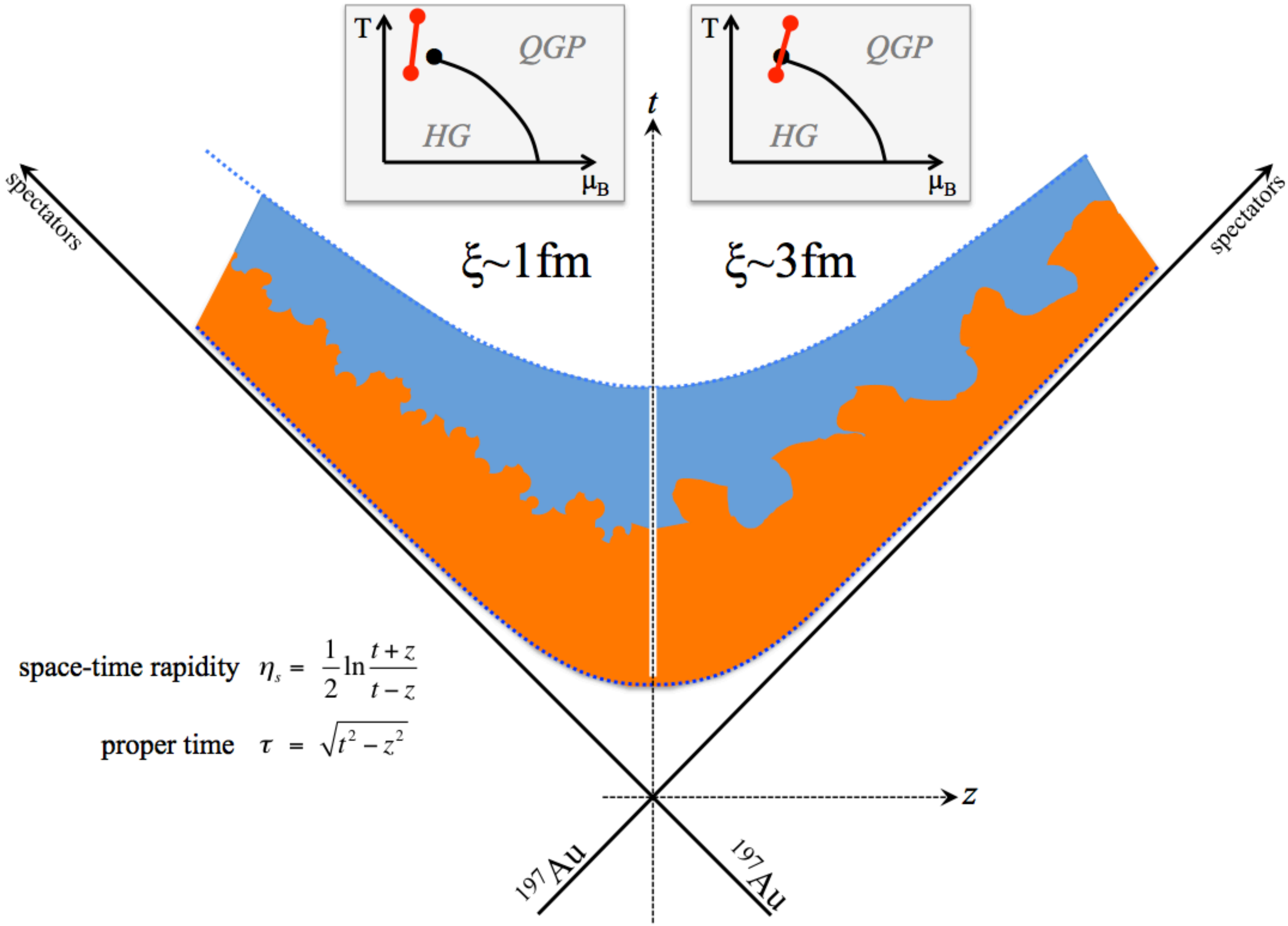
Rapidity Correlations

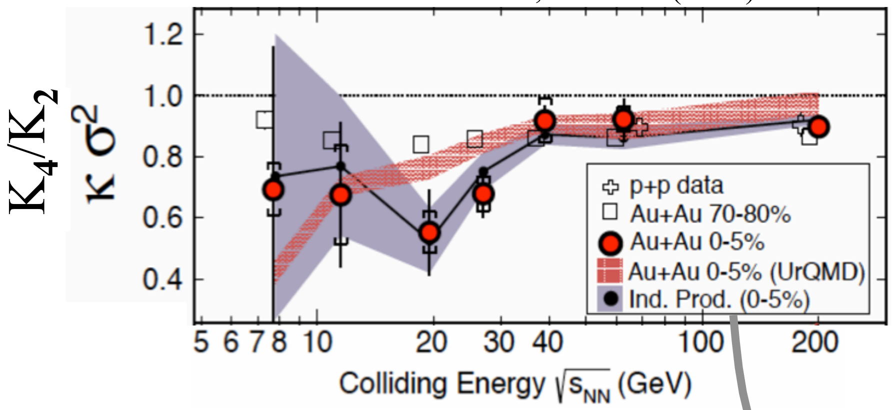
W.J. Llope for the STAR Collaboration
Wayne State University



Net-proton multiplicity cumulant ratios...

STAR net-p multiplicity cumulant ratios

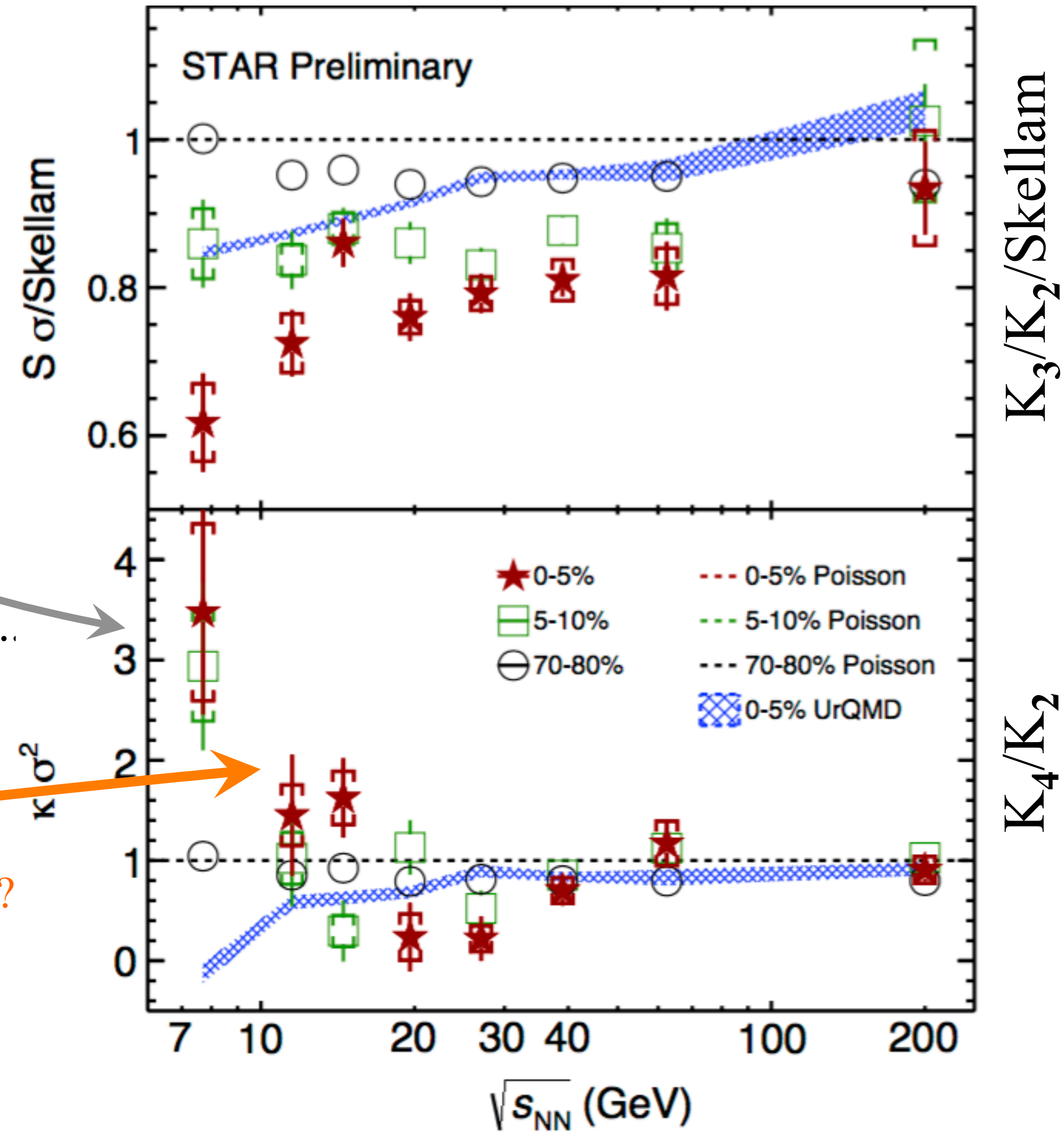
STAR, PRL 112 (2014) 032302

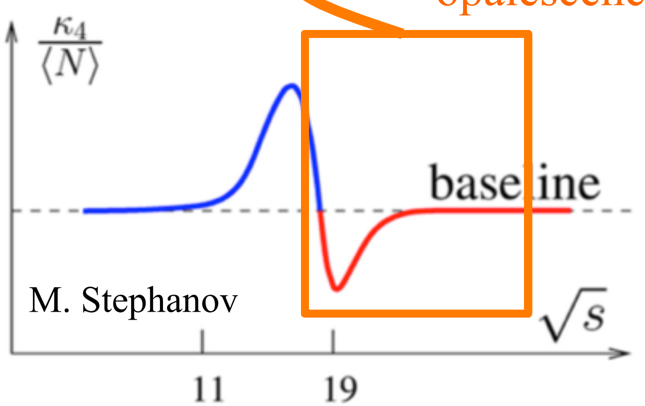


Widen the acceptance

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

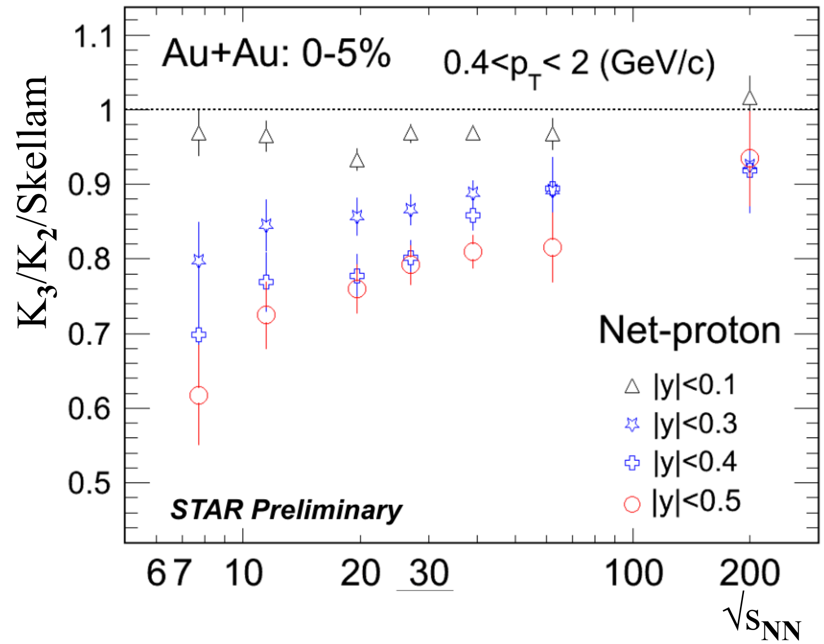
Net-proton multiplicity cumulant ratios and acceptance...

In a small acceptance, you will see Poissonian cumulant ratios, CP or not....

e.g. V. Koch, RIKEN BNL Research Center Workshop on Fluctuations, Correlations and RHIC Low Energy Runs, October 3-5, 2011
http://quark.phy.bnl.gov/~htding/fcrworkshop/Koch.pdf

decreasing rapidity acceptance in the analysis also drives the K_4/K_2 values to Poisson:

see also D. Mahapatra *et al.*,
Int. J. Mod. Phys A 17, 675 (2002)



Net-baryon Acceptance:

0% — 100%

Poisson fluctuations — Zero fluctuations (baryon # conservation)

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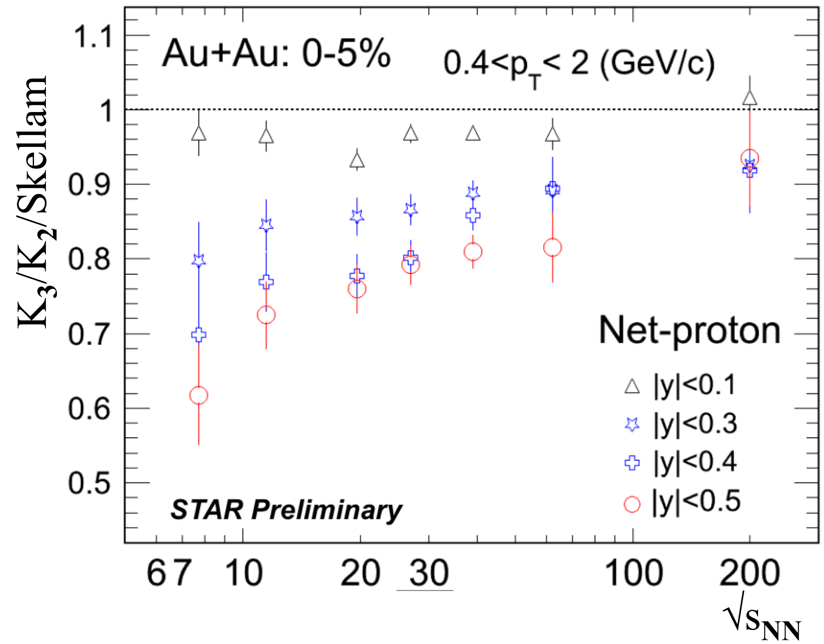

Net-baryon Acceptance:

0%

100%

Poisson fluctuations

Zero fluctuations (baryon # conservation)

Maximum signal?

No signal?

B. Ling & M. Stephanov, PRC **93**, 034915 (2016)

No signal!

In a small acceptance, you will see Poissonian cumulant ratios, CP or not....

e.g. V. Koch, RIKEN BNL Research Center Workshop on Fluctuations, Correlations and RHIC Low Energy Runs, October 3-5, 2011
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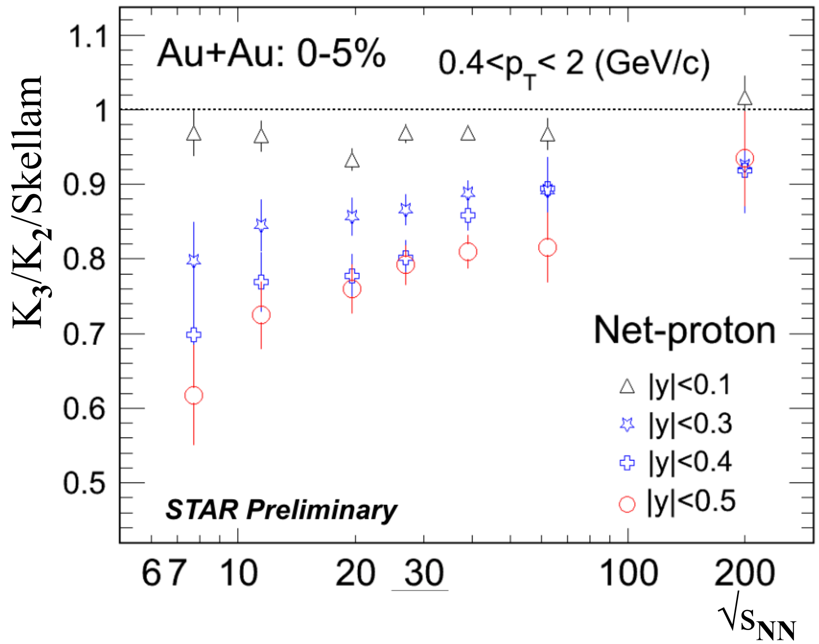


Net-baryon Acceptance:

0% 5% 14% 100%

Poisson fluctuations

Zero fluctuations (baryon # conservation)

net-protons
$0.4<P_T<0.8$, $|y|<0.5$
$C_1 \sim 8$ @ 19.6GeV

net-protons
$0.4<P_T<2.0$, $|y|<0.5$
$C_1 \sim 22$ @ 19.6GeV

Rapidity Correlations

$R_2(y_1,y_2)$ – developed at ISR & FNAL in 1970s to describe two particle correlations in (pseudo)rapidity
$R_2>0$ correlations, $R_2<0$ anticorrelations, $R_2=0$ uncorrelated.

$$R_2 = \frac{C_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} = \frac{\rho_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1$$

same event
mixed events or tensor product of 1D

lead to "cluster" picture...
- clusters decay to FS particles
- clusters uncorrelated w/ each other
- isotropic decay of clusters in their rest frames
- Lorentz-invariant translation of clusters in pseudorapidity

Exposes short and long-range correlations:
E & p conservation
minijets
HBT

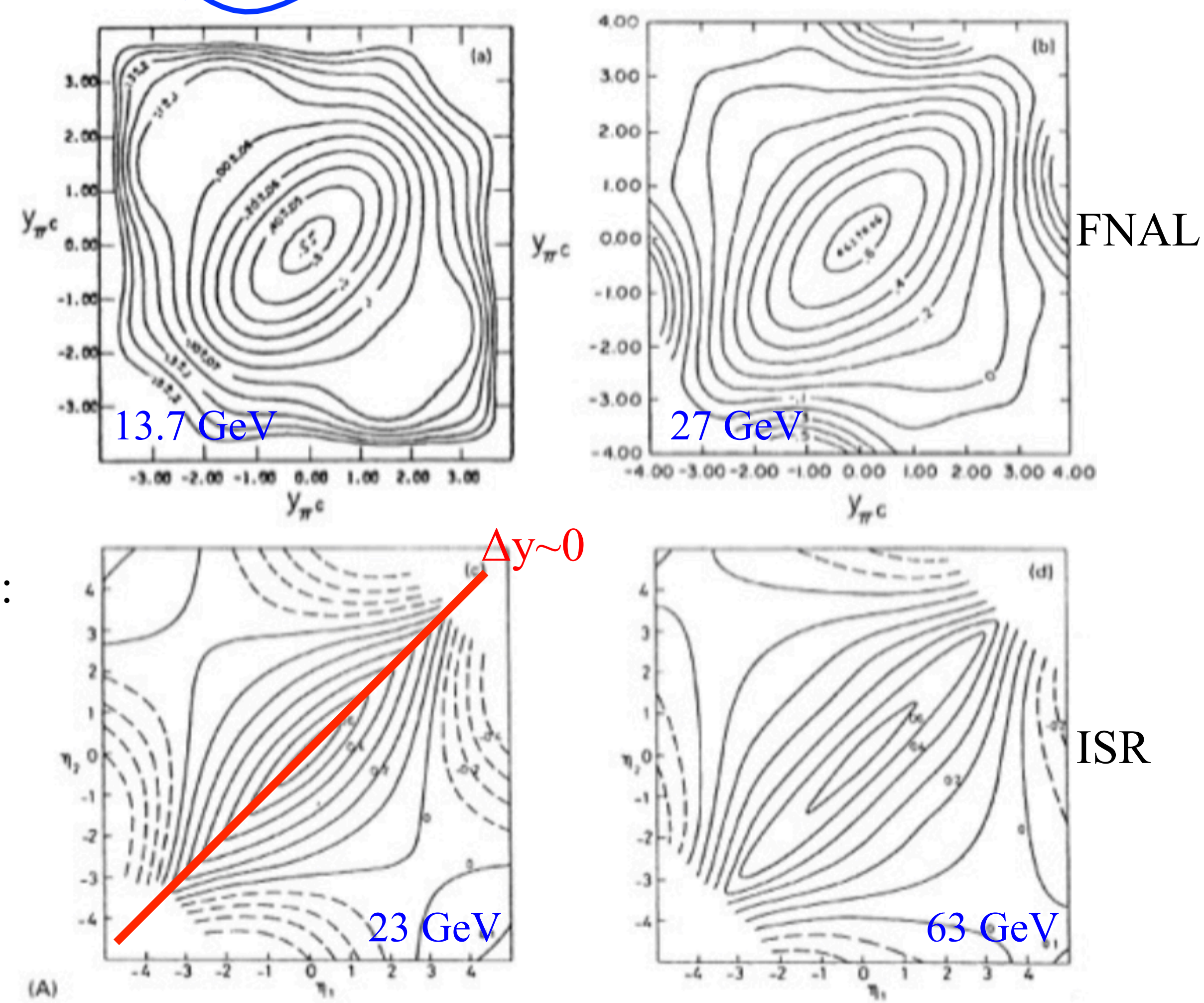
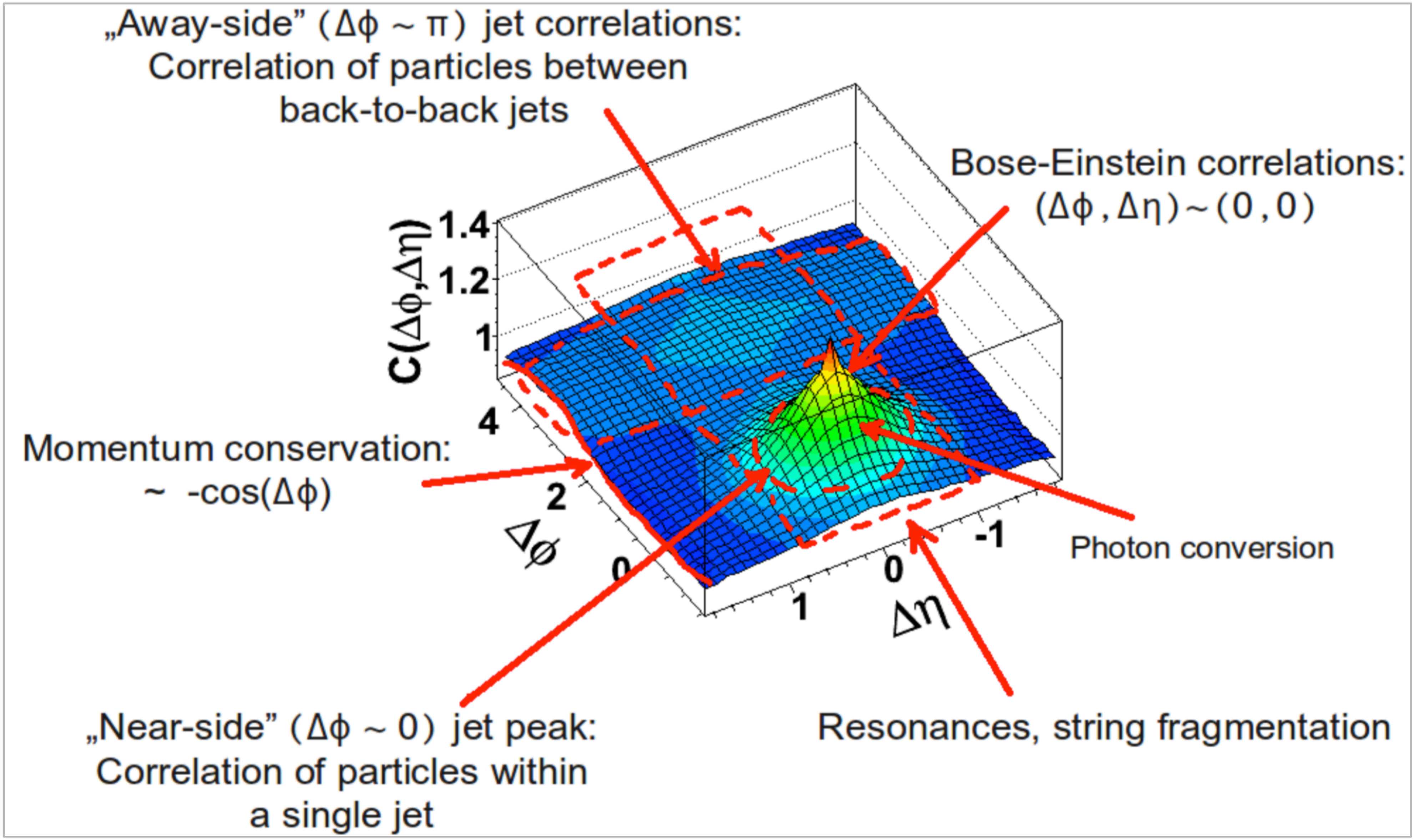


Figure 3.5: R_2^{cc} for $p+p$ collisions at FNAL (a-b)and CERN ISR (c-d): $\sqrt{s} = 13.7$, 27, 23, 63 GeV.

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

Lots of ways to correlate

Małgorzata Janik, X Workshop on Particle Correlations and Femtoscopy, Gyöngyös, Hungary, Aug 26, 2014



Fit 4-5 functions to the 2D correlators to extract strengths of near-side peak, momentum conservation, v_1 "dipole", v_2 "quadrupole", etc...

Recent interest from theory side for such information

Recall how fourier decomposition of azimuthal angle distrubutions leads to all sorts of interesting information on elliptic flow, flow fluctuations, triangularity....

A similar approach can be applied to study the shape of the fireball in the longitudinal direction!

Long-range rapidity correlations as fluctuating rapidity density of the fireball:

A. Bialas, A. Bzdak, and K. Zalewski, Phys. Lett. B **710**, 332 (2012).
A. Bialas and K. Zalewski, Acta Phys. Pol. B **43**, 1357 (2012).

...possibly with a significant asymmetric component in fireball's rapidity shape:

B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **103**, 172301 (2009).

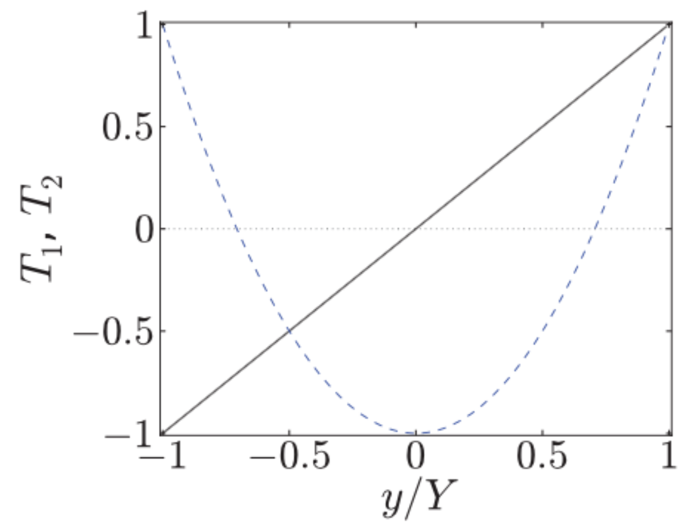
...Generalize!

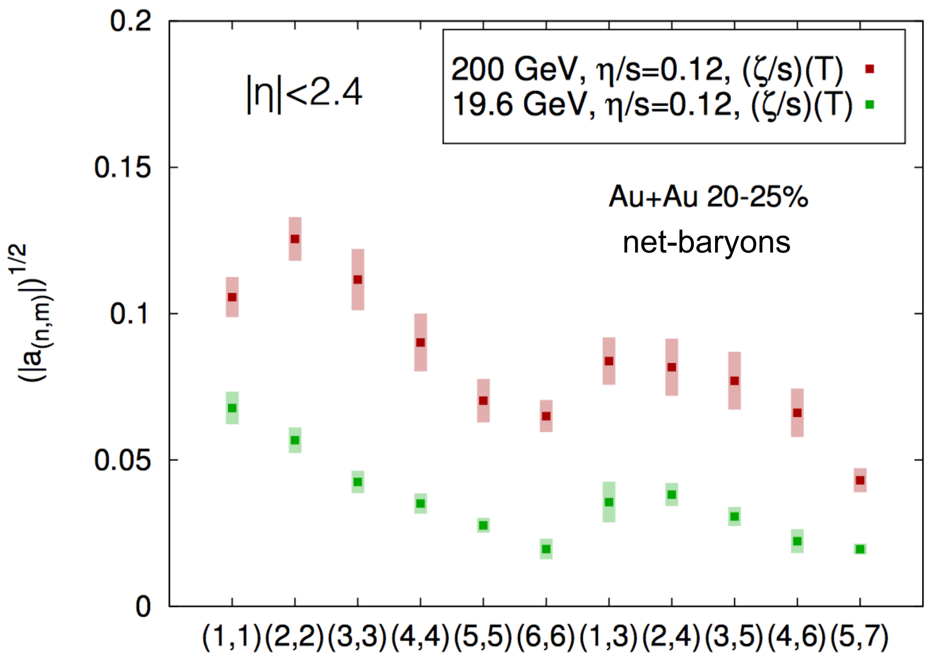
A. Bzdak and D. Teaney, Phys. Rev. C **87**, 024906 (2013)

$$C(y_1, y_2) \equiv \rho_2(y_1, y_2) - \rho(y_1)\rho(y_2)$$

...decompose rapidity correlator onto Chebyshev polynomials...

$$\frac{C_2(y_1,y_2)}{\langle\rho(y_1)\rangle\langle\rho(y_2)\rangle} = \sum_{i,k} \langle a_i a_k \rangle T_i(y_1/Y) T_k(y_2/Y)$$





information on the number of sources, baryon stopping mechanisms, viscosity, ...

See also:
A. Bzdak, Phys. Rev. C **85**, 051901(R) (2012)
T. Lappi & L. McLerran, Nucl. Phys. A **832**, 330 (2010)
A. Monnai, B. Schenke, PLB **752**, 317 (2016)
A. Bzdak (QM2015) 29/9/2015 16:00-16:20
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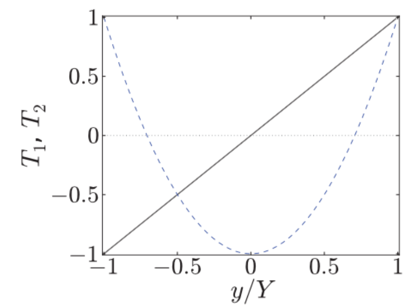

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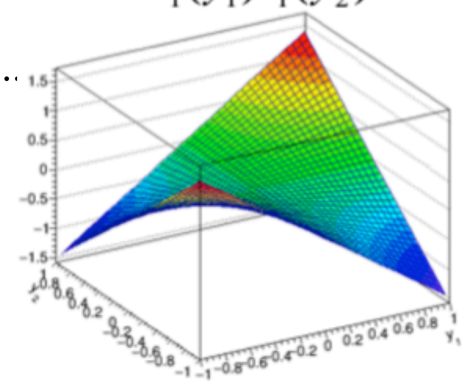
...decompose rapidity correlator onto Legendre polynomials...

$$\frac{C_2(y_1,y_2)}{\langle\rho(y_1)\rangle\langle\rho(y_2)\rangle} = \sum_{i,k} \langle a_i a_k\rangle T_i(y_1/Y)T_k(y_2/Y)$$

$T_1(y_1)T_1(y_2)$



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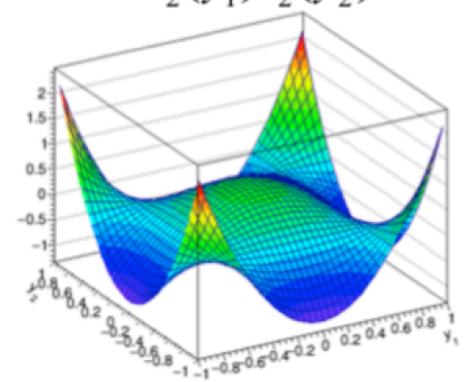

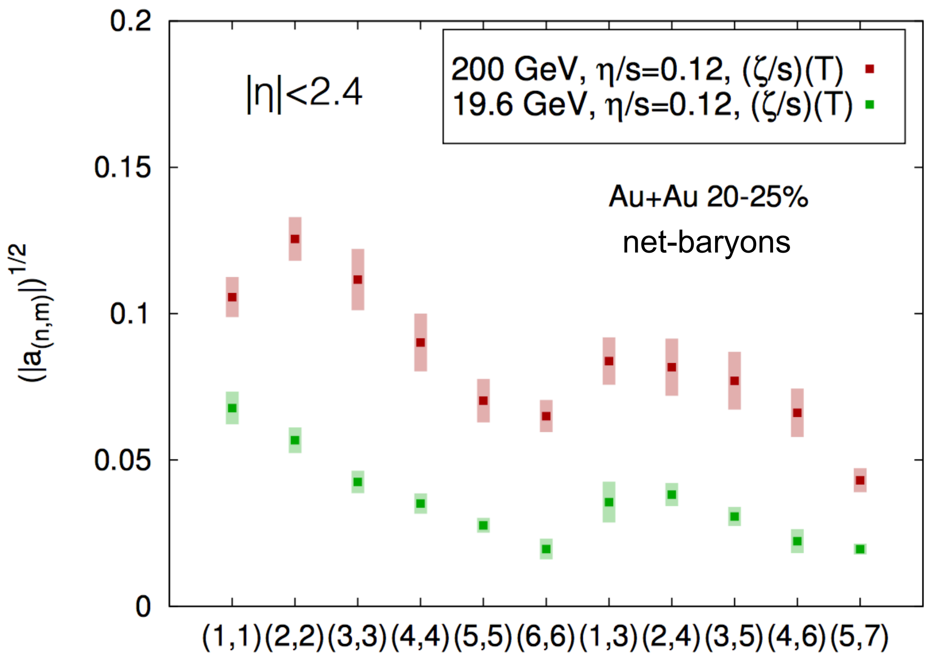

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$R_2(y_1,y_2)$ – developed at ISR & FNAL in 1970s to describe two particle correlations in (psuedo)rapidity
$R_2>0$ correlations, $R_2<0$ anticorrelations, $R_2=0$ no correlations.

Recently, this variable has reappeared with a new name: $C(y_1,y_2)$… $C(y_1,y_2) = R_2(y_1,y_2) + 1$

$$R_2 = \frac{C_2(y_1, y_2)}{\rho_1(y_1)\rho_1(y_2)} = \frac{\rho_2(y_1, y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1$$

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J. Jia, S. Radhakrishnan, and M. Zhou, PRC **93**, 044905 (2016), arXiv:1506.03496

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reflects the multiplicity fluctuations

represents residual centrality dependence in the shape of <N(y)>

With a special normalization, the residual centrality dependence is largely eliminated.

$$C_N(y_1,y_2) = \frac{C(y_1,y_2)}{C_p(y_1)C_p(y_2)}$$

$$C_p(y_1) = \frac{\int_{-Y}^{Y} C(y_1,y_2)dy_2}{2Y}, C_p(y_2) = \frac{\int_{-Y}^{Y} C(y_1,y_2)dy_1}{2Y}$$

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reflects the multiplicity fluctuations

represents residual centrality dependence in the shape of <N(y)>

encodes the dynamical shape fluctuations for events with the same centrality

With a special normalization, the residual centrality dependence is largely eliminated.

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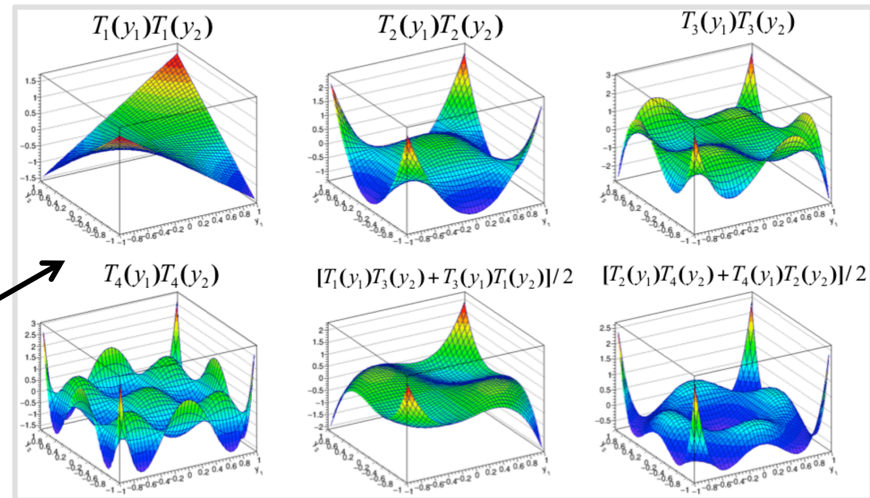


Dynamical shape fluctuations (and correlations) can be quantified by decomposing the measured distributions onto a basis set of Legendre polynomials, with "strength" coefficients $<a_{mn}>$

Rapidity analog of decomposition of azimuthal anistropies onto cos(nφ…) bases with strengths v_n

Note: $<a_{(n,m)}>$, $<a_n a_m>$, and $<a_{mn}>$ are all the same thing... (different people use different nomenclatures)

Relation of correlators to multiplicity cumulants

$$r_2 = \frac{\int dy_1 dy_2\ [\rho_1(y_1)\rho_1(y_2)]\ R_2(y_1,y_2)}{\int dy_1 dy_2\ [\rho_1(y_1)\rho_1(y_2)]} \quad \text{and} \quad K_2 = \langle N \rangle + \langle N \rangle^2 r_2$$

$$R_2 = \frac{\rho_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1 \rightarrow r_2 = \frac{\int dy_1 dy_2\ \rho_2(y_1,y_2) - \int dy_1 dy_2\ \rho_1(y_1)\rho_1(y_2)}{\int dy_1 dy_2\ \rho_1(y_1)\rho_1(y_2)}$$

$$r_2 = \frac{\int dy_1 dy_2\ \rho_2(y_1,y_2) - \int dy_1 \rho_1(y_1) \int dy_2 \rho_1(y_2)}{\int dy_1 \rho_1(y_1) \int dy_2 \rho_1(y_2)}$$

$$\int dy\ \rho_1(y) = \langle N \rangle$$

$$\int dy_1 dy_2\ \rho_2(y_1,y_2) = \langle N(N-1) \rangle$$

$$r_2 = \frac{\langle N(N-1) \rangle - \langle N \rangle^2}{\langle N \rangle^2}$$

$$K_2 = \langle N \rangle + \langle N \rangle^2 \frac{\langle N(N-1) \rangle - \langle N \rangle^2}{\langle N \rangle^2}$$

$$K_2 = \langle N \rangle + [\langle N(N-1) \rangle - \langle N \rangle^2]$$

$$K_2 = \langle N \rangle + [\langle N^2 \rangle - \langle N \rangle - \langle N \rangle^2]$$

$$K_2 = \langle N^2 \rangle - \langle N \rangle^2 \qquad \text{(variance)}$$

see also:
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)

integrals of R_k give multiplicity cumulants K_k … $K_3/K_2=S\sigma$, $K_4/K_2=\kappa\sigma^2$

Different ways to calculate R_2

"mixing" $$R_2 = \frac{\rho_2(y_1, y_2)}{\rho_2^{mix}(y_1, y_2)} - 1$$

shown at QM2017 (S. Jowzaee)
offsets in low multiplicity events

"convolution" $$R_2 = \frac{\rho_2(y_1, y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1$$

new in this talk
multiplicity baseline correction:

$$R_2^{baseline} = \frac{\langle N(N-1)\rangle}{\langle N\rangle^2} - 1$$

"weighting" $$R_2 = \frac{\rho_2^w(y_1, y_2)}{\rho_1^w(y_1)\rho_1^w(y_2)} - 1$$

e.g. ALICE arXiv:1612.08975

$\rho_2^w(y_1, y_2)$ filled with weight $1/[n(n-1)]$

$\rho_1^w(y)$ filled with weight $1/n$ n = multiplicity in each event

---

"Weighting" approach works fine for dealing with multiplicity effects
but destroys the mathematics of multiplicity cumulants from R_k integrals

Will concentrate here on existing results from mixing, and new ones from convolution

Note, low multiplicity offsets do not affect $\langle a_{mn} \rangle$ values!

Turning now to the ☆ data...

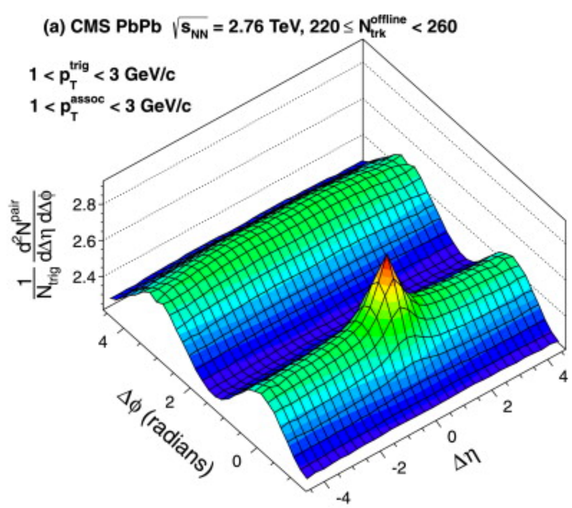
Track crossing effects are a pain, standard techniques are applied... (P_T ordering, reflection)

Denominator from mixing (sampling, *i.e.* QM results) and now convolution

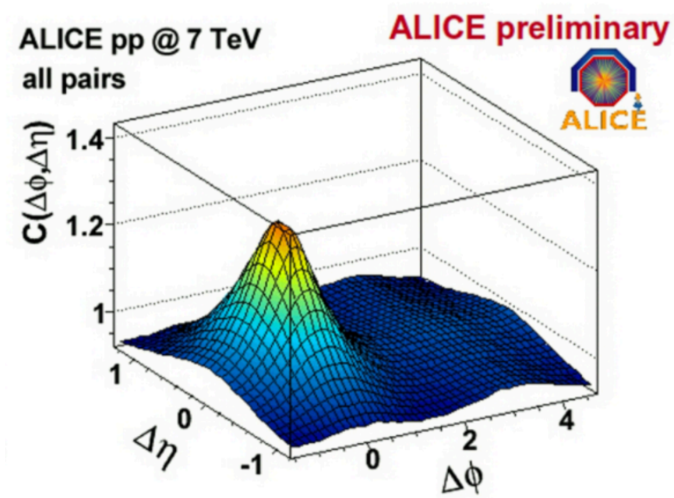
Not yet scaling R_2 by $N_{\mathbf{part}}$

Systematic uncertainities for convolution results not yet determined.

Short-range correlations not subtracted...



CMS, PLB 724, 213 (2013)



ALICE, arXiv:1402.3988 [hep-ex]

LHC plots generally smoother - event sample sizes are similar, but the LHC has many more pairs/event.

Datasets, cuts, centrality

Datasets: All 8 BES energies
200 GeV data from Run-10

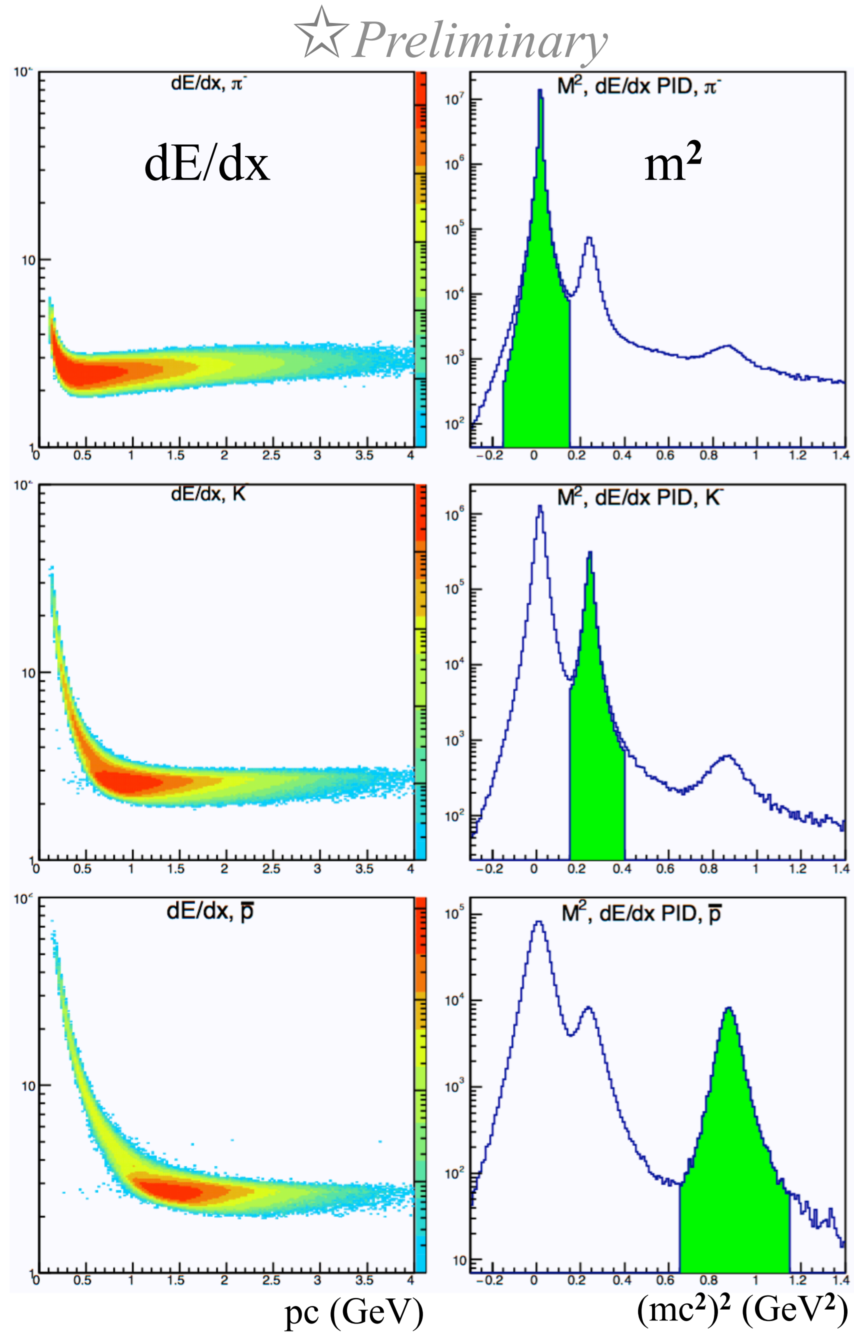
POI: $h^{\pm}$, $\pi^{\pm}$,$K^{\pm}$, & $p^{\pm}$
2σ on dE/dx, then require good TOF m^2
reject electrons

Cuts: |Zvtx|<30cm at all $\sqrt{s_{NN}}$
Nhitsfit>15
gDCA<2cm
p_T^{min} : 0.2 for h± & K±, 0.4 for p±
p_T^{max} : 2.0
p^{max} : 1.6 for h± & K±, 3.0 for p±

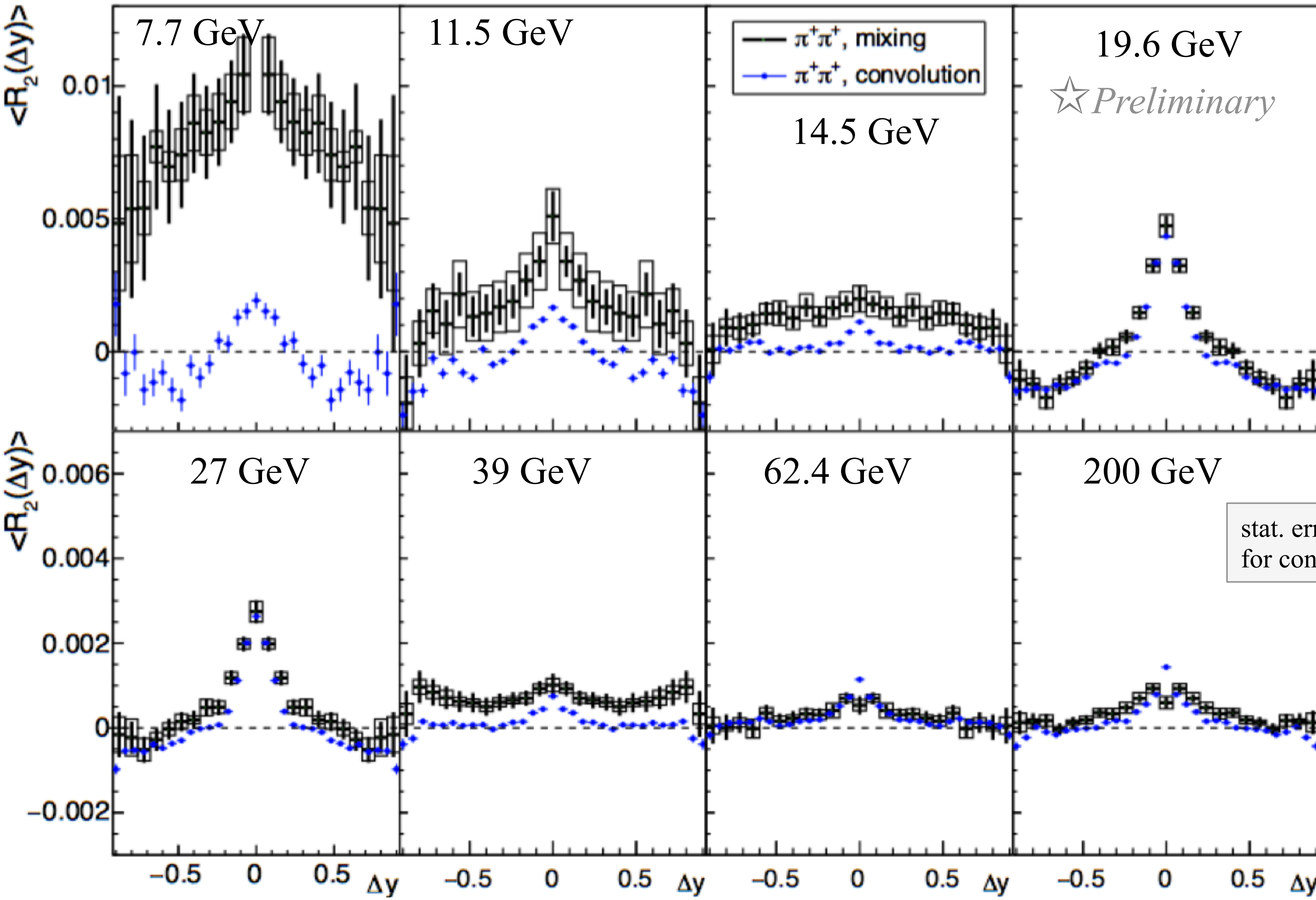
Centrality: N_{tracks} with 0.5<|η|<1 for h± & K±
$N_{\pi,K}$ with -1<η<1 for p±

Cuts & centrality intentionally very close to those used in recent ☆ multiplicity cumulant analyses.

Detailed "bad run" and "bad event in good run" QA



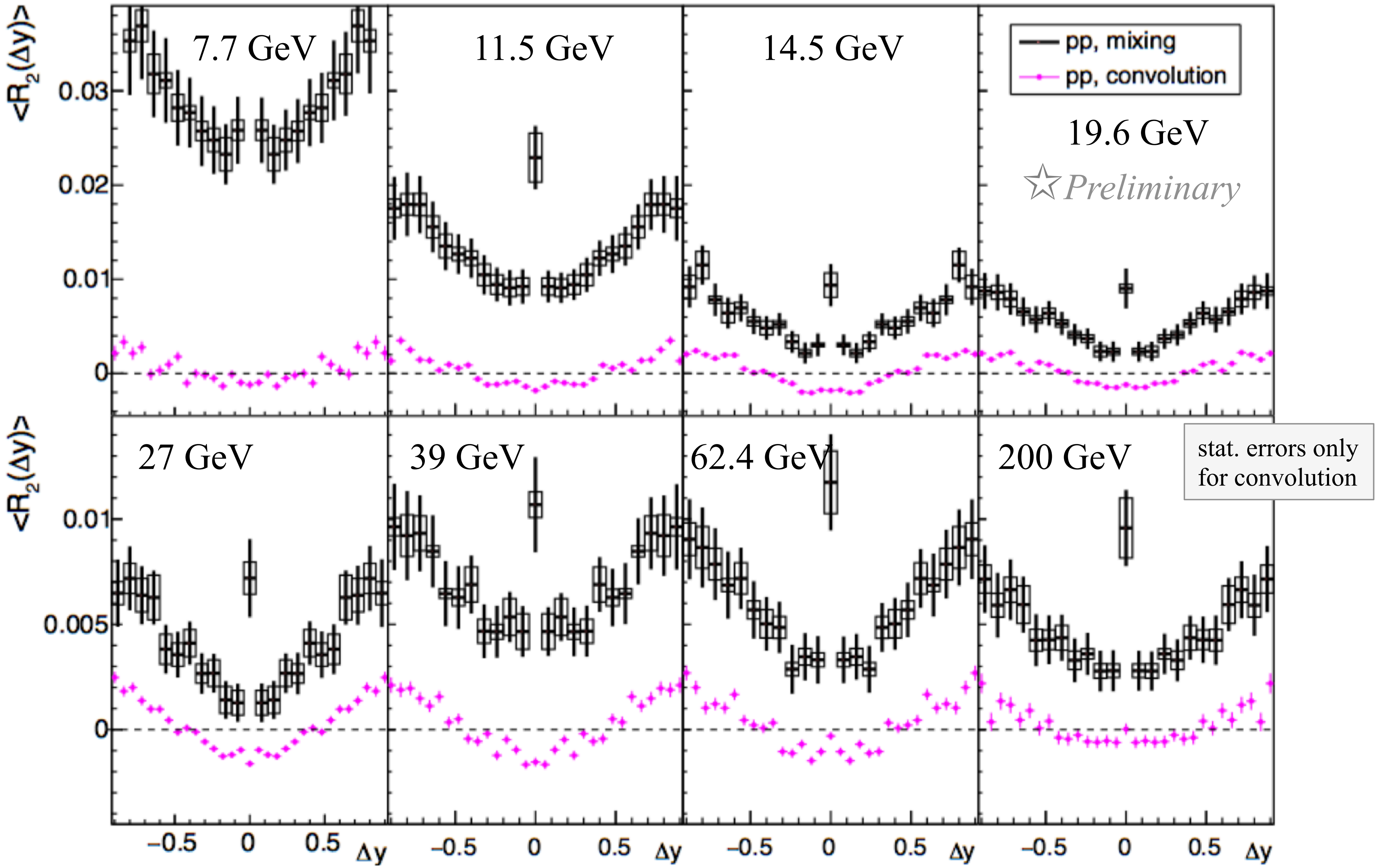
R2(Δy) for LS pions vs. $\sqrt{s_{NN}}$, 0-5% central, convolution & mixing



stat. errors only for convolution

Better control of finite multiplicity effects from convolution
Significant beam energy dependence

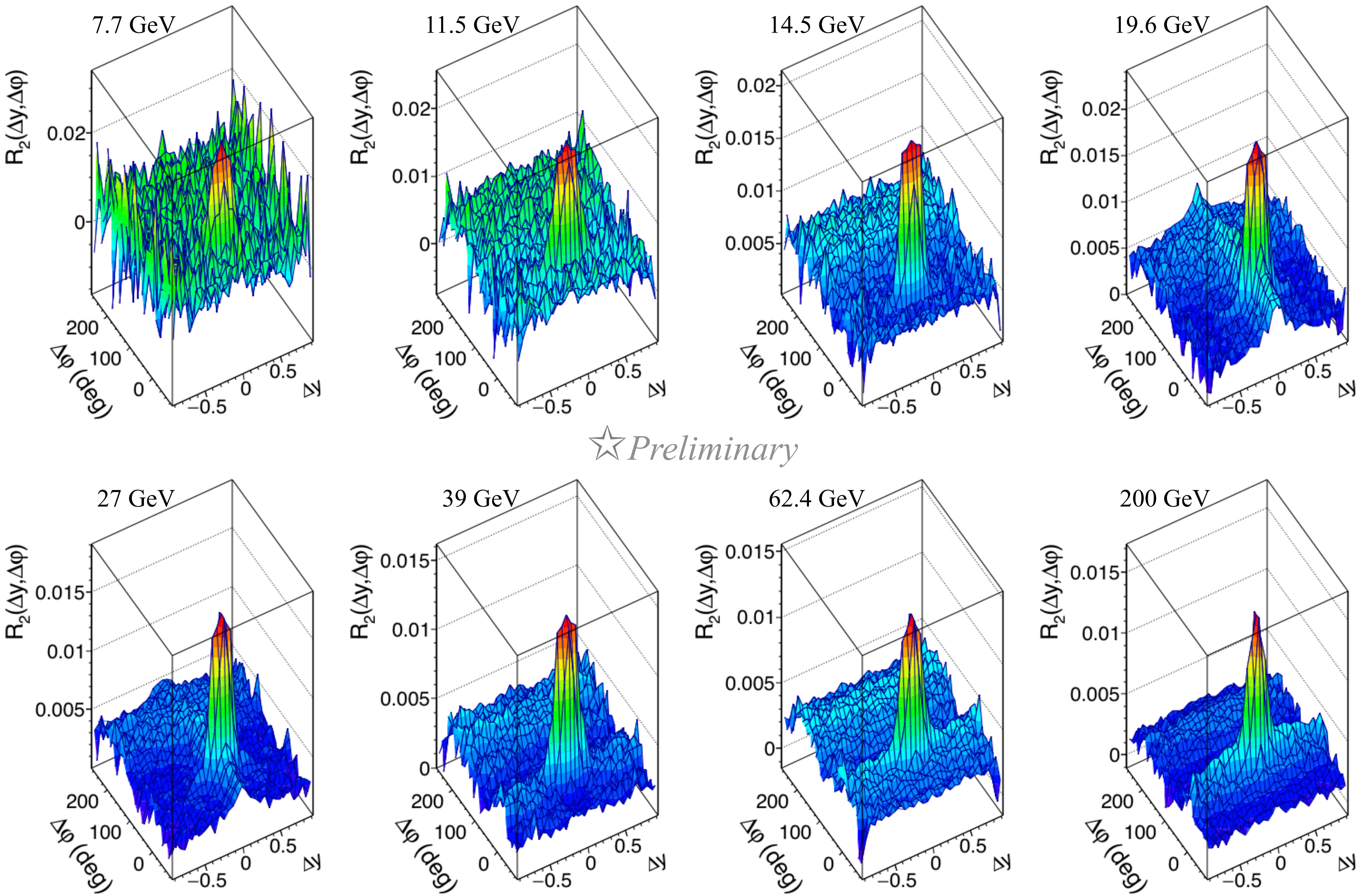
R2(Δy) for LS protons vs. $\sqrt{s_{NN}}$, 0-5% central, convolution & mixing



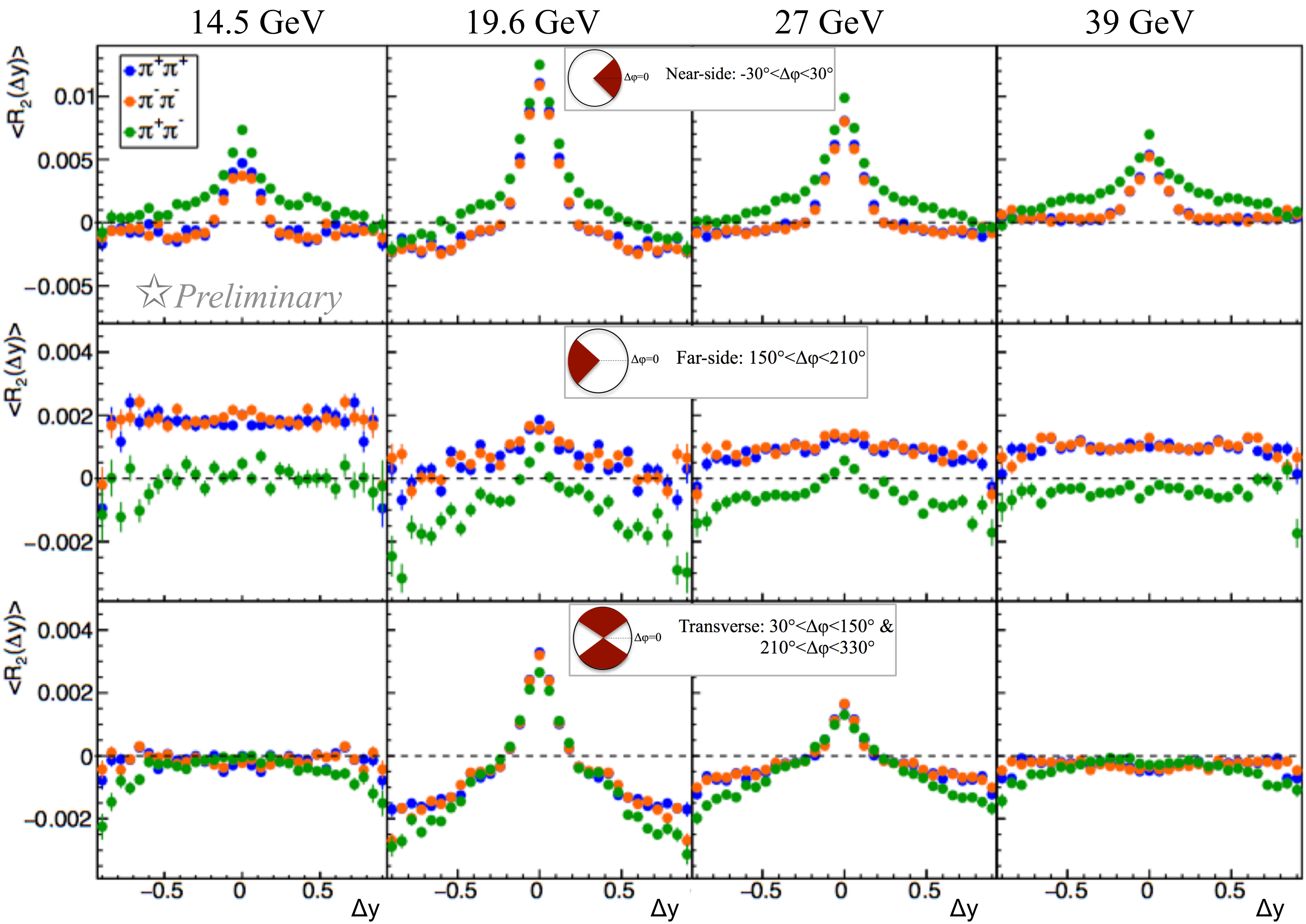
Better control of finite multiplicity effects from convolution

LS proton anticorrelation for Δy~0. Weak beam energy dependence.

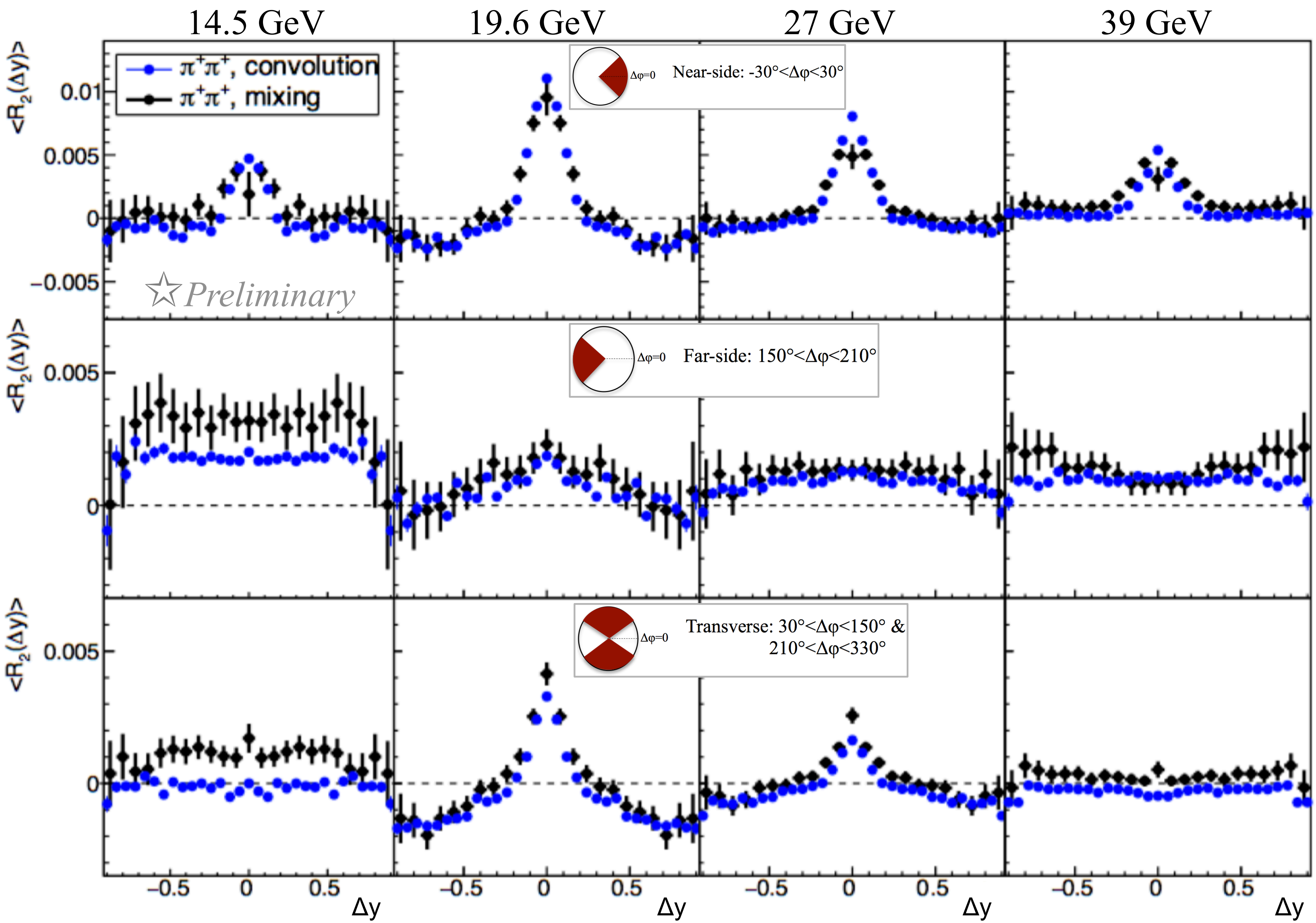
R2(Δy,Δφ) for LS pions vs. $\sqrt{s_{NN}}$, 0-5% central, convolution



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



R2(Δy) for LS pions vs. $\sqrt{s_{NN}}$, comparison of mixing and convolution

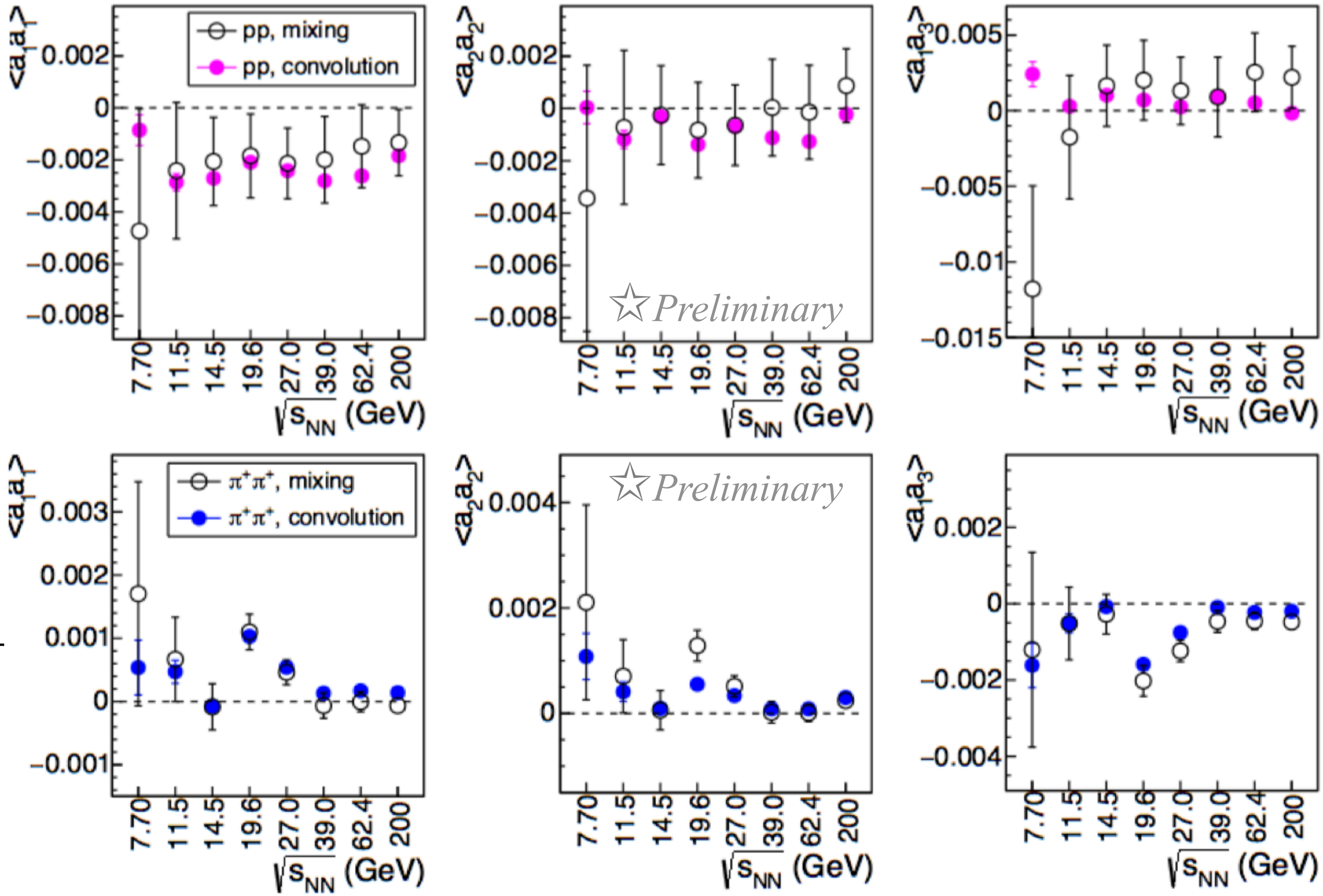


Like-sign protons and pions

open: mixing (presented at QM2017), solid: convolution (SRC not subtracted)

pp

$\pi^+\pi^+$



proton anticorrelation for Δy~0, beam energy dependence in pion correlations

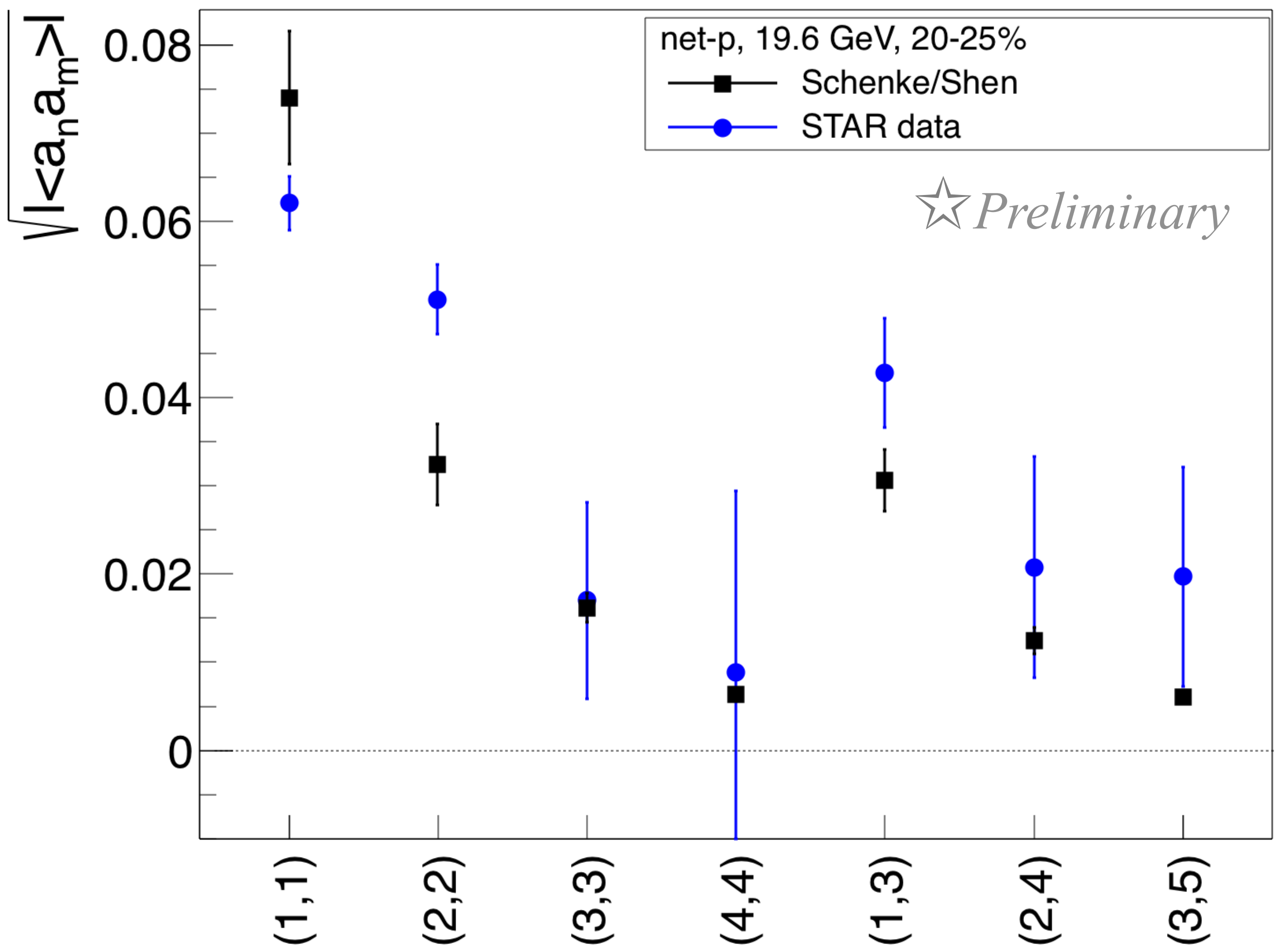
very preliminary comparison to viscous hydrodynamics

A first comparison to model calculations from B. Schenke & C. Shen

"net-protons" formed by convoluting pbar/p vs. y into a 2D histogram, then

$$C_2^{net-p} = \frac{C_2^{pp} - r_{\bar{p}/p} C_2^{\bar{p}\bar{p}}}{1 - r_{\bar{p}/p}}$$

$r_{\bar{p}/p}$ taken from: STAR, PRL **112**, 162301 (2014)



(SRC not subtracted)

Not trying to extract any physics conclusions from this plot here. Too early.

But magnitudes and trends are similar, which is encouraging.

Just starting these comparisons. We would love to collaborate with others too!
Most interested in particles alone (not net-particles), 0-5% central...

Trying to understand the Δφ–ridge reported at QM2017...

Recall: effect is beam energy localized, charge independent, & pions only

Appears when TOF PID is required. R_2 much larger and has no Δφ–ridge for dE/dx PID

TOF PID cleaner, and guarantees tracks are from the triggered crossing.

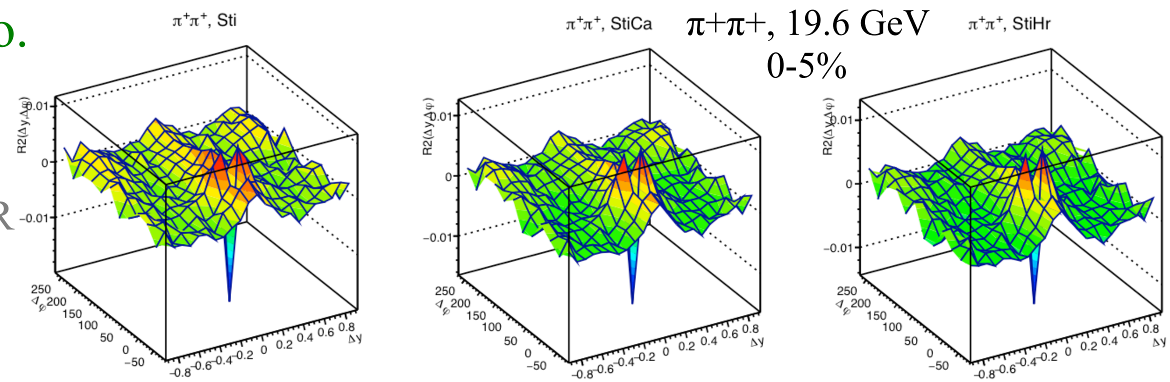
Not arising from specific Zvtx range, nor in some chronological section of the data

Seen in three completely independent analyses

Electrons? No, very few per event. Rejecting them makes no difference.

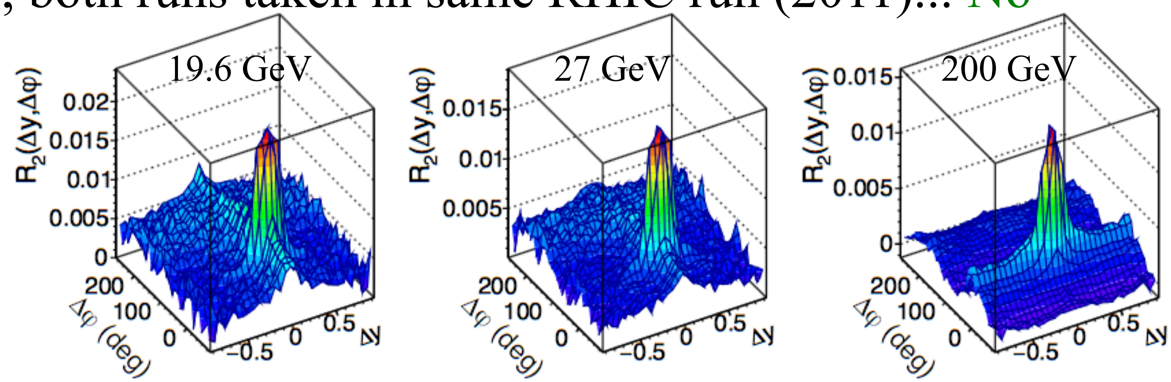
Bug in track crossing correction? No.

skip crossing correction, & compare three tracking codes: Sti, StiCA, StiHR



Seen at 19.6 GeV, less so at 27 GeV, both runs taken in same RHIC run (2011)... No

Was using Run-10 data at 200 GeV. Check 200 GeV data from Run-11:



We are still investigating it – Still too early to ascribe “physics” to this Δφ–ridge.

Summary

Rapidity correlation variables R_2 and C_N studied for LS and US pions and protons as function of $\sqrt{s_{NN}}$

C_N decomposed using basis set of Legendre polynomials to quantify the importance of different shaped (anti)correlations.

This approach is the analog in the rapidity direction of quantifying azimuthal anistropies with v_n observables.

Consistent results from two separate approaches (mixing, convolution)

from two completely independent codes.

Two proton anticorrelations at $\Delta y \sim 0$ ($a_{11}<0$). Beam energy independent.

Significant beam energy dependence of two-pion correlations.

Appears as a ridge at small Δy and extended in $\Delta\varphi$... (19.6-27 GeV, π only, charge independent)

Still investigating if this is experimental or physical.

First comparison of $\langle a_{mn} \rangle$ in STAR BES data to viscous hydrodynamics.

Basic trends of $\langle a_{mn} \rangle$ values vs. (m,n) in data and theory are similar

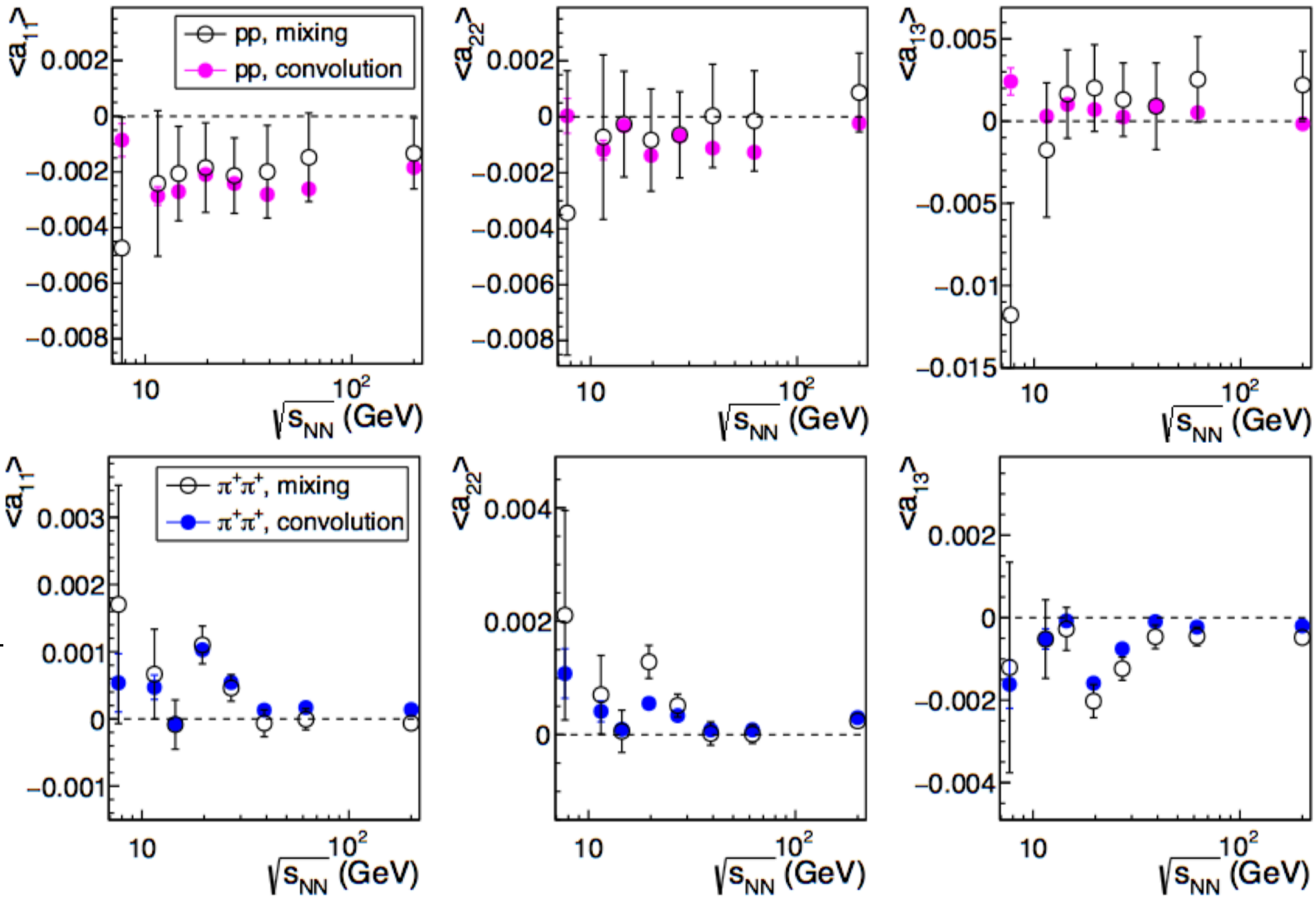
BACKUP SLIDES

open: mixing (presented at QM2017), solid: convolution

(SRC not subtracted)

pp

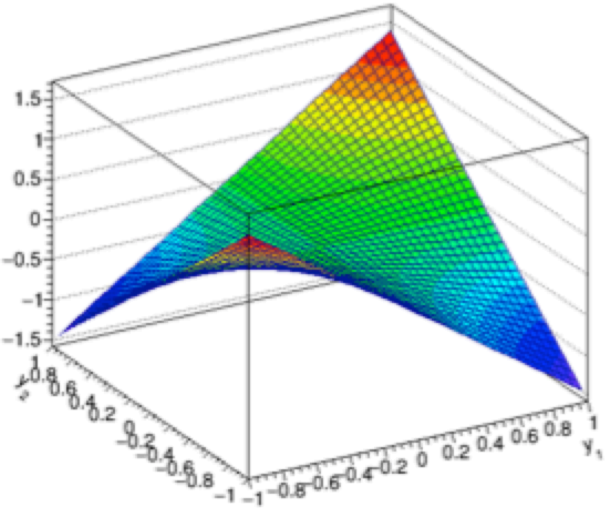
$\pi^+\pi^+$



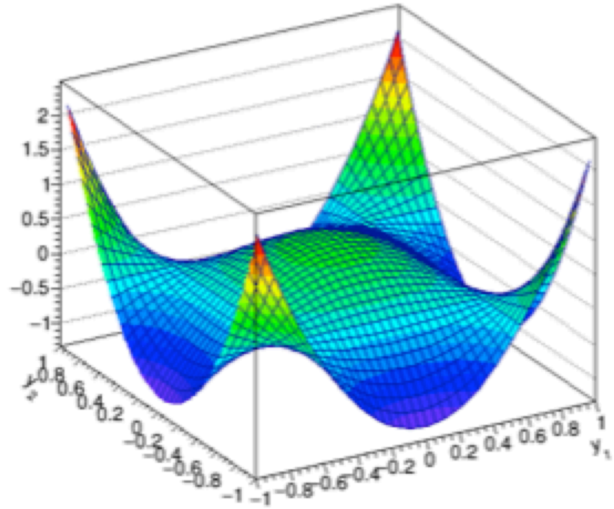
proton anticorrelation for Δy~0, beam energy dependence in pion correlations

Legendre basis functions

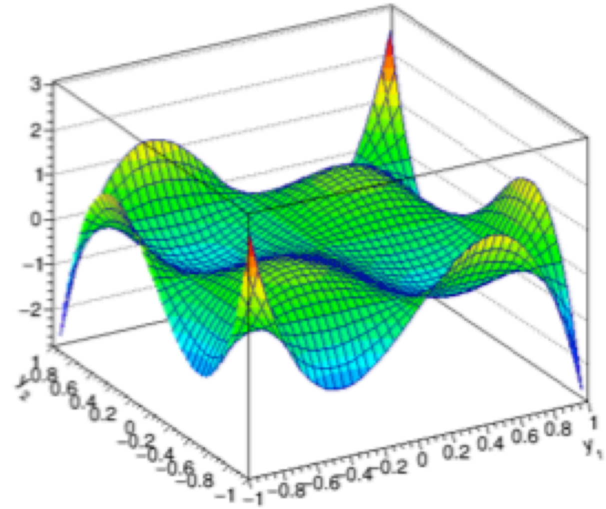
$T_1(y_1)T_1(y_2)$



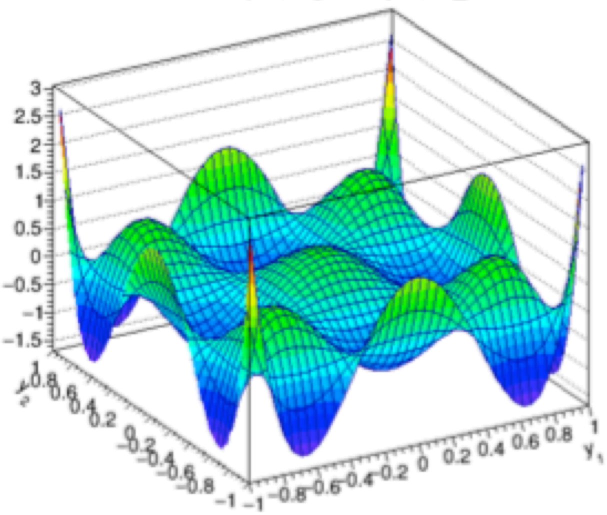
$T_2(y_1)T_2(y_2)$



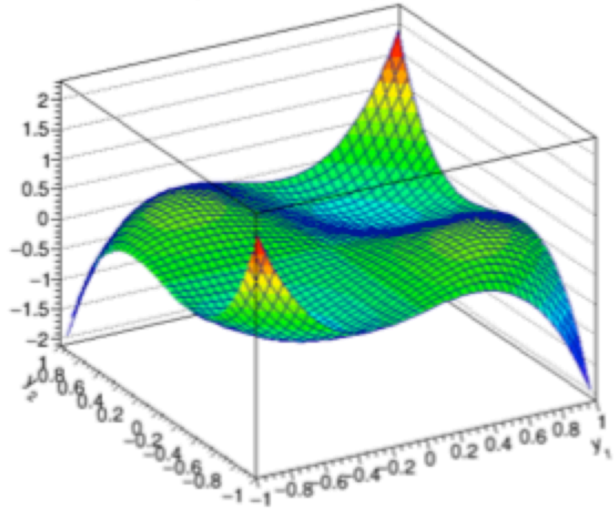
$T_3(y_1)T_3(y_2)$



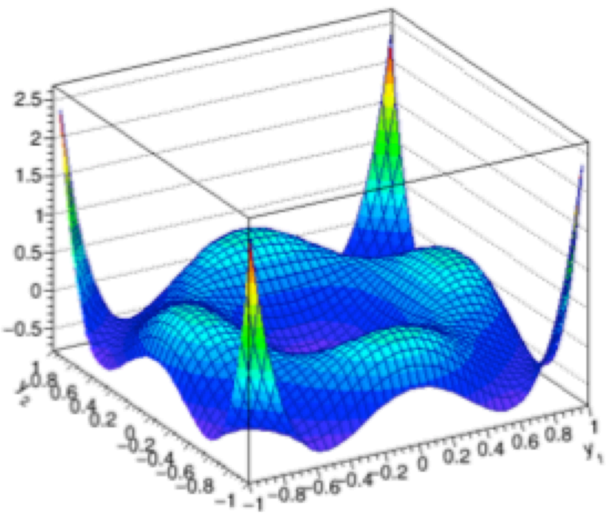
$T_4(y_1)T_4(y_2)$



$[T_1(y_1)T_3(y_2)+T_3(y_1)T_1(y_2)]/2$



$[T_2(y_1)T_4(y_2)+T_4(y_1)T_2(y_2)]/2$



PHYSICAL REVIEW A VOLUME 43, NUMBER 6 15 MARCH 1991

Structure of correlation functions

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(Received 9 October 1990)

$$C_2(x_1,x_2)=\rho_2(x_1,x_2)-\rho_1(x_1)\rho_1(x_2)\ ,$$

$$C_3(x_1,x_2,x_3)=\rho_3(x_1,x_2,x_3)-\sum_{(3)}\rho_2(x_1,x_2)\rho_1(x_3)+2\rho_1(x_1)\rho_1(x_2)\rho_1(x_3)\ ,$$

$$C_4(x_1,x_2,x_3,x_4)=\rho_4(x_1,x_2,x_3,x_4)-\sum_{(4)}\rho_3(x_1,x_2,x_3)\rho_1(x_4)-\sum_{(3)}\rho_2(x_1,x_2)\rho_2(x_3,x_4)$$
$$+2\sum_{(6)}\rho_2(x_1,x_2)\rho_1(x_3)\rho_1(x_4)-6\rho_1(x_1)\rho_1(x_2)\rho_1(x_3)\rho_1(x_4)\ .$$

See also:

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

Lower-order correlations explicitly removed.
R_k is just these rapidity cumulants C_k scaled by the number of pairs, triplets, quadruplets, ...
R_k thus manifestly independent of experimental inefficiencies by definition...

R_2 baseline: $R_3 = \frac{\langle n(n-1)\rangle}{\langle n\rangle^2} - 1$

R_3 baseline: $R_3 = \frac{\langle n(n-1)(n-2)\rangle}{\langle n\rangle^3} - 3\frac{\langle n(n-1)\rangle}{\langle n\rangle^3}\langle n\rangle + 2$

Robust indicator of N-fold (anti)correlations, explicitly as a function of Δy and $\langle y\rangle$…

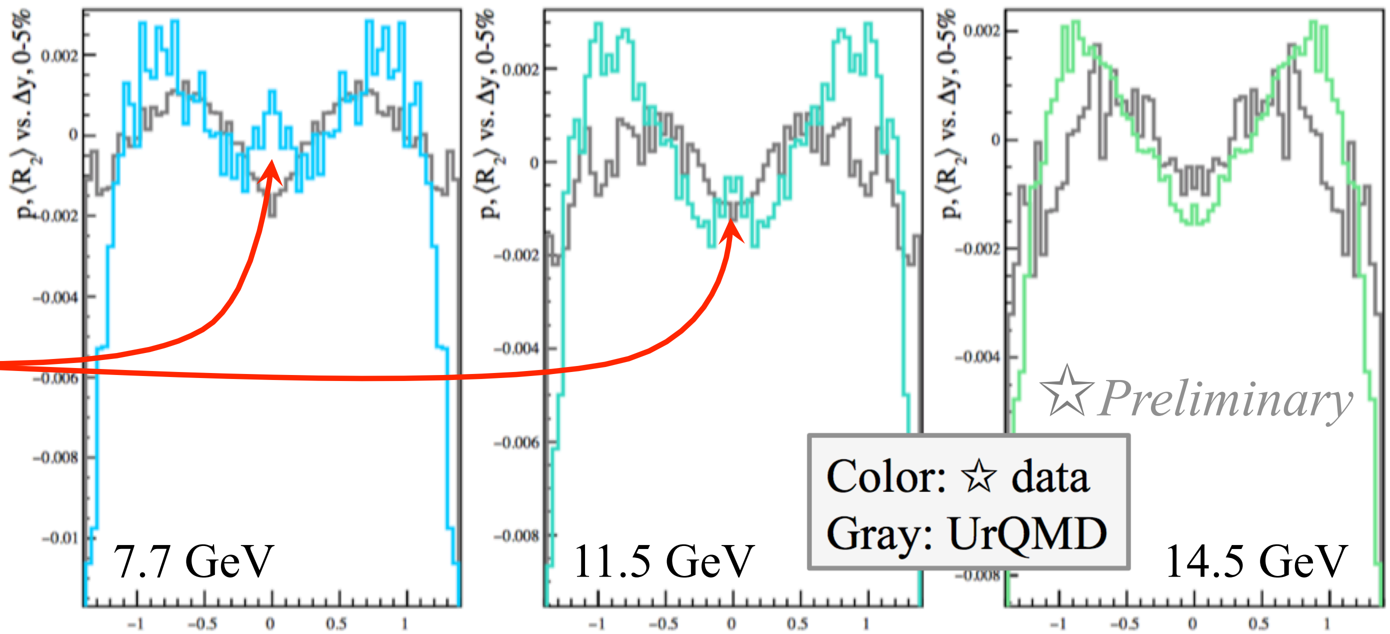
By construction, independent of single-particle inefficiencies…

Zvtx averaging

Pseudocorrelations
$\langle R_2 \rangle$ vs Δy

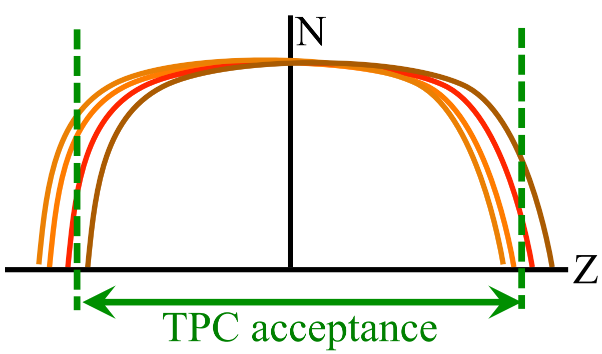
low Δy enhancement…

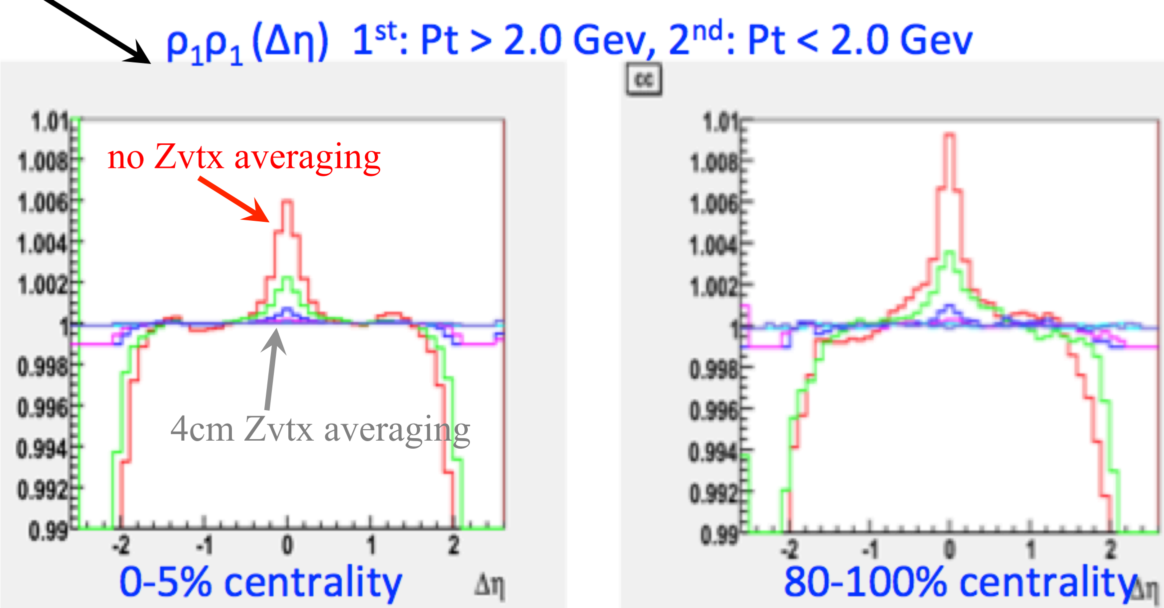
not seen in UrQMD evts…



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

See L. Tarini, Ph.D. Thesis, and his talk at the STAR Analysis Meeting, MIT, 7/10/2009





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

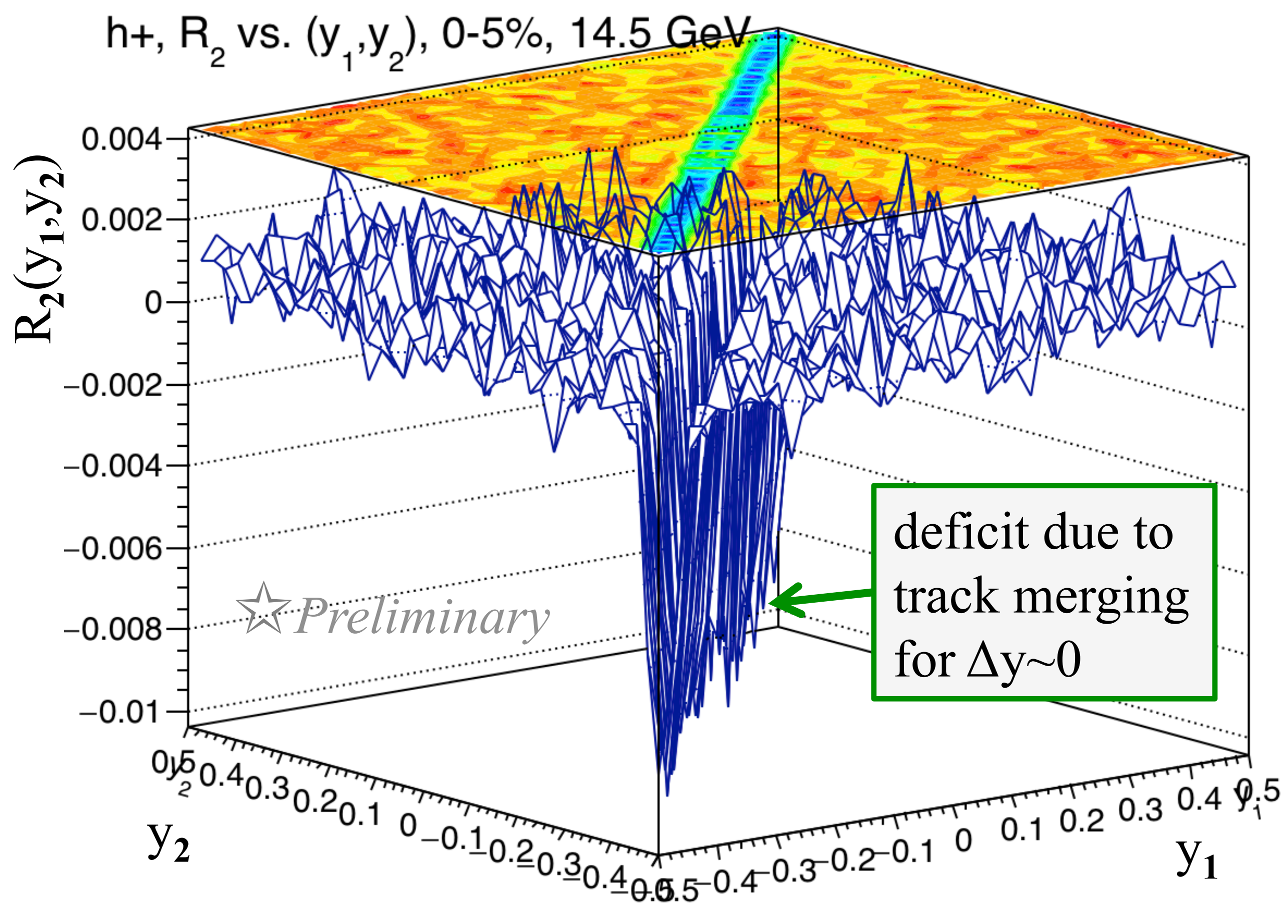
Slightly reduced efficiency for nearby tracks…

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 efficiency loss when two tracks are nearby (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

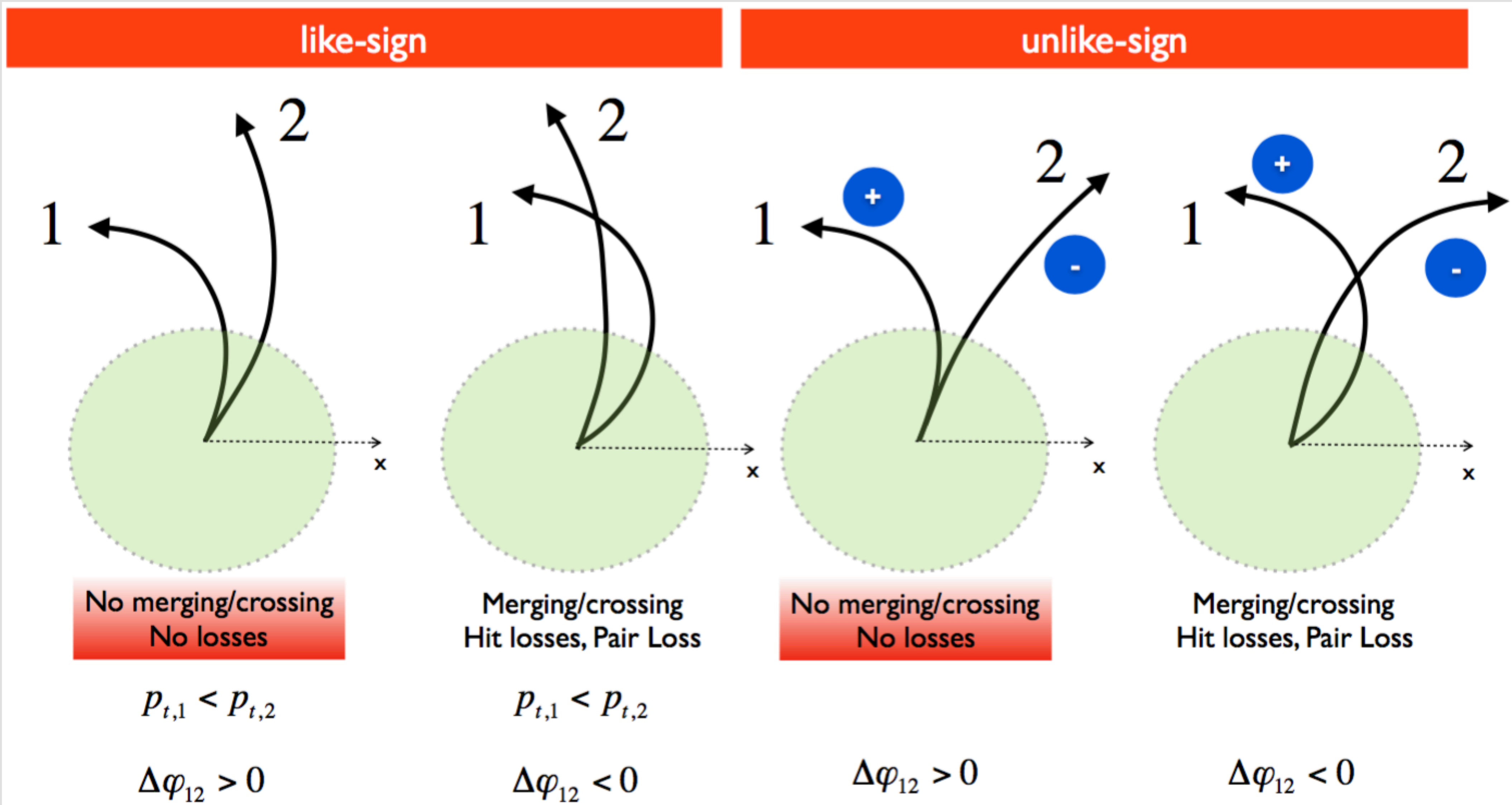


Image from P. Pujahari

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

US: nothing special in fill method

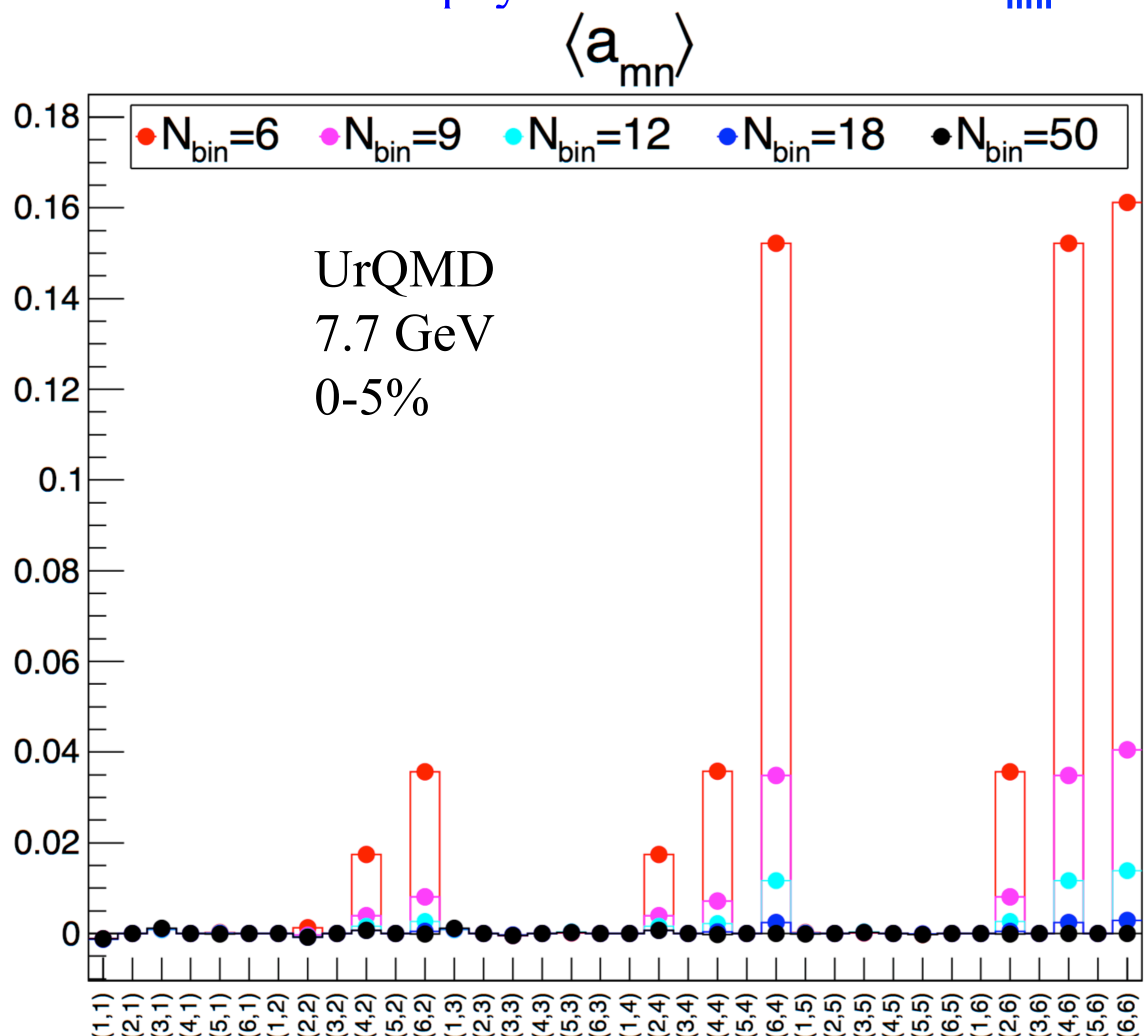
LS: pT order the tracks, fill numerator for upper triangle only, then symmetrize

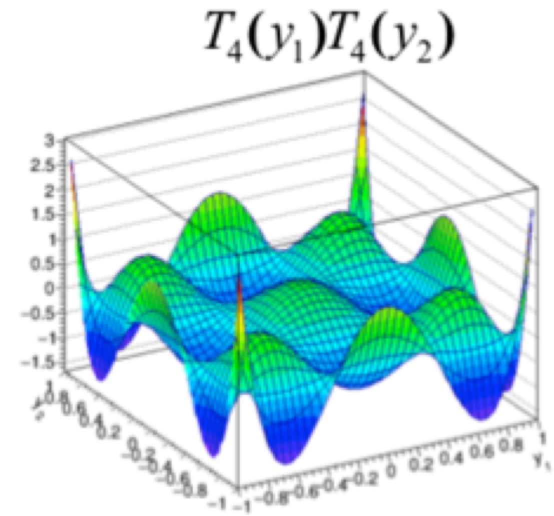
Track crossing correction, Binning, and math artifacts on $<a_{mn}>$

The cut used is $|\Delta y|<0.04$ and $-5\pi/12 \leq \Delta\varphi < 0$

Given this cut, I cannot bin the (y1,y2) parts of the TH3D too finely!
(or there will never be any counts in the $\Delta y=0$ bins)
Rapidity bin width must be near or larger than 2*0.04…

But this can cause non-physical artifacts in the $<a_{mn}>$ values!





Fixed perfectly by integrating $T_n(y)$ over the bin