Critical Point and Flying Neutrinos -
- NA61/SHINE at the CERN SPS

(SHINE – SPS Heavy Ion and Neutrino Experiment)

- Physics goals
- Detector and Status
- Flying Neutrinos
- Critical Point

Addendum-3 CERN-SPSC-2007-033, SPSC-P-330 (November 16, 2007)
Addendum-2: CERN-SPSC-2007-019, SPSC-P-330 (June 15, 2007)
Addendum-1: CERN-SPSC-2007-004, SPSC-P-330 (January 25, 2007)
Proposal: CERN-SPSC-2006-034, SPSC-P-330 (November 3, 2006)
Status Report: CERN-SPSC-2006-023, SPSC-SR-010 (September 5, 2006)
LoI: CERN-SPSC-2006-001, SPSC-I-235 (January 6, 2006)
EoI: CERN-SPSC-2003-031, SPSC-EOI-001 (November 21, 2003)

M. Gazdzicki, Frankfurt, Kielce
for the NA61 Collaboration

The NA61/SHINE Collaboration:

114 physicists from 24 institutes and 14 countries:

University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Cape Town University, Cape Town, South Africa
Jagellionian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
Swietokrzyska Academy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
LPNHE, Universites de Paris VI et VII, Paris, France
Pusan National University, Pusan, Republic of Korea
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

Physics goals (I):

Physics of strongly interacting matter

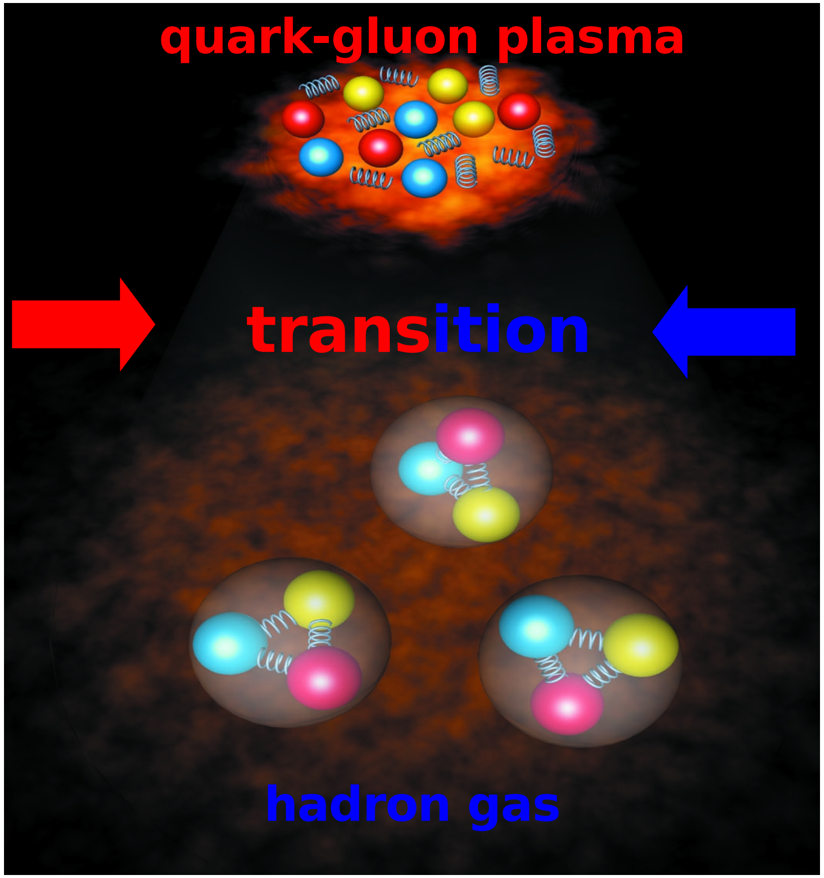
Discovery potential:

Search for the critical point of strongly interacting matter

Precision measurements:

Study the properties of the onset of deconfinement in nucleus-nucleus collisions

Measure hadron production at high transverse momenta in p+p and p+Pb collisions as reference for Pb+Pb results



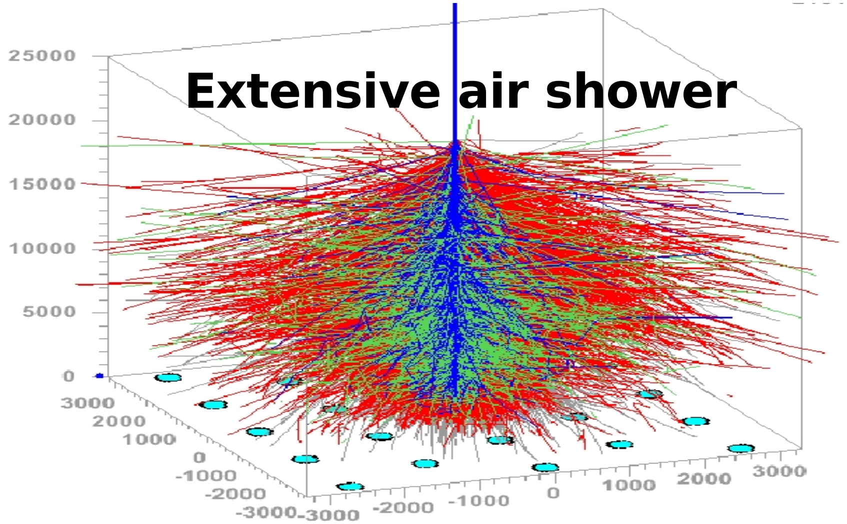
Physics goals (II):

Data for neutrino and cosmic ray experiments

Precision measurements:

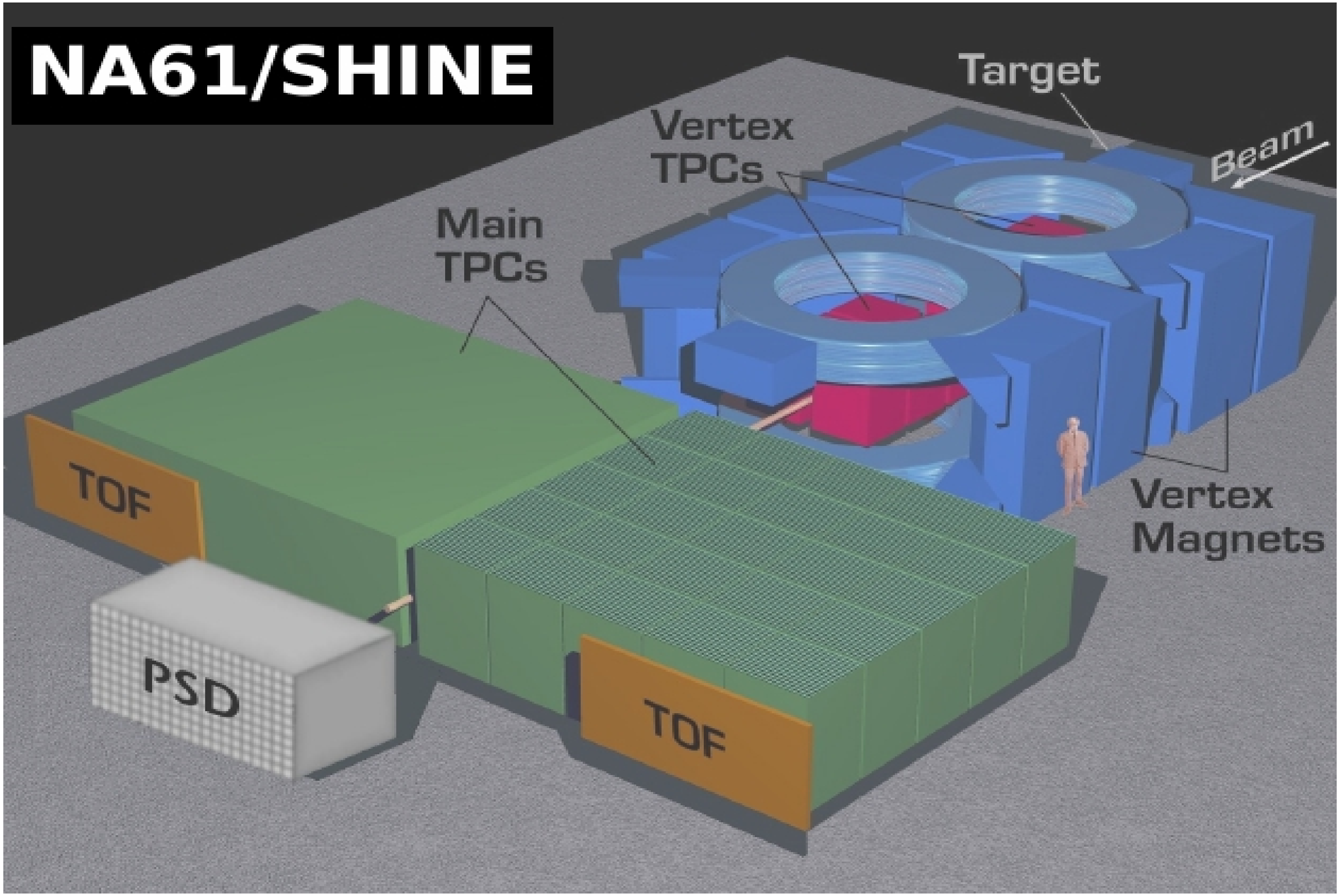
Measure hadron production in the T2K target needed for the T2K (neutrino) physics

Measure hadron production in p+C interactions needed for T2K and cosmic-ray, Pierre Auger Observatory and KASCADE, experiments



Detector

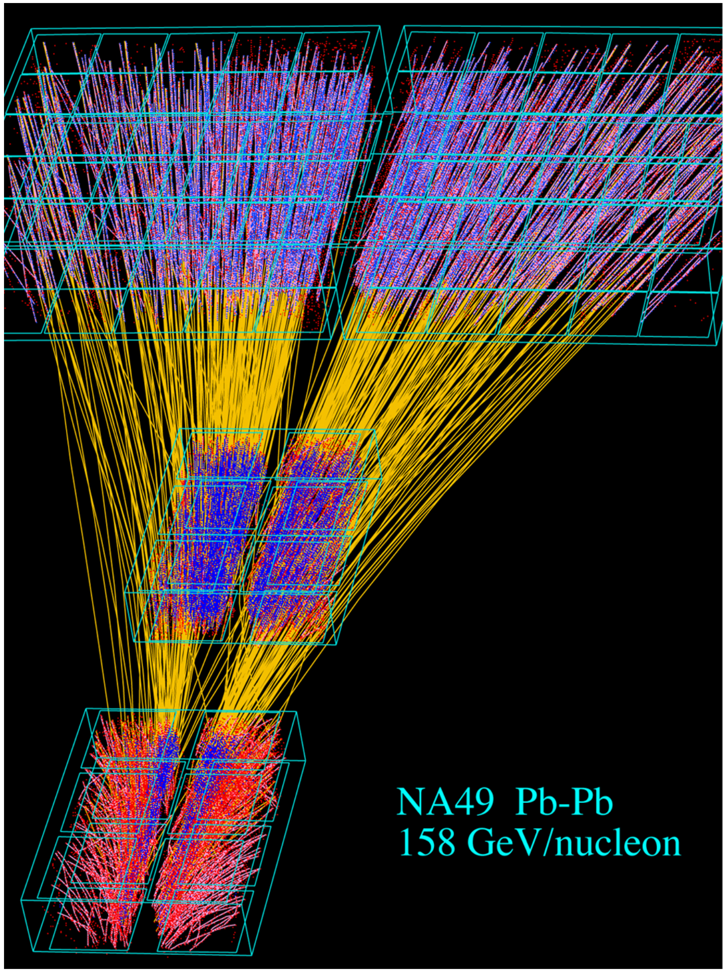
Upgraded NA49 apparatus



NA49: Nucl. Instrum. Meth. A430, 210 (1999)
Upgrades: CERN-SPSC-2006-034, SPSC-P-330


NA61/SHINE at the CERN SPS
LHC
NA61/
SHINE
SPS

NA49 facility:



- **Large acceptance: ≈50%**
- **High momentum resolution:**
  $\sigma(p)/p^2 \approx 10^{-4} \quad ((GeV/c)^{-1})$
- **Good particle identification:**
  $\sigma(TOF) \approx 60\,ps,$
  $\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04,$
  $\sigma(m_{inv}) \approx 5\,MeV$
- **High detector efficiency:**
  > 95%
- **Precise and rich physics results:**
  37 publications with final data

Tested in 2006 and 2007 runs:

- No degradation of the performance since the beginning of operation
- Reconstruction, calibration, simulation and analysis software works
- All necessary experts are in the collaboration

Report from the test run: CERN-SPSC-2006-023, SPSC-SR-010 (September 5, 2006)

Basic upgrades:

2007: Modification and replacement of the obsolete equipment,
construction of the forward ToF wall

→ **reestablish the full functionality of NA49 and T2K acc.**

(2007 total cost 300k CHF)

2008: Replacement of the TPC digital read-out and DAQ
(by an ALICE-like system):

→ **an expected event rate ≈ *100 Hz***

(2008 total cost 500k CHF)

2009: Replacement of the VETO Calorimeter by a
Projectile Spectator Detector:

→ **an increase of the resolution in the measurement of the number of projectile spectators by a factor ≈5 to $\Delta E/E \approx 50\%/E$,**

→ ***a* possible determination of the reaction plane**

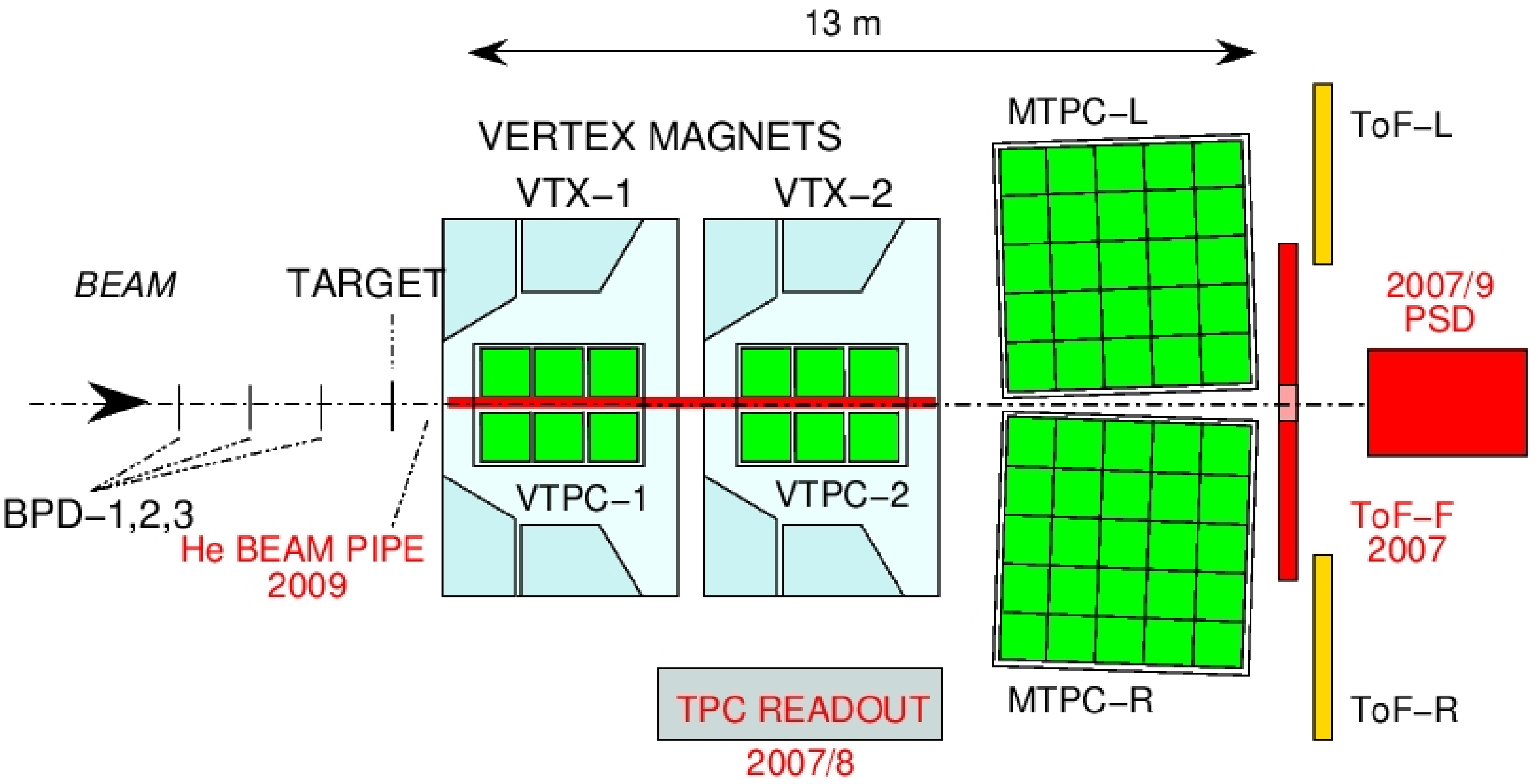
Installation of the Helium beam pipe in the VTPC cage

→ **a reduction of the delta-electron background by a factor of 10**

(2010 total cost 1000k CHF)

covered by the participating institutes

NA61 and basic upgrades:



NA61 status:

-approved experiment at the CERN SPS

-two test runs (2006 and 2007) were successfully performed

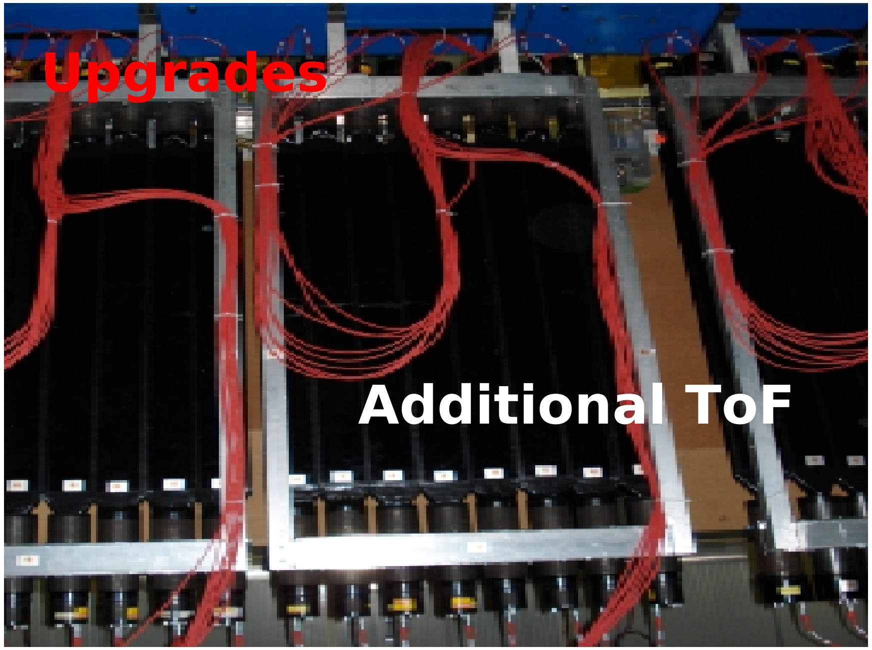
-the pilot physics run (32 days) was performed in 2007 (detector tests and the first data for T2K)

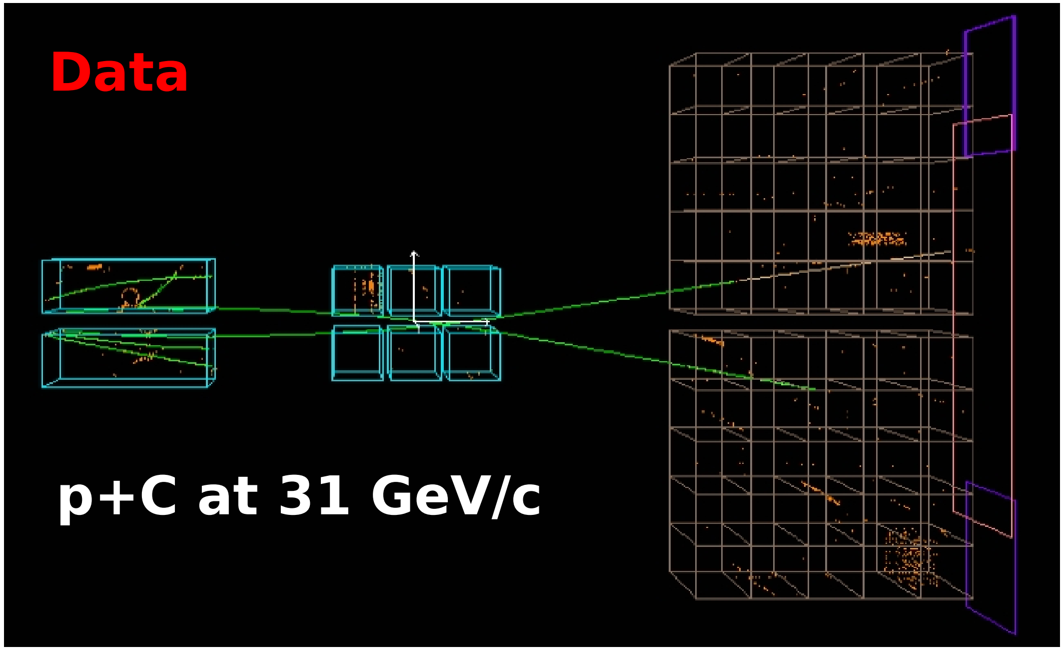
-the 2008 run (45 days) is approved (T2K, CR, high p_T)

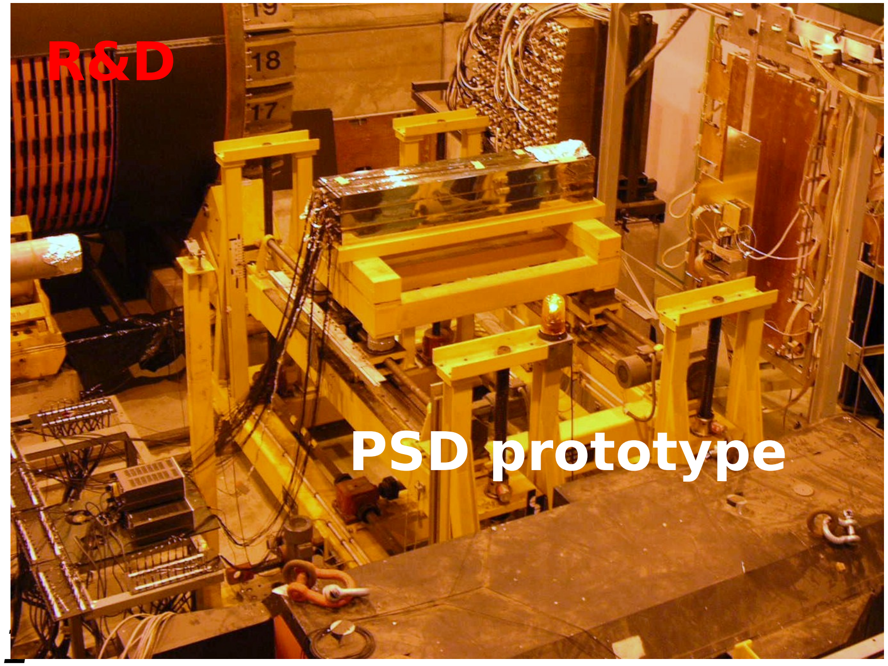
-the first ion run (S beam) is recommended and its scheduling is under discussion (2010?)

-the doors for the continuation of the NA61 program are clearly opened

The 2007 pilot run:







Dubna, Moscow and St. Petersburg in NA61:

Dubna:
- responsible for ToF-L/R walls:
detectors, software, calibration and analysis,
- software library, reconstruction and simulation chains,
- ToF and TPC data analysis,

Moscow:
- leading R&D and construction of the Projectile Spectator Detector and its read-out,
- data analysis

St. Petersburg:
- construction and installation of the He beam pipe,
- data analysis: fluctuations/correlations

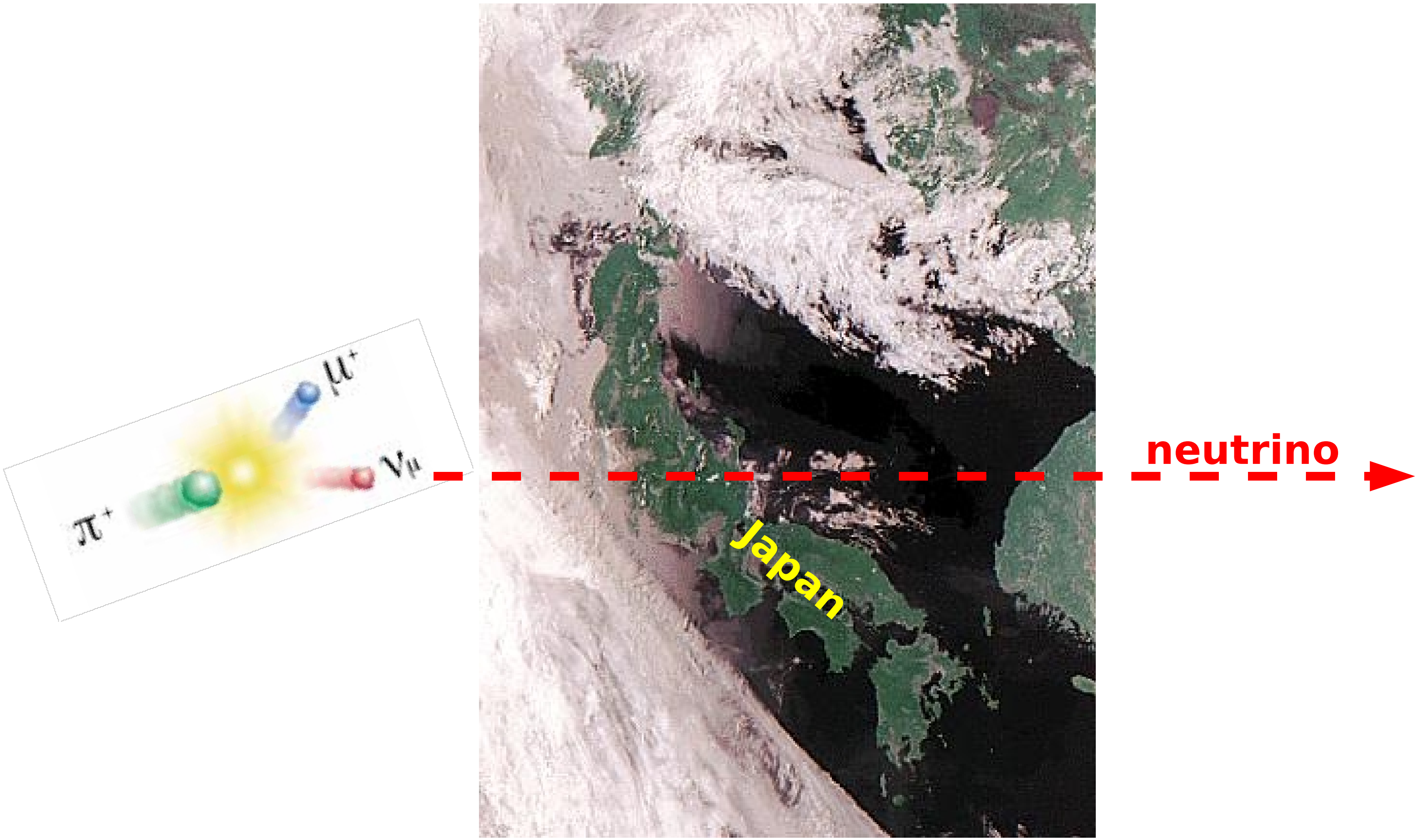
NA61 beam request

Beam	Energy (A GeV)	Year	Days	Physics	Status
p	30	2007	30	T2K, C-R, R&D	*performed*
p	30, 40, 50	2008	14	T2K, C-R	*approved*
π^-	158, 350	2008	3	C-R	*approved*
p	158	2008	28	High p_T	*approved*
S	10, 20, 30, 40, 80, 158	2009	30	CP&OD	*recommended*
p	10, 20, 30, 40, 80, 158	2009	30	CP&OD	*recommended*
In	10, 20, 30, 40, 80, 158	2010	30	CP&OD	*to be discussed*
p	158	2010	30	High p_T	*to be discussed*
C	10, 20, 30, 40, 80, 158	2011	30	CP&OD	*to be discussed*
p	10, 20, 30, 40, 80, 158	2011	30	CP&OD	*to be discussed*

Flying Neutrinos

The question:

What happens with neutrinos flying across Japan?



Mixing of neutrinos

- Mixing matrix connects mass and weak eigenstates

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} V_{\text{mixing}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo; Maki, Nagakawa, Sakata matrix

Simplification:
consider two families only
one mixing angle (just "rotation")

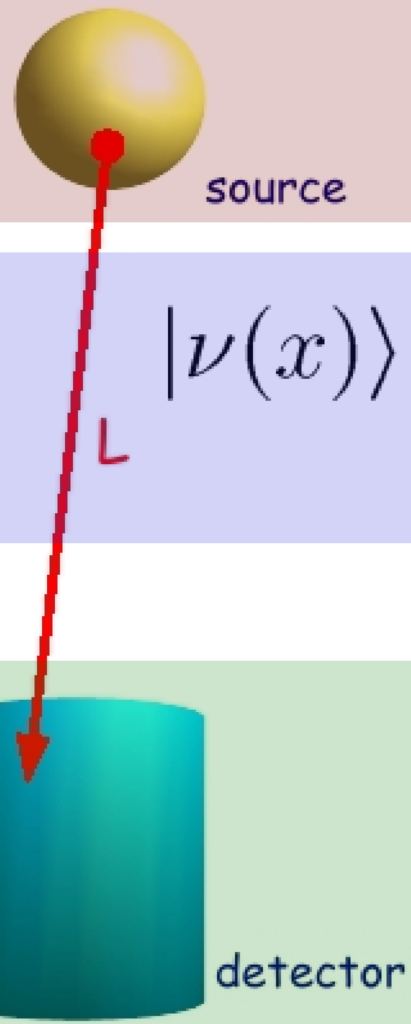
$$\begin{pmatrix} \nu_e & \nu_\mu \end{pmatrix} \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e & \nu_\mu \end{pmatrix} U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

after Jaap Panman

Neutrino oscillations

- Oscillations: rotation of states during propagation



$$|\nu(x_0)\rangle = |\nu_e\rangle = c|\nu_1\rangle + s|\nu_2\rangle$$

One given flavour produced by weak interaction

$$|\nu(x)\rangle = c|\nu_1\rangle e^{i(Et-\vec{k_1}\vec{x})} + s|\nu_2\rangle e^{i(Et-\vec{k_2}\vec{x})}$$

Mass eigenstates propagate at different velocity

$$P(\nu \to \nu_\mu) = |\langle \nu_\mu | \nu(t) \rangle|^2$$

Weak interaction selects component of one flavour

after Jaap Panman

Neutrino detection probability

$$|\nu(x)\rangle = c|\nu_1\rangle e^{i(Et-\vec{k_1}\vec{x})} + s|\nu_2\rangle e^{i(Et-\vec{k_2}\vec{x})}$$

$$|\vec{k}| \approx E - \frac{m^2}{2E}$$

- propagation

$$|\nu(L)\rangle = e^{-iEt}\left[c \cdot e^{-i\frac{m_1^2}{2E}L}\,|\nu_1\rangle + s \cdot e^{-i\frac{m_2^2}{2E}L}\,|\nu_2\rangle\right]$$

- Probability to detect other flavour

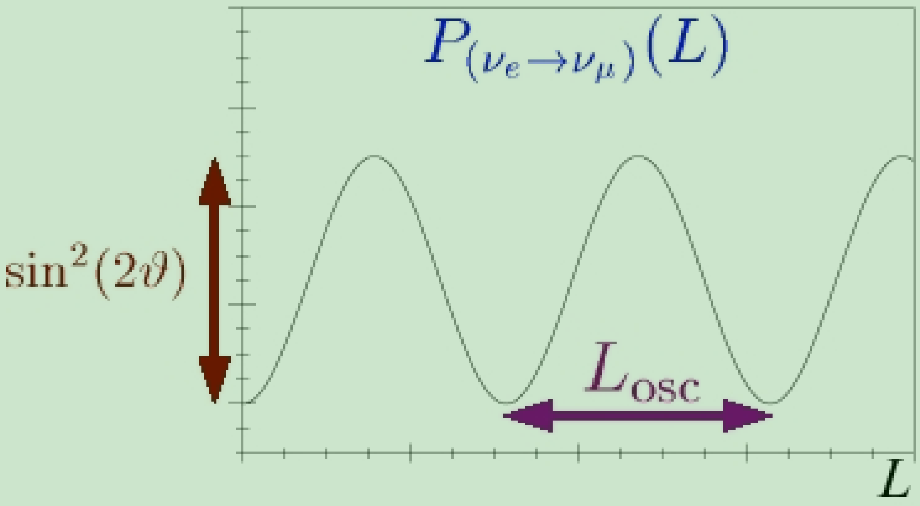
$$\begin{aligned} P_{(\nu_e\to\nu_\mu)} &= |\langle\nu_\mu|\nu(L)\rangle|^2 \\ &= \left|-sce^{-i\frac{m_1^2}{2E}L} + cse^{-i\frac{m_2^2}{2E}L}\right| \\ &= 4s^2c^2\left(1-\cos\frac{m_1^2-m_2^2}{2E}L\right) \\ &= \sin^2(2\vartheta)\sin^2\left(\frac{\Delta m_{12}^2}{4E}L\right) \end{aligned}$$

after Jaap Panman

Neutrino oscillation length

- Oscillation probability $$P_{(\nu_e \to \nu_\mu)}(L) = \sin^2(2\vartheta)\sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2)}{E(\mathrm{GeV})}L(\mathrm{km})\right)$$

- Probability to see original flavour $$P_{(\nu_e \to \nu_e)}(L) = 1 - P_{(\nu_e \to \nu_\mu)}(L)$$

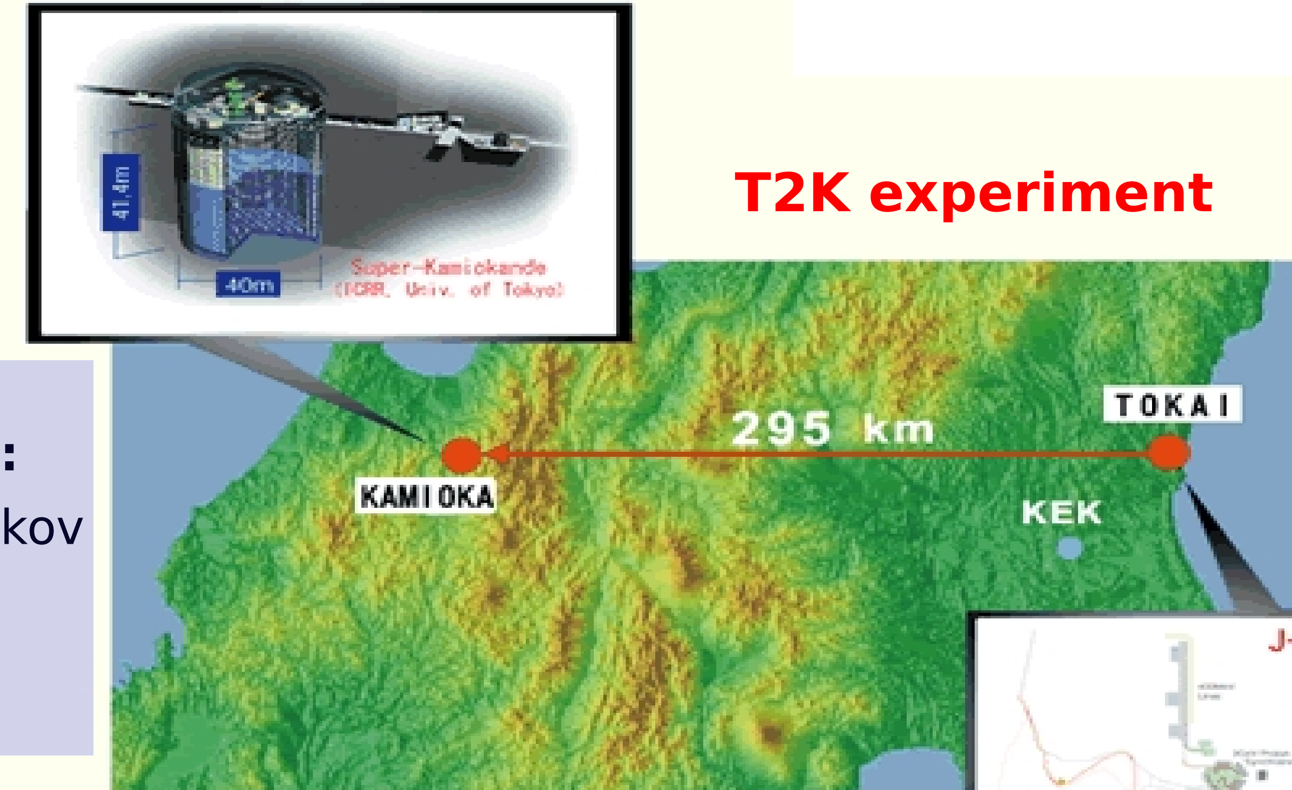


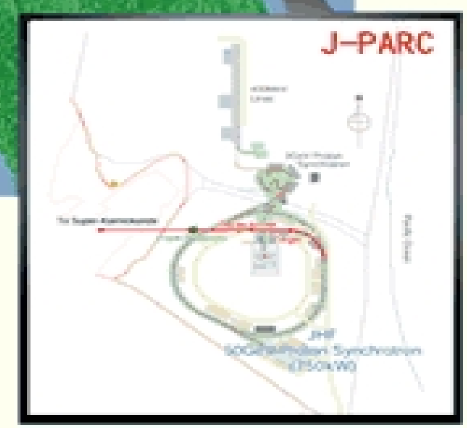
$$L_{\mathrm{osc}}(\mathrm{km}) = 2\pi\,\frac{E(\mathrm{GeV})}{1.27\,\Delta m^2(\mathrm{eV}^2)}$$

after Jaap Panman

Neutrino flying across Japan

T2K experiment





Super-Kamiokande:
Water Cherenkov Detector (50k tons, 13k PMTs)

J-PARC:
0.75 MW,
50 GeV PS

Approved since 2003, first beam in 2009.

Goals:

- **search for $\nu_\mu \rightarrow \nu_e$ appearance $\Rightarrow$ $\sin^2 2\theta_{13}$**
- **measurement of $\nu_\mu \rightarrow \nu_\mu$ disappearance $\Rightarrow$ $\sin^2 2\theta_{23}$ and Δm^2_{23}**

Measuring neutrino oscillations

An example of $\nu_\mu \rightarrow \nu_\mu$ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) = \frac{\text{number of } \nu_\mu \text{ neutrinos flying to S-K at J-PARC}}{\text{number of } \nu_\mu \text{ neutrinos flying through S-K}}$$

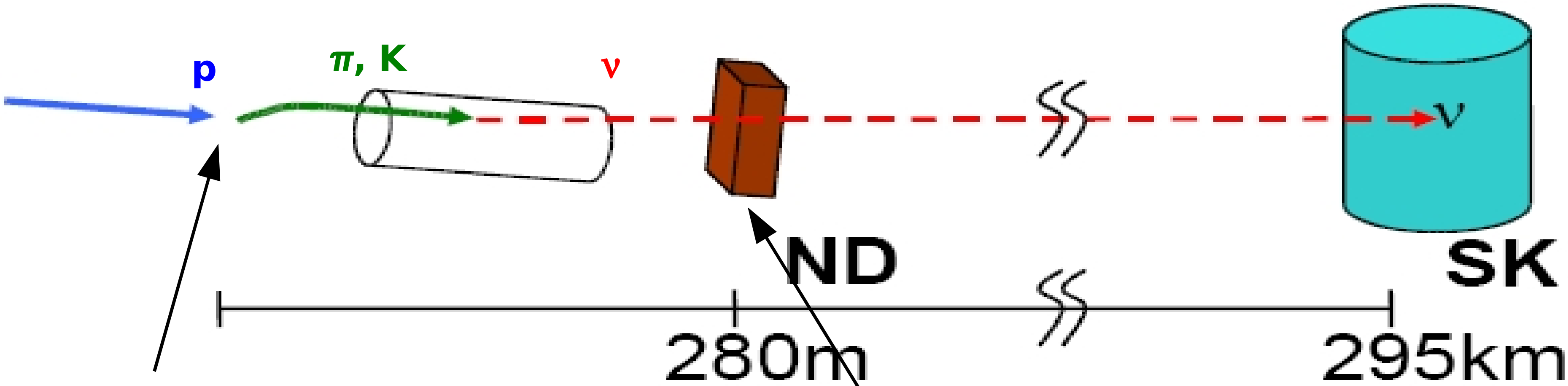
number of ν_μ neutrinos flying through S-K from:

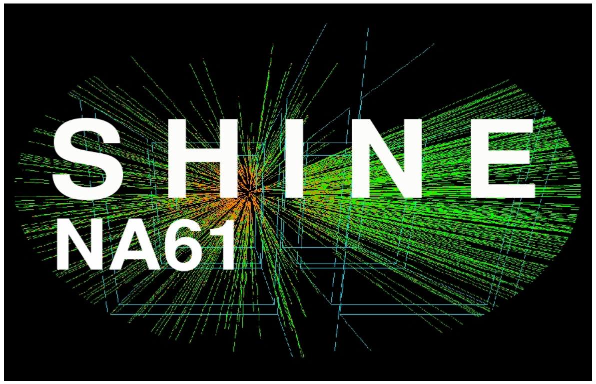
- number of neutrino interactions in S-K,
- interaction cross-section (large uncertainties) and
- S-K geometry and material

number of ν_μ neutrinos flying to S-K at J-PARC from:

- measurement of the neutrino flux in the detector near J-PARC (large uncertainties) and/or
- calculation of the neutrino flux resulting from pion and kaon decays: data on pion and kaon production in p+(T2K target) interactions are needed

Measuring neutrino oscillations



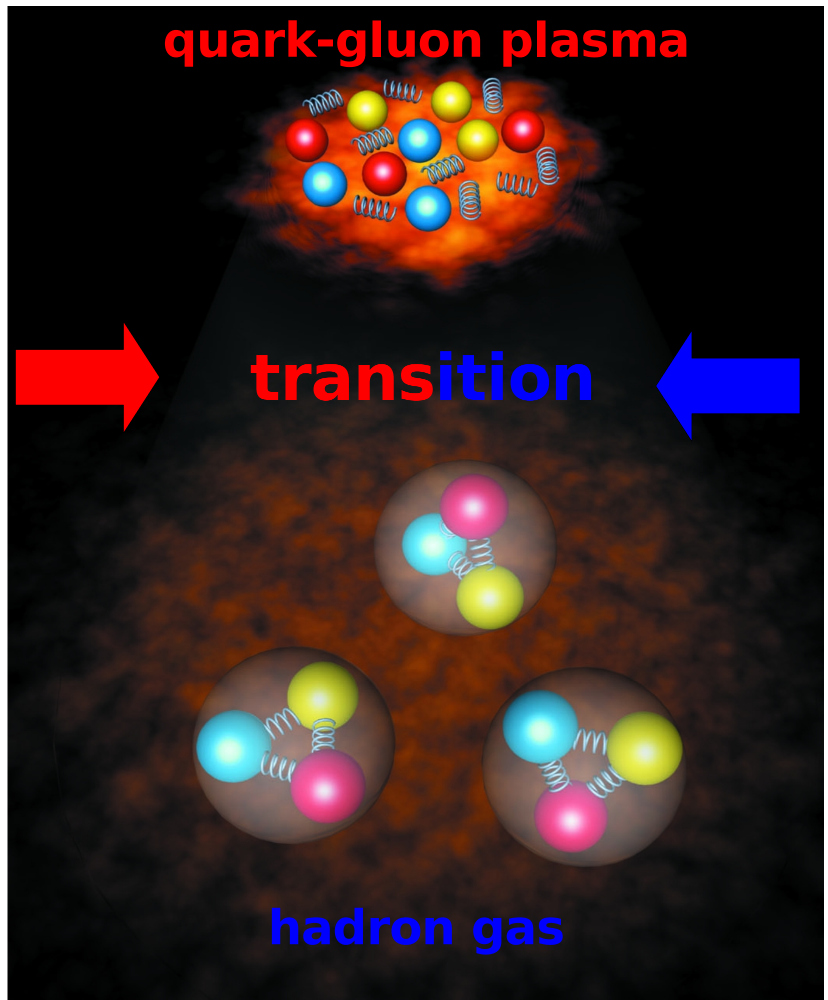


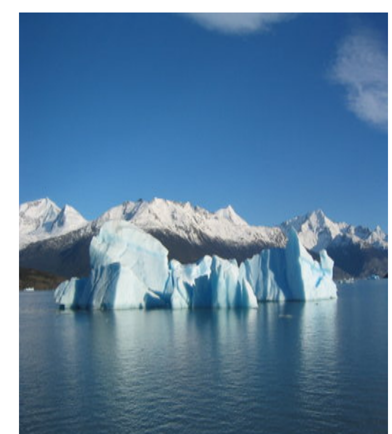
Near Detector needed to reduce uncertainties resulting from poorly known neutrino interaction cross-sections

High precision data on pion and kaon production on the T2K target needed to get the initial neutrino flux

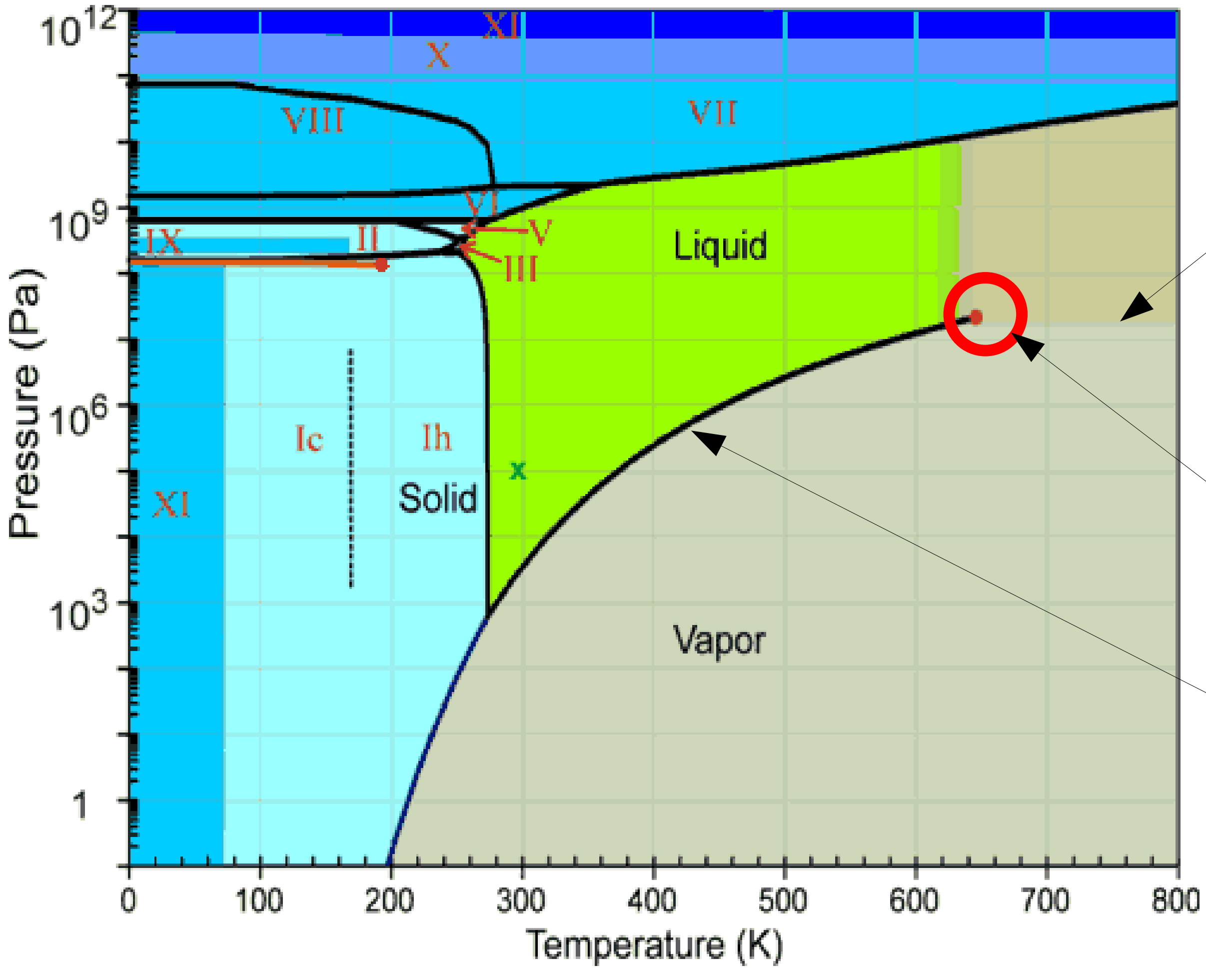
Critical Point

The question:
What happens when strongly interacting matter gets hotter and denser?





Phase diagram of water



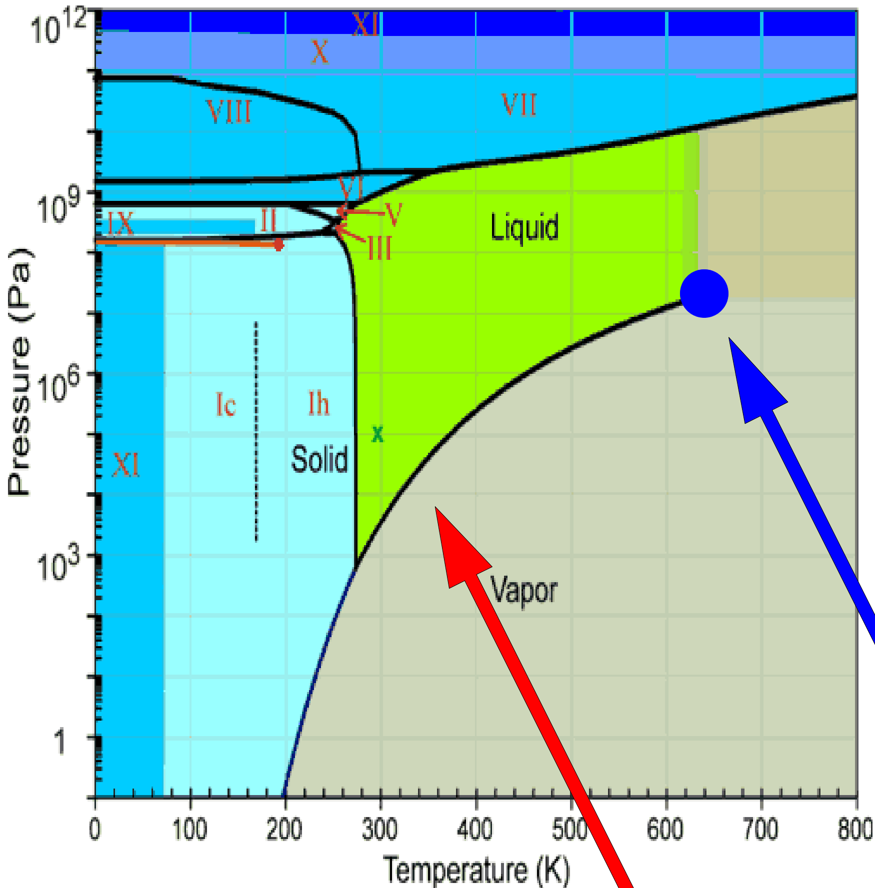
cross-over

critical point

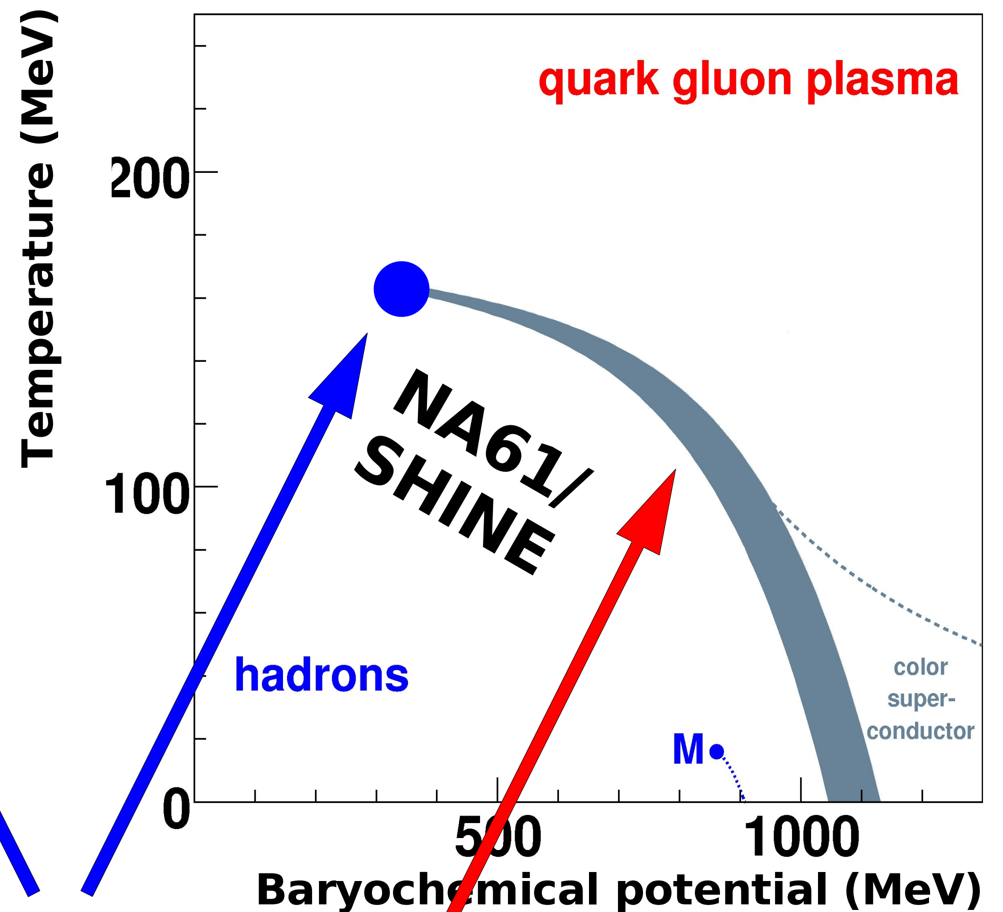
1st order phase transition

Water and strongly interacting matter

water

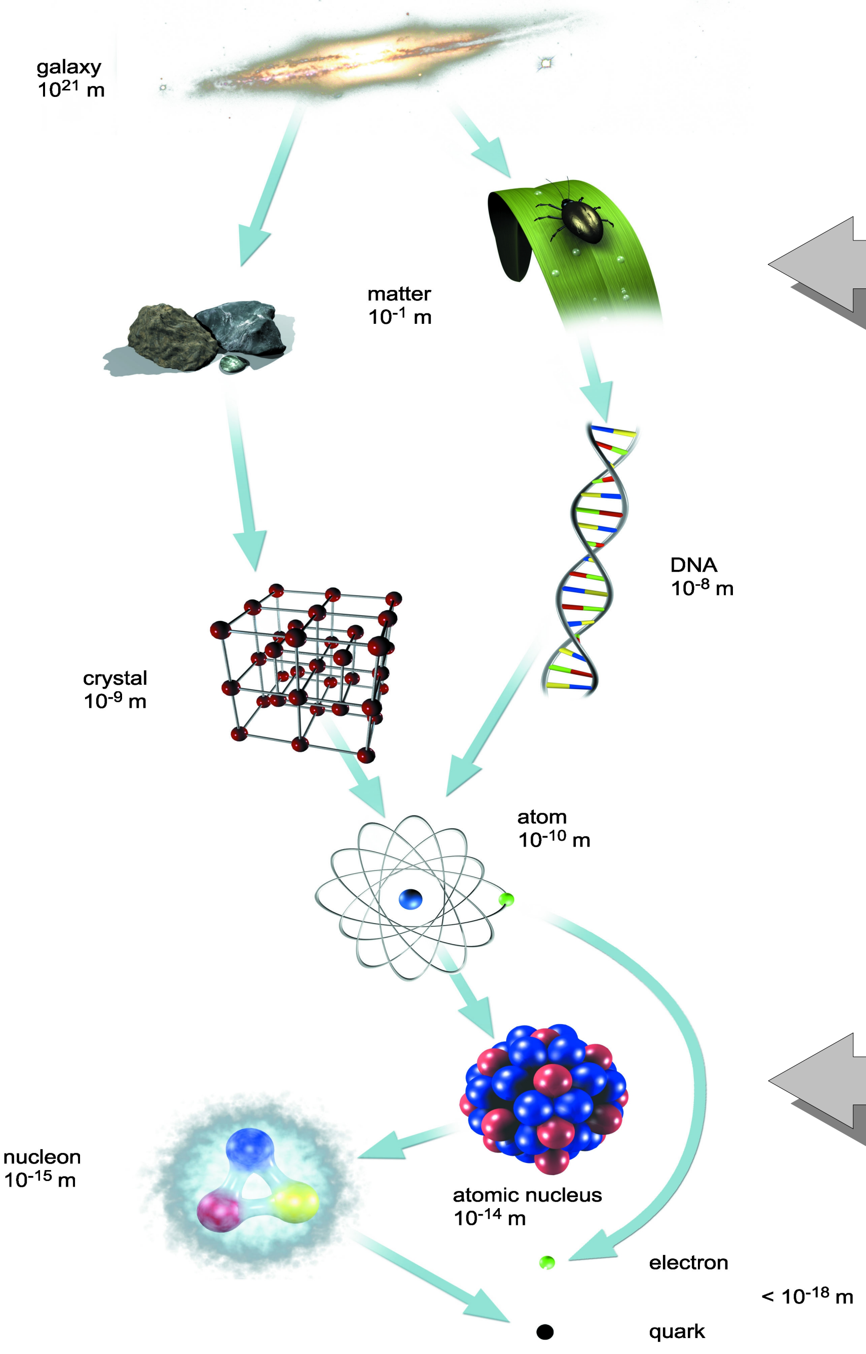


strongly interacting matter



critical point

1st order phase transition



In our daily life ...

droplets of water

10^{-12}

droplets of strongly interacting matter

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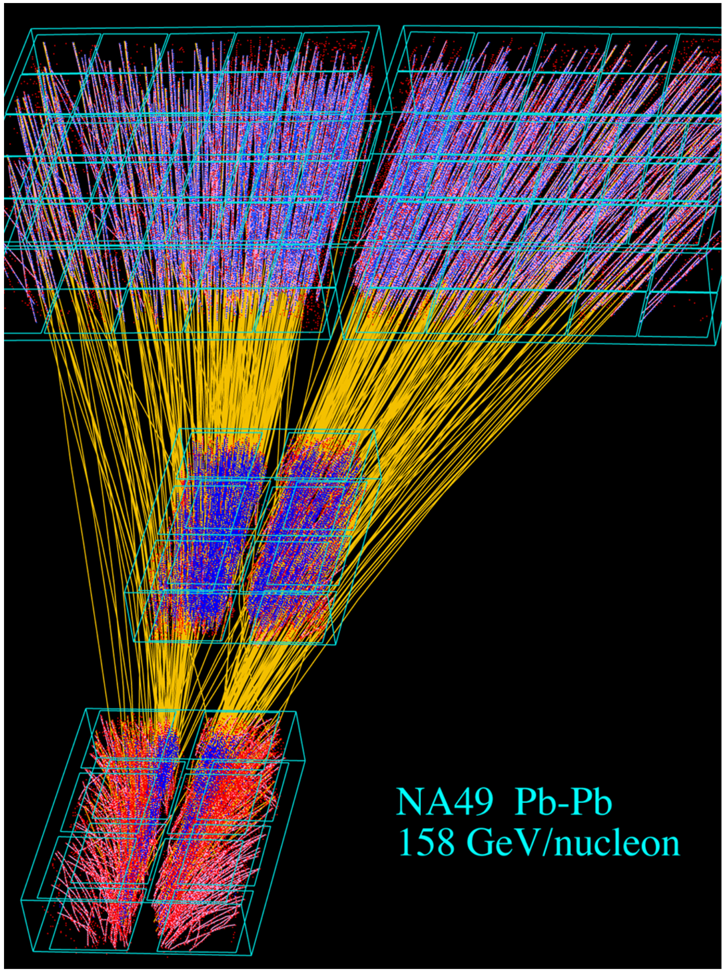
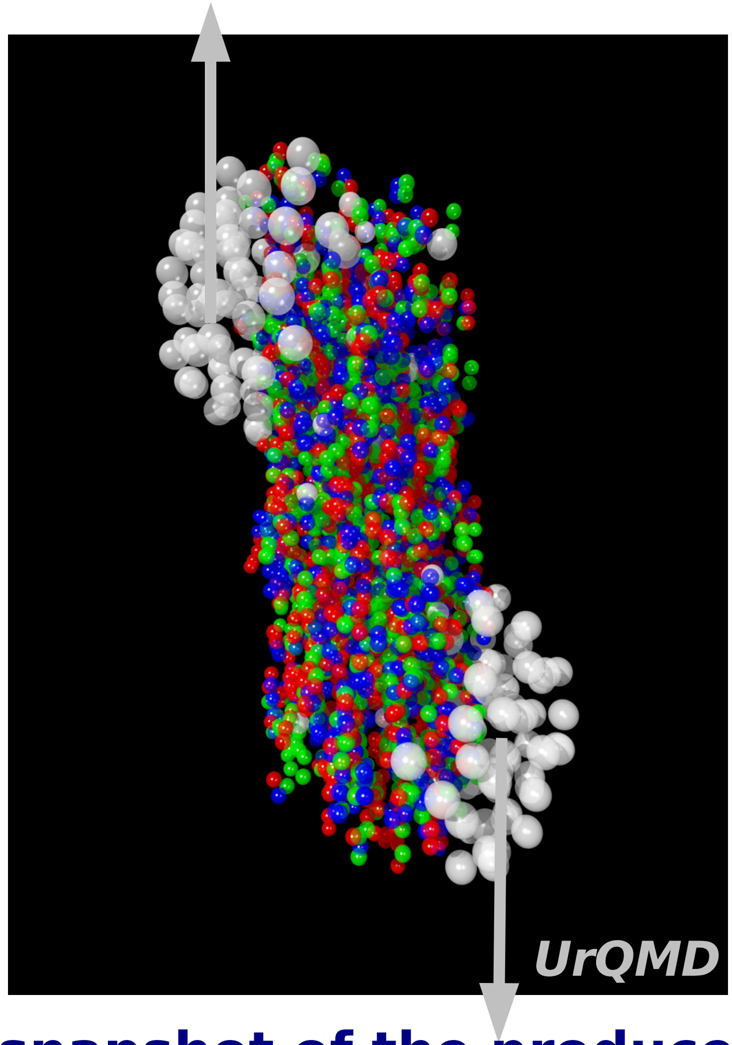
the properties of strongly interacting matter can be studied only in collisions of nuclei

Nucleus-nucleus collisions



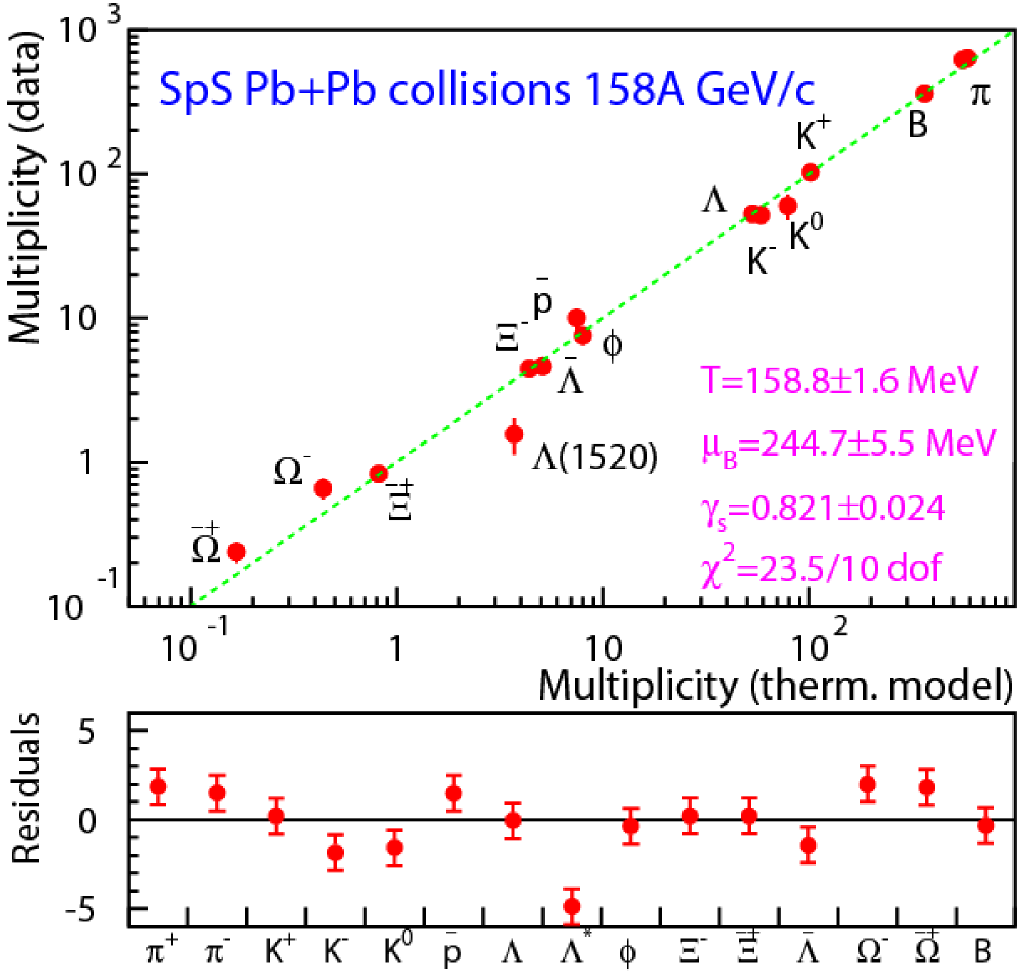
produced particles measured in the NA49 apparatus (scale 10 m)



snapshot of the produced matter after the collision (scale 10^{-14} m)

Particle production follows rules of thermodynamics

$$\langle n_i \rangle = \frac{(2J_i+1)\,V}{(2\pi)^3} \int d^3p \, \frac{1}{\gamma_s^{-S_i} exp[(E_i - (\mu_B + \mu_S + \mu_Q))/T] \pm 1}$$

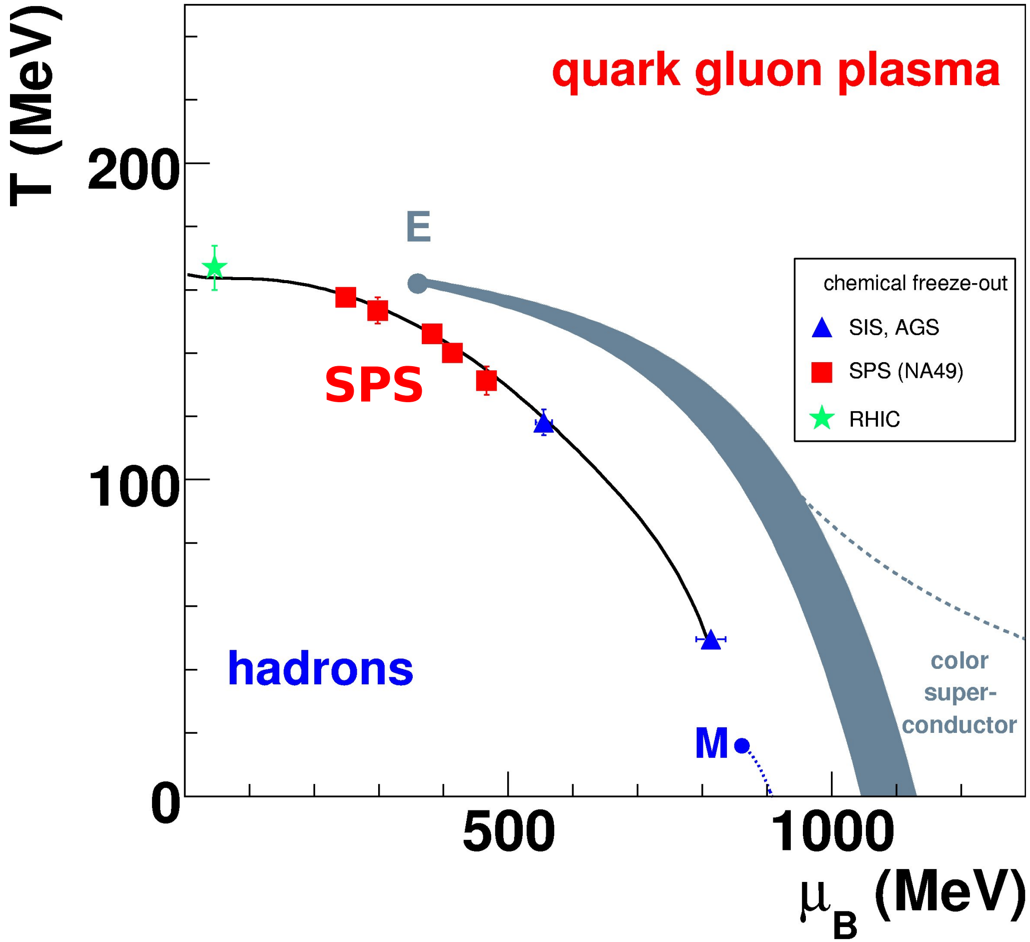


fit parameters

chemical freeze-out of matter created in A+A collisions

Becattini, Broniowski Florkowski, Gorenstein, Redlich, ...

Freeze-out parameters in Pb+Pb collisions



Freeze-out points of central heavy ion collisions at SPS are close to the phase boundary

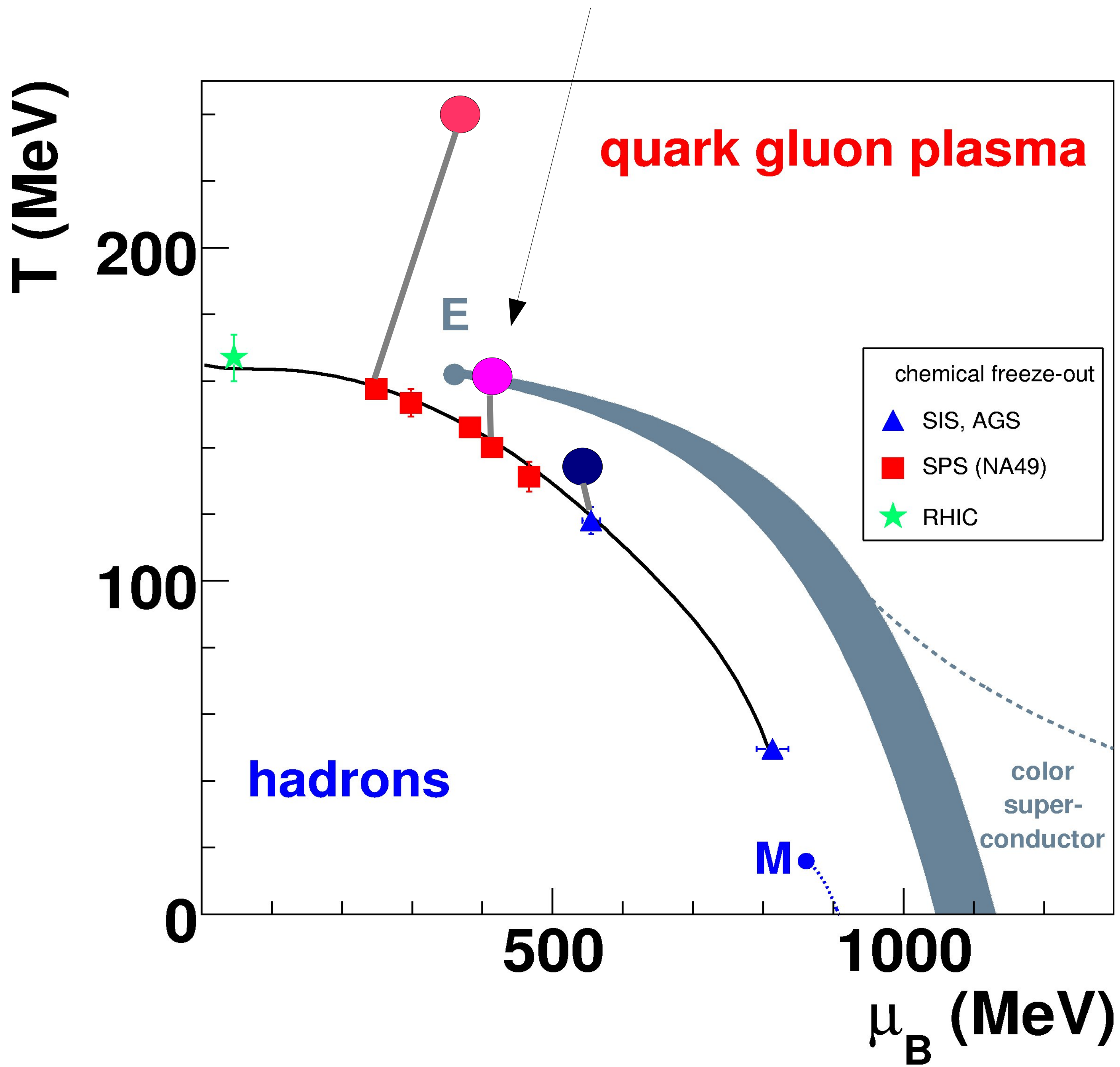
↓

Its possible that the early stage crosses the phase boundary at SPS energies (onset of deconfinement)

HG fits: Becattini et al.,
Cleymans, Redlich et al.

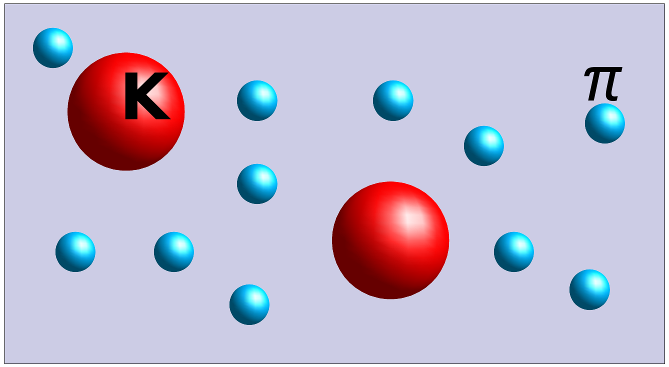
CP: Fodor, Katz

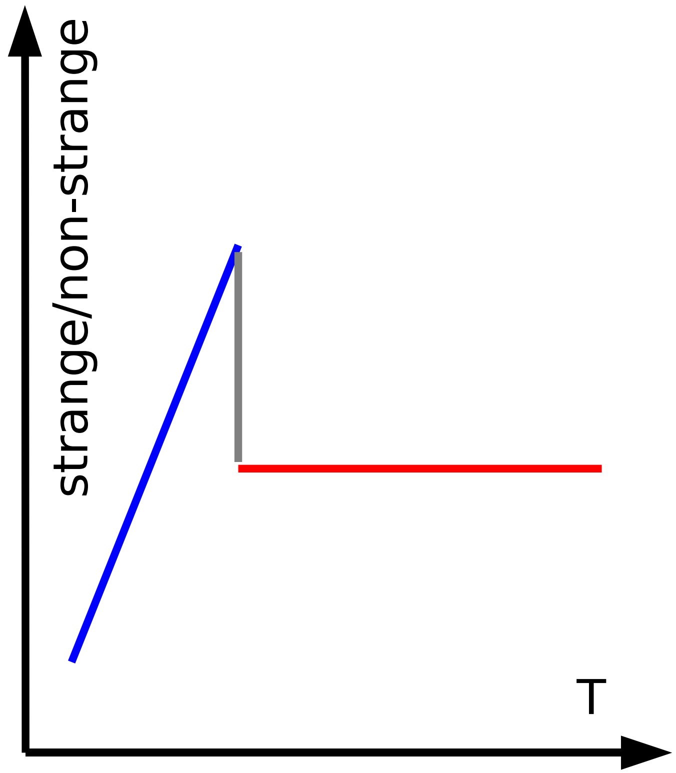
Onset of deconfinement



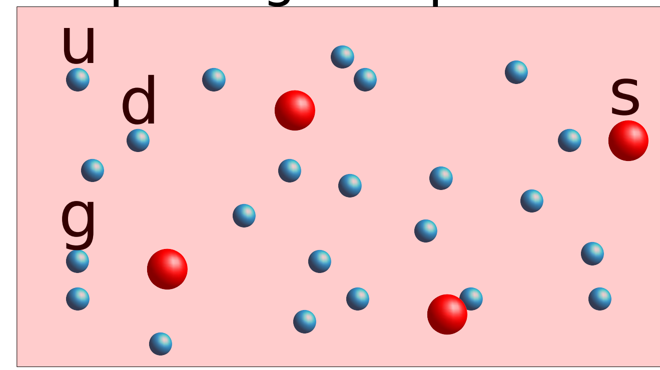
Onset of deconfinement: the toy model of the horn

hadron gas





quark-gluon plasma



$$\frac{\langle K\rangle}{\langle \pi\rangle} \propto \frac{M T^{3/2}}{T^3} \cdot e^{-M/T}$$

$$\frac{\langle s\rangle}{\langle u+d+g\rangle} \propto \frac{T^3}{T^3} = const(T)$$

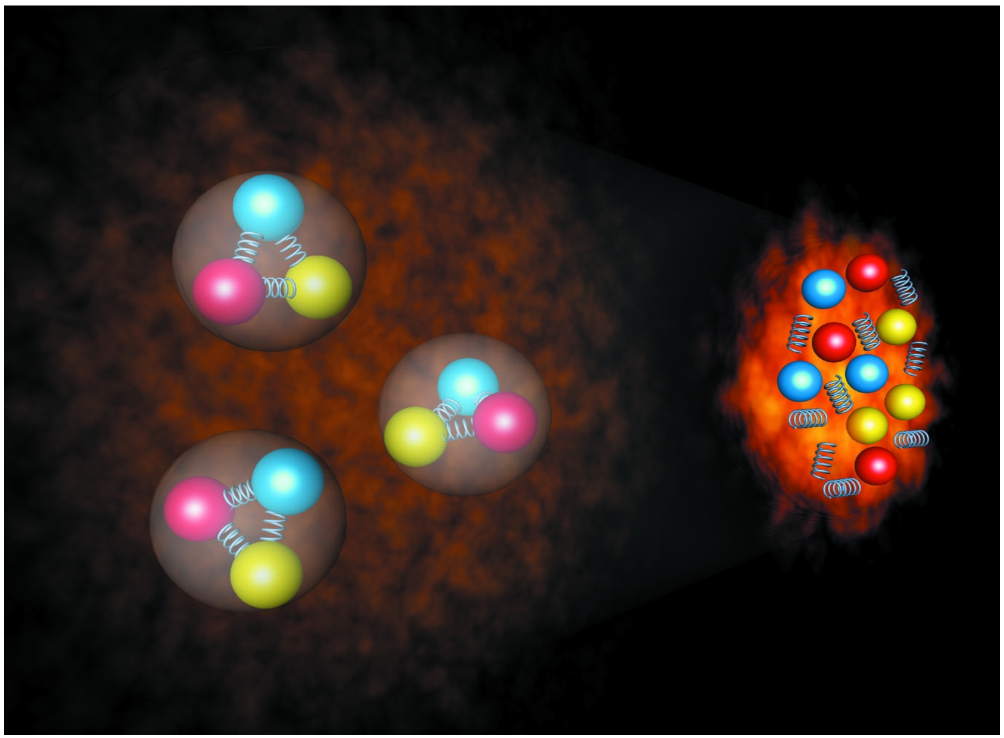
$$\langle n\rangle = \frac{g V}{(2\pi)^3} \int d^3 p \, \frac{1}{e^{E/T} \pm 1}$$

$$\approx g V \frac{2\pi^2}{4\cdot 45} T^3$$ for light particles

$$\approx g V \left(\frac{M T}{2\pi}\right)^{3/2} e^{-M/T}$$ for heavy particles

Onset of deconfinement

hadrons mixed QGP

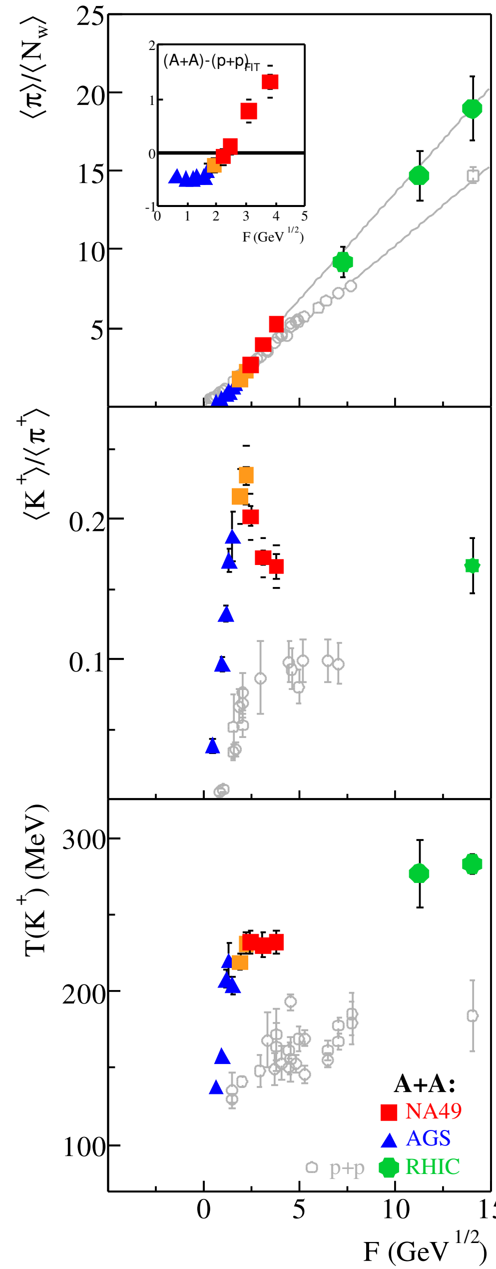


AGS SPS RHIC

collision energy

AGS SPS RHIC

Hadron production properties



Kink

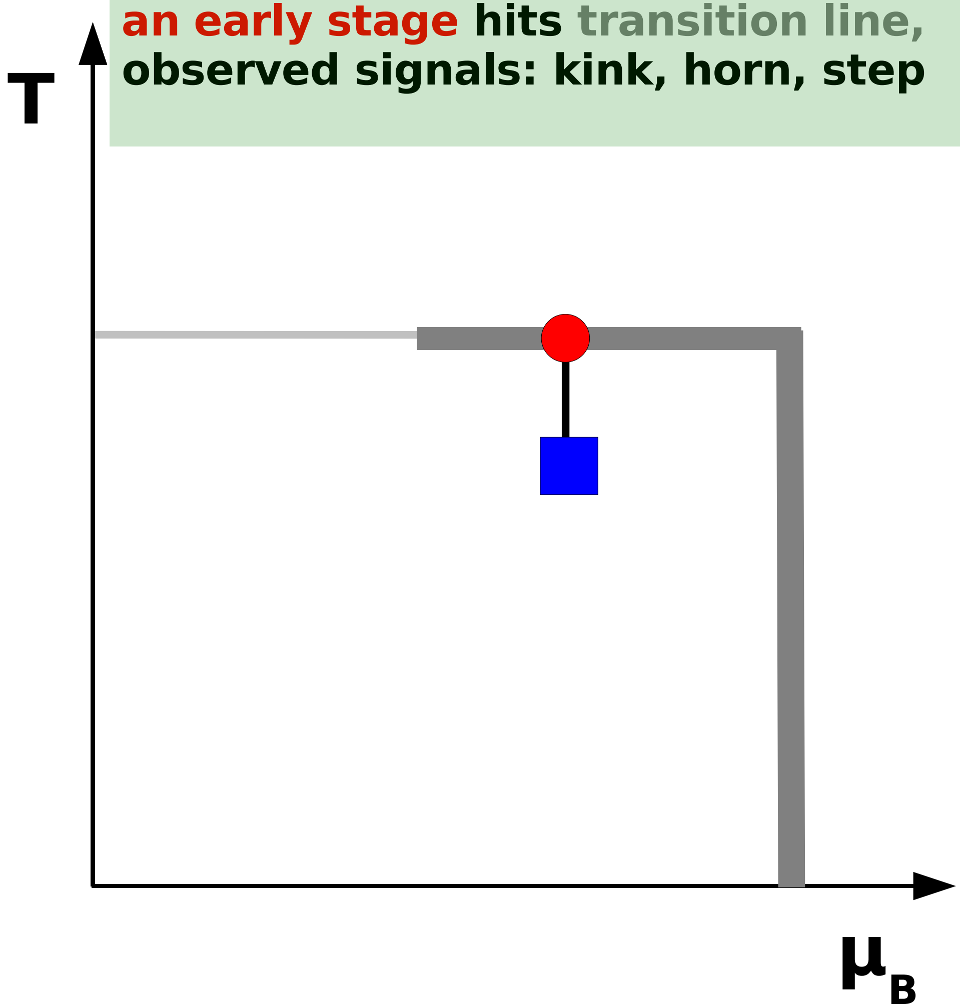
Horn

Step

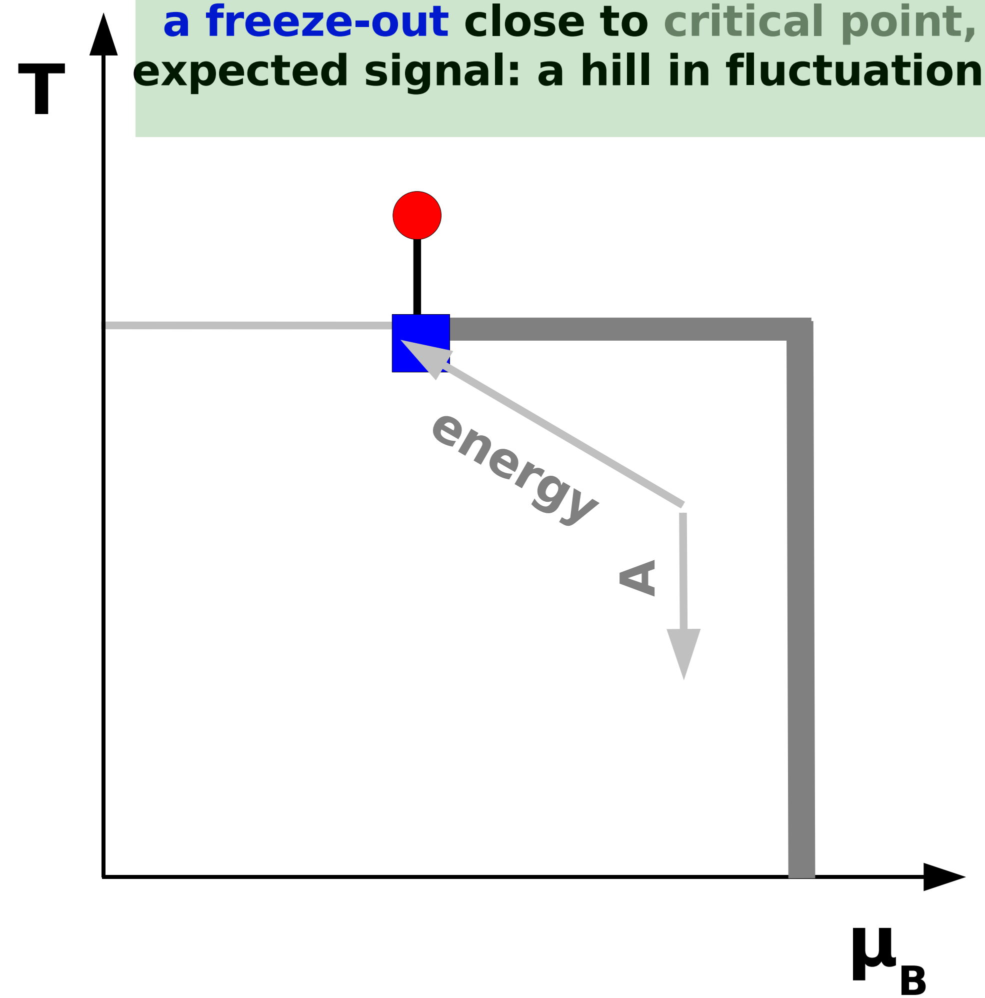
collision energy

Two main events in nucleus-nucleus collisions

Onset of Deconfinement:
an early stage hits transition line,
observed signals: kink, horn, step

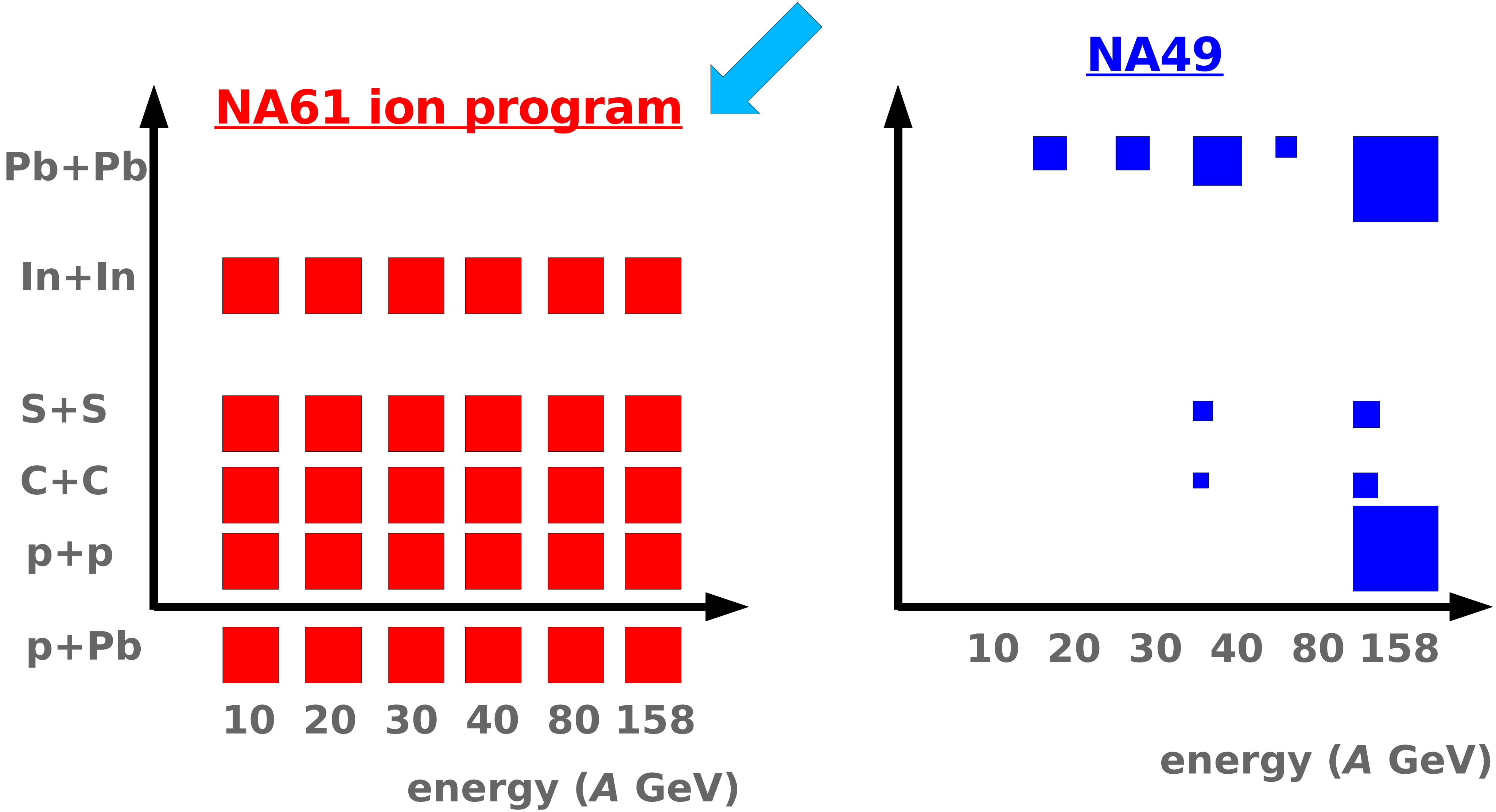


Critical Point:
a freeze-out close to critical point,
expected signal: a hill in fluctuations



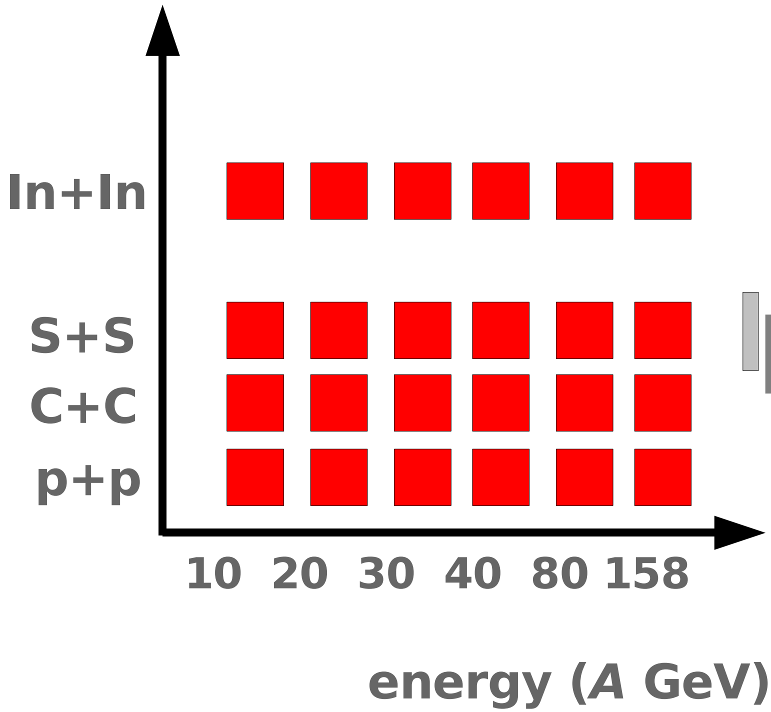
E(OoD) ≈ 30*A* GeV ≤ E(OoC)

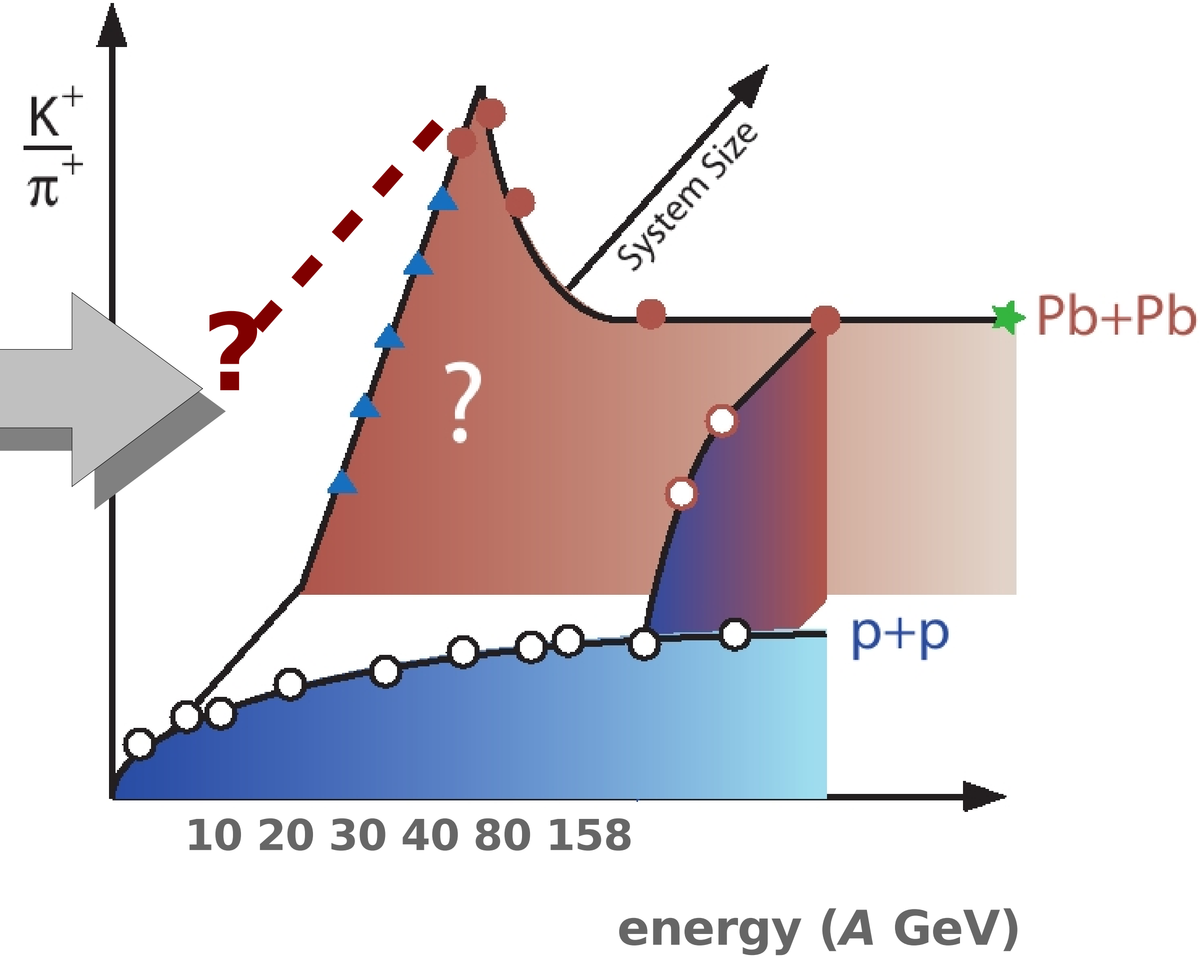
NA61/SHINE energy-system size scan



= $2 \cdot 10^6$ registered collisions

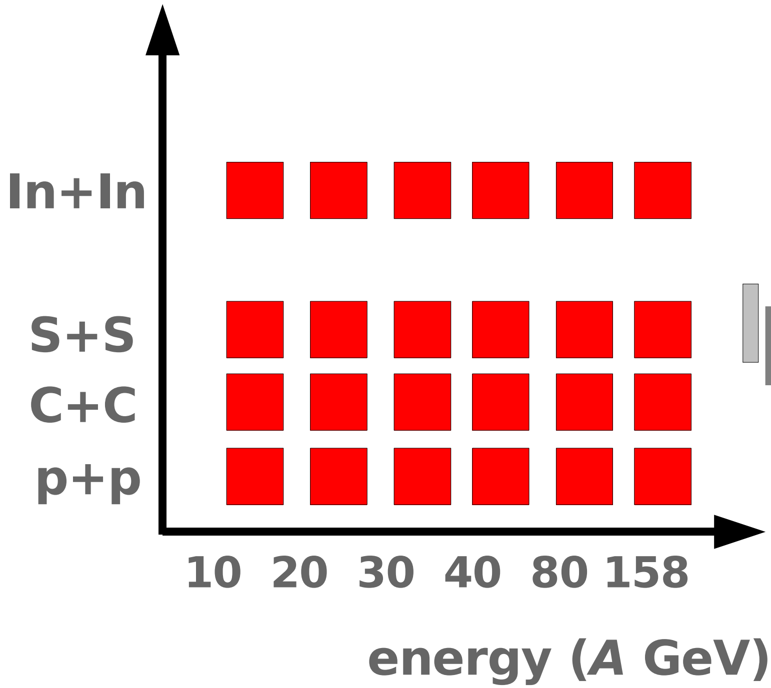
Study the onset of deconfinement

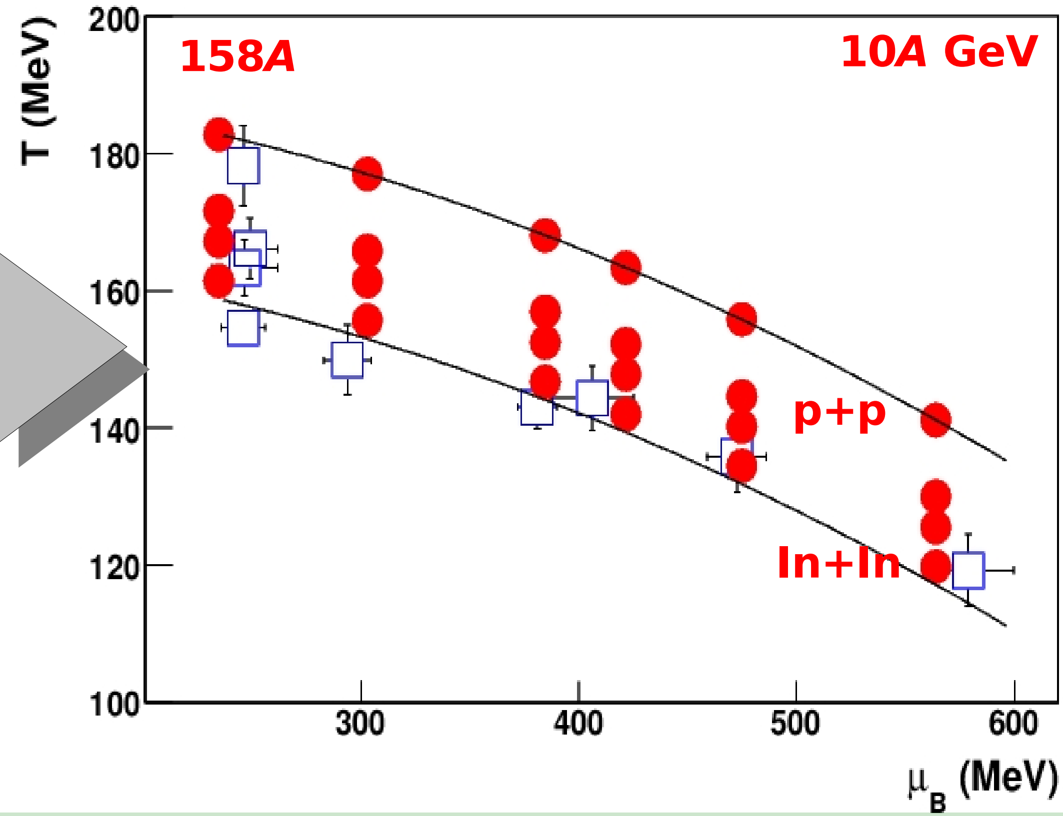


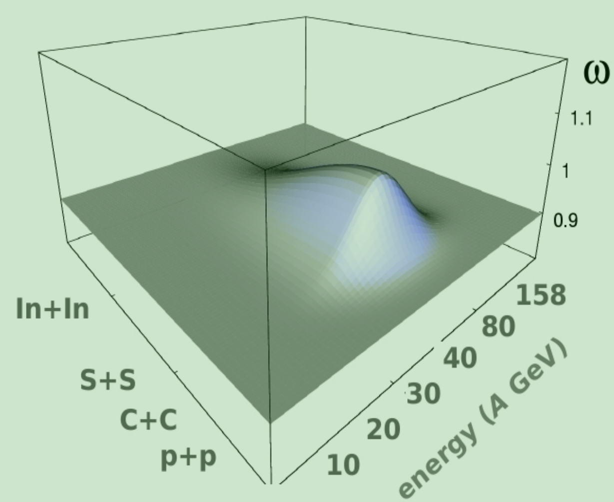


Search for the onset of the horn in collisions of light nuclei

Search for the critical point

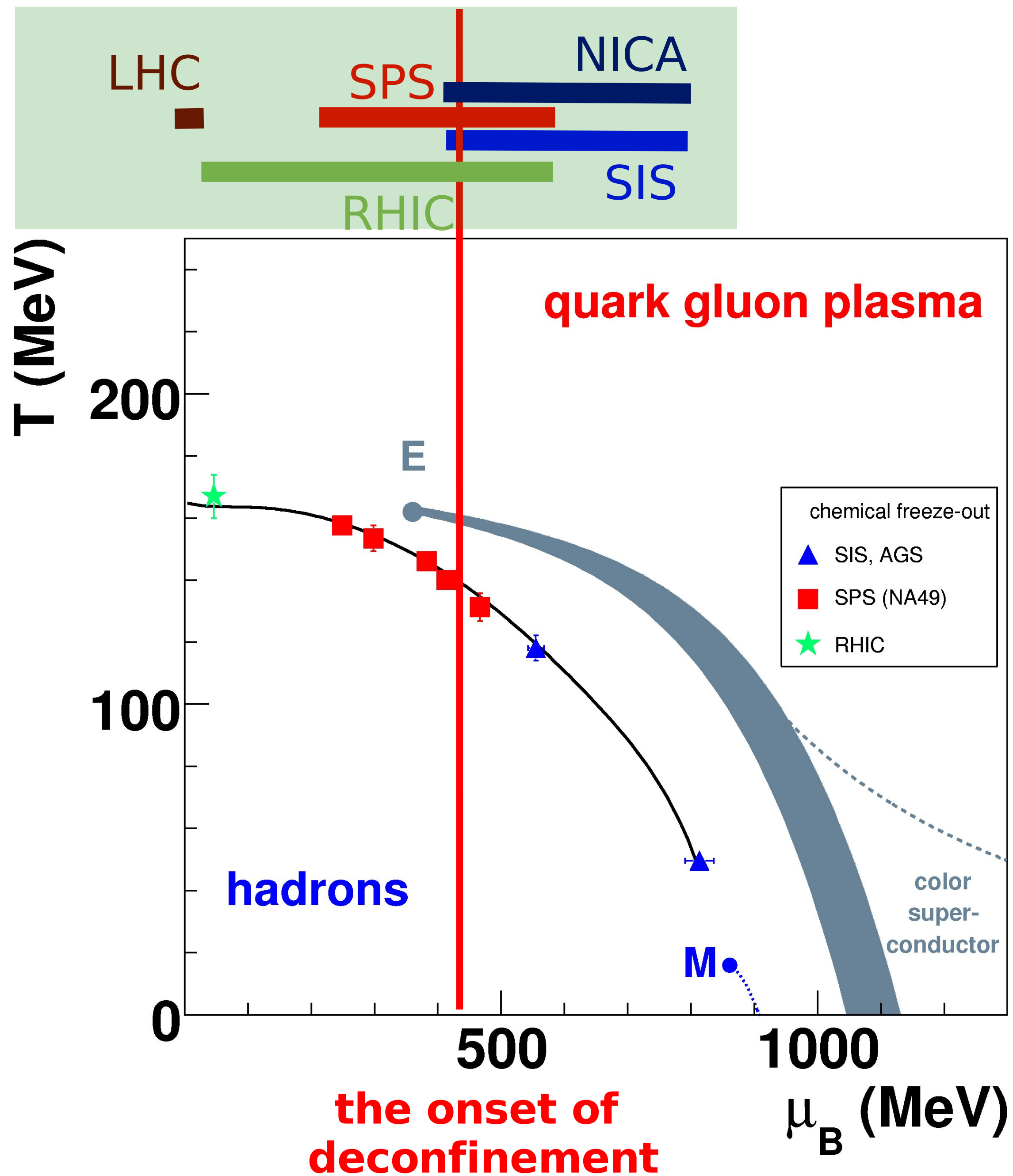






Search for the hill of fluctuations

Experimental landscape



Experimental landscape: the complementary programs

Facility:	**SPS**	**RHIC**	**NICA**	**SIS-300**
Exp.:	**NA61**	**STAR** **PHENIX**	**MPD**	**CBM**
Start:	**2010**	**2010**	**2013**	**2015**
Pb Energy: **(GeV/(N+N))**	**4.9-17.3**	**4.9-50**	**≤9**	**≤8.5**
Event rate: **(at 8 GeV)**	**100 Hz**	**1 Hz(?)**	**≤10 kHz**	**≤10 MHz**
Physics:	**CP&OD**	**CP&OD**	**OD&HDM**	**OD&HDM**

CP – critical point
OD – onset of deconfinement, mixed phase, 1st order PT
HDM – hadrons in dense matter

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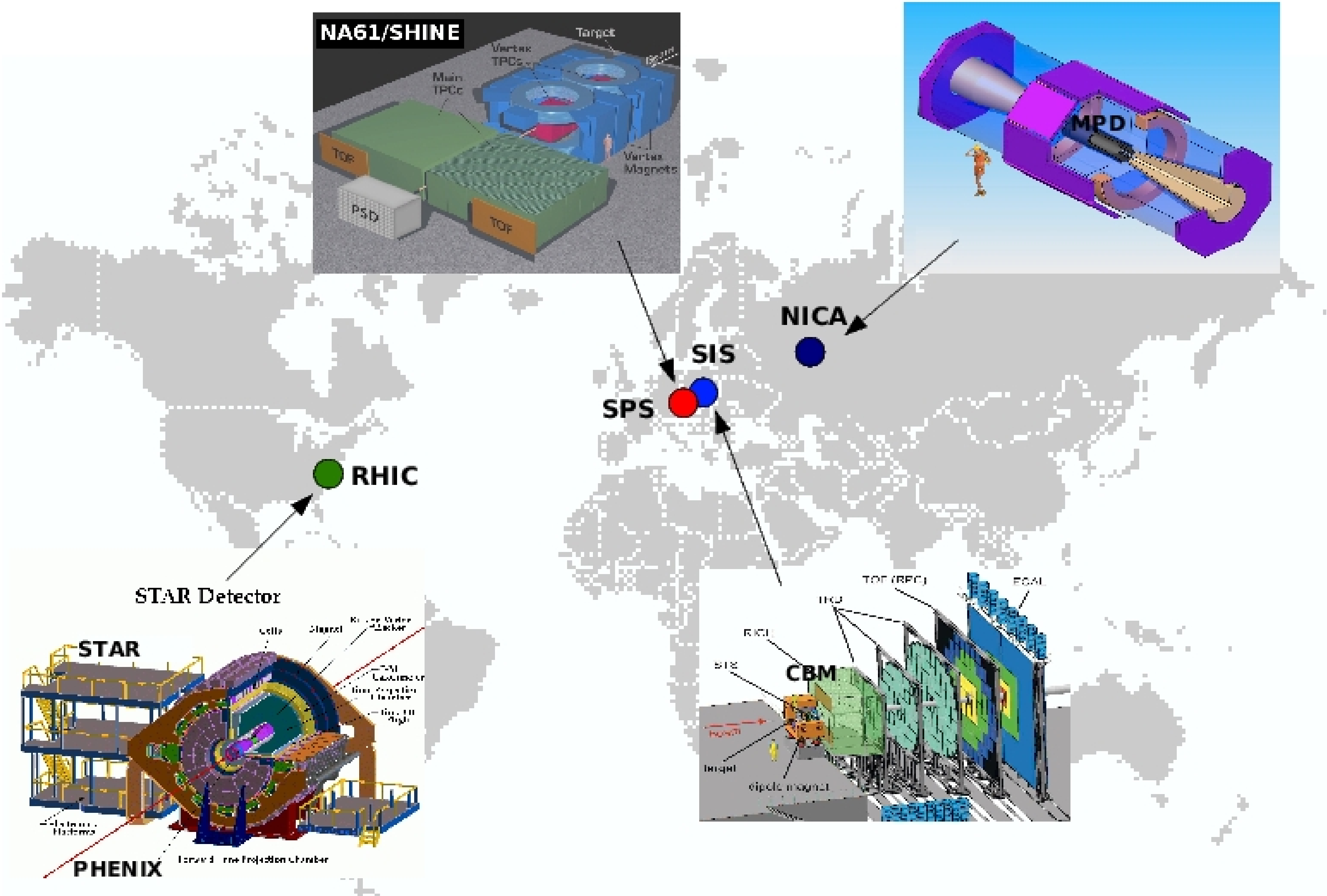

Summary

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

It has the potential to discover the critical point of strongly interacting matter and guarantees a broad set of important precision measurem

It is complementary to the efforts of other international and national laboratories, FAIR, JINR, KEK and RHIC and to the heavy ion program at the CERN LHC

It is of common interest for different physics communities, heavy ions, neutrino and cosmic-rays

Additional slides