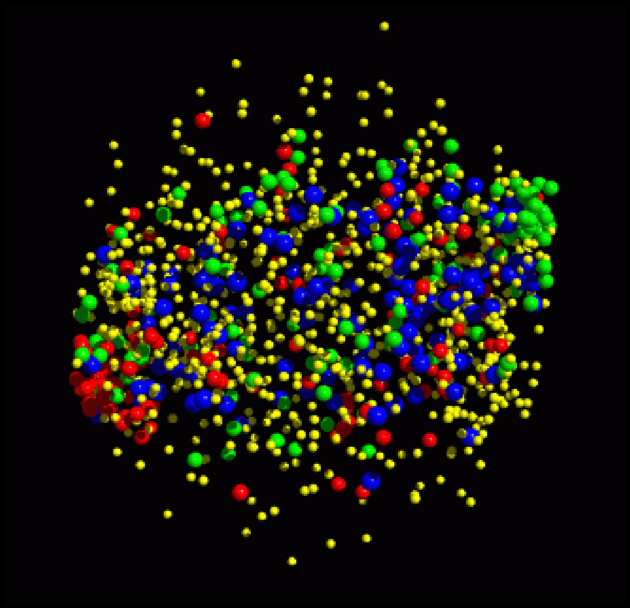
Nuclear Matter at High Baryon Density



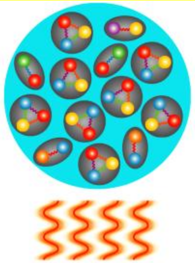
Peter Senger (GSI)

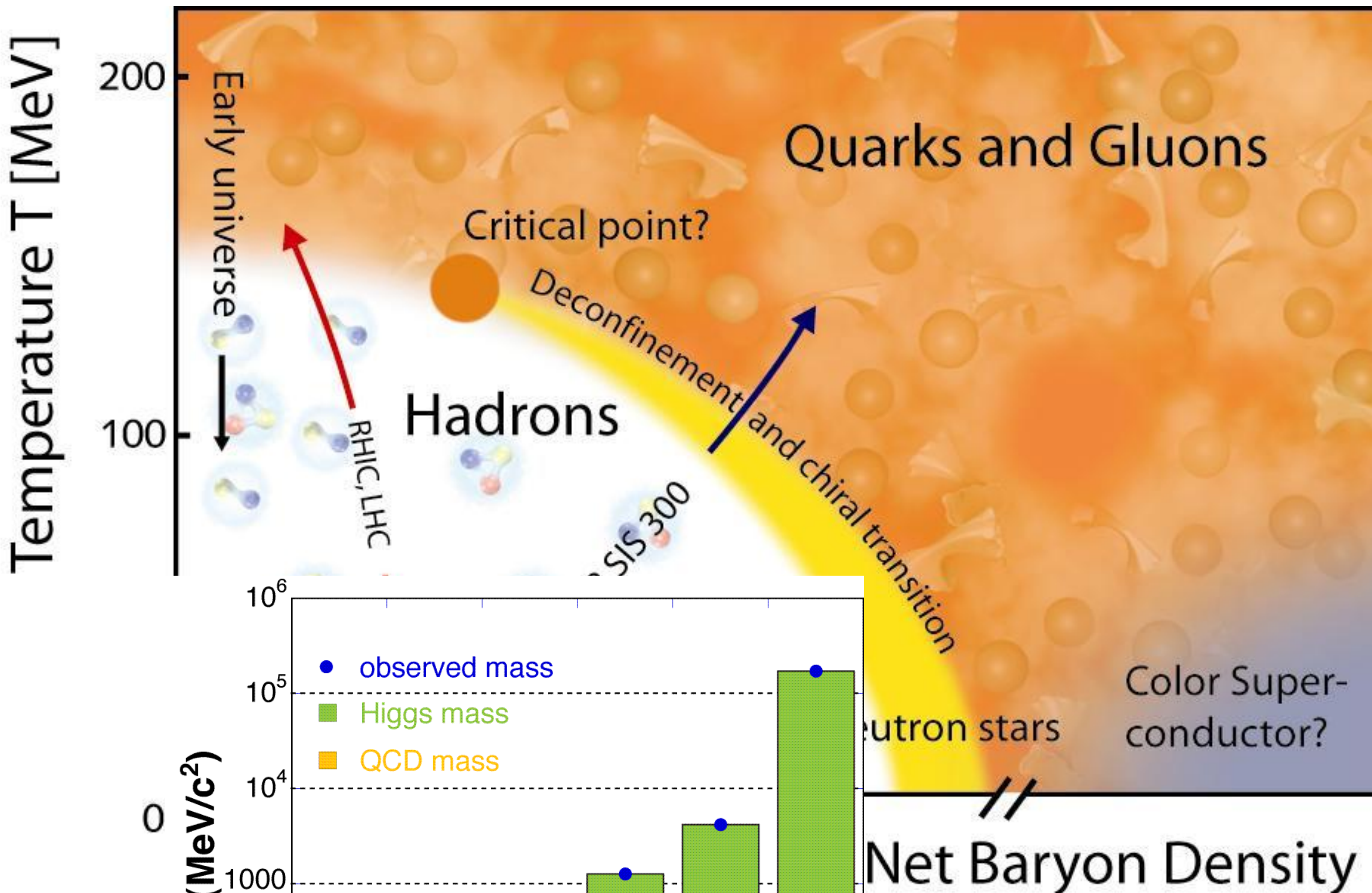
Outline:

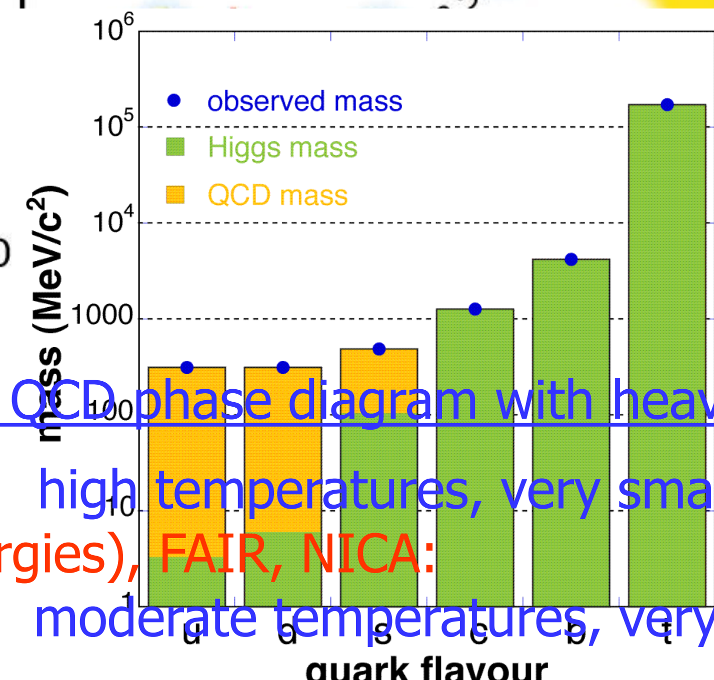
- Physics case
- Experimental data (NA49, STAR)
- Future facilities: CBM/FAIR and MPD/NICA

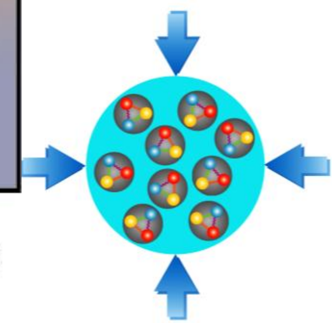
10th ICFA Seminar, October 3-6, 2011, CERN

The phase diagram of strongly interacting matter









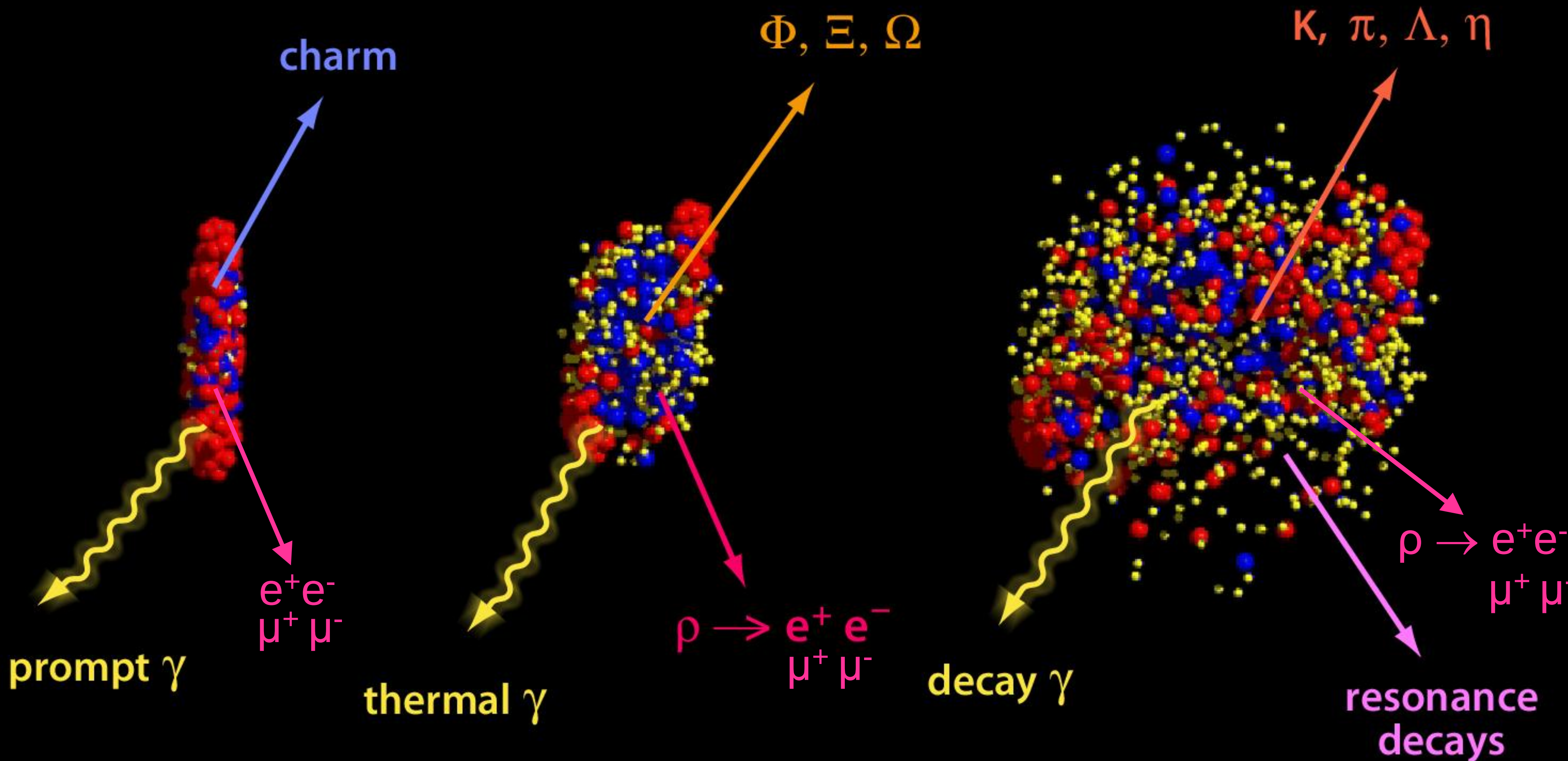
Exploring the QCD phase diagram with heavy-ion collisions:

RHIC & LHC: high temperatures, very small net-baryon density

SPS (low energies), FAIR, NICA:
moderate temperatures, very high net-baryon density

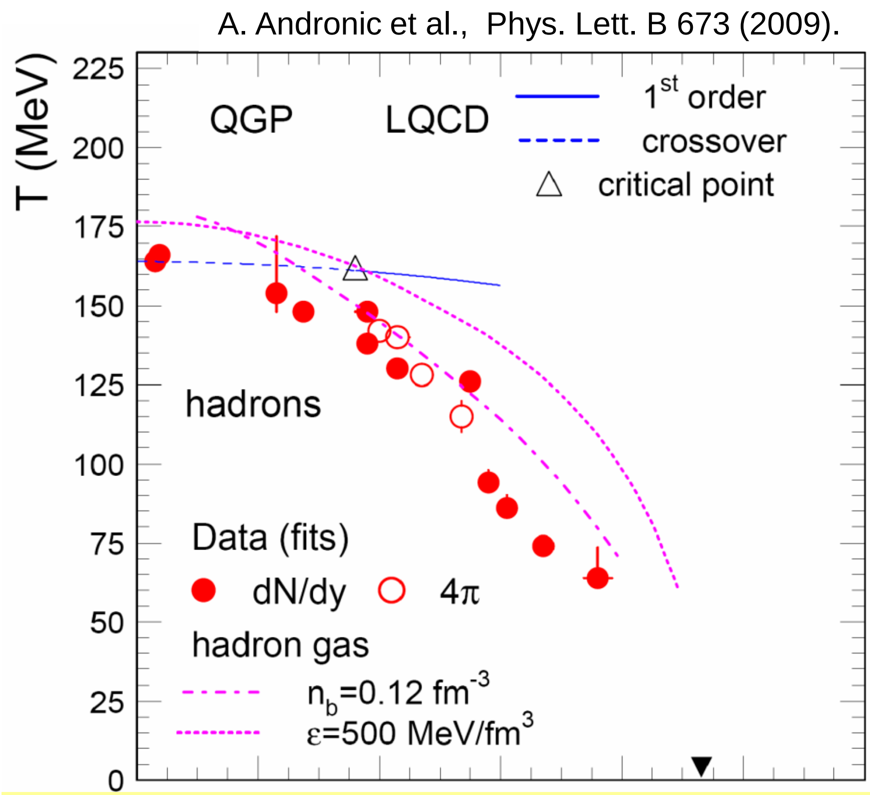
Messengers from the dense fireball

UrQMD transport calculation U+U 23 AGeV



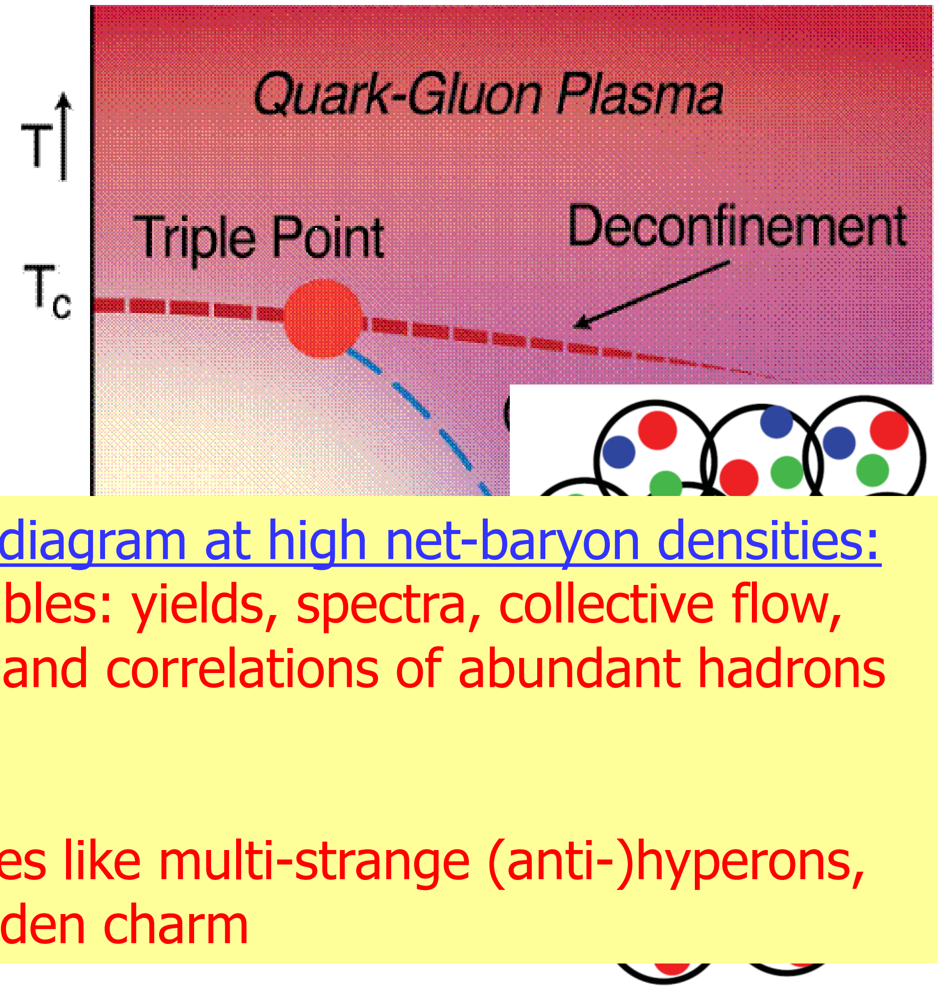
Up to date only freeze-out probes have been measured at energies between 2 and 40 A GeV

The QCD Phase diagram: facts and speculations



Experimental results:

- Freeze-out curve (T, μ_B) with $T_{ch} \approx$ 160 MeV at μ_B=0
- partonic matter at high T



Experiments scanning the QCD phase diagram at high net-baryon densities:

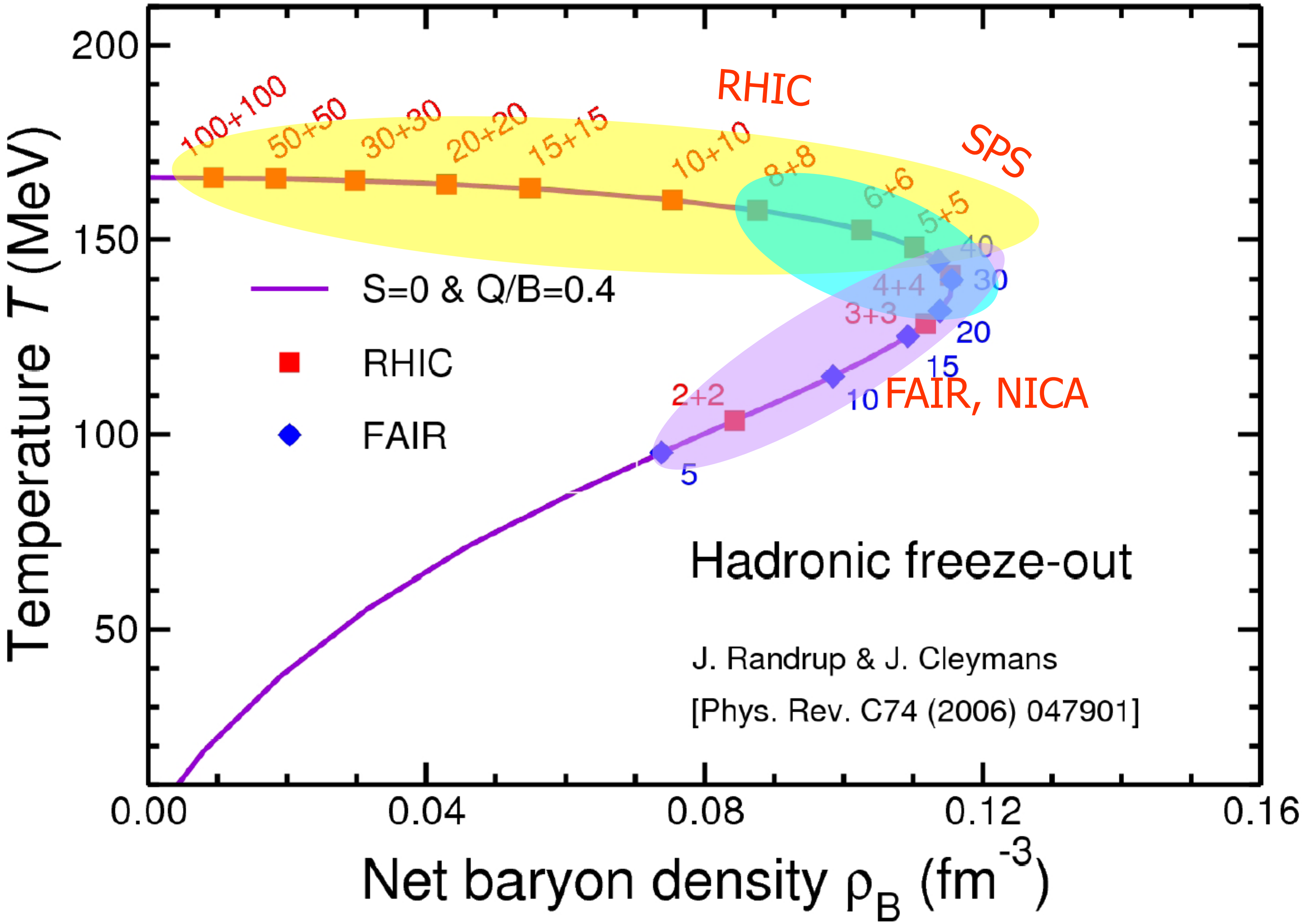
RHIC low-energy scan → bulk observables: yields, spectra, collective flow, fluctuations, and correlations of abundant hadrons

NA49/61@SPS → bulk observables

MPD@NICA → bulk observables

CBM@FAIR → bulk and rare observables like multi-strange (anti-)hyperons, dileptons, open and hidden charm

Freeze-out conditions

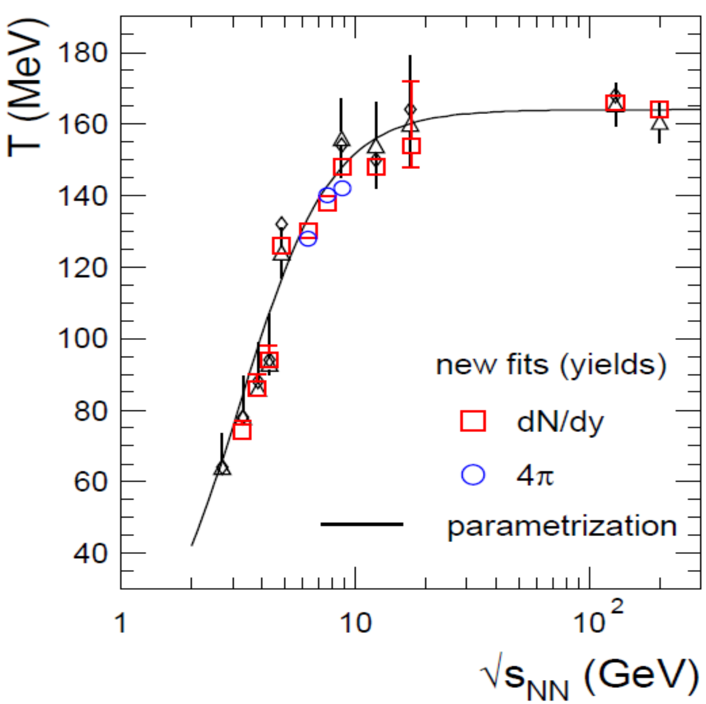


Phase transition at high net-baryon densities?

Observations at low SPS energies:

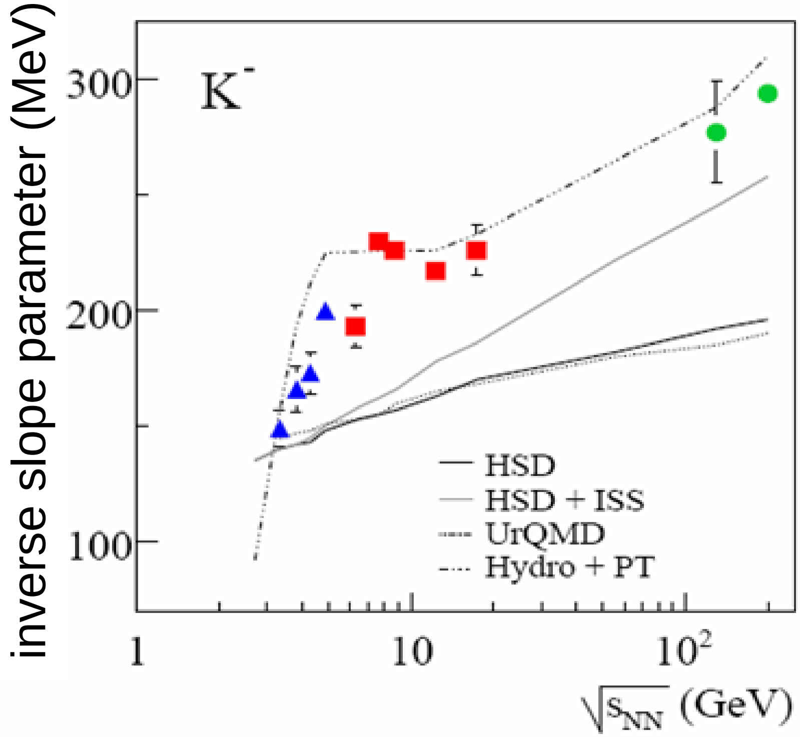
limiting chemical freeze-out temperature

A. Andronic, P. Braun-Munzinger, J. Stachel, arXiv:0901.2909



limiting transverse flow

[NA49, PRC 77, 024903 (2008)]

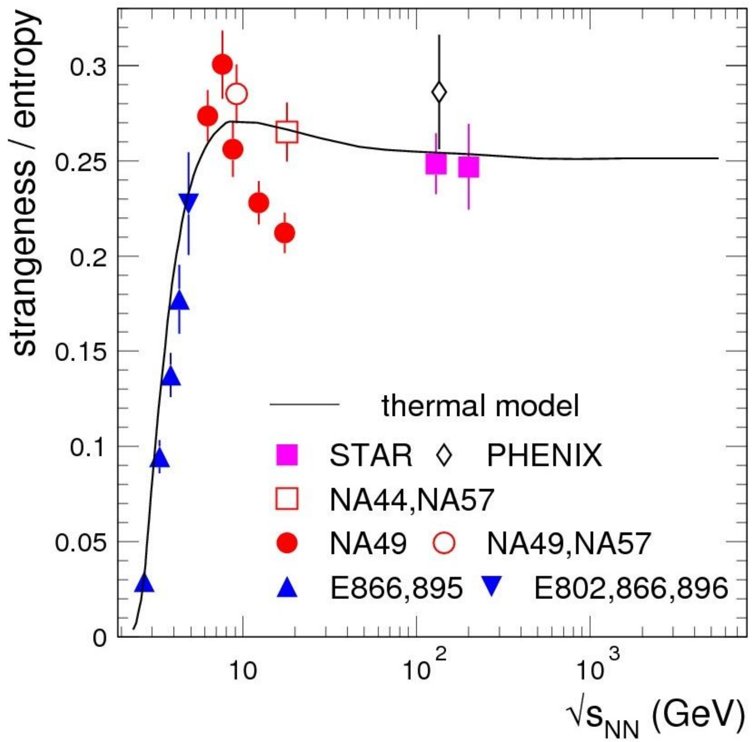


Phase transition at high net-baryon densities?

Observations at low SPS energies:

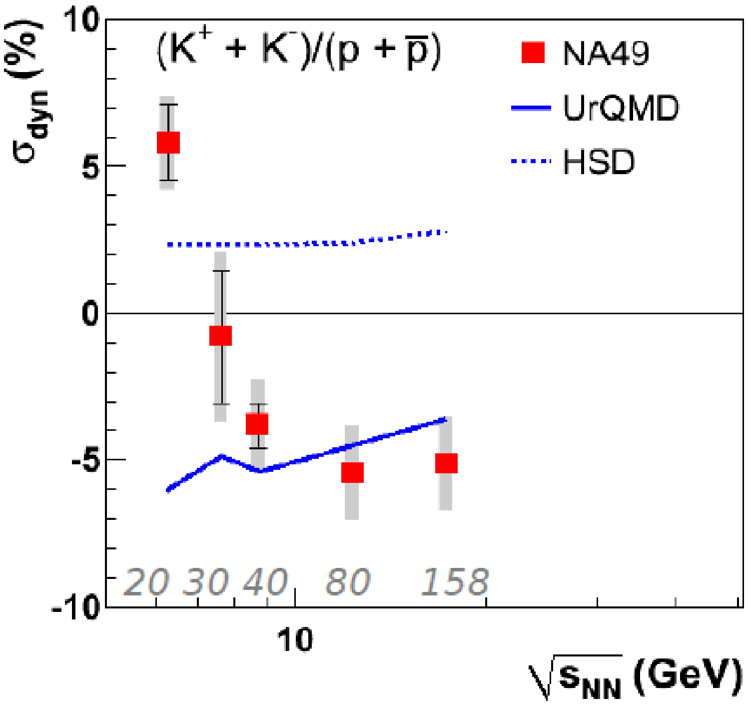
maximum in the strangeness/entropy ratio

A. Andronic, P. Braun-Munzinger, J. Stachel, Phys. Lett. B673 (2009)



enhanced dynamical event-by-event fluctuations

NA49: arXiv:1101.3250



New results from the RHIC beam energy scan

- *Turn off signature of QGP*

  NCQ scaling of v_2

  suppression of R_{AA}

  charge separation w.r.t reaction plane

  ...
- *QCD critical point*

  higher moments of conserved quantities

  particle ratio fluctuations

  ...
- *Softening of EOS*

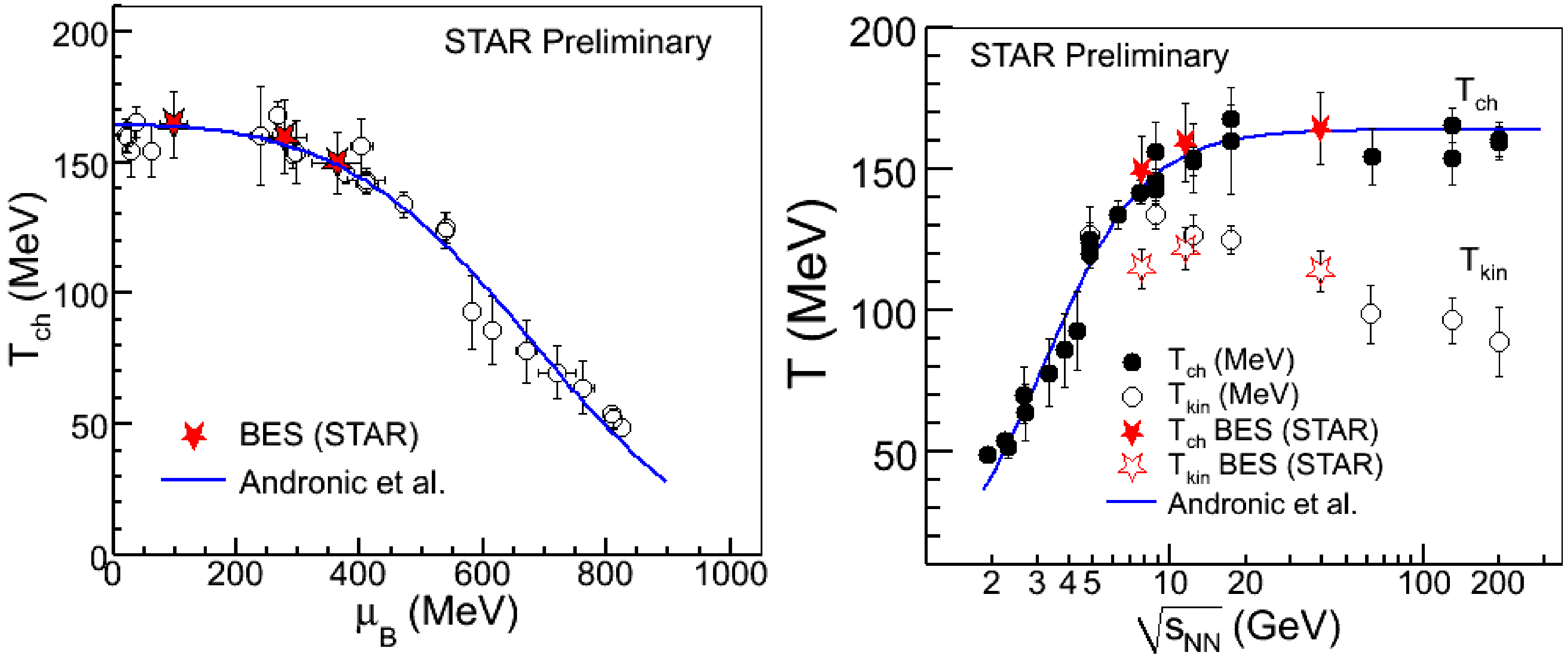
  azimuthal HBT

  azimuthal anisotropy v_1, v_2, ...

  ...

Year	$\sqrt{s_{NN}}$ (GeV)	*# of good events*
2010	7.7	~5M
	11.5	~11M
	39	~170M
2011	19.6	~17M
2011	5	-
2012	27	-

Freeze-out conditions

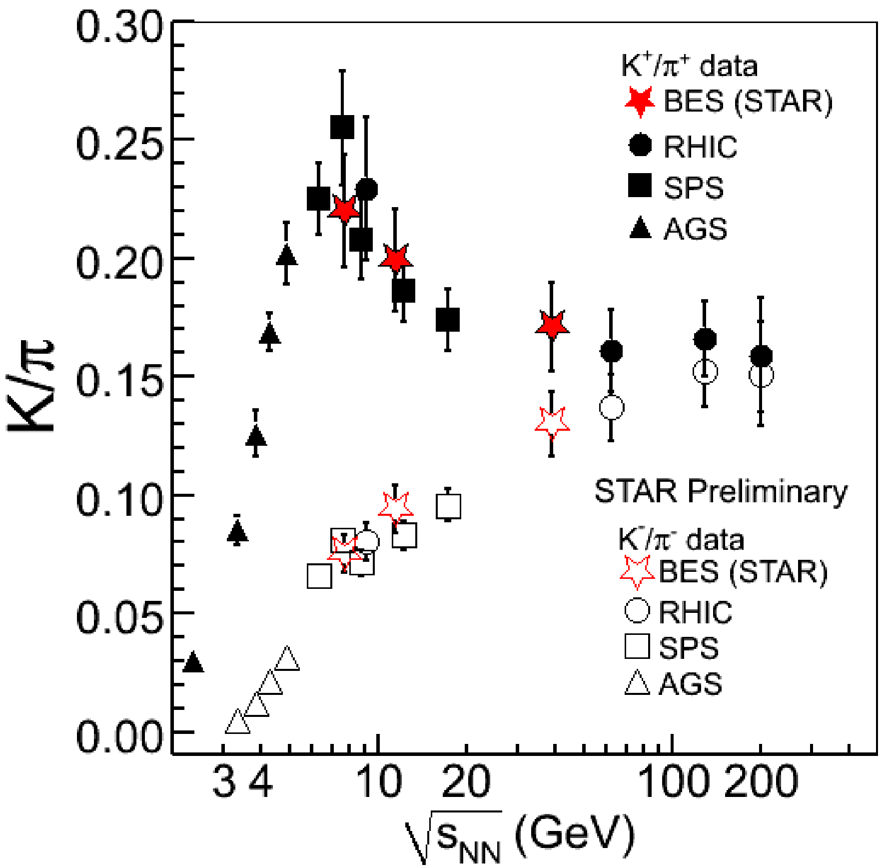


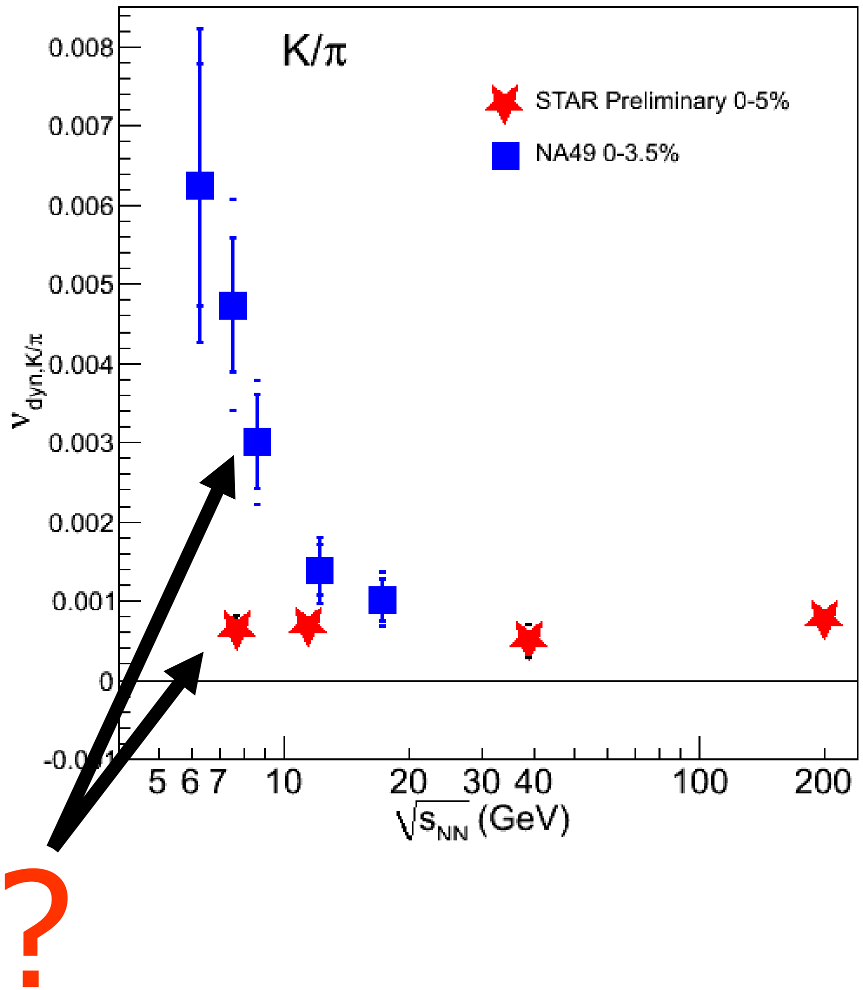
A. Andronic et al., NPA 834 (2010) 237

Strange/nonstrange particles: NA49 vs. STAR

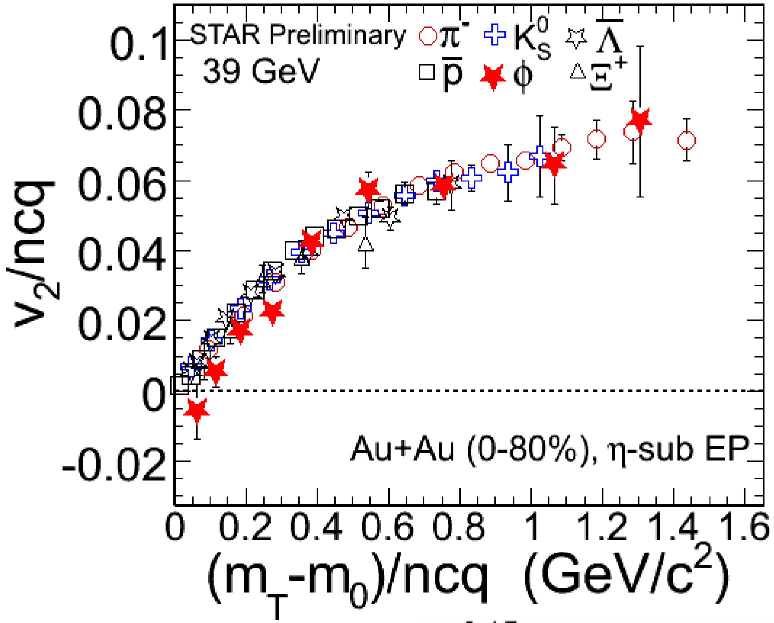
integrated yields

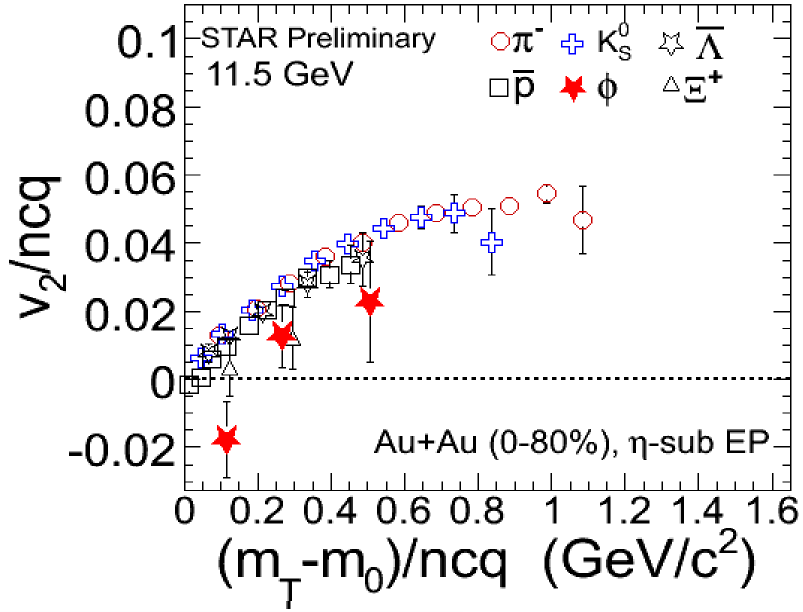
event-by-event dynamical fluctuations

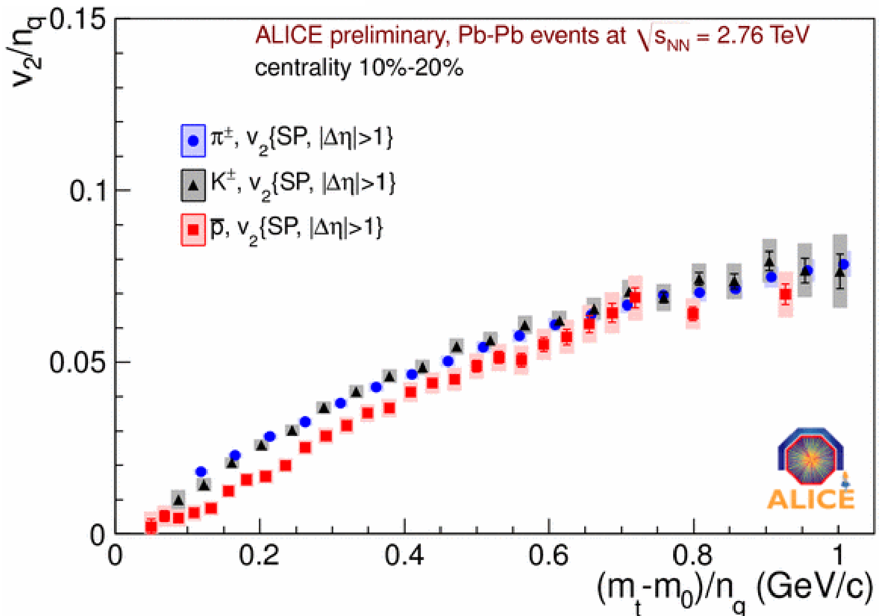




Constituent quark number scaling of elliptic flow v_2: flow generation in the partonic phase?

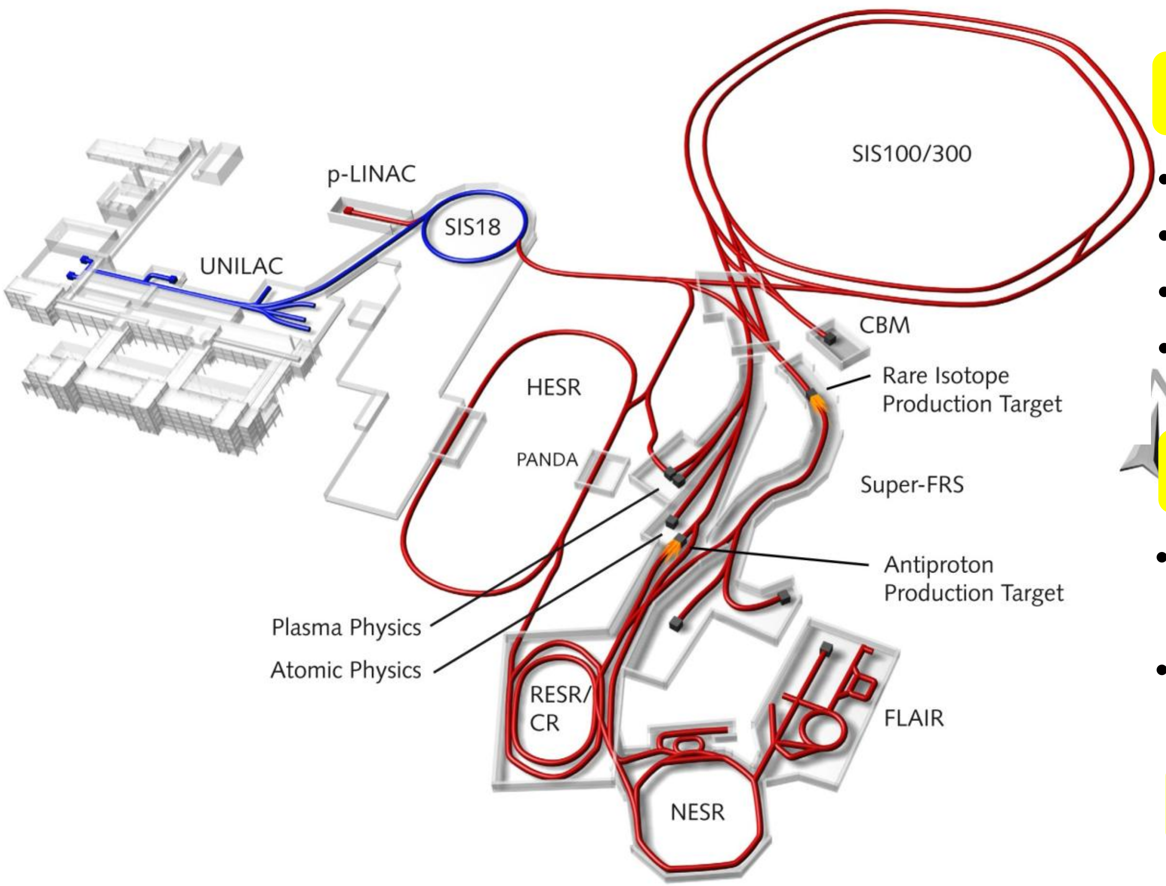






?

Facility for Antiproton and Ion Research (FAIR)



primary beams

- $5x10^{11}$/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- factor 100-1000 increased intensity
- $4x10^{13}$/s 90 GeV protons
- 10^{10}/s ^{238}U 35 GeV/u (Ni 45 GeV/u)

secondary beams

- rare isotopes 1.5 - 2 GeV/u;
  factor 10 000 increased intensity
- antiprotons 3(0) - 30 GeV

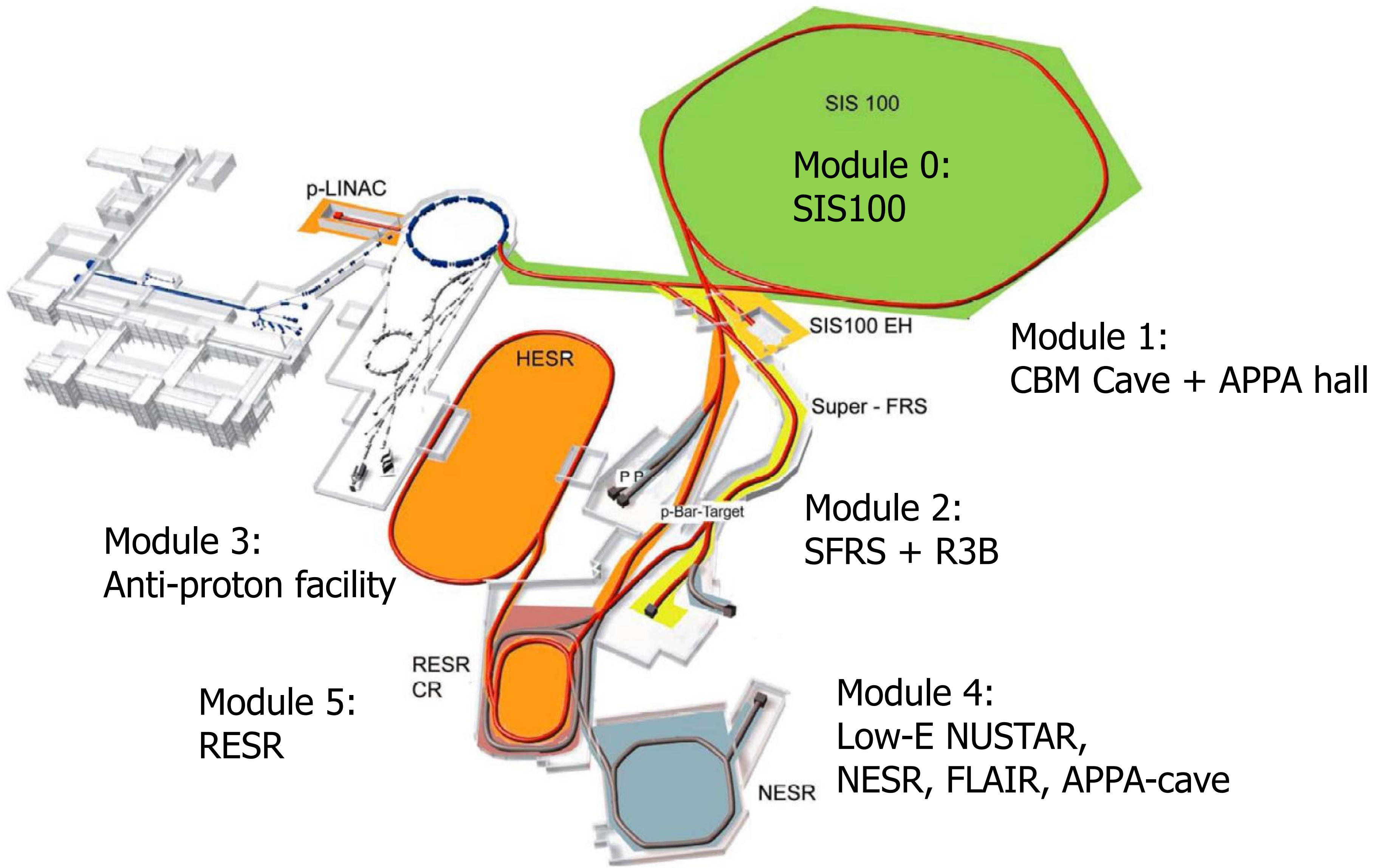
storage and cooler rings

- beams of rare isotopes
- e – A Collider
- 10^{11} stored and cooled antiprotons
  0.8 - 14.5 GeV

accelerator technical challenges

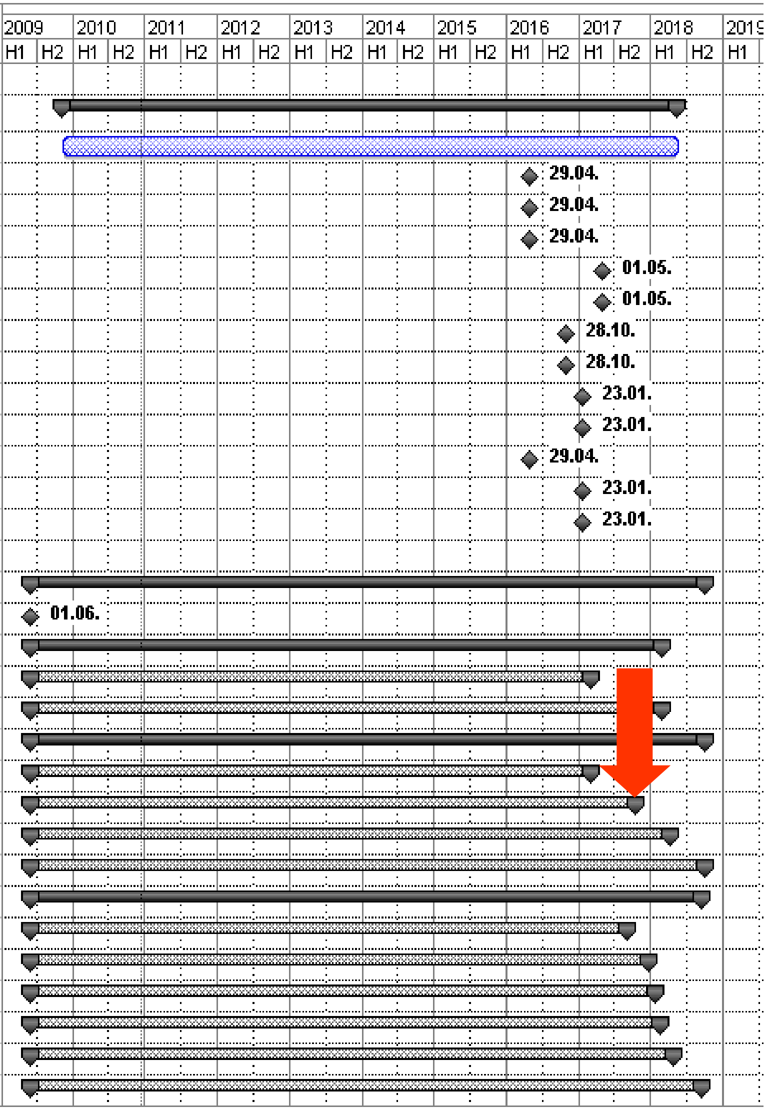
- Rapidly cycling superconducting magnets
- high energy electron cooling
- dynamical vacuum, beam losses

The FAIR start version (modules 0 – 3)



Schedule FAIR Accelerators

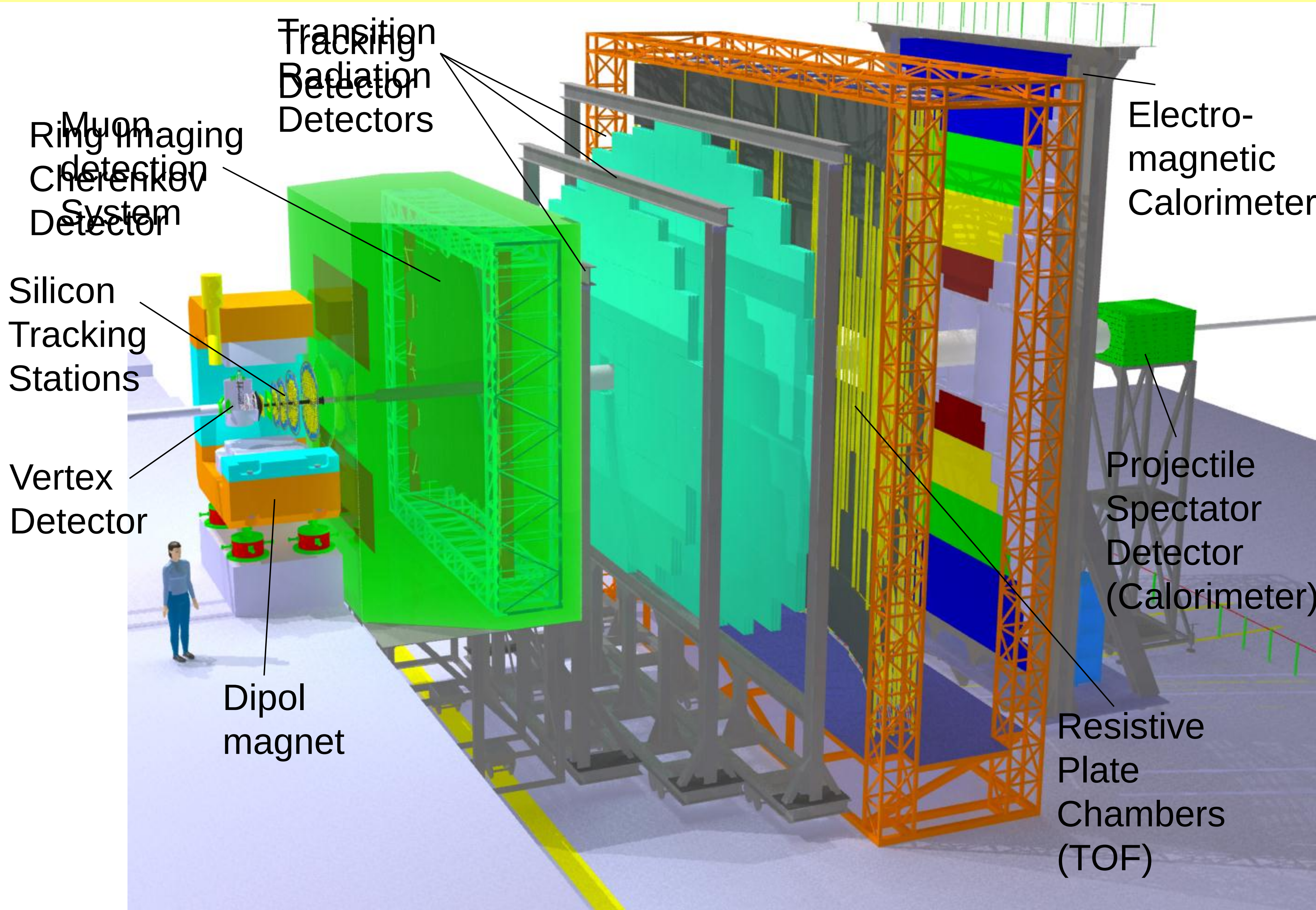
Nr.	Vorgangsname	Anfang	Ende
1			
2	**FAIR Civil Construction**	**Fr 06.11.09**	**Mi 09.05.18**
3	Planning, Tendering, Construction of Site and Buildings	Fr 06.11.09	Mi 09.05.18
4	Ready to move in HEBT Connection SIS18- SIS100	Fr 29.04.16	Fr 29.04.16
5	Ready to move in HEBT SIS100	Fr 29.04.16	Fr 29.04.16
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**	**Mo 01.06.09**	**Do 22.02.18**
20	**HEBT Connection SIS18 - SIS100 (T1S1, T1S2, T1S3, T1S4)**	**Mo 01.06.09**	**Mi 01.03.17**
103	**Super FRS**	**Mo 01.06.09**	**Do 22.02.18**
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**
935	**HESR**	**Mo 01.06.09**	**Fr 14.09.18**



FAIR start version cost coverage
(status April 2011)

Country	Contribution in Mio Euro 2005	Relative Contr. in percent
China*	1,60	0,2%
Finnland	5,00	0,5%
Frankreich	27,00	2,6%
Deutschland	705,00	68,6%
Großbritannien*	5,00	0,5%
Indien	36,00	3,5%
Polen	23,74	2,3%
Rumänien	11,87	1,2%
Rußland	178,05	17,3%
Slowenien	12,00	1,2%
Spanien**	11,87	1,2%
Schweden	10,00	1,0%
Total	**1027,13**	**100,0%**

The Compressed Baryonic Matter Experiment



CBM physics topics and observables

The equation-of-state at high ρ_B

- collective flow of hadrons
- particle production at threshold energies (multistrange hyperons, open charm?)

Deconfinement phase transition at high ρ_B

- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^{\pm}$, Λ_c) (e.g. melting of J/ψ and ψ')
- excitation function of low-mass lepton pairs

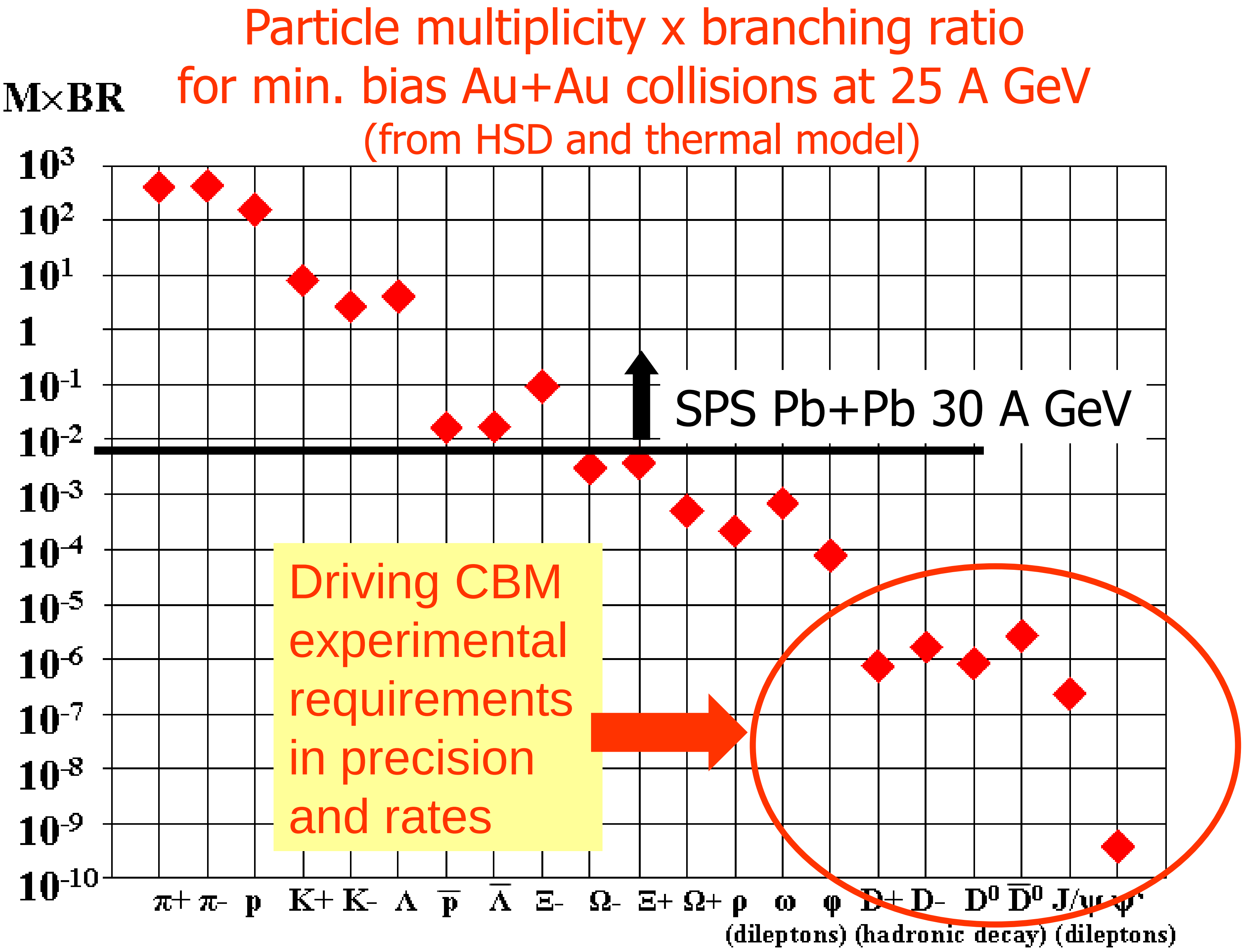
QCD critical endpoint

- excitation function of dynamical event-by-event fluctuations

Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons ($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$, D)

Experimental challenges

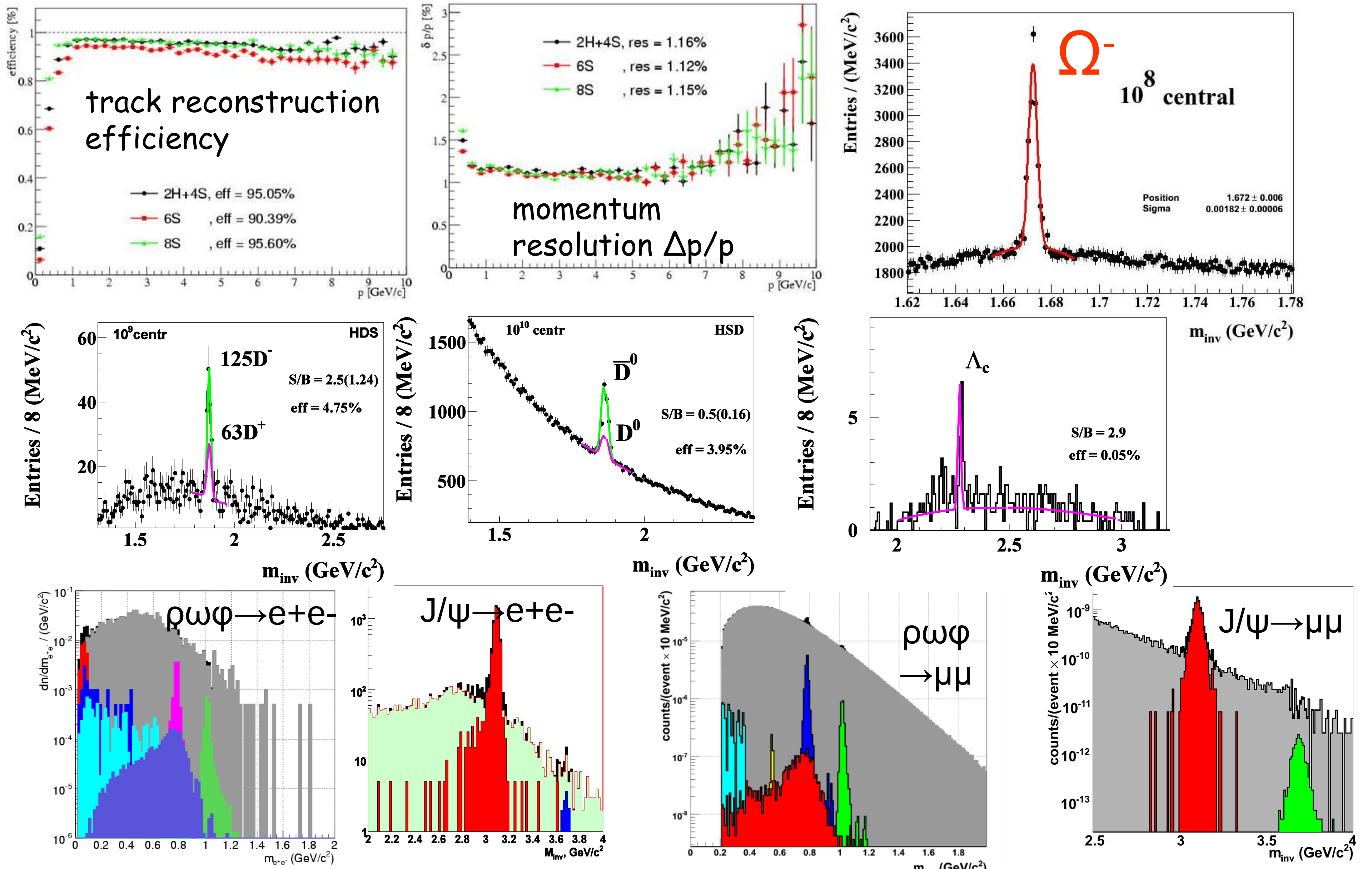


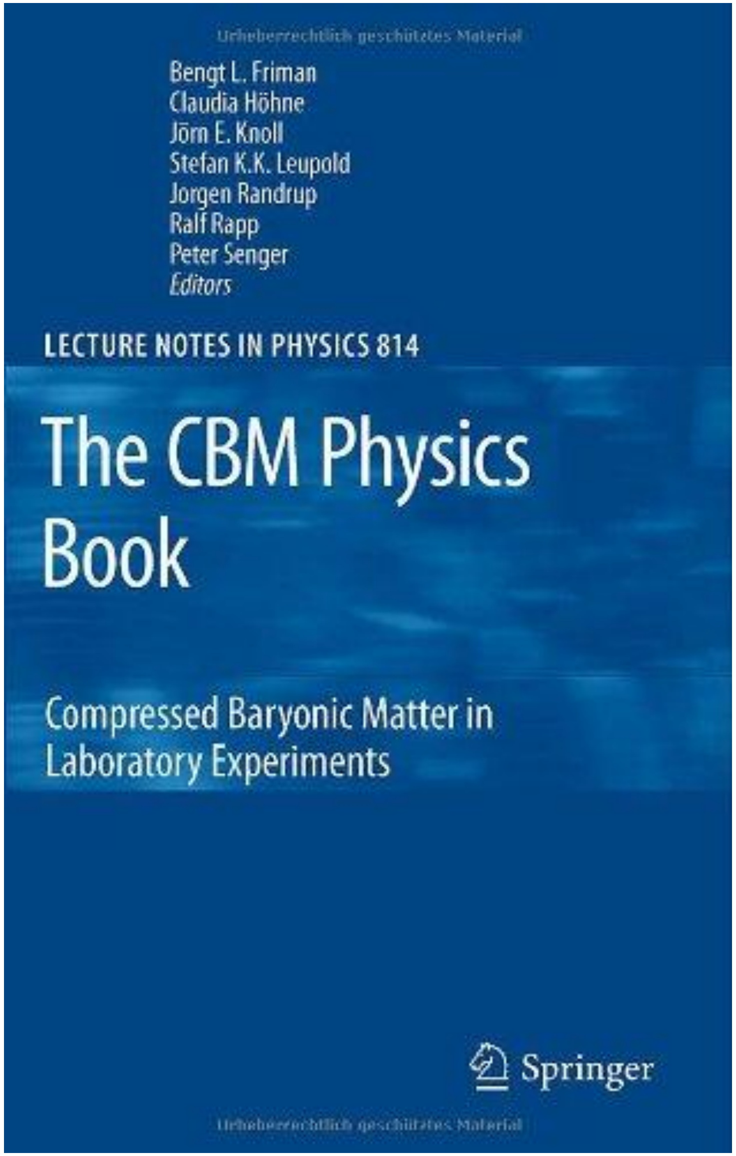
Experimental challenges

Central Au+Au collision at 25 AGeV (UrQMD + GEANT4):
160 p 400 π^- 400 π^+ 44 K^+ 13 K^-

- 10^5 - 10^7 Au+Au reactions/sec
- determination of (displaced) vertices ($\sigma \approx 50$ μm)
- identification of leptons and hadrons
- fast and radiation hard detectors
- self-triggered readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

Conceptual design and feasibility studies: Au+Au central collisions at 25 A GeV



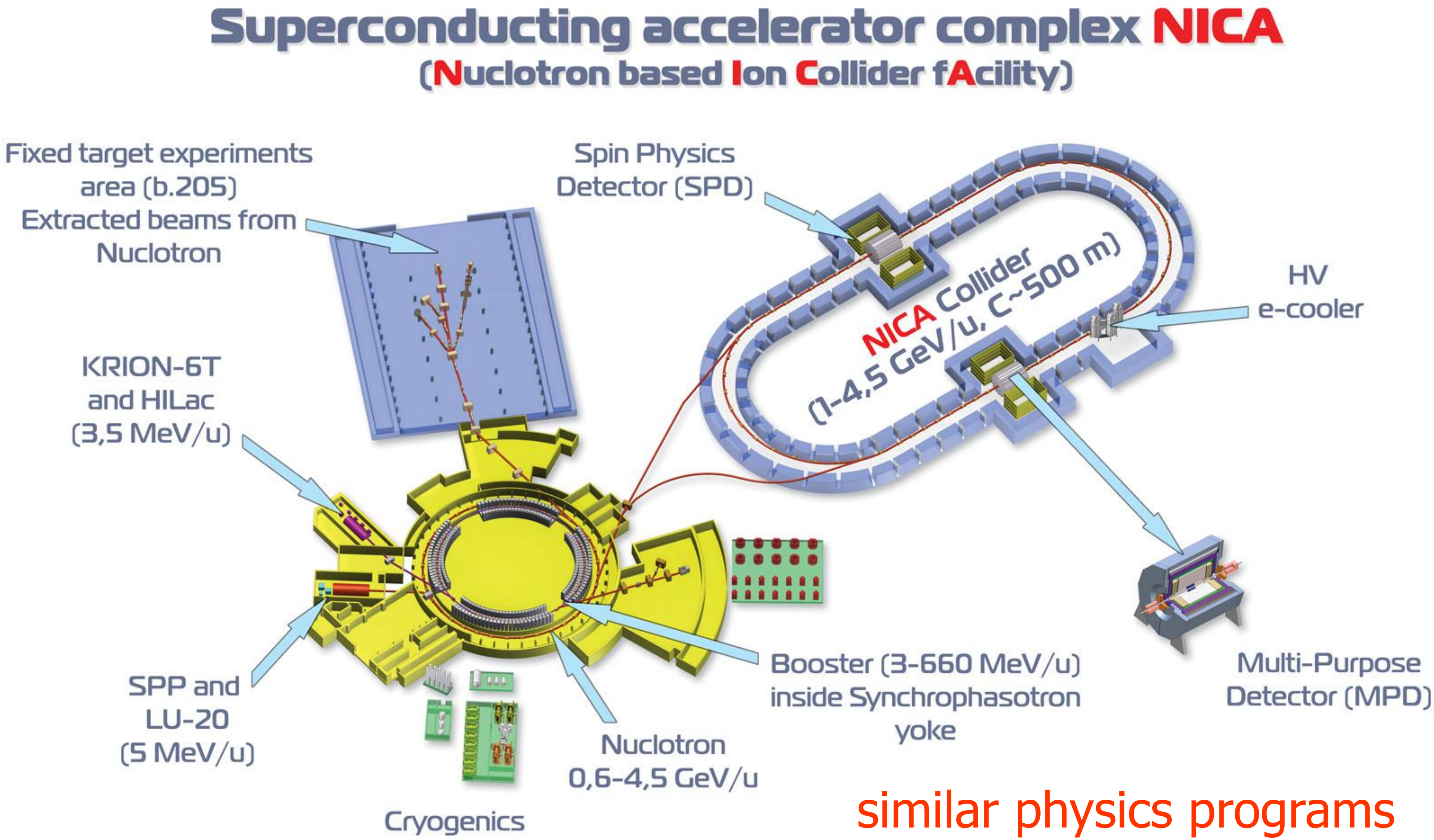


The CBM Physics Book

Foreword by Frank Wilczek

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

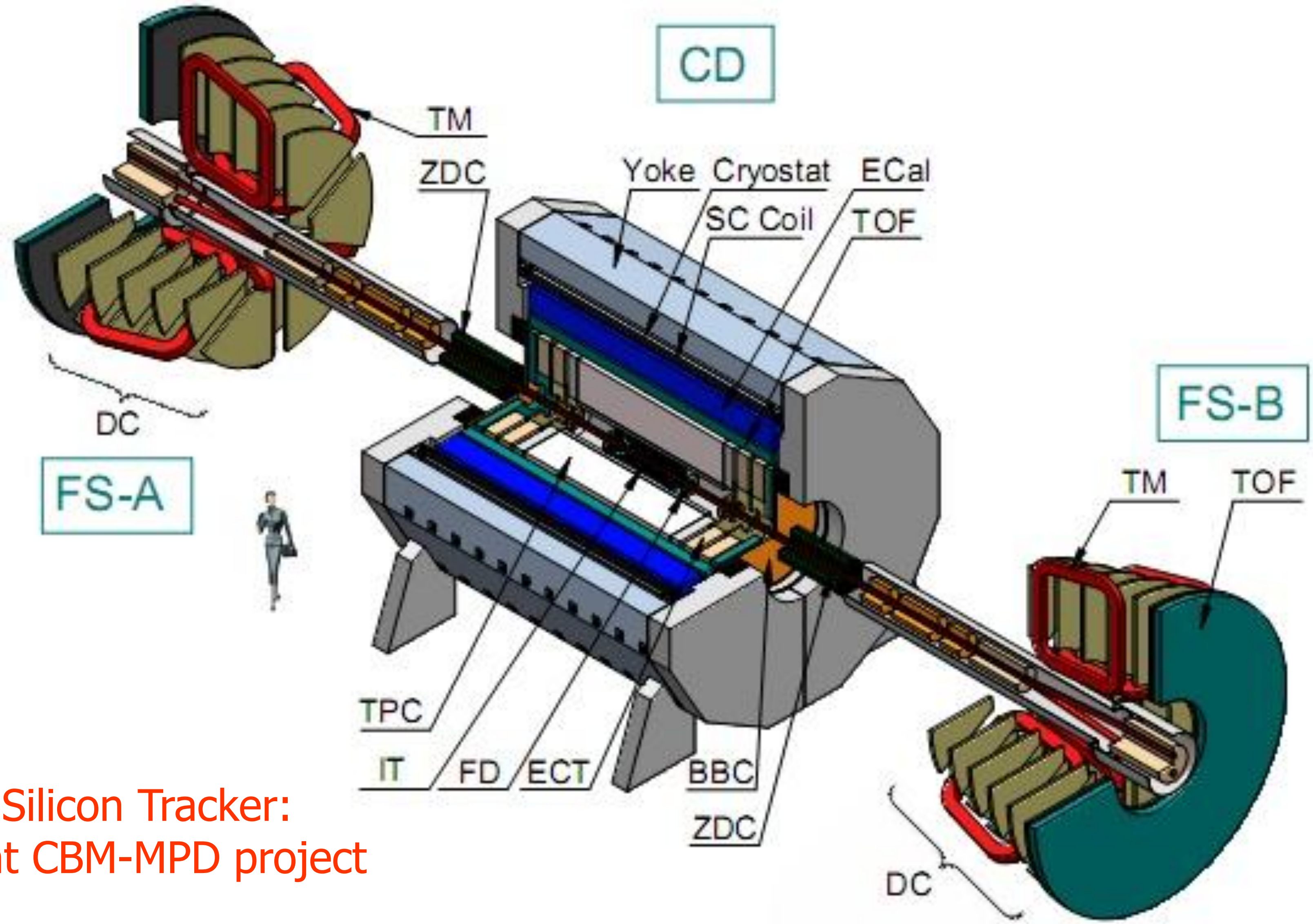
Electronic Authors version:
http://www.gsi.de/documents/DOC-2009-Sep-120-1.pdf



similar physics programs of MPD and CBM

NICA homepage: http://nica.jinr.ru

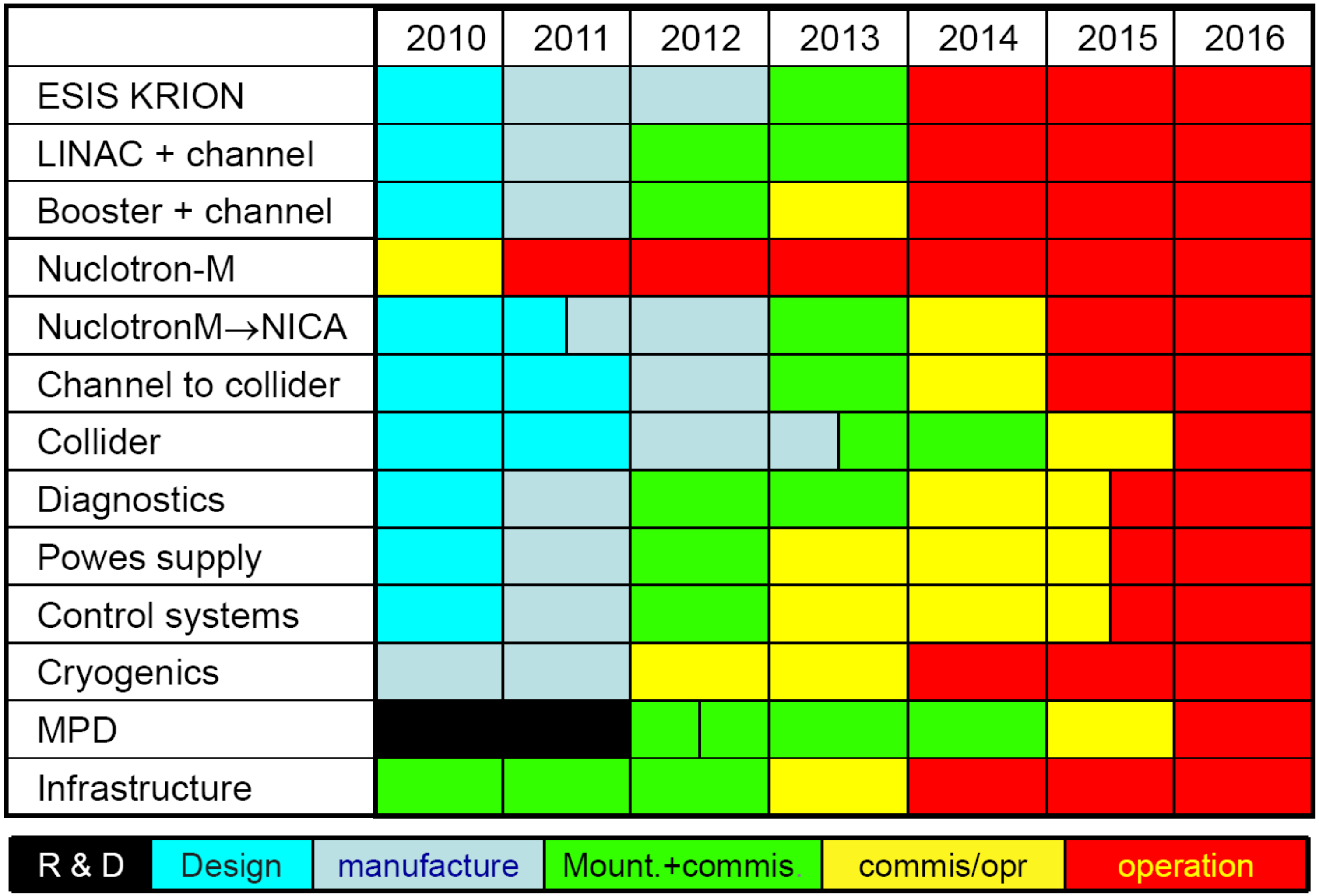
The Multi-Purpose Detector (MPD) at NICA



Silicon Tracker:
Joint CBM-MPD project

NICA White Paper: http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

NICA time-line



Experiments on superdense nuclear matter

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

Experiments on superdense nuclear matter

Experiment	Observables for beam energies at about $\sqrt{s_{NN}}$ = 8 GeV (high baryon density region)			
	hadrons	correlations, fluctuations	dileptons	charm
STAR@RHIC BNL	yes	yes	no	no
NA61@SPS CERN	yes	yes	no	no
MPD@NICA Dubna	yes	yes	no	no
CBM@FAIR Darmstadt	yes	yes	yes	yes

Advantage of collider experiments:
Uniform phase-space coverage when measuring excitation functions.
➔ complementary measurements with CBM@FAIR and MPD@NICA

Summary

Physics case:

- Scanning the QCD phase diagram in the region of neutron star core densities
- Exploring the properties of dense hadronic/partonic matter
- Searching for structures in the QCD phase diagrams and for new forms of QCD matter

Observables:

- Hadrons incl. multi-strange (anti-) hyperons
- Dileptons
- Open and hidden charm
- Collective flow, correlations, fluctuations

Facilities

- RHIC low energy scan (STAR)
- NA61 at SPS
- MPD at NICA
- CBM at FAIR ➔ full set of observables

Backup

CBM: Estimated particle yields for minimum bias Au+Au collisions at 25 AGeV

particle, mass (MeV)	N	decay mode	BR	R/s (MHz)	T	ε (%)	Y/s	Y/10 w
η (547)	6.6	$\mu^+\mu^-$	$5.8\cdot10^{-6}$	0.25	y	3	0.28	$1.7\cdot10^{6}$
K^+ (494)	8	-	-	0.025	n	20	$4\cdot10^{4}$	$2.4\cdot10^{11}$
K^- (494)	2.6	-	-	0.025	n	20	$1.3\cdot10^{4}$	$7.8\cdot10^{10}$
K_s^0 (497)	5.4	$\pi^+\pi^-$	0.69	0.025	n	10	$9.3\cdot10^{3}$	$5.6\cdot10^{10}$
ρ (770)	4.6	e^+e^-	$4.7\cdot10^{-5}$	0.025	n	5.4	0.29	$1.8\cdot10^{6}$
ρ (770)	4.6	$\mu^+\mu^-$	$4.6\cdot10^{-5}$	0.25	y	2.7	1.4	$8.6\cdot10^{6}$
ω (782)	7.6	e^+e^-	$7.1\cdot10^{-5}$	0.025	n	7.2	1	$6\cdot10^{6}$
ω (782)	7.6	$\mu^+\mu^-$	$9\cdot10^{-5}$	0.25	y	3.7	6.3	$38\cdot10^{6}$
φ (1020)	0.256	e^+e^-	$3\cdot10^{-4}$	0.025	n	9.6	0.18	$1\cdot10^{6}$
φ (1020)	0.256	$\mu^+\mu^-$	$2.9\cdot10^{-4}$	0.25	y	6	1.	$6.7\cdot10^{6}$
Λ (1115)	6.4	$p\,\pi^-$	0.64	0.025	n	10.6	$1.1\cdot10^{4}$	$6.5\cdot10^{10}$
Ξ^- (1321)	0.096	$\Lambda\,\pi^-$	0.999	0.025	n	2.1	50.4	$3\cdot10^{8}$
Ω^- (1672)	0.0044	$\Lambda\,K^-$	0.68	0.025	n	1	0.75	$4.5\cdot10^{6}$
D^0 (1864)	$7.5\cdot10^{-6}$	$K^-\pi^+$	0.038	0.1	y	3.25	$8.5\cdot10^{-4}$	$5.1\cdot10^{3}$
D^0 (1864)	$7.5\cdot10^{-6}$	$K^-\pi^+\pi^+\pi^-$	0.075	0.1	y	0.37	$2.1\cdot10^{-4}$	$1.3\cdot10^{3}$
$\bar{D}^0$ (1864)	$2.3\cdot10^{-5}$	$K^+\pi^-$	0.038	0.1	y	3.25	$2.6\cdot10^{-3}$	$1.6\cdot10^{4}$
D^+ (1869)	$8\cdot10^{-6}$	$K^-\pi^+\pi^+$	0.092	0.1	y	4.2	$3.1\cdot10^{-3}$	$1.9\cdot10^{4}$
D^- (1869)	$1.8\cdot10^{-5}$	$K^+\pi^-\pi^-$	0.092	0.1	y	4.2	$7\cdot10^{-3}$	$4.2\cdot10^{4}$
Λ_c(2285)	$4.9\cdot10^{-4}$	$pK^-\pi^+$	0.05	0.1	y	0.5	$1.2\cdot10^{-2}$	$7.4\cdot10^{4}$
J/ψ (3097)	$3.8\cdot10^{-6}$	e^+e^-	0.06	1-10	y	14	0.032 - 0.32	$1.9\cdot10^{5-6}$
ψ′ (3686)	$5.1\cdot10^{-8}$	e^+e^-	$7.3\cdot10^{-3}$	1-10	y	15	$5.6\cdot10^{-(5-4)}$	$3.4\cdot10^{2-3}$
J/ψ (3097)	$3.8\cdot10^{-6}$	$\mu^+\mu^-$	0.06	10	y	16	0.36	$2.2\cdot10^{6}$
ψ′ (3686)	$5.1\cdot10^{-8}$	$\mu^+\mu^-$	$7.3\cdot10^{-3}$	10	y	19	$7.1\cdot10^{-4}$	$4.3\cdot10^{3}$

MPD@NICA: Estimated particle yields

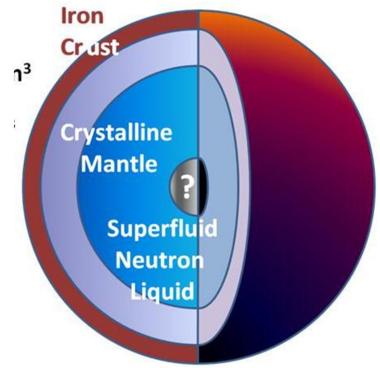
Example: min. bias Au+Au collisions at $\sqrt{s_{NN}}$ = 7.1 GeV

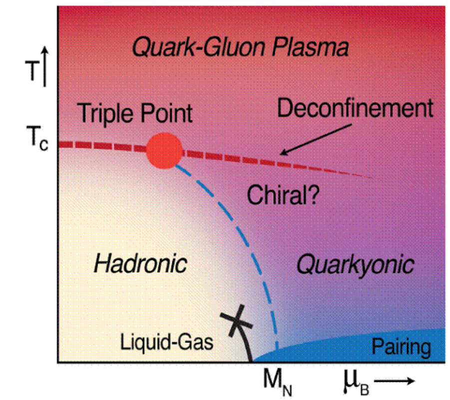
Assumption: max. NICA luminosity L = 10^{27}cm^{-2}s^{-1}

Particle (mass)	Multi-plicity	decay mode	BR	Rate kHz	ε (%)	yield (s^{-1})	yield 10 w
K^+ (494)	8	--	--	6	20	$9.6\cdot10^{3}$	$5.8\cdot10^{10}$
K^- (494)	2.6	--	--	6	20	$3.1\cdot10^{3}$	$1.9\cdot10^{10}$
ρ (770)	4.6	e^+e^-	$4.7\cdot10^{-5}$	6	2	$2.6\cdot10^{-2}$	$1.5\cdot10^{5}$
ω (782)	7.6	e^+e^-	$7.1\cdot10^{-5}$	6	2	$6.5\cdot10^{-2}$	$3.9\cdot10^{5}$
φ (1020)	0.26	e^+e^-	$3\cdot10^{-4}$	6	2	$9.4\cdot10^{-3}$	$5.7\cdot10^{4}$
Ξ^- (1321)	0.1	$\Lambda\pi^-$	1	6	1	6	$3.6\cdot10^{7}$
Ω^- (1672)	$4.4\cdot10^{-3}$	ΛK^-	0.68	6	1	0.18	$1.0\cdot10^{6}$
D^0 (1864)	$7.5\cdot10^{-6}$	$K^+\pi^-$	0.038	6	1	$1.7\cdot10^{-5}$	100
J/ψ (3097)	$3.8\cdot10^{-6}$	e^+e^-	0.06	6	5	$6.8\cdot10^{-5}$	410

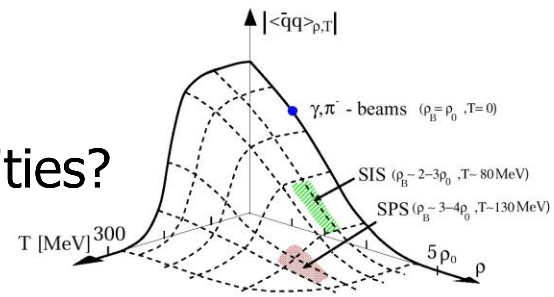
Nuclear matter physics at SIS100

- Nuclear equation-of-state, quarkyonic matter at high densities?
  What are the properties and the degrees-of-freedom of nuclear matter at neutron star core densities?



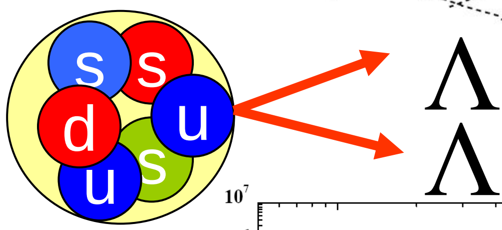


- Hadrons in dense matter:
  What are the in-medium properties of hadrons?
  Is chiral symmetry restored at very high baryon densities?

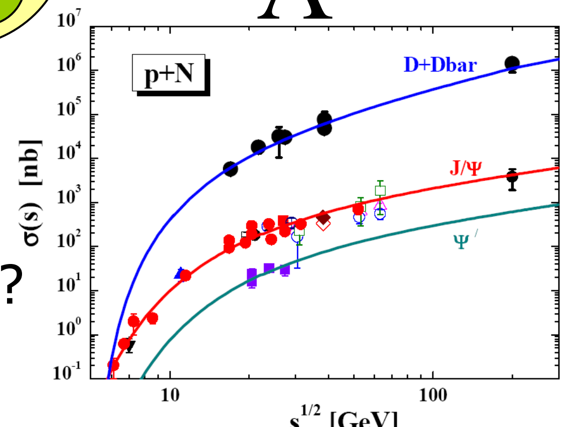


- Strange matter:
  Does strange matter exist in the form of heavy multi-strange objects?

?

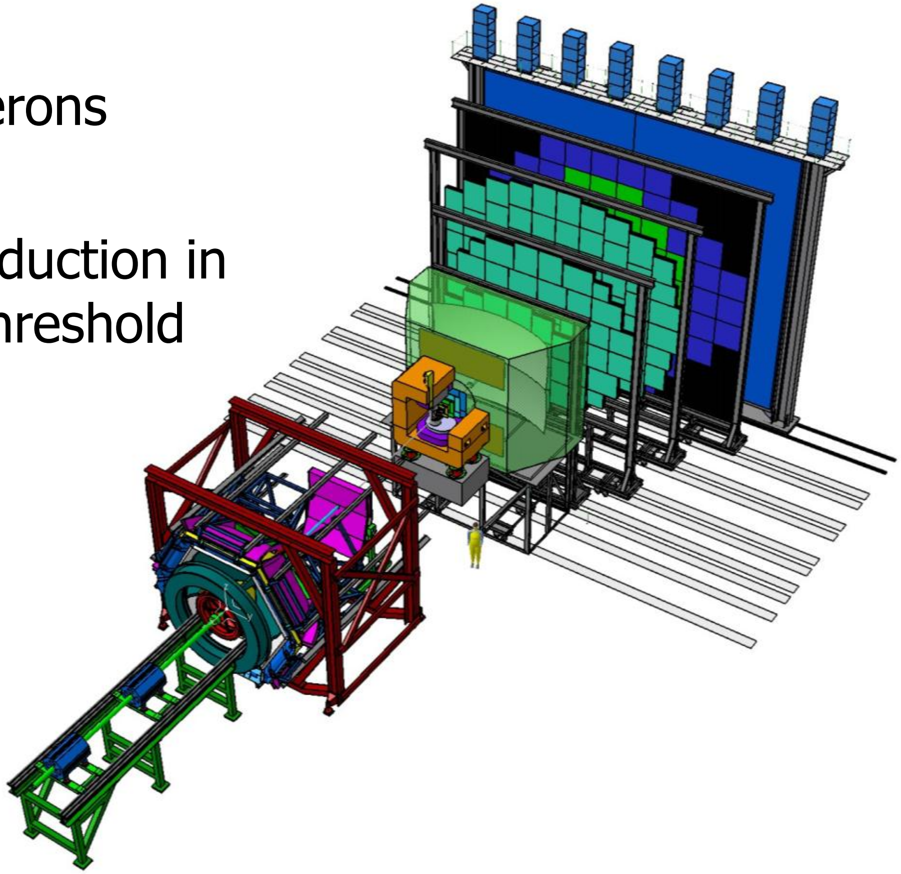


- Heavy flavor physics:
  How ist charm produced at low beam energies, and how does it propagate in cold nuclear matter?



Nuclear matter physics at SIS100

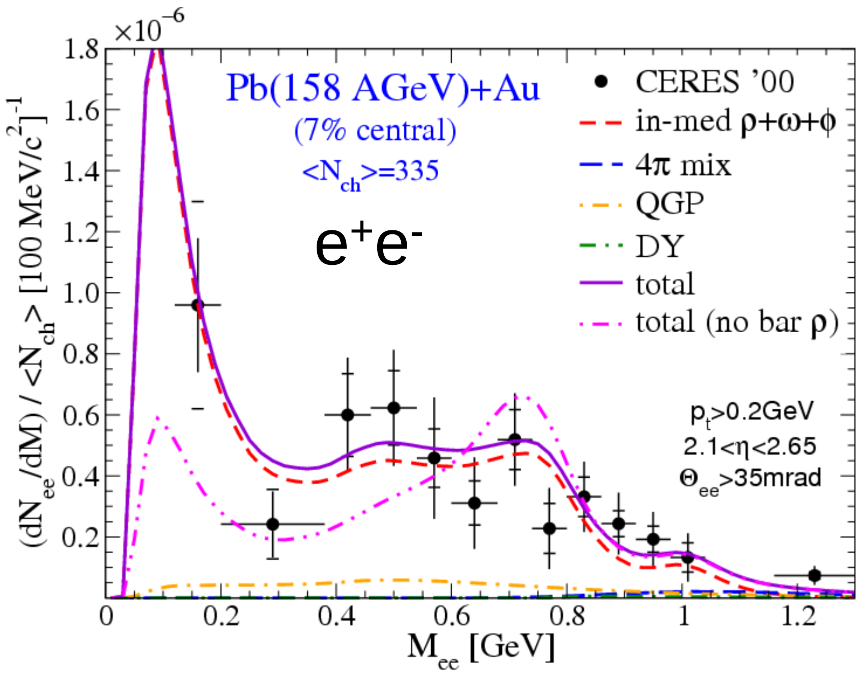
- Nuclear equation-of-state at high baryon densities:
  Observables: multi-strange hyperons, collective flow, stopping
- Hadrons in dense matter:
  Observables: low-mass vector mesons (up to Ni+Ni with HADES)
- Strange matter:
  Observables: (multi-) strange hyperons
- Heavy flavor physics:
  Open charm and charmonium production in p+A and A+A collisions around threshold beam energies

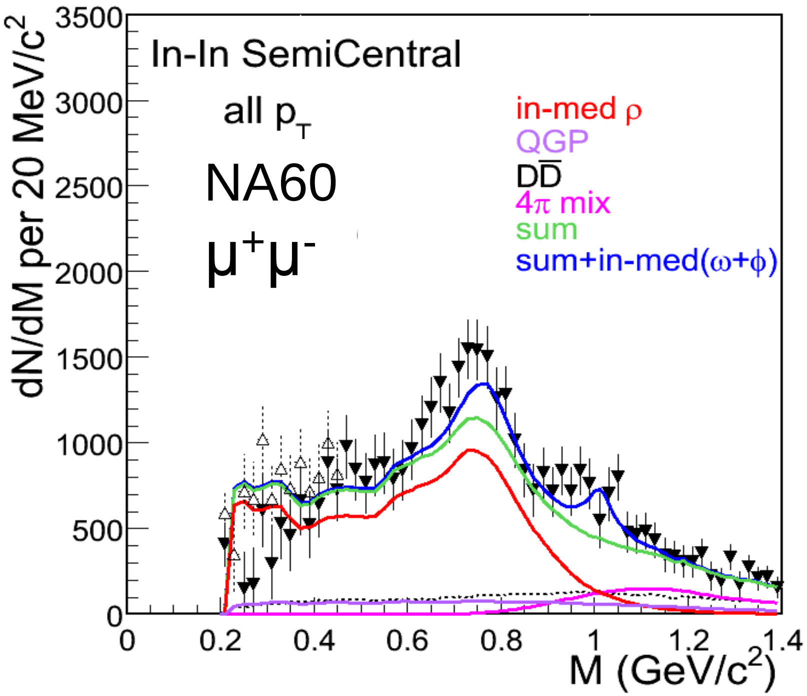


Beams at SIS100:
protons up to 30 GeV
Ca+Ca up to 14 AGeV
Au+Au up to 11 AGeV

Electromagnetic radiation from the fireball

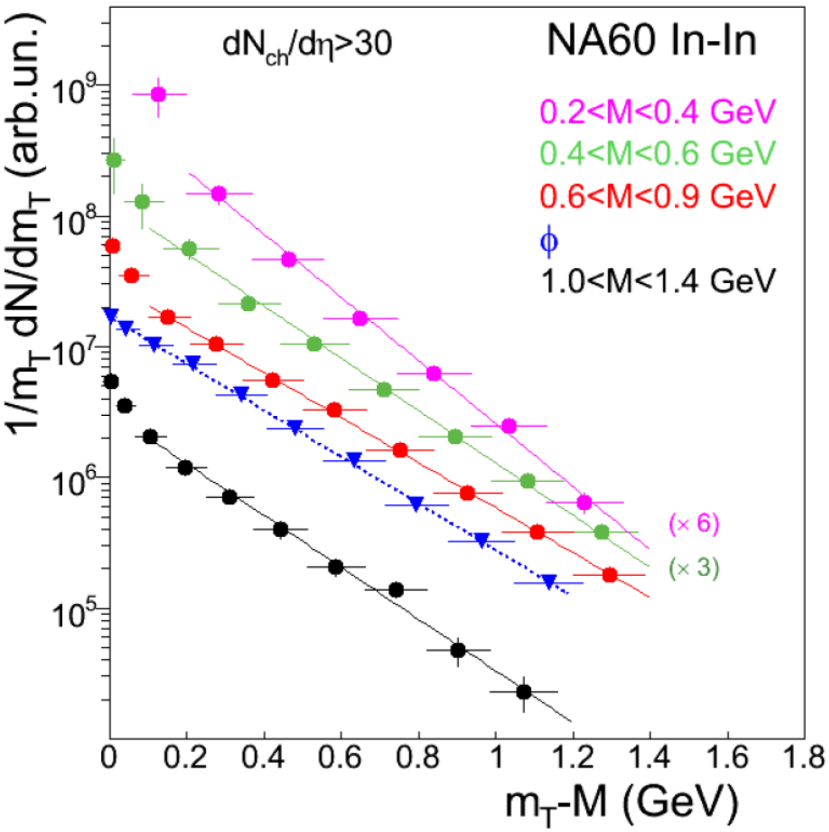
Calculations: H. van Hees, R. Rapp, arXiv:0711.3444v1 [hep-ph]



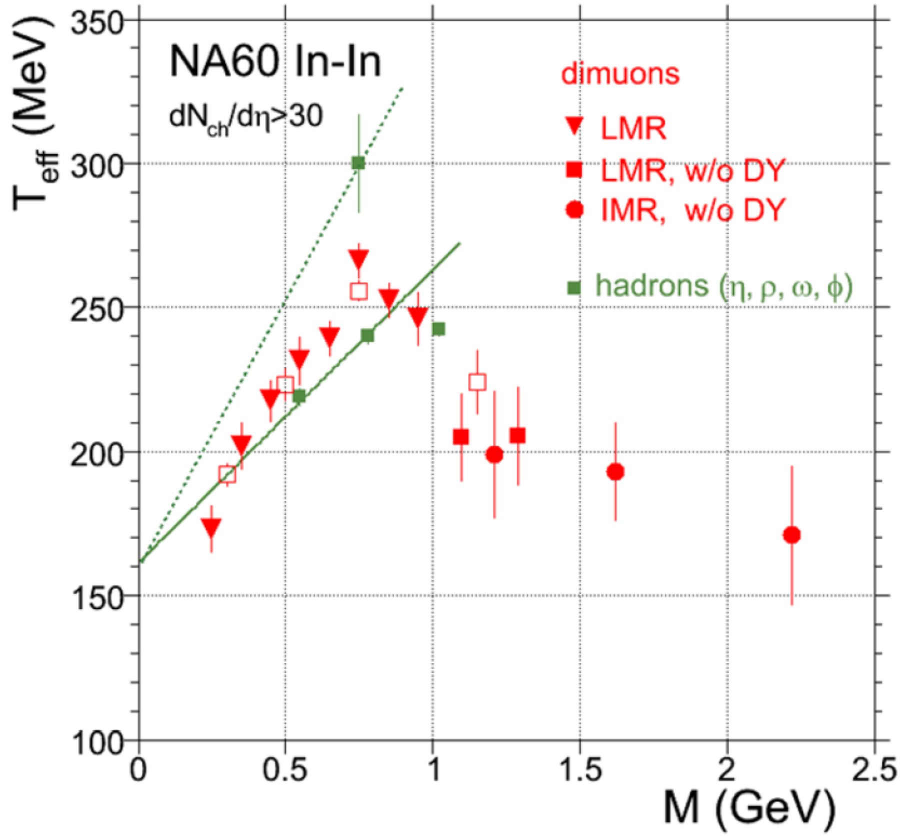


Transverse flow of dilepton pairs

parameterisation $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp(-m_T/T_{eff})$

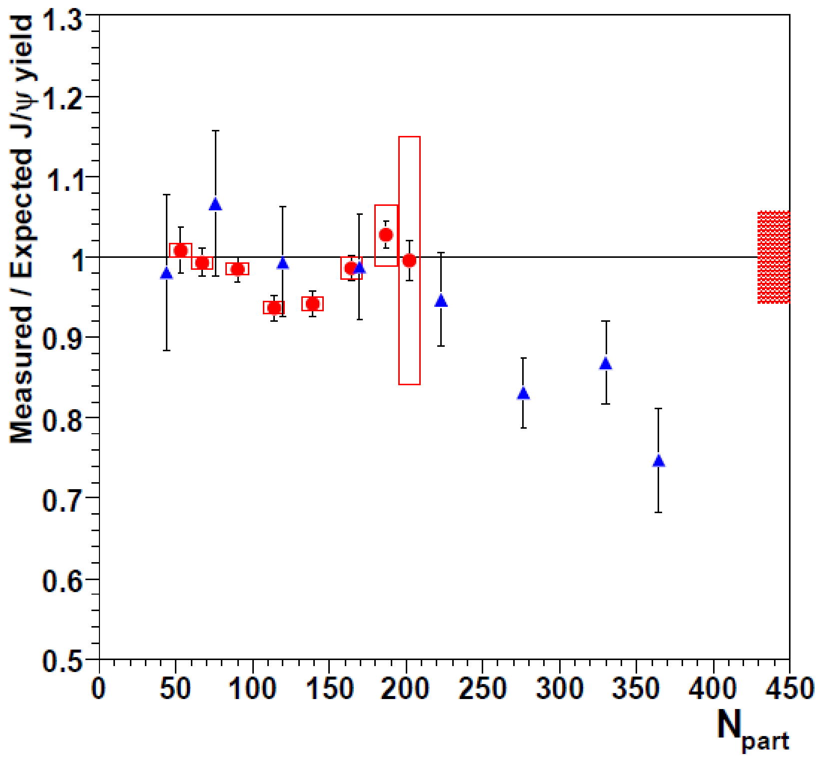


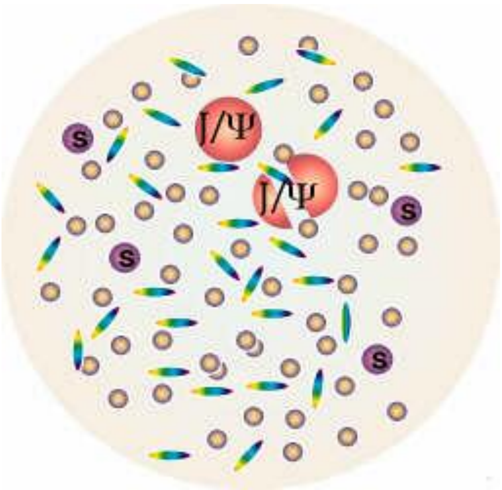
NA60: PRL 100,022302(2008)



Anomalous J/ψ suppression

Di-muon measurements at CERN-SPS





NA60: Nucl.Phys.A830:345c-352c,2009

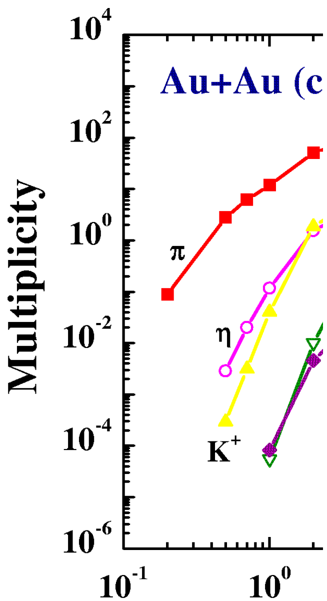
Searching for the deconfinement phase transition: Charm production in hadronic and partonic matter

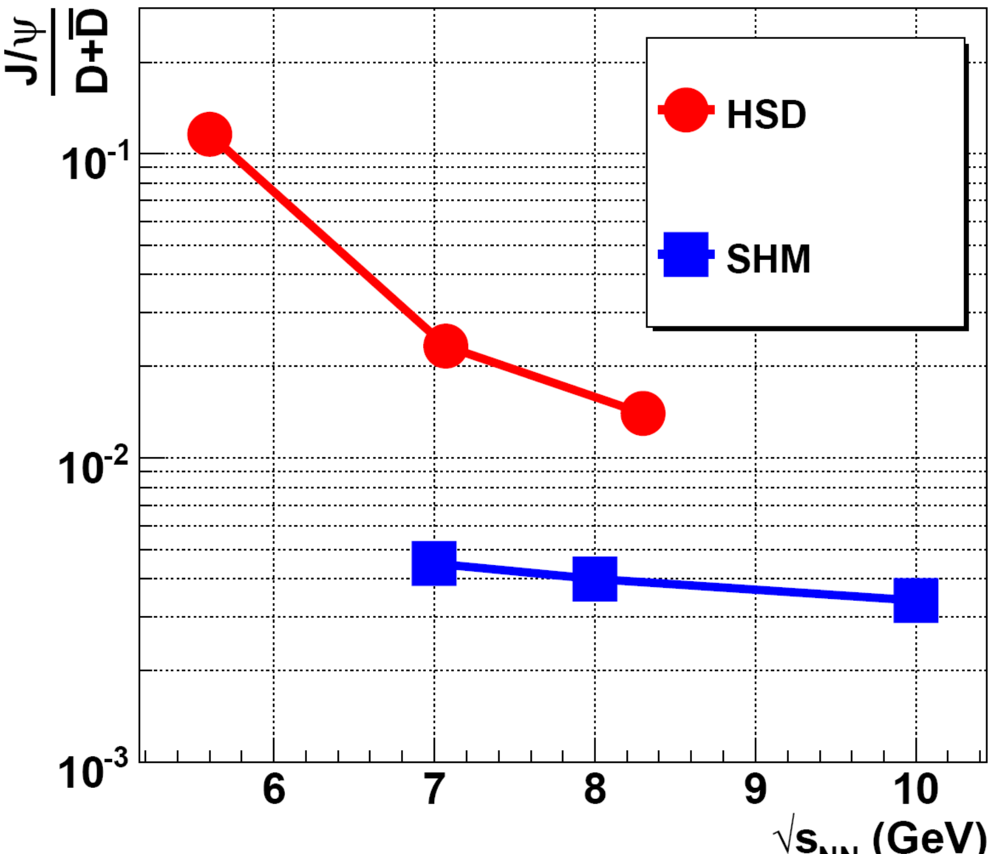
Hadronic model (HSD)

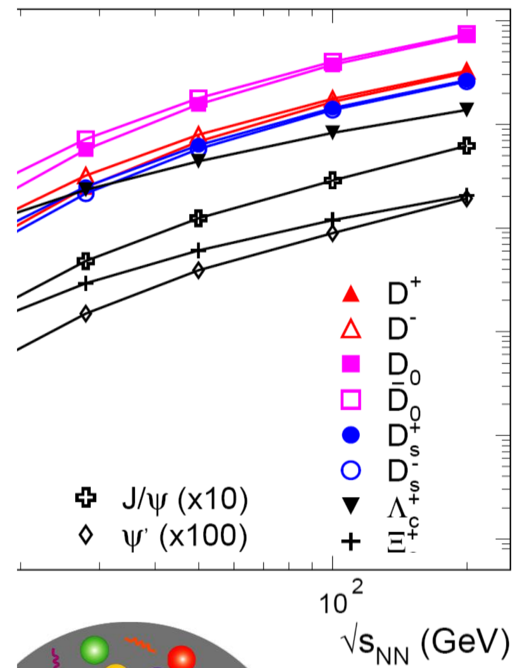
O. Linnyk, E.L. Bratkovskaya, W. Cassing, H. Stöcker, Nucl.Phys.A786:183-200,2007

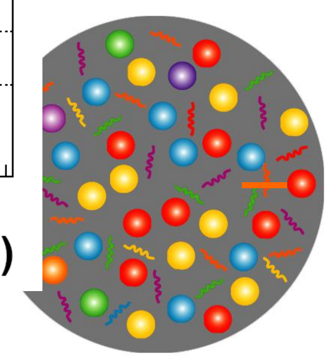
Statistical hadronization model (SHM) (c-cbar production in partonic phase)

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0708.1488









NN –

NN –

NN → J/ψ NN