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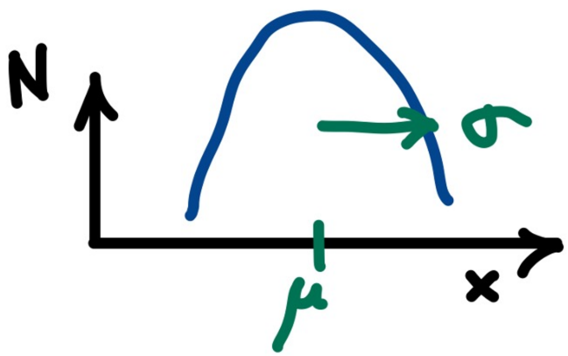
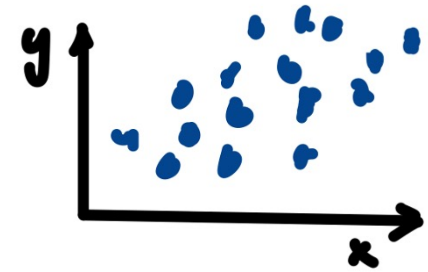
Correlations and fluctuations at STAR

w.j. llope for the STAR Collaboration
BES Tea Seminar Series, may 20, 2022





Outline:

- How to calculate a correlation function (CF), and what does it mean?
- Simple model showing relationship between correlations and fluctuations
- Mathematical relationships between multiplicity cumulants and CF integrals
  - 2-particle angular CFs and 3-particle rapidity CFs
- The physical correlations
- STAR results on 2-particle π,K,p correlations in the BES-I (collider) data
- Light nucleus CFs compared to proton CFs
- proton and light nucleus CFs in the 3.05 GeV (fixed target) data

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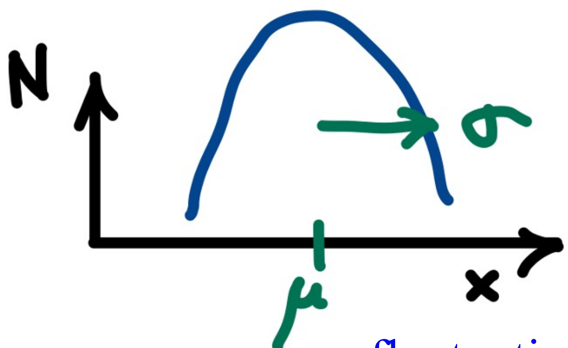
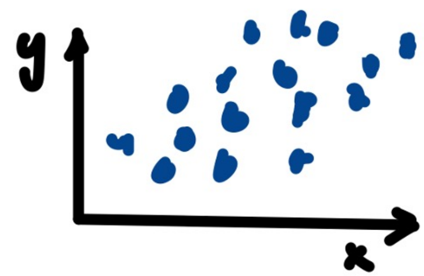
how many?



where do they go?



fluctuations are the integral of the correlations, or

(positive) correlations cause (excess) fluctuations

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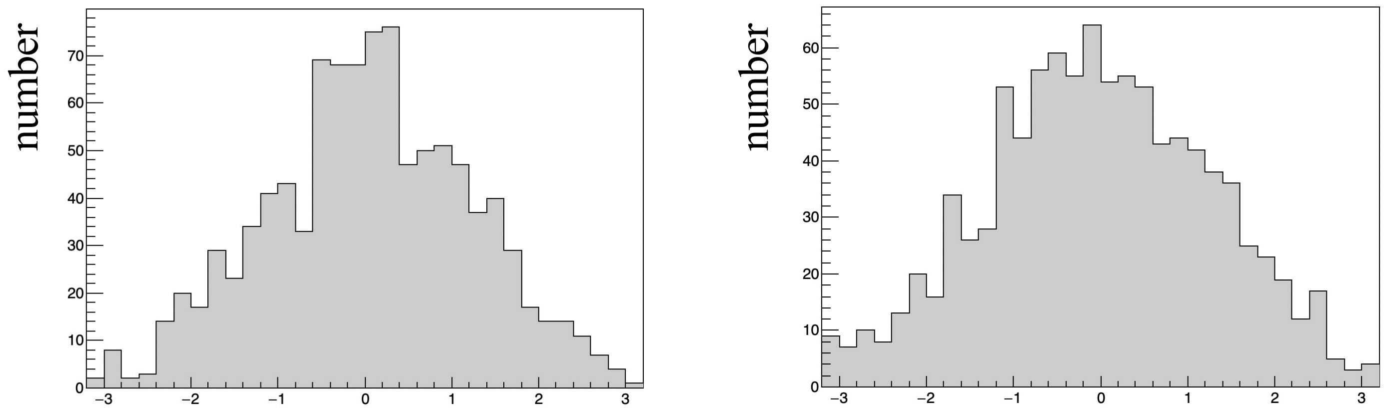
Correlations

Imagine that we have a population of n things, each with multiple attributes

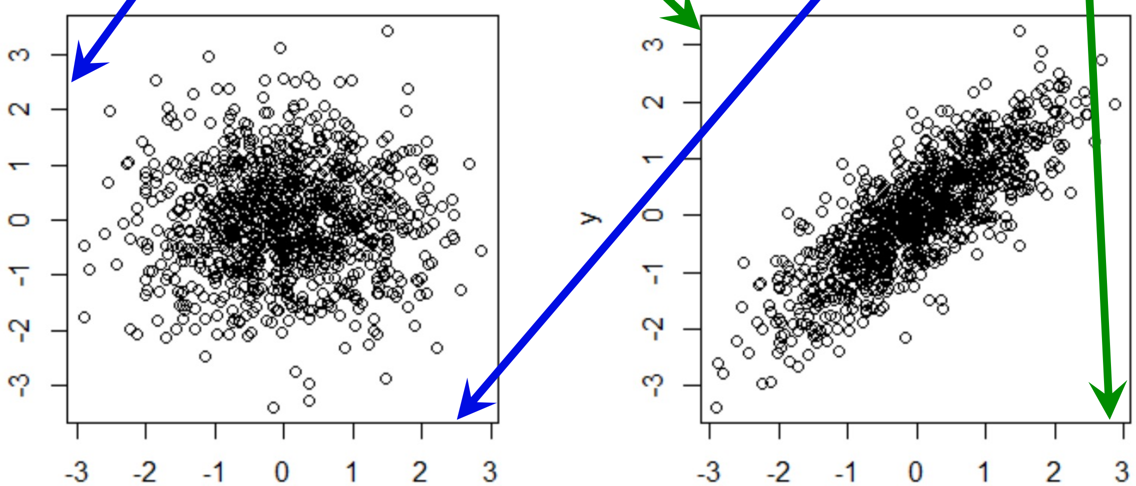


attribute1 attribute2

These 1D histograms are filled once for each member of the population, or n times
we can also get means, variances, etc, for each attribute separately.

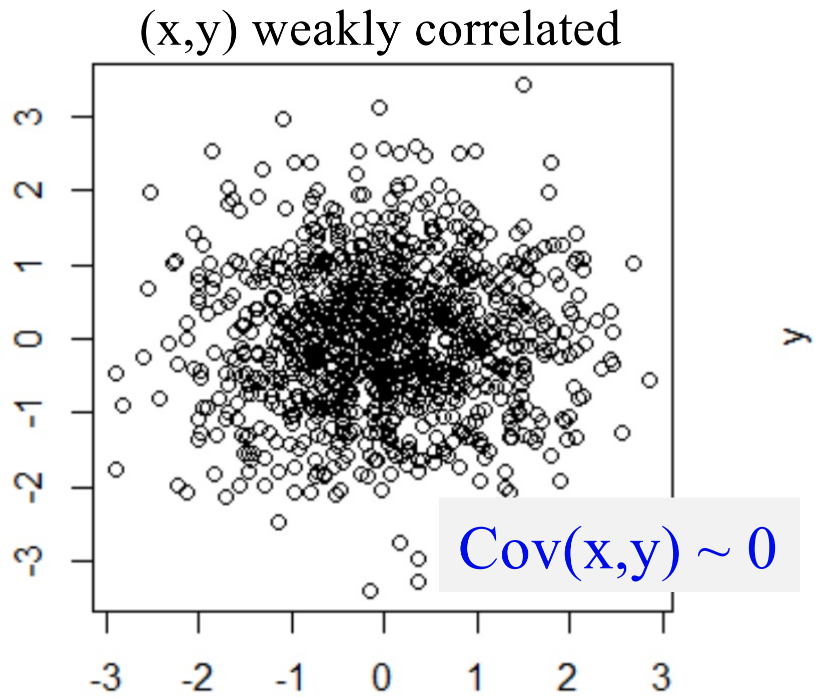
That is not all can learn though – make the two-dimensional plot!

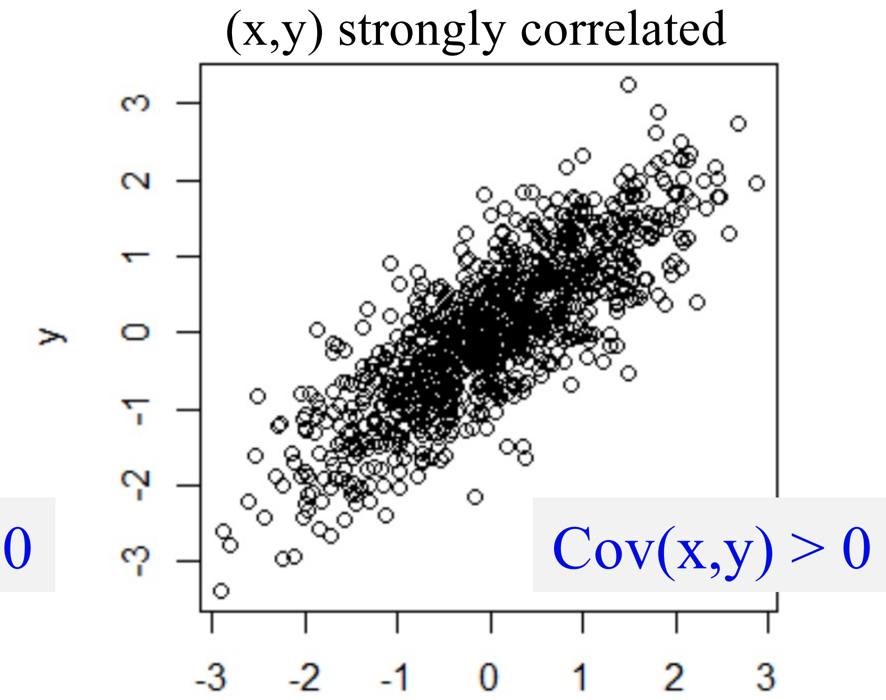
one possible correlation plot



another possible correlation plot

(“number axis” now out of the page)





Studying the correlation of the two variables has resulted in

New knowledge! ...knowing the value of one variable constrains the possible values of the other variable.

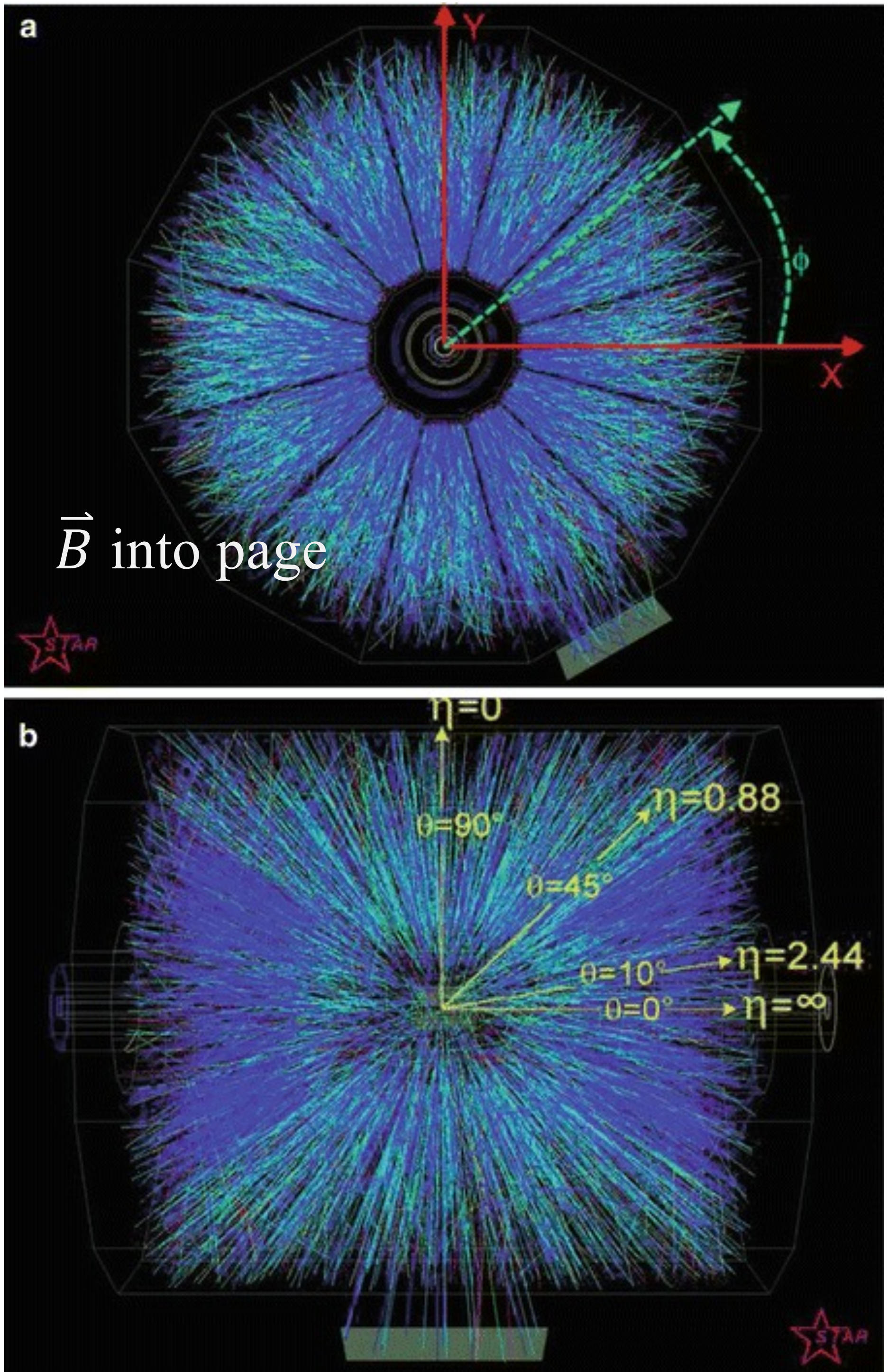
Your population tends to this correlation. What causes it?

Quantify the amount of correlation with the **covariance**:

$$\mathrm{Cov}(x,y) = \langle xy \rangle - \langle x \rangle \langle y \rangle$$

Cov(x,y)>0 x,y correlated
Cov(x,y)~0 x,y uncorrelated
Cov(x,y)<0 x,y anticorrelated

The “attributes” in this case



Time Projection Chamber (TPC)

measures 3 components of the momentum of “all” charged tracks in a certain acceptance.

Perpendicular to the beam-line

tracks curve in 0.5T magnetic field

each track has azimuthal angle, ϕ

$$\phi = \tan^{-1}(p_y/p_x)$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

Parallel to the beam-line

tracks are straight

each track has polar angle, θ

We prefer (pseudo)rapidity over polar angle

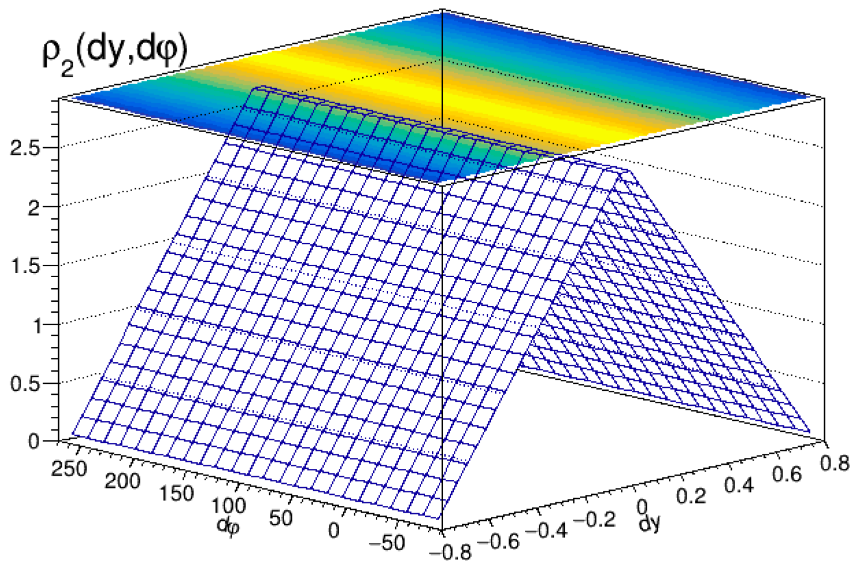
$$y = \frac{1}{2}\ln\frac{(E+p_z)}{(E-p_z)} \qquad \eta = -\ln(\tan\frac{\theta}{2})$$

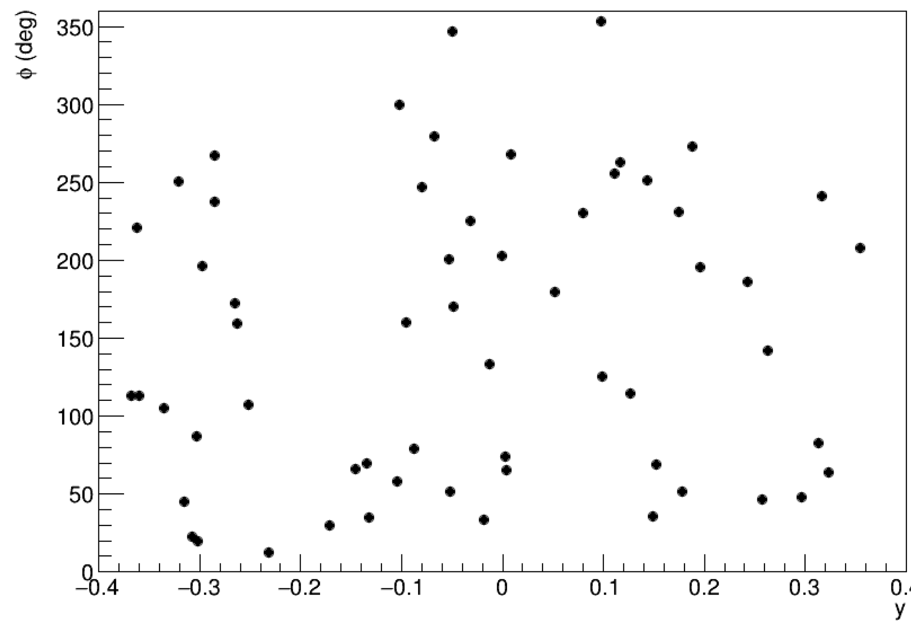
Angular Correlation Function

$$\mathrm{Cov}(x,y) = \langle xy \rangle - \langle x \rangle \langle y \rangle \longrightarrow C_2 = \rho_2 - \rho_1 \rho_1$$

"the correlator"

```
in each event, there are N tracks in the acceptance
     i-loop over tracks in this event
     j-loop over tracks in this event
          if (i==j) continue
          dy   = y[i] - y[j];      // Pair dy
          dphi = phi[i] – phi[j]   // Pair dphi
          rho2 ->Fill(dy,dphi,1.) // count it!
With N events processed
          rho2 /= Nevents
```





$$C_2 = \rho_2 - \rho_2^{ref}$$

density of pairs from same events
measured in same acceptance
but with all correlations broken

- mixing particles from 2 different events
- convolution of 3D single-particle dists

$$\int \rho_1(y,\phi,p_T) \cdot d\Omega = \langle N \rangle$$

$$\int \rho_2(dy,d\phi) \cdot d\Omega = \langle N(N-1) \rangle$$

Now just form the ratio!

ρ_2 : pair number density

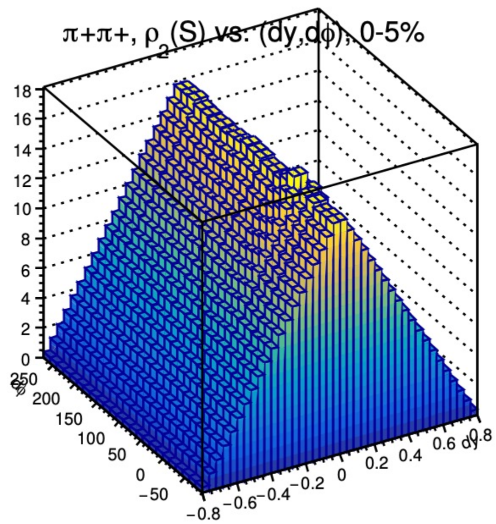
$\rho_1\rho_1$: reference density

$C_2 = \rho_2 - \rho_1\rho_1$: correlator

$R_2 = C_2/\rho_1\rho_1$: correlator per pair

$$R_2(dy, d\phi) = \frac{\rho_2(dy, d\phi)}{\rho_1\rho_1(dy, d\phi)} - 1$$

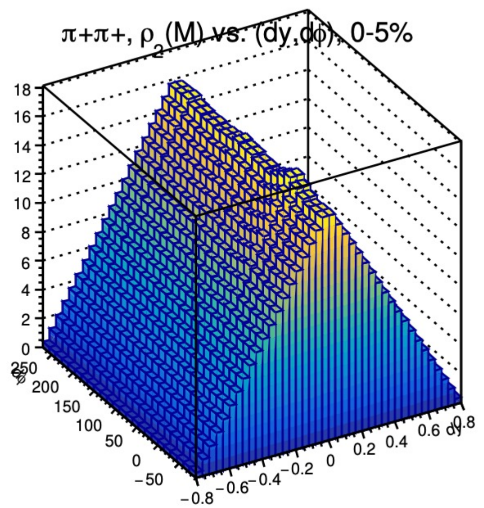
"number of correlated pairs per total pair"



$\rho_2(dy,d\phi)$

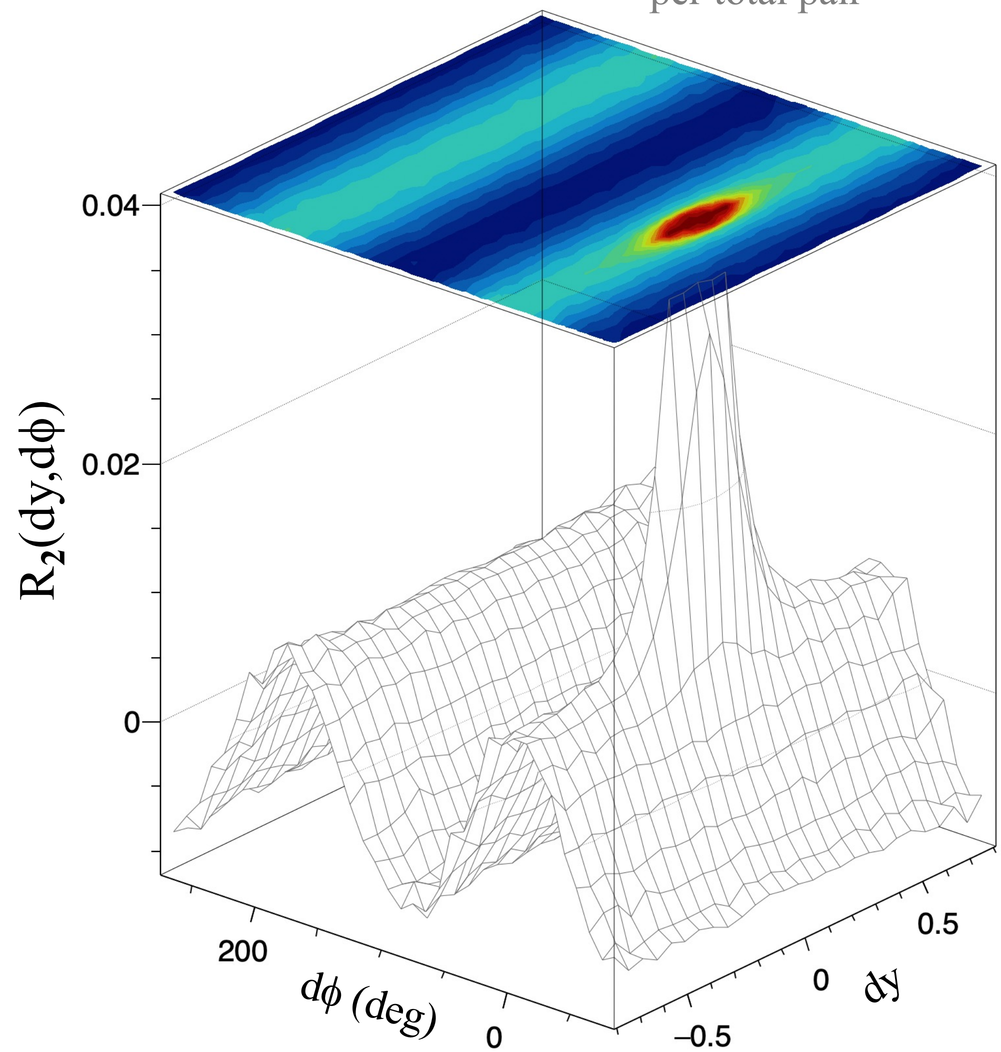
"numerator"

- 1 =



$\rho_1\rho_1(dy,d\phi)$

"denominator"



What does "correlation" mean?

An ensemble of events that exhibits **positive correlations** has some interesting features.
We notice

for some particles, their position depends on the position of other particle(s)

but we *also* notice

the multiplicity distribution for that ensemble has "excessive cumulants":

The variance, K_2, and perhaps the higher cumulants, K_k, exceed the mean, K_1

"Correlations" do not solely affect the relative positions of particles.

They also affect the multiplicities of particles in the event too!

Let's build up this situation with a simple model

start without any "correlations"

then add small average number <Na> of pairs from a SRC source to the events

Explore how the correlation functions,
and the accompanying multiplicity distribution for that same ensemble of events,
each and both reflect the existence of "correlations"

Multiplicity cumulants, and correlation functions, are measuring the same thing.

Each has some (dis)advantages over the other, so both approaches are needed.

A simple *pairs* event generator capturing correlations physics

Set mean number of tracks per event: $N_m = 36.2$

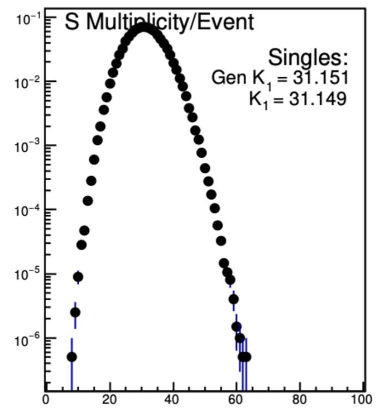
A correlation source emits *pairs*. The number of pairs it emits per evt is Poisson distributed.

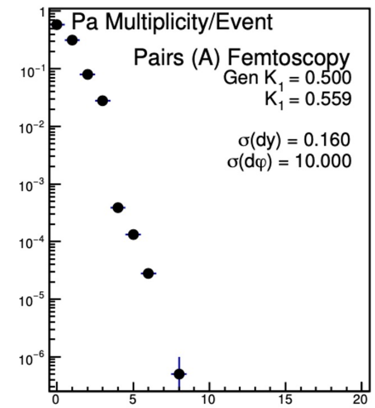
Correlation source "a" emits, on average, <Na> pairs per event. (e.g. "femtoscopy")

Correlation source "b" emits, on average, <Nb> pairs per event. (e.g. "resonances")

Number of "singles" (tracks uncorrelated with all other tracks) is also poisson distributed.

$<S> = N_m - 2*<Na> - 2*<Nb> \ldots$





In any single event, there are an *integer* *# of pairs* from the correlation sources: Na, Nb, ..

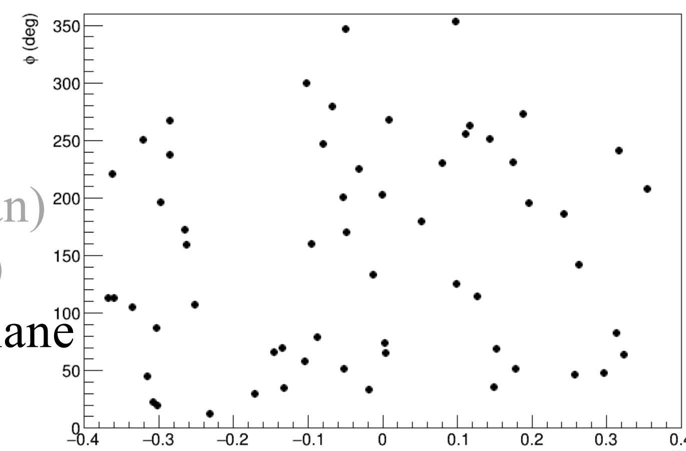
S←Poisson(<S>)   # singles

Na←Poisson(<Na>)   # pairs corr proc A

Nb←Poisson(<Nb>)   # pairs corr proc B

N = S + 2*Na + 2*Nb   total in evt

If <Na> or <Nb> !=0, N is *not* Poisson distributed



Each "single" track is placed in the acceptance randomly.

A: place 2nd track in pair w.r.t. 1st particle (narrow 2D Gaussian)

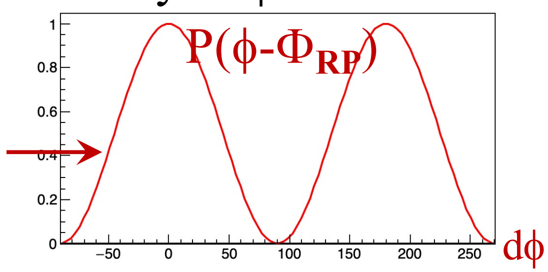
B: place resonance randomly, then decay it (Minv correlation)

Elliptic flow: Nv2 single tracks randomly in ϕ w.r.t. random plane

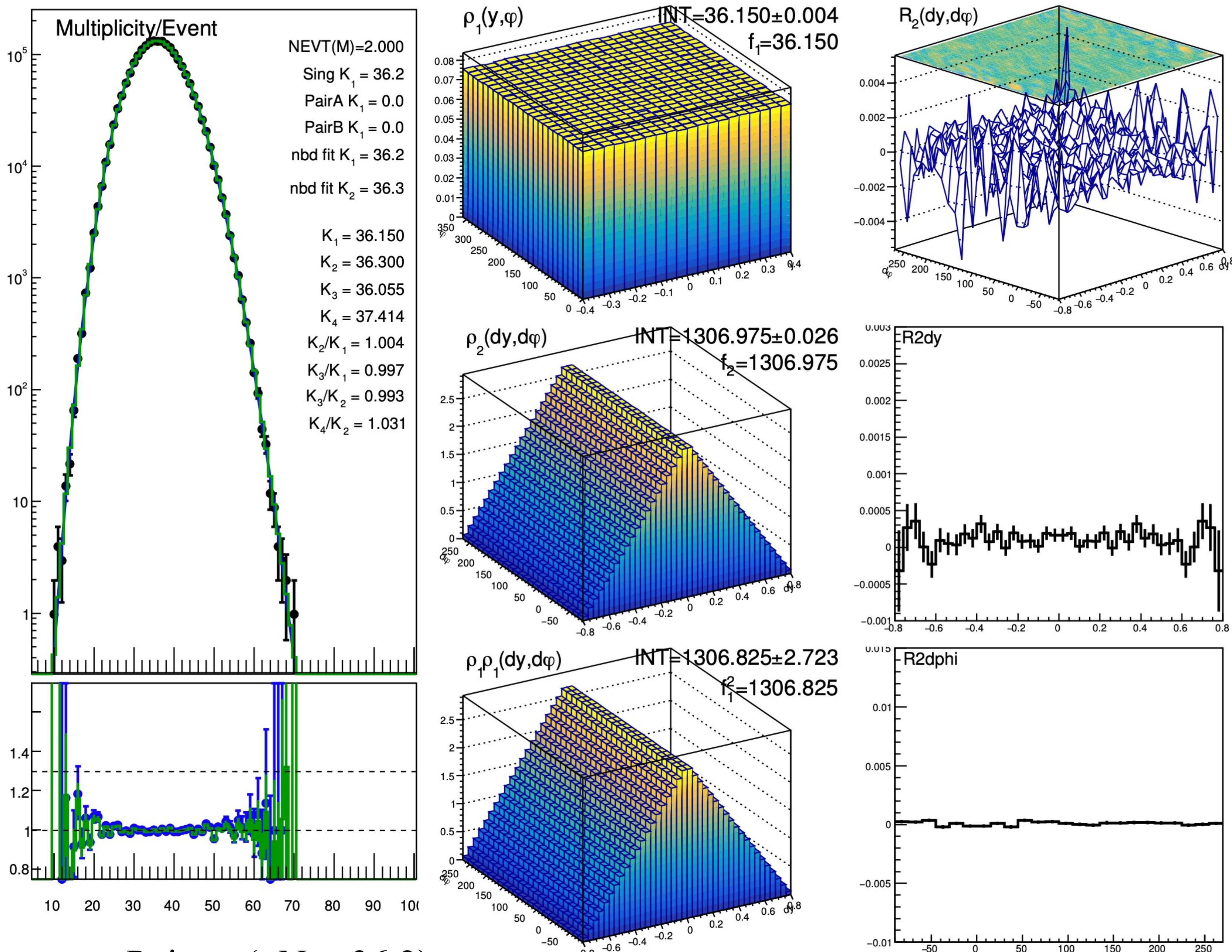
$\Phi_{RP} \leftarrow \text{Random}[0,2\pi)$

$d\phi_i \leftarrow$ Random from fcn.

$\phi_i = \Phi_{RP} + d\phi_i$



<N>=36.2, no correlations

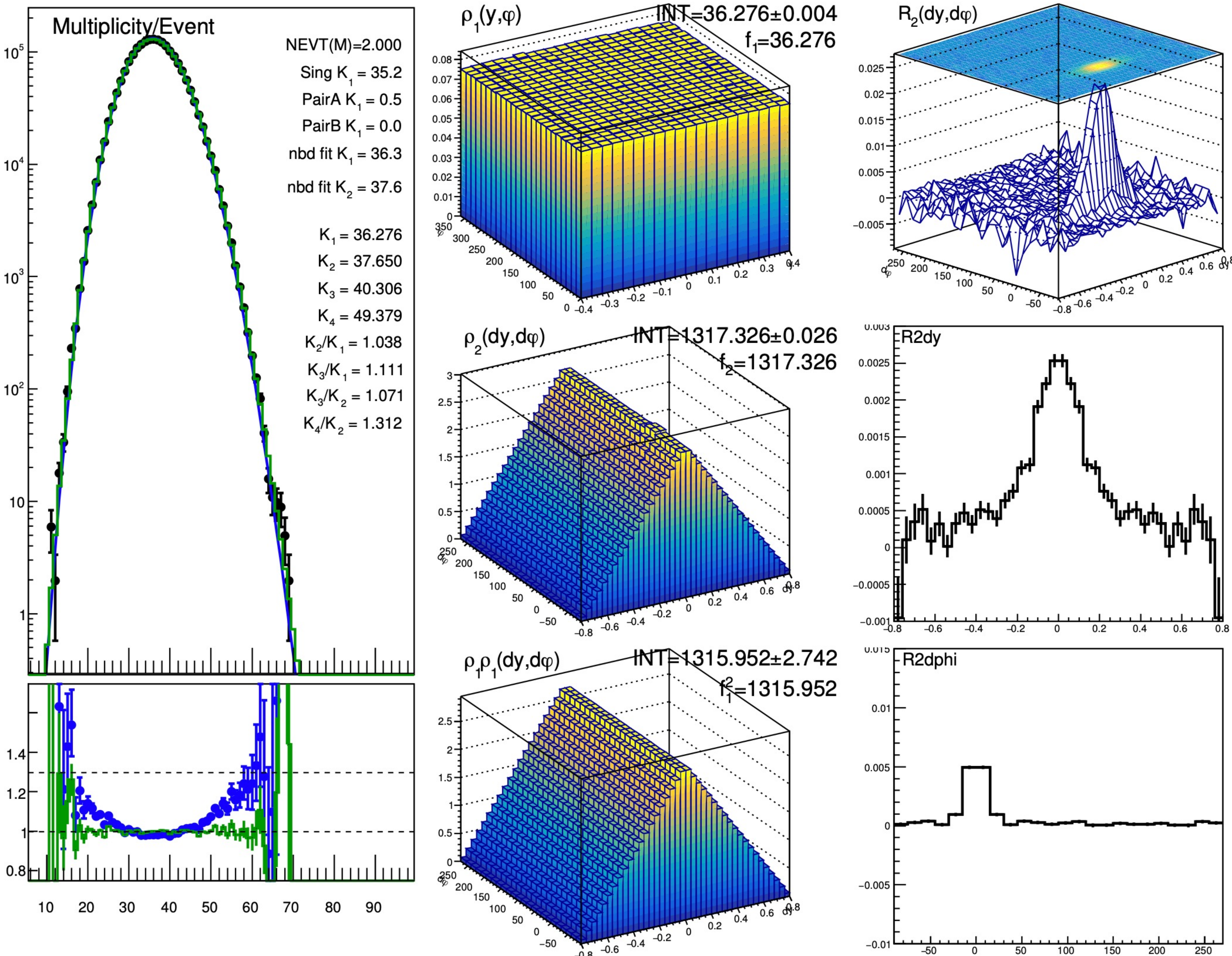


green: Poisson(<N>=36.2)
blue: Actual

"densities"

"correlation function"

<N>=36.2, <Na>=0.5 (femtoscopy)



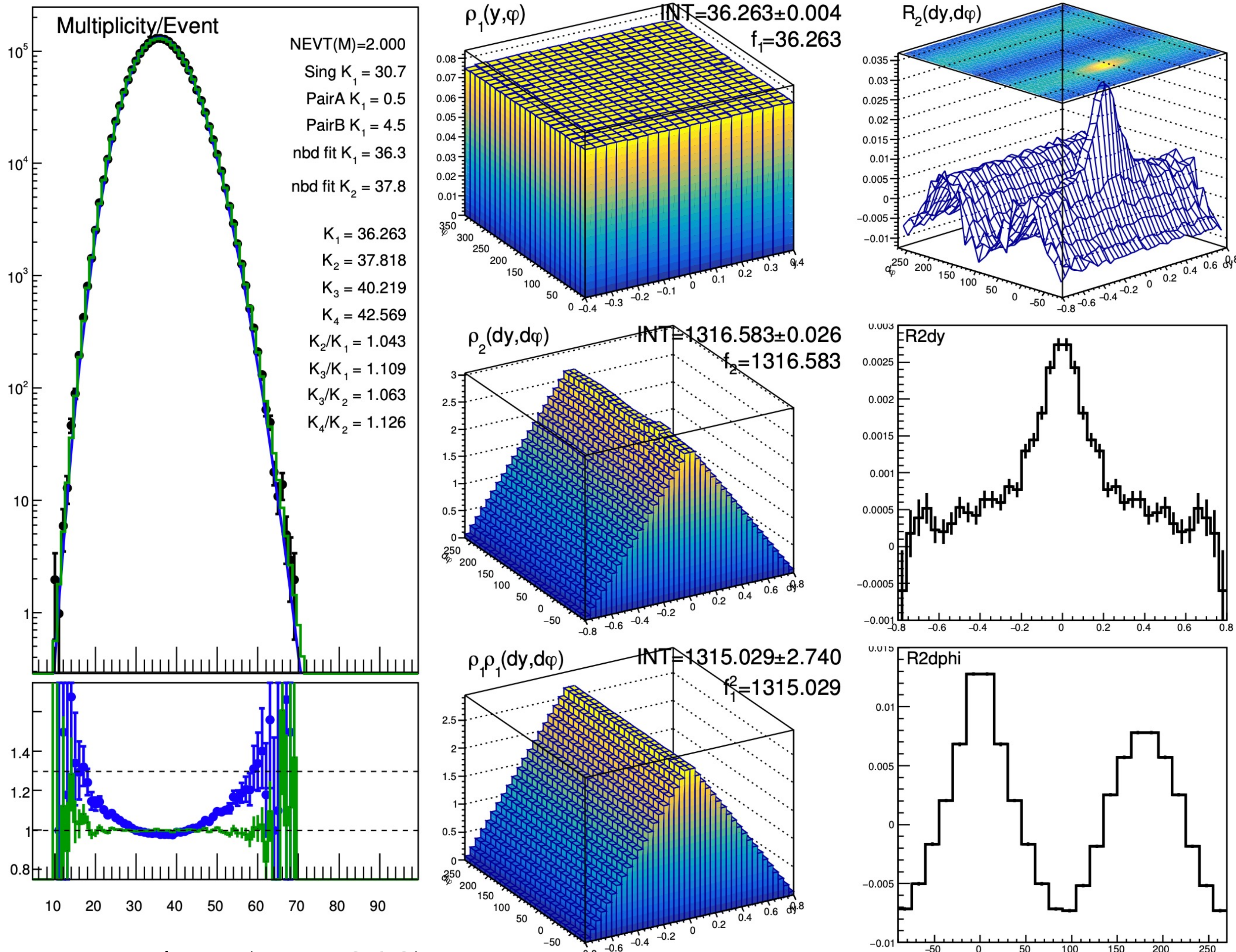
green: Poisson(<N>=36.2)
blue: Actual

"densities"

"correlation function"

☆ Correlations & Fluctuations

<N>=36.2, <Na>=0.5 (femtoscopy), <Nv2>=4.5 (elliptic flow)

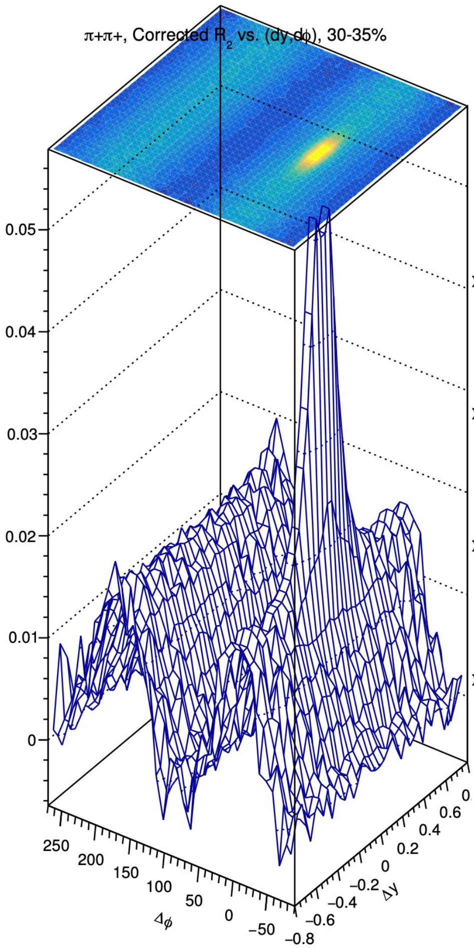


green: Poisson(<N>=36.2)
blue: Actual

"densities"

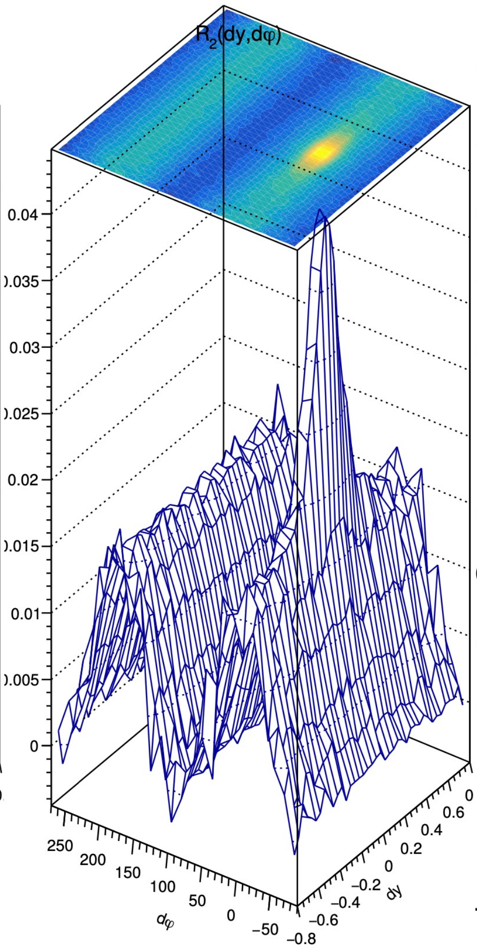
"correlation function"

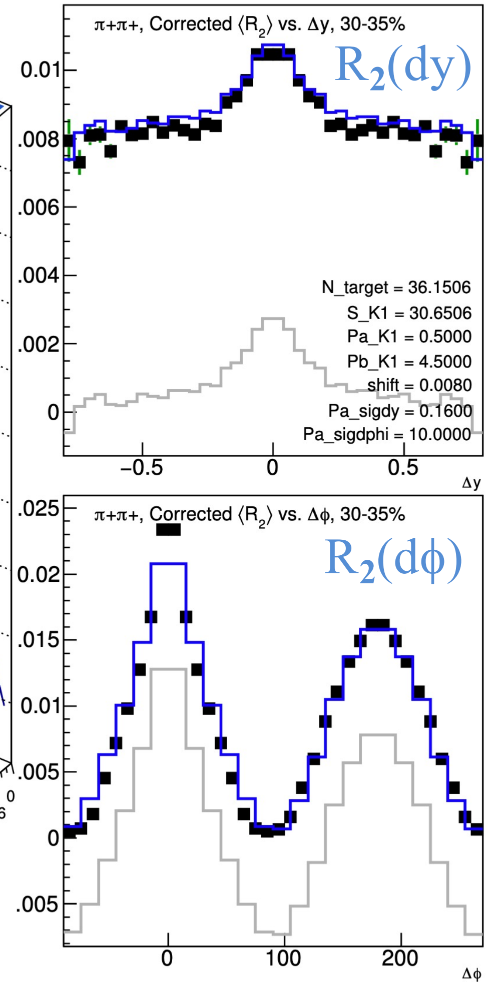
Data



STAR, Phys. Rev. C 101, 014916 (2020)

Simulation





This example CF implies:
<Na>~1/2 pairs/evt SRC
<Nv2>~4.5 tracks/evt

the shape is qualitatively reproduced.

note the vertical offset!

(actual multiplicity distribution is also wider than simulated mult dist!)

In this example, there is an additional positive correlation throughout the whole space. Don’t ignore this.

- correlation is being projected over? Look more carefully at full space (6D, at least)
- correlation is from a source much wider than the acceptance (*e.g.* in dy)

and/or this strength could be the projection of a 3- or 4-particle (or more) correlation source

Fluctuations are the **integral** of the Correlations

Multiplicity Cumulants = Poisson + [deviations from Poisson]

E.L. Berger, NPB **85**, 61 (1975)
P. Carruthers *et al.*, PRL **63**, 1562 (1989)
P. Carruthers, PRA **43**, 2632 (1991)
A. Bzdak *et al.*, PRC **95**, 054906 (2017)

$$K_1 = \langle N \rangle$$

$$K_2 = \langle N \rangle + c_2$$

$$K_3 = \langle N \rangle + 3c_2 + c_3$$

$$K_4 = \langle N \rangle + 7c_2 + 6c_3 + c_4$$

$$c_k = \int C_k(y_1, \ldots, y_k)\; dy_1 \ldots dy_k$$

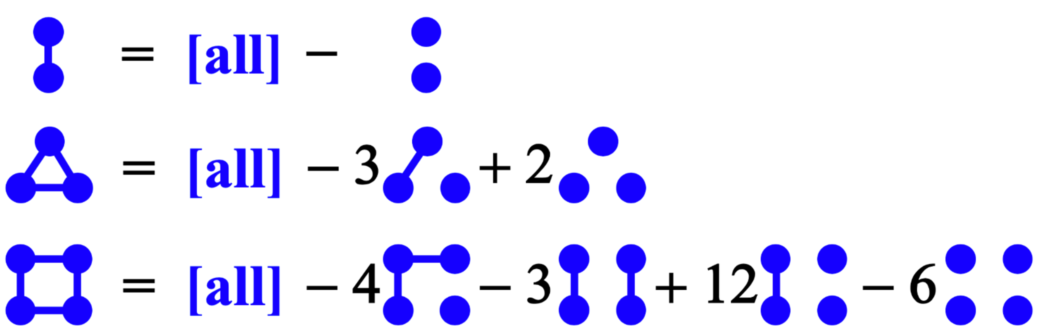
"Correlators"

L. Foà, Phys. Lett. **C22**, 1 (1975)
H. Bøggild, Ann. Rev. Nucl. Sci. **24**, 451 (1974)
M. Jacob, Phys. Rep. **315**, 7 (1999)

$$C_2 = \rho_2 - \rho_1\rho_1$$

$$C_3 = \rho_3 - 3\rho_2\rho_1 + 2\rho_1\rho_1\rho_1$$

$$C_4 = \rho_4 - 4\rho_3\rho_1 - 3\rho_2\rho_2 + 12\rho_2\rho_1\rho_1 - 6\rho_1\rho_1\rho_1\rho_1$$



$$C_2 = C_2(\Delta y, \Delta\varphi)$$

$$C_2 = C_2(y_1, y_2)$$

$$C_3 = C_3(y_1, y_2, y_3)$$

$$C_4 = C_4(y_1, y_2, y_3, y_4)$$

Explicit subtraction of lower-order correlations…

Three-particle correlators, C_3 or R_3, also exactly "calibrated"

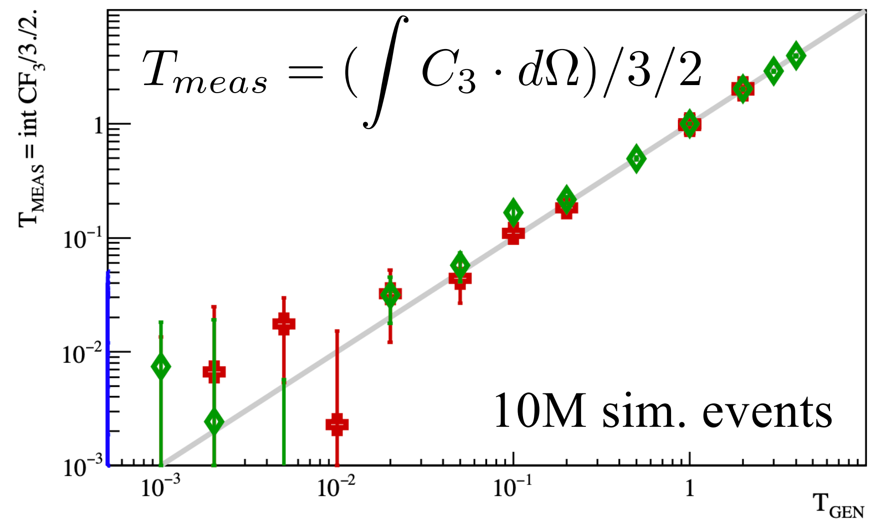
Repeat same simple simulation, but add SRC pairs *and triplets:* $\langle P_{GEN}\rangle$ and/or $\langle T_{GEN}\rangle$!= 0

- number of pairs/evt, P, Poisson-distributed over events, mean=$\langle P_{GEN}\rangle$
- number of triplets/evt, T, Poisson-distributed over events, mean=$\langle T_{GEN}\rangle$
- particles in pairs and triplets are "clusters" with small $\sigma_y \sim 0.1$

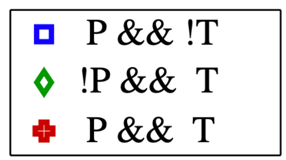
Compare integrals of C_2 and C_3 to known input rates of clusters in the events

$$C_2 = \rho_2 - \rho_1\rho_1$$

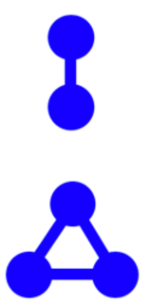
$$C_3 = \rho_3 - 3\rho_2\rho_1 + 2\rho_1\rho_1\rho_1$$



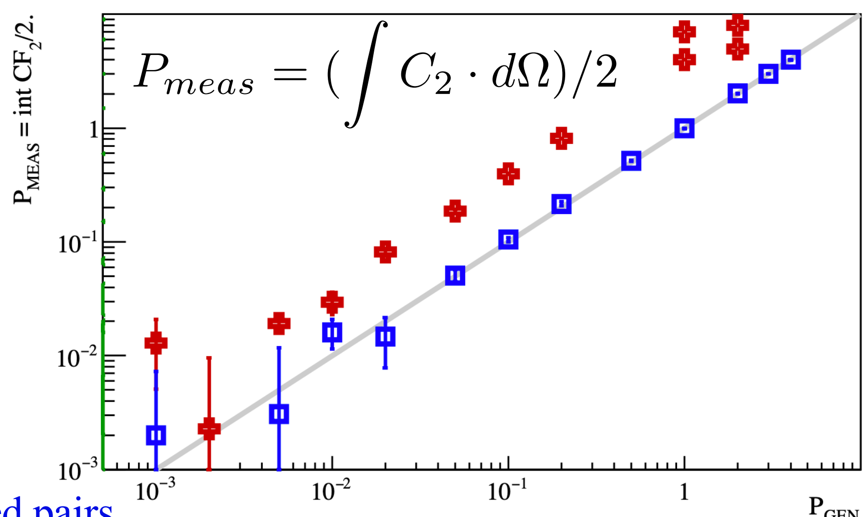
$\langle S\rangle = N_m - 2^*P_{GEN} - 3^*T_{GEN}$
N_m=30
10M events

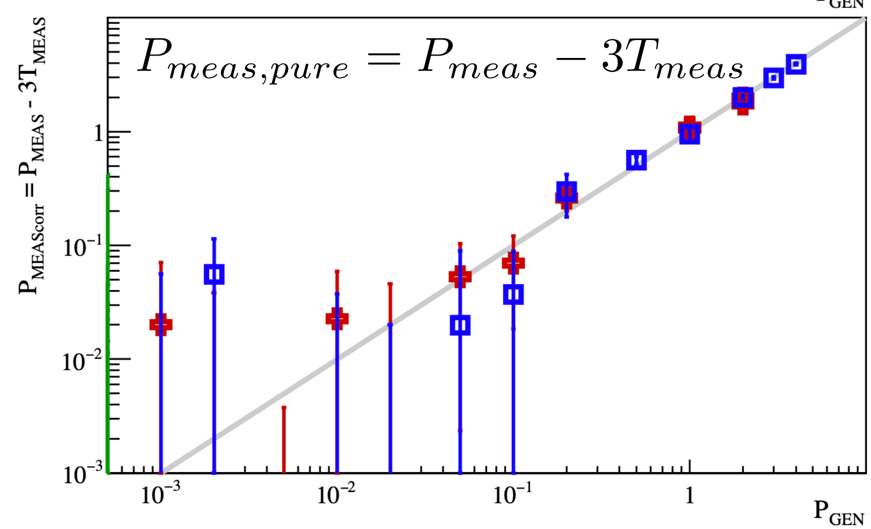


triplets or 3 pairs?



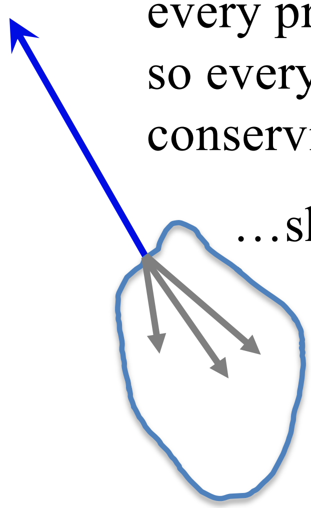
Three correlated pairs for every correlated triplet!





Some other types of correlations

momentum conservation



every process conserves momentum
so every track must have "partners"
conserving the momentum!

…should add "back-to-back-ness"
enhance correlations $\Delta\phi \sim 180^o$
anticorrelation for $\Delta\phi \sim 0^o$

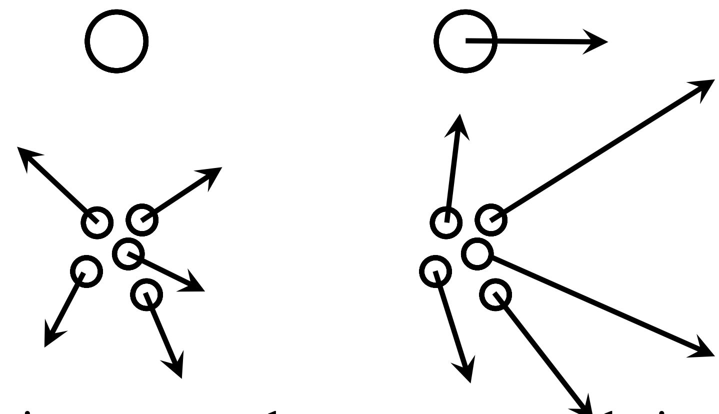
i.e. correlations that
go like $-\cos(\Delta\phi)$

resonances/clusters

cluster at rest | cluster moving

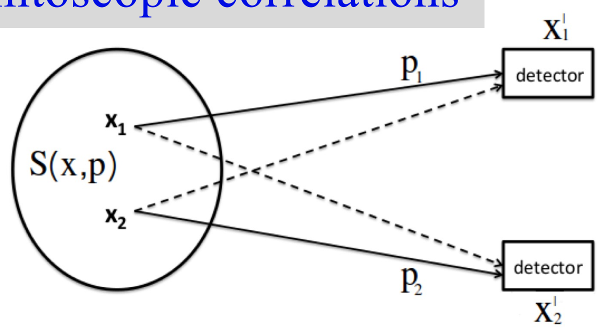
before decay:

after decay:



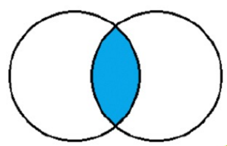
clustering causes short-range correlations
due to kinematic focussing

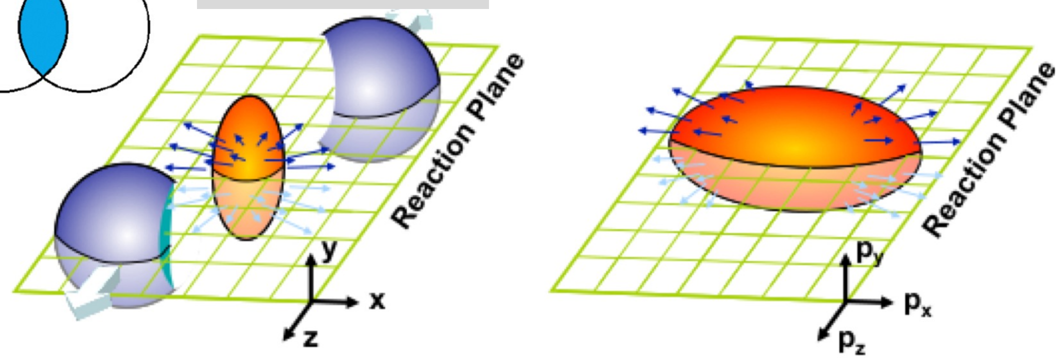
femtoscopic correlations



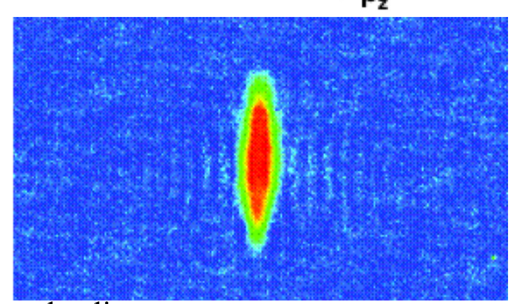
identical particles – must symmetrize the WF.
interference over paths produces correlations
related to size of emitting source.
short-range correlations exist at small $\Delta \boldsymbol{p}$ only.

elliptic flow



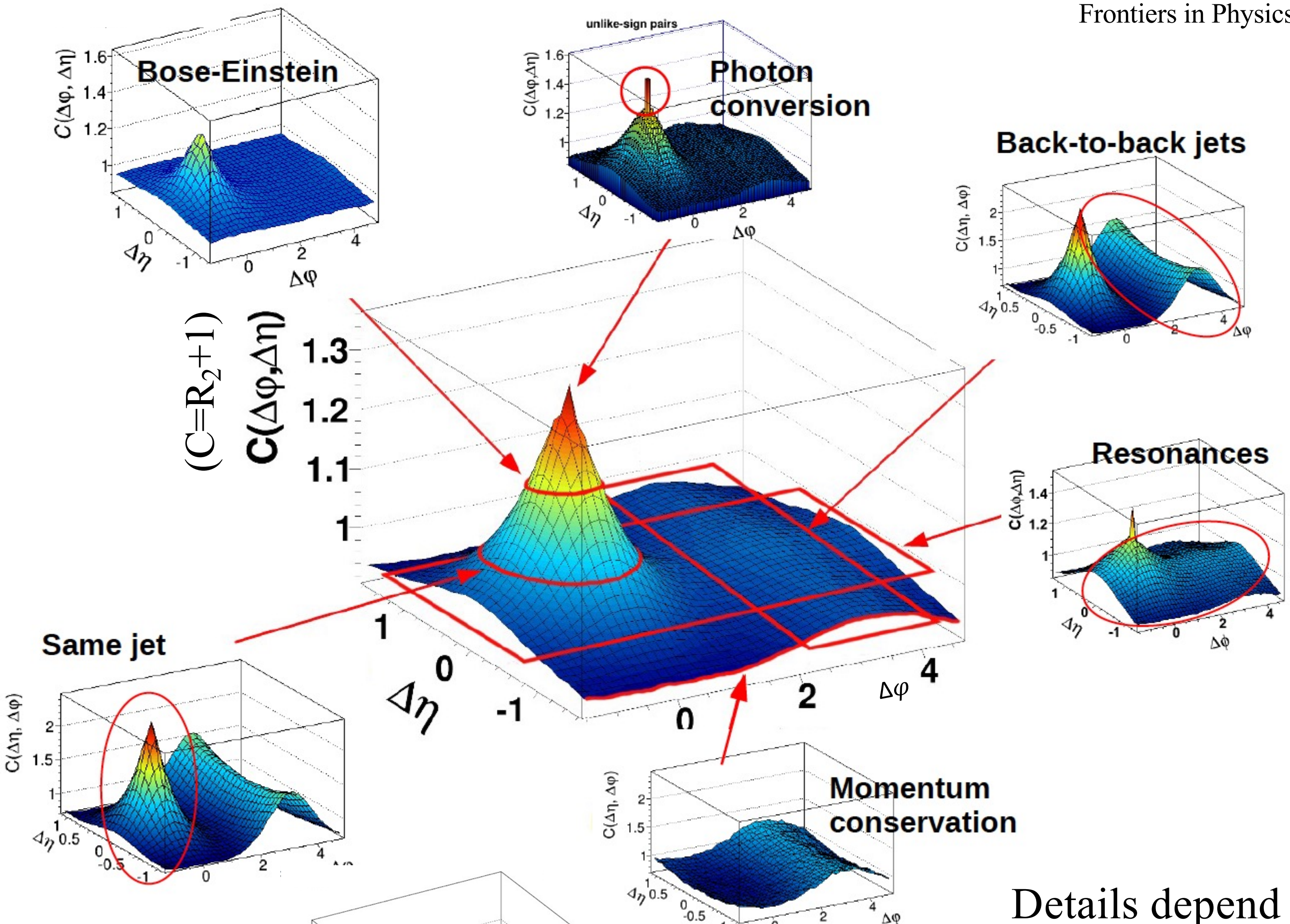


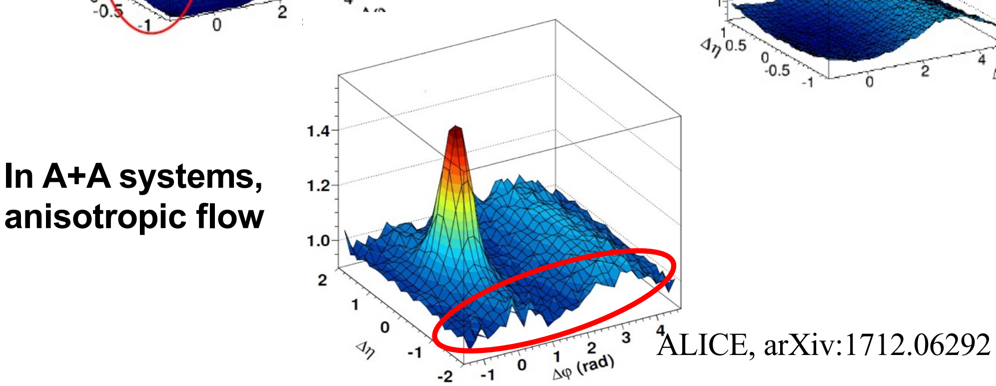
results in correlations
that go like $\cos(2\Delta\phi)$



Li ions in a trap

M. Janik, International conference on New Frontiers in Physics, 2015





ALICE, arXiv:1712.06292

Details depend on exactly what particle species are in each pair.

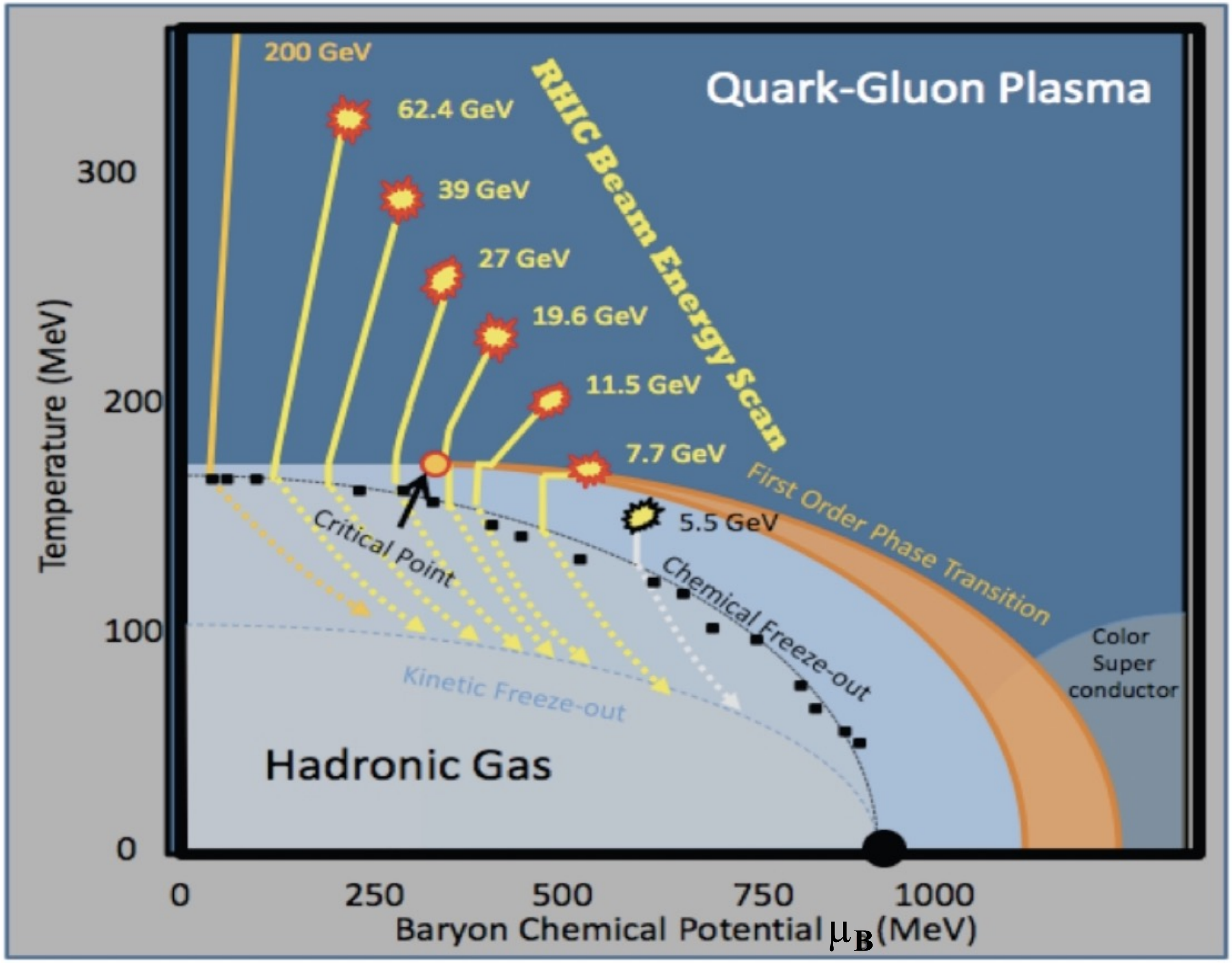
Unexpected correlations always deserve extra attention!

The nuclear matter phase diagram

Top beam energy at RHIC:
analytic crossover
from QGP to HG.

The rest of this figure is
a (well-informed) guess.

Decreasing the beam energy
increases μ_B
decreases $\bar{p}/p$...

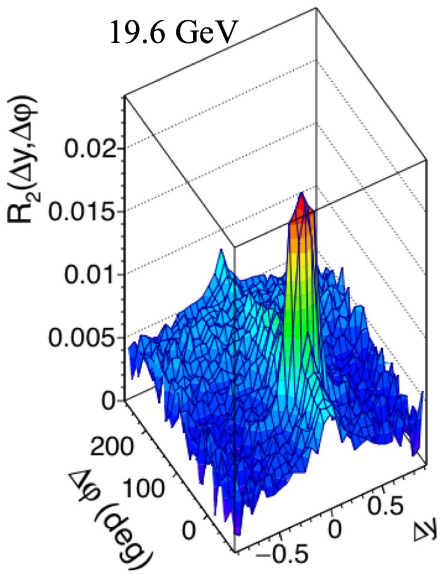


Systematic study of the data as a function of the beam energy allows a "scan" in streaks across the phase diagram...

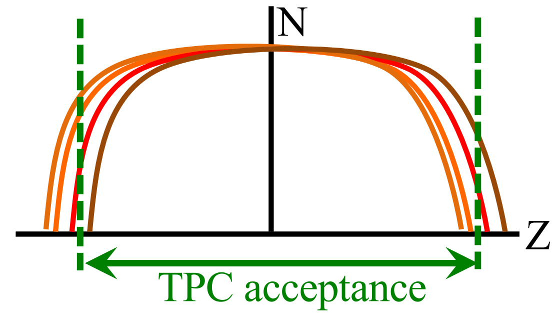
Try to understand all *apparent* correlations

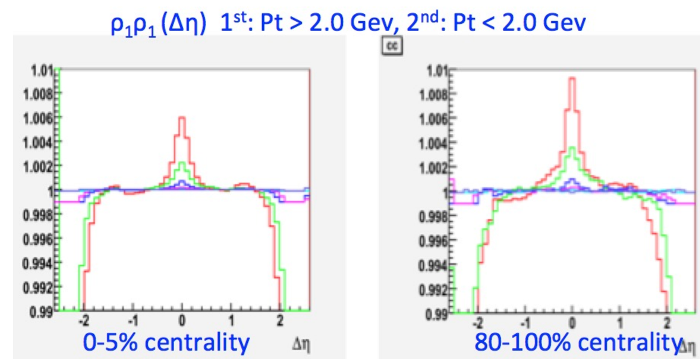
Sometimes one needs to see the CF to understand its integral (K)

A few possible advantages from going through the correlations C_k to get the fluctuations K_k



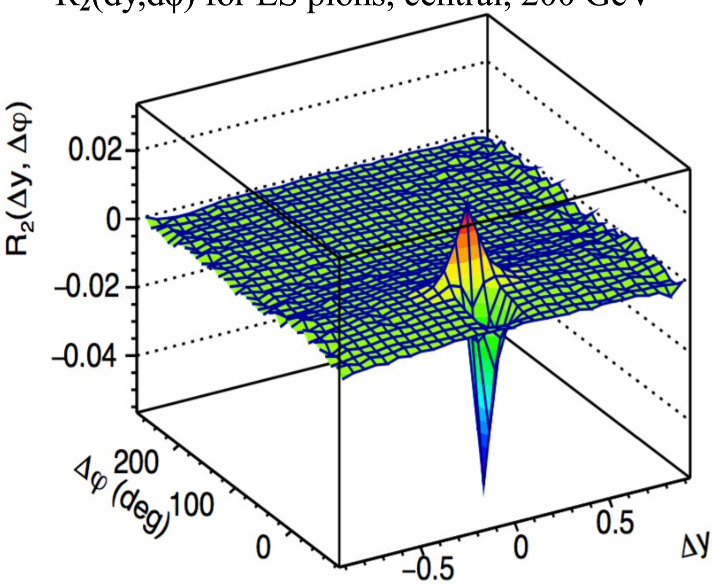
If K_k deviate from Poisson, one can locate the kinematical location of these deviations by looking at C_k





Zvtx-smearing pseudo-correlations:
C_k **require** "Zvtx-averaging" over narrow (2cm) bins.

R₂(dy,dϕ) for LS pions, central, 200 GeV



"track crossing" is a *pair inefficiency*
which may not be entirely treated with some single-particle efficiency correction techniques

Efficiency corrections for CFs are a *lot* simpler…

```
rho2->Fill(dy,dphi,1.)
```

⟶

```
rho2->Fill(dy,dphi,1./ε[i]/ε[j])
```

The fluctuations are integrals of the correlations

multiplicity cumulants C_k

cumulant ratios compared lattice susceptibility ratios

critical point search via cumulant ratios

quantifying importance of different correlations processes

differential view of fluctuations

kinematic location of deviations from Poisson!

integration provides equivalent information

efficiency corrections are simpler

(Positive) correlations cause (excess) fluctuations

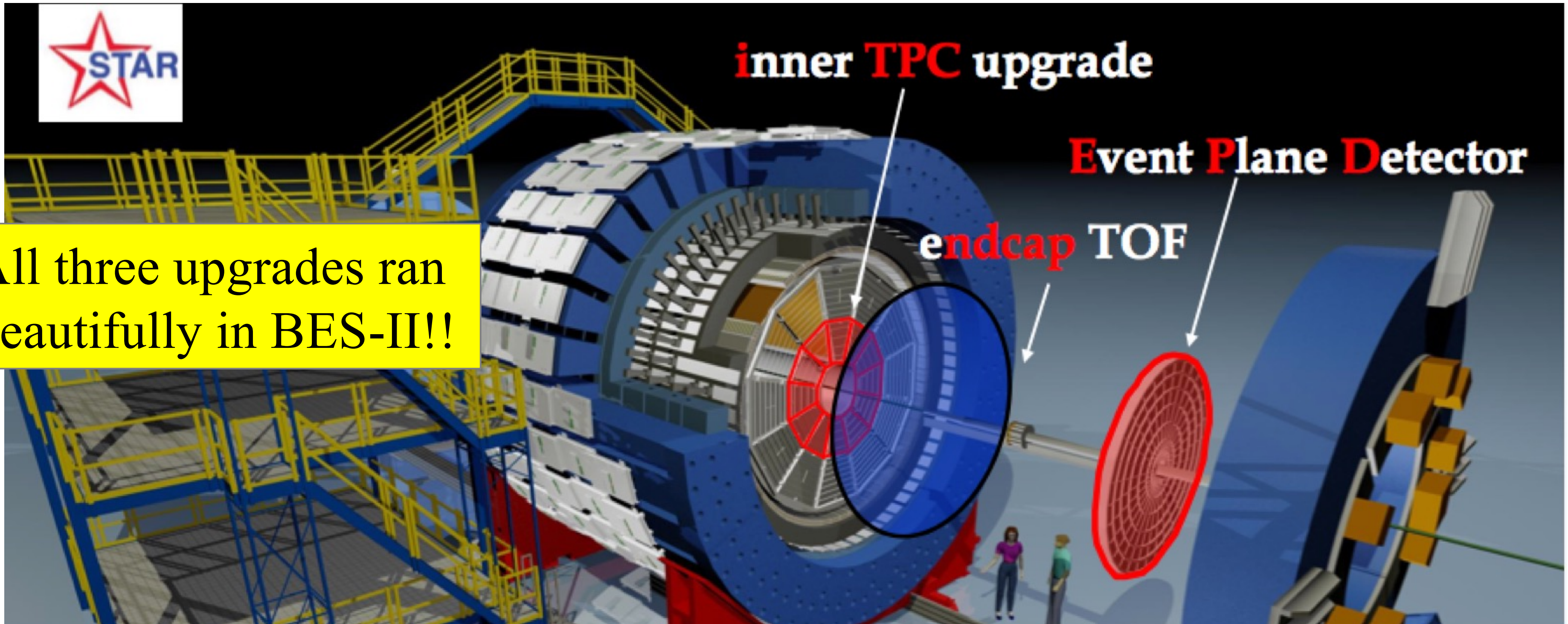
Let’s move on to the experimental data !

systematic uncertainties not yet calculated.

BES-II data has been collected!

Note: the following collider results were obtained with BES-I data (2010-2014, +2018 fxt)

Major upgrades since have widened the y and pt acceptance & improved the tracking & PID!



All three upgrades ran beautifully in BES-II!!

iTPC Upgrade:

- Rebuilds inner sectors of the TPC
- Continuous Coverage
- Extends η coverage from 1.0 to 1.5
- Improves dE/dx
- Lowers p_T cut-in from 125 to 60 MeV/c

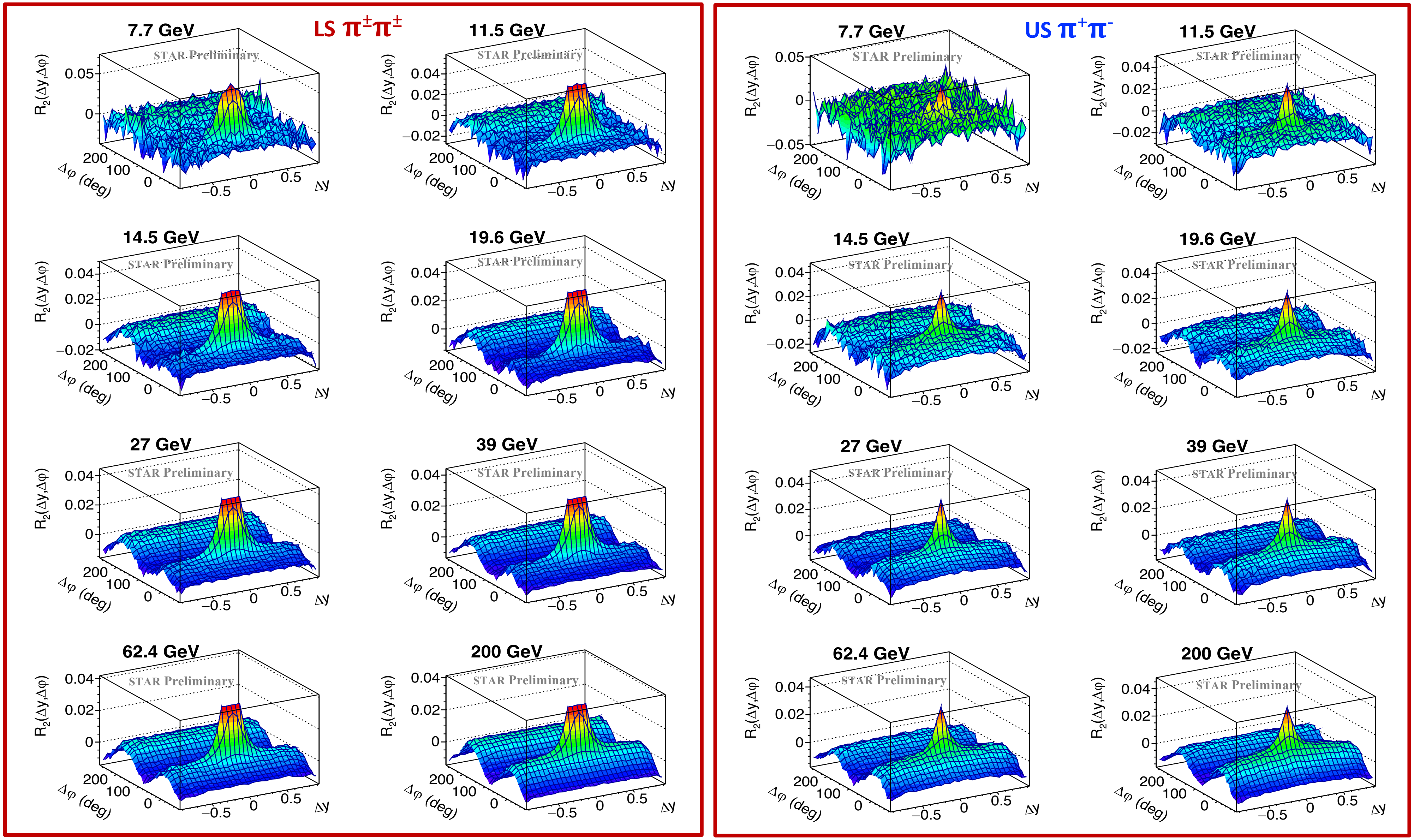
EndCap TOF Upgrade:

- PID at η = 0.9 to 1.5
- Allows higher energy range of Fixed-Target program
- Provided by CBM-FAIR

EPD Upgrade:

- Allows a better and independent reaction plane measurement critical to BES physics
- Improves trigger
- Reduces background

2-pion Correlations (30-40% central)



STAR, Phys. Rev. C 101, 014916 (2020)

two-pion correlations show very strong short-range peak at ($\Delta\phi,\Delta y$=0) on top of strong elliptical flow

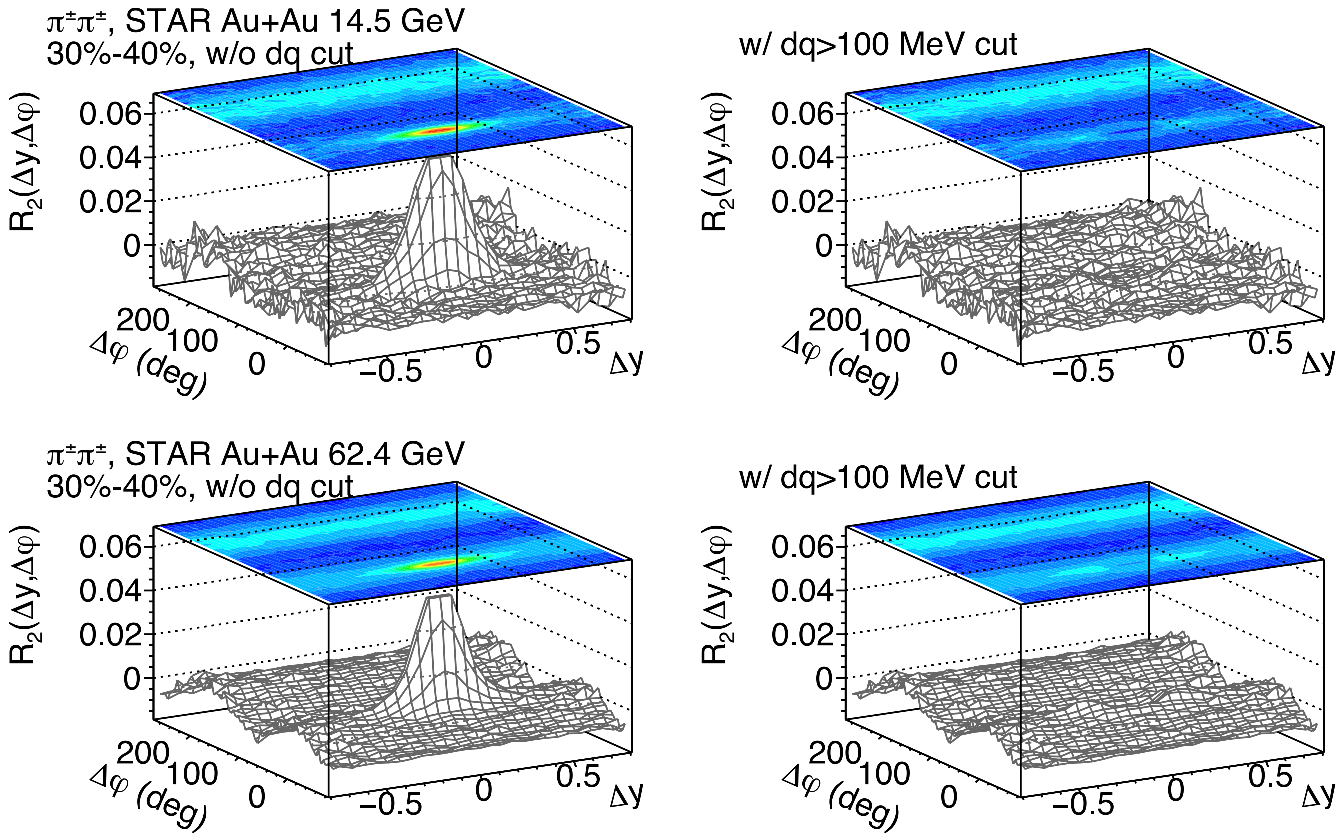
SRC: femtoscopy vs. minijets

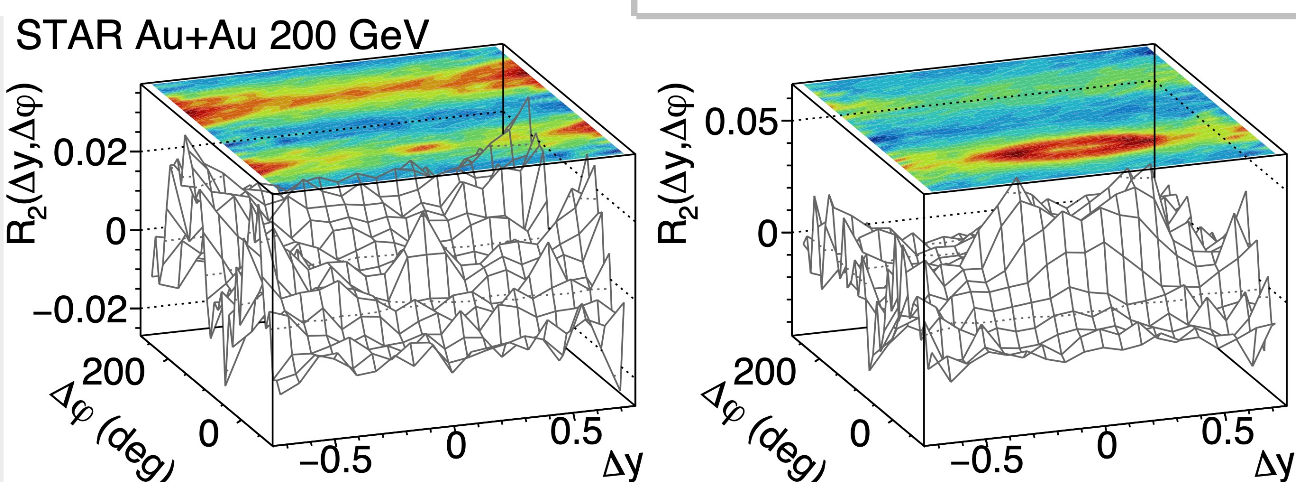
STAR, Phys. Rev. C 101, 014916 (2020)

If the big peak is femtoscopic, then it should disappear with a cut of *e.g.* $d\boldsymbol{p} > 100$ MeV.

and it *does*!

The pion SRC in our data is entirely femtoscopic.
($0.2 < p_T < 2.0$ GeV)

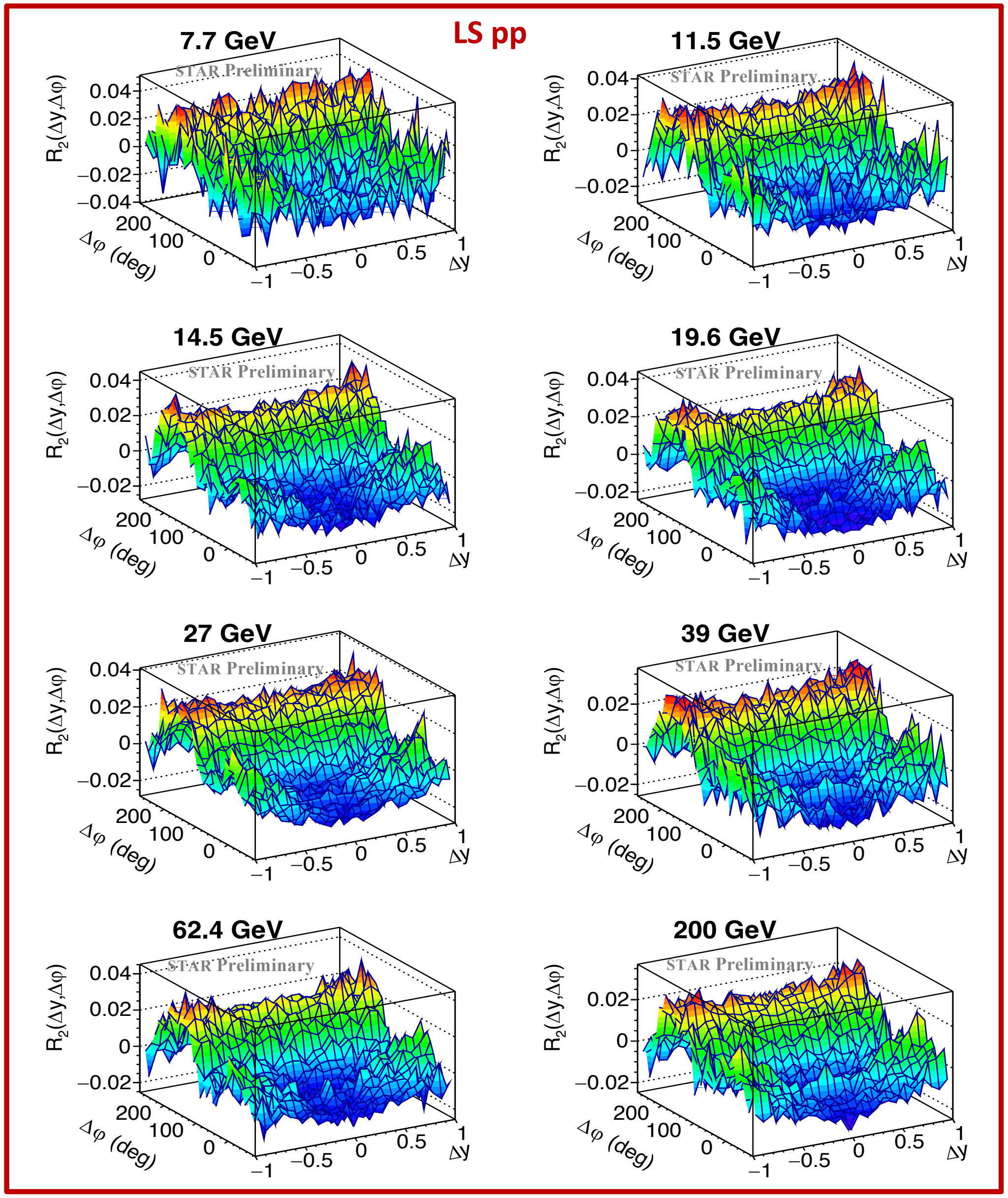


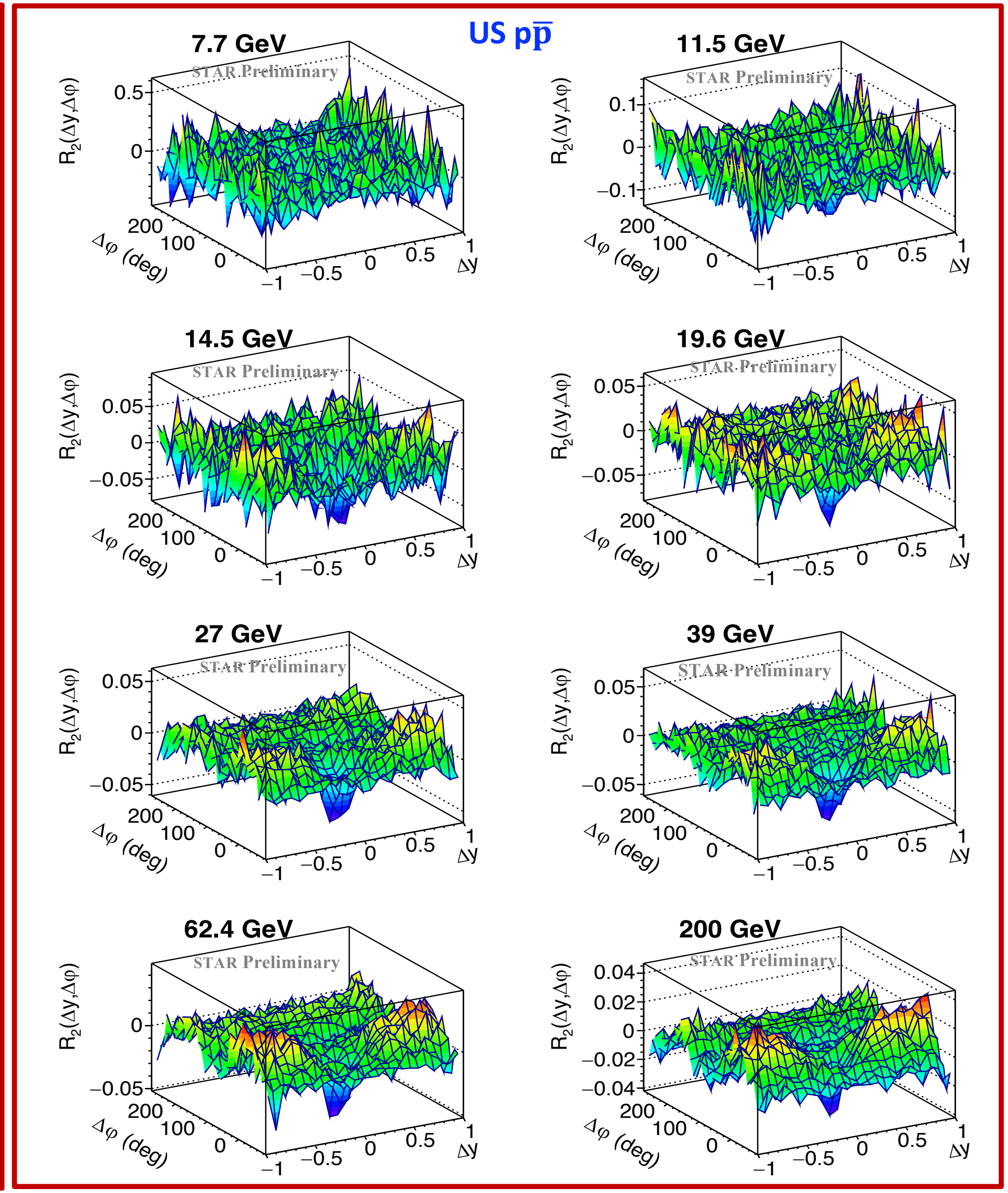


$K^{\pm}K^{\pm}$ $K^{\pm}K^{\mp}$

in K^+K^- correlations, we can clearly see $\phi \rightarrow K^+ + K^-$

2-proton Correlations (30-40% central)

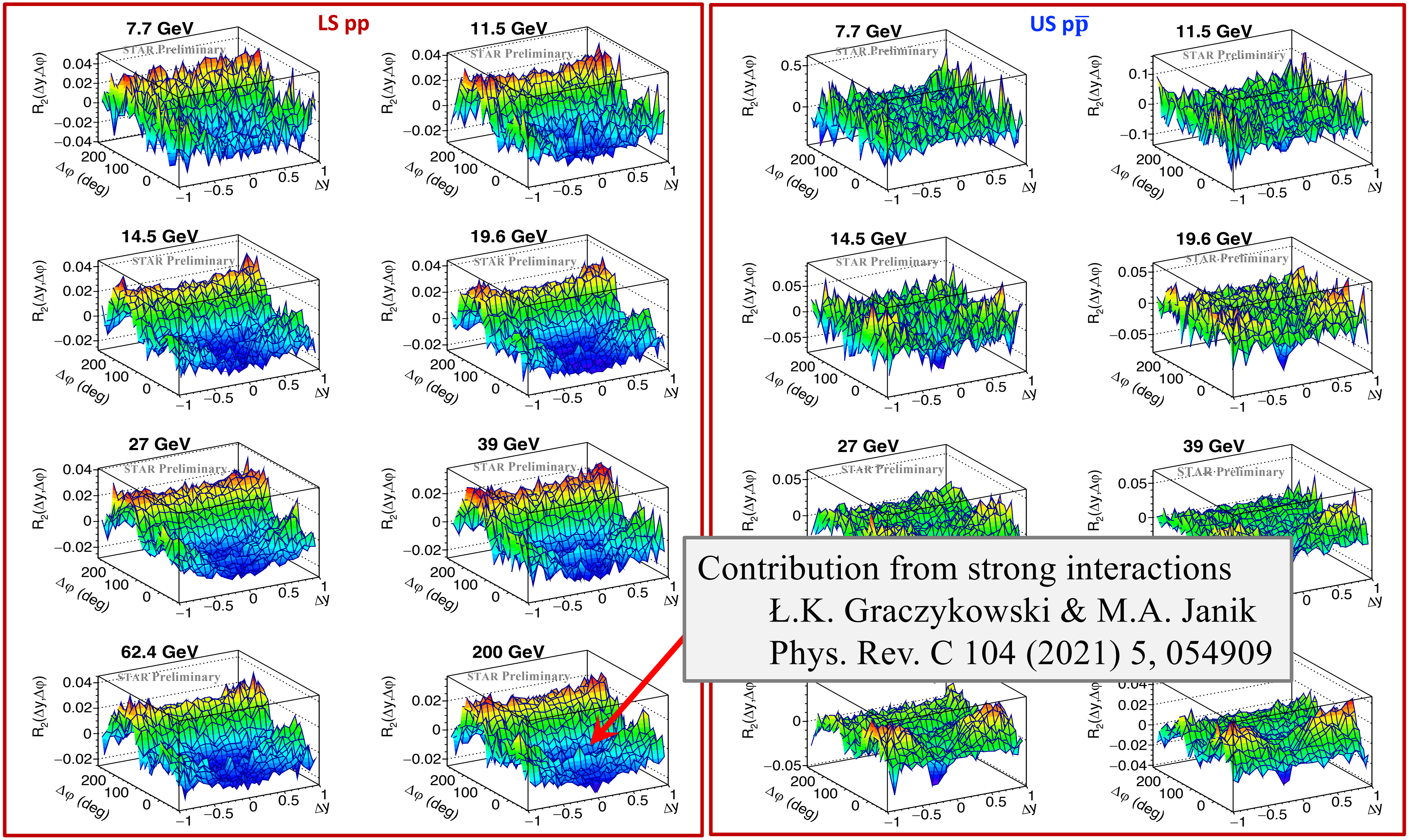




STAR, Phys. Rev. C 101, 014916 (2020)

Strong, nearly beam energy independent, near-side **anti**correlation in LS protons.
US results suggest proton annihilation, but LS proton results are much longer range…

2-proton Correlations (30-40% central)



Contribution from strong interactions
Ł.K. Graczykowski & M.A. Janik
Phys. Rev. C 104 (2021) 5, 054909

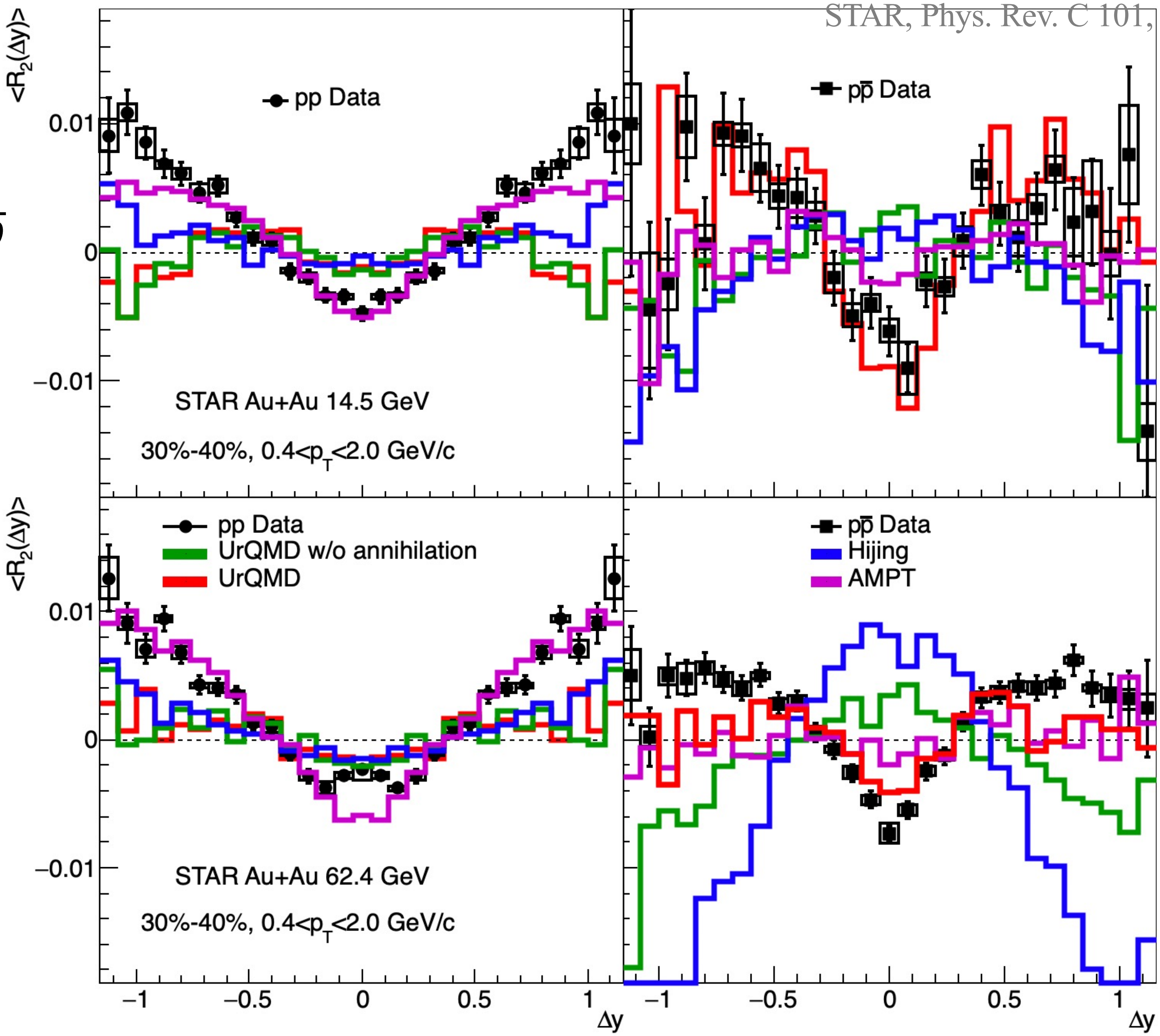
STAR, Phys. Rev. C 101, 014916 (2020)

Strong, nearly beam energy independent, near-side **anti**correlation in LS protons.
US results suggest proton annihilation, but LS proton results are much longer range…

Comparison of 2-proton R_2 with many different models

STAR, Phys. Rev. C 101, 014916 (2020)

like-sign
pp & $\overline{pp}$



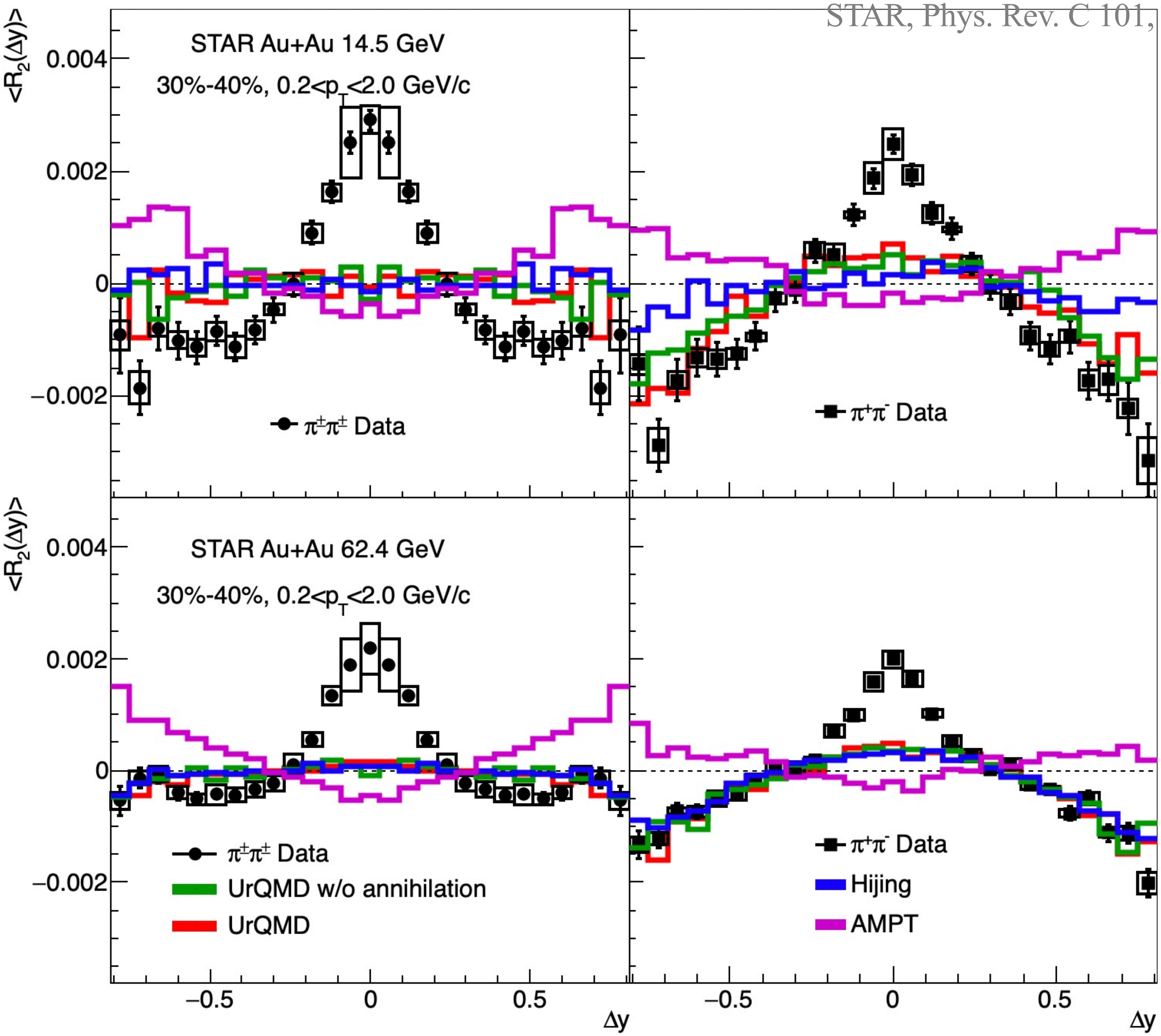
unlike-sign
$p\bar{p}$

None of these models reproduce the observed 2-particle correlations

Comparison of 2-pion R_2 with many different models

STAR, Phys. Rev. C 101, 014916 (2020)

like-sign $\pi^{\pm}\pi^{\pm}$



unlike-sign $\pi^{\pm}\pi^{\mp}$

None of these models reproduce the observed 2-particle correlations

Light nucleus correlation functions

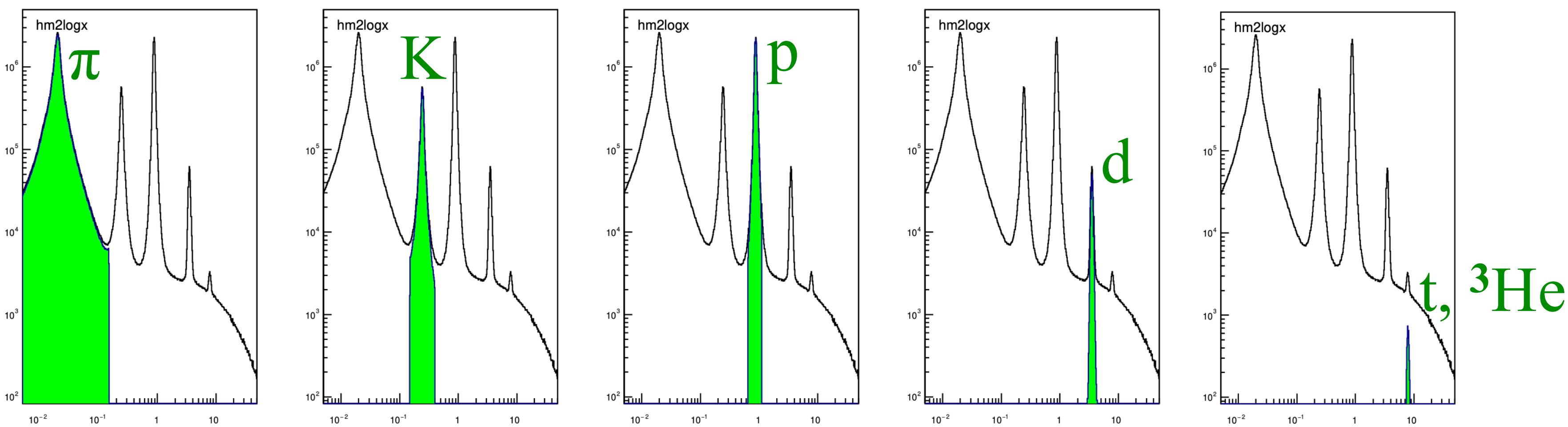
STAR, Phys. Rev. C 101, 014916 (2020)
Bzdak *et al.*, Phys. Rev. C 95, 054906 (2017)

Two-proton CFs in collider mode data are *negative.*

If nuclei are coalesced from nucleons, do nucleus CFs follow the nucleon CFs?

As CP signals go, my impression is that
we’re looking for beam-energy-localized enhanced baryon-clustering…

Light nuclei are clusters of baryons. Do light nuclei exhibit enhanced correlations?



start with results on light nucleus CFs in “collider” mode: $7.7 \leq \sqrt{s_{\mathrm{NN}}} \leq 200$

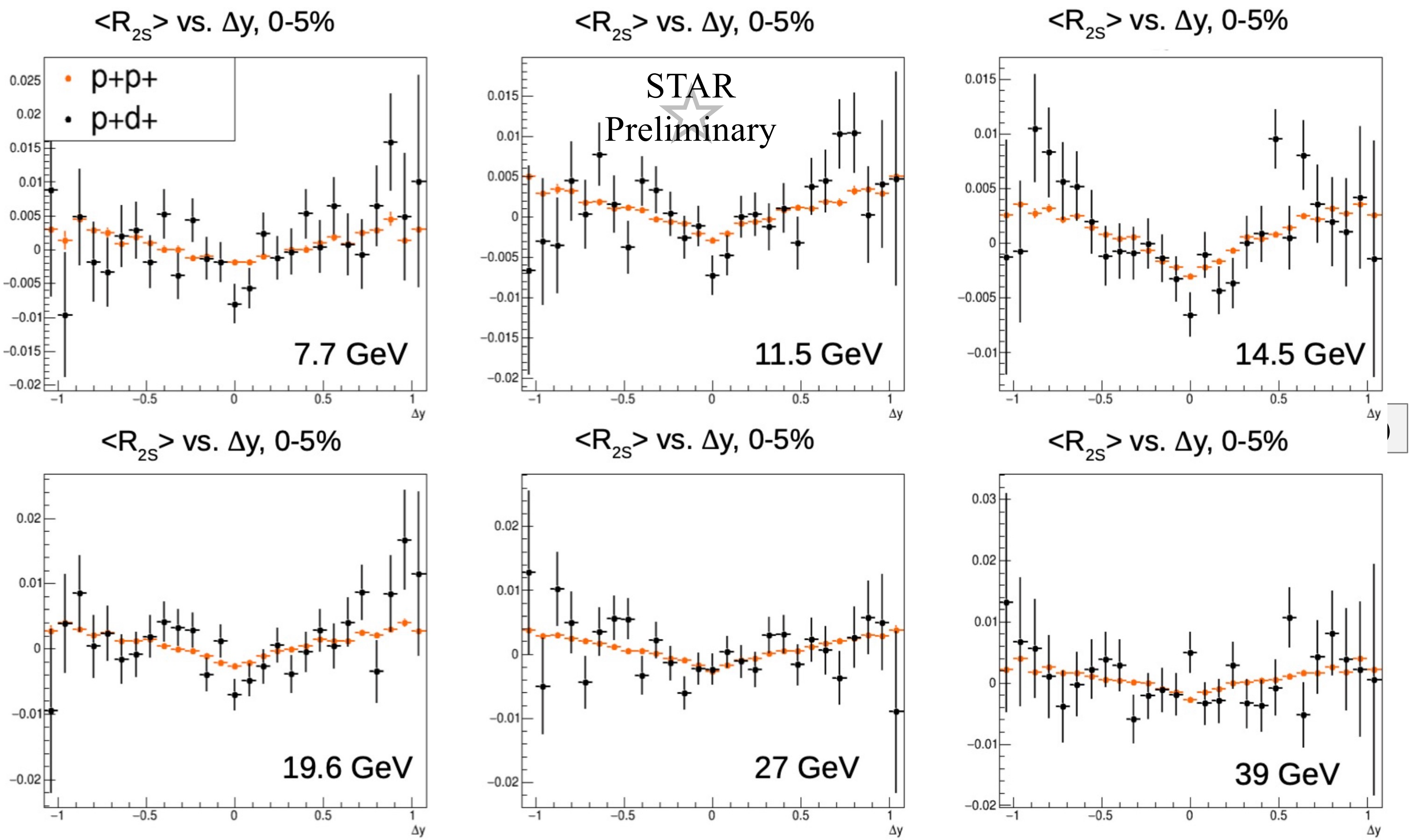
then turn to light nucleus CFs in “fixed target” mode: $\sqrt{s_{\mathrm{NN}}} = 3.05\ \mathrm{GeV}$

pp and pd R_{2S}(dy) for Au+Au, 0-5%, BES-I data, Pt/A>0.4 GeV

note: collider mode N_A<<1

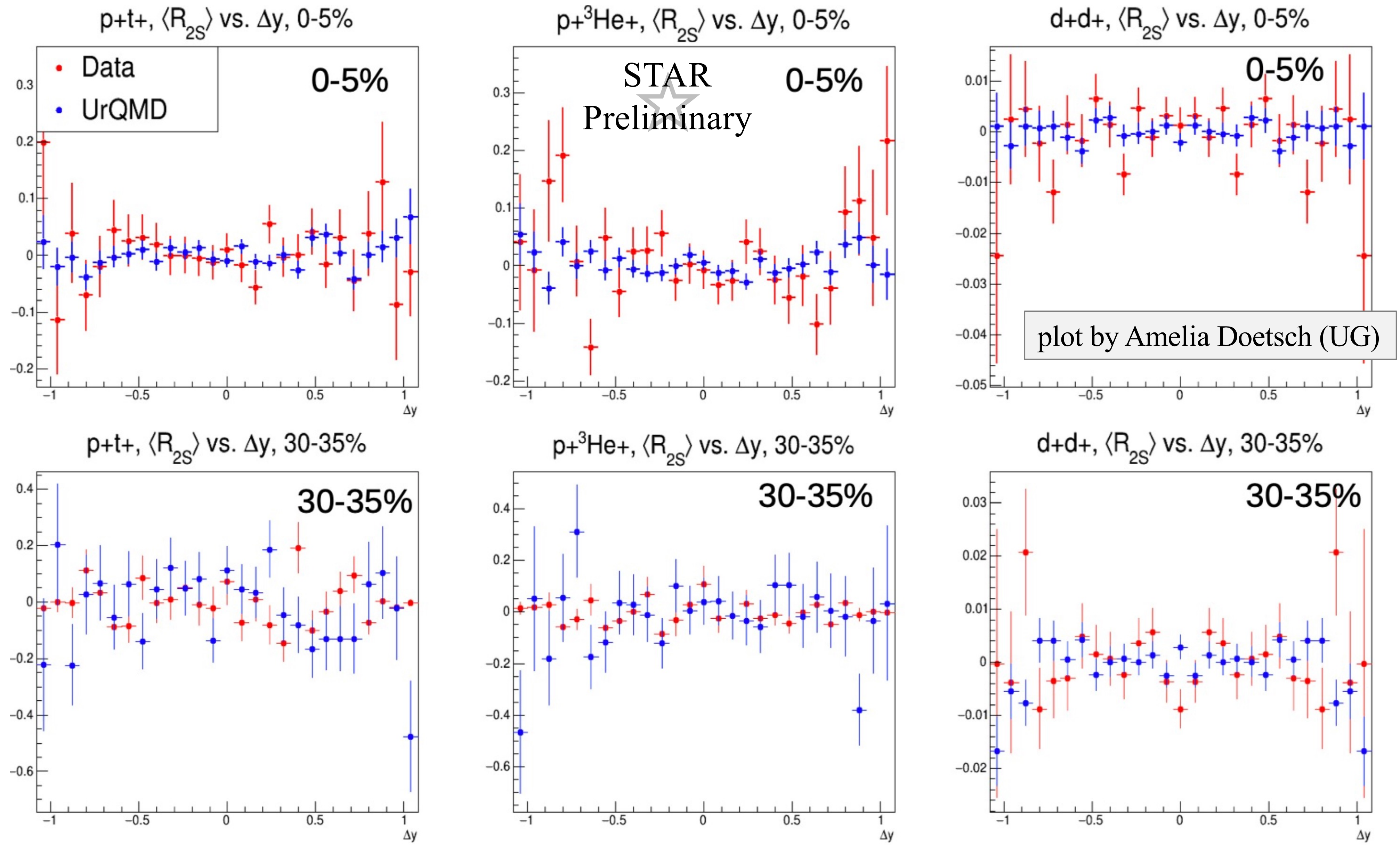
$$R_{2S} = R_2 - R_2^{base}$$

$$R_2^{base} = (\langle n_1 n_2 \rangle)/(\langle n_1 \rangle \langle n_2 \rangle) - 1$$
$$R_2^{base} = \langle n(n-1) \rangle / \langle n \rangle^2 - 1$$



Collider mode: pp and pd correlations per pair are consistent with each other
same near-side anticorrelation

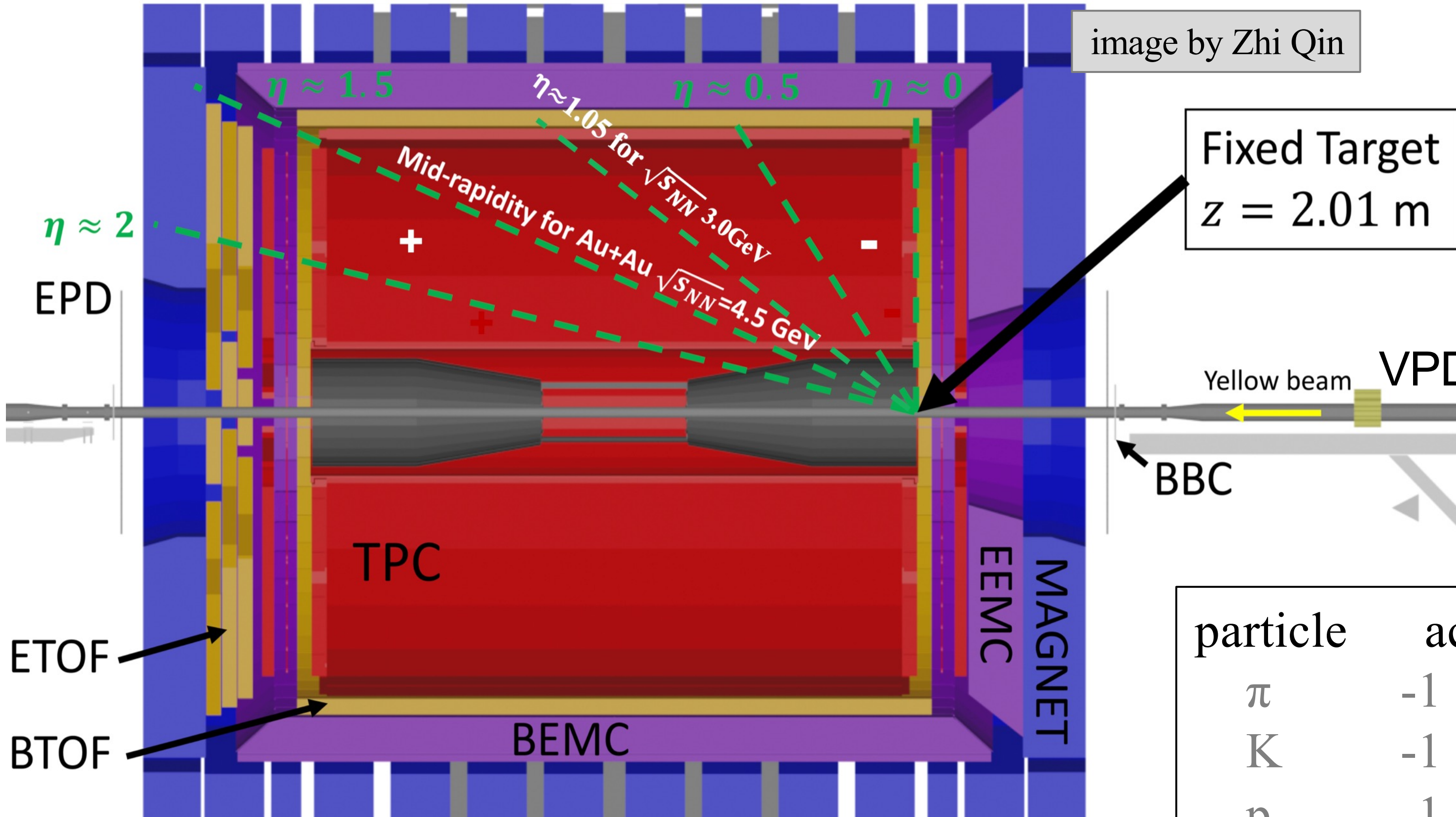
Comparison of pt, p³He, and dd R_{2S}(dy) at 14.5 GeV



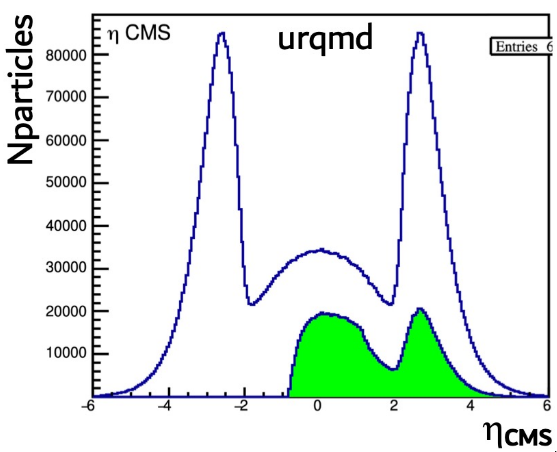
Collider mode: no significant correlation signal in heavier pairs
revisit with BES-II data

STAR in Fixed-Target mode

RHIC has a hard time providing colliding beams at energies less than 7.7 GeV…
To gain access to such low $\sqrt{s_{NN}}$, STAR installed a solid Au target at the edge of the TPC:



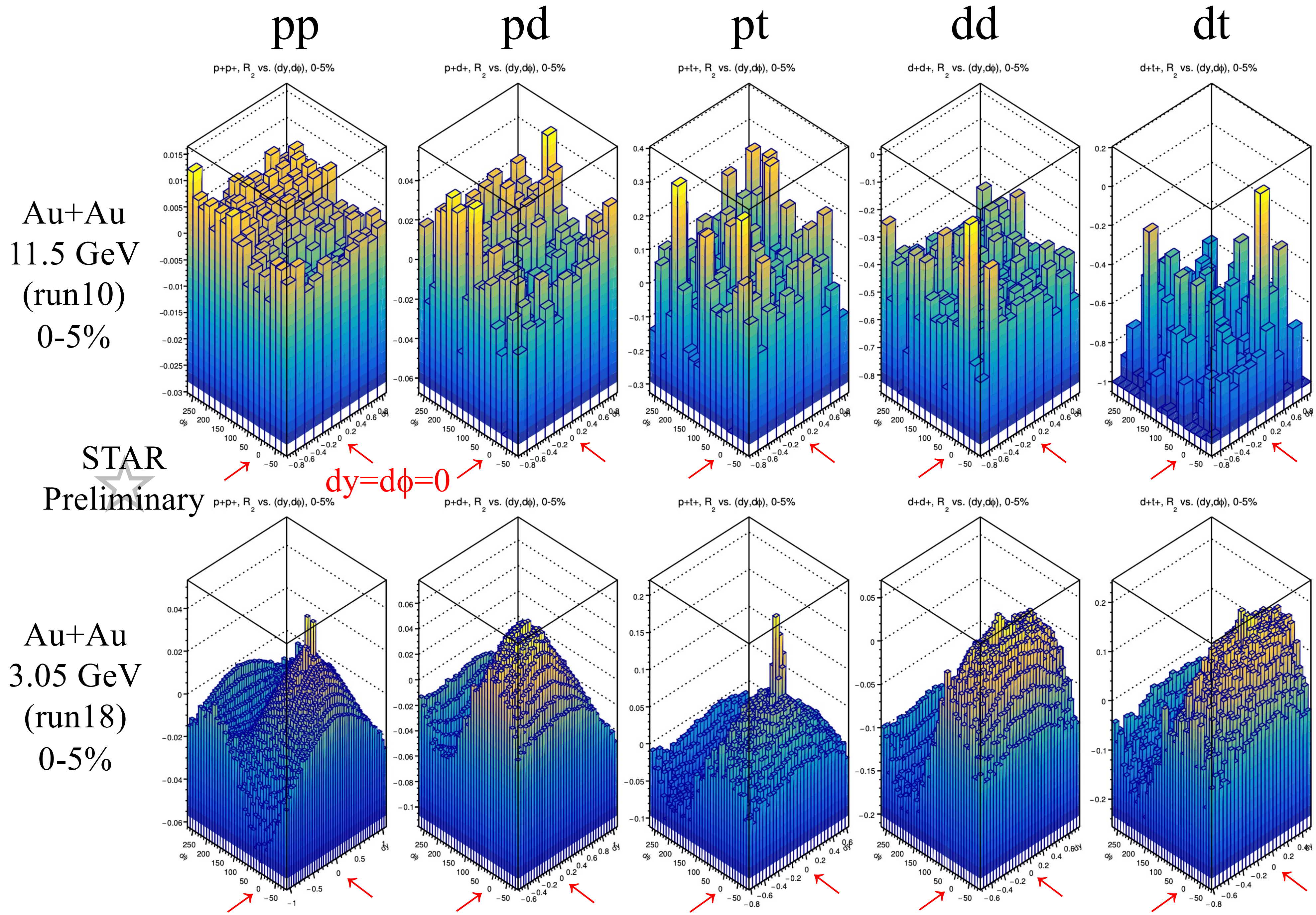
particle	acceptance
π	$-1 < y < 0.4$
K	$-1 < y < 0.2$
p	$-1 < y < 0.1$
d	$-1 < y < -0.2$
t	$-1 < y < -0.1$
^{3}He	$-1 < y < -0.1$



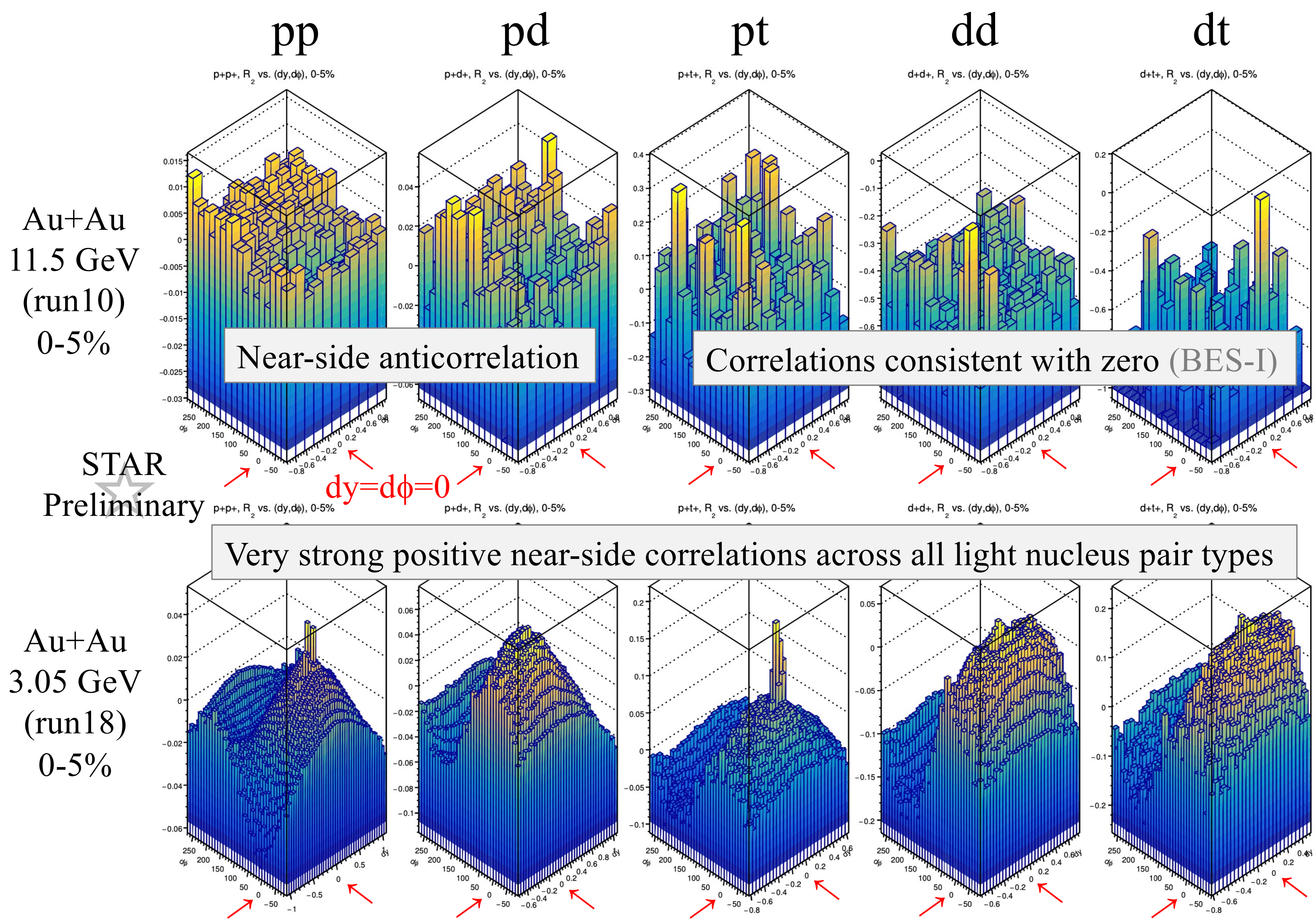
FXT Acceptance:

- Not symmetric about y_{CM}
- Non-zero for a *spectator source* for the first time in STAR

Light nucleus $R_2(dy,d\phi)$ at higher vs lower root-s

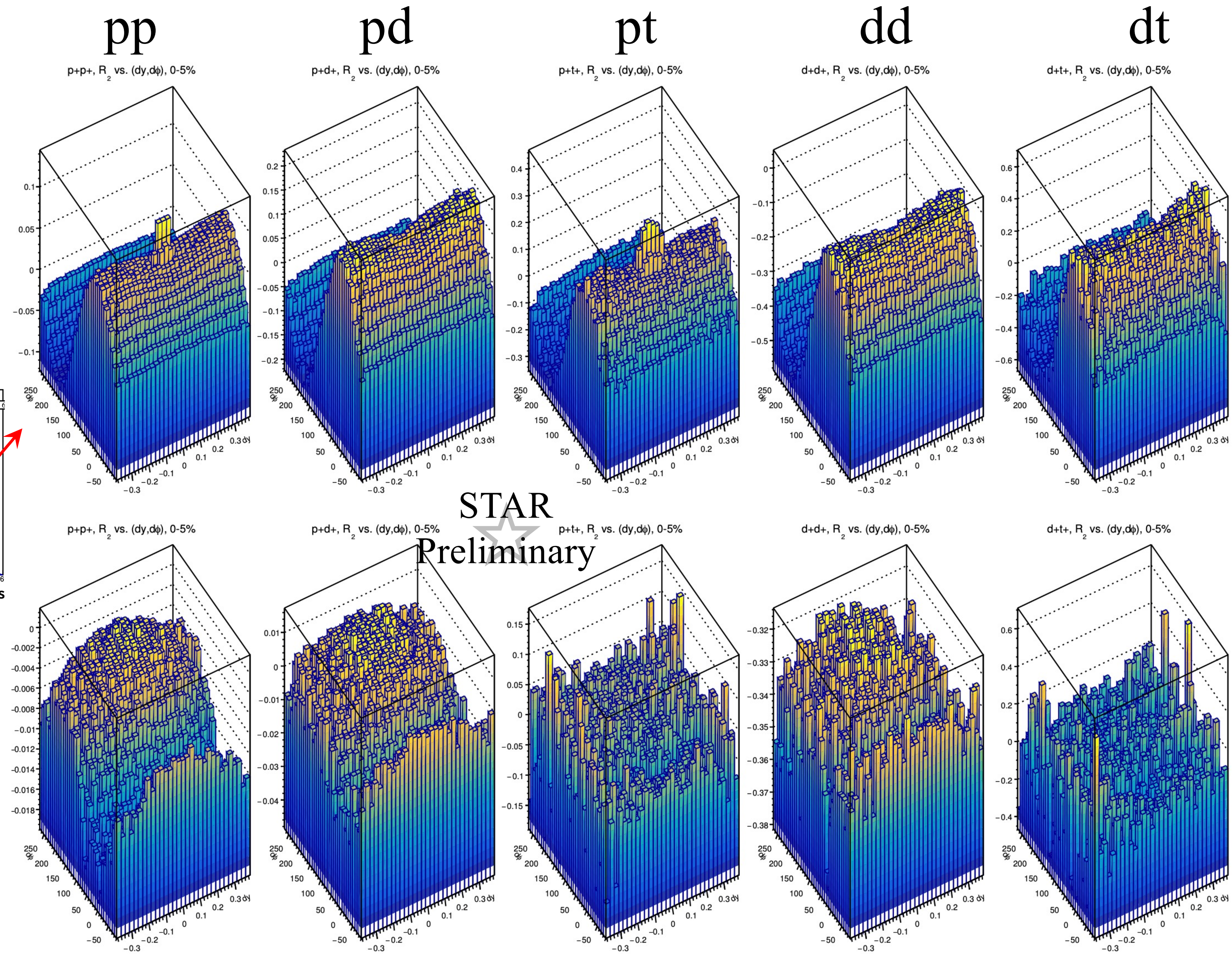


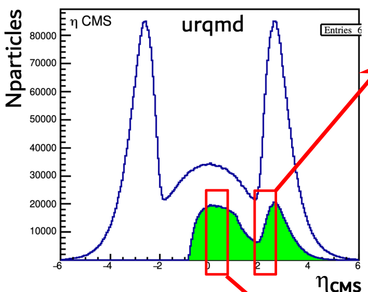
Light nucleus $R_2(dy,d\phi)$ at higher vs lower root-s



Light nucleus $R_2(dy,d\phi)$ in Spectator vs Participant rapidity windows

Au+Au
3.05 GeV
(run18)
0-5%
Spectator
$-0.6<y<-1.0$



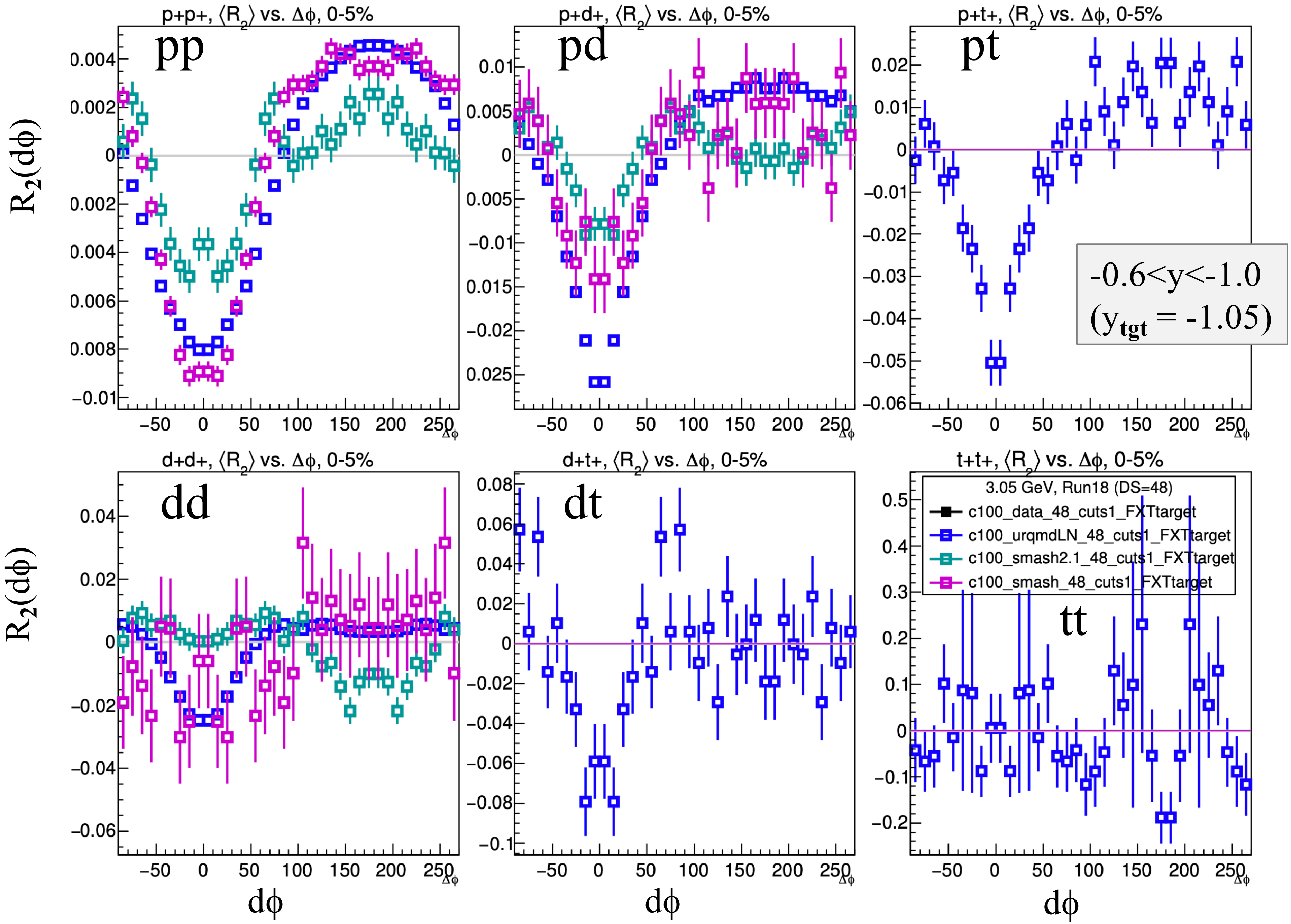


Au+Au
3.05 GeV
(run18)
0-5%
Participant

Strong *negative* near-side correlations at mid-rapidity, & *positive* for a spectator source

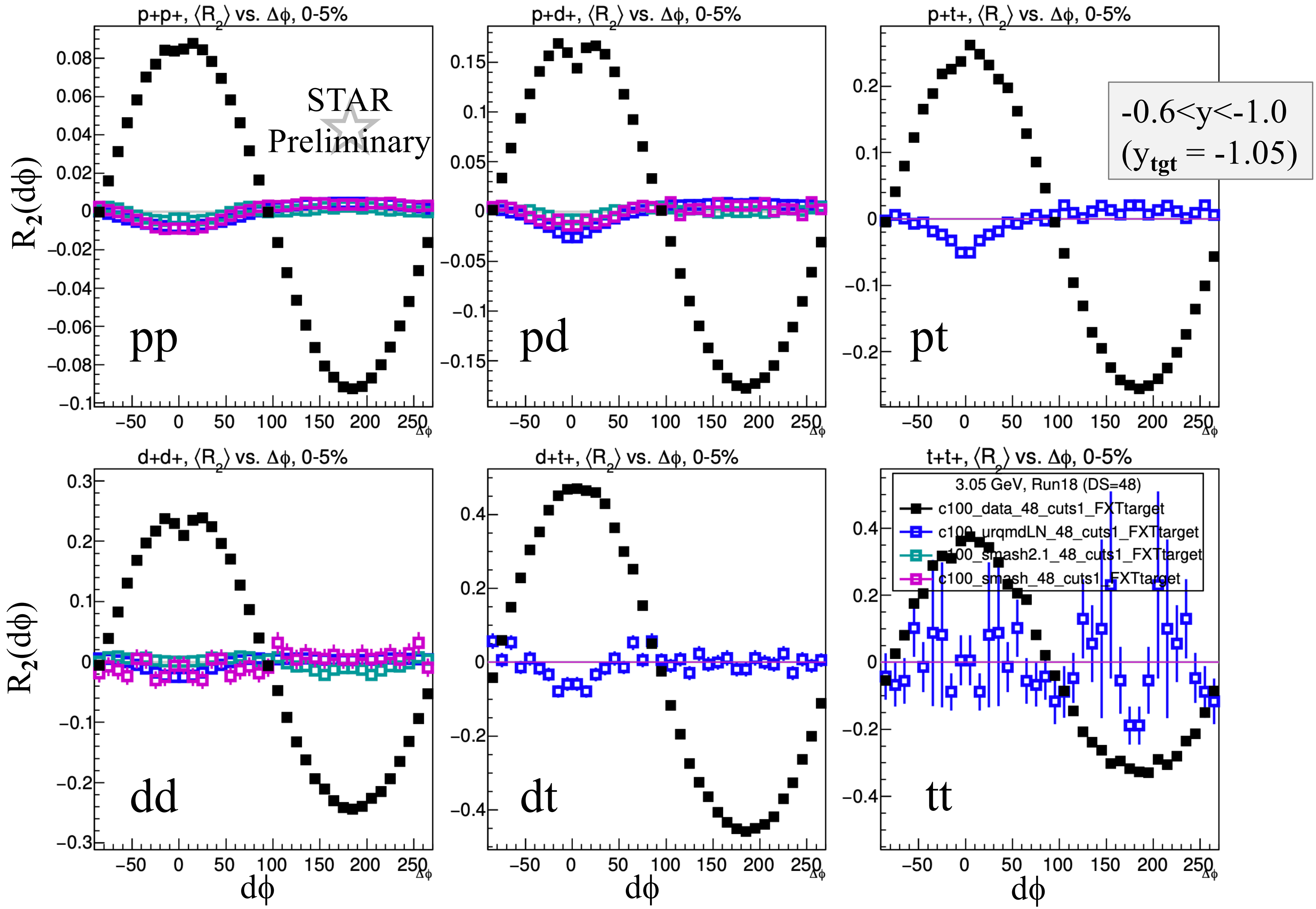
Light nucleus $R_2(d\phi)$ from models, Au+Au, 3.05 GeV, 0-5%, target rapidity

UrQMD3.3+coalescence Smash2.1 Smash2.2



Light nucleus $R_2(d\phi)$ with data, Au+Au, 3.05 GeV, 0-5%, **target rapidity**

Data UrQMD3.3+coalescence Smash2.1 Smash2.2



Light nucleus $R_2(d\phi)$ with data, Au+Au, 3.05 GeV, 0-5%, **target rapidity**

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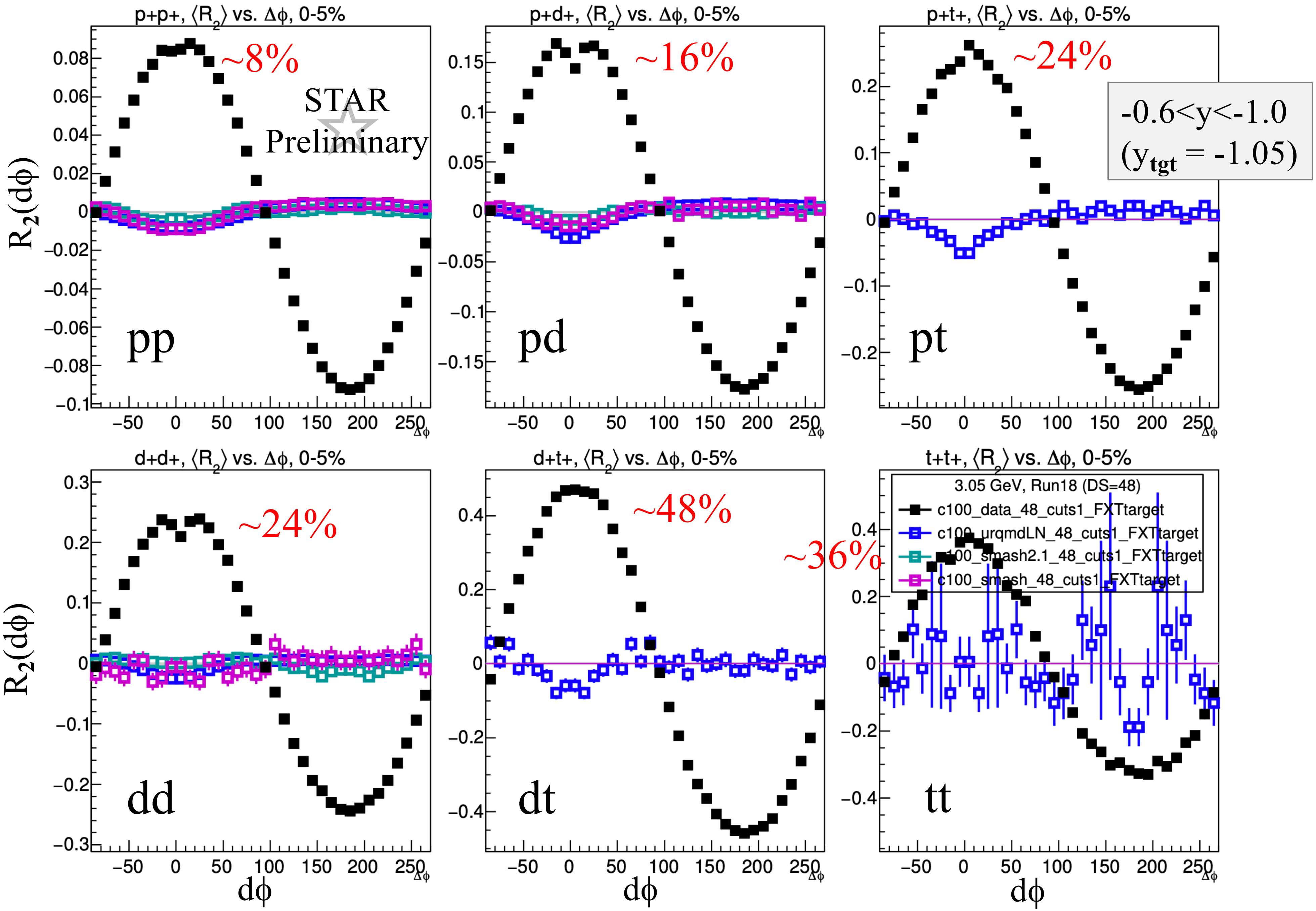


Summary and conclusions

k-particle (k=2,3,4) correlations functions: indicate the presence of any correlation sources inside the acceptance, despite massive combinatoric backgrounds

These integrate precisely into factorial cumulants, thus providing information both about correlations and fluctuations

The integrals of these CFs provide complementary information to fluctuations studies based e.g. on the cumulants of the multiplicity distribution.

We need to understand both the integrals of these CFs and the multiplicity cumulants, especially if unexpected positive correlations, *a.k.a.* excess fluctuations, are seen.

Results from STAR at $\sqrt{s_{NN}} > 7.7$ GeV (BES-I Collider mode) STAR, Phys. Rev. C 101, 014916 (2020)

- Strong near-side positive correlations in light meson pairs is femtoscopic (not minijets)
- Proton CFs in collider mode show an unexpected near-side anticorrelation
  - This anticorrelation per pair remarkably independent of beam-energy 7.7-200 GeV
- NEW pd and dd CFs follow the pp CFs at the same energy.
- Heavier light-nucleus pairs consistent with zero correlations (but BES-II data in hand!)

Results from STAR at $\sqrt{s_{NN}} = 3.05$ GeV (2018, fixed target)

see also talks by K. Mi, & J. Ball at QM22, and C. Fu at QPT21 !

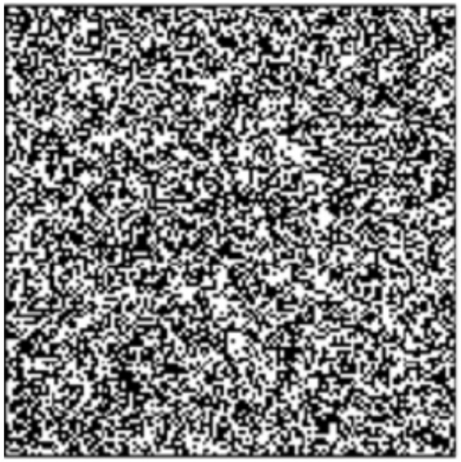
- Significant STAR acceptance for two sources in every event.
- NEW *Very* Strong near-side positive correlations across all proton and light-nucleus pairs.
- These strong correlations are coming mainly from a spectator source ("target" source).

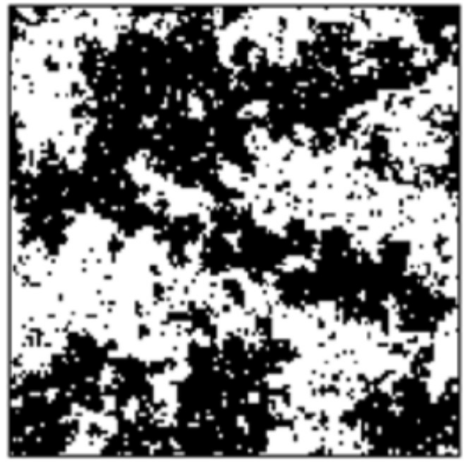
BACKUP SLIDES

Enhanced clustering at the critical point?

2D Ising model (spins)

T>Tc *T=Tc*

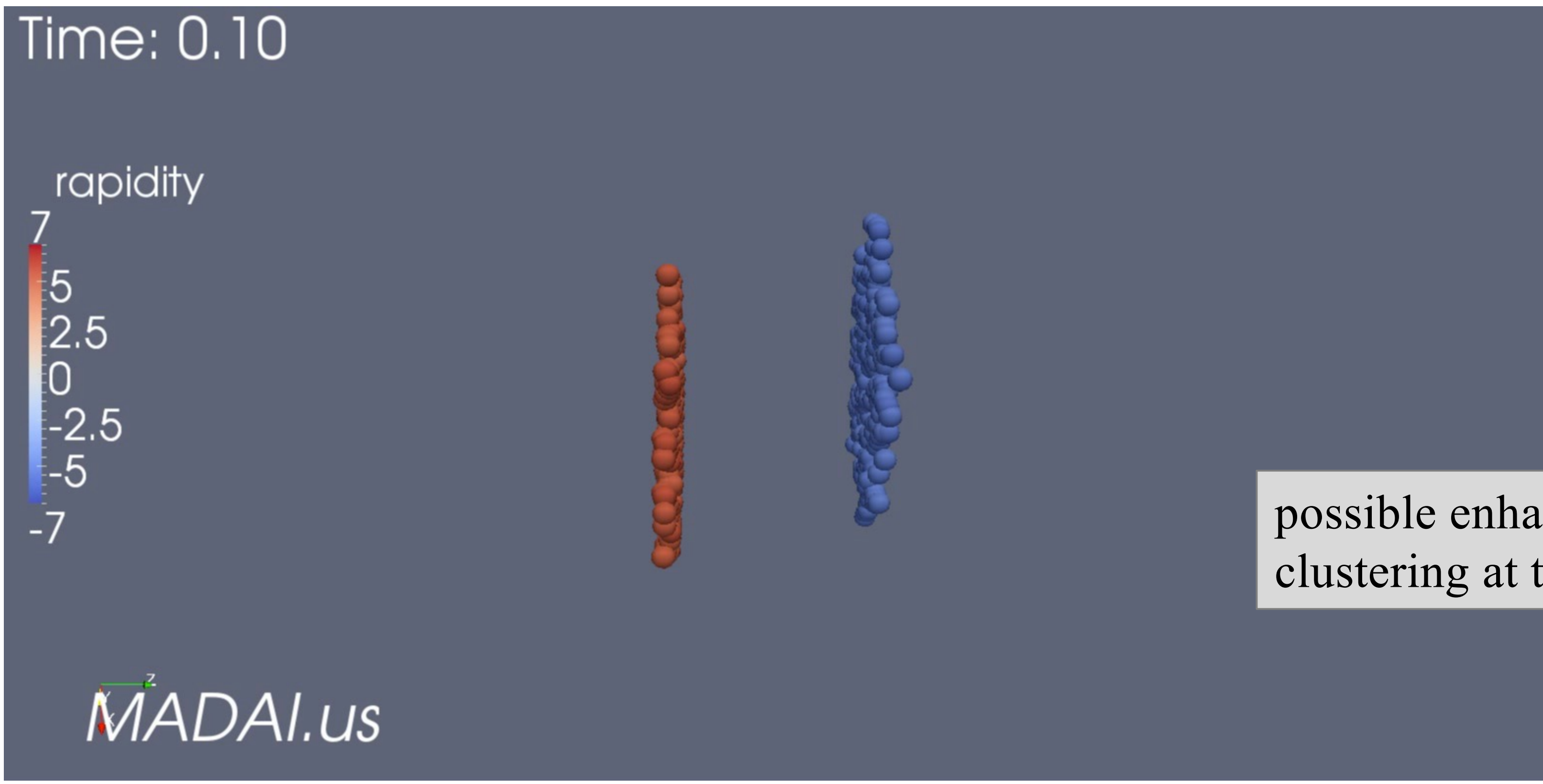




spin pattern at Tc becomes *fractal* (scale-invariant)

large domains of each phase

increased ***correlation length***



possible enhanced clustering at the CP?

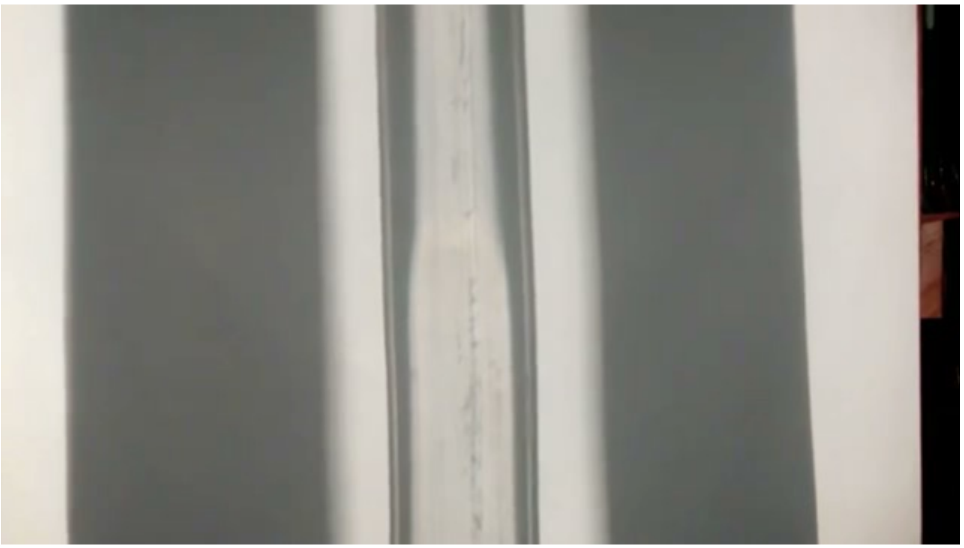
An experimental avenue to finding a possible Critical Point

So how could we find a Critical Point if it exists?

Assume that it's going to have the same basic features of other CPs

divergence of the susceptibilities, χ… *e.g.* magnetism transitions 0801.4256v2

divergence of the correlation lengths, ξ… *e.g.* critical opalescence



Brown University Undergraduate Physics Demonstration

liquid SF_6 at 37atm heated to ~43.9 C and then cooled

CO_2 near the liquid-gas transition

$T > T_C$ $T \sim T_C$ $T < T_C$

T. Andrews. Phil. Trans. Royal Soc., 159:575, 1869

M. Smoluchowski, *Annalen der Physik, 25 (1908) 205 - 226*

A. Einstein, *Annalen der Physik, 33 (1910) 1275-1298*

In the Nonlinear Sigma Model, the cumulants of the occupation numbers (integral=multiplicity) are also related to ξ…

the higher the order of the moment, the stronger the dependence on ξ…

M. Stephanov arXiv:0809.3450v1

$$\kappa_2 = \langle \sigma_0^2 \rangle = \frac{T}{V}\,\xi^2\,; \qquad \kappa_3 = \langle \sigma_0^3 \rangle = \frac{2\lambda_3 T}{V}\,\xi^6\,;$$

$$\kappa_4 = \langle \sigma_0^4 \rangle_c \equiv \langle \sigma_0^4 \rangle - \langle \sigma_0^2 \rangle^2 = \frac{6T}{V}\,[2(\lambda_3\xi)^2 - \lambda_4]\,\xi^8$$

"signal" of CP is then nonmonotic behavior of cumulants (ratios) *vs.* $\sqrt{s_{NN}}$

Multiplicity cumulants (or moments) are the Fluctuations

Experimentally: The average values of specific powers of deviates give cumulants & cumulant ratios (or moments and moments products)....

No. of particles in a single event...

Average No. of particles in all "similar" events...

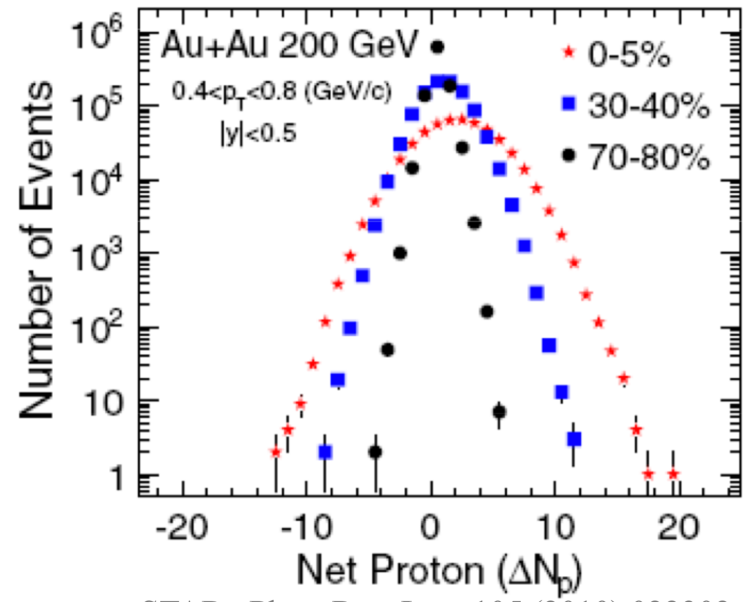
$$\delta x \equiv x - \langle x \rangle$$

$$\kappa_{2x} \equiv \langle\langle x^2 \rangle\rangle \equiv \langle\, (\delta x)^2\, \rangle$$

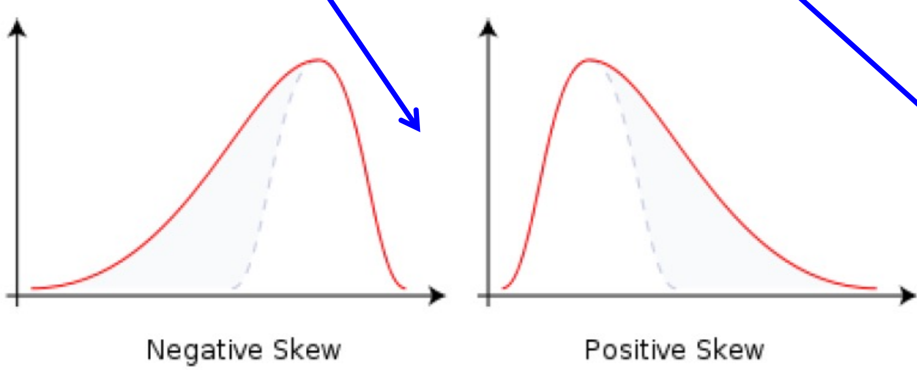
$$\kappa_{3x} \equiv \langle\langle x^3 \rangle\rangle \equiv \langle\, (\delta x)^3\, \rangle$$

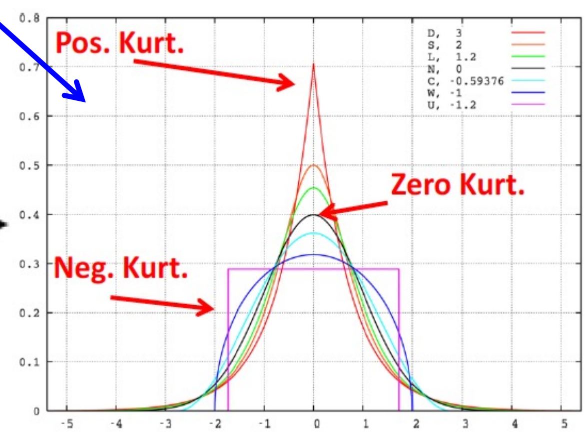
$$\kappa_{4x} \equiv \langle\langle x^4 \rangle\rangle \equiv \langle\, (\delta x)^4\, \rangle - 3\, \langle\, (\delta x)^2\, \rangle^2$$

$$\text{skewness} = \frac{\kappa_3}{\kappa_2^{3/2}}, \ \text{kurtosis} = \frac{\kappa_4}{\kappa_2^2}$$



STAR, Phys. Rev. Lett. 105 (2010) 022302





Particle Identification

Most common charged particles: pions (π), protons (p), and kaons (K)

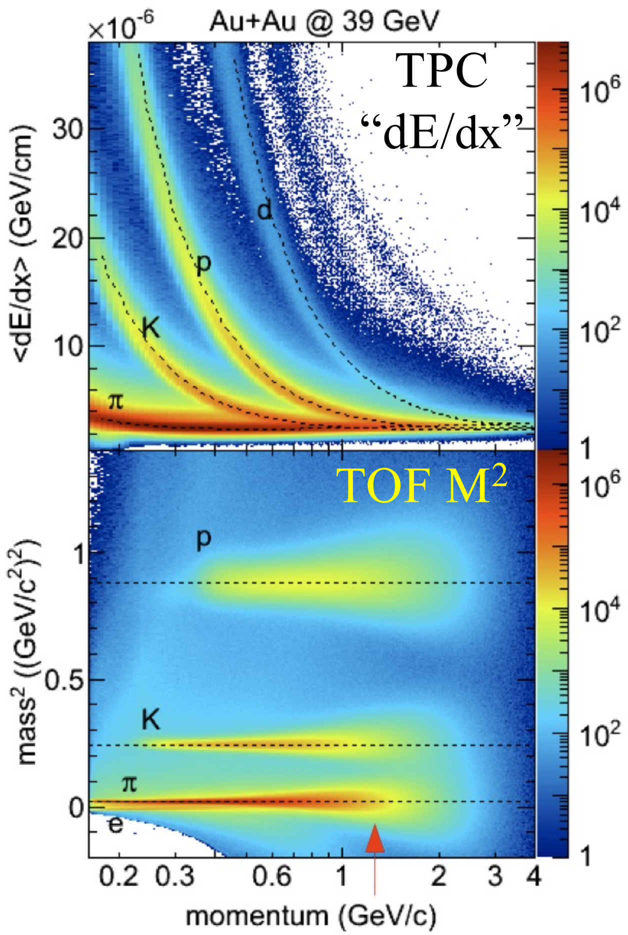
π and K are *mesons* (2 quarks), protons are *baryons* (3 quarks). (baryon number is conserved)

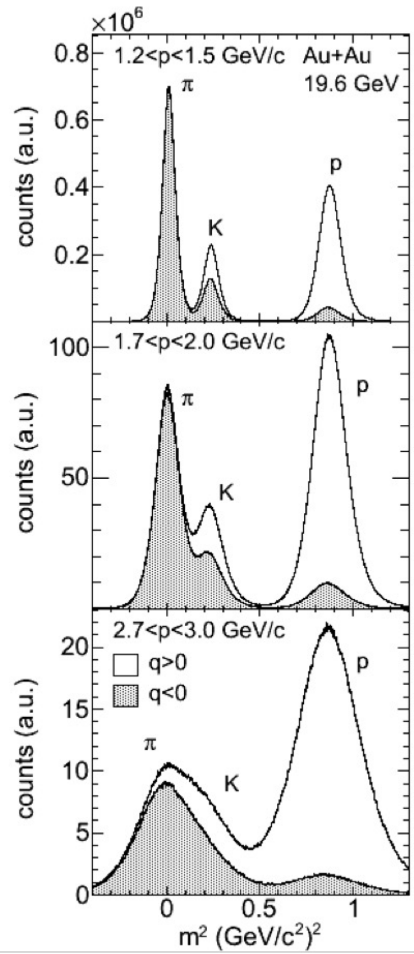
K contains *strangeness*, π and p do not.

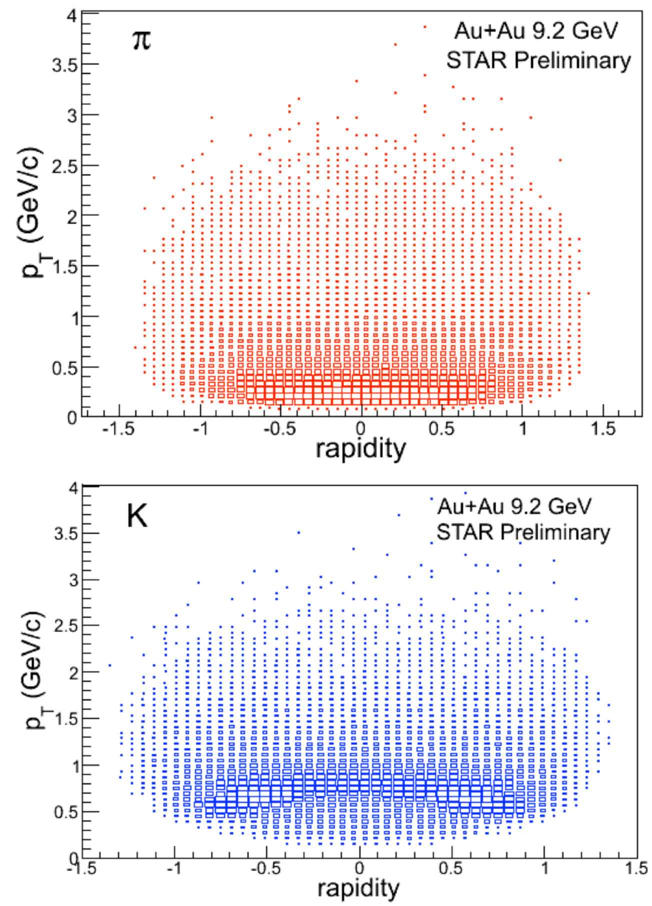
Identify tracks via TPC gas "dE/dx" or Time-of-Flight

TPC → $S = \beta c t$ ← TOF

TPC → $p = m\gamma\beta c$







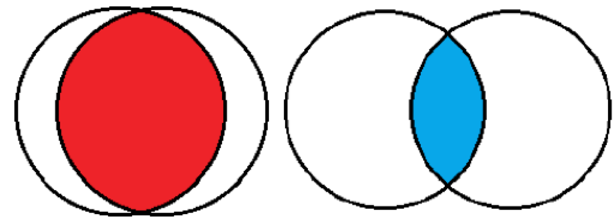
High efficiency particle identification from TPC and TOF, wide acceptance: $|\eta| \leq 1$ & 2π in φ

Centrality: how "head-on" was the collision

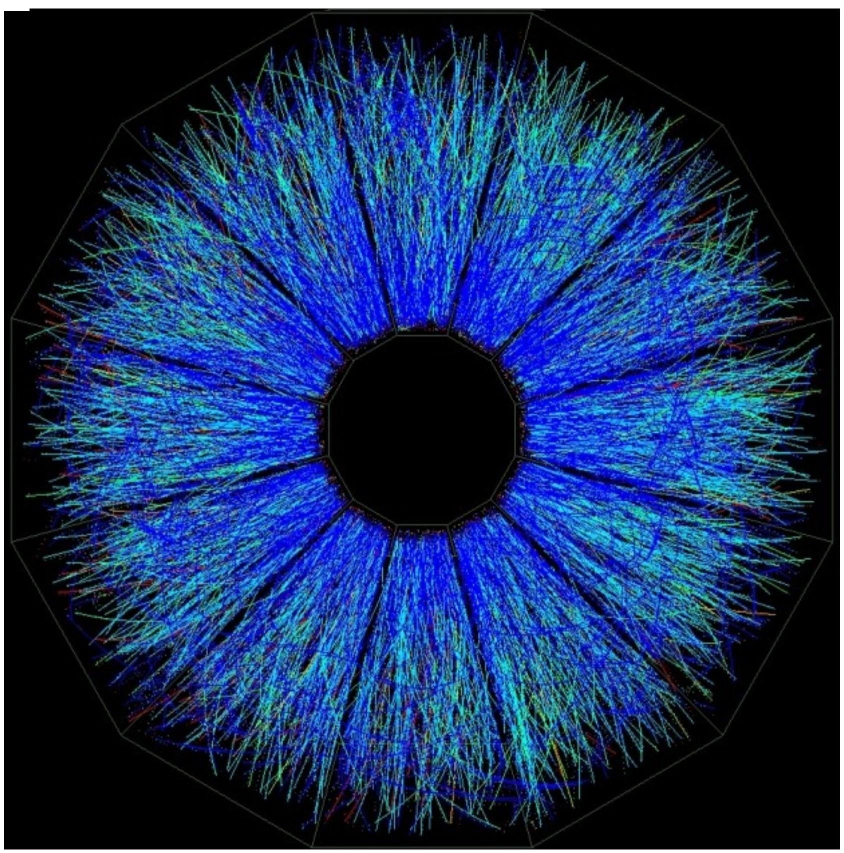
Impact parameter, b, is inferred from track multiplicities and a so-called Glauber calculation...

It is a very small distance! $0 \leq b \leq 2R_{Au} \sim 14\times10^{-15}$ m

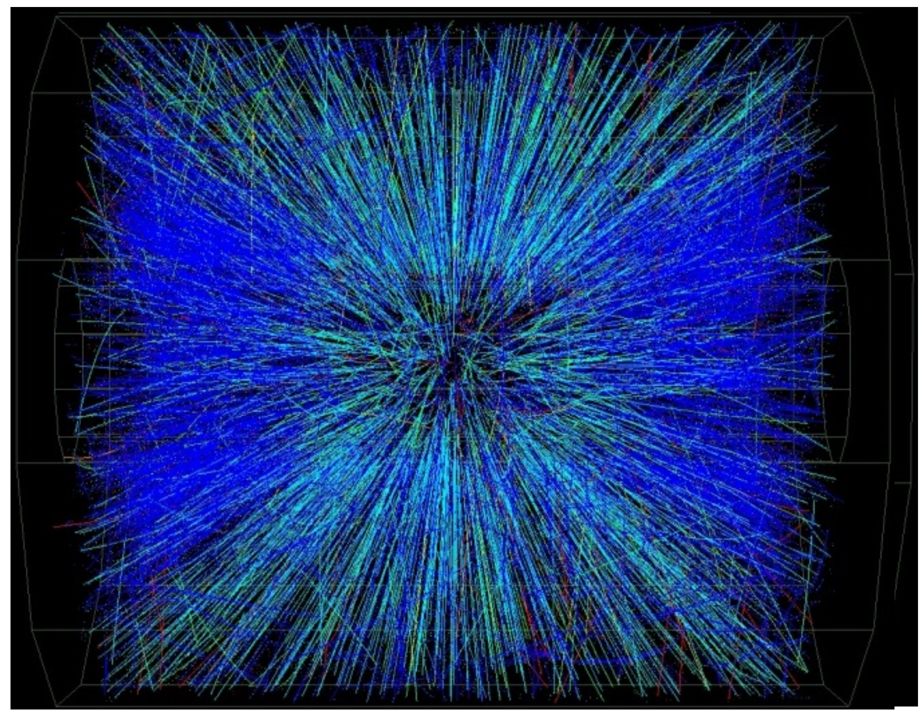
Looking along the beam axis:



STAR Online Event Display



front view: x-y plane



side view: x-z plane

Peripheral Event

Central Event

Note! We had to sacrifice half of the TPC to measure the centrality. STAR will be upgraded!