Studies on the QCD Phase Diagram at SPS and FAIR

Rencontres de Vietnam
International Conference on
Heavy Ion Collisions in the LHC Era
Quy Nhon, Vietnam
15 – 21 July, 2012

Christoph Blume
University of Frankfurt

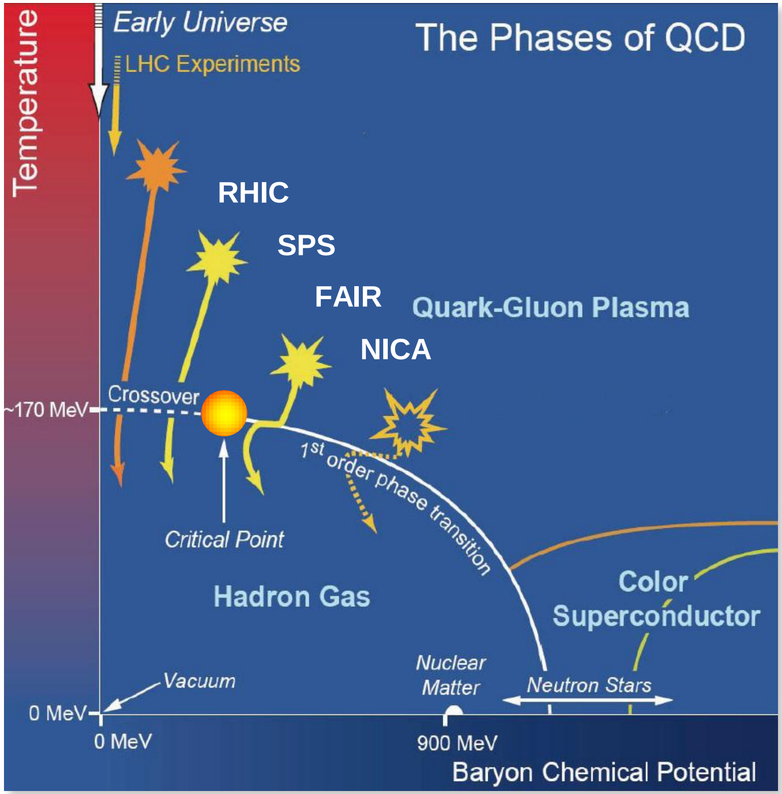
The QCD Phase Diagram

Topic of this talk

Part of phase diagram with $\mu_B > 0$
$\mu_B = 0$: LHC physics

Questions to experiments

1) Is it possible to locate the onset of deconfinement ?
2) Is there any evidence for a 1^{st} order phase transition ?
3) Can one find any indication for a possible critical point ?



The QCD Phase Diagram
Experimental Access

Control parameter: $\sqrt{s_{NN}}$

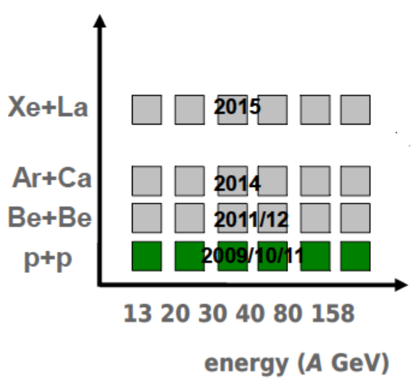
Allows to scan different regions of phase diagram

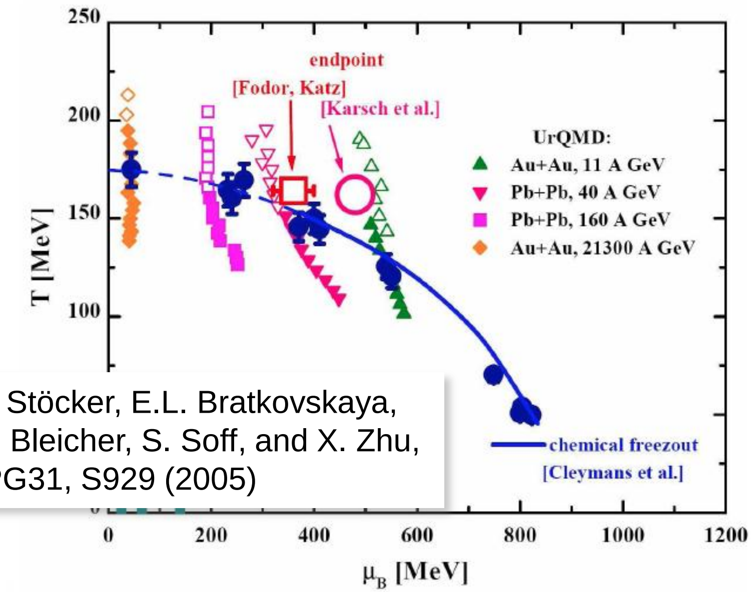
System freezes out at different positions along freeze-out curve

Trajectory might cross critical area

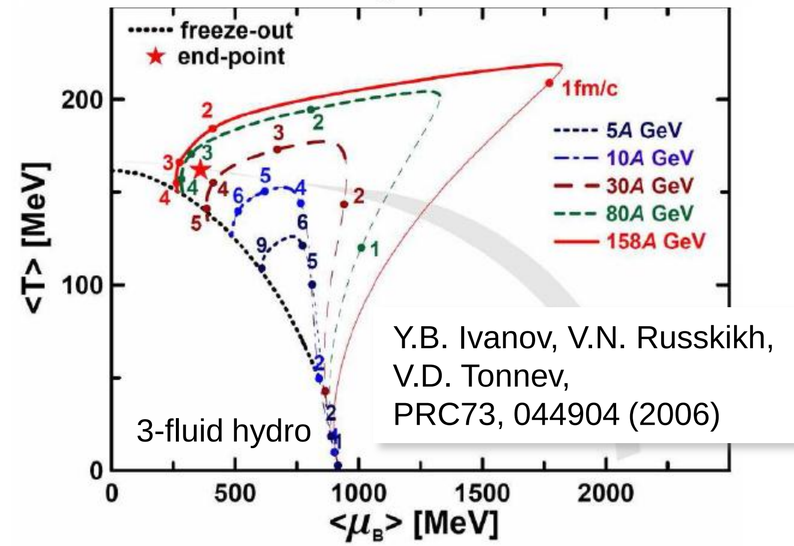
Variation of system size

Program of NA61@SPS





H. Stöcker, E.L. Bratkovskaya, M. Bleicher, S. Soff, and X. Zhu, JPG31, S929 (2005)



Y.B. Ivanov, V.N. Russkikh, V.D. Tonnev, PRC73, 044904 (2006)

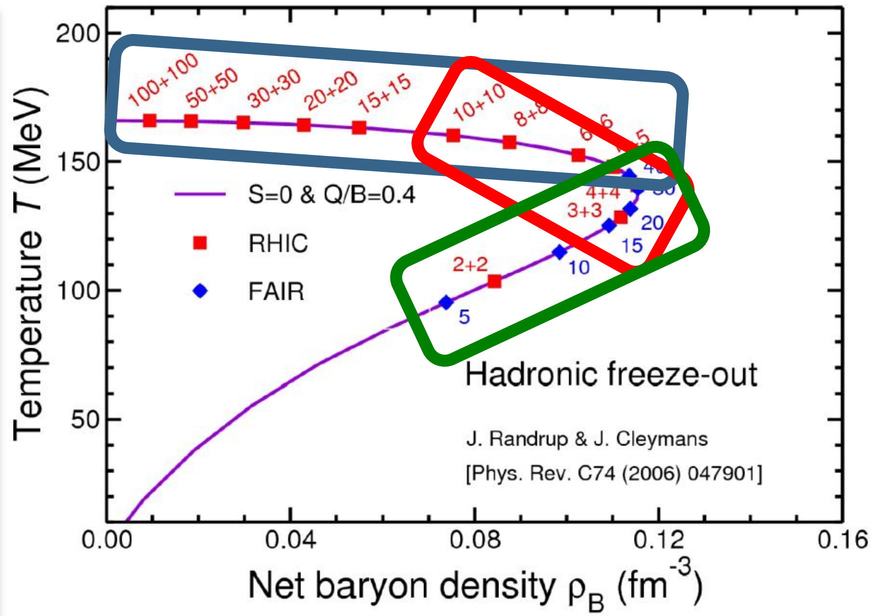
The QCD Phase Diagram
Experimental Access

Region of
high baryon density

RHIC-BES

SPS

FAIR / NICA



Broad experimental program

Past: **SPS** (and AGS)
→ NA49

Present: **SPS** and RHIC
→ NA61/SHINE

Future: **FAIR** and NICA
→ CBM

Experimental Data

Beam Energy Scan at the CERN-SPS

Energy scan program

Pb+Pb reactions

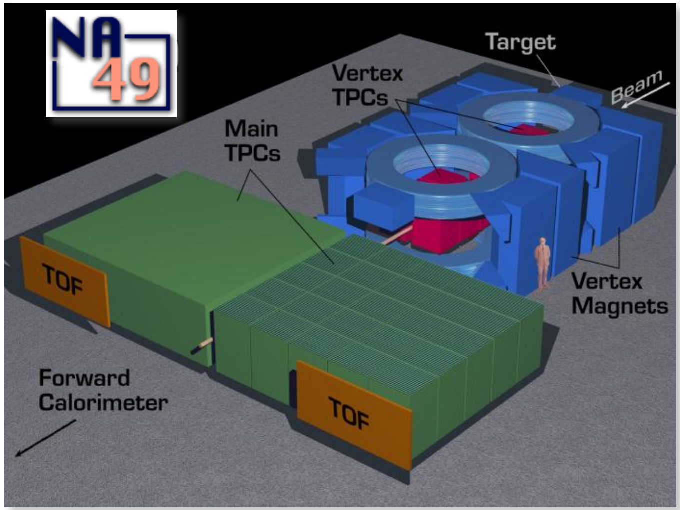
Year	1998 1999	2000	2002
$\sqrt{s_{NN}}$ (GeV)	8.8	12.3 17.3	6.3 7.6
E_{beam} (AGeV)	40	80 158	20 30

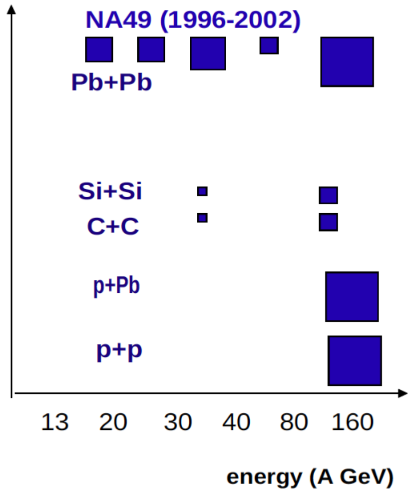
Covers ~250 MeV < μ_B < ~470 MeV

Experiments:

Fixed target setup

NA49 (all energies)
NA45 (40, 80, 158 AGeV)
NA57 (40, 158 AGeV)





Sensitivity to EOS
HG → QGP: rapid change of the number of degrees of freedom

Flow observables
Radial flow: p_t spectra

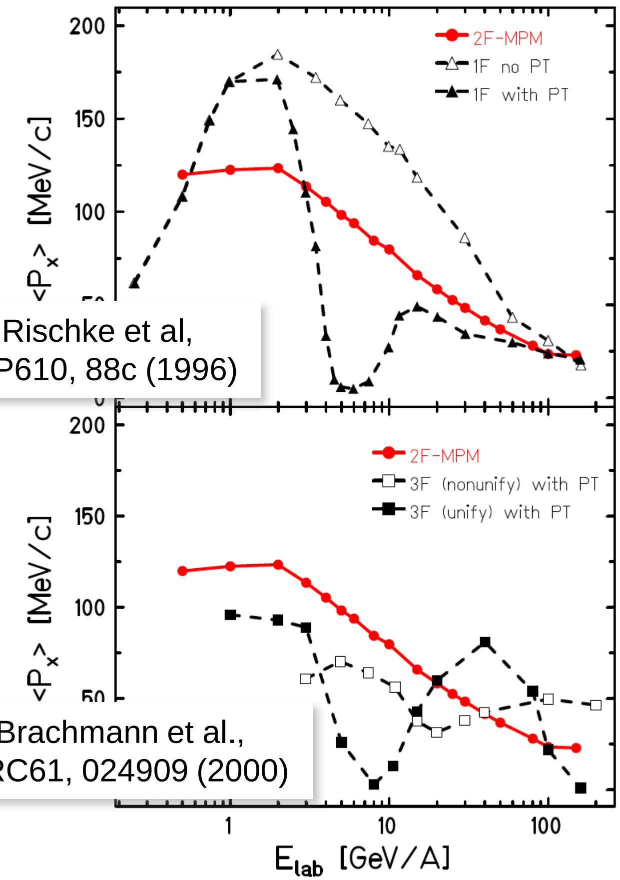
Directed flow: collapse of proton v_1

Elliptic flow: disappearance of partonic collectivity (NCQ-scaling)?

HBT radii

$\sqrt{s_{NN}}$ dependence of particle production
Statistical model of early stage

M. Gaździcki and M.I. Gorenstein, APPB30, 2705 (1999)



D. Rischke et al, HIP610, 88c (1996)

J. Brachmann et al., PRC61, 024909 (2000)

Structures in $\sqrt{s_{NN}}$ dep.

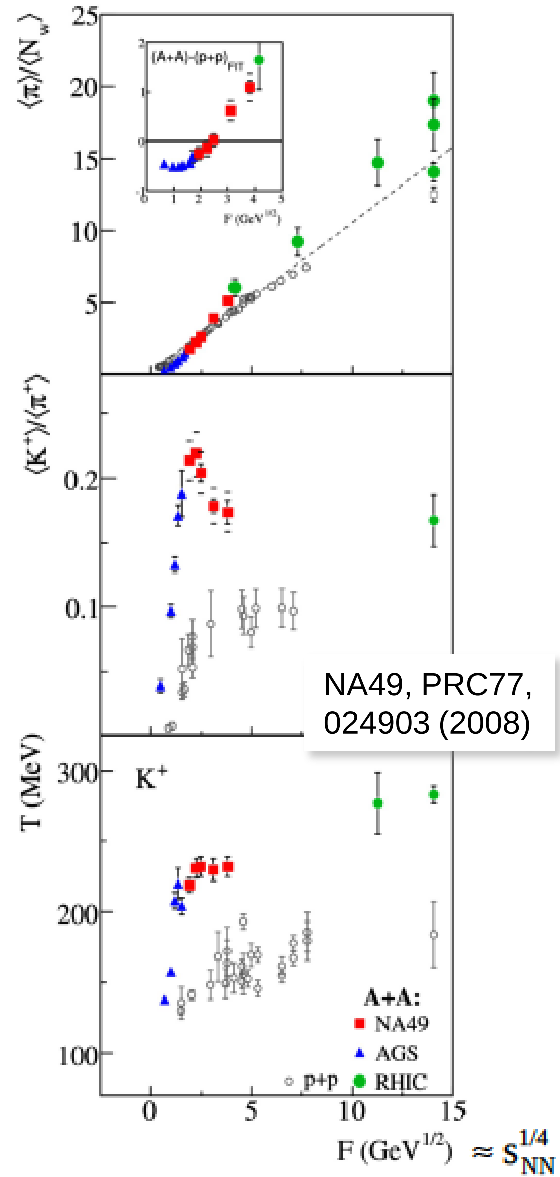
Increase of relative pion production

Sharp maximum in K^+/π^+ ratio

Change in of $\sqrt{s_{NN}}$ dep. of kaon slopes

Not seen in p+p

All occur at $\sqrt{s_{NN}} \approx 8$ GeV



NA49, PRC77, 024903 (2008)

Onset of Deconfinement
Kaon to Pion Ratios

Prominent structure in K^+/π^+ ratio

Not seen in p+p

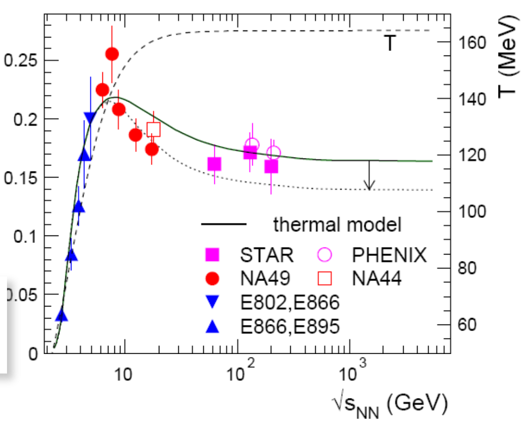
Not described by transport models

Good agreement between SPS and RHIC !

Proposed signature for PT

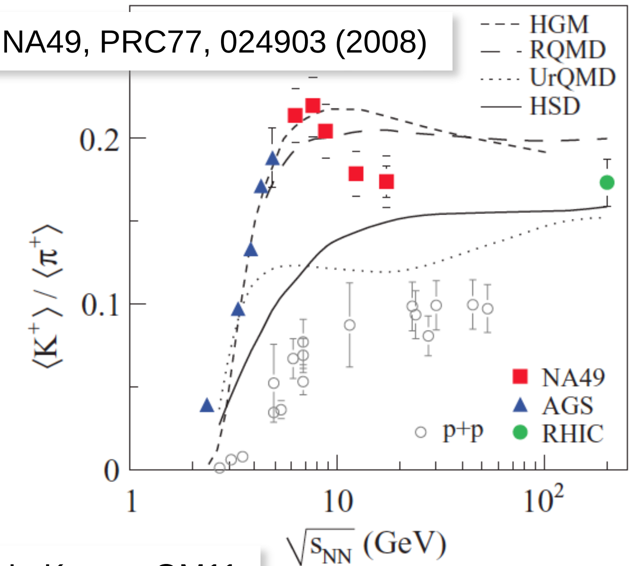
M. Gaździcki and M.I. Gorenstein, APPB30, 2705 (1999)

Recent statistical model curve:

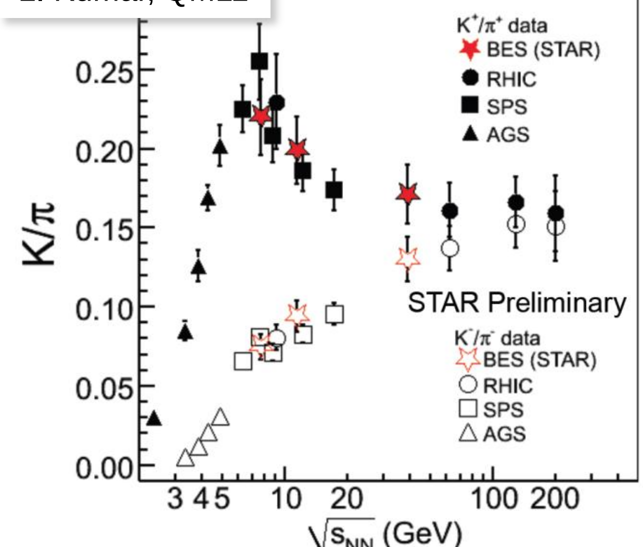


A. Andronic et al., PLB673, 142 (2009)

NA49, PRC77, 024903 (2008)

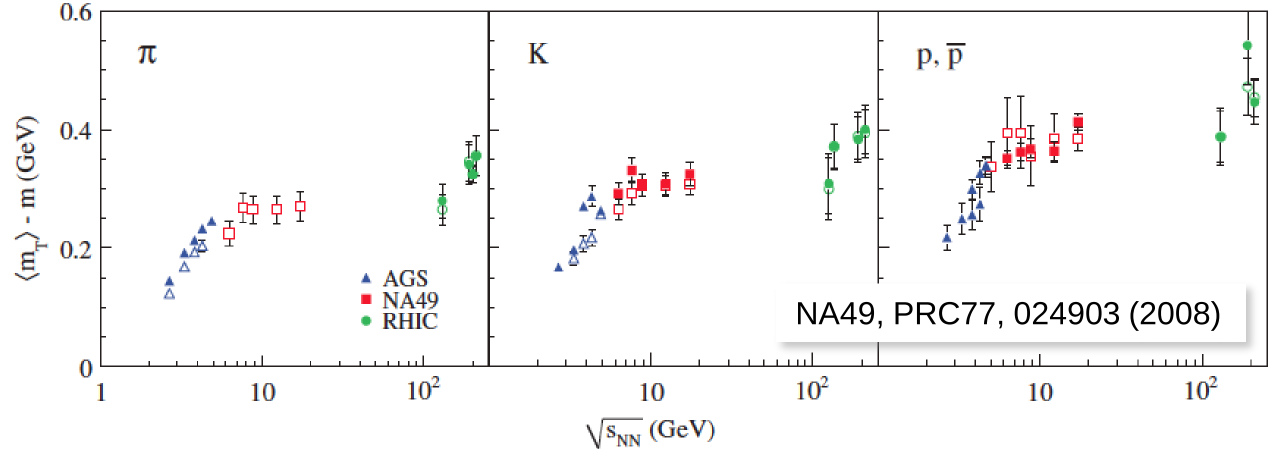


L. Kumar, QM11



Onset of Deconfinement

Transverse Momentum Spectra: $\langle m_t \rangle$ - m_0



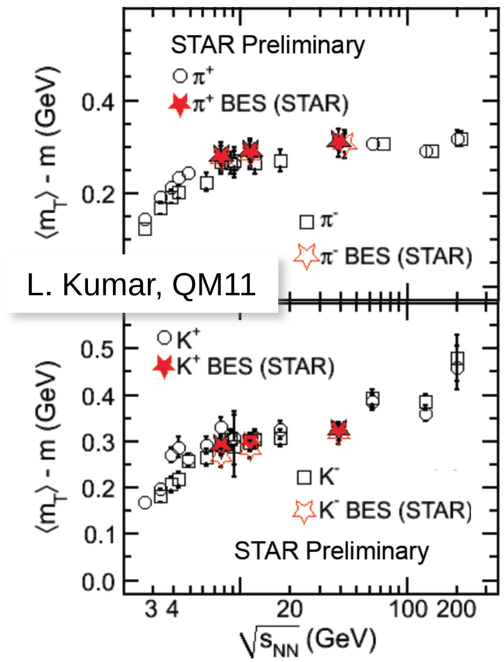
Evolution of radial flow

Steep increase at low energies

Moderate increase at higher energies

Good agreement between SPS and RHIC

Indicative for change in EOS?



Critical Point
Observables

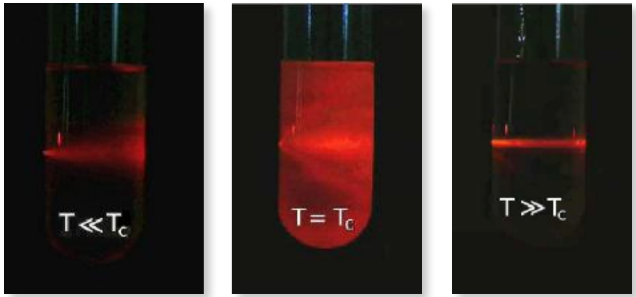
Critical opalescence
Correlation lengths and
susceptibilities diverge

Heavy ion reactions
System size limited ⇒ critical region
Correlation length $\xi \approx$ radius of system

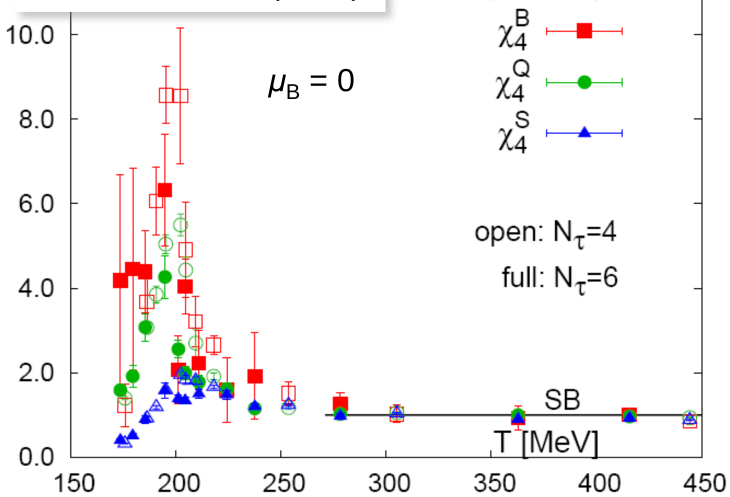
Enhanced fluctuations
Multiplicity
Average p_t
Particle ratios

Conserved quantities
Strangeness S
Baryon number B
Charge Q

Higher moments more sensitive



M. Cheng et al.,
PRD79, 074505 (2009)



Critical Point

Average p_t and Multiplicity Fluctuations

Average p_t fluctuations

Quantified by Φ_{pt}

$$\Phi_x \equiv \sqrt{\frac{\langle Z_x^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z_x^2}} \qquad Z_x \equiv \sum_{i=1}^{N_j} (x_i - \overline{x}) \qquad z_x \equiv x - \overline{x}$$

Multiplicity fluctuations

Quantified by scaled variance

$$\omega = \frac{Var(n_-)}{<n_->} = \frac{<n_-^2> - <n_->^2}{<n_->}$$

No $\sqrt{s_{NN}}$ dependence seen

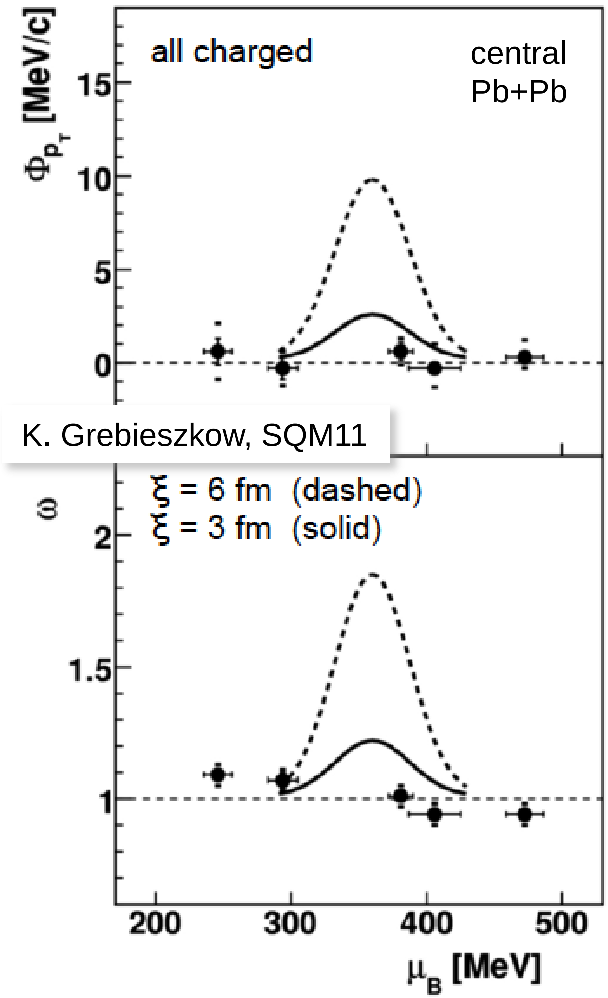
Critical point expectation

μ_B from stat. model fit:
F. Becattini et al.,
PRC73, 044905 (2006)

Position of critical point:
Z. Fodor and S. Katz
JHEP 0404, 050 (2004)

Amplitude of fluct. :
M. Stephanov et al.
PRD60, 114028 (1999)

Width of critical region:
Y. Hatta and T. Ikeda,
PRD67, 014028 (2003)



NA49, PRC79, 044904 (2009)

Critical Point
Particle Ratio Fluctuations

Sensitivity to CP ?

No evidence for non-monotonic behavior in energy dependence

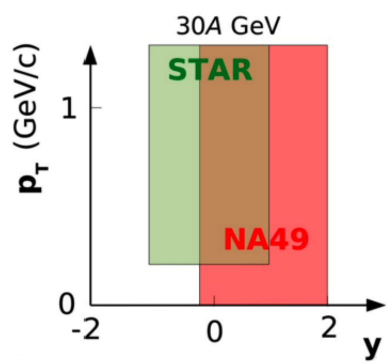
Comparison NA49 ↔ STAR

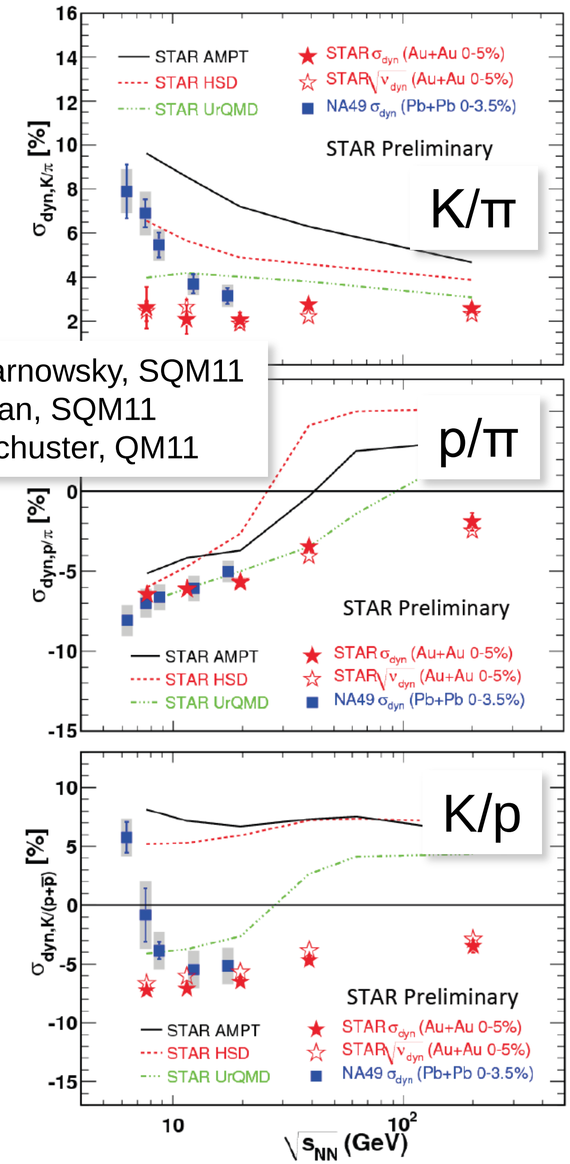
Good agreement for p/π

Deviations for K/π + K/p at lowest $\sqrt{s_{NN}}$

NA49, PRC83, 061902 (2011)
NA49, PRC79, 044910 (2009)
STAR, PRL103, 092301 (2009)

Difficult to resolve due to different acceptances:

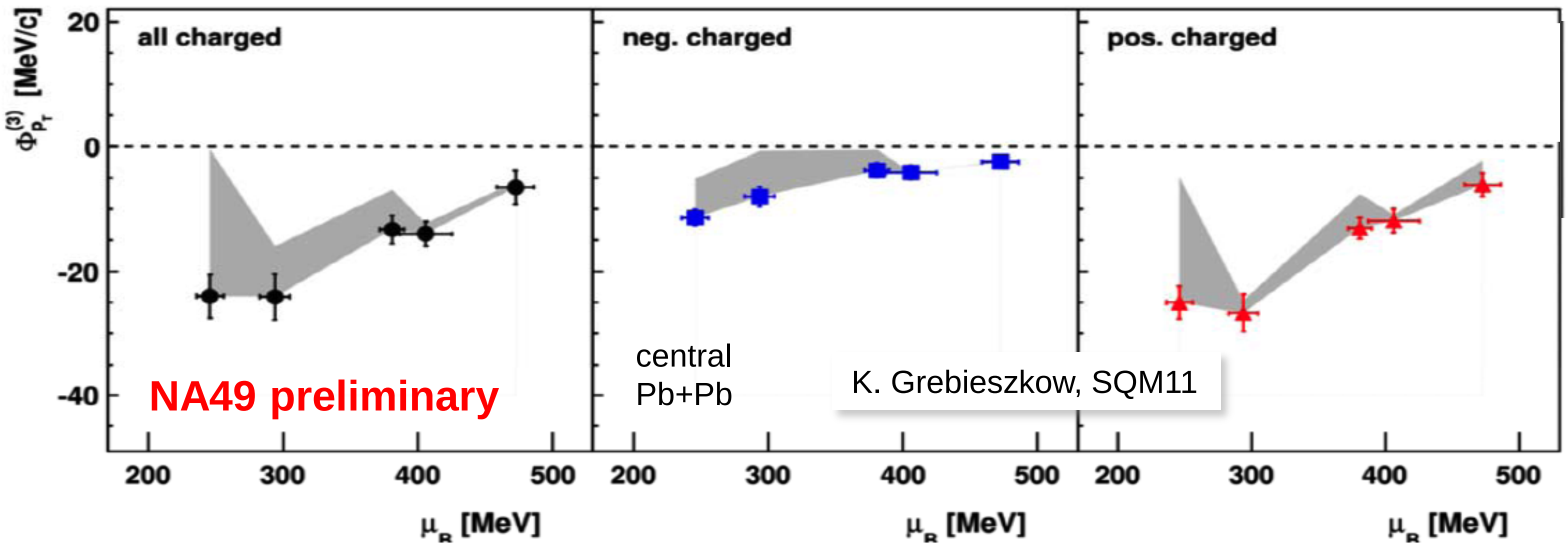




T. Tarnowsky, SQM11
J. Tian, SQM11
T. Schuster, QM11

Critical Point

Higher Moments of $\langle p_t \rangle$-Fluctuations



3[rd] **moments as a function of $\sqrt{s_{NN}}$**

$$\Phi^{(n)}_{p_t} = \left(\frac{\langle Z^2_{p_t} \rangle}{\langle N \rangle}\right)^{1/n} - \left(\bar{z}^n_{p_t}\right)^{1/n}$$

$$z_{p_t} = p_t - \bar{p}_t \qquad Z_{p_t} = \sum_{i=1}^{N} (p_t - \bar{p}_t)$$

Sensitive to higher power of correlation length *ξ*

E. g. $\langle N^4 \rangle \propto \xi^7$ compared to $\langle N^2 \rangle \propto \xi^2$

S. Mrówczynski
PLB **465**, 8 (1999)

M.A. Stephanov
PRL **102**, 032301 (2009)

Critical Point

System Size Dep. of Multiplicity Fluctuations

Multiplicity fluctuations

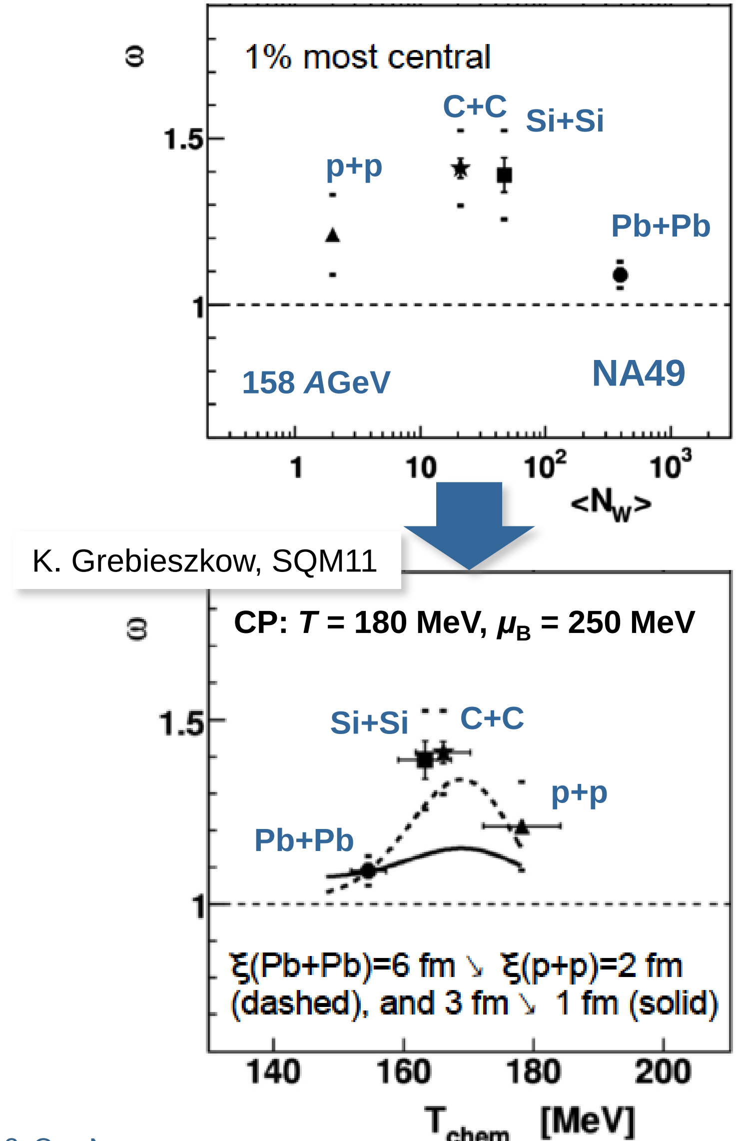
Quantified by scaled variance

$$\omega = \frac{Var(n_-)}{<n_->} = \frac{<n_-^2> - <n_->^2}{<n_->}$$

Clear change with N_w seen

Maximum for C+C and Si+Si

Connection to CP possible?



Critical Point

Di-Pion (Sigma) Intermittency

$\pi^+\pi^-$ Pairs above di-pion threshold

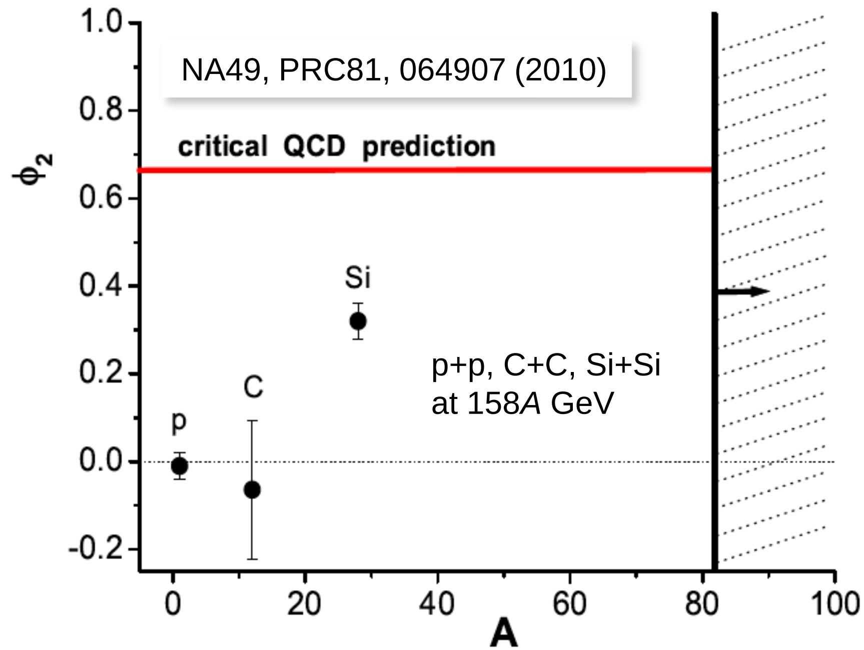
$$(2m_\pi + \epsilon_1)^2 \leq (p_{\pi^+} + p_{\pi^-})^2 \leq (2m_\pi + \epsilon_2)^2$$

Factorial moments $F_2(M)$
M: Number of bins in p_t

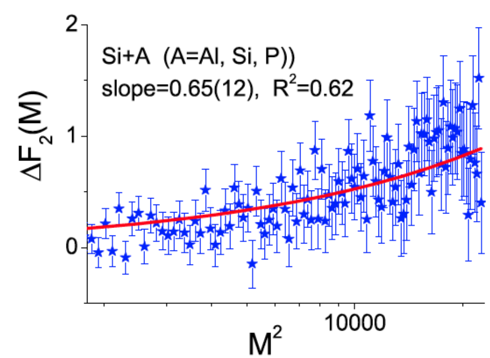
Subtract mixed event background
$\Rightarrow \Delta F_2(M)$

Search for power law behavior
$\Delta F_2(M) \sim (M^2)^{\Phi 2}$
Φ_2 : critical exponent

$\Phi_2 > 0$ for Si+Si
Coulomb effects become
an issue for larger systems



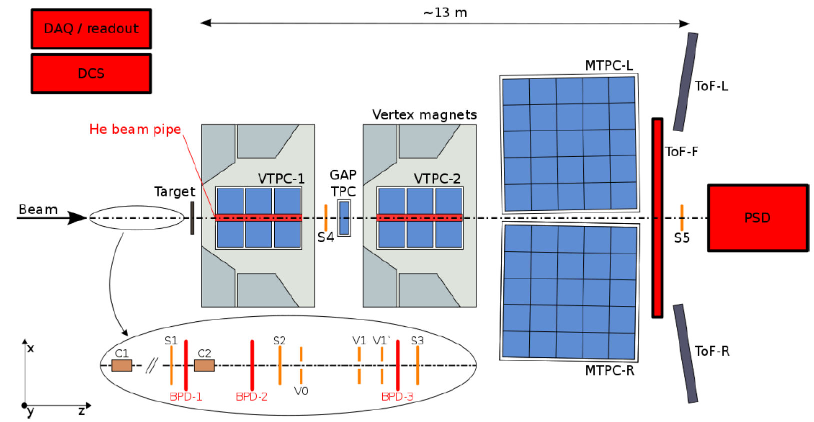
Analysis with identified protons:



NA61 / SHINE
Experimental Setup and Program

Upgrade of NA49 setup

Faster readout
Projectile Spectator Detector (PSD)
Secondary ion beam line
(fragment separator)

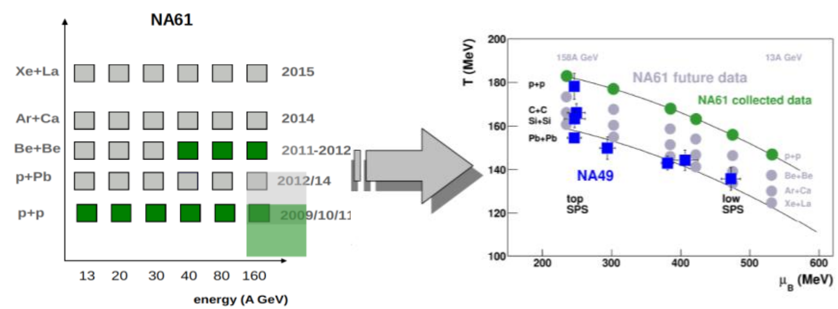


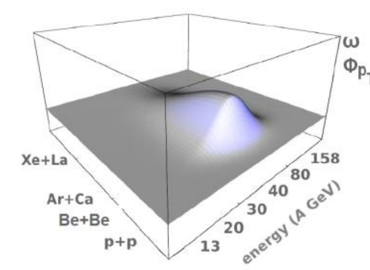
top view – not to scale
upgrades marked in red

Program

2D scan: energy + system size

Already done: p+p energy scan, p+C
Be+Be (three energies)





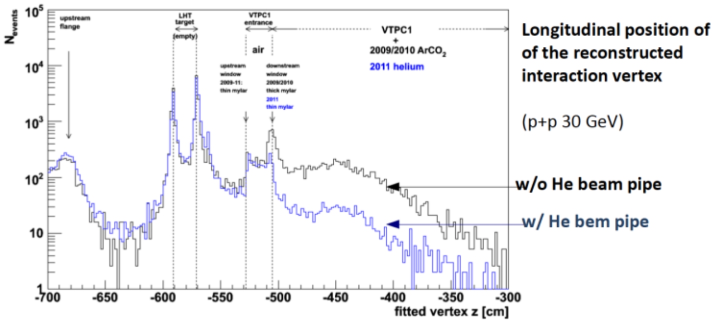
NA61 / SHINE
Recent Upgrades

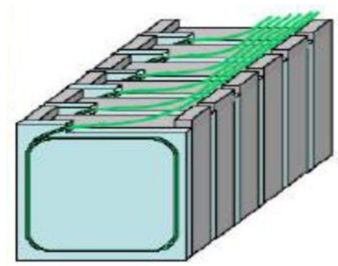
Forward TOF wall
Extended PID acceptance

New TPC readout and DAQ
x10 higher event rate (80 Hz)

He beam pipe
Reduces background from δ-electrons

Important for fluctuation measurements

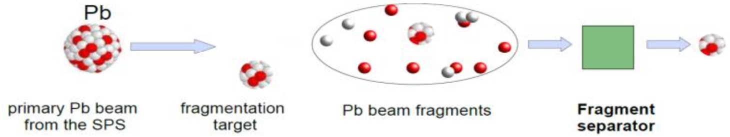


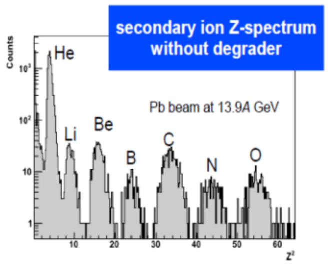


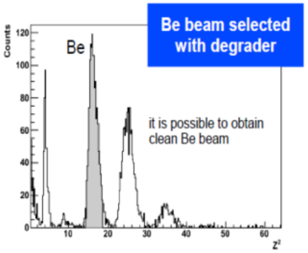
Participant Spectator Detector (PSD)
Same development as for CBM@FAIR

High resolution: $55\%/\sqrt{E} + 2\%$

Secondary ion beam
Degrader (Cu plate) for high beam purity







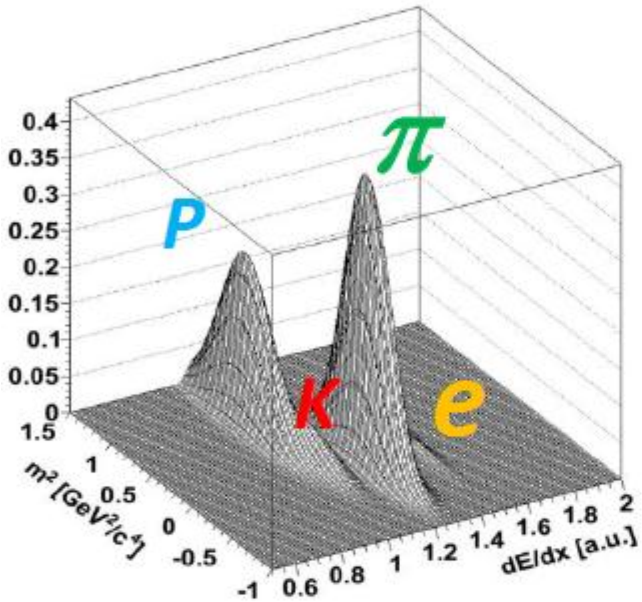
Particle Identification

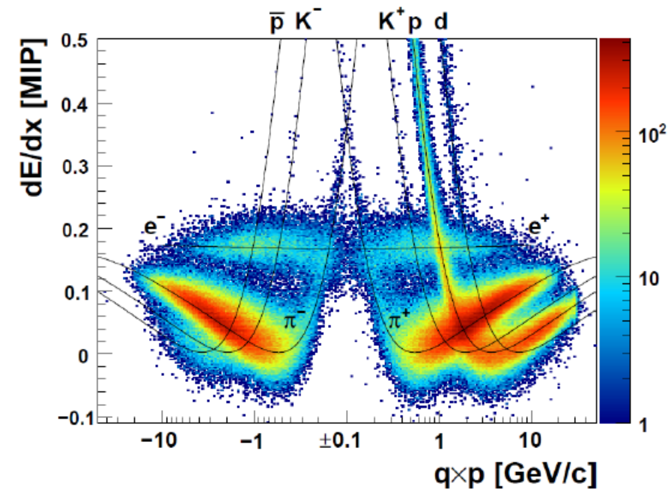
PID techniques

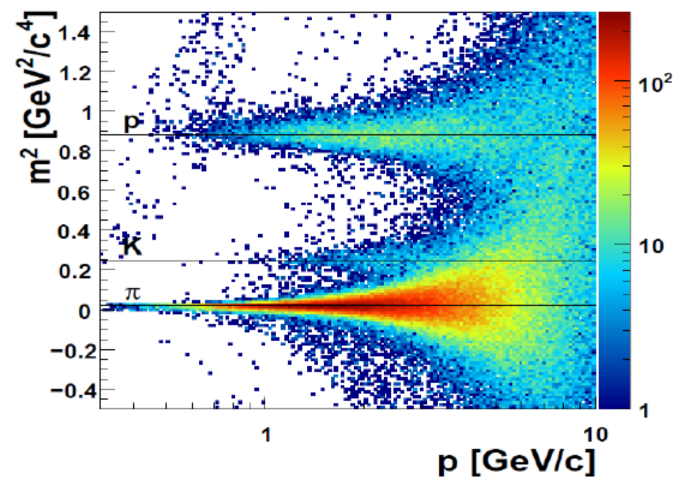
dE/dx in TPC

TOF information

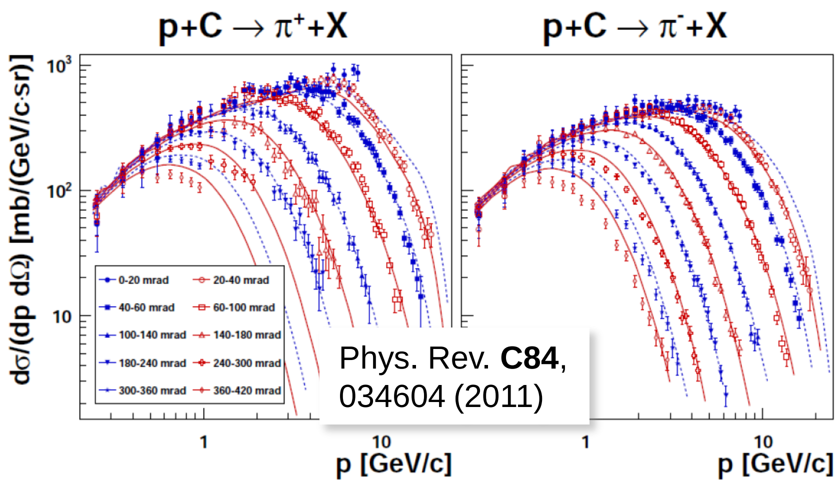
Wide momentum range covered



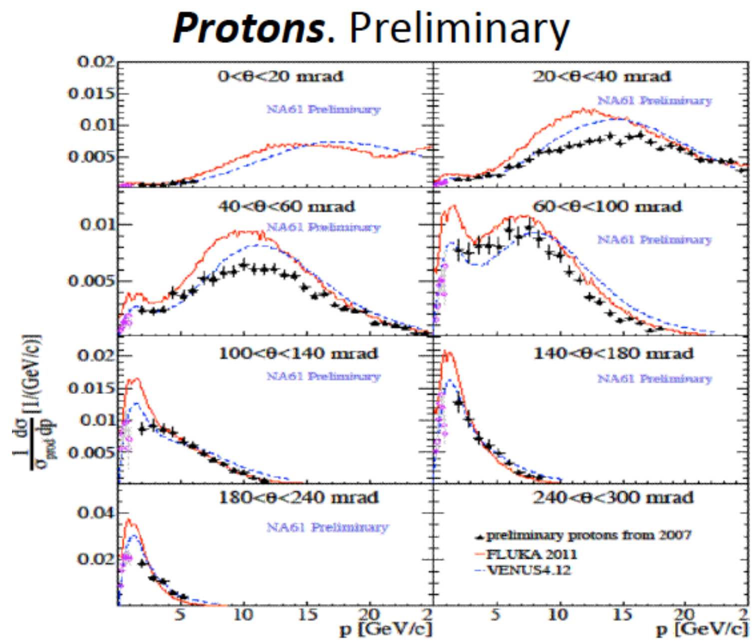




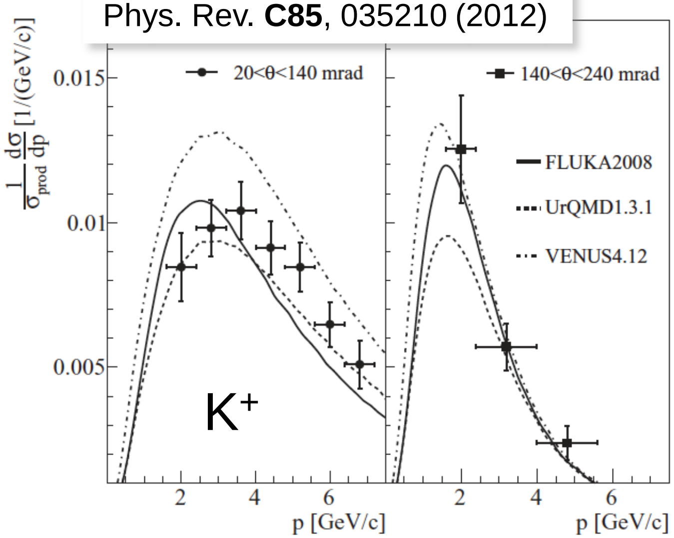
NA61 / SHINE
Results for p+C Collisions at 31GeV/*c*

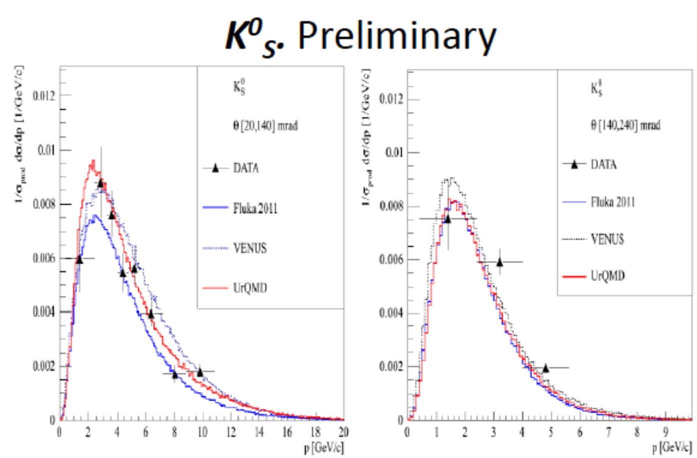


Phys. Rev. **C84**, 034604 (2011)



Phys. Rev. **C85**, 035210 (2012)



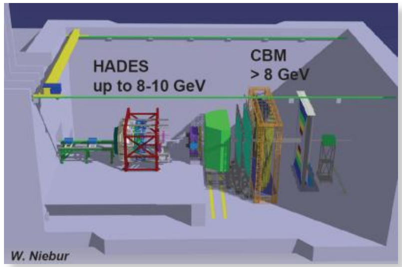


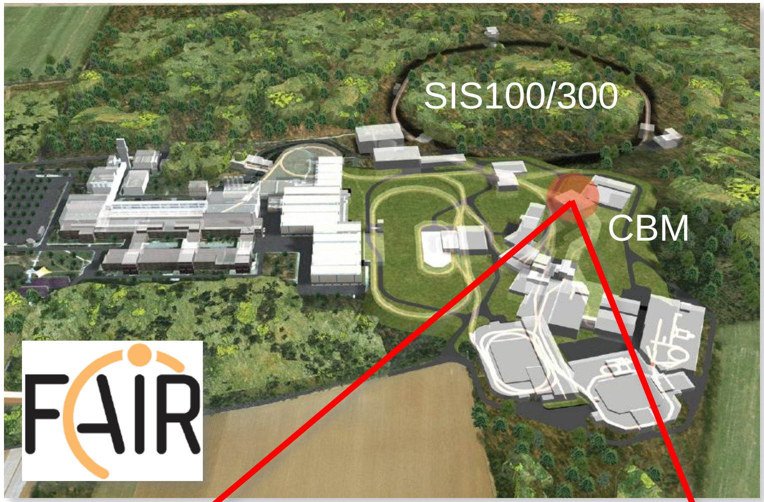
CBM at FAIR
Experimental Setup and Program

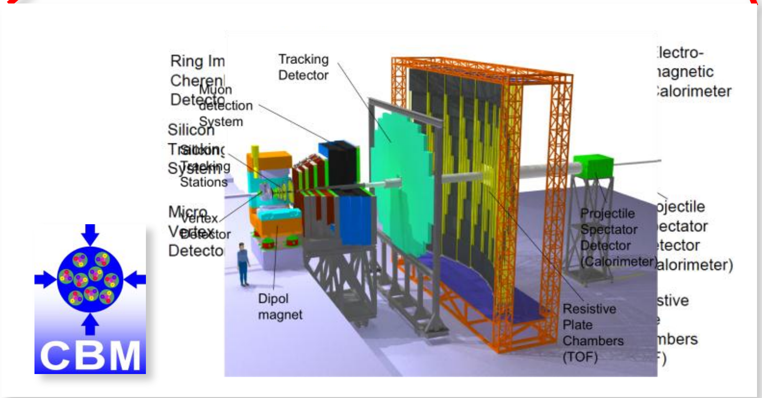
Compressed Baryonic Matter
Fixed target experiment at SIS-100/300
Ion beams with highest luminosity 10^9/s
Beam energies 10 – 45 *A*GeV
Begin data taking 2019

Program
Rare probes: J/ψ, open charm
Multi-strange baryons
Di-leptons, photons
All hadronic observables

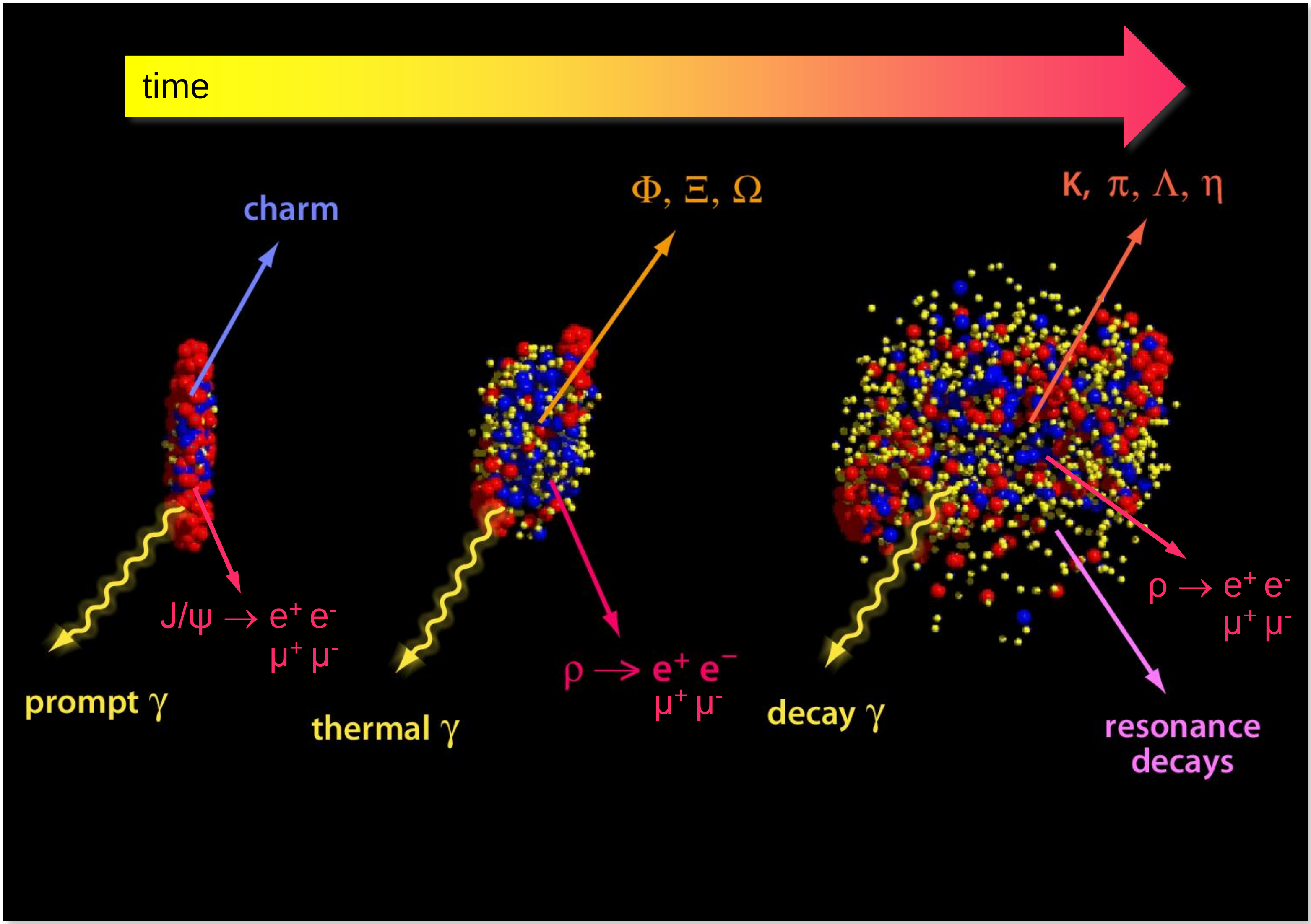
Startup with SIS-100
HADES @ FAIR
E_{beam} < 10 *A*GeV



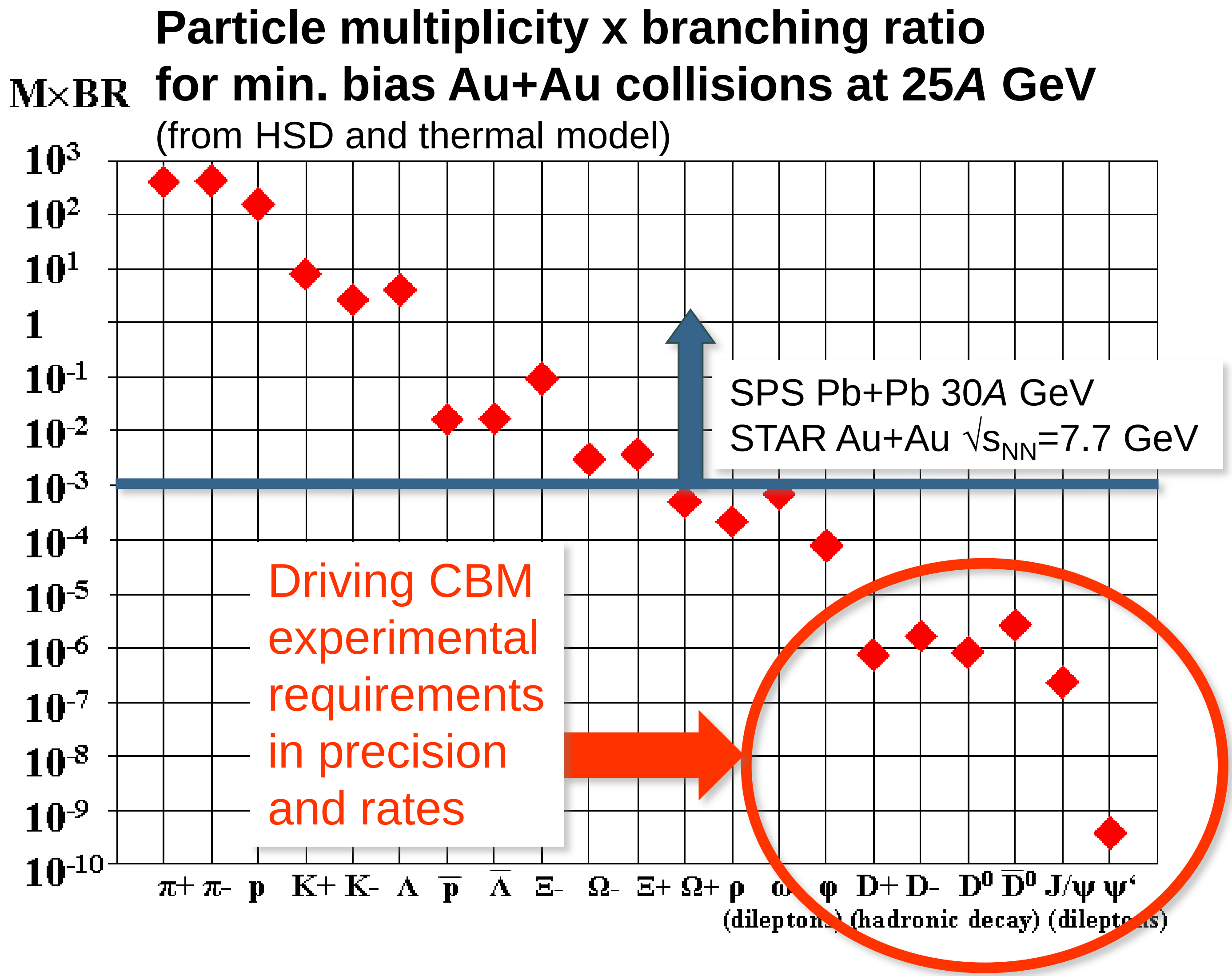




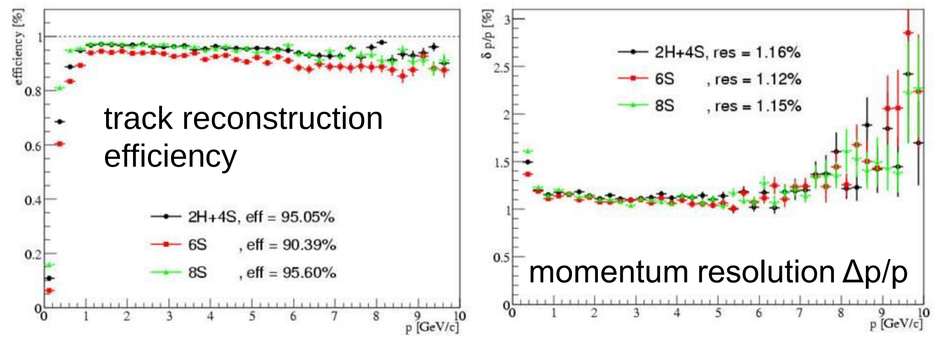
CBM at FAIR
Observables

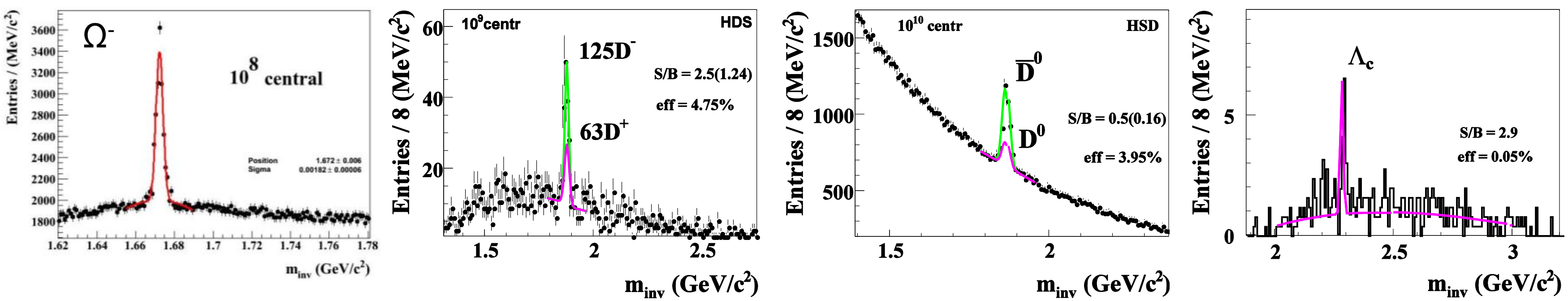


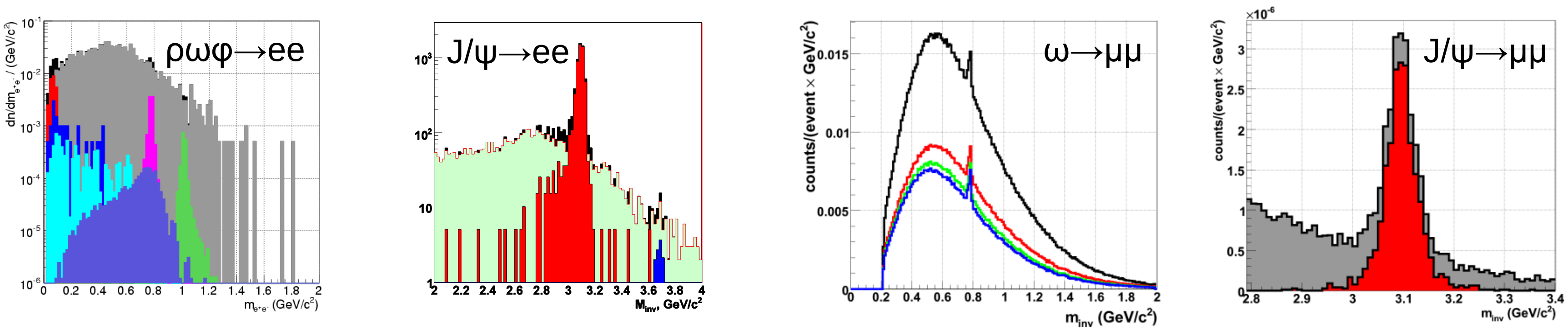
CBM at FAIR
Rare Probes



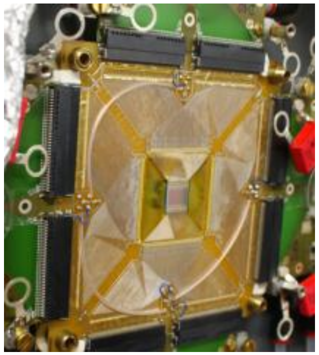
CBM at FAIR
Performance Studies



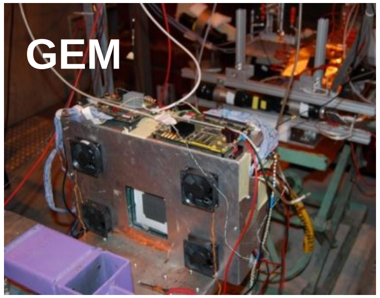




CBM at FAIR
Technical Developments

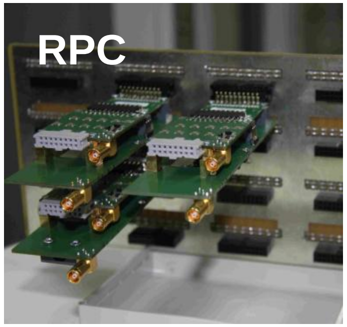


radiation-hard double-sided silicon microstrip detectors

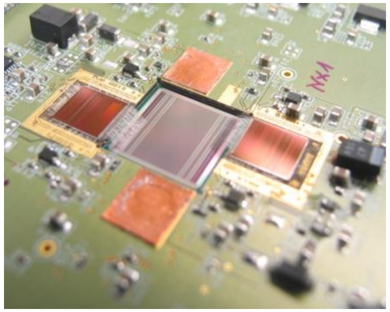


5 MHz/cm², 15 m²

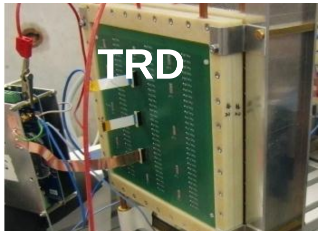
fast on-line event selection using many-core architectures



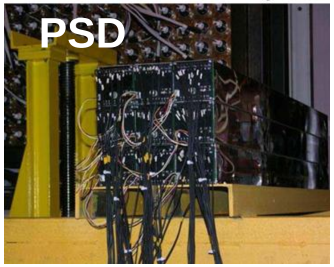
25 kHz/cm², 60 ps, 100 m²

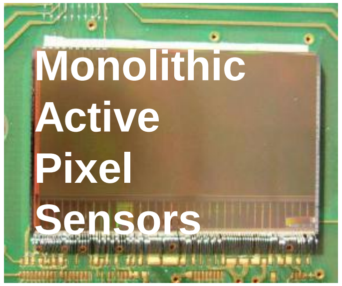


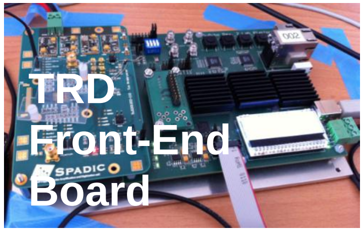
self-triggering read-out chip 128 ch, 32 MHz

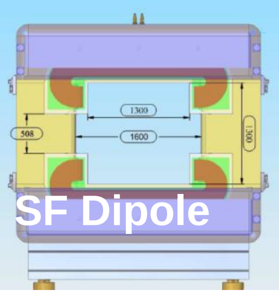


100 kHz/cm², 700 m²







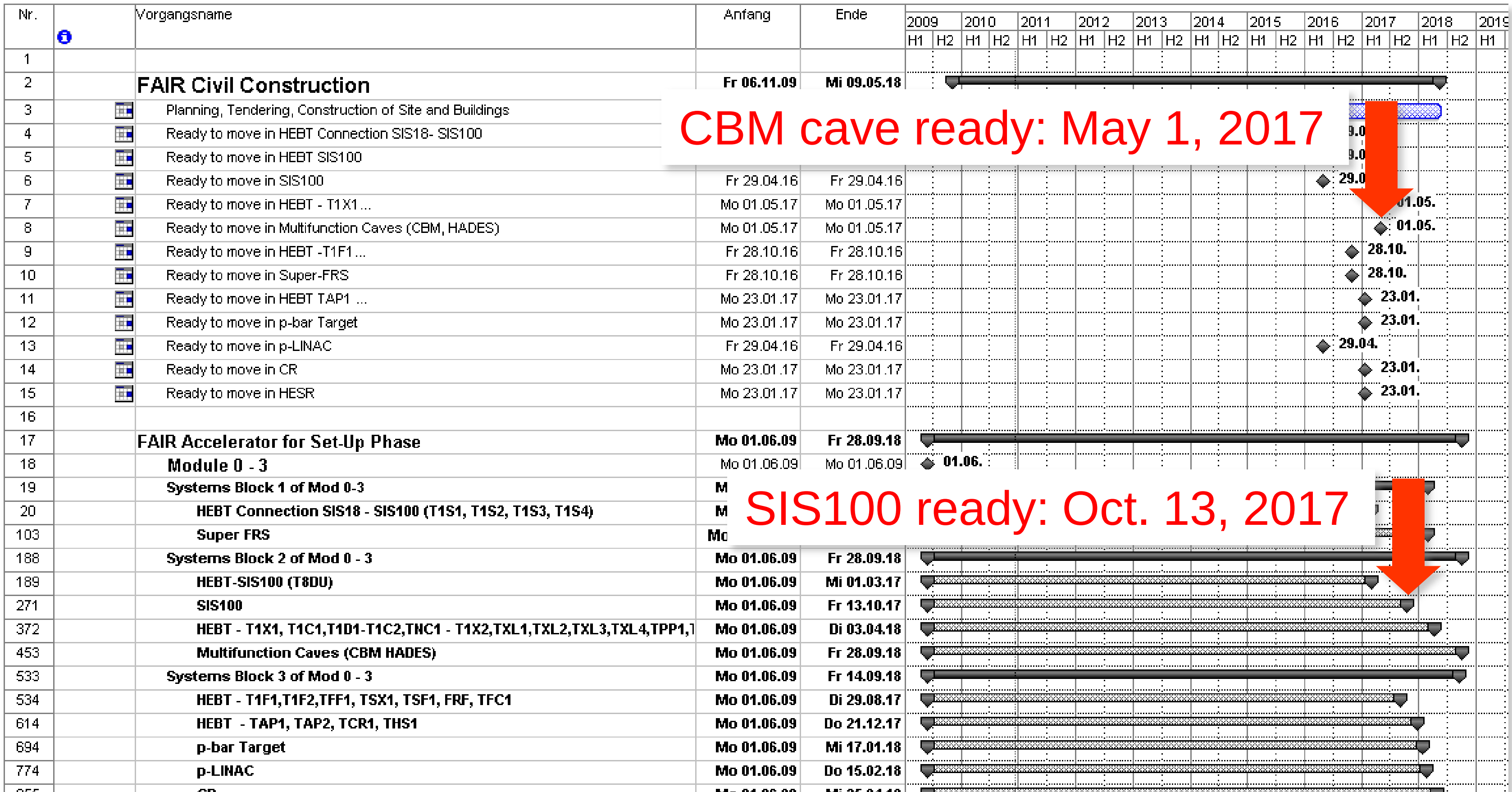


CBM at FAIR
Comparison of Low Energy Programs

Experiment	Observables at about $\sqrt{s_{NN}}$ = 8 GeV			
	hadrons	correl., fluct. w. high stat.	dileptons	charm
STAR@RHIC	yes	no	no	no
NA61@SPS	yes	no	no	no
MPD@NICA	yes	yes	no	no
CBM@FAIR	yes	yes	yes	yes

Experiment	Energy range (Au/Pb beams)	Reaction rates Hz
STAR@RHIC	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1 – 800 (limitation by luminosity)
NA61@SPS	E_{kin}= 20 – 160 A GeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limitation by detector)
MPD@NICA	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (luminosity of $10^{27}cm^{-2}s^{-1}$)
CBM@FAIR	E_{kin}= 2.0 – 35 A GeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV	10^5 – 10^7 (limitation by detector)

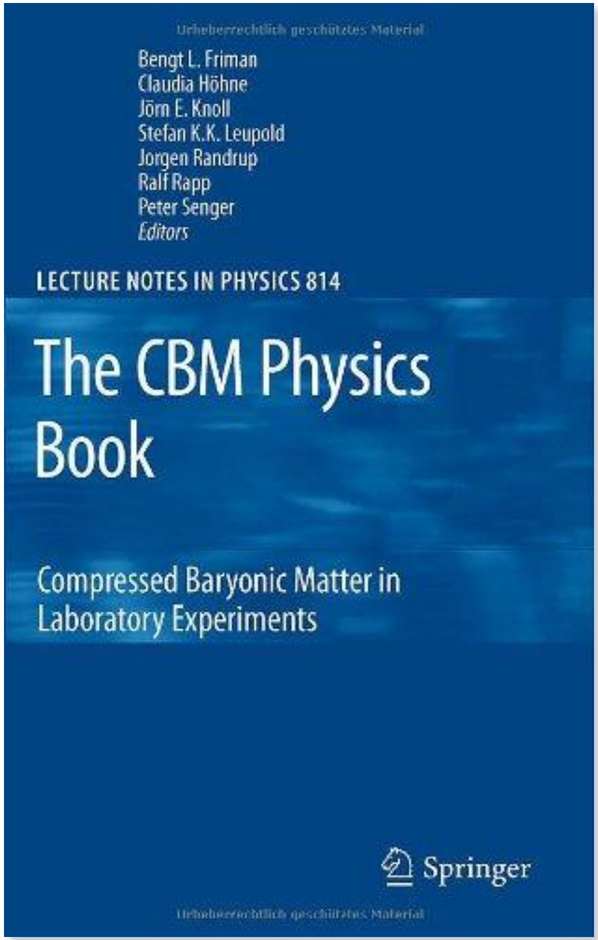
CBM at FAIR
Timeline



Nr.	Vorgangsname	Anfang	Ende
1			
2	**FAIR Civil Construction**	**Fr 06.11.09**	**Mi 09.05.18**
3	Planning, Tendering, Construction of Site and Buildings		
4	Ready to move in HEBT Connection SIS18- SIS100		
5	Ready to move in HEBT SIS100		
6	Ready to move in SIS100	Fr 29.04.16	Fr 29.04.16
7	Ready to move in HEBT - T1X1 ...	Mo 01.05.17	Mo 01.05.17
8	Ready to move in Multifunction Caves (CBM, HADES)	Mo 01.05.17	Mo 01.05.17
9	Ready to move in HEBT -T1F1 ...	Fr 28.10.16	Fr 28.10.16
10	Ready to move in Super-FRS	Fr 28.10.16	Fr 28.10.16
11	Ready to move in HEBT TAP1 ...	Mo 23.01.17	Mo 23.01.17
12	Ready to move in p-bar Target	Mo 23.01.17	Mo 23.01.17
13	Ready to move in p-LINAC	Fr 29.04.16	Fr 29.04.16
14	Ready to move in CR	Mo 23.01.17	Mo 23.01.17
15	Ready to move in HESR	Mo 23.01.17	Mo 23.01.17
16			
17	**FAIR Accelerator for Set-Up Phase**	**Mo 01.06.09**	**Fr 28.09.18**
18	**Module 0 - 3**	Mo 01.06.09	Mo 01.06.09
19	**Systems Block 1 of Mod 0-3**	**M**	
20	**HEBT Connection SIS18 - SIS100 (T1S1, T1S2, T1S3, T1S4)**	**M**	
103	**Super FRS**	**Mo**	
188	**Systems Block 2 of Mod 0 - 3**	**Mo 01.06.09**	**Fr 28.09.18**
189	**HEBT-SIS100 (T8DU)**	**Mo 01.06.09**	**Mi 01.03.17**
271	**SIS100**	**Mo 01.06.09**	**Fr 13.10.17**
372	**HEBT - T1X1, T1C1,T1D1-T1C2,TNC1 - T1X2,TXL1,TXL2,TXL3,TXL4,TPP1,T**	**Mo 01.06.09**	**Di 03.04.18**
453	**Multifunction Caves (CBM HADES)**	**Mo 01.06.09**	**Fr 28.09.18**
533	**Systems Block 3 of Mod 0 - 3**	**Mo 01.06.09**	**Fr 14.09.18**
534	**HEBT - T1F1,T1F2,TFF1, TSX1, TSF1, FRF, TFC1**	**Mo 01.06.09**	**Di 29.08.17**
614	**HEBT - TAP1, TAP2, TCR1, THS1**	**Mo 01.06.09**	**Do 21.12.17**
694	**p-bar Target**	**Mo 01.06.09**	**Mi 17.01.18**
774	**p-LINAC**	**Mo 01.06.09**	**Do 15.02.18**
855	**CR**	**Mo 01.06.09**	**Mi 25.04.18**

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
R&D detectors & read-out systems			construction detectors & read-out systems				installation, commissioning		first data taking	

The CBM Physics Book



Foreword by Frank Wilczek

Springer Series:
Lecture Notes in Physics, Vol. 814
1st Edition., 2011, 960 p., Hardcover
ISBN: 978-3-642-13292-6

Electronic Authors version:
http://www.gsi.de/documents/DOC-2009-Sep-120-1.pdf

Conclusions

Already a wealth of data on the market

Energy scan at the CERN-SPS (NA49)
Beam Energy Scan (BES) at RHIC (STAR)
Good agreement between experiments (except K/π and K/p fluct. at low $\sqrt{s_{NN}}$)

Onset of deconfinement

Many interesting and non-trivial structures
K^+/π^+ ratios, radial flow, directed flow of (anti)protons
Onset of partonic collectivity observable?

Search for the critical point

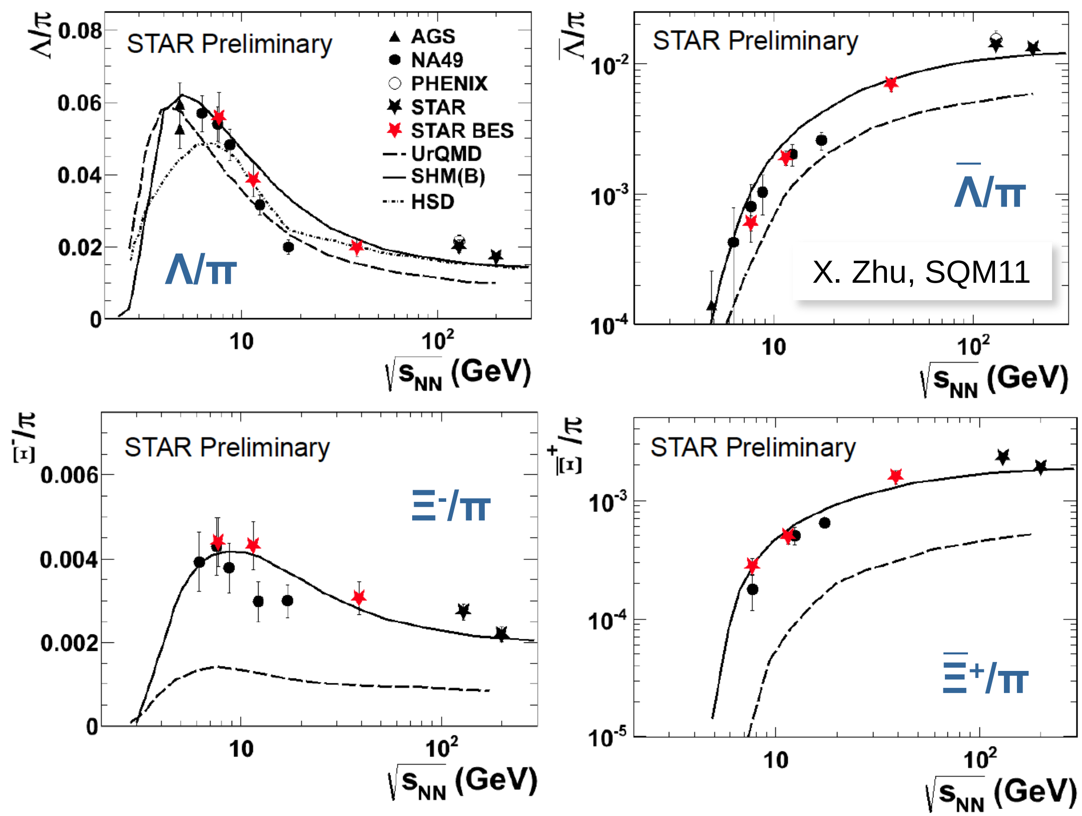
Many promising ideas being tested
Higher moments, conserved quantities (e.g. net-protons)
No clear evidence yet

Much more to come in the future

CERN-SPS: NA61
FAIR: CBM

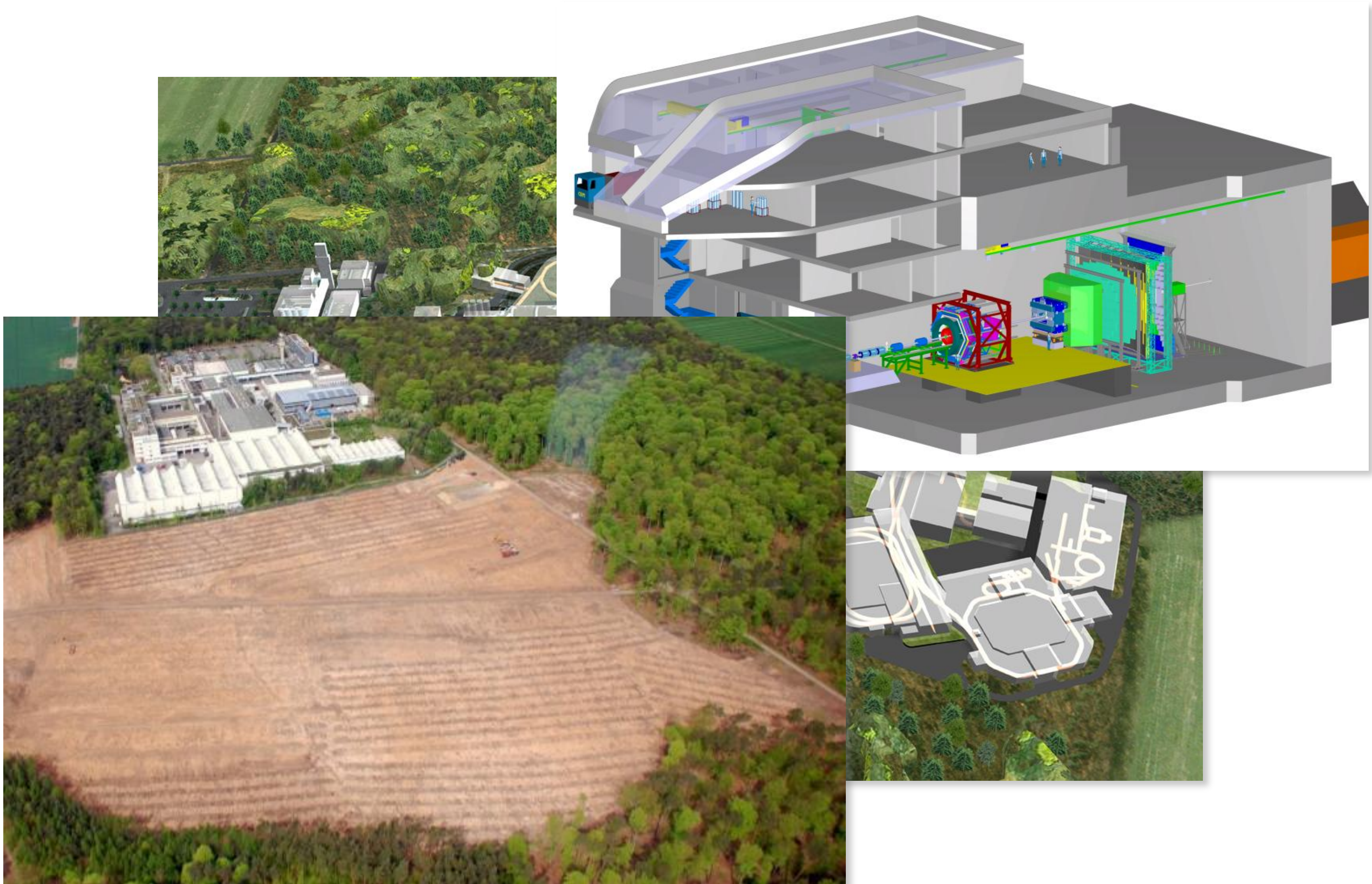
Backup

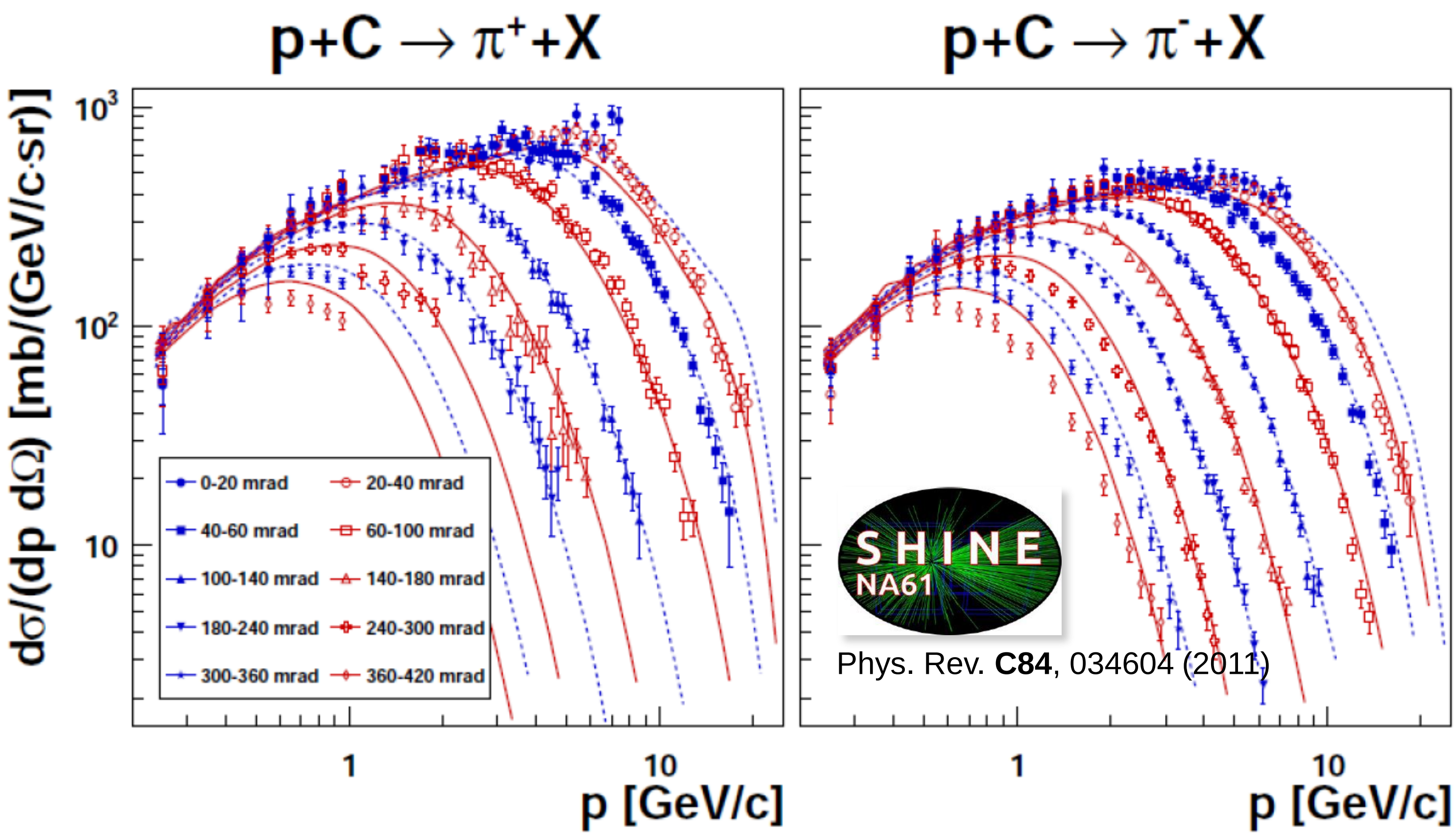
Onset of Deconfinement
Strange Baryon to Pion Ratios



Good agreement between SPS and RHIC

Close to statistical model curve





p+C at 31 GeV/c

Comparison to FLUKA2008

Onset of Deconfinement

Kinetic Freeze-Out Parameter

Blast wave fits: T_{kin}, $\langle \beta_T \rangle$

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh \rho(r)}{T_{kin}}\right)$$

E. Schnedermann and U. Heinz, PRC50, 1675 (1994).

$T_{kin} < T_{ch}$ for $\sqrt{s_{NN}} > 10$ GeV

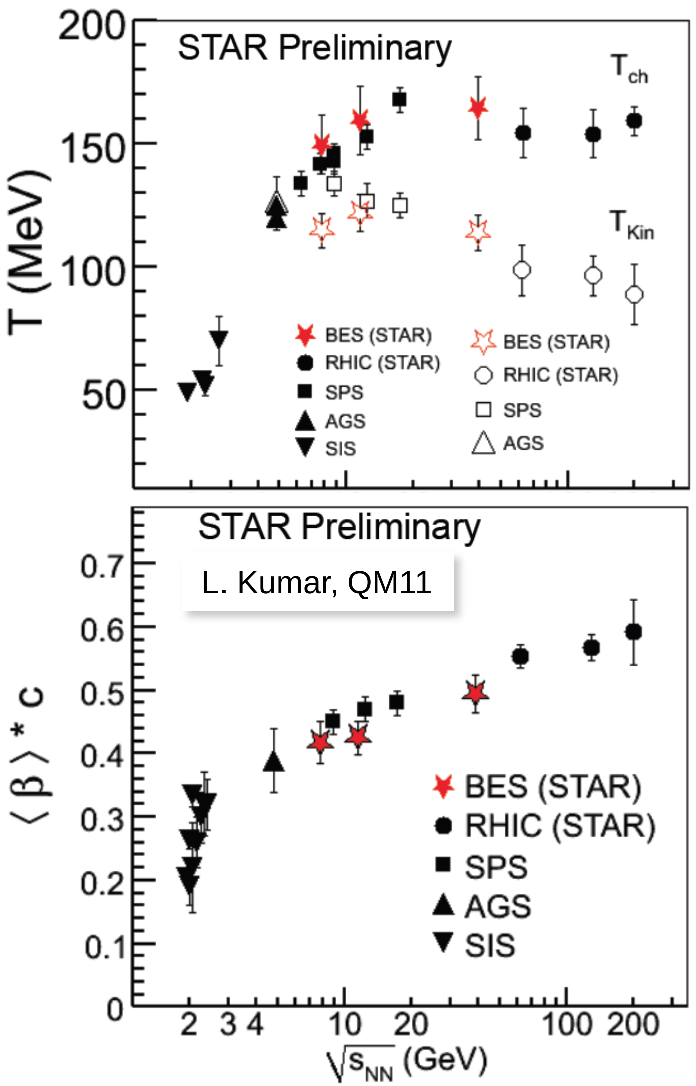
Difference increases with increasing energy (drop of T_{kin})

→ more time for cooling of system

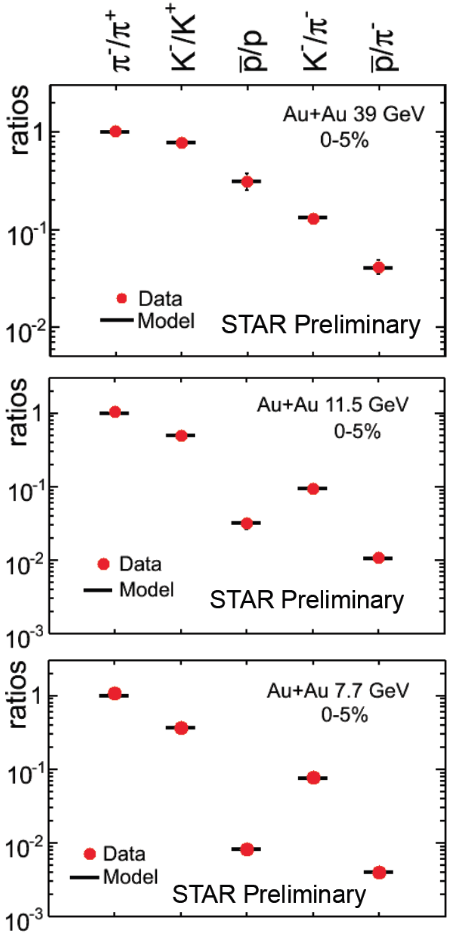
Continuous increase of $\langle \beta_T \rangle$

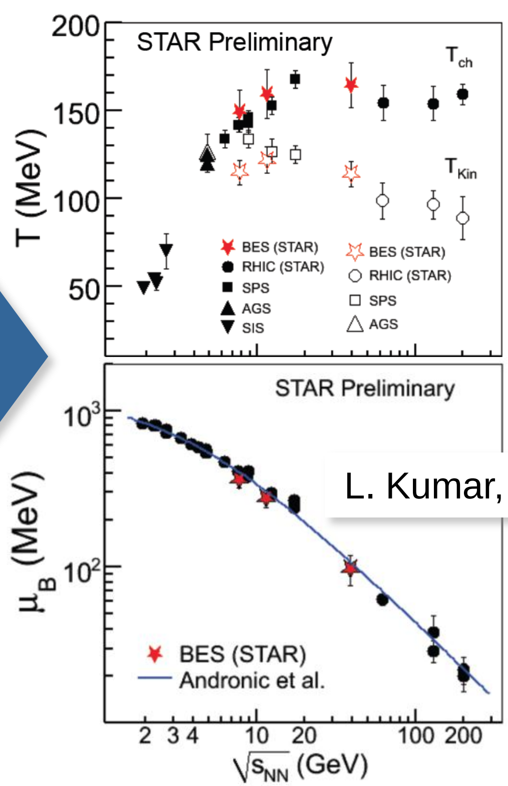
Steep increase at low energies

Moderate increase at higher energies

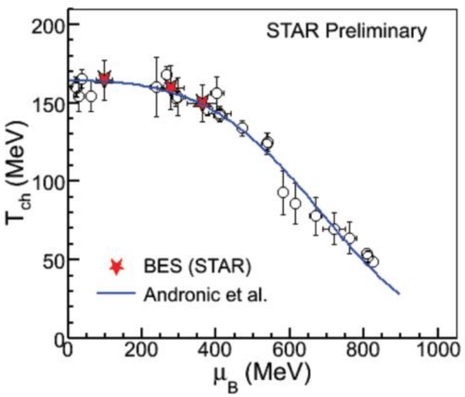


The QCD Phase Diagram
Chemical Freeze-Out





L. Kumar, QM11



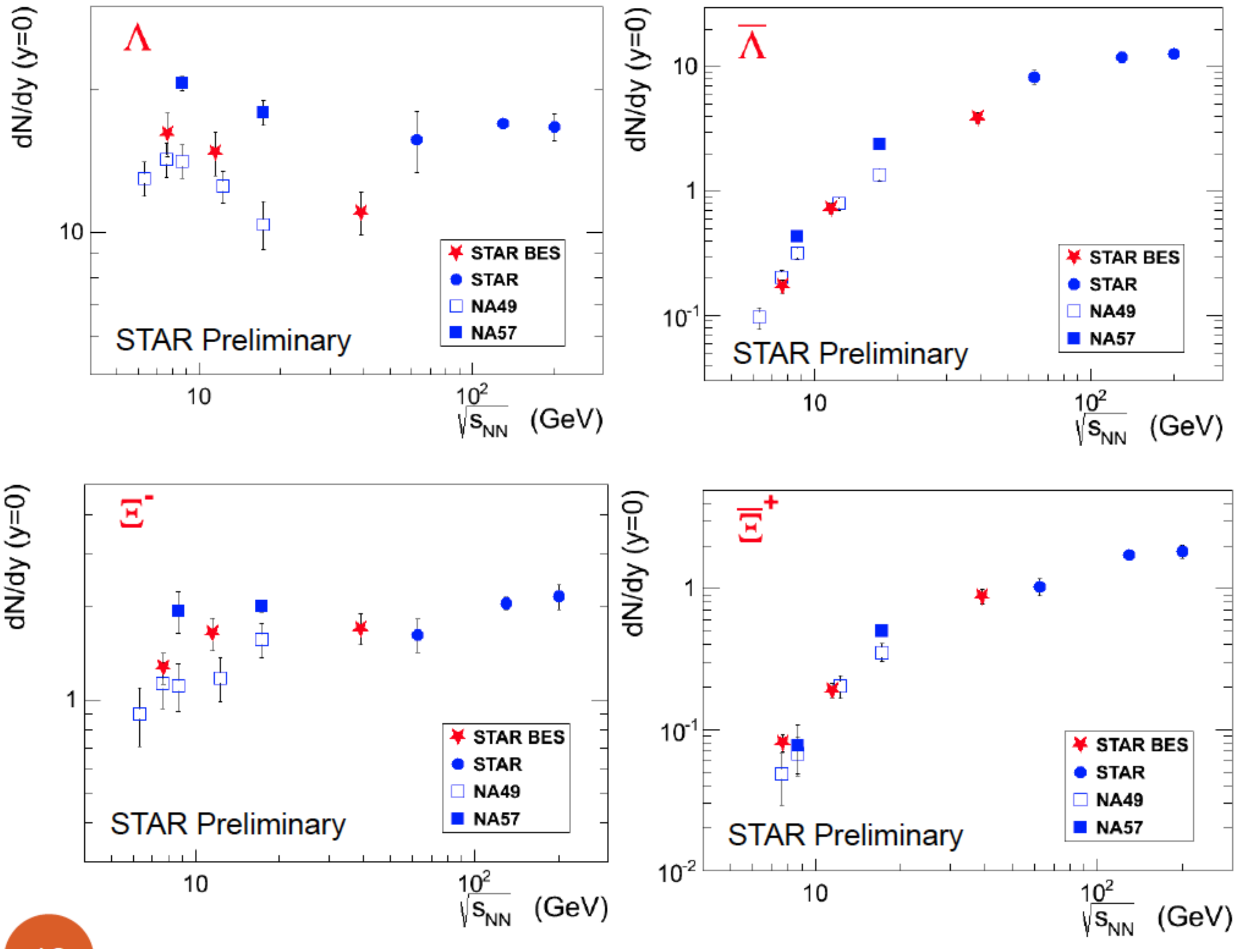
Statistical model fits

Freeze-out parameters:

V, *T*, μ_B, (γ_S)

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu \cdot q_j/T} \pm 1 \right]^{-1}$$

X. Zhu, SQM11



Λ
dN/dy (y=0)
STAR Preliminary
STAR BES
STAR
NA49
NA57
$\sqrt{s_{NN}}$ (GeV)
$\bar{\Lambda}$
Ξ^-
$\bar{\Xi}^+$

Transport models

HSD, UrQMD1.6
Do not match data (except UrQMD2.3)

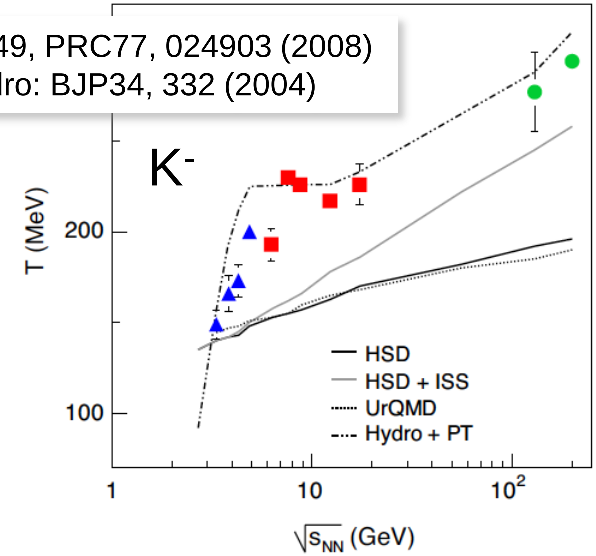
Hydro models

Structure consistent with change of EOS
1st order phase transition

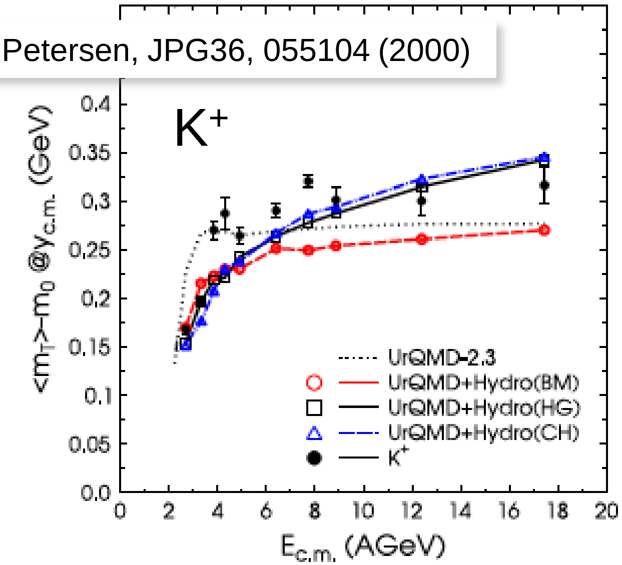
But:

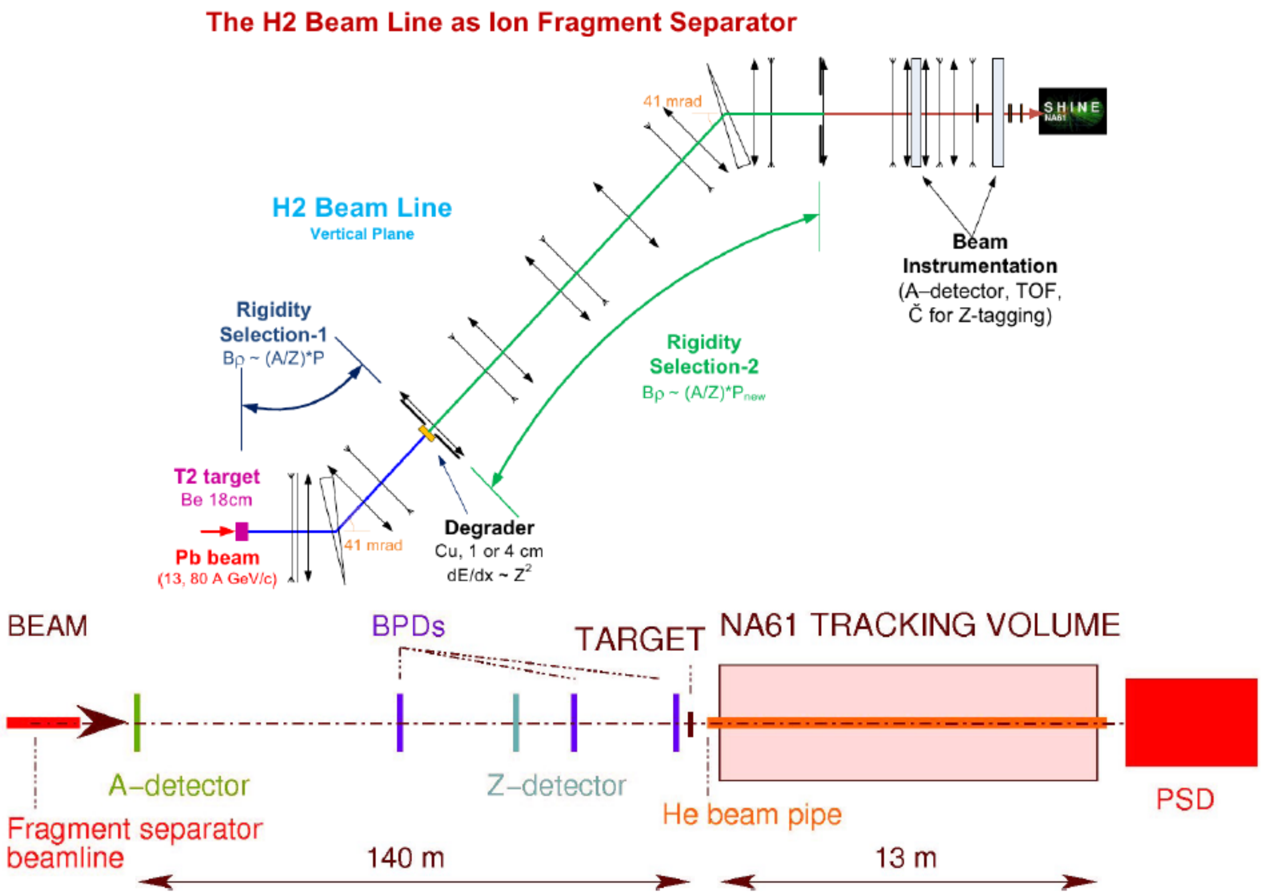
Strong influence of freeze-out description
Difficult to establish unique connection

NA49, PRC77, 024903 (2008)
Hydro: BJP34, 332 (2004)



H. Petersen, JPG36, 055104 (2000)





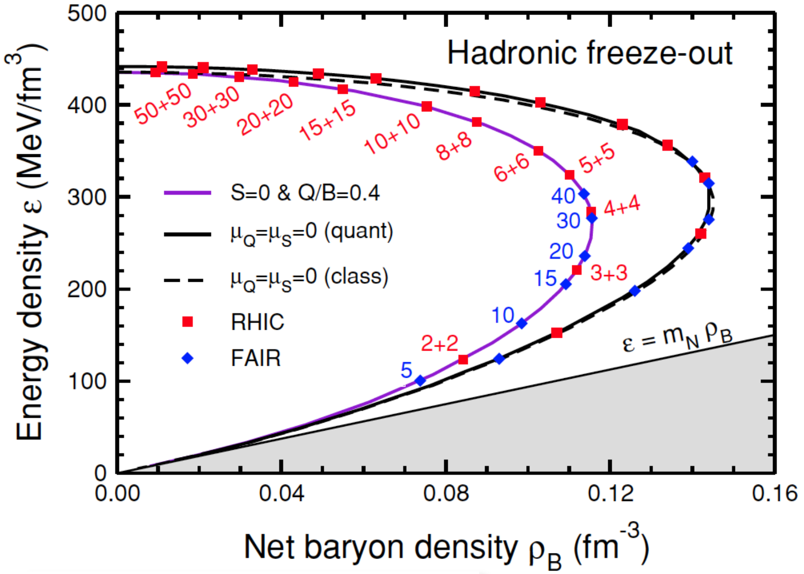
A. Aduszkiewicz, SQM11

The QCD Phase Diagram

High Baryon Density

Net baryon density

Reaches maximum in interesting regions of $\sqrt{s_{NN}}$



J. Randrup and J. Cleymans, PRC74, 047901 (2006)

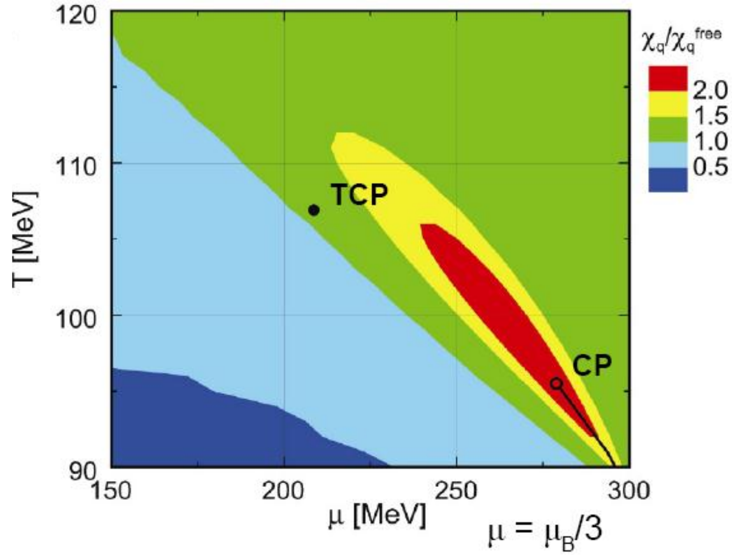
Critical Point
Theoretical Predictions

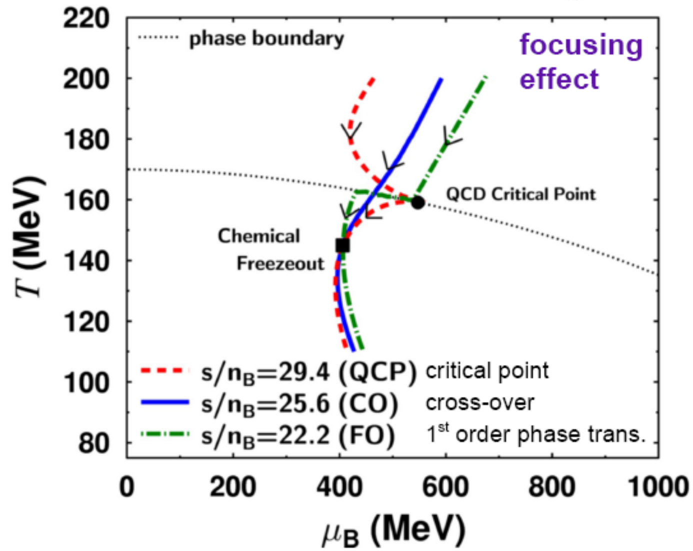
Critical region
Larger area in T - μ_B plane

Y. Hatta and T. Ikeda,
Phys. Rev. D67,
014028 (2003)

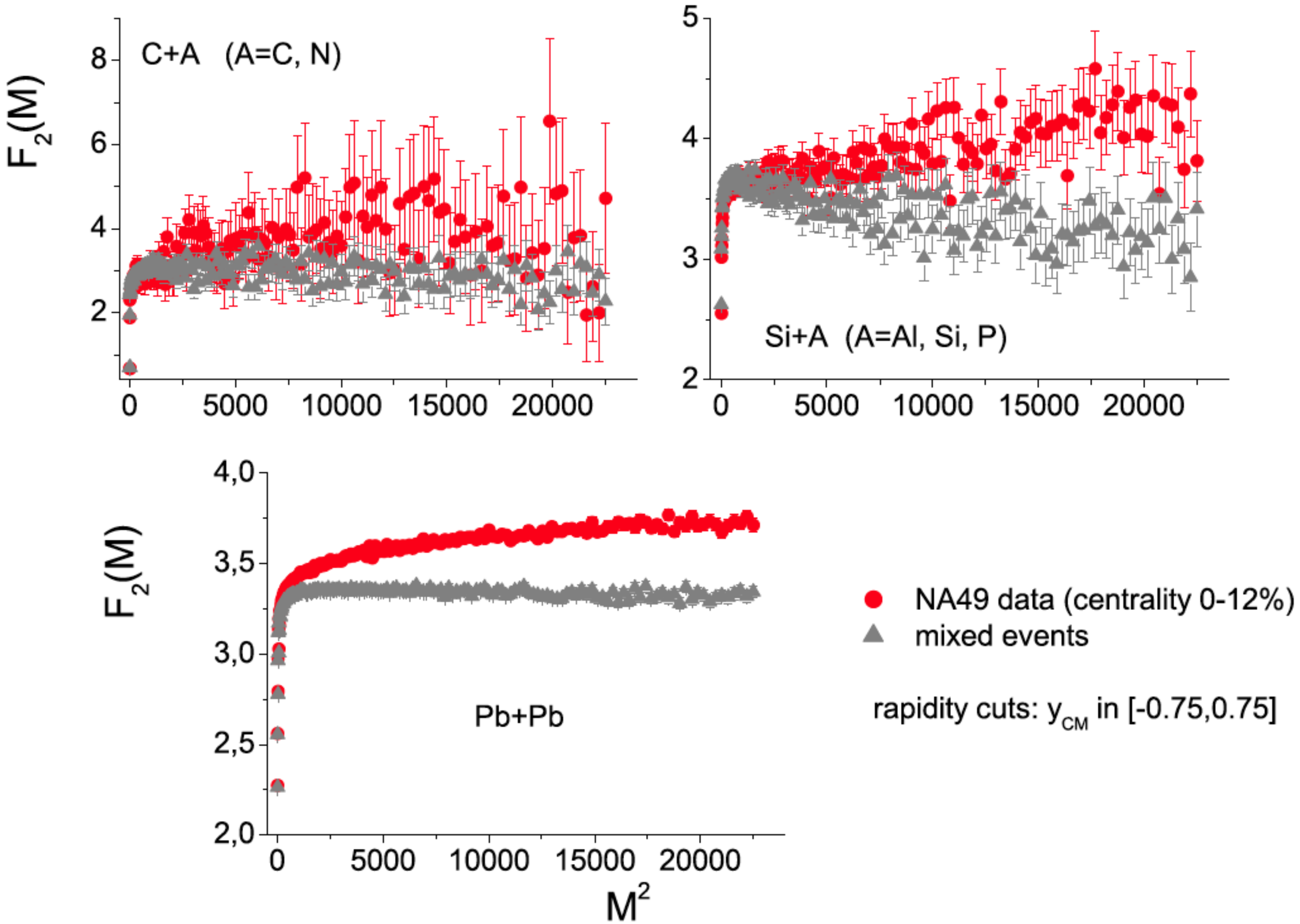
Focusing effect
Proximity of critical point might influence isentropic trajectories (n_B/s = const.)

Askawa et al.,
Phys. Rev. Lett. 101,
122302 (2008)

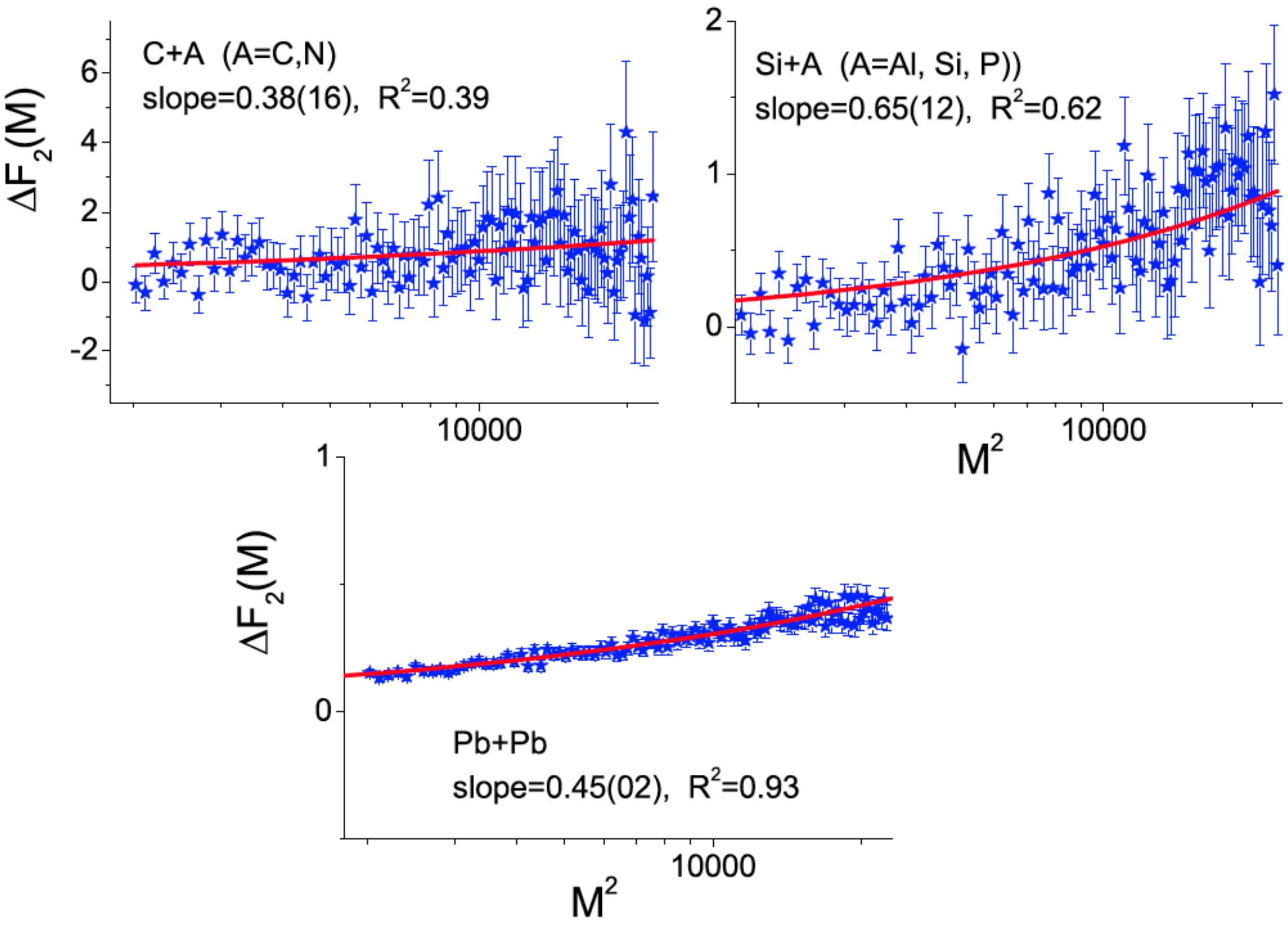


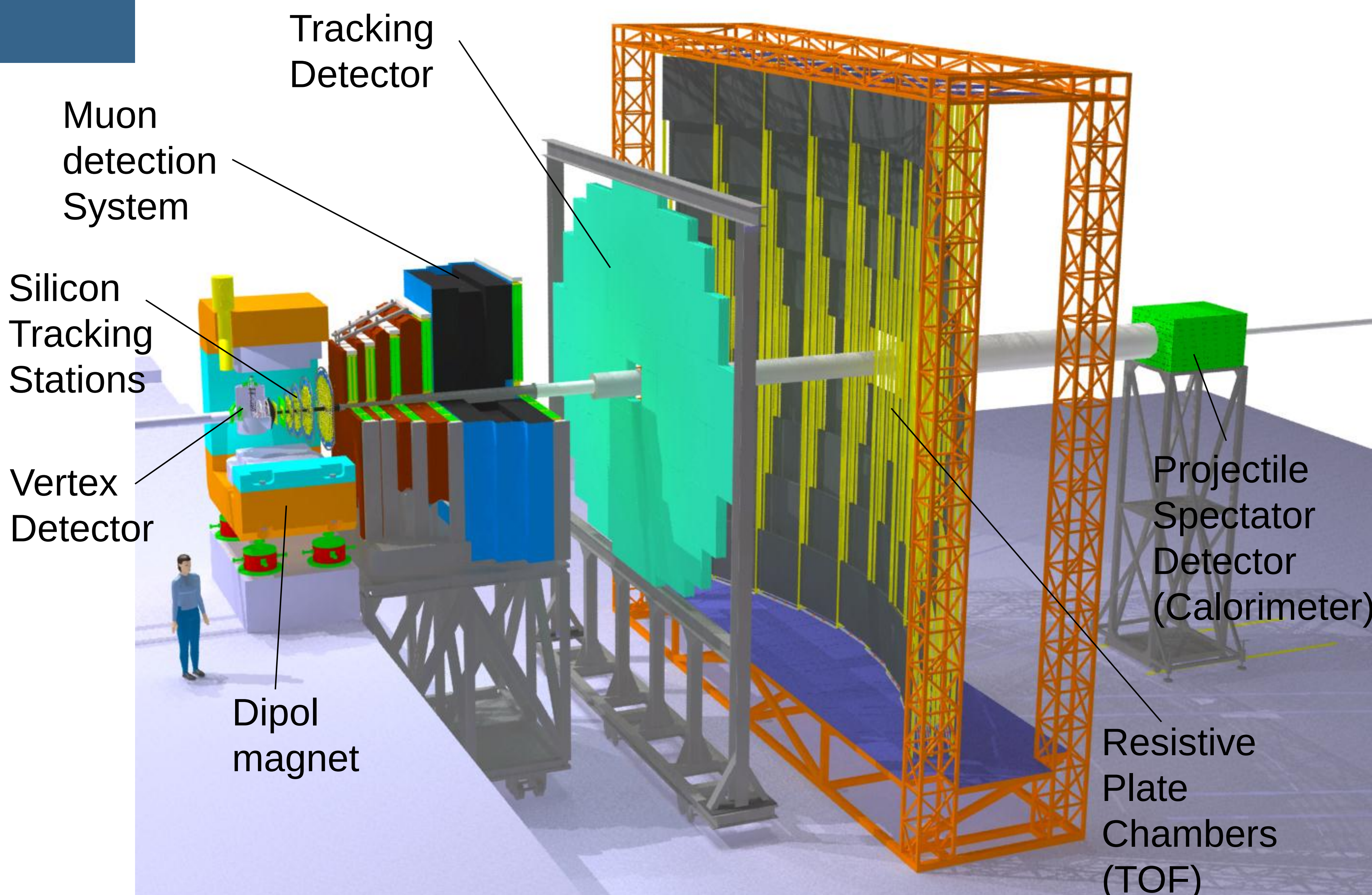


Factorial moment analysis of protons at 158A GeV



The correlator $\Delta F_2(M)$ for 3 considered systems at 158A GeV




Tracking Detector
Muon detection System
Silicon Tracking Stations
Vertex Detector
Dipol magnet
Projectile Spectator Detector (Calorimeter)
Resistive Plate Chambers (TOF)