Tomasz Cetner and Katarzyna Grebieszkow
Warsaw University of Technology

for the NA61/SHINE Collaboration

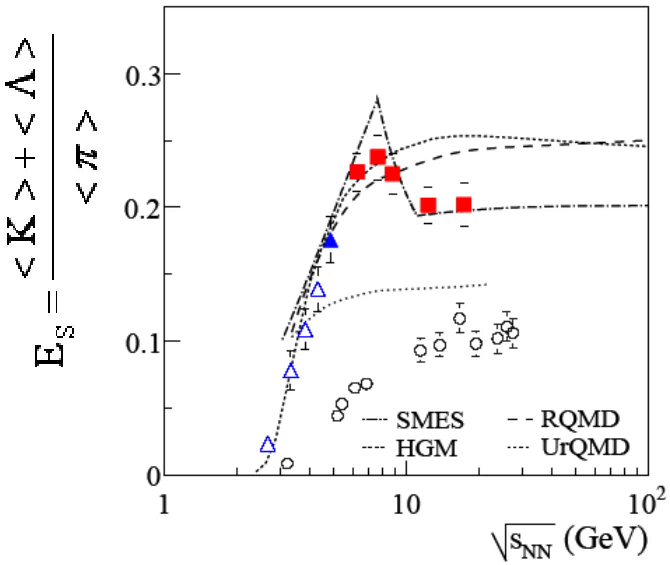
Energy dependence of transverse momentum and multiplicity fluctuations at the CERN SPS

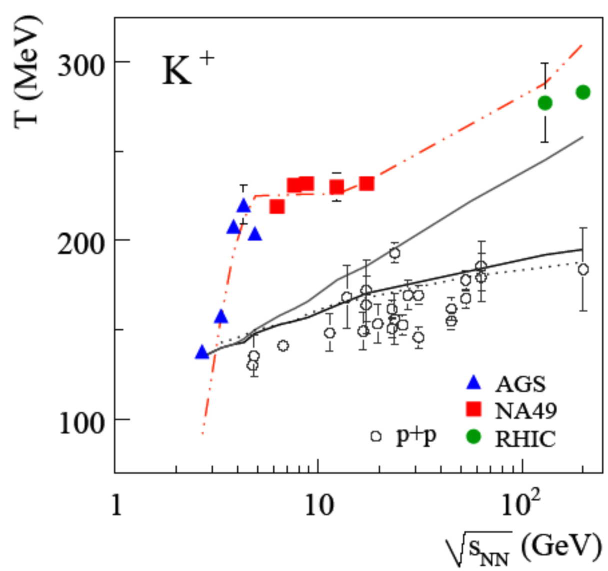
Critical Point and Onset of Deconfinement (CPOD)
23 - 29 August 2010 at Joint Institute for Nuclear Research (Dubna)

The most interesting region of the phase diagram is covered by the CERN SPS!

1. Evidence for **Onset of deconfinement** (kink, horn, step) **is observed by NA49** at **$E_{OD} \cong$ 30A GeV**

(Alt et al., PR**C77**, 024903 (2008))





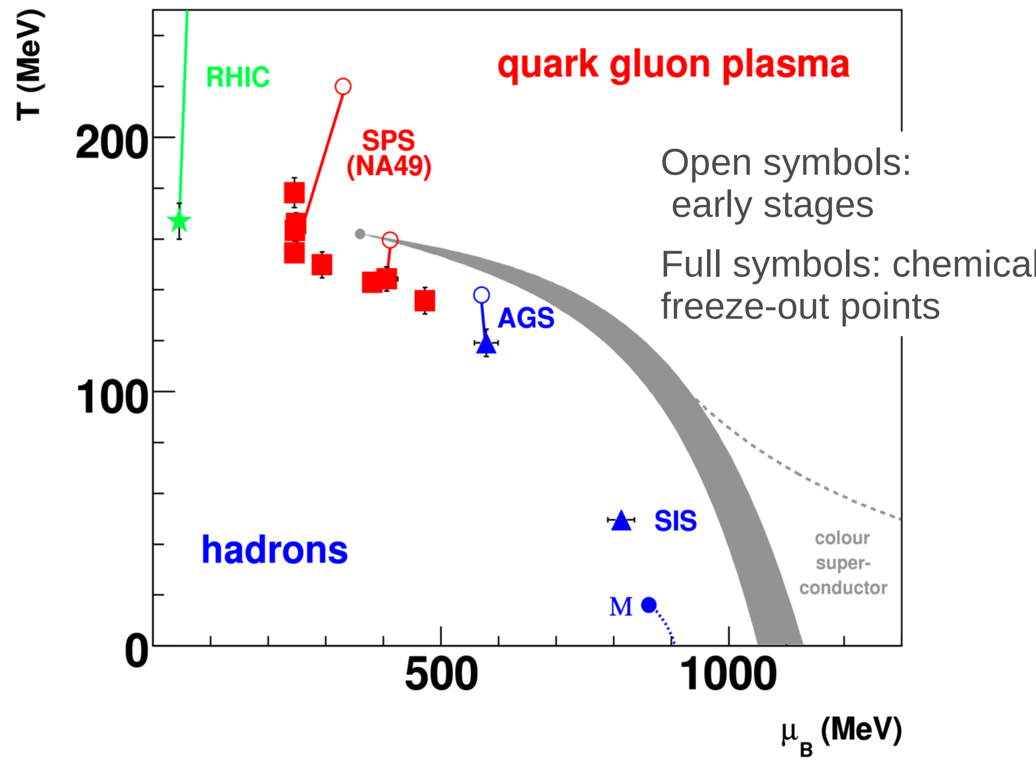
2. **Critical point** of strongly interacting matter may be located at SPS energies

(T^{CP}, μ_B^{CP}) = (162± 2, 360± 40) MeV

(Fodor and Katz, JHEP **0404**, 050 (2004))

μ_B^{CP} = 360 MeV $\Leftarrow E_{CP} \cong$ 50A GeV

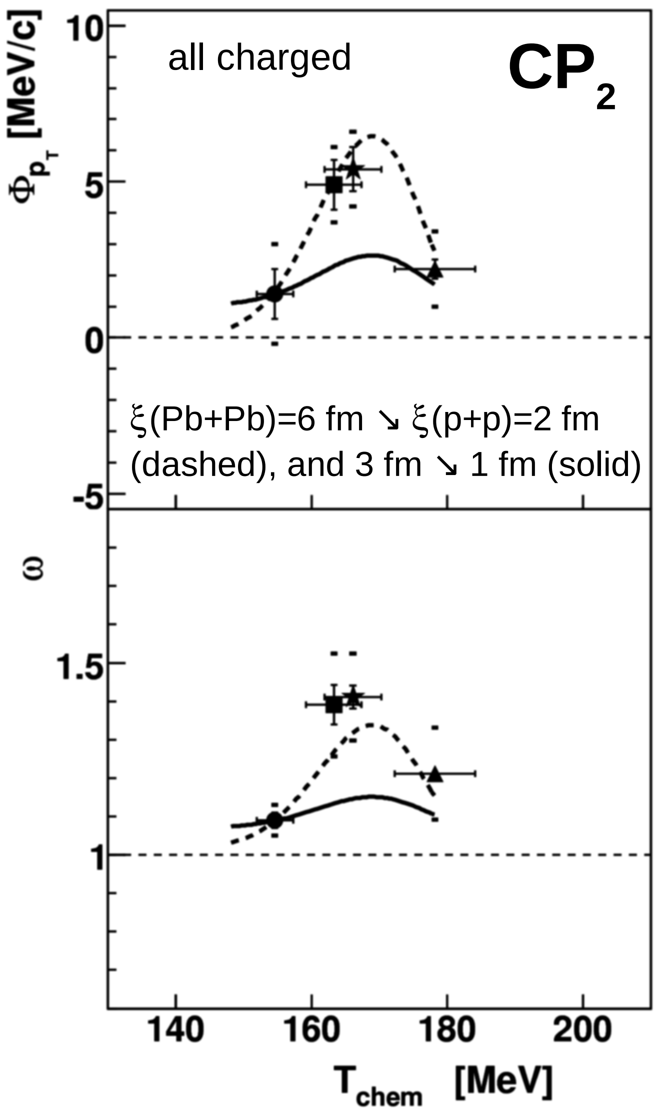
(Beccatini et al., PR**C73**, 044905 (2006))

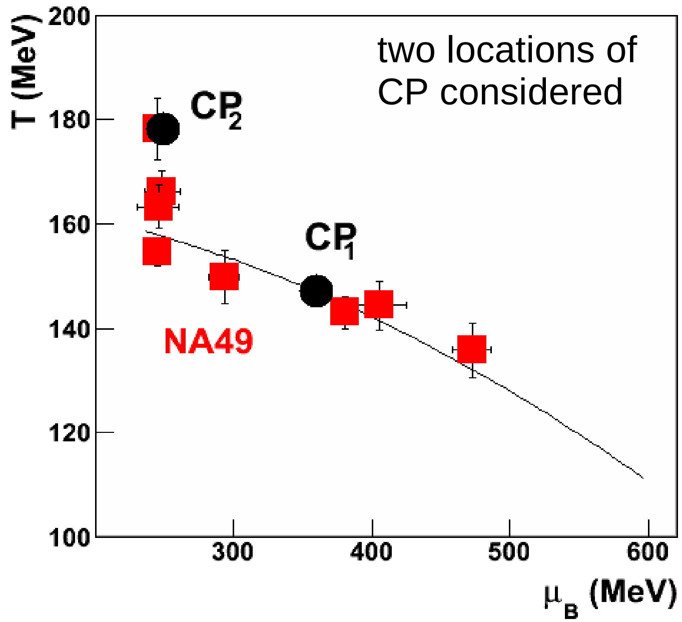


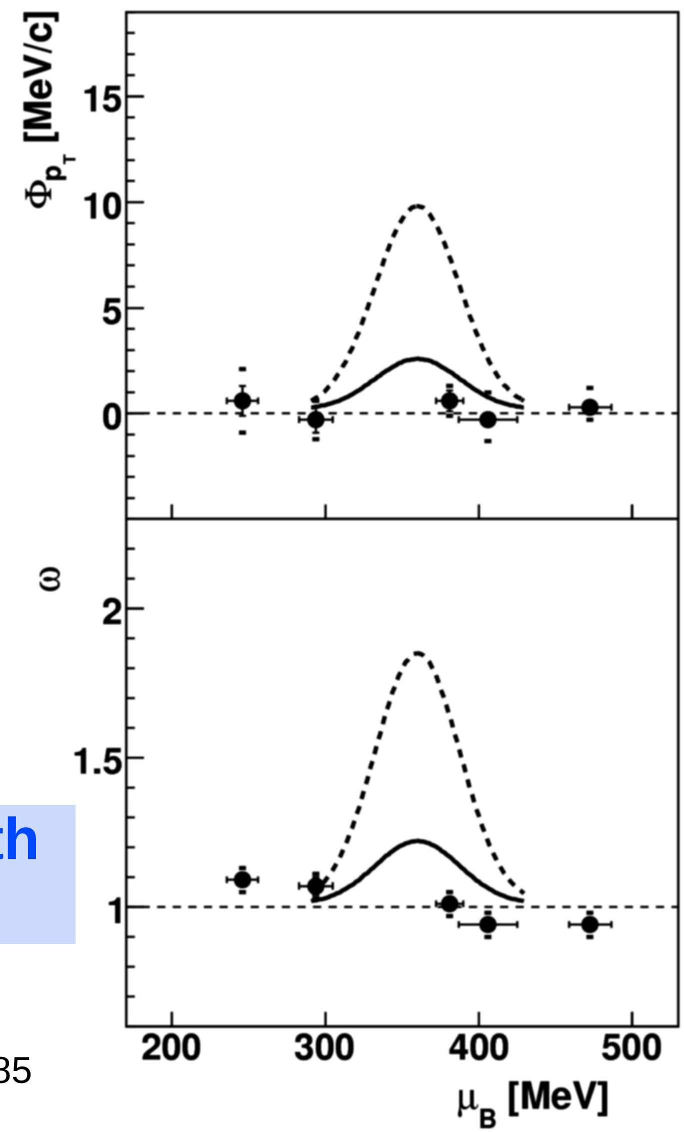
For strongly interacting matter maximum of CP signal expected when freeze-out happens near CP

System size dependence
(p+p, C+C, Si+Si, and Pb+Pb)
of average p_T and multiplicity fluctuations at 158A GeV

Energy dependence of average p_T and multiplicity fluctuations for central Pb+Pb







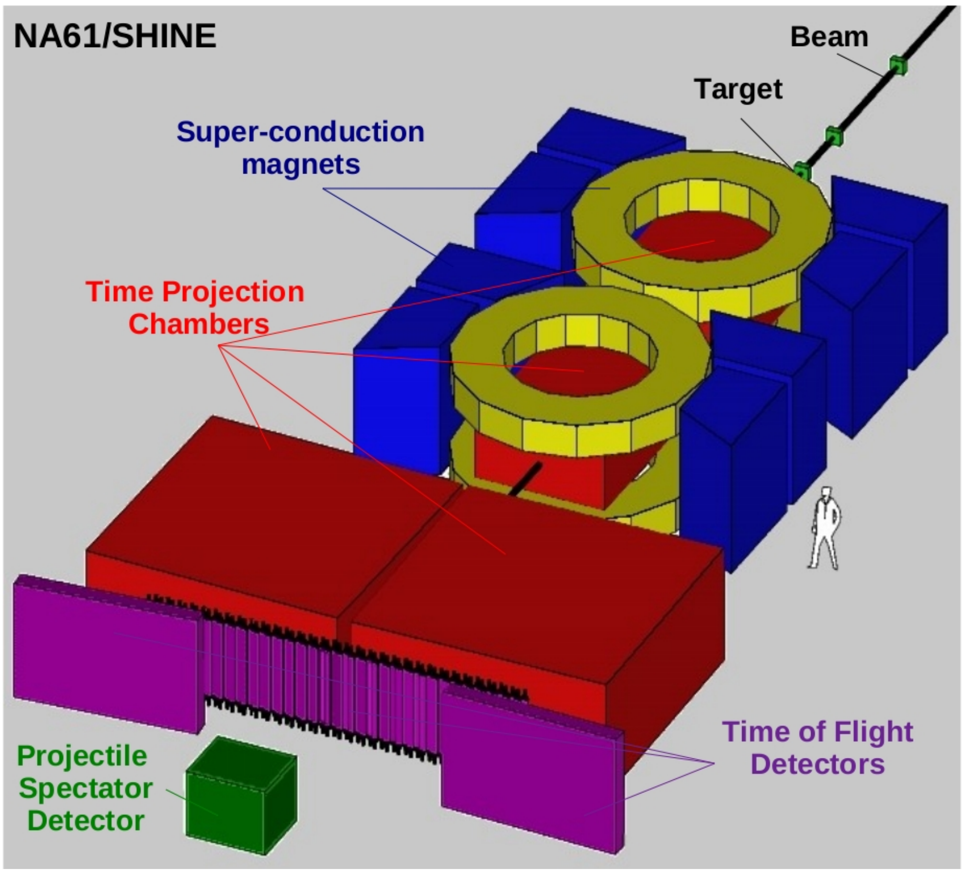
Maximum of Φ_{pT} and ω observed for C+C and Si+Si

Data are consistent with the CP_2 predictions

Grebieszkow et al., Nucl. Phys. **A830**, 547C-550C (2009), and arXiv:0909.0485

SHINE (fixed target) experiment at CERN SPS

SHINE – SPS **H**eavy **I**on and **N**eutrino **E**xperiment



Successor of the NA49 experiment

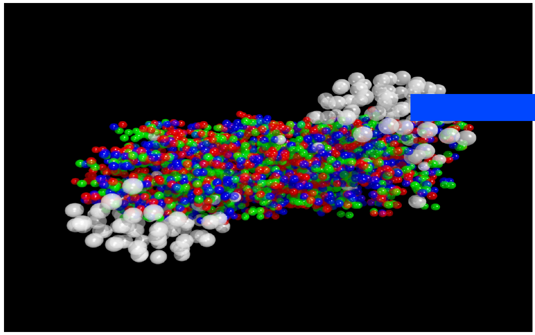
Main upgrades:

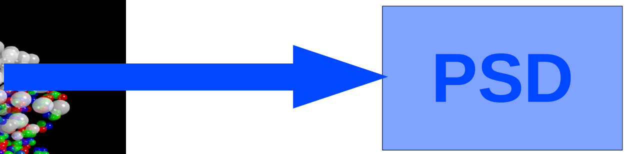
- 2007: Construction of the **forward ToF wall** to identify particles with $p < 3$ GeV/c and $\Theta < 400$ mrad (extended ToF acceptance to $p \approx 1$ GeV/c)
- 2008: Replacement of the TPC digital **read-out** and **DAQ** (increase of the event rate by a factor of ≈ 10)
- Under construction: Replacement of Forward Calorimeter (VETO) by **Projectile Spectator Detector**

PSD resolution:
$\sigma(E)/E \approx 0.5/\mathrm{sqrt}(E/(1\mathrm{GeV}))$
5 x better than in NA49
Resolution of 1 nucleon !
Important for multiplicity fluctuations

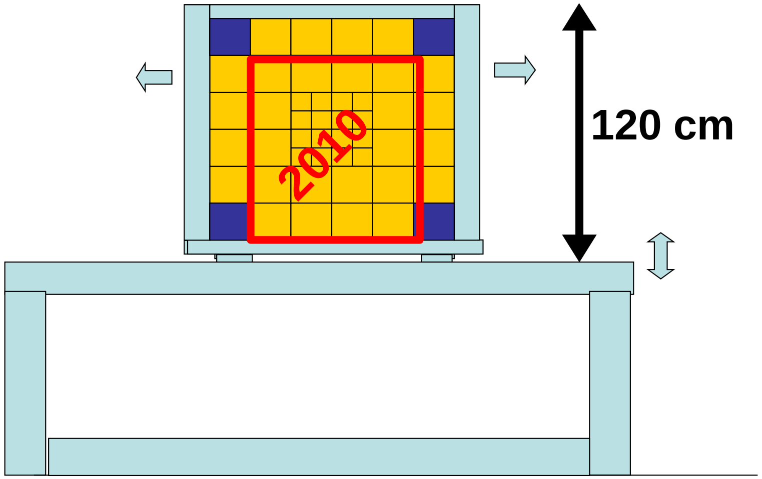
NA61 upgrades: CERN-SPSC-2006-034, SPSC-P-330
data taking since 2007

Projectile Spectator Detector (PSD) 2011 ↗





Total weight
~ 17 tons!



Front view of the PSD on moving platform.

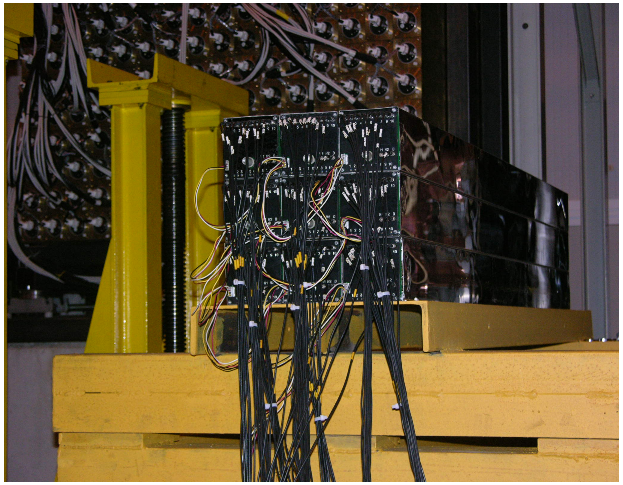
Precise measurement of the energy of projectile spectators. Needed for

- centrality selection (on trigger level)
- measurement of event-by-event fluctuations (to reduce N_{part} fluctuations)
- Reconstruction of the reaction plane

Resolution of 1 nucleon (!) in the studied energy range

Main features of PSD:

- high energy resolution ~55%/√E
- high granularity: transverse homogeneity of energy resolution, reaction plane measurements

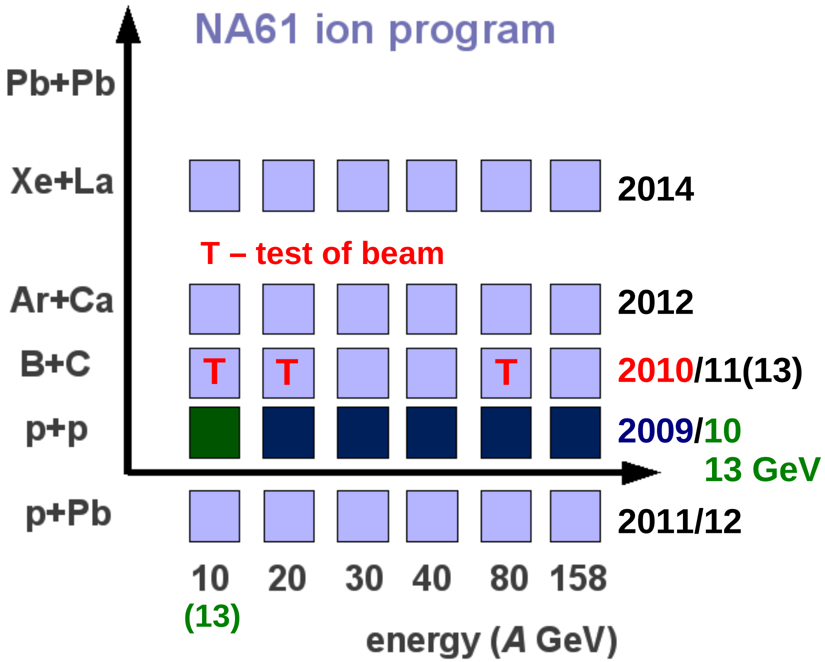


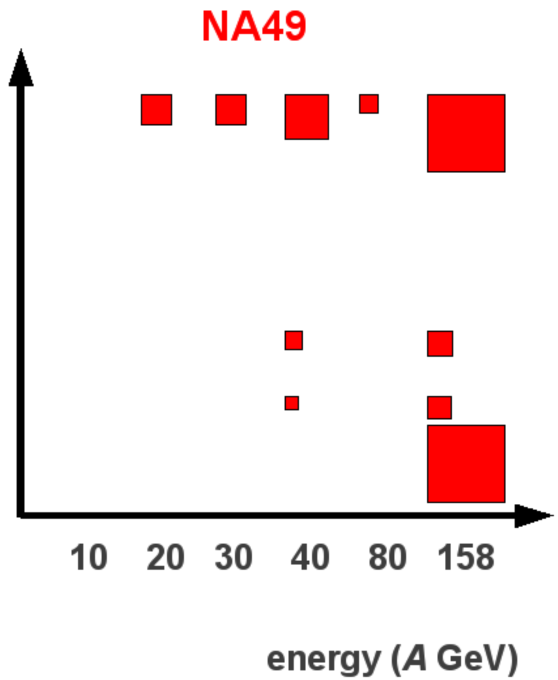
NA61 PSD supermodule

NA61/SHINE physics program

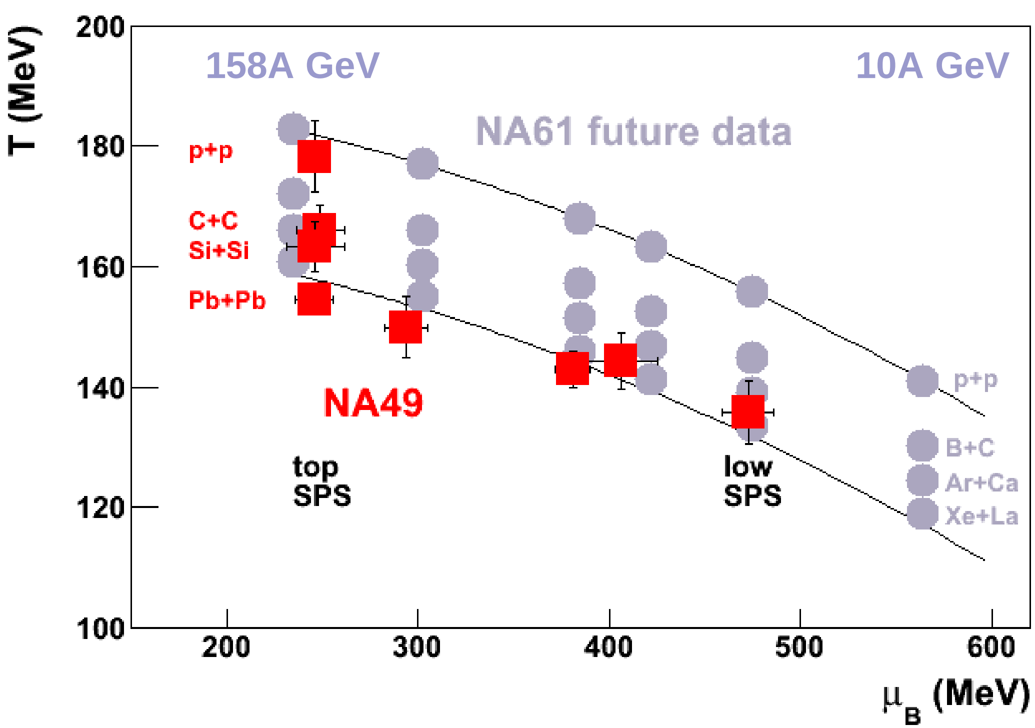
Hadron production in p+p, p+A, h+A, A+A at various energies

- Search for the Critical Point
- Study of the properties of the Onset of Deconfinement
- High p_T physics (energy dependence of the nuclear modification factor)
- Precision data on hadron production (spectra)
  - calculation of neutrino spectrum for the T2K experiment
  - improve simulations of cosmic-ray air showers for Pierre-Auger and KASCADE experiments





Data sets planned to be recorded by NA61 within the **ion program** and those recorded by NA49



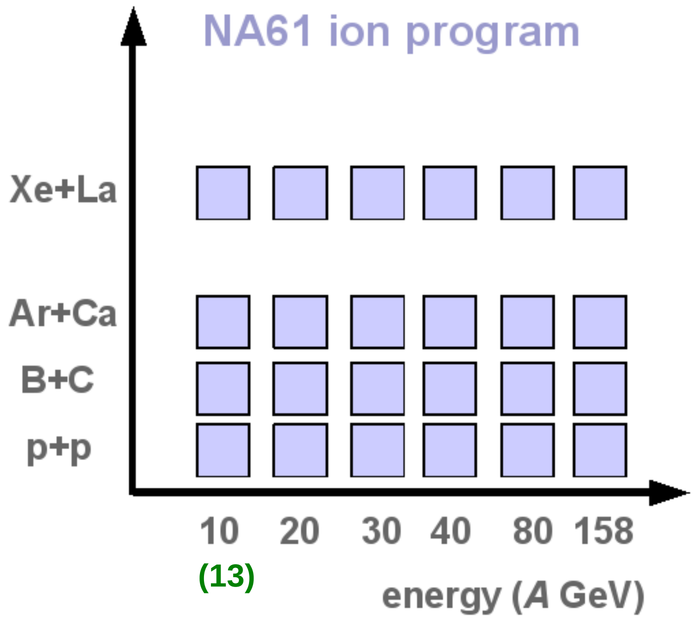
Comprehensive scan in the whole SPS energy range (10A-158A GeV) with **light and intermediate mass nuclei**

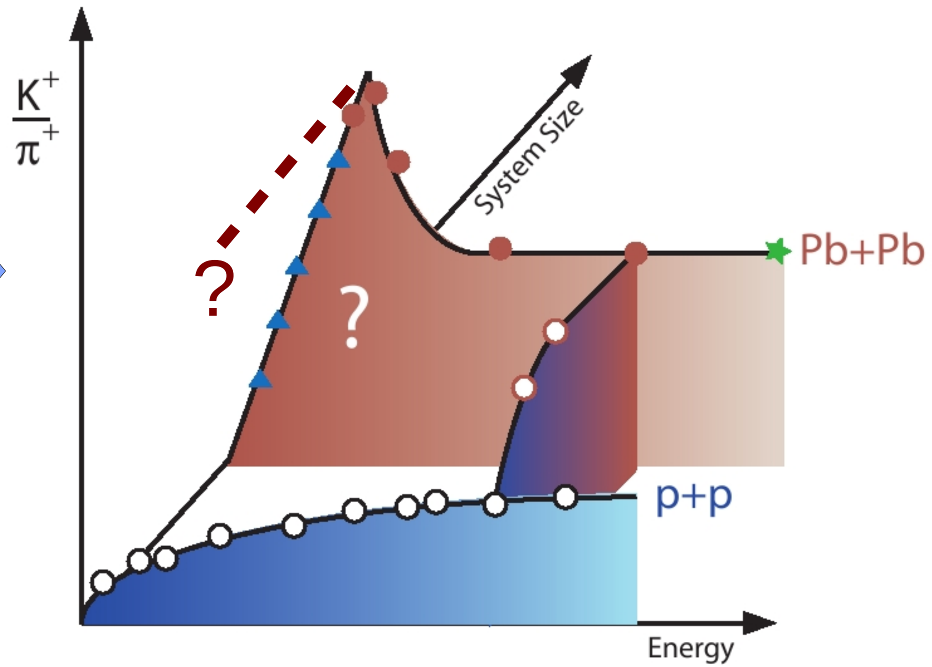
First time in history when such a 2D scan (energy, system size) will be performed

Estimated (NA49) and expected (NA61) chemical freeze-out points accordingly to Beccatini et al., PR**C73**, 044905 (2006)

NA61 plans: Onset of Deconfinement

Search for the onset of the horn in collisions of light nuclei



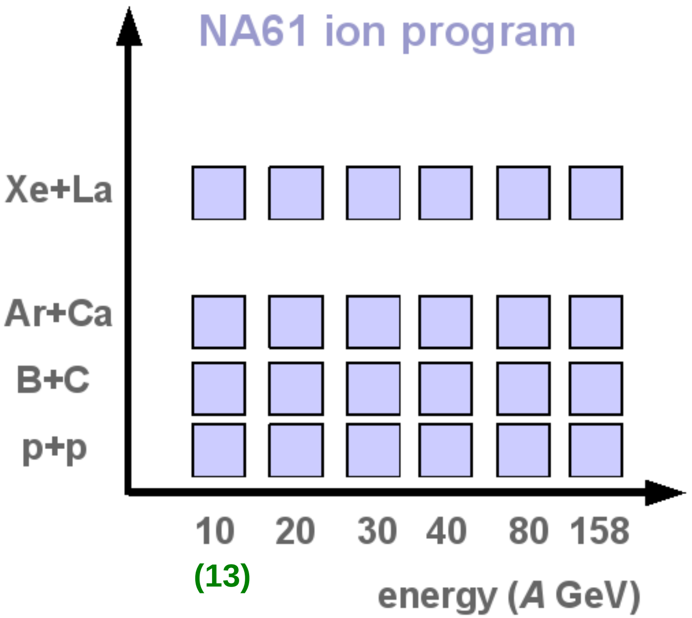


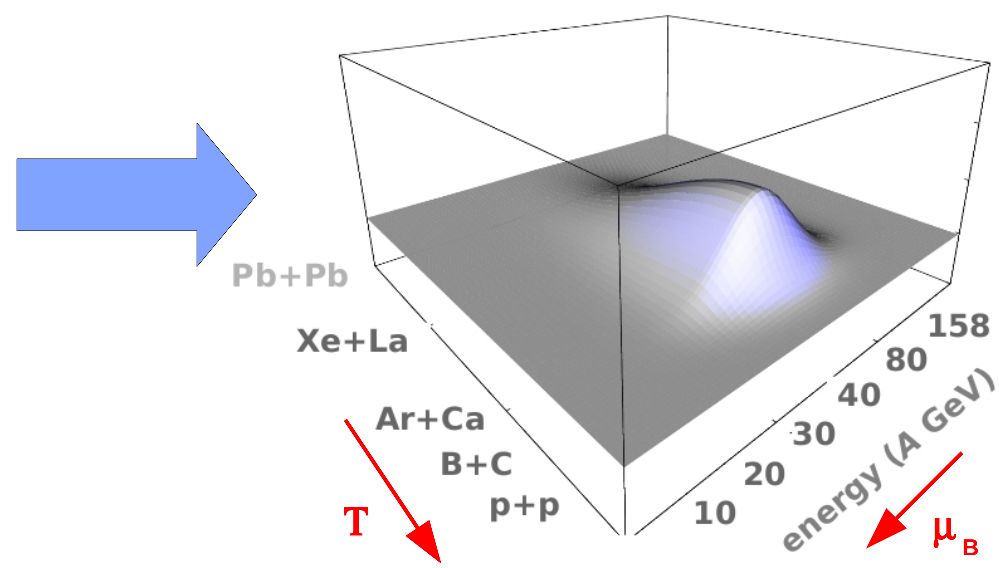
Expectation for energy and system size scan: similar structures (kink, horn, step); vanishing for small systems

In particular the "horn" like structure is expected to be similar for Ar+Ca and Pb+Pb collisions and then rapidly disappear for smaller systems

NA61 plans: Search for the Critical Point

Search for the hill of fluctuations





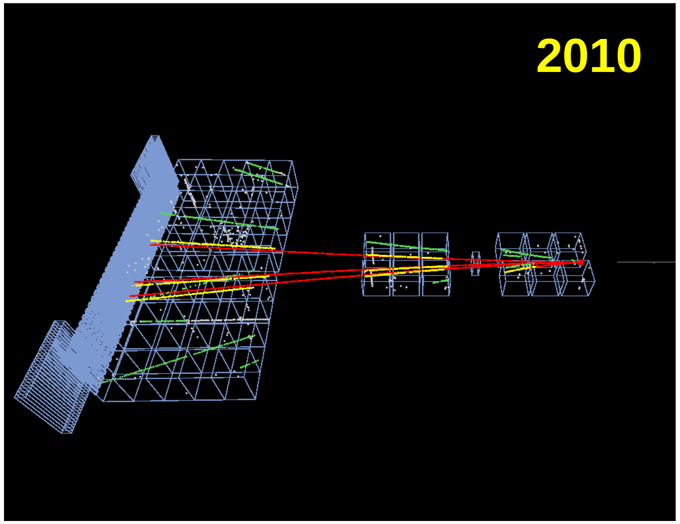
CP signal
ω, Φ_{pT}, ...

Increase of critical point signal (multiplicity and average p_T fluctuations, etc.) **for system freezing-out near the critical point**

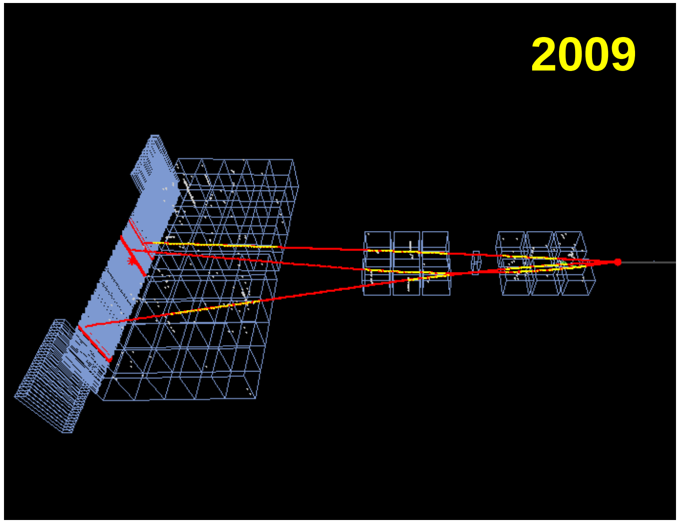
Non-monotonic dependence of critical point signal on control parameters (energy, centrality, ion size) can help to locate the critical point

Where we are today ?

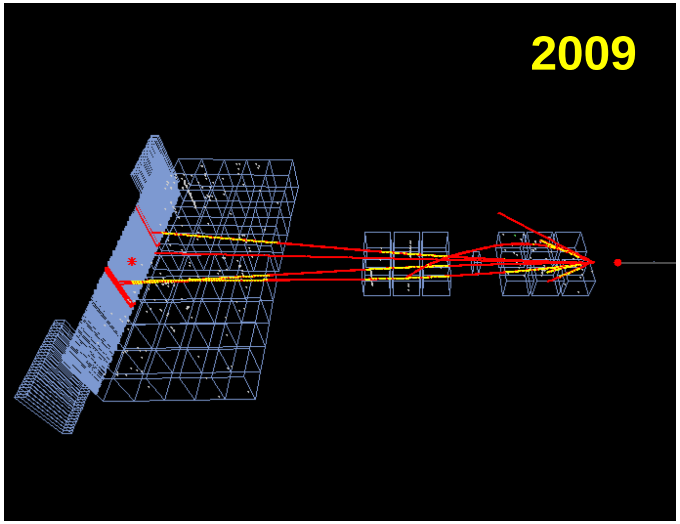
Start of the ion program: 2009/10 data taking periods (data are under calibration)



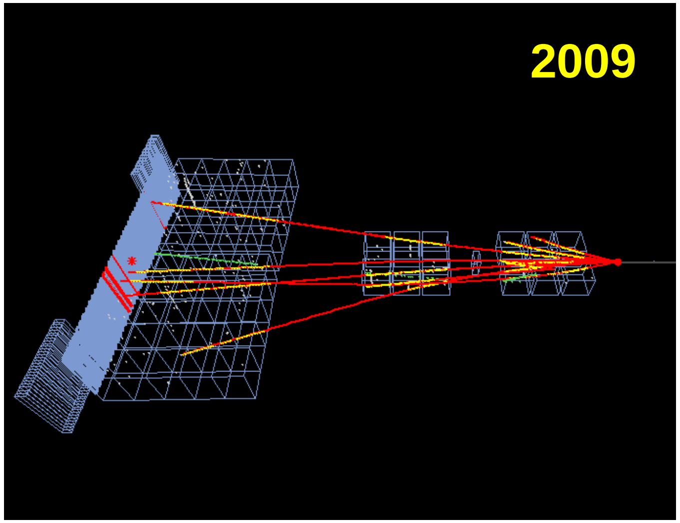
p+p at 13 GeV/c,
~700k events



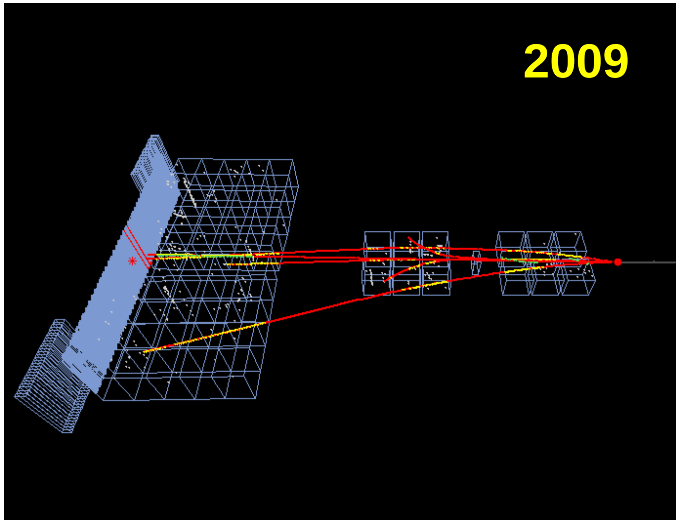
p+p at 20 GeV/c,
2M events



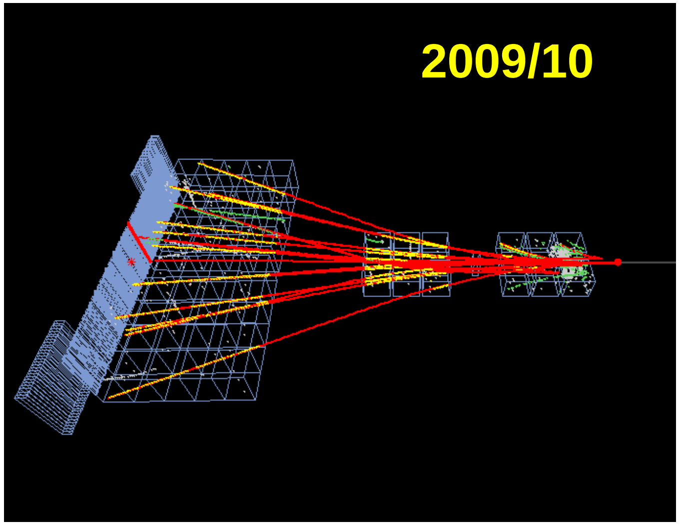
p+p at 31 GeV/c,
3M events



p+p at 40 GeV/c,
6M events

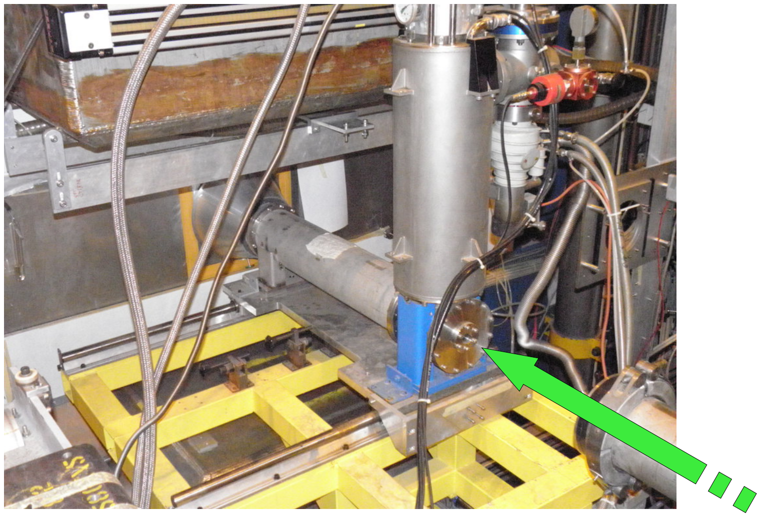


p+p at 80 GeV/c,
4M events



p+p at 158 GeV/c,
4M events

- NA61 interaction trigger selects mostly **Target** interaction but small fraction of unwanted **Non-Target** interactions is also included (the problem mostly concerns p+p interactions)

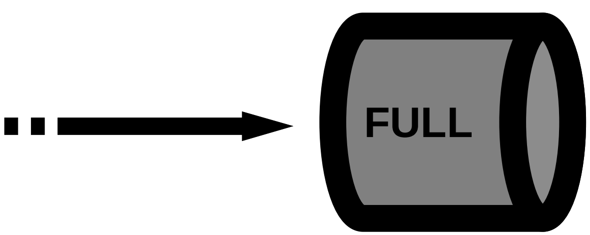


beam

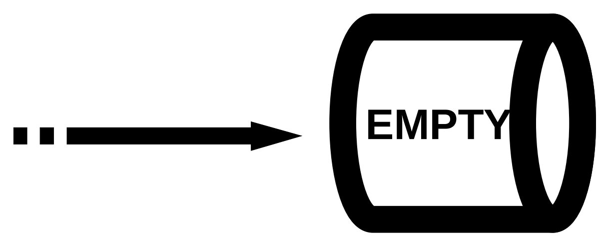
p+p interactions in NA61

Target: 20cm long liquid hydrogen (LH);
contamination from Non-Target interactions
(collisions with windows, air/gas, etc.)

- In order to make corrections for those Non-Target interactions, NA61 acquires data also without target: EMPTY (for LH target) or OUT (for solid targets)



p+p full
target
interactions



p+p empty
target
interactions

Here will be presented a **procedure of extracting Non-Target events for fluctuation measures**

We will use α as a fraction of Target interactions within **Full** data sample:

$$\alpha = \frac{n_T^F}{n^F}$$

where n^F_T is the number of Target interactions within Full data sample and n^F is the total number of interactions within Full data sample

For an event variable W we can write:

$$\langle W \rangle_T^F = \frac{1}{\alpha}\left[\langle W \rangle^F - (1-\alpha)\langle W \rangle_{NT}^F\right]$$

$< W >^F_T$ is what we would like to calculate in the end: event mean value for Target interactions (within Full data sample)

$< W >^F$ is what we directly calculate from Full data sample: the event mean value for whole Full data sample

$< W >^F_{NT}$ is what we want to extract: event mean value for Non-Target interactions (within Full data sample)

Assumption

Event mean values for Non-Target interactions are the same within Full and Empty data samples calculated independently

$$\langle W \rangle_{NT}^{F} = \langle W \rangle_{NT}^{E}$$

As Empty data sample consists only of Non-Target interactions:

$$\langle W \rangle_{NT}^{F} = \langle W \rangle^{E}$$

And Target interactions are only in Full data sample:

$$\langle W \rangle_{T}^{F} = \langle W \rangle_{T}$$

Event mean value for interactions on Target:

$$\langle W \rangle_{T} = \frac{1}{\alpha}\left[\langle W \rangle^{F} - (1-\alpha)\langle W \rangle^{E}\right] \quad (*)$$

How to calculate α (using main vertex Z distribution)

Let us define $$c = \frac{n^F_{NT}}{n^E_{NT}}$$

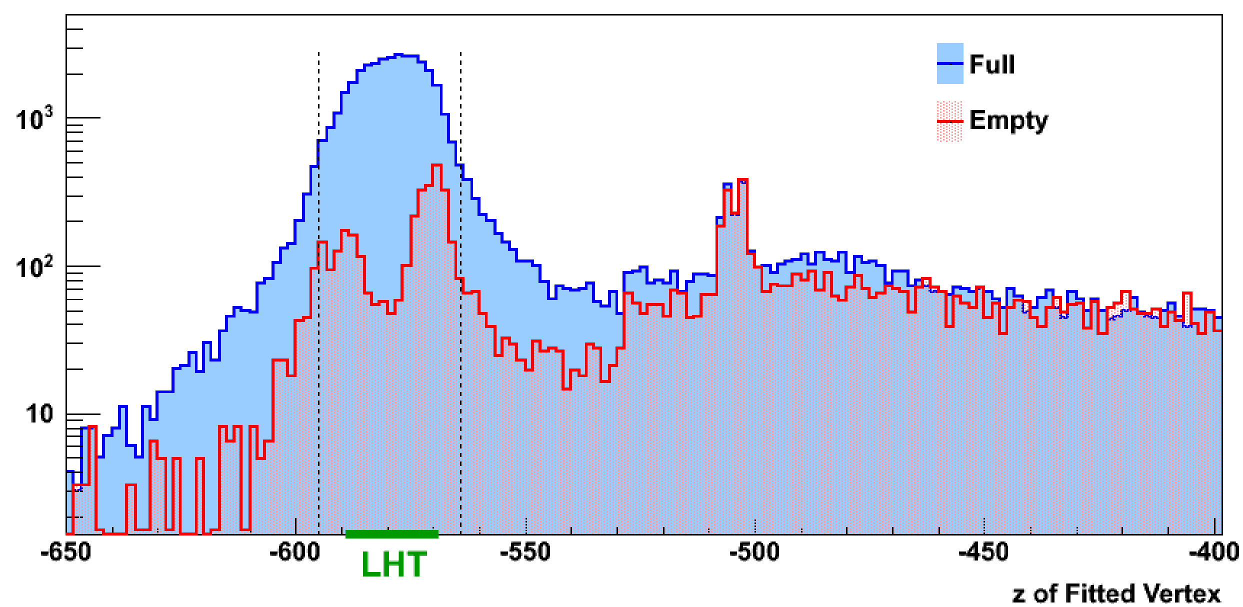
which depends on the **sizes of used Full and Empty data samples**

This leads to: $$\alpha = \frac{n^F - c \cdot n^E}{n^F}$$

40 GeV/c, **uncalibrated data**, small fraction of statistics; only to illustrate the method

We estimated values of *c* as a ratio of number of events with vertex Z position far from target (-450*cm* to 100*cm*):

$$c \approx \left[\frac{n^F}{n^E} \right]_{v_z > -450cm}$$



Scaled variance ω

Definition: $$\omega = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

Calculate:

- α – fraction of interactions on Target within Full data sample
- $< N >$ and $< N^2 >$ independently for Full and Empty data (traditional way)
- the same but for interactions on target:

$$\langle N \rangle_T = \frac{1}{\alpha}[\langle N \rangle^F - (1-\alpha)\langle N \rangle^E]$$

$$\langle N^2 \rangle_T = \frac{1}{\alpha}[\langle N^2 \rangle^F - (1-\alpha)\langle N^2 \rangle^E]$$

- ω_T - scaled variance for interactions on Target:

$$\omega = \frac{\langle N^2 \rangle_T - \langle N \rangle_T^2}{\langle N \rangle_T}$$

Φ measure of fluctuations

Definition: $$\Phi = \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z^2}}$$

where $$Z = \sum_{i=1}^{N} (x_i - \bar{x}) = \sum_{i=1}^{N} x_i - N\,\bar{x}$$ (calculated per event)

$$z = x - \bar{x}$$ (calculated per particle)

x is a per-particle quantity that is a subject of Φ analysis (e.g. p_T)

$\overline{z^2}$ and $\langle Z^2 \rangle$ include quantities that are **not event mean** values, and cannot be corrected using equation (*) - see slide 14

One can rewrite the equation for Φ so that it only contains averages over events

↓

$$\Phi = \sqrt{\frac{\langle X^2 \rangle}{\langle N \rangle} - \frac{2\langle X \rangle \langle N X \rangle}{\langle N \rangle^2} + \frac{\langle X \rangle^2 \langle N^2 \rangle}{\langle N \rangle^3}} - \sqrt{\frac{\langle X_2 \rangle}{\langle N \rangle} - \frac{\langle X \rangle^2}{\langle N \rangle^2}} \qquad (**)$$

where $X = \sum_{i=1}^{N} x_i$ and $X_2 = \sum_{i=1}^{N} x_i^2$

(Liu et al., Eur. Phys. J. **C8**, 649 (1999);
Mrówczyński, Phys. Lett. **B465**, 8 (1999))

Every quantity with < > in equation above is an event mean value and can be corrected using equation (*)

$$\text{e.g. } \langle X \rangle_T = \frac{1}{\alpha}\left[\langle X \rangle^F - (1-\alpha)\langle X \rangle^E\right]$$

And also quantities that seem to be more complicated:

$$\langle N X \rangle_T = \frac{1}{\alpha}\left[\langle N X \rangle^F - (1-\alpha)\langle N X \rangle^E\right]$$

The above is true because every quantity between brackets < > is calculated independently for each event

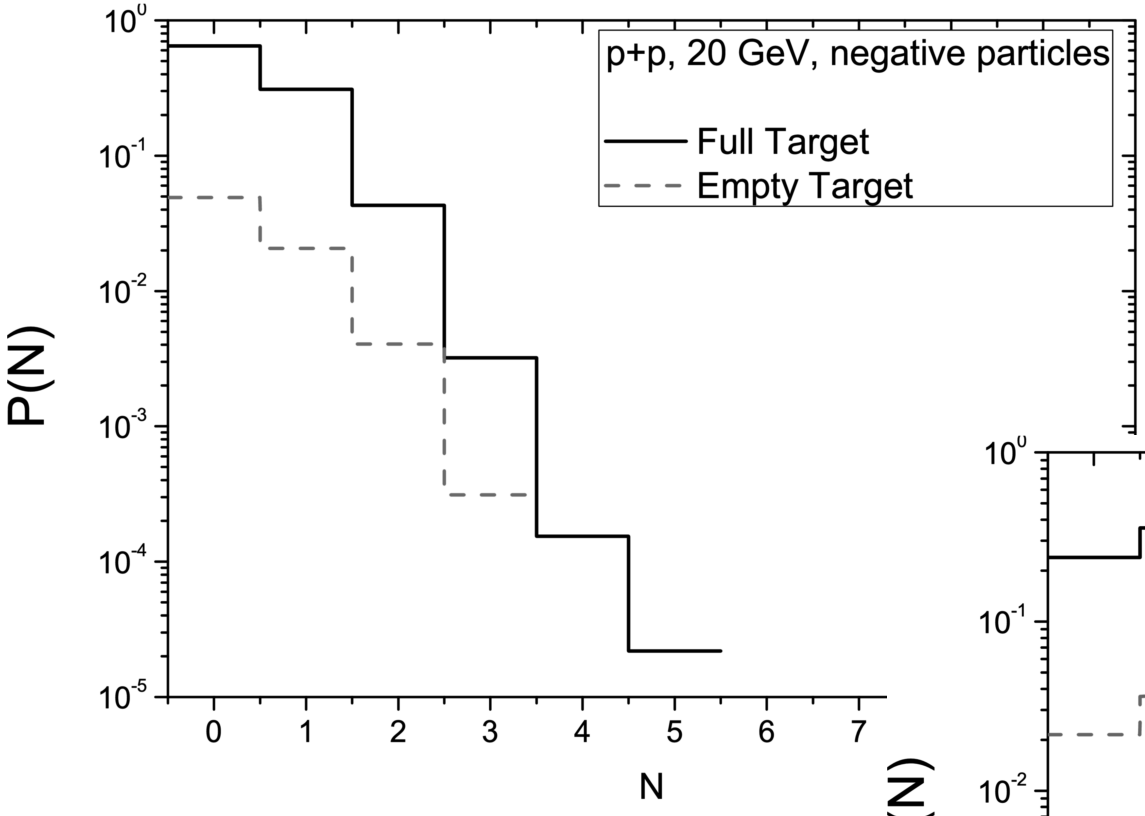
Procedure highlight for Φ measure:

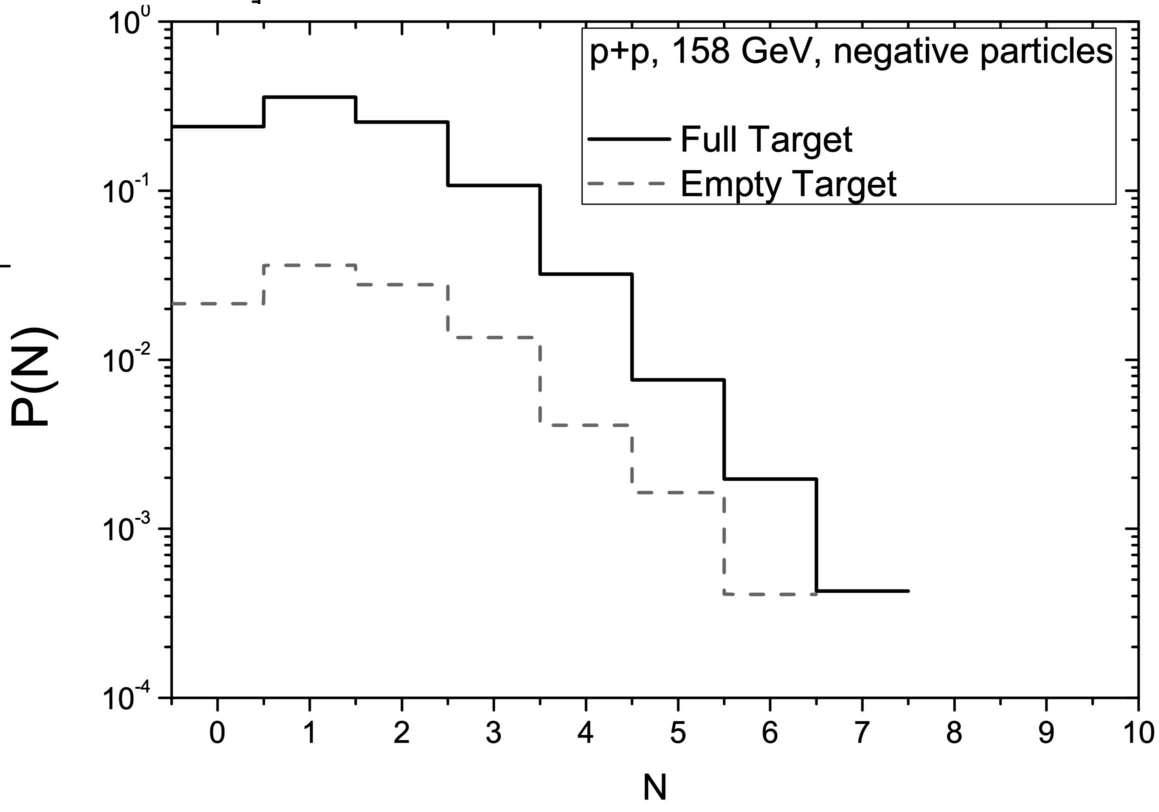
Calculate:

- α – fraction of interactions on Target within Full data sample
- All < > values independently for Full and Empty data (traditional way)
- All < > values for interactions on Target using equation (*)
- Value of Φ measure for interactions on Target using equation (**)

First multiplicity distributions in p+p

!! uncalibrated data, small fraction of statistics, **not corrected yields !!**

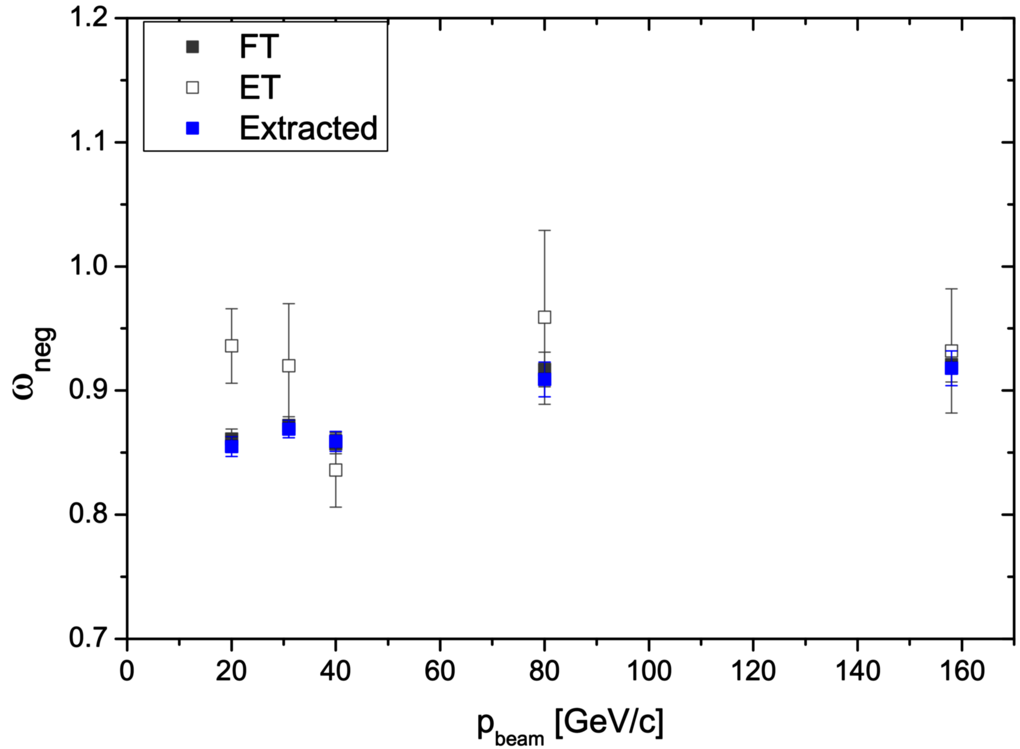




M. Rybczyński

First results on multiplicity fluctuations in p+p

!! uncalibrated data, small fraction of statistics; only to illustrate the method **!!**



p_{beam} [GeV/c]	α
20	0.926
31	0.940
40	0.908
80	0.900
158	0.895

$$\langle N \rangle = \sum N \cdot P(N)$$

$$V(N) = \langle N^2 \rangle - \langle N \rangle^2$$

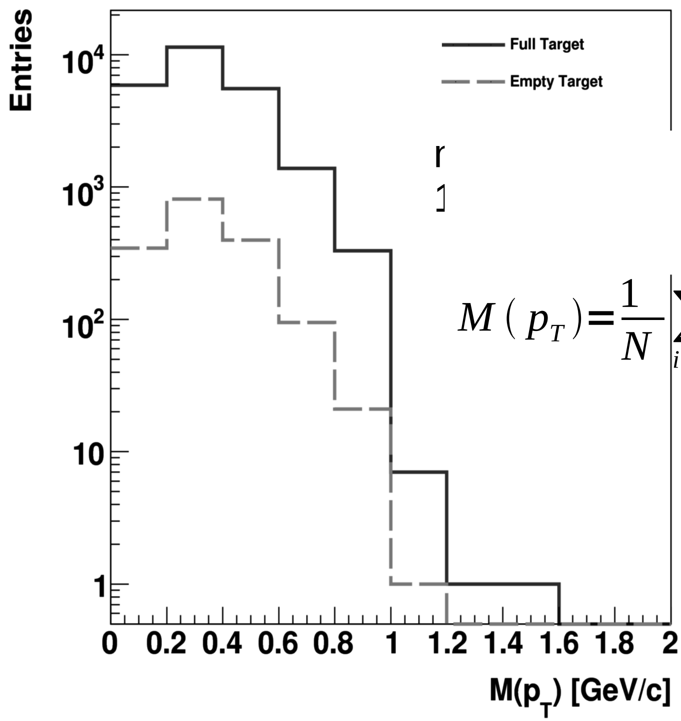
$$\text{scaled variance} \quad \omega = \frac{V(N)}{\langle N \rangle}$$

For uncalibrated data the difference between Full Target (FT) and 'Extracted' (|Extracted - FT|/Extracted) is lower than 1%

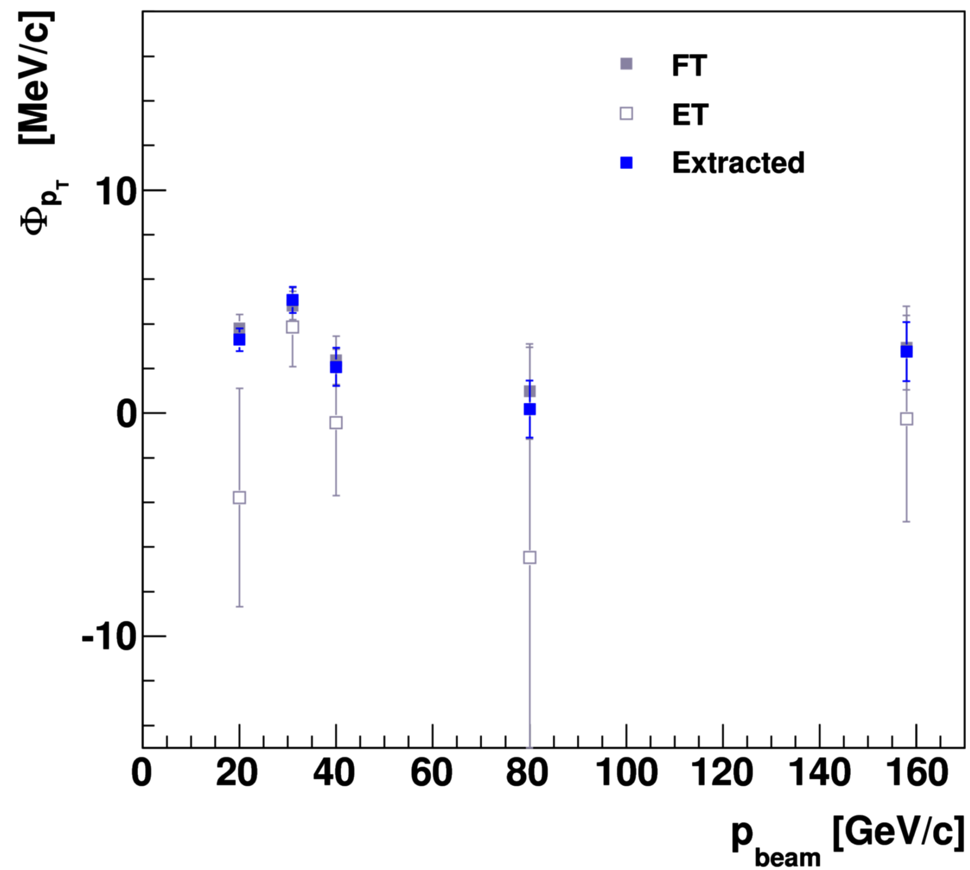
M. Rybczyński

First results on average p_T fluctuations in p+p

!! uncalibrated data, small fraction of statistics; only to illustrate the method **!!**



$$M(p_T) = \frac{1}{N} \sum_{i=1}^{N} p_{T_i}$$



Correction for Non-Target interactions is small

M. Bogusz

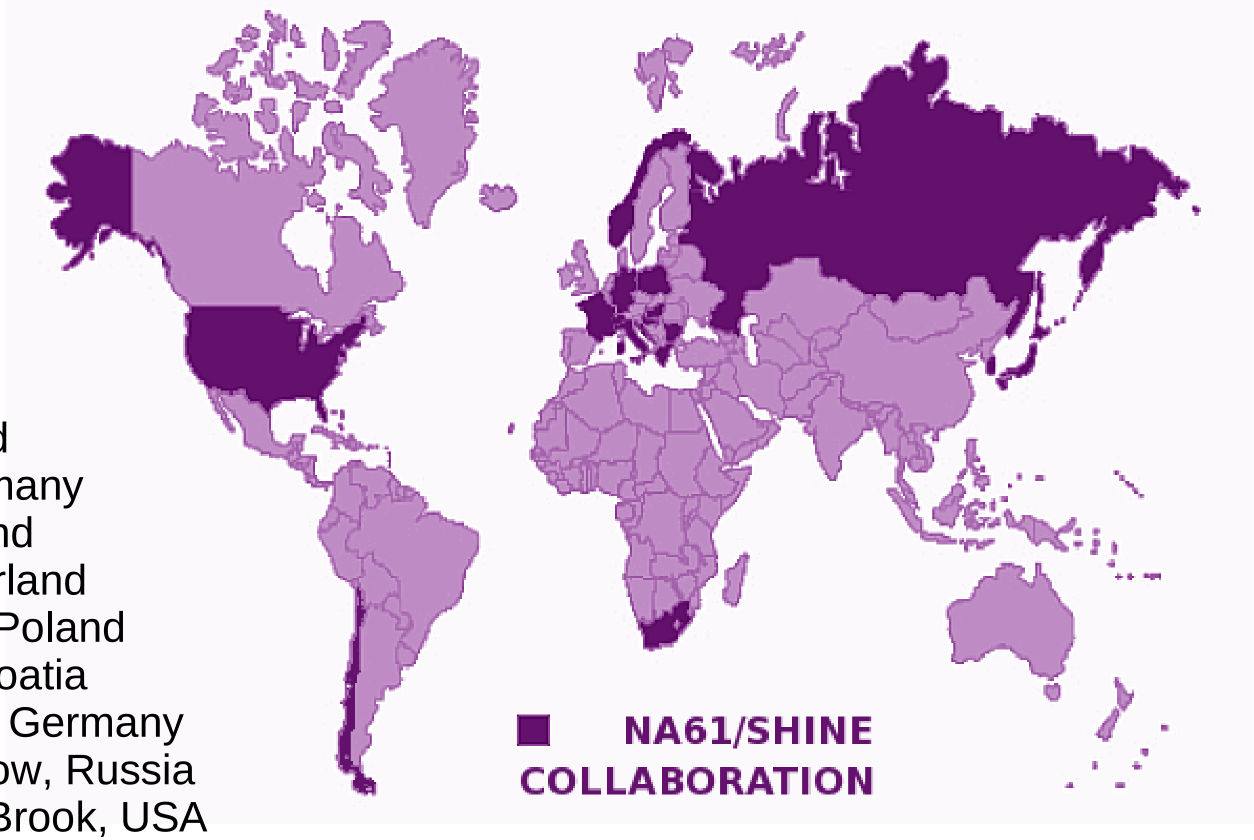
Summary

- NA61/SHINE ion program explores the most interesting region of the phase diagram of strongly interacting matter

- NA61/SHINE has the potential to discover the critical point of strongly interacting matter and guarantees systematic data on the onset of deconfinement

- Data taking has started in NA61/SHINE; first results of the program on p+p collisions will be available within the coming year

NA61/SHINE Collaboration:



1. University of Athens, Athens, Greece
2. University of Bari and INFN, Bari, Italy
3. University of Bergen, Bergen, Norway
4. University of Bern, Bern, Switzerland
5. ETH, Zurich, Switzerland
6. University of Warsaw, Warsaw, Poland
7. University of Frankfurt, Frankfurt, Germany
8. Jagiellionian University, Cracow, Poland
9. University of Geneva, Geneva, Switzerland
10. Jan Kochanowski University, Kielce, Poland
11. Rudjer Boskovic Institute, Zagreb, Croatia
12. Fachhochschule Frankfurt, Frankfurt, Germany
13. Institute for Nuclear Research, Moscow, Russia
14. State University of New York, Stony Brook, USA
15. Cape Town University, Cape Town, South Africa
16. KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
17. Joint Institute for Nuclear Research, Dubna, Russia
18. Forschungszentrum Karlsruhe, Karlsruhe, Germany
19. LPNHE, Universités de Paris VI et VII, Paris, France
20. Pusan National University, Pusan, Republic of Korea
21. Faculty of Physics, University of Sofia, Sofia, Bulgaria
22. St. Petersburg State University, St. Petersburg, Russia
23. Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
24. Soltan Institute for Nuclear Studies, Warsaw, Poland
25. Warsaw University of Technology, Warsaw, Poland
26. Universidad Tecnica Federico Santa Maria, Valparaiso, Chile

Back-up slides

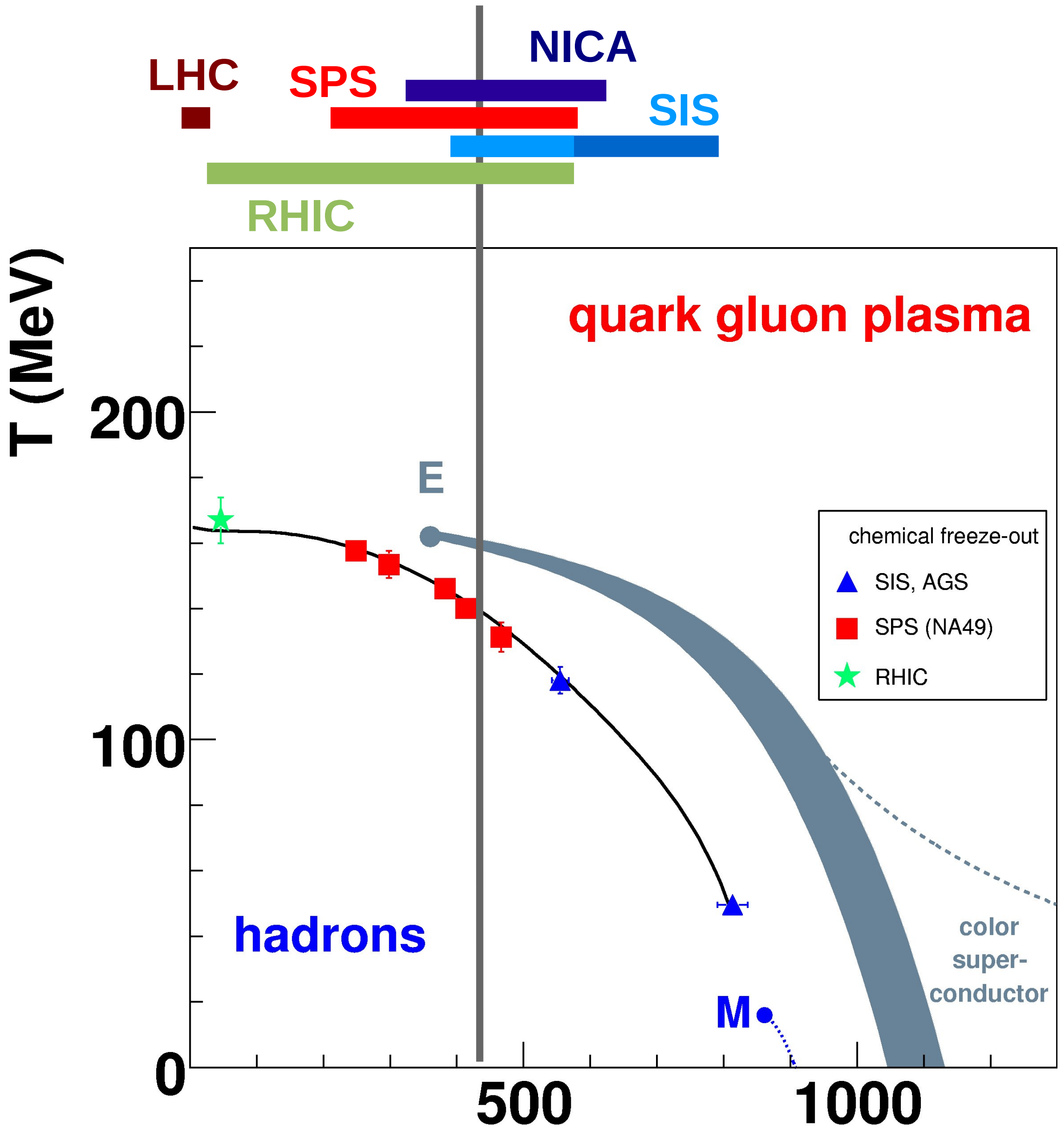
The NA61/SHINE ion program gives the unique opportunity to reach exciting physics goals in a very efficient and cost effective way

It will be complemented by the efforts of other international and national laboratories, **FAIR**, **JINR** and **BNL** and by the heavy ion program at the **CERN LHC**

Facility	SPS	RHIC	NICA	SIS-100 (SIS-300)	LHC
Laboratory	CERN Geneva	BNL Brookhaven	JINR Dubna	FAIR GSI Darmstadt	CERN Geneva
Exper.	NA61/SHINE	STAR PHENIX	MPD	HADES, CBM	ALICE ATLAS CMS
Start	2009(11)	2010	2014	2015 (2017)	2009
cms energy [GeV/(N+N)]	4.9 – 17.3	5 – 39	4 – 11	2.3 – ~5 (~5 – 8.5)	5500 14000 (p+p)
Physics	CP & OD	CP & OD	OD & HDM	HDM (OD & CP)	PDM

CP – critical point
OD – onset of deconfinement, mixed phase, 1st order phase transition
HDM – hadrons in dense matter
PDM – properties of deconfined matter

Programs complementary to NA61/SHINE



the onset of deconfinement

New period in the experimental study of A+A collisions at the SPS energy range started in 2009 with the p+p energy scan of NA61/SHINE at the CERN SPS

RHIC Beam Energy Scan program began this year. We look forward to the start of the corresponding programs at NICA and FAIR as well as to exciting first data from the CERN LHC

Event-by-event transverse momentum and multiplicity fluctuations

Φ_{pT} - measures transverse momentum fluctuations on event-by-event basis

single-particle variable $z_{p_T} = p_T - \bar{p}_T$

$\bar{p}_T$ - inclusive average

event variable $Z_{p_T} = \sum_{i=1}^{N} (p_{T_i} - \bar{p}_T)$

(summation runs over particles in a given event)

$$\Phi_{p_T} = \sqrt{\frac{\langle Z_{p_T}^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z_{p_T}^2}}$$

$\langle ... \rangle$ - averaging over events

ω - measures multiplicity fluctuations on event-by-event basis

Scaled variance of multiplicity distribution

$$\omega = \frac{V(N)}{\langle N \rangle}$$

where variance $V(N) = \langle N^2 \rangle - \langle N \rangle^2$

If A+A is a **superposition** of independent N+N

Φ_{pT} (A+A) = Φ_{pT} (N+N)

Φ_{pT} is independent of N_{part} fluctuations

ω (A+A) = ω (N+N) + < n > ω_{part}

< n > - mean multiplicity of hadrons from a single N+N

ω_{part} - fluctuations in N_{part}

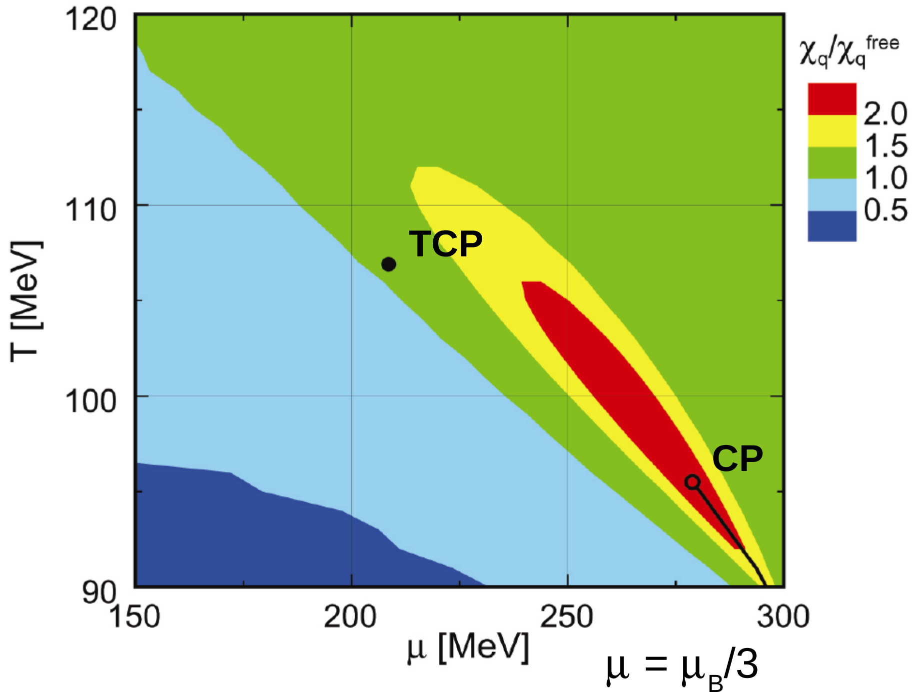
ω is strongly dependent on N_{part} fluctuations

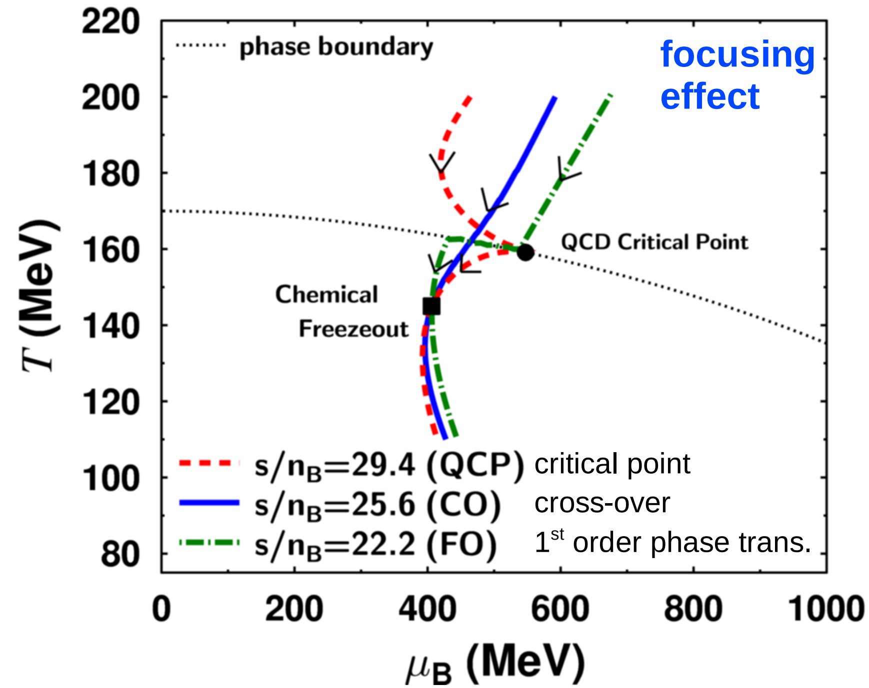
For a system of **independently emitted particles** (no inter-particle correlations)

Φ_{pT} = 0

For **Poissonian multiplicity distribution**

ω =1





For a given chemical freeze-out point three isentropic trajectories (n_B/s = const.) are shown

Hatta and Ikeda, PR**D67**, 014028 (2003)

Askawa et al., PRL**101**, 122302 (2008)

Effect of critical point extends over a critical region with $\sigma(\mu_B)$ and $\sigma(T)$

The presence of the critical point can deform the trajectories describing the evolution of the expanding fireball in the (T,μ_B) phase diagram

⇒We do not need to hit precisely the critical point because **a large region can be affected!**