Search for the critical behavior at NA61/SHINE

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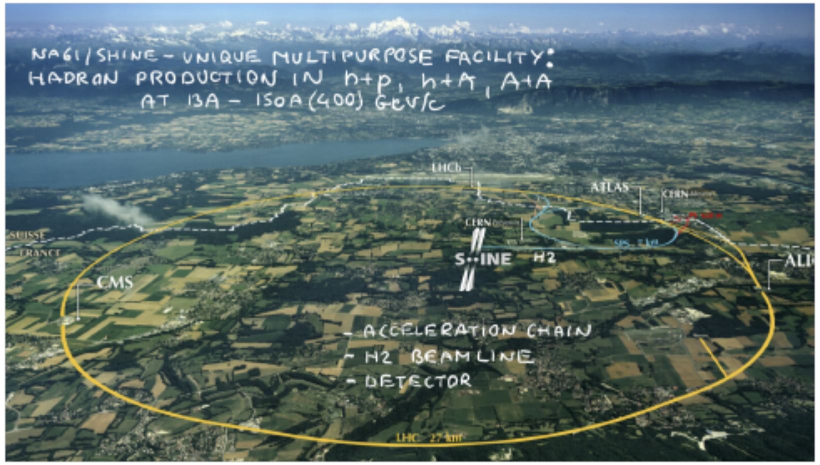
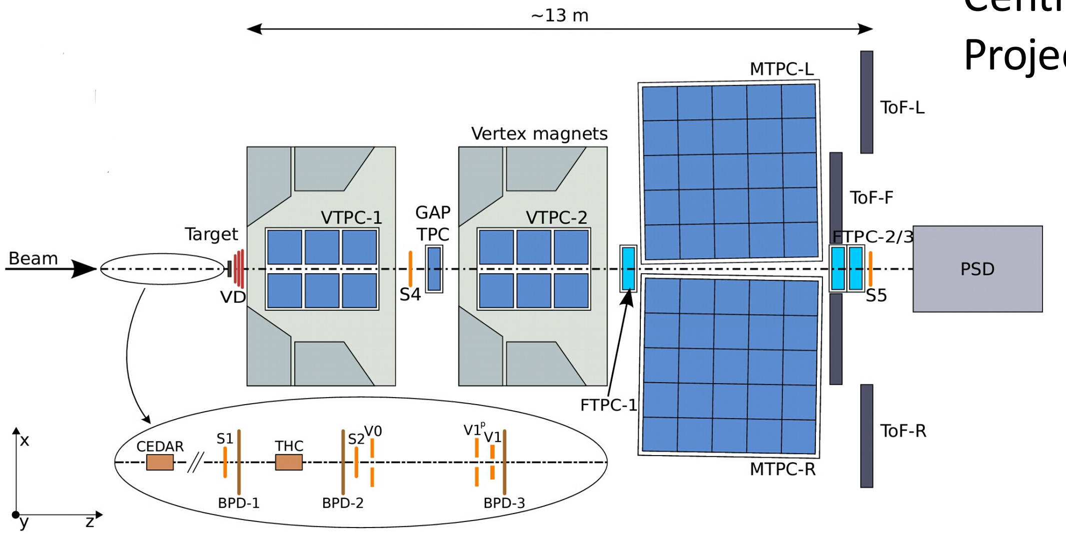
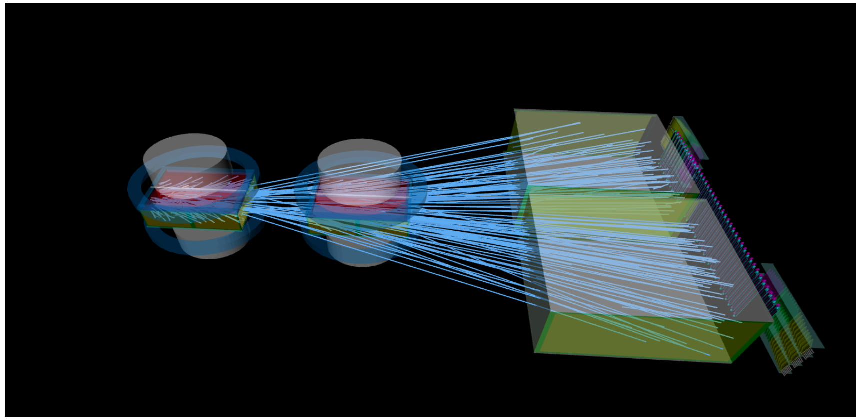
NA61/SHINE Experiment



- NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a particle physics fixed-target experiment at CERN SPS
- Scan in beam momenta (13A - 150/158*A* GeV/*c*) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb)
- Large acceptance hadron spectrometer - full coverage in the forward hemisphere (down to p_T = 0 GeV/*c*)
- Centrality selection in A+A collisions by measuring of forward energy with Projectile Spectator Detector (PSD)

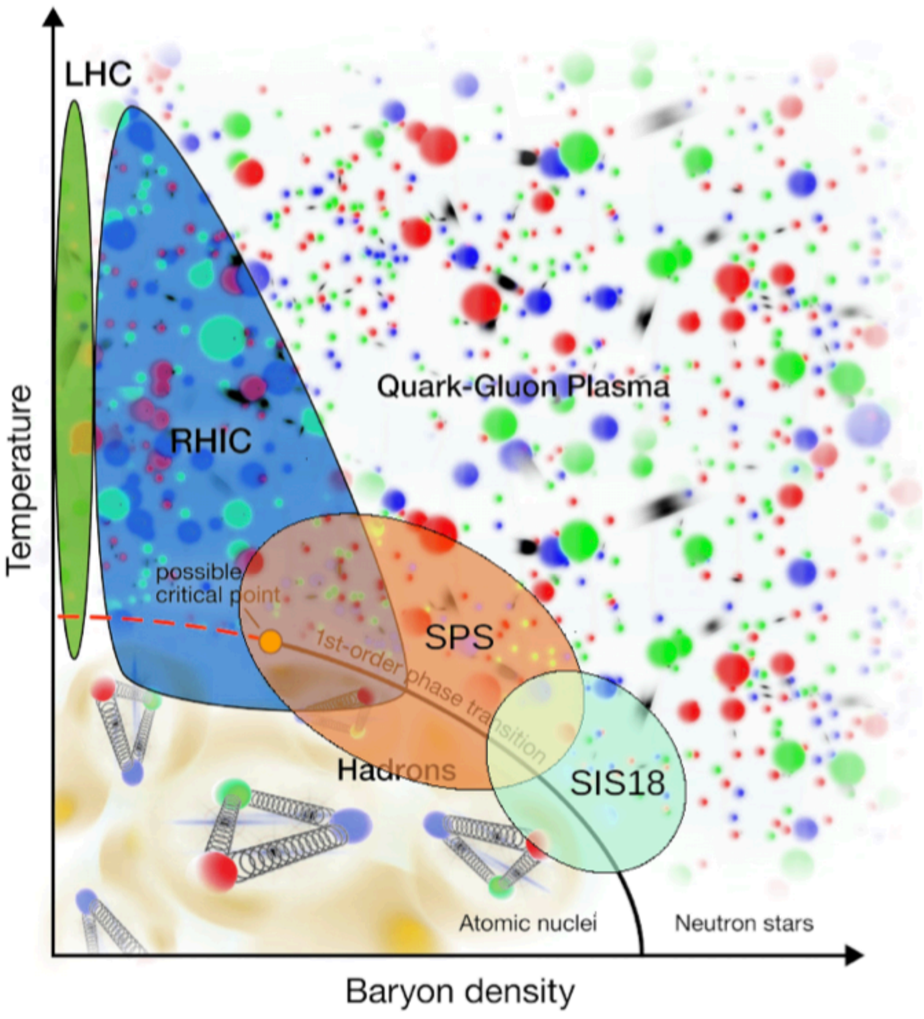


Schematic picture of the NA61/SHINE experiment NA61 JINST 9: 06005



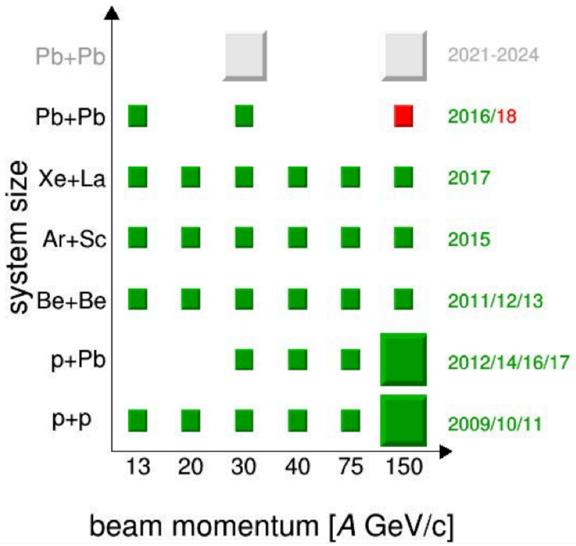
Event browser http://shine3d.web.cern.ch/shine3d/

Strong interactions programme at NA61/SHINE

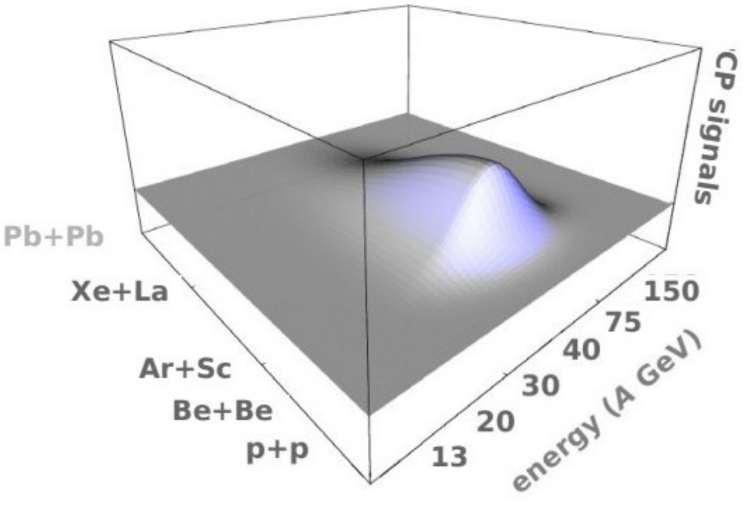


Sketch of the phase diagram of strongly interacting matter

- study the properties of the onset of deconfinement
- search for the critical point (CP) of strongly interacting matter



Data taking schedule



Sketch of the expected «critical hill»

What is the CP signal amplitude?
What if it is shadowed by volume fluctuations?

Search for the critical behavior at NA61/SHINE

1. Multiplicity and transverse momentum fluctuations (p+p @20 – 158 GeV/*c*, ^{7}Be+^{9}Be @150*A* GeV/*c*)	⟺	Search for non-monotonic behavior of CP signatures via pseudorapidity dependence study
2. Femtoscopy studies (^{7}Be+^{9}Be @150*A* GeV/*c*)	⟺	Measure spatial correlations within Bose-Einstein momentum correlations with Levy source
3. Intermittency analysis (NA49, ^{7}Be+^{9}Be and Ar+Sc 150/158*A* GeV/*c*)	⟺	Study of local power-law fluctuations of baryon density
4. Two-particle correlations (^{7}Be+^{9}Be @13*A* – 150*A* GeV/*c*)	⟺	Study in $\Delta\eta$ - $\Delta\phi$ space to disentangle different sources of correlations

Fluctuation studies: proper measures

Intensive fluctuation measure: independent of the number of sources or the system volume

ω[N] = 1 for the Poisson distribution of A, ω[N] = 0 in the absence of A fluctuations

$$\omega[\mathrm{N}] = \frac{\langle \mathrm{N}^2\rangle - \langle \mathrm{N}\rangle^2}{\langle \mathrm{N}\rangle}$$

Gazdzicki et al. PRC 88:024907

Strongly intensive fluctuation measures:

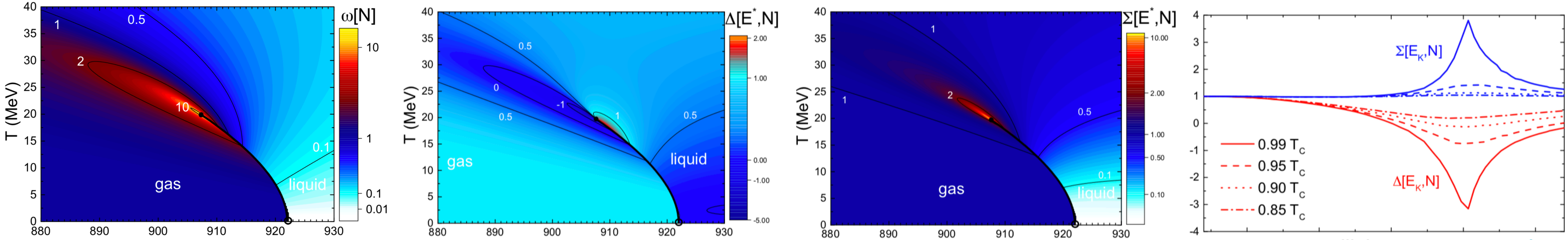
- Independent of the volume and its fluctuations in Ideal Boltzmann gas in Grand Canonical Ensemble (IBG GCE)
- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for independent particle model
- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for the IBG in GCE and CE
- $\Sigma[P_T, N] = \Delta[P_T, N] = 0$ in the absence of fluctuations

$$\Sigma[\mathrm{P_T}, \mathrm{N}] = \frac{1}{\mathrm{C}_\Sigma}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] + \langle \mathrm{P_T}\rangle\omega[\mathrm{N}] - 2\cdot\left(\langle \mathrm{P_T}\cdot \mathrm{N}\rangle - \langle \mathrm{P_T}\rangle\langle \mathrm{N}\rangle\right)\right]$$

$$\Delta[\mathrm{P_T}, \mathrm{N}] = \frac{1}{\mathrm{C}_\Delta}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] - \langle \mathrm{P_T}\rangle\omega[\mathrm{N}]\right], \qquad \mathrm{C}_\Sigma = \mathrm{C}_\Delta = \langle \mathrm{N}\rangle\omega(\mathrm{p_T})$$

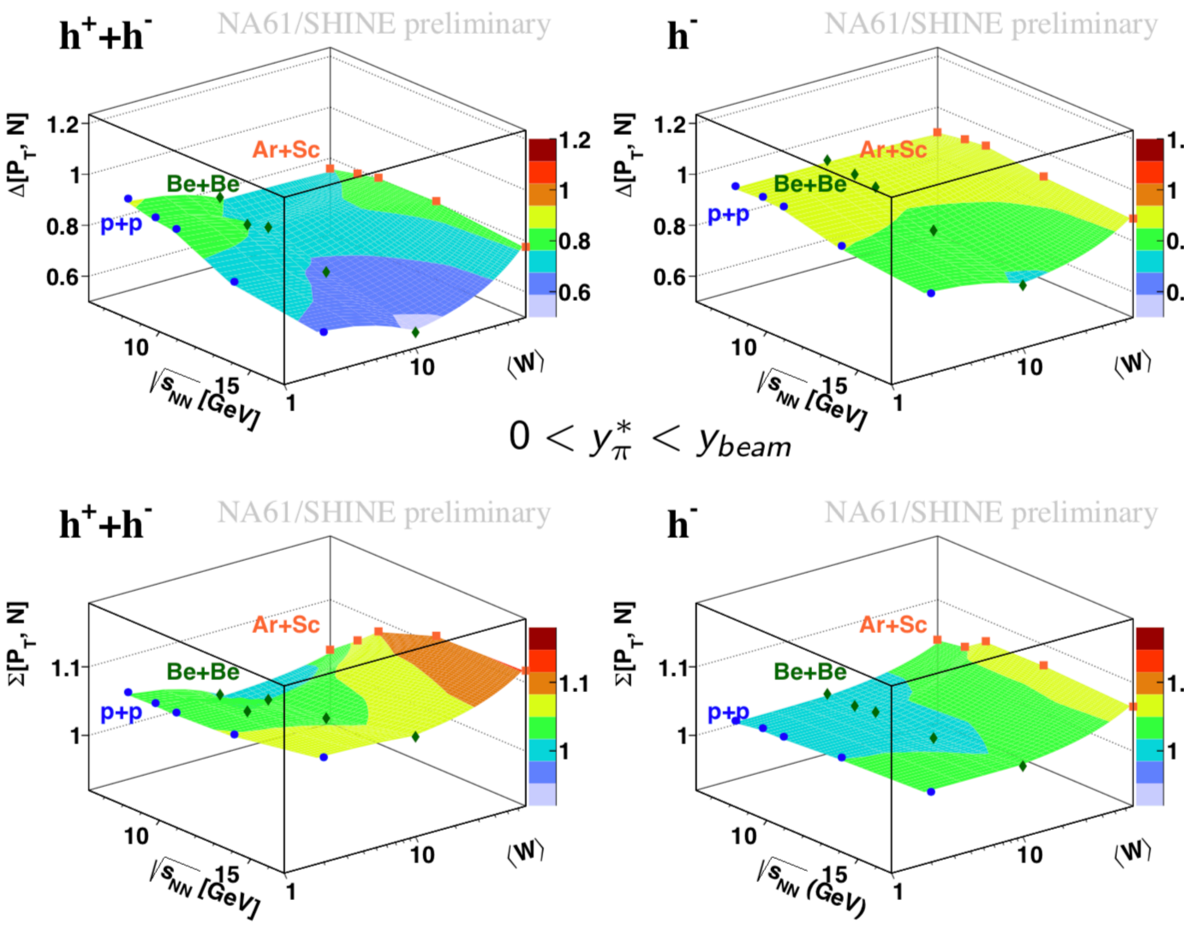
Possible sensitivity: nucleon system with van der Waals EOS in GCE formulation in the vicinity of the Critical Point

Vovchenko, Gorenstein, Stoecker, PRL 118: 182301, Vovchenko, et al., JPA 48: 305001



Fluctuation studies: results and analysis extension

No prominent structures which could be related to the critical point. Should we extend the analysis?

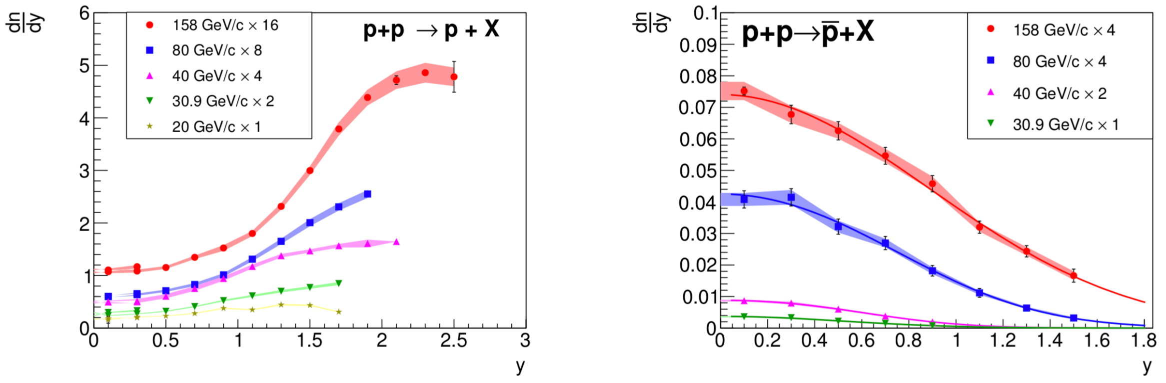


Andronov, Acta Phys. Pol. B Proc. Suppl. 10 449

Since each rapidity is associated with a different value of μ and therefore **probes a different part of the (μ-T)** phase diagram ..

Becattini F, Manninen J and Gazdzicki M PRC 73 044905

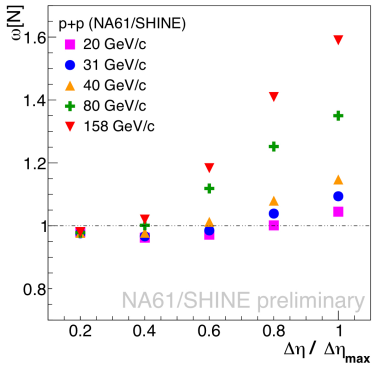
and the ratio of p and $\bar{p}$ in inelastic p + p at the SPS energies changes significantly with rapidity

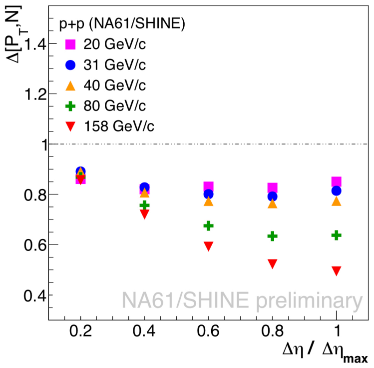


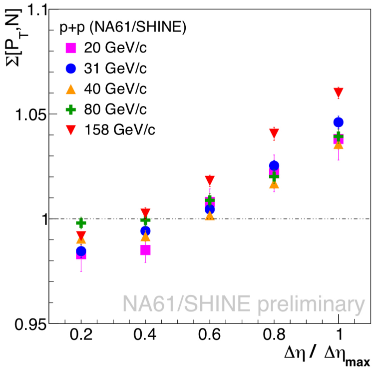
NA61, EPJC 77 10: 671

Let's study **pseudorapidity dependence of fluctuations**

Fluctuation studies: pseudorapidity dependence

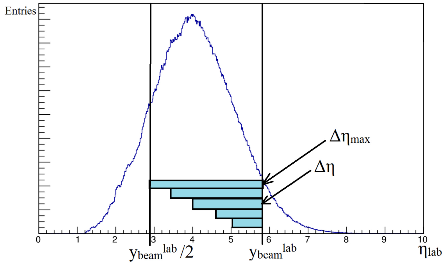




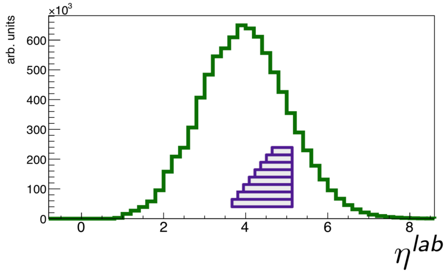


Conclusion:

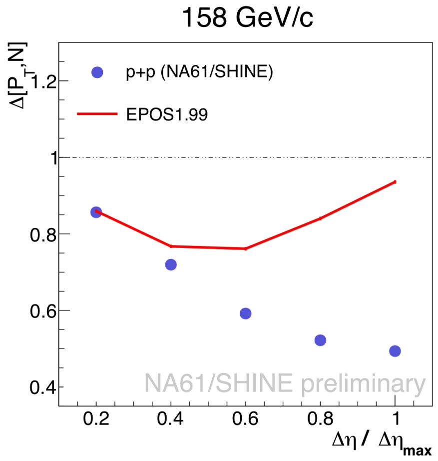
check for all energies and different pseudorapidity intervals in p+p and Be+Be did not reveal any specific structure,

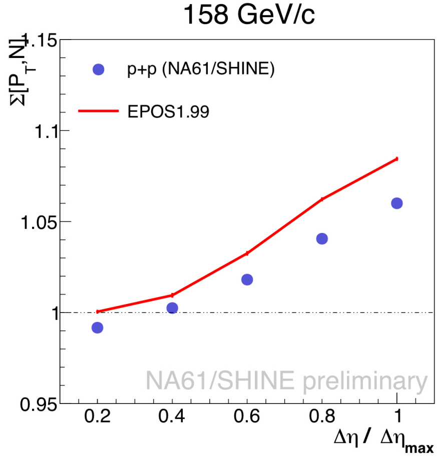


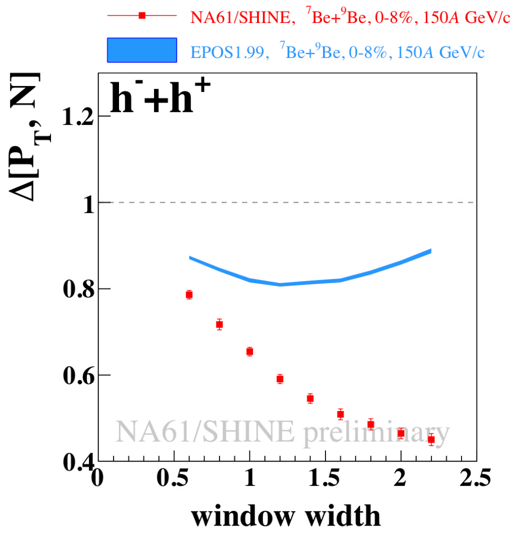
D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225

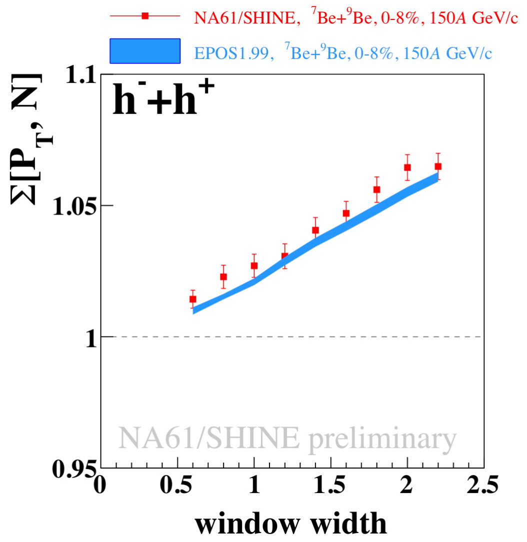


Andronov, KnE Energy and Physics 3 1:226









however, **important**: similar behavior for p+p and Be+Be data,
significant discrepancy with EPOS1.99 in both for $\Delta[P_T, N]$

Femtoscopy: critical exponents

History:

R. Hanbury Brown, R.Q.Twiss observed Sirius with radiotelescopes

R. Hanbury Brown and R. Q. Twiss 1956 Nature 178

Intensity correlations as a function of detector distance to measure size of point-like sources

In high energy physics (G. Goldhaber): momentum ***q*** correlation of pions maps source ***S(q)*** at femto-scale $C(q) \cong 1 + |\widetilde{S}(q)|^2$

G. Goldhaber et al 1959 Phys.Rev.Lett. 3 181

Heavy Ions: expanding medium, increasing mean free path: anomalous diffusion (Csanad et al., Braz.J.Phys. 37 (2007) 1002)

Levy-stable distribution: $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$

Levy parameters appearing in correlation function: $C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$

- ***Levy scale R*** - determines length of homogeneity
- ***Correlation strength λ*** - describes core-halo ratio

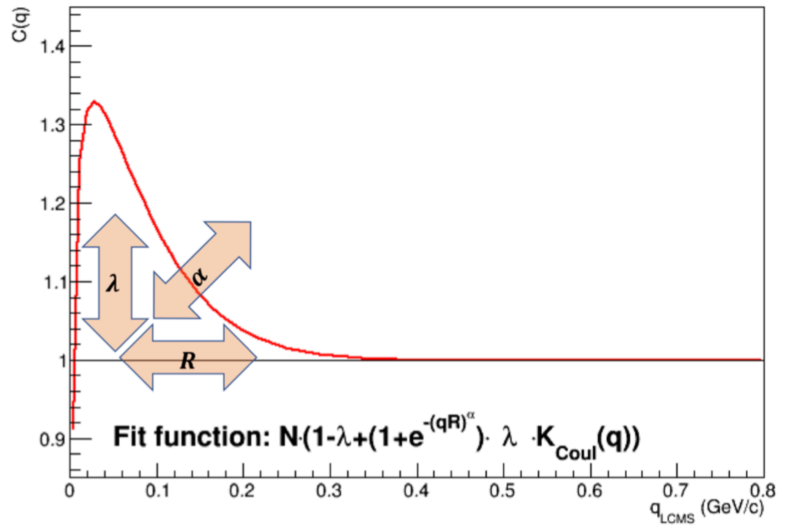
(core: primordial pions, halo: resonance decay products and general background)

- ***Levy exponent α*** - stability exponent determines source shape:

α = 2: Gaussian, predicted from simple hydro

α < 2: anomalous diffusion, generalized limit theorem

α = 0.5: conjectured value at the critical point (CEP)



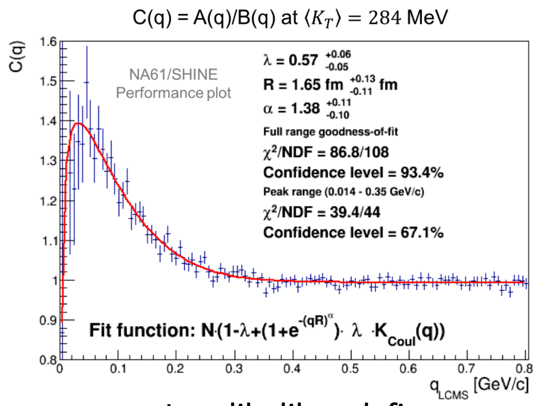
B. Porfy for NA61/SHINE, CPOD 2018

Spatial correlation at the critical point: $\sim r^{-(d-2+\eta)}$, **Levy-exponent α is identical to correlation exponent η**

Csörgo et al., EPJ C36 (2004) 67

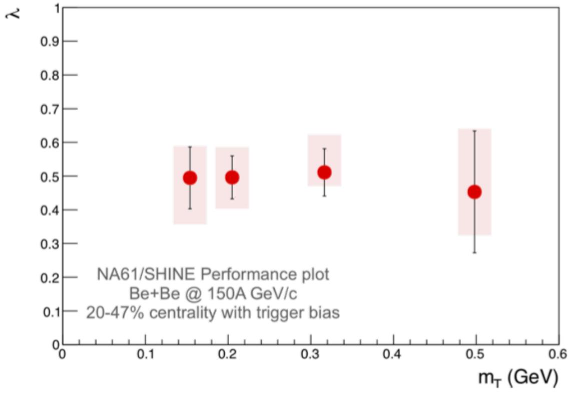
Femtoscopy: performance results of NA61/SHINE

Performance NA61/SHINE results

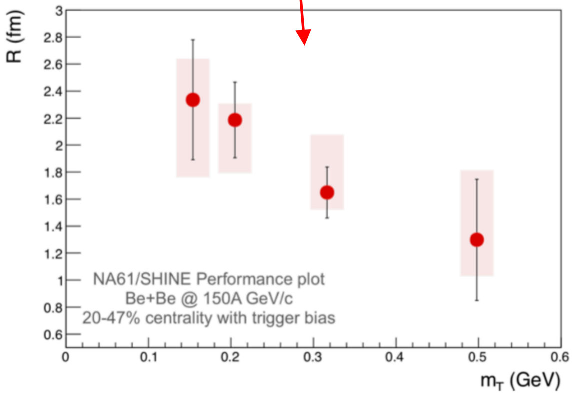


Log-likelihood fit

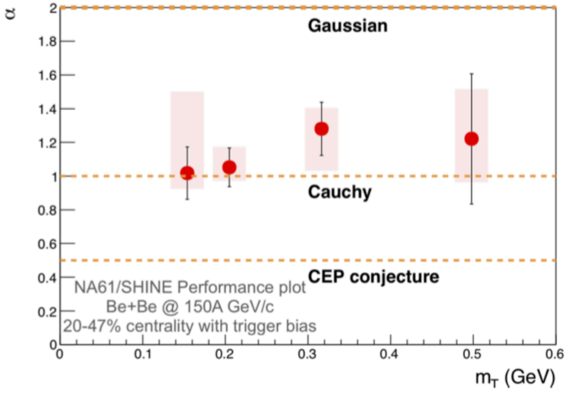
“Hole” at low m_T?



Decreases with m_T (radial flow)?

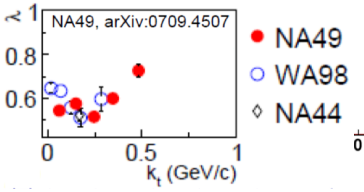


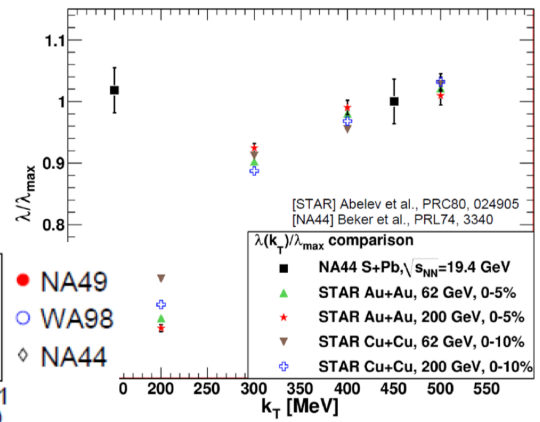
Distance from Gauss (α = 2), Cauchy (α = 1) or CEP conjecture (α = 0.5)?

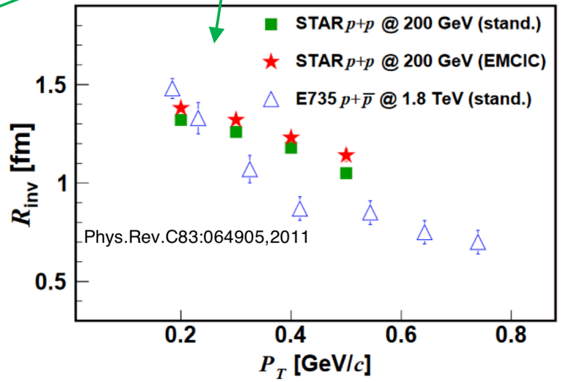


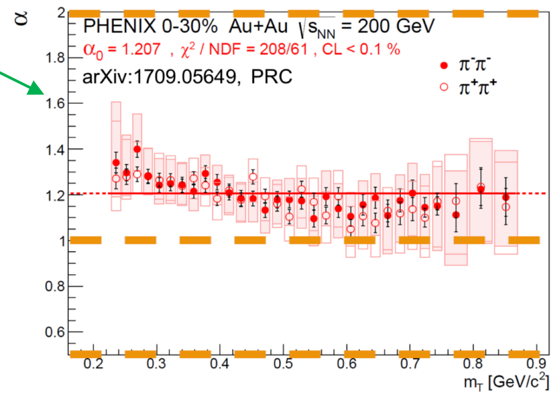
- **NA61/SHINE Levy HBT measure is possible**
- Moving on to measure 0-20% identified HBT
- Next step, measuring Levy HBT in Ar+Sc

World data

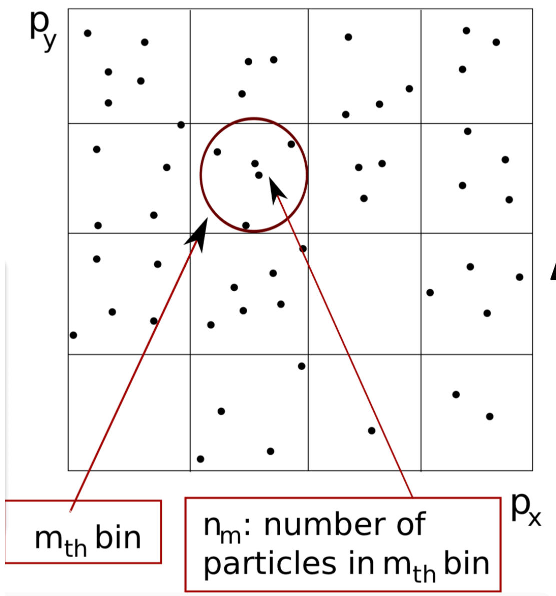








Intermittency analysis: factorial moments



Experimental observation of local, power-law distributed fluctuations

⇓

J. Wosiek, Acta Phys. Polon. B 19 (1988) 863-869
A. Bialas and R. Hwa, Phys. Lett. B 253 (1991) 436-438

Intermittency in transverse momentum space (net protons at mid-rapidity)

Approach: https://indico.cern.ch/event/760216/contributions/3153684/attachments/1721653/2779754/Davis_CPOD2018.pdf

- Transverse momentum space is partitioned into M^2 cells
- Calculate second factorial moments $\mathbf{F_2(M)}$ as a function of cell size ⇔ number of cells M
- Background of non-critical pairs must be subtracted at the level of factorial moments to clean experimental data

$$F_2(M) \equiv \frac{\left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i-1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^2}$$

$$\langle n(n-1)\rangle = \underbrace{\langle n_c(n_c-1)\rangle}_{\text{critical}} + \underbrace{\langle n_b(n_b-1)\rangle}_{\text{background}} + \underbrace{2\langle n_b n_c\rangle}_{\text{cross term}}$$

$$\underbrace{\Delta F_2(M)}_{\text{correlator}} = \underbrace{F_2^{(d)}(M)}_{\text{data}} - \lambda(M)^2 \cdot \underbrace{F_2^{(b)}(M)}_{\text{background}} - 2 \cdot \underbrace{\lambda(M)}_{\text{ratio } \frac{\langle n\rangle_b}{\langle n\rangle_d}} \cdot (1-\lambda(M))\, f_{bc}$$

For ***λ(M) < 1***, two approximations can be applied:

1. Cross term can be neglected
2. Non-critical background moments can be approximated by (uncorrelated) mixed event moments:

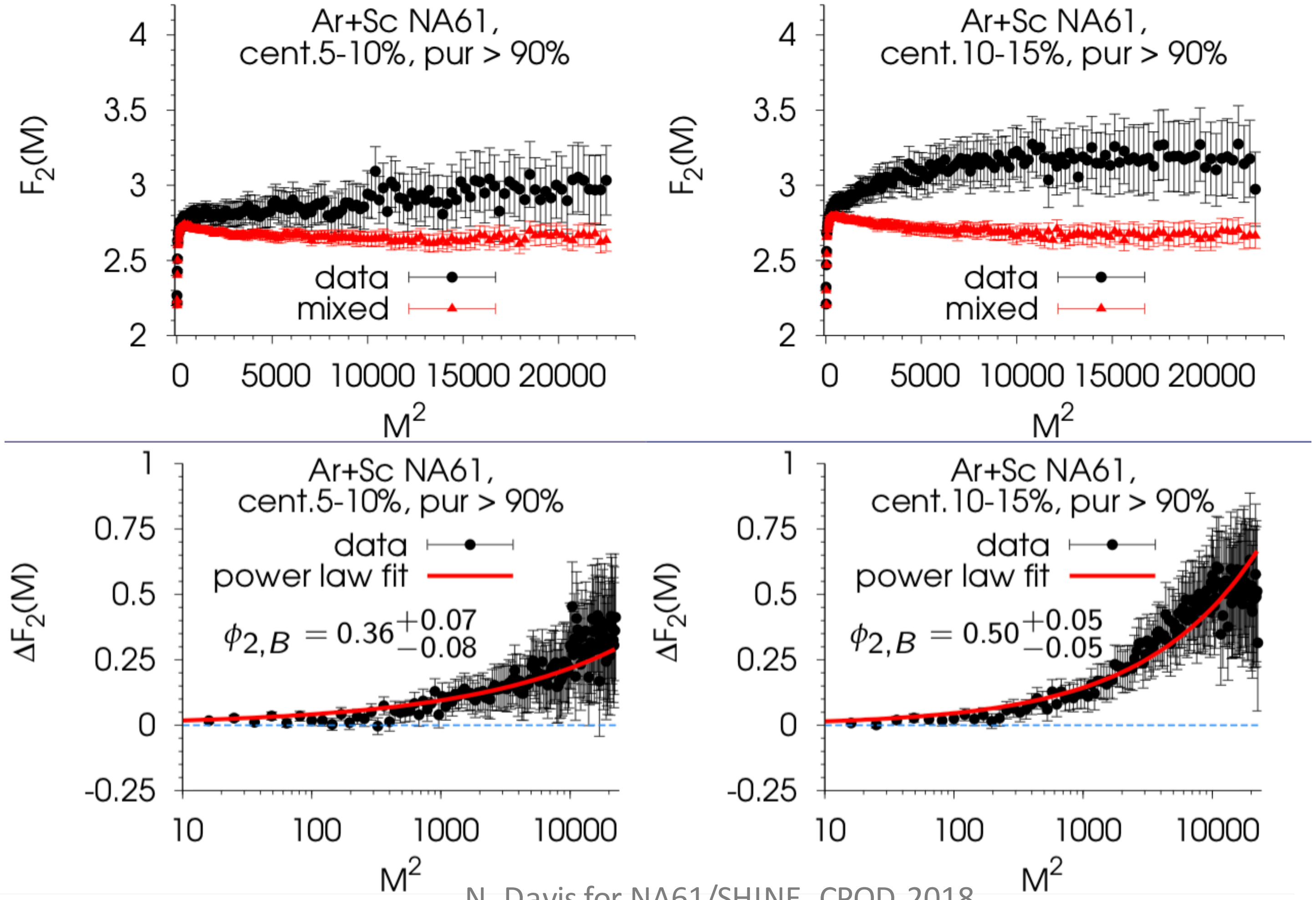
$$\Delta F_2(M) \simeq \Delta F_2^{(e)}(M) \equiv F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

And for a critical system $\mathbf{\Delta F_2(M)}$ **scales** with cell size (number of cells, M) as:

$$\Delta F_2(M) \sim \left(M^2\right)^{\varphi_2}$$

Intermittency analysis: Ar+Sc at 150*A* GeV/*c*

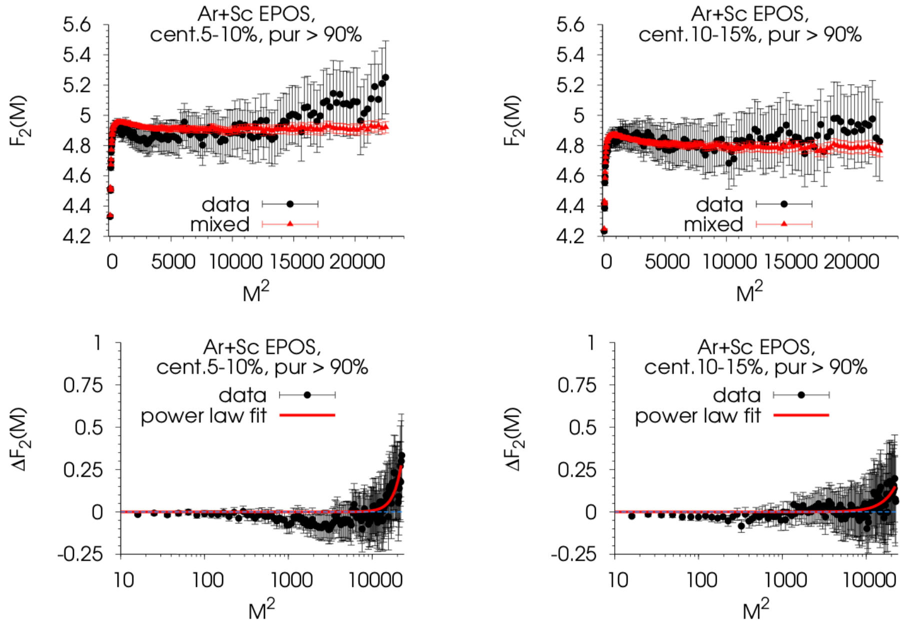
NA61/SHINE preliminary results



N. Davis for NA61/SHINE, CPOD 2018

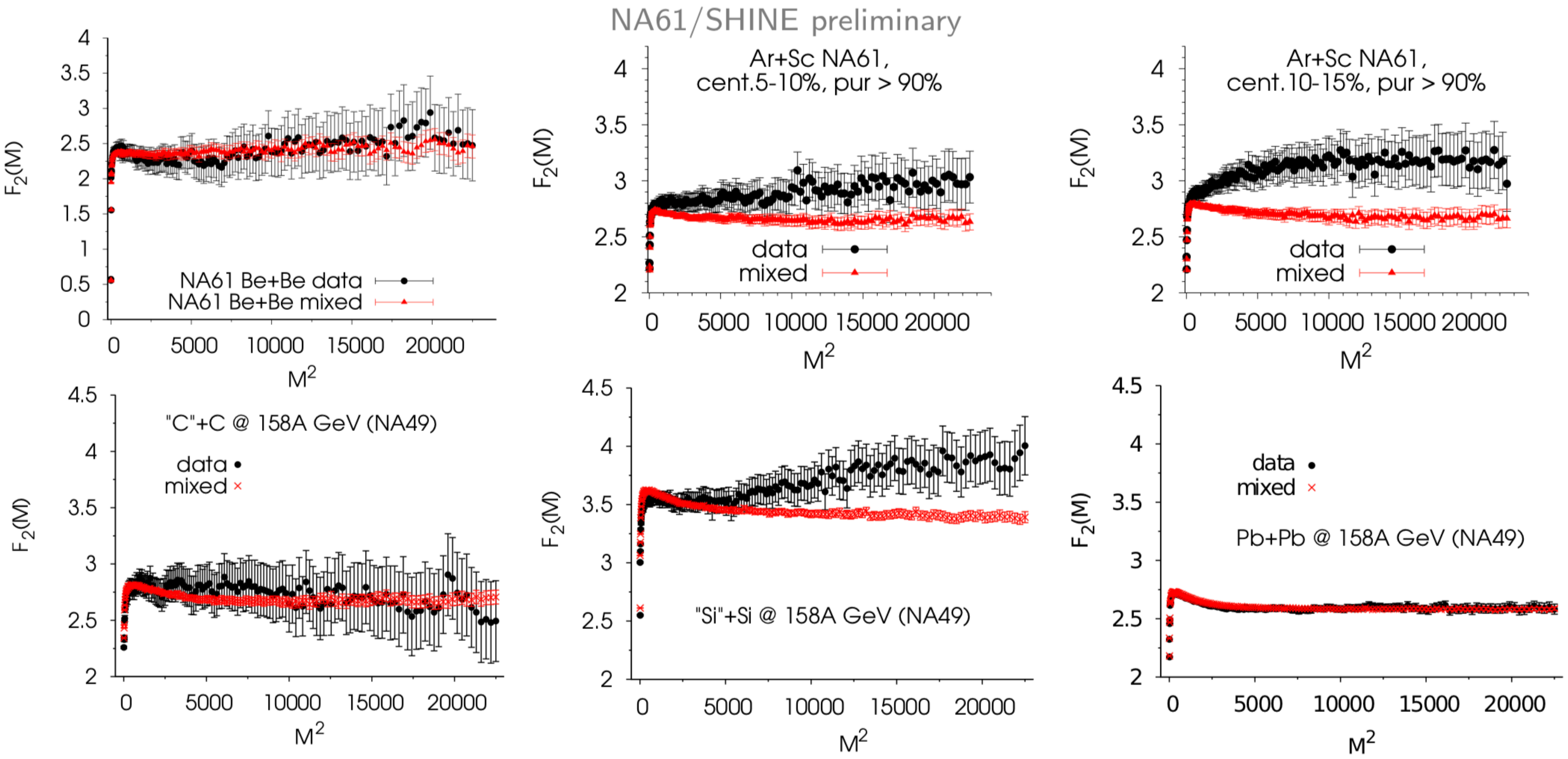
EPOS reproduces results for 5-10% centrality

EPOS does not reproduce observed effect for 10-15% centrality

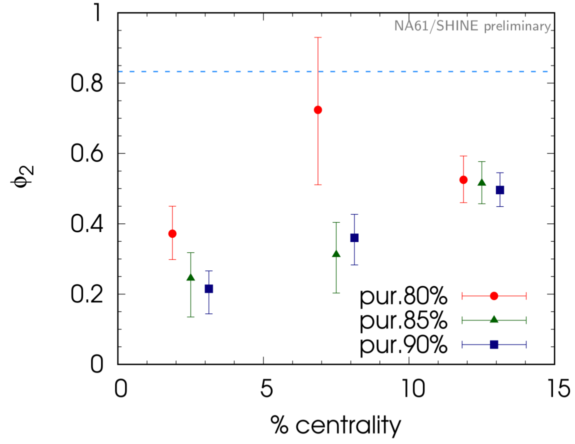


Intermittency analysis: summary NA49 and NA61/SHINE

N. Davis for NA61/SHINE, CPOD 2018



Intermittency index ϕ_2
for Ar+Sc at 150*A* GeV/*c*



Estimated intermittency index for for "Si"+Si at 158*A* GeV/*c*

ϕ_2 = 0.96+0.38(stat.) ± 0.16(syst.)

T. Anticic et al., EPJ. C 75:587 (2015)

- Indication of intermittency effect in middle-central NA61/SHINE Ar+Sc collisions
- **First possible evidence of CP signal in NA61/SHINE**
- Effect quality increases with increased proton purity selection (up to 90%), EPOS does not reproduce observed effect

Two-particle correlations: $\Delta\eta$-$\Delta\phi$

Study of correlations in azimuthal angle and pseudorapidity difference between two particles in the same event:

- $\Delta\eta = | \eta_1 - \eta_2 |$
- $\Delta\varphi = | \varphi_1 - \varphi_2 |$

$$C^{raw}(\Delta\eta, \Delta\phi) = \frac{N^{pairs}_{bkg}}{N^{pairs}_{signal}} \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)};$$

$$S(\Delta\eta, \Delta\phi) = \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\phi}; \quad B(\Delta\eta, \Delta\phi) = \frac{d^2 N^{bkg}}{d\Delta\eta d\Delta\phi}$$

Note:

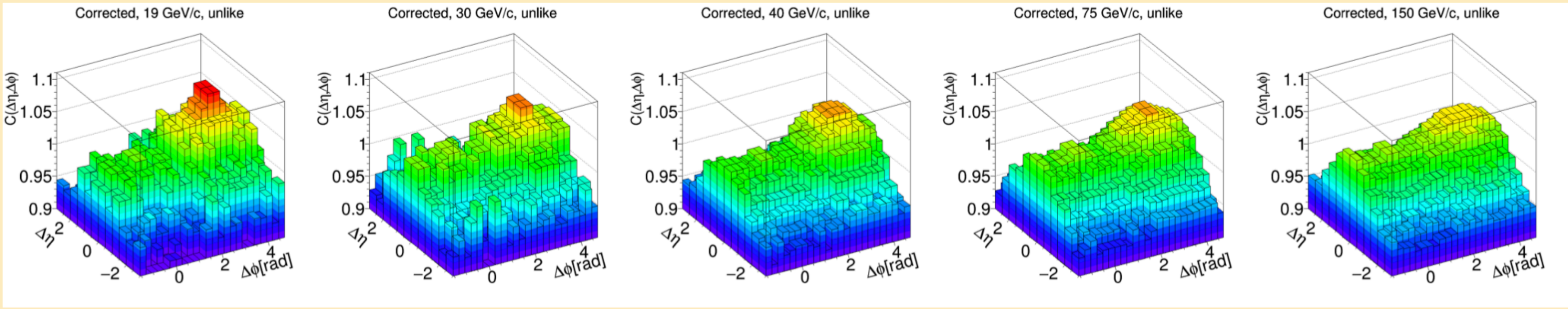
- To improve statistics azimuthal angle distribution is folded: if $\Delta\varphi > \pi$ then $\Delta\varphi$ becomes $\Delta\varphi = 2\pi - \Delta\varphi$
- Signal and background distributions are calculated and normalized in restricted $\Delta\eta$ region: $0 < \Delta\eta < 3$
- Correlation functions are mirrored around $(\Delta\eta, \Delta\varphi) = (0, 0)$ point in order to emphasize the trend
- Event and track cuts select the 5% most violent collisions with particles produced in strong and EM processes within the NA61/SHINE acceptance

Preliminary results for ^{7}Be+^{9}Be are obtained for all charge combinations (all, like-sign, unlike-sign, positively charged, negatively charged) and for the full momentum range (13*A* – 150*A* GeV/*c*). **Comparison (not shown) with published p+p NA61/SHINE data revealed an increase of quantum statistics contribution in higher beam momenta in Be+Be.**

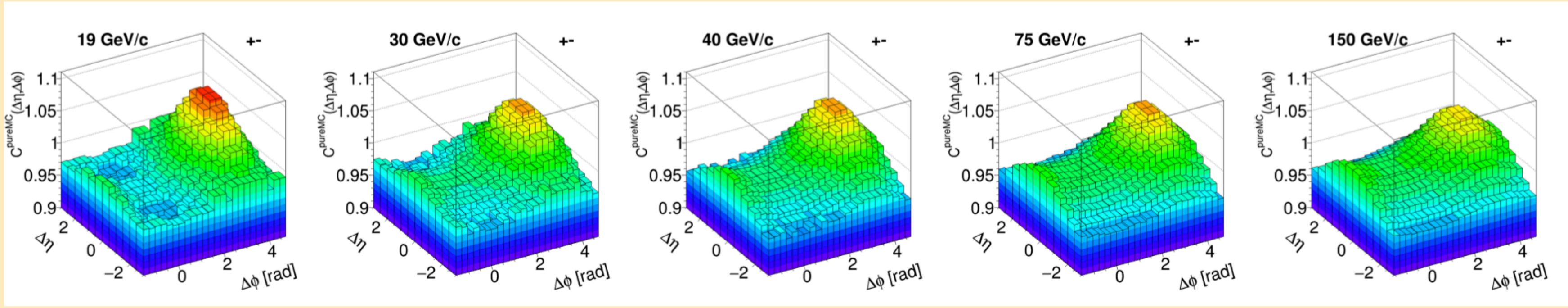
Two-particle correlations: some Be+Be NA61/SHINE data

Preliminary NA61/SHINE results

NA61/SHINE data



EPOS1.99 with NA61/SHINE acceptance



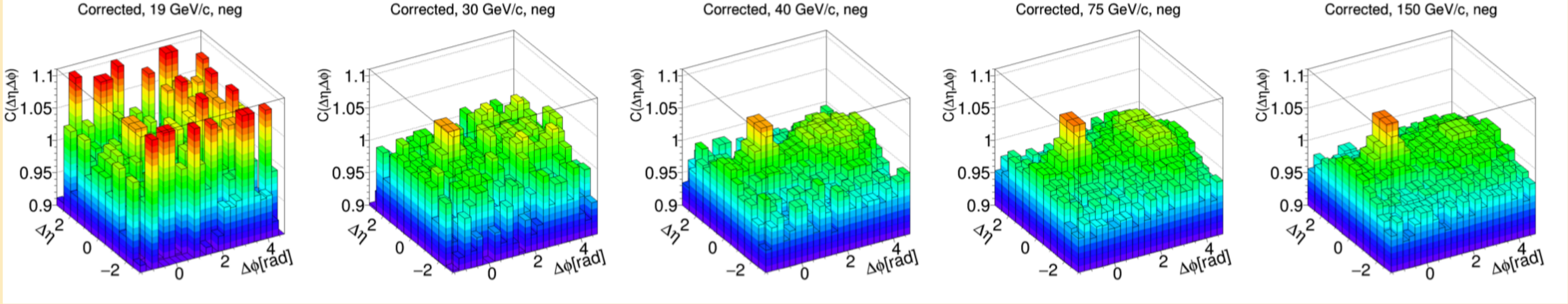
- Maximum at $(\Delta\eta, \Delta\varphi) = (0, \pi)$ – probably resonance decays and momentum conservation
- A hill at $(0, 0)$ in unlike-sign is Coulomb attraction (products of photons conversion were rejected during analysis)
- EPOS reproduces data qualitatively well except of Coulomb peak at $(\Delta\eta, \Delta\varphi) = (0, 0)$

B. Maksiak for NA61/SHINE, QM 2018

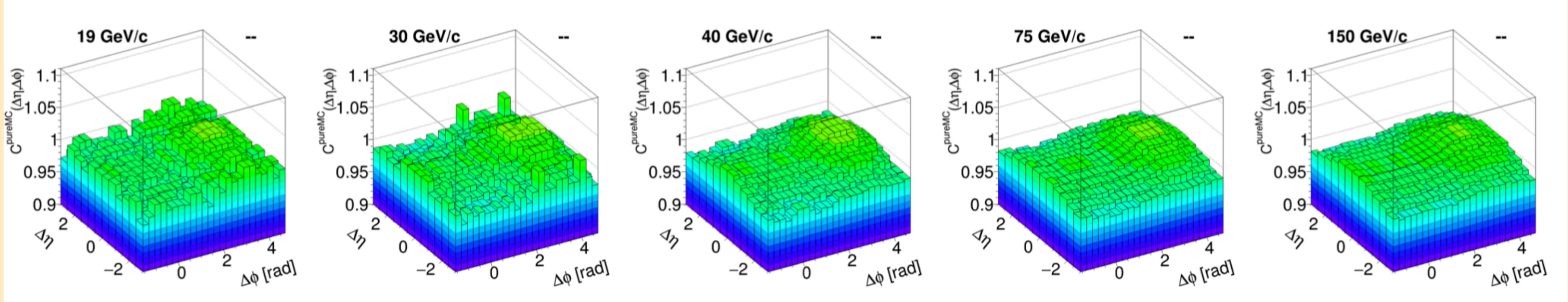
Two-particle correlations: some Be+Be NA61/SHINE data

Preliminary NA61/SHINE results

NA61/SHINE data



EPOS1.99 with NA61/SHINE acceptance



- Almost no away-side enhancement: low multiplicity of double-negative resonances
- Peak at $(\Delta\eta, \Delta\varphi) = (0, 0)$ prominent – Bose-Einstein statistics
- EPOS does not reproduce peak at $(\Delta\eta, \Delta\varphi) = (0, 0)$ due to lack of implementation of quantum statistics

B. Maksiak for NA61/SHINE, QM 2018

Summary and outlook

- Results on system size vs. energy dependence of N and $[P_T, N]$ fluctuations for particles produced in strong processes within the NA61/SHINE acceptance **show no indication of the critical point so far**

- Pseudorapidity dependence of fluctuation measures revealed a **significant discrepancy** between p+p and Be+Be data and EPOS1.99 for $\Delta[P_T, N]$ measure

- Two-particle correlations revealed two main structures:
  - **away-side enhancement** due to momentum conservation and resonance decays
  - **near-side peak** due to Coulomb attraction in unlike-sign pairs of particles and quantum statistics in like-sign ones (problematic in EPOS1.99 simulations)

- First measurements of **Levy HBT** within NA61/SHINE acceptance – performance results!

- Indication of **intermittency effect** in middle-central NA61/SHINE Ar+Sc collisions:
  First possible evidence of CP signal at NA61/SHINE ?

Stay tuned and have a SHINY day!

This work is supported by the Russian Science Foundation, grant 17-72-20045

Back up slides

Intermittency analysis: details

First released Intermittency results of preliminary analysis in Ar+Sc at 150*A* GeV/*c* at CPOD 2018, **details**:

https://indico.cern.ch/event/760216/contributions/3153684/attachments/1721653/2779754/Davis_CPOD2018.pdf

Intermittency analysis: details

Event & Track cuts

Event cuts

- Target IN/OUT,
- BPD status,
- WFA particles (4.5 μs),
- WFA interaction (25 μs),
- BPD3X(Y) charge,
- S5 $(0 \rightarrow 170)$,
- T2 trigger (eAll),
- Vertex track fitted to the main vertex,
- Vertex fit quality = ePerfect,
- Fitted vertex position -580 ± 10 cm,
- PSD Module Energy Sum cut (inner/outer),
- Centrality 0-20% (based on PSD)
- nTracksFit/nTracksAll > 0.25 if nTracksFit ≤ 50 (Andrey)

Track cuts

- Track status,
- Charge ± 1,
- Impact point $[\pm 4\text{cm}; \pm 2\text{cm}]$,
- Total number of clusters ≥ 30,
- VTPCs clusters ≥ 15,
- NO GTPC clusters,
- dE/dx clusters ≥ 30,
- $0.5 \leq \frac{\#\text{Points}}{\#\text{Potential Points}} \leq 1.0$
- TTD cut > 2 cm
- dE/dx ≤ 1.8 (dE/dx fit issue)
- proton selection (scan)
- 3.98 GeV/c $\leq p_{tot} \leq$ 126 GeV/c (for dE/dx proton ID – scan)

Intermittency analysis: details

Event & Track cuts – EPOS

Event cuts

- Target IN/OUT,
- BPD status,
- Vertex track fitted to the main vertex,
- Vertex fit quality = ePerfect,
- Fitted vertex position -580 ± 10 cm,
- Centrality 10% (based on nFSpec)

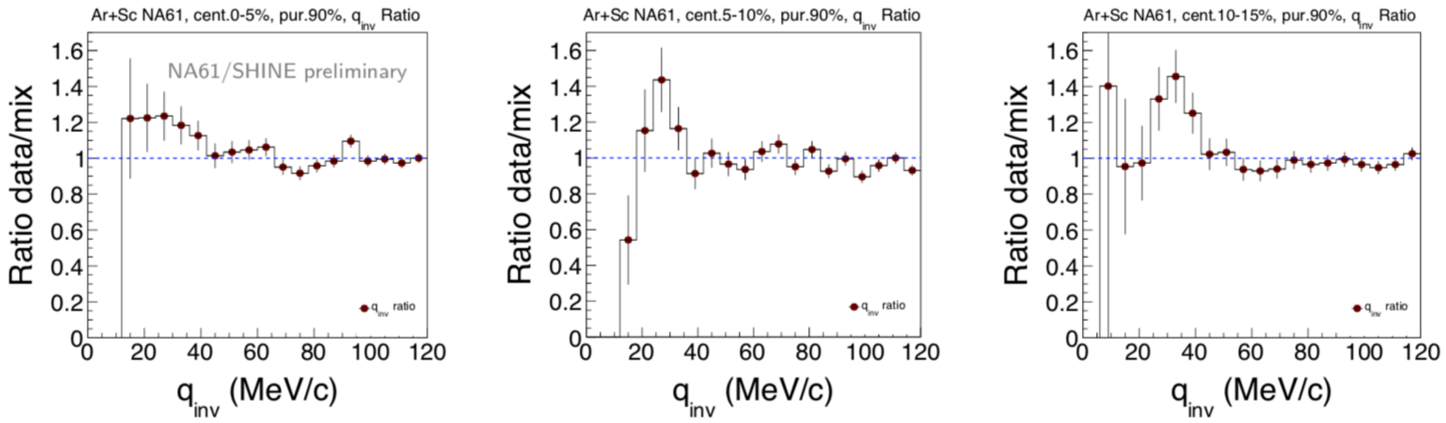
Track cuts

- Track status,
- Charge ± 1,
- Impact point $[\pm 4\text{cm}; \pm 2\text{cm}]$,
- Total number of clusters ≥ 30,
- VTPCs clusters ≥ 15,
- NO GTPC clusters,
- TTD cut > 2 *cm*,
- proton selection – matching closest simTrack,
- 3.98 GeV/c $\leq p_{tot} \leq$ 126 GeV/c (to match effect of dE/dx p_{tot} cut),
- acceptance cut

Intermittency analysis: details

Split tracks & the q_{inv} cut

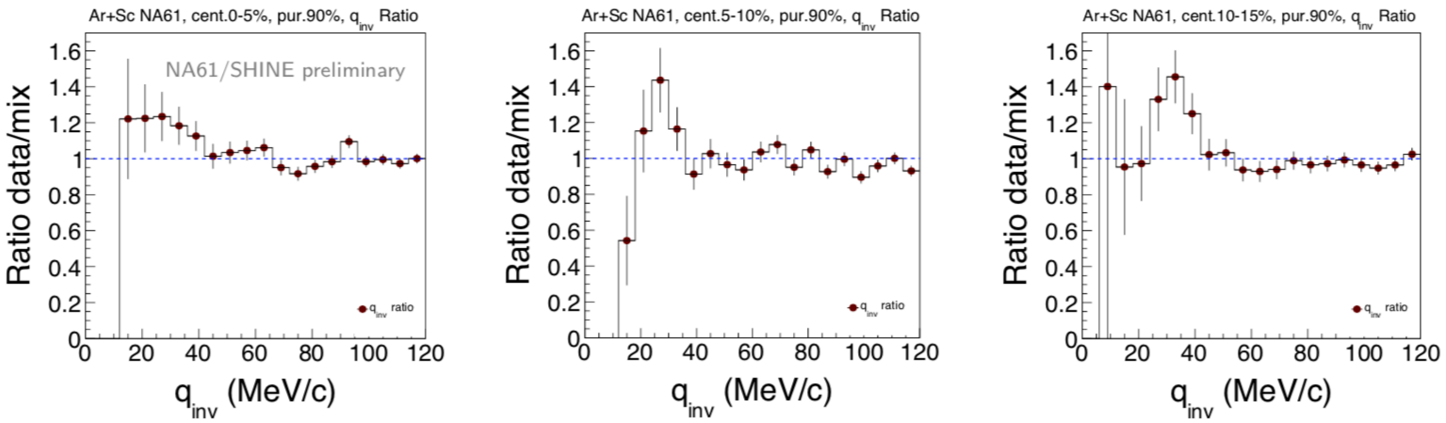
- Events may contain split tracks: sections of the same track erroneously identified as a pair of tracks that are close in momentum space.
- Three cuts to root them out:
  1. Ratio of points / potential points in a track (removes most)
  2. Minimum track distance in the detector (pair cut)
  3. q_{inv} cut (pair cut, physics-significant)
- q_{inv} distribution of track pairs probed in order to root the rest out:
  $q_{inv}(p_i, p_j) \equiv \frac{1}{2}\sqrt{-(p_i - p_j)^2}$, p_i : 4-momentum of i^{th} track.
- We calculate the ratio of $q_{inv}^{data} / q_{inv}^{mixed}$.



Intermittency analysis: details

Split tracks & the q_{inv} cut

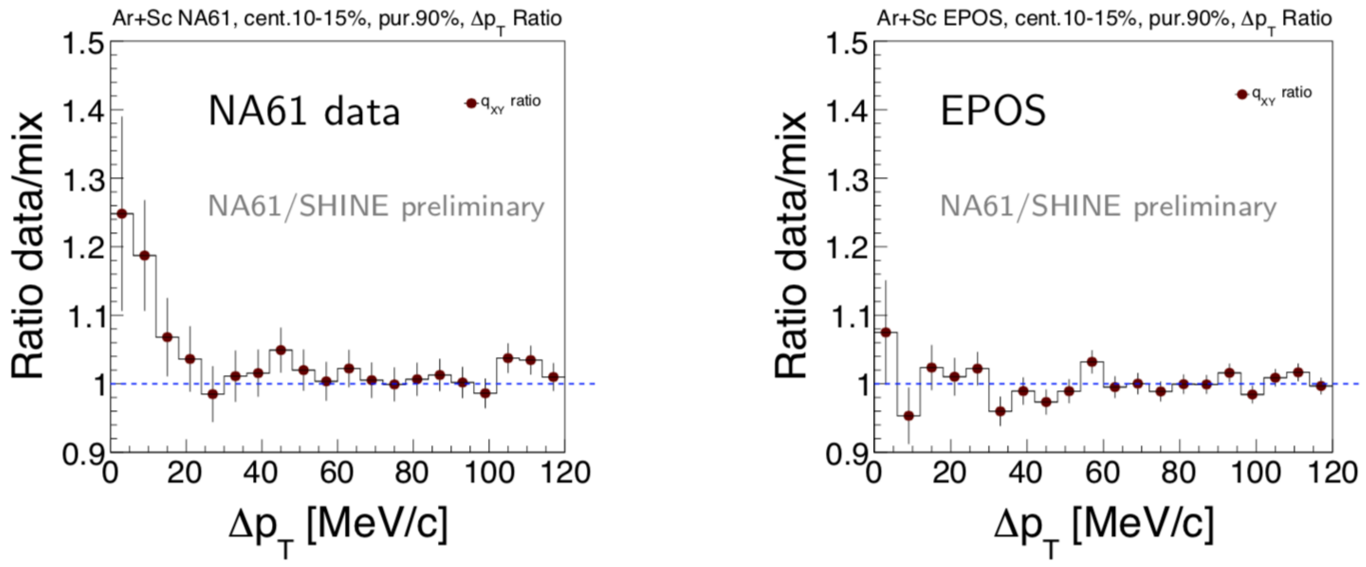
- A peak at low q_{inv} (below 20 MeV/c) indicates a possible split track contamination that must be removed.
- Anti-correlations due to F-D effects and Coulomb repulsion must be removed before intermittency analysis ⇒ "dip" in low q_{inv}, peak predicted around 20 MeV/c [Koonin, PLB 70, 43-47 (1977)]
- Universal cutoff of $q_{inv} > 7$ MeV/c applied to all sets before analysis.



Intermittency analysis: details

Δp_T distributions: NA61 data vs EPOS

- Ar+Sc at 150A GeV/c: $\Delta p_T = 1/2\sqrt{(p_{X_1} - p_{X_2})^2 + (p_{Y_1} - p_{Y_2})^2}$ distributions of protons selected for intermittency analysis



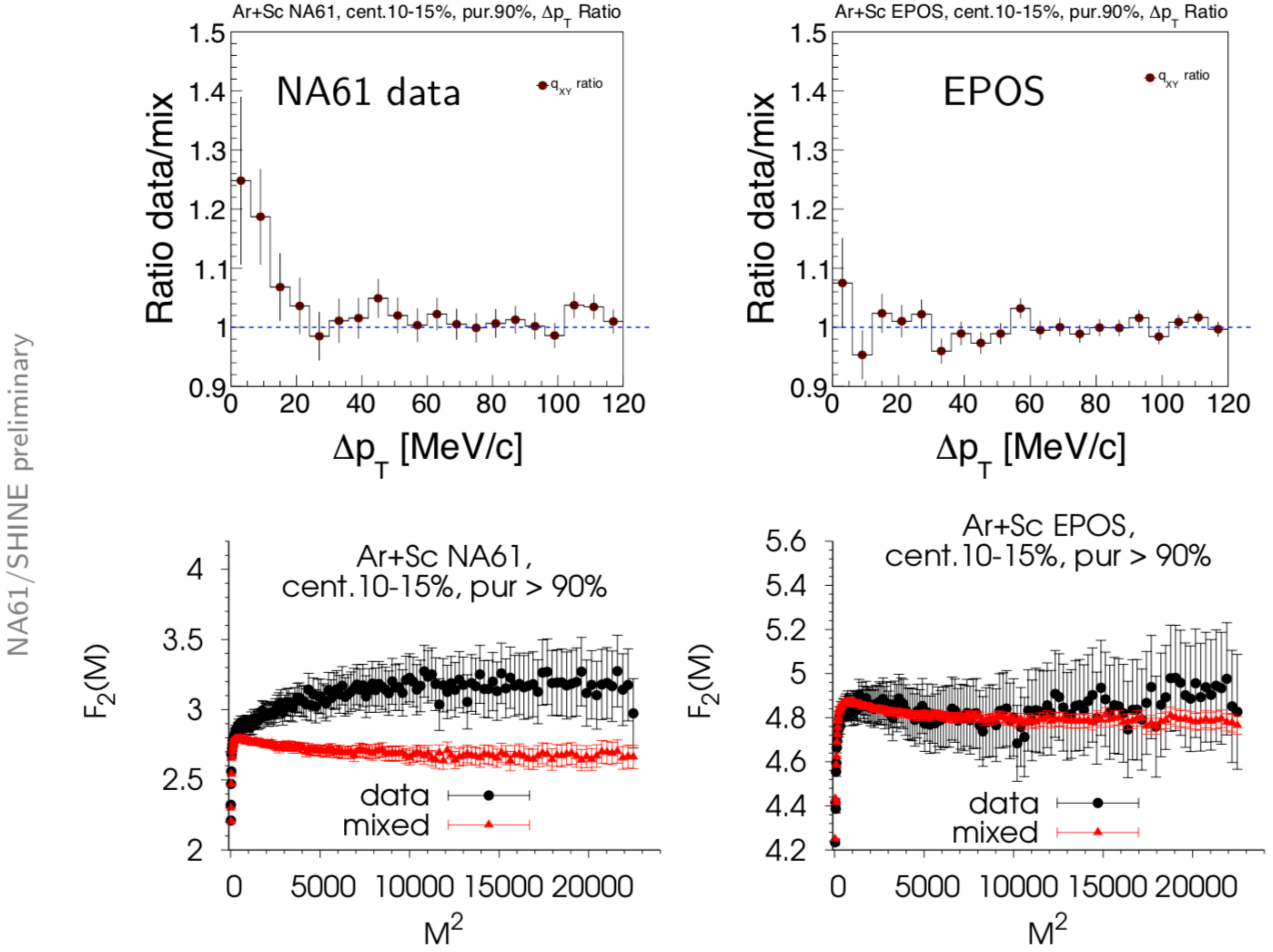
Significant peak at $\Delta p_T \to 0$

Flat distribution

- In NA61 data, we see strong correlations in $\Delta p_T \to 0 \Rightarrow$ indication of intermittent behaviour

Intermittency analysis: details

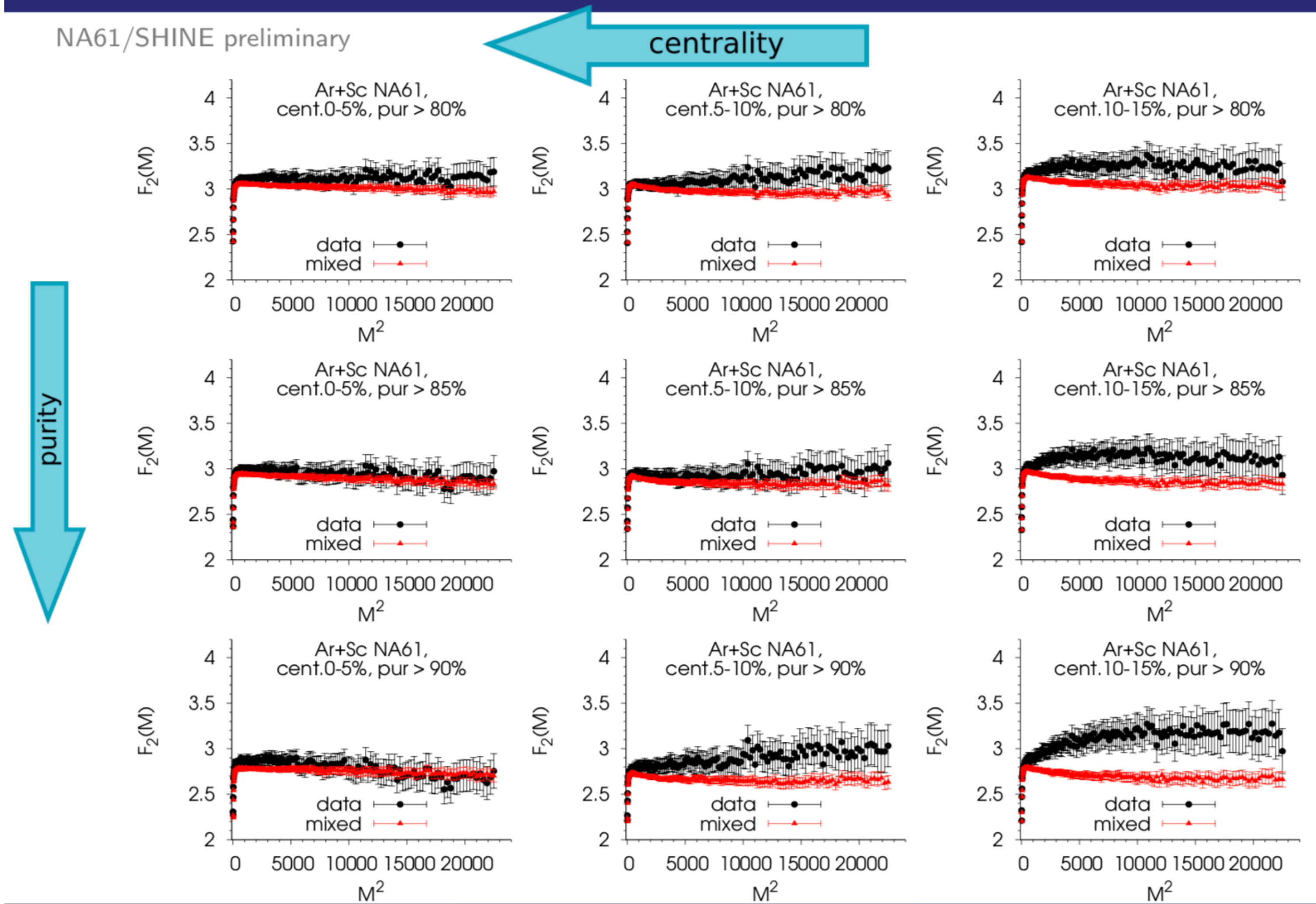
Δp_T distributions & $F_2(M)$: NA61 data vs EPOS



Intermittency analysis: details

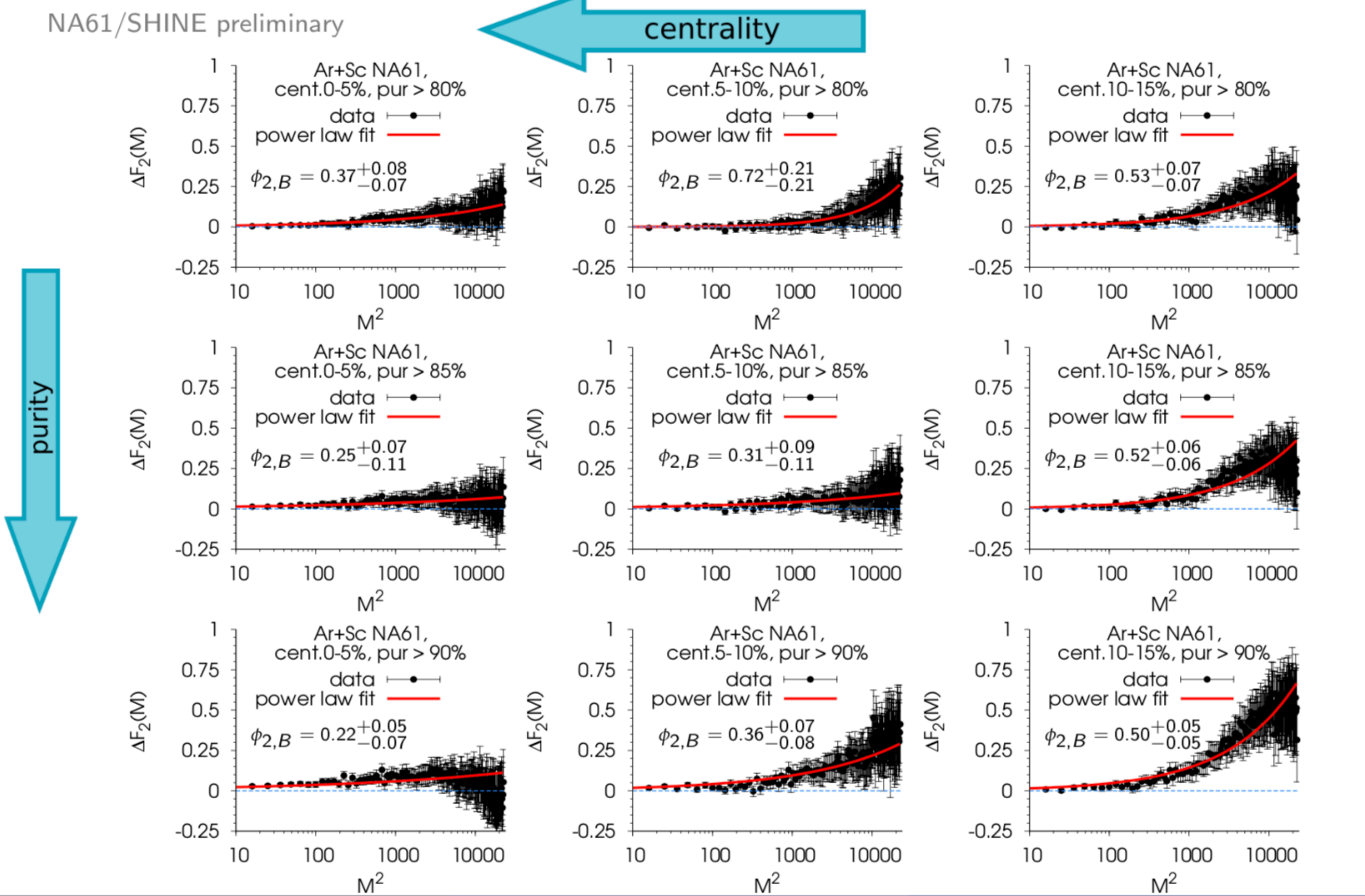
NA61/SHINE: Ar+Sc at 150A GeV/c: $F_2(M)$

NA61/SHINE preliminary

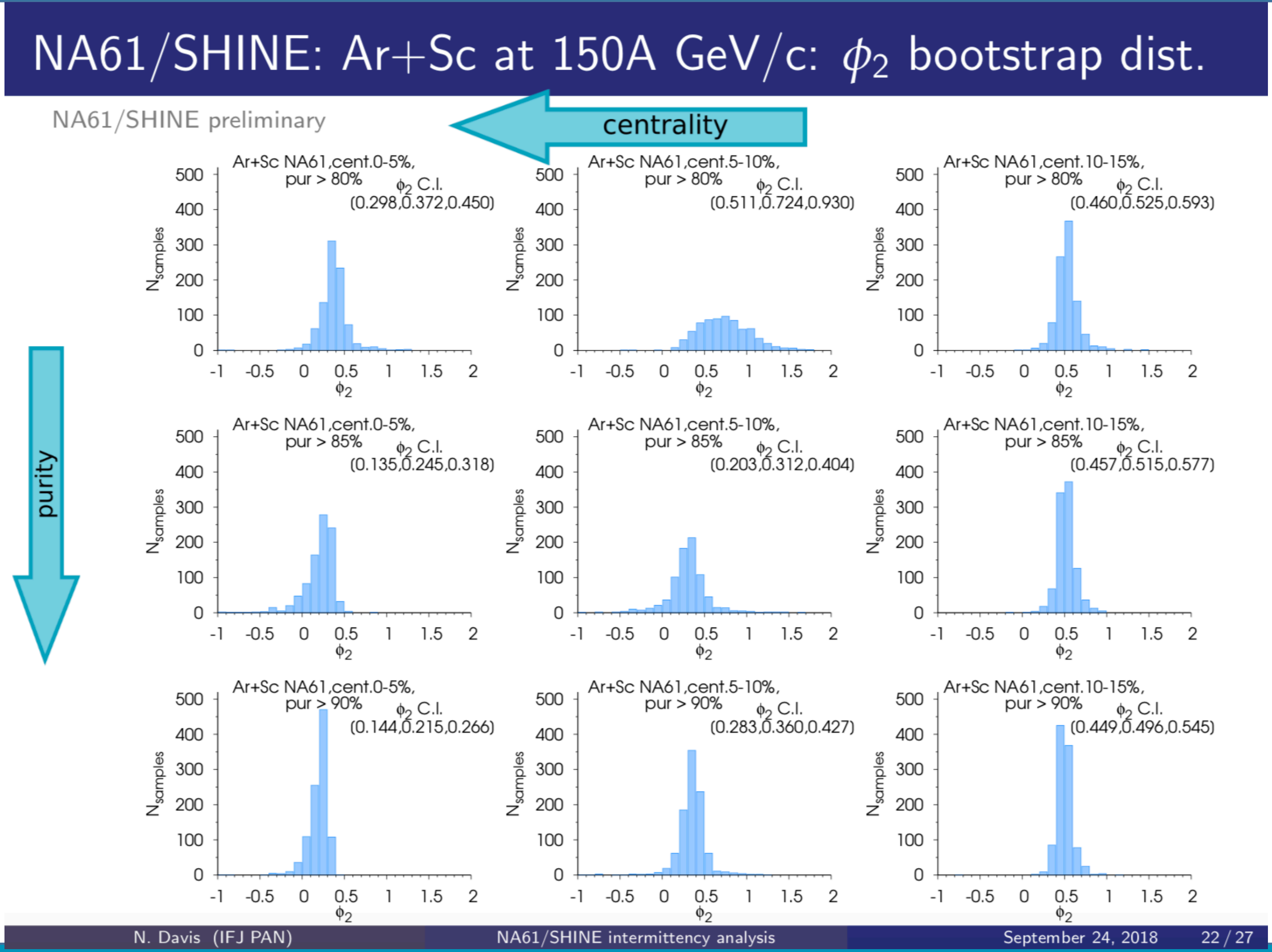


Intermittency analysis: details

NA61/SHINE: Ar+Sc at 150A GeV/c: $\Delta F_2(M)$

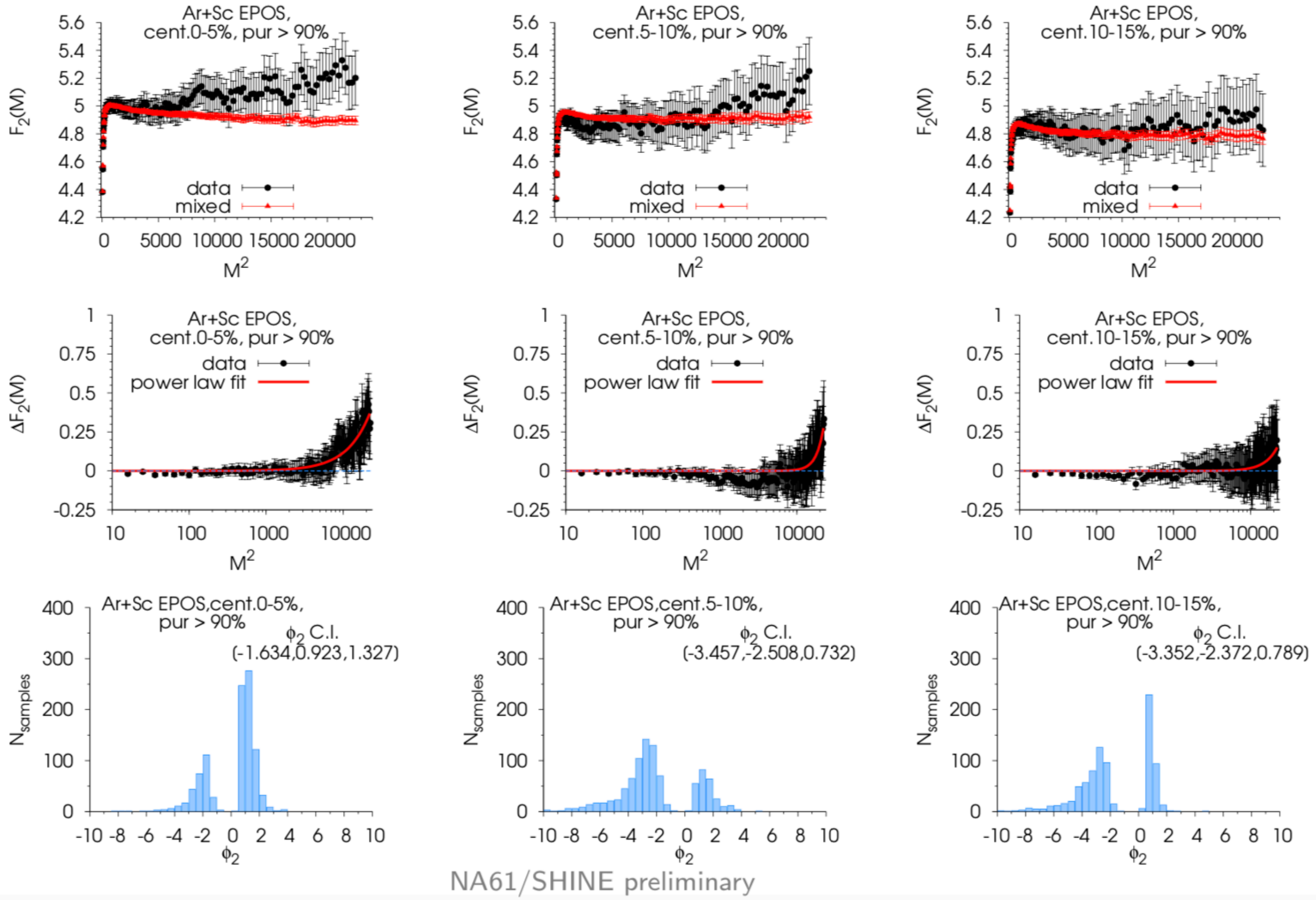


Intermittency analysis: details



Intermittency analysis: details

Ar+Sc EPOS: $F_2(M)$, $\Delta F_2(M)$, ϕ_2 bootstrap distribution



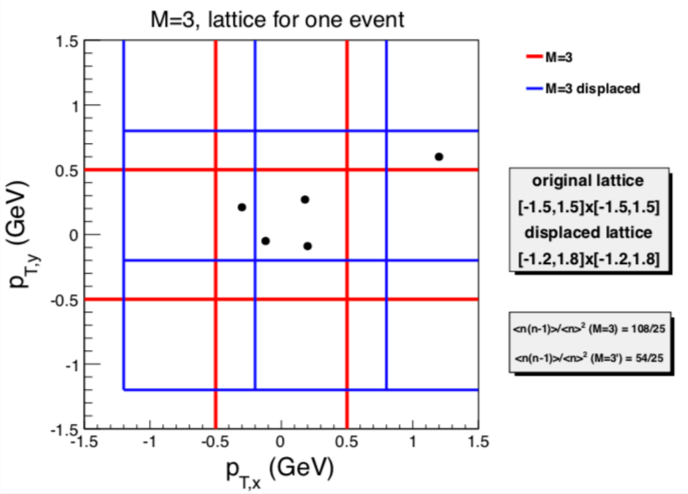
Intermittency analysis: details

Improving calculation of $F_2(M)$ via lattice averaging

- Problem: With low statistics/multiplicity, lattice boundaries may split pairs of neighboring points, affecting $F_2(M)$ values (see example below).

- Solution: Calculate moments several times on different, slightly displaced lattices (see example)
- Average corresponding $F_2(M)$ over all lattices. Errors can be estimated by variance over lattice positions.
- Lattice displacement is larger than experimental resolution, yet maximum displacement must be of the order of the finer binnings, so as to stay in the correct p_T range.

Displaced lattice — a simple example



Intermittency analysis: details

Mixing for:

$$\Delta F_2(M) \simeq \Delta F_2^{(e)}(M) \equiv F_2^{\mathrm{data}}(M) - F_2^{\mathrm{mix}}(M)$$

1. Set of 1…N events with n_i with i = 1…N multiplicity in i-th event

2. Going through all events: label each particle with number 1 … N_particles (N_particles = sum of n_i for I = 1…N) and associate number of the event it belongs to

3. To create mixed event with multiplicity n_m we do:

a) Select a particle randomly from the N_particles
b) Check that its event label is different than ALL previously selected particles for THIS mixed event
c) If it is, add particle to this mixed event; if it is not, we have a conflict, so we reject this particle and go back to step a)
d) Repeat until the desired multiplicity n_m has been reached

4. Repeat process until we have the desired number of mixed events (typically >10 times the original number of events)