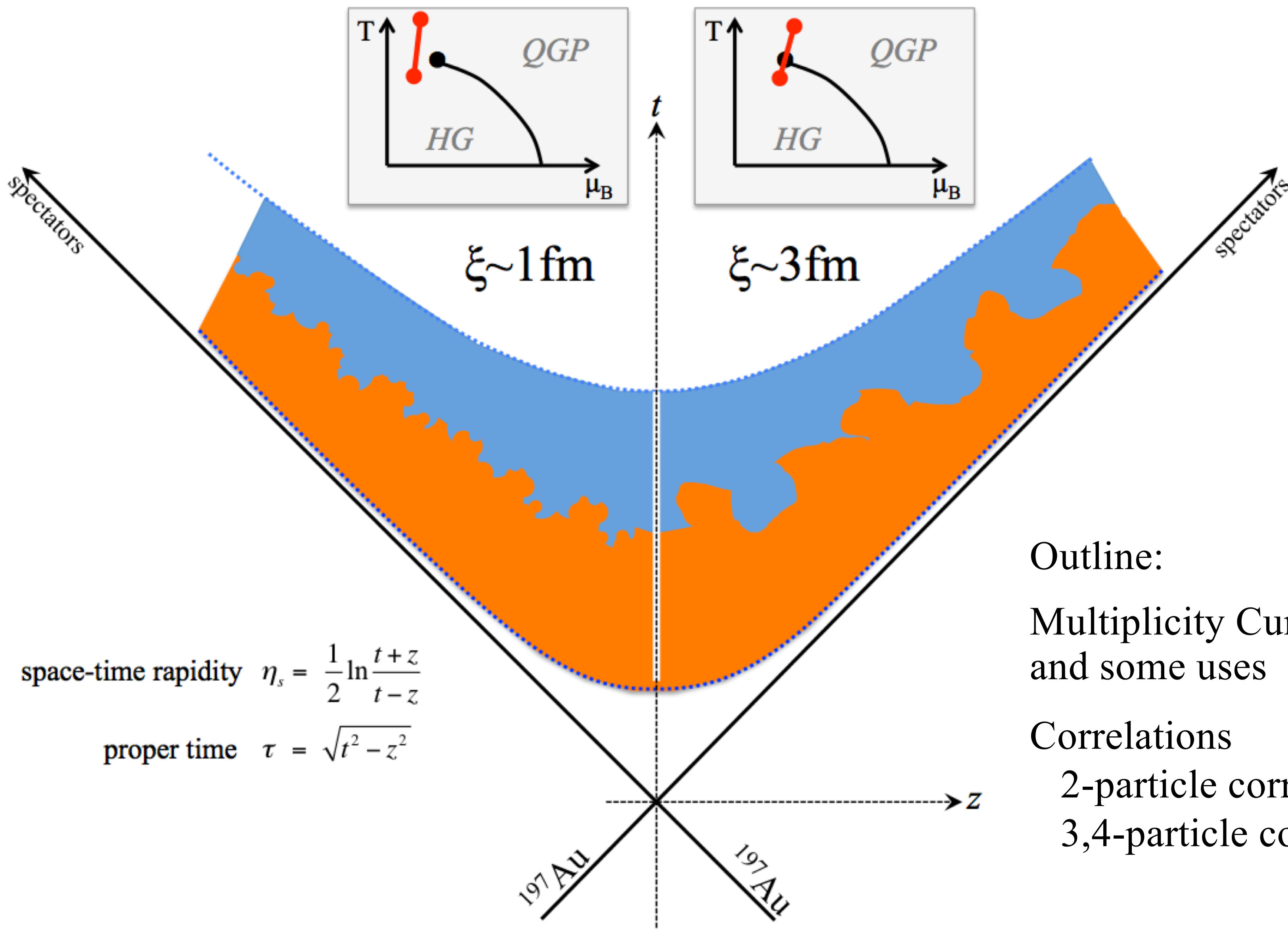
Fluctuations and Correlations in the STAR BES-I Data

W.J. Llope, Wayne State University



space-time rapidity $\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$

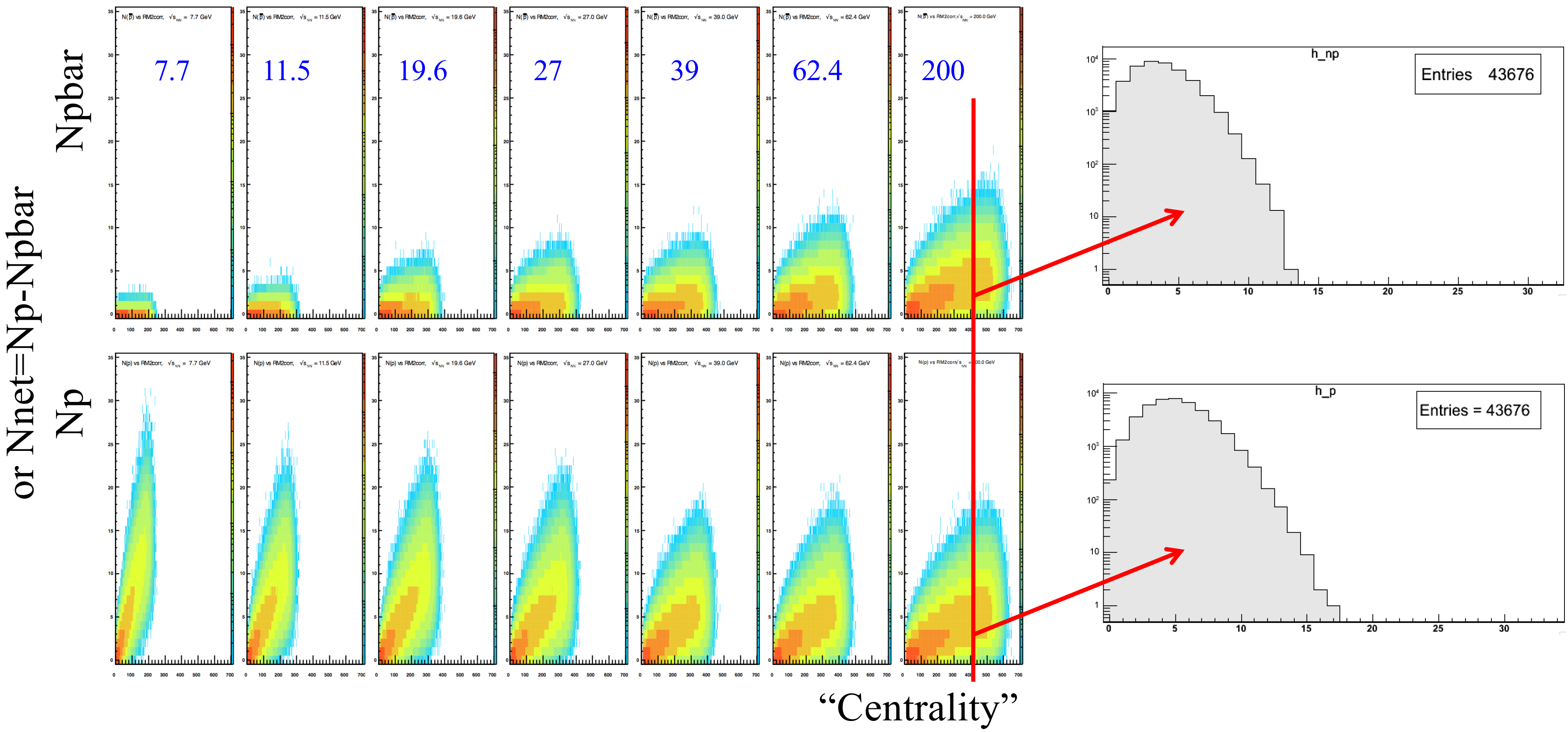
proper time $\tau = \sqrt{t^2 - z^2}$

Outline:

Multiplicity Cumulants and some uses

Correlations
- 2-particle correlations
- 3,4-particle correlations

Multiplicity Cumulants (K_k)



$$K_1 = \langle x \rangle \qquad \delta x = x - \langle x \rangle$$

$$K_2 = \langle \delta x^2 \rangle$$

$$K_3 = \langle \delta x^3 \rangle$$

$$K_4 = \langle \delta x^4 \rangle - 3\langle \delta x^2 \rangle^2$$

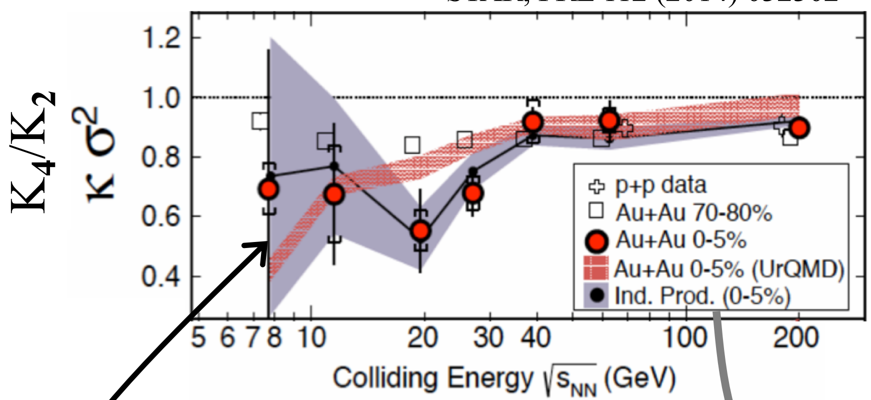
Efficiency corrections assuming efficiencies are binomially distributed...

STAR calculates weighted-averages of K_k and K-ratios within 5%- or 10%-wide centrality bins

Net-proton multiplicity cumulant ratios...

STAR net-p multiplicity cumulant ratios

STAR, PRL 112 (2014) 032302



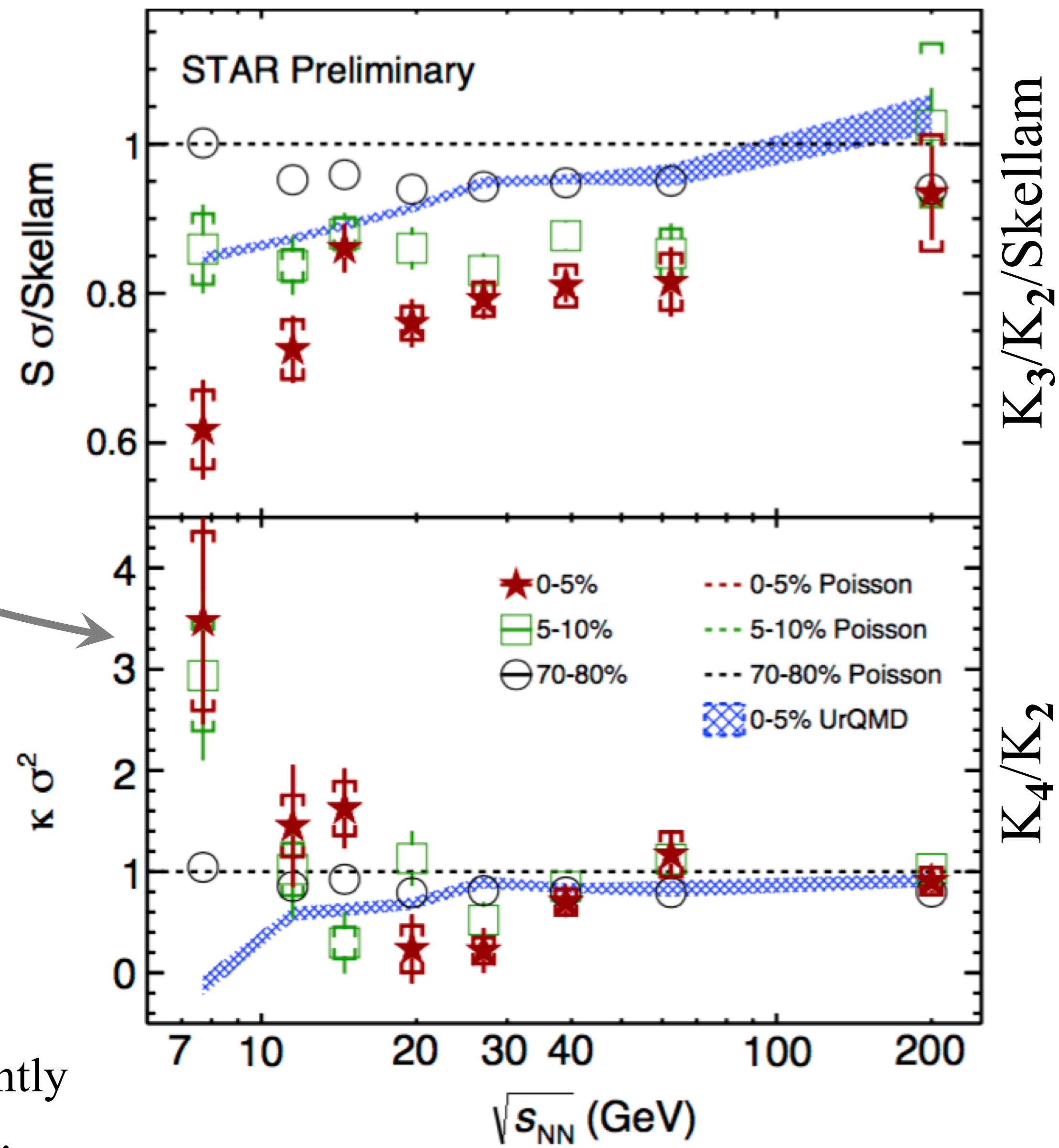
Widen the acceptance
from $0.4<P_T<0.8$ to $0.4<P_T<2.0$...

Gray band: "Independent Production"

$$K_{net} = K_{pos} + (-1)^k K_{neg}$$

Also holds for $0.4<P_T<2.0$

→ numbers of protons are not significantly correlated with the number of antiprotons. (Does not rule out CP).



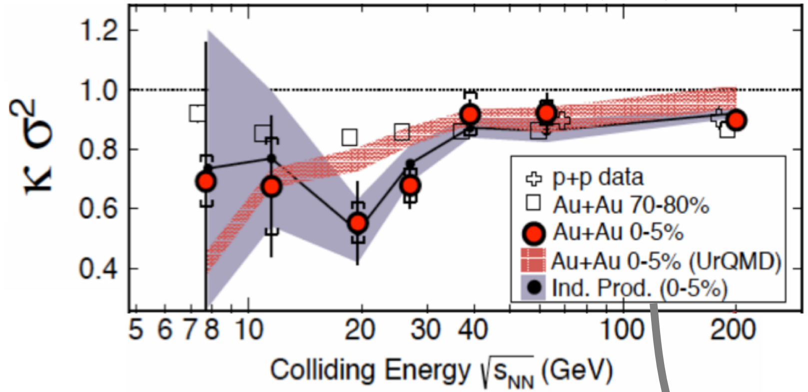
A wider acceptance increased the multiplicities and made the deviations from Poisson larger

Net-proton multiplicity cumulant ratios...

STAR net-p multiplicity cumulant ratios

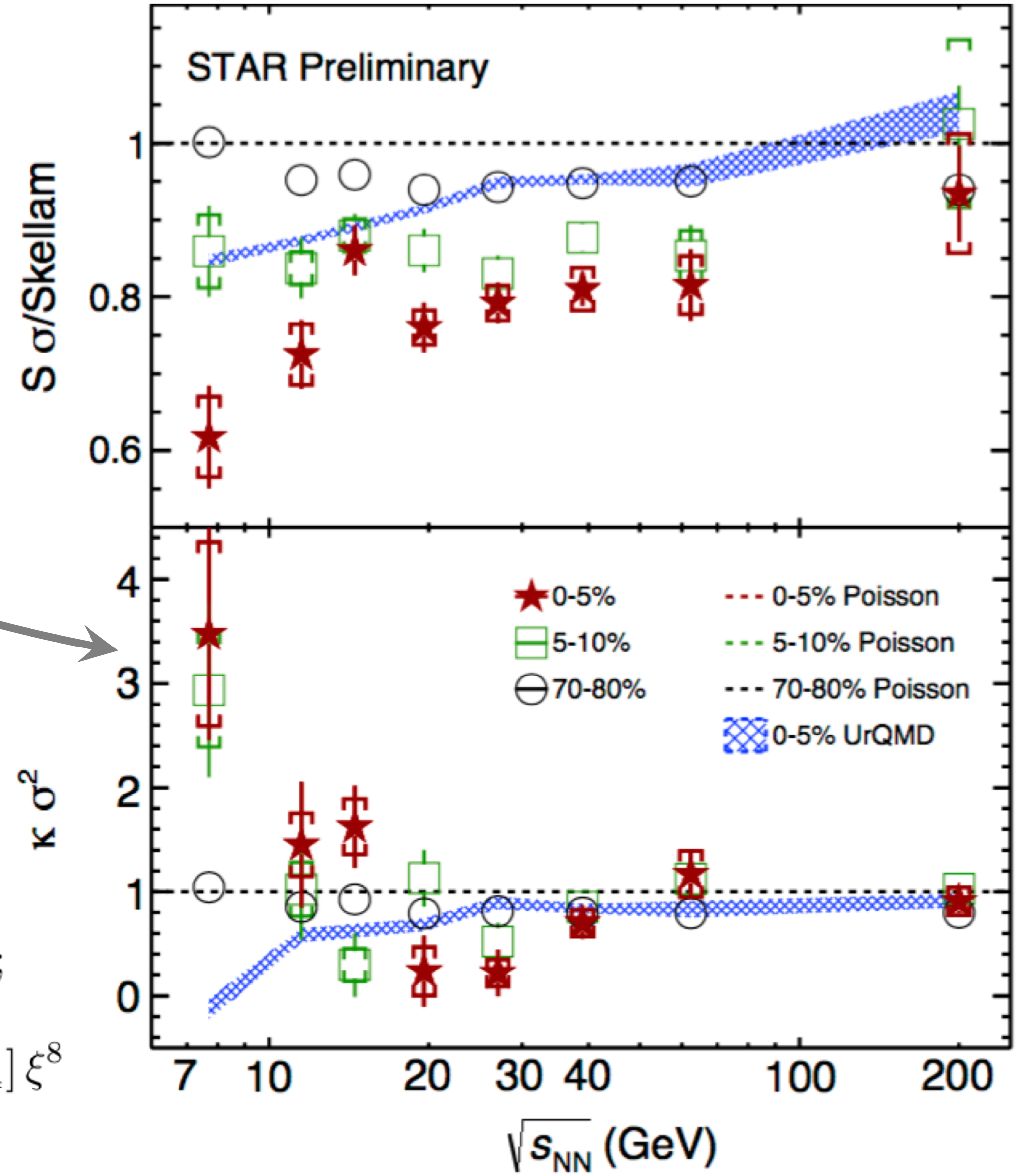
STAR, PRL 112 (2014) 032302

K_4/K_2



Widen the acceptance

from $0.4<P_T<0.8$ to $0.4<P_T<2.0$...



K_3/K_2/Skellam

K_4/K_2

Critical point searches:

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

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

Sensitivity increases with k in k-particle fluctuations.

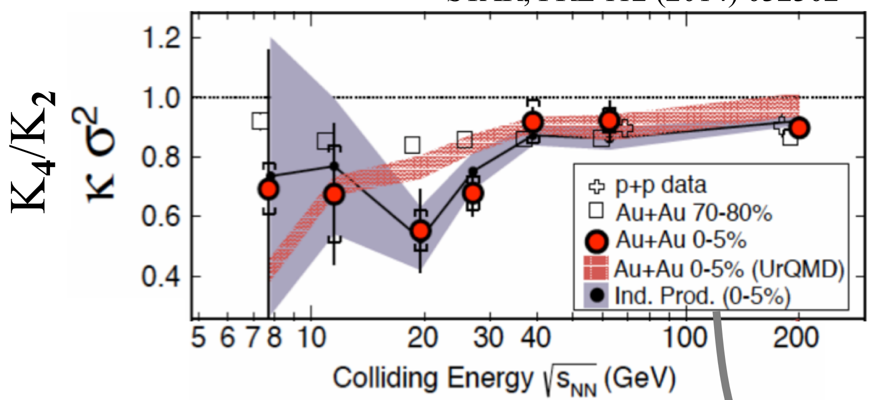
M. Stephanov

A wider acceptance increased the multiplicities and made the deviations from Poisson larger

Net-proton multiplicity cumulant ratios...

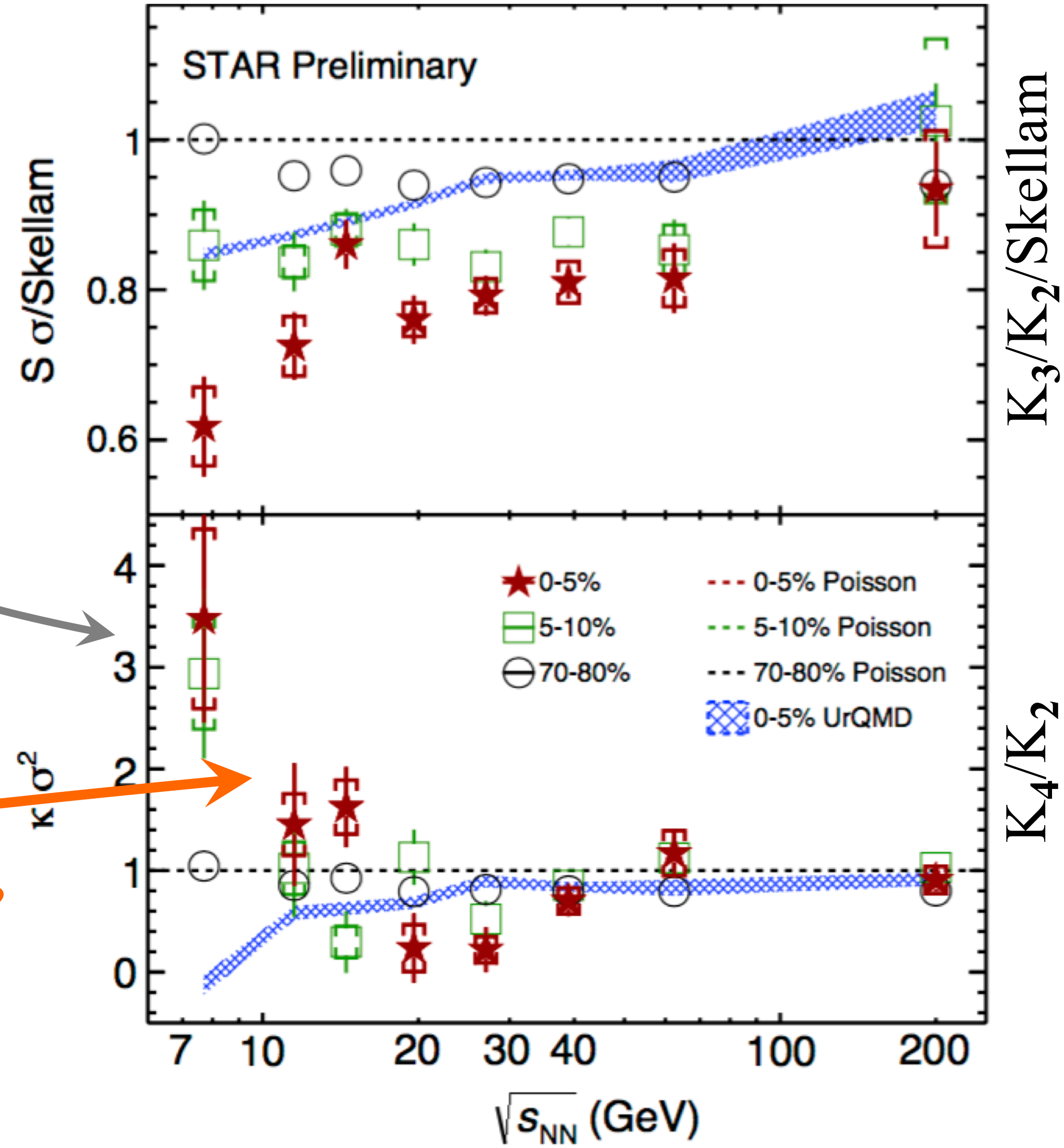
STAR net-p multiplicity cumulant ratios

STAR, PRL 112 (2014) 032302

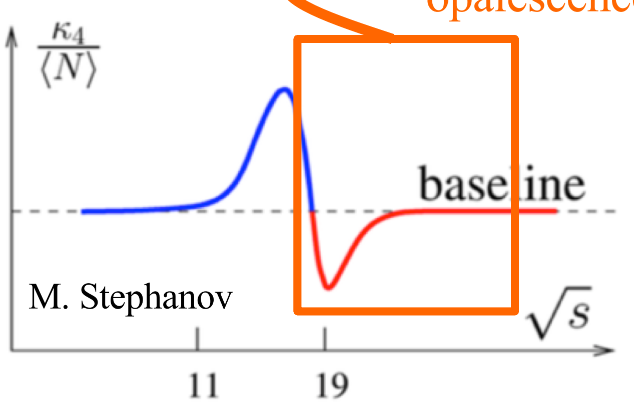


Widen the acceptance

from $0.4<P_T<0.8$ to $0.4<P_T<2.0$...



critical opalescence?

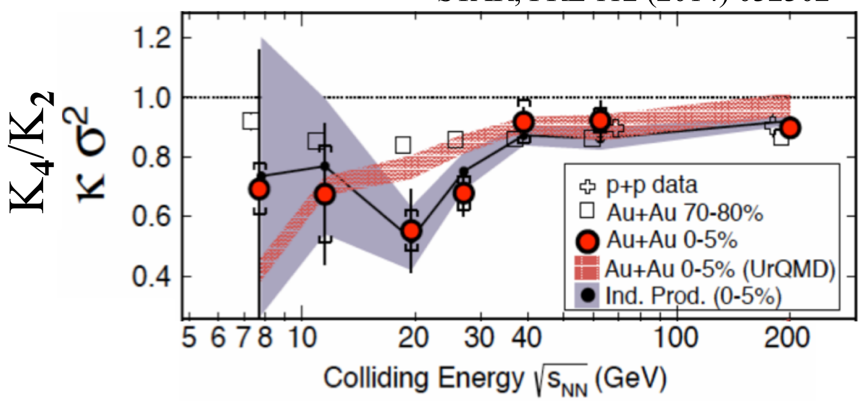


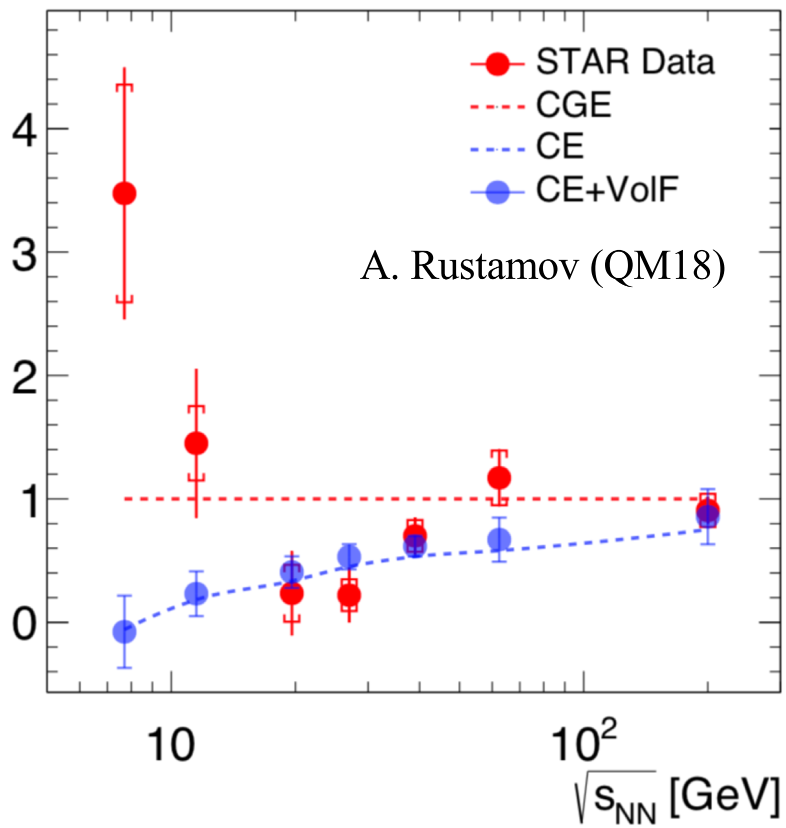
A wider acceptance increased the multiplicities and made the deviations from Poisson larger

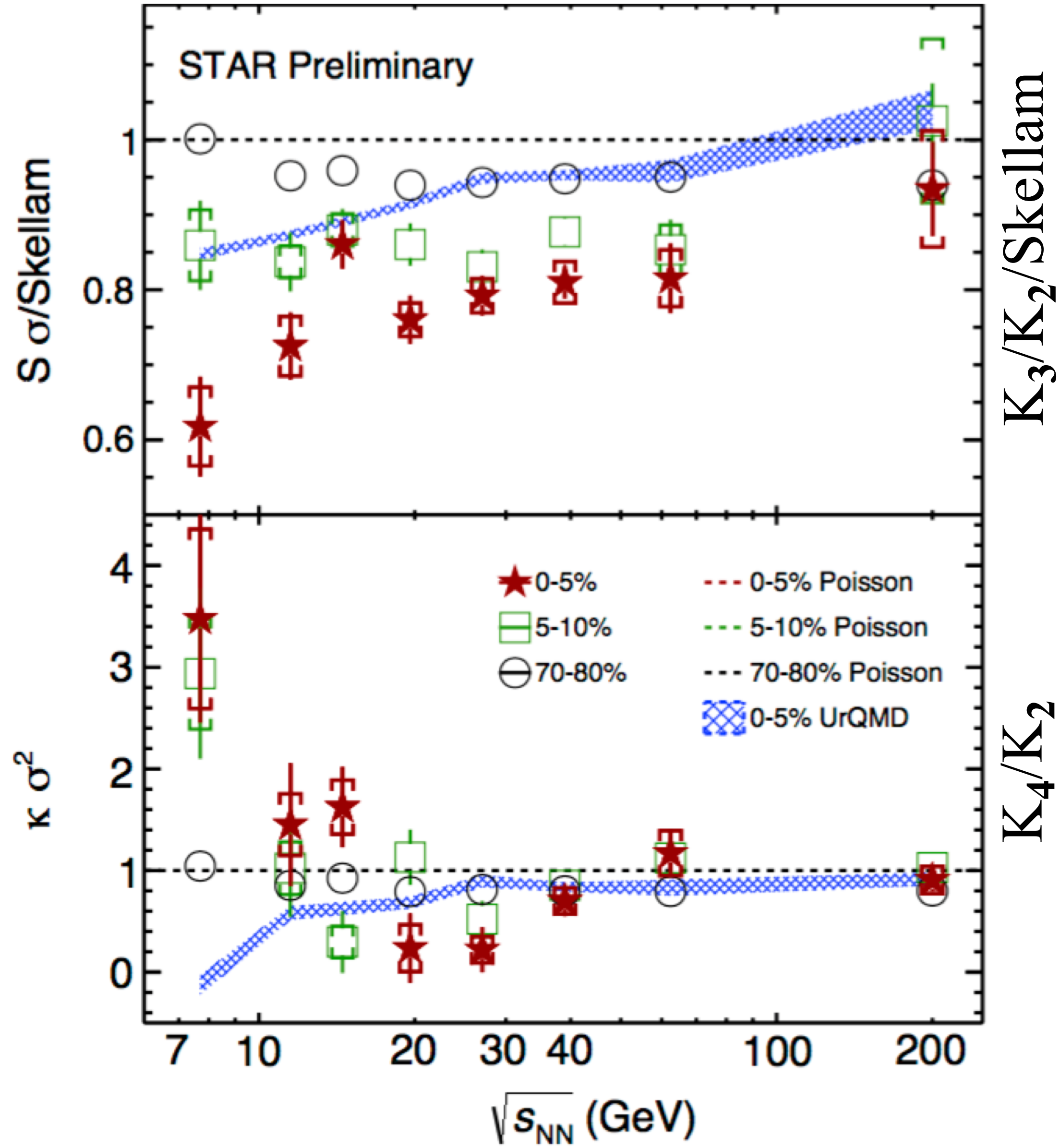
Net-proton multiplicity cumulant ratios...

STAR net-p multiplicity cumulant ratios

STAR, PRL 112 (2014) 032302





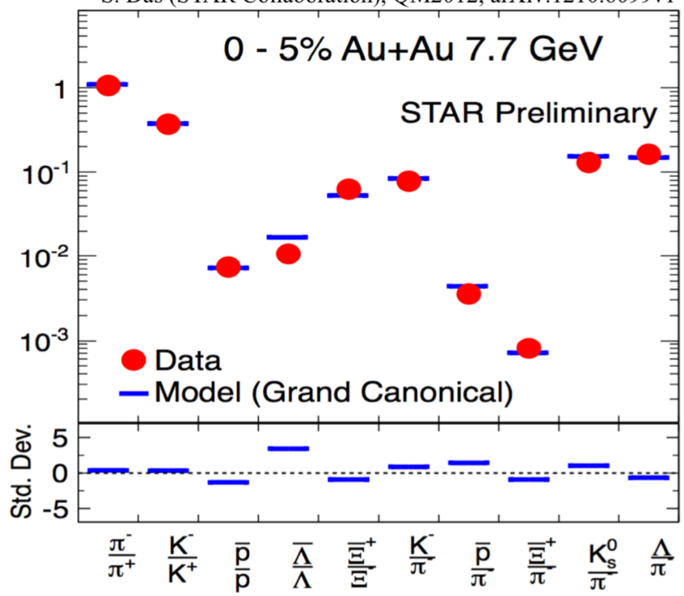


A wider acceptance increased the multiplicities and made the deviations from Poisson larger

Constraining freeze-out (μ_B, T) parameters…

…with statistical hadronization models (`THERMUS`, `FIST`, *etc.*)

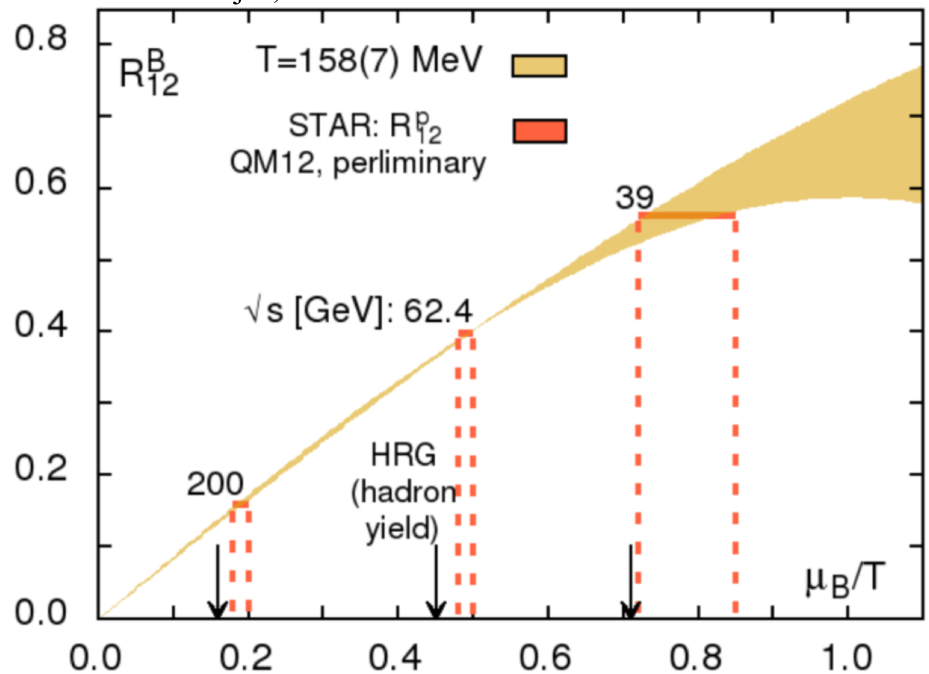
S. Das (STAR Collaboration), QM2012, arXiv:1210.6099v1



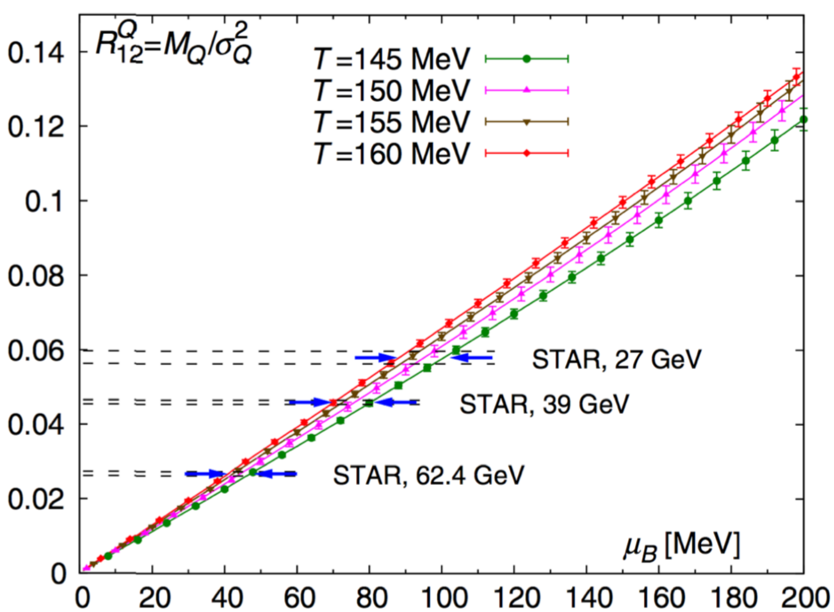
…with Lattice QCD

Basically, assume K ratios are χ ratios

S. Mukherjee, WWND 2013



A. Bazavov *et al.*, PRL 109, 192302 (2012)
S. Borsányi *et al.*, PRL 111, 062005 (2013)



Comparisons to HRG can include acceptance/cuts.
(C. Ratti *et al.*)

Fluctuations are the integral of the Correlations

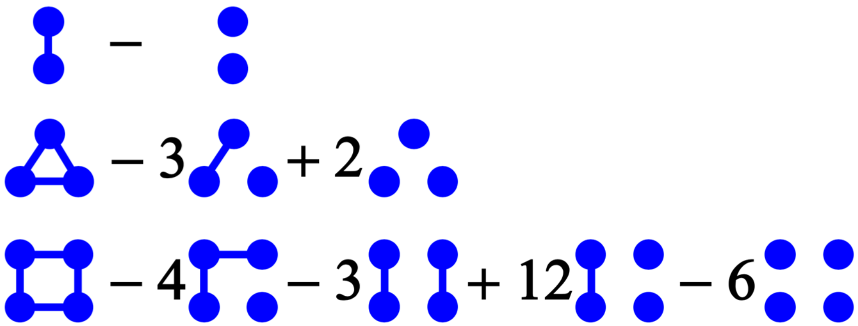
"Correlation Functions"

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…

"Multiplicity Cumulants"

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)

$$K_1 = \langle N \rangle$$

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

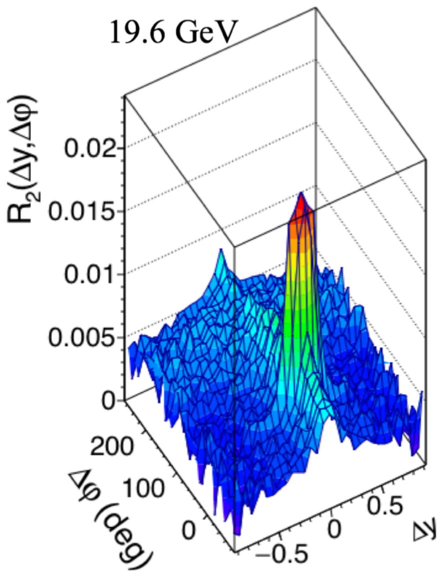
$$K_3 = \langle N \rangle + 3c_2 + c_3$$

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

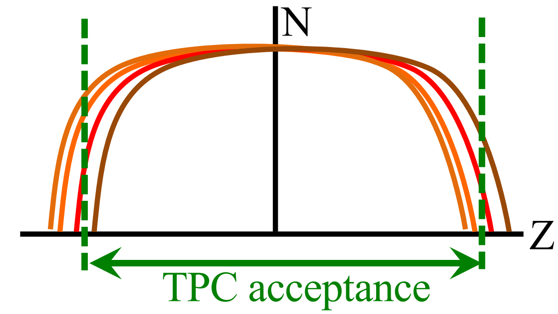
$$c_k = \int C_k(y_1, \ldots, y_k)\; dy_1 \ldots dy_k$$

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

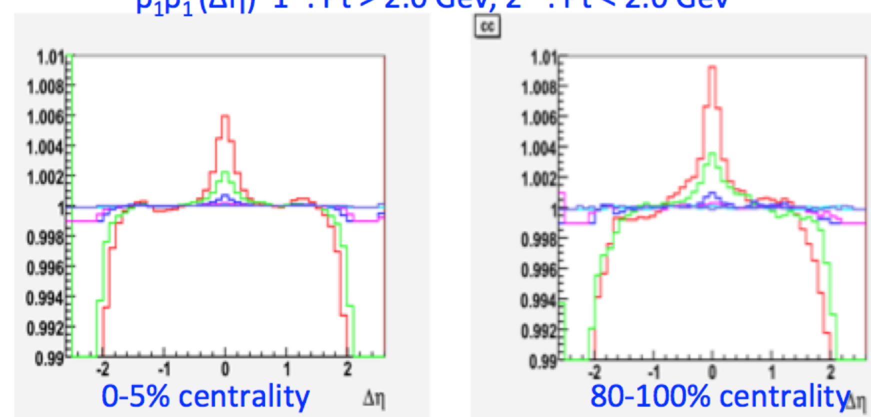
A few possible advantages from going through the correlations C_k to get the fluctuations K_k



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



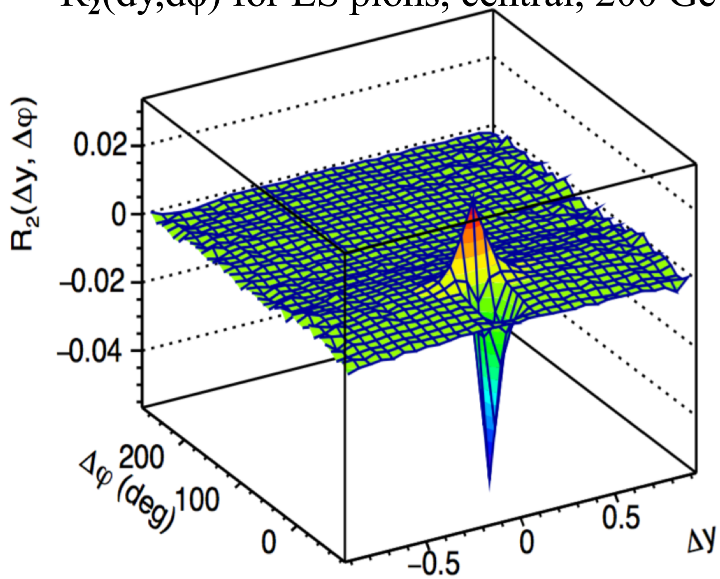
$\rho_1\rho_1(\Delta\eta)$ 1st: Pt > 2.0 Gev, 2nd: Pt < 2.0 Gev



Zvtx-smearing pseudo-correlations:
C_k **require** "Zvtx-averaging" over narrow (1-2cm) bins. Not done for available STAR K_k results.

(note STAR net-p results use 1m-wide Zvtx bins at 7.7 GeV)

$R_2(dy,d\phi)$ 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

Common to use "reduced" form of C_k to remove trivial pair multiplicity dependence

$$R_k = C_k(y_1, ..., y_k) / \prod_{i=1}^{k} \rho_1(y_i) \qquad R_2 = \frac{C_2}{\rho_1\rho_1} = \frac{\rho_2 - \rho_1\rho_1}{\rho_1\rho_1} = \frac{\rho_2}{\rho_1\rho_1} - 1$$

With the integral:

$$r_k = \frac{\int \rho_1(y_1)...\rho_1(y_k)\ R_k(y_1, ..., y_k)\ dy_1...dy_k}{\int \rho_1(y_1)...\rho_1(y_k)\ dy_1...dy_k} = c_k / \langle N \rangle^k$$

Then the multiplicity cumulants can equivalently be obtained via:

$$K_1 = \langle N \rangle$$

$$K_2 = \langle N \rangle + \langle N \rangle^2 r_2$$

$$K_3 = \langle N \rangle + 3\langle N \rangle^2 r_2 + \langle N \rangle^3 r_3$$

$$K_4 = \langle N \rangle + 7\langle N \rangle^2 r_2 + 6\langle N \rangle^3 r_3 + \langle N \rangle^4 r_4$$

Alternate approach to measuring multiplicity cumulants that retains all the knowledge of full correlation functions underneath...

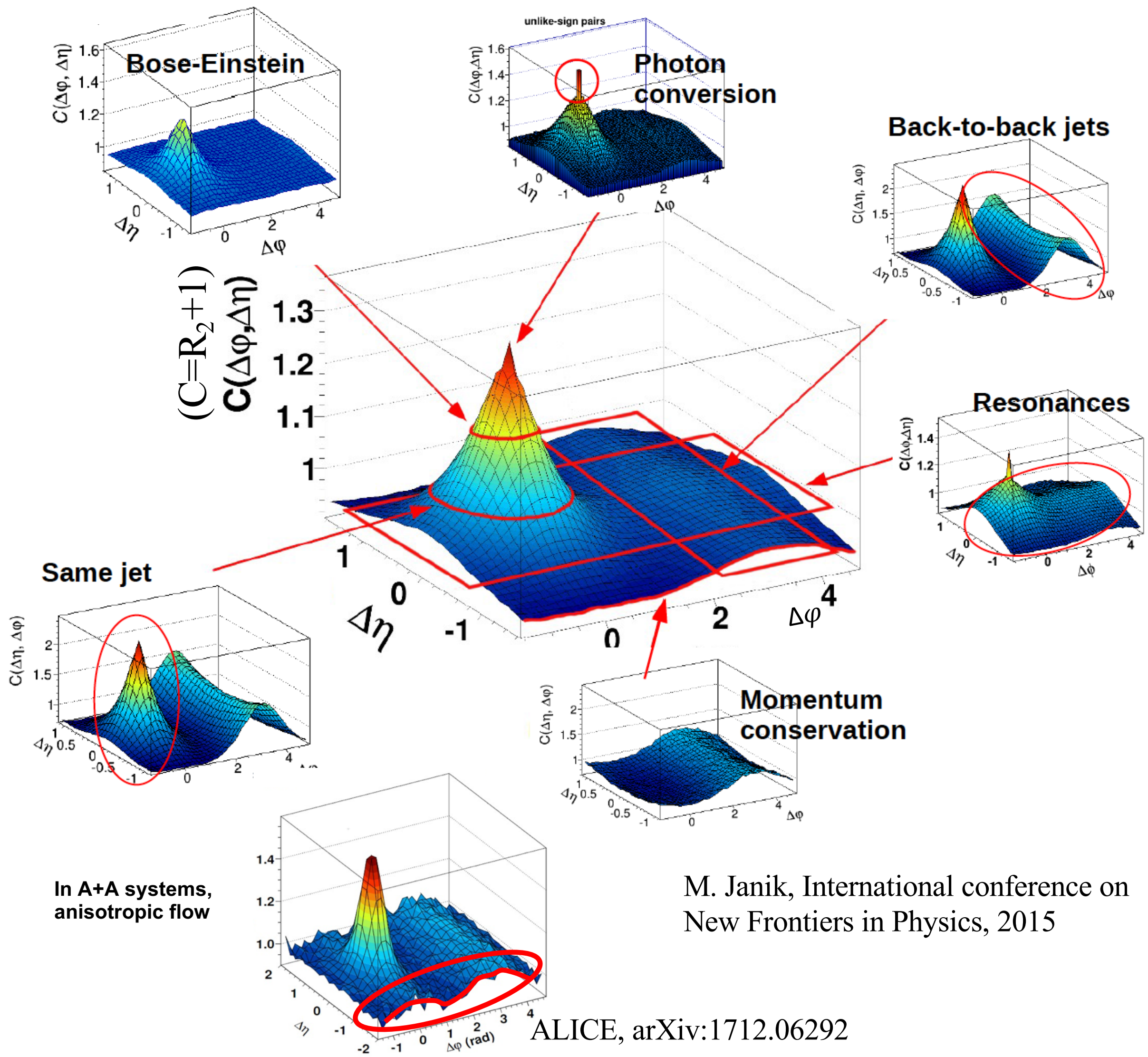
2-particle "angular" correlations

$$R_2(\Delta y, \Delta\varphi) = \frac{\rho_2(\Delta y, \Delta\varphi)}{\rho_1(y_1, \varphi_1) \otimes \rho_1(y_2, \varphi_2)} - 1$$

Same correlator normalized to number of uncorrelated pairs

– uncorrelated: $R_2 = 0$
– correlations: $R_2 > 0$
– anticorrelations: $R_2 < 0$

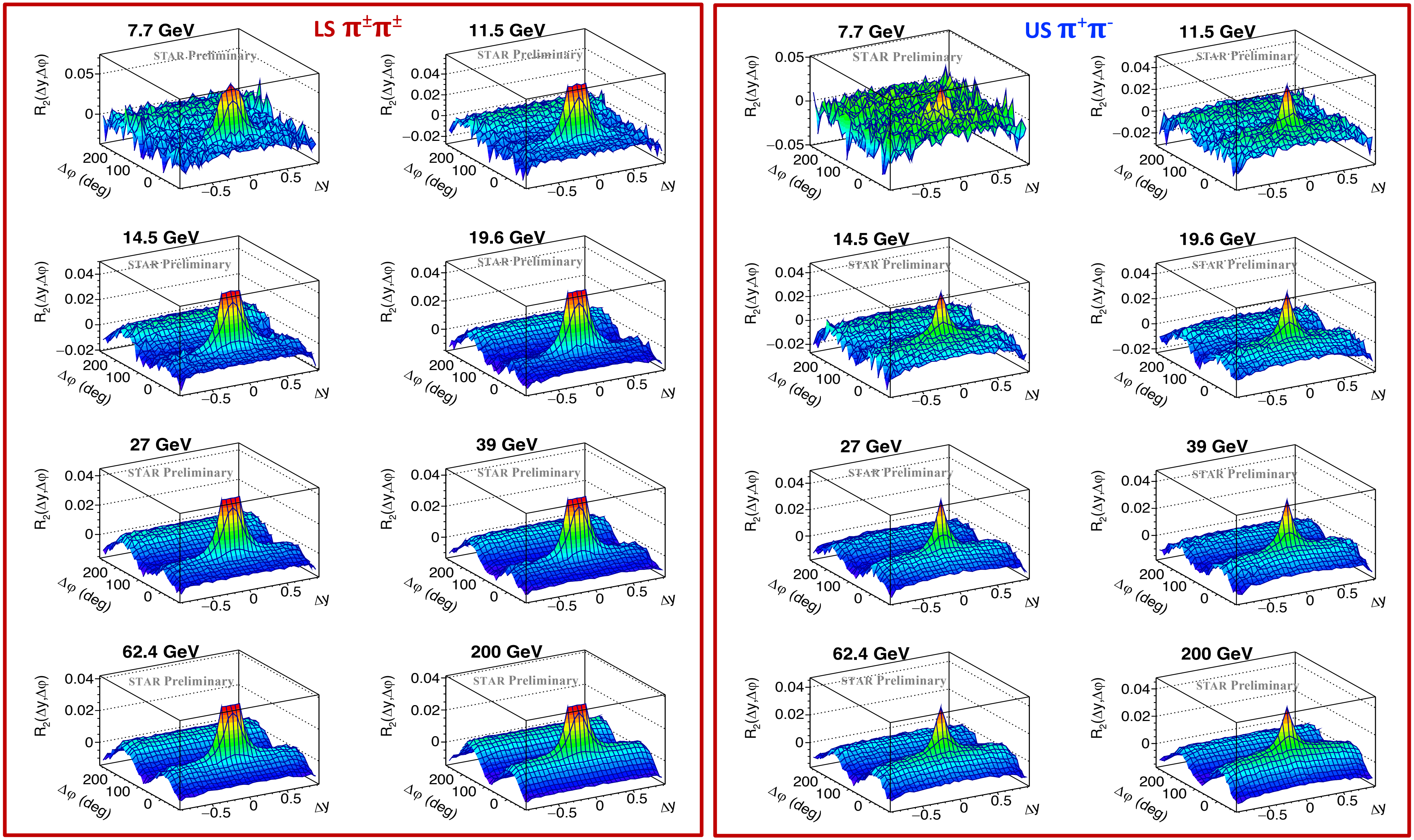
- Different physical phenomena exhibit different "shapes" in the $R_2(\Delta y,\Delta\phi)$ distributions
  - ➢ Short-range correlations (resonance decays, jet fragmentation, Bose-Einstein correlations)
  - ➢ Long-range correlation (di-jets, the "ridge," conservation laws)
  - ➢ QCD Critical Point?



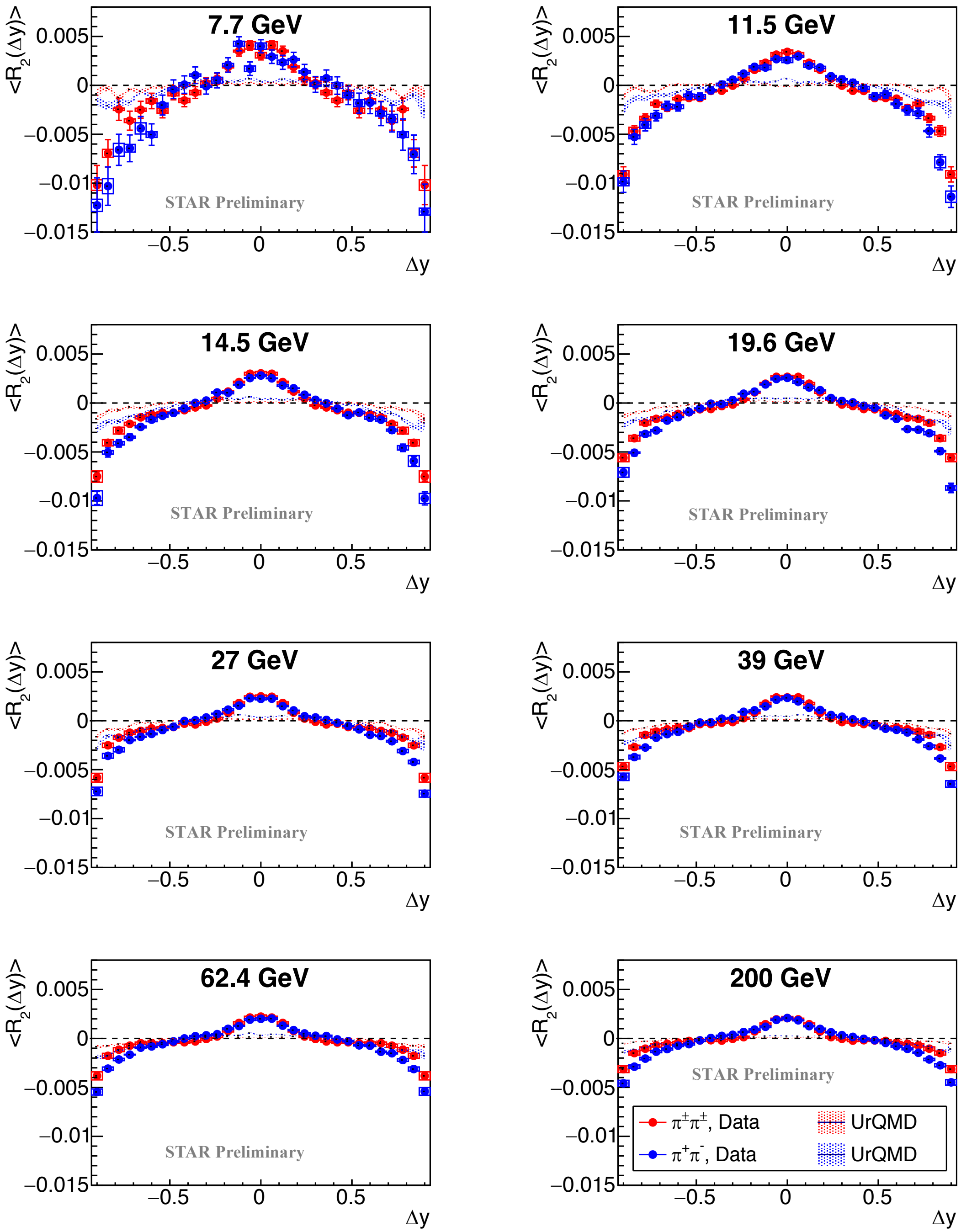
M. Janik, International conference on New Frontiers in Physics, 2015

ALICE, arXiv:1712.06292

2-pion Correlations (30-40% central)



2-pion Correlations projected onto dy (30-40% central)



Near-side enhancement in $\pi^{\pm}\pi^{\pm}$ & $\pi^{+}\pi^{-}$

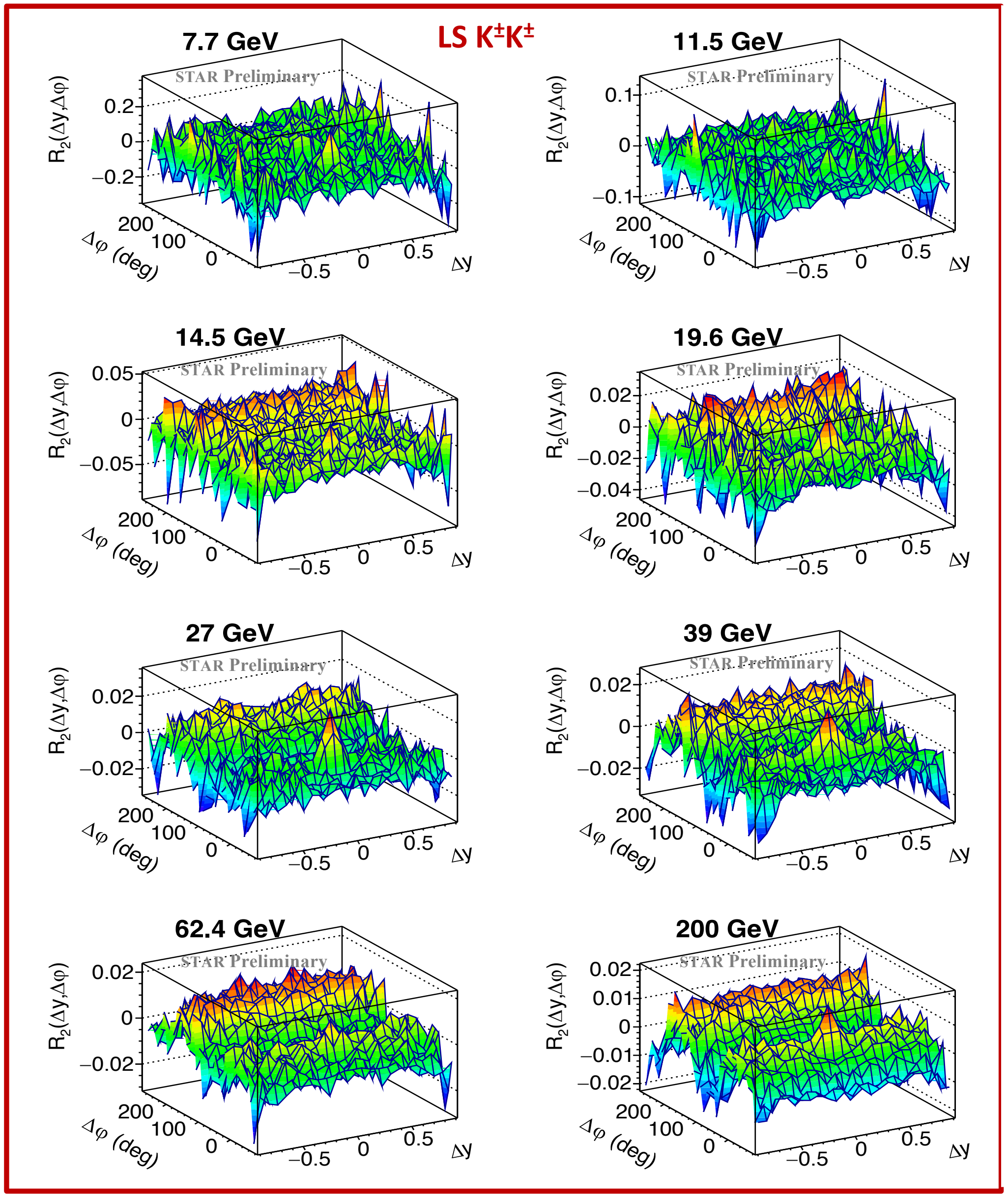
SRC from jet fragmentation and resonance decays

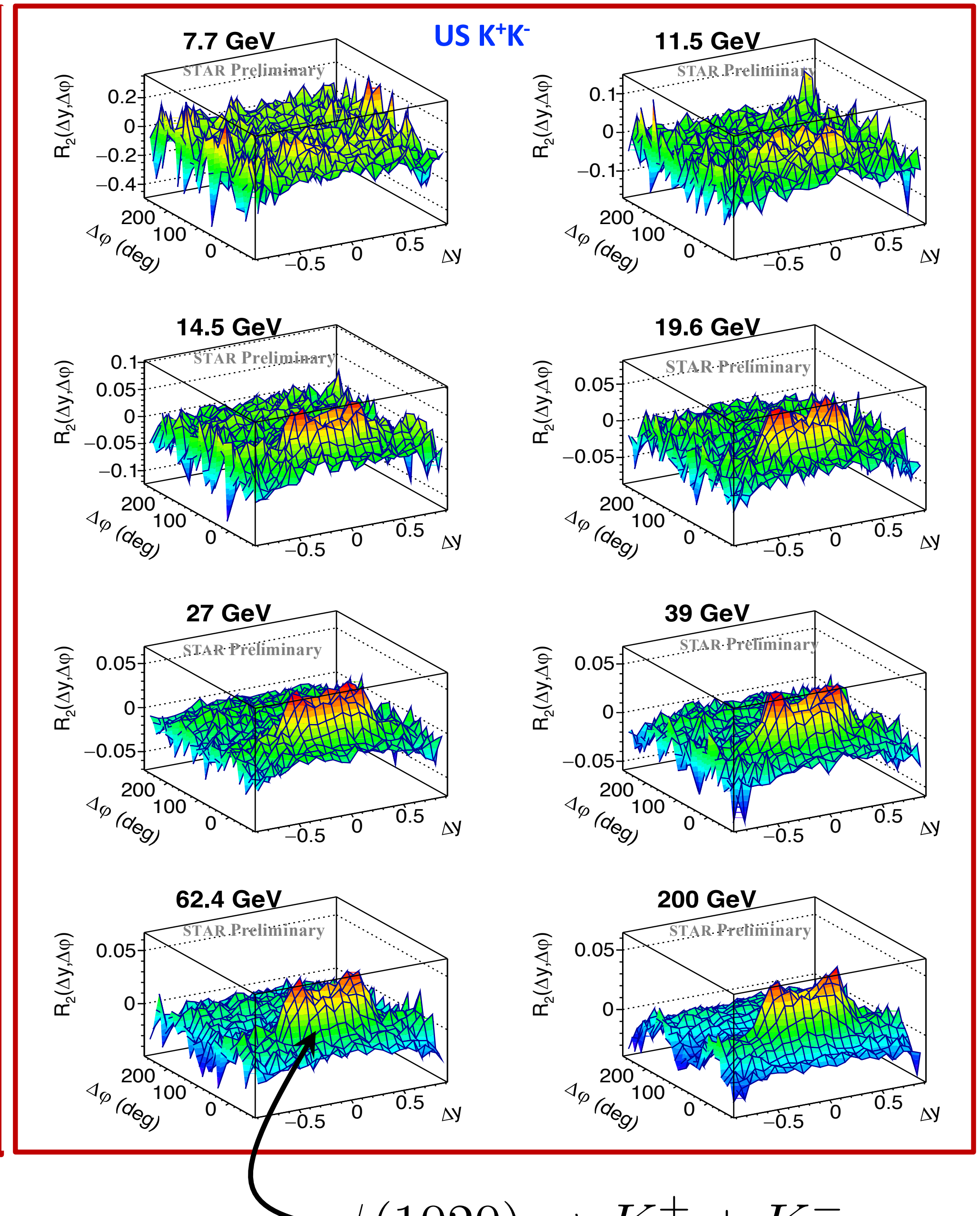
Small differences between like-sign & unlike-sign charge combinations

Correlations decrease slightly with increasing beam energy

UrQMD does not reproduce the observed SRC

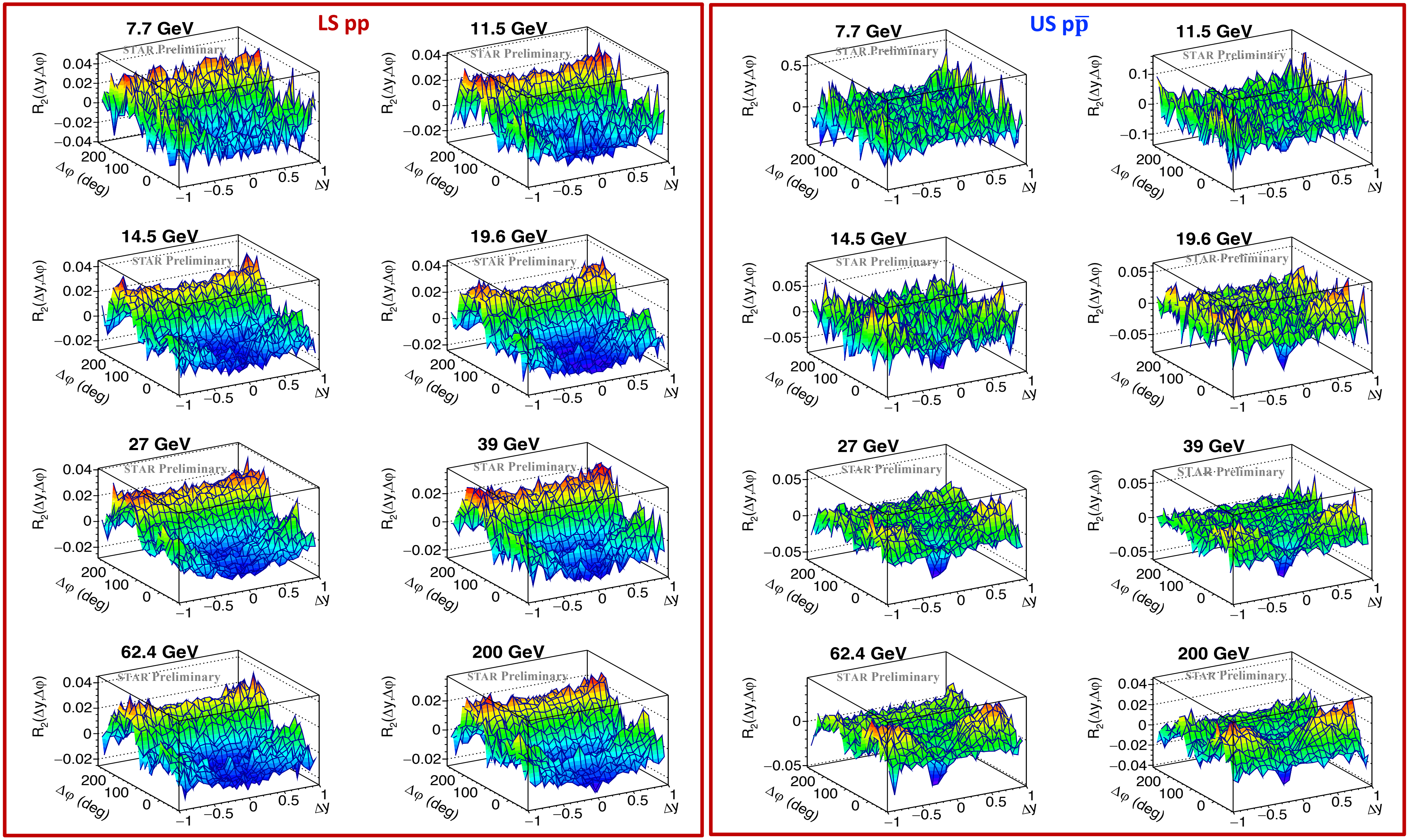
2-kaon Correlations (30-40% central)





$$\phi(1020) \rightarrow K^+ + K^-$$

2-proton Correlations (30-40% central)



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

2-proton Correlations (30-40% central)

A near-side anticorrelation is observed in 2-proton correlations

Observed for the first time in an A+A system

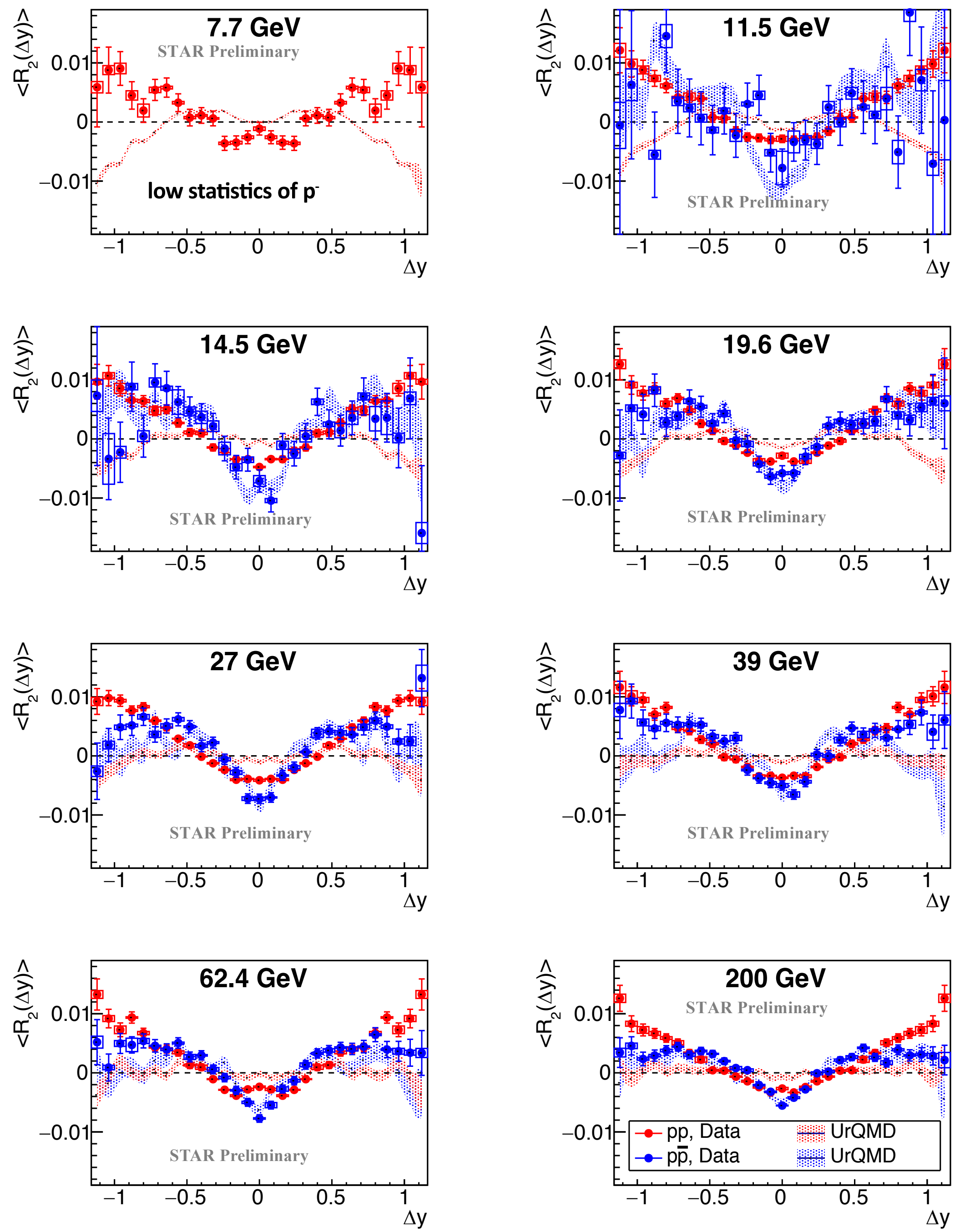
Anti-correlation in like-sign baryons has been seen in small systems:

- e^+e^- collisions at 29 GeV by TPC/Two-Gamma Collaboration (SLAC)
  - H. Aihara et al. PRL 57 (1986) 3140
- p+p at $\sqrt{s_{NN}}$=7 TeV by ALICE (LHC)
  - ALICE Coll., EPJ. C (2017) 77:569

The anticorrelation is observed in both like-sign and unlike-sign charge combinations

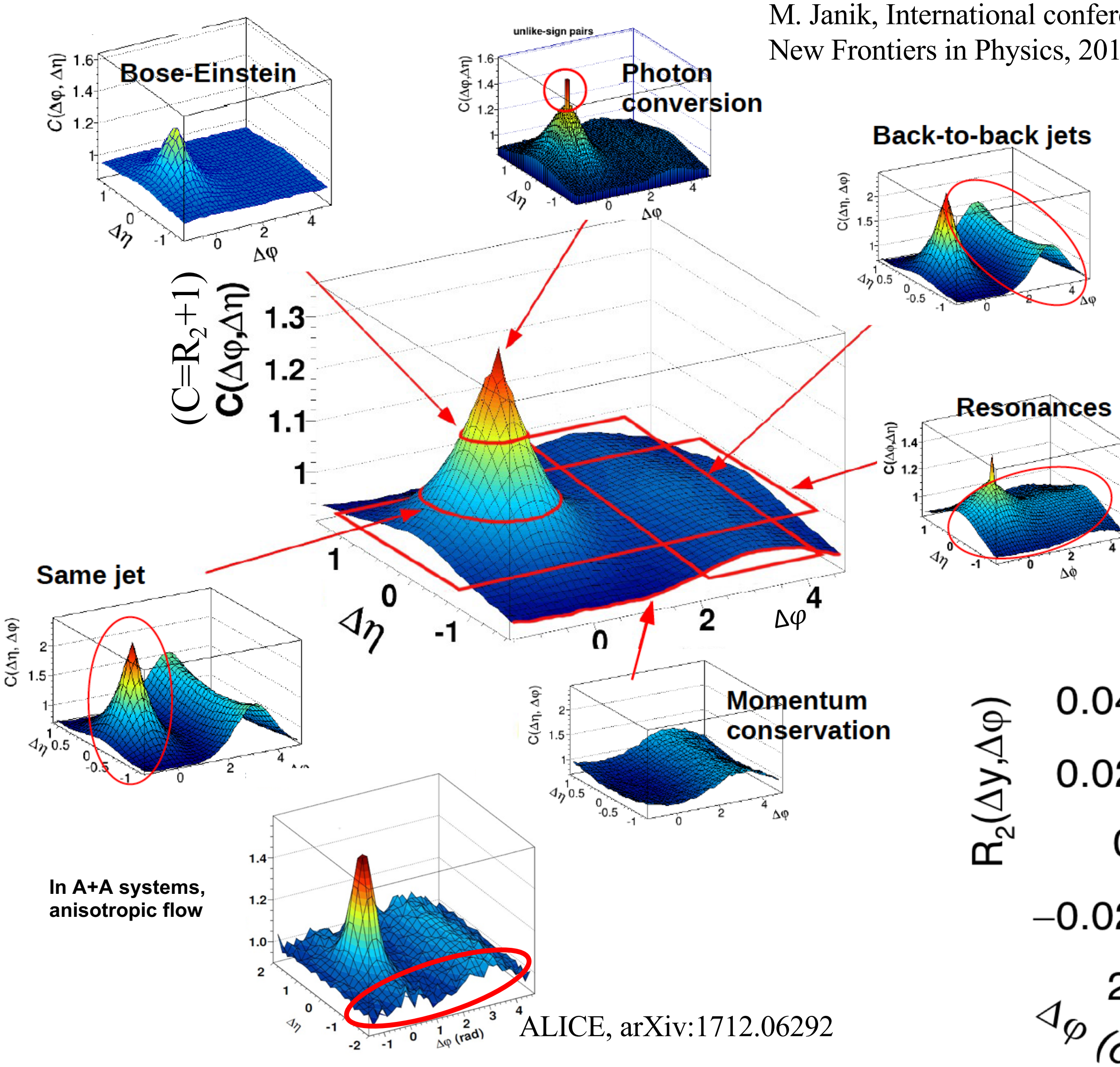
- It is narrower in Δy for $p\bar{p}$ w.r.t. pp

UrQMD reproduces the observed anti-correlation in unlike-sign pairs, but not like-sign pairs...

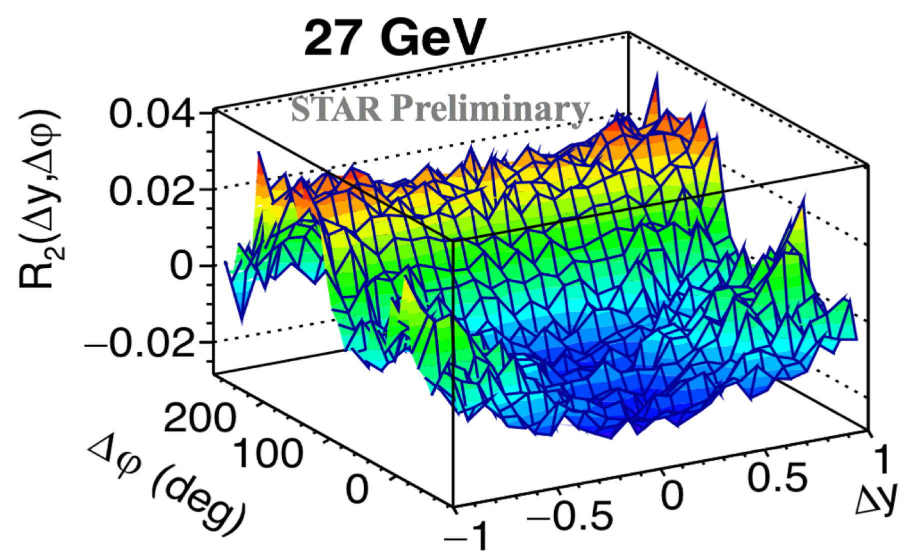


ALICE's thorough exploration of this pp near-side anticorrelation

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



ALICE, arXiv:1712.06292



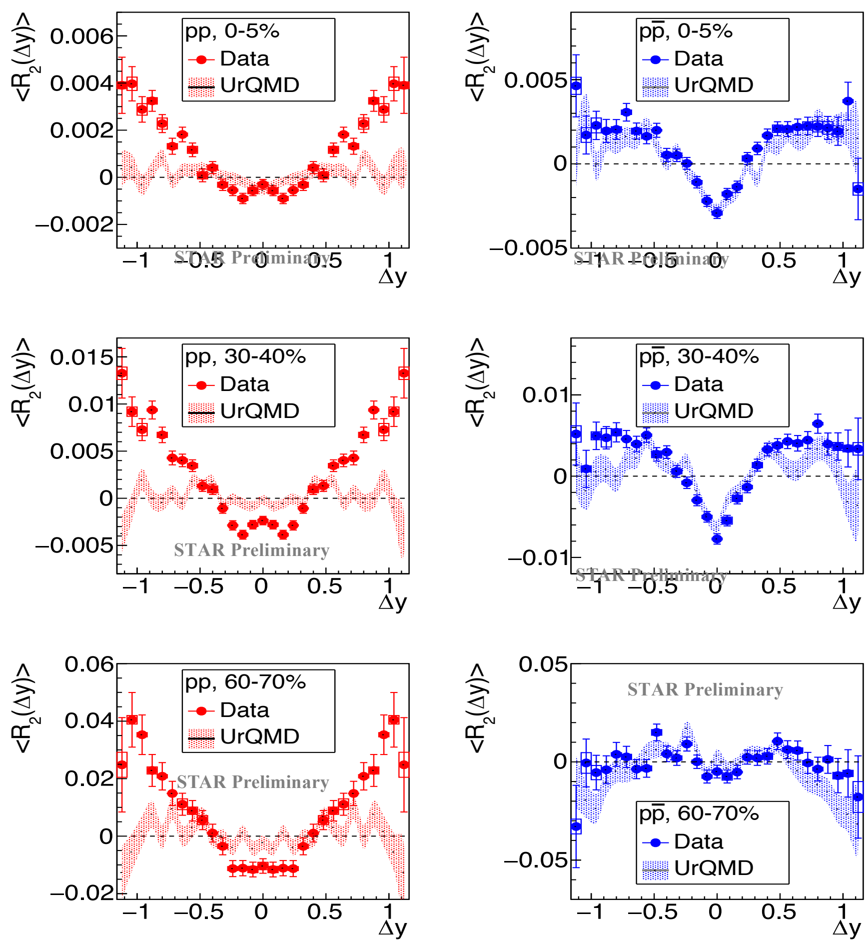
see Malgorzata Janik's excellent CERN seminar on the ALICE results:
https://mediastream.cern.ch/MediaArchive/Video/Public/WebLectures/2017/632396/632396_mobile_480p_1000.mp4

Centrality dependence in 2-proton correlations

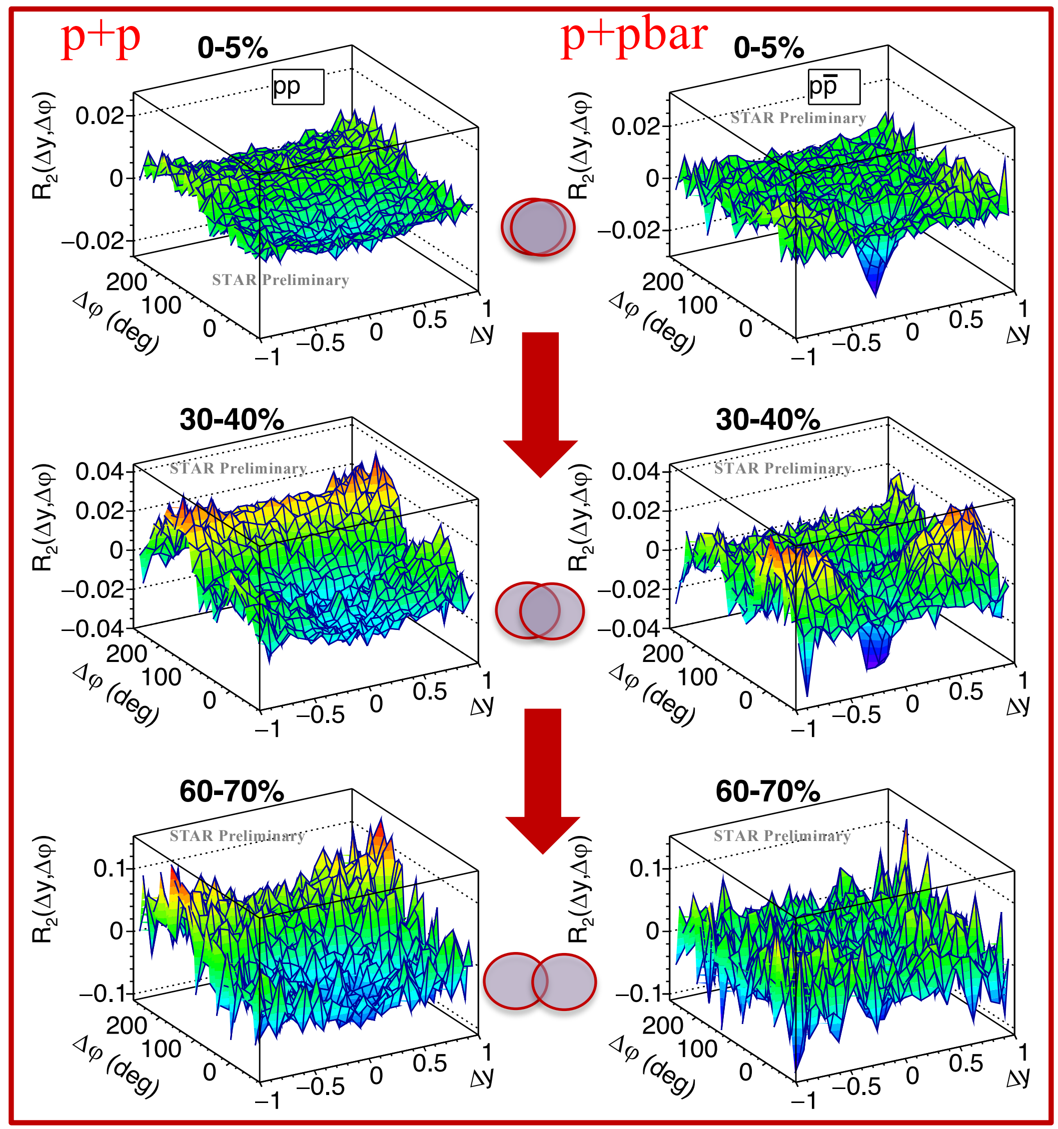
Anticorrelations increase with decreasing centrality. Insignificant dependence on P_T

For all centralities, the anticorrelation in unlike-sign proton pairs $p\bar{p}$ is narrower in Δy w.r.t. like-sign pairs pp

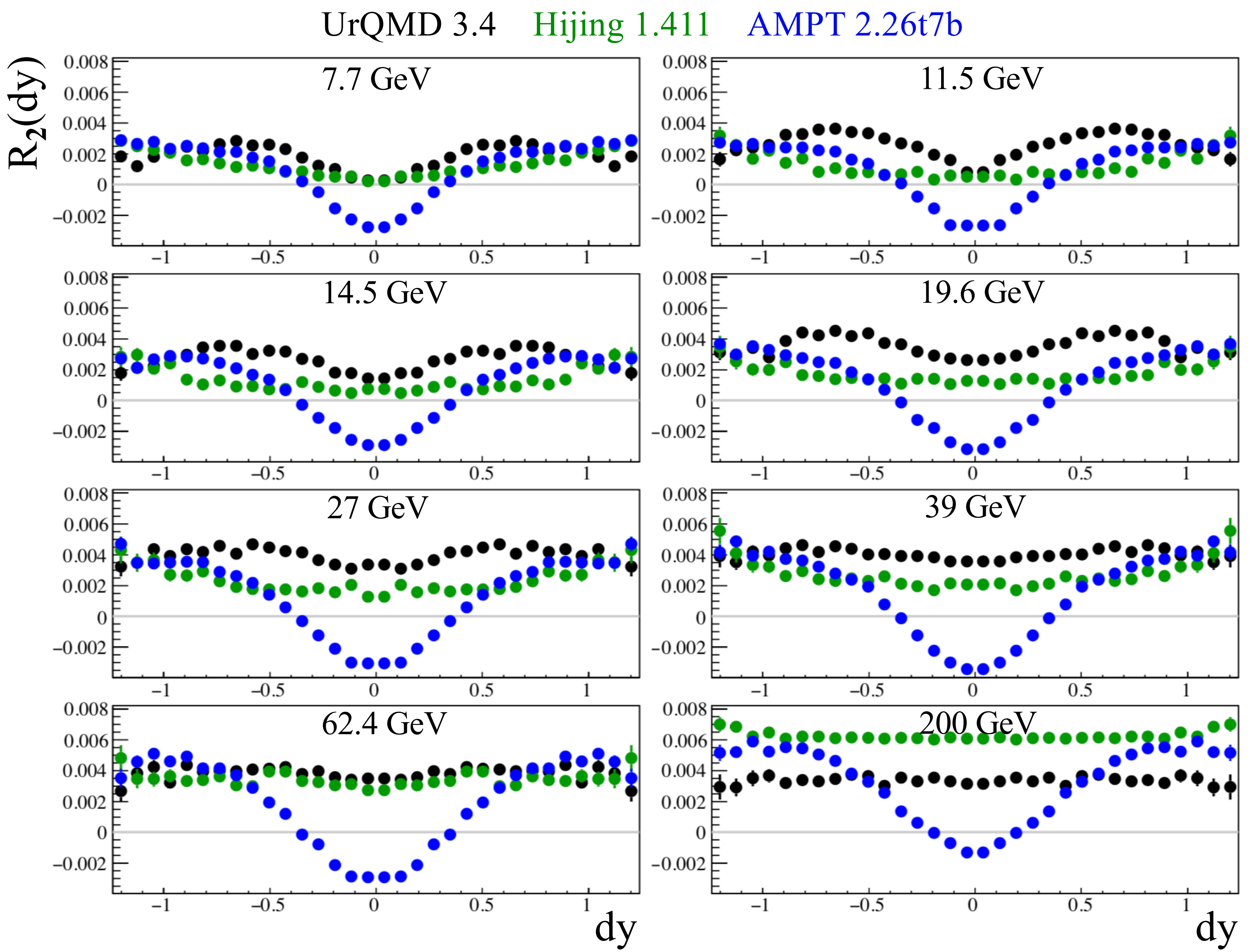
UrQMD simulation well reproduces the anti-correlation for unlike-sign proton pairs at the different centralities



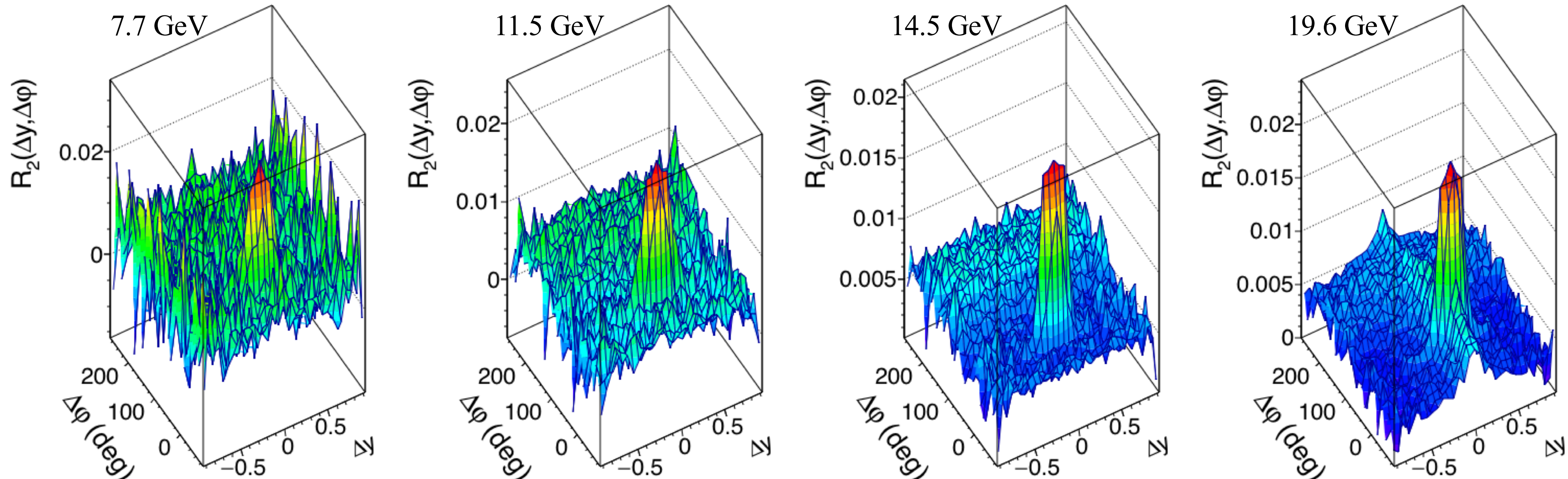
62.4 GeV, 2-proton correlations



LS protons, 0-5% central

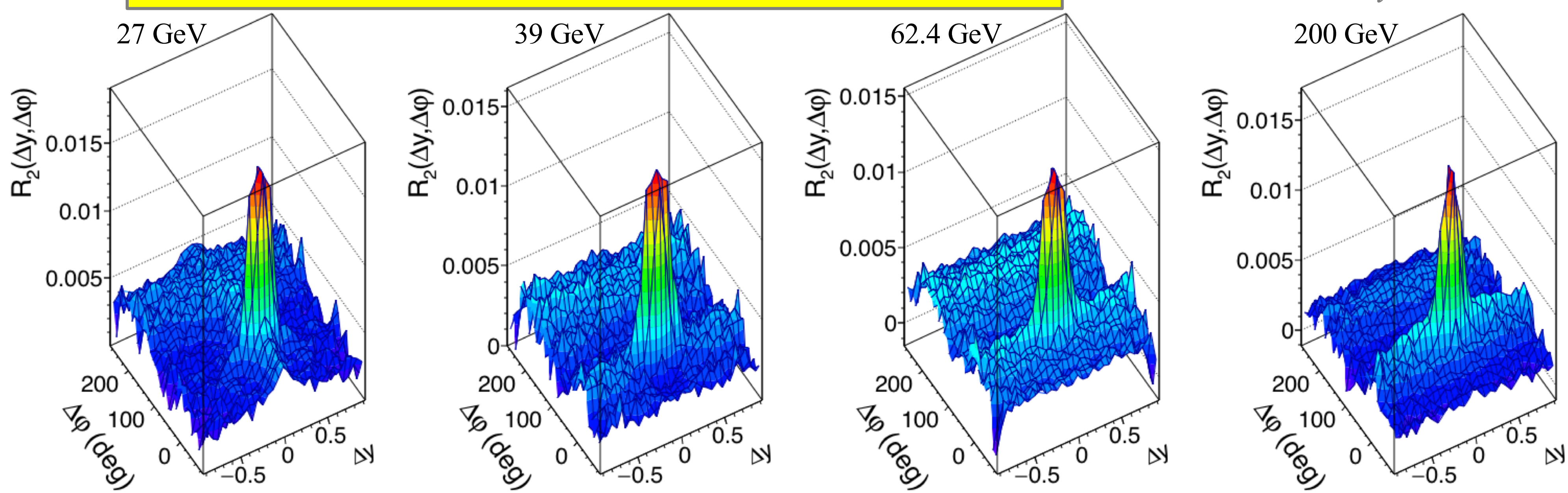


R2(Δy,Δφ) for LS pions vs. $\sqrt{s_{NN}}$, 0-5% central, convolution

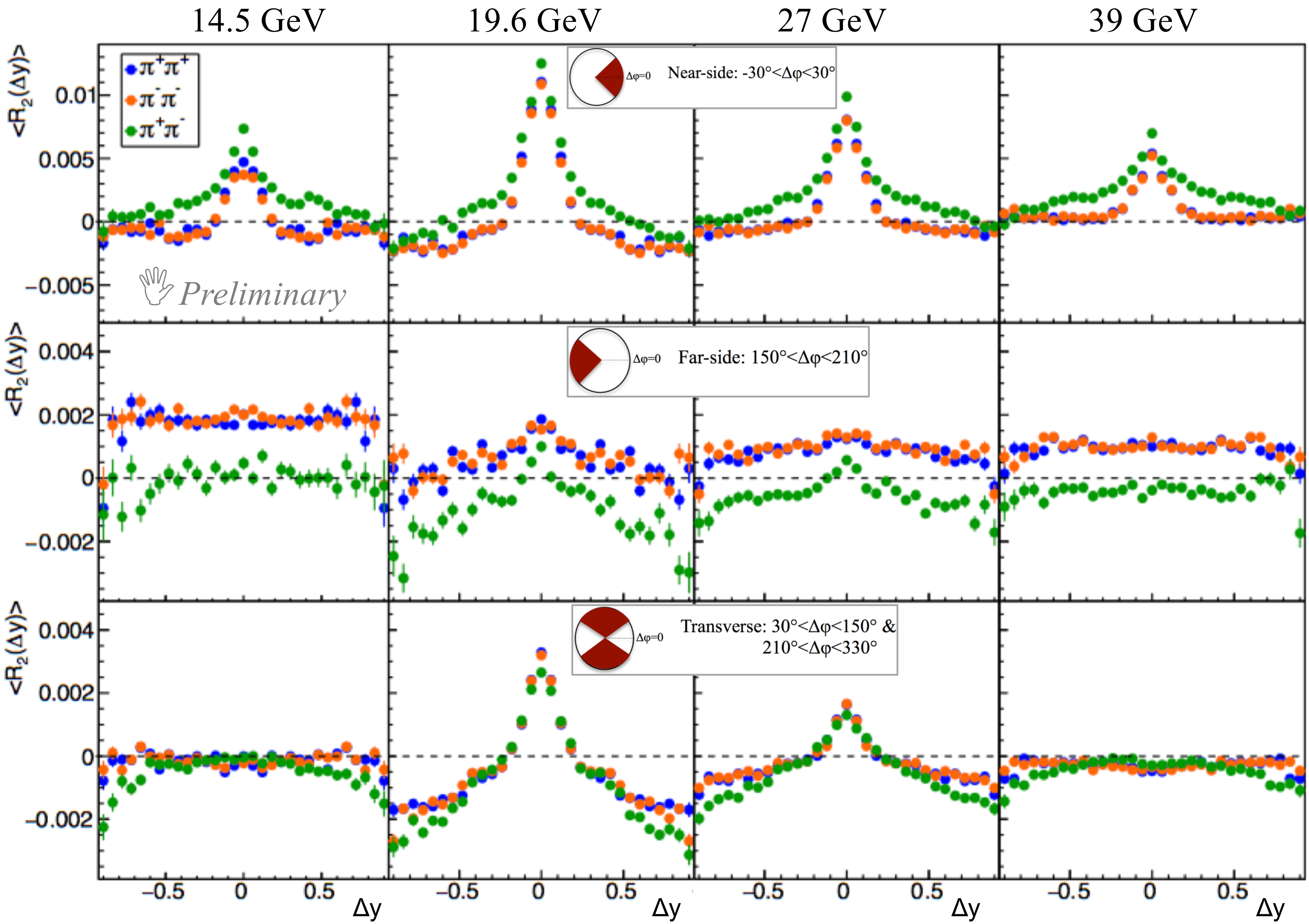


Older 2-pion CF results shown at QM17 and CPOD17

STAR Preliminary

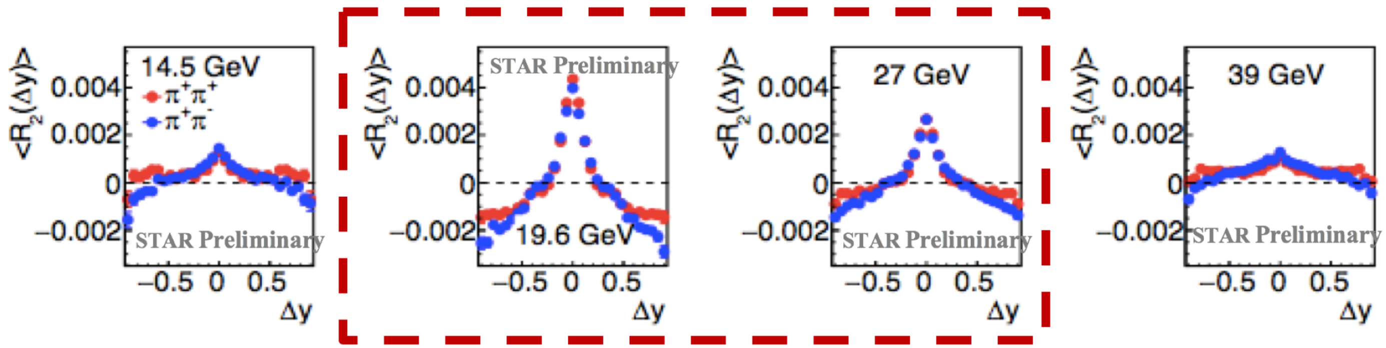


R2(Δy) for LS pions vs. $\sqrt{s_{NN}}$, 0-5% central, convolution, Δφ regions



The 2-pion "phi ridge"

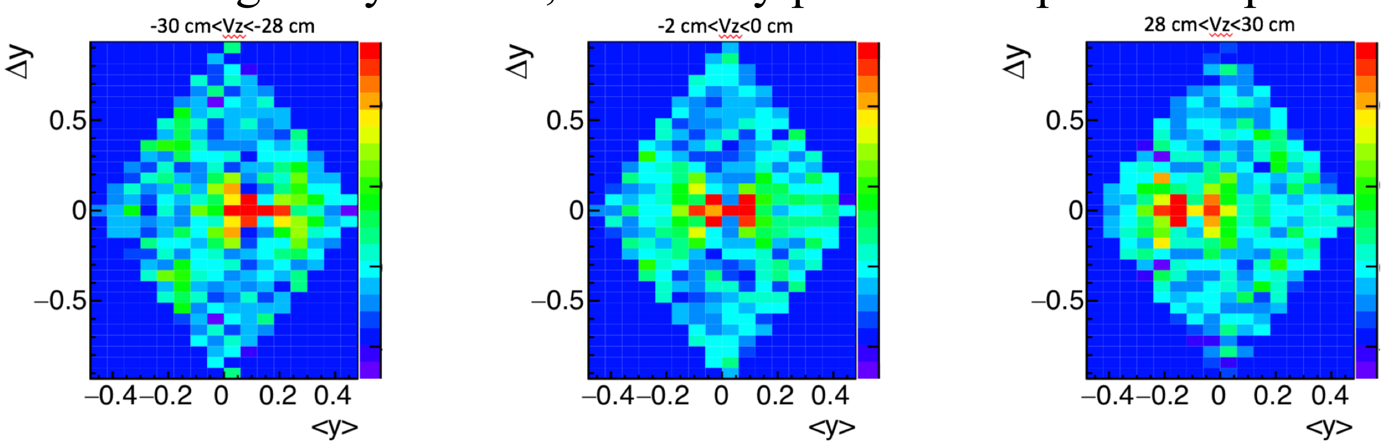
QM/CPOD 2017 results based on PID: TPC+TOF in all p range



root(s_{NN})-localized..
charge-independent..

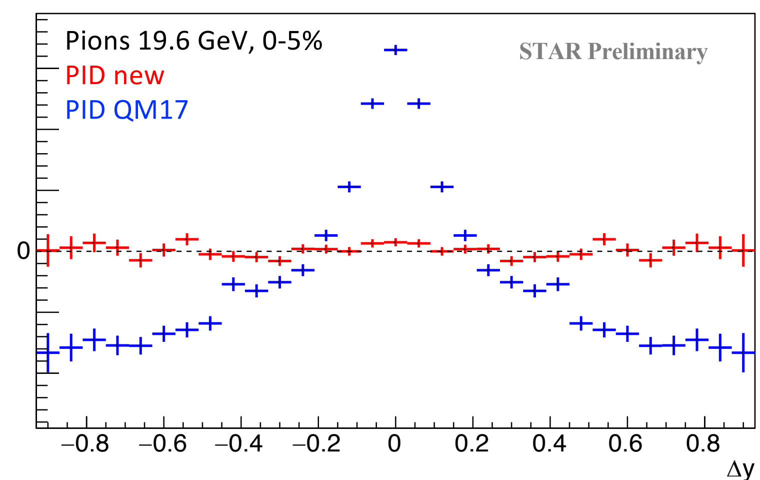
but in *pions*…

After doing many checks, we finally proved this peak is experimental, not physical…



Peak stays near Z=0 when Z_{vtx} moved around.

Can be removed either with a Zvtx-dependent rapidity cut, or by a more efficient PID method…



R_3 and R_4

A paper on our identified 2-particle correlations versus the beam energy and centrality in the Au+Au BES-I data is in the STAR internal review process.

My main interest at the moment is measuring R_3 & R_4 (and C_3 & C_4)

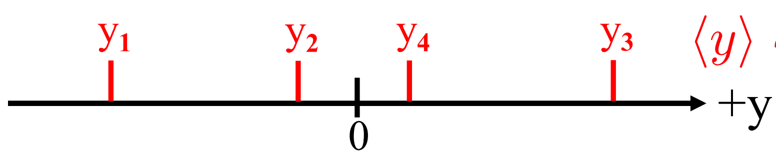
$$R_3 = \frac{C_3}{\rho_1\rho_1\rho_1} = \frac{\rho_3}{\rho_1\rho_1\rho_1} - 3\frac{\rho_2\rho_1}{\rho_1\rho_1\rho_1} + 2$$

$$R_4 = \frac{C_4}{\rho_1\rho_1\rho_1\rho_1} = \frac{\rho_4}{\rho_1\rho_1\rho_1\rho_1} - 4\frac{\rho_3\rho_1}{\rho_1\rho_1\rho_1\rho_1} - 3\frac{\rho_2\rho_2}{\rho_1\rho_1\rho_1\rho_1} + 12\frac{\rho_2\rho_1\rho_1}{\rho_1\rho_1\rho_1\rho_1} - 6$$

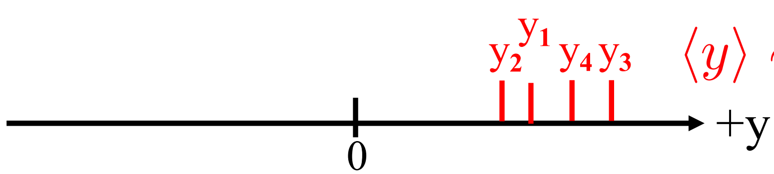
Direct measure of "true" 3- and 4-particle correlations…
Insensitive to single-particle inefficiencies, explicitly subtract any pair inefficiencies…

As interest is focused on beam energies of ~20 GeV and lower, consider only LS protons.

Projection approach used for now: $R_k(y_1, \ldots, y_k) \rightarrow \langle R_k(\langle y \rangle, D_y) \rangle$



$\langle y \rangle \sim 0, D_y \sim \text{large}$



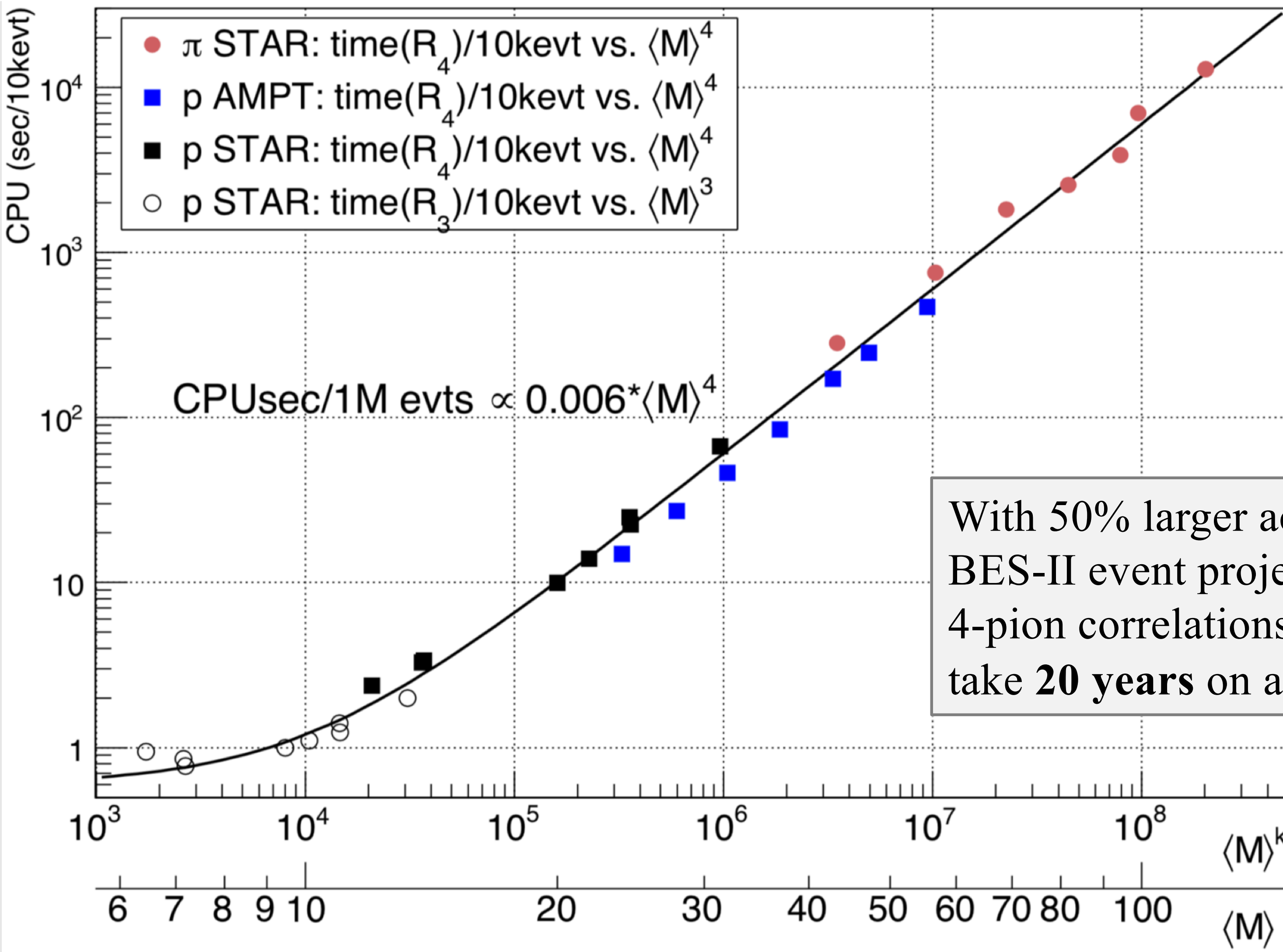
$\langle y \rangle \sim \text{any}, D_y \sim \text{small}$

$$\langle y \rangle = \frac{1}{k}\sum_{i=1}^{k} y_i$$

$$D_y = \sum_{i=1}^{k} |y_i - \langle y \rangle|$$

R_3 and R_4

R_4 requires 4 nested loops over all M identified particles in each event

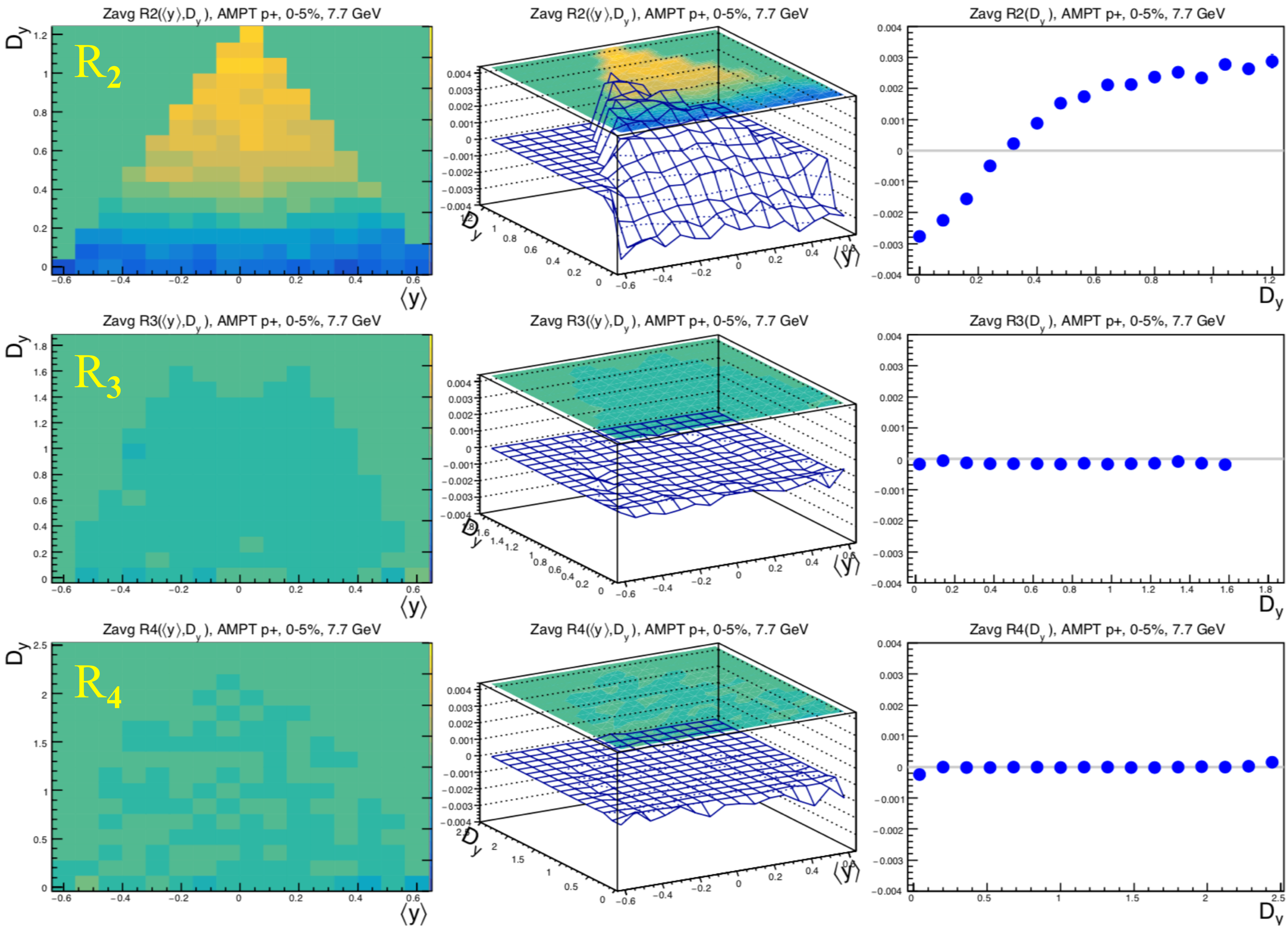


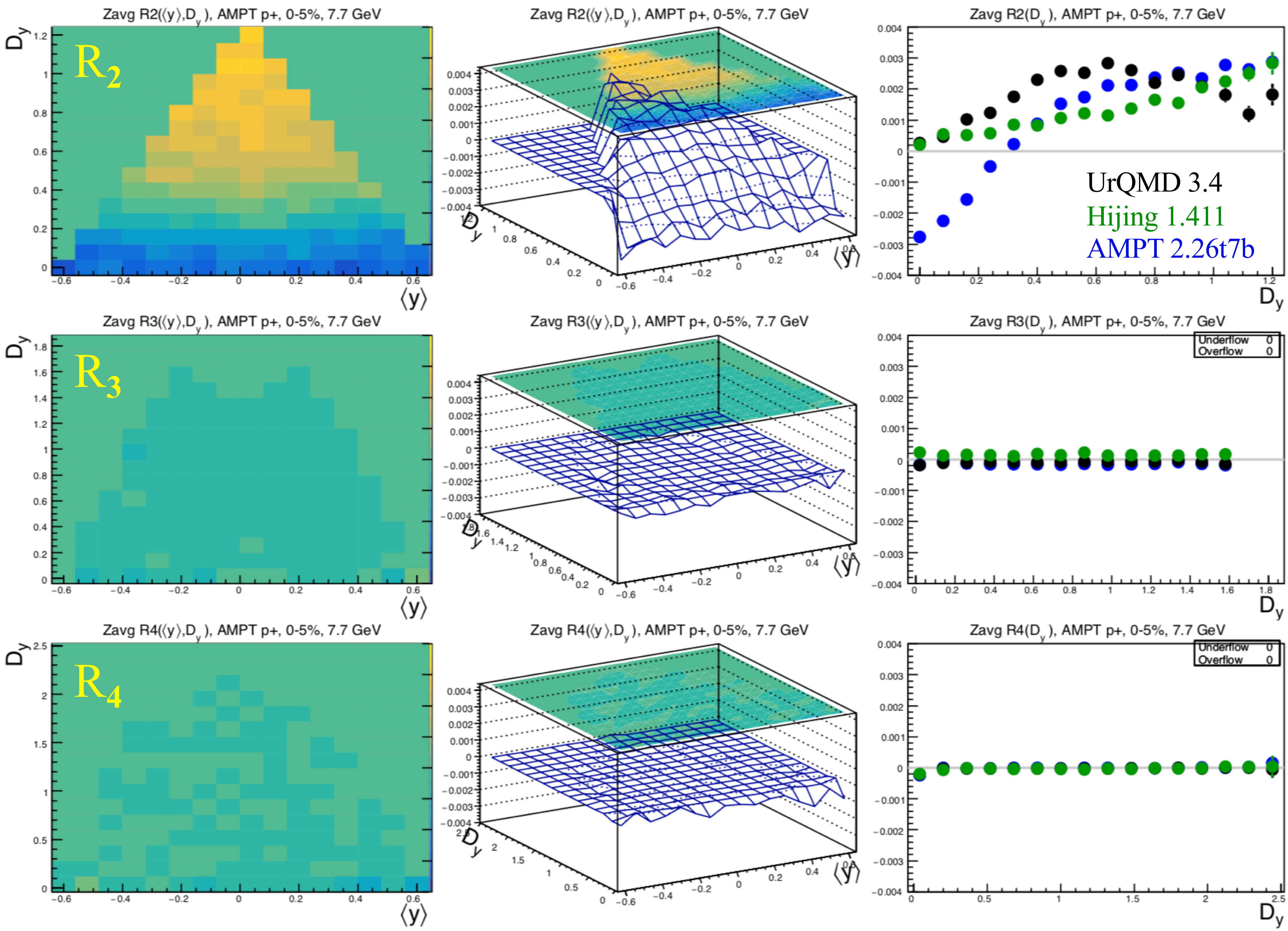
With 50% larger acceptance and BES-II event projections, estimate 4-pion correlations at 19.6 GeV will take **20 years** on a single modern CPU

So, I break up the dataset into separate jobs of ~100k events each and run in parallel…

Natural then to calculate uncertainties via "subgroup" method…

LS protons, 0-5% central, AMPT




Zavg R2(⟨y⟩,D_y), AMPT p+, 0-5%, 7.7 GeV
Zavg R2(D_y), AMPT p+, 0-5%, 7.7 GeV
Zavg R3(⟨y⟩,D_y), AMPT p+, 0-5%, 7.7 GeV
Zavg R3(D_y), AMPT p+, 0-5%, 7.7 GeV
Zavg R4(⟨y⟩,D_y), AMPT p+, 0-5%, 7.7 GeV
Zavg R4(D_y), AMPT p+, 0-5%, 7.7 GeV
R_2
R_3
R_4
D_y
⟨y⟩
UrQMD 3.4
Hijing 1.411
AMPT 2.26t7b
Underflow 0
Overflow 0

Summary

The correlations C_k (and the pair-normalized R_k) provide a more differential view of the particle distributions than does the multiplicity cumulants.

- Allow direct treatment of Zvtx smearing, track crossing, ...
- Able to localize any enhanced (anti)correlations kinematically

2 proton correlations do not look like 2 pion or 2 kaon correlations

- mid-range anti-correlation for US protons
  - deepens with centrality and beam energy – likely annihilation
- long-range anti-correlation for LS protons
  - cause unknown, not reproduced by some popular event generators

Moving toward 3- and 4- particle correlations in the STAR BES-I data

- Presently projecting in a way that should "see" mid-range clustering
  - Any suggestions appreciated!

- No observable 3- and 4-proton rapidity correlations in the models...

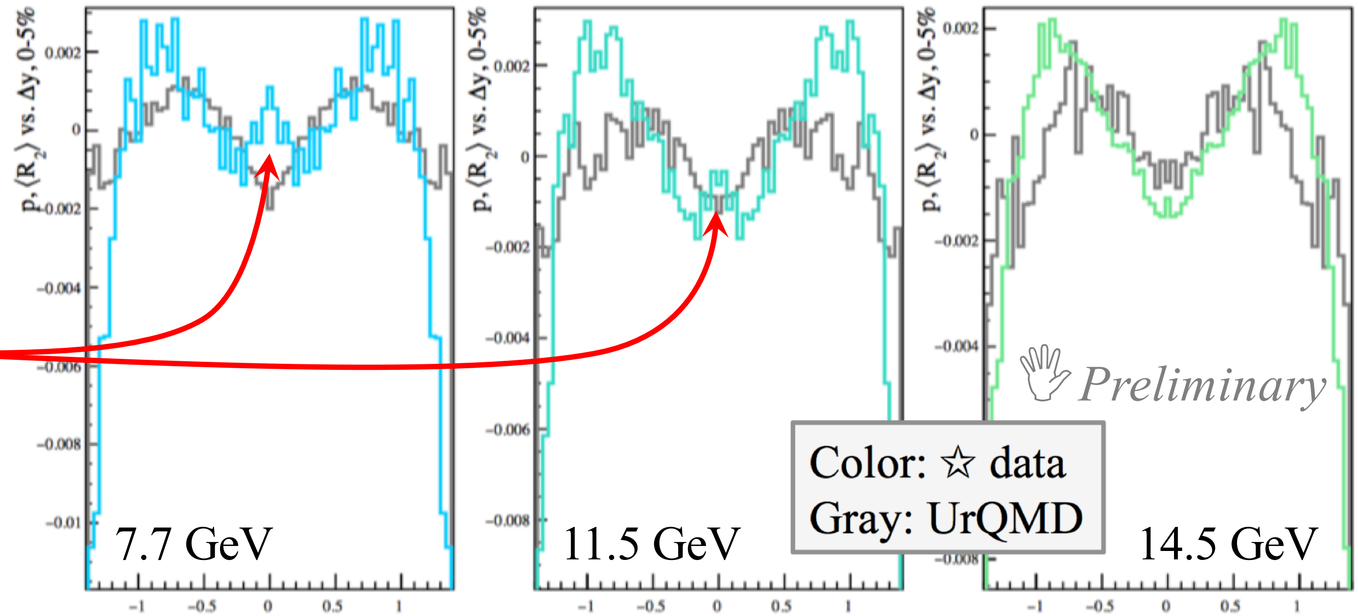
BACKUP SLIDES

Zvtx averaging

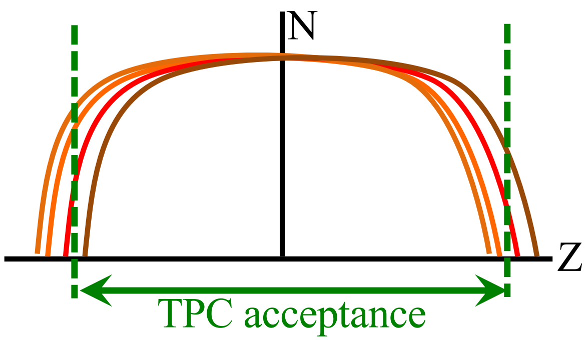
Pseudocorrelations
$\langle R_2 \rangle$ vs Δy

low Δy enhancement…

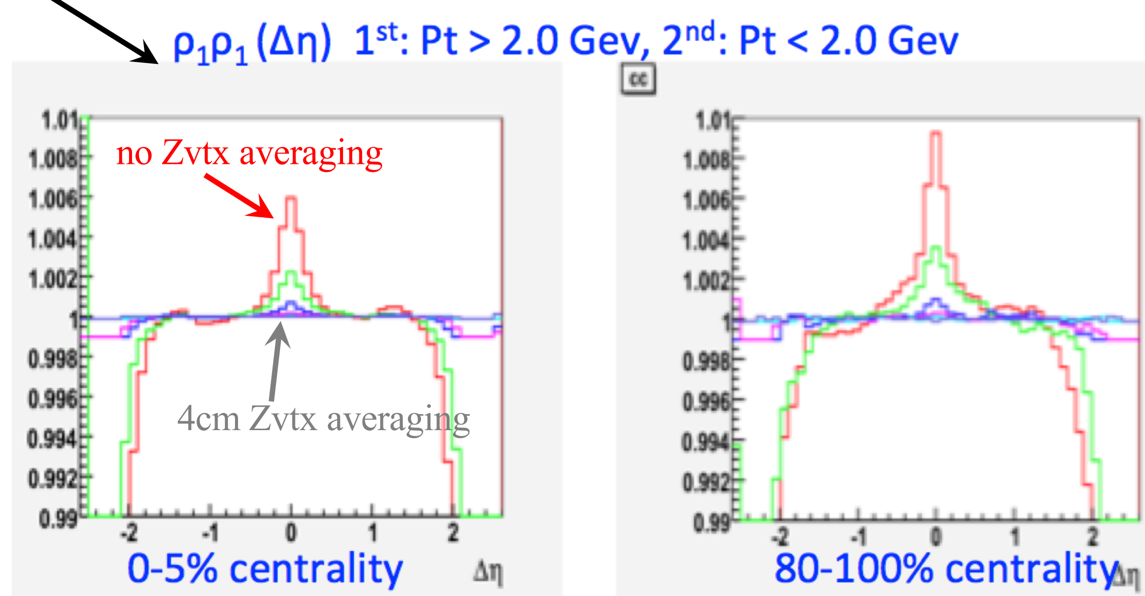
not seen in UrQMD evts…



Caused by rapidity dependence of experimental efficiency coupled with Zvtx smearing…



✔ Analyze in 2cm-wide Zvtx bins then weight-average the results…



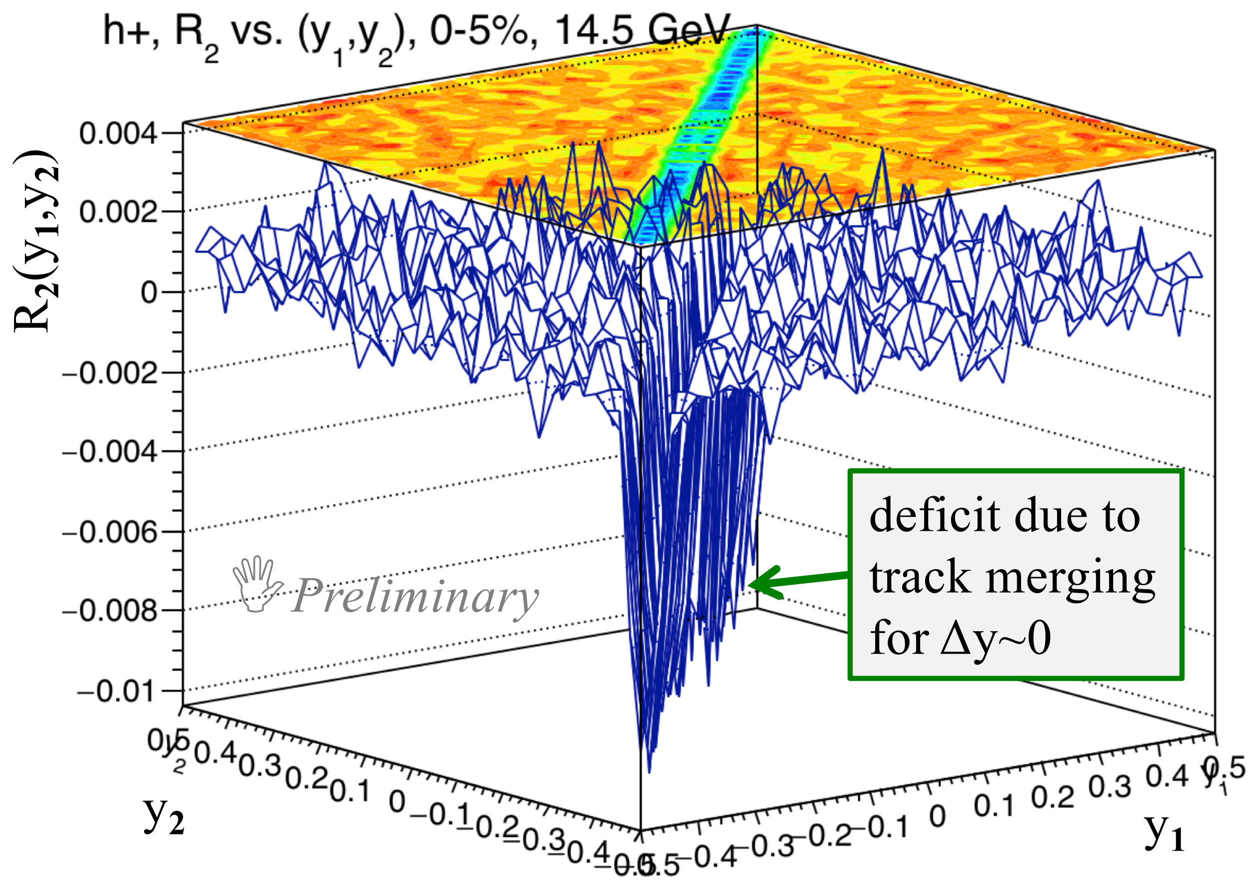
Slightly reduced efficiency for nearby tracks…

Very strong trench in R_2 when particle multiplicities/event of POI get large:
h± for all centralities and $\sqrt{s_{NN}}$, and only most central for K±

Numerator and denominator of R_2 & C_N uses only measured tracks…
but there is a slight **2-particle** inefficiency when two tracks are close (Δy~0)

The STAR track-finder ″sti″ does not share spacepoints!

a new one does ″stiCA″ (10%)



Beating the track merging deficits at Δη~0

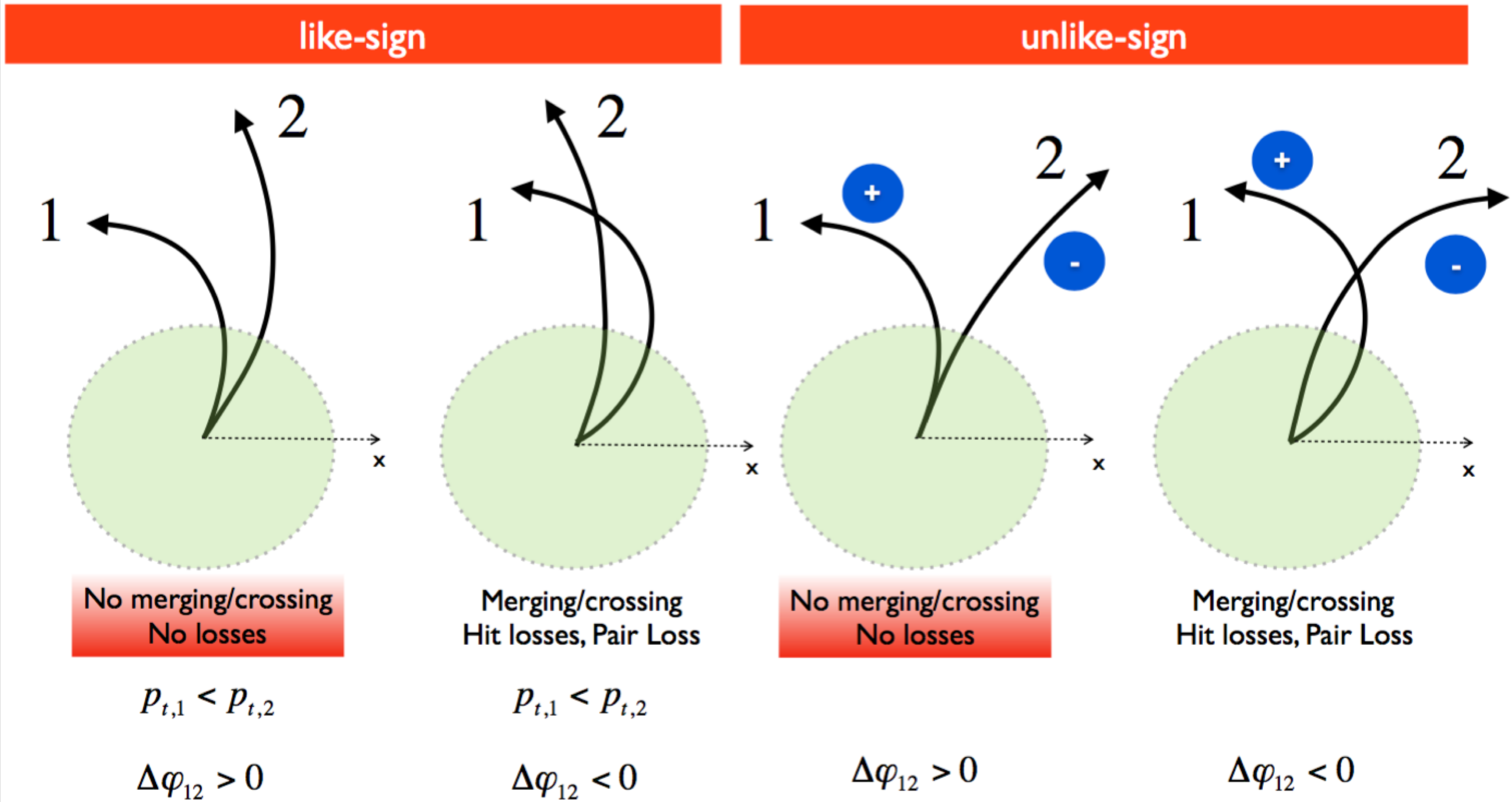


Image from P. Pujahari

LS & US: reflect clean area in Δφ to replace problem area

US: nothing special in fill method

LS: pT order the tracks, fill numerator for upper triangle only, then symmetrize