Searching for the critical point of strongly interacting matter in nucleus-nucleus collisions at CERN SPS

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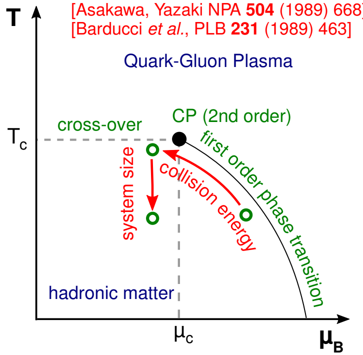
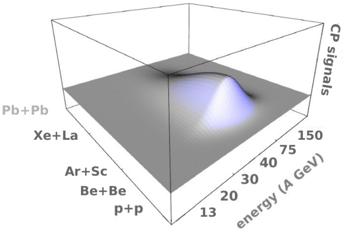
Exploring the phase diagram with heavy-ion collisions



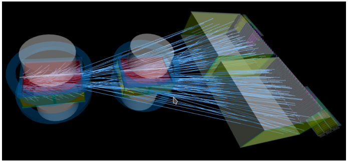
- Objective: detection of the Critical End Point (CP) of strongly interactive matter in the phase diagram
- Hill of fluctuations expected around the CP;
- Look for observables tailored for the CP; scan phase diagram by varying energy and size of collision system $\Rightarrow$
- Change freeze-out conditions (T, μ_B)



[M. Gazdzicki *et al.*, APPB **47** (2016) 1201]

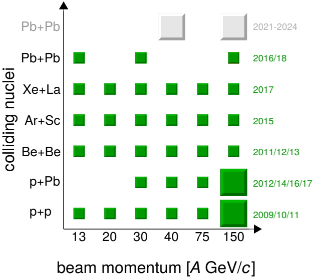
- 2nd order phase transition → scale invariance → power-law form of correlation function for large distances ⇔ small momentum transfer $\Delta\vec{k}$

The NA61/SHINE experiment



- Fixed-target, high-energy collision experiment at CERN SPS;
- Large variety of beams / hydrogen & nuclear targets;
- Large acceptance;
  good hadron ID;
  almost complete coverage in the projectile hemisphere;
  good momentum resolution;

- Goals: neutrino – cosmic ray – strong interactions programme
  - Study of strong + EM effects in a variety of nucleus-nucleus, proton-proton & proton-nucleus collisions;
  - Search for critical point signatures;



- Particle ID through dE/dx & TOF in the TPCs;
- Centrality determination through energy deposit of projectile spectators;

Intensive vs strongly intensive quantities

1. Extensive quantities ⇒ proportional to W (WNM) or V

- $\langle N \rangle$, σ^2, $S\sigma^3, \kappa\sigma^4 \ldots$

2. Intensive quantities ⇒ ratios of extensive, e.g.

- scaled variance $\omega[N] = \frac{\sigma^2[N]}{\langle N \rangle}$

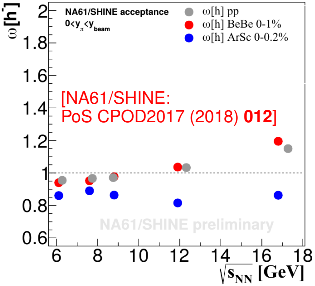
– still depend on $P(W)$

3. strongly intensive quantities ⇒ Independent of $P(W)$, e.g.

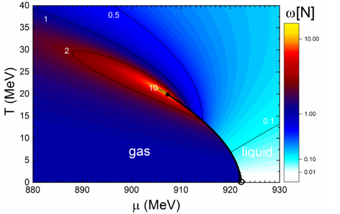
- $\langle K \rangle / \langle \pi \rangle$
- $\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N \rangle} \left[\langle N \rangle \omega[P_T] + \langle P_T \rangle \omega[N] - 2\left(\langle P_T N \rangle - \langle P_T \rangle \langle N \rangle\right) \right]$,
  $P_T \equiv \sum_{i=1}^{N} p_{T_i}$

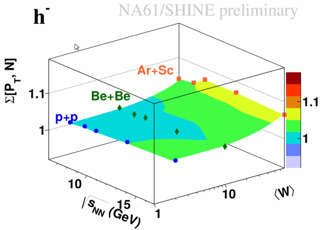
[Gazdzicki, Gorenstein, PRC **84** (2011) 014904];
[Gazdzicki, Gorenstein, Mackowiak-Pawlowska, PRC **88** (2013) 024907]

(Strongly) intensive measures in NA61/SHINE

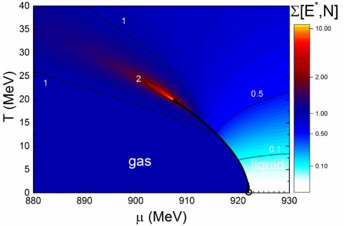


[Vovchenko, Anchishkin, Gorenstein, Poberezhnyuk, Stoecker, Acta Phys.Polon.Supp. **10** (2017) 753]



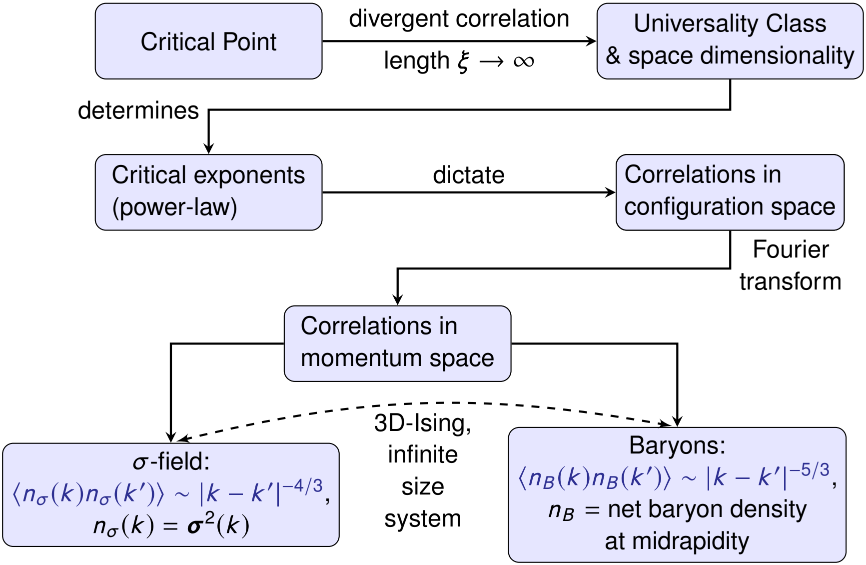


[NA61/SHINE: Acta Phys.Polon.Supp. **10** (2017) 449]



No prominent structures that could be related to the critical point are observed so far. . .

Self-similar density fluctuations near the CP

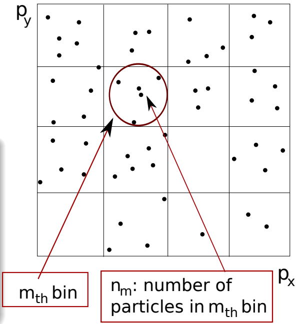


Observing power-law fluctuations: Factorial moments

Experimental observation of local, power-law distributed fluctuations $\Rightarrow$ Intermittency[1-3] in transverse momentum space (net protons at mid-rapidity)

(Critical opalescence in ion collisions[3])

- Net protons used as proxy for net baryons (same critical fluctuations[4]); finally, protons can be used (dominant contribution) & anti-protons dropped.
- Transverse momentum space is partitioned into M^2 cells
- Calculate second factorial moments $F_2(M)$ as a function of cell size $\Leftrightarrow$ number of cells M:



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

where $\langle \ldots \rangle$ denotes averaging over events.

[1] [J. Wosiek, *Acta Phys. Polon.* **B 19** (1988) 863-869]
[2] [A. Bialas and R. Hwa, *Phys. Lett.* **B 253** (1991) 436-438]
[3] [F.K. Diakonos, N.G. Antoniou and G. Mavromanolakis, PoS (CPOD2006) 010, Florence]
[4] [Y. Hatta and M. A. Stephanov, PRL**91**, 102003 (2003)]

Factorial moments – removal of noncritical background

- Non-critical pairs & experimental noise must be subtracted from $F_2(M)$.
- Intermittency will be revealed at the level of subtracted moments $\Delta F_2(M)$.
- Crucial parameter: Ratio λ of background to total proton multiplicity.
- For $\lambda \lesssim 1$ (background domination), non-critical background is approximated by (uncorrelated) mixed event moments; Critical Monte Carlo (CMC) then shows[1] we can write:

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

- For a critical system, ΔF_2 scales with cell size (number of cells, M) as:

$$\Delta F_2(M) \sim \left(M^2\right)^{\varphi_2} \quad ; \quad \varphi_2 : \text{intermittency index}$$

Theoretical prediction[1] for φ_2

universality class, effective actions $\begin{cases} \varphi_{2,cr}^{(p)} = \frac{5}{6} \; (0.833\ldots) \\ \text{net baryons (protons)} \end{cases}$

[1] [Antoniou, Diakonos, Kapoyannis and Kousouris, Phys. Rev. Lett. **97**, 032002 (2006).]

Statistical uncertainties & systematic effect estimation

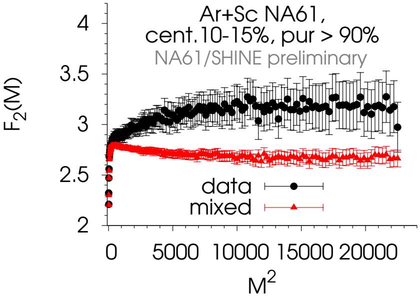
- Bootstrap method used to calculate statistical uncertainties
- Bootstrap samples of events created by sampling of events with replacement
- $\Delta F_2(M)$ calculated for each bootstrap sample; variance of sample values provides statistical error of $\Delta F_2(M)$

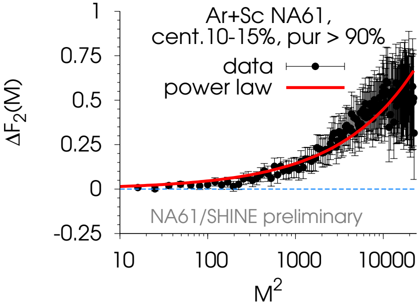
  [W.J. Metzger, *"Estimating the Uncertainties of Factorial Moments"*, HEN-455 (2004).]
- Systematic uncertainties arise from:
  - Misidentification of protons & detector effects (e.g. acceptance)
  - The fact that $F_2(M)$ are correlated for different bin sizes M
  - Selection of M-range to fit for power-law
- Bin correlations are partially handled by the bootstrap φ_2 distribution[1], but that is insufficient! The effect of bin correlation has to be investigated through Critical and background Monte Carlo simulation.
- Other systematic uncertainties are estimated by varying proton and M-range selection

[1] [B. Efron, *The Annals of Statistics* **7**,1 (1979)]

Ar+Sc @ 150A GeV/c – $F_2(M)$, $\Delta F_2(M)$ (mid-central)

- Mid-rapidity protons @ 17 GeV



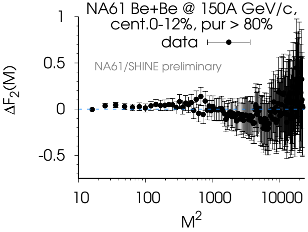


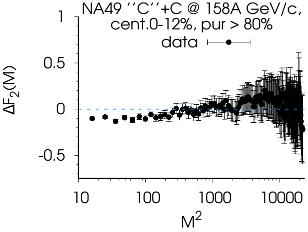
Indication of intermittency effect in $\Delta F_2(M)$ – however, systematic uncertainties are hard to estimate due to strong correlation of points for different M

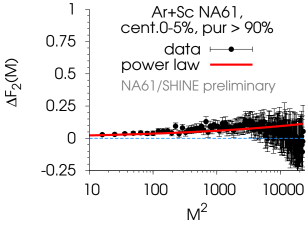
[NA61/SHINE: PoS(CPOD2017) **054**]

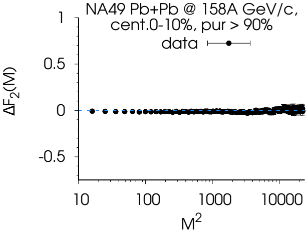
$\Delta F_2(M)$ – Be+Be, “C”+C, Pb+Pb, Ar+Sc (central)

- Mid-rapidity protons @ 17 GeV





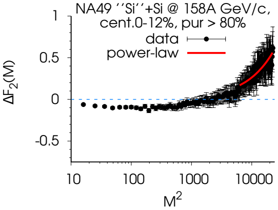


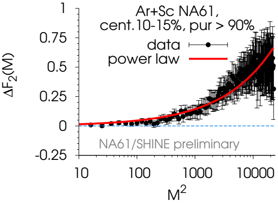


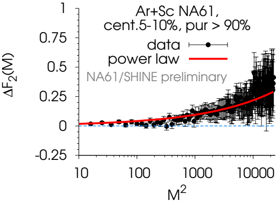
No signal visible in central Be+Be, “C”+C, Ar+Sc and Pb+Pb

[NA49: EPJC **75** (2015) 587];
[NA61/SHINE: PoS(CPOD2017) **054**]

- Mid-rapidity protons @ 17 GeV







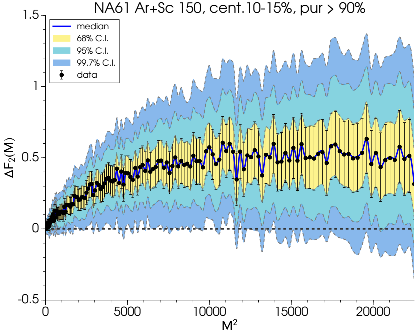
A deviation of $\Delta F_2(M)$ from zero seems apparent in central “Si”+Si and mid-central Ar+Sc

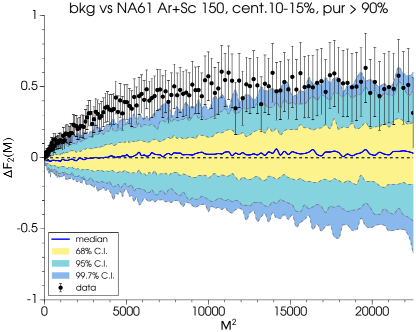
[NA49: EPJC **75** (2015) 587];
[NA61/SHINE: PoS(CPOD2017) **054**]

Ar+Sc 150 $\Delta F_2(M)$ – statistical significance of signal

1. $\Delta F_2(M)$, NA61 Ar+Sc @ 150 GeV/c bootstrap distributions
2. $\Delta F_2(M)$, random background sub-sample distributions

- Contour map of $\Delta F_2(M)$ distributions





1. $\gtrsim 95\%$ of $\Delta F_2(M)$ values above zero in Ar+Sc 150
2. $\gtrsim 95 - 99\%$ of random background $\Delta F_2(M)$ values below Ar+Sc 150 average

Conclusions

- NA61/SHINE pursues a program for the critical point search using a variety of observables;
- Studies of intensive and strongly intensive quantities show no evidence of the "critical hill" predicted for the CP;
- A possible non-zero signal in proton intermittency could be present for "Si"+Si and Ar+Sc collisions, in a well-defined region of the phase diagram;
- No intermittency signal is observed for other systems (Be+Be, "C"+C, Pb+Pb);
- Work on intermittency analysis is ongoing:
  - Plans to expand the analysis to other energies for Ar+Sc, as well as different system sizes (e.g. Xe+La);
  - A consistent method of estimating systematic uncertainties of factorial moments is being sought – must take into account bin correlation.


Thank You!

Acknowledgements

This work was supported by the National Science Centre, Poland under grant no. 2014/14/E/ST2/00018.

Backup Slides

Subtracting the background from factorial moments

- Experimental data is noisy $\Rightarrow$ a background of non-critical pairs must be subtracted at the level of factorial moments.
- Intermittency will be revealed at the level of subtracted moments $\Delta F_2(M)$.

Partitioning of pairs into critical/background

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

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

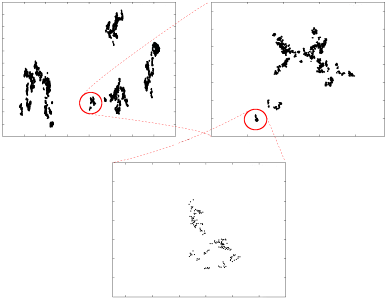
- The cross term can be neglected under certain conditions (non-trivial! Justified by Critical Monte Carlo* simulations)

** [Antoniou, Diakonos, Kapoyannis and Kousouris, Phys. Rev. Lett. 97, 032002 (2006).]*

Critical Monte Carlo (CMC) algorithm for baryons

- Simplified version of CMC* code:
  - Only protons produced
  - One cluster per event, produced by random Lévy walk: $\tilde{d}_F^{(B,2)} = 1/3 \Rightarrow \phi_2 = 5/6$
  - Lower / upper bounds of Lévy walks $p_{min,max}$ plugged in.
  - Cluster center exponential in p_T, slope adjusted by T_c parameter.
  - Poissonian proton multiplicity distribution.

Lévy walk example



Input parameters

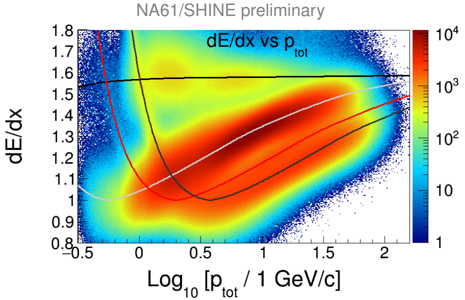
Parameter	p_{min} (MeV)	p_{max} (MeV)	λ_{Poisson}	T_c (MeV)
Value	$0.1 \rightarrow 1$	$800 \rightarrow 1200$	$\langle p \rangle_{\text{non-empty}}$	163

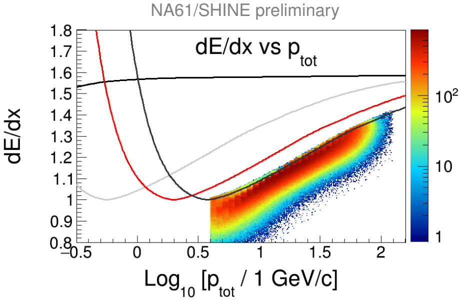
** [Antoniou, Diakonos, Kapoyannis and Kousouris, Phys. Rev. Lett. 97, 032002 (2006).]*

NA61/SHINE: $^{40}Ar + ^{45}Sc$ at 150A GeV/c

- First released results of preliminary analysis in Ar+Sc at 150A GeV/c – CPOD2018 Conference (Corfu, September 2018).
- NA61/SHINE CP task force created to verify and extend these results. Task force is spearheaded by IFJ Krakow group, with important contributions from Athens (NKUA), Warsaw (WUT, NCNR) and Frankfurt (FIAS).
- Intermittency analysis process:
  - Proton selection via particle energy loss dE/dx
  - Removal of split tracks – q_{inv} distribution & cut of proton pairs
  - Probe Δp_T distribution of proton pairs for power-law like behaviour in the limit of small p_T differences
  - Calculate factorial moments $F_2(M), \Delta F_2(M)$ for selected protons
  - Calculate intermittency index ϕ_2 (when possible) & estimate its statistical uncertainty
- Results were obtained for:
  - 0-5%, 5-10% and 10-15% centrality bins
  - 80%, 85% and 90% minimum proton purity selections

Proton selection





- Employ p_{tot} region where Bethe-Bloch bands do not overlap (3.98 GeV/c $\leq p_{tot} \leq$ 126 GeV/c)
- Fit dE/dx distribution with 4-gaussian sum for $\alpha = \pi, K, p, e$ – Bins: p_{tot}, p_T
- 30 Bins in $Log_{10}(p_{tot})$: $10^{0.6} \rightarrow 10^{2.1}$ GeV/c
- 20 Bins in p_T: 0.0 $\rightarrow$ 2.0 GeV/c
- Proton purity: probability for a track to be a proton, $\mathcal{P}_p = p/(\pi + K + p + e)$
- Additional cut along Bethe-Blochs (avoid low-reliability region between p and K curves)

Ar+Sc at 150A GeV/c: NA61 data vs EPOS

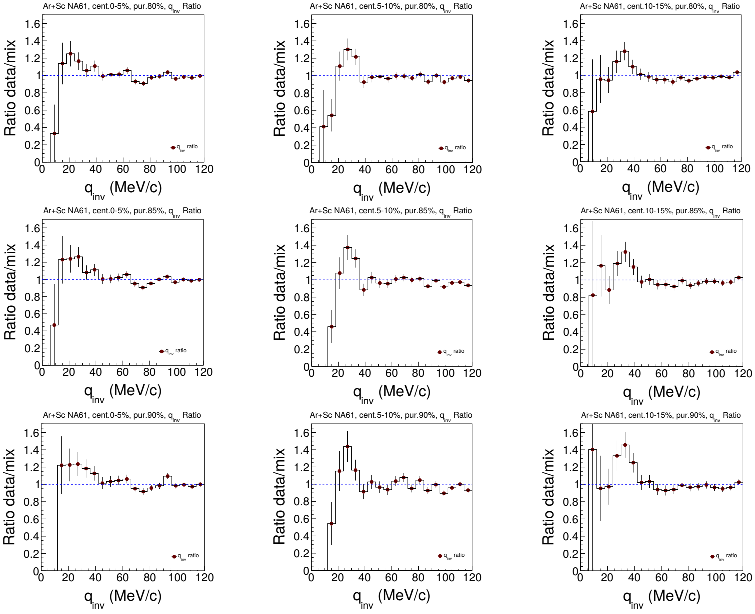
EPOS – proton p_T statistics

Centrality	#events	$\langle p \rangle_{\|p_T\| \leq 1.5\ GeV,\ \|y_{CM}\| \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
0- 5%	293,412	3.06 ± 1.60	2.89 ± 1.70	0.35 - 0.43
5-10%	252,362	2.72 ± 1.45	2.49 ± 1.58	0.35 - 0.43
10-15%	274,072	2.45 ± 1.33	2.16 ± 1.48	0.35 - 0.43

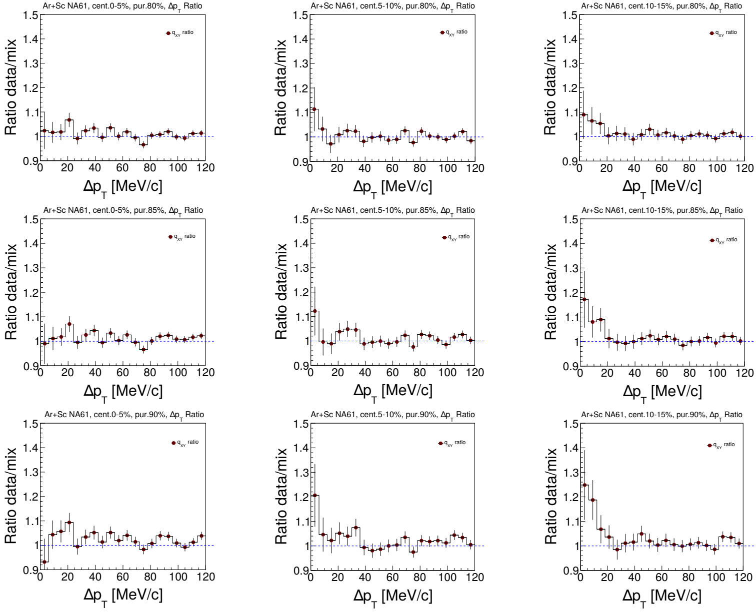
$^{40}Ar + {}^{45}Sc$ NA61 data – proton p_T statistics

Centrality	#events	$\langle p \rangle_{\|p_T\| \leq 1.5\ GeV,\ \|y_{CM}\| \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
0- 5%	144,362	3.44 ± 1.79	3.30 ± 1.89	0.46 - 0.58
5-10%	148,199	3.00 ± 1.61	2.79 ± 1.73	0.46 - 0.58
10-15%	142,900	2.81 ± 1.53	2.58 ± 1.66	0.45 - 0.57

q_{inv} proton distributions – NA61/SHINE

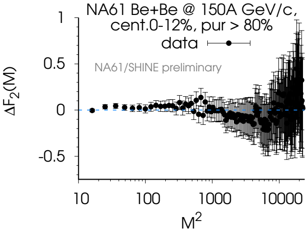


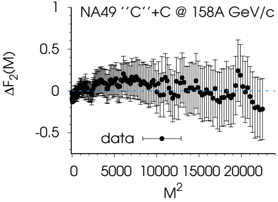
Δp_T proton distributions – NA61/SHINE

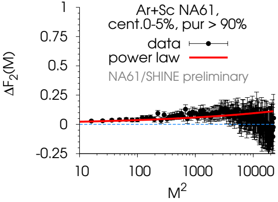


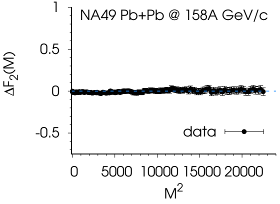
$\Delta F_2(M)$ – Be+Be, “C”+C, Pb+Pb, Ar+Sc (central)

- Mid-rapidity protons @ 17 GeV









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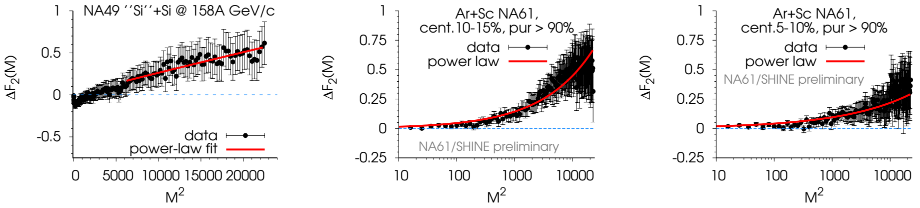
[NA49: EPJC **75** (2015) 587];
[NA61/SHINE: PoS(CPOD2017) **054**]

$\Delta F_2(M)$ – "Si"+Si, Ar+Sc (mid-central)

- Mid-rapidity protons @ 17 GeV



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