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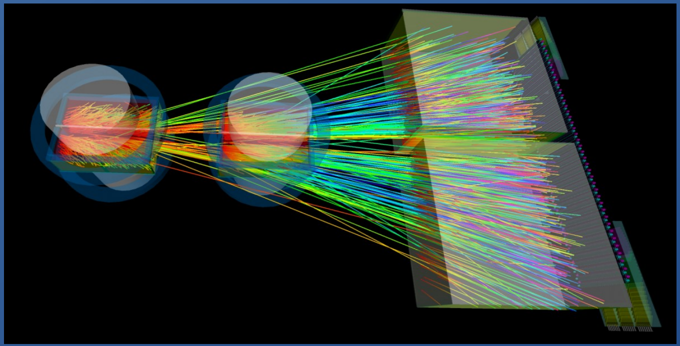
for the NA61/SHINE Collaboration

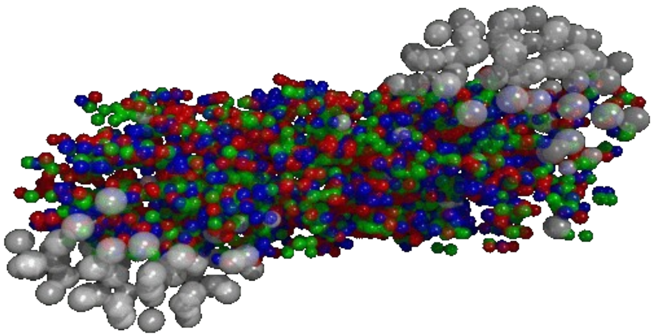
New results on spectra and fluctuations from NA61/SHINE

"Critical Point and Onset of Deconfinement 2018"
Corfu, Greece, September 24th – 28th, 2018

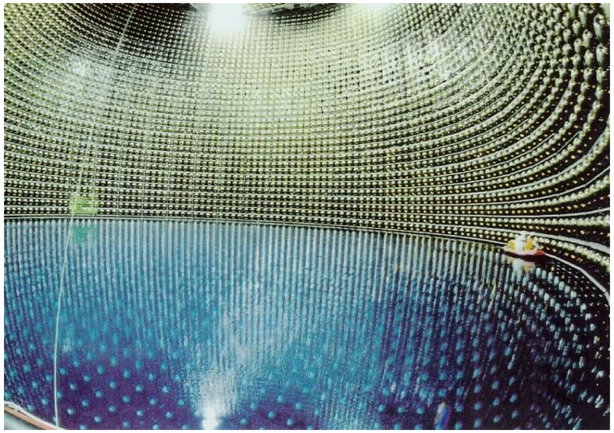


NA61/SHINE program

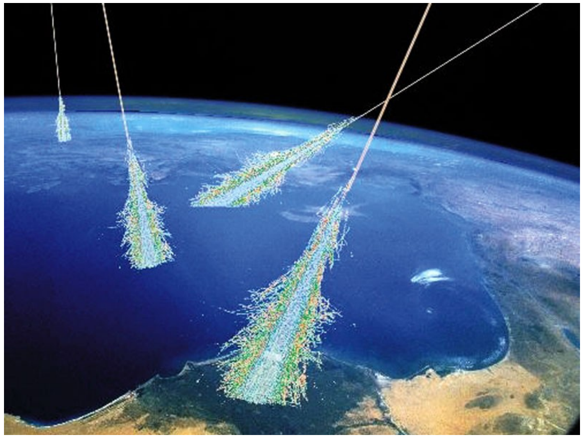
- Physics of **strongly interacting matter** → subject of this talk
- Data for neutrino and cosmic ray experiments
  - Originally: **precision data on hadron production (spectra)**
    - **reference measurements** of p+C interactions **for the T2K experiment** for computing neutrino fluxes from the T2K beam targets
    - **reference measurements** of p+C, p+π, p+p, and π+C interactions **for cosmic-ray physics** (Pierre-Auger and KASCADE experiments) for improving air shower simulations
  - Extensions
    - **h+*A*** measurements for the **Fermilab neutrino program**
    - analysis for **experiments located in space** - measurement of Nuclear Fragmentation Cross Sections (NFCS) of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy (background for dark matter searches with space-based experiments as AMS)



UrQMD



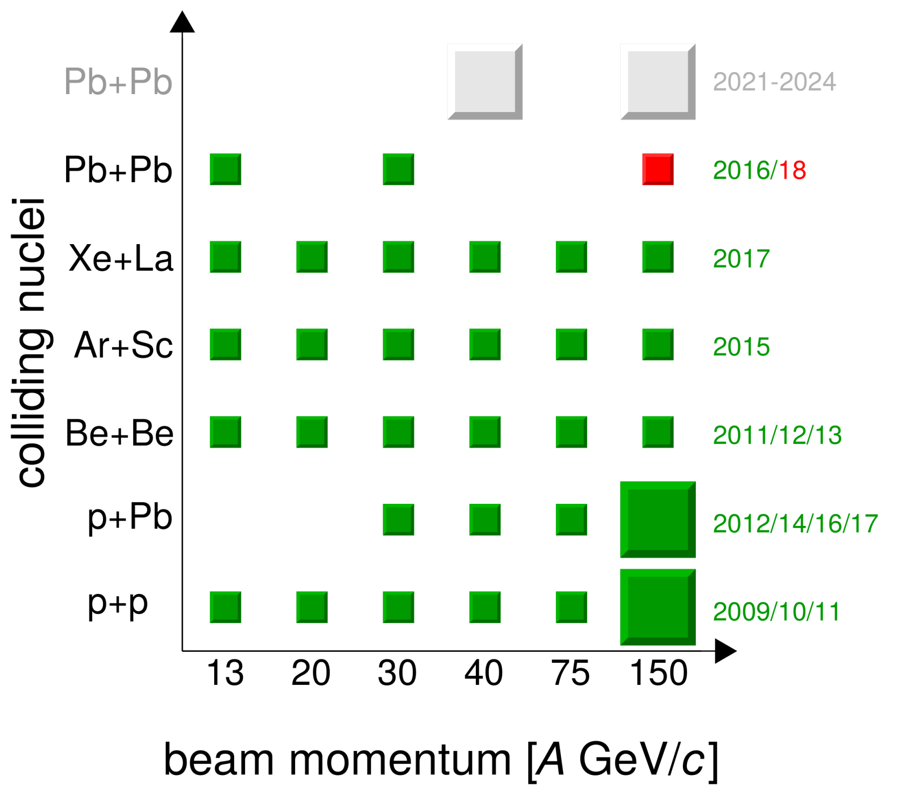
Super Kamiokande



NASA

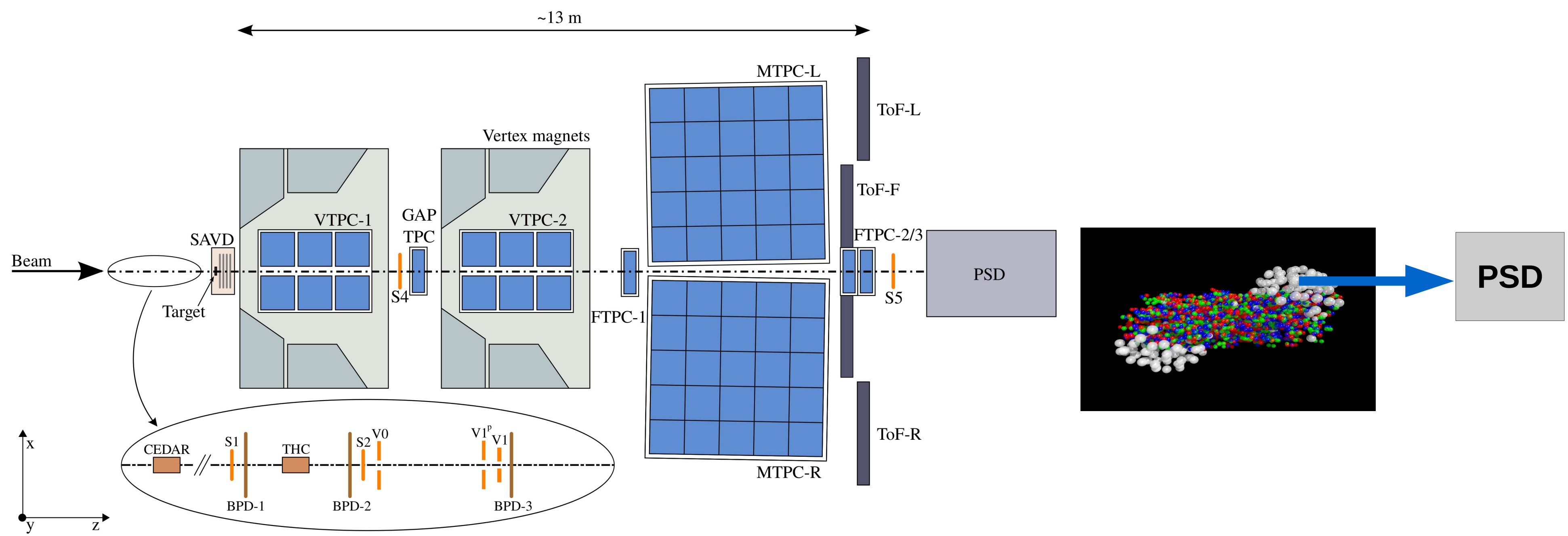
NA61/SHINE strong interactions program

Comprehensive scan in the whole SPS energy range (beam momentum 13*A* - 150/158*A* GeV/*c* ⇔ $\sqrt{s_{NN}}$= 5.1 - 16.8/17.3 GeV) with **light and intermediate mass nuclei**



- **Search for the critical point** → search for non-monotonic behavior of CP signatures: fluctuations of N, average p_T, etc., intermittency, when system freezes out close to CP
- **Study of the properties of the onset of deconfinement** → search for the onset of the horn/kink/step/dale in collisions of light nuclei
- Study **high p_T particles** (energy dependence of nuclear modification factor)
- **Extended by Pb+Pb** → **open charm** measurements, **collective effects**, etc.

Fixed target NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) in the north area of the CERN SPS



- Beam and trigger detectors
- **Vertex Detector** (SAVD) for open charm measurement
- Four large volume **Time Projection Chambers (TPCs)**: VTPC-1, VTPC-2 (inside superconducting magnets), MTPC-L, MTPC-R; measurement of dE/dx, charge and momentum. Four smaller TPCs (GAP TPC, FTPC-1/2/3)
- **Time of Flight (ToF)** detector walls
- **Projectile Spectator Detector (PSD)** for centrality measurement and determination of reaction plane

Highlights of NA61 results at CPOD 2018:

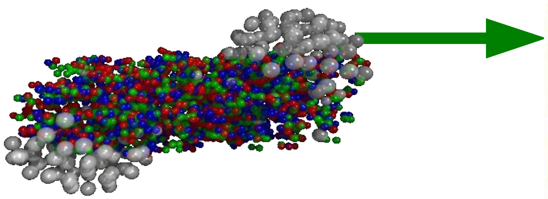
- Recent measurements of **identified hadron spectra and multiplicities in Be+Be and Ar+Sc** collisions at SPS energies →Maciej Lewicki (Tuesday)
- Recent results from **proton intermittency analysis** in nucleus-nucleus collisions from NA61/SHINE at CERN SPS → Nikolaos Davis (Monday)
- NA61/SHINE prospects for **Bose-Einstein correlation** measurements → Barnabas Porfy (Wednesday)
- **Anisotropic flow measurement** from NA61/SHINE and NA49 experiments at CERN SPS → Ilya Selyuzhenkov (Friday)
- **$K^*(892)^0$ production in p+p** interactions **at 158 GeV/*c*** from NA61/SHINE → Angelika Tefelska (Friday)
- **Open charm measurements** at CERN SPS energies in the NA61/SHINE experiment - status and plans → Anastasia Merzlaya (Friday)

Also at this conference:

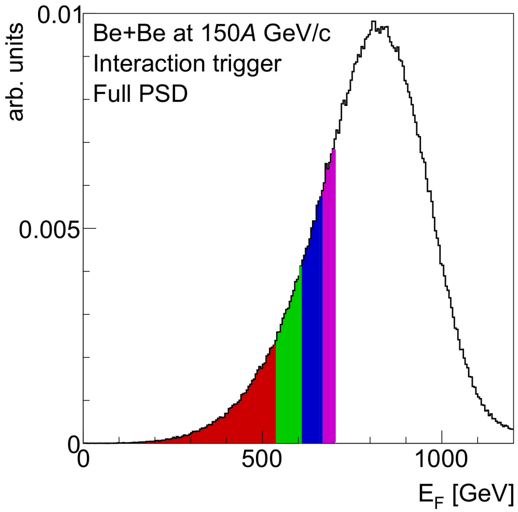
- **Forward hadron calorimeter (PSD)** of NA61/SHINE for heavy ion studies and its upgrade for experiments beyond 2020 → Sergey Morozov (Friday)
- **Electromagnetic effects** and the longitudinal evolution of the system at CERN SPS energies → Nikolaos Davis (Friday)

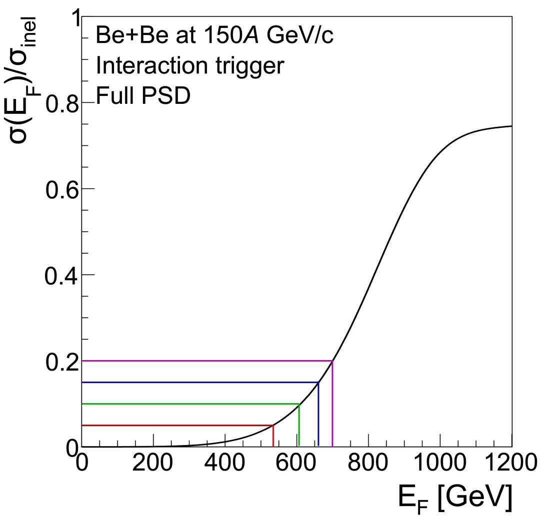
Centrality selection in ion collisions

- Multiplicity based event selection biases multiplicity fluctuations! To avoid this bias centrality is measured using **Projectile Spectator Detector** (PSD)
- PSD is located on the beam axis and measures the forward energy E_F related to the non-interacting nucleons of the beam nucleus
- Intervals in E_F allow to select different centrality classes



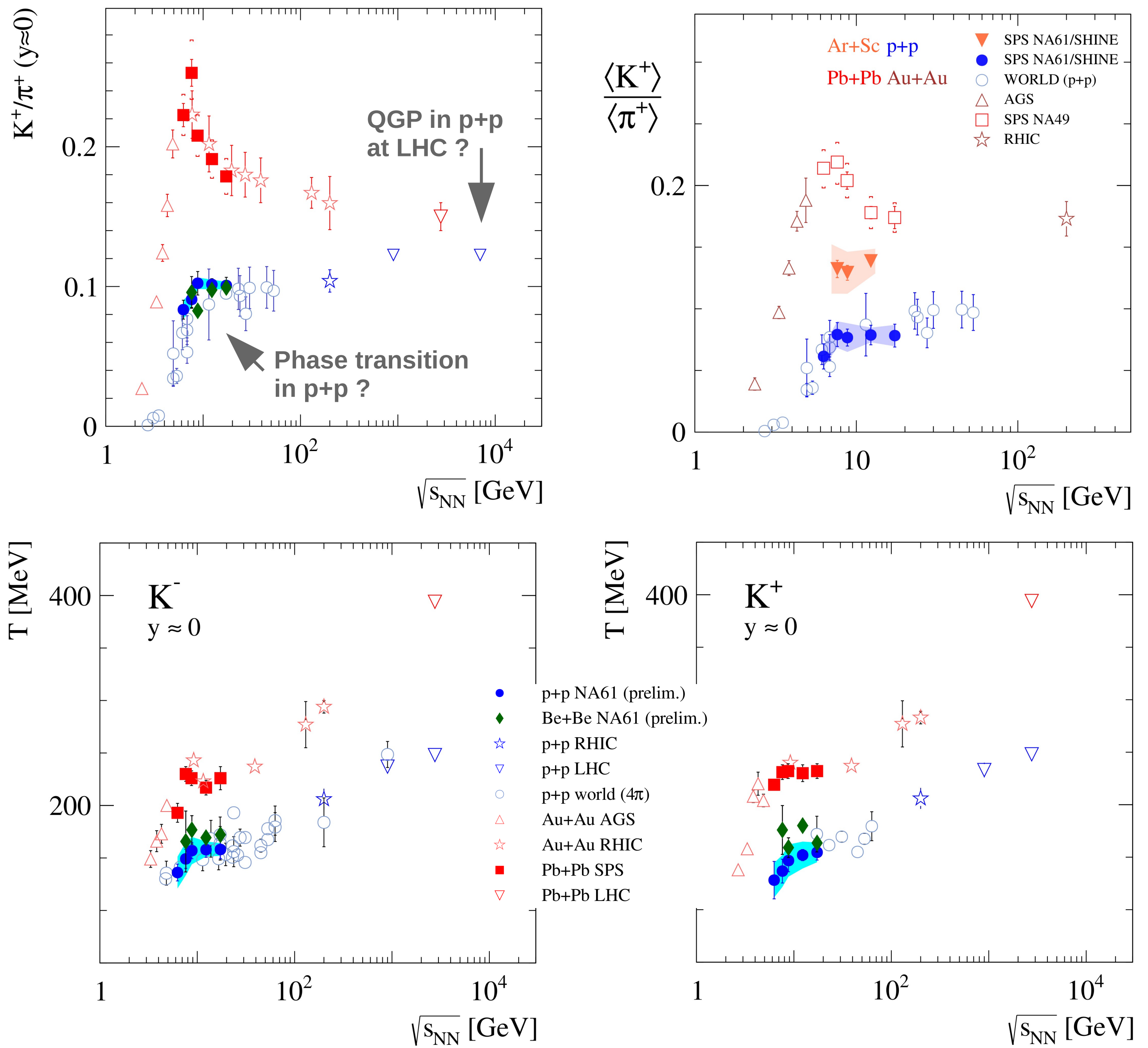
0 - 5% **5 - 10%** **10 - 15%** **15 – 20%**





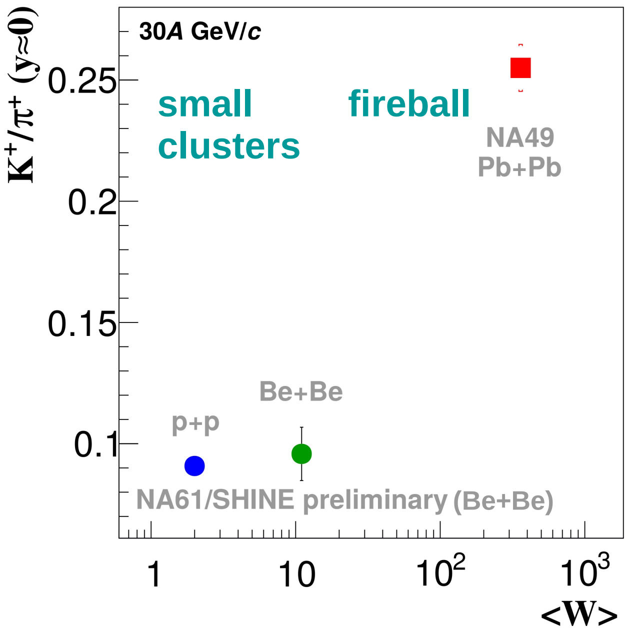
Can we see the onset of deconfinement in light and intermediate mass systems?

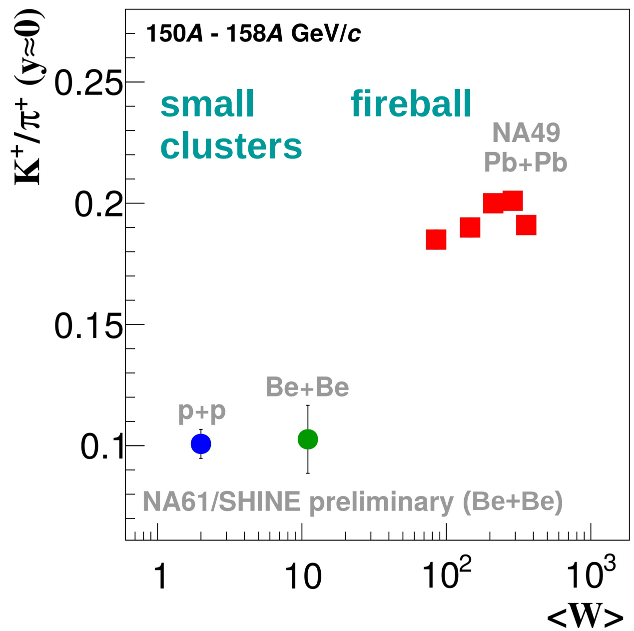
CPOD 2017 status of **horn and step** plots – properties of the **onset of deconfinement**



- For Pb+Pb sharp peak (**horn**) in K^+/π^+ ratio due to onset of deconfinement (OD)
  (APPB 30, 2705, 1999)
- For Pb+Pb plateau (**step**) in the inverse slope parameter (T) of m_T spectra due to OD (constant T and p in mixed phase)
- Even **in p+p** the energy dependence of K^+/π^+ and T exhibits **rapid changes in the SPS energy** range
- **Be+Be** results **close to p+p**

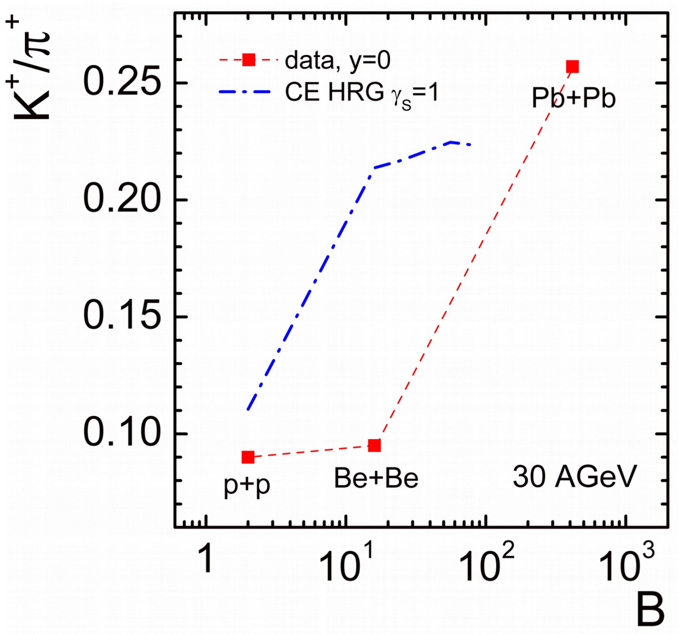
System size dependence of K^+/π^+ ratio at mid-rapidity

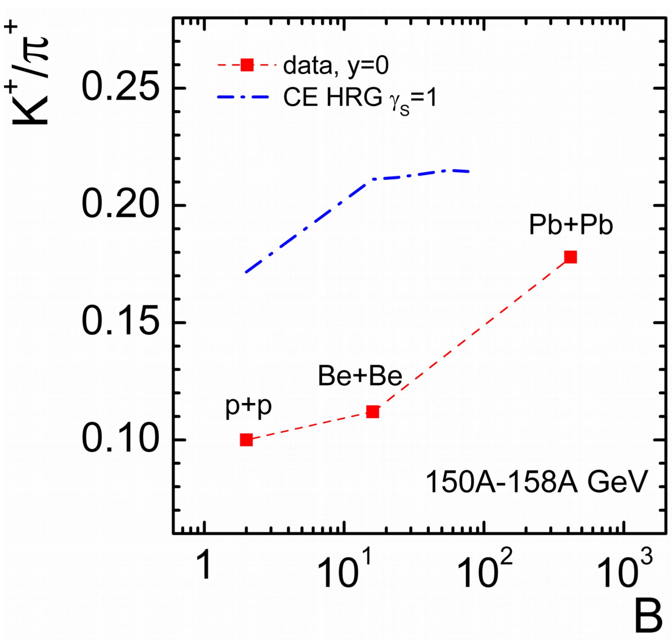




- **Be+Be** results are **close to p+p**
- **Rapid change** from p+p and Be+Be **to heavy Pb+Pb**

p+p: NA61, EPJC 77, 671, 2017
Pb+Pb: NA49, PR C77, 024903 2008; PR C86, 054903, 2012





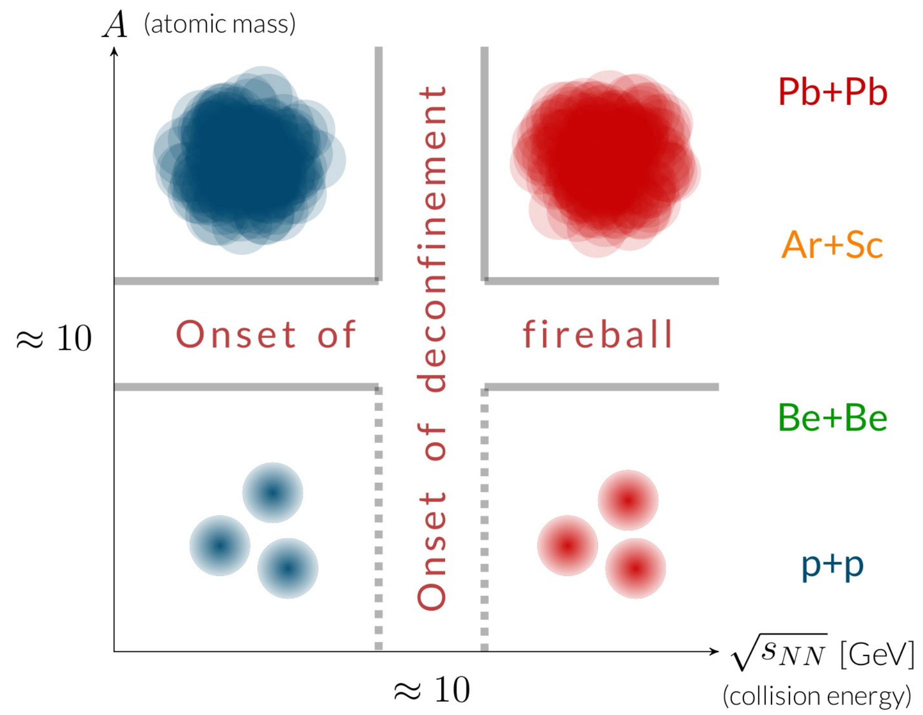
- Hadron Resonance Gas model in CE formulation (γ_S=1) cannot describe NA61 data

Begun, Gorenstein, Motornenko, Vovchenko [in preparation]; see also arXiv:1805.01901, arXiv:1512.08025

Two onsets in nucleus-nucleus collisions

Onset of deconfinement ≡ beginning of QGP formation

Onset of fireball ≡ beginning of formation of a large cluster which decays statistically



small clusters

Independent, non-statistical small clusters; wounded nucleon model

percolation

Large clusters, not necessarily decaying statistically

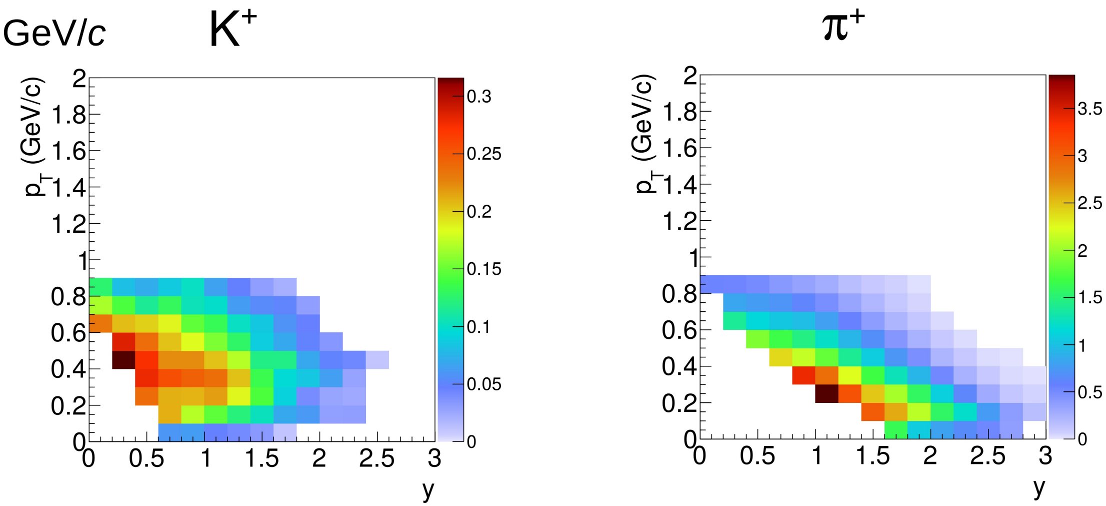
fireball

Large object that decays statistically

New results on identified particles in 0-20% central Be+Be

See talk by
M. Lewicki
for more results

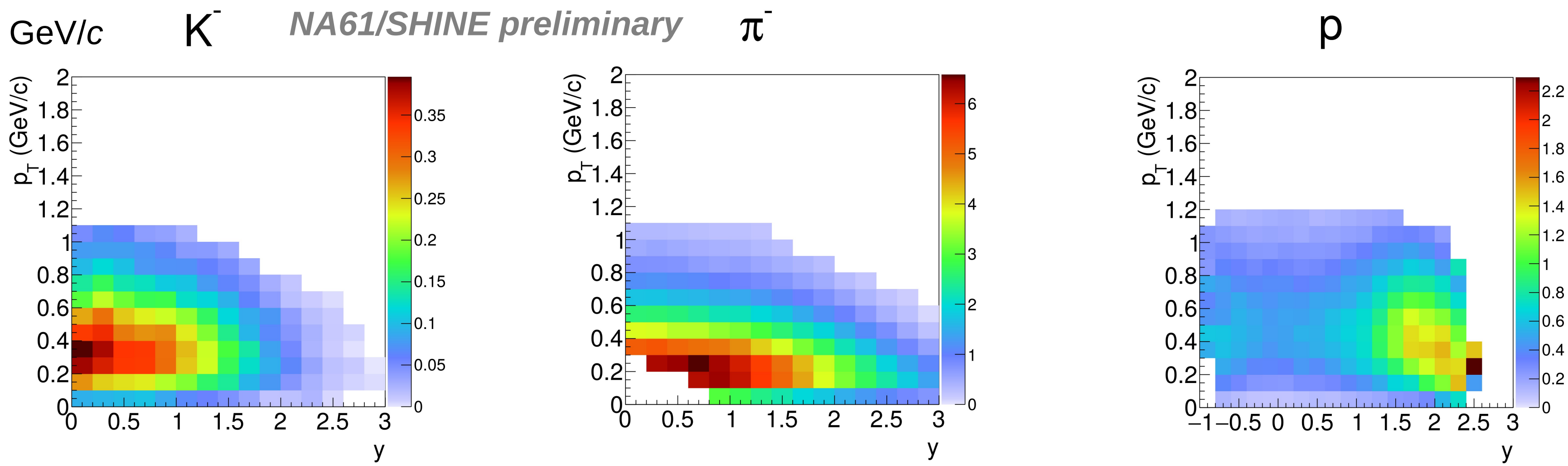
30*A* GeV/*c*



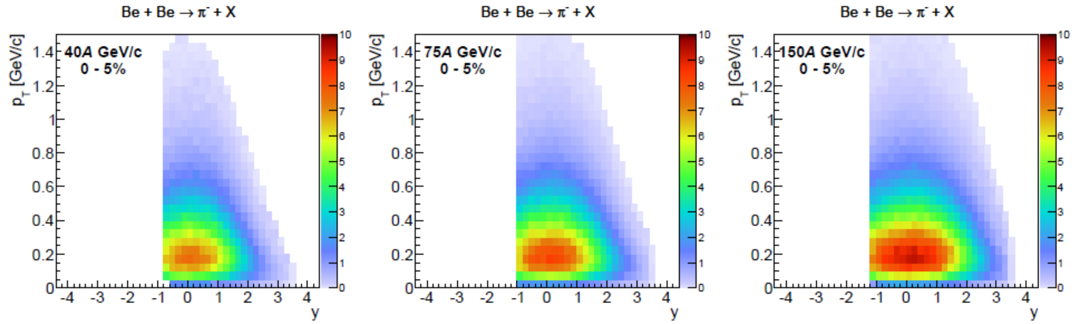
Double differential spectra $d^2n/(dp_T dy)$ of $\pi^{+/-}$, $K^{+/-}$ and protons in rapidity and transverse momentum for central (0-20%) Be+Be collisions. Results obtained using **dE/dx method**

150*A* GeV/*c*

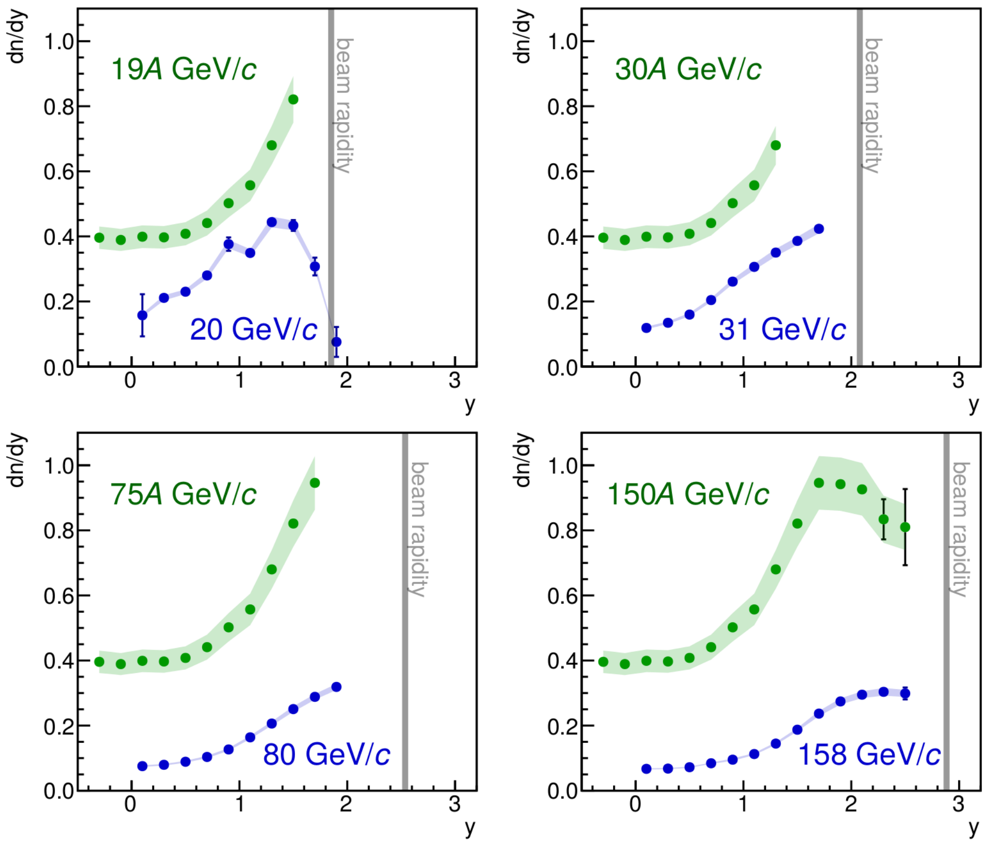
NA61/SHINE preliminary



Results for negatively charged pions from **h- method** (CPOD 2014):



Rapidity distribution of protons - comparison of 0-20% Be+Be and inelastic p+p



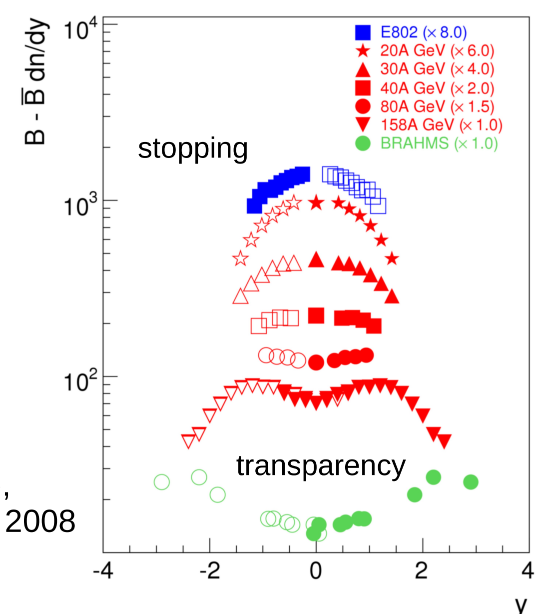
Be+Be:
NA61/SHINE preliminary

p+p: NA61,
EPJC 77, 671, 2017

Proton rapidity distribution
measured in:

p+p
Be+Be (preliminary)

Central Pb+Pb / Au+Au



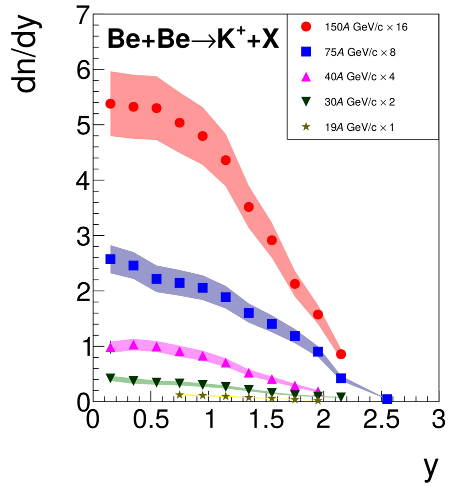
Blume (for NA49),
JPG 35, 044004, 2008

- **Shape of distributions** is qualitatively **similar in Be+Be and p+p**
- Proton, net-proton and net-baryon **spectra in Pb+Pb** are **qualitatively different**

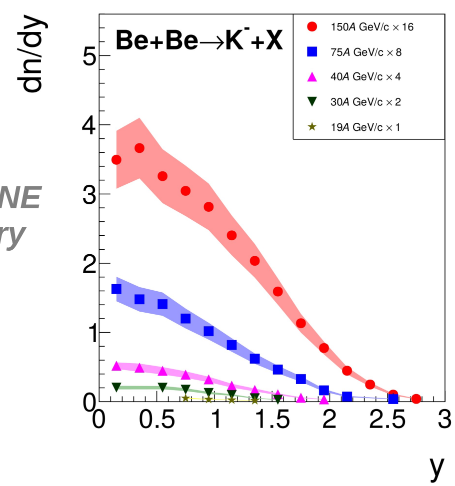
New results on $K^{+/-}$ rapidity spectra in 0-20% central Be+Be

Rapidity spectra fitted with:

$$\frac{dn}{dy} = A \cdot \left(A_{sym} e^{-\frac{(y-y_0)^2}{\sigma_0}} + e^{-\frac{(y+y_0)^2}{\sigma_0}} \right)$$

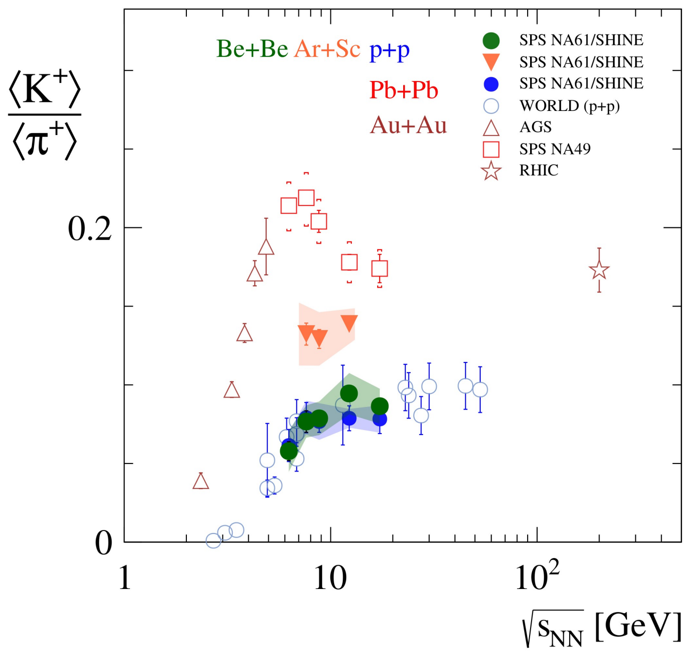


NA61/SHINE preliminary



"Horn" in 4π acceptance

Be+Be 2018; Ar+Sc 2017

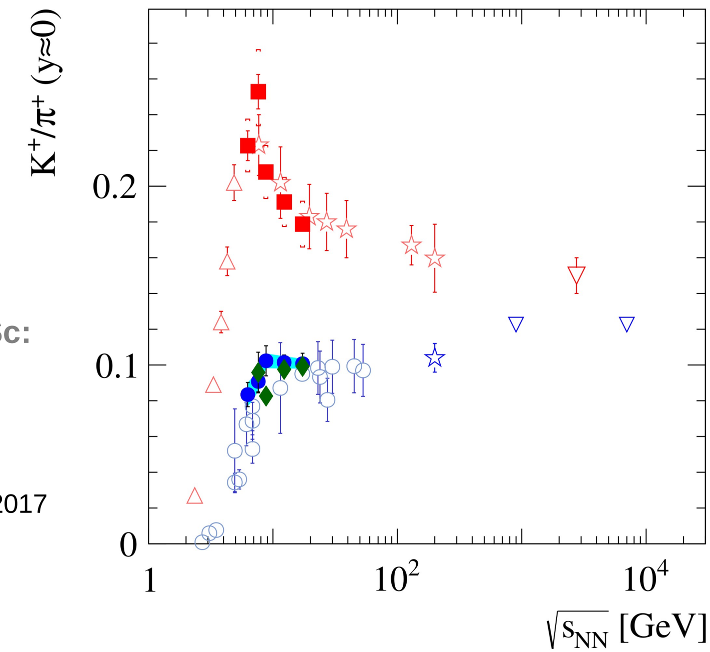


Be+Be, Ar+Sc: NA61/SHINE preliminary

NA61 p+p: EPJC 77, 671, 2017

"Horn" at mid-rapidity

Be+Be 2017



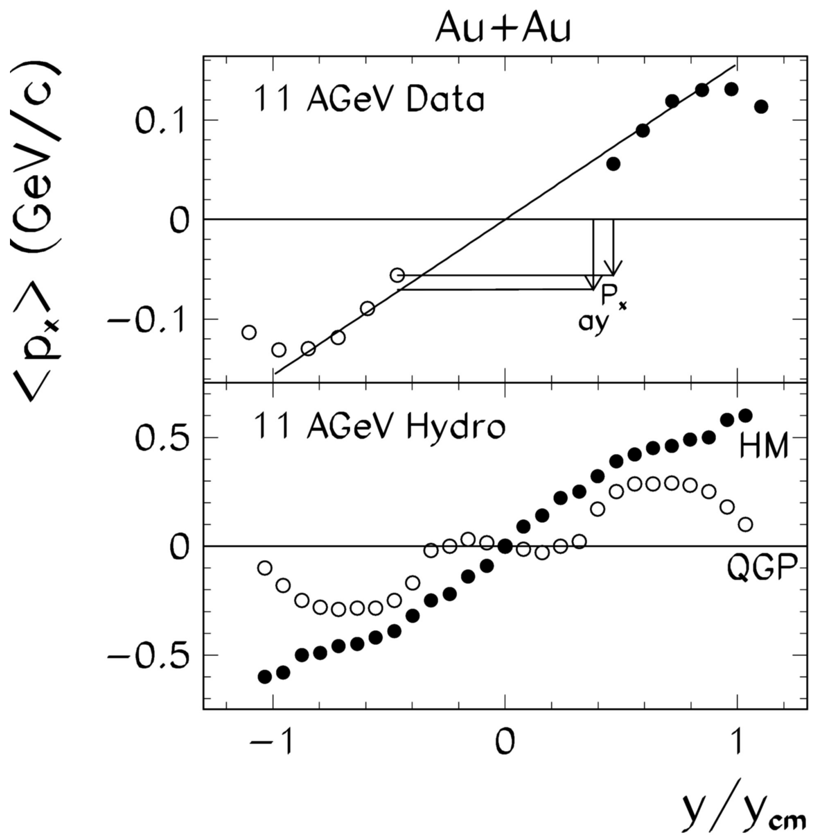
- **Be+Be** results are **close to p+p** (both at mid-rapidity and in 4π acceptance)
- "Onset of fireball" for collisions of nuclei heavier than Be

Can we study the properties of the onset of deconfinement using anisotropic flow?

Directed flow and the onset of deconfinement

Directed flow v_1 was considered to be **sensitive to 1st order phase transition** (softening of EOS) Csernai, Rohrich, PL B458, 454, 1999; Stoecker, NP A750, 121, 2005; Brachmann et al. PR C61, 024909, 2000. Expected: **non-monotonic behaviour** (positive→negative→positive) **of proton dv_1/dy as a function of beam energy** - "collapse of proton flow"

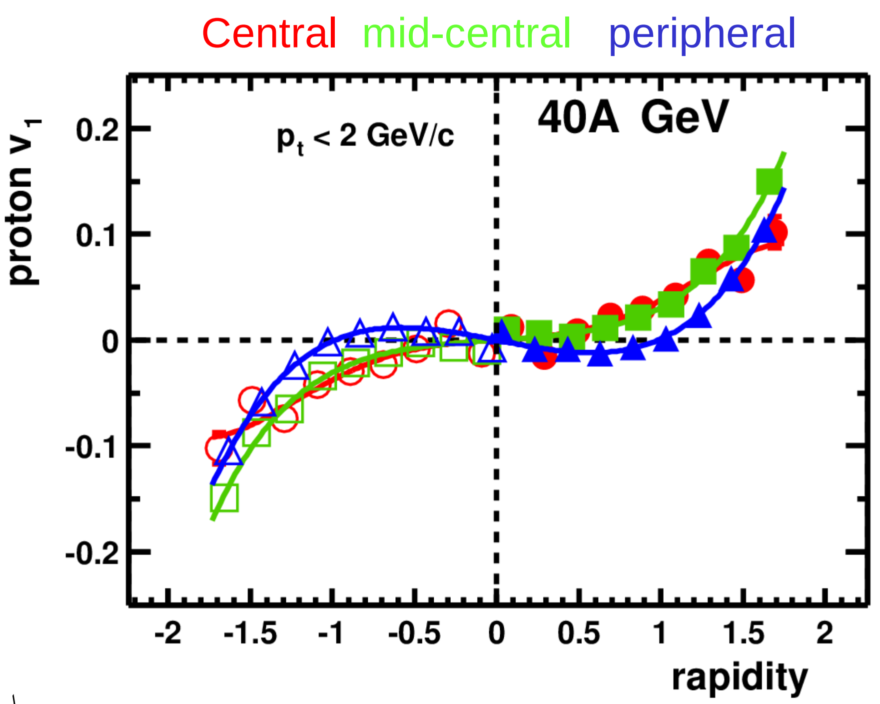
Predictions of hydrodynamical model:



QGP: ideal hydro with 1st order PT
Csernai, Rohrich, PL B458, 454, 1999

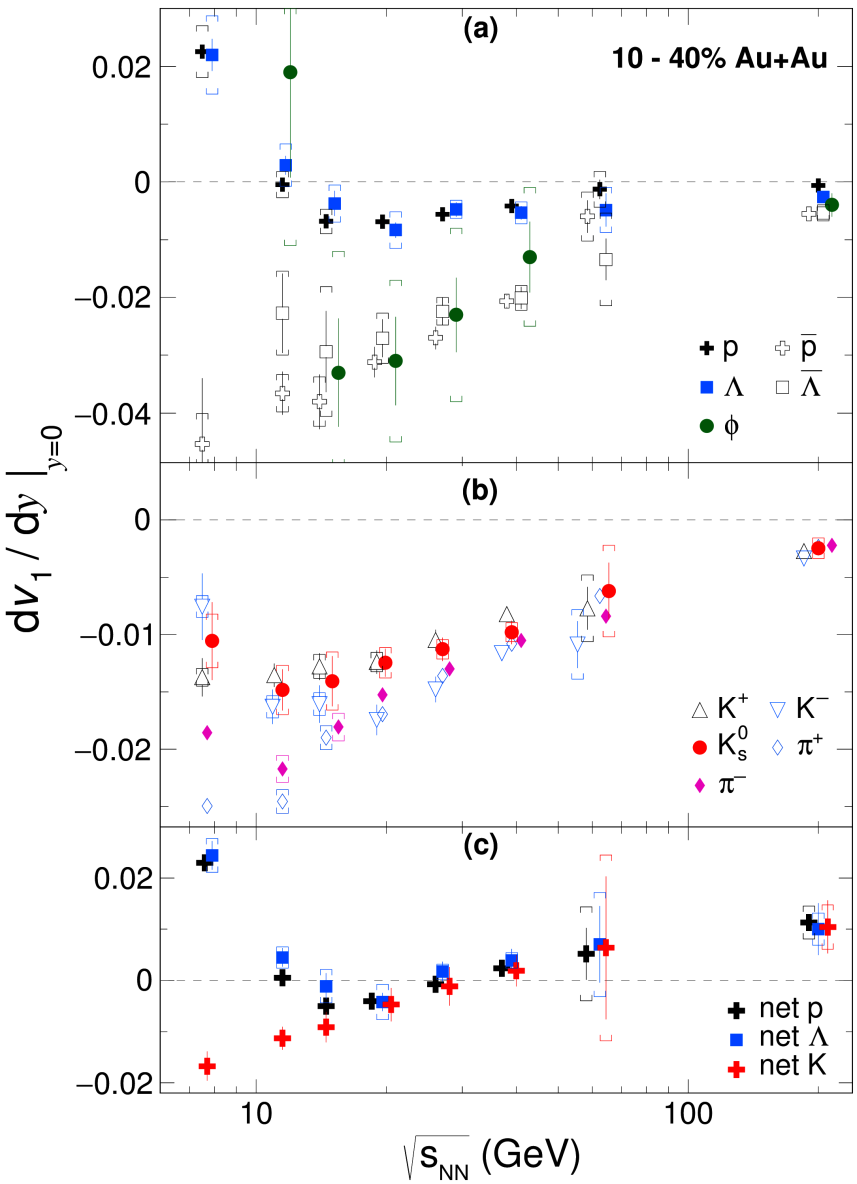
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow measured by NA49
at middle SPS energy ("anti-flow" of protons at mid-rapidity):



NA49, PR C68, 034903, 2003

STAR results on energy dependence of dv_1/dy



- **v_1 slopes for protons and net-protons** change signs at lower energies and **show minimum at 10-20 GeV** (14.5 GeV for net-protons)
- **Similar behaviour for Λ and protons**

→ **consistent with hydro models with (1st order) phase transition**

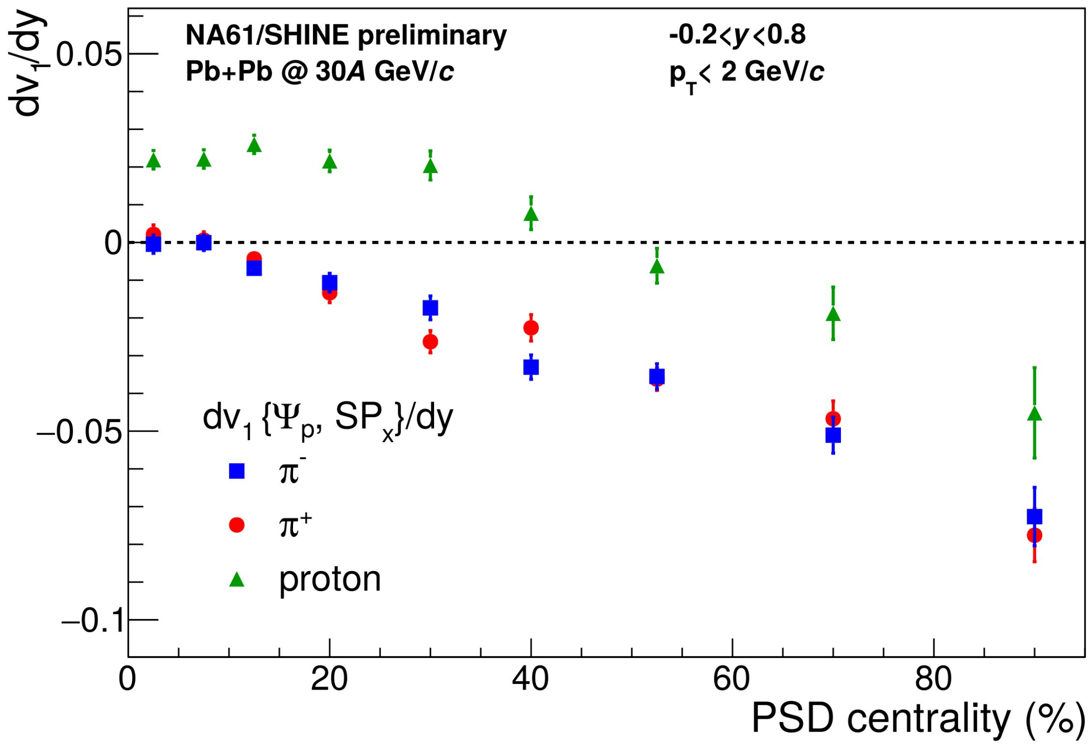
STAR, PRL 120, 062301, 2018

See also:
Older STAR results → PRL 112, 162301, 2014
STAR fixed target ($\sqrt{s_{NN}}$ = 4.5 GeV) → NP A967, 808, 2017
STAR centrality dep. (Au+Au, diff. energ.) → NP A956, 260, 2016

NA61/SHINE centrality dependence of dv_1/dy in Pb+Pb at $\sqrt{s_{NN}}$ = 7.6 GeV

(30*A* GeV/*c* beam momentum; according to K^+/π^+ "horn" in Pb+Pb this is **the energy of the onset of deconfinement**)

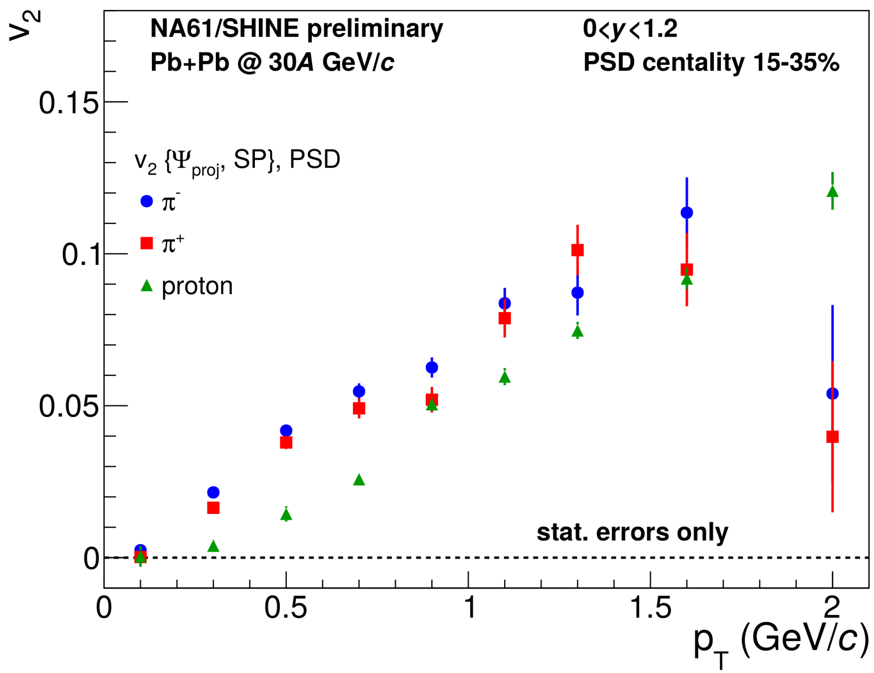
- NA61 fixed target setup → tracking and particle identification over wide rapidity range
- Flow coefficients are measured relative to the spectator plane estimated with Projectile Spectator Detector (PSD) → unique for NA61

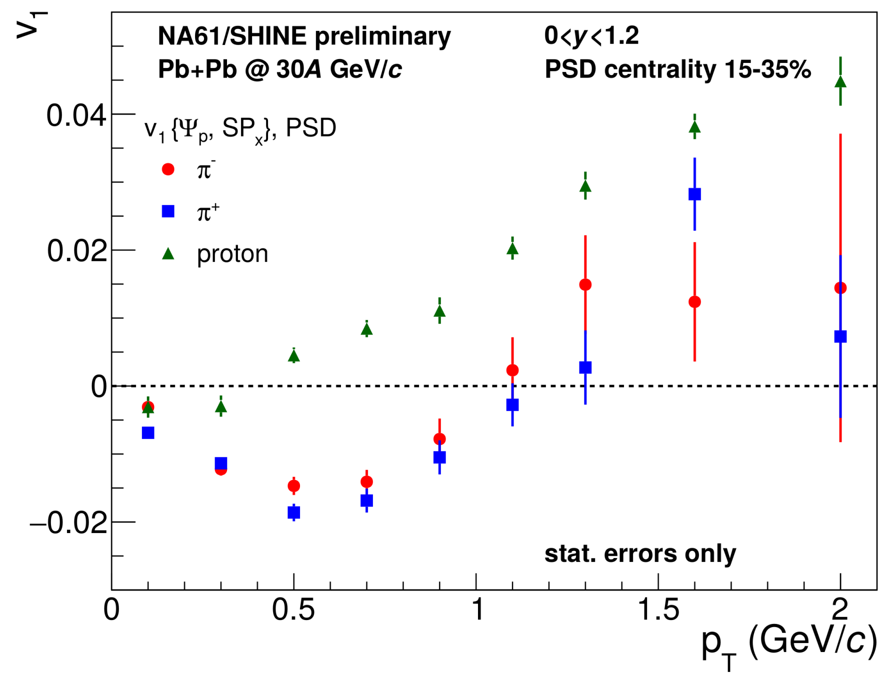


- Slope of pions v_1 is always negative
- **Slope of protons v_1 changes sign for centrality of about 50%**

Results for Pb+Pb at 13*A* and 150*A* GeV/c as well as six energies of Xe+La are coming soon

Particle type dependence of elliptic and directed flow





- Clear mass hierarchy of v_2 due to radial flow
- Difference between π^+ and π^- v_2 is small

- Significant mass dependence of v_1
- Difference between π^+ and π^- v_1 is sensitive to electromagnetic effects → see charged pions yield asymmetry

For more results from NA61 and new analysis of NA49 data w.r.t. to spectator plane see talk by I. Selyuzhenkov

Can we see the electromagnetic interactions between charged pions and spectators ?

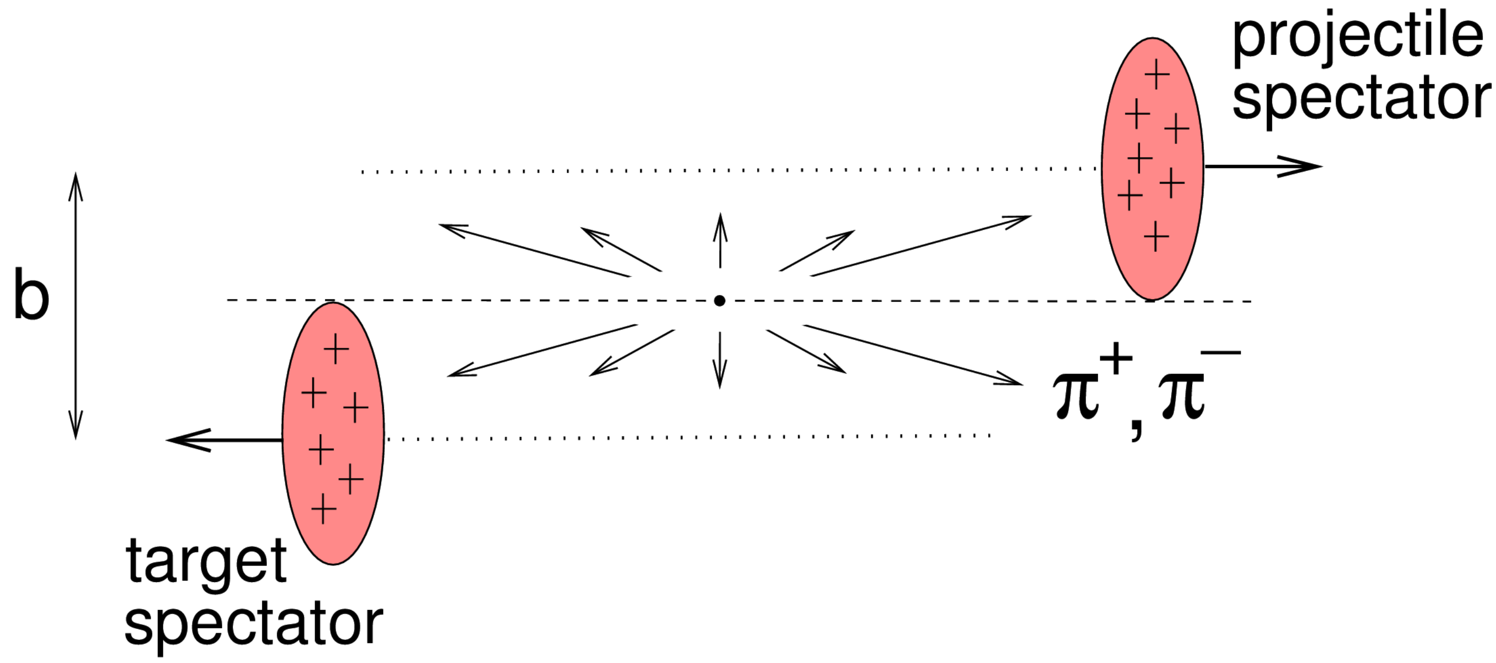
π^+/π^- ratio and spectator-induced electromagnetic effects

- Spectators (in non-central collisions) follow their initial path with unchanged momenta; charged spectators generate electromagnetic fields

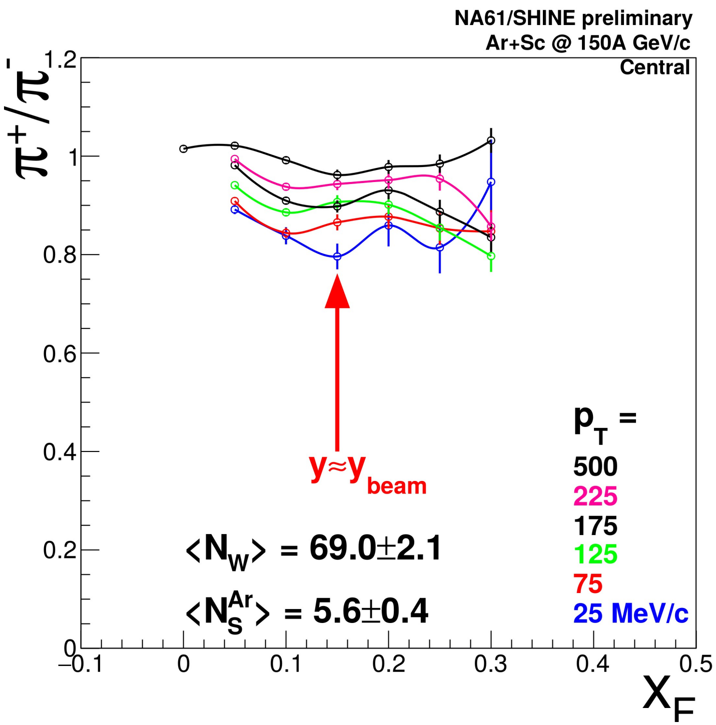
- Charged pion trajectories can be modified by electromagnetic interactions (repulsion for π^+ and attraction for π^-) with the spectators → the effect is sensitive to the space-time evolution the system

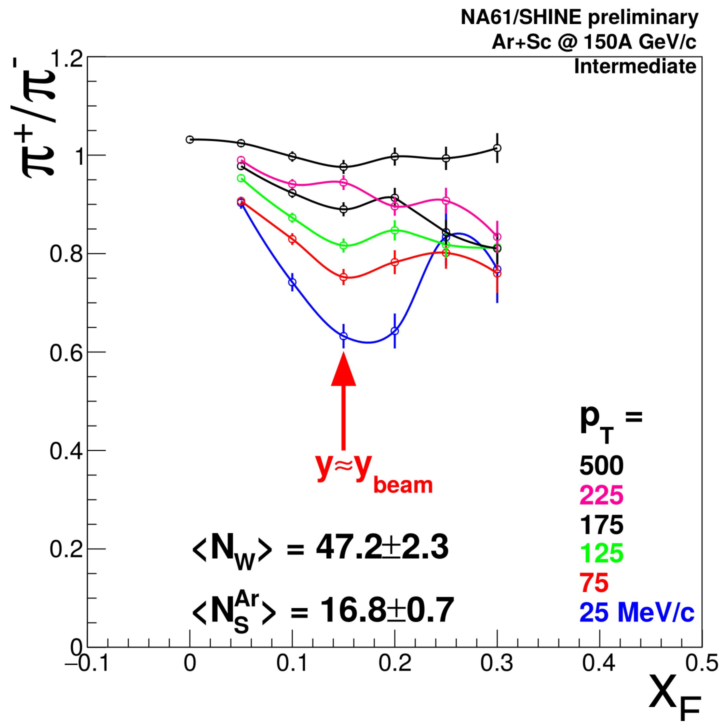
- π^+/π^- ratio allows to study spectator-induced electromagnetic effects → new information on the space and time evolution of the particle production process

Rybicki, Szczurek PR C75, 054903, 2007;
Rybicki, Szczurek PR C87, 054909, 2013



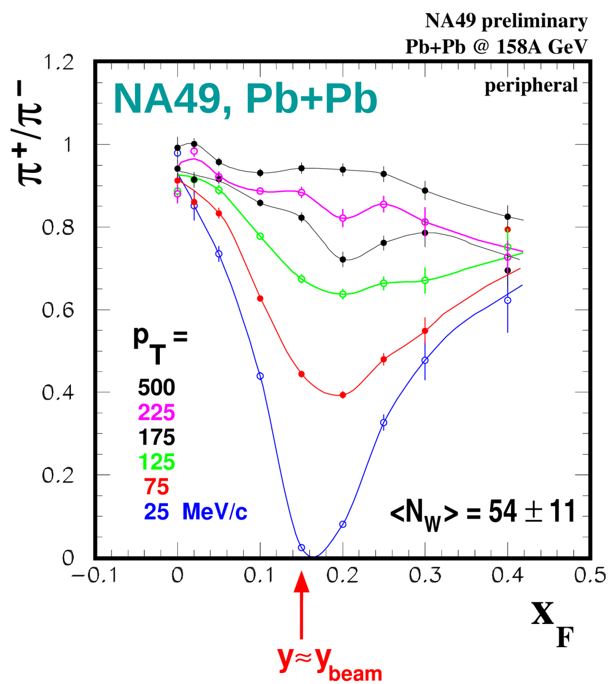
π^+/π^- ratio in centrality selected Ar+Sc at 150*A* GeV/*c*





See talk by N. Davis (Friday) for comparison with models

$x_F = p_L/p_L^{beam}$ (in c.m.s.)

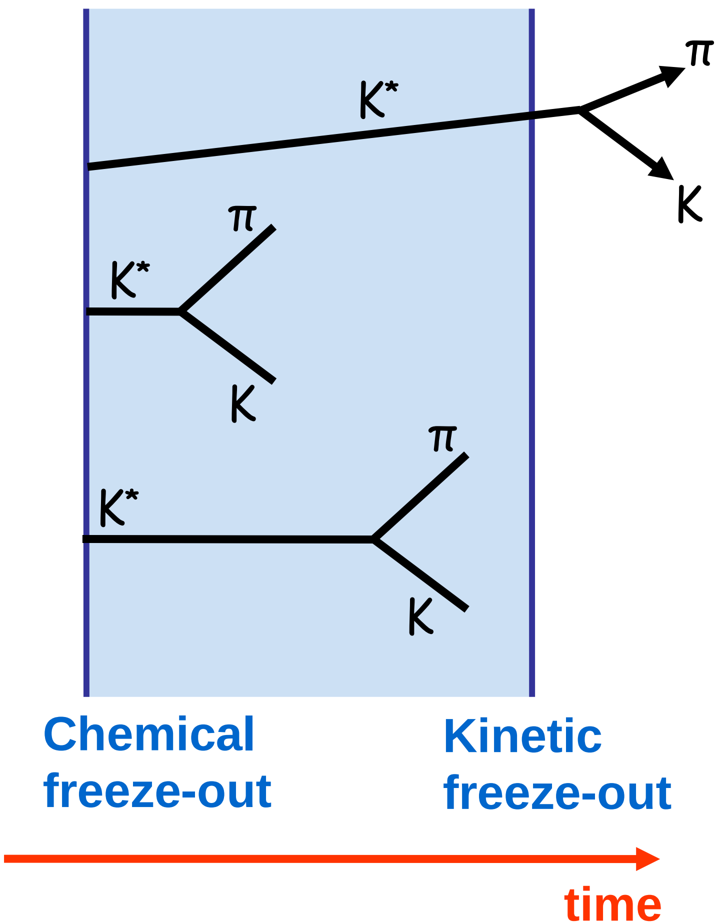


Rybicki (for NA49), PoS EPS-HEP 2009, 031, 2009

- **Repulsion of π^+** is the **strongest for pions** with rapidities **close to beam rapidity (spectators)** and with low p_T
- First observation of spectator-induced EM effects in small systems at SPS
- Similar **effect seen in intermediate centrality Ar+Sc** and (NA49) **peripheral Pb+Pb**

Can we contribute to understanding of the time evolution of the fireball?

Motivation of K^* measurement



- K^* lifetime (≈ 4 fm/*c*) comparable with time between freeze-outs →
- Some **resonances may decay inside fireball**; momenta of their decay products can be modified due to elastic scatterings → problems with experimental reconstruction of resonance via invariant mass →
- **Suppression of K^* production**
- Assuming no regeneration processes (Fig.) time between freeze-outs can be determined from (STAR, PR C71, 064902, 2005):

$$\frac{K^*}{K}(\text{kinetic}) = \frac{K^*}{K}(\text{chemical}) \cdot e^{\frac{-\Delta t}{\tau}}$$

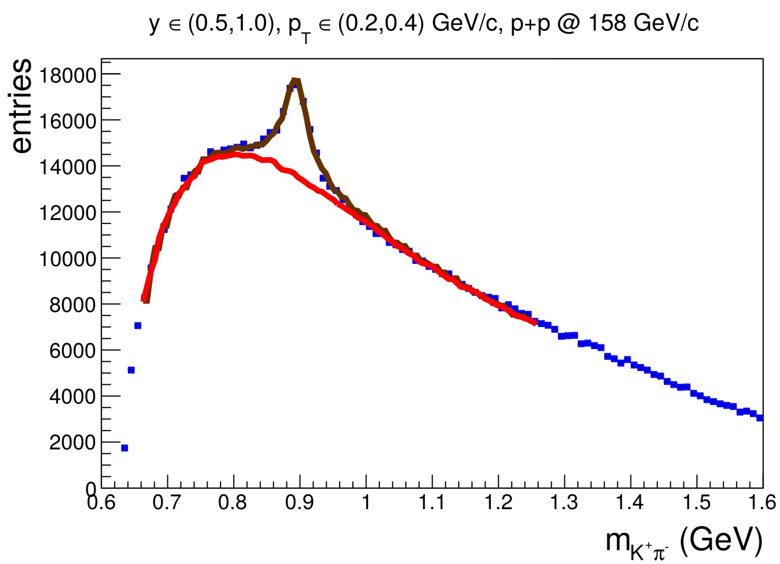
use Pb+Pb or Au+Au ratio — use p+p ratio

Δt – time between kinetic and chemical freeze-outs

τ – $K^*(892)^0$ lifetime = 4.17 fm/*c*; PDG, PR D98, 030001, 2018

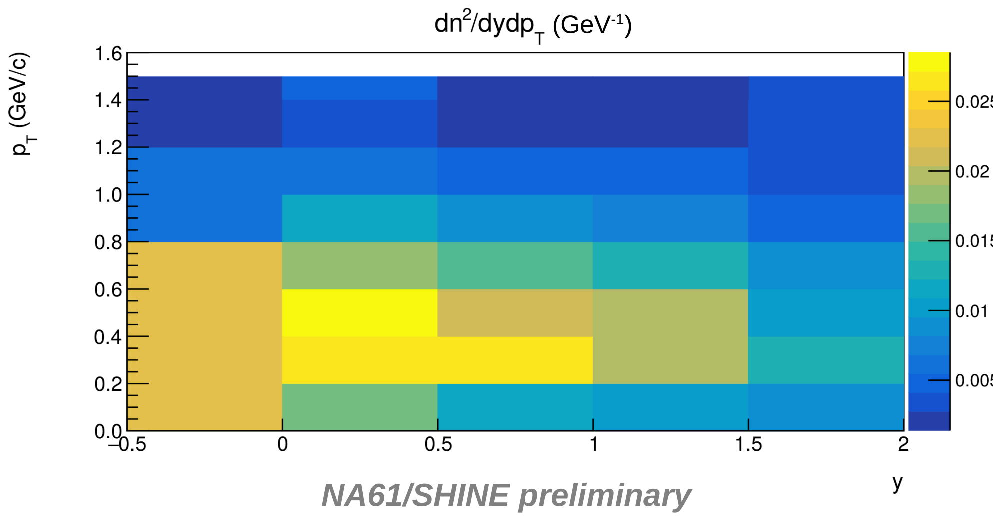
The picture assumes that conditions at chemical freeze-out of p+p and Pb+Pb are the same

$K^*(892)^0$ production in inelastic p+p collisions at 158 GeV/*c*

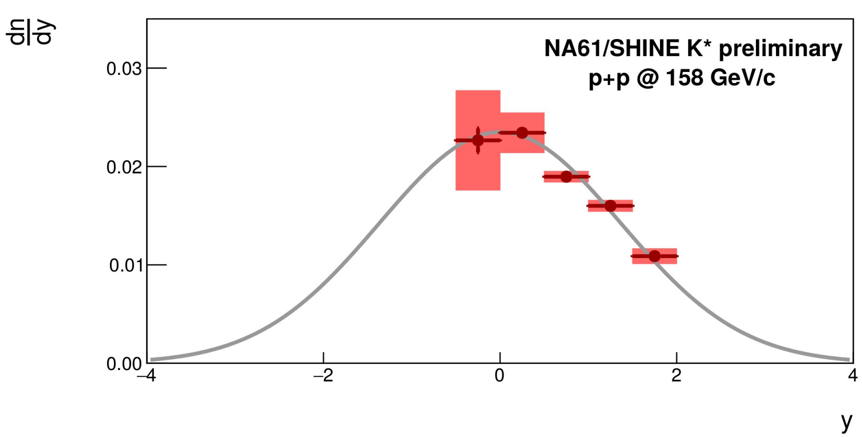


Background: template of $K^+\pi^-$ pairs from mixed events and from Monte Carlo

See talk by
A. Tefelska
for more results



p_T - extrapolated and integrated rapidity distribution

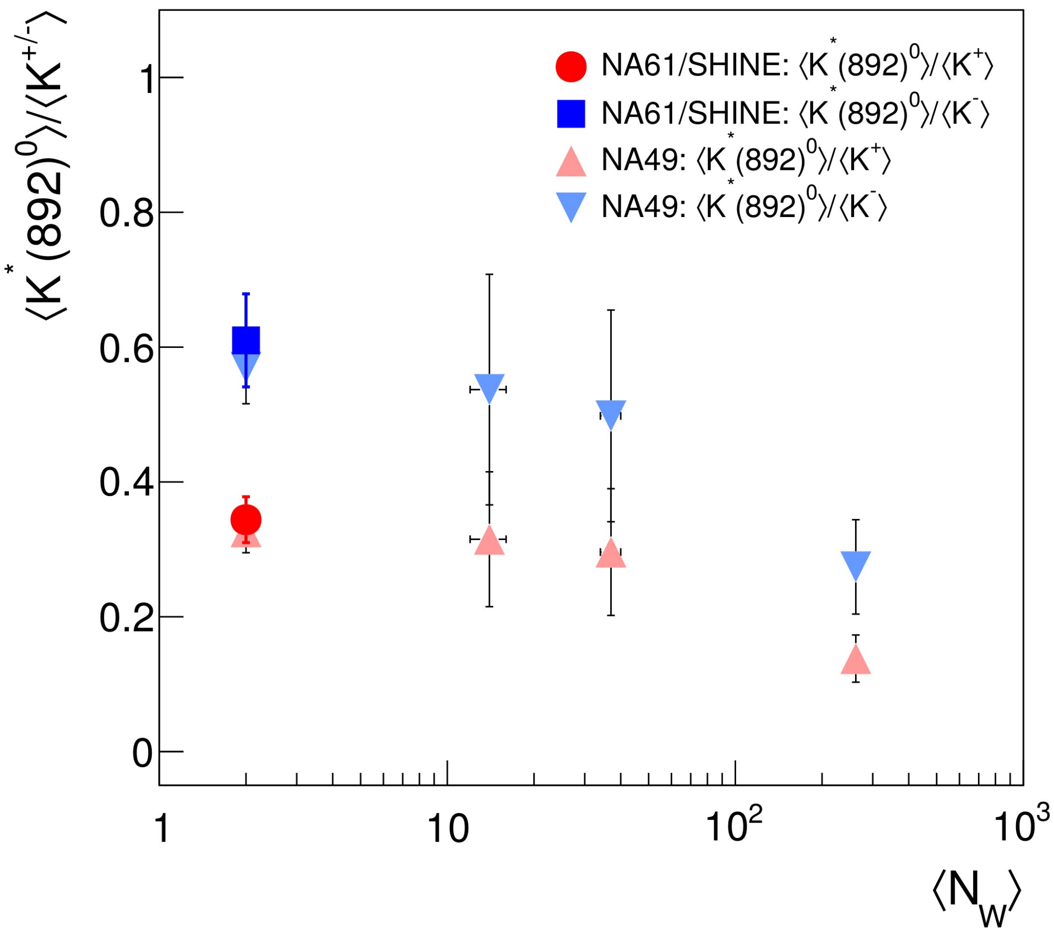


4π multiplicity:

$\langle K^*(892)^0 \rangle = 0.08058 \pm 0.00059 \pm 0.0026$

NA49 (in $0 < p_T < 1.5$ GeV/*c*):
$\langle K^*(892)^0 \rangle = 0.0741 \pm 0.0015 \pm 0.0067$
PR C84, 064909, 2011

System size dependence of $K^*(892)^0$ to charged kaon ratio at 158*A* GeV/*c*



NA61/SHINE $K^{+/-}$ (p+p): EPJC 77, 671, 2017
NA49 K^*: PR C84, 064909, 2011
NA49 $K^{+/-}$ (p+p): EPJC 68, 1, 2010
NA49 $K^{+/-}$ (C+C, Si+Si): PRL 94, 052301, 2005
NA49 $K^{+/-}$ (Pb+Pb): PR C66, 054902, 2002 →
rescaled from 5% to 23.5% most central

Assuming:

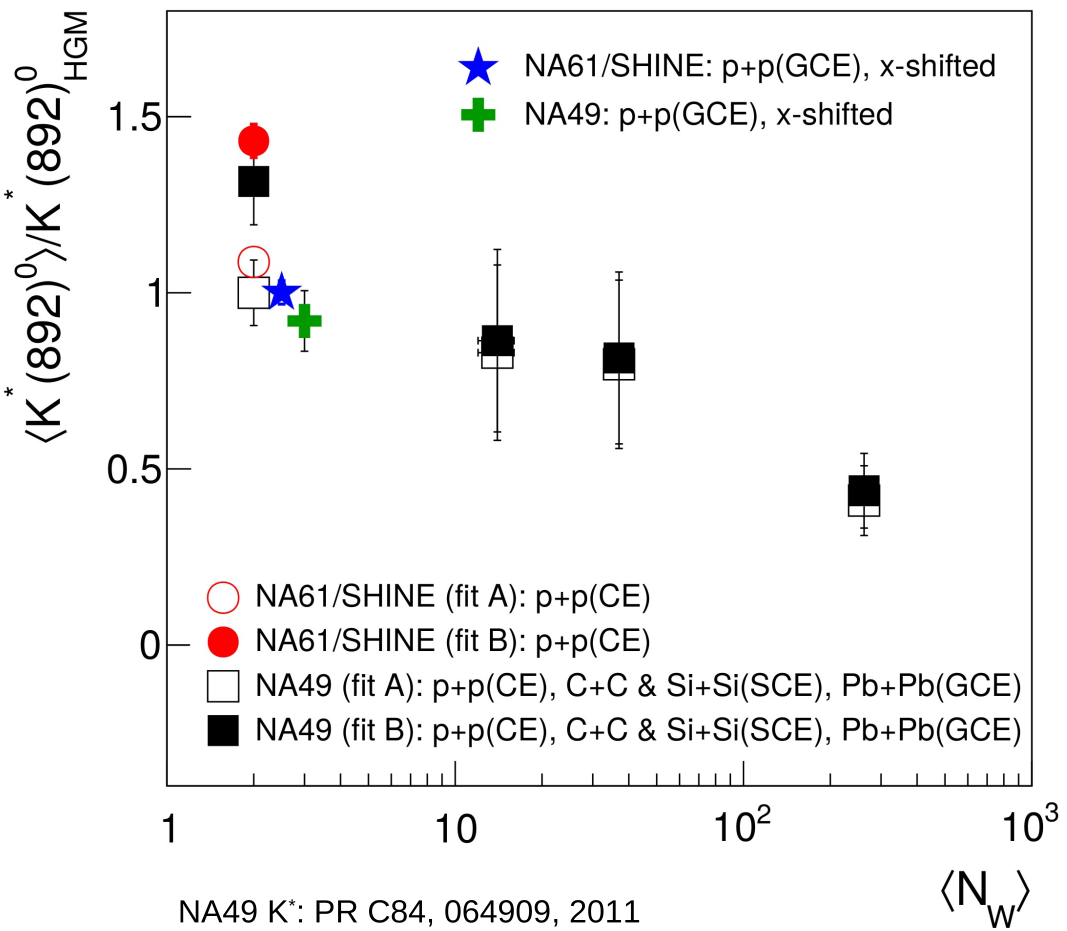
- losses of $K^*(892)^0$ before kinetic freeze-out are due to rescattering effects
- no regeneration processes

time between chemical and kinetic freeze-outs (Δt):

- 3.8 ± 1.1 fm/*c* for $K^*(892)^0/K^+$
- 3.3 ± 1.2 fm/*c* for $K^*(892)^0/K^-$

- **Δt at SPS > Δt at RHIC** (2 ± 1 fm/*c*, STAR, PR C71, 064902, 2005) suggesting that regeneration effects may start to play significant role for higher energies
- Regeneration may happen also at SPS → obtained **Δt is the lower limit of time between freeze-outs**

Comparison of $K^*(892)^0$ production with Hadron Resonance Gas Models



NA49 K^*: PR C84, 064909, 2011

- HRG by F. Becattini et al.
  PR C73, 044905, 2006
  - p+p: CE
  - C+C and Si+Si: SCE (exact strangeness conservation, GC treatment of Q and B)
  - Pb+Pb: GCE
  - Fit B: uses "standard" γ_S; for p+p Ξ and Ω baryons excluded from fit
  - Fit A: γ_S replaced by $\langle s\bar{s}\rangle$; for p+p ϕ meson excluded from fit
  - Pb+Pb HGM (5%) yields rescaled to be compared with NA49 23.5% central events
- HRG by V. Begun et al. arXiv:1805.01901
  - p+p: GCE with ϕ meson included

- Deviation from HGM model increases with increasing system size
- For larger systems (C+C ↑) no significant difference between fit A and fit B
- Small **p+p collision can be described by GCE**
- **p+p data can be described by CE only** for fit A (**ϕ meson excluded** from fit)

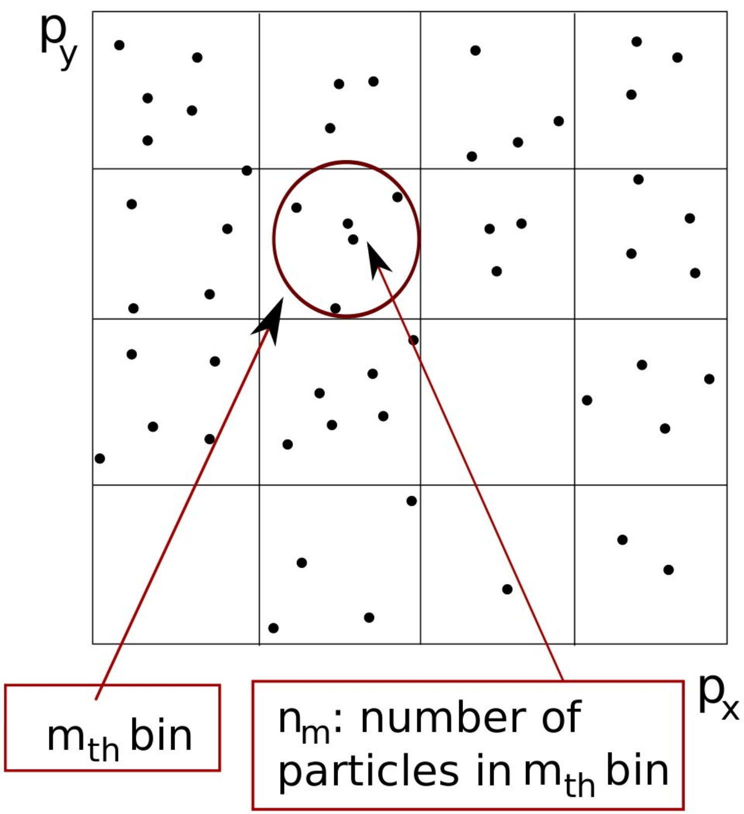
Can we see critical point from proton density fluctuations?

Intermittency signal in protons predicted to be increased close to CP

Analysis of **local power-law fluctuations of baryon density** by calculating the scaling of 2nd factorial moments $F_2(M)$ with cell size ↔ number of cells in (p_x, p_y) space (intermittency)

Białas, Peschanski, NP B273, 703, 1986;
Turko, PL B227, 149, 1989;
Diakonos et al., PoS, CPOD2006, 010, 2010

protons at mid-rapidity



Second order factorial moment in transverse momentum space:

$$F_2(M)=\frac{\left\langle \frac{1}{M^2}\sum_{m=1}^{M^2} n_m(n_m-1)\right\rangle}{\left\langle \frac{1}{M^2}\sum_{m=1}^{M^2} n_m\right\rangle^2}$$

M^2 – number of bins
(M bins in p_x and M bins in p_y)

Combinatorial background subtracted (by mixed events) 2nd factorial moment should scale according to power-law for M ≫ 1

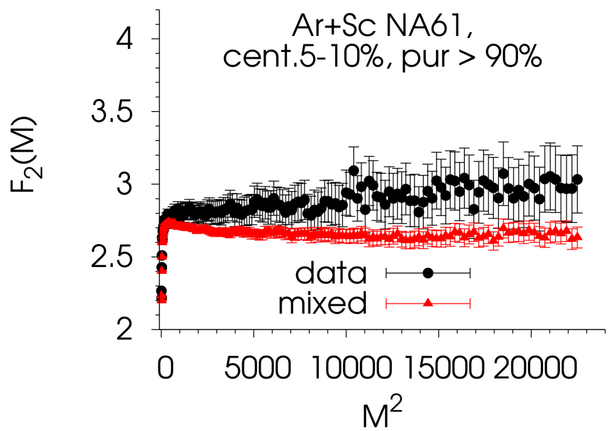
$$\Delta F_2(M) \sim (M^2)^{\phi_2}$$

$$\phi_2 = 5/6 \quad \text{for CP}$$

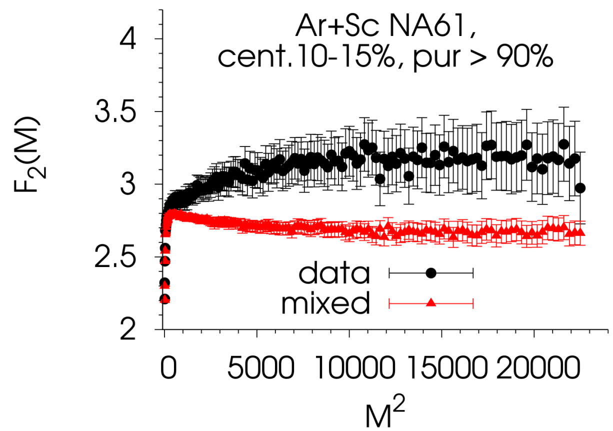
Antoniou et al., PRL 97, 032002, 2006

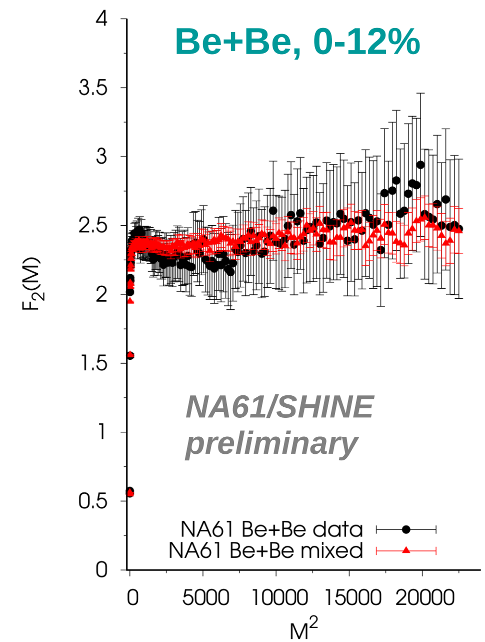
Proton intermittency in NA61 Ar+Sc and Be+Be at 150*A* GeV/*c*

Ar+Sc, 5-10%

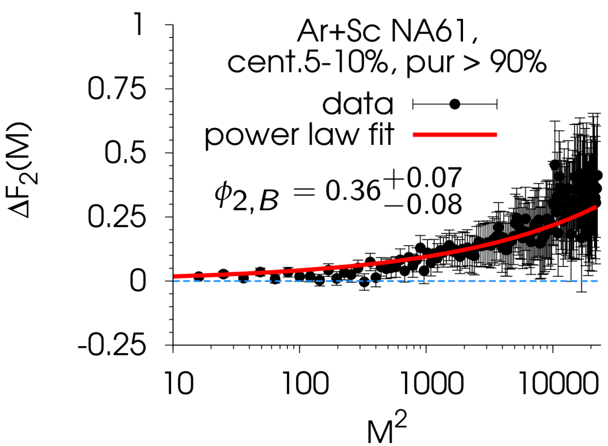


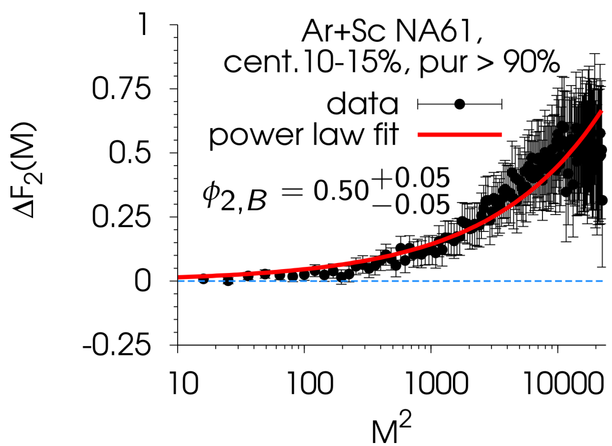
Ar+Sc, 10-15%





NA61/SHINE preliminary



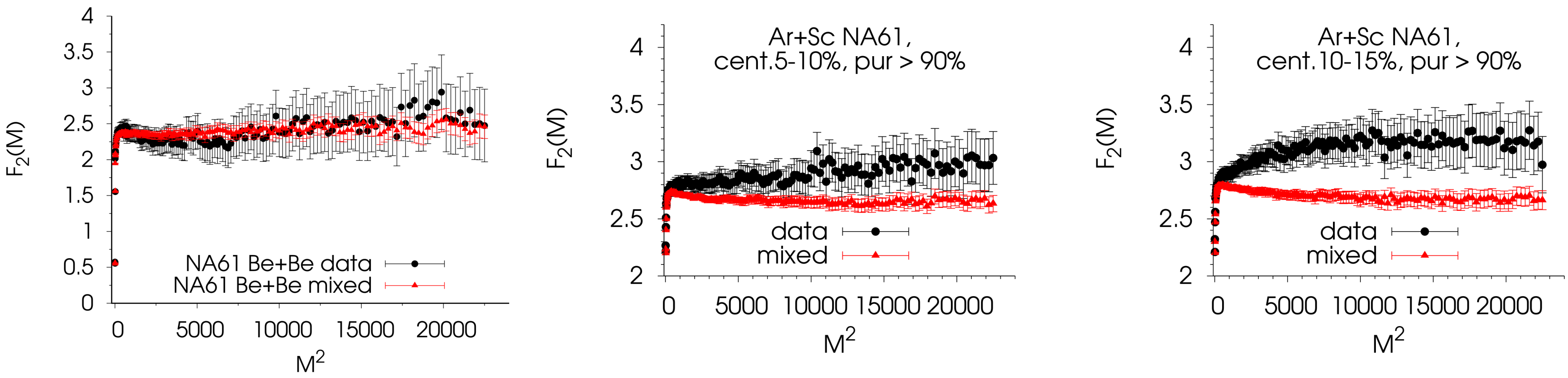


- **Indication of intermittency effect in** mid-central **Ar+Sc** → first possible evidence of CP signal in NA61/SHINE
- No intermittency signal in Be+Be

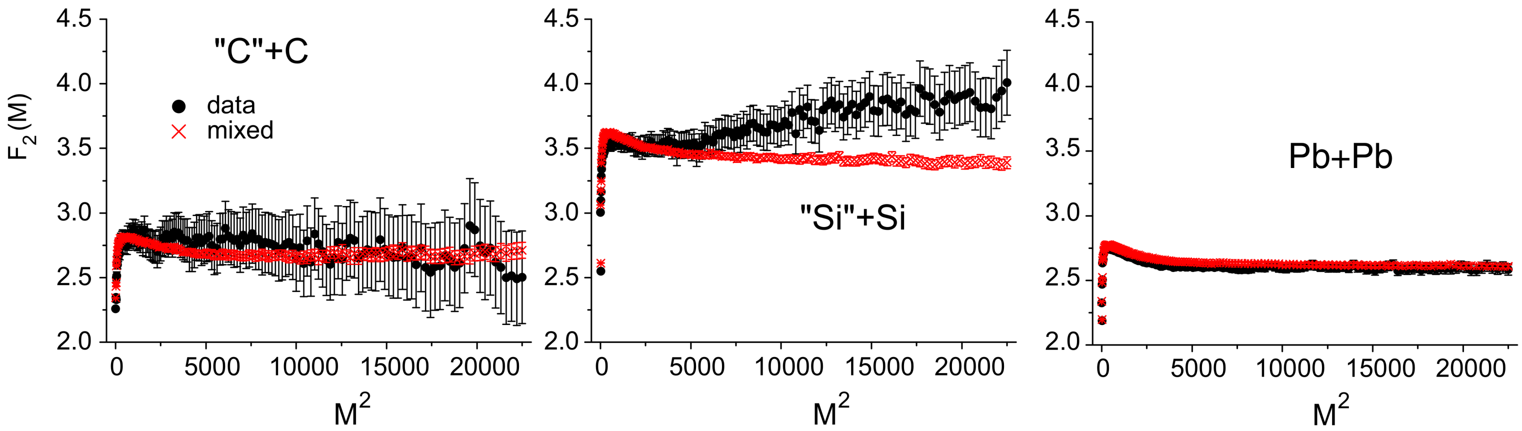
See talk by
N. Davis (Monday)
for more results

Proton intermittency – comparison of NA61 and NA49 at 150(8)*A* GeV/*c*

NA61, Be+Be, 0-12% **NA61, Ar+Sc, 5-10%** **NA61, Ar+Sc, 10-15%**



“C”+C, 0-12% **“Si”+Si, 0-12%** **Pb+Pb, 0-10%**



NA49

EPJC 75, 587, 2015

Fragmentation “C” beam: mixture of ions with Z=6 and 7; “Si” beam: mixture of ions with Z=13, 14, 15

Older intriguing results for intermediate mass systems **at 150(8)*A* GeV/*c***

- Intermittency signal of di-pions in Si+Si → NA49, PR C81, 064907, 2010
- Increased transverse momentum and multiplicity fluctuations in Si+Si and C+C → Grebieszkow (for NA49), NP A830, 547C, 2009; NA49, PR C92, 044905, 2015

Can we extend critical point search by looking at $\Delta\eta$ dependence of fluctuations?

Strongly intensive measures Δ and Σ (here applied to P_T and N fluctuations) → PR C88, 024907, 2013

$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right] \qquad P_T = \sum_{i=1}^{N} p_{T\,i}$$

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

Δ = Σ = 0 for no fluctuations

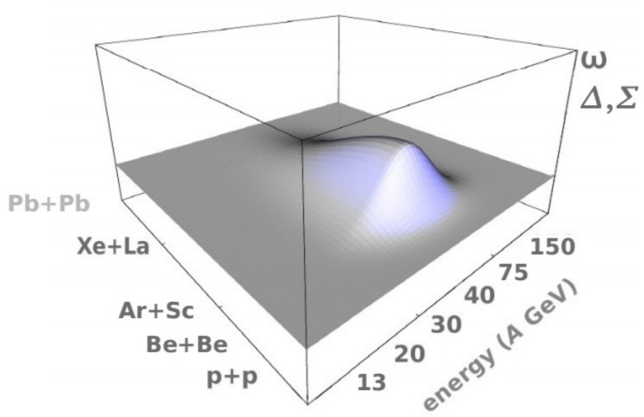
Δ = Σ = 1 for Independent Particle Model

$$\omega[P_T] = \frac{\langle P_T^2\rangle - \langle P_T\rangle^2}{\langle P_T\rangle} \qquad \omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}} \qquad \omega[N] = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}$$

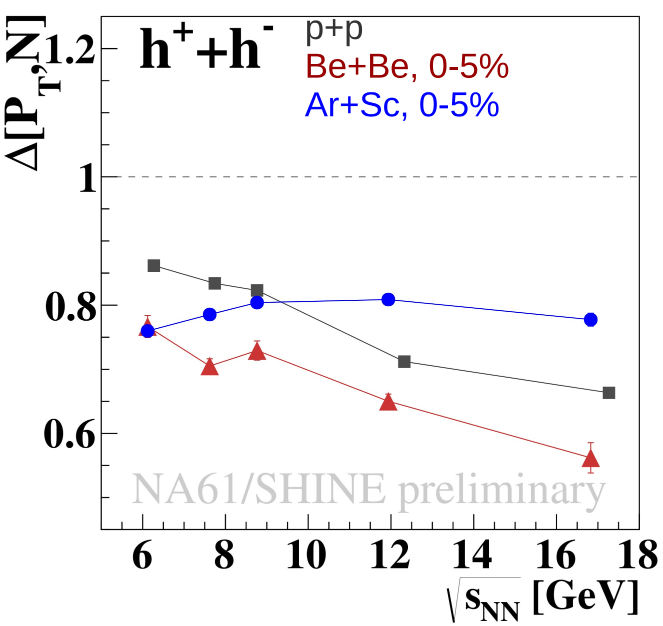
- $\Delta[P_T, N]$ uses only first two moments: $\langle N\rangle$, $\langle P_T\rangle$, $\langle P_T^2\rangle$, $\langle N^2\rangle$
- $\Sigma[P_T, N]$ uses also correlation term: $\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle$

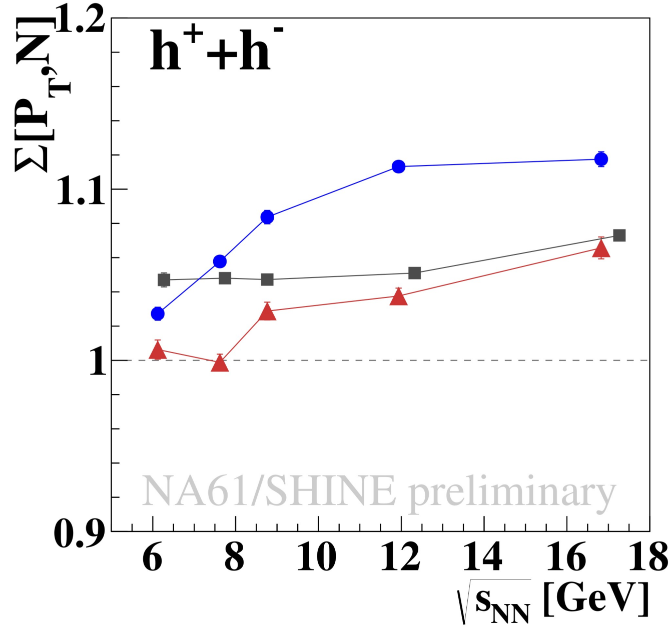
thus Δ and Σ can be sensitive to several physics effects in different ways

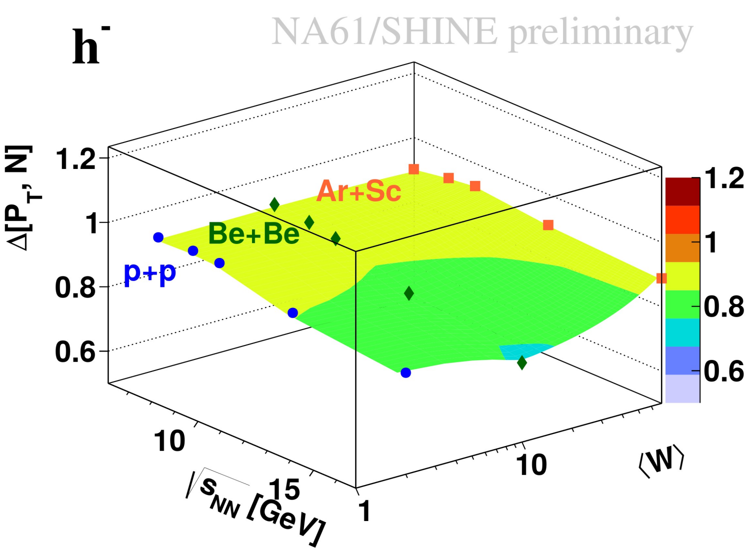
Expected: non-monotonic behavior of CP signatures

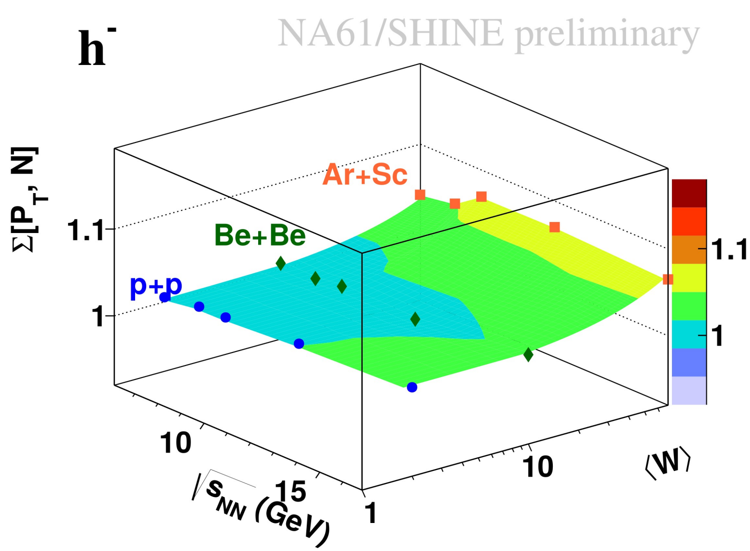


2016: fluctuations in Ar+Sc, Be+Be and p+p within the same acceptance $0 < y_{\pi} < y_{beam}$







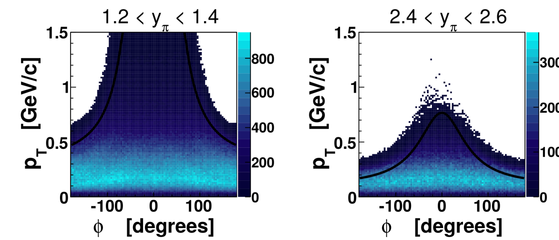


- $\Delta[P_T, N] < 1$ and $\Sigma[P_T, N] \geq 1$ for all systems; may be due to BE stat. (PL B730, 70, 2014; PR C88, 024907, 2013; PL B439, 6, 1998; PL B465, 8, 1999) and/or P_T/N vs N anti-correlation (PR C89, 034903, 2014)
- Increase of Δ and Σ deviation from 1 with energy may be due to increasing azimuthal acceptance
- So far there are **no prominent structures which could be related to critical point**

Comparison to NA49 *A+A* at 158*A* GeV/*c*

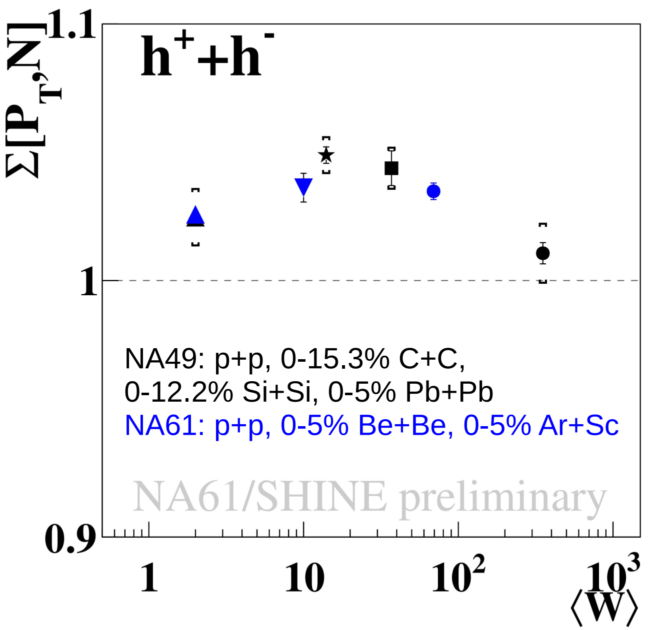
within NA49 two different acceptances

System size scan – wide azimuthal acc.
(the same for all systems)



NA49: PR C92, 044905, 2015

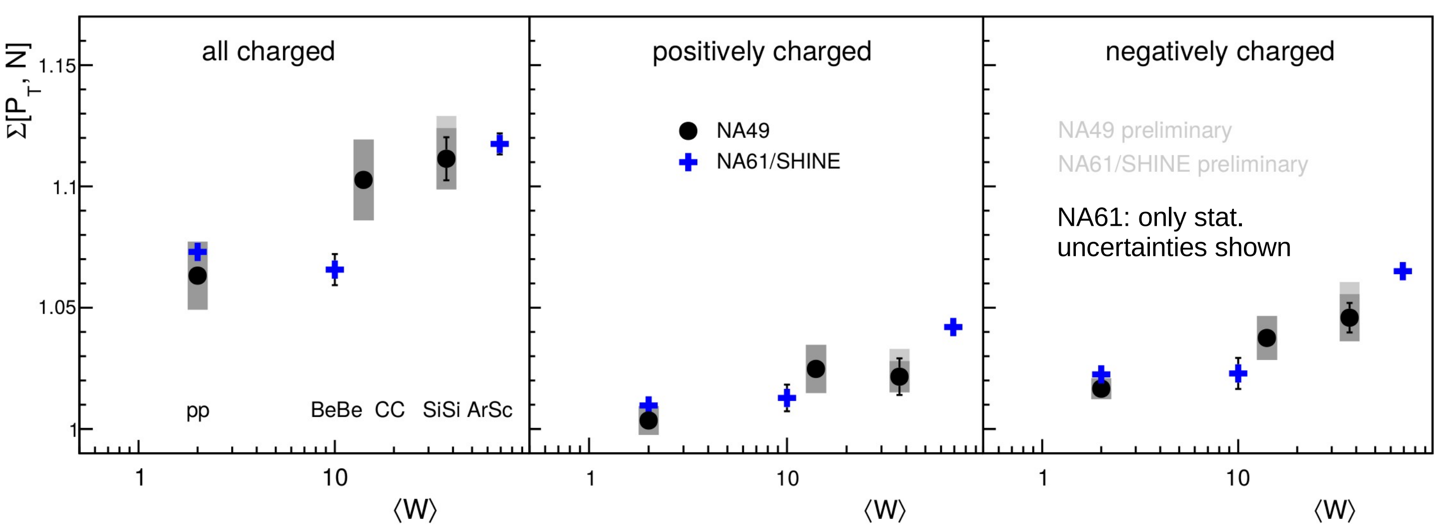
1.1 < y_π < 2.6



System size dependence of $\Sigma[P_T, N]$ at 150/158*A* GeV/*c*: **NA49 and NA61 points show consistent trends**. $\Delta[P_T, N]$ (not shown here) is more centrality width sensitive (points are scattered)

NA49: preliminary (PoS EPS-HEP2017, 167, 2017)

0 < y_π < y_{beam}



- Fluctuations are larger for larger rapidity interval
- **Increase of Σ from p+p to Ar+Sc / Si+Si**. We are waiting for Xe+La and Pb+Pb results from NA61

Δη dependence of fluctuations

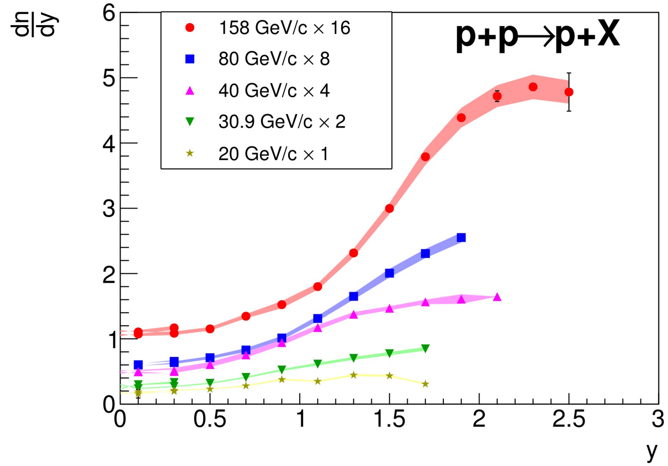
Rapidity width dependence analysis allows to study fluctuations at different baryochemical potentials

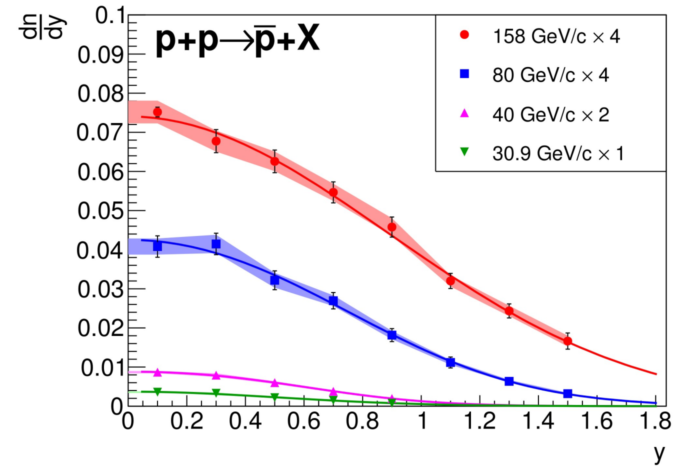
$$\frac{\bar{p}}{p} = e^{-(2\mu_B)/T}$$

Extension of the phase diagram scan!

NA61, EPJC 77, 671, 2017

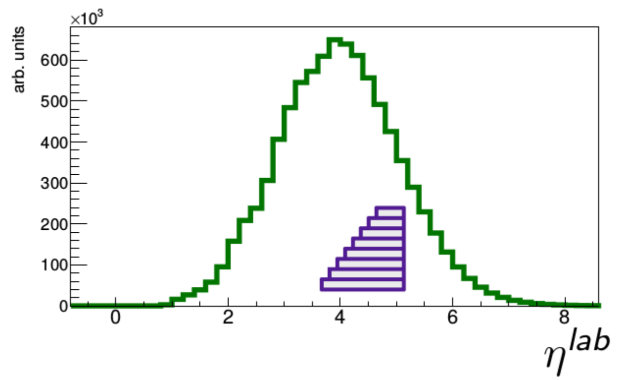
Rapidity spectra of protons and anti-protons in inelastic p+p collisions at SPS energies show that anti-proton to proton ratio significantly changes with rapidity



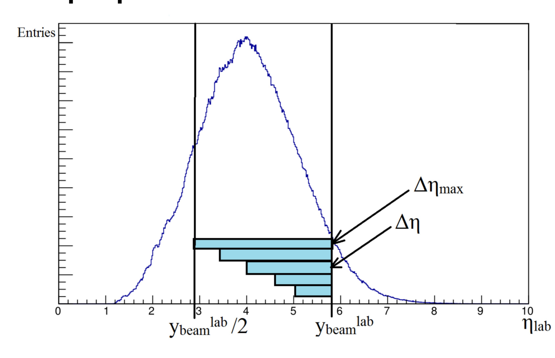


Sketch of psedorapidity (lab) uncorrected spectrum of charged hadrons with proposed analysis windows

Be+Be at 150*A* GeV/*c*

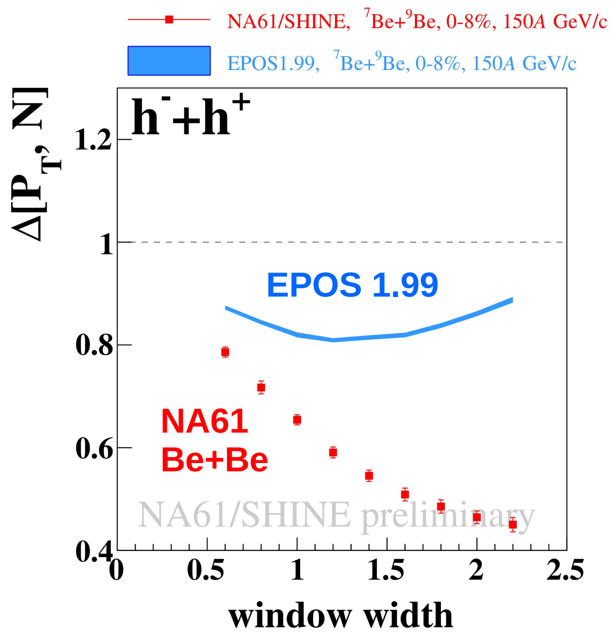


p+p at 158 GeV/*c*

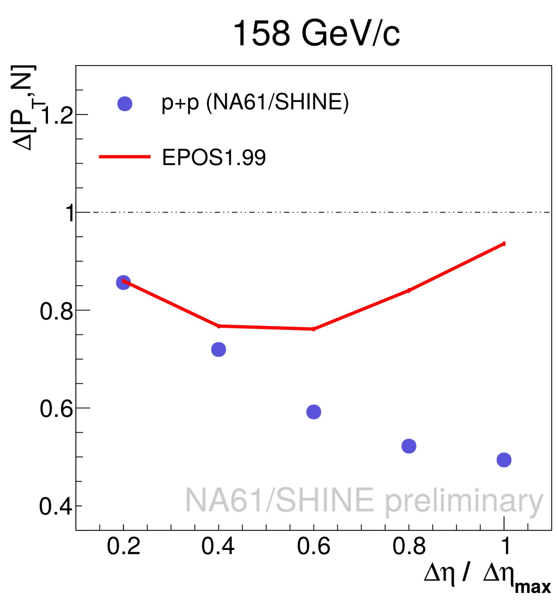


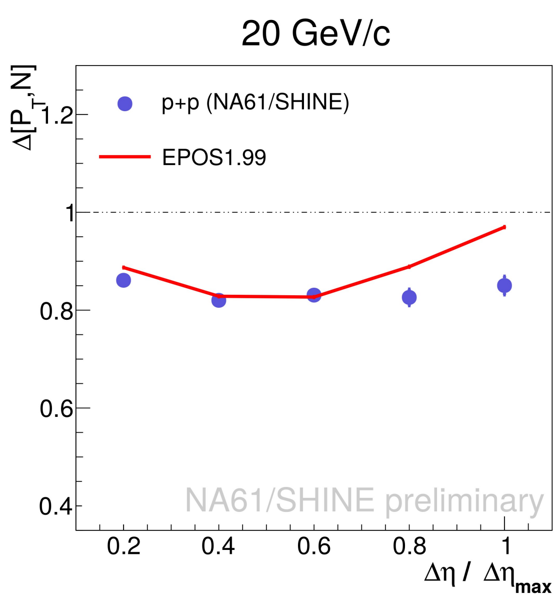
$\Delta\eta$ dependence of P_T and N fluctuations in Be+Be and p+p

Be+Be at 150*A* GeV/*c*



p+p at 158 GeV/*c* and 20 GeV/*c*



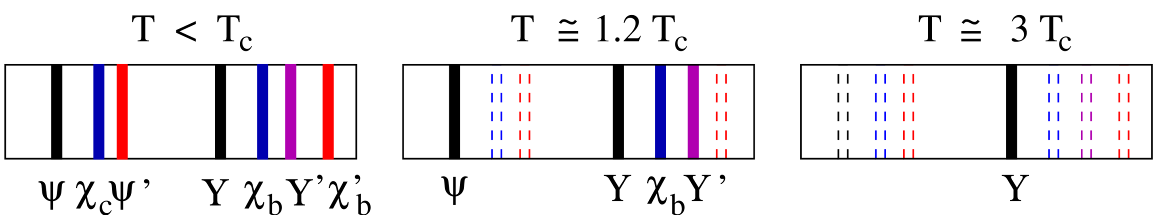


Note: slightly different $\Delta\eta$ range in Be+Be and p+p

- **Non-trivial $\Delta[P_T, N]$ dependence on $\Delta\eta$ window** seen **for p+p and Be+Be at 150/158*A* GeV/*c***; not reproduced by EPOS
- Disagreement of data to model not present in p+p at 20 GeV/*c* (Be+Be lower energies to be analyzed)
- $\Sigma[P_T, N]$ agrees with EPOS (not shown; studied for Be+Be at 150*A* GeV/*c* and p+p at 20-158 GeV/*c*)

Future: Can we help to calibrate QGP thermometer?

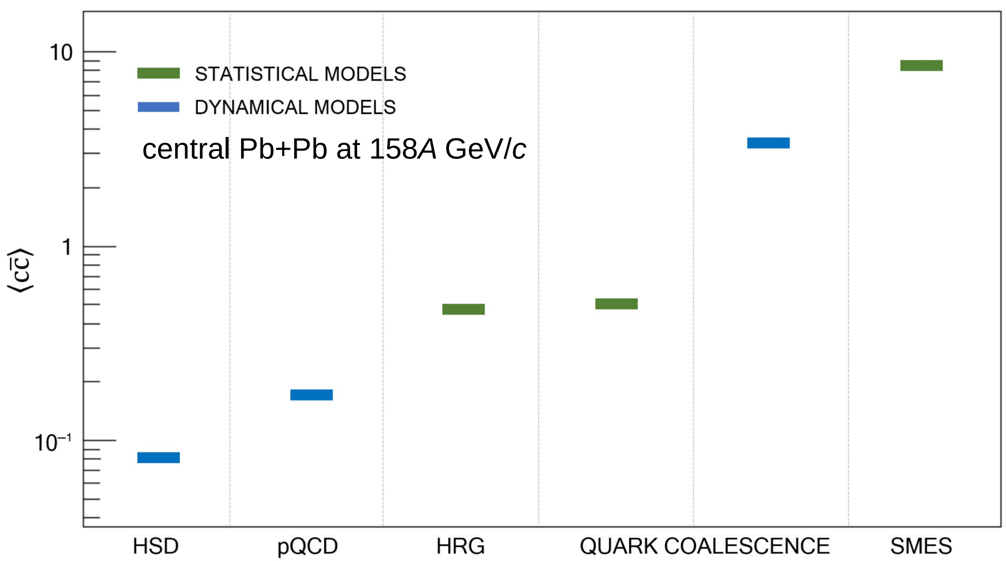
Quarkonium states as thermometer (list of melt states depends on temperature)



Satz, NP A783, 249, 2007

Mechanisms of charm production – validating models

- Models (implementing sequential melting + regeneration effects + initial state effects + …) try to describe charmonium states; cross-section for charm quarks production is an important parameter, but:
- **Predictions of different models differ** by two orders of magnitude!



HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17, 1367, 2008; Song, private communication

pQCD
Gavai, et al., IJMP A10, 2999, 1995
Braun-Munzinger, Stachel, PL B490, 196, 2000

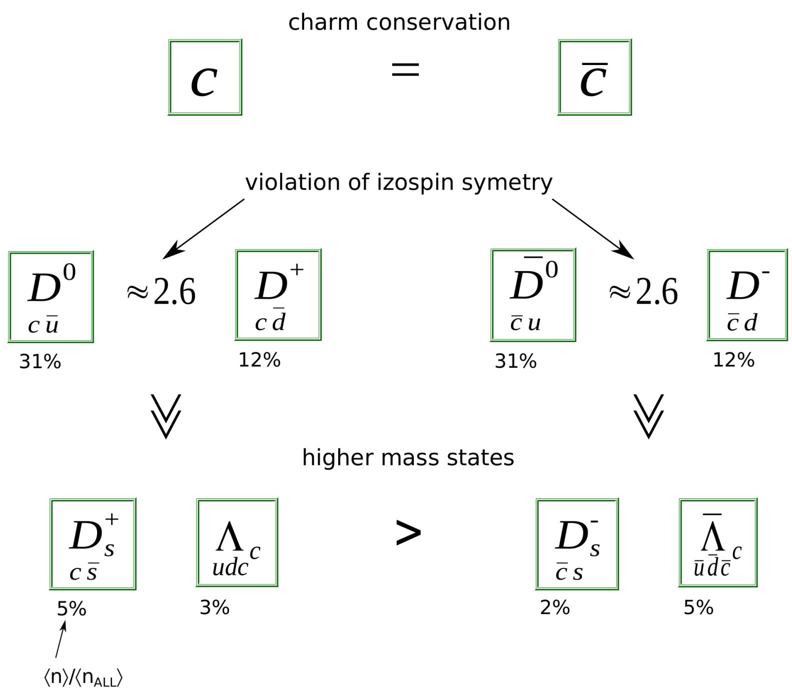
Quark Coalesc. Dyn.
Levai et al. JP G27, 703, 2001

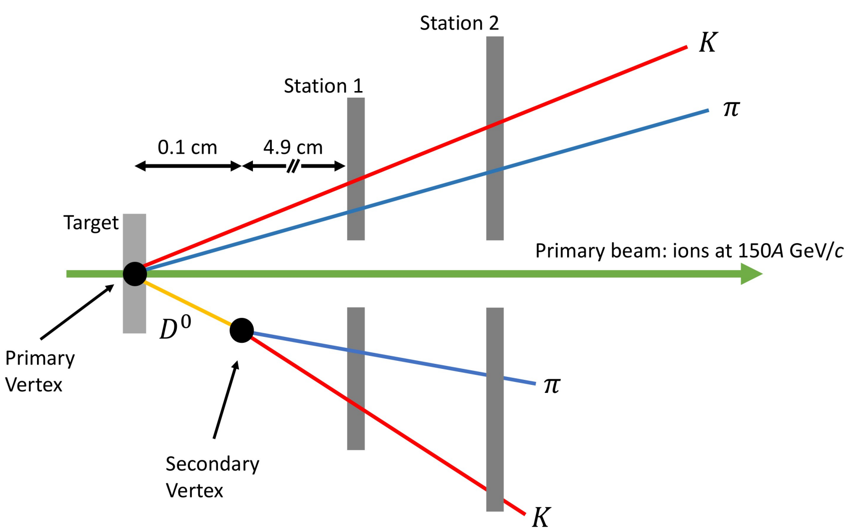
HRG; Quark Coalesc. Stat.
Kostyuk et al. PL B531, 195, 2002

SMES
Gazdzicki, Gorenstein, APP B30, 2705, 1999

We can measure $\langle c\bar{c}\rangle$ produced in full phase space in NA61/SHINE

0-20% Pb+Pb at 150*A* GeV/*c*





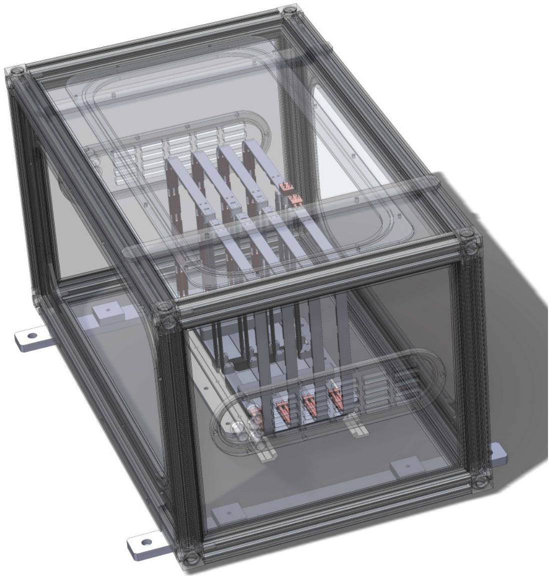
Hadrons containing charm considered for measurements in NA61/SHINE

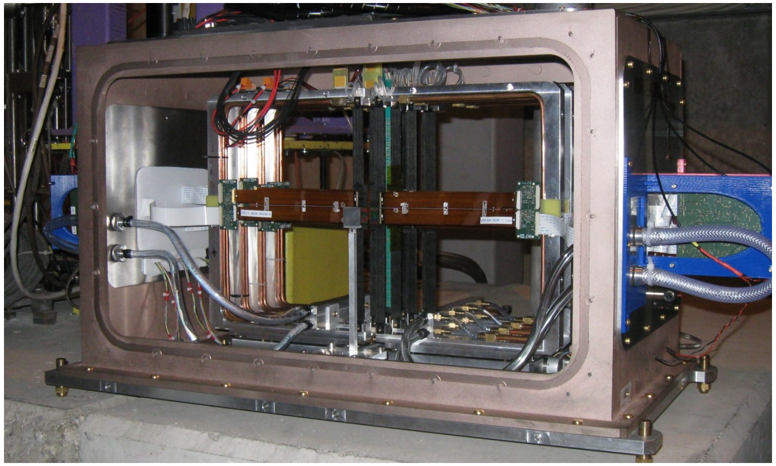
Hadron	Decay channel	$c\bar{\tau}$ [μm]	BR
D^0	$\pi^+ + K^-$	123	3.89%
D^+	$\pi^+ + \pi^+ + K^-$	312	9.22%
D_S^+	$\pi^+ + K^- + K^+$	150	5.50%
Λ_c	$p + \pi^+ + K^-$	60	5.00%

Measuring D^0, anti-D^0, D^+, D^- is likely sufficient for good $\langle c\bar{c}\rangle$ estimate

- Daughters of D^0 recognized as pair forming secondary vertex displaced from primary vertex
- $c\tau(D^0) \approx 122$ μm but due to Lorentz boost ($\beta\gamma \approx 10$) displacement is on the level of 1 mm
- Lorentz Boost makes measurements significantly easier than in case of collider experiments

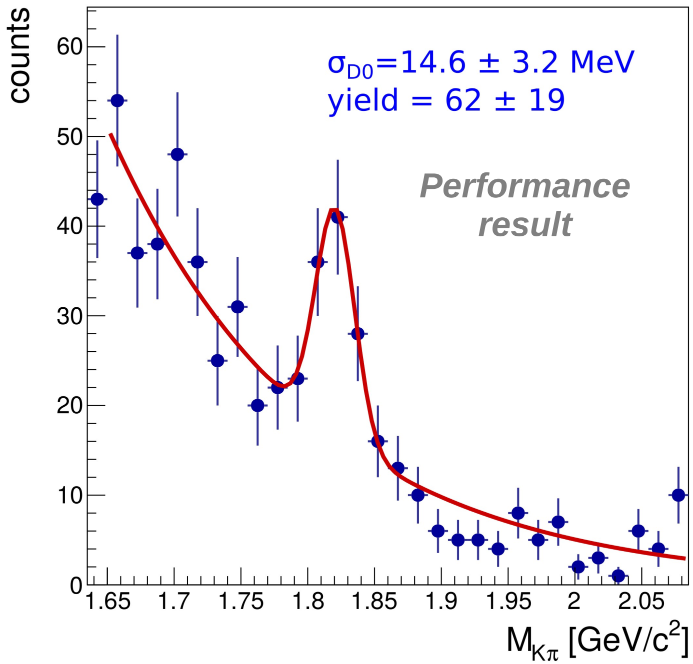
Small Acceptance Vertex Detector and performance D^0 signal





- 16 MIMOSA-26 sensors located on two horizontally movable arms
- Target holder integrated with SAVD base plate

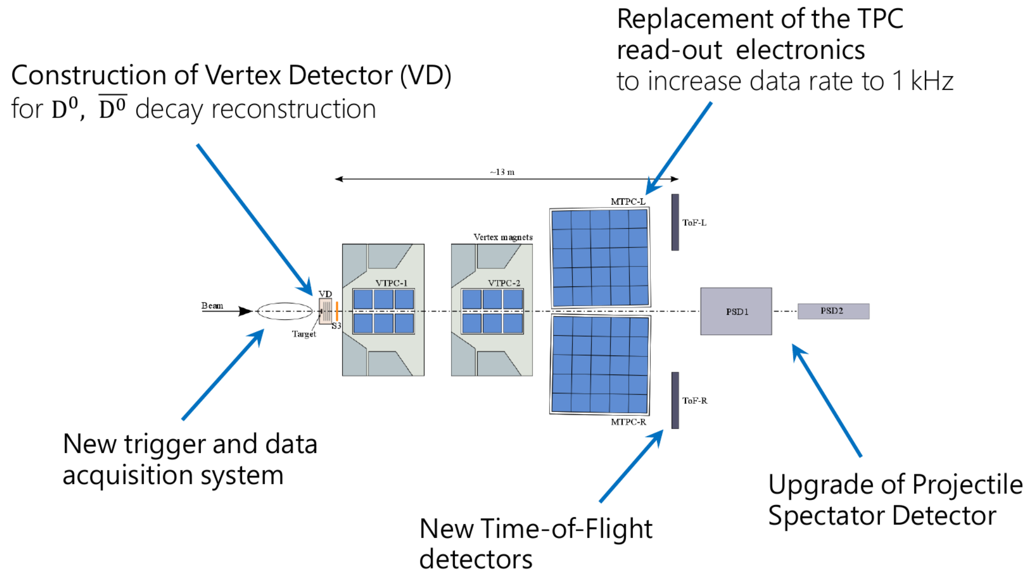
Small Acceptance Vertex Detector (SAVD) was commissioned in 2015. Pilot Pb+Pb at 150*A* GeV/*c* data was recorded in 2016. Vertex fit resolution on the level of 50 μm

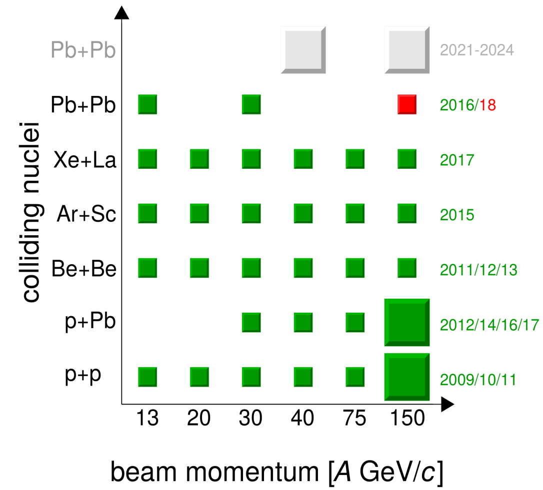


Search for D^0 signal

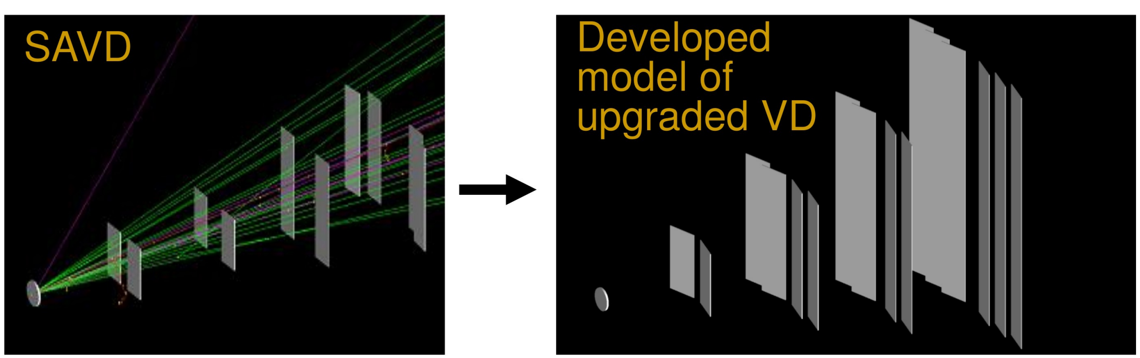
- TPC and SAVD track matching (interpolation)
- Applied cuts include longitudinal distance of pair vertex to primary vertex
- PID of V^0 products not used yet (should reduce background by factor of 5)

Detector upgrade foreseen during long shutdown (2019-2020)
→ motivated mainly by charm production requirements





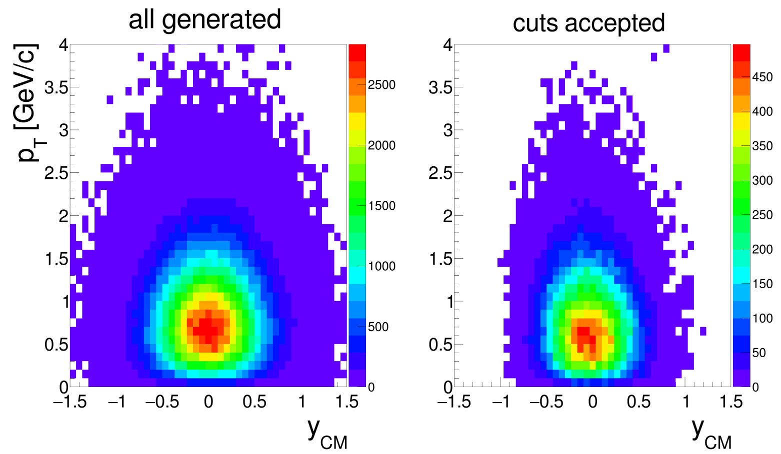
New Vertex Detector will allow for precise measurements of charm hadron production in 2021-2024



Upgraded VD will be based on the same layout and mechanical support as SAVD, but:

- MIMOSA-26 sensors will be replaced by ALPIDE developed for ALICE-ITS
- 16 (SAVD) → 46 (VD) sensors
- 32 cm^2 (SAVD) → 180 cm^2 (VD) active surface → larger acceptance for each station
- 115.2 μs (SAVD)→ 10 μs (VD) time resolution

Detection efficiency and expected accuracy for open charm in NA61

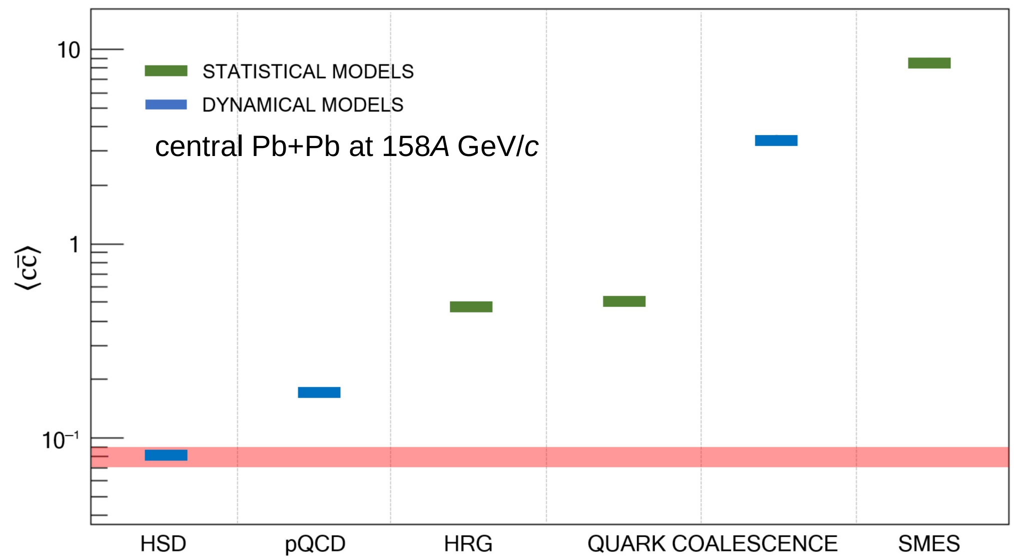


Vertex Detector:
D^0 and anti-D^0 detection efficiency (including geometrical acceptance and analysis quality cuts) will be about **13% in $D^0 \rightarrow \pi^+ K^-$** channel (**3 times better than for SAVD**) and about 9% in $D^+ \rightarrow \pi^+ \pi^+ K^-$ channel

MC: D^0 + anti-D^0 mesons produced in (500M) Pb+Pb collisions at 150*A* GeV/*c* and reconstructed by VD

Width of red band, at location assuming HSD predictions, shows foreseen accuracy of NA61/SHINE 2020+ result

See talk by A. Merzlaya for more details

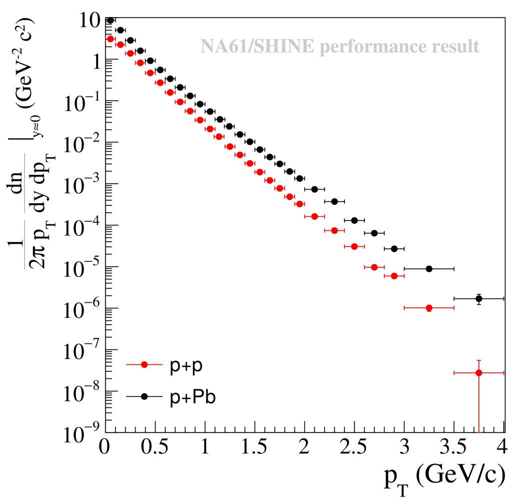


Can we measure high p_T particles and multi-strange hadrons in NA61?

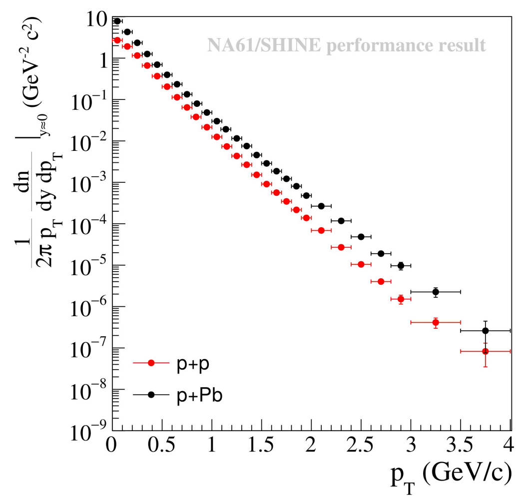
Measurement of high p_T particles in NA61

- In NA49 p_T spectra of identified hadrons were measured: up to 4 GeV/*c* in Pb+Pb and up to 2 GeV/*c* in p+p and p+Pb (due to limited statistics)
- Goal of NA61/SHINE: extend measurements for p+p and p+Pb and determine R_{AA}, R_{pA}

Particles with positive charge



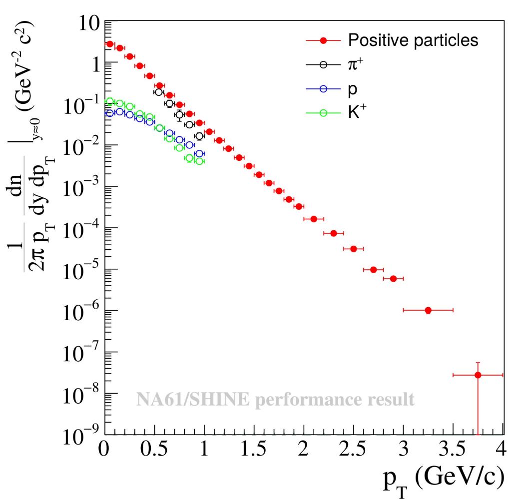
Particles with negative charge



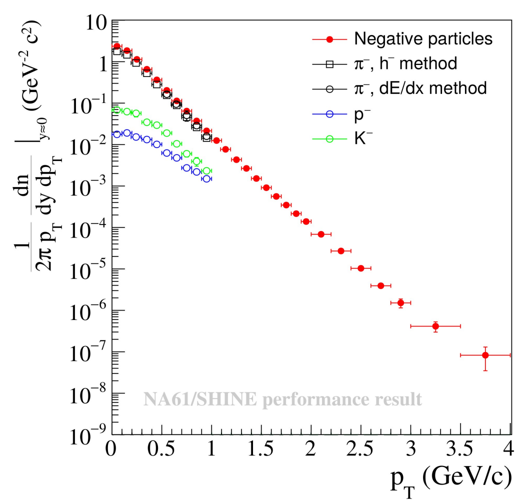
Performance results: **mid-rapidity** spectra of **negatively and positively charged particles** in **p+p and p+Pb at 158 GeV/*c***; identified particles coming soon

p+p and p+Pb at 158 GeV/*c*

Particles with positive charge

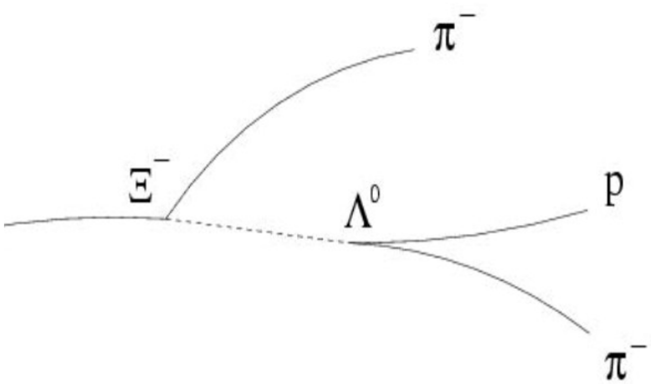


Particles with negative charge

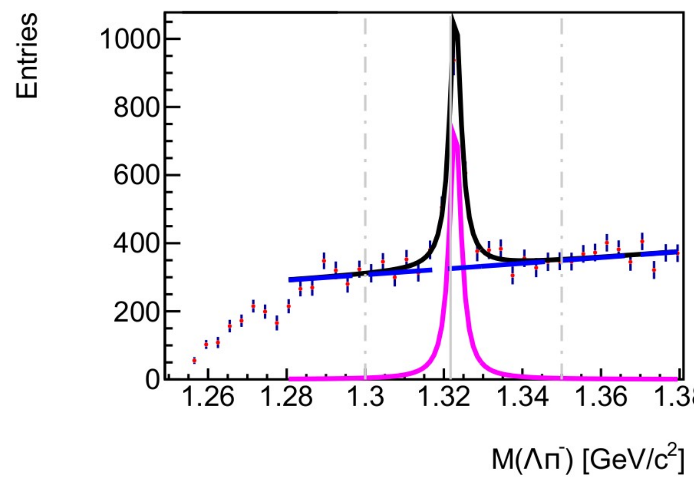


p+p at 158 GeV/*c* – comparison with existing NA61 results for identified particles (EPJC 77, 671, 2017)

Ξ^- spectra in p+p collisions at 158 GeV/*c*

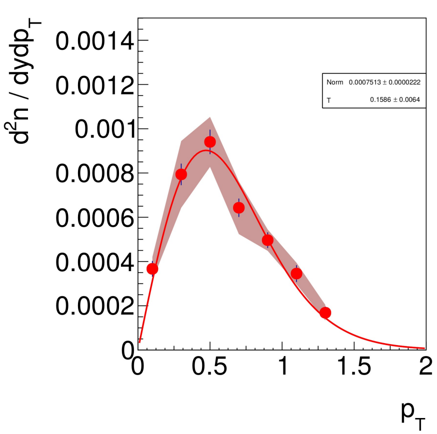


Xi y ∈[-0.25,0.25), p_T ∈[0.40,0.60)

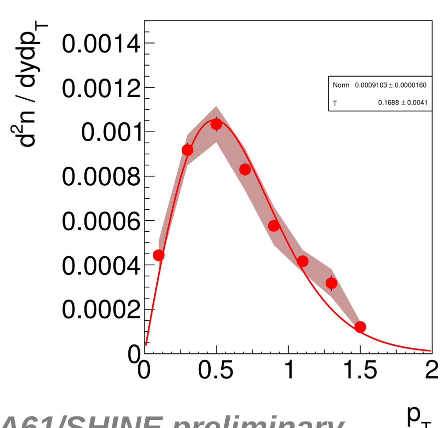


Double differential spectra $d^2n/(dp_T dy)$ presented in transverse momentum bins:

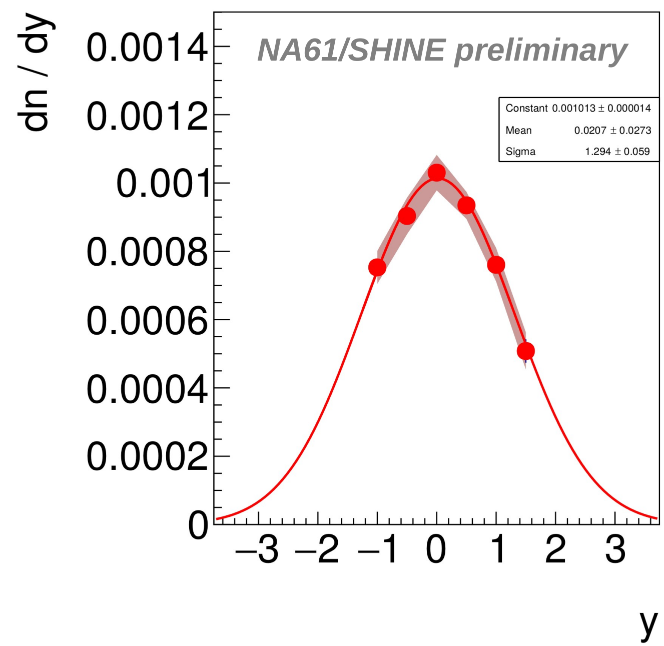
Ξ y ∈ [-1.25,-0.75)



Ξ y ∈ [0.25,0.75)



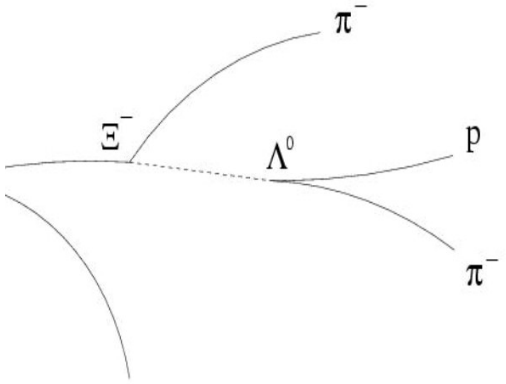
NA61/SHINE preliminary



4π multiplicity:

$\langle \Xi^- \rangle$ = 0.0033 ± 0.0001 ± 0.0006

Plans for pentaquarks search in NA61

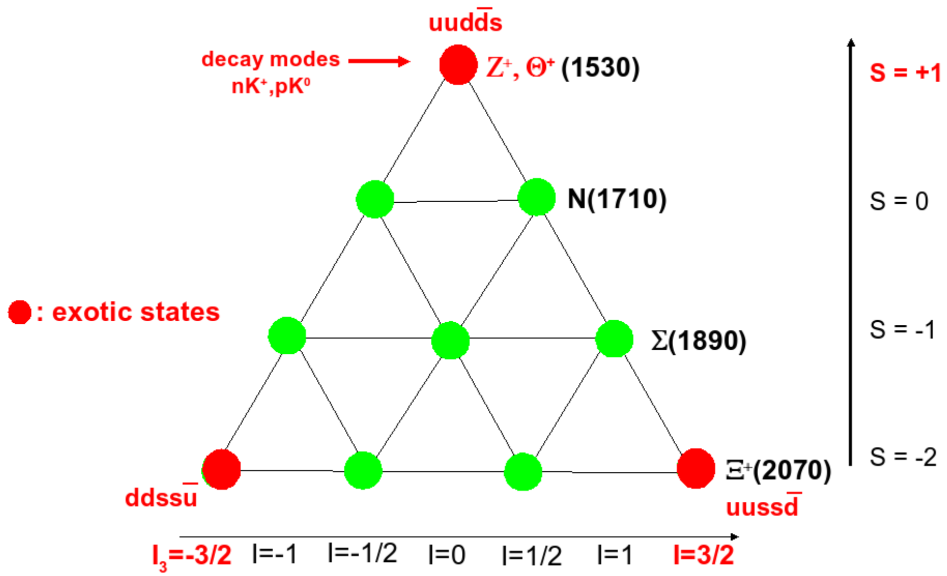


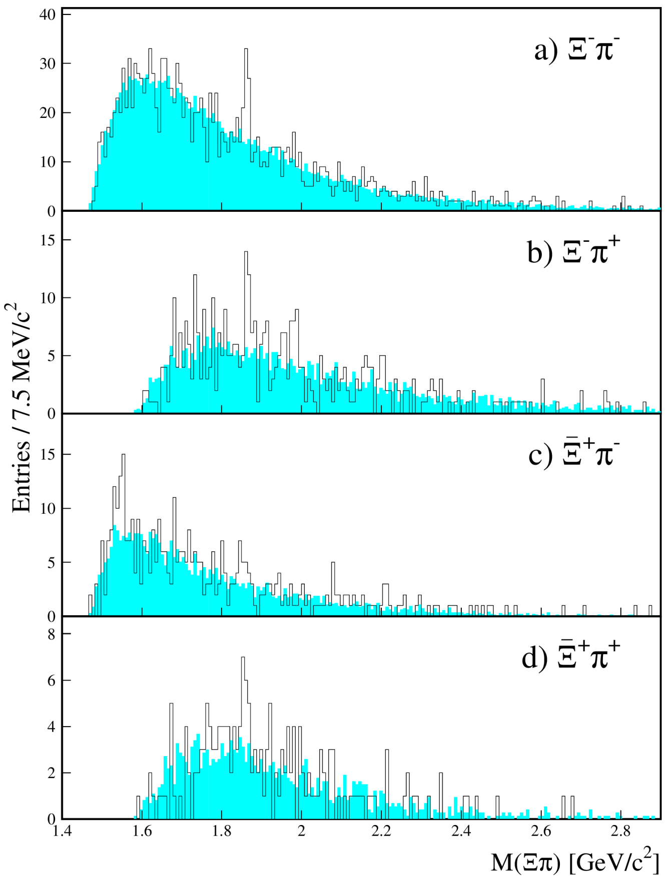
Ξ combined with pion will allow to search for pentaquarks continuing previous NA49 study

NA49, PRL 92, 042003, 2004

Anti-decuplet of baryons ($J^P=1/2^+$) predicted in chiral soliton model

Diakonov, Petrov, Polyakov, ZP A359, 305, 1997





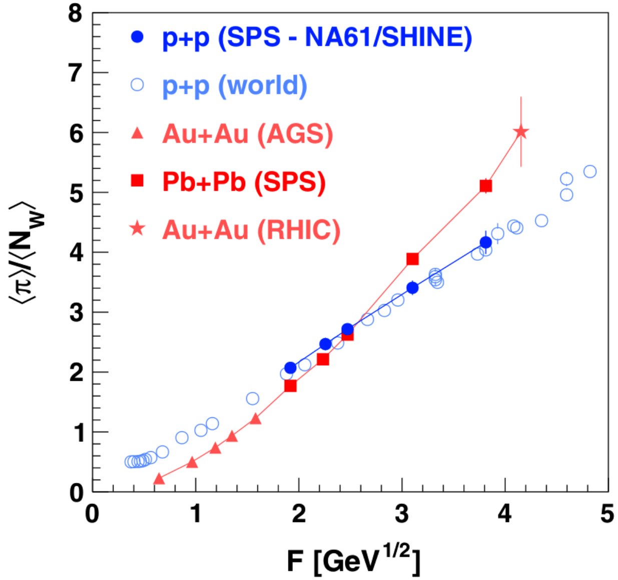
Summary

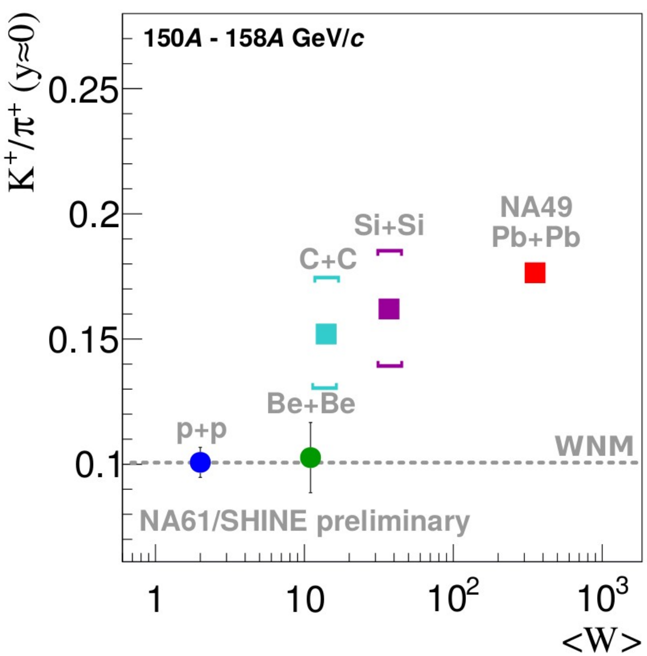
- New **Be+Be** results at **4π confirm the similarity between p+p and Be+Be**
- The first **NA61 results on anisotropic flow in Pb+Pb at 30*A* GeV/*c*** were obtained. Protons dv_1/dy change sign for centrality of about 50% → another **tool to study the properties of the onset of deconfinement**
- Intermediate centrality **Ar+Sc collisions at 150*A* GeV/*c*** show the effects of **electromagnetic interactions between** produced **pions and spectators**
- First, high precision results on **$K^*(892)^0$ production in inelastic p+p** collisions at 158 GeV/*c* were obtained → can be used to **estimate time between freeze-outs**
- Indication of **intermittency effect in middle-central Ar+Sc at 150*A* GeV/*c*** was shown→ first possible **evidence of CP signal** in NA61/SHINE
- $\Delta\eta$ dependence of fluctuations studied to extend the phase diagram scan. Non-trivial **$\Delta[P_T, N]$ dependence on $\Delta\eta$ window** is seen **for p+p and Be+Be at 150*A* GeV/*c***
- Future **open charm measurements** in NA61/SHINE will help to “calibrate” QGP thermometer
- Analysis of **high p_T particles** in p+p and p+Pb and **multi-strange hadrons** in p+p is well advanced

Thank you

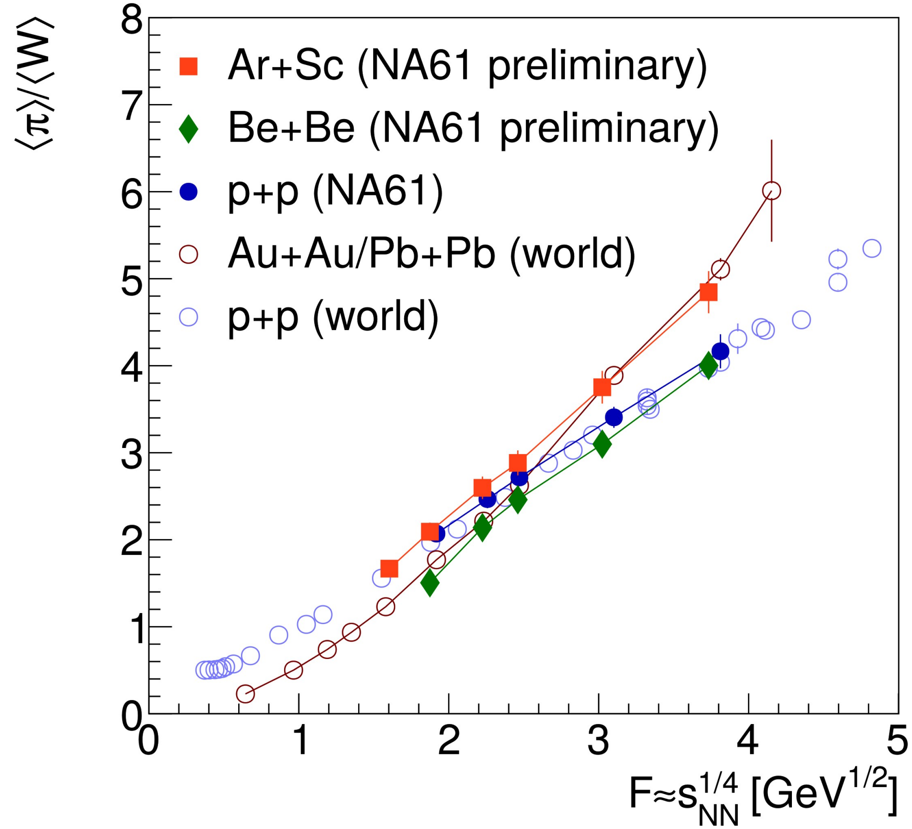
Back-up slides

NA61, EPJ C74, 2794, 2014





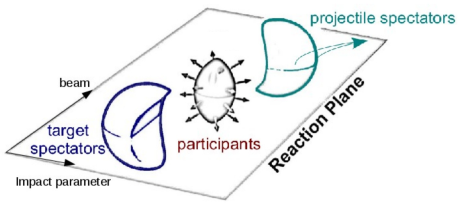
NP A967, 35, 2017 (QM 2017);
arXiv:1711.00318 (SQM 2017)



Collision geometry and the anisotropic transverse flow

Asymmetry in coordinate space converts due to interaction into momentum asymmetry with respect to the symmetry plane:

$$\rho(\varphi)=\frac{1}{2\pi}[1+2\sum_{n=1}^{\infty} v_n \cos(n(\varphi-\Psi_s))] \qquad v_n=\langle \cos(n[\varphi-\Psi_s]) \rangle$$

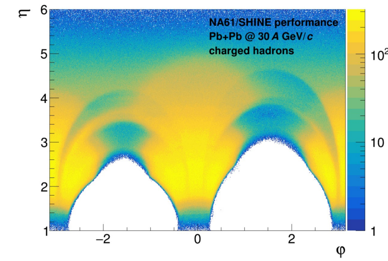


Ψ_s can be estimated from produced particles (Ψ_{pp}) or projectile (target) spectators Ψ_{proj} (Ψ_{targ})

Needed components to calculate v_n:

- momentum (φ, Y, p_T)
- centrality estimation
- particle identification
- symmetry plane (Ψ_s) estimation

Corrections for detector azimuthal non-uniformity



QnVector Corrections Framework

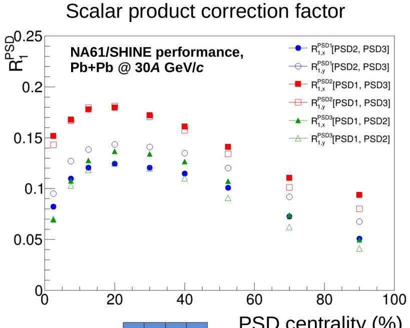
- Data driven corrections for azimuthal acceptance non-uniformity
  I. Selyuzhenkov and S. Voloshin [PRC77 034904 (2008)]
- QnVector Corrections Framework (used by ALICE)
  J. Onderwaater, V. Gonzalez, I. Selyuzhenkov
  https://github.com/jonderwaater/FlowVectorCorrections
- Recentering, twist, and rescaling corrections applied
  time dependent (run-by-run) and as a function of centrality

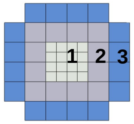
Flow Analysis Framework

- Extended Q_n-vector corrections for p_T/*y*-differential
- Multi-dimensional correlations of u and Q-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)

Scalar product method with 1st harmonic Q-vector

Scalar product correction factor





u and Q-vectors:

$$u_n=\begin{pmatrix}\cos n\varphi \\ \sin n\varphi\end{pmatrix} \qquad Q_n=\sum_j u_n^j$$

Directed flow:

$$v_1=\frac{\langle 2u_{1,i}Q_{1,i}\rangle}{R_{1,i}} \qquad i,j,k=[x,y]$$

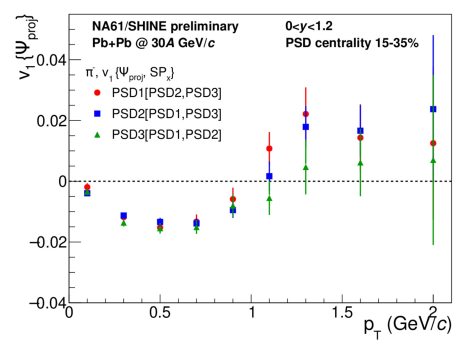
Elliptic flow:

$$v_2=\frac{4\langle u_{2,i}Q_{1,j}^A Q_{1,k}^B\rangle}{R_{1,j}^A R_{1,k}^B}$$

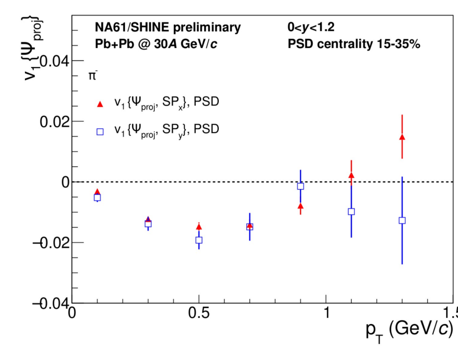
First harmonic resolution correction factor:

$$R_{1,i}^A[B,C]=\sqrt{2\frac{\langle Q_{1,i}^A Q_{1,i}^B\rangle\langle Q_{1,i}^A Q_{1,i}^C\rangle}{\langle Q_{1,i}^B Q_{1,i}^C\rangle}}$$

"Systematics" for directed flow (v_1) components

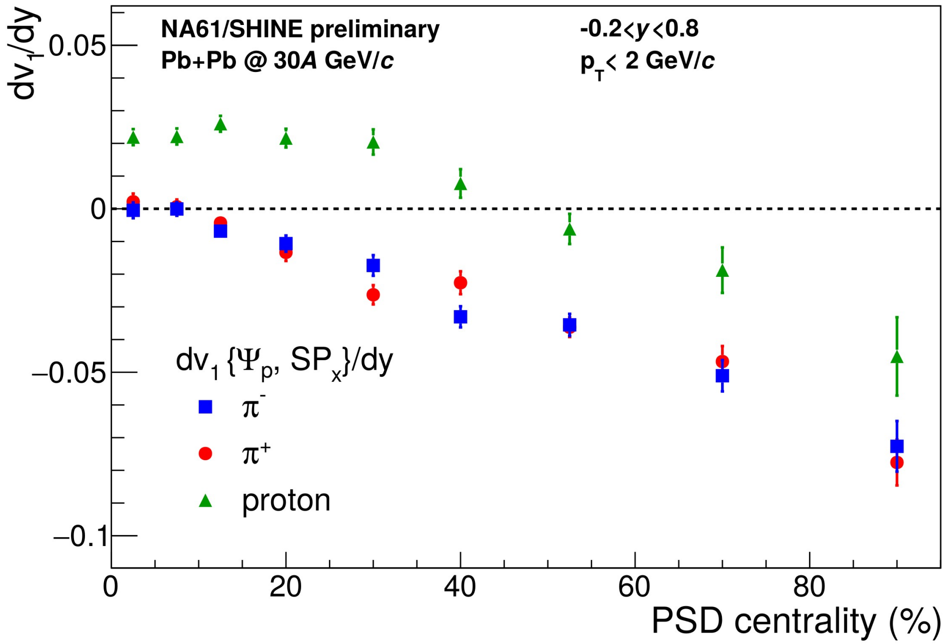


Consistent results for PSD subevents



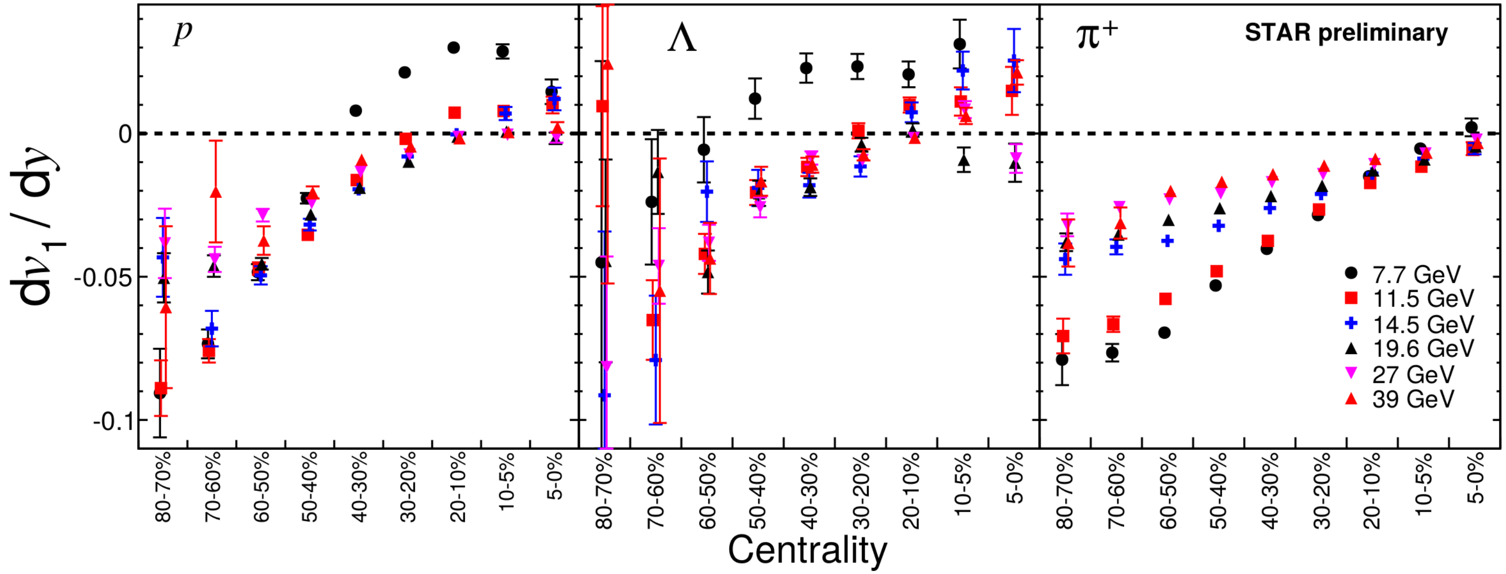
x/y components show consistent results, while results for y-component shows larger errors

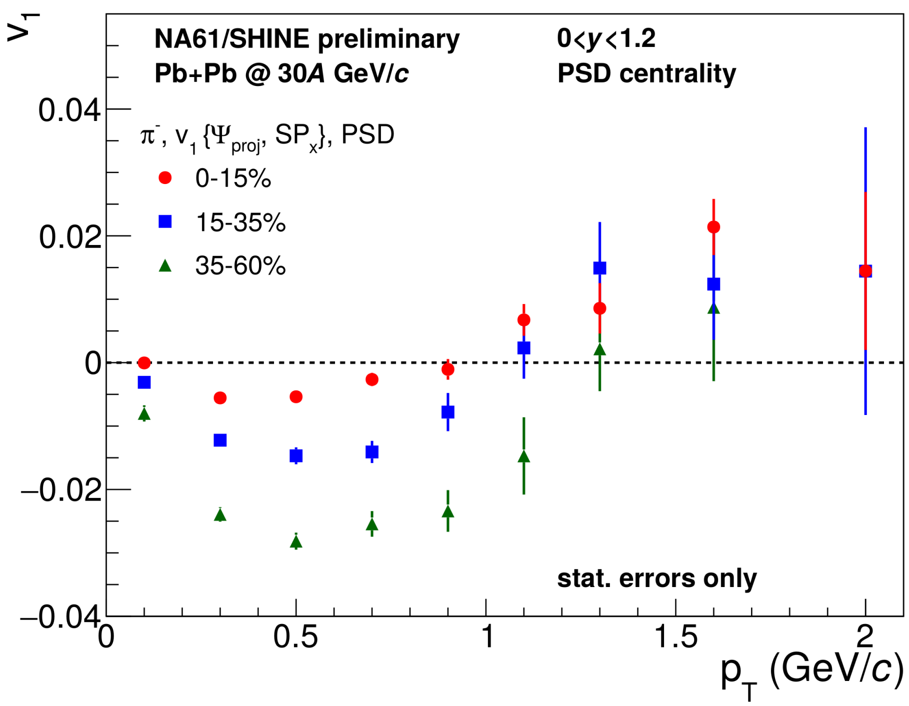
For preliminary results: only x-component is used and PSD subevents are combined

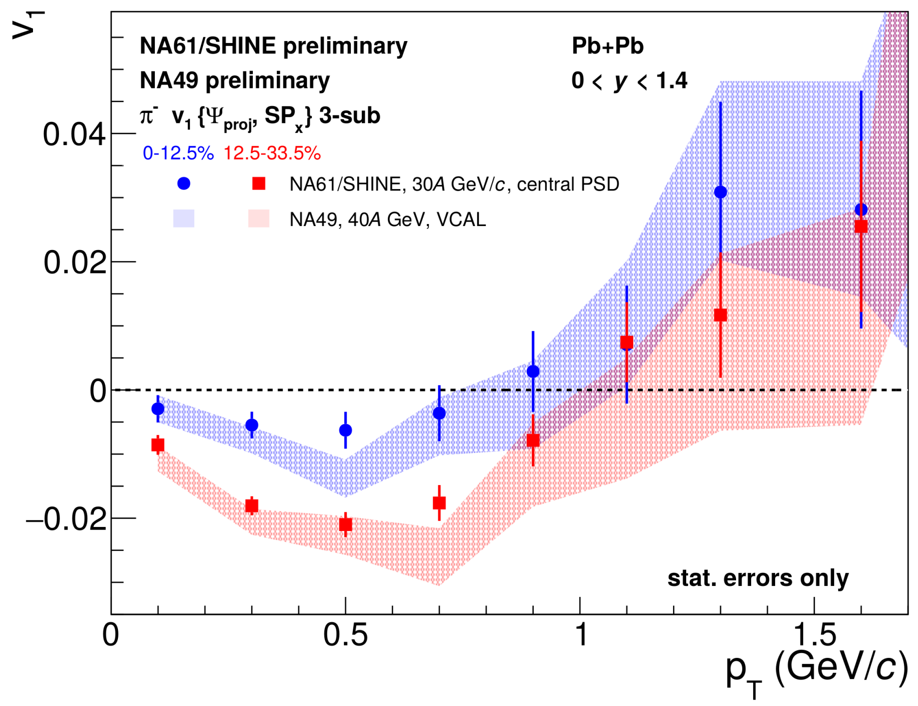


NA61/SHINE (QM 2018):
Centrality dependence of dv_1/dy for
Pb+Pb at $\sqrt{s_{NN}}$ = 7.6 GeV
(at energy of the onset of deconfinement)

STAR BES (QM 2015):
Centrality dependence of dv_1/dy for
Au+Au (several energies)
→ NP A956, 260, 2016







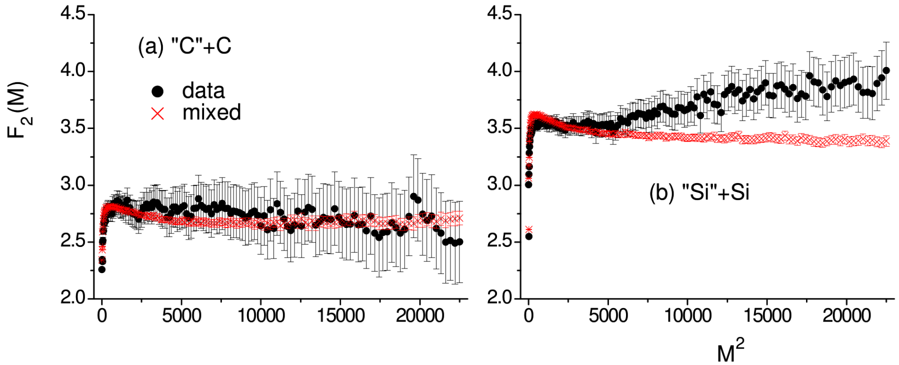
Charged pion v_1 vs p_T

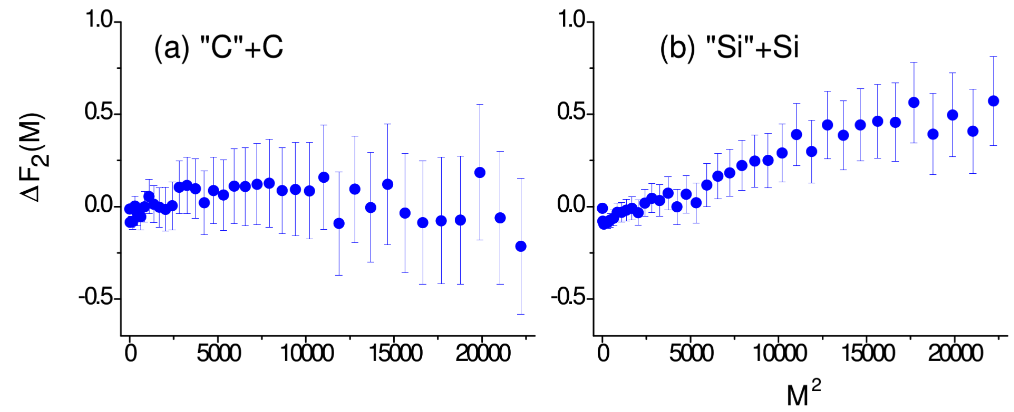
- Strong centrality dependence of v_1
- $v_1(p_T \sim 0$ GeV/$c) = 0$
- v_1 changes sign at $p_T \sim 1$ GeV/c

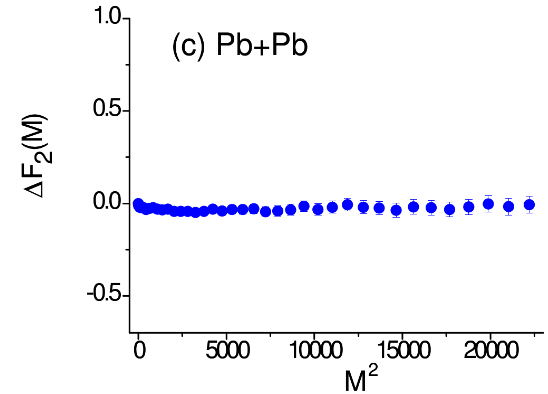
Similar results to new NA49 analysis of pions relative to the spectator plane

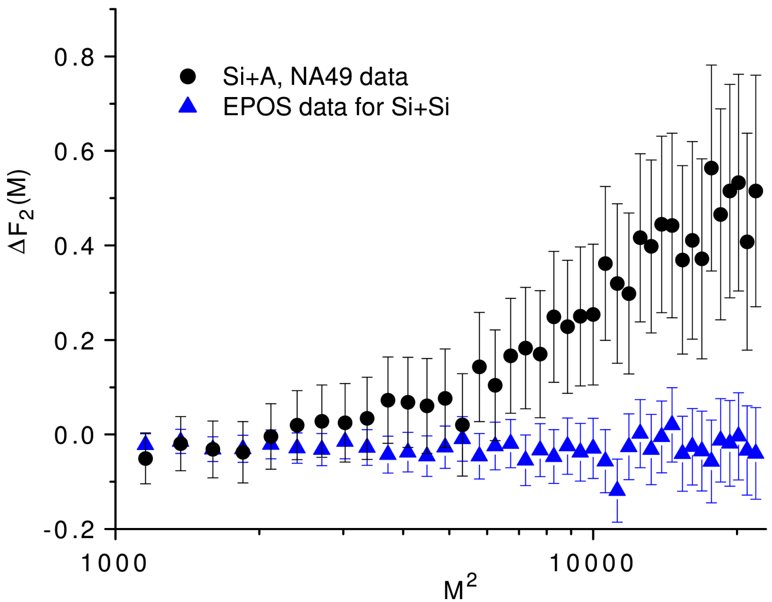
NA49: Golosov, Selyuzhenkov, Klochkov, Kashirin, QM 2018 poster (#367)

System size dependence of protons intermittency at 158*A* GeV/*c* (NA49)









$\sqrt{s_{NN}}$ = 17.3 GeV

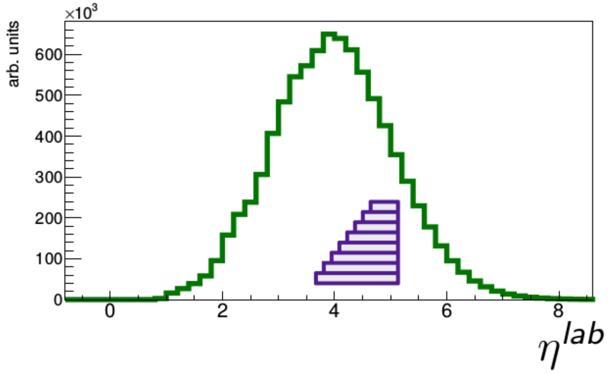
NA49, EPJC 75, 587, 2015

NA49 value for A+Si (A=Si, Al, P):

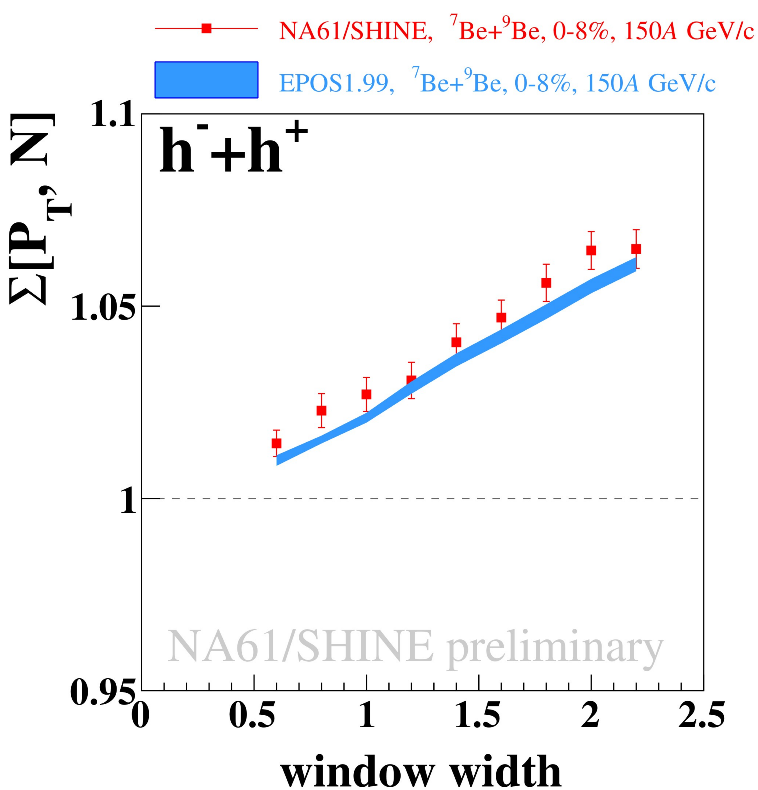
$\phi_2 = 0.96^{+0.38}_{-0.25}$ (stat.) ± 0.16 (sys.)

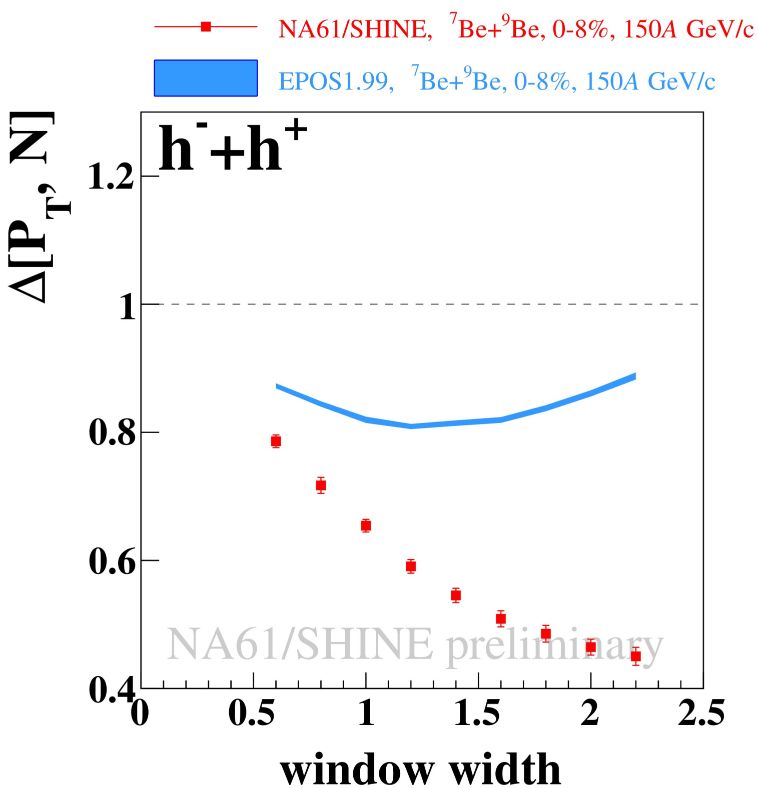
consistent with theoretically **expected value** (5/6 = 0.833..) for a system freezing out **at CP**

Strongly intensive fluctuation measures: one window case, Be+Be

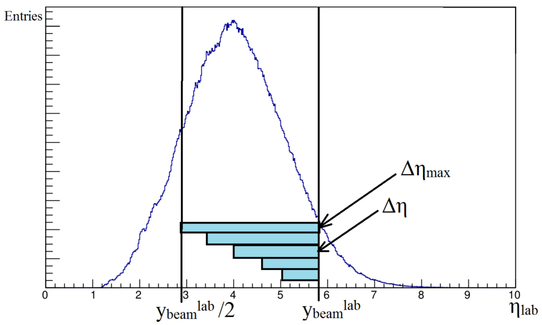


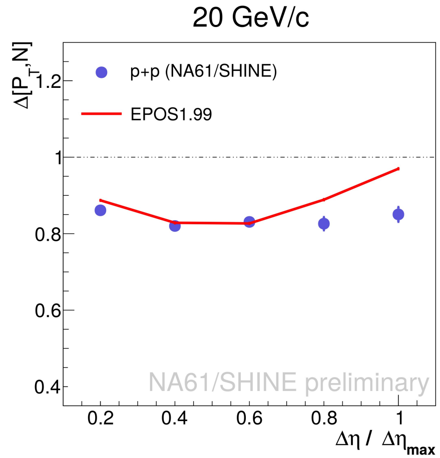
Rapidity width dependence studies will allow to probe different baryochemical potentials

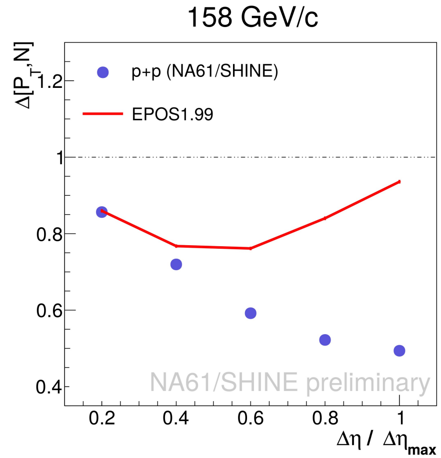


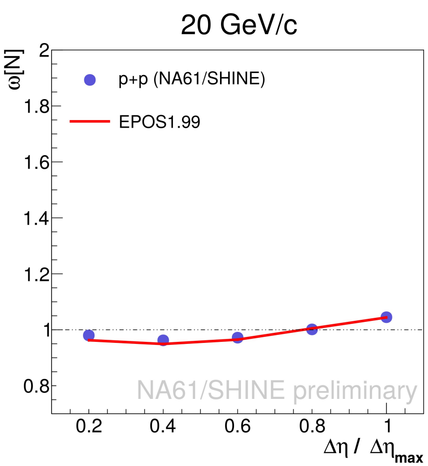


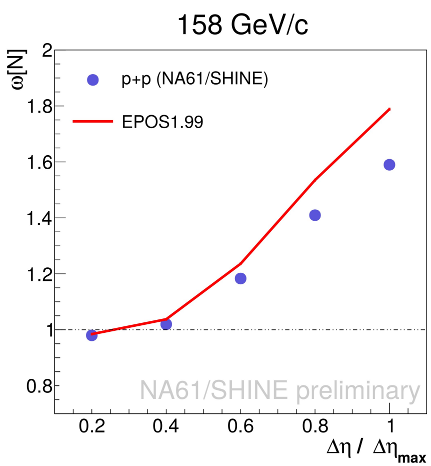
Intensive and strongly intensive fluctuation measures: one window case, p+p

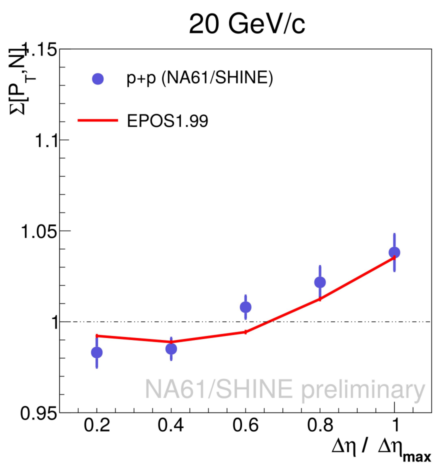


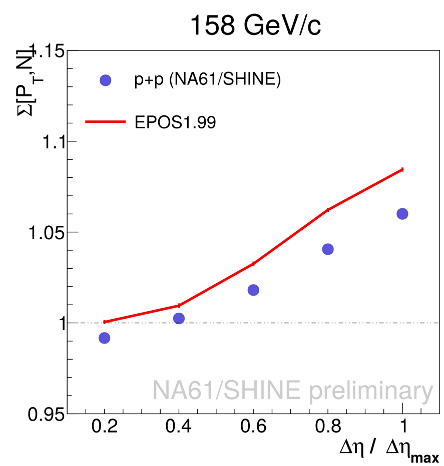


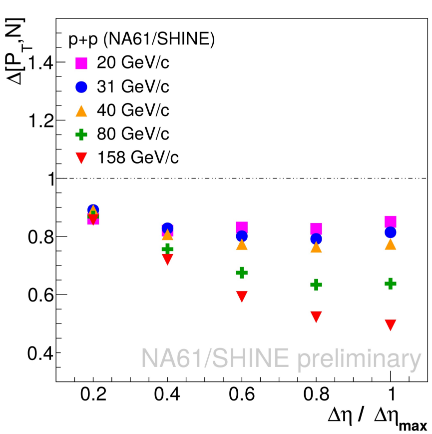


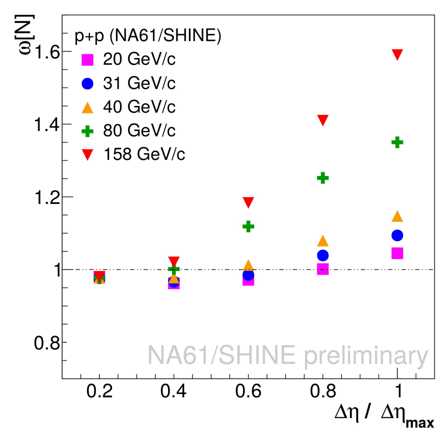


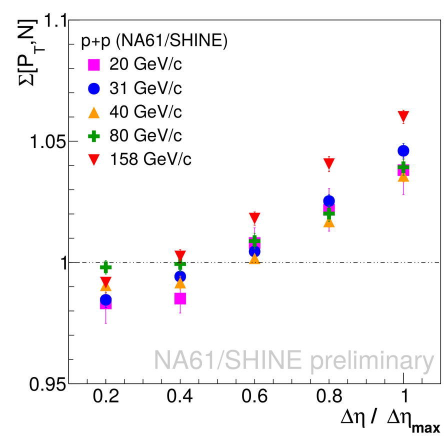






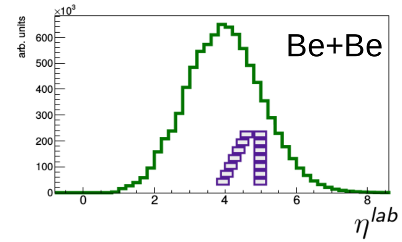


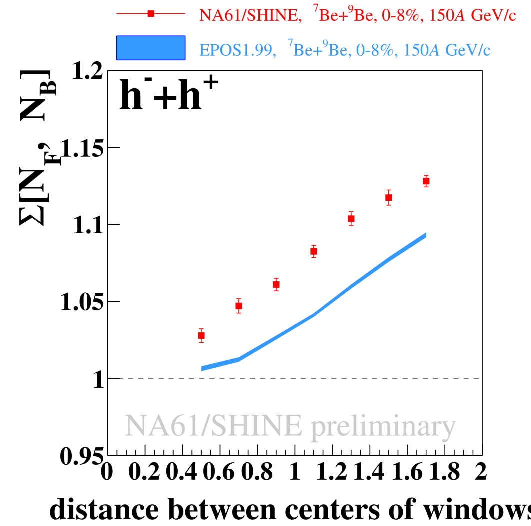


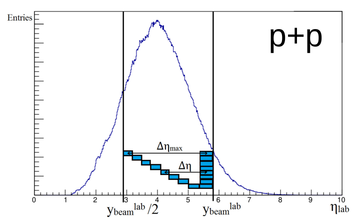


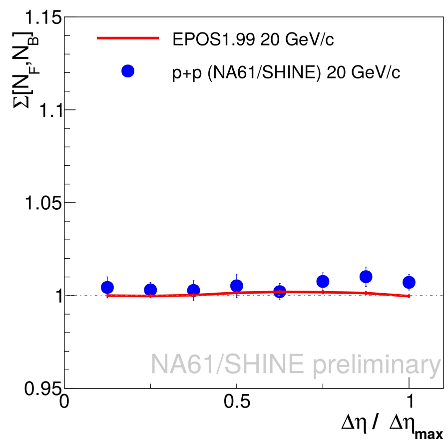
Strongly intensive fluctuation measures: two windows case

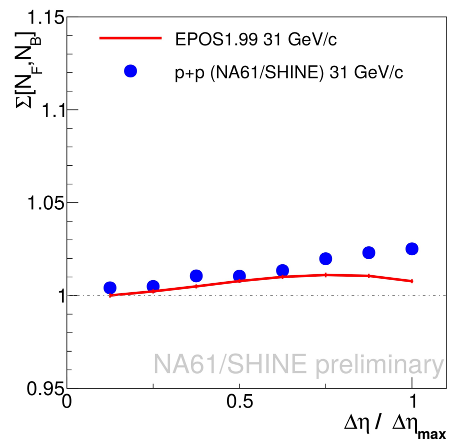
$$\Sigma[N_F, N_B] = \frac{\langle N_B\rangle \omega[N_F] + \langle N_F\rangle \omega[N_B] - 2\,cov(N_F, N_B)}{\langle N_B\rangle + \langle N_F\rangle}$$

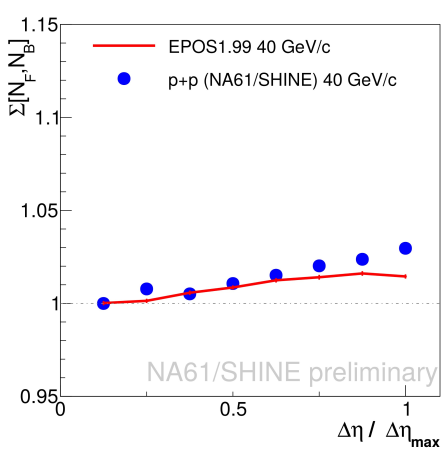


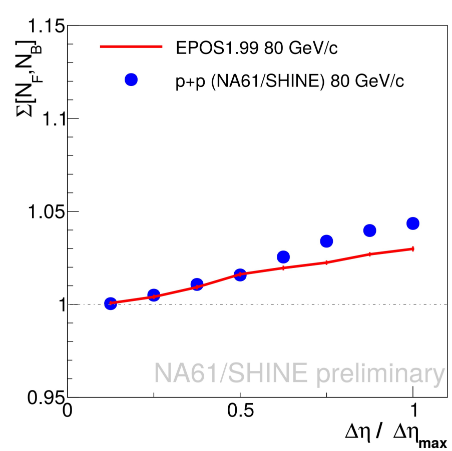


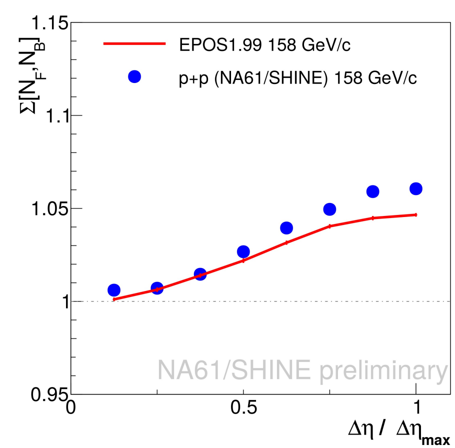






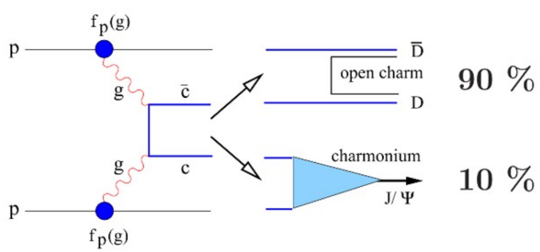




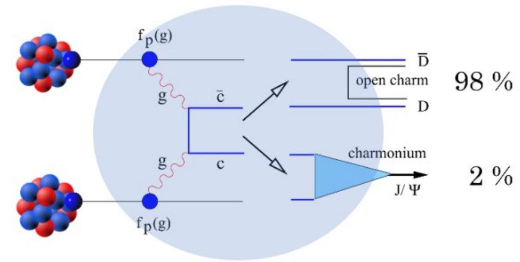


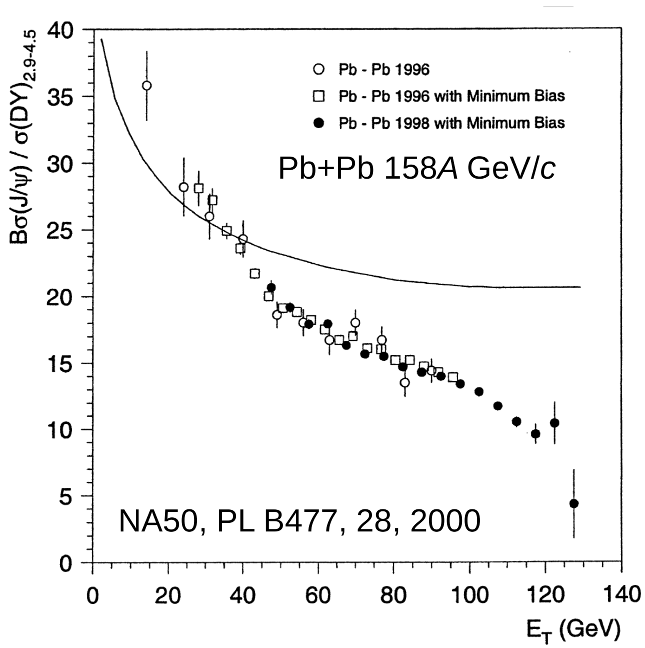
J/Ψ production as signal of deconfinement

$\langle c\bar{c}\rangle$ hadronizes in vacuum



$\langle c\bar{c}\rangle$ hadronizes in medium





Probability of $\langle c\bar{c}\rangle$ hadronizing to J/Ψ

$$P(c\bar{c}\rightarrow J/\Psi)\equiv\frac{\langle J/\Psi\rangle}{\langle c\bar{c}\rangle}\equiv\frac{\sigma_{J/\Psi}}{\sigma_{c\bar{c}}}$$

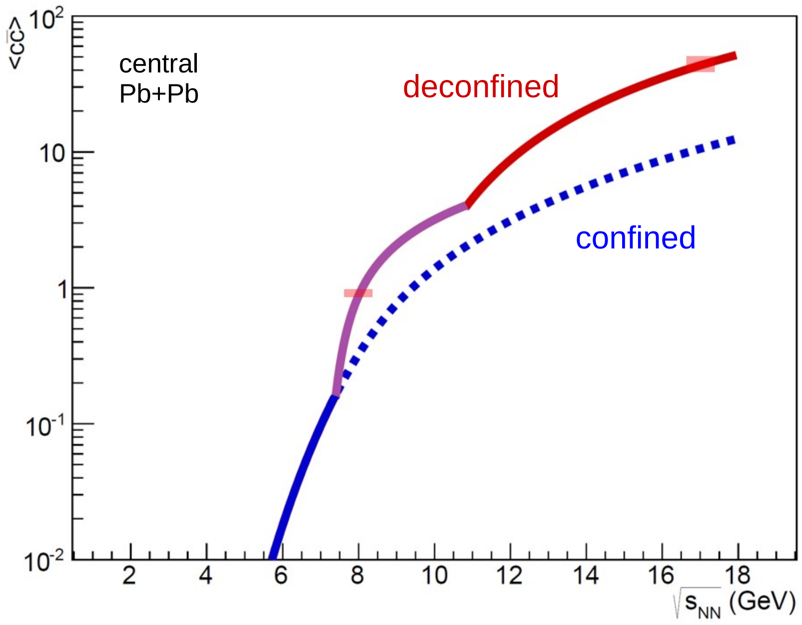
- At CERN SPS ⟨J/Ψ⟩ data provided by NA38, NA50, NA60
- $\langle c\bar{c}\rangle$ data not available at SPS
- Interpretation of NA50 data based on:

$\langle c\bar{c}\rangle\sim\langle \mathrm{DY}\rangle$ Is it really true?
Need for precise data in Pb+Pb

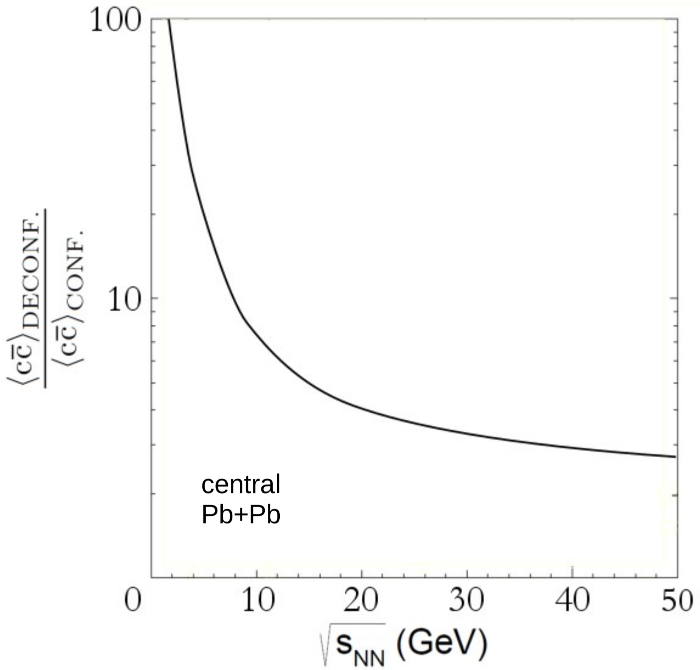
Mechanisms of charm production – validating models

Models can also show different energy dependences of $\langle c\bar{c}\rangle$ in deconfined to confined state ratio

Statistical Model of the Early Stage
Poberezhnyuk et al. APP B48, 1461, 2017;
Poberezhnyuk, priv. comm.



pQCD-inspired model
Kostyuk et al. PL B519, 207, 2001



Red bands - expected accuracy of NA61/SHINE results for two energies: 40*A* GeV/*c* ($\sqrt{s_{NN}}$ = 8.6 GeV) and 150*A* GeV/*c* ($\sqrt{s_{NN}}$ = 16.7 GeV), assuming the SMES model yields

NA61/SHINE data taking plan related to the charm program

Original plan from Addendum 10 (SPSC-P-330-ADD-10):

Year	Beam	#days	#events	$\#(D^0 + \overline{D^0})$	$\#(D^+ + D^-)$
2022	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2023	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2024	Pb at 40*A* GeV/*c*	42	250M	3.6k	2.1k

Number of recorded events and reconstructed D mesons:

← Min bias Pb+Pb at 150*A* GeV/*c*

← 30% most central Pb+Pb at 40*A* GeV/*c*

Accepted update from Addendum 11 (SPSC-P-330-ADD-11):

Physics data taking in 2021: 4 weeks of data taking in Pb+Pb collisions at 150*A* GeV/*c*. The run will allow to record about 30% (about 150M events) of the total statistics of events for this reaction (Pb+Pb at 150*A* GeV/*c*) requested in the Addendum 10.

	0–10%	10–20%	20–30%	30–60%	60–90%	0–90%
$\#(D^0 + \overline{D^0})$	31k	20k	11k	13k	1.3k	76k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k	46k
$\langle W \rangle$	327	226	156	70	11	105

← centrality selected Pb+Pb assuming 500M min bias events