Flow at SIS energies - overview of SIS18 results and prospect for SIS100

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For the HADES and CBM collaborations

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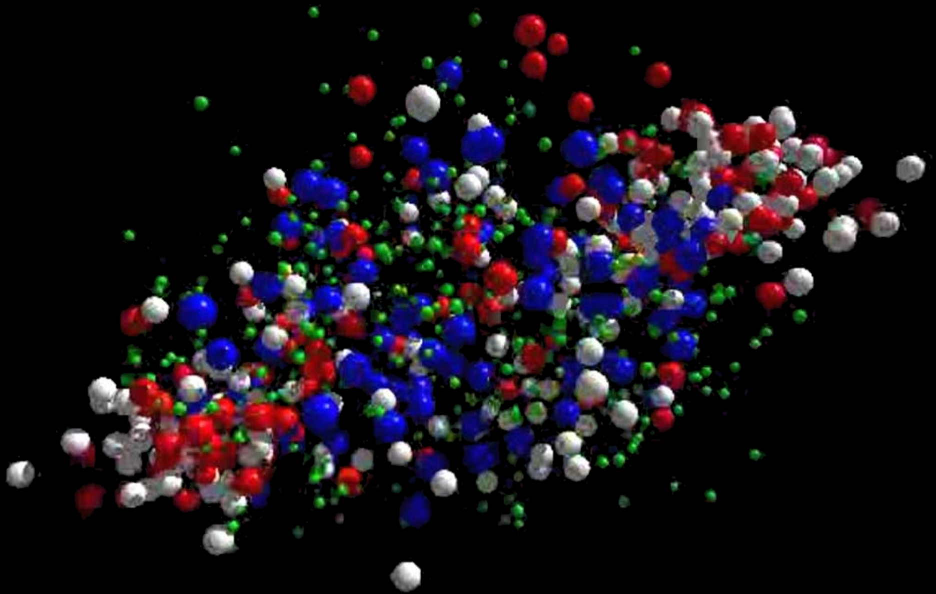
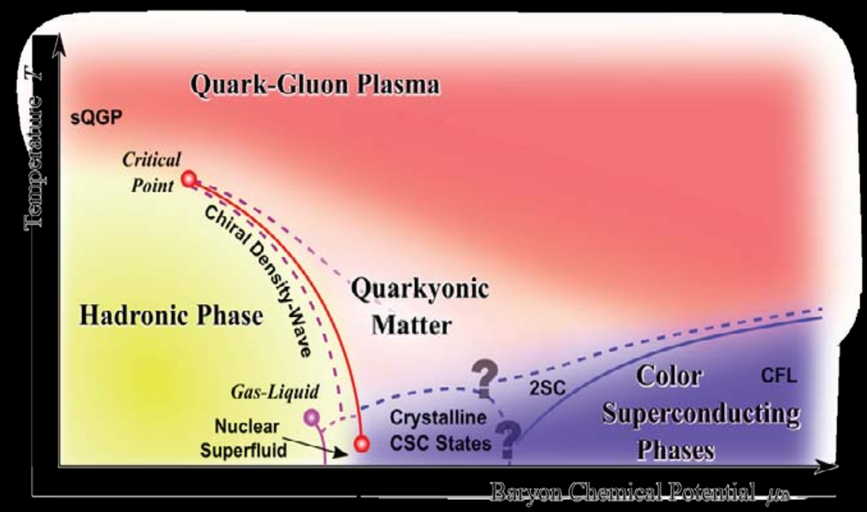
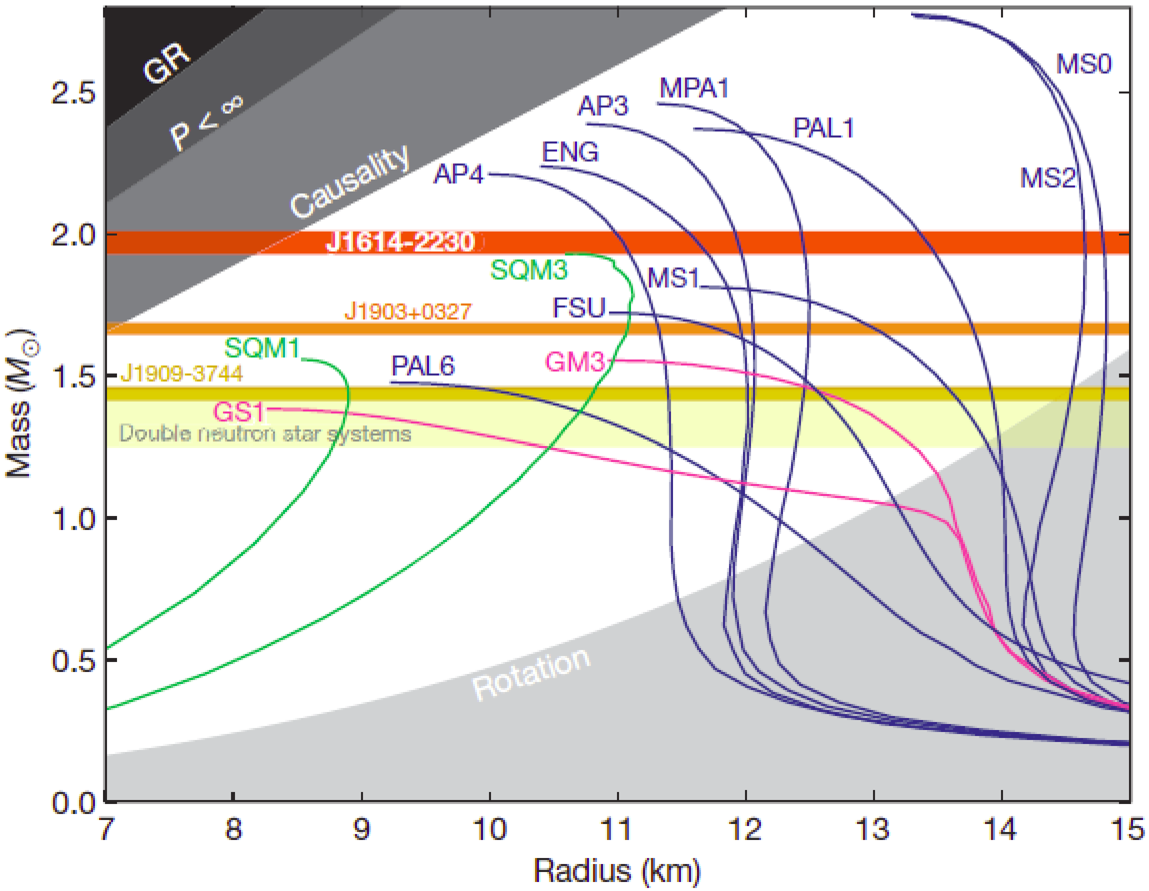
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education





Outline:
- Motivation
- Flow @ SIS18
- Flow @ FAIR energies
- Conclusion

Neutron stars and EOS



The plot shows non-rotating mass versus physical radius for several typical EOSs:
blue, nucleons;
pink, nucleons plus exotic matter;
green, strange quark matter.
The horizontal bands show the observational constraint. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_{\odot}$, which rules out almost all currently proposed hyperon or boson condensate equations of state. Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not ‘free’ quarks. See: PB Demorest et al. Nature 467, 1081–1083 (2010)

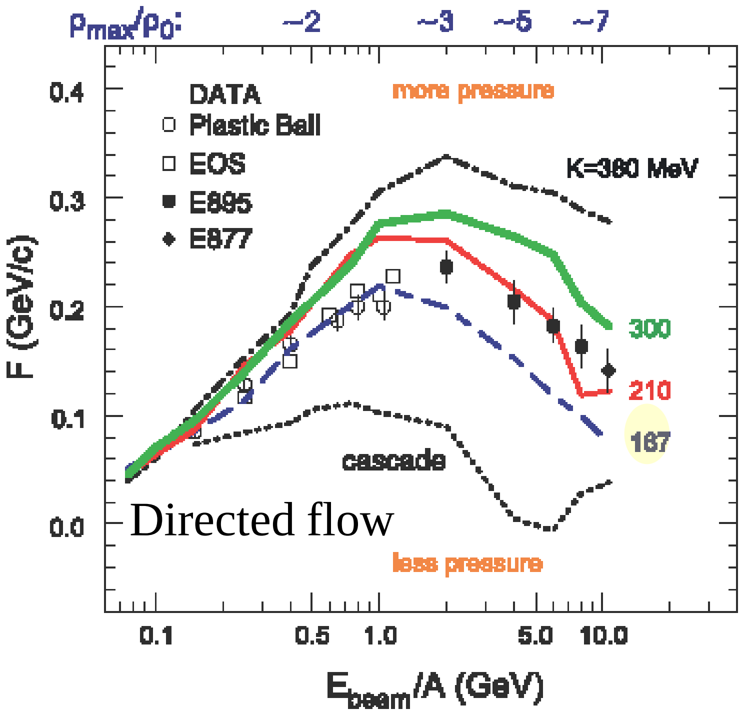
Exploring the EOS in HI Collisions Stiff or Soft?

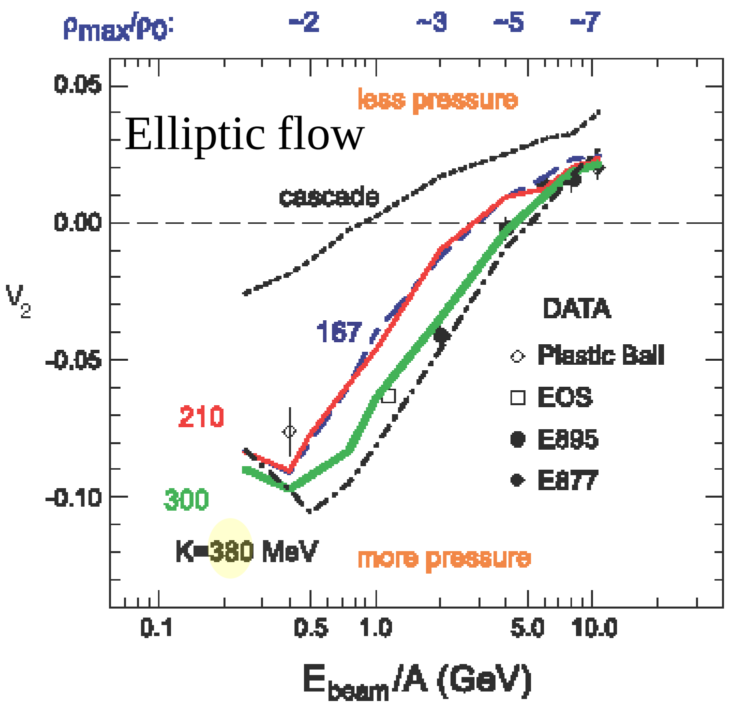
- Effect of mean-field potentials

$$F = d\langle p_x/A\rangle/dy'$$

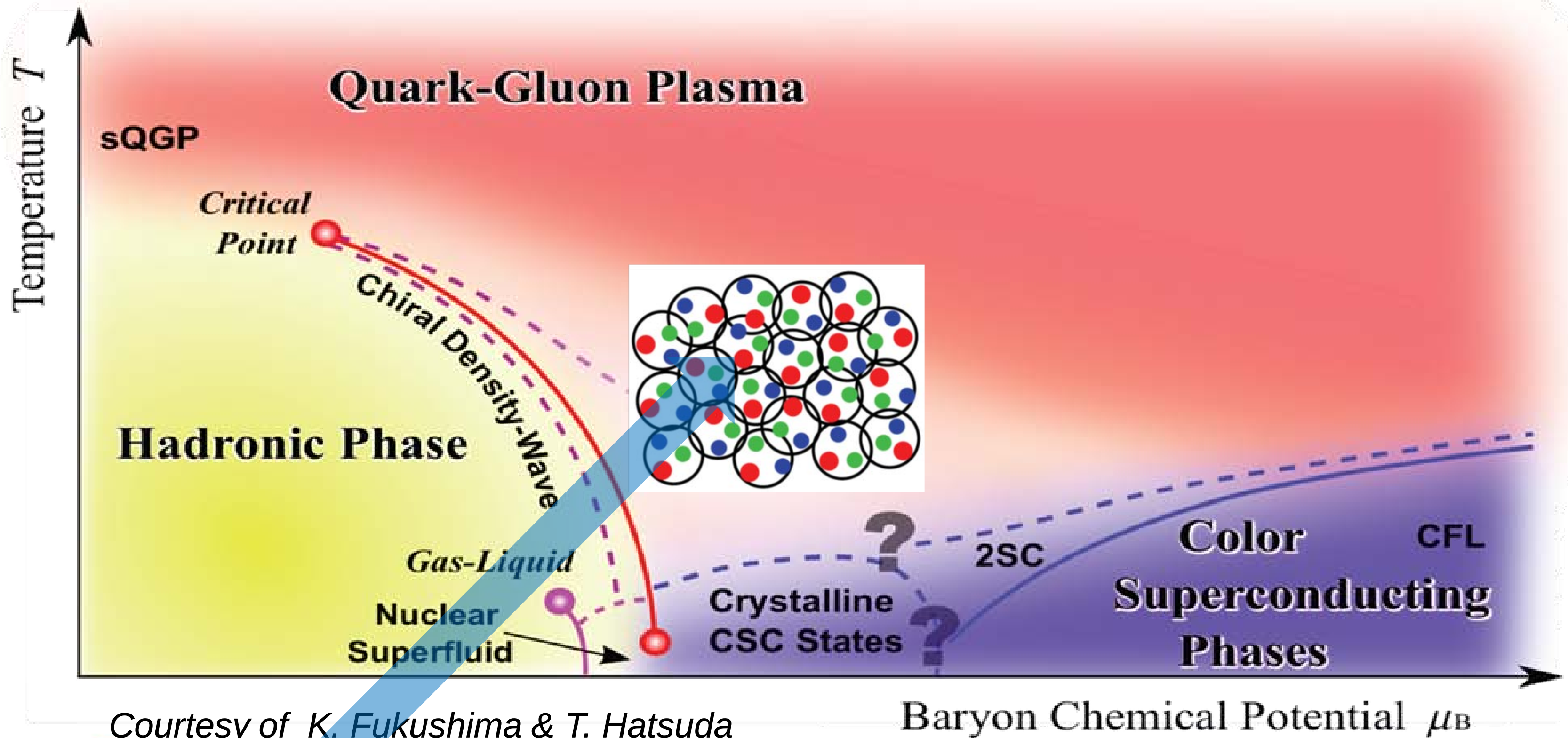
$$\kappa = 9\rho^2 \frac{\partial^2}{\partial \rho^2}\left(\frac{E}{A}\right)$$

Science Vol. 298 (2002), Issue 5598, pp. 1592-1596

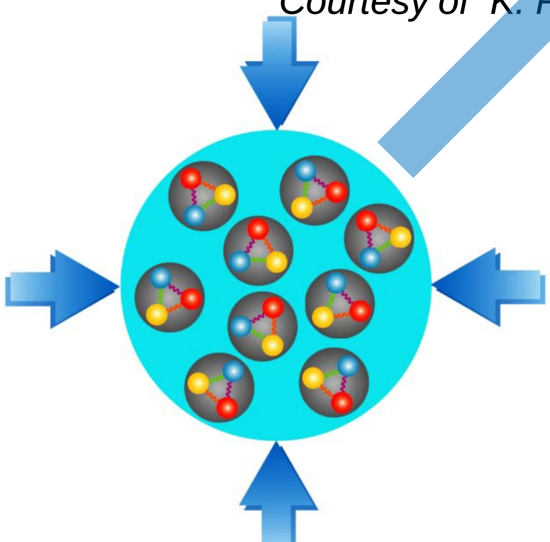




Exploring the QCD phase diagram



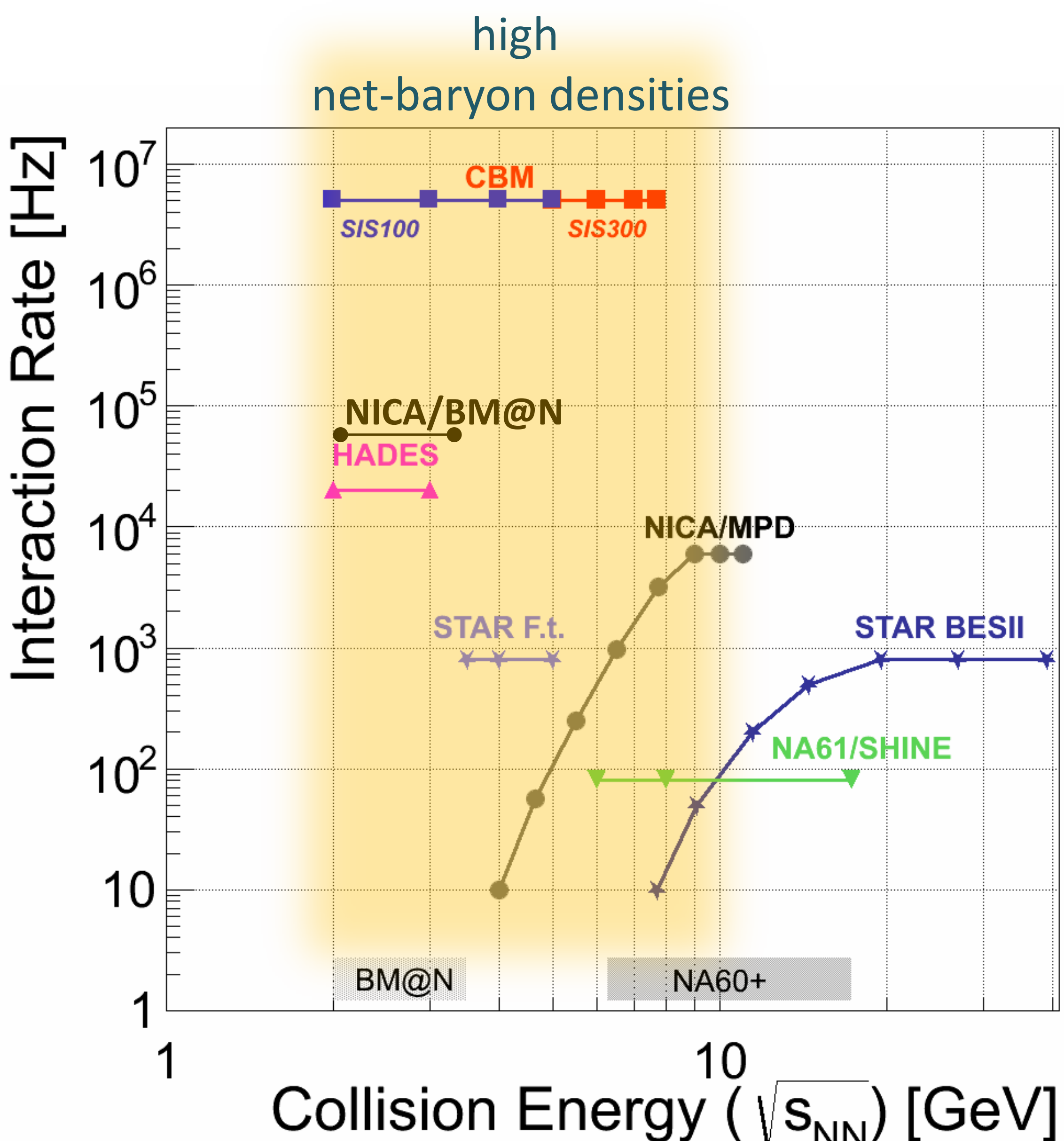
Courtesy of K. Fukushima & T. Hatsuda



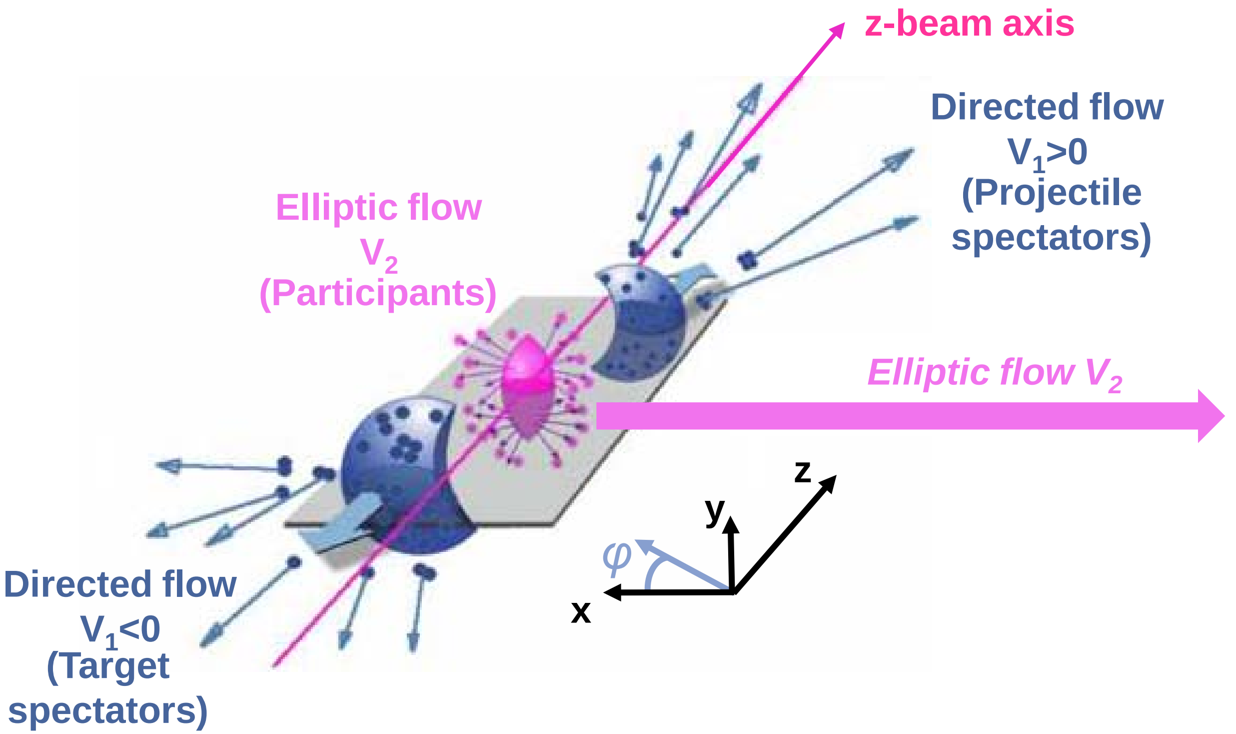
At high baryon density:

- N of baryons >> N of antibaryons
  Densities like in neutron star cores
- L-QCD not (yet) applicable
- Models predict first order phase transition with mixed or exotic phases
- Experiments: BES at RHIC, NA61 at CERN SPS, HADES and CBM at GSI/FAIR, NICA at JINR

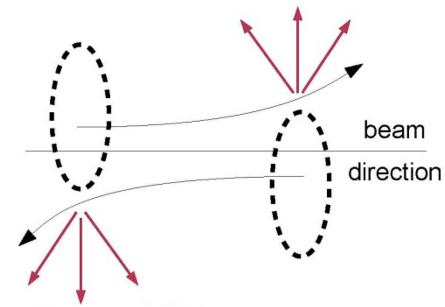
Experiments exploring dense QCD matter



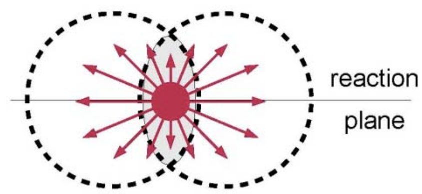
Flow decomposition



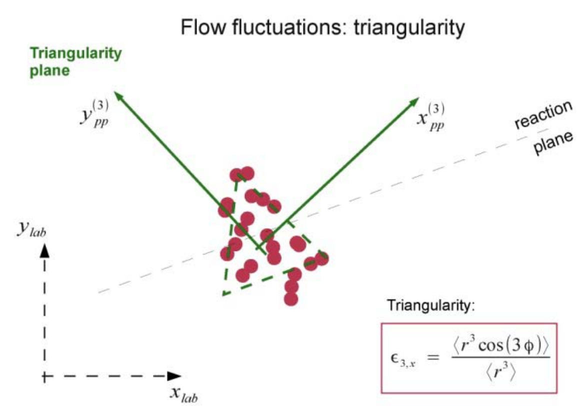
v_1 - directed flow



v_2 - elliptic flow



v_3 - triangular flow



In non-central collisions flow of particles is usually described by Fourier decomposition with respect to reaction plane:

$$\frac{dN}{d(\Delta\phi)} \sim 1 + 2\sum_{n=1} v_n(p_t,\eta)\cos(n\Delta\phi)$$

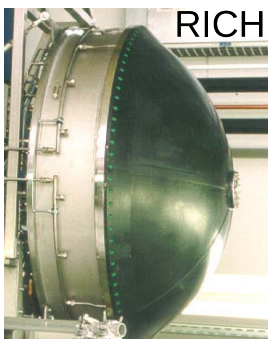
A.Kugler:ICNFP2017

Experimental layout: HADES@SIS18

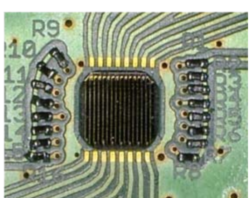
- installed at GSI SIS 18
- six identical sectors
- almost full azimuthal angle
- polar angle 18° - 85°
- high rate counting ~50kHz event rate

Toroidal Magnet

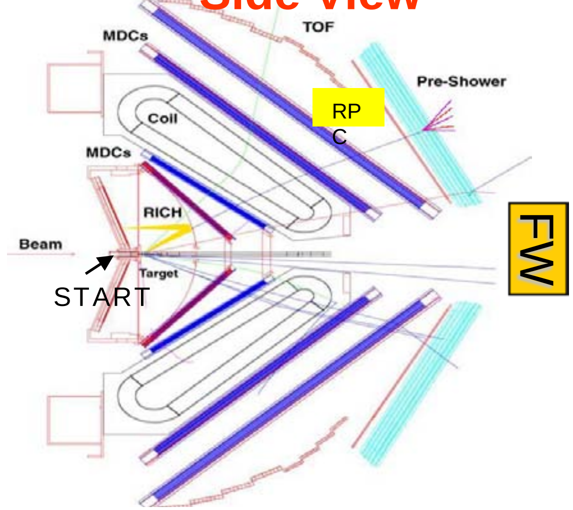
RICH



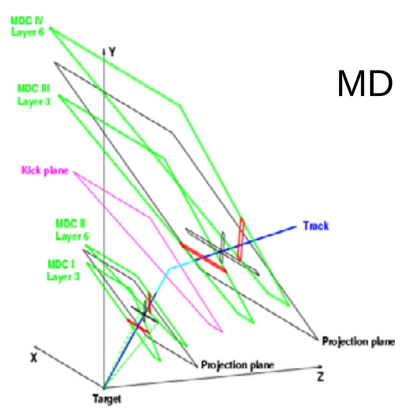
Start detector



Side View

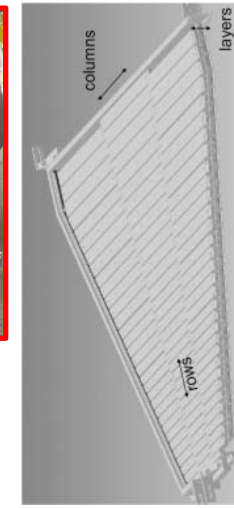


MDC

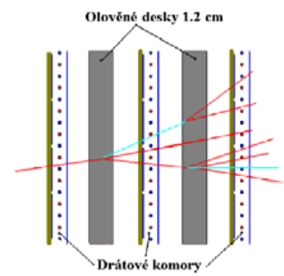


TOF

RPC



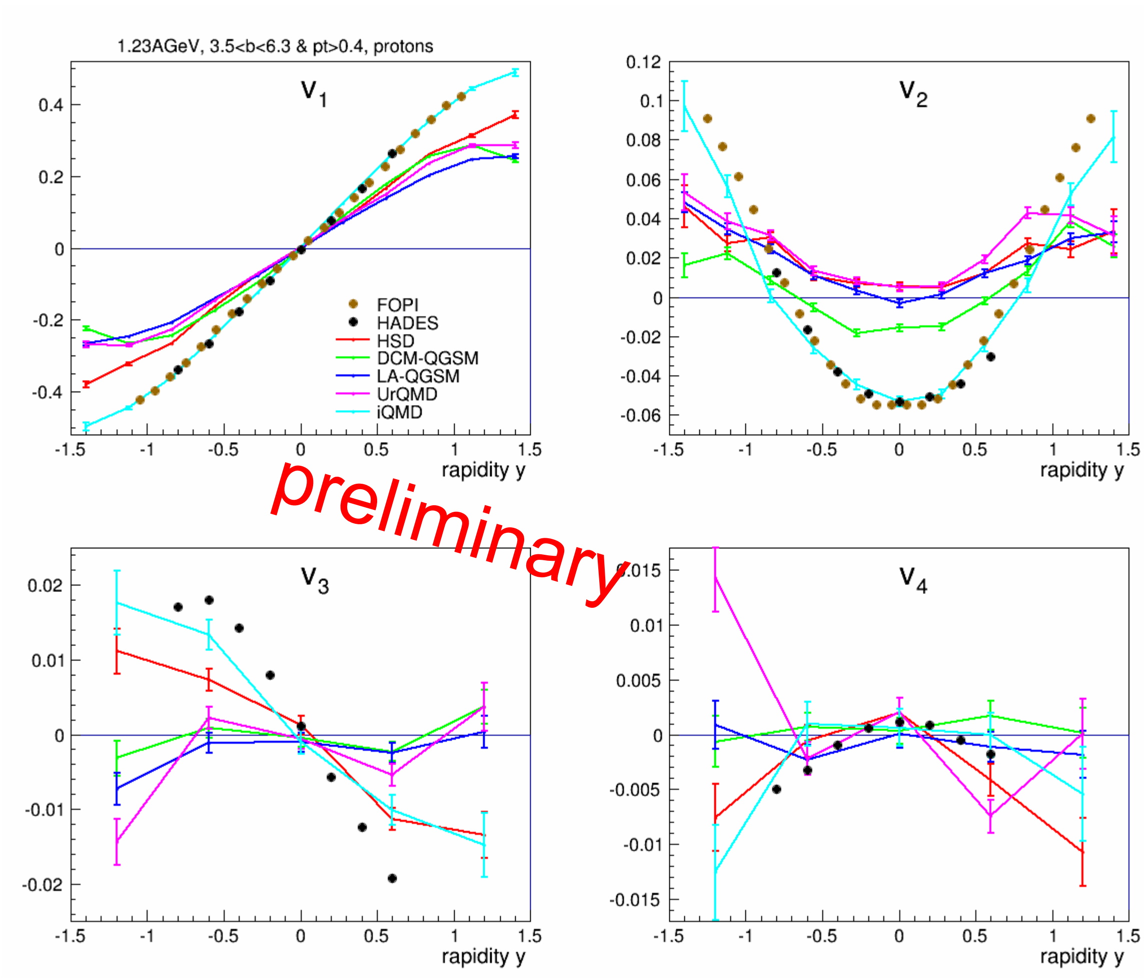
Shower



Forward hodoskope

Proton flow @ SIS18

Upgraded HADES; high statistics data sample; Au+Au @ 1.23 A GeV

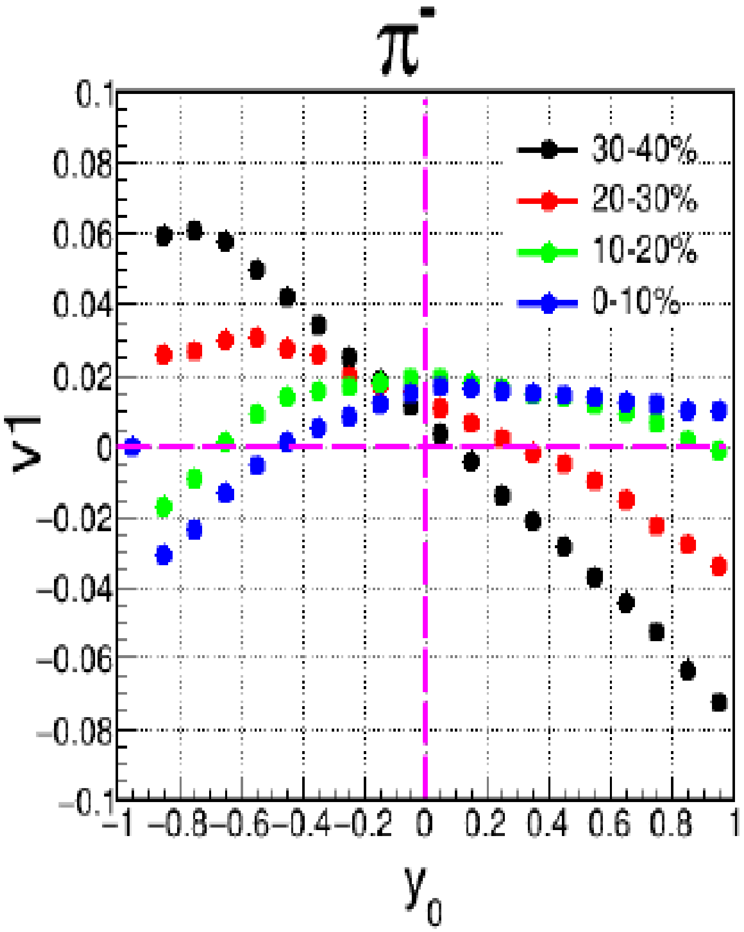


- $4x10^9$ events (HADES)
- v1&v2 from FOPI and HADES agree
- data described by IQMD with soft EOS & momentum dependence
- other models do not describe data below 2 AGeV
- non-zero triangular v3 component described by IQMD

Transport models:

100k events provided by Yvonne Leifels (IQMD), Volker Friese (UrQMD), Marina Golubeva (DCM-QGSM), Konstantin Gudima (LA-QGSM), Elena Bratkovskaya (HSD). Calculations by V.Mikhaylov,

Charged Pion flow @SIS18



Problem: Observed directed flow did not vanish at midrapidity!!!

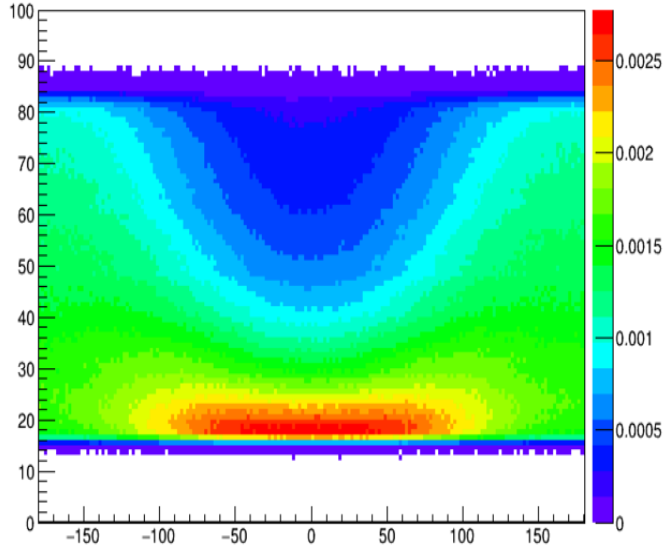
V1(0)≠0

Detector effect?

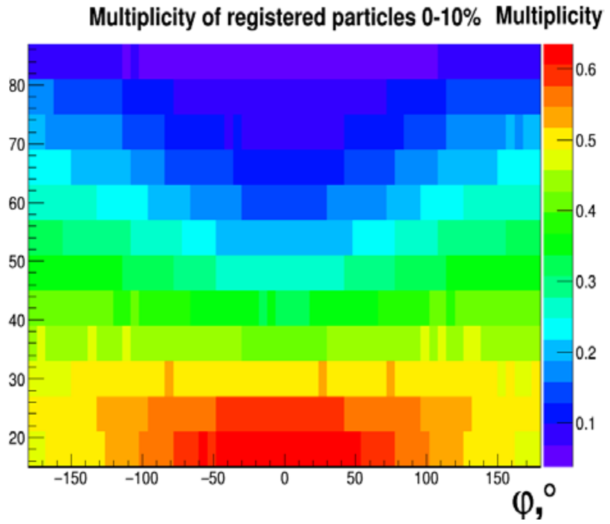
Charged Pion flow @SIS18

- Particle multiplicity variation more than factor of 2 along Δφ in single event
- Reconstruction efficiency depends on particle multiplicity.
- Flow data distorted due to efficiency loss at high particle multiplicity
- correction must be done on **event per event basis**

Experiment

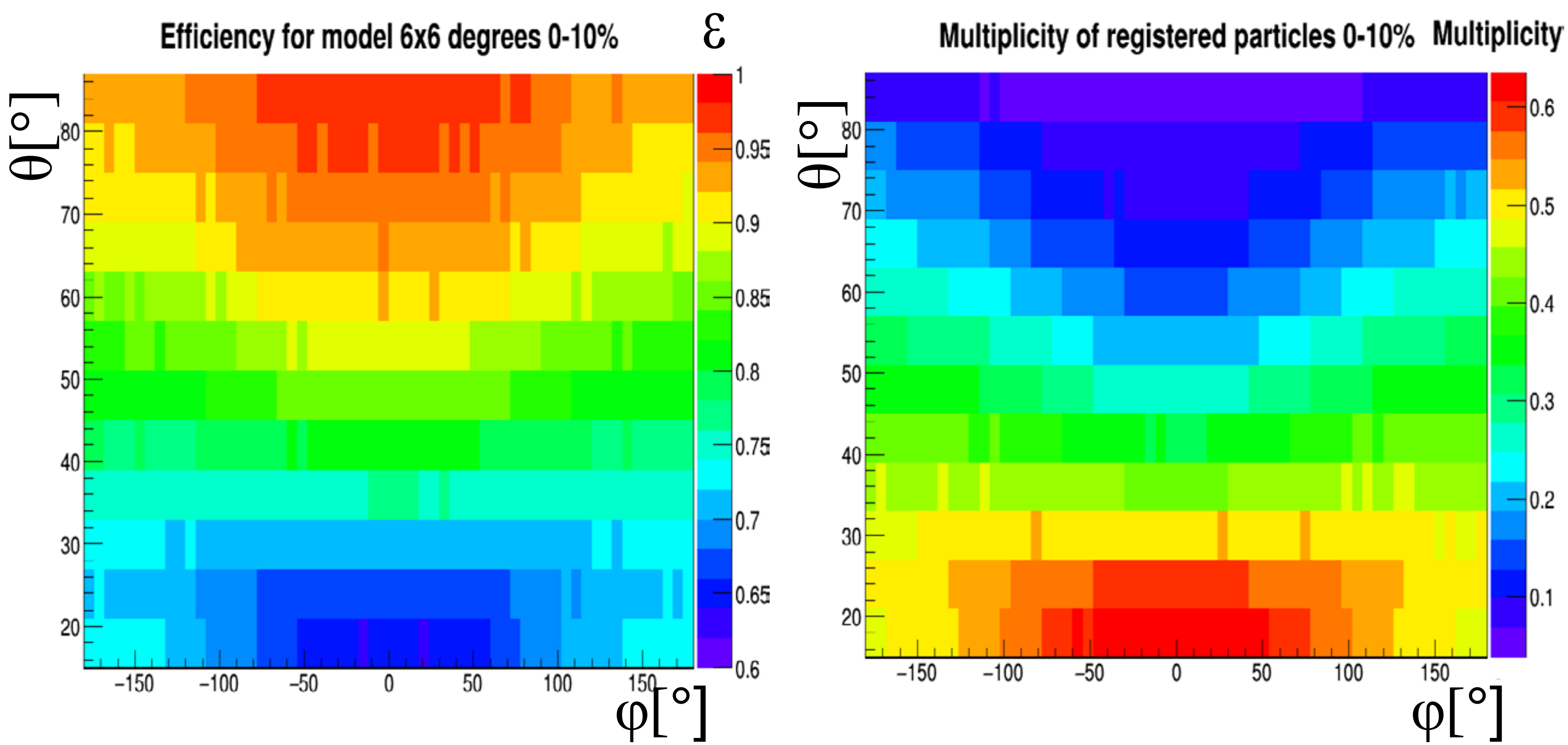


Simulation



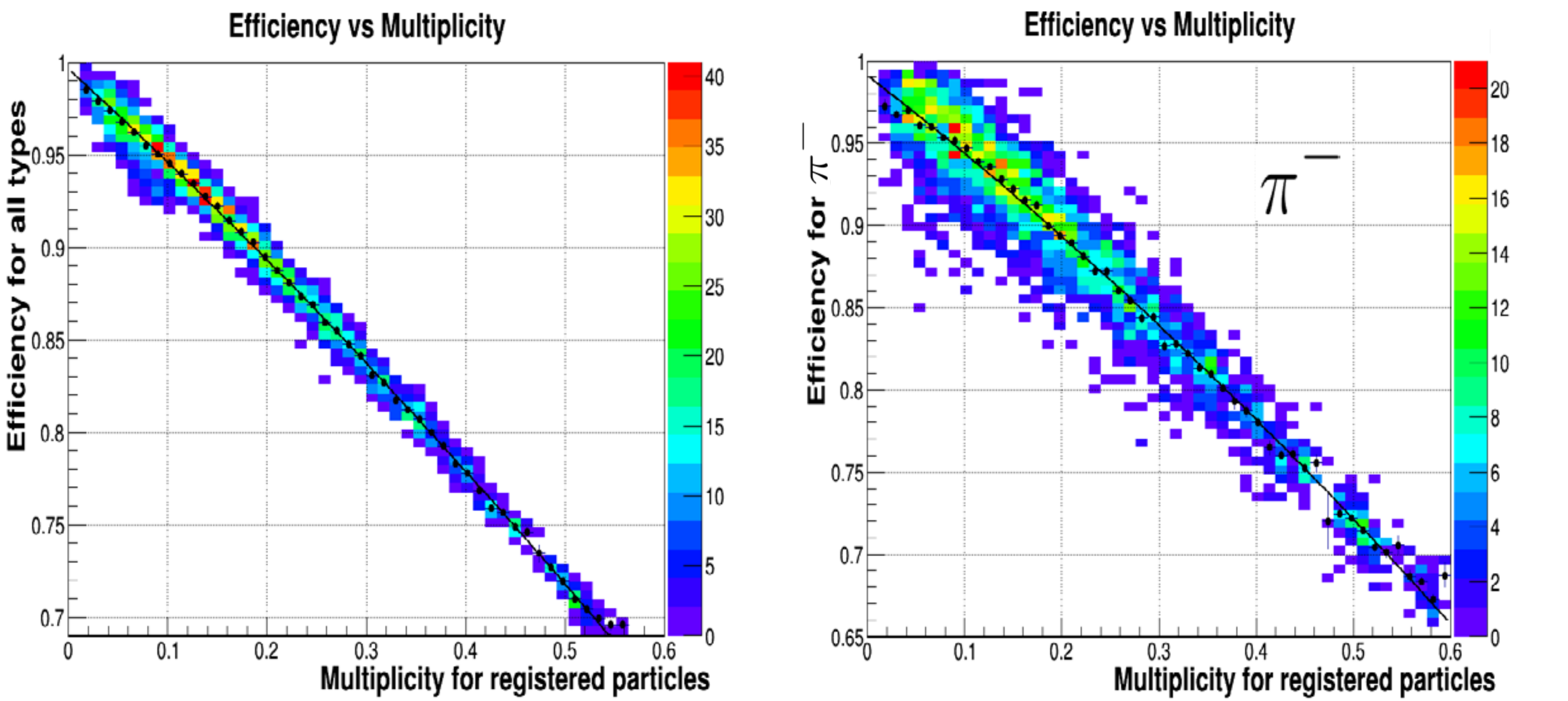
Track multiplicity in ϑ vs Δφ space per event dominated by protons

Simulations: Efficiency of registration



Efficiency of registration is a number between 0 and 1 showing which part of all particles was registered

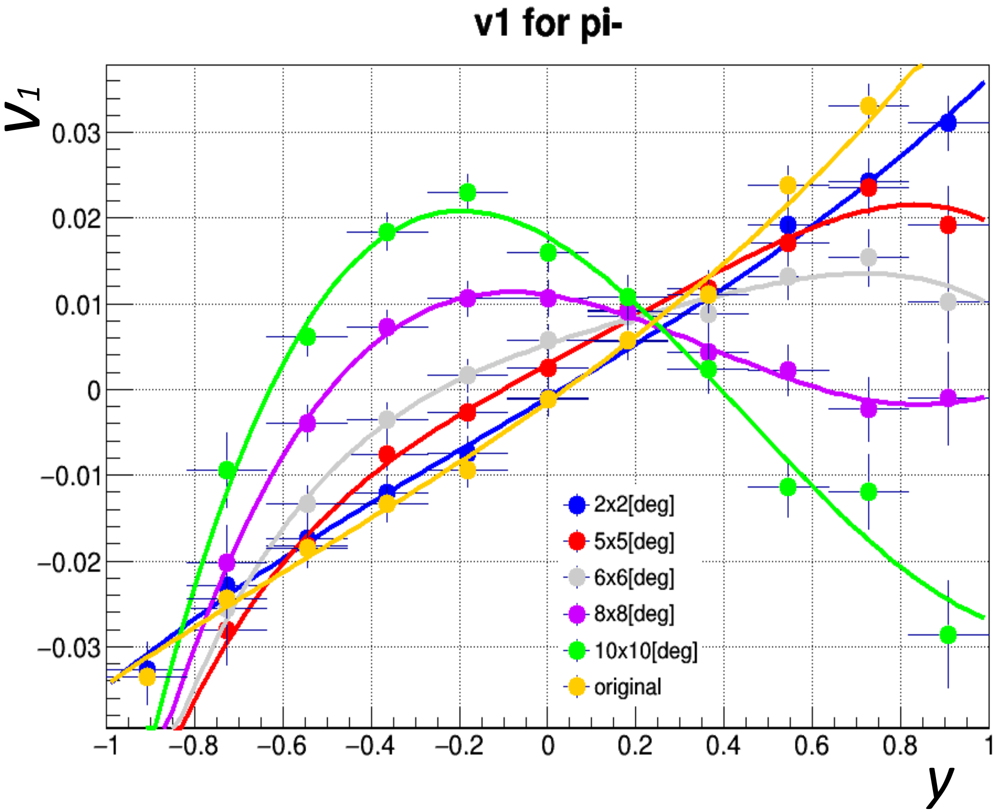
Efficiency dependence on multiplicity



$$\varepsilon = 1 - k * \langle mult \rangle$$

Pions:Simulation of occupancy effect

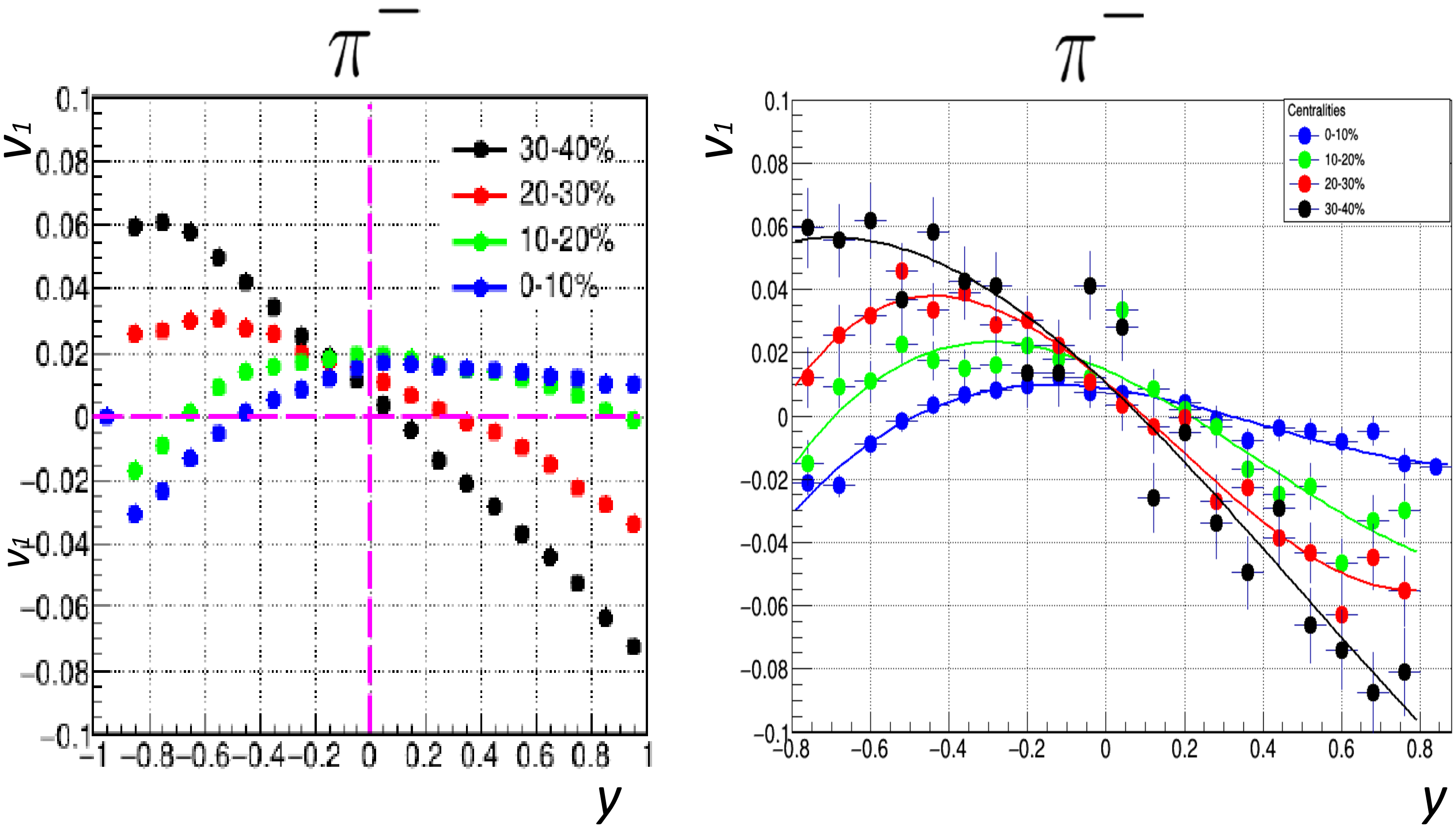
Simulations for different granularity



Pions:Comparison of experiment with simulations

Data without correction

Simulation for indicated centralities



Correction method

- Express efficiency of registration as a linear function of the mean multiplicity of particles

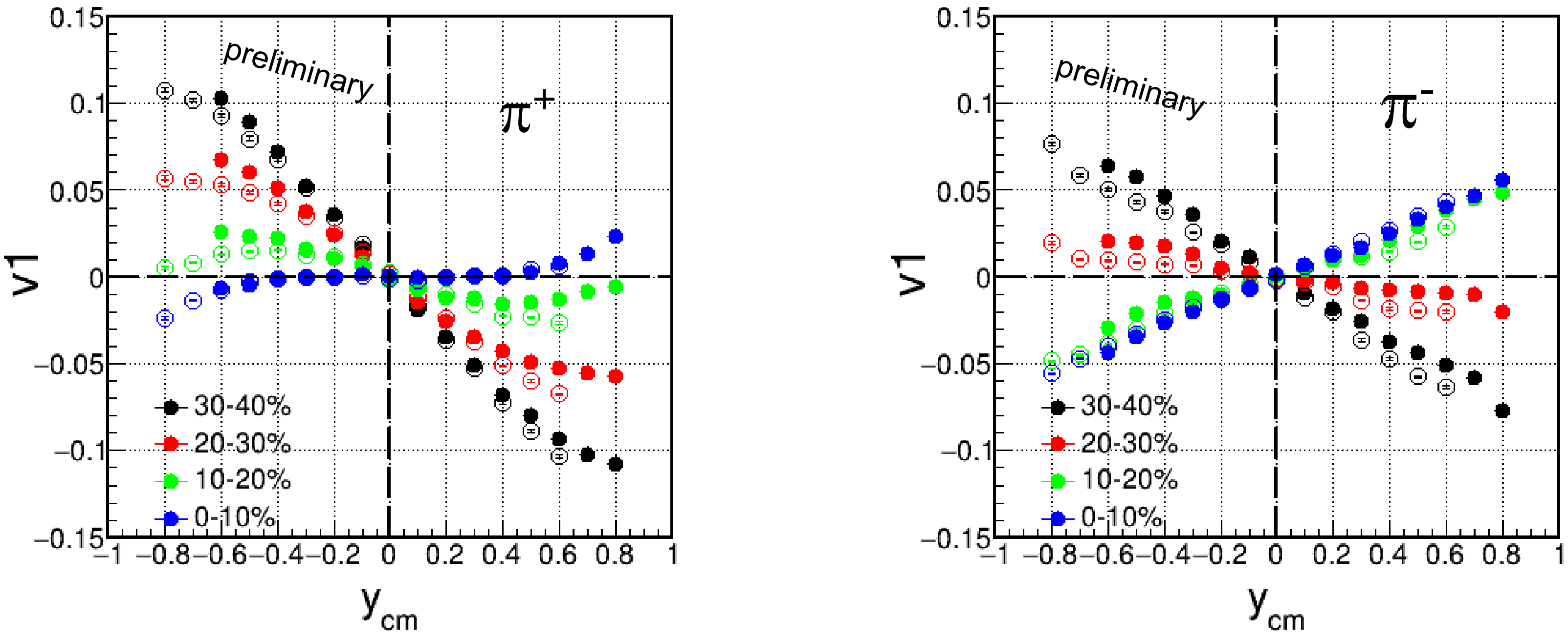
$$\varepsilon = 1 - k * \langle mult \rangle$$

- Construct a correction matrix in the azimuthal and polar angles

- Record the histogram information about the flow taking into account the correction matrix.

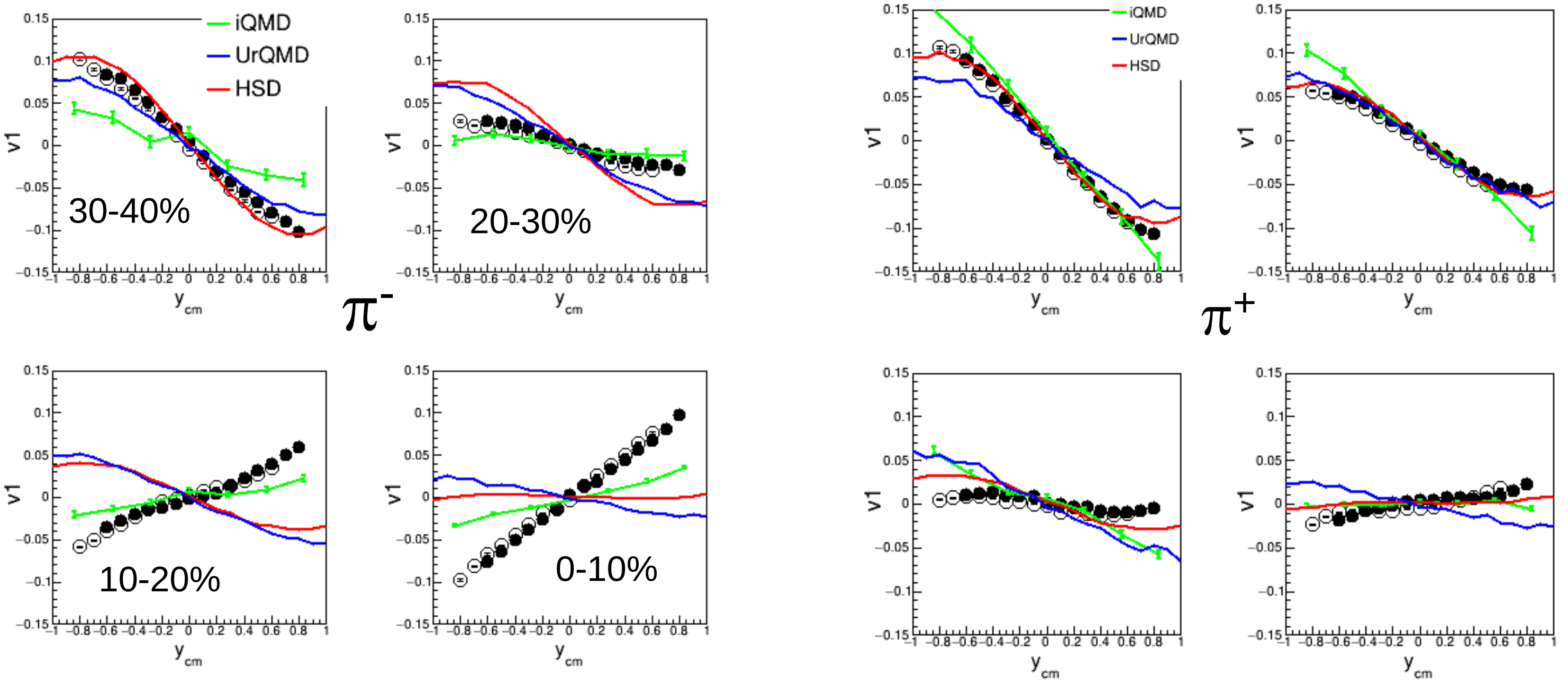
- Select the parameter *k* such that the directed flows are symmetric and pass through the zero point

Charged Pion flow:corrected data



Charged pion flow

Comparison to theory



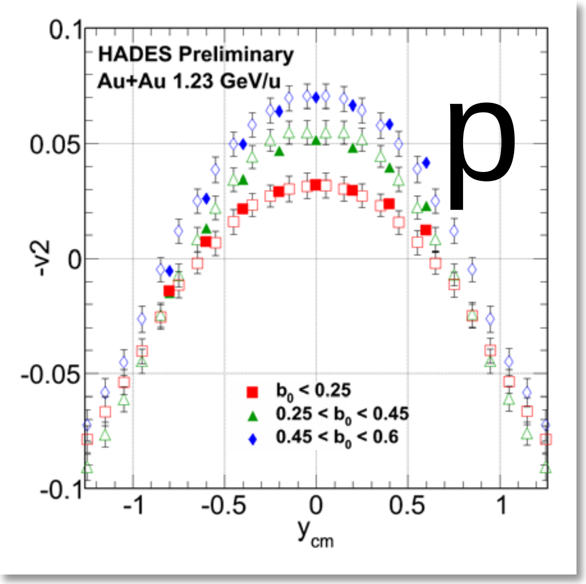
HADES: Flow of Hadrons @ SIS18

Physics case

Nuclear matter equation-of-state at high net-baryon densities

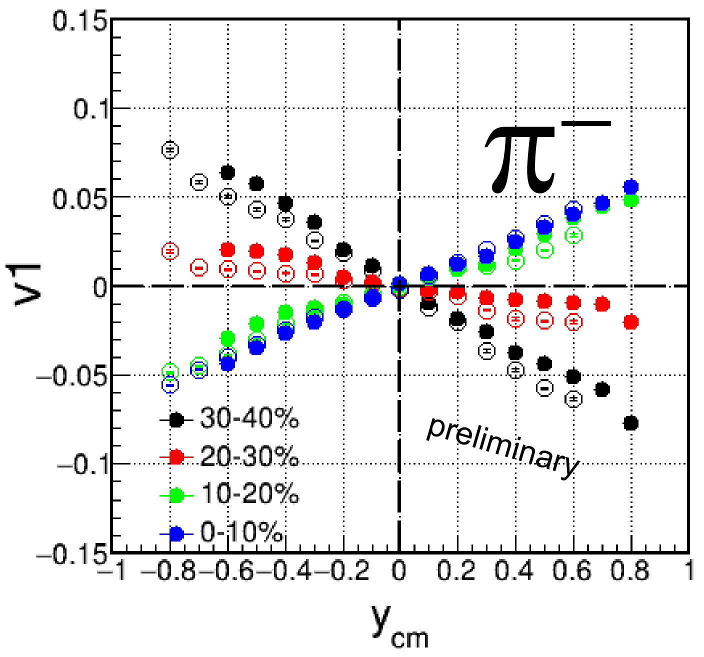
Observables

Excitation function of yields, spectra, and collective flow of (strange) hadrons in heavy-ion collisions

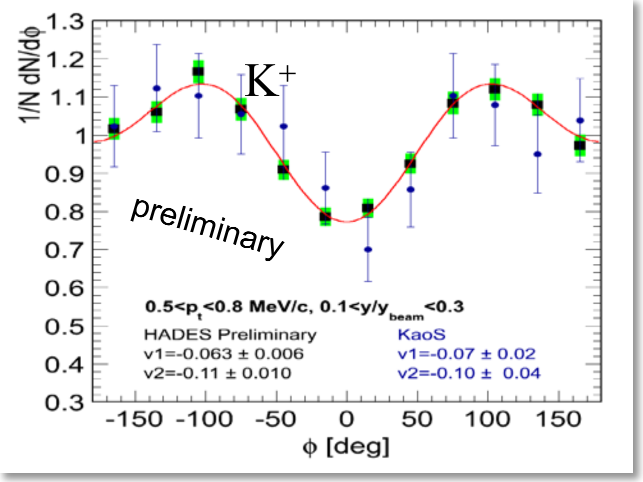


Open symbols: W. Reisdorf et. al. FOPI collab. Nucl. Phys. A 876 (2012)

Au+Au 1.23 *A*GeV

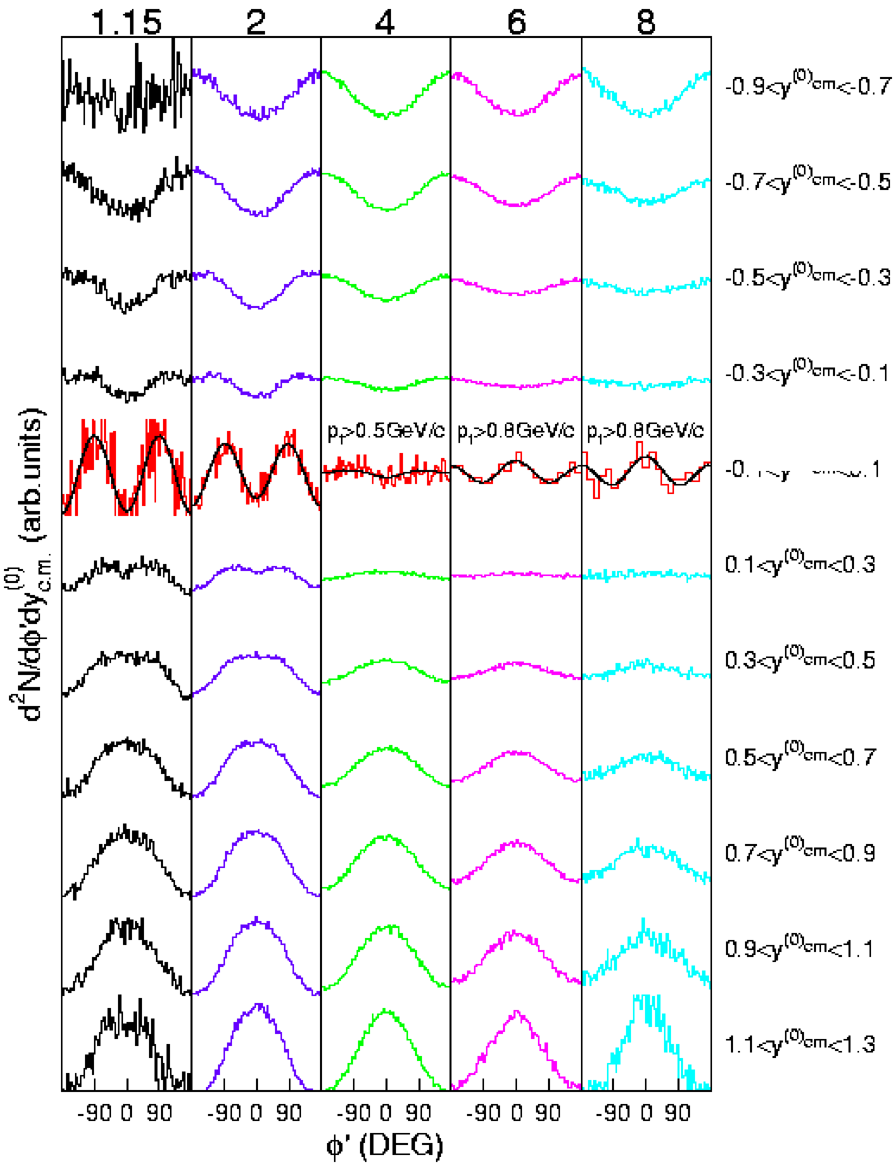


Au+Au 1.23 *A*GeV



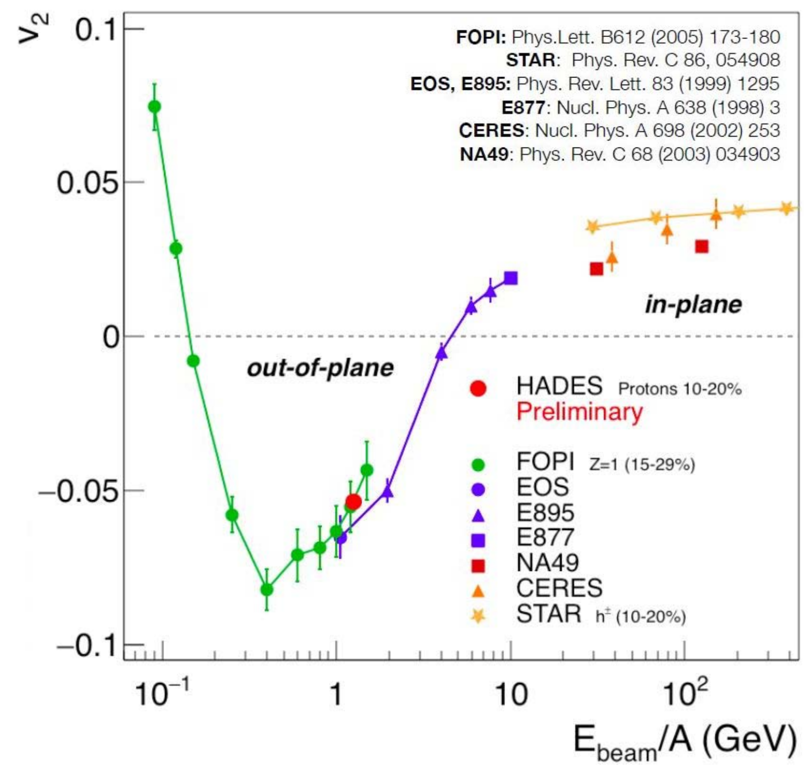
Proton flow @ FAIR energies

Azimutal Distributions with respect to the reaction plane



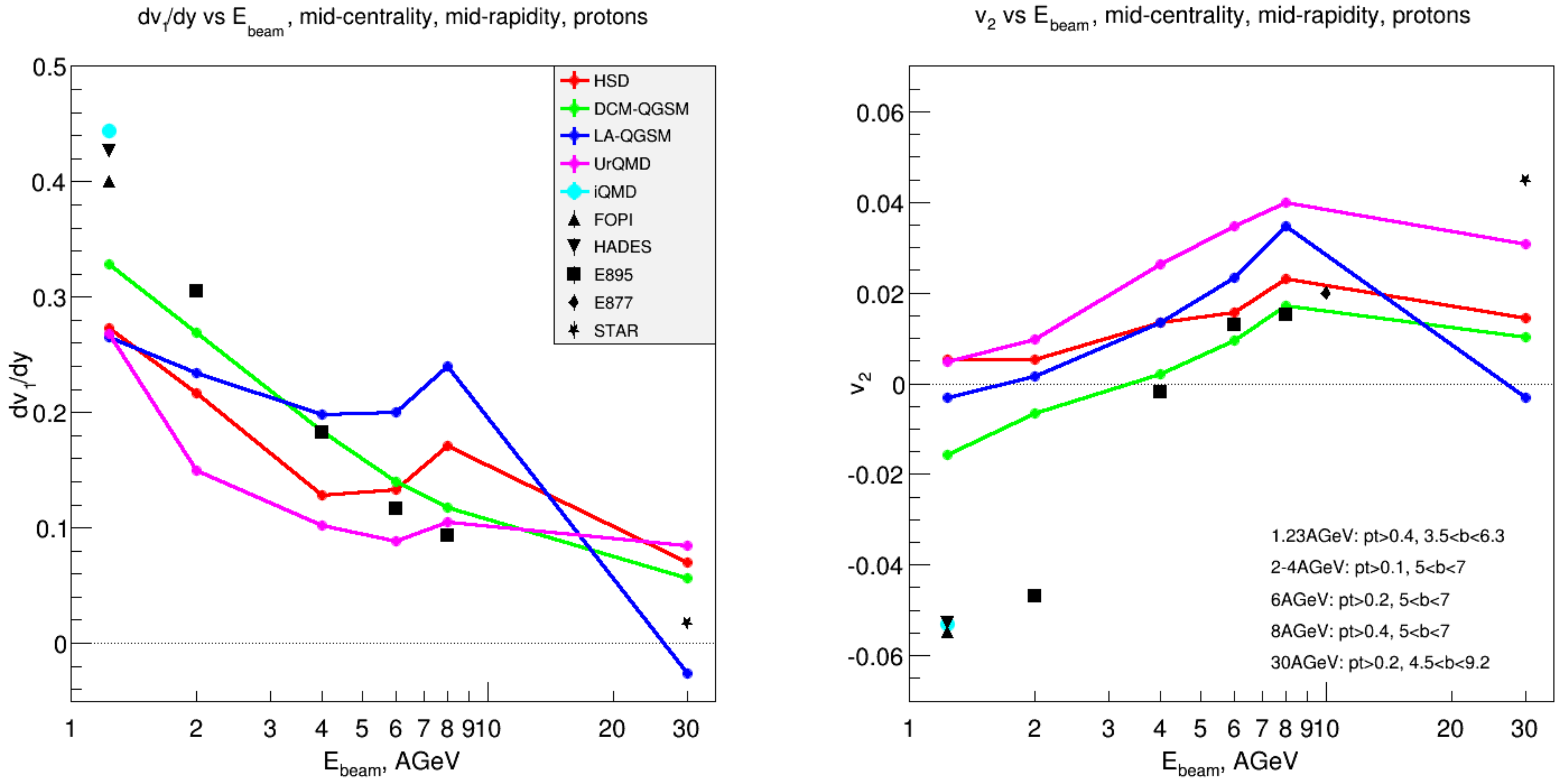
DATA
Reaction: Au + Au
Centrality: 0.5 < Mul< 0.75 Mulmax
(5 fm < b < 7fm)

C.Pinkenburget al., (E895), Phys.Rev.Lett. 83 (1999) 1295
nucl-ex/9903010



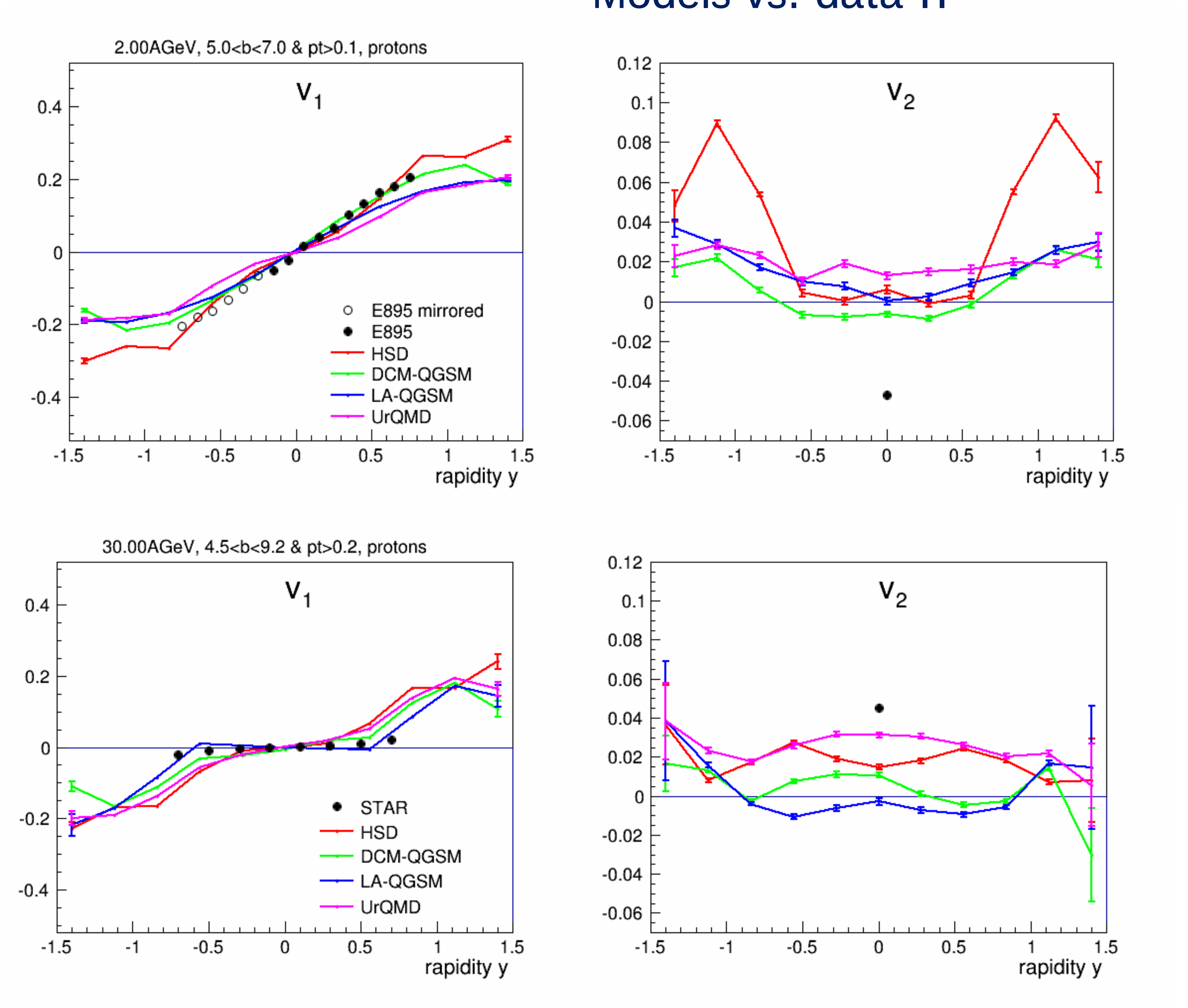
Proton flow @ FAIR energies

Models vs. data I



Proton flow @ FAIR energies

Models vs. data II

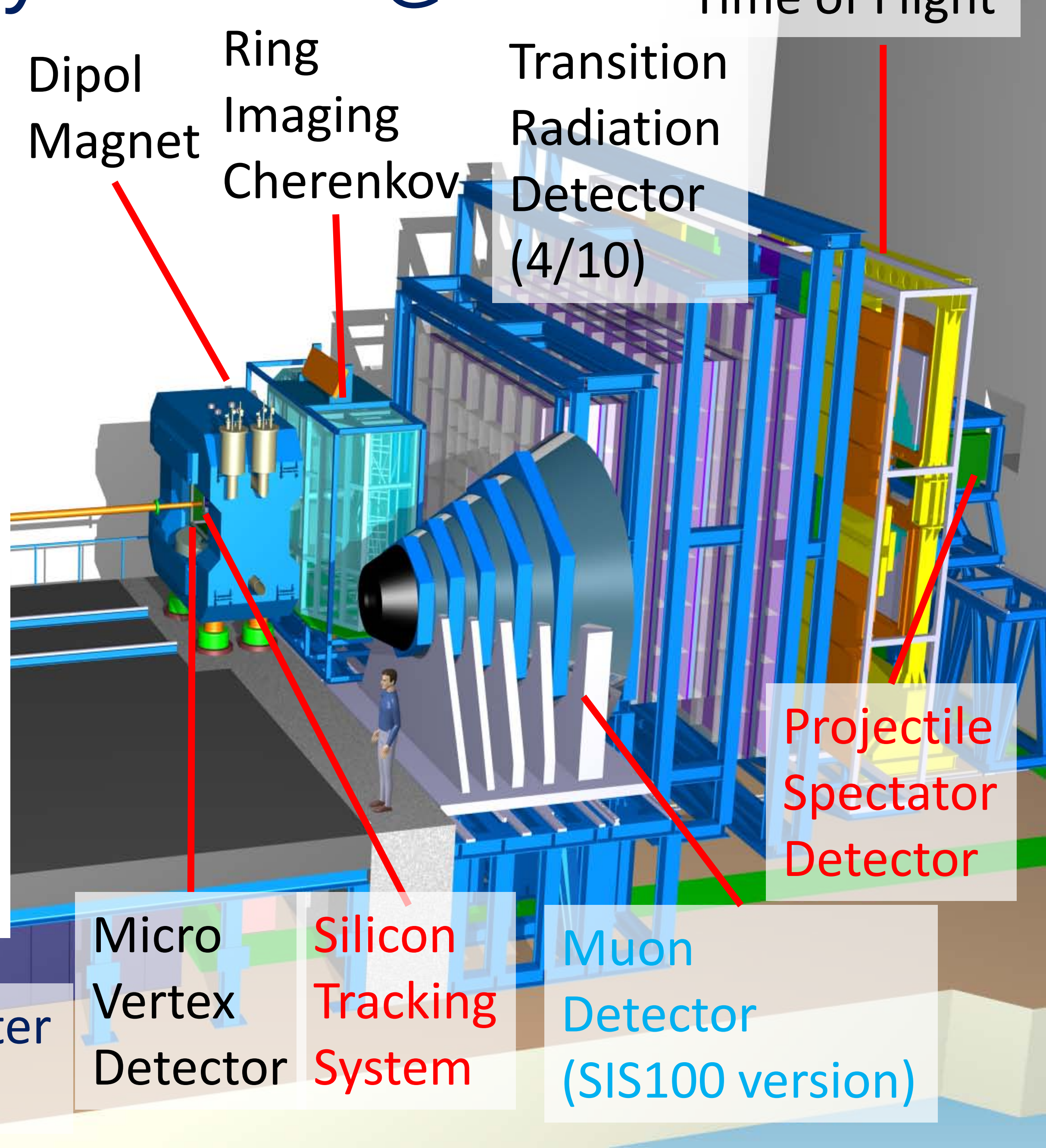


Experimental requirements

- 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 and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

Experimental layout: CBM@FAIR

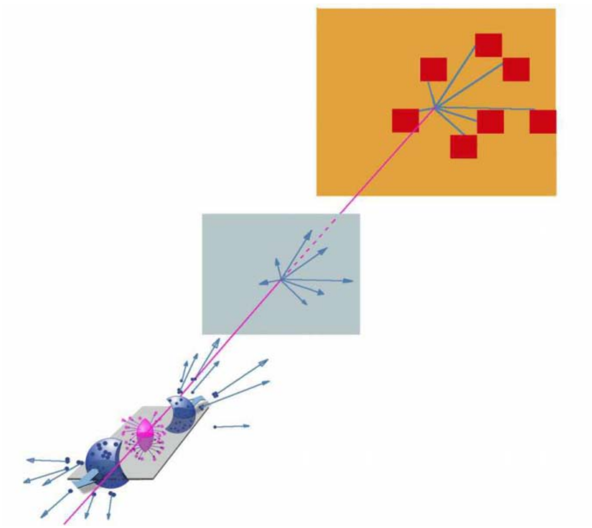
- Dipole magnet – for momentum measurement
- MVD – Pixel detector for vertex determination
- STS – Radiation-hard Silicon strip detector for tracking
- RICH – Ring Imaging Cherenkov detector for electron identification
- TRD – Transition Radiation Detectors for electron identification
- RPC – Resistive Plate Chambers for time-of-flight measurement
- PSD – Projectile Spectator Detector for centrality and reaction plane determination
- Muon – detector for muon identification



CBM: Projectile Spectator Detector

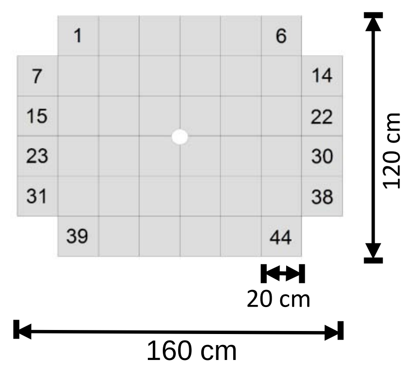
Full compensating modular lead-scintillator sandwich calorimeter

- Measurement of centrality: *$b \sim A - N_{spect}$*
- Reconstruction of the reaction plane



Main features:

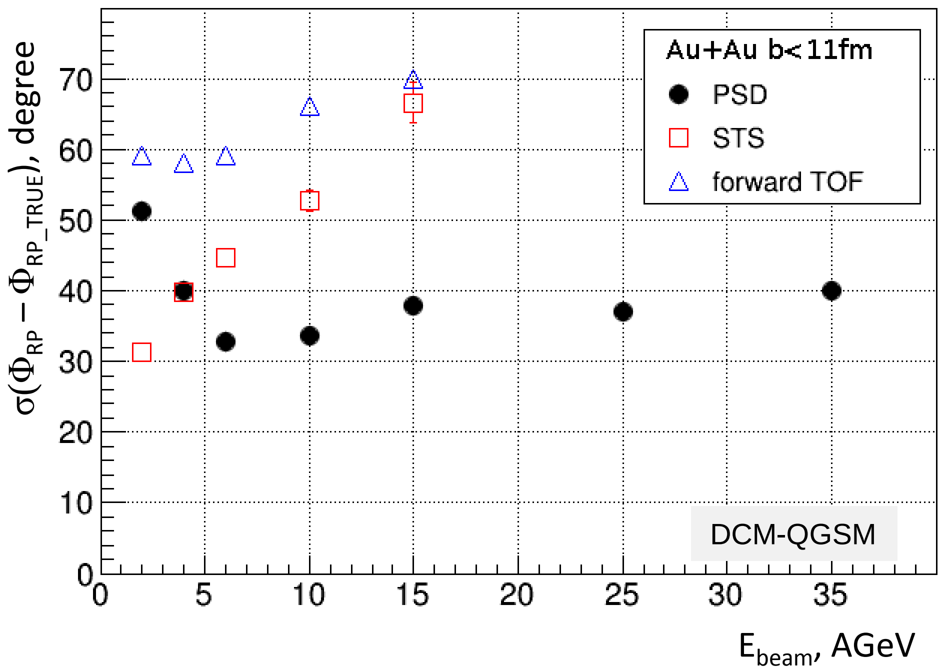
- high transverse granularity
  transverse homogeneity of energy resolution,
  reaction plane measurements
- lead/scintillator sampling ratio 4:1 (16 mm / 4 mm),
  compensating calorimeter (e/h = 1)
  high energy resolution <60%/√E(GeV)
- longitudinal segmentation (10 sections per module)
  particle identification, calibration, improved energy resolution
- light readout from each section by novel APDs
  large dynamic range up to 10^4 ph.el.,
  no nuclear counting effect
- ability to operate at high count rate and at high radiation dose



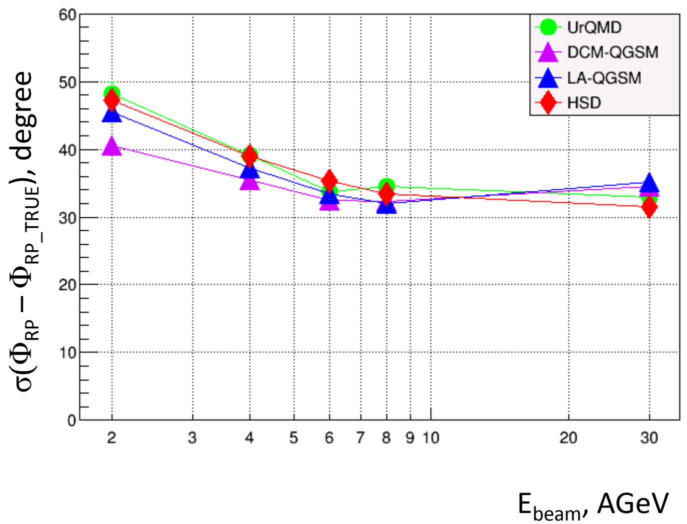
60 sandwiches in one module
45 modules of 20 x 20 x 120 cm^3
Total weight ~ 22 tons, 8 m (SIS100) / 15 m (SIS300) from target
Beam hole (d = 6 cm) for intensity up to 10^9 ions/sec
CBM beam energy up to 11 AGeV (SIS100) / 35 AGeV (SIS300)

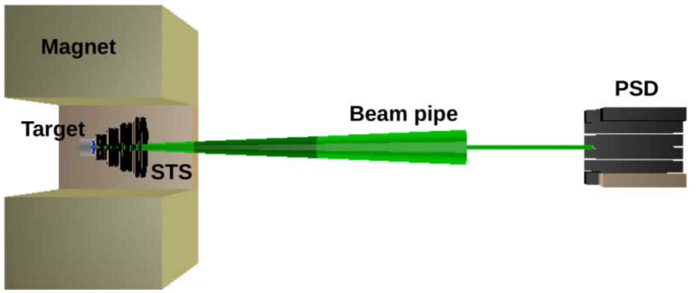
CBM PSD: flow

Reaction plane resolution, σ



Reaction plane resolution

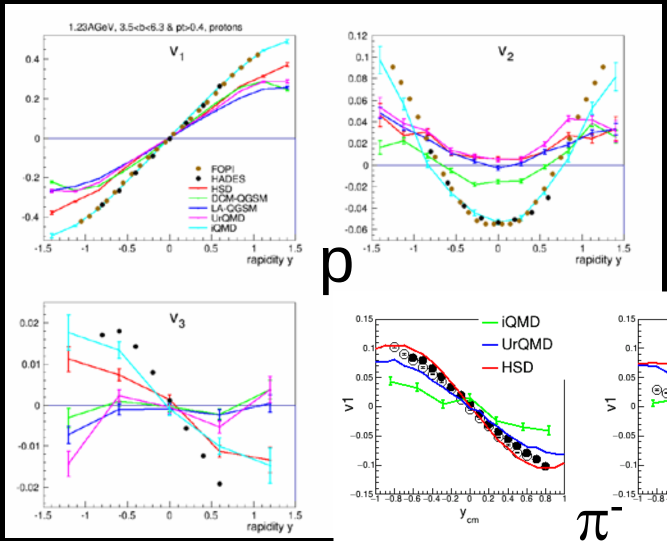


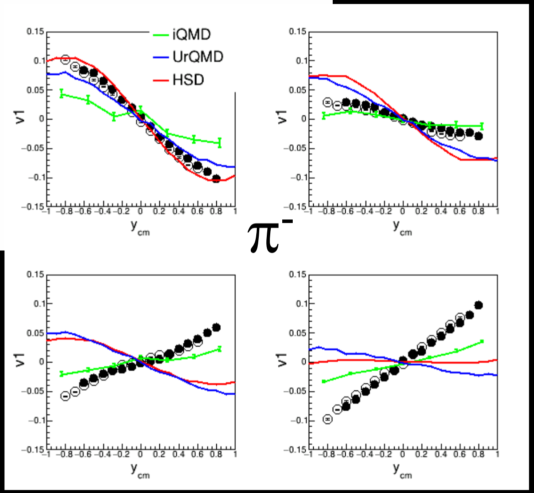


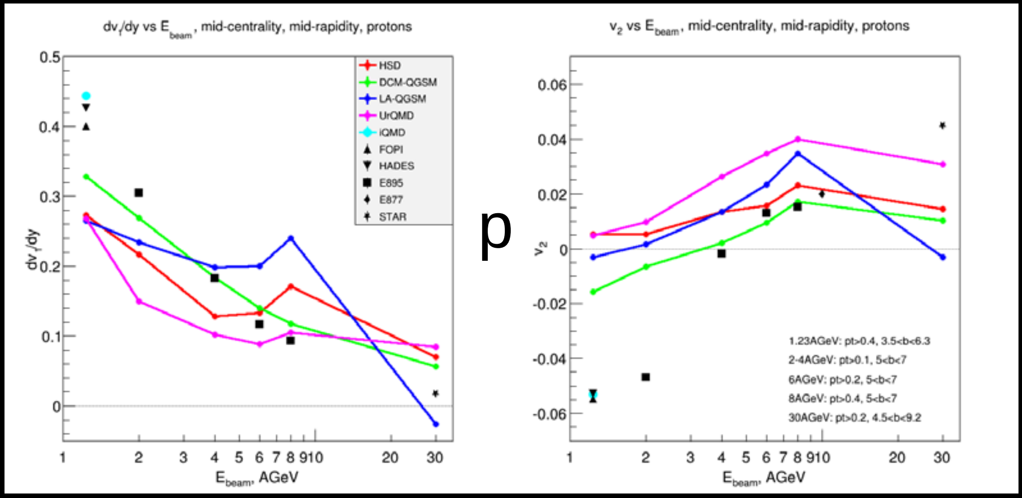
- PSD significantly improves the resolution at energies higher than 4 AGeV.
- Collision event plane resolution is sufficient for precision measurements of directed (v_1) and elliptic (v_2) flow with CBM after a few months of operation

Summary

- High statistic data sample for Au+Au @1.23 A GeV obtained by HADES @SIS18
- Directed (v1) and Elliptic (v2) and even Triangular (v3) flow observed for protons in data is properly described in IQMD described in IQMD simulations@SIS18
- However flow of charged pions is not properly described by any model @SIS18
- FAIR energy range: current models fail to describe even proton flow
- to come: multi-strange hadrons, strange matter, fluctuations, flow anisotropies, dileptons ….







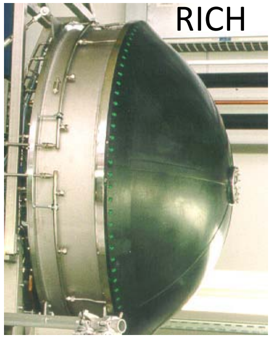
THANK YOU

Experimental layout: HADES @ FAIR

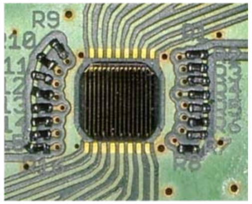
- installed at GSI SIS 18 will move to CBM cave at FAIR
- six identical sectors
- almost full azimuthal angle
- polar angle 18° - 85°
- high rate counting ~50 kHz event rate

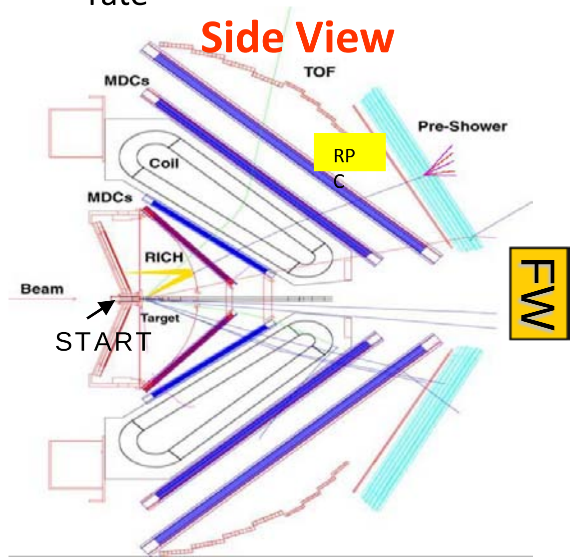
Toroidal Magnet

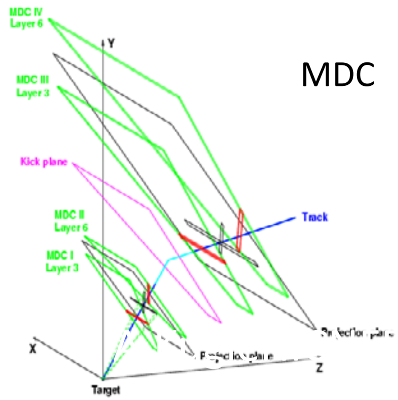
RICH



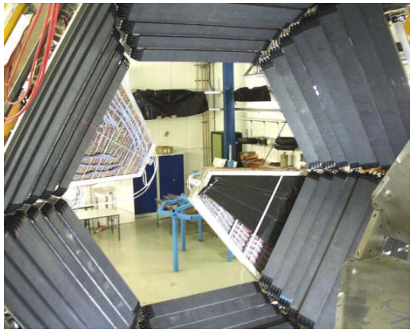
Start detector



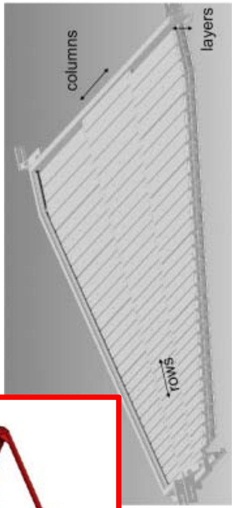


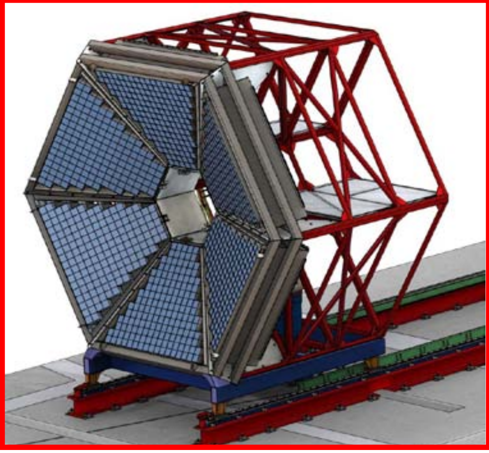


TOF



RPC

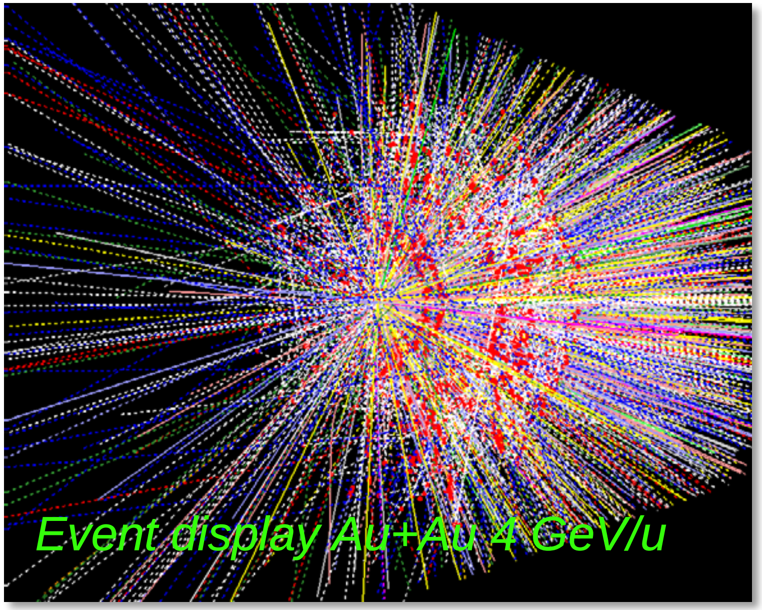




ECAL detector

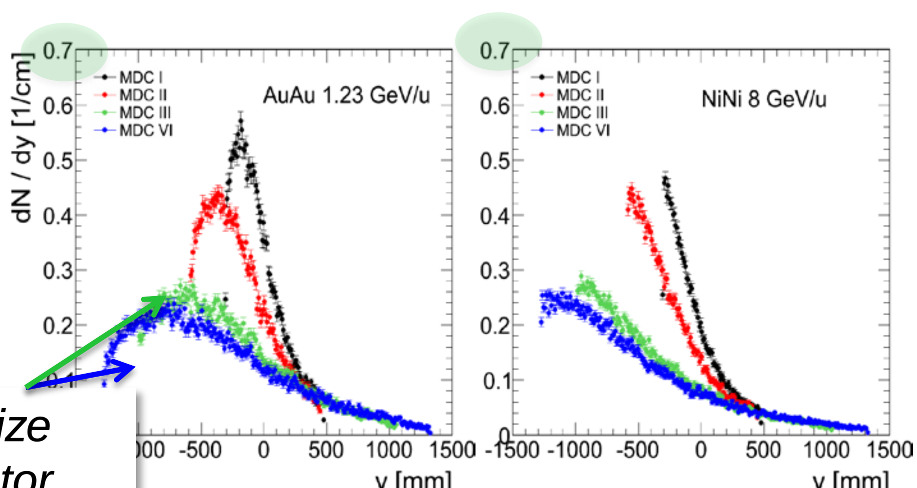
- planned for SIS 100@FAIR
- 978 modules of lead glass + photomultiplier
- polar angle 12° - 45°
- novel electronic for read out

HADES @ FAIR: limits on multiplicity –> up to Ni+Ni colllisions

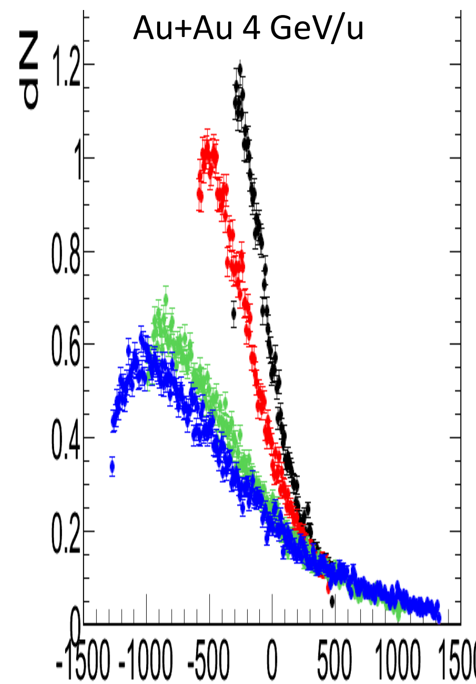


- **Challenge:** limited granularity of MDCI & MDCII →
  - sophisticated tracking algorithm
- Au+Au 1.23 GeV/u successfully measured in May 2012
- Ni+Ni 8 GeV/u ≈ Au+Au at 1.23 GeV/u
- Au+Au 4 GeV/u occupancy increases by factor of 2!

Occupancy in tracking chambers (b_{max} = 1 fm)



Cell size is factor of 2 larger



y – radial coordinate in drift chamber

First measurements with HADES/CBM @FAIR

Hadrons incl. Hyperons, Hypernuclei, Dileptons
in Au+Au (C+C) collisions from 2-11 (2-15) A GeV.

- p,π,K,K*, ρ,ω,ϕ,Λ,Λ,Λ*,Σ*, $Ξ^-$,$Ξ^+$,Ξ*,$Ω^-$,$Ω^+$,Ω*,fragments
- fluctuations, correlations, flow
- determination of centrality and reaction plane.

Physics cases

- Equation-of-state of matter at neutron star core densities
- Phase transitions from hadronic matter to quarkyonic or partonic matter at high net-baryon densities
- Electro-magnetic radiation from the dense fireball (→ temperature, caloric curve)
- Chiral symmetry restoration in dense baryonic matter
- Hypernuclei: Λ-N, Λ-Λ interaction

Key experimental requirement: extremely high rates

The HADES collaboration

- → Catania, Italy
- → Coimbra, Portugal
- → Cracow, Poland
- → GSI Damstadt, Germany
- → TU Darmstadt, Germany
- → Dresden, Germany
- → Dubna, Russia
- → Frankfurt, Germany
- → Giessen, Germany
- → Lisboa, Portugal
- → München, Germany
- → Milano, Italy
- → Moscow, Russia
- → Nicosia, Cyprus
- → Orsay, France
- → Rez, Czech Rep.
- → Santiago de Compostela, Spain

18 institution partners
~100 collaborators

The CBM Collaboration: 60 institutions, 530 members

Croatia:
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungary:
KFKI Budapest
Budapest Univ.

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FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
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Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
Tübingen Univ.
Wuppertal Univ.
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Bose Inst. Kolkata
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
IOP Bhubaneswar
IIT Kharagpur
IIT Indore
Gauhati Univ.

Korea:
Pusan Nat. Univ.

Romania:
NIPNE Bucharest
Univ. Bucharest

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Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.
Warsaw TU

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Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
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