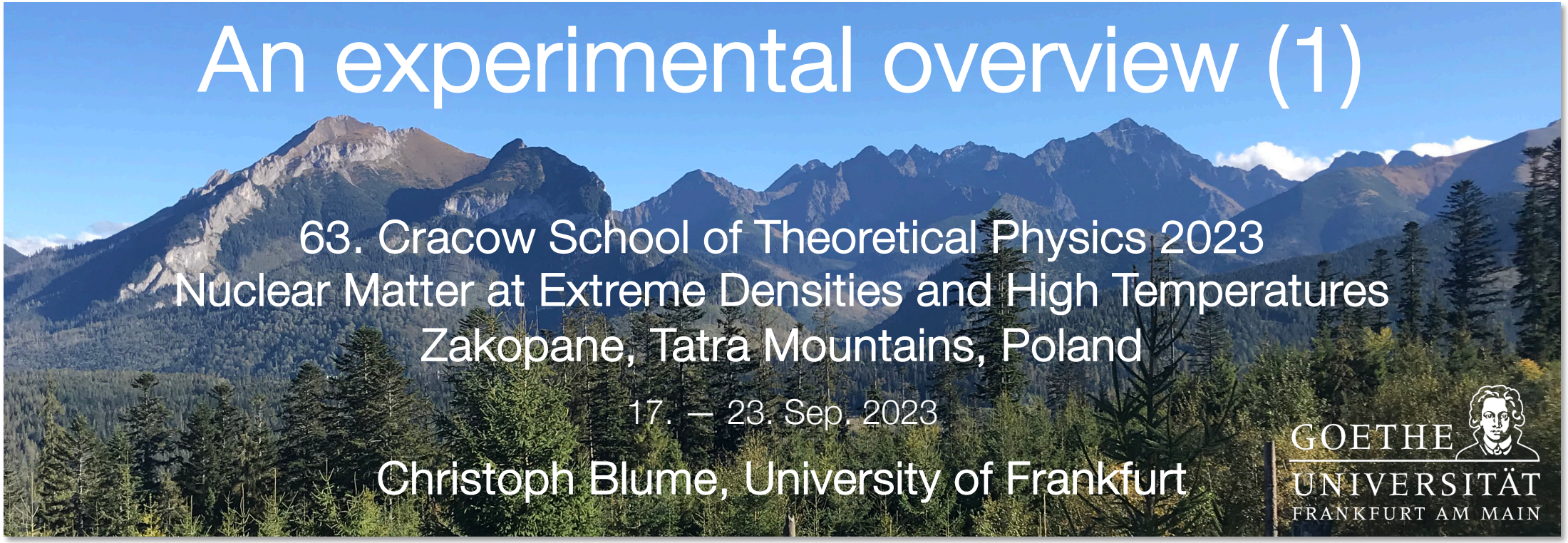
The QCD phase diagram at high densities



Overview

Introduction

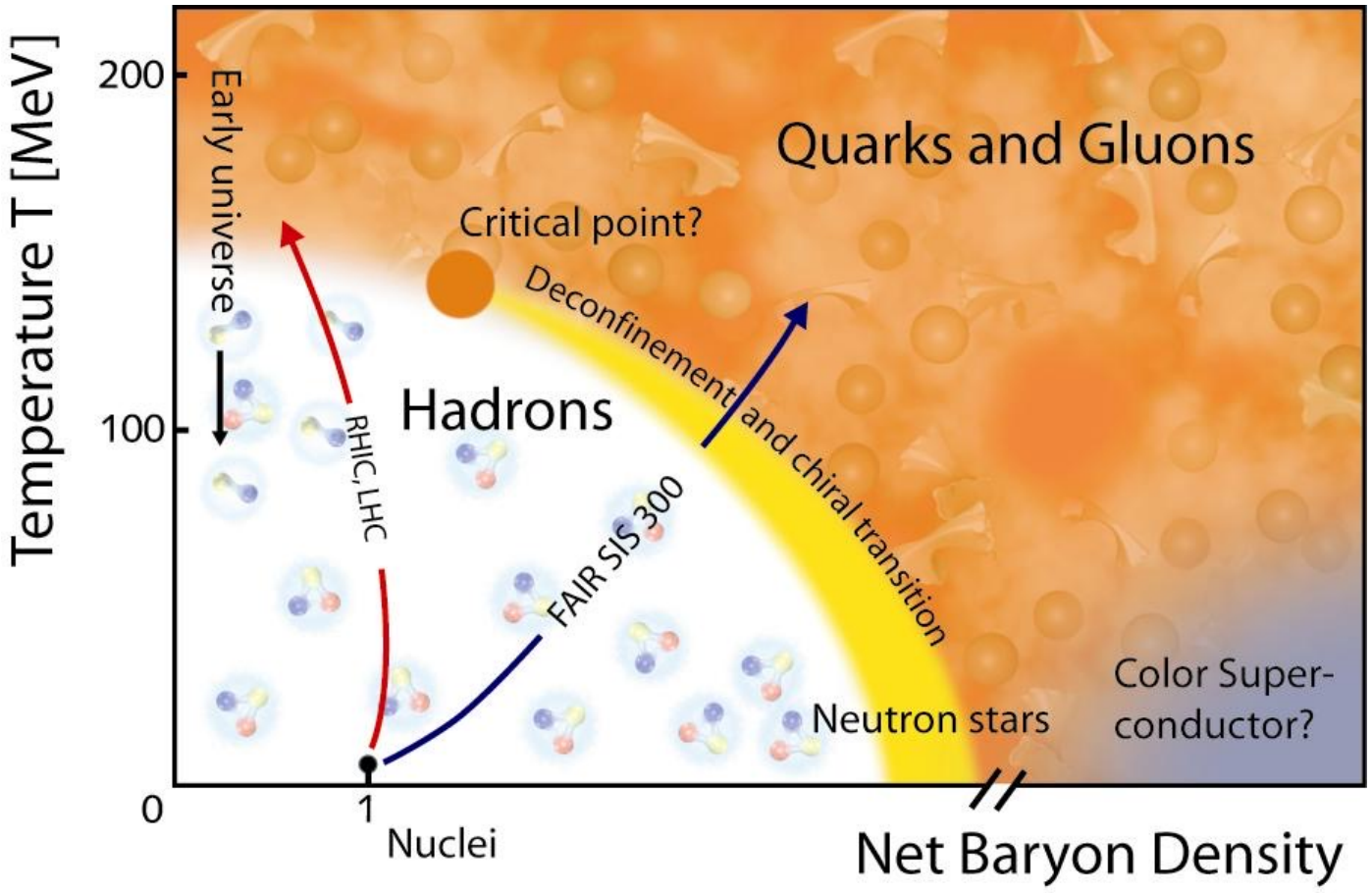
- QCD phase diagram
- Relation to neutron stars

Experiments at high μ_B

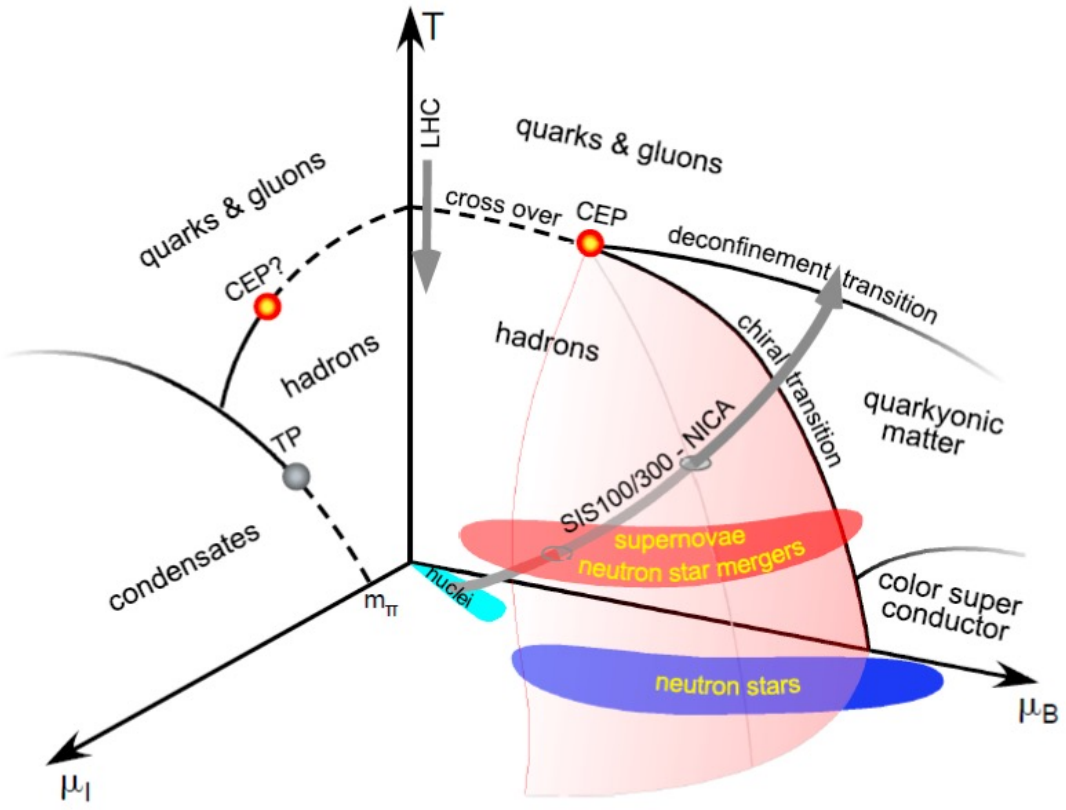
Observables

- Collectivity + Vorticity
- Criticality ($\Longrightarrow$ Anar's lecture)
- Strangeness in Matter
- Emissivity

QCD Phase Diagram

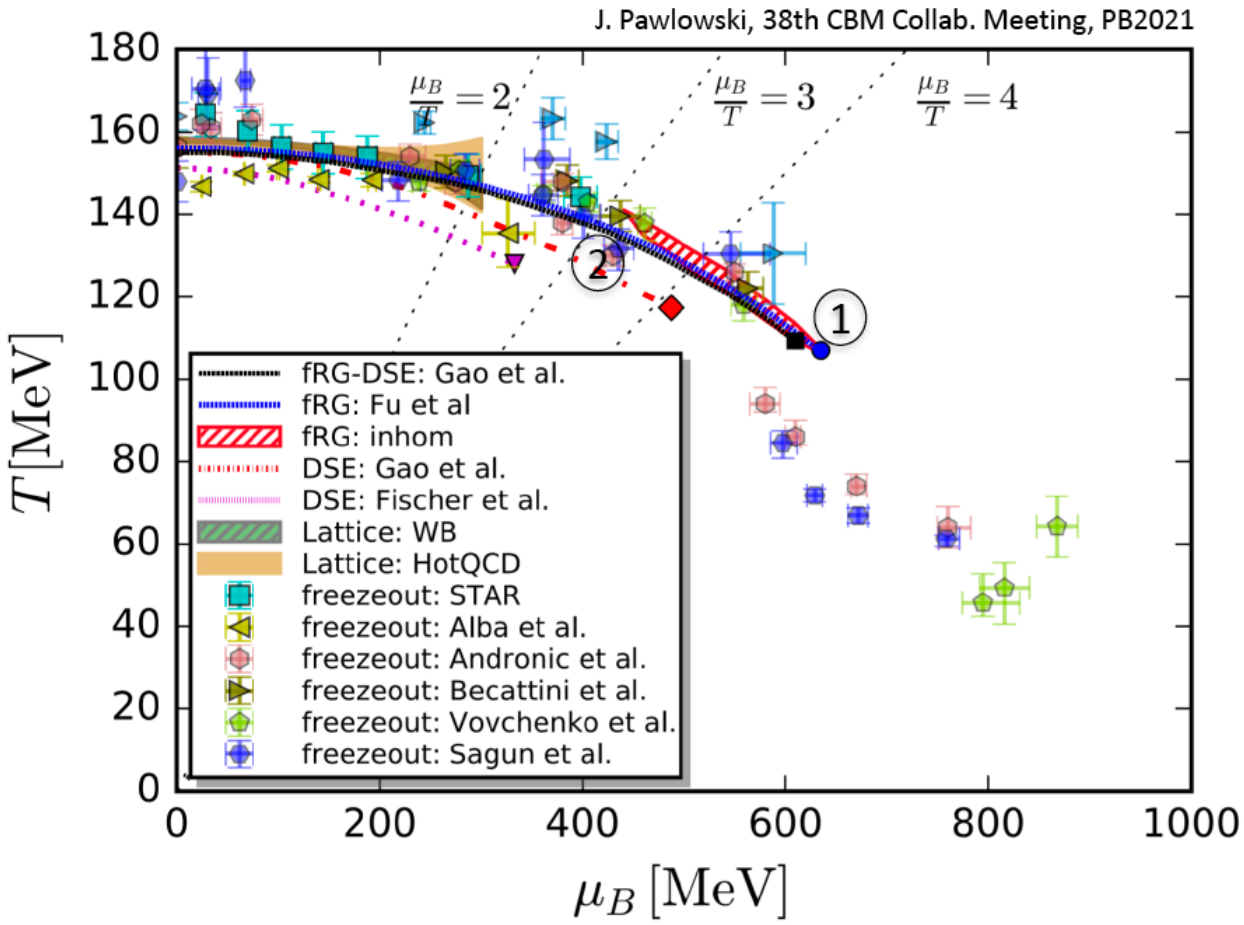


QCD Phase Diagram



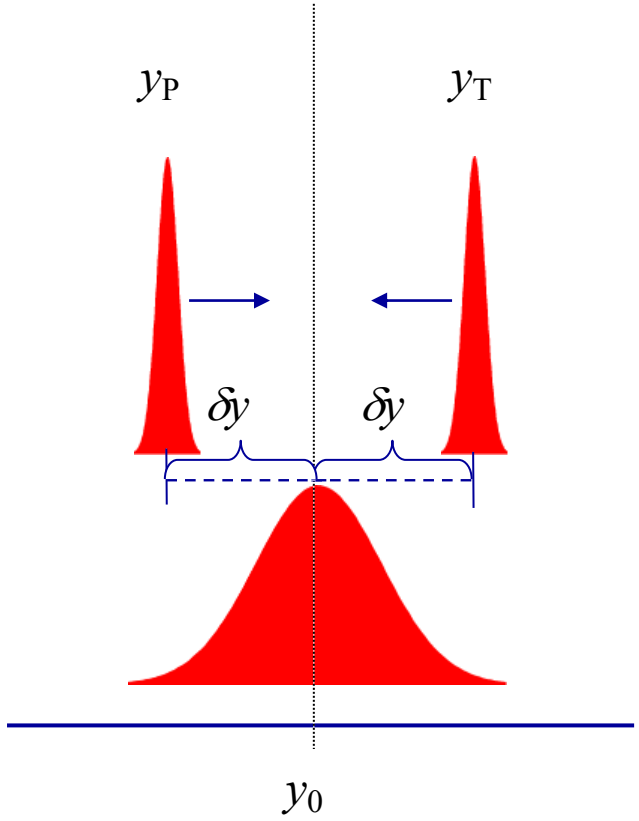
NUPECC Long Range Plan 2017

QCD Phase Diagram

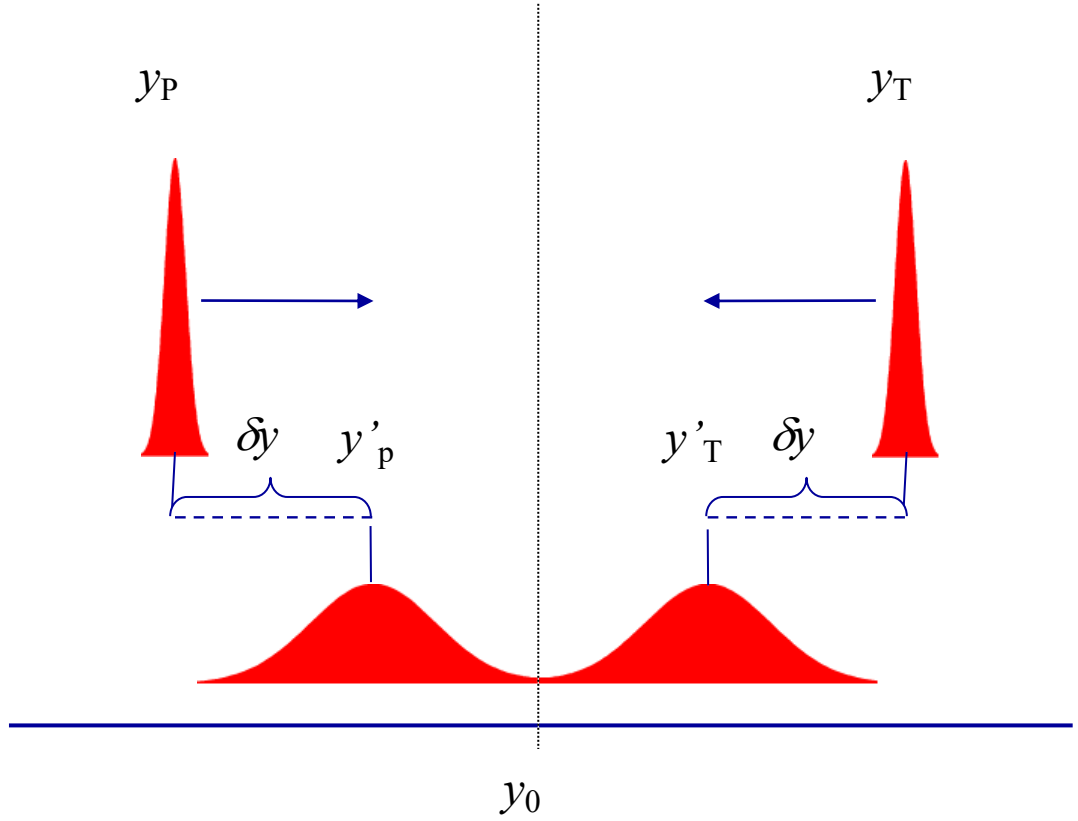


Baryon Number Distributions

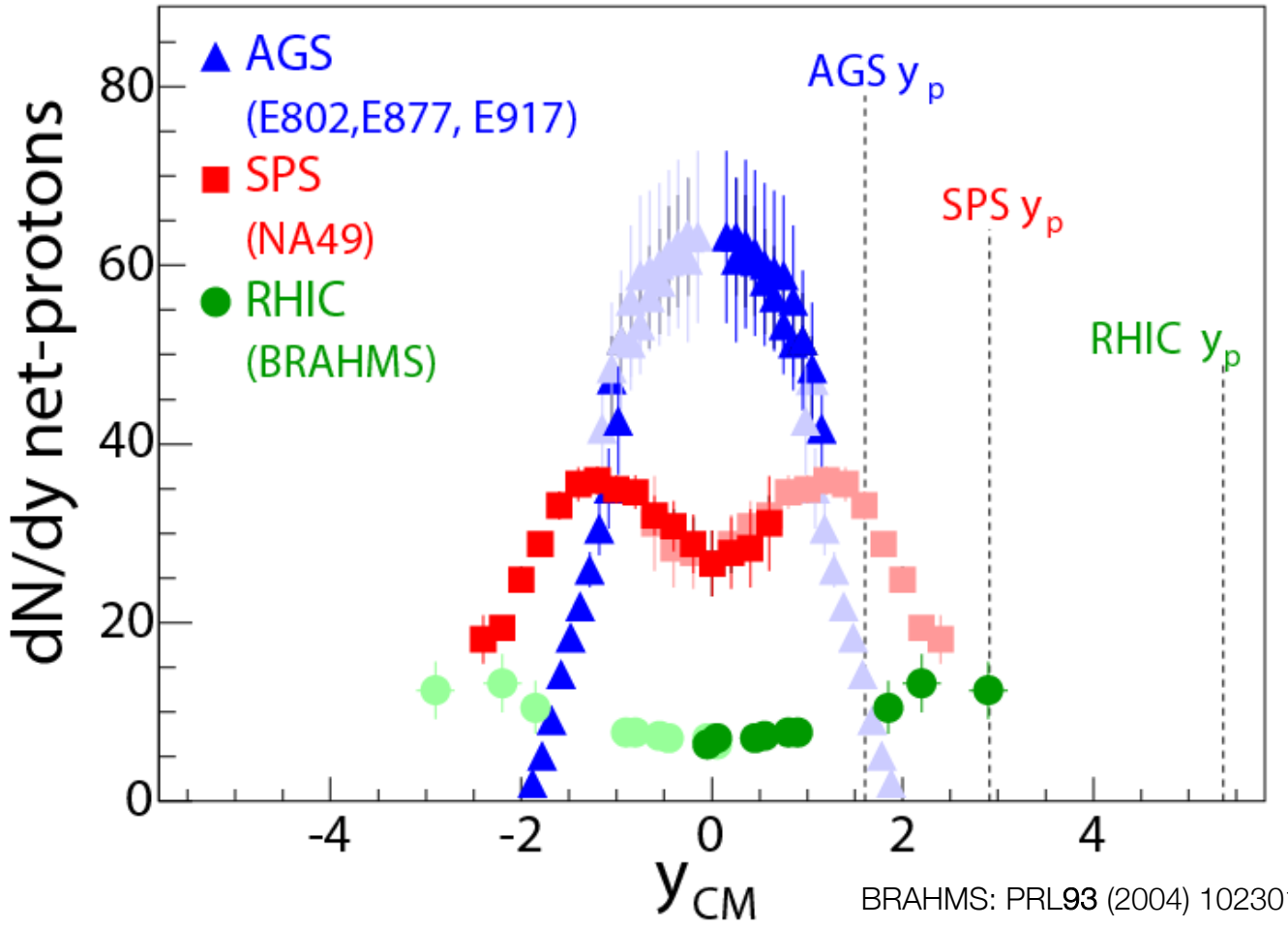
Lower energies:



Higher energies:

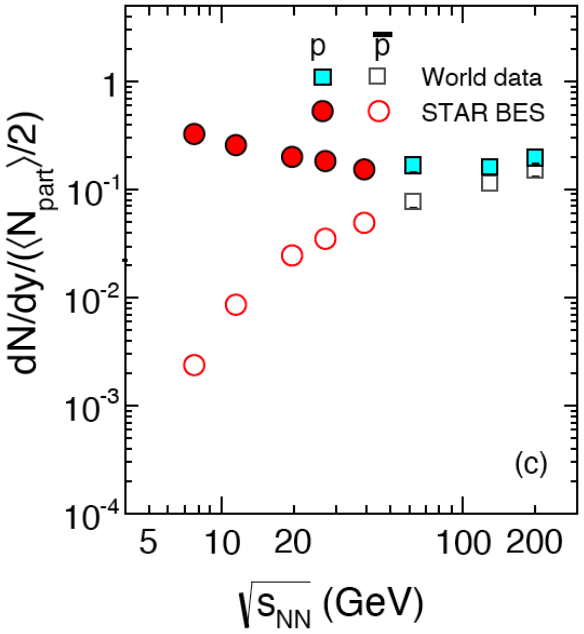


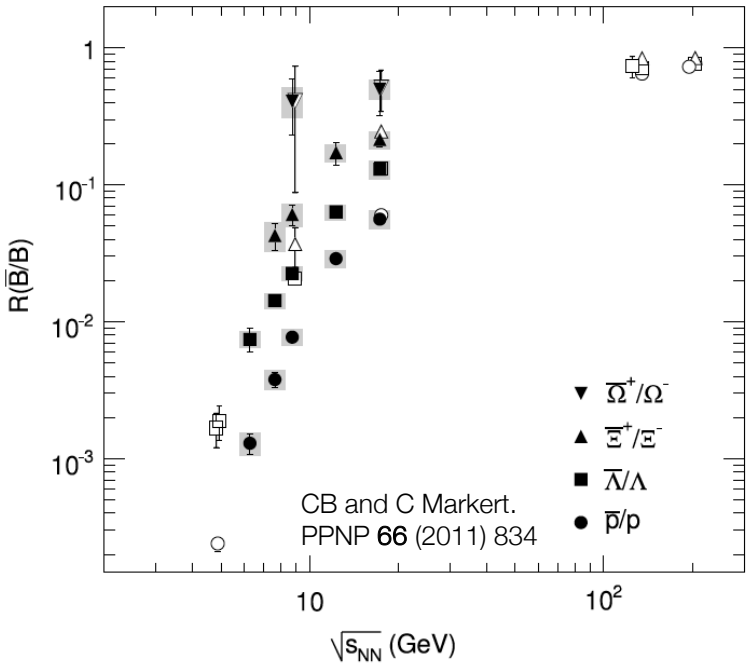
Baryon Number Distributions

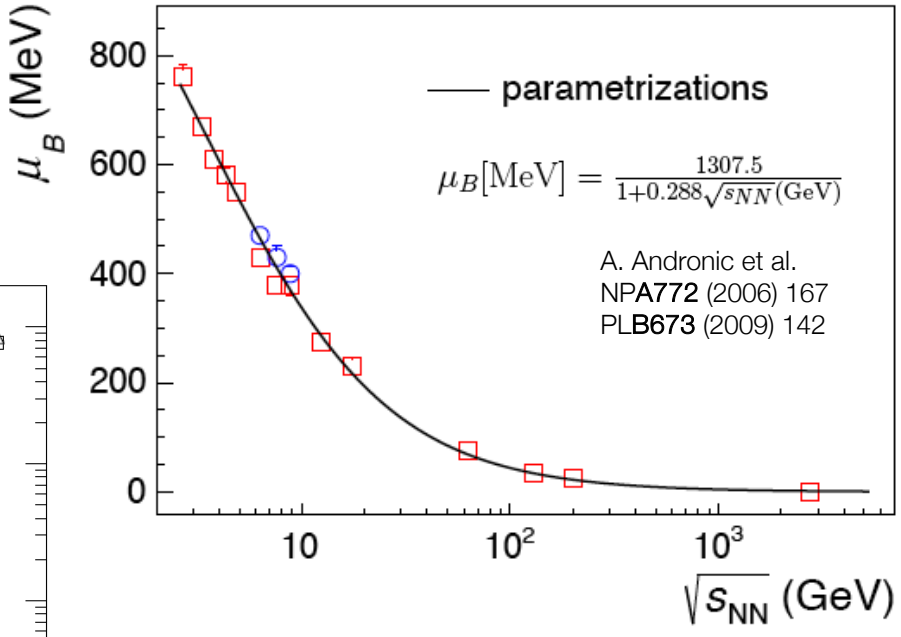


BRAHMS: PRL93 (2004) 102301

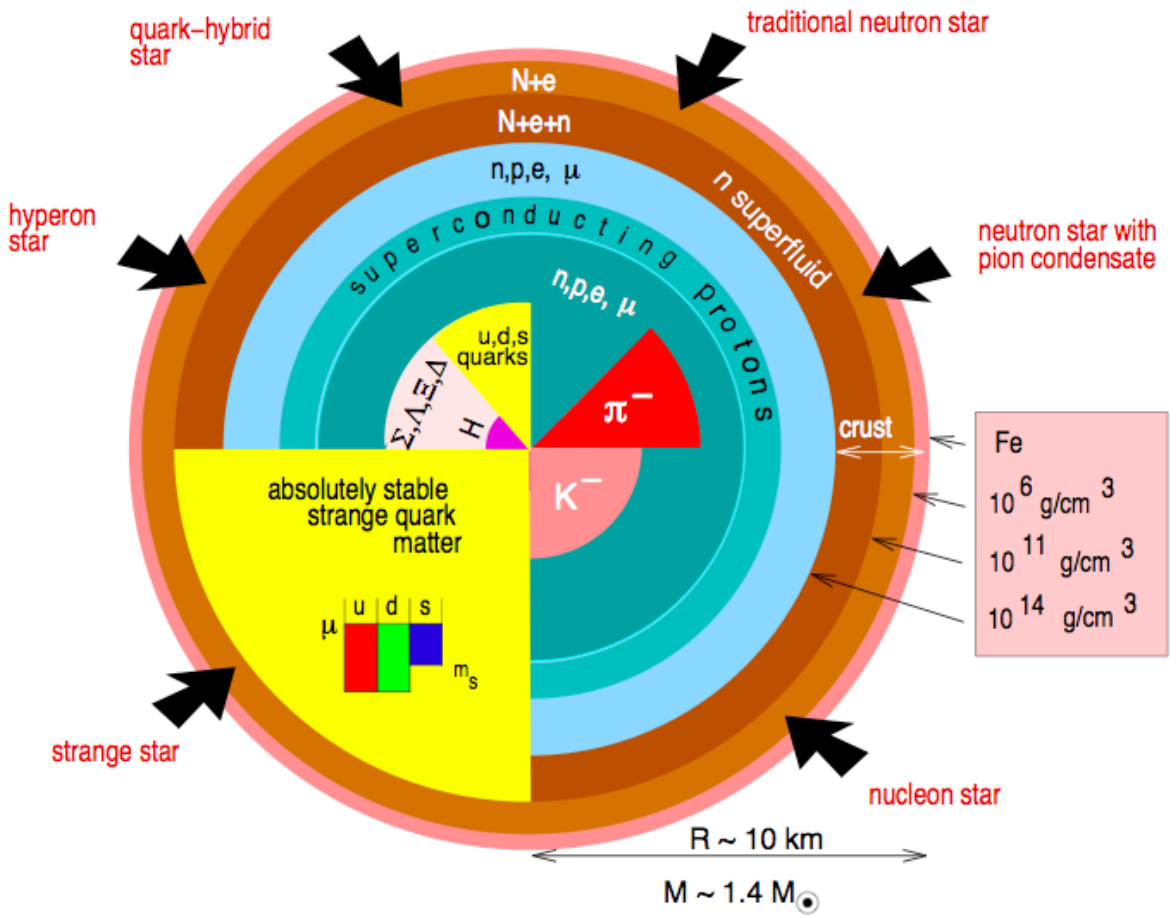
Baryochemical Potential

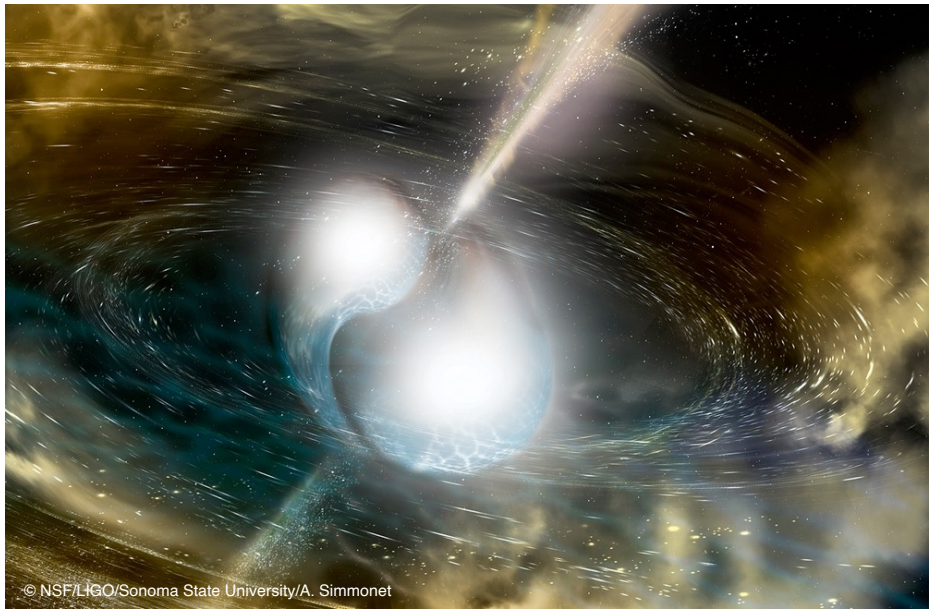






Relation to Neutron Stars





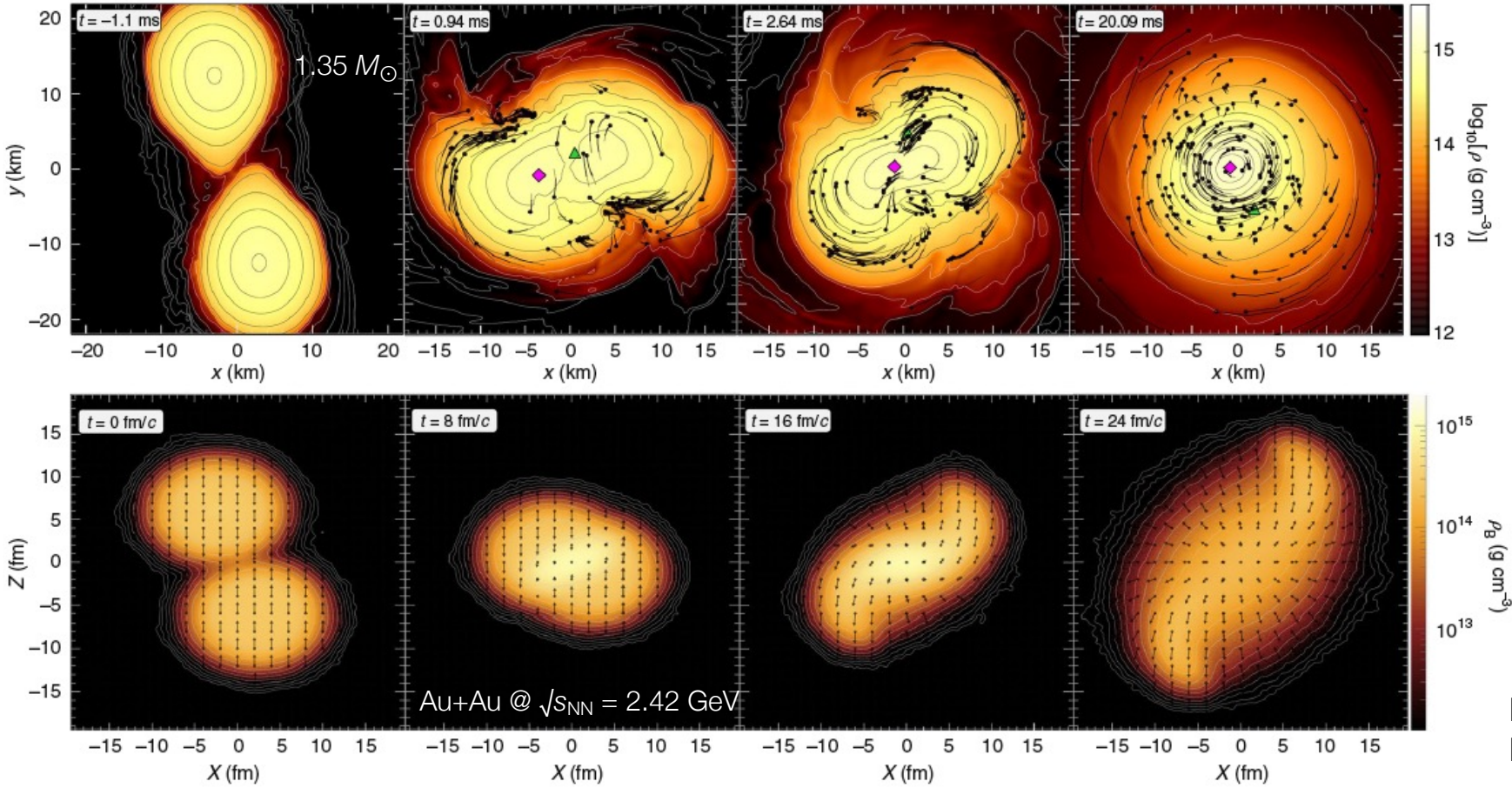
Neutron star mergers
Observed via gravitational waves

GW170817: B.P. Abott et al. (LIGO + VIRGO)
Phys. Rev. Lett. **119** (2017) 1611001

Neutron Star Mergers + Heavy-Ion Coll.

NS:

HIC:



HADES Coll., Nature Phys. **15** (2019) 1040

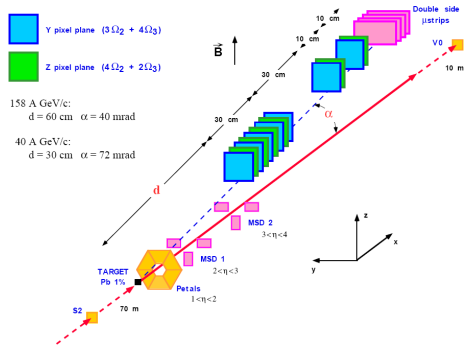
Experiments at High μ_B

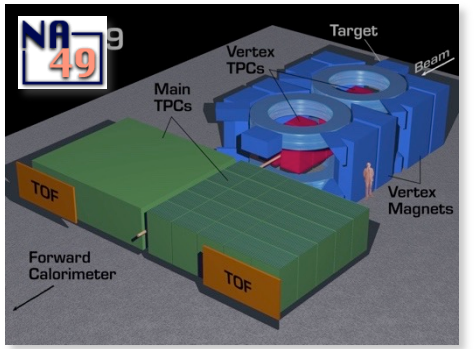
Existing and Historic HI-Facilities

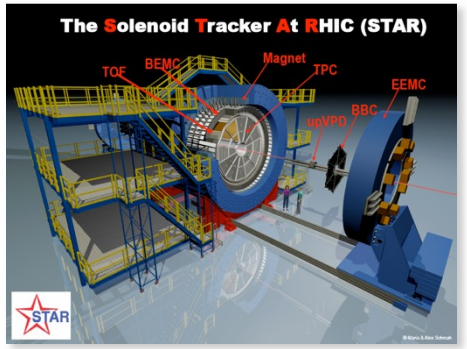
Accelerator	Place	HI-Periods	Max. Energy	Experiments
Bevalac	LBNL, Berkeley	1984 - 1993	< 2 AGeV	Plastic Ball, Streamer Chamber, EOS, DLS
Synchro-Phasotron	JINR, Dubna	1974 - 1985	> 100 AMeV	
AGS	BNL, Brookhaven	1986 - 1994	14.5/11.5 AGeV	E802, ..., E917
SPS	CERN, Geneva	1986 - today	200/158 AGeV	NA34,... , WA80,... NA61, *NA60+*
SIS18	GSI, Darmstadt	1992 - today	2 AGeV	FOPI, KAOS, HADES
RHIC	BNL, Brookhaven	2000 – today	$\sqrt{s_{NN}}$ = 200 GeV	STAR, PHENIX, **sPHENIX** BRAHMS, PHOBOS
LHC	CERN, Geneva	2009 – today	$\sqrt{s_{NN}}$ = 5.5 TeV	ALICE, CMS, ATLAS, LHCb
Nuclotron	JINR, Dubna		6 AGeV	BM@N

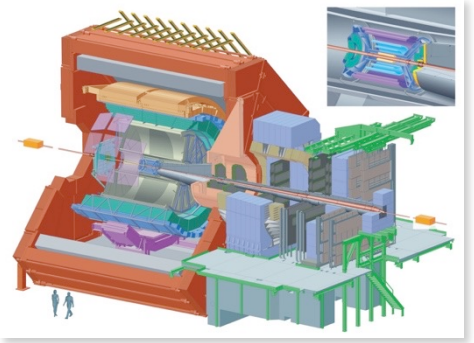
HI-Experiments

- GSI-SIS
  - FOPI, KAOS, HADES
- BNL-AGS
  - E866, E877, E891, E895, …
- CERN-SPS (Pb beam)
  - WA97, NA44, NA45, NA50, NA49, NA57, NA61, NA60+
- BNL-RHIC
  - STAR (BES), PHENIX, BRAHMS, PHOBIOS, sPHENIX
- CERN-LHC
  - ALICE, ATLAS, CMS, LHCb
- New low energy programs
  - CBM@FAIR, NICA, J-PARC-HI, HIAF, RAON



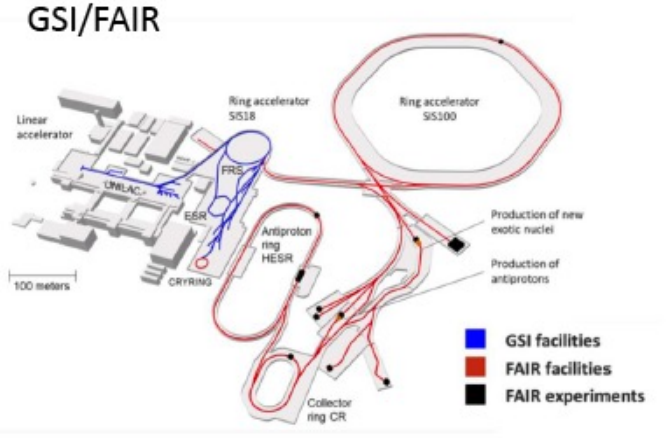




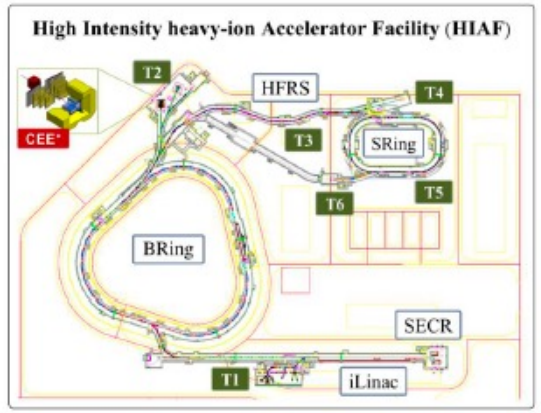


Future HI-Facilities

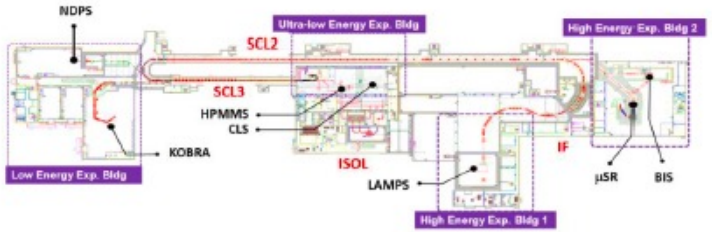
GSI/FAIR



HIAF

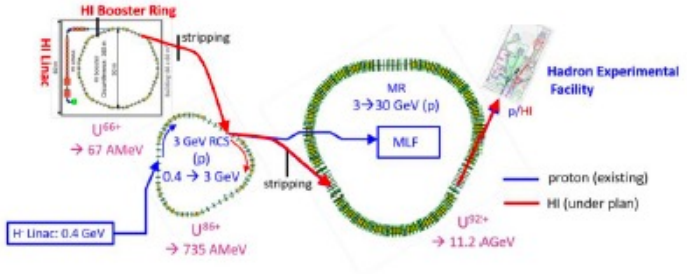


RAON



NICA

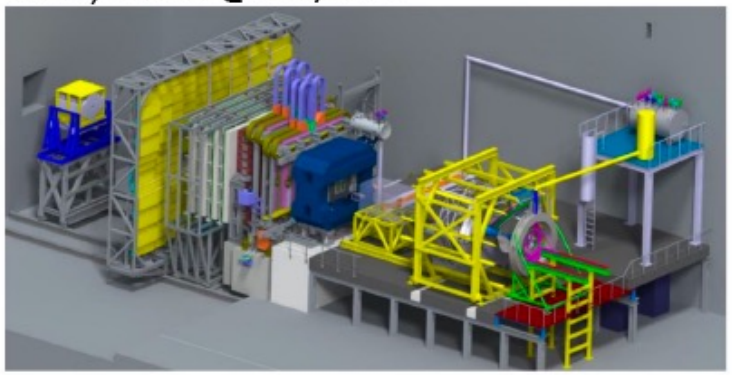
J-PARC



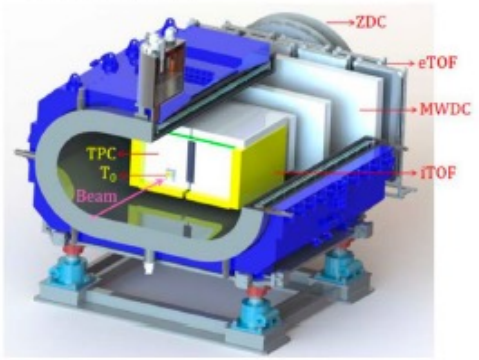
N. Herrmann, CPOD22

Future HI-Experiments at High-μ_B

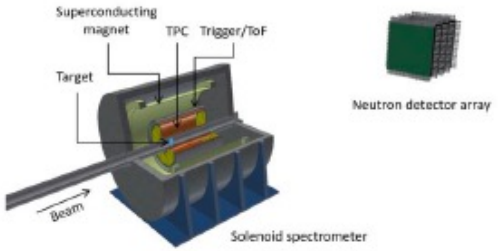
CBM,HADES @ GSI/FAIR



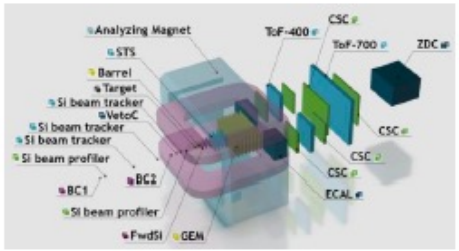
CEE @ HIAF



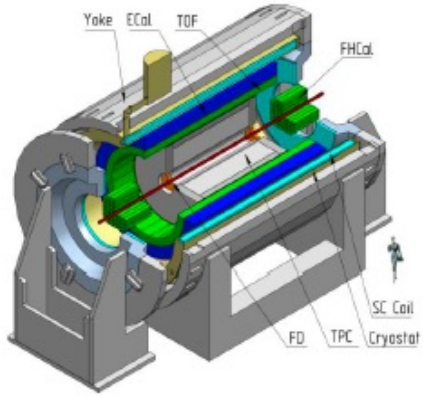
LAMPS @ RAON



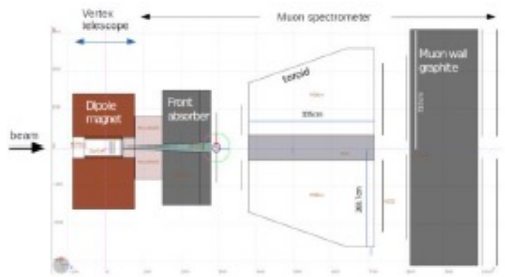
BM@N @ NICA



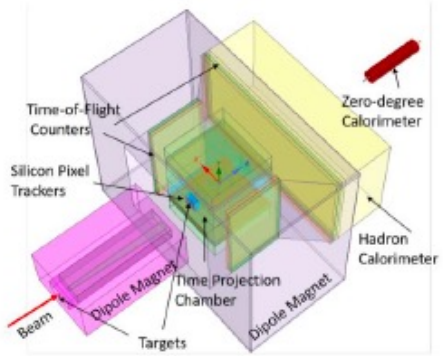
MPD @ NICA



NA60+ @ SPS

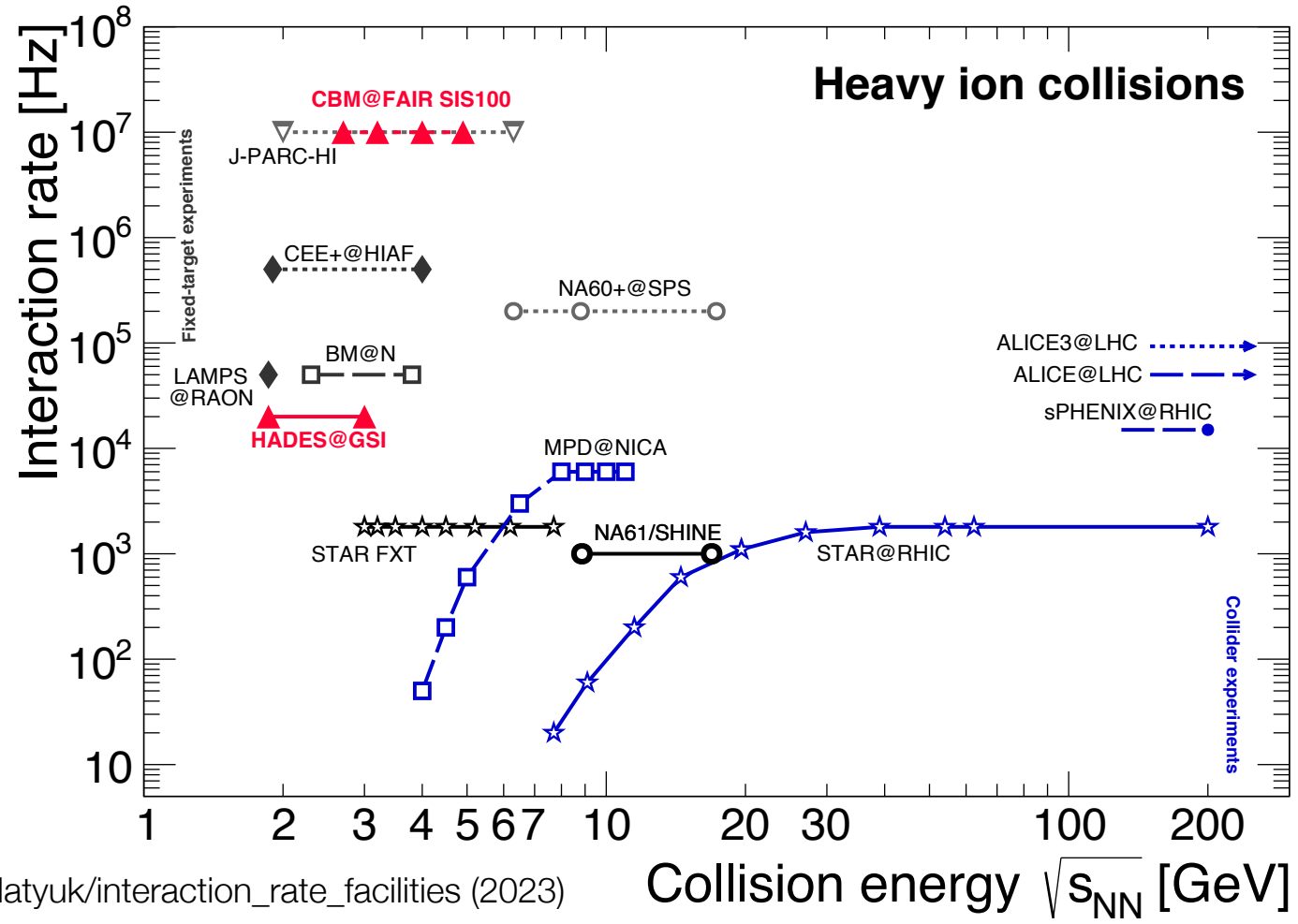


DHS @ J-PARC



N. Herrmann, CPOD22

Overview on Experiments



T. Galatyuk,
https://github.com/tgalatyuk/interaction_rate_facilities (2023)

Fixed Target ↔ Collider

Fixed Target

- Pros:
  - High luminosities are easy to achieve
  - Easy access to detectors
  - Lorentz-boost helps in the measurement of weak decays

- Cons:
  - Only lower center-of-mass energies reachable
  - Particles are compressed into forward angles
  - Detector acceptance changes with center-of-mass energies

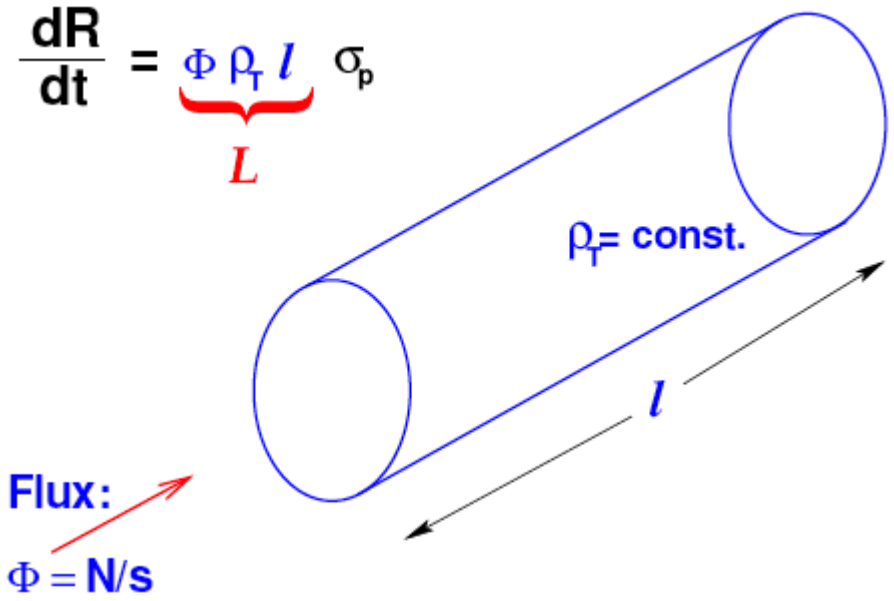
Fixed Target ↔ Collider

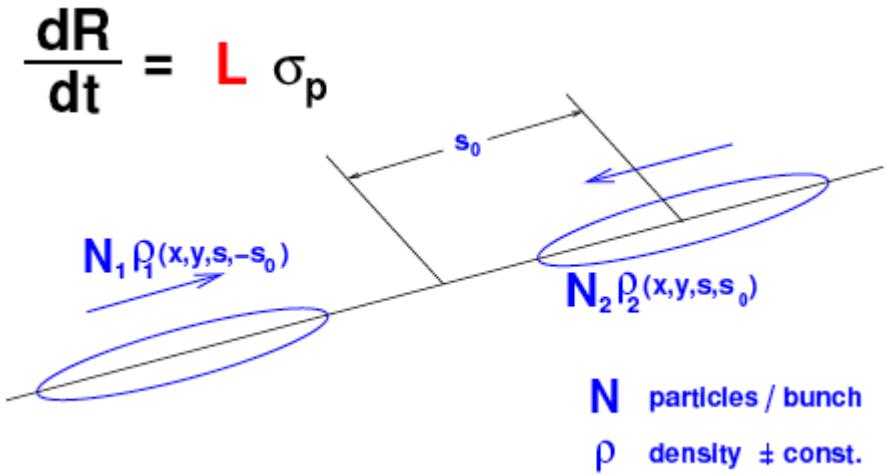
Collider

- Pros:
  - High center-of-mass energies reachable
  - Particles are produced perpendicular to beam
  - Acceptance independent of center-of-mass energy

- Cons:
  - High luminosities are difficult to achieve
  - Technically more complicated
  - No easy access to detectors

Fixed Target ↔ Collider: Luminosity





Figures: W. Herr and B. Muratori, CERN

Reaction rate: $\mathrm{d}R / \mathrm{d}t = L \cdot \sigma_p$

Cross section of relevant process: σ_p

Luminosity for collider (Gaussian bunch profiles):

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

Fixed Target ↔ Collider: CM-Energy

Center-of-mass energy in nucleon-nucleon system (collider):

$$E_{CM} = \sqrt{s_{NN}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

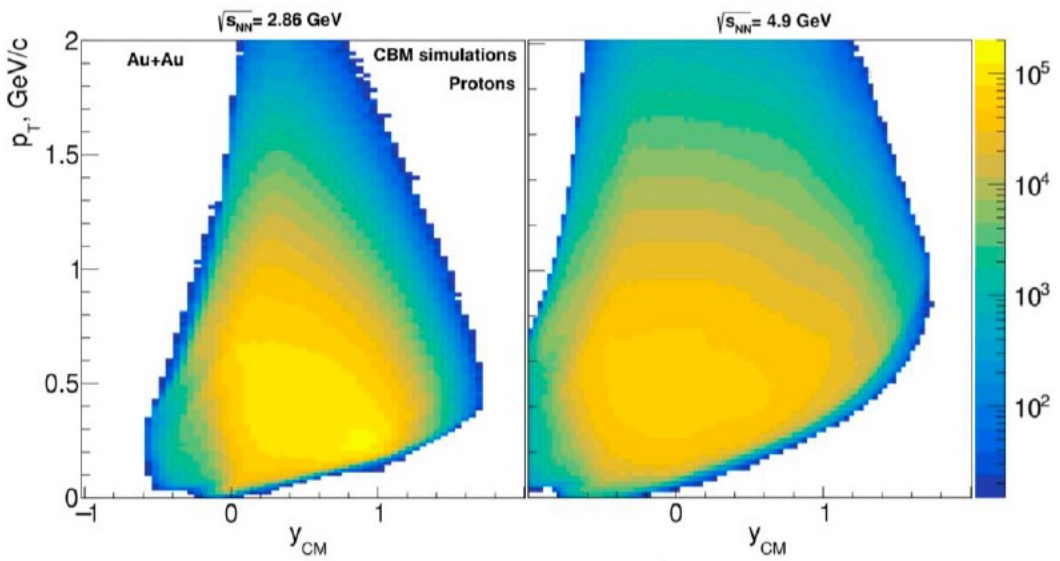
$$s_{NN} = (P_1 + P_2)^2 \qquad \text{with } P = \text{4-momenta}$$

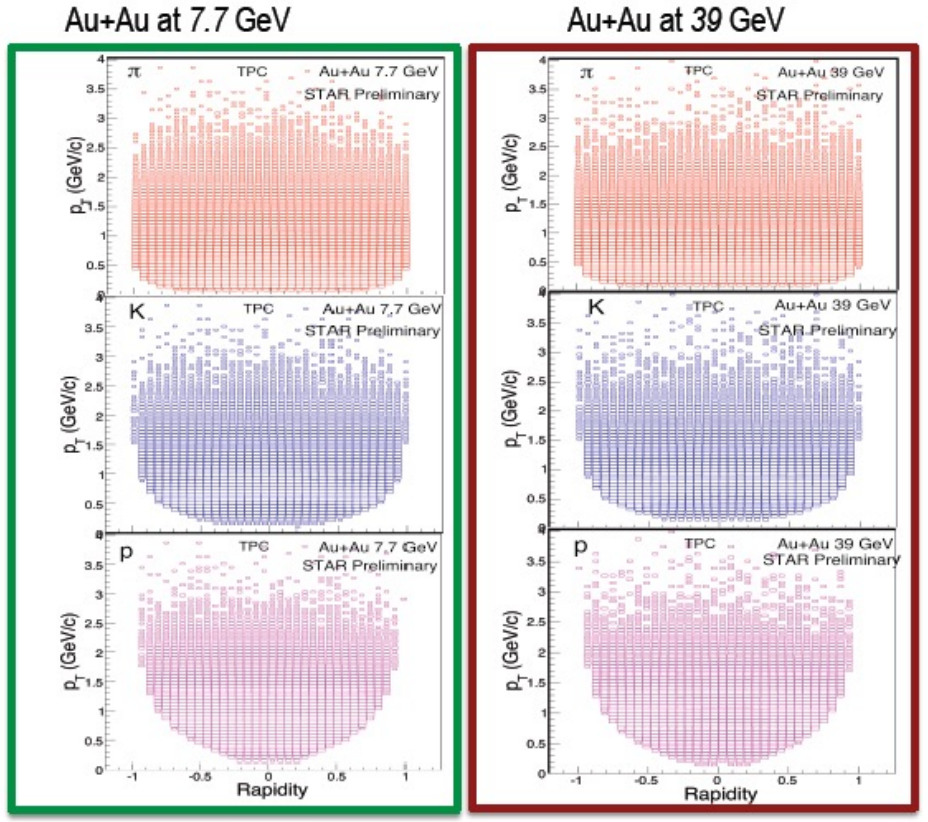
One particle at rest (fixed target):

$$E_{CM} = \sqrt{s_{NN}} = \left[m_1^2 + m_2^2 + 2\,E_1 E_2\,(1 - \beta_1\beta_2\,\cos\theta)\right]^{1/2}$$

$$= \left[m_1^2 + m_2^2 + 2\,E_{1,lab}\,m_2\right]^{1/2}$$

Fixed Target ↔ Collider: Acceptance

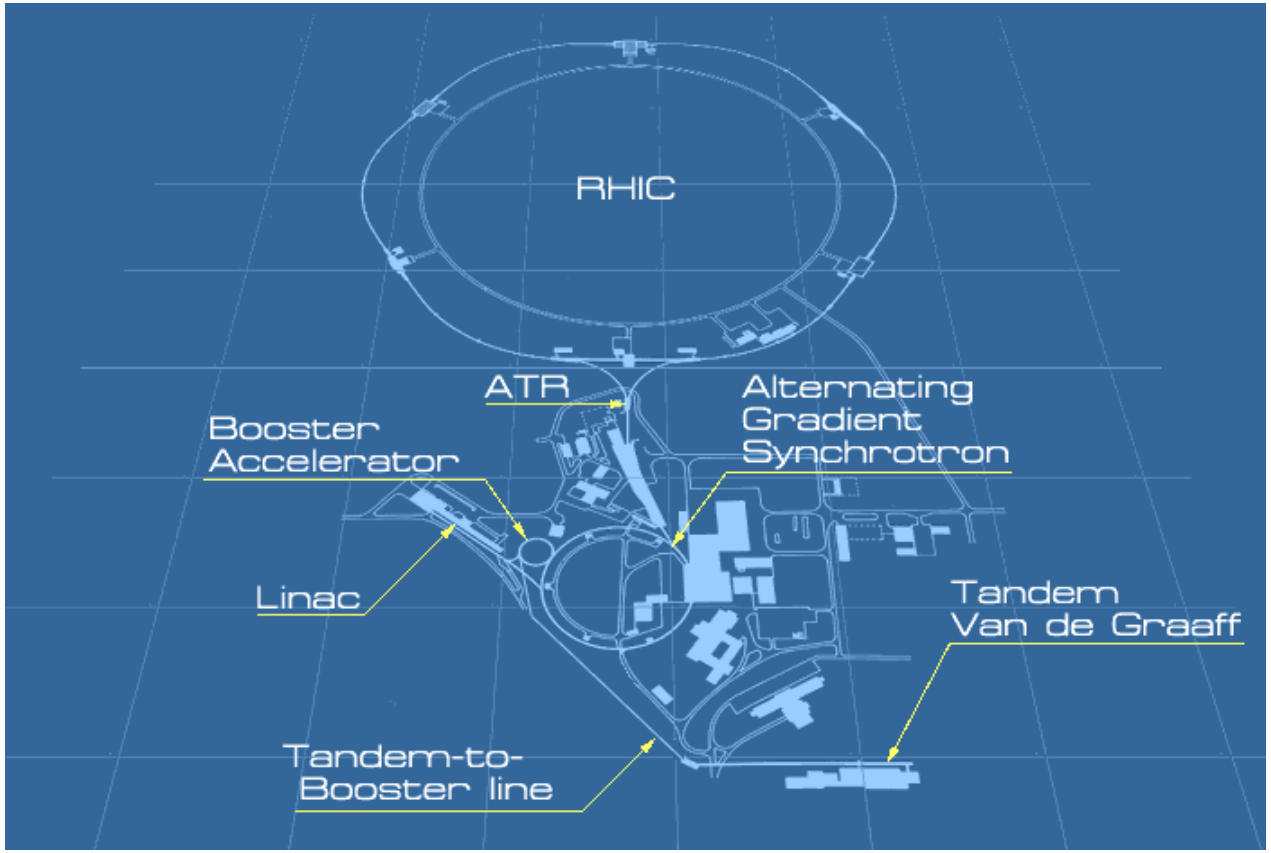


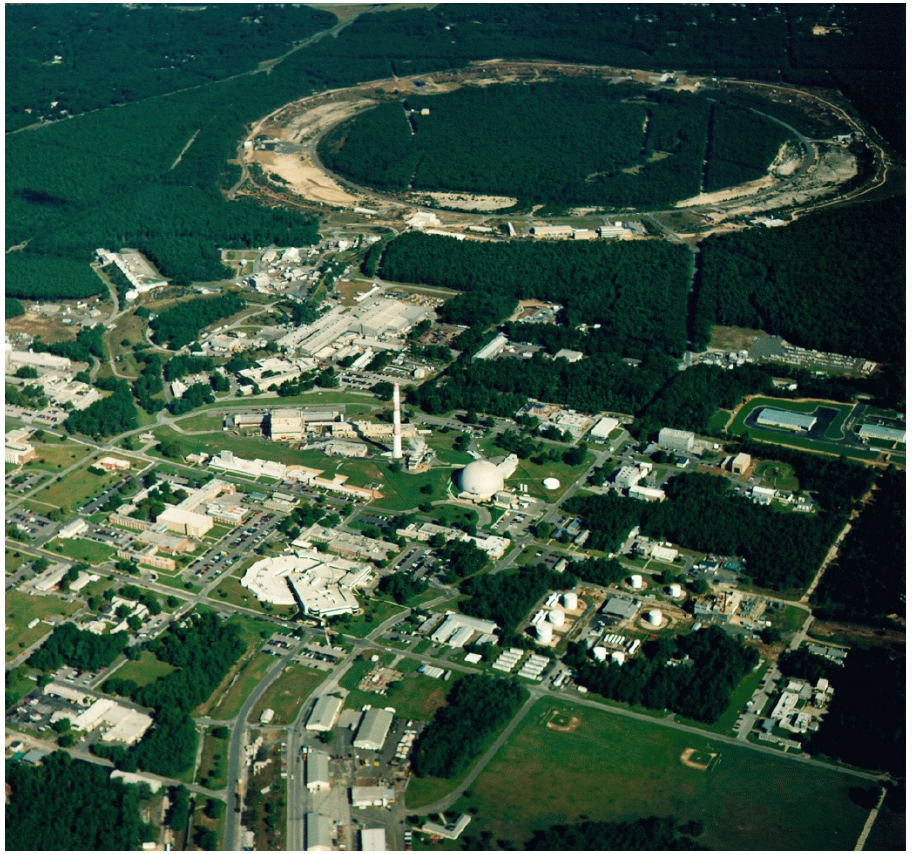


Fixed Target (CBM)

Collider (STAR)

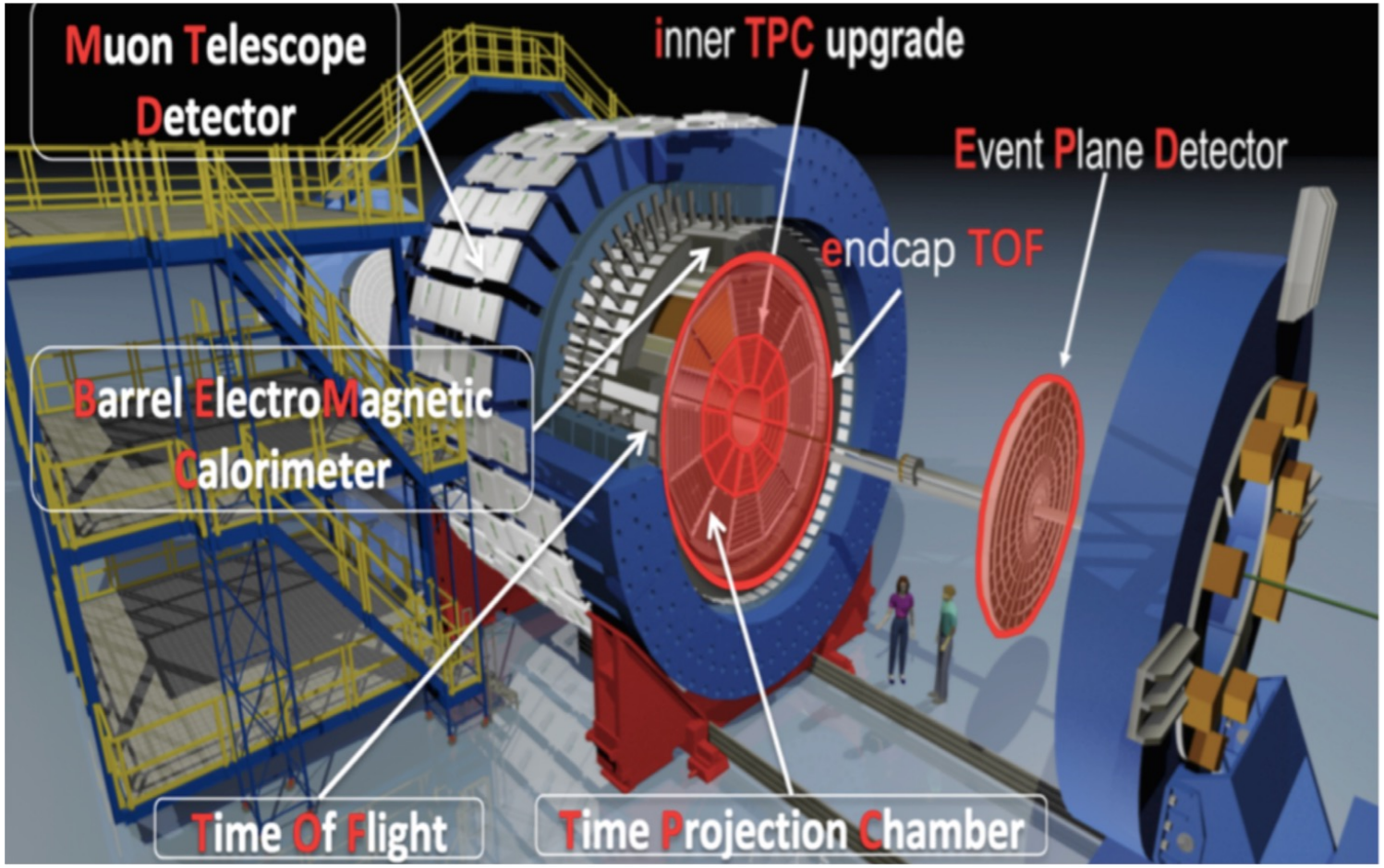
Brookhaven National Laboratory (BNL)





RHIC: Relativistic Heavy-Ion Collider

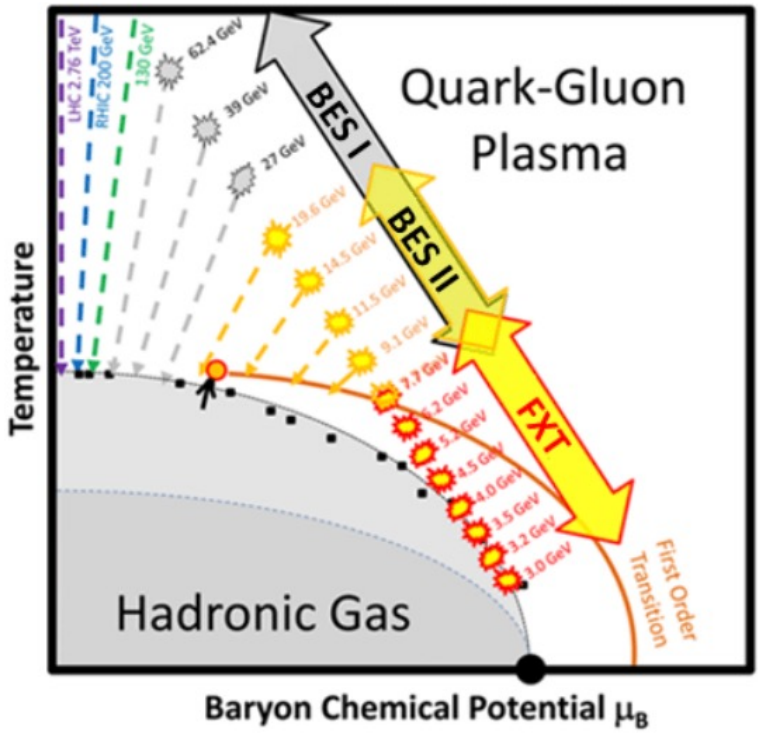
STAR Experiment at RHIC

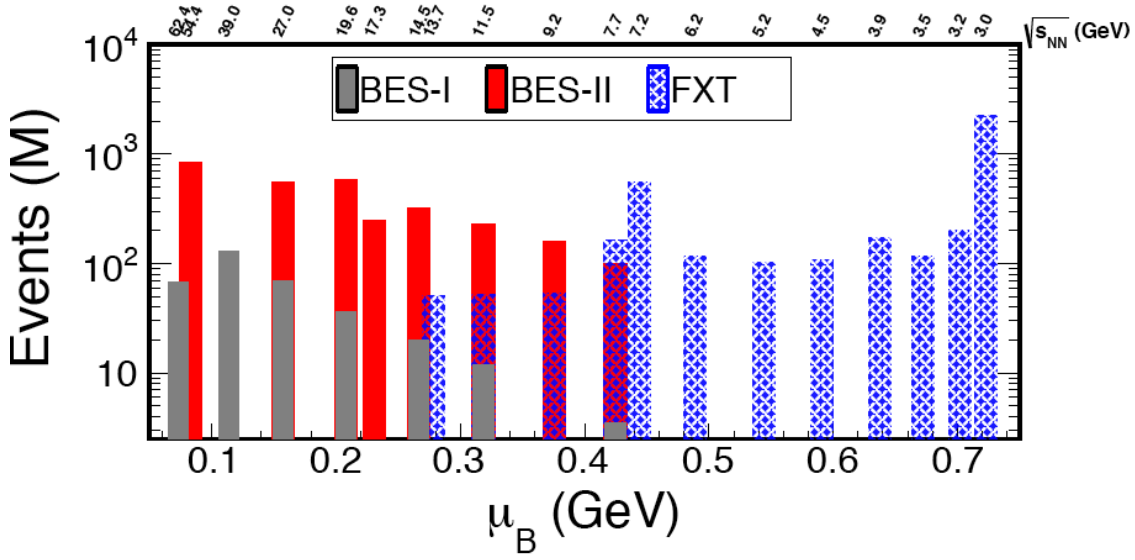


Tracking: TPC ($|\eta| < 1.5$)

PID: TPC + TOF ($|\eta| < 0.9$)

STAR Beam Energy Scan (BES)

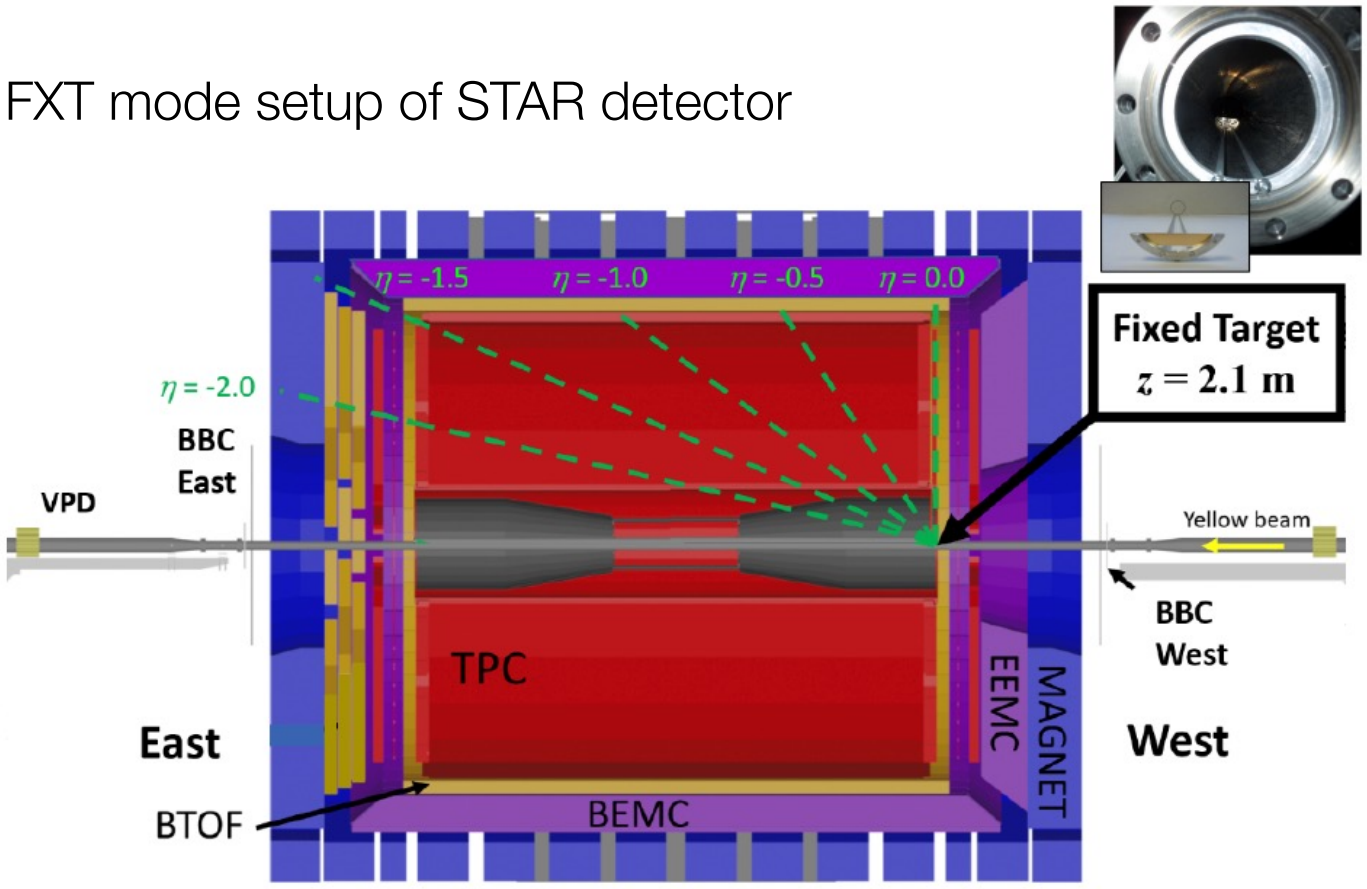




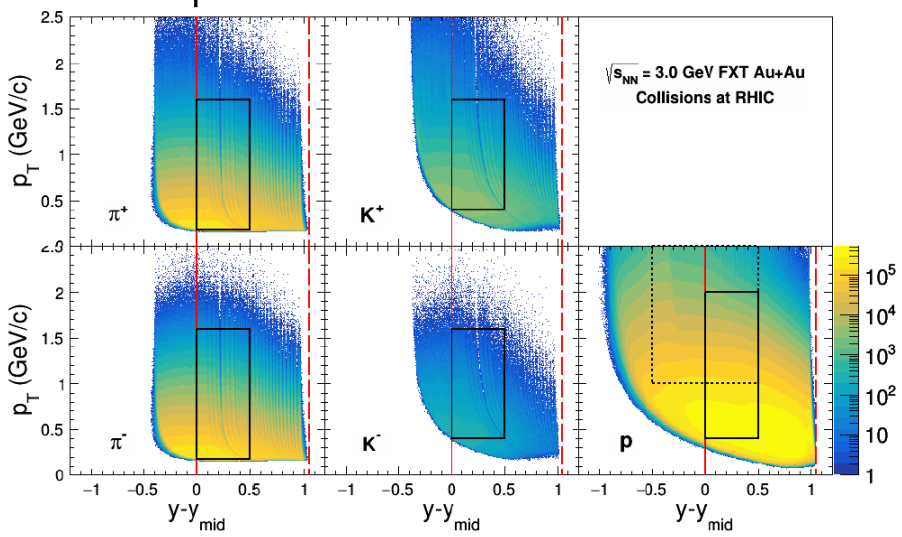
STAR data cover μ_B-values in the range of 20 – 800 MeV

STAR Fixed Target Mode (FXT)

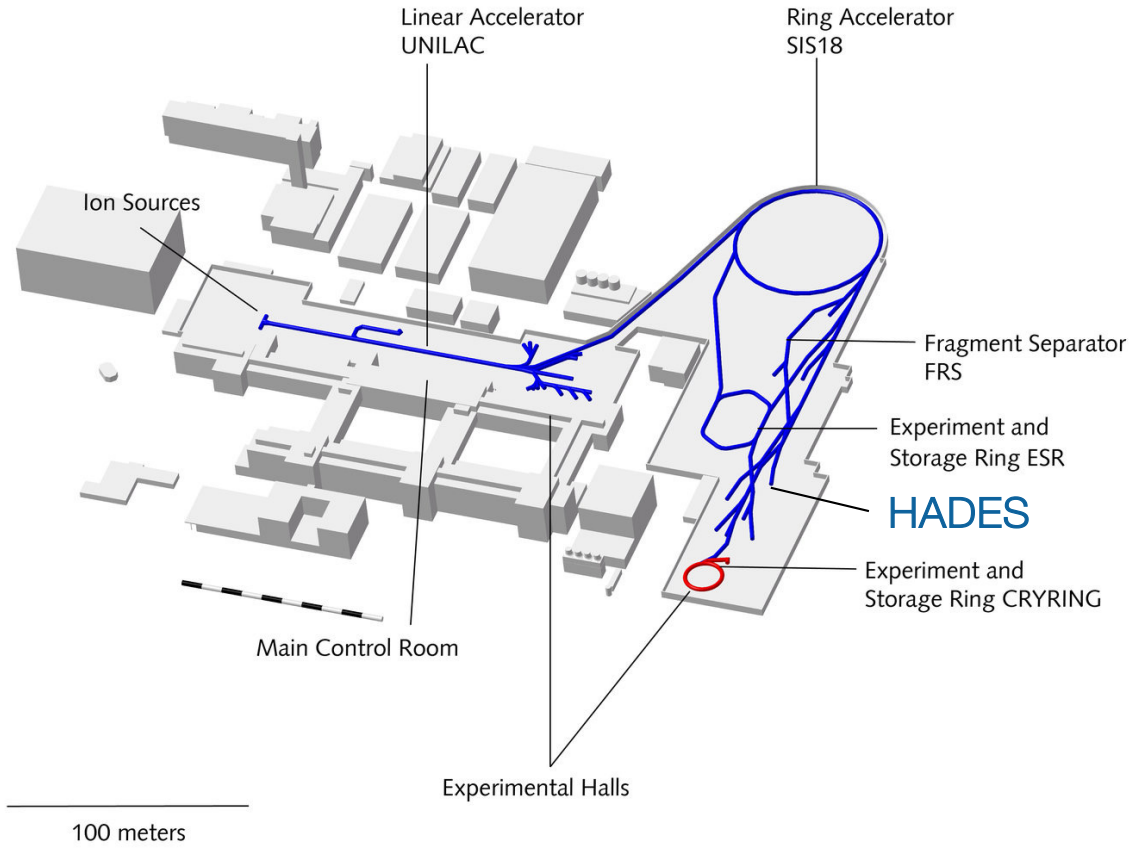
FXT mode setup of STAR detector

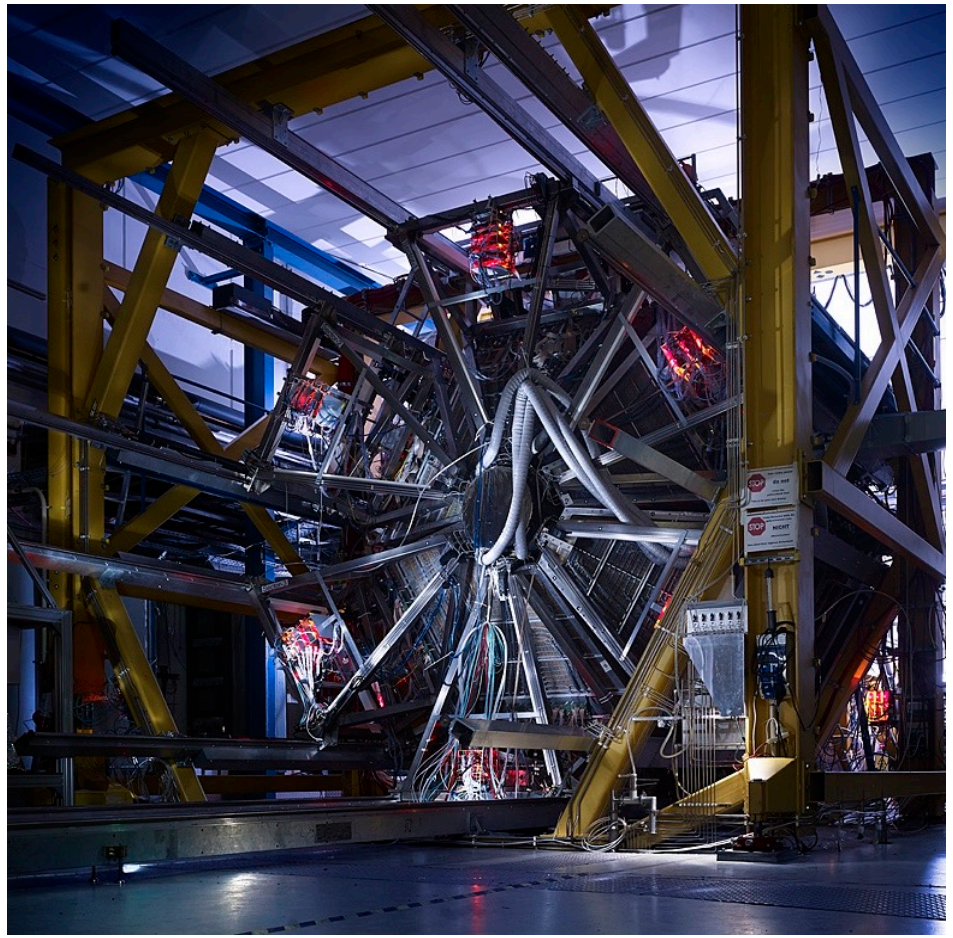


Acceptances in FXT mode

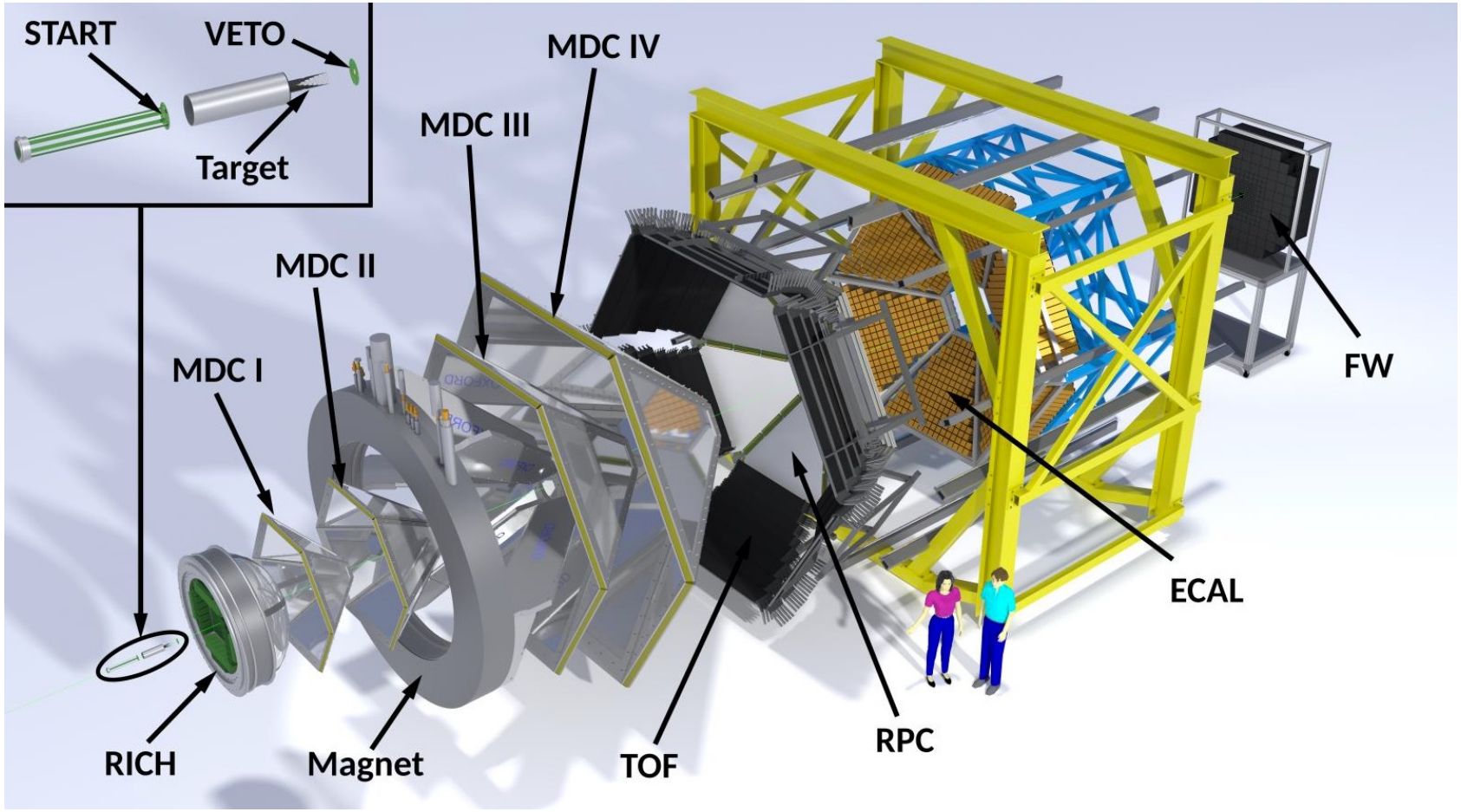


Experiments at GSI/FAIR: HADES

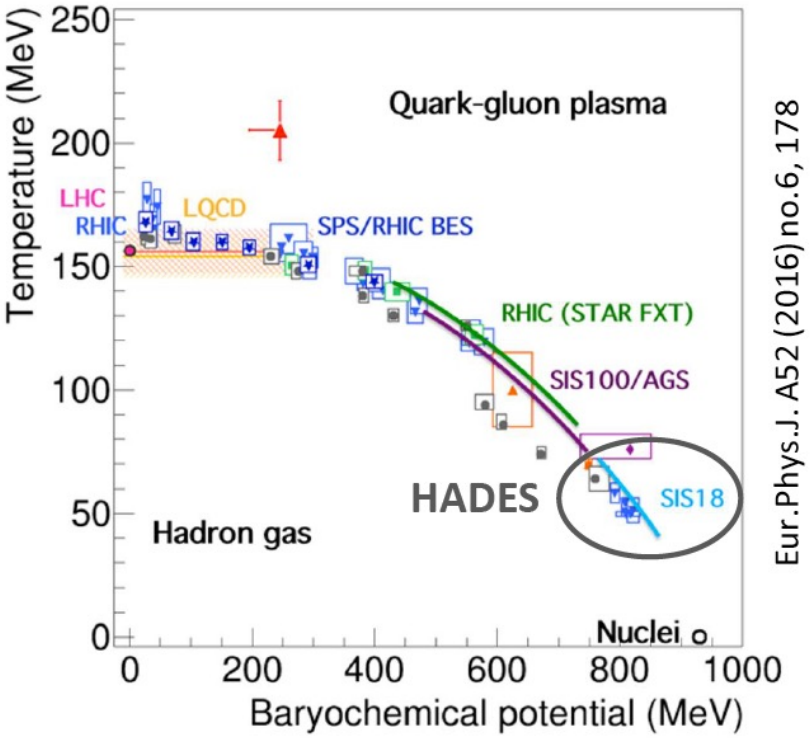


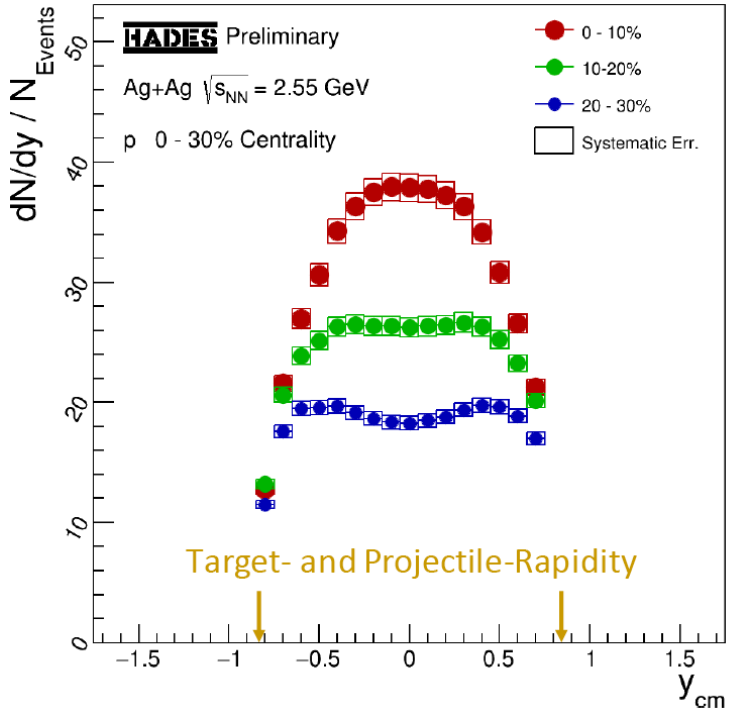


Experiments at GSI/FAIR: HADES



Experiments at GSI/FAIR: HADES



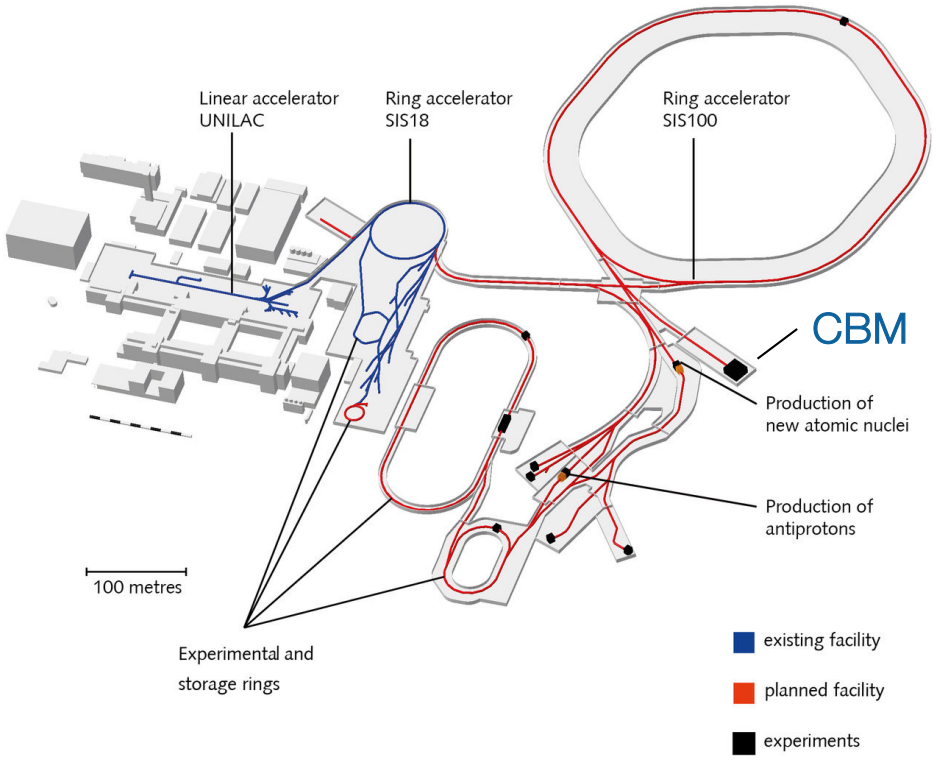


High μ_B region ($\mu_B \approx 750 - 800$ MeV)

Baryon dominated reaction systems (full stopping)

~ 50% of nucleons in light clusters

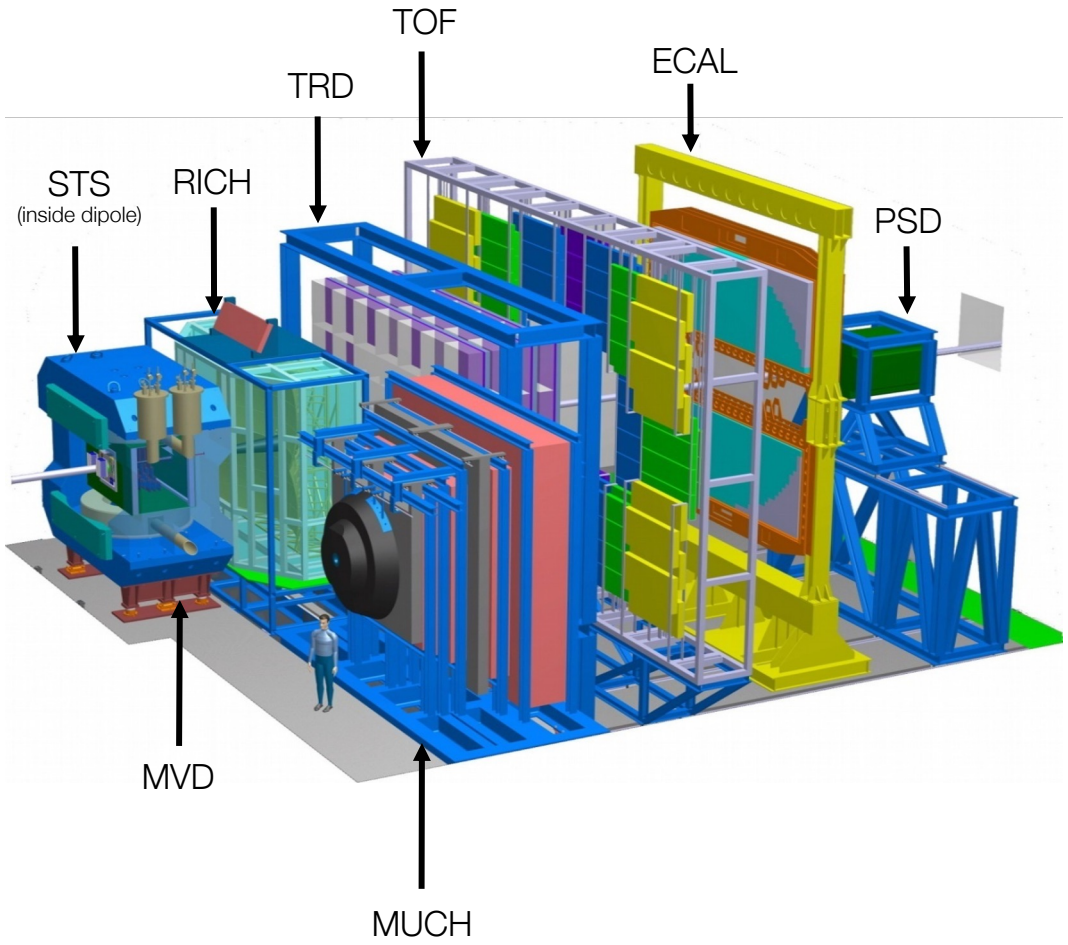
Experiments at FAIR: CBM



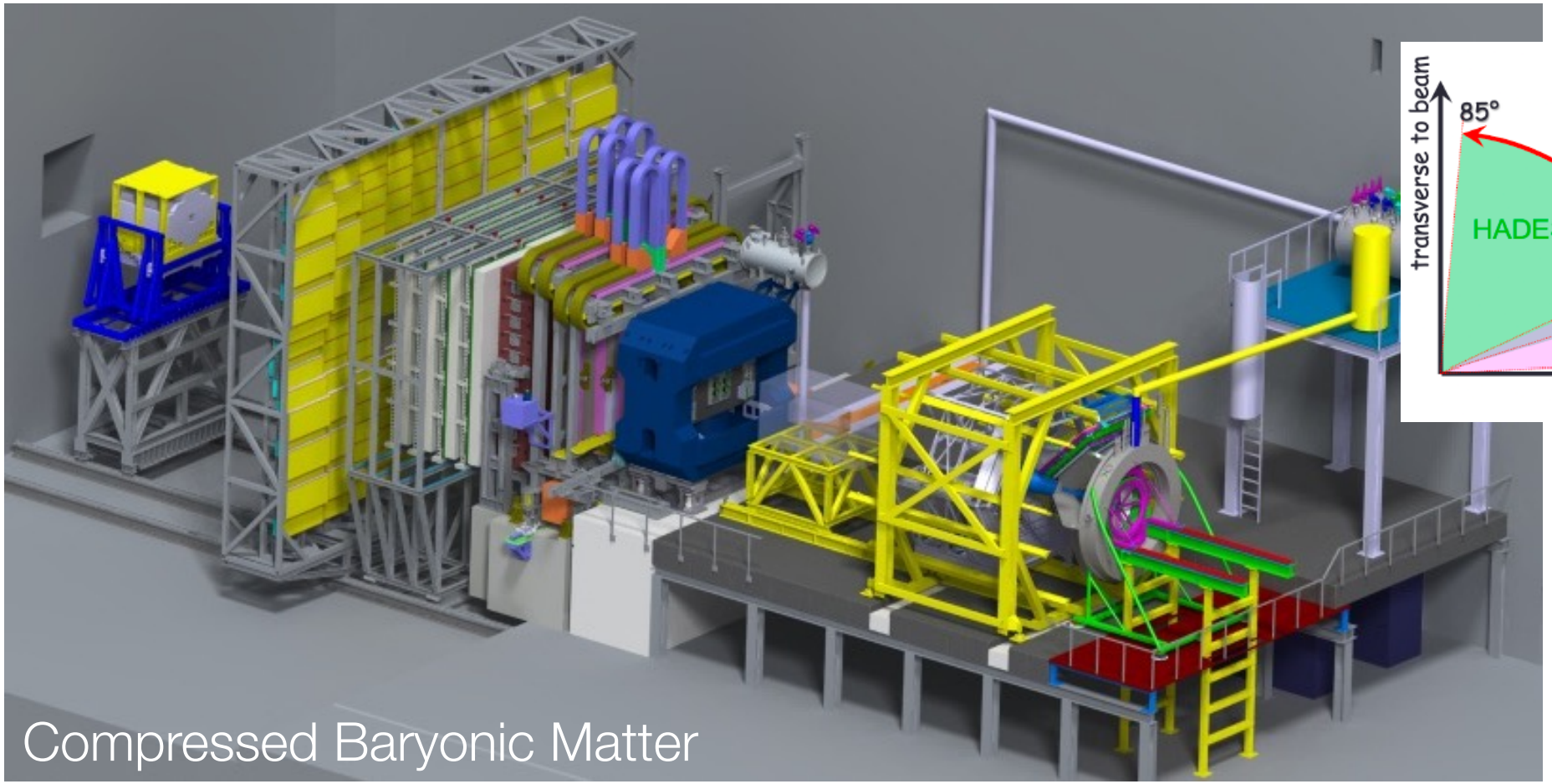
Experiments at FAIR: CBM

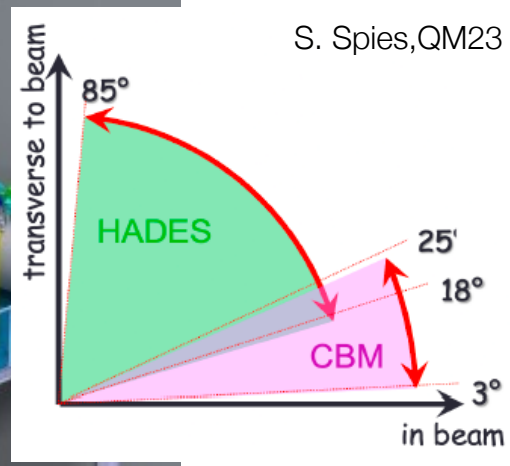
Compressed Baryonic Matter

- Peak interaction rate: 10 MHz (Au+Au)
  (300 kHz for MVD)
- Fast and radiation hard detectors
- Free-streaming DAQ
- 4D-tracking (space + time)
- Online event reconstruction and selection
- Data rate: 1 TB/sec

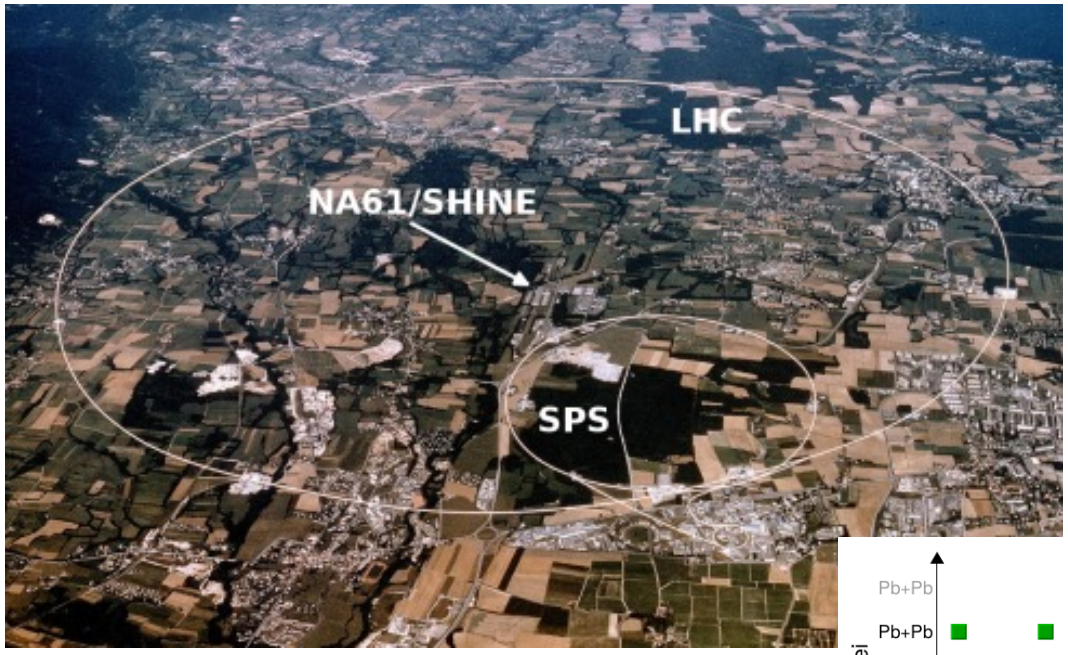


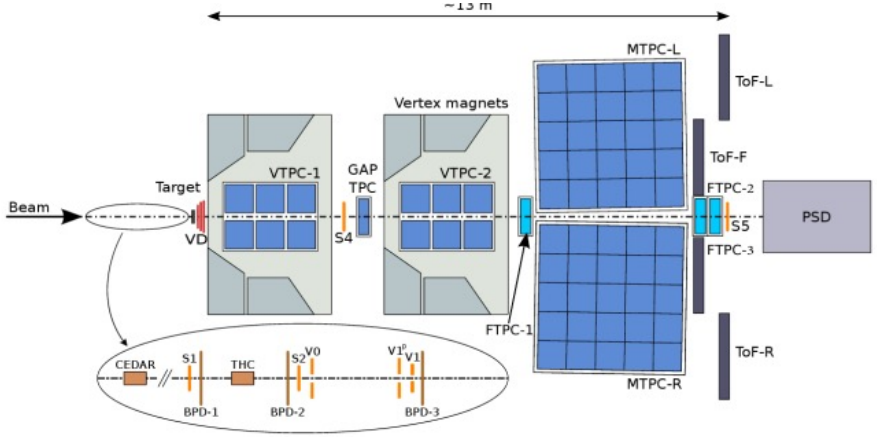
Experiments at FAIR: HADES + CBM

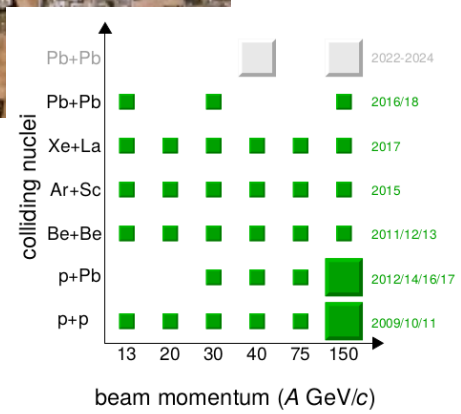


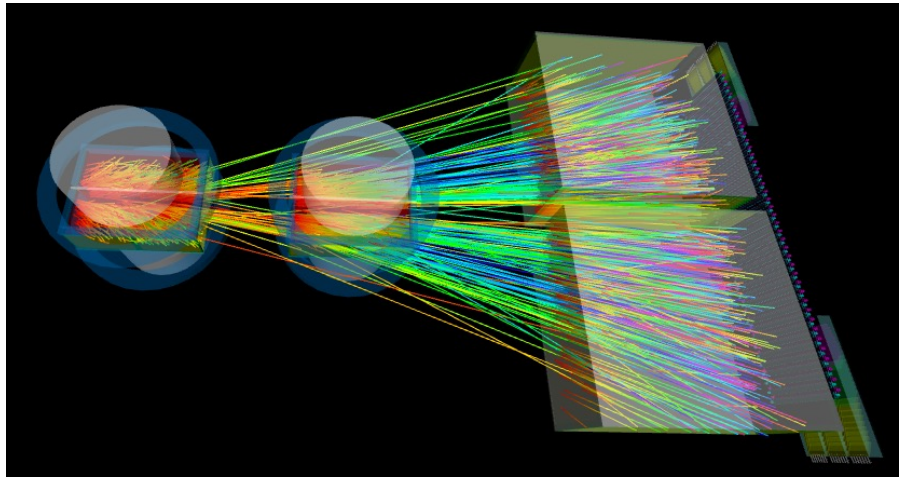


Experiments at SPS: NA61/SHINE





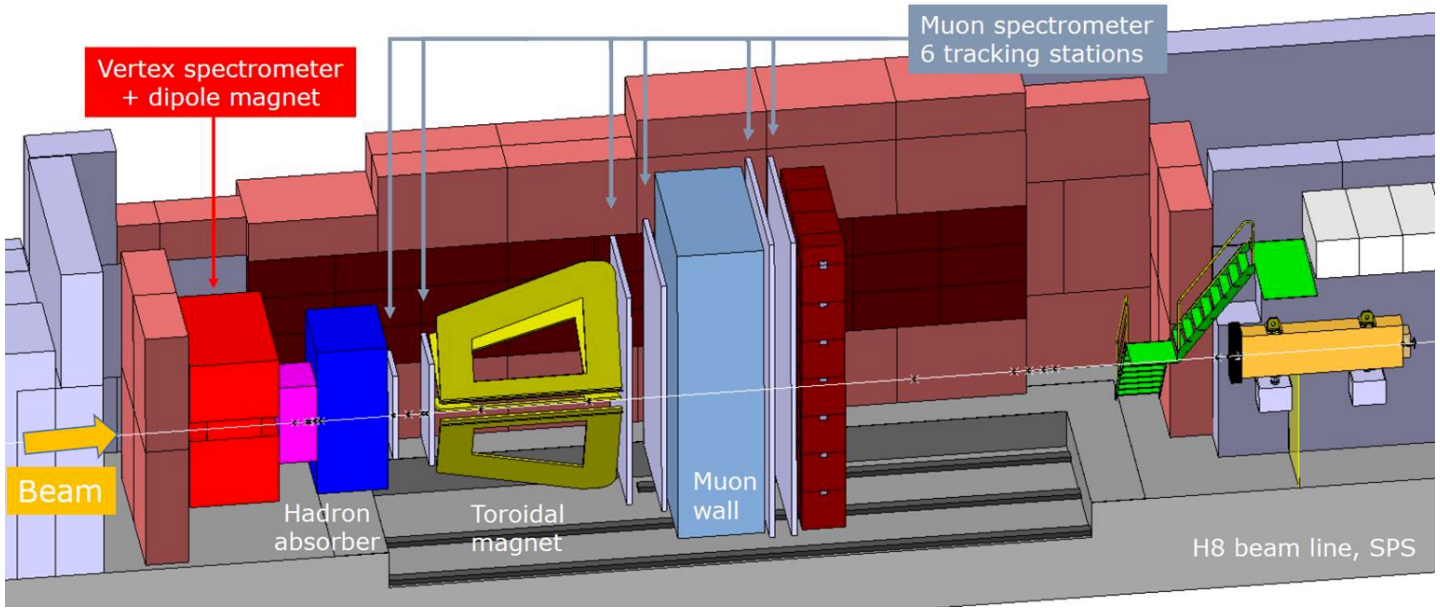


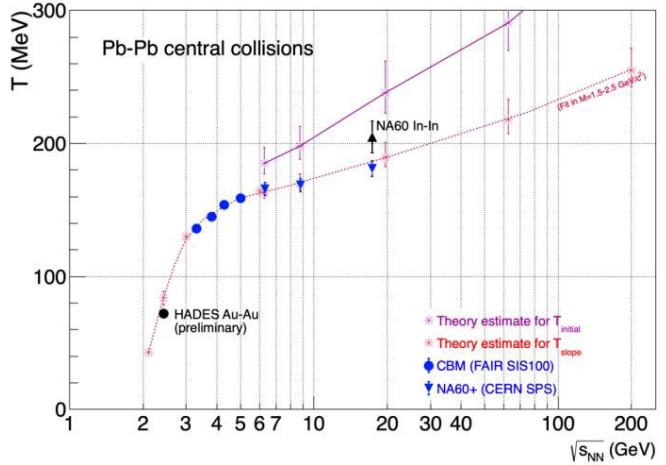


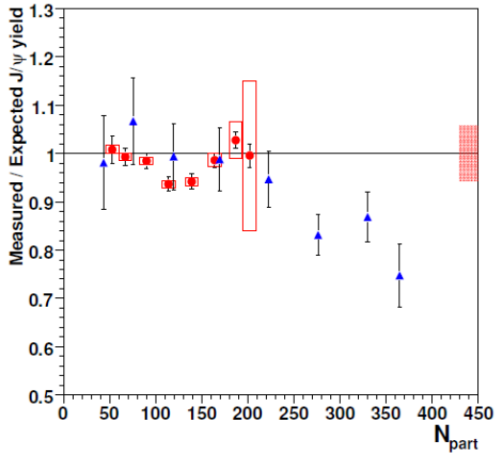
Upgraded NA49 setup

Energy and system size scan

Experiments at SPS: NA60+







Di-muon spectrometer at high luminosity SPS beam line H8 (10^6 ions/s)

Beam energy scan (~6 GeV < $\sqrt{s_{NN}}$ 17 GeV)

Charmonia, thermal di-leptons, open charm