlation to estimate any physical observable of interest





$$E\frac{d^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

$$v_n(p_T, y) = \langle \cos(n(\phi - \psi_n)) \rangle$$

1. N. Mallick, S. Prasad, A. N. Mishra, R. Sahoo, and G. G. Barnaföldi, Phys.Rev.D 105, 114022 (2022).
2. N. Mallick, S. Prasad, A. N. Mishra, R. Sahoo, and G. G. Barnaföldi, Phys.Rev.D 107, 094001 (2023).

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2. Deep learning estimator

A multiphase transport model (AMPT)

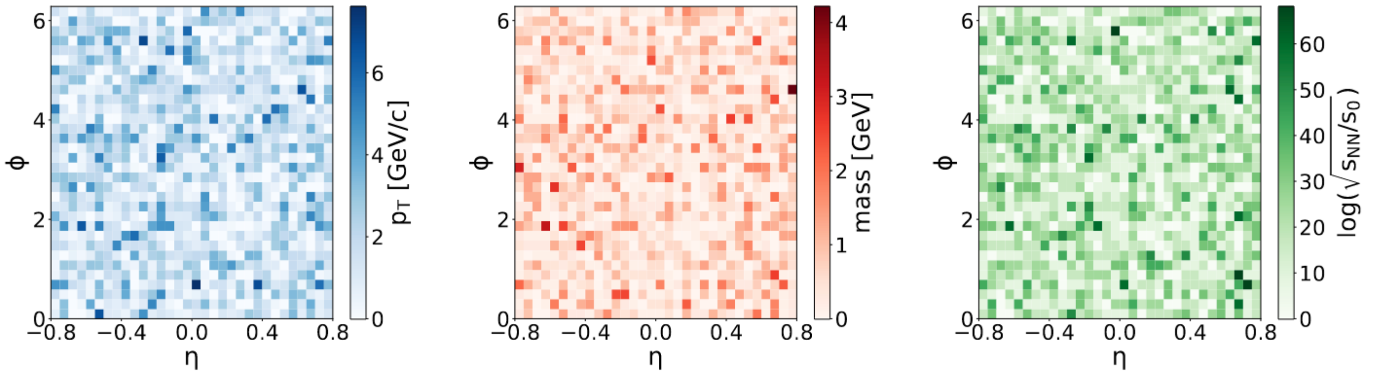
1. Initialization: Glauber MC with HIJING
2. Parton Cascade: Zhang's Parton Cascade
3. Hadronization: Quark Coalescence Model
4. Hadron Cascade: A Relativistic Transport Model

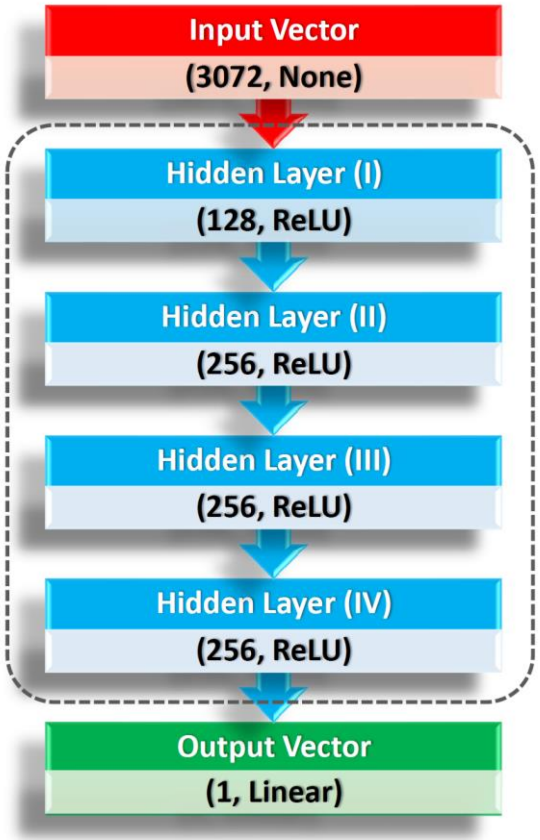
Input, output, and training

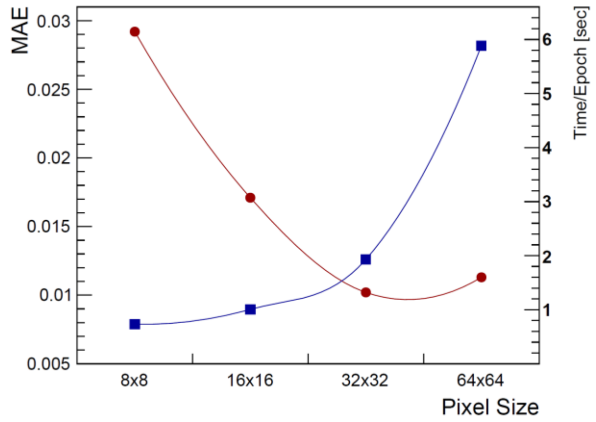
- Particle freezeout surface to elliptic flow mapping
- $(\eta - \phi)$ space as the primary input space
- p_T, mass, and $\log \sqrt{s_{NN}/s_0}$ weighted layers serve as the secondary input space
- Model trained on Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV (Minimum Bias)
- Feature size = $32 \times 32 \times 3 = 3072$ per event
- Increasing sparsity and model parameters with pixel size
- Optimzer: *adam* , Loss function: *mse*
- Max epoch: 100

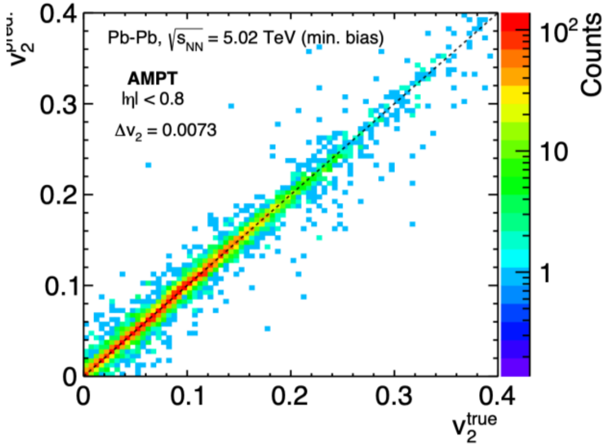
  Batch Size: 32, callback = *early_stopping*
- Training: 2×10^5 events (~60 GB)
- Validation: 10% Events

Pb-Pb collisions, $\sqrt{s_{NN}} = 5.02$ TeV, AMPT simulation



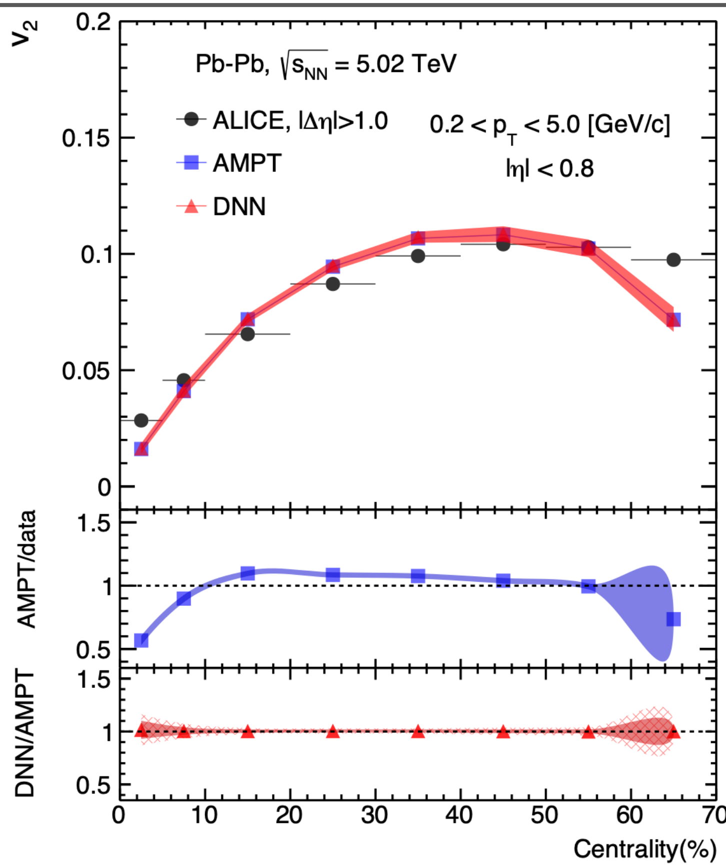


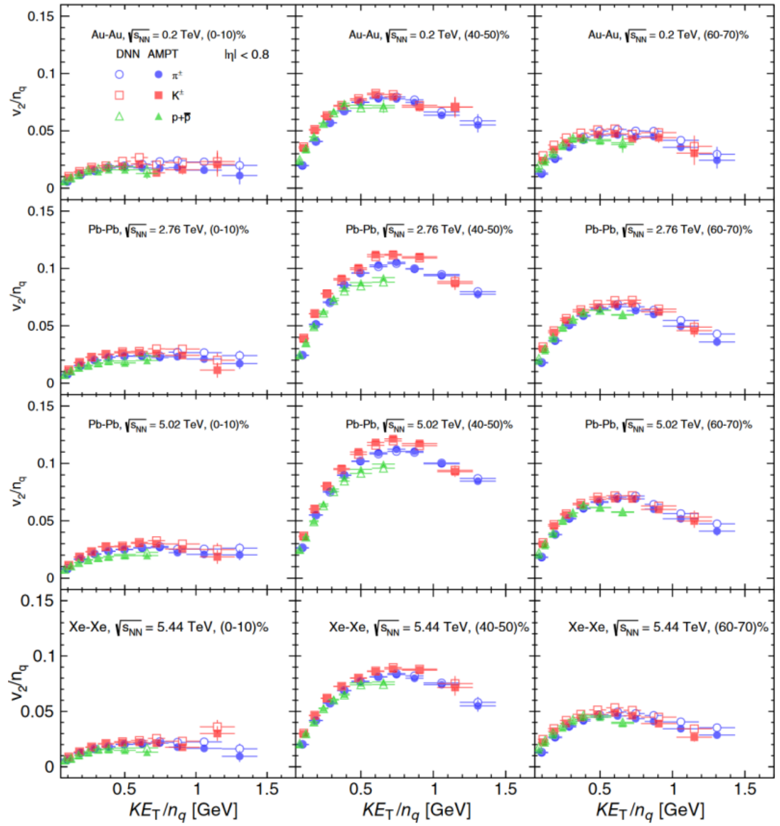




3. Results

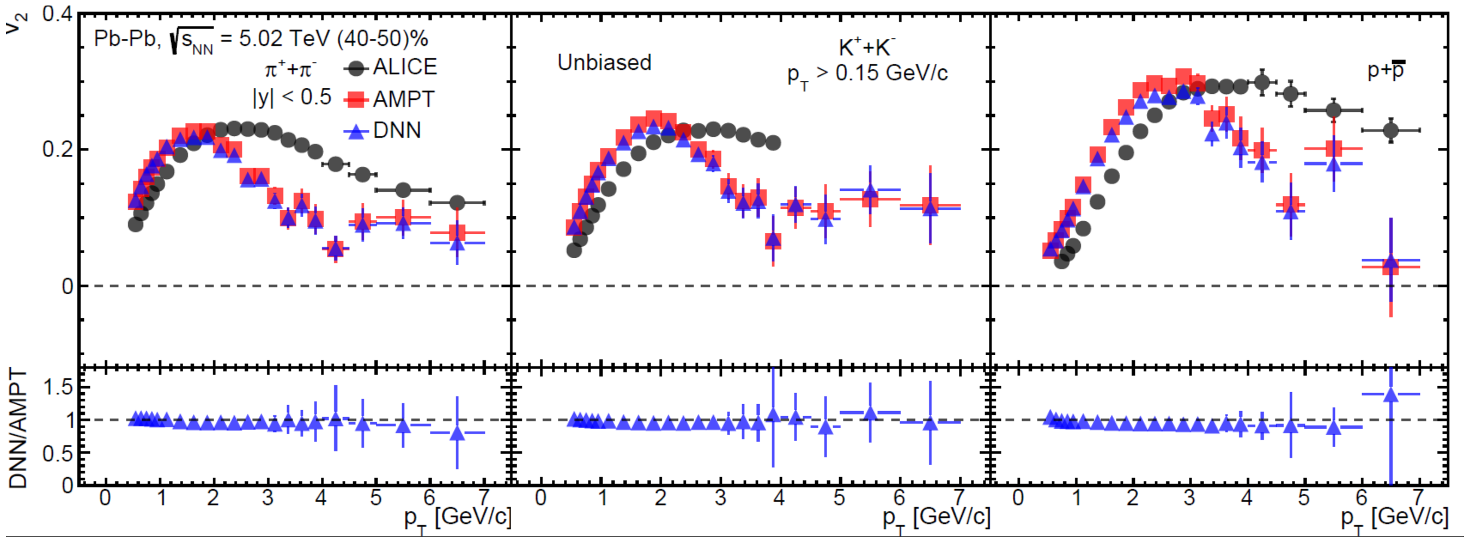
- Predictions are obtained for the collision centrality, energy, system size, particle mass, particle species, and transverse momentum dependence of elliptic flow
- The number-of-constituent-quark scaling behavior across different collision systems at different energies is also predicted by the DNN
- AMPT explains the data to a reasonable extent from low-p_T to intermediate-p_T but deviates for high-p_T





Summary

- DNN preserves the centrality, p_T, energy, and meson-baryon dependent behavior of elliptic flow
- Applicable to RHIC and LHC energies
- Faster and more efficient prediction as compared to the conventional methods



The Future of Quantum Supercomputing and Space

What is the future of Quantum Supercomputing and Space?

Mr Cameron Ikin

Capricorne Spacial Agence

ISMD 2023

Capricorne Spatial Agence
The New Space Age

Quantum Supercomputers and Multiparticle Dynamics.

- <u>How might Quantum Supercomputers involve Multiparticle Dynamics?</u>
- Multiparticle Dynamics, is a form of study which is most definitely involved in the Space Industry.
- Since this involvement will couple with an inevitable increase in demand of computer calculation capability, it is very likely that Quantum Supercomputers and Multiparticle Dynamics will have a close relationship.
- Quantum Supercomputers could conduct the calculations required for Multiparticle Dynamics with much more efficiency and accuracy capability.
- This will enhance this form of study and ensure any work done in the Space Industry, will be more efficient and with greater accuracy.

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he New Space Age

Quantum Supercomputers and the New Space Age.

- How can Quantum Supercomputers influence the New Space Age?
- An increased interest, investment and production, has transformed the older space industry, into a 'New Space Age.'
- This New Space Age, will require increased calculation capabilities into the future.
- The Quantum Supercomputer can achieve this high calculation standard.
- Many Quantum Supercomputers can achieve significantly advanced calculation capabilities.
- Systems, like the Capricorn Model 1, can be engineered to be deployed in space itself.

The Likely Role of Quantum Supercomputers within Space.

- Explore, Evaluate and Nominate the likely role of Quantum Supercomputers and Space.
- Since we now know that requirement for more advanced calculations in the New Space Age, has been mandated.
- We can now determine the specific role of Quantum Supercomputers and Space.
- The New Space Age will greatly benefit from the deployment of Quantum Supercomputers, such as the Capricorn Model 1, into space itself.
- Space-based systems could conduct tasks such as; monitoring/controlling space traffic, assisting with updates/repairs on space equipment, managing data traffic flow amongst space systems, independent self location/movement decisions and linking in with future space systems.

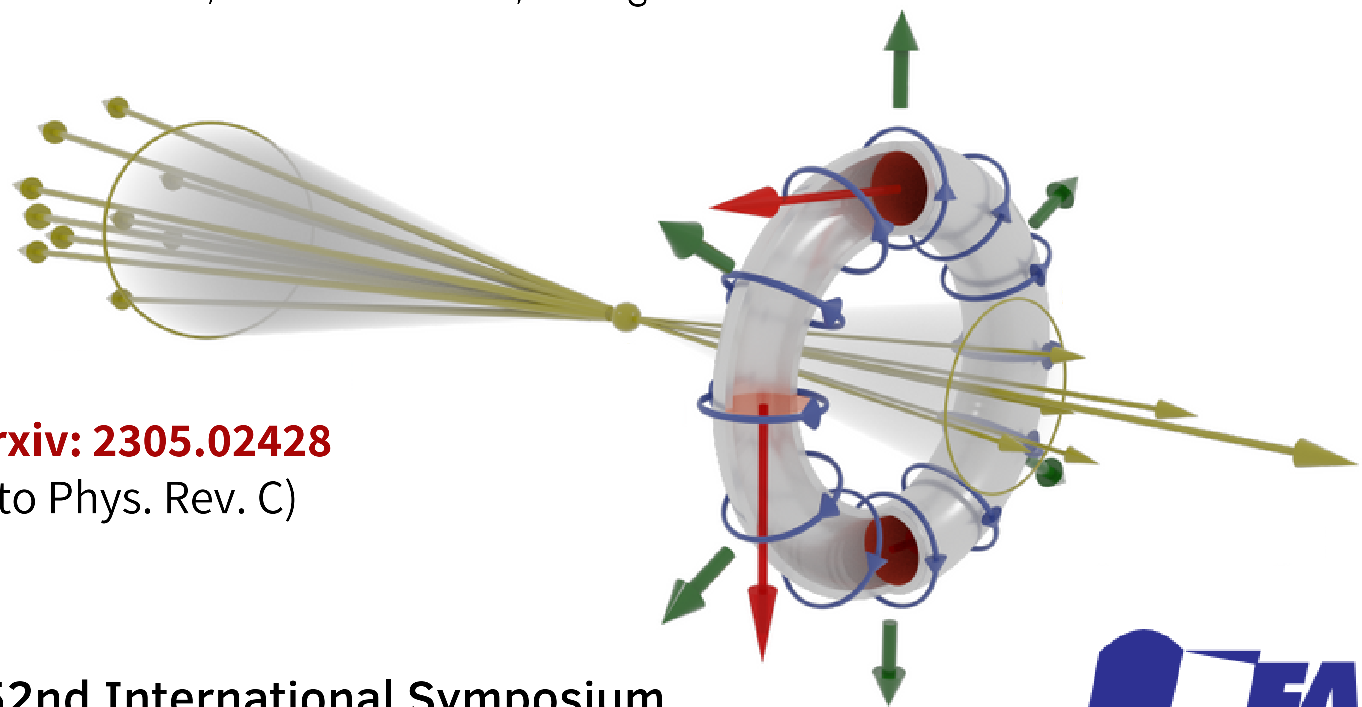
Predictions of how Quantum Supercomputers will assist the New Space Age.

- Predictions of the role of Quantum Supercomputers in the New Space Age and how it will crucially assist this emerging industry.
- Since we now acknowledge that there will be an increased demand for calculation rates in the New Space Age, there will also be numerous ways that Quantum Supercomputers, like the Capricorn Model 1, can assist the New Space Age.
- We have already determined that a space-based system, like the Capricorn Model 1, would be of great benefit to the New Space Age.
- Further applications of Quantum Supercomputing can assist the New Space Age even further.
- An entire network of Quantum Supercomputing Systems could be dedicated to developing the substantial calculation networks that the New Space Age will most definitely require.
- These dedicated systems could eventually advance to the point where operators in this field could rely on the Quantum Supercomputers to make the majority of decisions and for it to take actions required by the human operators.

Jet-medium interactions through vortex ring formation inside the QGP

UNICAMP

Vítor Hugo Ribeiro, David Dobrigkeit Chinellato, Michael Annan Lisa, Willian Matioli Serenone, Chun Shen, Jun Takahashi, Giorgio Torrieri.



Based on Arxiv: 2305.02428
(Submitted to Phys. Rev. C)

ISMD 2023
Gyöngyös, Hungary

52nd International Symposium on Multiparticle Dynamics

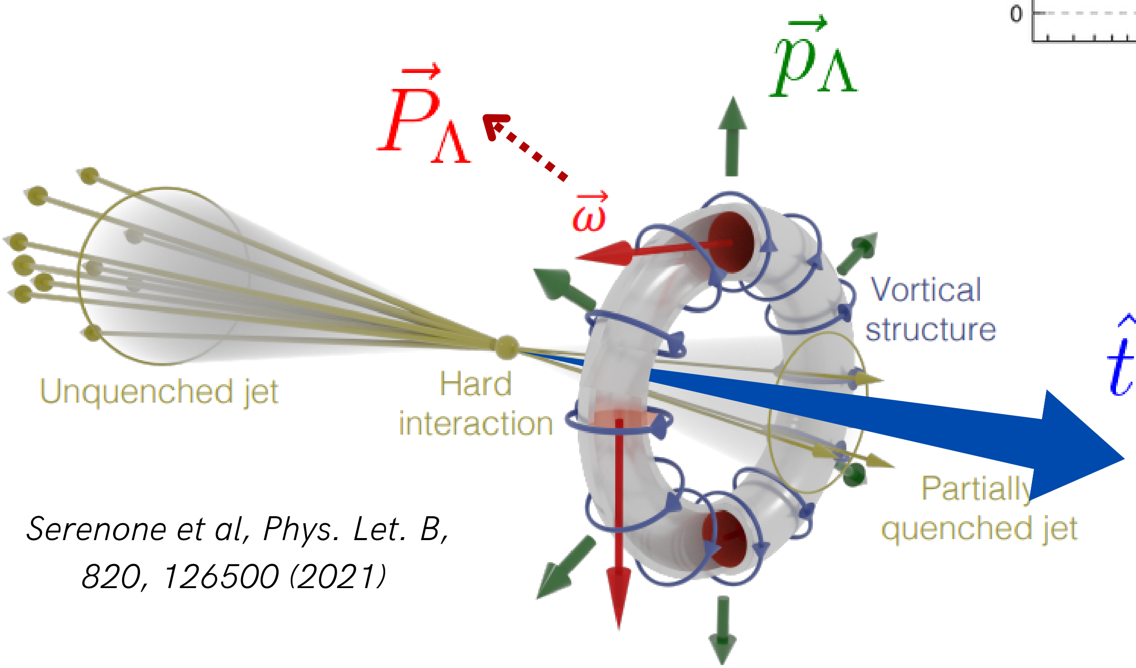
FAPESP
Grant #: 2017/05685-2
Grant #: 2021/10750-3

Jets as a source of vorticity

Jet Quenching

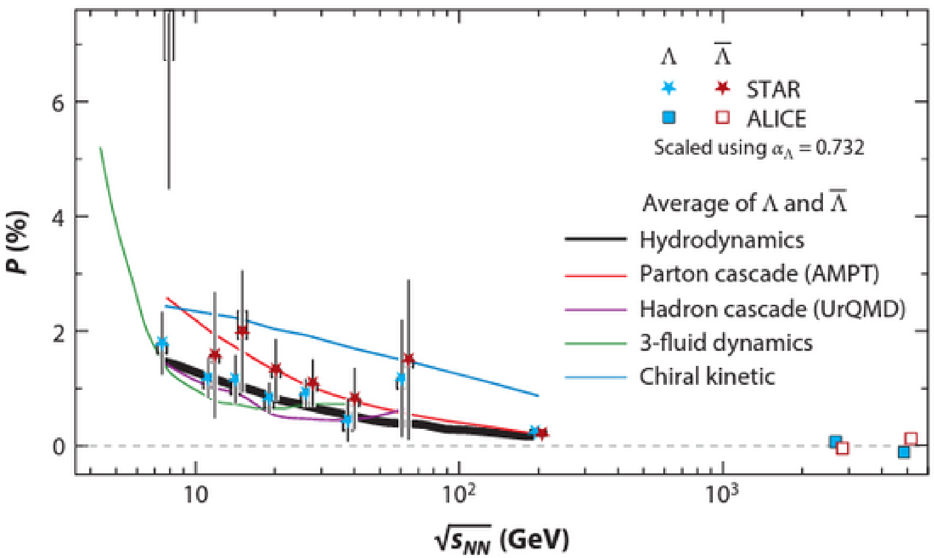
- Jet Energy Loss
- Fluid behavior

The energy absorbed from the jet thermalizes and behaves as a fluid!



Serenone et al, Phys. Let. B, 820, 126500 (2021)

Vorticity driven polarizaztion



Annu. Rev. Nucl. Part. Sci. 2020.70:395-423

Ring Observable

- isolate the circular **pattern of the ring effects.**

$$\mathcal{R}^t_\Lambda = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p}_\Lambda)}{|\hat{t} \times \vec{p}_\Lambda|} \right\rangle$$

Jets as a source of vorticity

Jet Quenching

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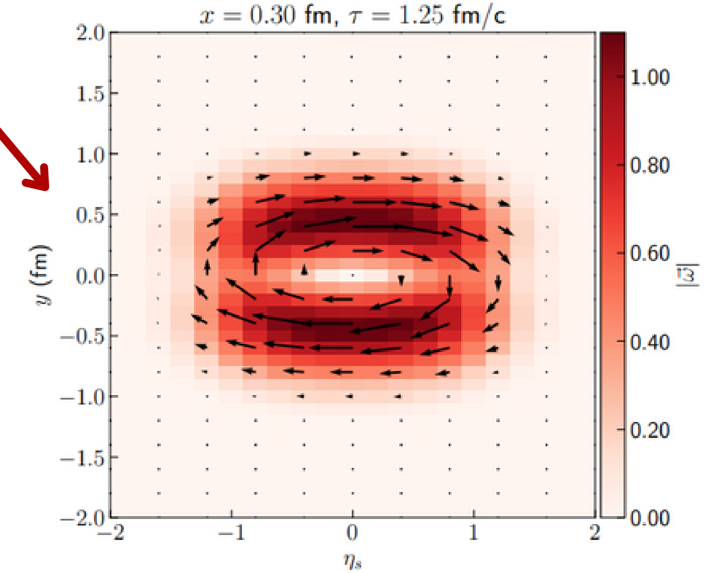
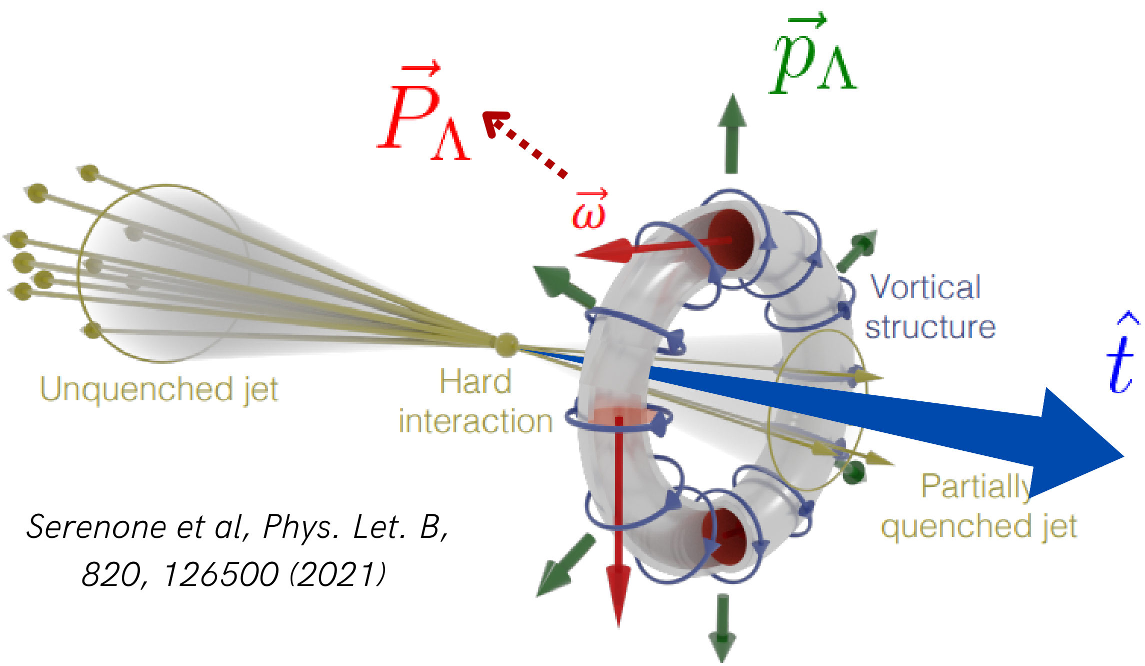
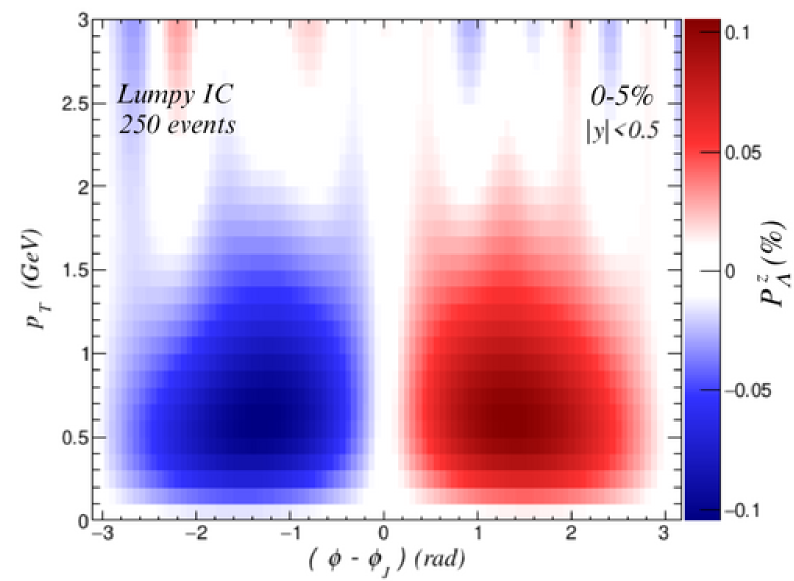
Scenario of vorticity ring formation already evaluated in **PLB, 820, 126500 (2021)**





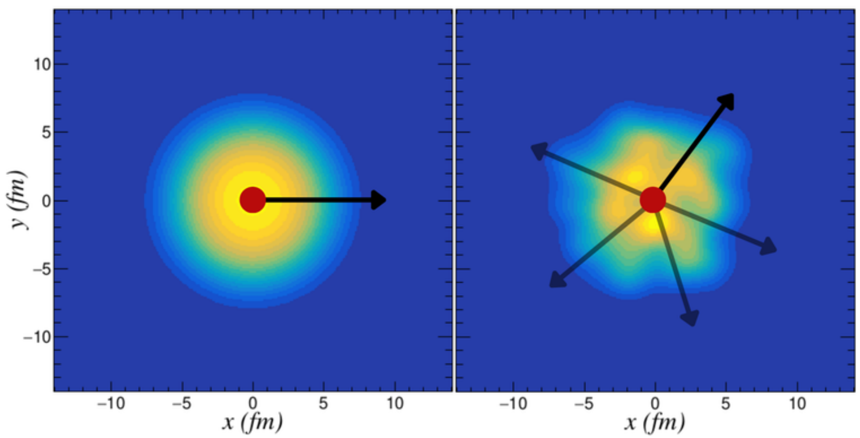
Serenone et al, Phys. Let. B, 820, 126500 (2021)



Systematic Study

Smooth IC vs. Lumpy IC

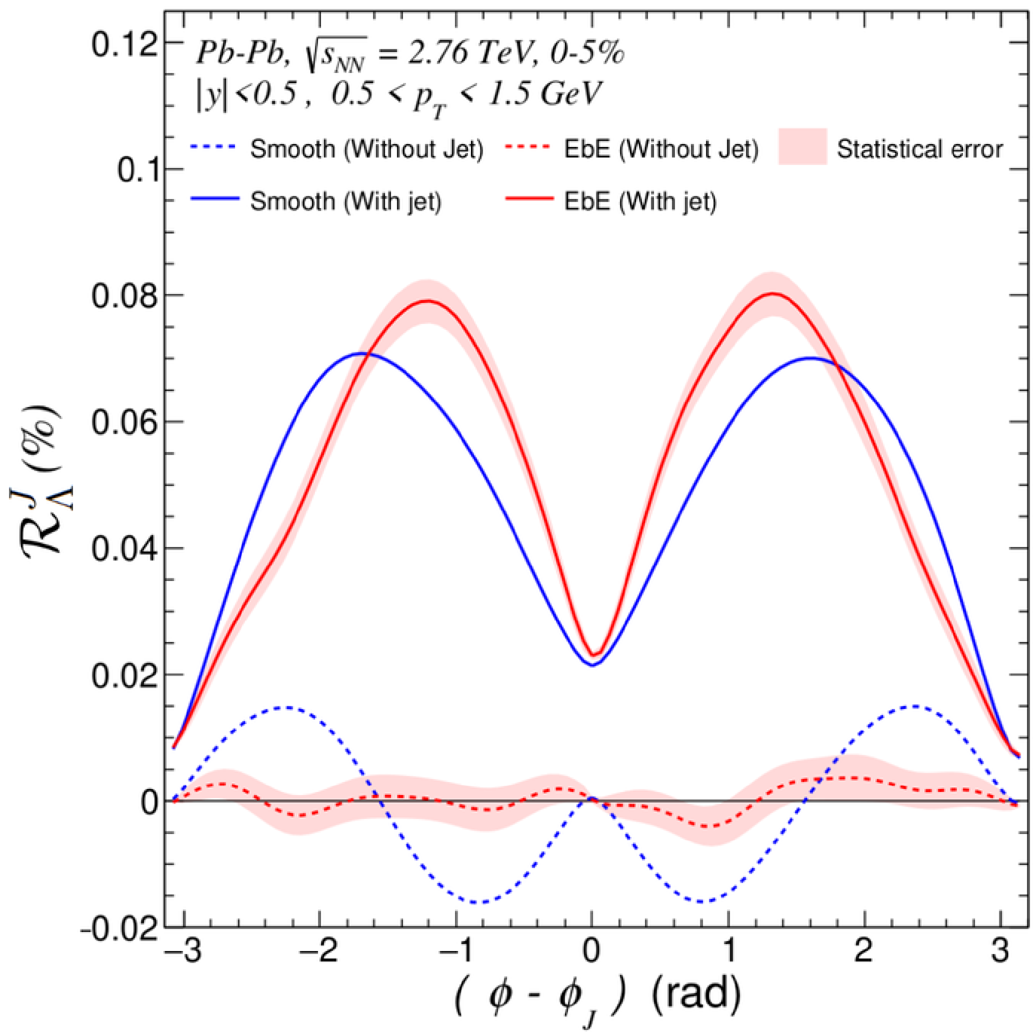
(1 event) (250 events)



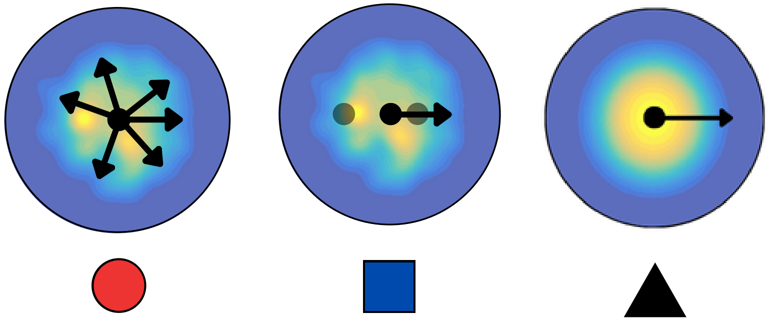
Jet pointing $+\hat{x}$

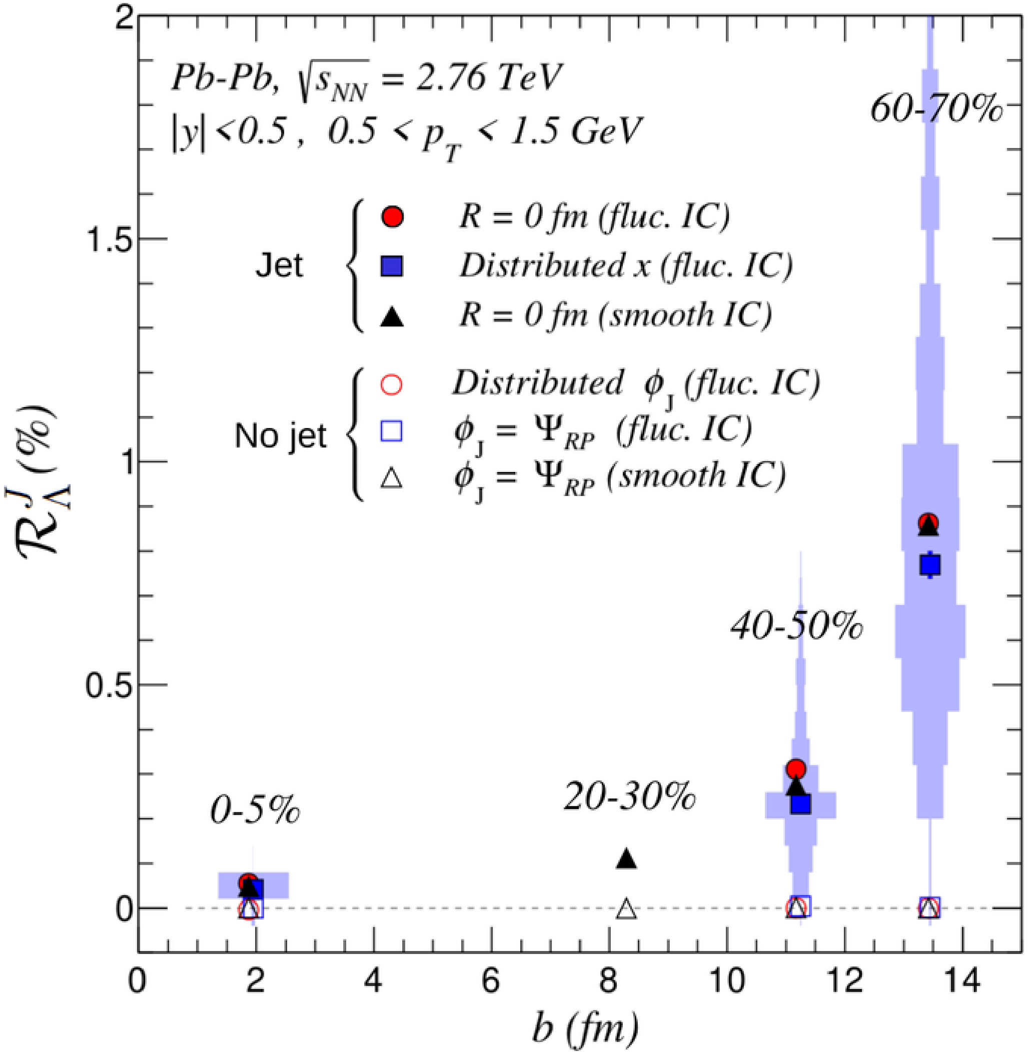
Randomization of jet direction

- The randomization of the jet's direction **suppresses the influence of background polarization.**
- Both analyses are **qualitatively similar** and present the same order of magnitude.



Systematic Study





Ebe distribution of distributed x

- Signal consistent with **zero** in **events without jet quenching;**
- **Jet-medium excitations induce non-zero measurements;**
- The ring observable is **robust** with different types of scenarios.

Thanks for your attention!