Results from the NA61/SHINE energy and system size scan program

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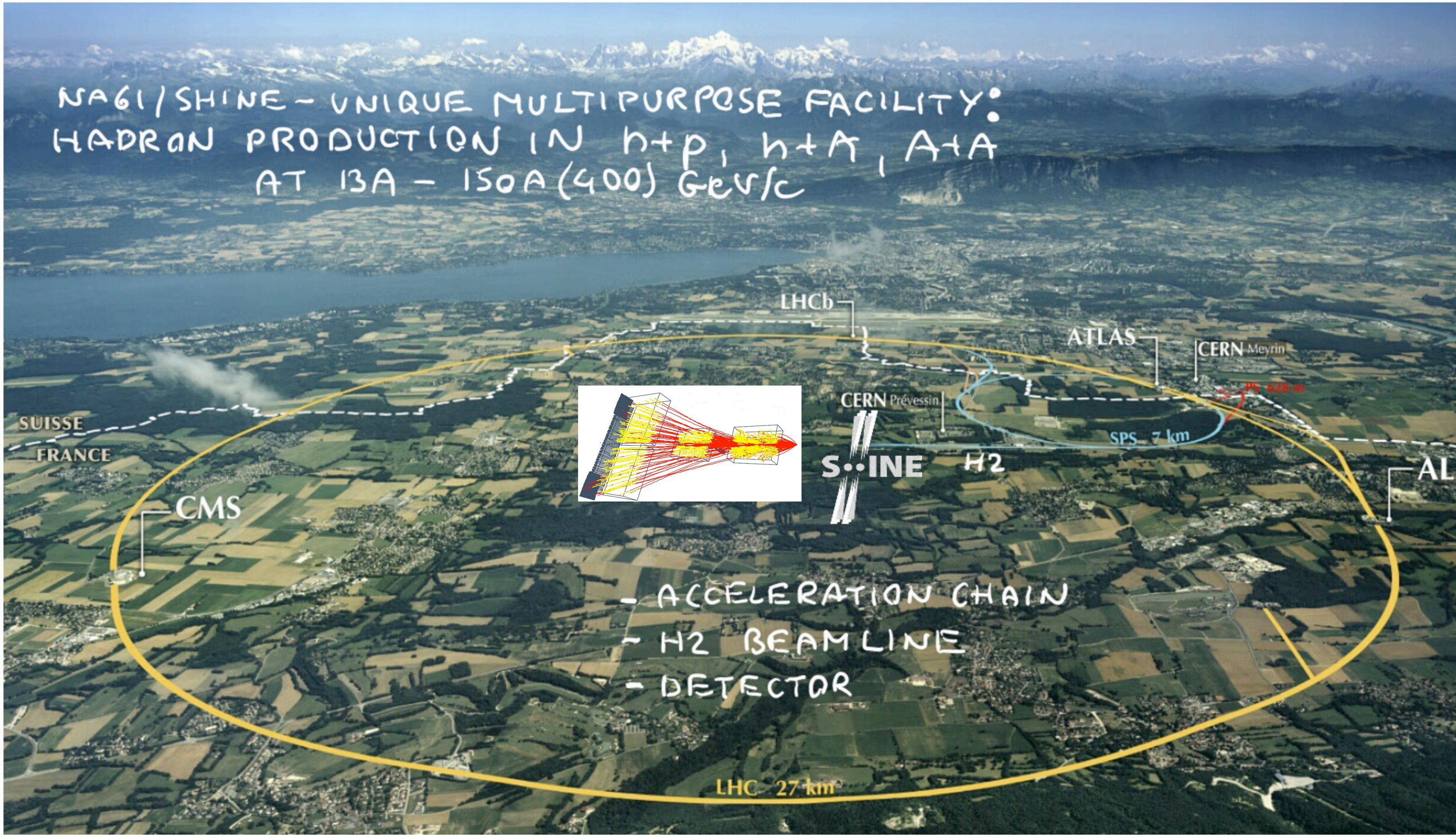
for the NA61/SHINE collaboration

Laboratory of Ultra-High Energy Physics

St. Petersburg State University

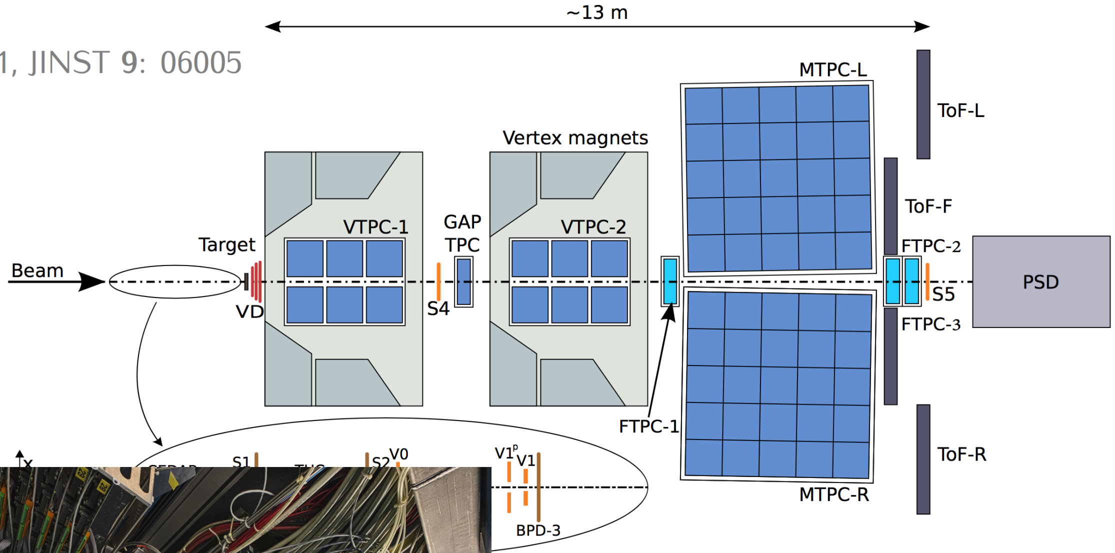
AYSS - 2018
26/4/18

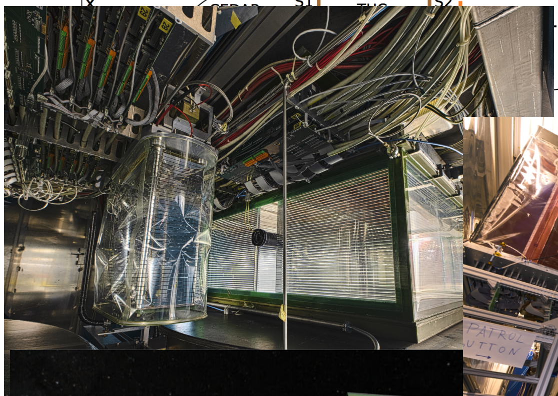
Super Proton Synchrotron Heavy Ion and Neutrino Experiment

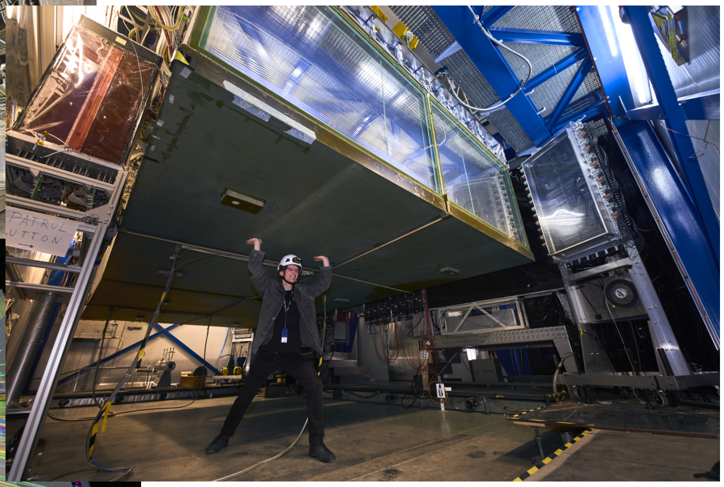


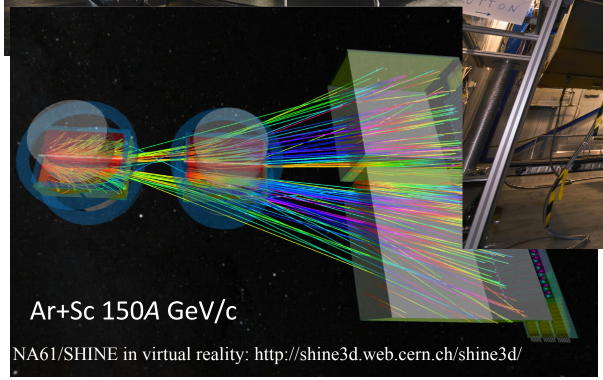
NA61/SHINE experiment

NA61, JINST **9**: 06005





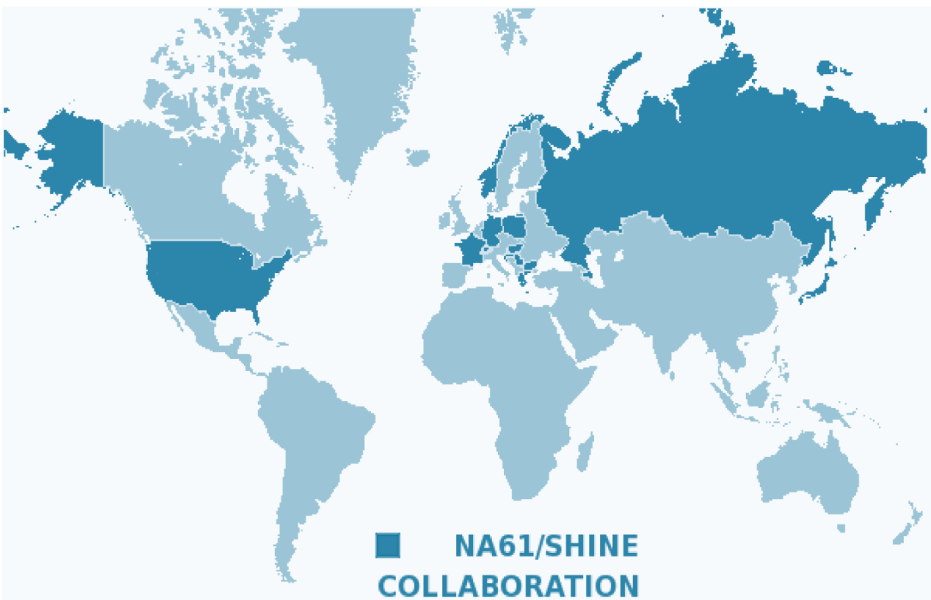




- Large acceptance hadron spectrometer - coverage of the full forward hemisphere, down to $p_T = 0\ \mathrm{GeV}/c$
- Performs measurements on hadron production in h+p, h+A, A+A at 13*A* – 150(8)*A* GeV/*c*
- Event selection in A+A collisions by measurements of forward energy with PSD
- Recent upgrades:
  - Vertex detector (open charm measurements)
  - FTPC-1/2/3

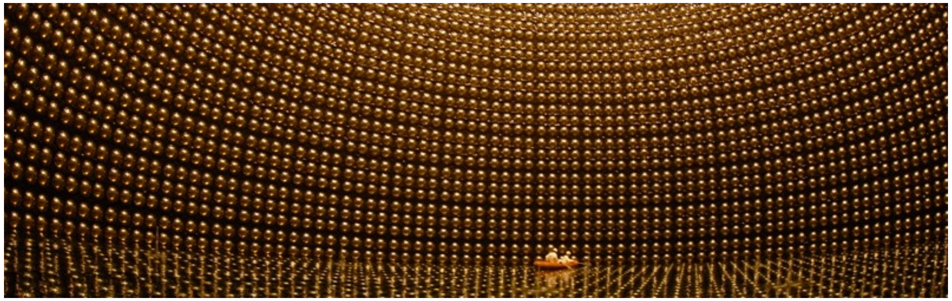
NA61/SHINE experiment

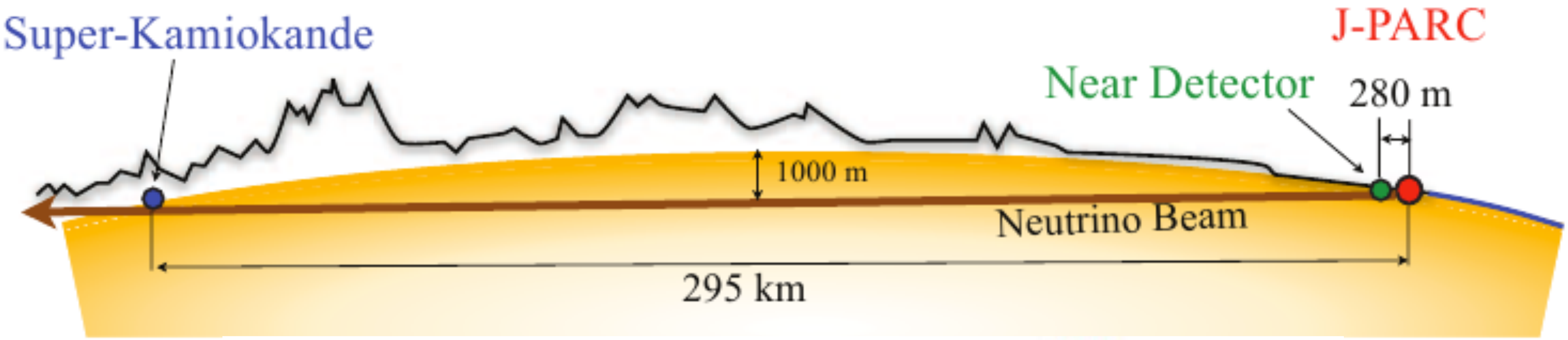
≈ 140 physicists
14 countries
28 institutions

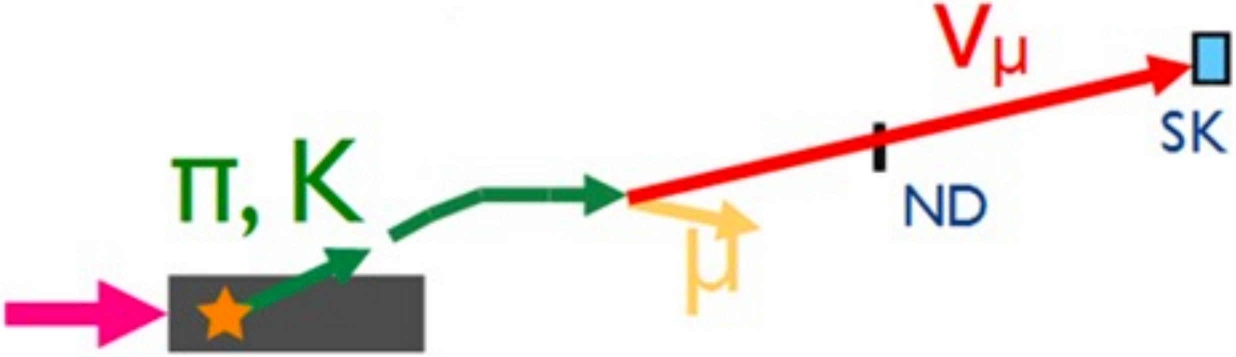


Three main programs:
- **Heavy ions physics**
- Neutrino physics
- Cosmic ray physics

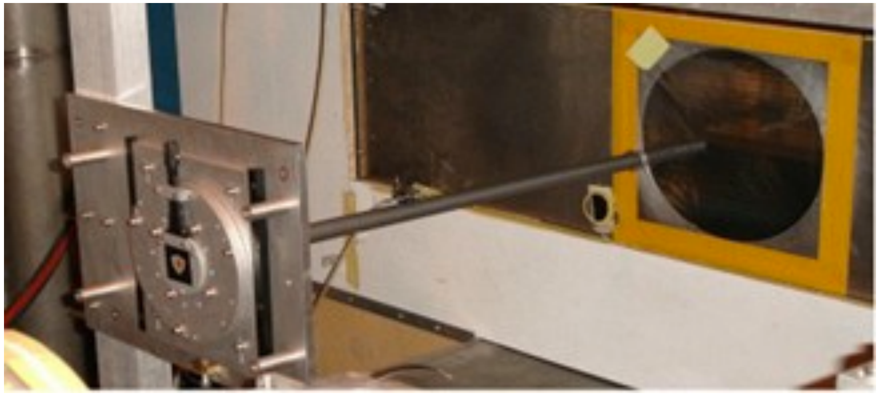
T2K: long baseline neutrino oscillation experiment

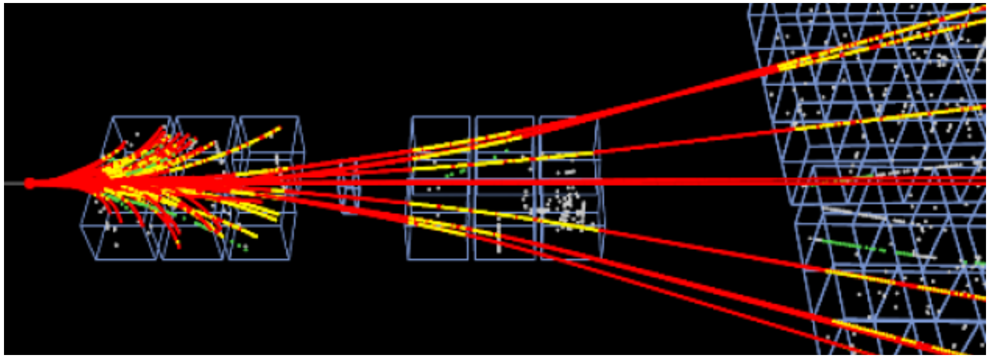






NA61/SHINE → parameters of neutrino beams produced at J-PARC (Japan) and Fermilab (USA)





T2K replica target (90 cm)

p+C at 31 GeV/c

NA61/SHINE, measurements of π ± , K± and proton yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS, submitted to Eur. Phys. J. C.

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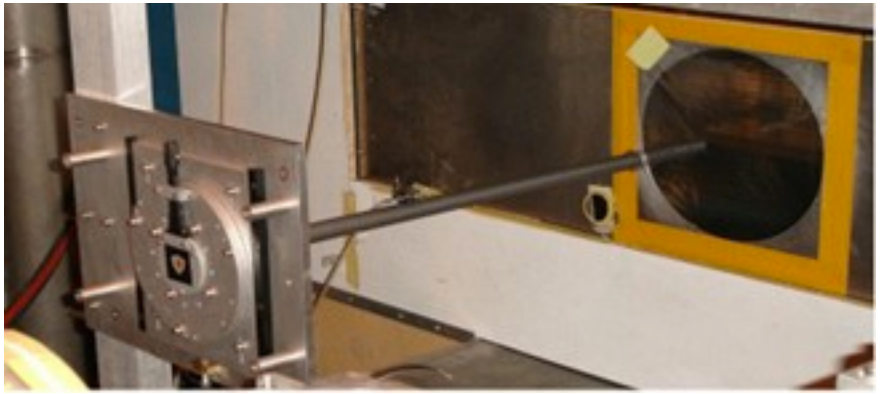

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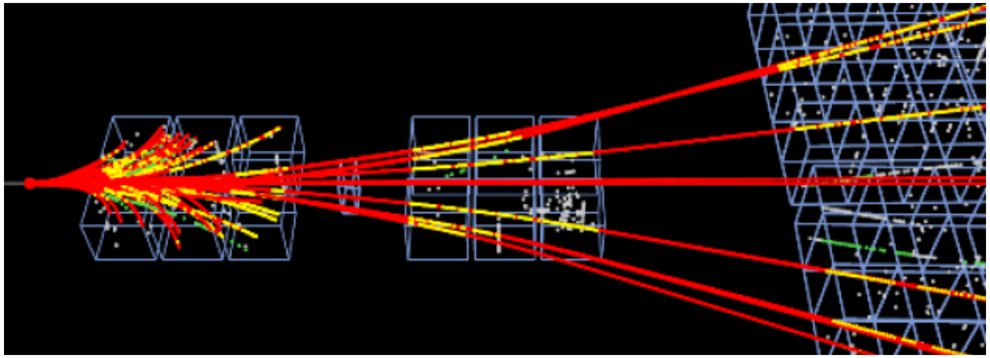

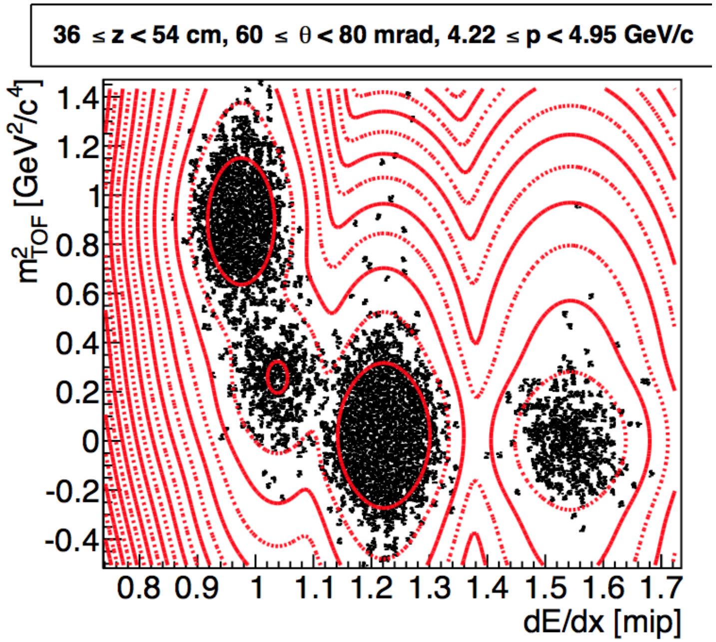

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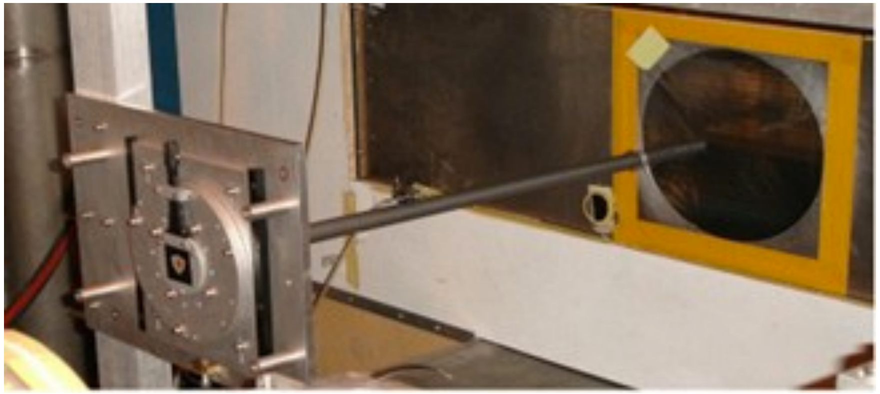

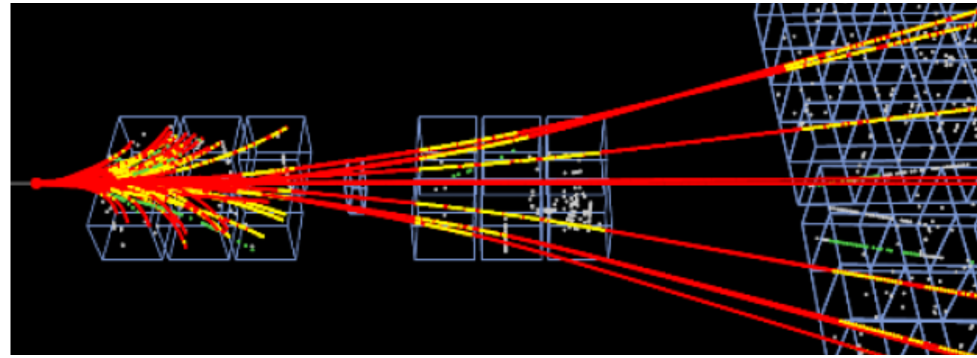

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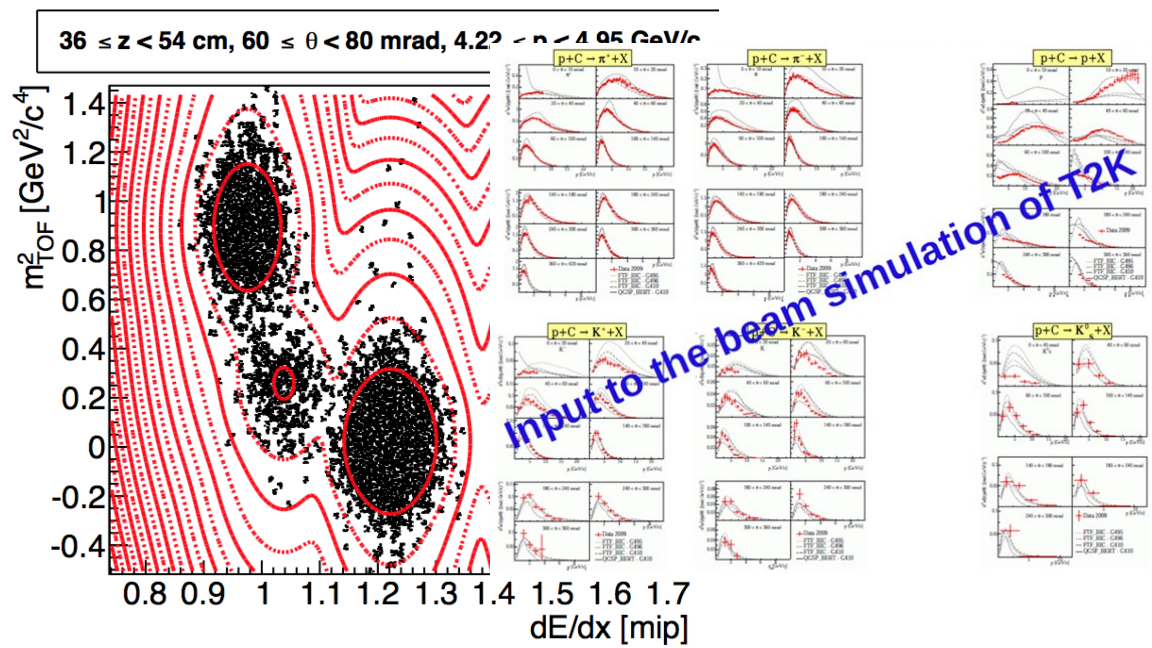

p+C at 31 GeV/c

Systematic uncertainties of (anti) neutrino flux:
25% → 3-4%

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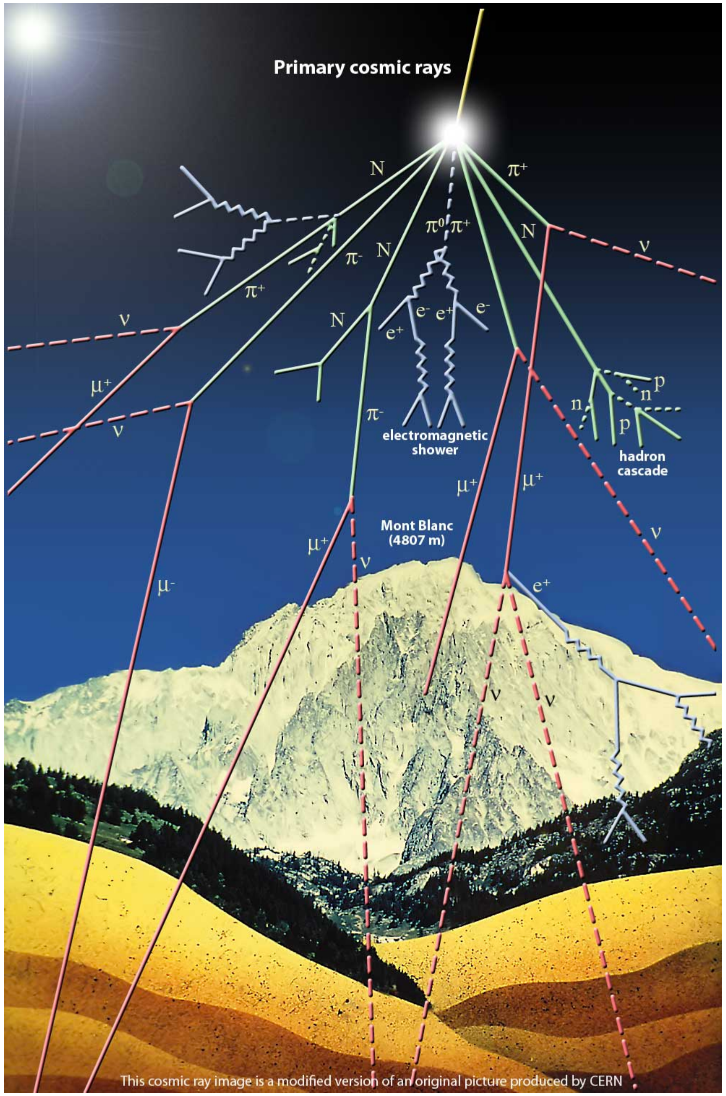
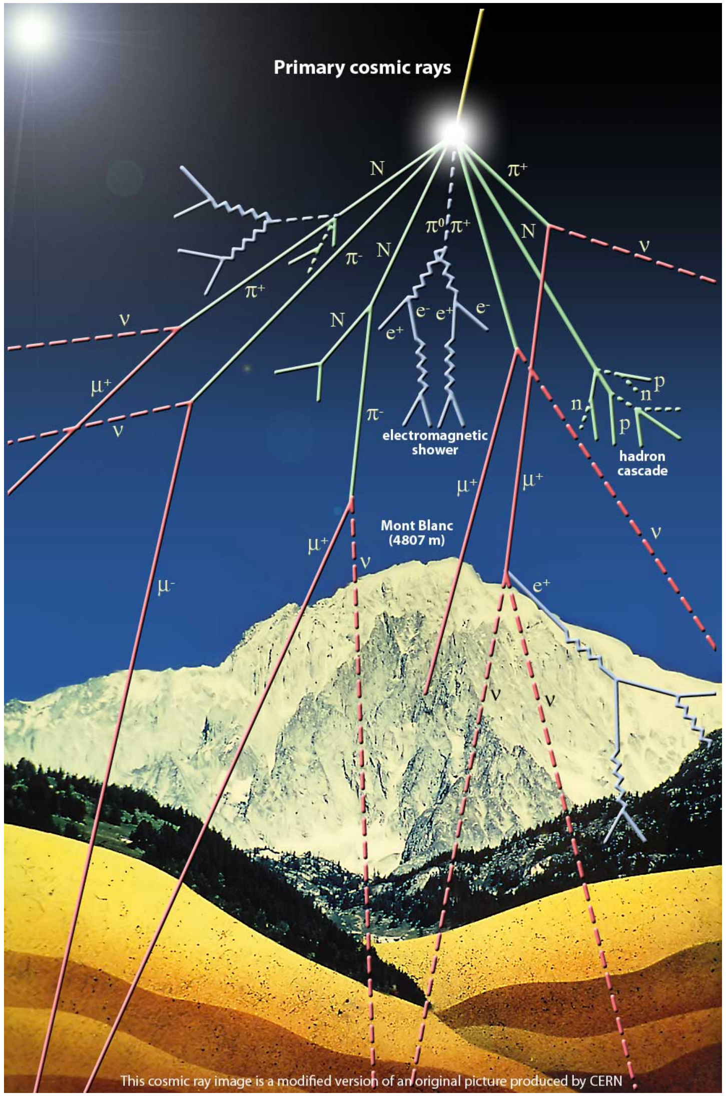
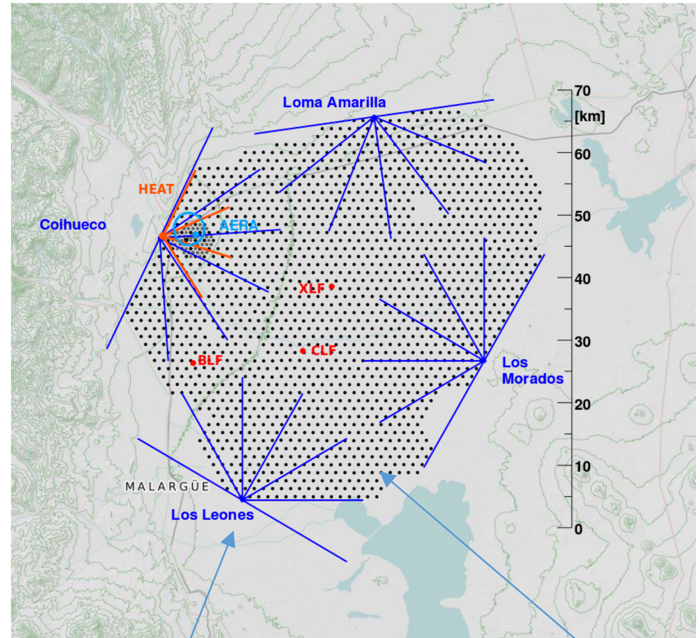

Primary cosmic rays
electromagnetic shower
hadron cascade
Mont Blanc (4807 m)
This cosmic ray image is a modified version of an original picture produced by CERN



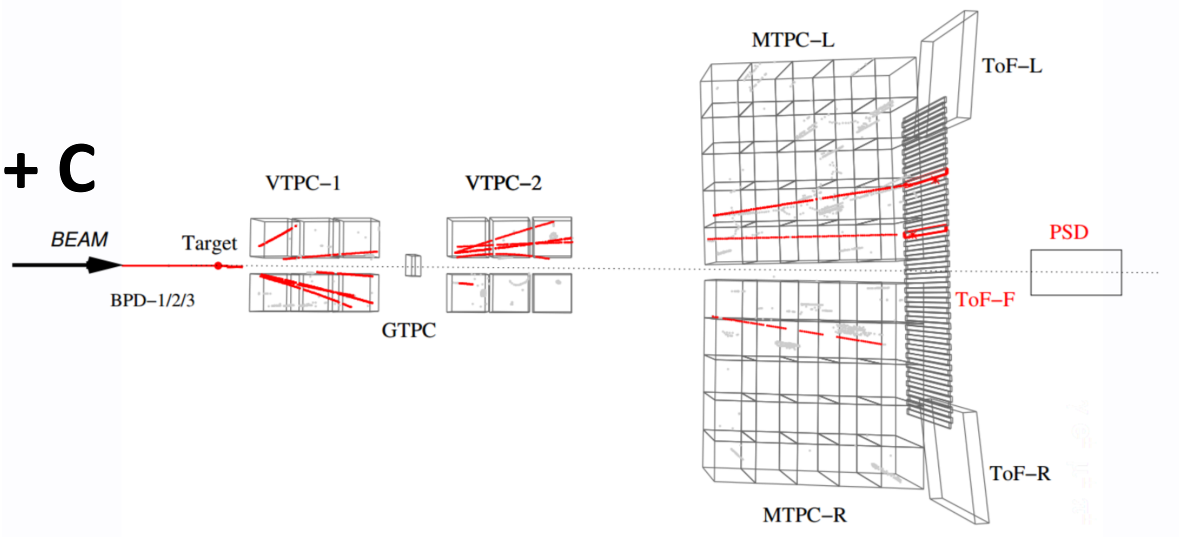
Pierre Auger Observatory



Muons at ground are mostly produced in π-air interactions at ~ 100 GeV, I.C.Maris, ICRC 2009

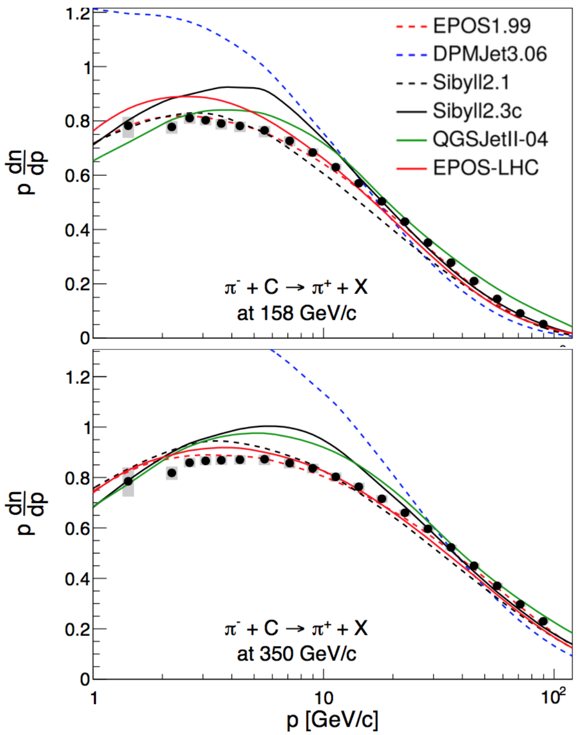
Measurements of hadron-nucleus interactions to improve modeling of cosmic ray showers.

$\pi^- + C$



NA61/SHINE Collab. Eur. Phys. J. C 77 (2017) 626
[arXiv:1705.08206]

Measurements of hadron-nucleus interactions to improve modeling of cosmic ray showers.



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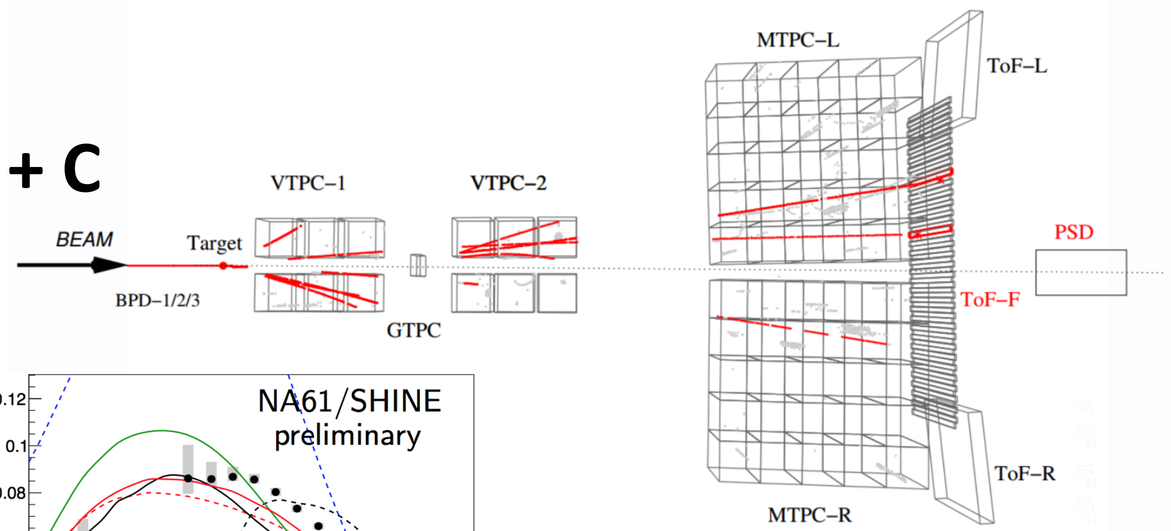

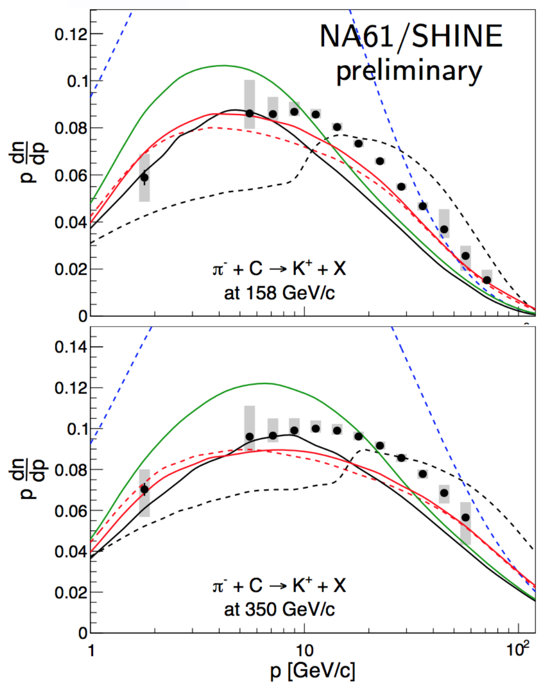

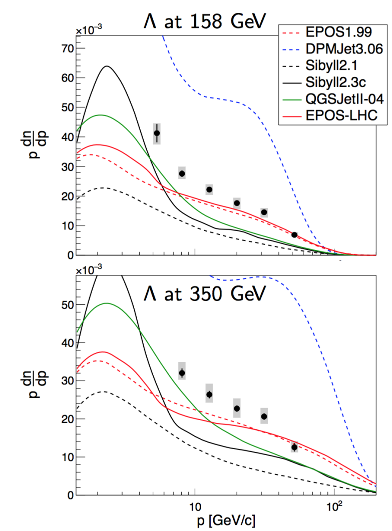

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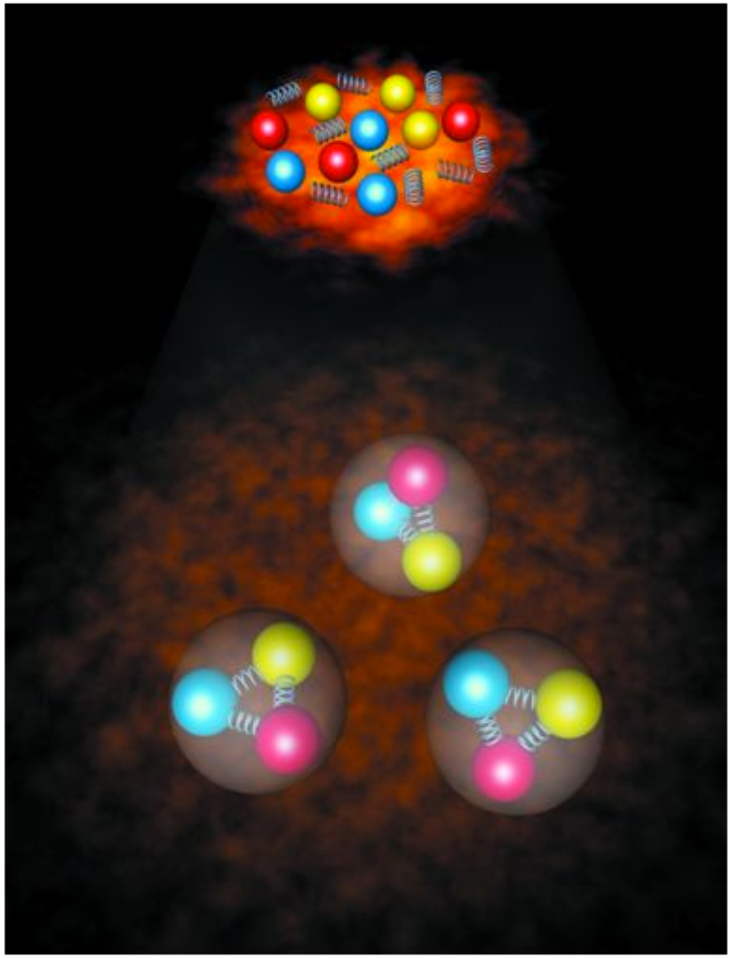
[arXiv:1705.08206]

Phases of water

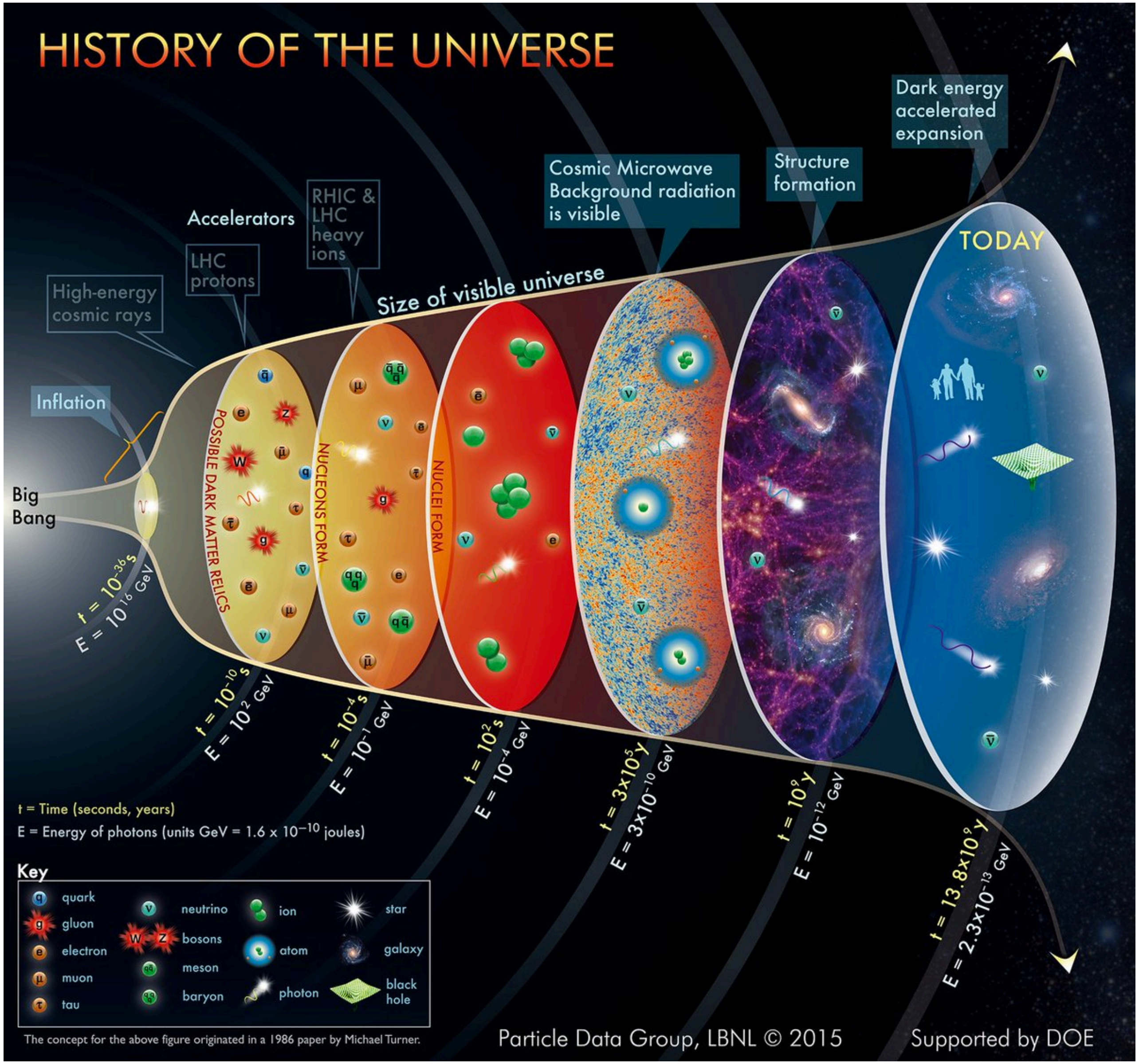
Phases of matter: Quark-Gluon Plasma

Phases of water

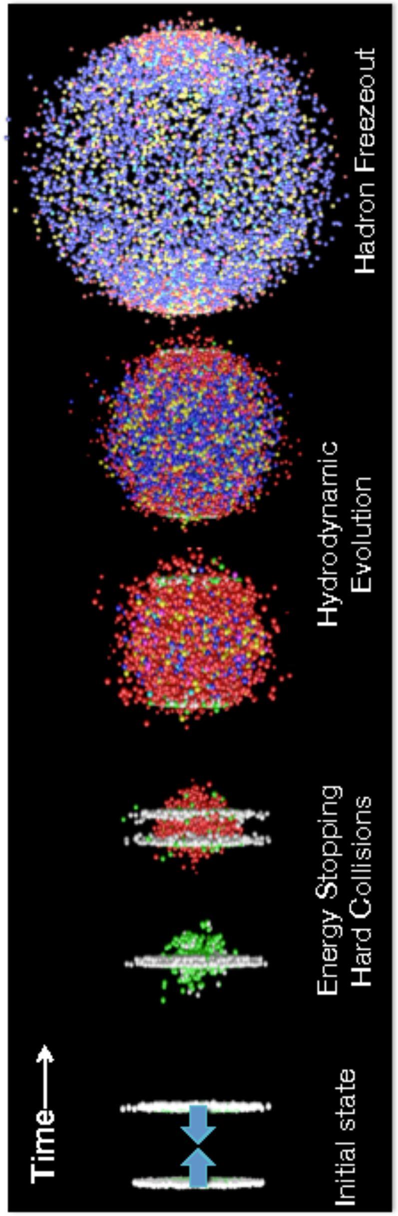
Phases of strongly interacting matter

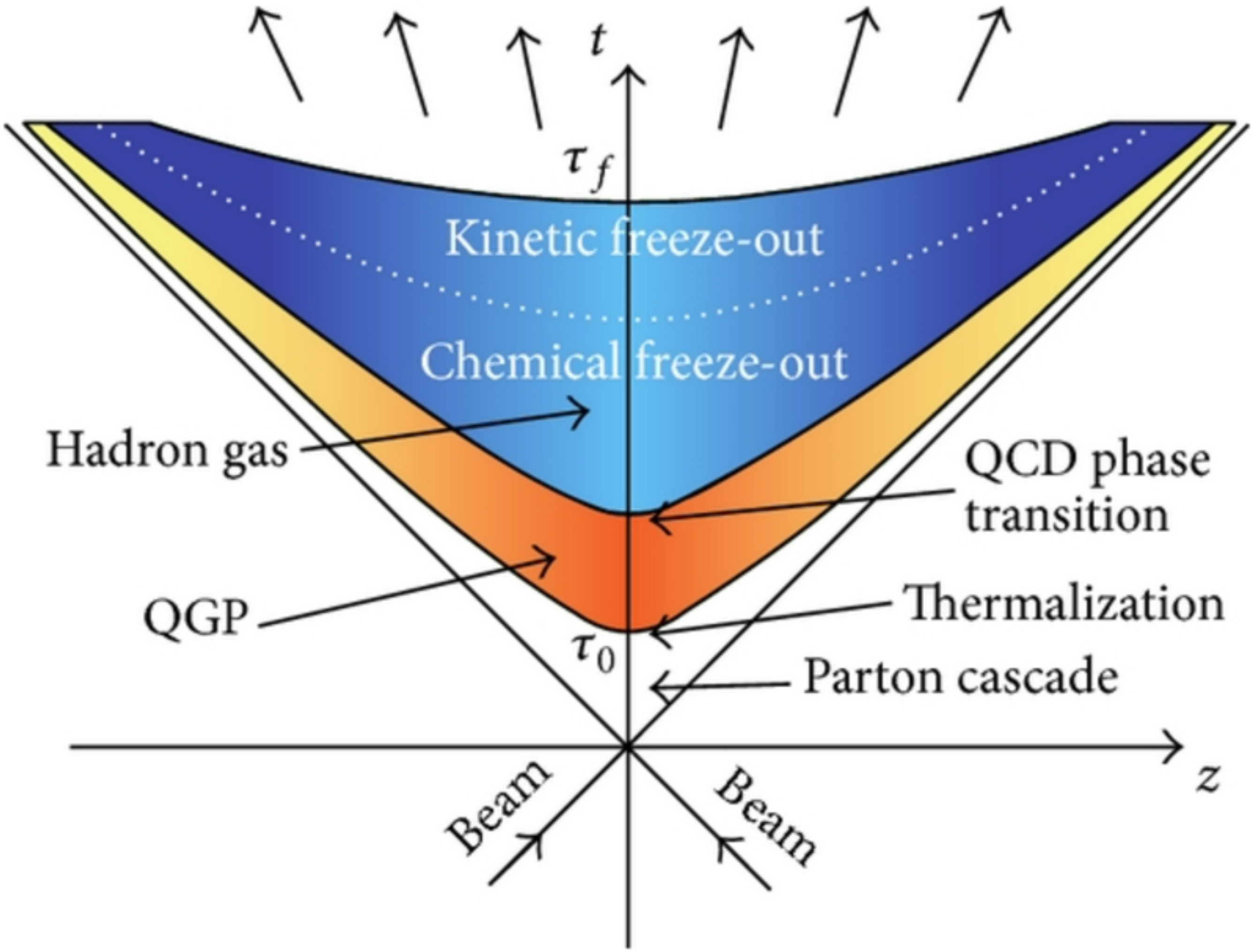


Phases of matter: Quark-Gluon Plasma



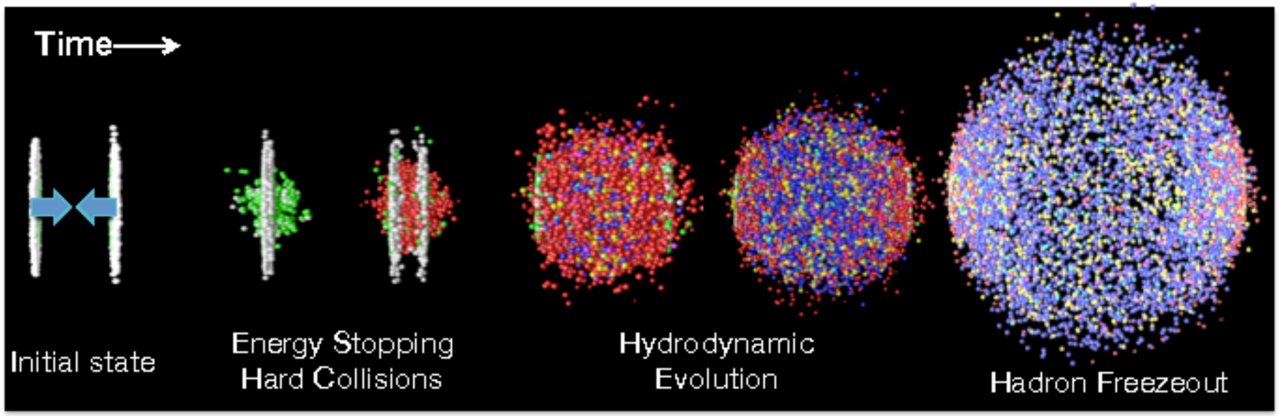
Heavy ion collisions

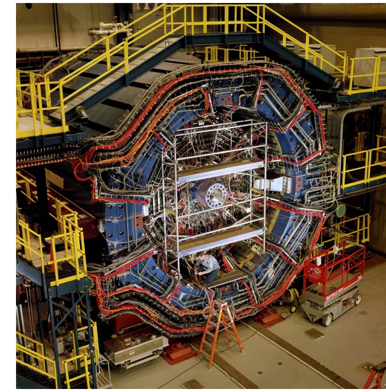




Tawfik, Shalaby, Balance Function in High-Energy Collisions, AHEP, 2014

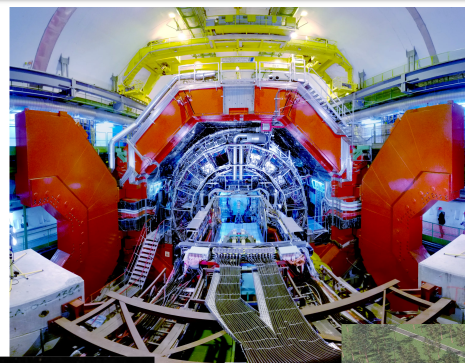
Heavy ion collisions





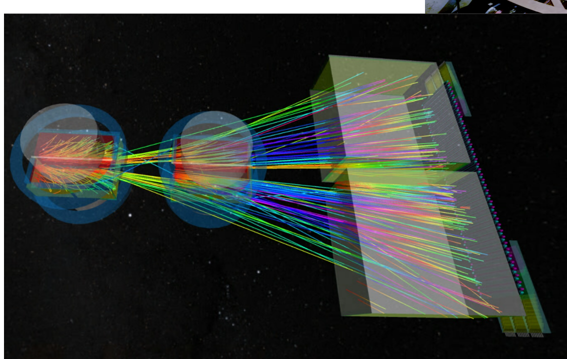
QGP now:

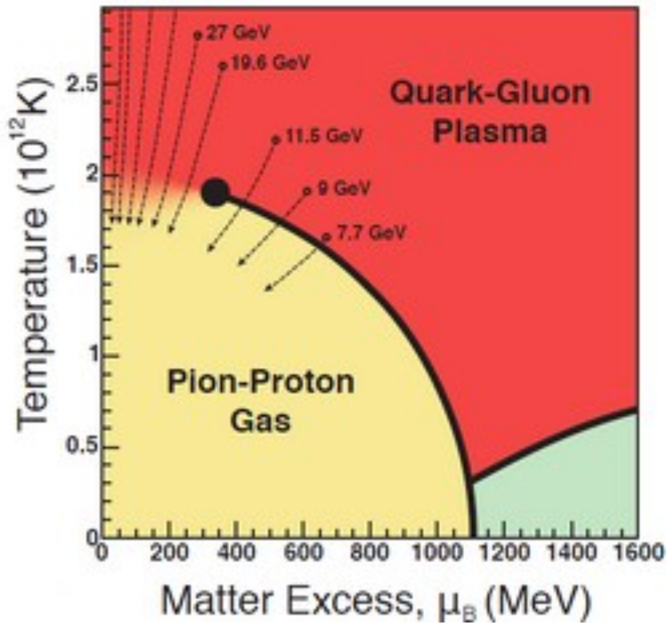
- LHC (CERN)
- RHIC (USA)
- SPS (CERN)
- Nuclotron (JINR)



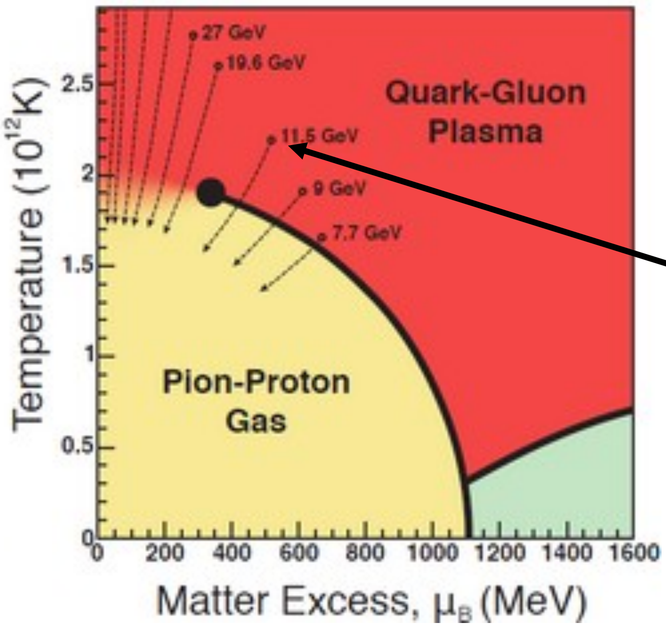
QGP future:

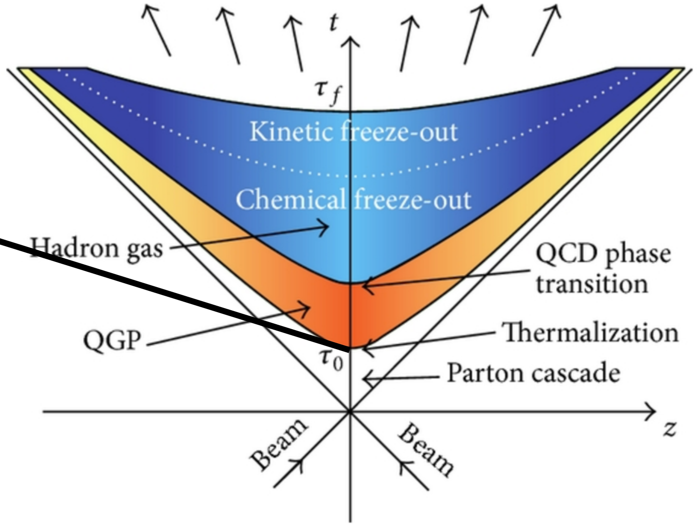
- NICA (JINR)
- FAIR (GSI)
- J-PARC





All phase diagrams of strongly interacting matter are only hypothetical, except $\mu_B \sim 0$ where lattice QCD could be implemented.





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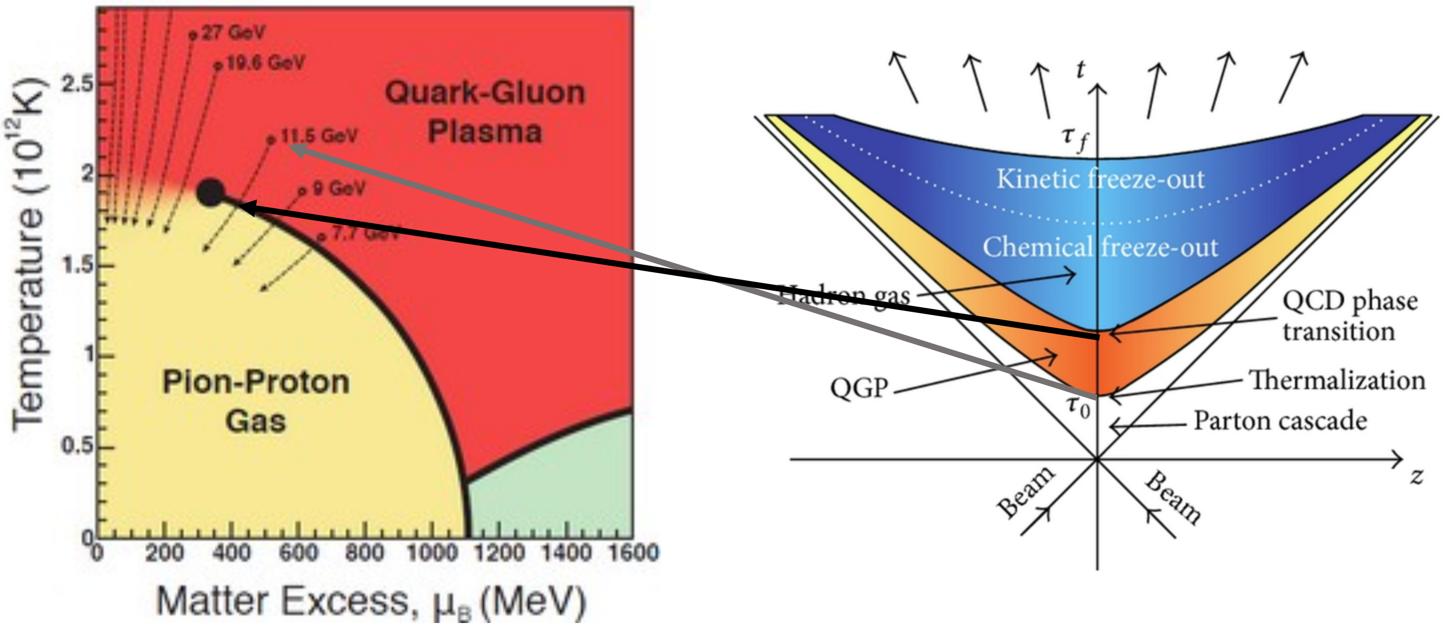
NA61/SHINE Heavy ion program



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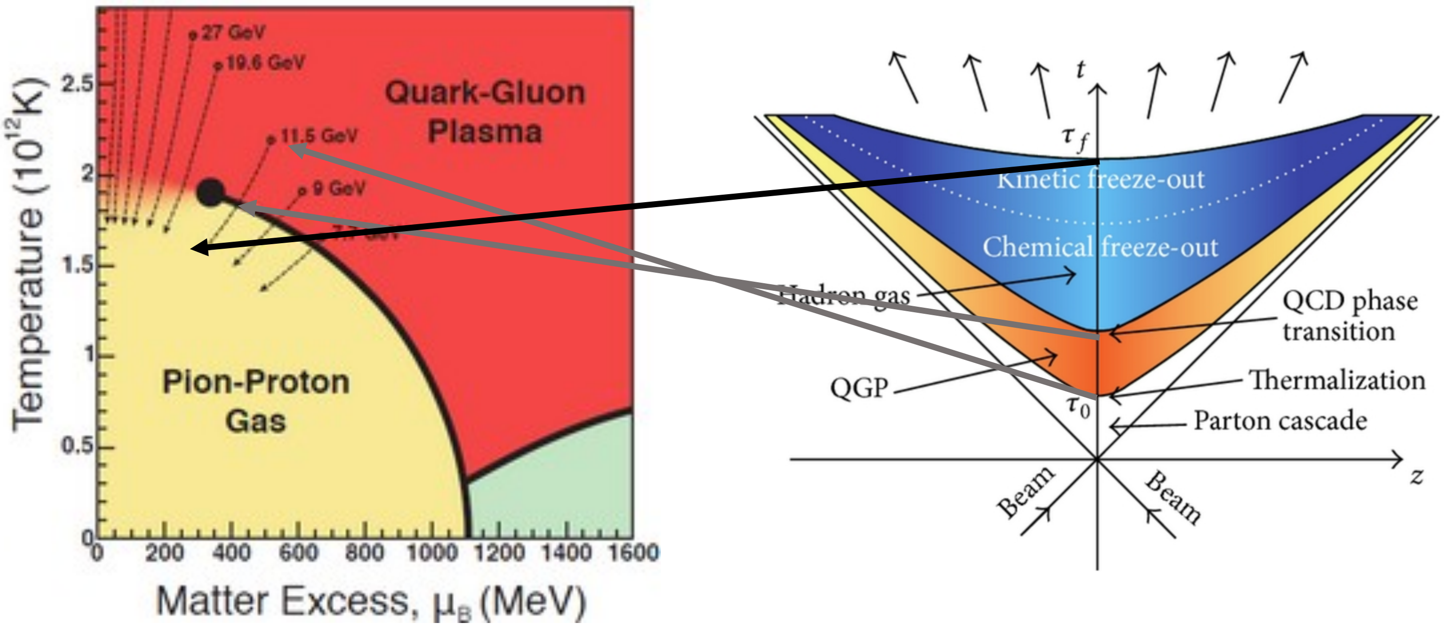

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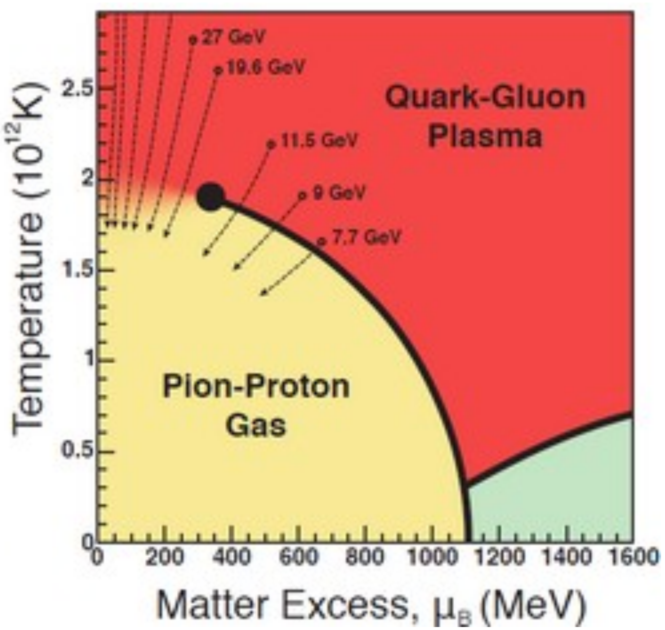
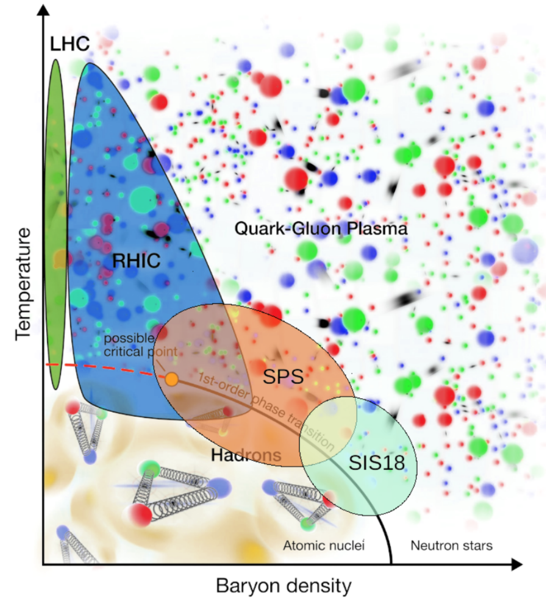


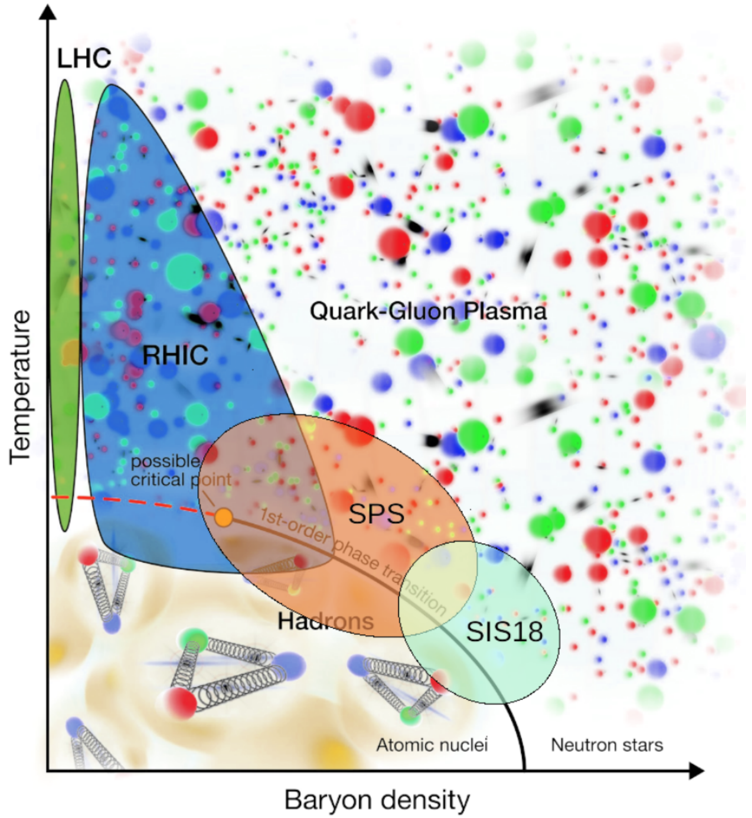


All phase diagrams of strongly interacting matter are only hypothetical, except $\mu_B \sim 0$ where lattice QCD could be implemented.

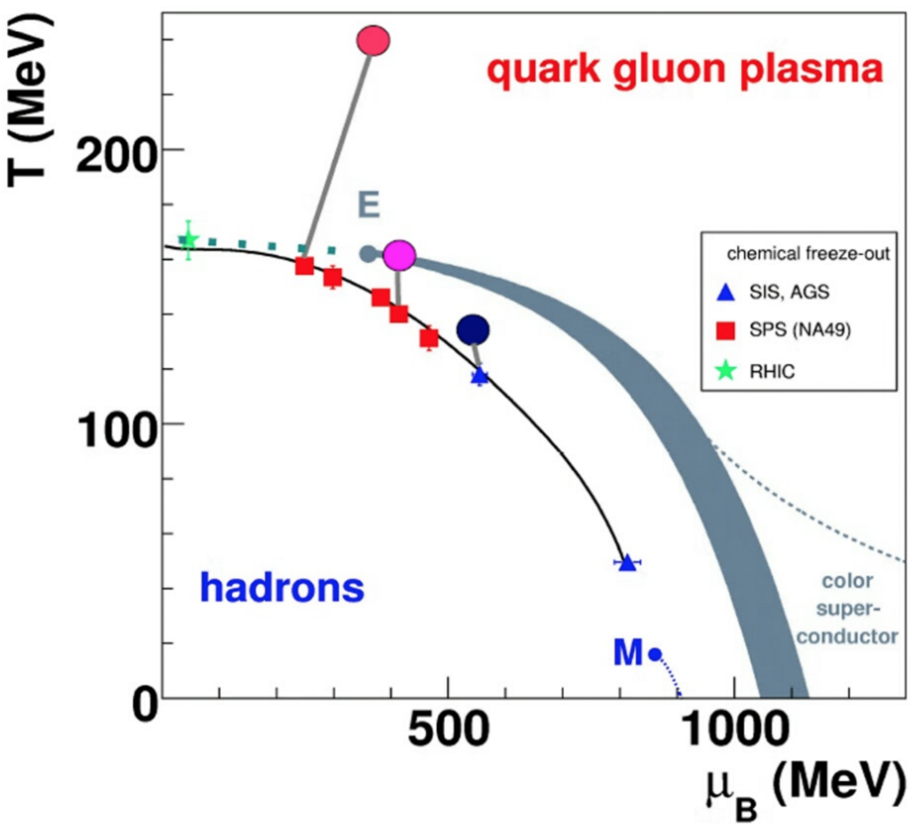
NA61/SHINE Heavy ion program:

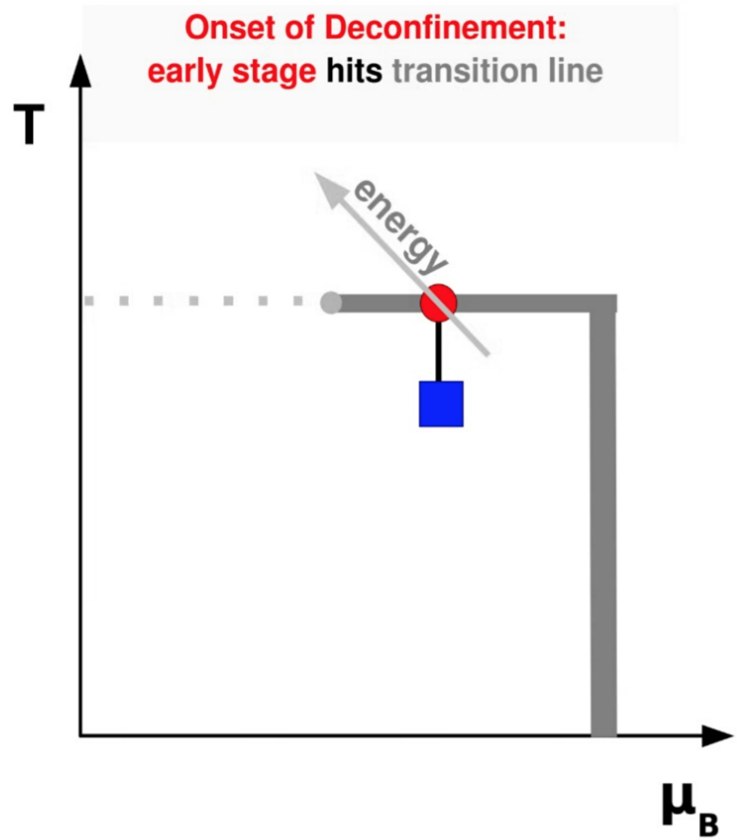
- Study of the properties of the onset of deconfinement
- Search for the critical point

- Study of the onset of fireball



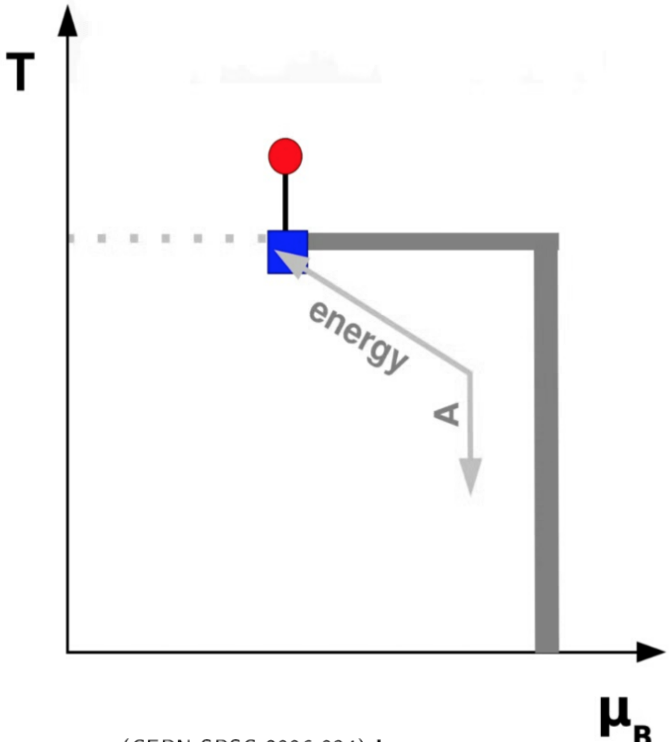
Beginning of creation of quark-gluon plasma in nucleus-nucleus collisions with increasing collision energy





Critical point

A hypothetical end point of the first order transition line

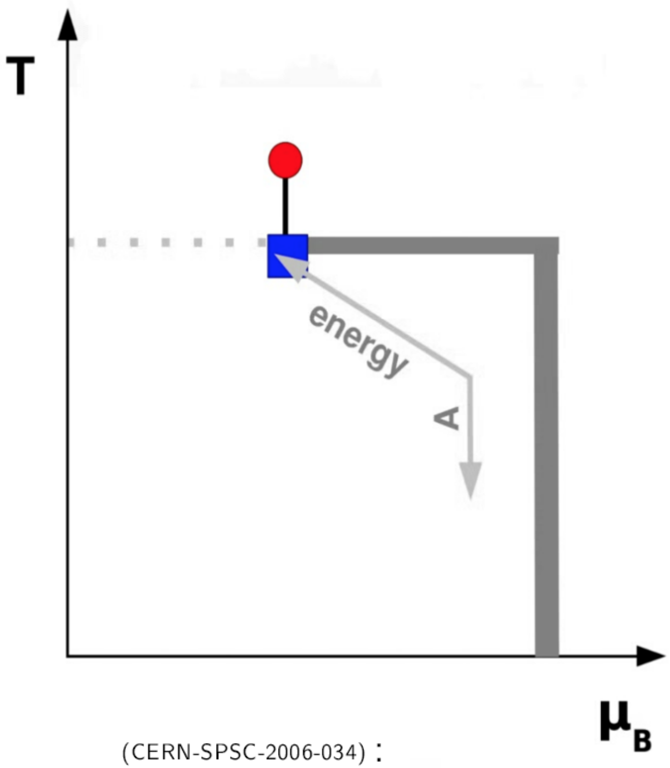


(CERN-SPSC-2006-034) :

Search for the critical point in A+A collisions

Scan in energy ($\sqrt{S_{NN}}$) and system size (A)

A hypothetical end point of the first order transition line



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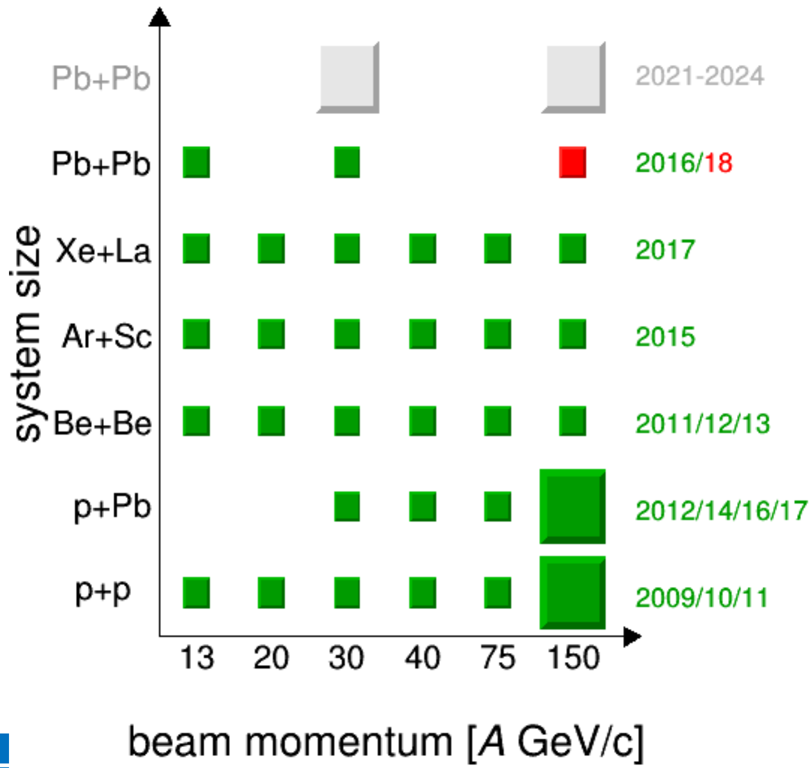

NA61/SHINE energy and system scan

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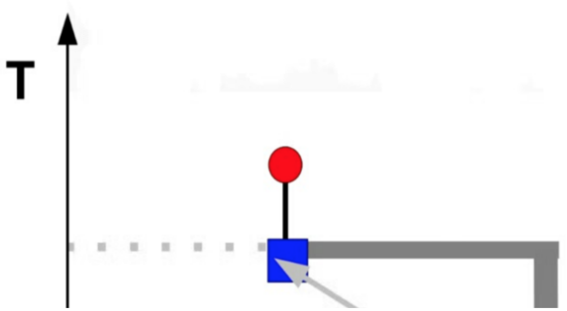

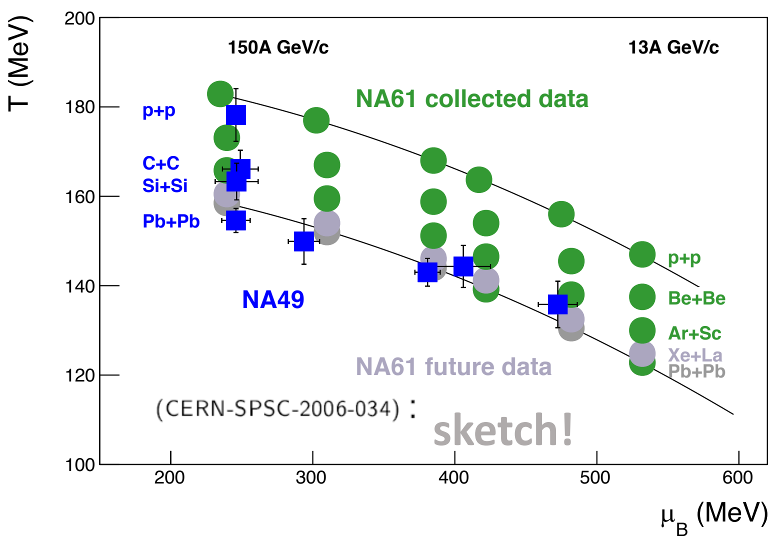

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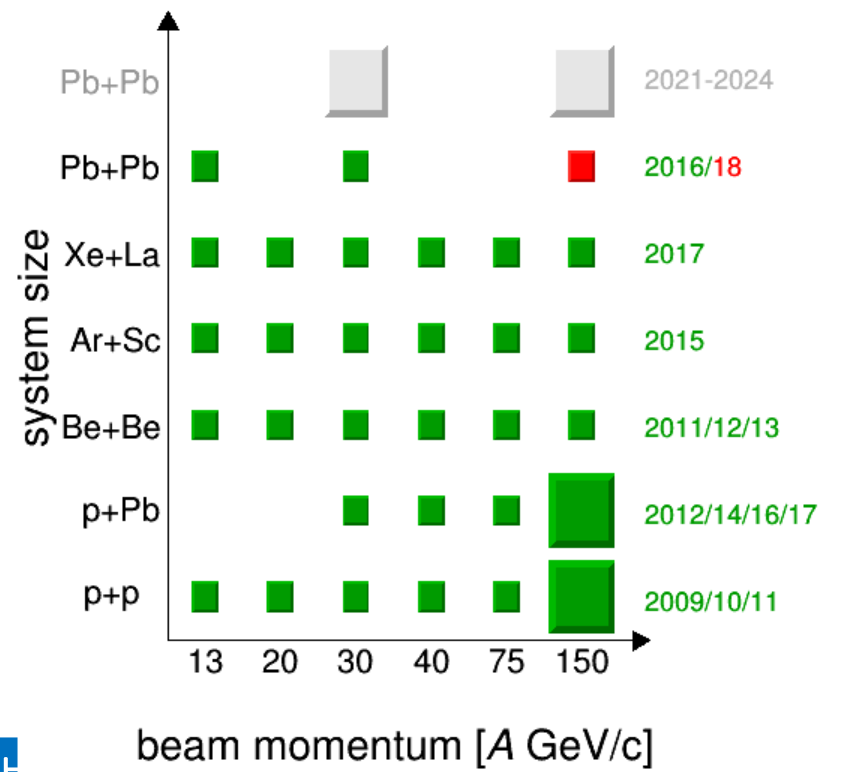
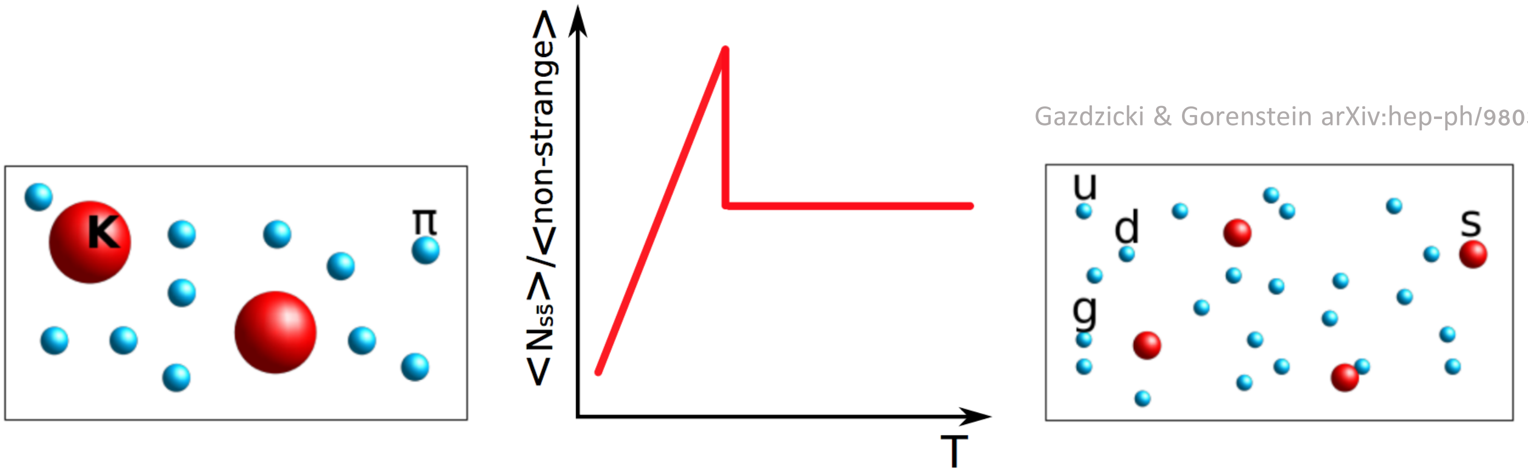


Statistical Model of Early Stage: crossing the phase transition leads to a decrease of the strange/non-strange particle ratio - the horn-like structure



Gazdzicki & Gorenstein arXiv:hep-ph/9803462v3 1998

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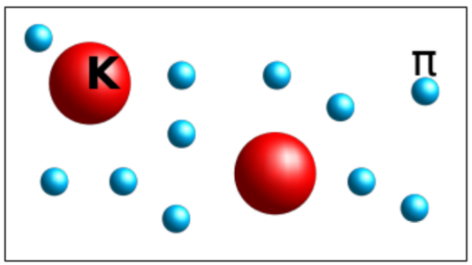

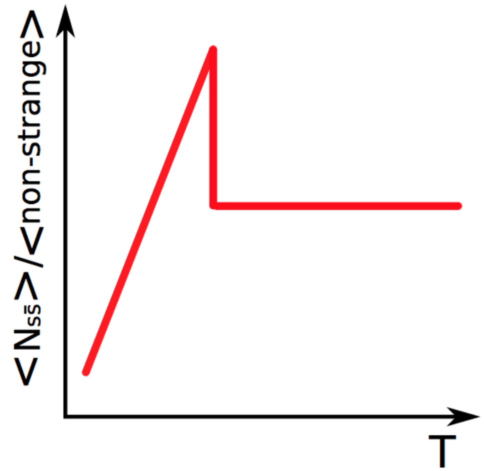

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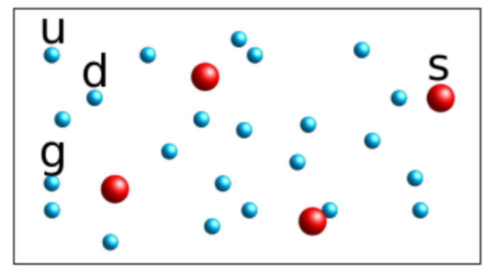
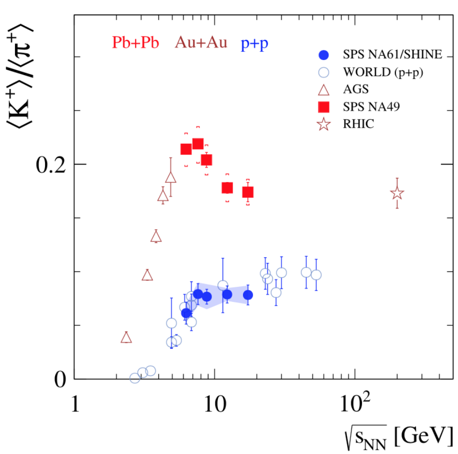
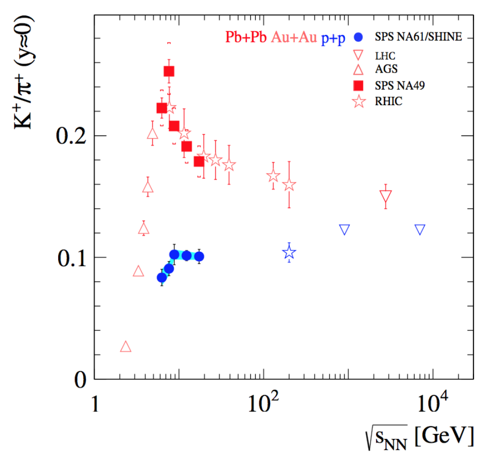


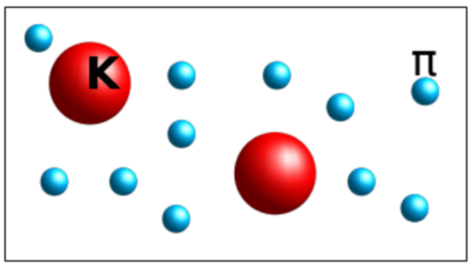


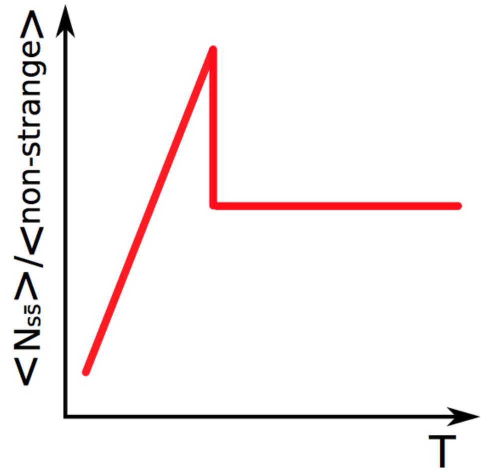


The phase transition!

Onset of deconfinement

Statistical Model of Early Stage: crossing the phase transition leads to a decrease of the strange/non-strange particle ratio - the horn-like structure





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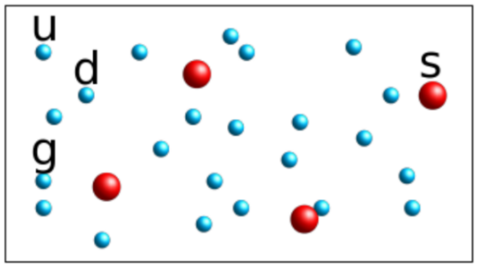
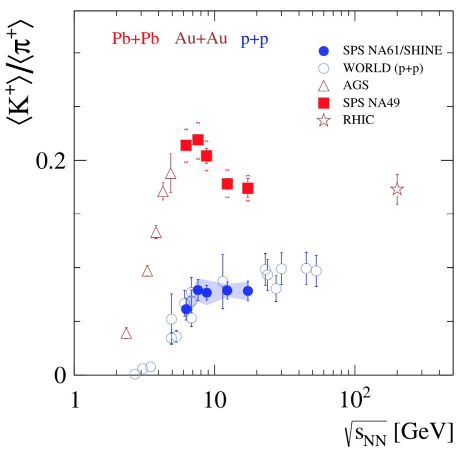
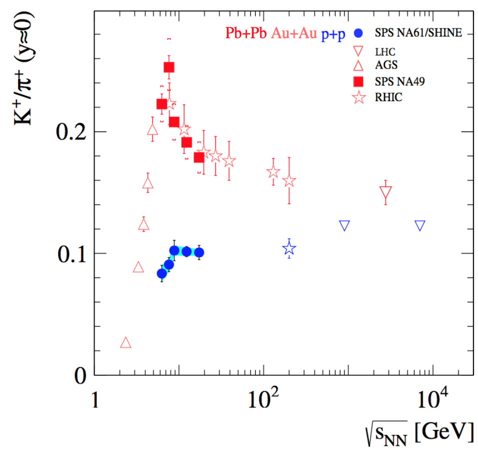






The phase transition!

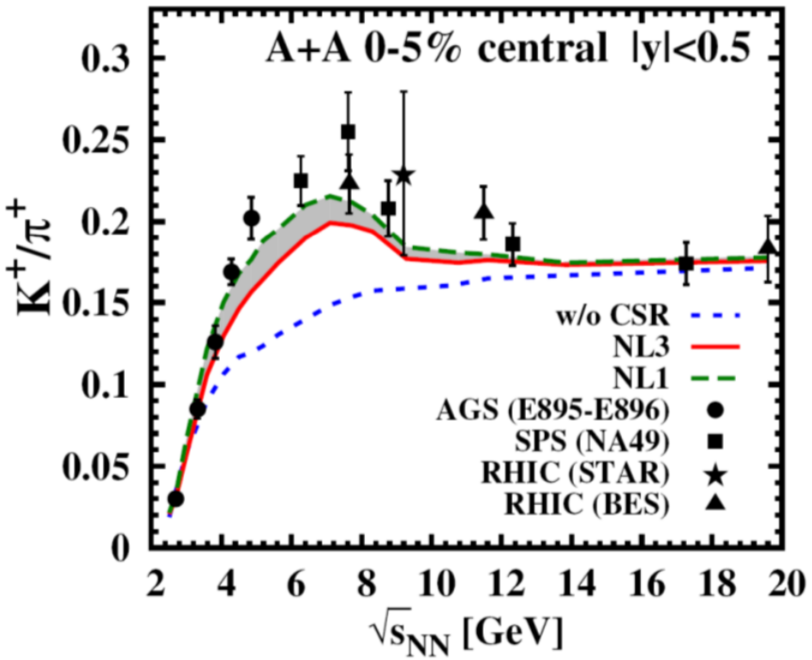
In p+p?

QGP in p+p at LHC?
ALICE collaboration, Nature Physics 13, 535–539 (2017)

Parton-**H**adron-**S**tring-**D**ynamics (PHSD)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;

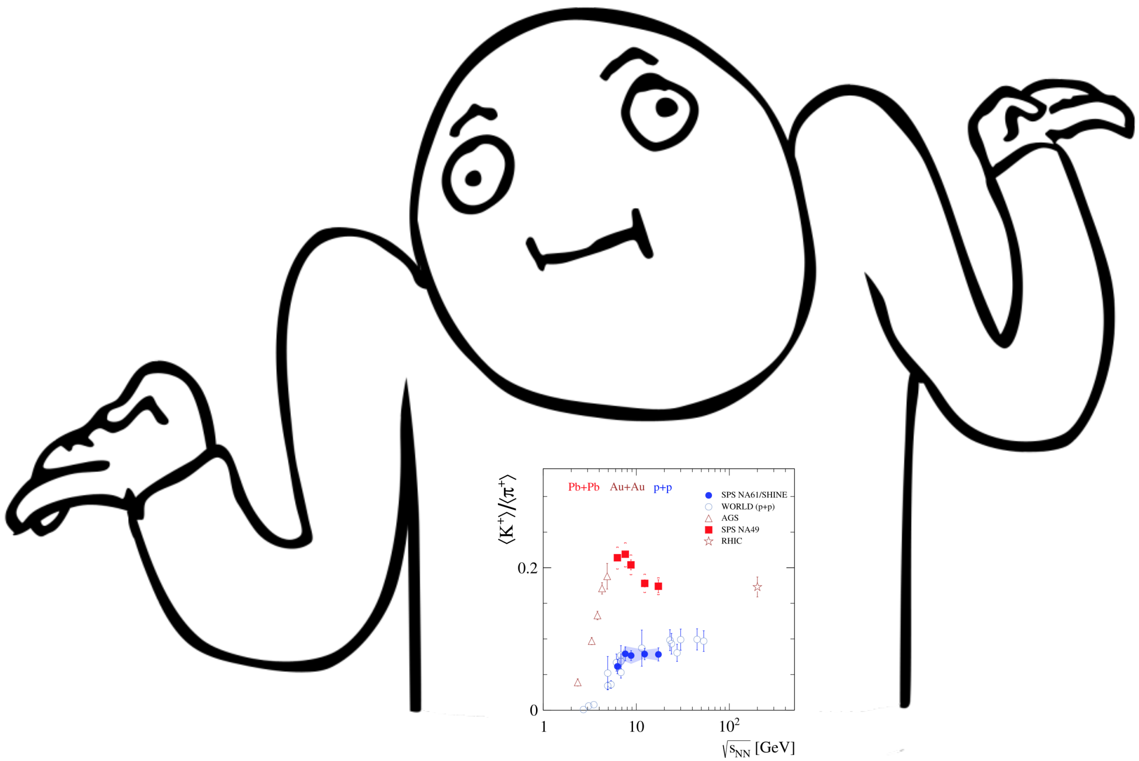
PHSD model with & without Chiral Symmetry Restoration



- PHSD without CSR does not show the horn-like behavior.
- PHSD with CSR describes data!

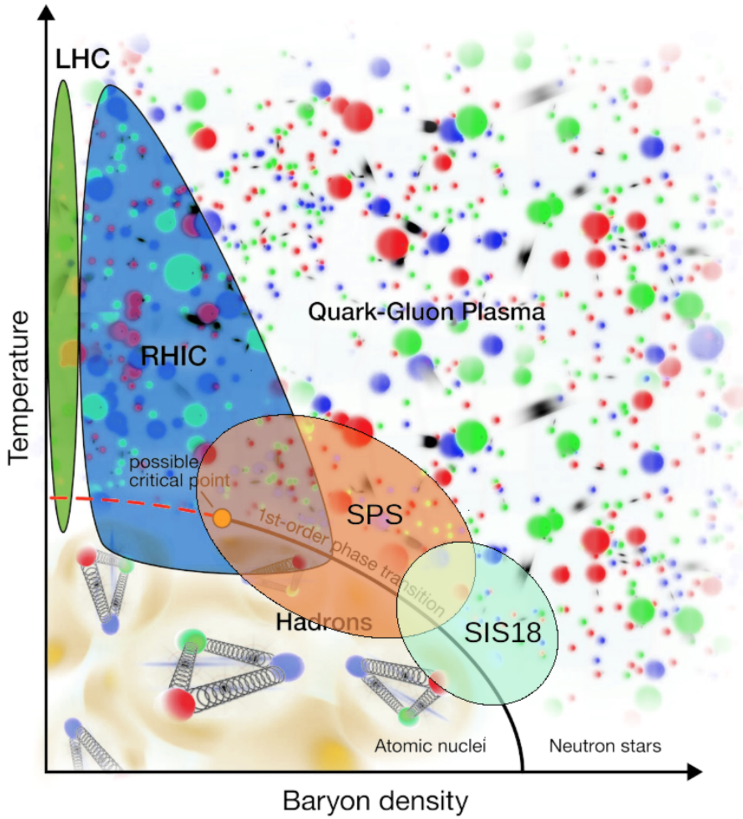
Palmese et al. , PRC94 (2016) 044912

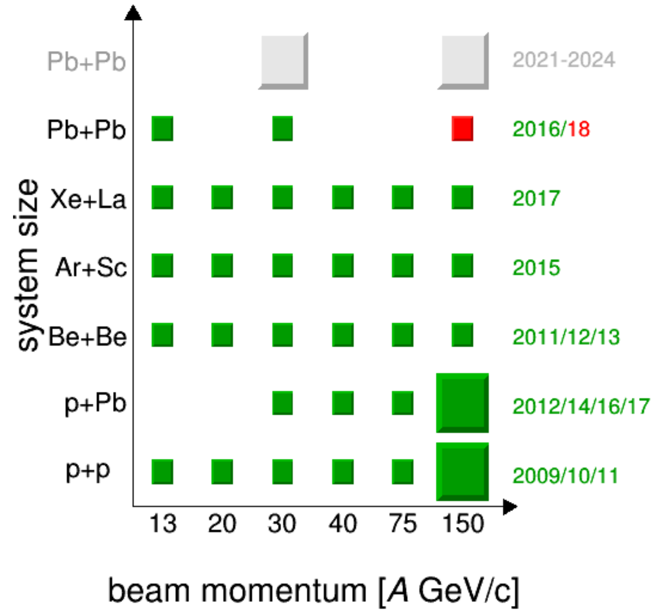
Onset of deconfinement or **chiral symmetry restoration**
(or both)**?**

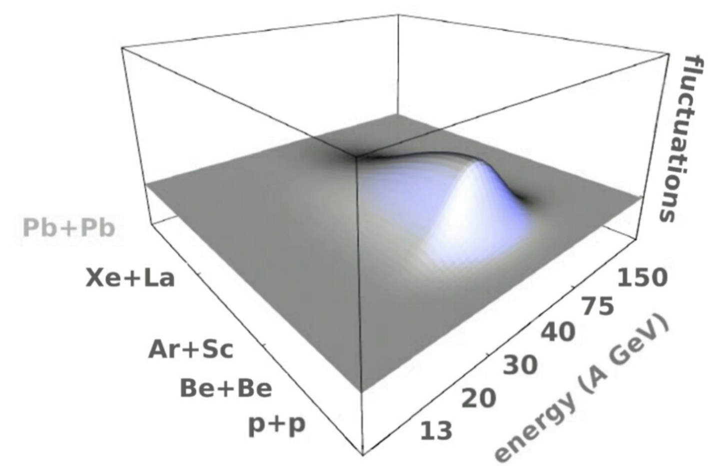


We need more data!
(manpower to analyze it)

Critical point search







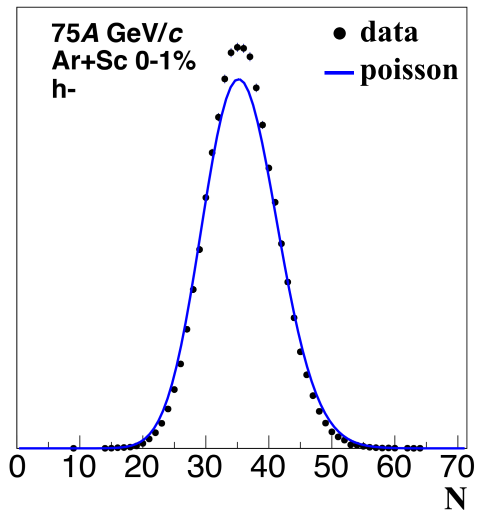
How to estimate the strength of multiplicity fluctuations?

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

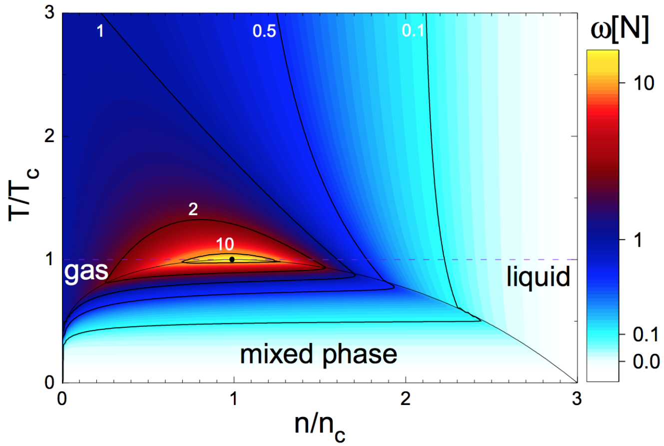
For the models with independent particle sources (wounded nucleons model):

$$\omega[N] = \omega[n] + \bar{n}\omega[N_s]$$

where $\mathbf{n}$ is a multiplicity from a single source (wounded nucleon). Consequently $\boldsymbol{\omega}[\mathbf{N}]$ depends on the number of sources $\mathbf{N_s}$ fluctuations



Van der Waals EOS in GCE formulation



Vovchenko, *et al.*, JPA **48**: 305001

Strongly intensive fluctuation measures

Baseline of search for critical behavior: quantities with trivial properties in the reference models (e.g. WNM or IB-GCE)

$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right)$$
$$\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2cov(P_T, N)\right)$$
$$\text{where } P_T = \sum_{i=1}^{N} p_{Ti}$$

N - multiplicity of charged hadrons in an experimental acceptance

$\omega[p_T]$ - scaled variance of inclusive p_T distribution

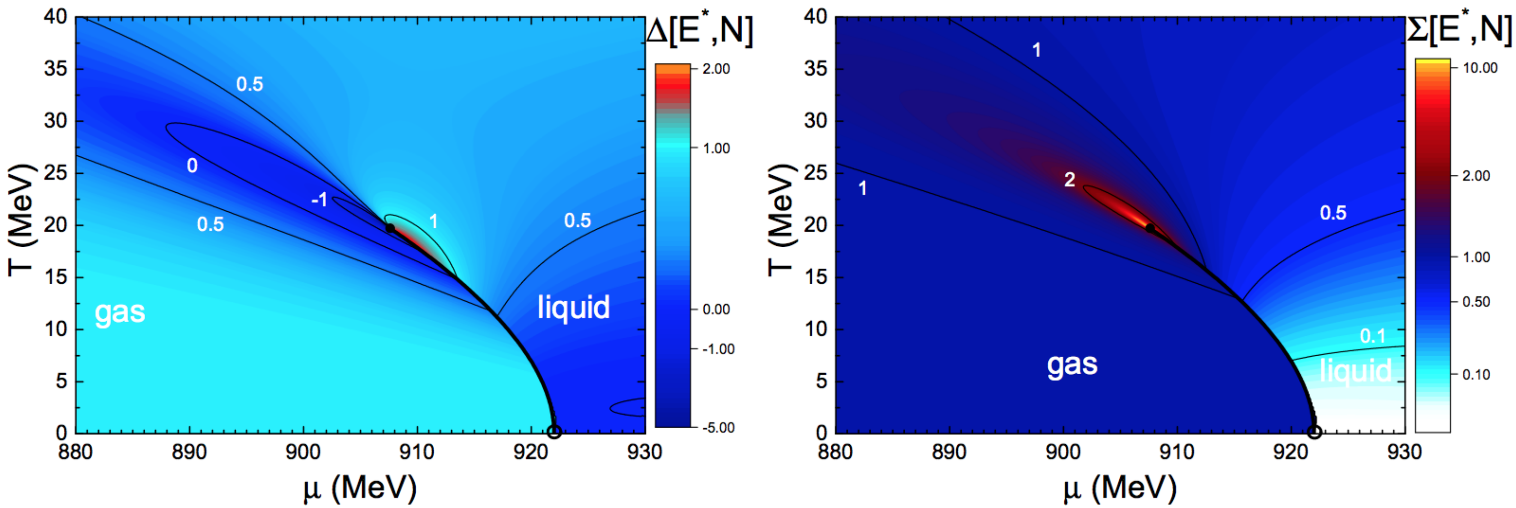
- Independent of $\Delta[P_T, N] = \Sigma[P_T, N] = 1$ for the independent particle production model
- $\Delta[P_T, N] = \Sigma[P_T, N] = 0$ in the absence of fluctuations

Gorenstein, Gazdzicki, PRC 84:014904
Gorenstein, et al., PRC 88 2:024907

Strongly intensive fluctuation measures

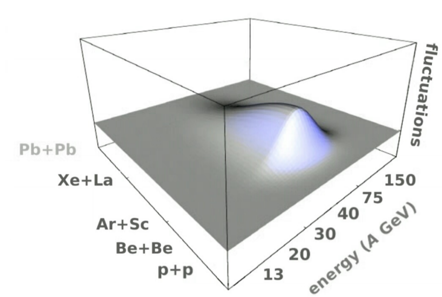
Sensitive to critical point

Van der Waals EOS in GCE formulation, E^* is excitation energy

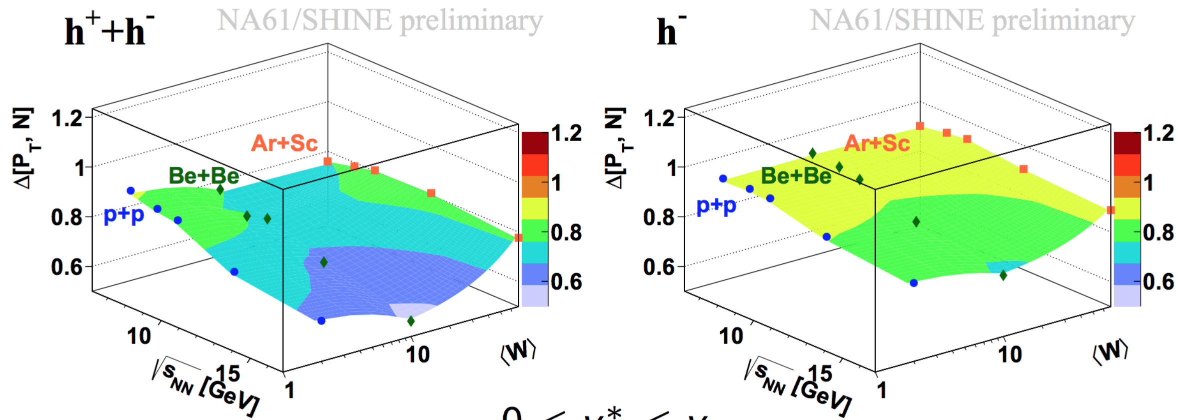


Vovchenko, et all., arXiv:1610.01036v1 [nucl-th]

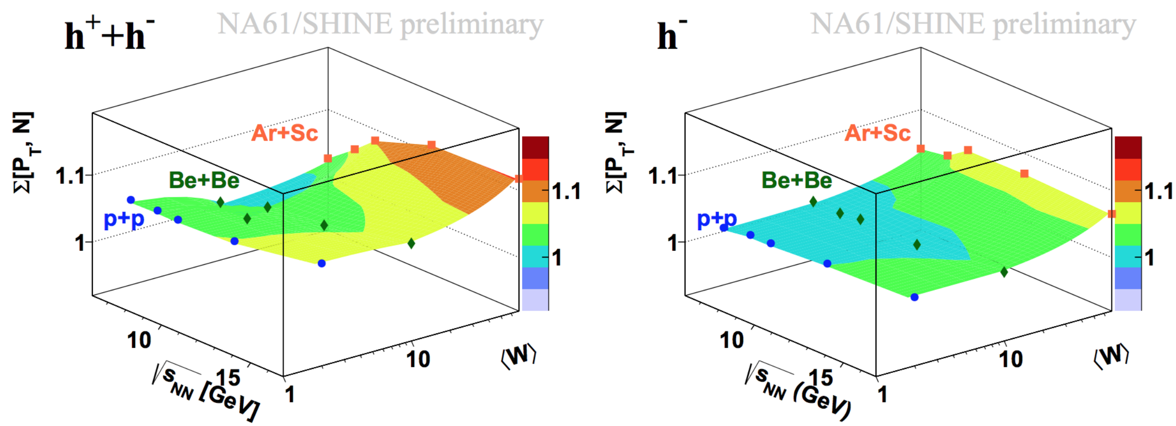
Analysis of strongly intensive fluctuation measures is expected to give more profound insight into the critical point location

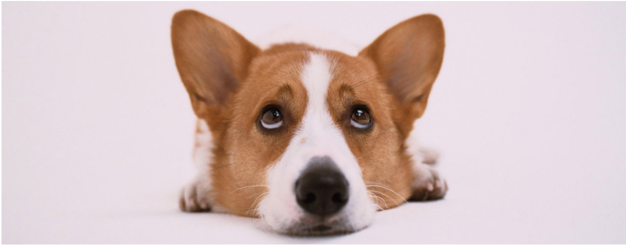


Critical point search: fluctuation analysis



$0 < y^*_\pi < y_{beam}$



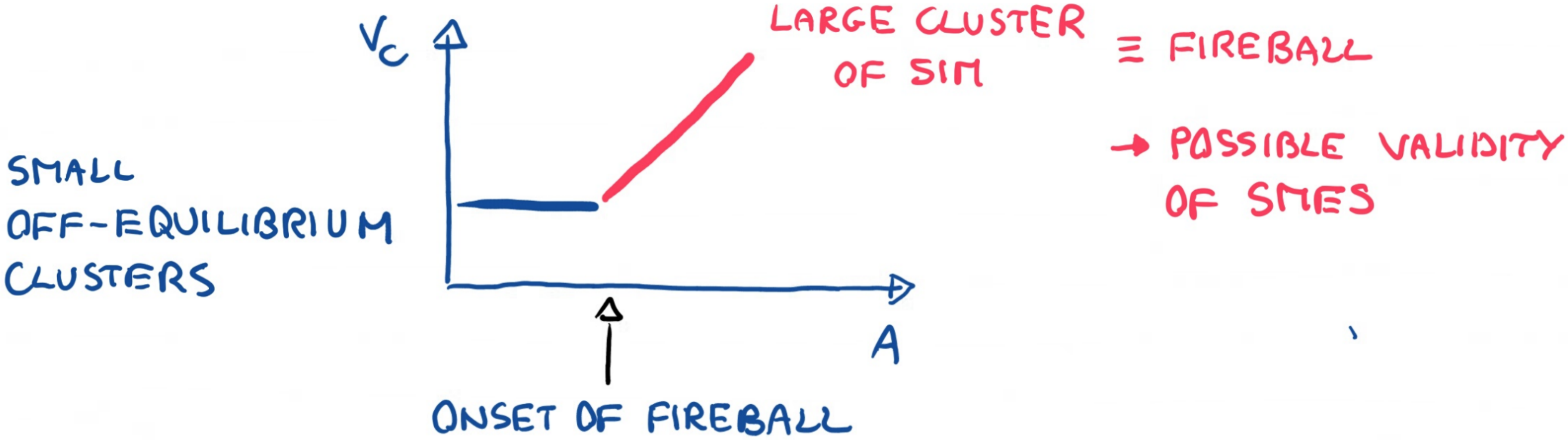


No prominent structures which could be related to the critical point are so far

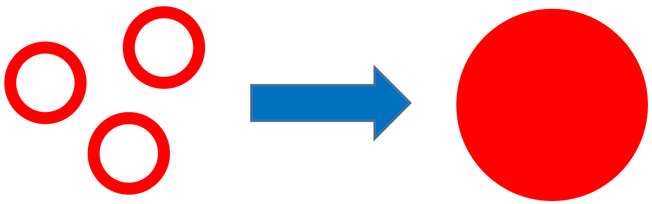
E. Andronov, Acta Phys.Polon.Supp. 10 (2017) 449

Onset of fireball

Beginning of creation of large cluster of strongly interacting matter in A+A collisions with increasing nuclei mass number.



non-equilibrium

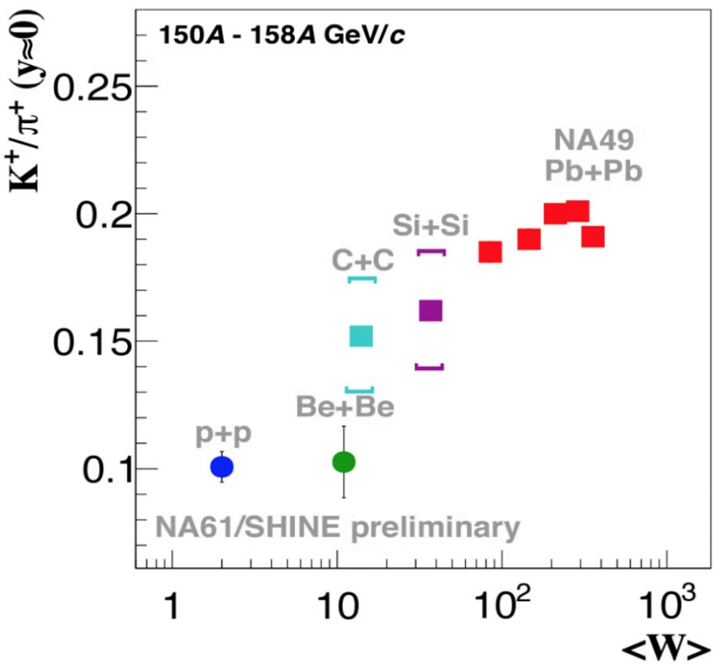


equilibrium?

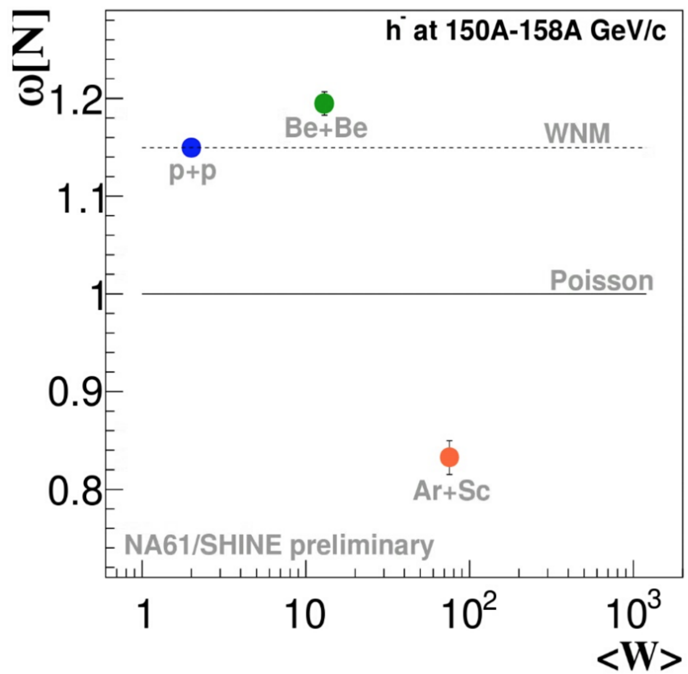
NA61/SHINE: Onset of fireball

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

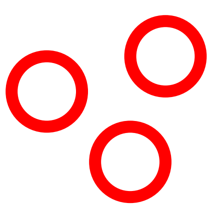
Mean multiplicity ratio



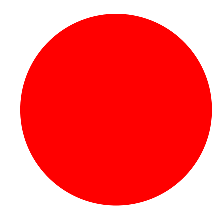
Multiplicity fluctuations



⟨W⟩ - number of wounded nucleons

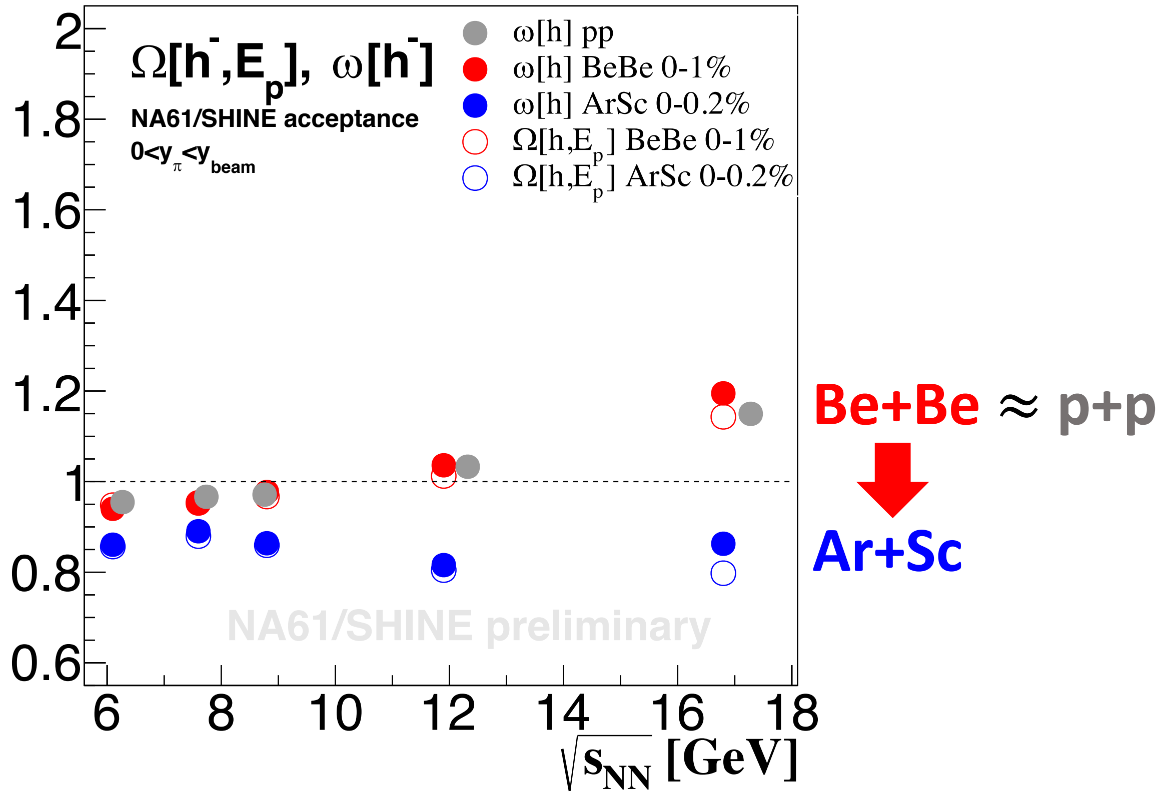


Onset of fireball



A.Seryakov for NA61/SHINE, arXiv:1712.03014 [hep-ex]

Multiplicity fluctuation

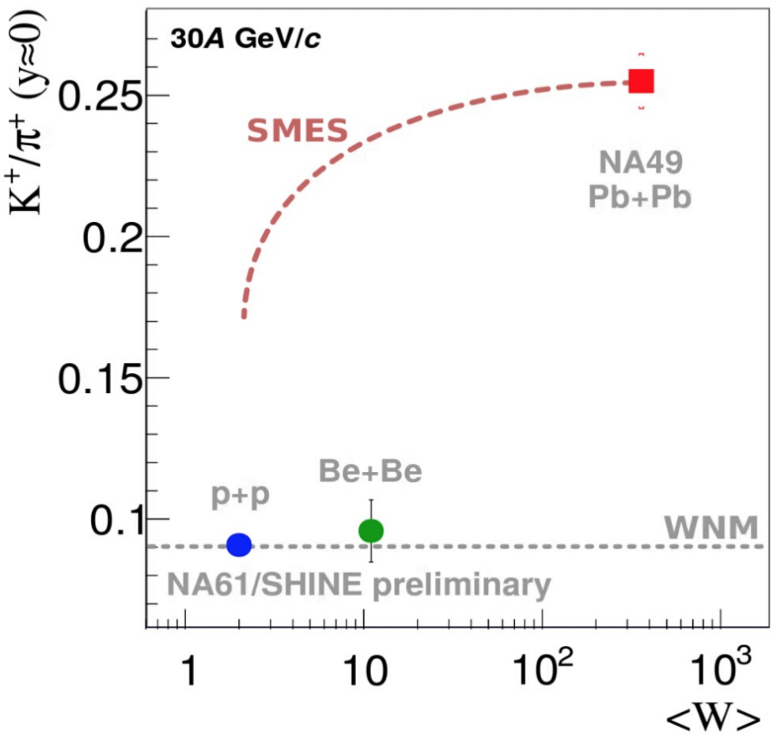


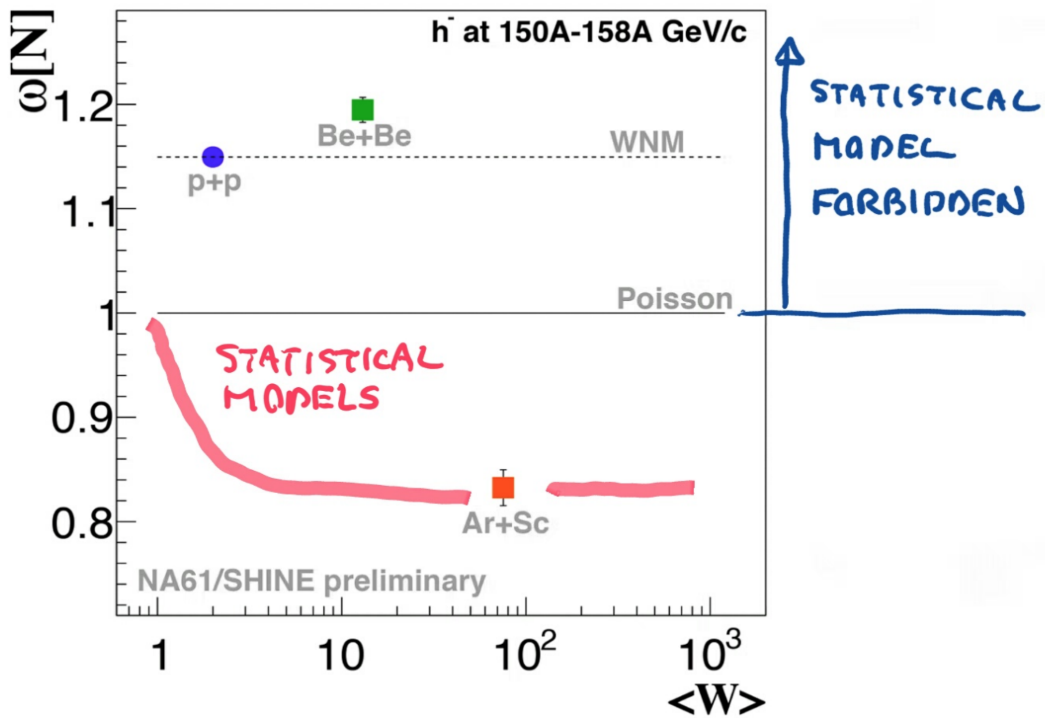
Rapid change of A-dependence at A ≈ 10 observed at all SPS collision energies

A.Seryakov for NA61/SHINE, arXiv:1712.03014 [hep-ex]

Begun, et all., arXiv:nucl-th/0404056v1

- p+p and Be+Be contradict statistical models
- Ar+Sc and Pb+Pb contradict wounded nucleons model

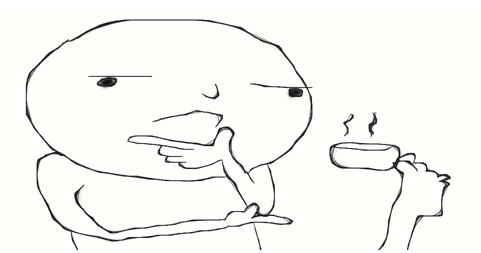




Ar+Sc and Pb+Pb ≈ large volume "statistical" cluster

ON INTERPRETATION OF ONSET OF FIREBALL:
PERCOLATION APPROACH

WITH INCREASING A DENSITY OF CLUSTERS (STRINGS, PARTONS, ...) INCREASES. THUS PROBABILITY TO OVERLAP MANY ELEMENTARY CLUSTERS MAY RAPIDLY INCREASE WITH A $\to$ PERCOLATION MODELS.



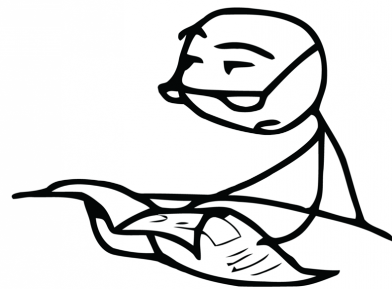
Baym, Physica **96A**: 131
Celik, Karsch, Satz PLB **97**: 128
Braun, Pajares, NPB **390**: 542
Armesto, *et al.*, PRL **77**: 3736
Cunqueiro, *et al.*, PRC **72**: 024907

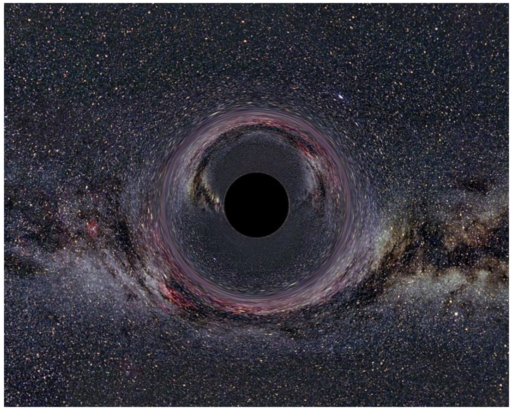
ON INTERPRETATION OF ONSET OF FIREBALL:
AdS/CFT CORRESPONDENCE

MALDACENA, INT. J. THEOR. PHYS. 38 (1999) 1113

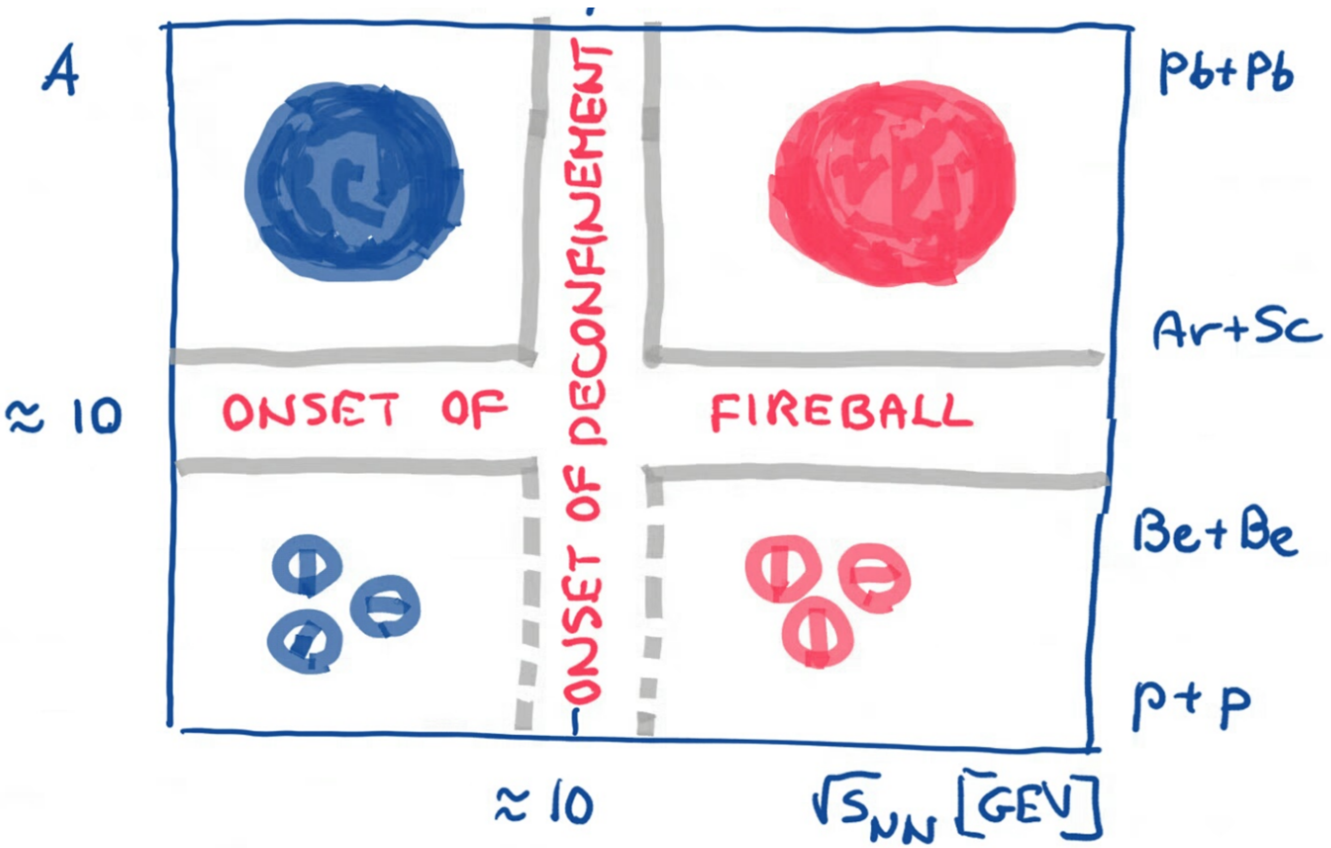
AdS (GRAVITY): FORMATION OF A BLACK HOLE HORIZON (INFORMATION TRAPPING SURFECE) TAKES PLACE WHEN CRITICAL VALUES OF MODEL PARAMETERS ARE REACHED

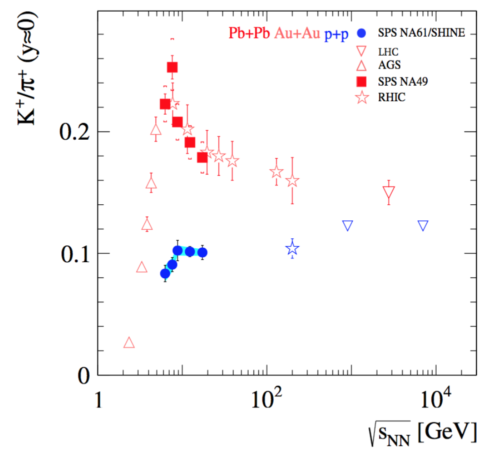
CFT (QCD): ONLY STARTING FROM A SUFFICIENTLY LARGE NUCLEAR MASS NUMBER THE FORMATION OF THE TRAPPING SURFACE IN A+A COLLISIONS IS POSSIBLE → ONSET OF FIREBALL

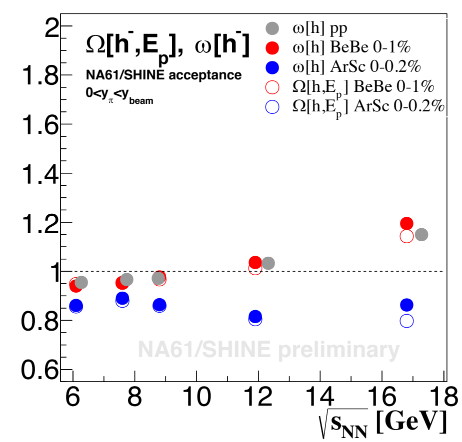




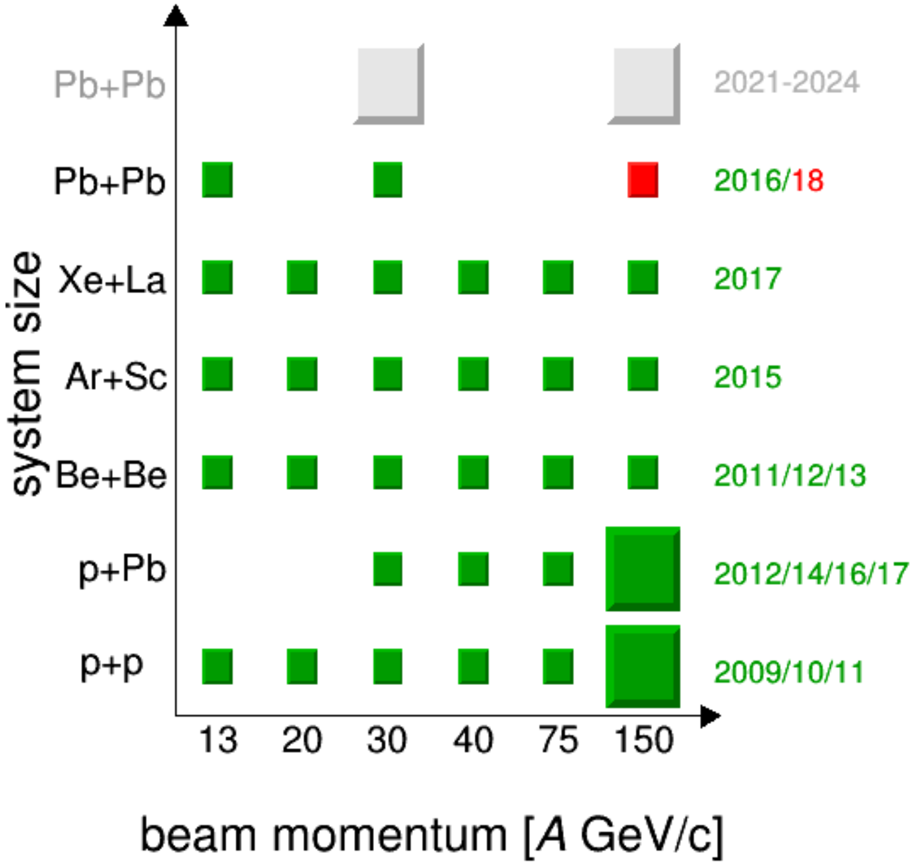
E. Shuryak Prog. Part. Nucl. Phys. 62 (2009) 48–101, arXiv:0807.3033 [hep-ph]
S. Lin and E. Shuryak Phys. Rev. D79 (2009) 124015, arXiv:0902.1508 [hep-th].


A
≈ 10
Pb+Pb
Ar+Sc
Be+Be
p+p
ONSET OF
FIREBALL
ONSET OF DECONFINEMENT
≈ 10
√sNN [GEV]


K+/π+ (y≈0)
Pb+Pb Au+Au p+p
SPS NA61/SHINE
LHC
AGS
SPS NA49
RHIC
√sNN [GeV]


Ω[h-,Ep], ω[h-]
NA61/SHINE acceptance
0<yπ<ybeam
ω[h] pp
ω[h] BeBe 0-1%
ω[h] ArSc 0-0.2%
Ω[h,Ep] BeBe 0-1%
Ω[h,Ep] ArSc 0-0.2%
NA61/SHINE preliminary
√sNN [GeV]

The data taking program will be finished this year.
What is next?

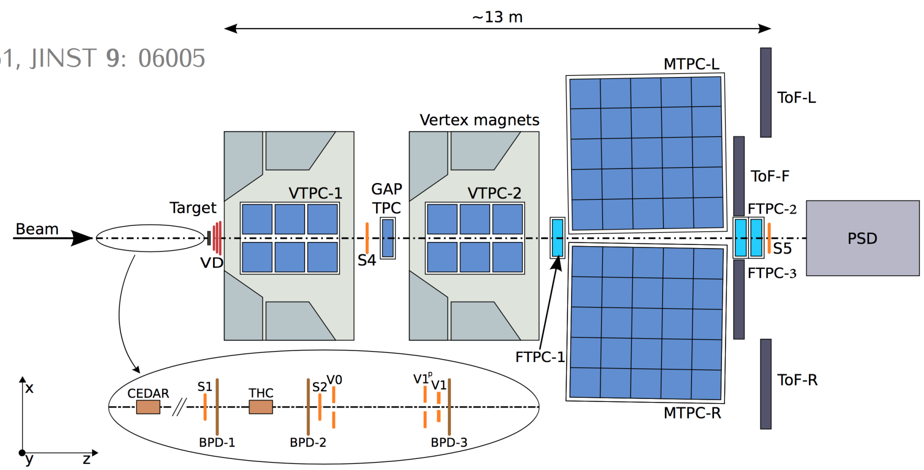


Dedicated talk by Wojciech Brylinski on Wednesday

Heavy ion program - **open charm at SPS** (2022-2024)

- What is the mechanism of charm production?
- How does the onset of deconfinement impact charm production?
- How does the formation of quark gluon plasma impact J/ψ production?

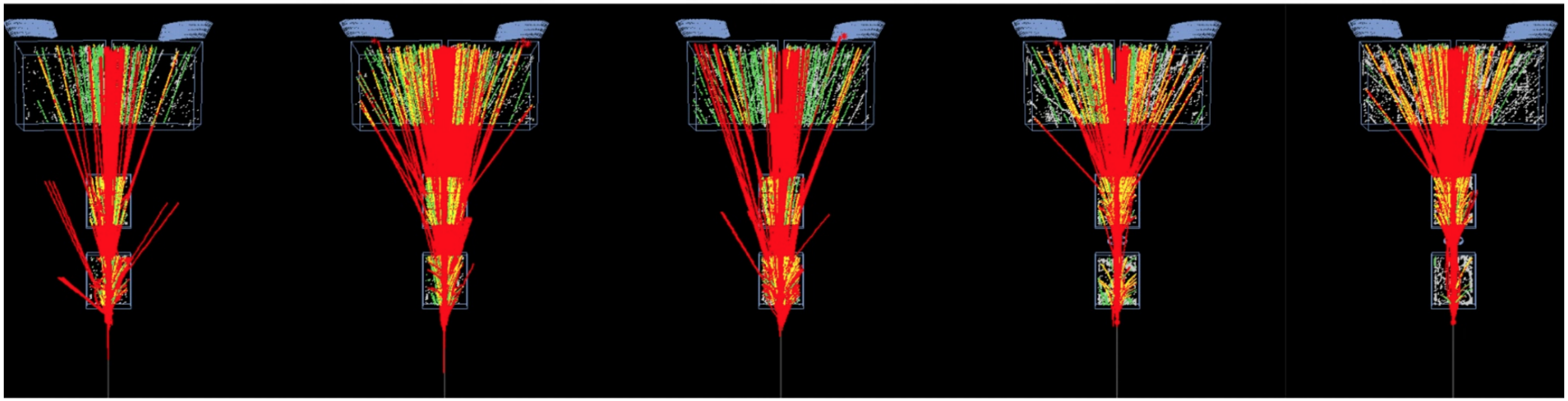
NA61, JINST **9**: 06005



Upgrade:

- New hadron calorimeter (PSD)
- New TPC readout
- New DAQ and trigger systems
- New vertex detector (VD)
  T.Lazareva "Pixel detectors" on Wednesday

New cosmic rays and neutrino programs

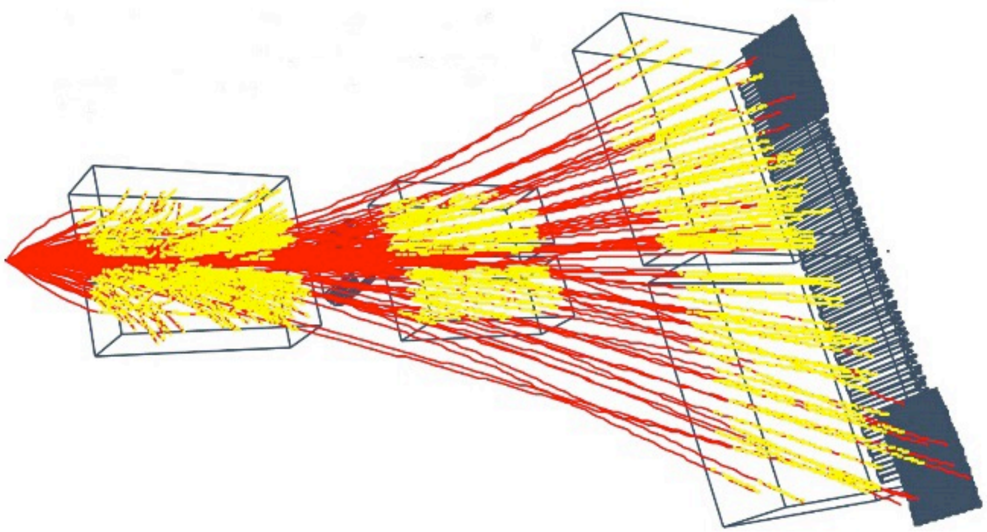


Have a shiny day!

Thank you!

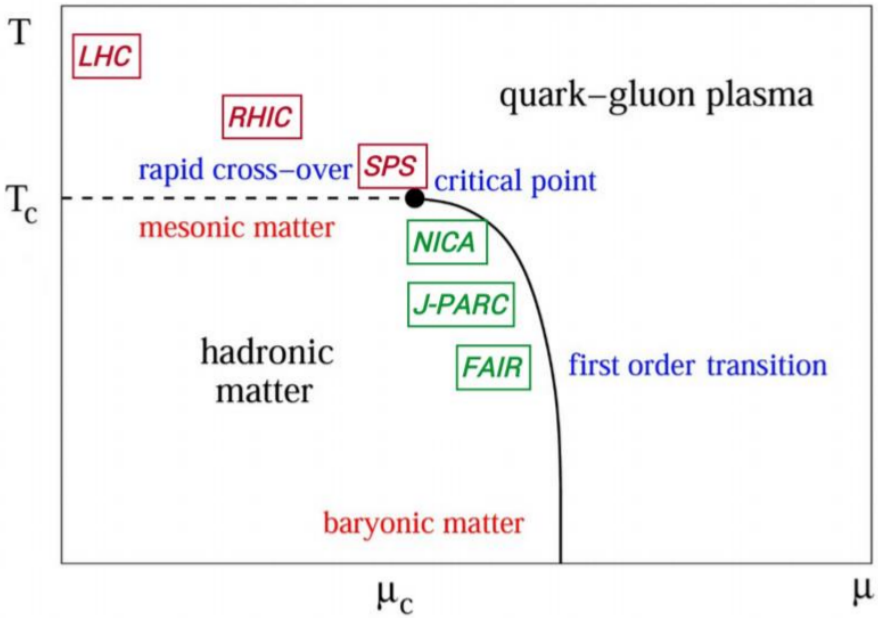
seryakov@yahoo.com

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



Uniqueness of NA61 open charm program

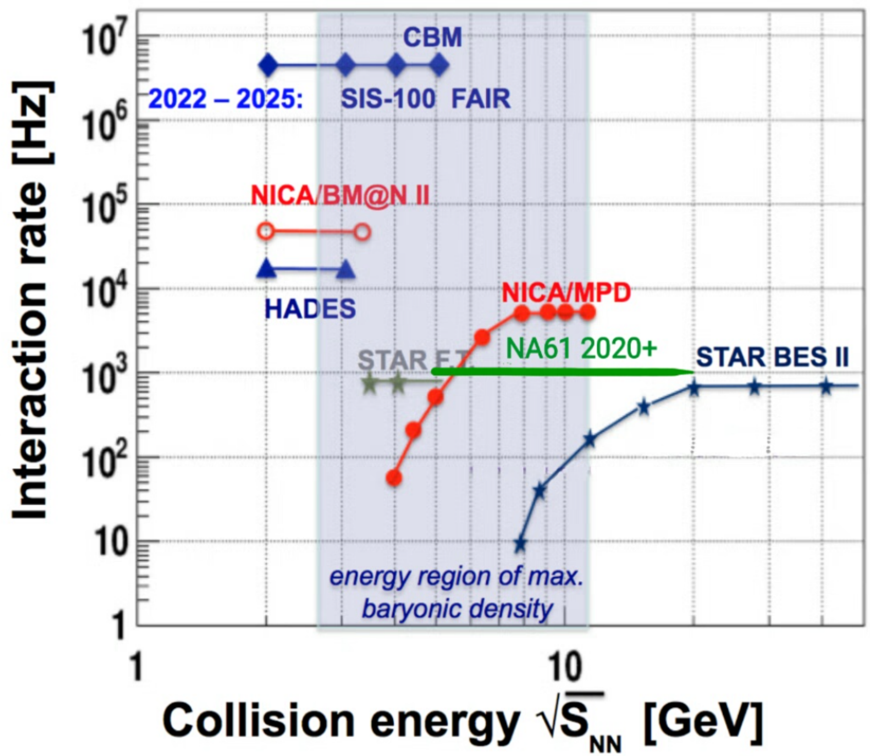
Landscape of present and future heavy ion experiments



NA61/SHINE is able to measure open charm:

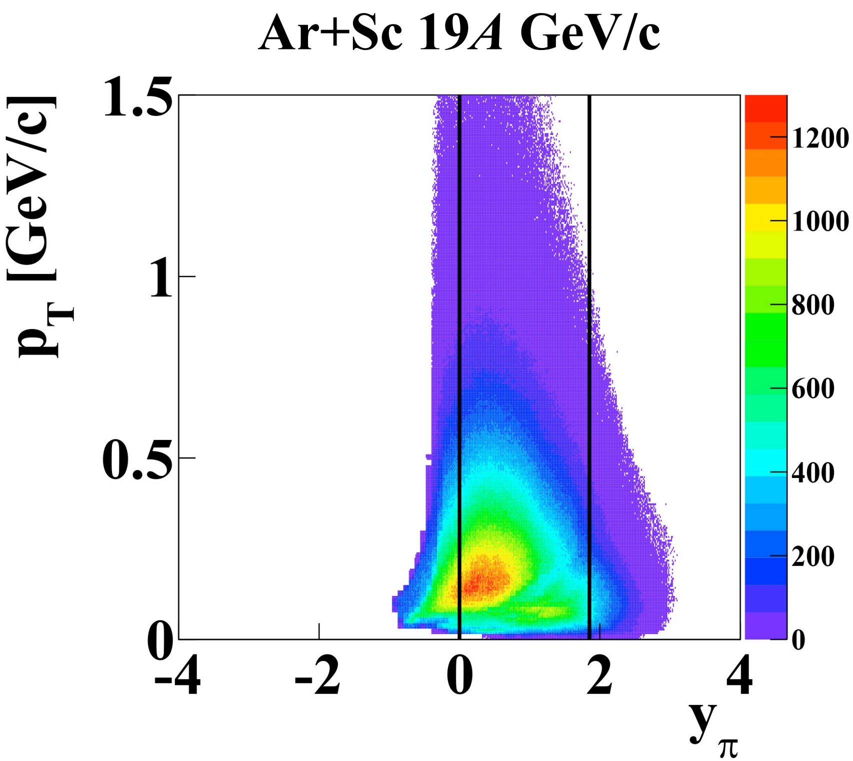
- in heavy ion collisions,
- in full phase space,
- in the near future.

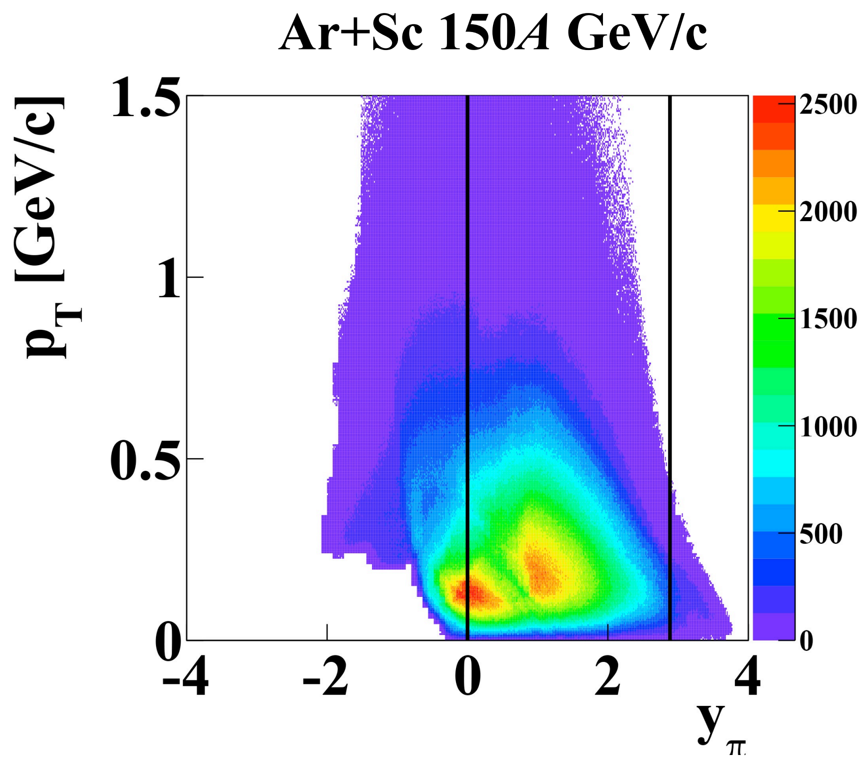
- LHC and RHIC at high energies ($\sqrt{s_{NN}} \geq 200$ GeV):
  measurements in limited phase space due to collider geometry and kinematics
- RHIC BES ($3 - 39$ GeV):
  measurement not under consideration
- NICA (< 11 GeV):
  under consideration during stage 2
- J-PARC (< 6 GeV) :
  maybe possible after 2025
- FAIR SIS-100 (< 5 GeV):
  not possible at SIS-100,
  planned at SIS-300 (< 7 GeV)



UPDATED COMPILATION BY CBM

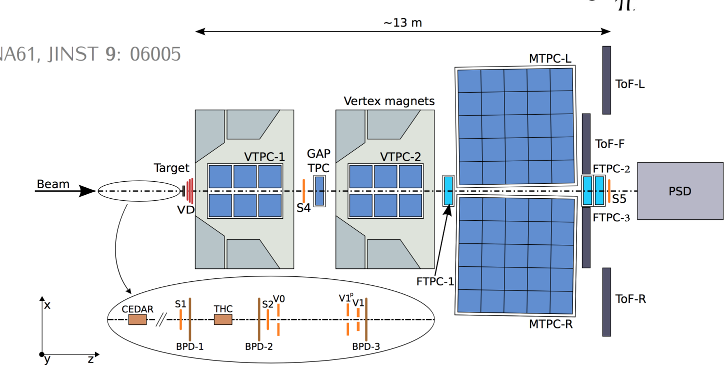
NA61/SHINE acceptance

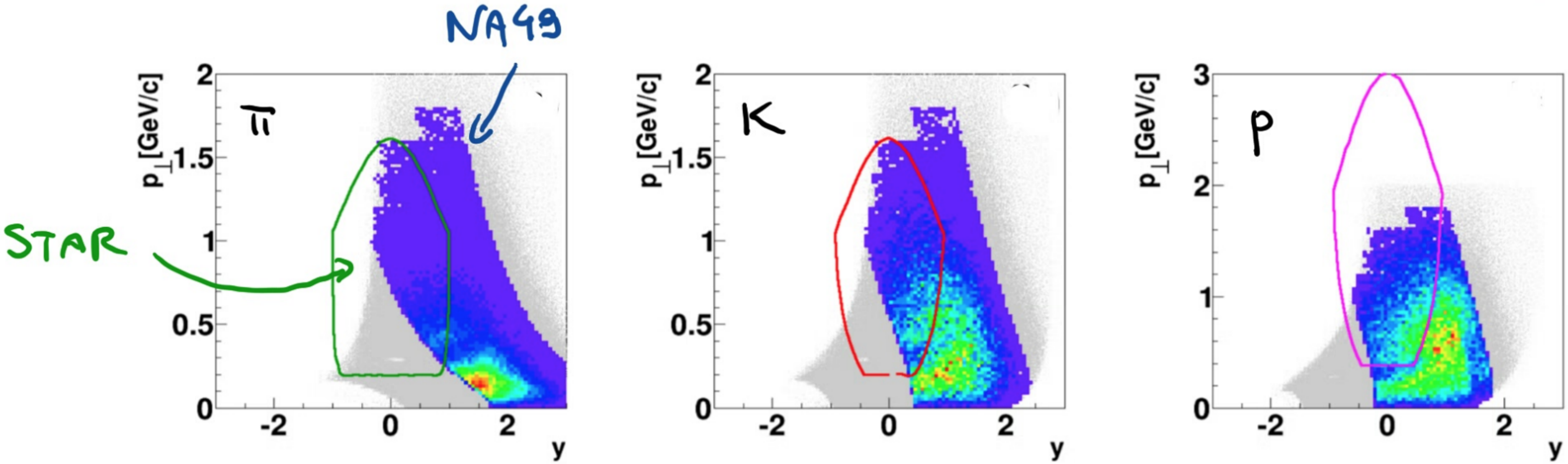




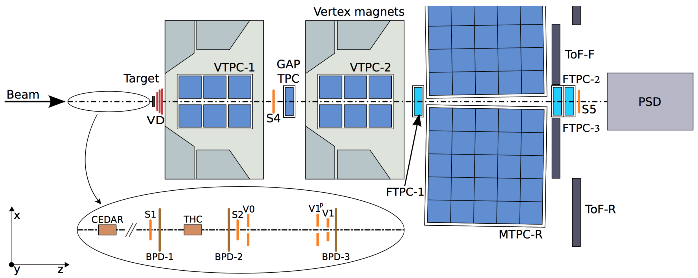
- Acceptance is different for different energies
- Acceptance is smaller for heavy ions

NA61, JINST 9: 06005

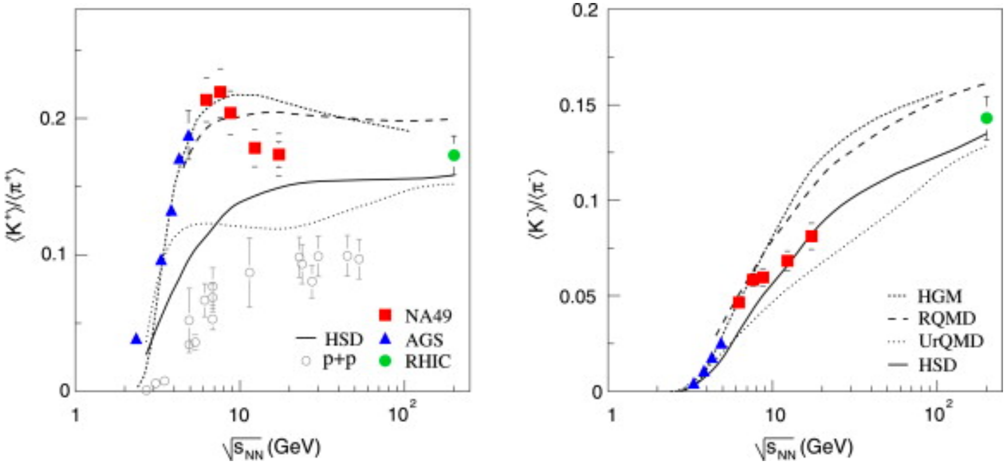




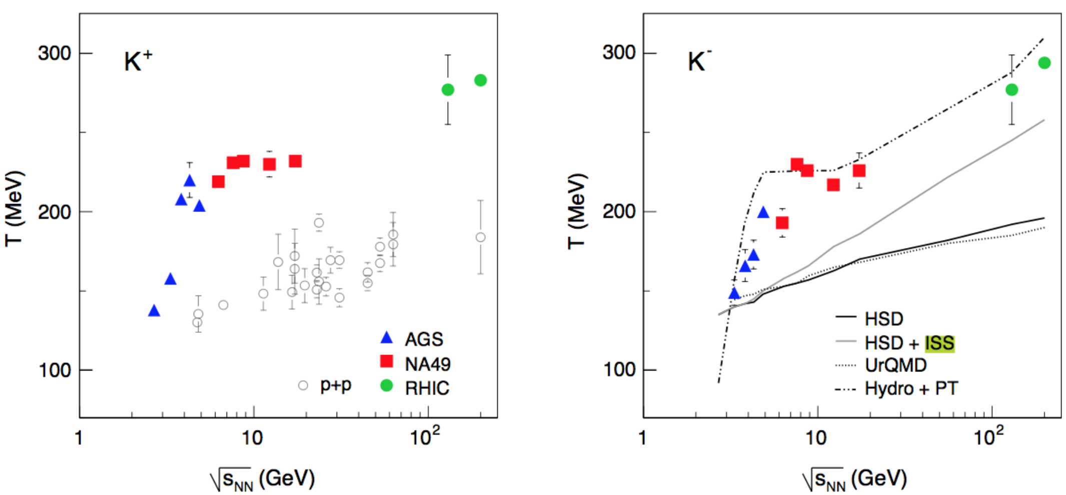
NA49, PHYS. REV. C 87 (2013) 024902



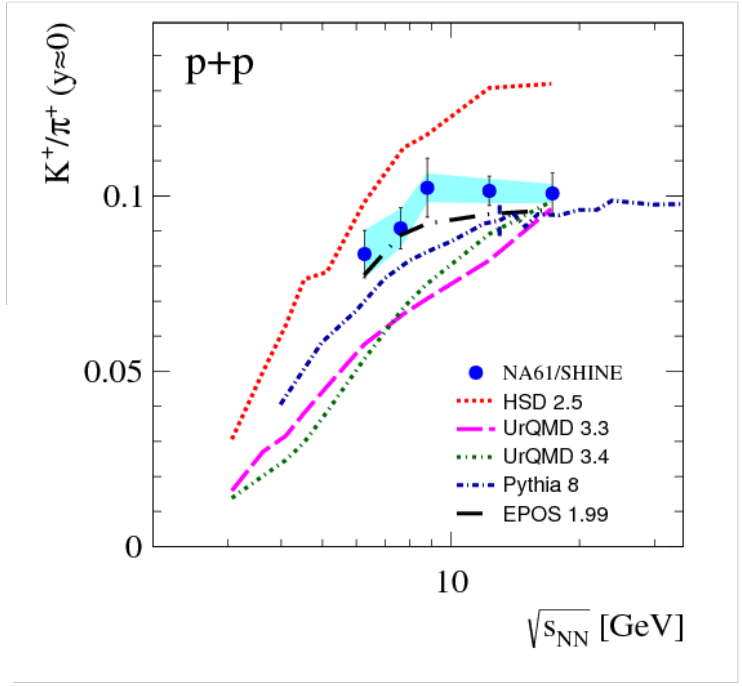
Kaon to pion: comparison with models



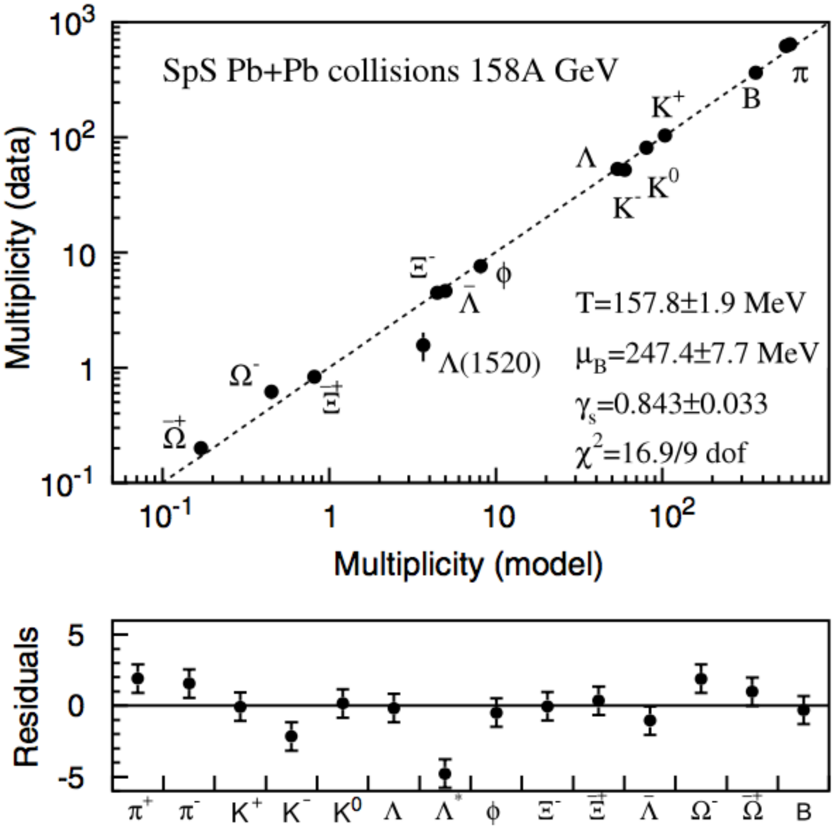
C. Blume, C. Markert / Progress in Particle and Nuclear Physics 66 (2011) 834–879

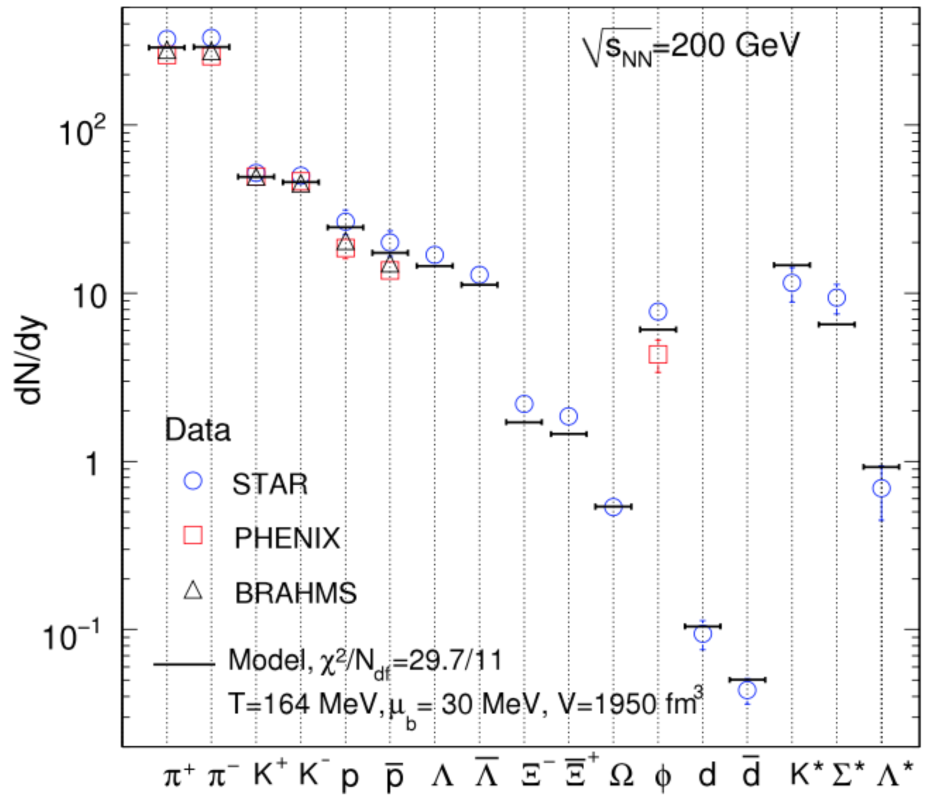


https://doi.org/10.1016/j.ppnp.2011.05.001v

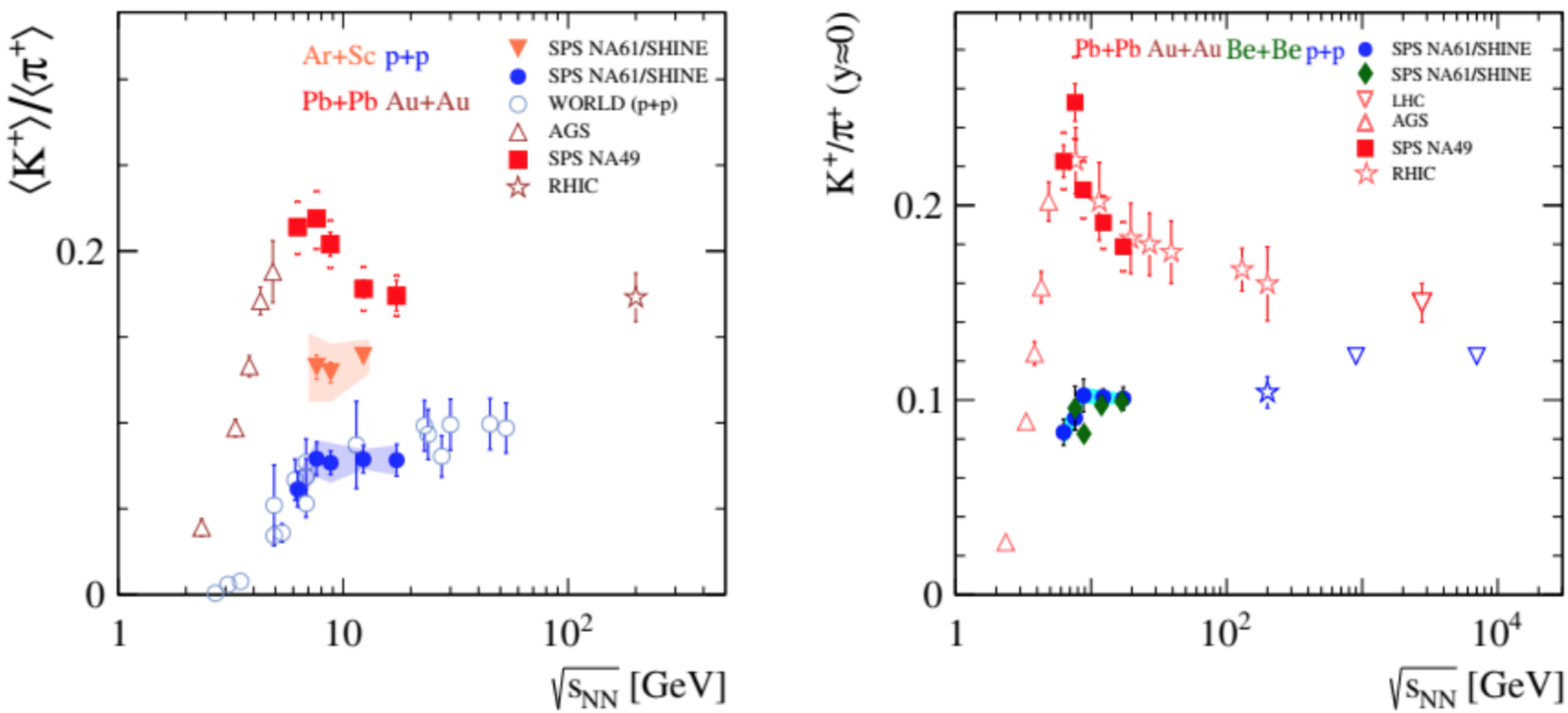


C. Blume, C. Markert / Progress in Particle and Nuclear Physics 66 (2011) 834–879





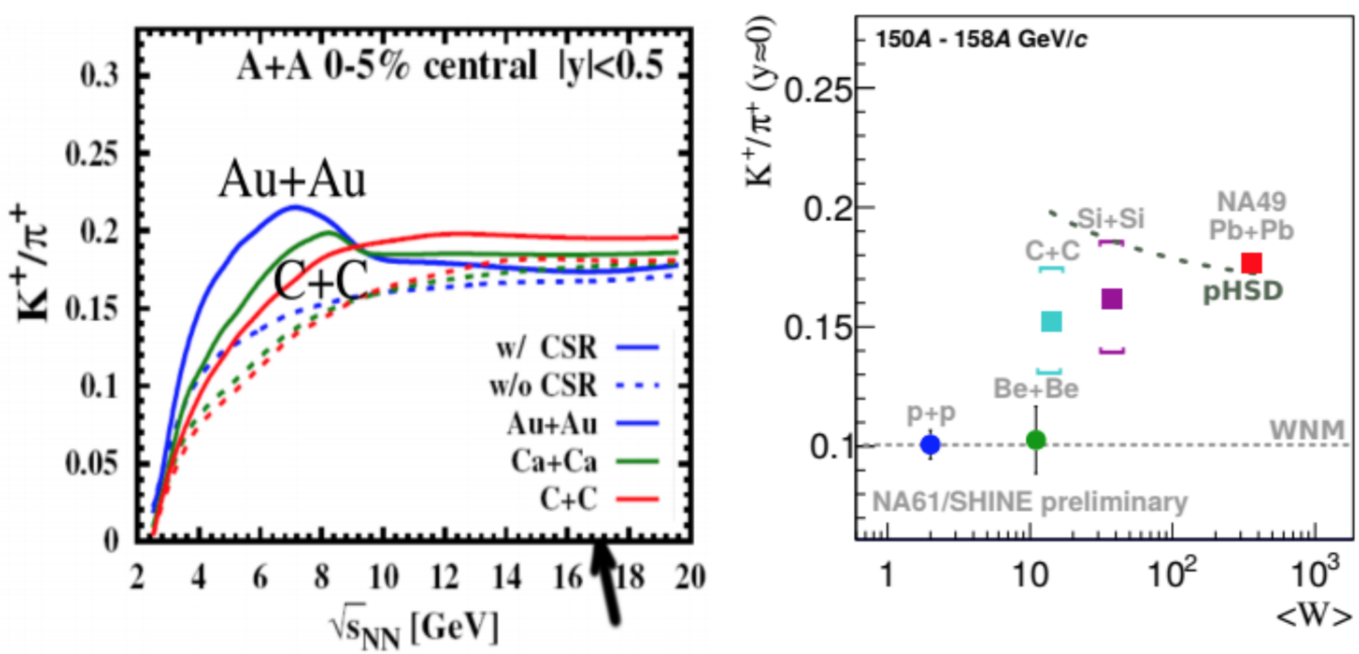
System size dependence of strangeness production



- Ar+Sc placed in between light and heavy systems.
- Be+Be almost overlaps with p+p.

PHSD and Onset of fireball

System size dependence of strangeness production - PHSD



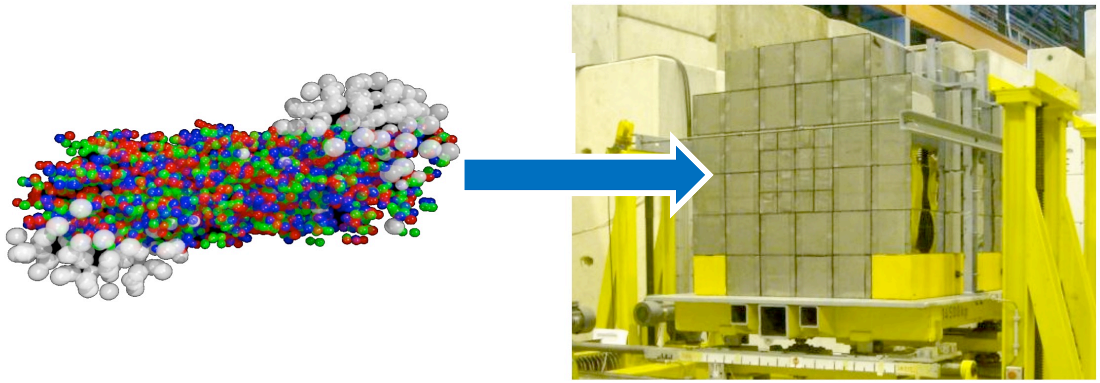
- **PHSD** predicts increase of strangeness production with system size at low (<10 GeV) collision energies and decrease at high (>10 GeV) collision energies.
- **PHSD** predictions in disagreement with data at high energies.

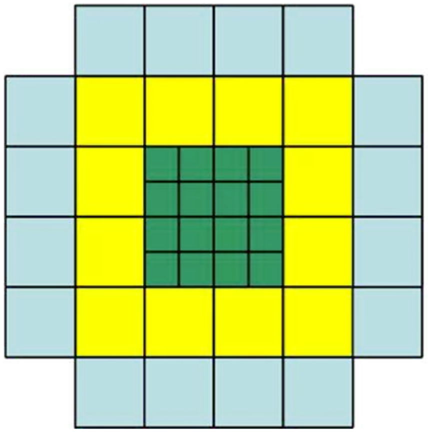
Palmese et al., PRC94 (2016) 044912

Event selection is based only on the forward energy related to projectile spectators

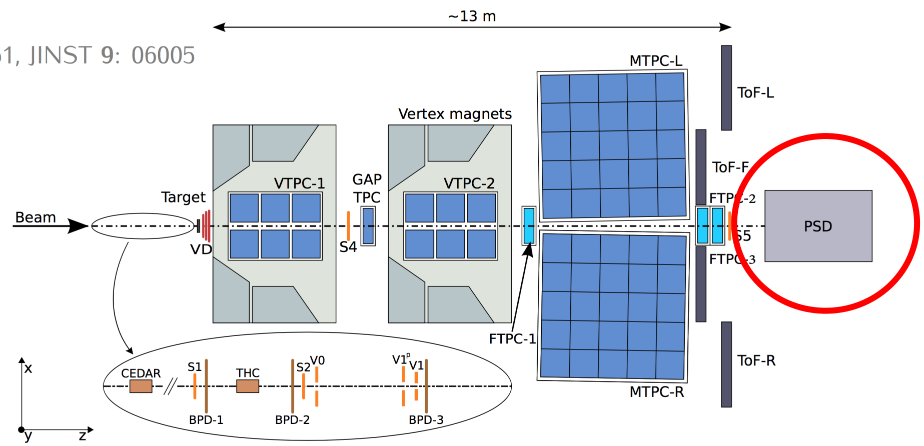
The forward energy consists of two components:

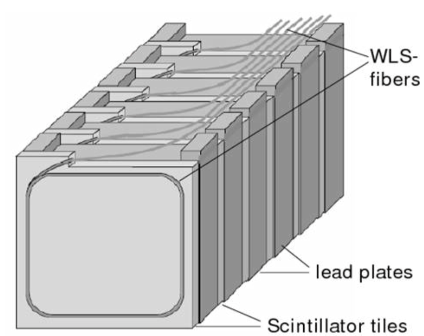
- spectators
- produced particles





NA61, JINST 9: 06005

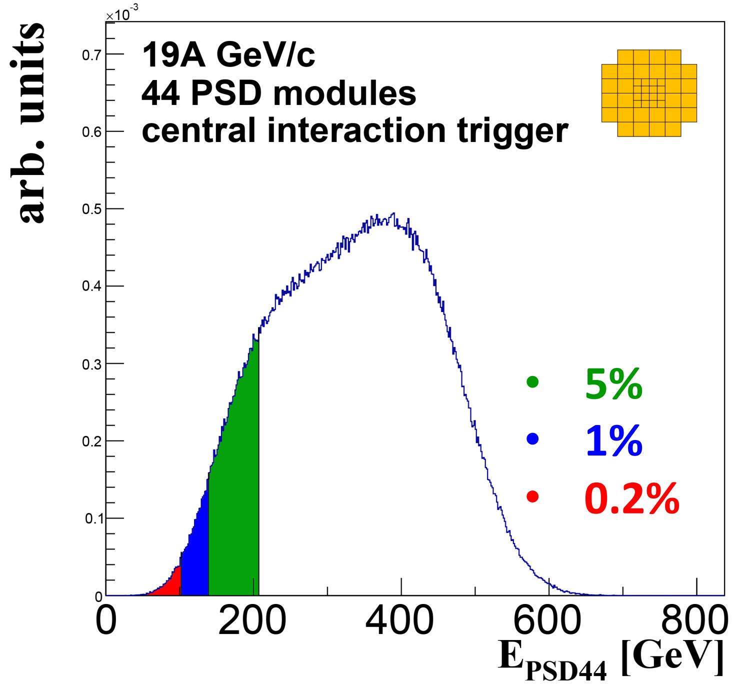


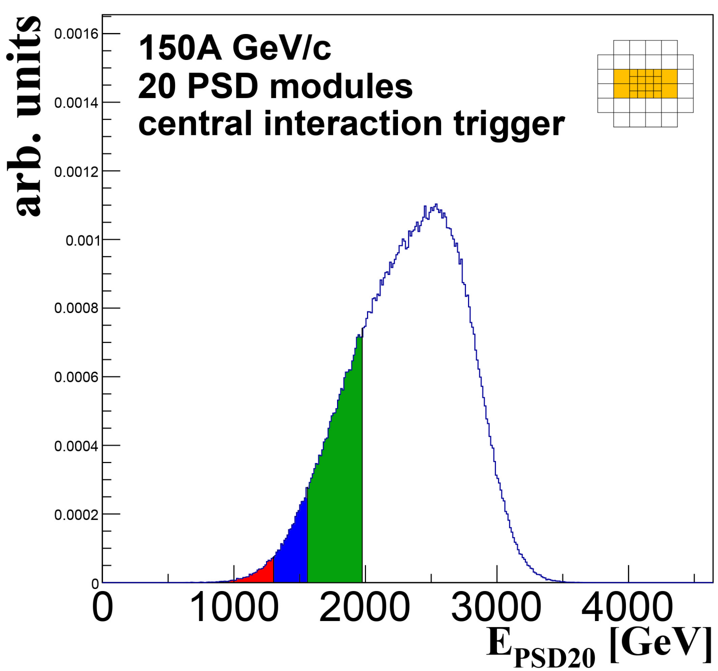


Events selection

- The measured energy allows selection of the ”centrality classes”

Ar+Sc





For cross-sections look PoS CPOD2014 (2015) pp.053

Strongly intensive quantities

A new strongly intensive quantity can be constructed:

$$\Omega[A,B] = \omega[A] - \frac{\langle AB\rangle - \langle A\rangle\langle B\rangle}{\langle B\rangle}$$

R. V. Poberezhnyuk, M. I. Gorenstein, M. Gazdzicki, arXiv:1509.06577v2 [hep-ph] 23 Sep 2015

and if A and B are uncorrelated from a single source ($\langle ab\rangle = \langle a\rangle\langle b\rangle$), then

$$\Omega[A,B] = \omega[a]$$

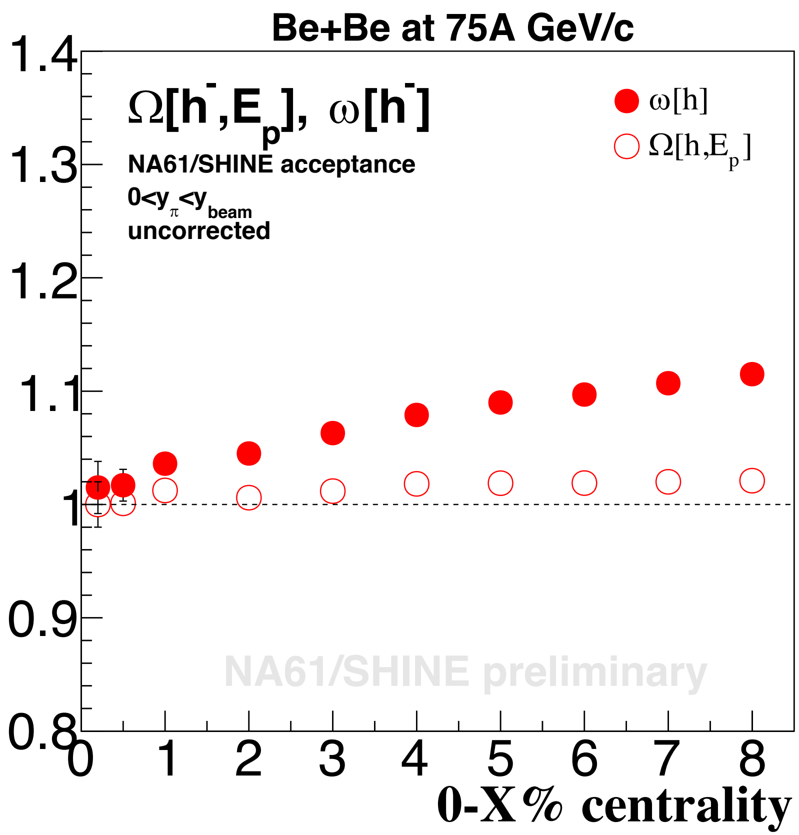
where $\omega[a]$ is scaled variance of A from a single source.

If A = **N** and B = $\mathbf{E_{beam}} - \mathbf{E_{PSD}} = \mathbf{E_P}$, then

$$\Omega[N, E_P] = \omega[n]$$

If a centrality interval is narrow enough, we can expect:

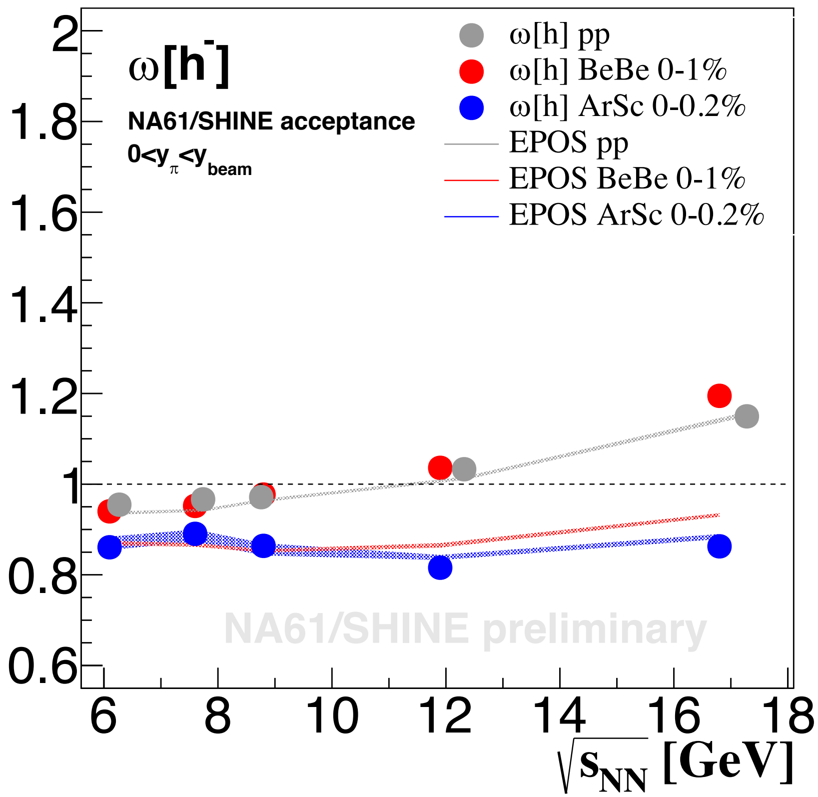
$$\Omega[N, E_P] \approx \omega[N]$$



$\Omega[N, E_P]$ almost does not depend on centrality – strongly intensive!

$\Omega[N, E_P]$ and $\omega[N]$ converges to a common limit for very central events

Is this common limit $\omega[n]$?

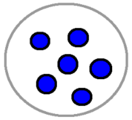


$\omega[N]$ is significantly larger for inelastic p+p interactions and for the central Be+Be collisions than for central Ar+Sc collisions!

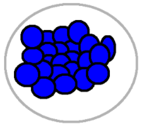
EPOS 1.99 describes p+p & Ar+Sc but fails in Be+Be

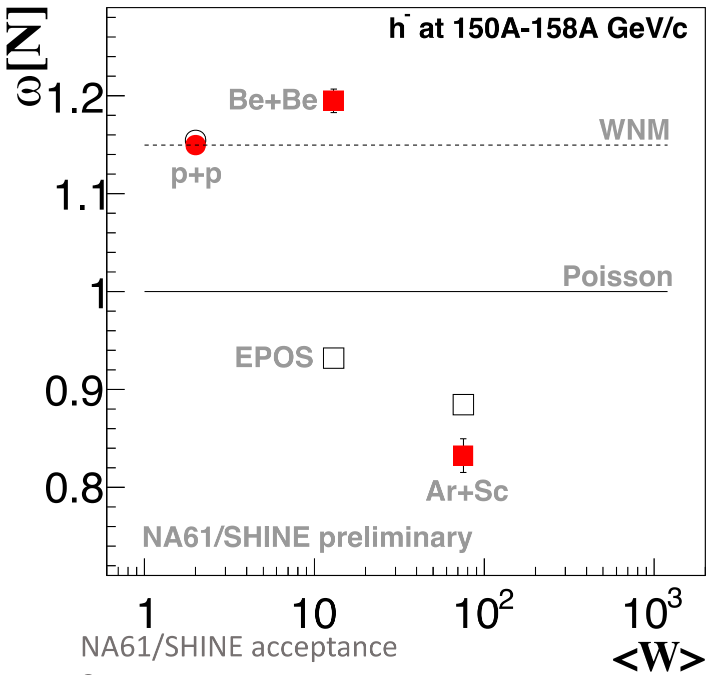
Multiplicity fluctuations: system size dependence

ω[N] is significantly larger for inelastic p+p interactions and for the central Be+Be collisions than for central Ar+Sc collisions!



Onset of fireball





NA61/SHINE acceptance

$0 < y_{\pi} < y_{beam}$

p+p – inelastic

Be+Be – 0-1%

Ar+Sc – 0-0.2%

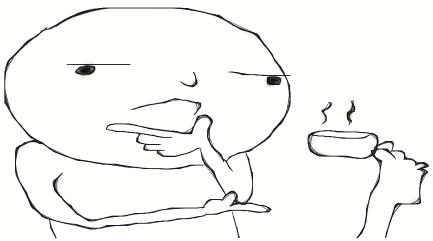
Why ω[N] in **central** Be+Be collisions is close to p+p value?

Why ω[N] is suppressed for central Ar+Sc (and Pb+Pb?) collisions in comparison to p+p and Be+Be?

Possible explanations:

- percolation models

  Baym, Physica **96A**: 131
  Celik, Karsch, Satz PLB **97**: 128
  Braun, Pajares, NPB **390**: 542
  Armesto, *et al.*, PRL **77**: 3736
  Cunqueiro, *et al.*, PRC **72**: 024907



- AdS/CFT correspondence

  E. Shuryak Prog. Part. Nucl. Phys. 62 (2009) 48–101, arXiv:0807.3033 [hep-ph]
  S. Lin and E. Shuryak Phys. Rev. D79 (2009) 124015, arXiv:0902.1508 [hep-th].

- Anything else?