Measurements and understanding of fundamental properties of hot and dense nuclear matter with HADES

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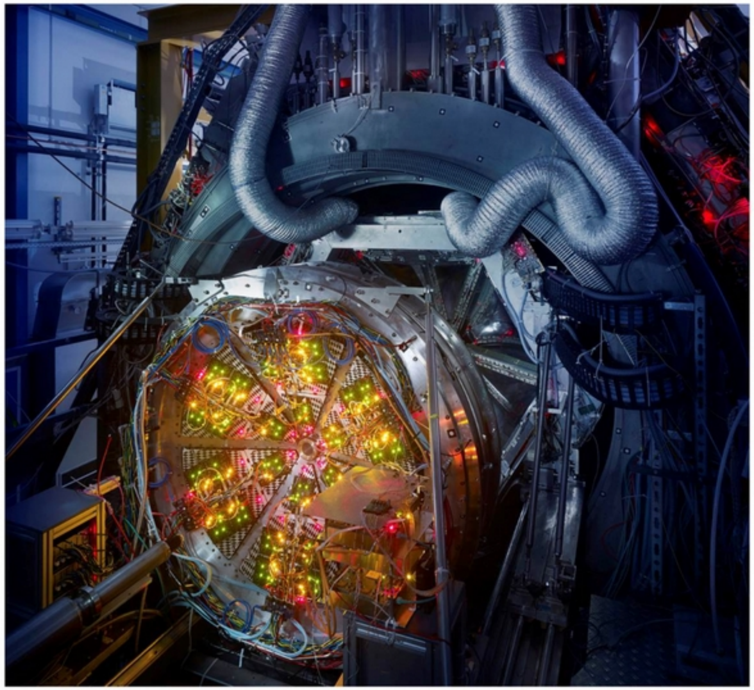
for the HADES Collaboration



- Motivation
- HADES
- Hadronic probes
- Electromagnetic probes
- Collective properties
- Future
- Summary

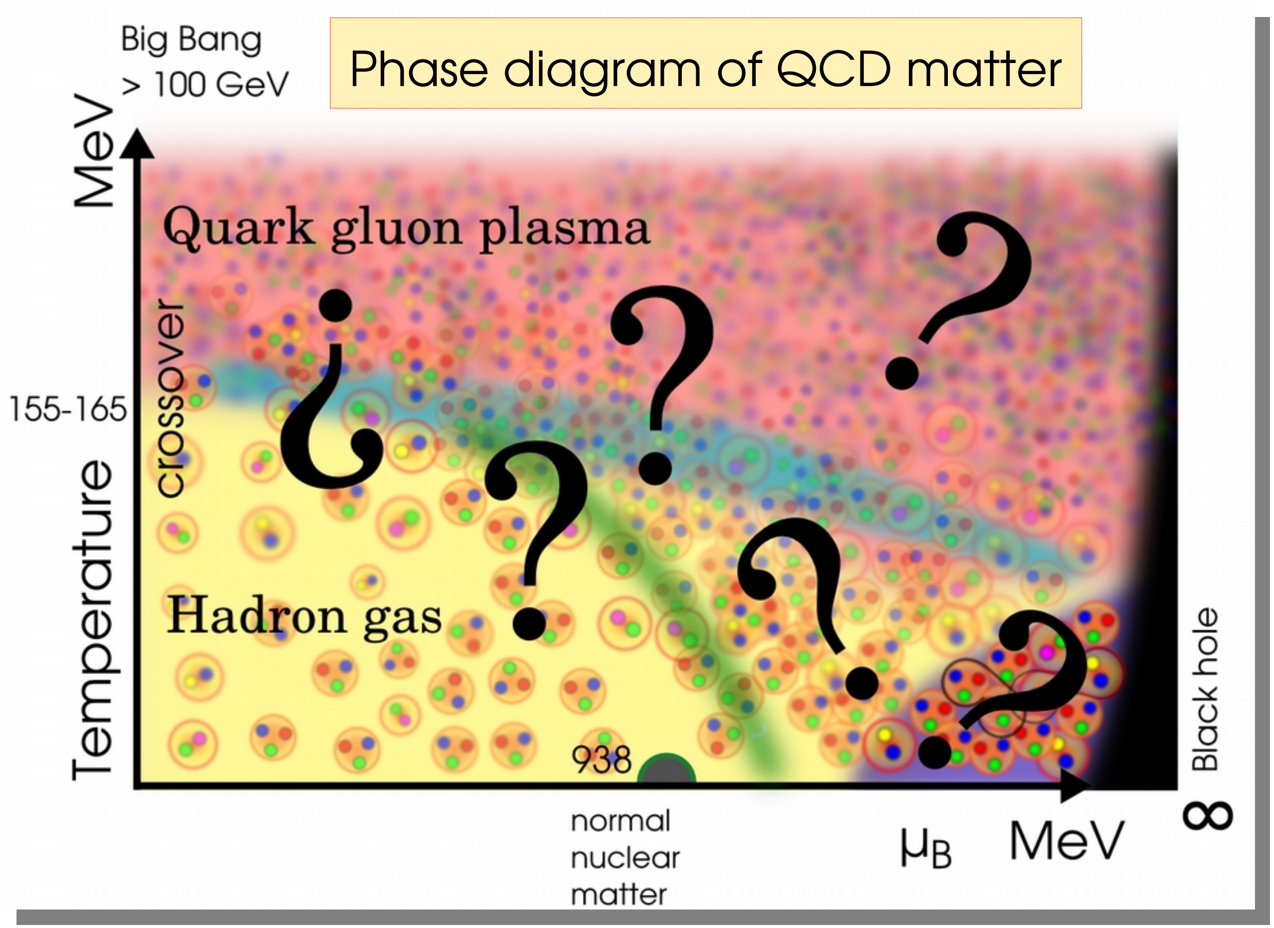
Mass generation mechanisms: from where visible matter gets its mass?

Color confinement: why do free quarks have not been observed?

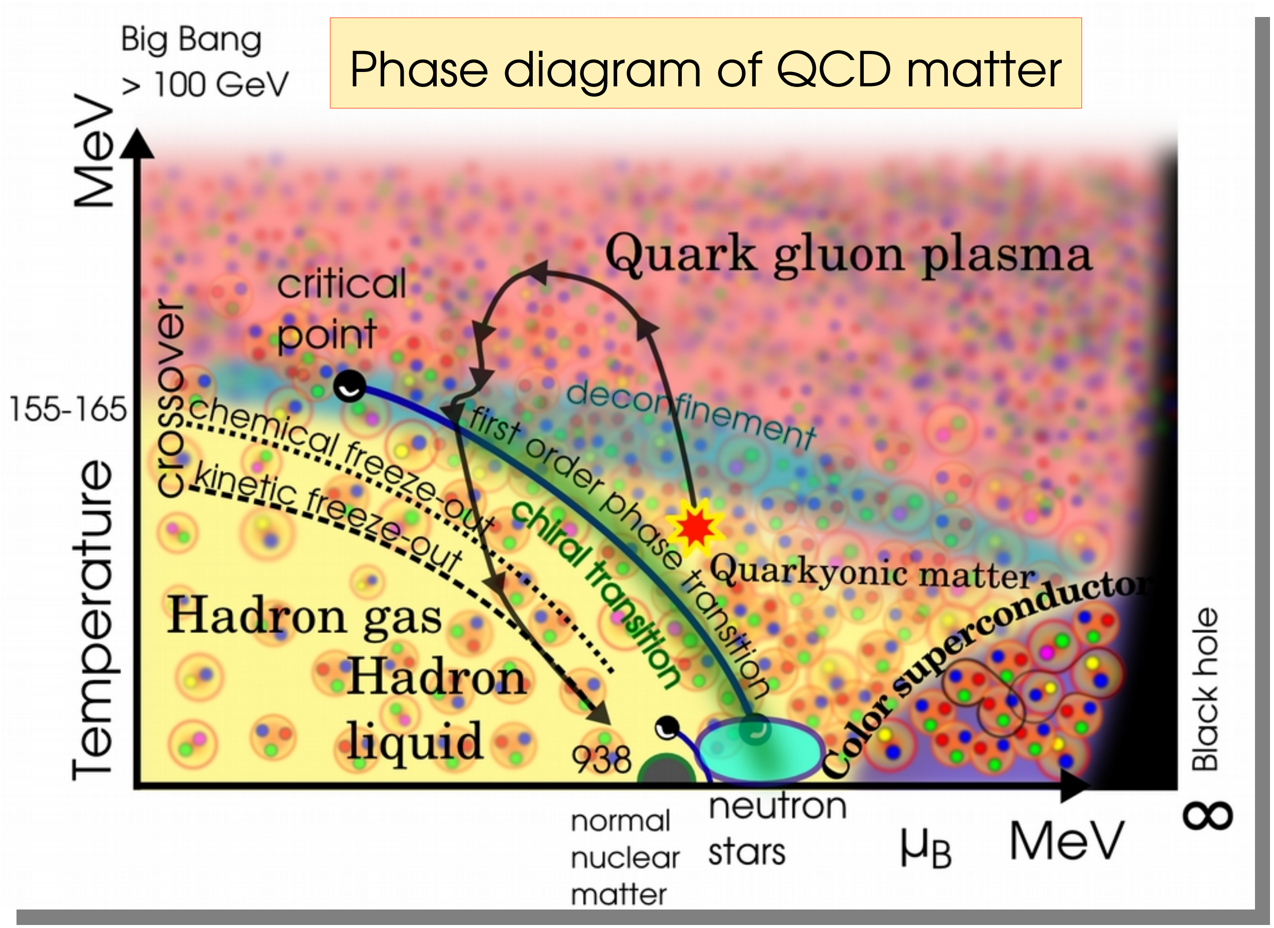
What are the fundamental degrees of freedom of QCD matter?

What are the microscopic and macroscopic properties of QCD matter at high energy and baryon density?

What is the equation of state of QCD matter?

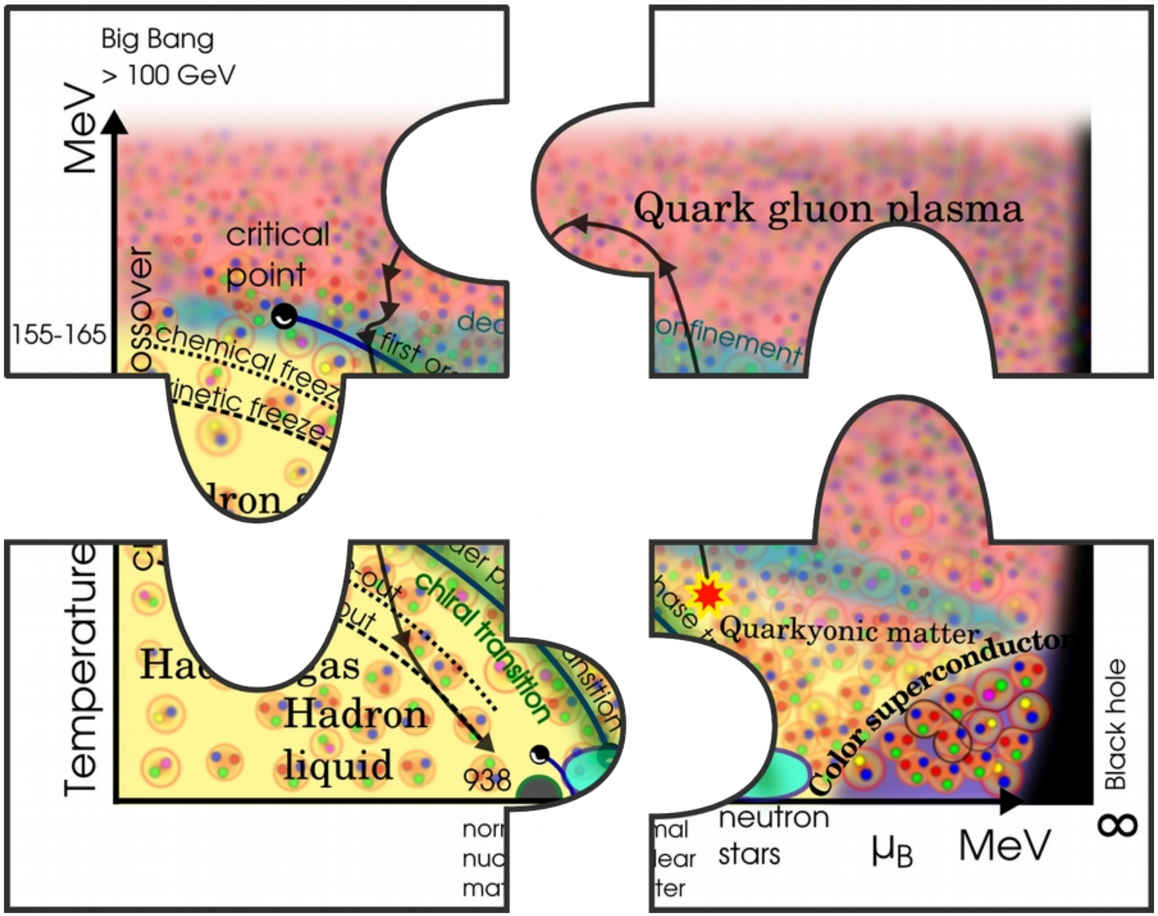


We expect the nuclear matter to behave similarly to other known substances.



- Absence of good **external** probes.
- It is impossible to create in the laboratory **extensive**, **stable** and externally **controlled** hot and dense matter.

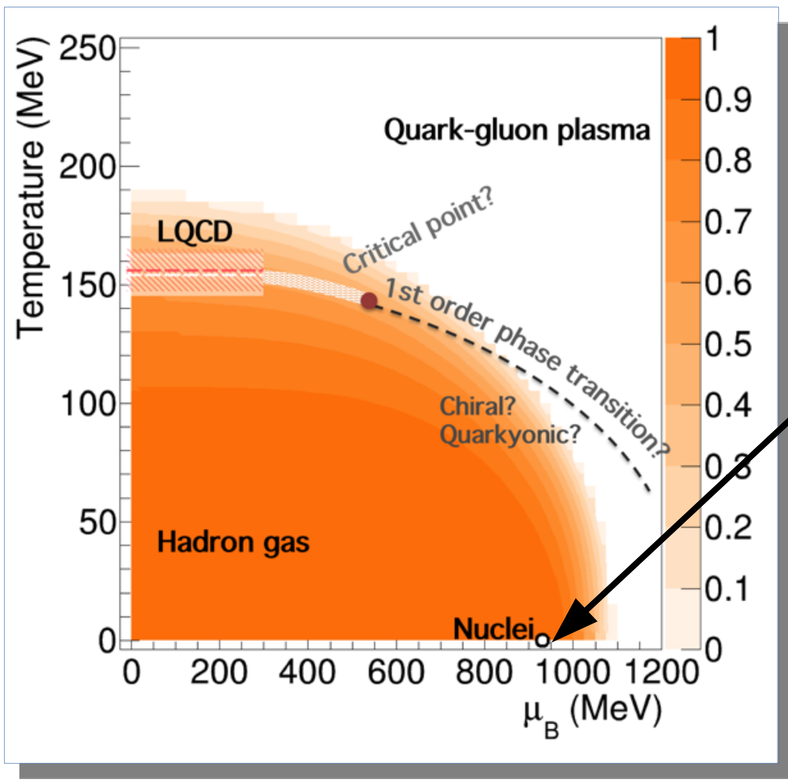
Heavy ion collisions permit a dynamic access to certain regions of the diagram.



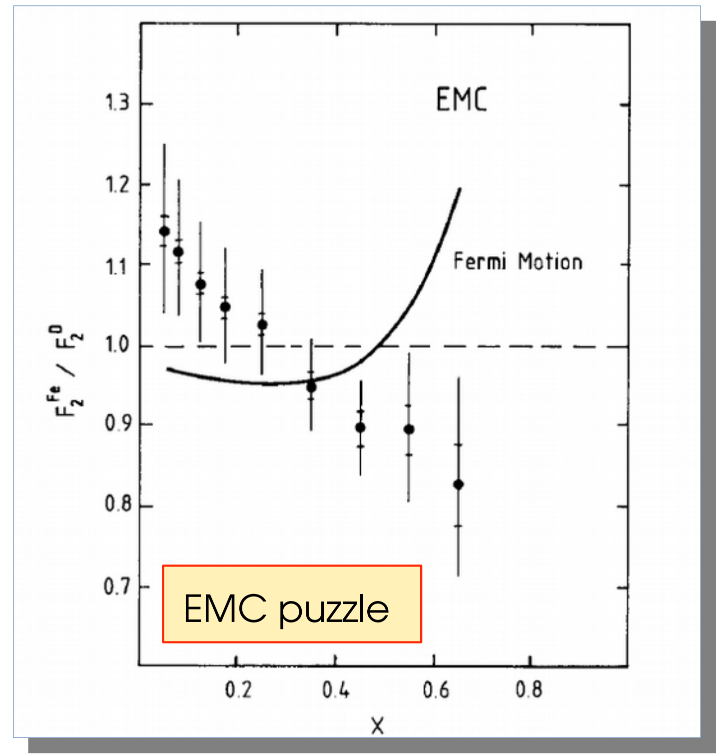
EOS constraints from
- Astrophysics:
  - neutron stars
  - CMB
  - Gravitational waves
- Heavy Ion Collisions
- Lattice QCD
- DIS off nuclei

Melting of the chiral condensate

Hadrons in medium



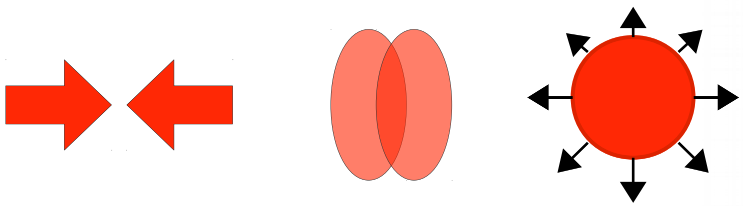
$$\frac{\langle \bar{q}q \rangle_{T,\mu_B}}{\langle \bar{q}q \rangle_{T=0,\mu_B=0}}$$ B.-J. Schaefer and J. Wambach

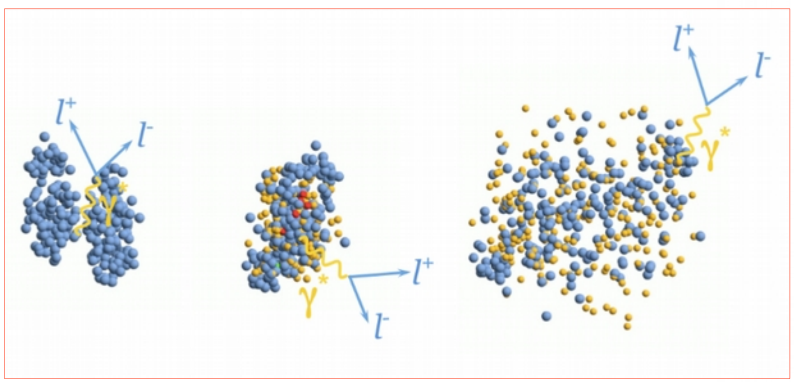


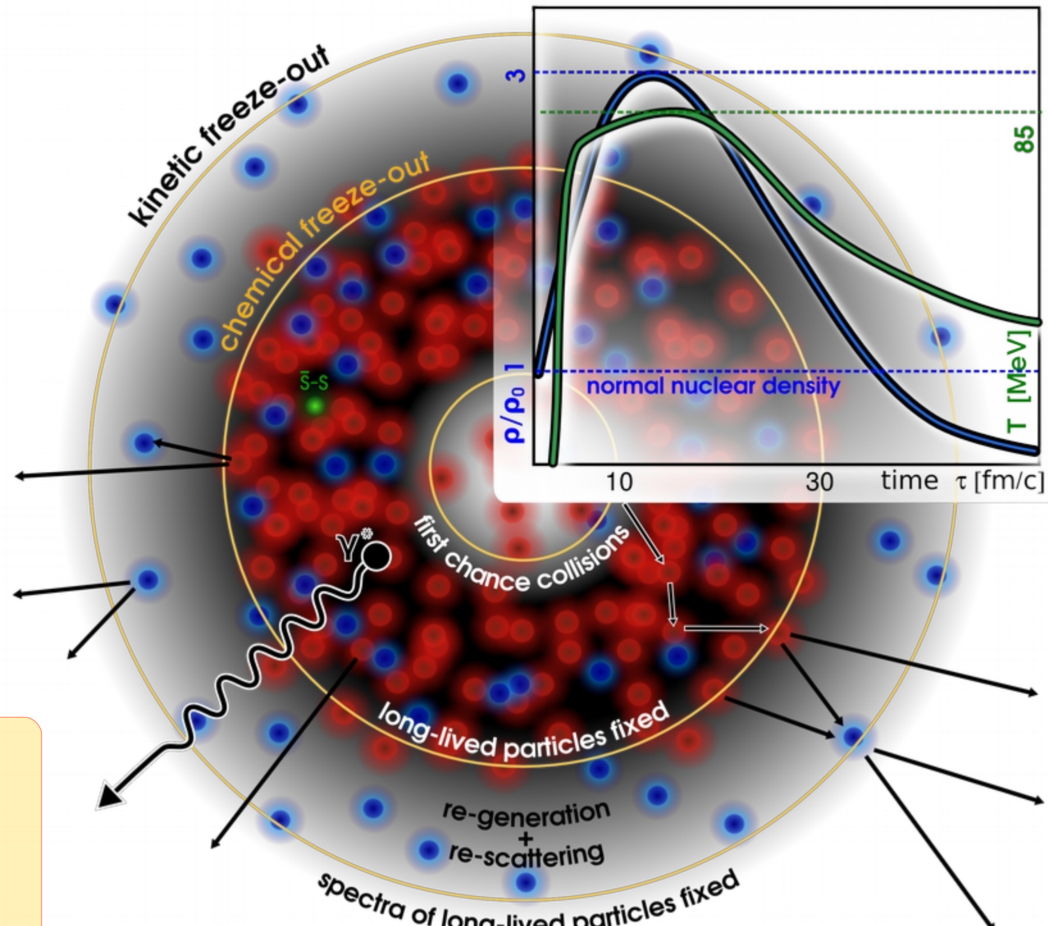
J.J. Aubert, EMC Collaboration, Phys. Letters, 123B, 1983

Medium effects appear already in normal nuclear matter: EMC effect

Time evolution of a heavy ion collision



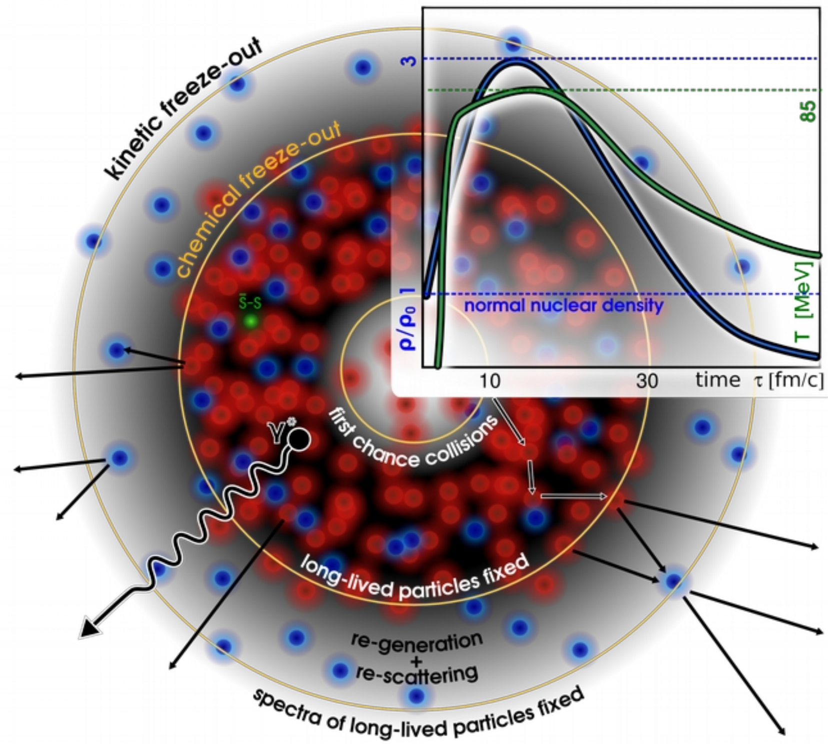




RARE PROBES

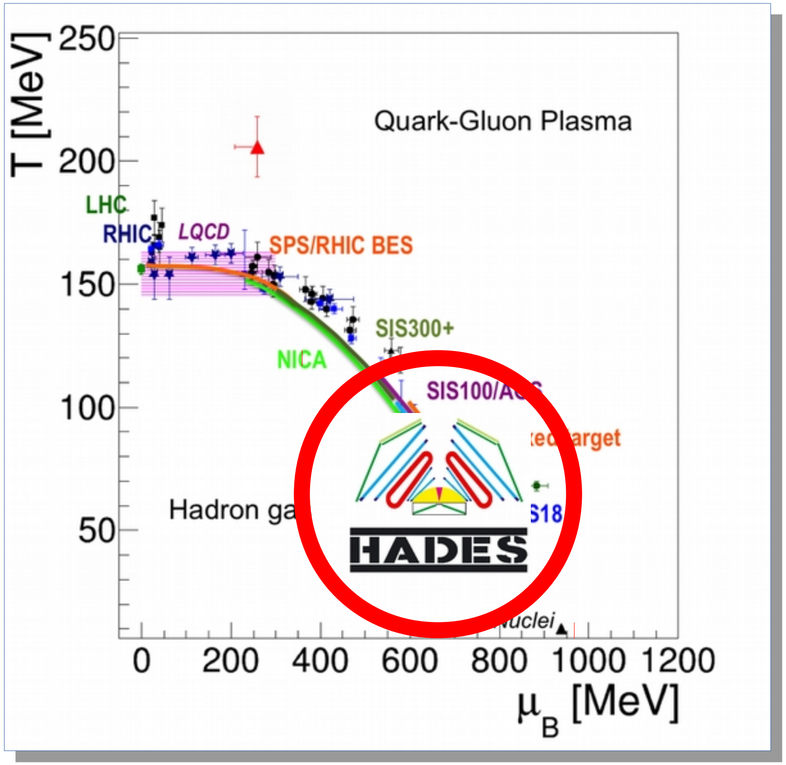
- di-leptons do not interact strongly!
- strangeness is conserved

- Particles production yields and ratios
- Strangeness, charm, beauty
- Di-leptons
- Resonances
- Collective phenomena
  - Flow
  - Chiral-magnetic effect
- Correlations, fluctuations & quantum effects
  - BEC
  - Coulomb
  - Fluctuations of conserved numbers
- Short range correlations
- …
- ...



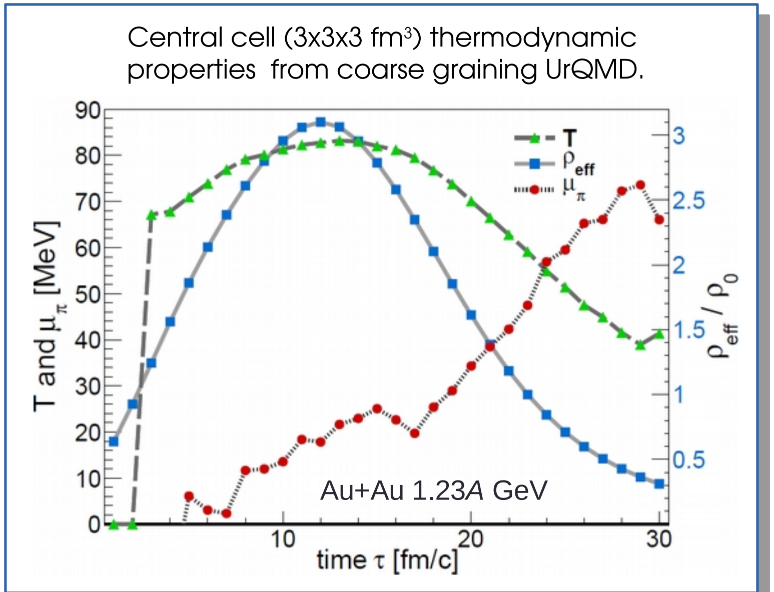
The high density side of the QCD matter phase diagram

From SHM analysis of hadron yields we know that:



Heavy-ion collision at SIS18 energies:

- Baryon-reach system
- Long lifetime of the dense "fireball" > 20 fm/c
- Intermediate temperatures 50 – 80 MeV



T. Galatyuk, F. Seck, et al.,arXiv-1512-08688

HADES measures elementary and HIC with beams from SIS18 and in future from SIS100

HADES strategy: we measure both the AA and NN collisions

Heavy ion physics:

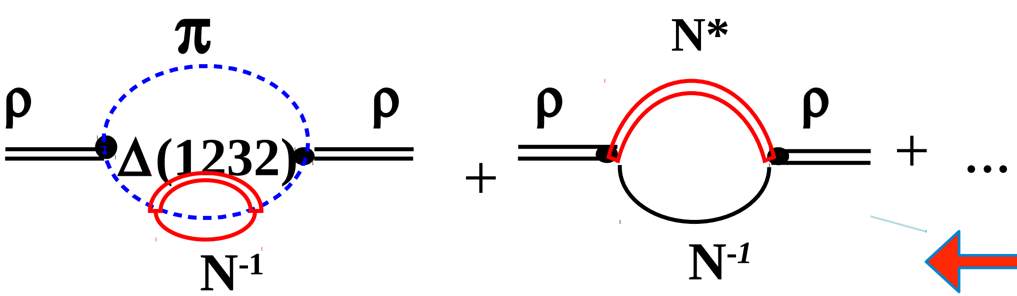
- in medium hadron properties
- Nuclear matter emissivity μ_B, T

ρ meson

Proton-proton, pion-proton

- Vector Meson baryon couplings
- em transition FF

ρ meson in nuclear matter:

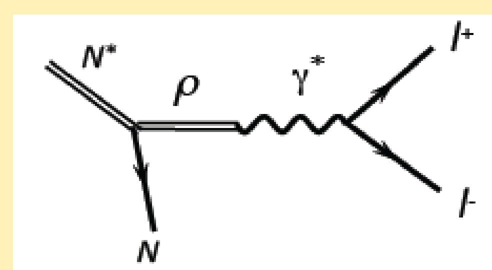


$\Sigma_{\rho\pi\pi}$ $\Sigma_{\rho R(\Delta, N^*)}$

dominant role of baryonic resonances for in-medium Self-Energy $\Sigma_{\rho R}$

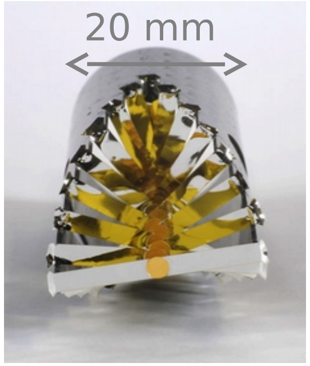
baryonic loops directly related to :

Resonance Dalitz decay

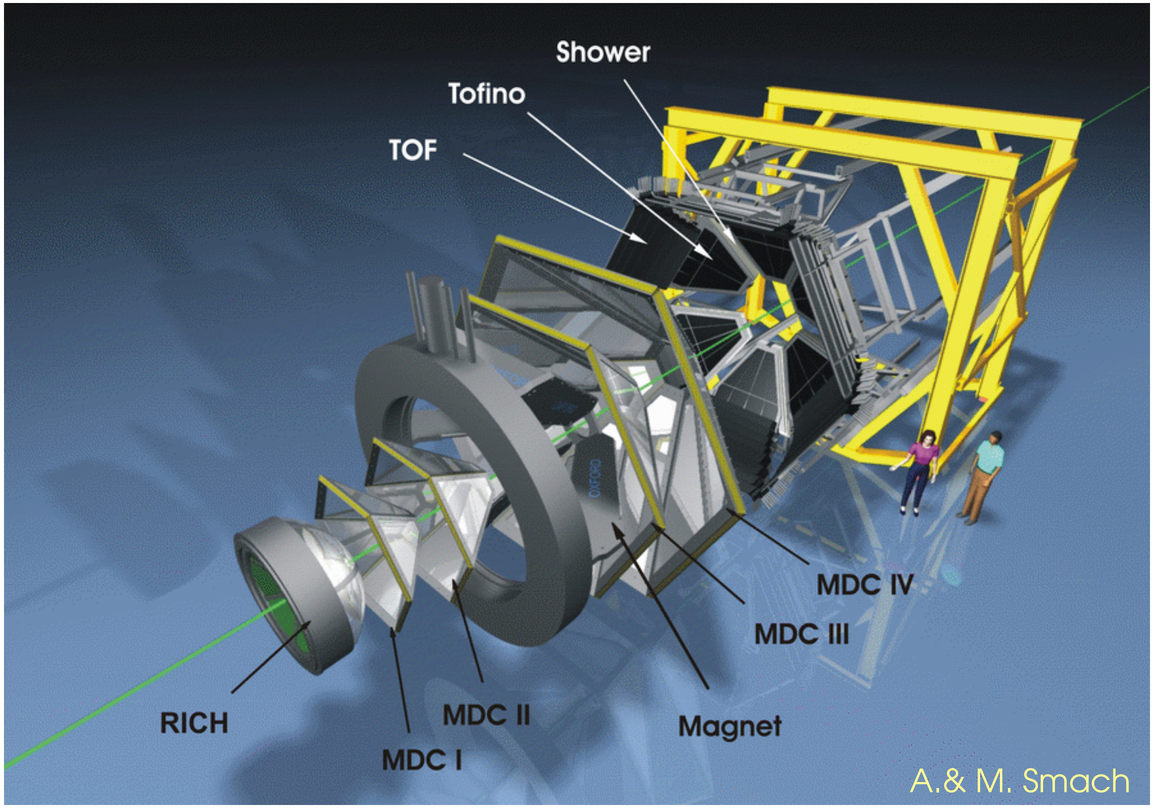


Meet the HADES

High **A**cceptance **D**i-**E**lectron **S**pectrometer

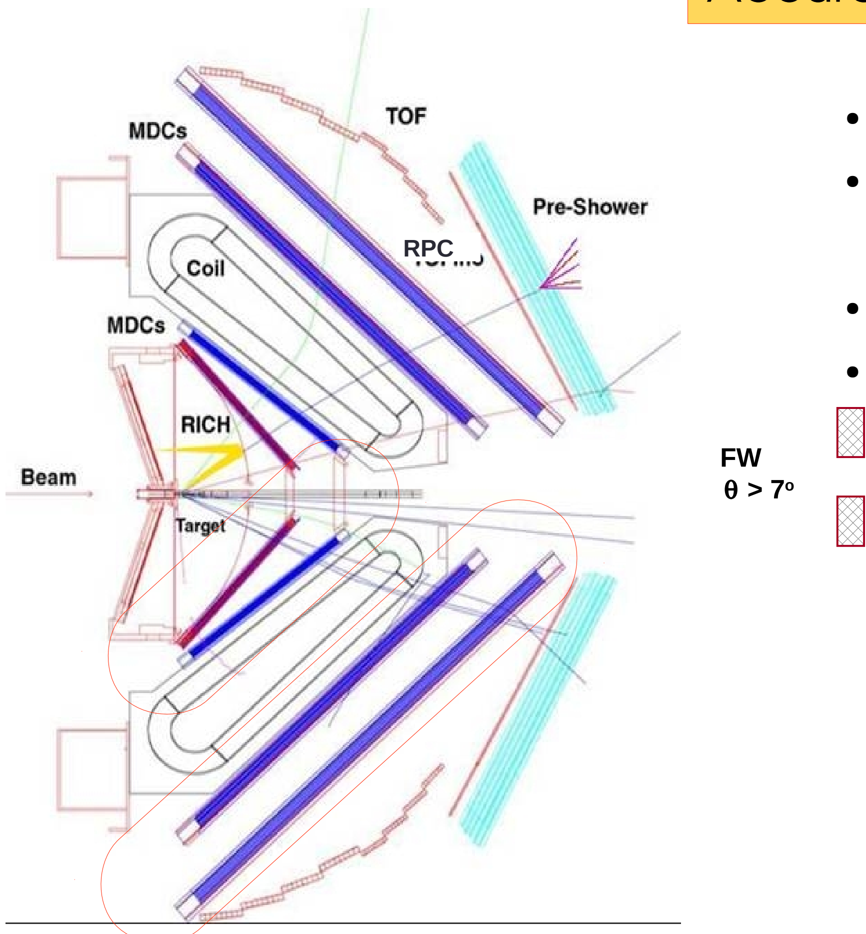


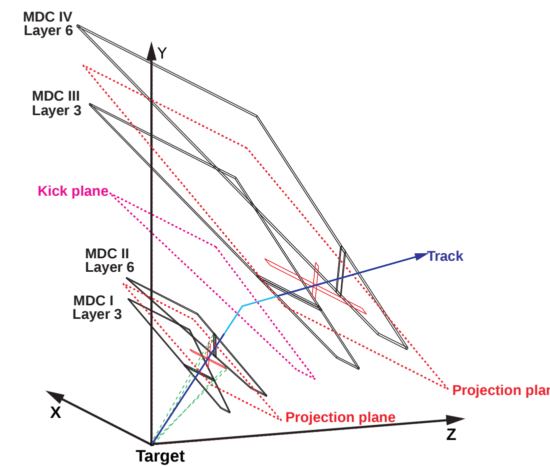
- SIS18 accelerator at GSI
- Proton and ion beams 1-2A GeV
- Secondary high intensity pion beam
- Fix target, low mass, high rate, high resolution spectrometer



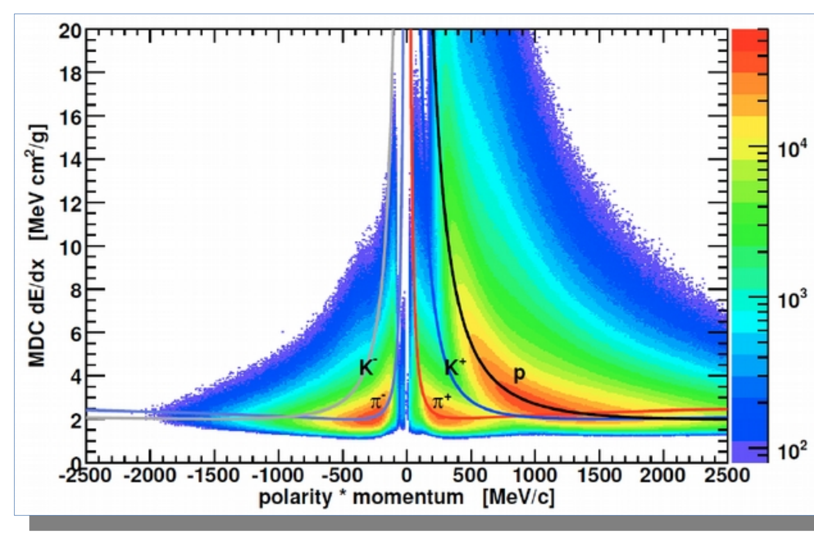
Accurate low mass tracking

- 24 MDC chambers
- Superconducting low mass toroidal magnet
- Position resolution < 150 μm
- Momentum resolution < 2%

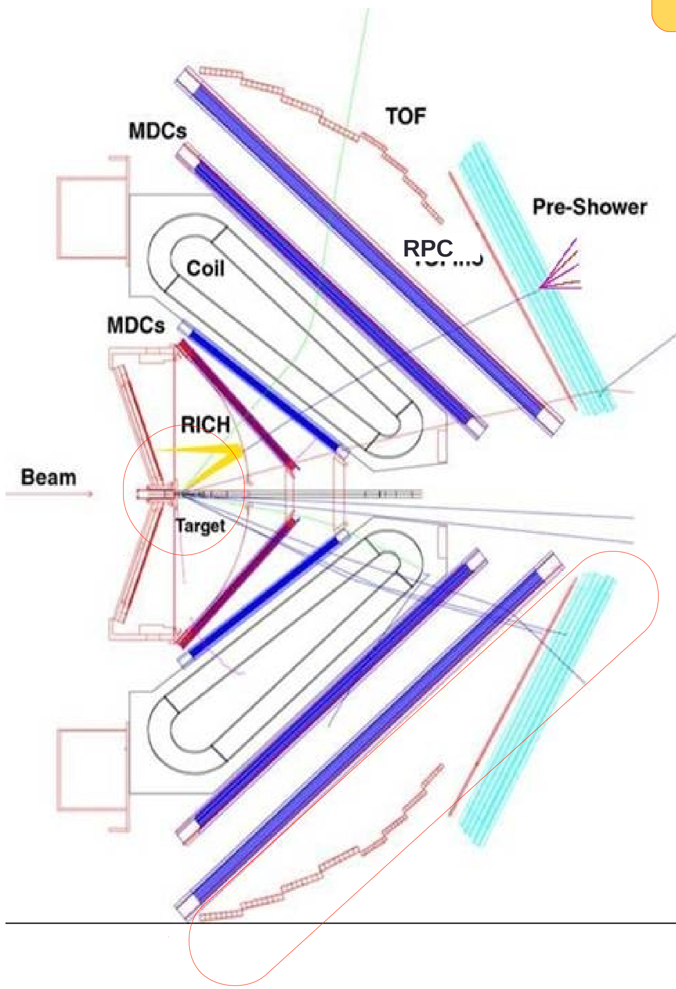


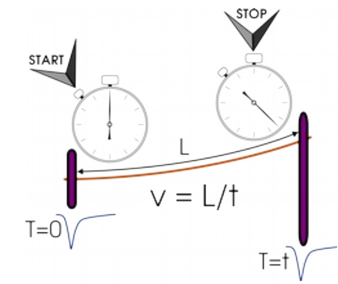


PID dE/dx vs momentum



accurate TOF measurement



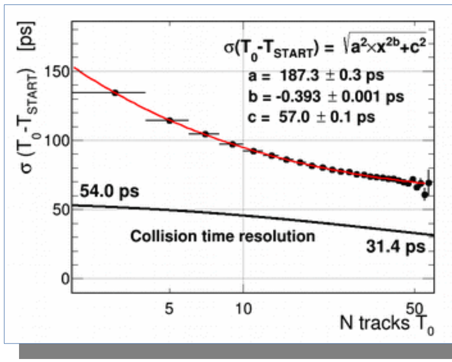


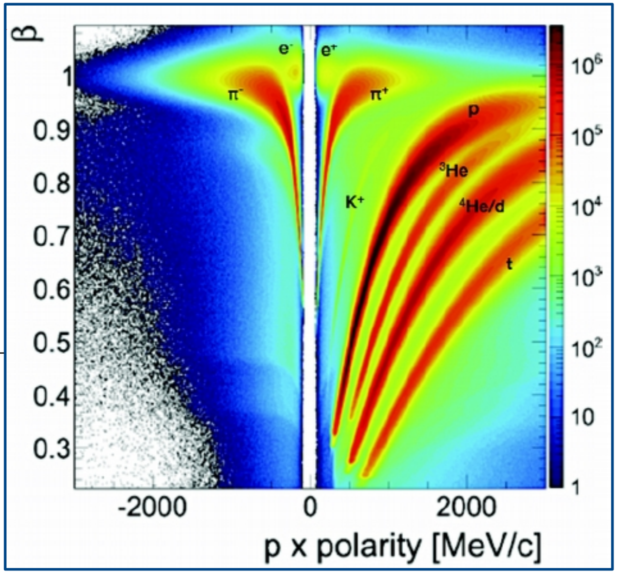
- Diamond START σt < 60 ps
- Resistive Plate Chambers Wall σt < 70 ps θ < 45
- Scintillator TOF Wall σt < 150 ps θ > 45

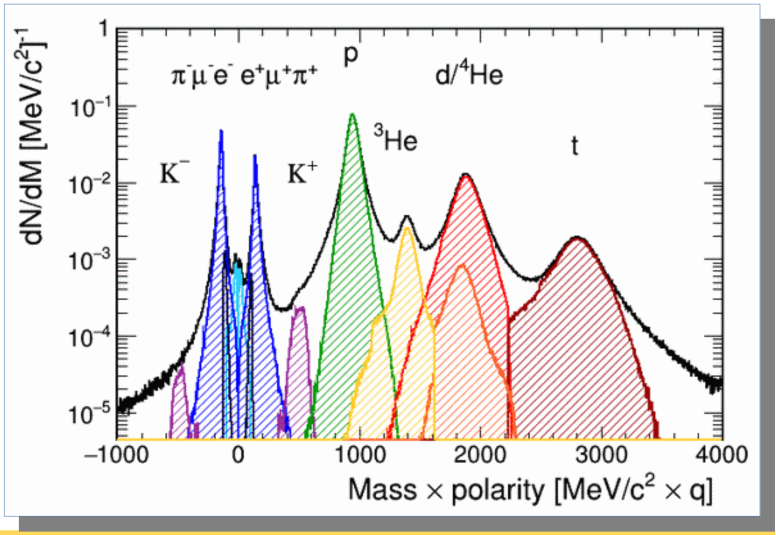
Diamond START + T_0 technique :

31 ps collision time accuracy in AuAu

FW
θ > 7°







High purity electron and positron identification

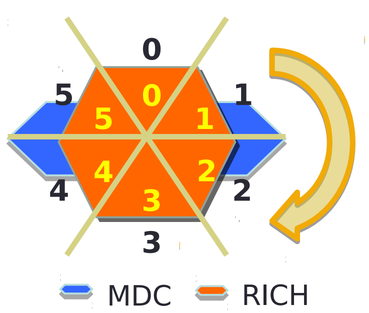
Multivariate analysis (neural network) using:

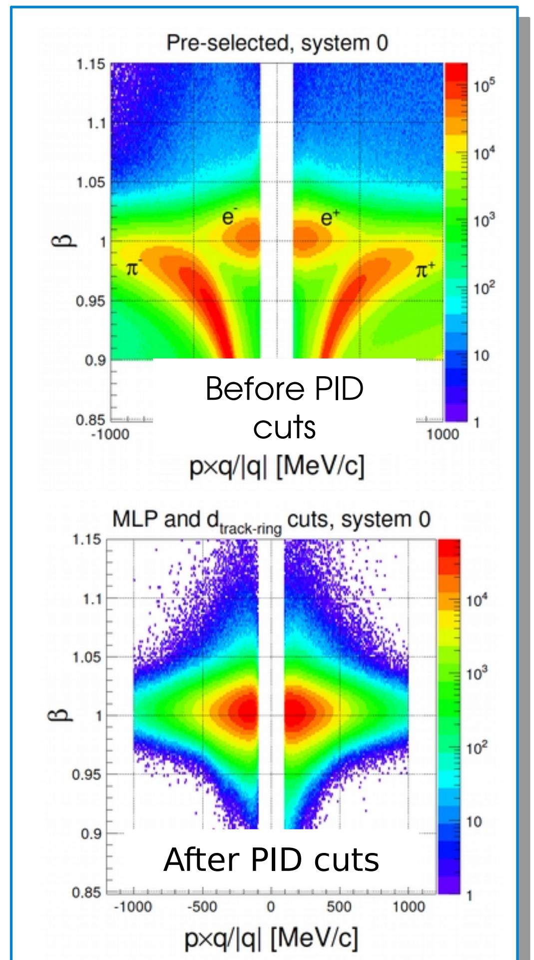
- Particle velocity
- dE/dx in MDC and ToF
- Electromagnetic shower
- Cherenkov radiation

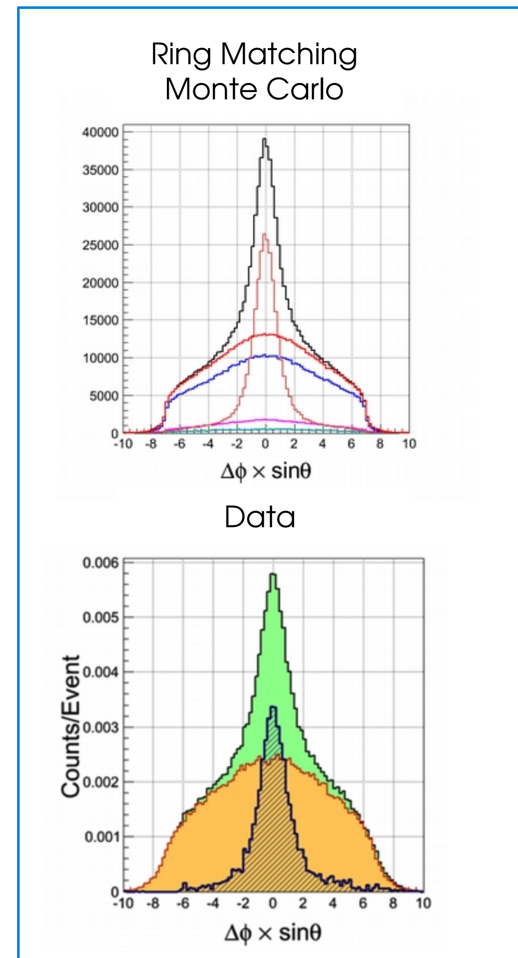
} NN response

Purity derived from "RICH rotation"

- Random matches MDC - RICH

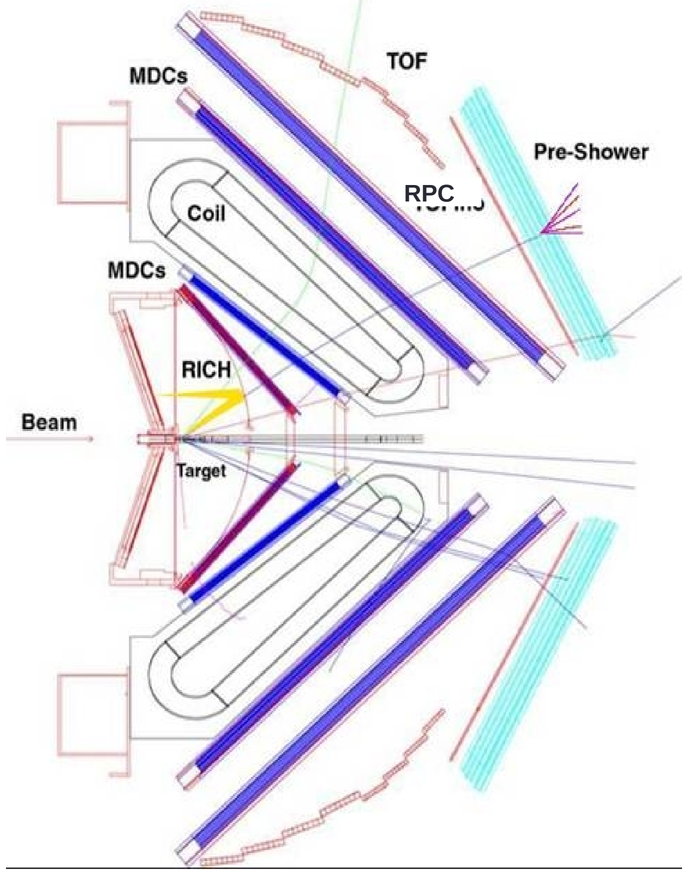


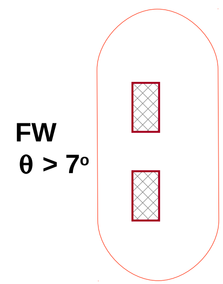


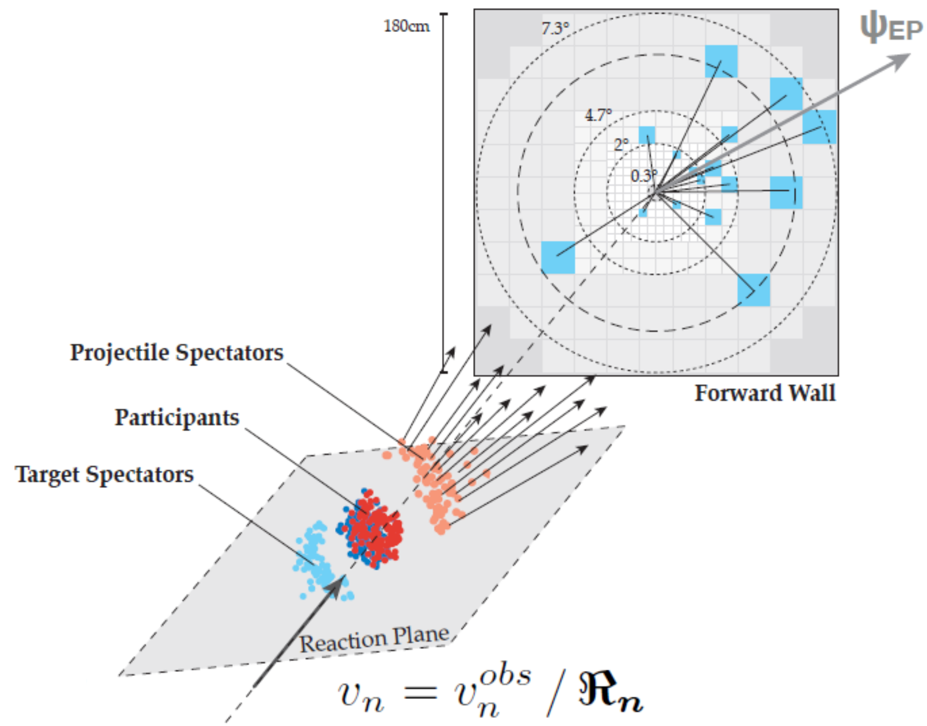


Highly tuned Monte Carlo with detailed detectors response!

Event reaction plane + centrality measured with the Forward Wall





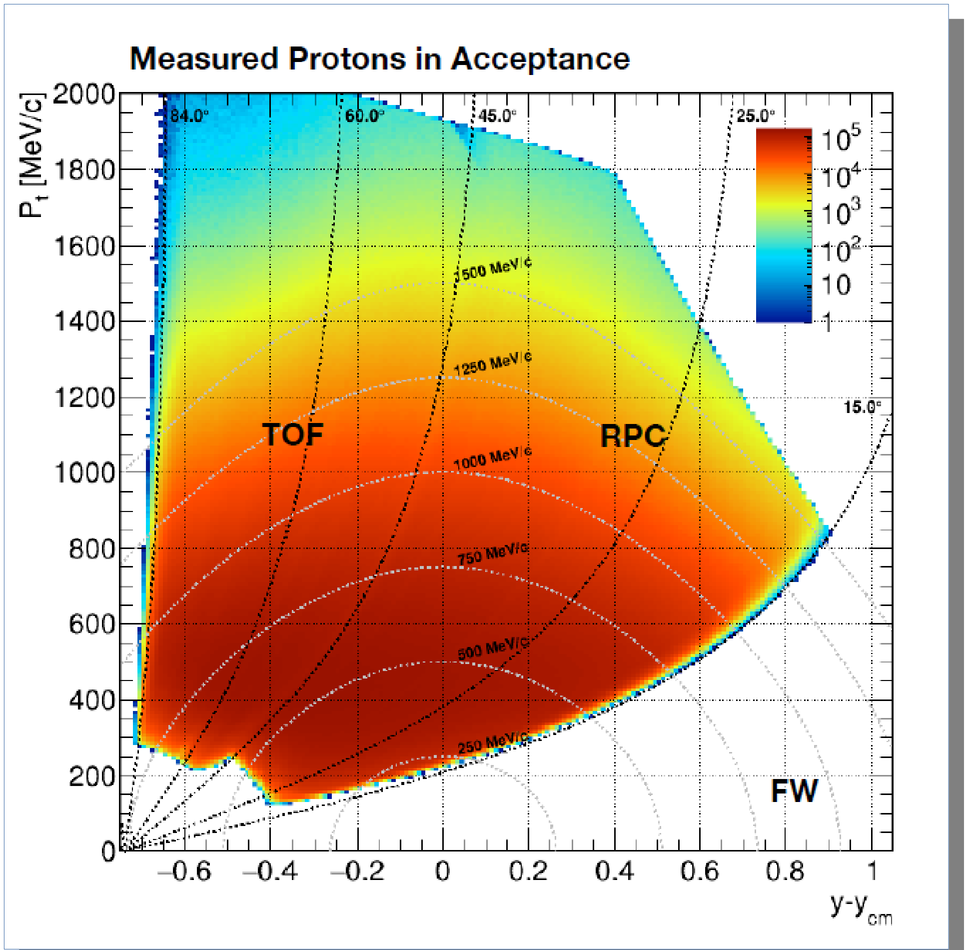


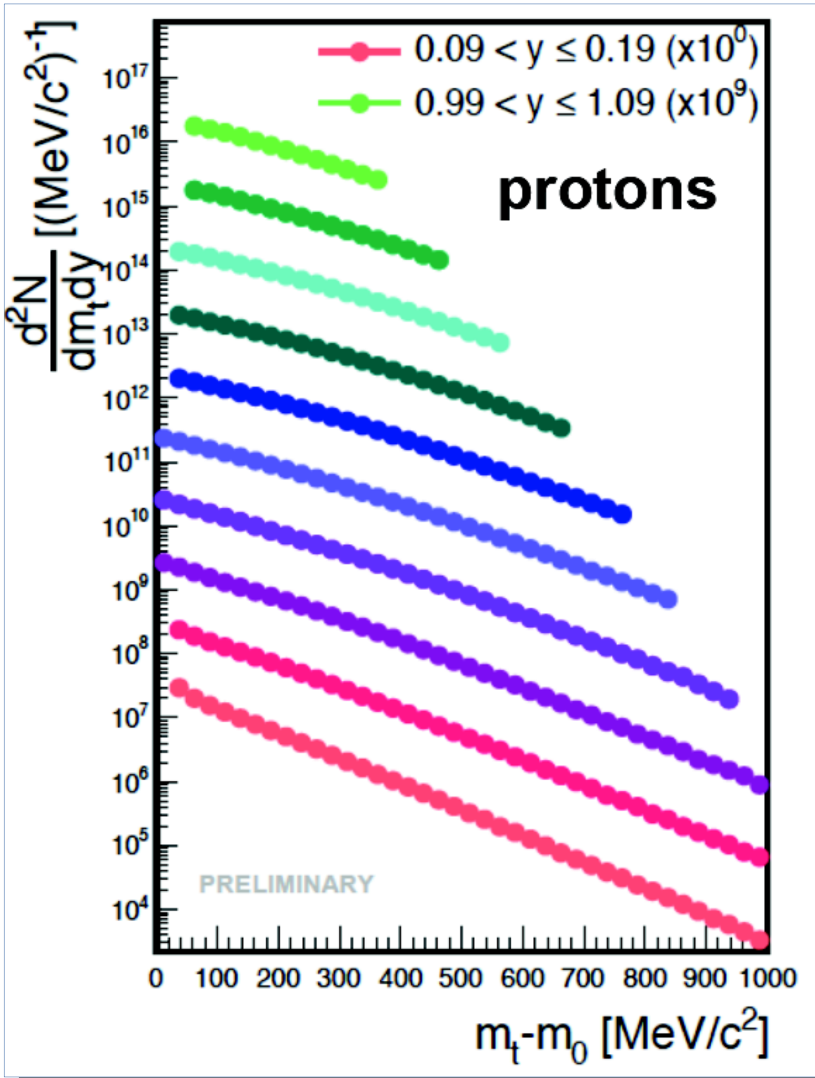
$$v_n = v_n^{obs} \,/\, \mathfrak{R}_n$$

$$\mathfrak{R}_n = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

$$= \sqrt{2\,\langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle}$$

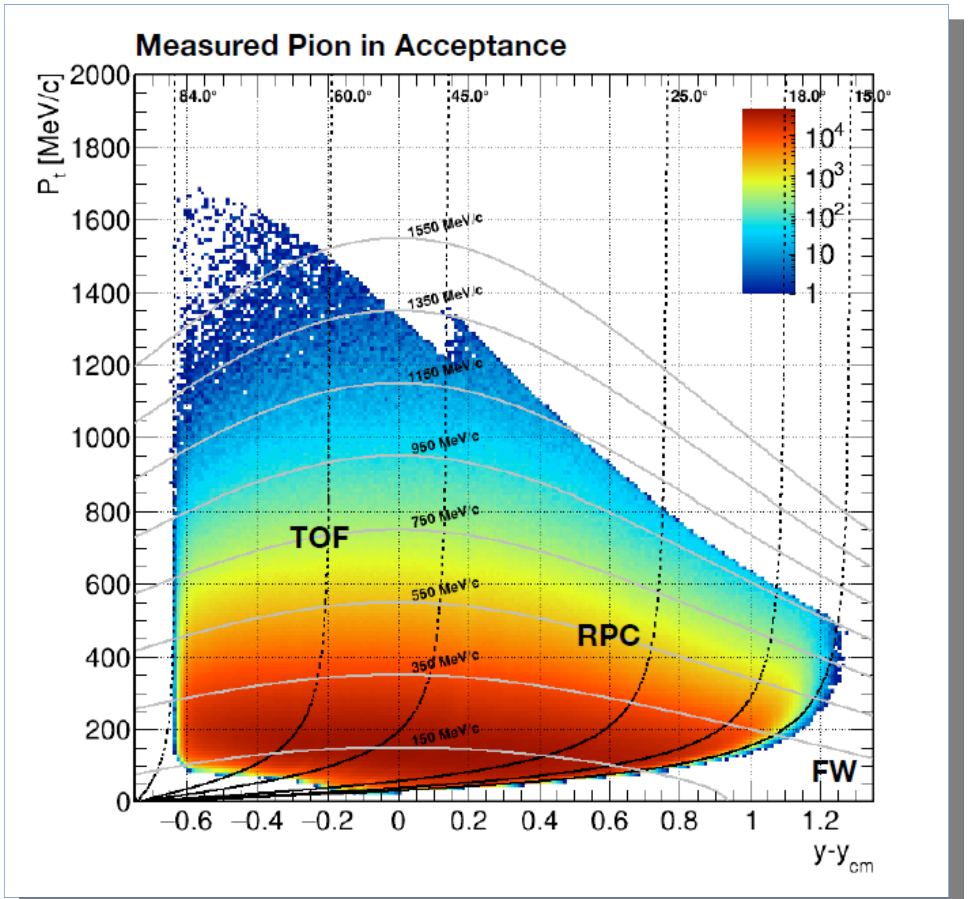
Protons: acceptance & differential distributions

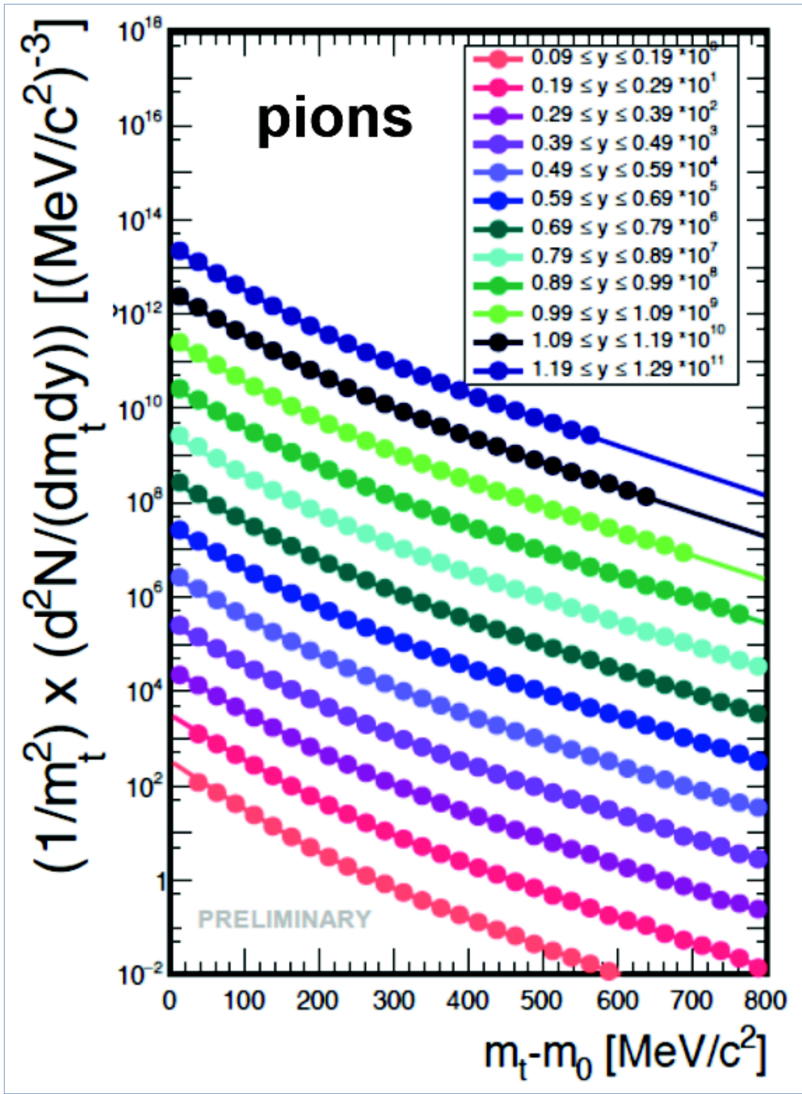




High purity & statistics data allow a **precise differential analysis**

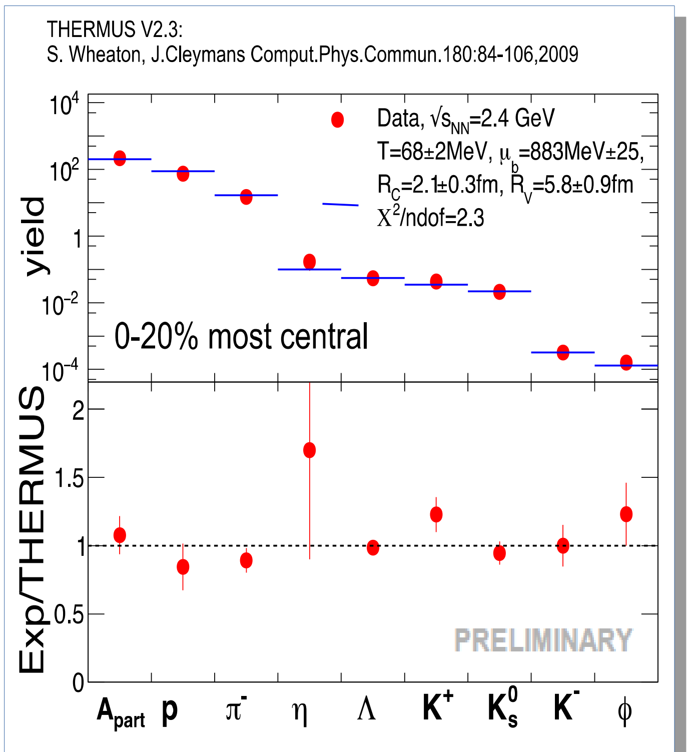
Pions: acceptance & differential distributions





Hadron yields in Au+Au 1.23A GeV (√s=2.4)

Hadron yields and their centrality dependence in accord with the assumption of a "thermalized" system.



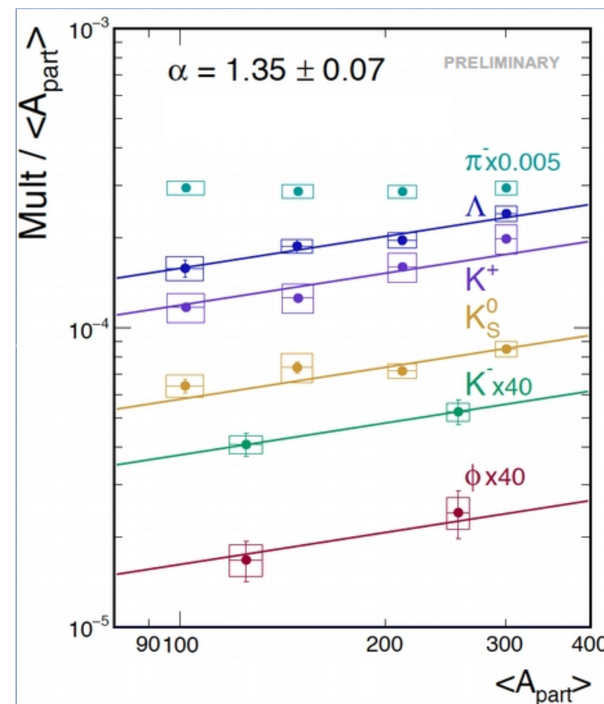
Rc - strangeness correlation radius

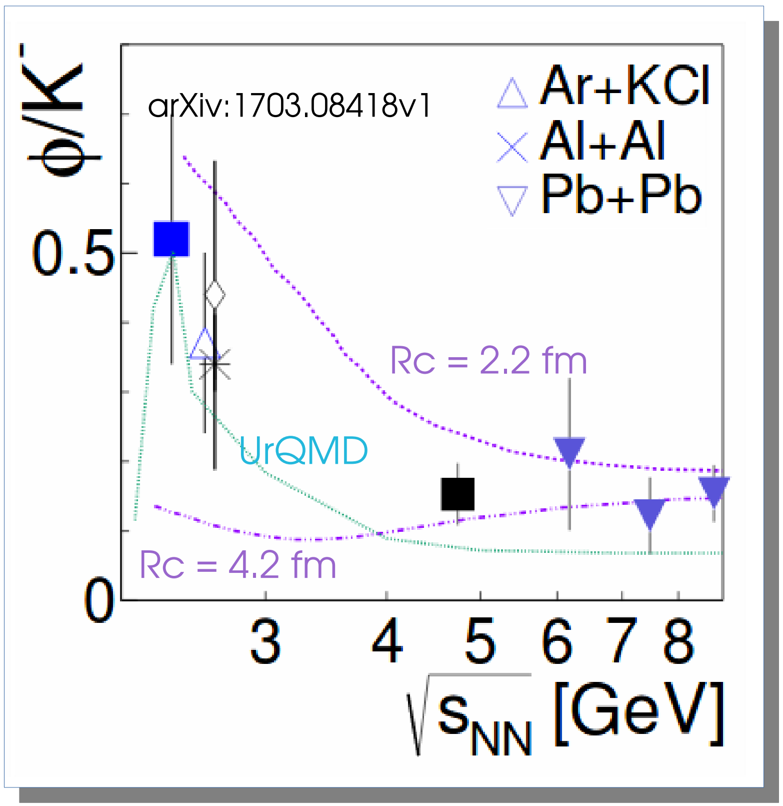
Statistical Hadronization Model fit (THERMUS v2.3) of particle yields.

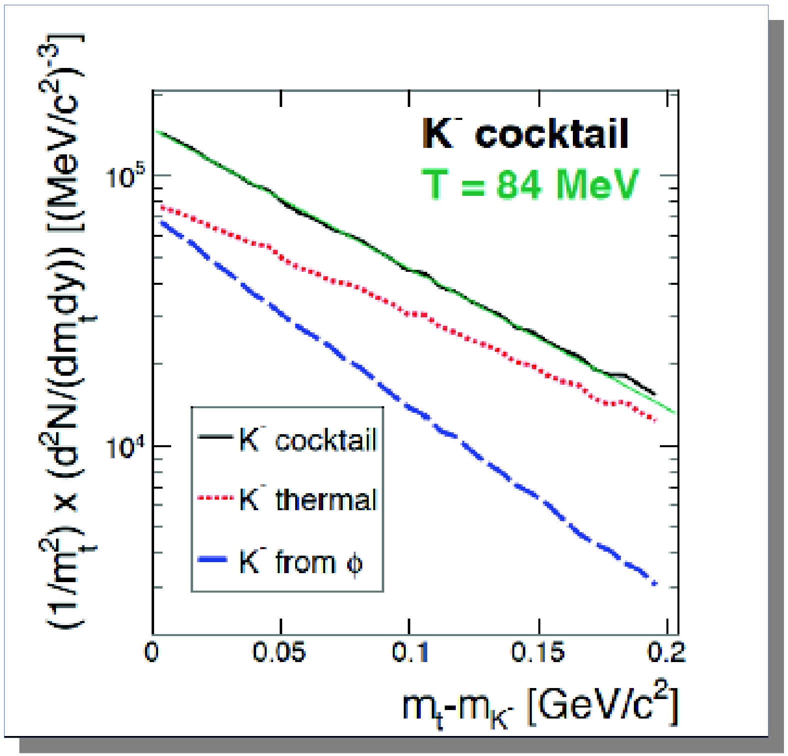
- Resonance feed-down taken into account.
- Good description of strange hadrons.

Universal participant number scaling!

- Not expected for multi-step production



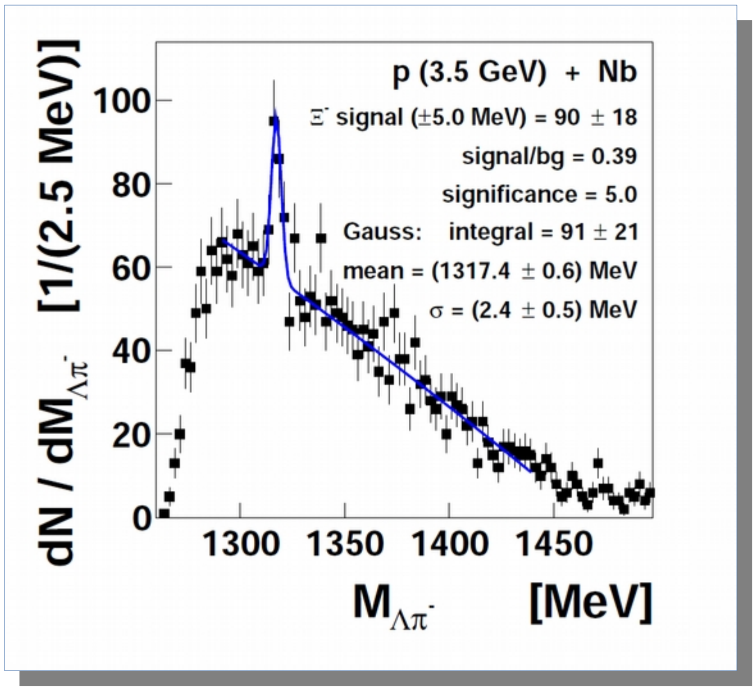




25% K- produced from phi

K^- from ϕ decays lower the effective temperature

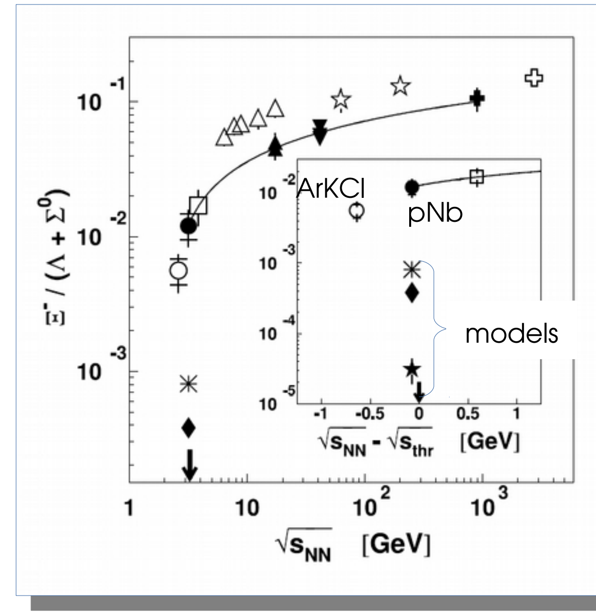
Excess of double strange Ξ- in Ar+KCl (1.74A GeV) & p+Nb (3.5 GeV)



Phys.Rev.Lett. 114 (2015) 212301

Phys.Rev.Lett. 103 (2009) 132301

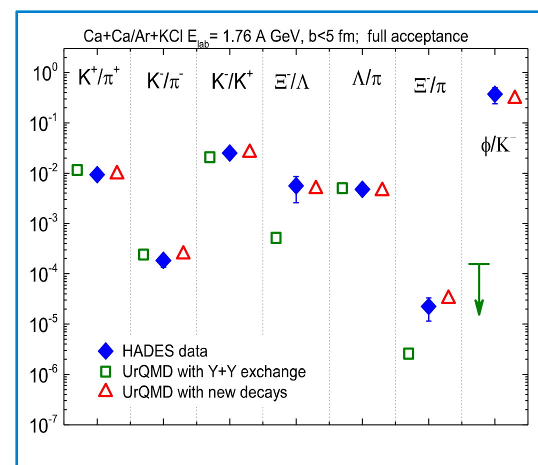
Observed Ξ^- yield in Ar+KCl & p+Nb much above expectation from SHM & transport.



Disrepancy with UrQMD can be solved by introducing decays in the high mass tail:

$N^* \rightarrow \Xi + K + K$

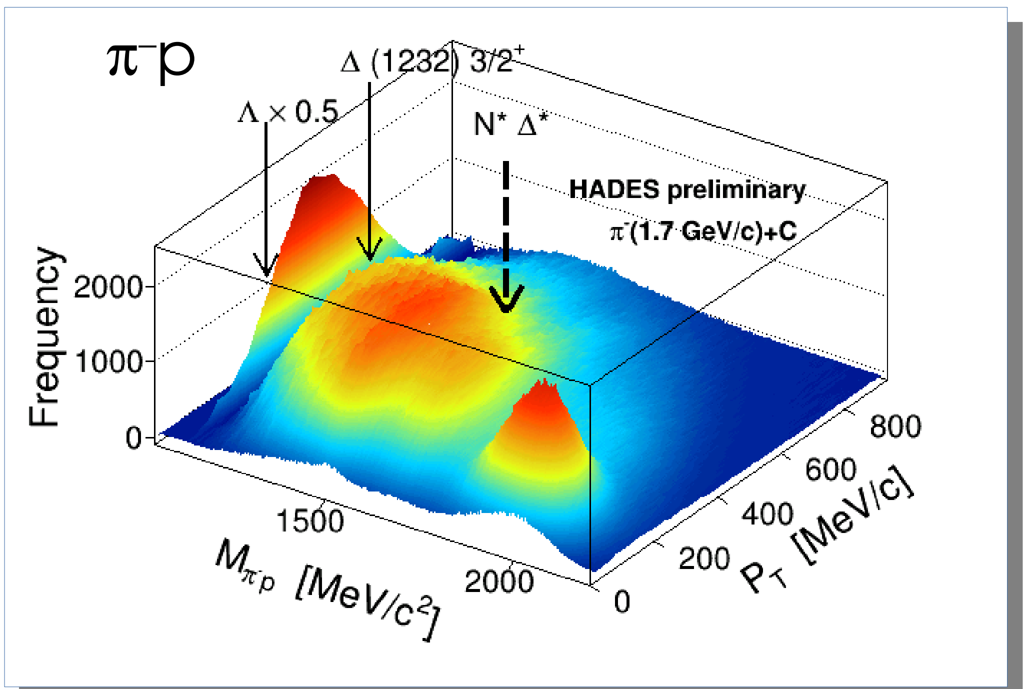
problem: branching ratios are unknown!

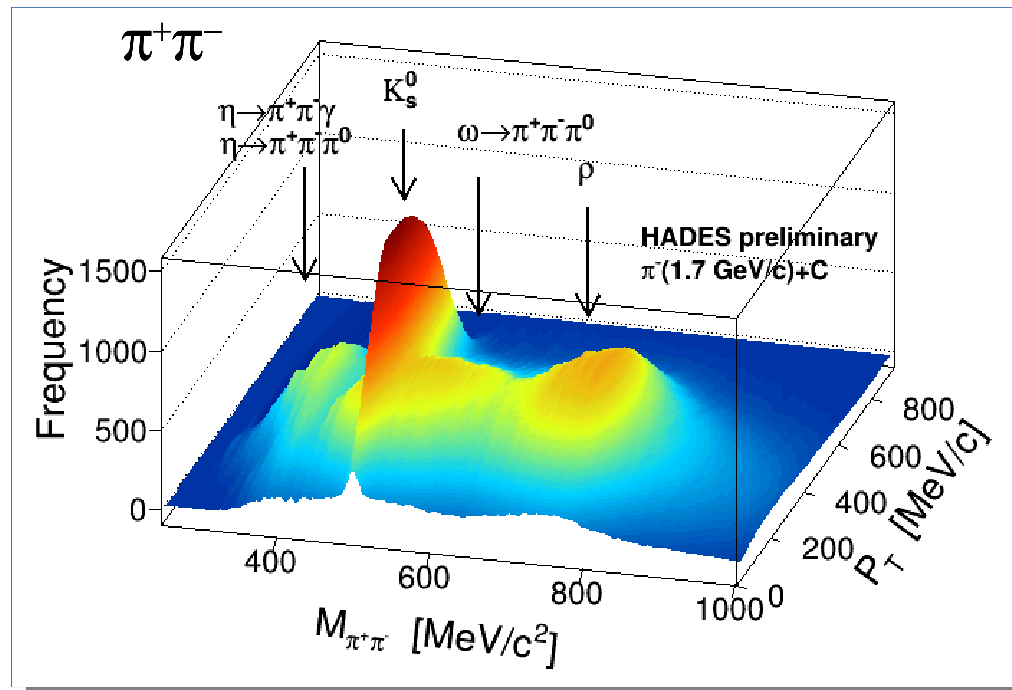


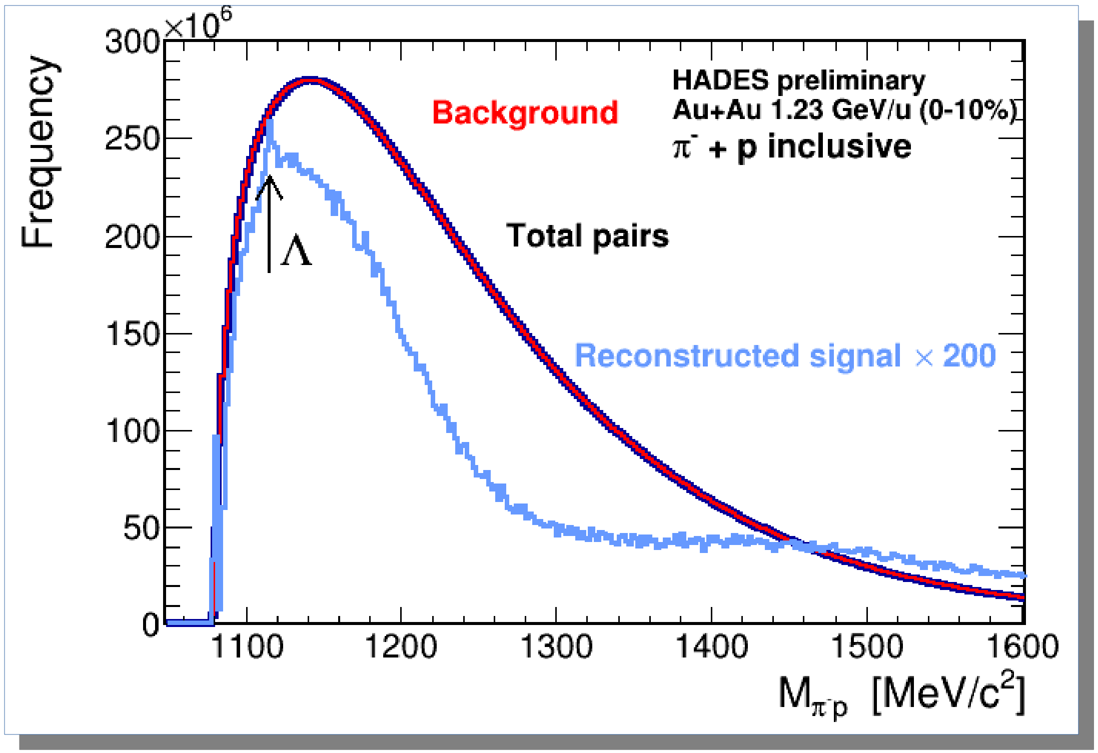
Jan Steinheimer et al.; arXiv-1503-07305

Inclusive differential reconstruction of resonances in $p\pi^{\pm}$ and $\pi^{+}\pi^{-}$ channels

Inclusive reconstruction in $\pi^{-} + C$ (1.7 GeV/c)





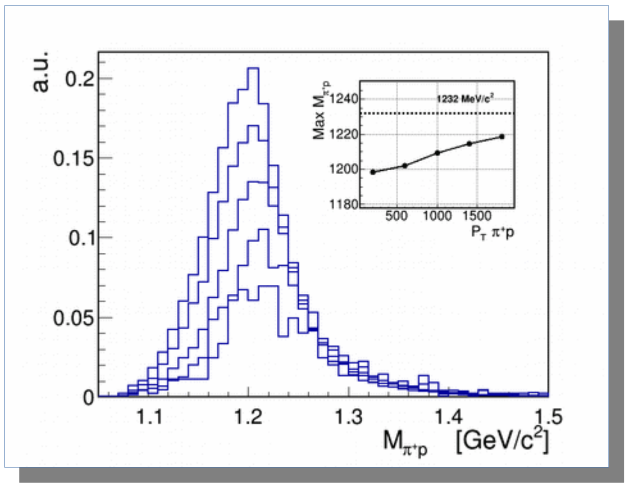


Inclusive reconstruction of broad resonances in Au+Au (1.23*A* GeV)

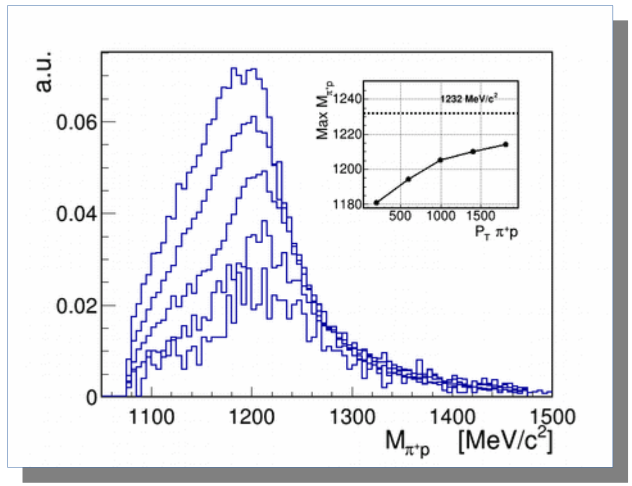
- ~1/100-1/1000 Signal to background ratio
- Dedicated iterative algorithm to fix the reconstructed shape & yield issues of the event mixing technique.
- Large statistics for multi-differential analysis (Mass, P_T, Y)

Selections of **UrQMD** Δ^{++} from 5 P_T bins 0 – 400, – 800, – 1200, – 1600, – 2000 MeV/c

No further re-scattering

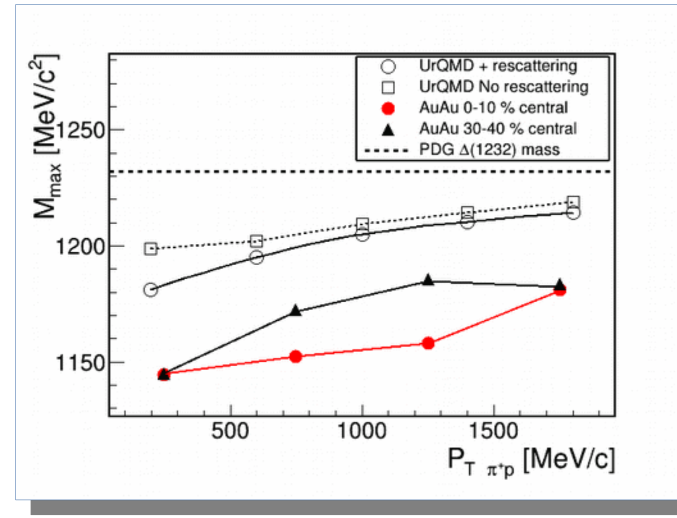


Further re-scattering allowed

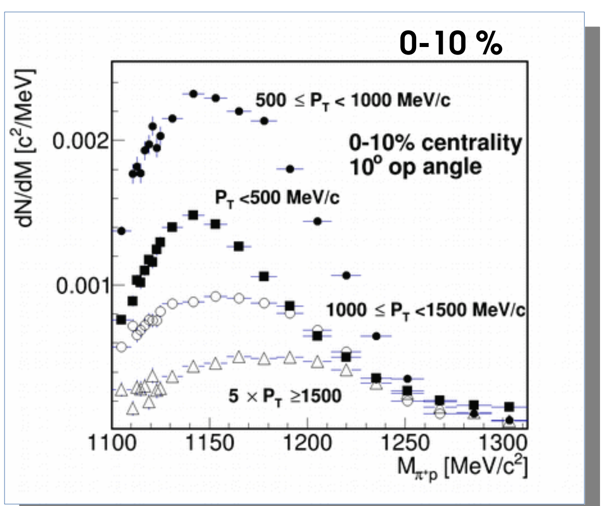


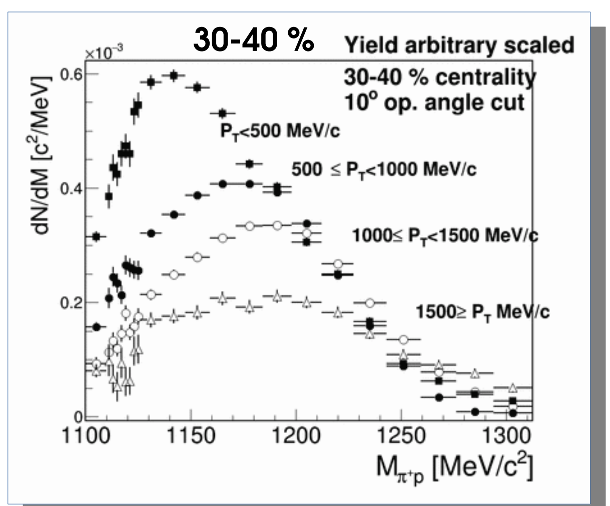
* simulated data courtesy F. Seck

Maximum Δ^{++} real - sim

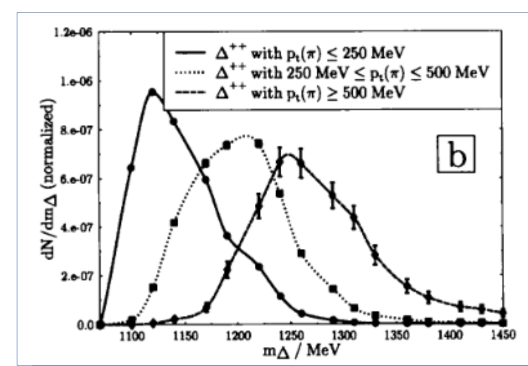


Selection of Δ^{++} from AuAu data. 0-500 500-1000 1000-1500 1500-2000 MeV/c



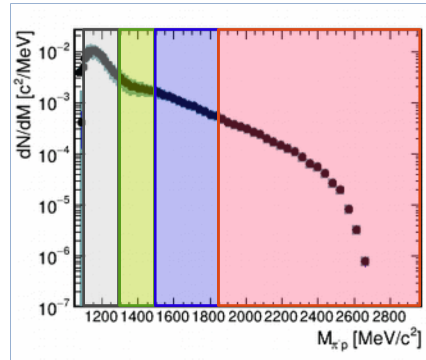


Theory prediction

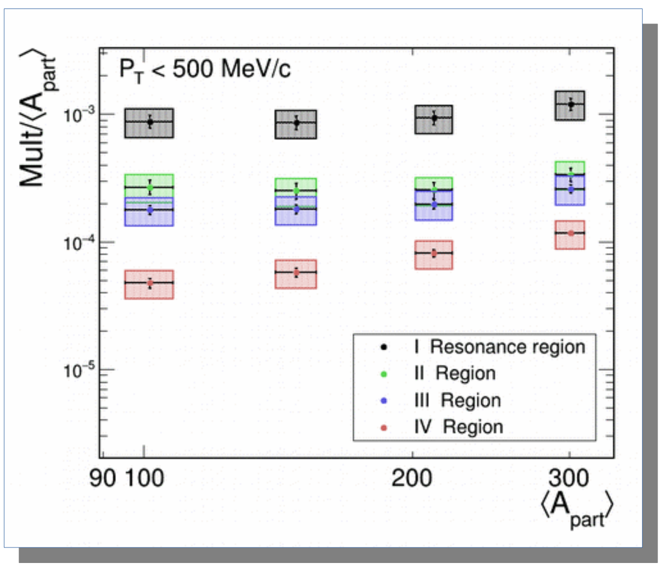


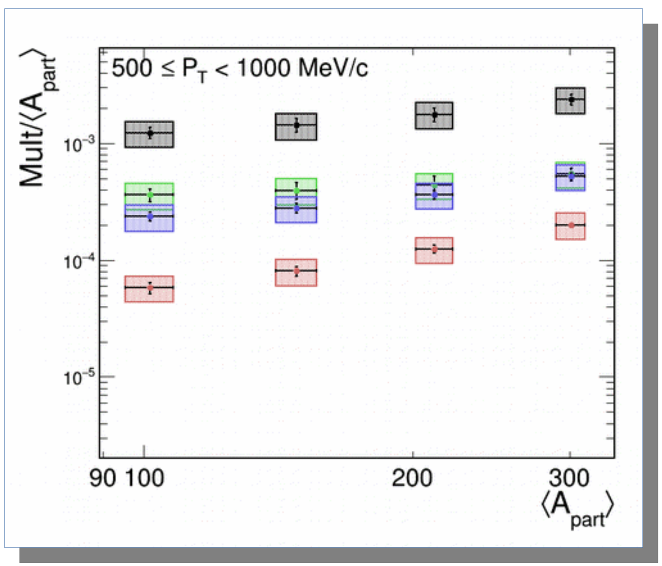
S.A. Bass, et al, Physics Letters B, Volume 335, Issue 3, 1994,

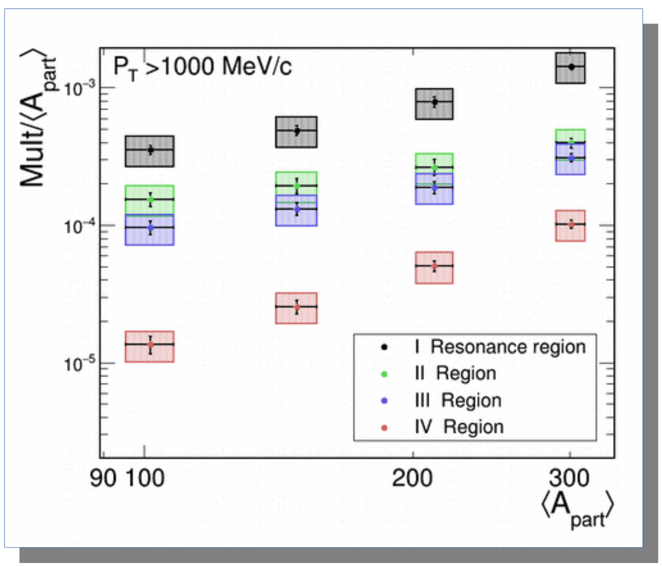
Resonance Region	M (MeV/c^2)
I	1100-1300
II	1300-1500
III	1500-1850
IV	>1850



$\pi^- p$





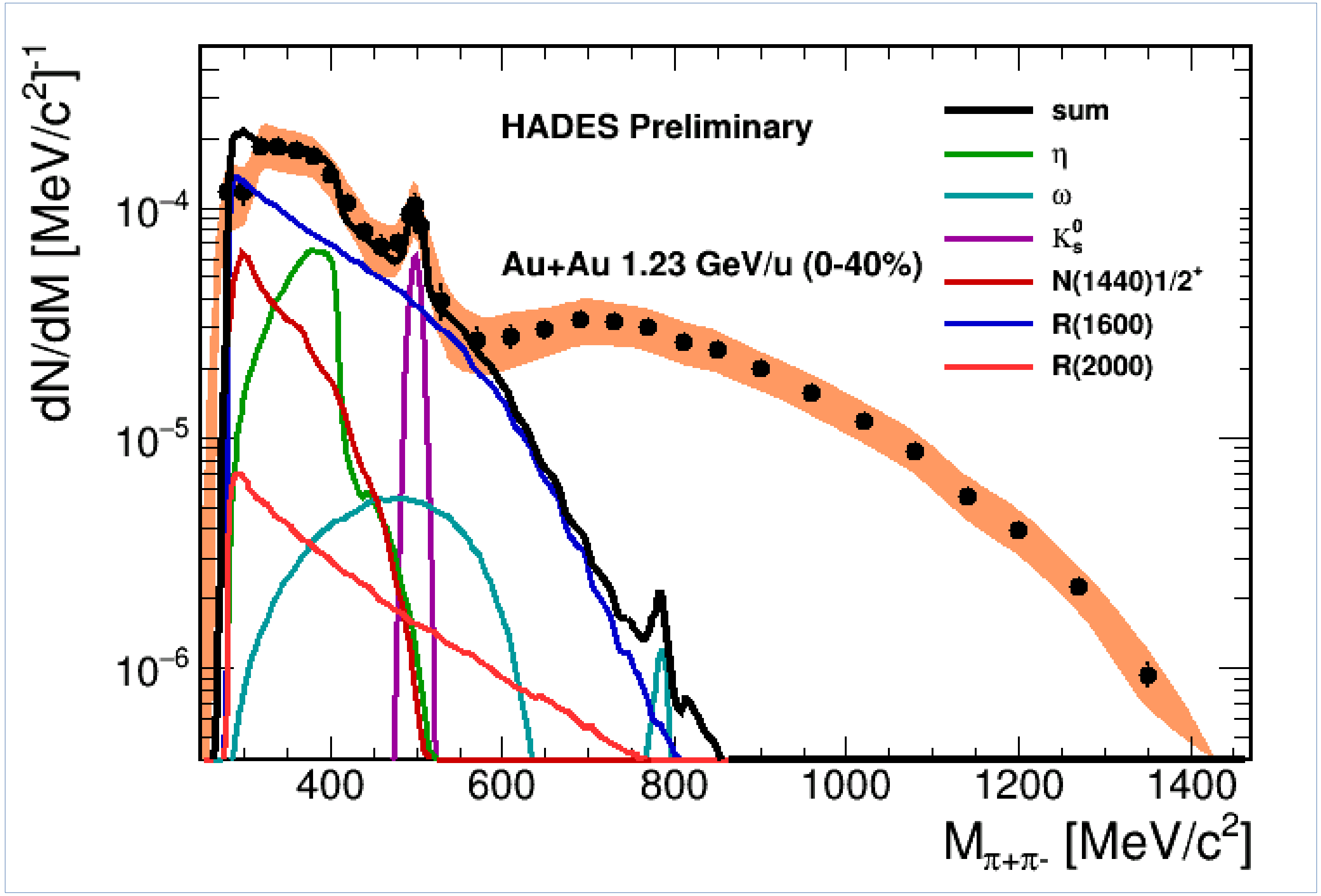


Non linear A_{part} dependence observed, in particular for the high P_T particles

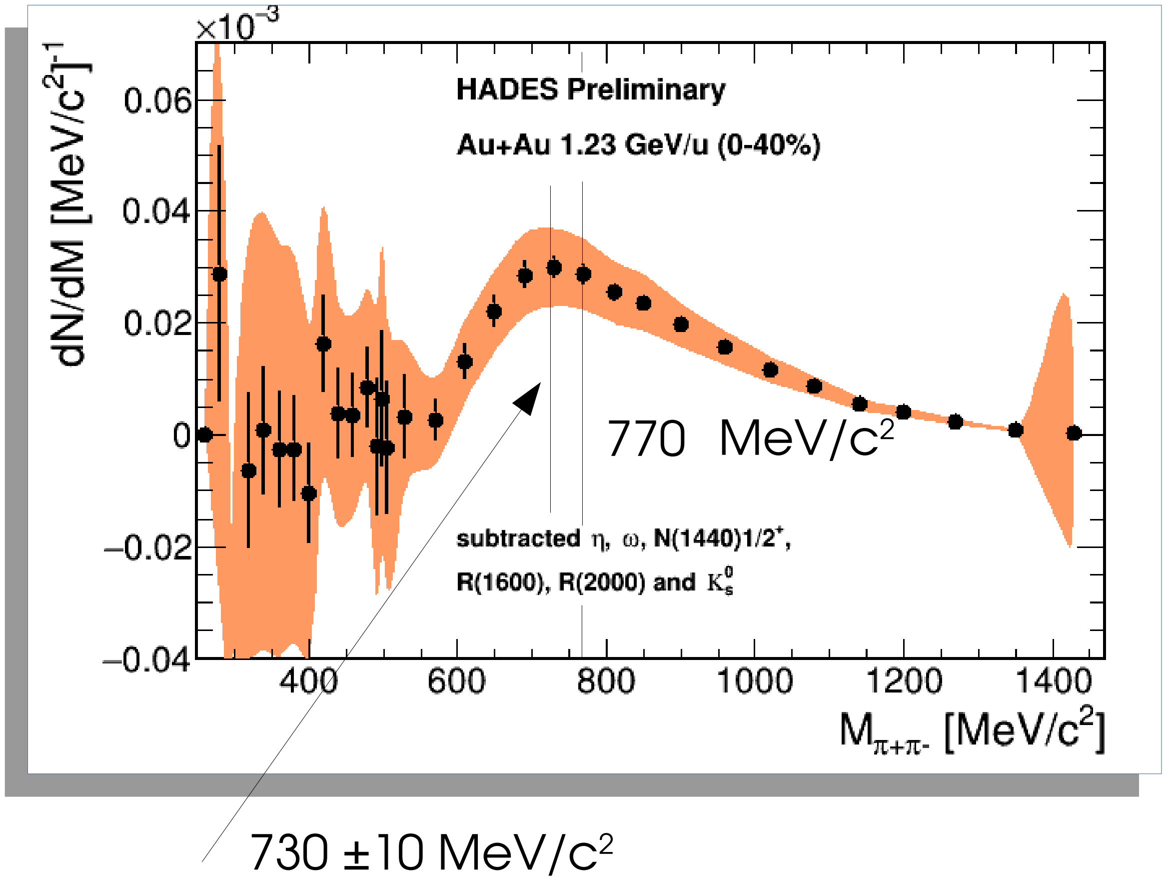
$\pi^+\pi^-$ + PLUTO thermal cocktail

Sources:

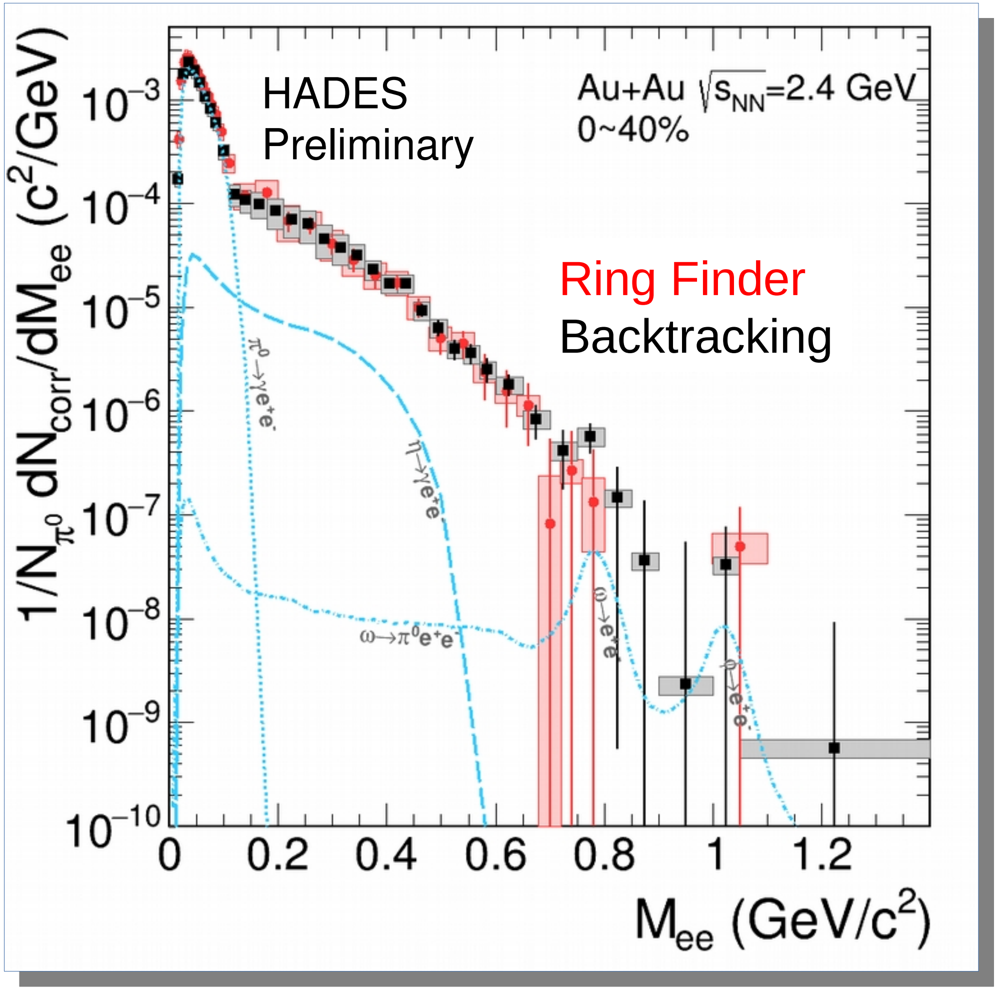
- η = 0.1/Event from $\gamma\gamma$ & world data.
- ω = 0.0029 (THERMUS2 fit) x 2.
- K^0_s yield from Gaussian fit to the data.
- N(1440) 0.4/Event
- R(1600) & R(2000) heavy virtual resonances with decay channel to N$\pi\pi$. Introduced to include the impact of the tail observed in the pp channels.



Most of the sources are long lived

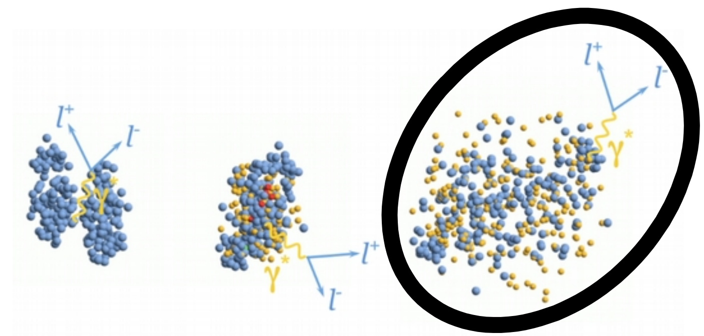


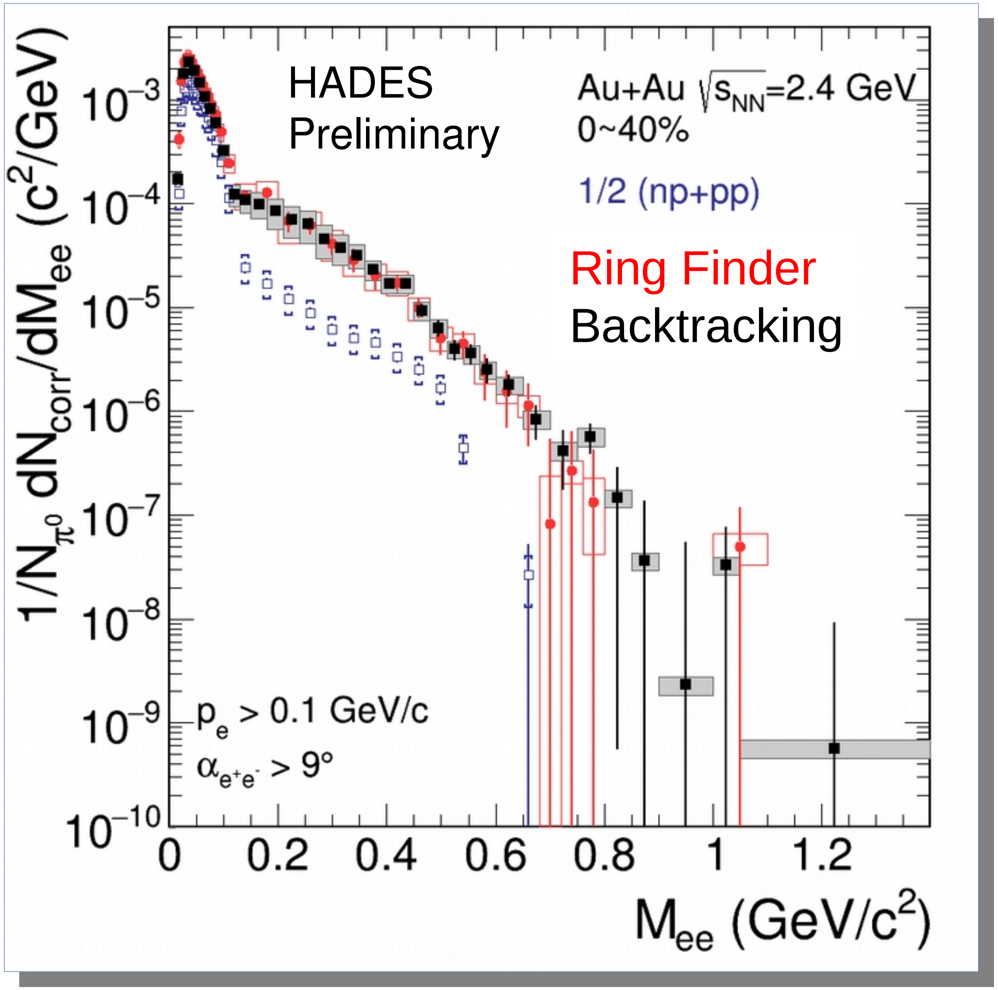
Clear ρ^0 signal in the 40% most central AuAu collisions at 1.23*A* GeV



- π^0 from charged pions multiplicity, cross-checked with the conversion method
- η from the γ conversion
- ϕ from the K^+K^- channel
- ω from the Statistical Hadronization Model

Cocktail takes care of the contributions after the freeze-out



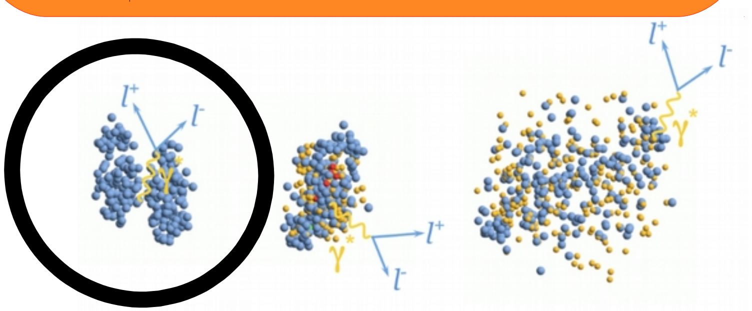


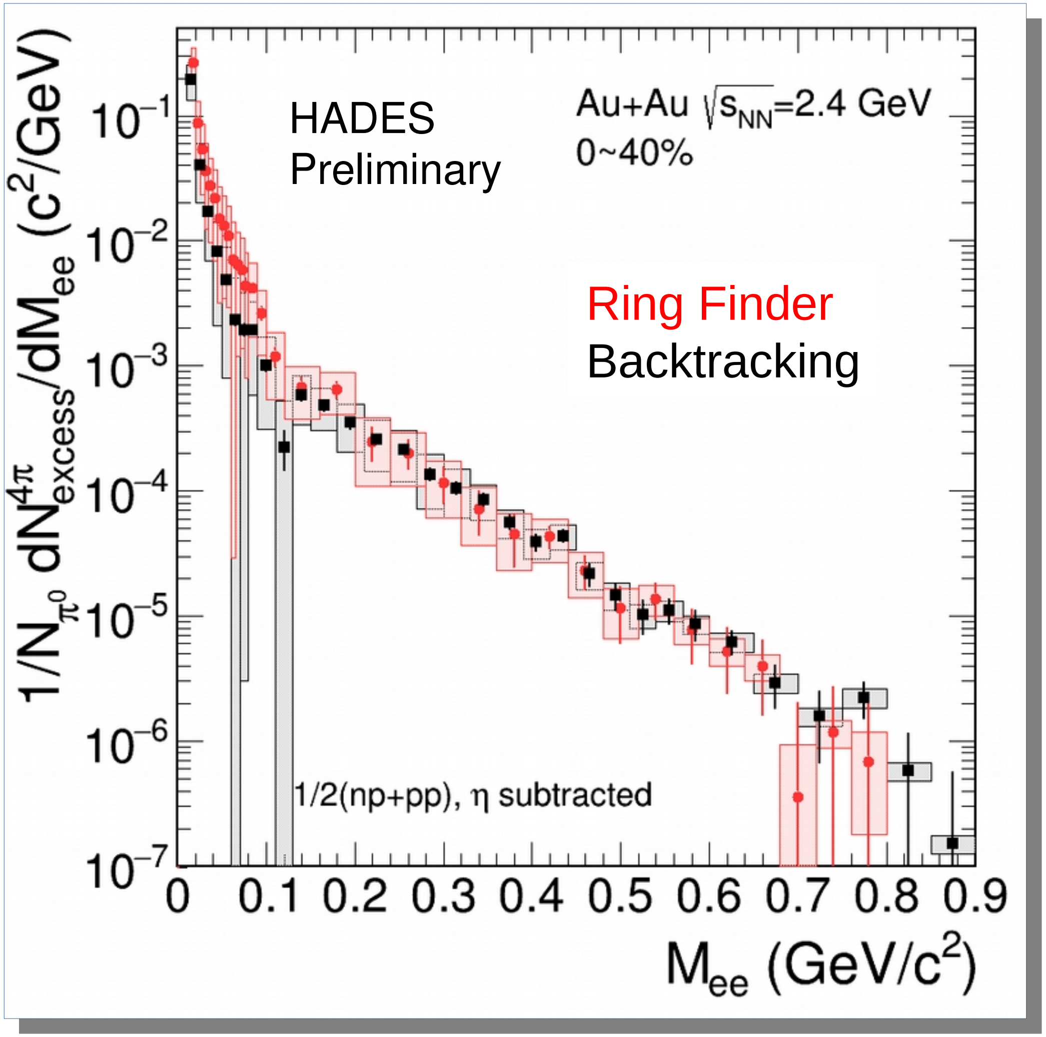
Reference measurement of elementary NN collisions at the same energy

First-chance collisions contributions

Above 0.15 GeV/c² clear enhancement
compared to the reference

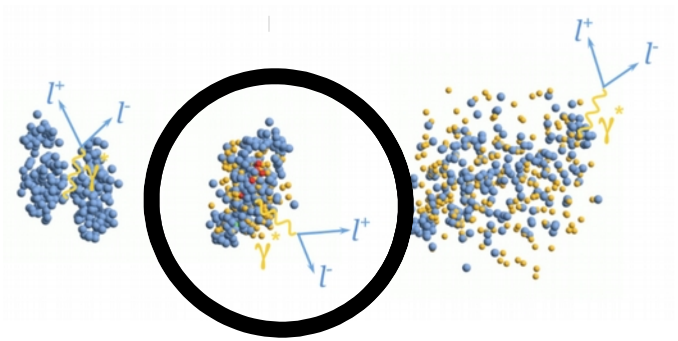
Medium radiation



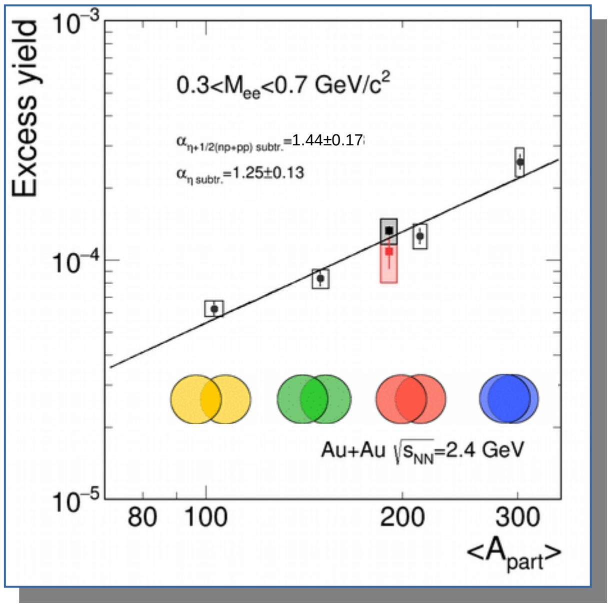


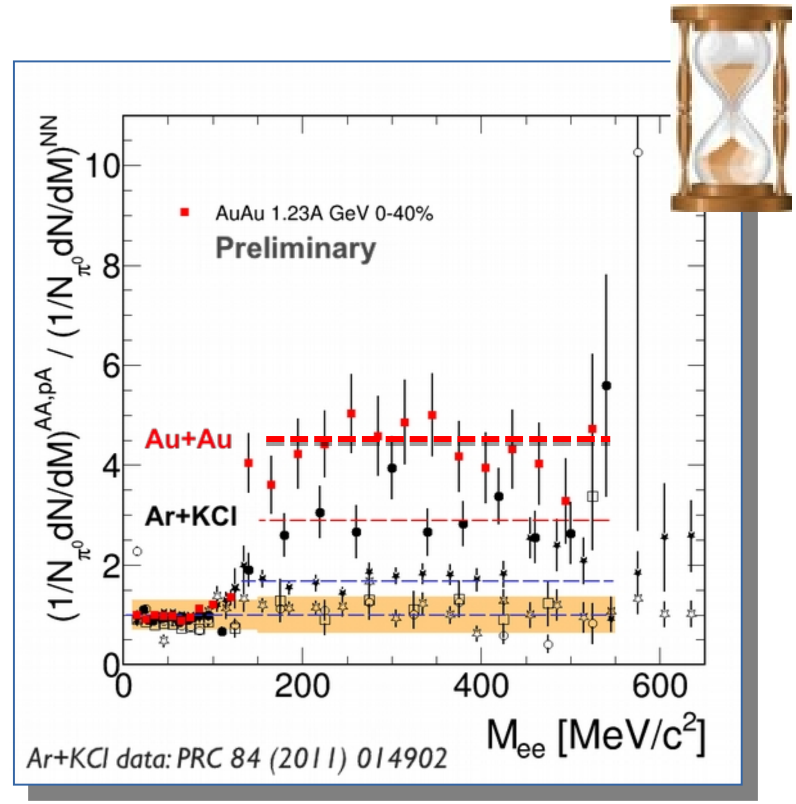
The excess radiation from the medium

- Isolation of the excess by subtracting the experimentally measured reference
- Correcting it for geometrical acceptance of the detector



Excess radiation 0.3 < M_{ee} < 0.7 GeV/c^2

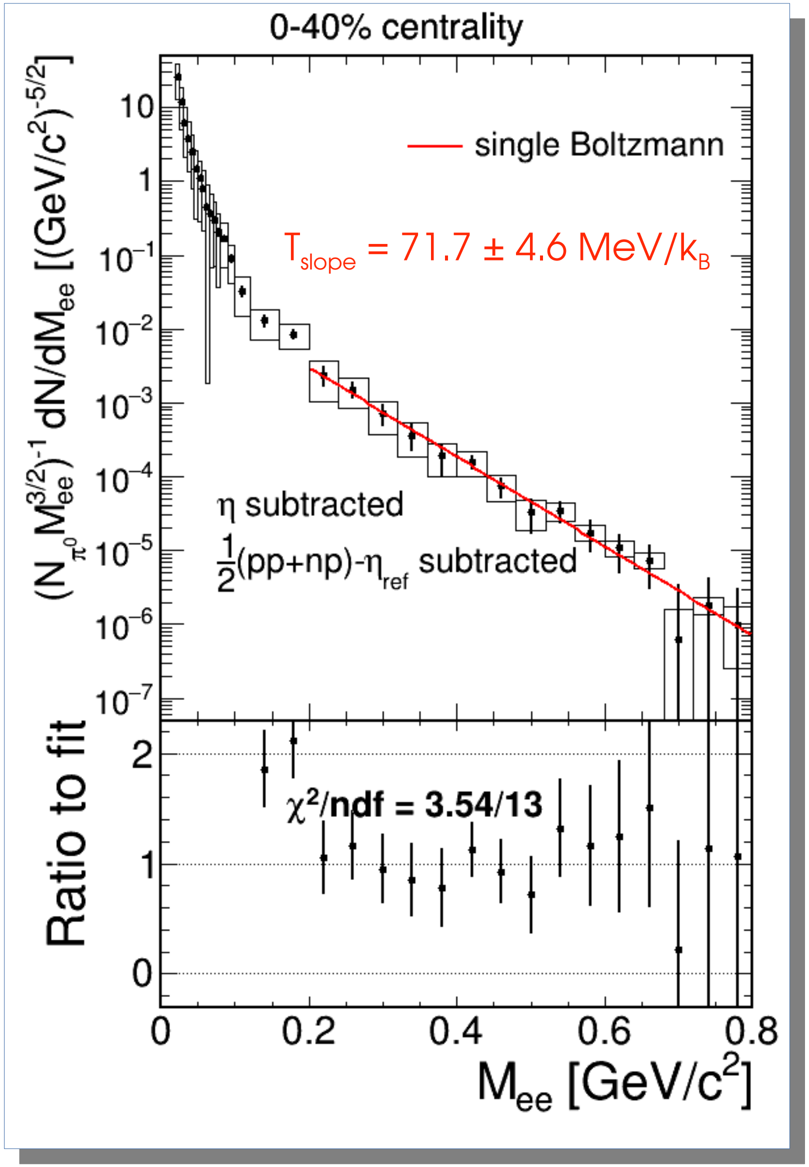




Strong excess dependence ~$A_{part}^{1.3}$

Medium radiation goes beyond incoherent superposition of NN collisions

- Regeneration of baryonic resonances
- **Dilepton chronometer** of the collision time

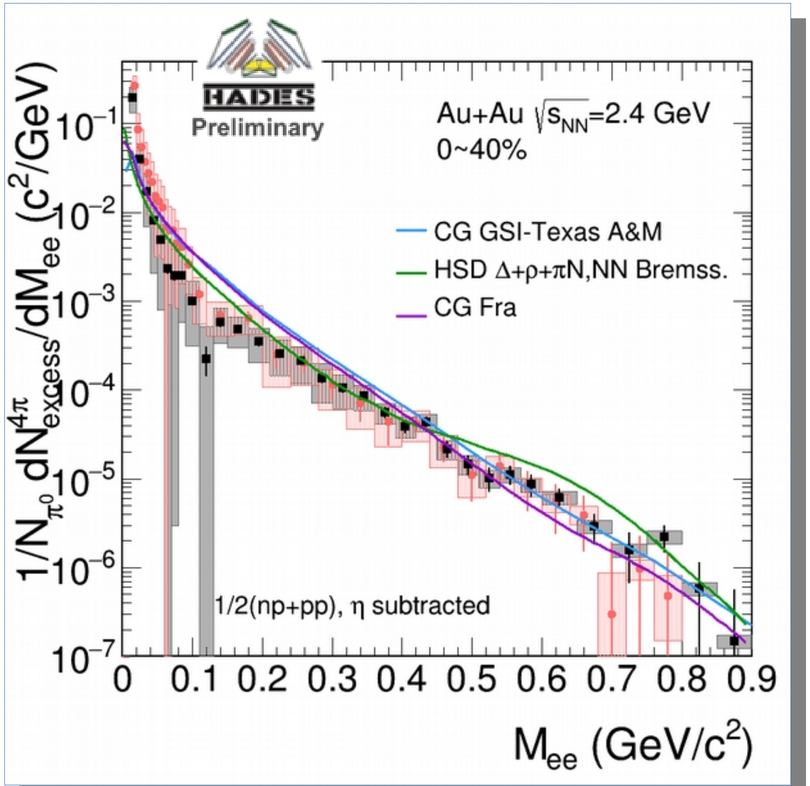


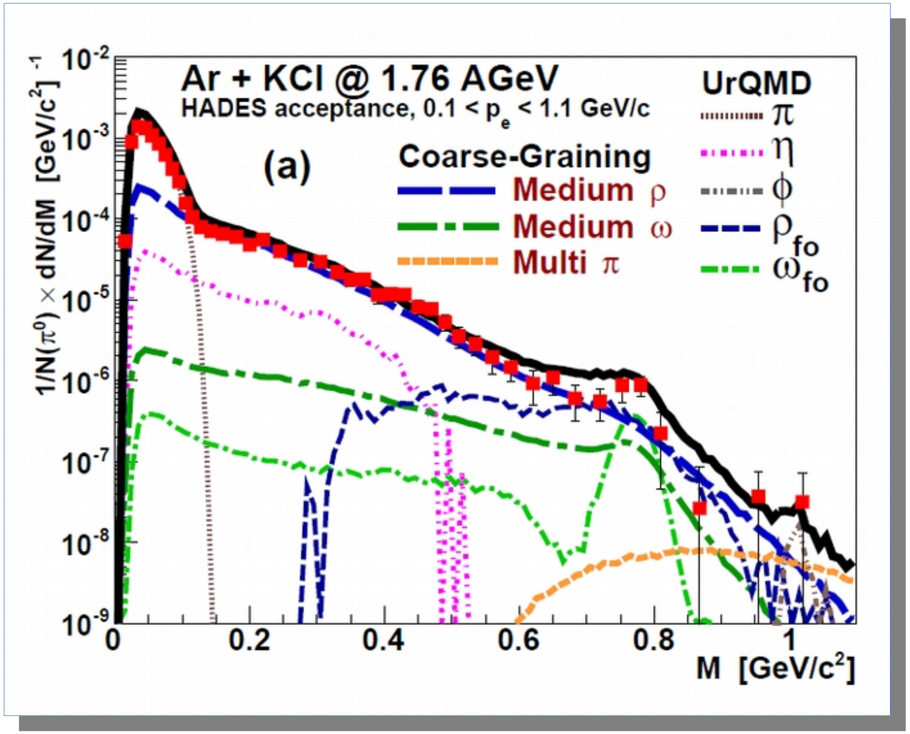
- Invariant mass spectrum not affected by the blue shift – **fit yield the true source temperature**
- Almost exponential shape :

consistent with significant drop of the quark condensate

(order parameter of chiral symmetry restoration)

Theoretical description of excess and dilepton spectra in Au+Au and Ar + KCl





Medium contribution calculated through **ρ in-medium spectral function** with thermodynamic parameters obtained from UrQMD ambient

Statistics is enough for multidifferential analysis.

CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG FRA: Phys. Rev. C 92, 014911 (2015)
HSD: Phys. Rev. C 87, 064907 (2013)

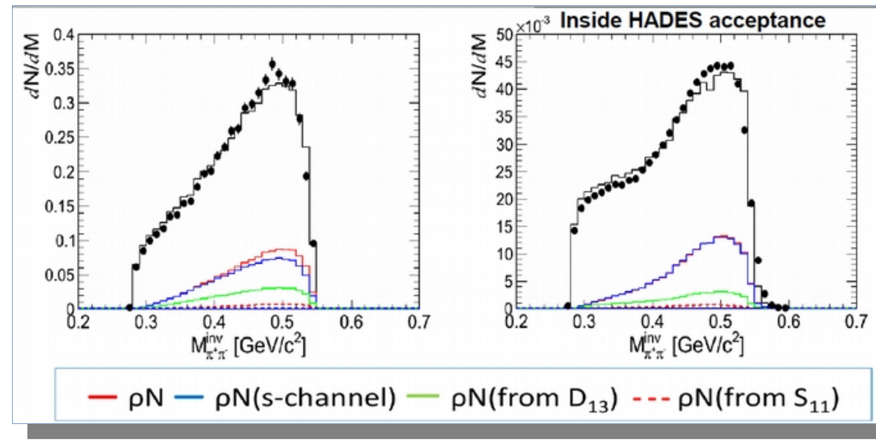
Sources:

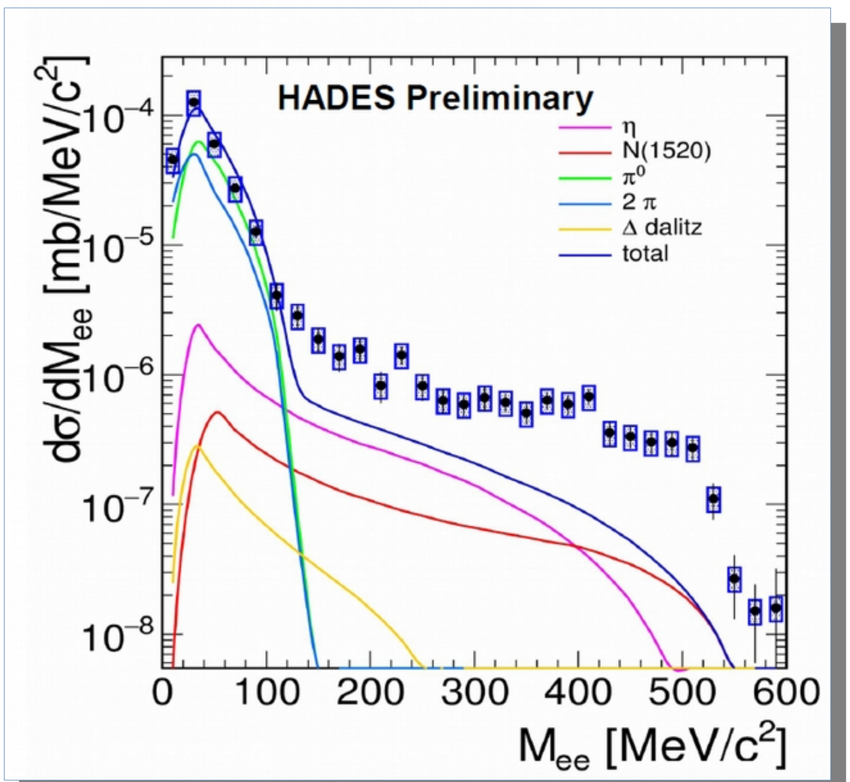
- $\sigma(\pi^- p \to \pi^0 X)$
  $\pi^0 \to e^+e^-\gamma$
- $\pi^- p \to N(1520)$
  Dalitz decay with a constant form factor
- $\sigma(\pi^- p \to \eta\, X)$
  $\eta \to e^+e^-\gamma$

- π^-+C treated as a quasi-free process
- Cross sections taken from database (Landolt-Bornstein)

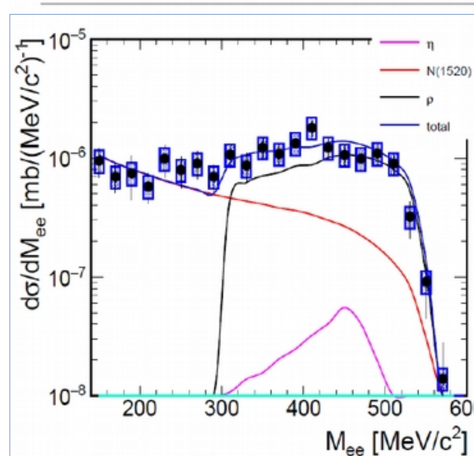
Dilepton ration in **pion induced reactions** (0.69 GeV/c)

Dominant **ρ** contribution in the intermediate region

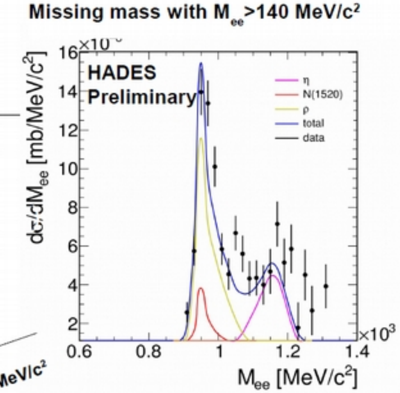




Exclusive channel: $\pi^- p \to n e^+ e^-$



Missing mass with M_{ee}>140 MeV/c²

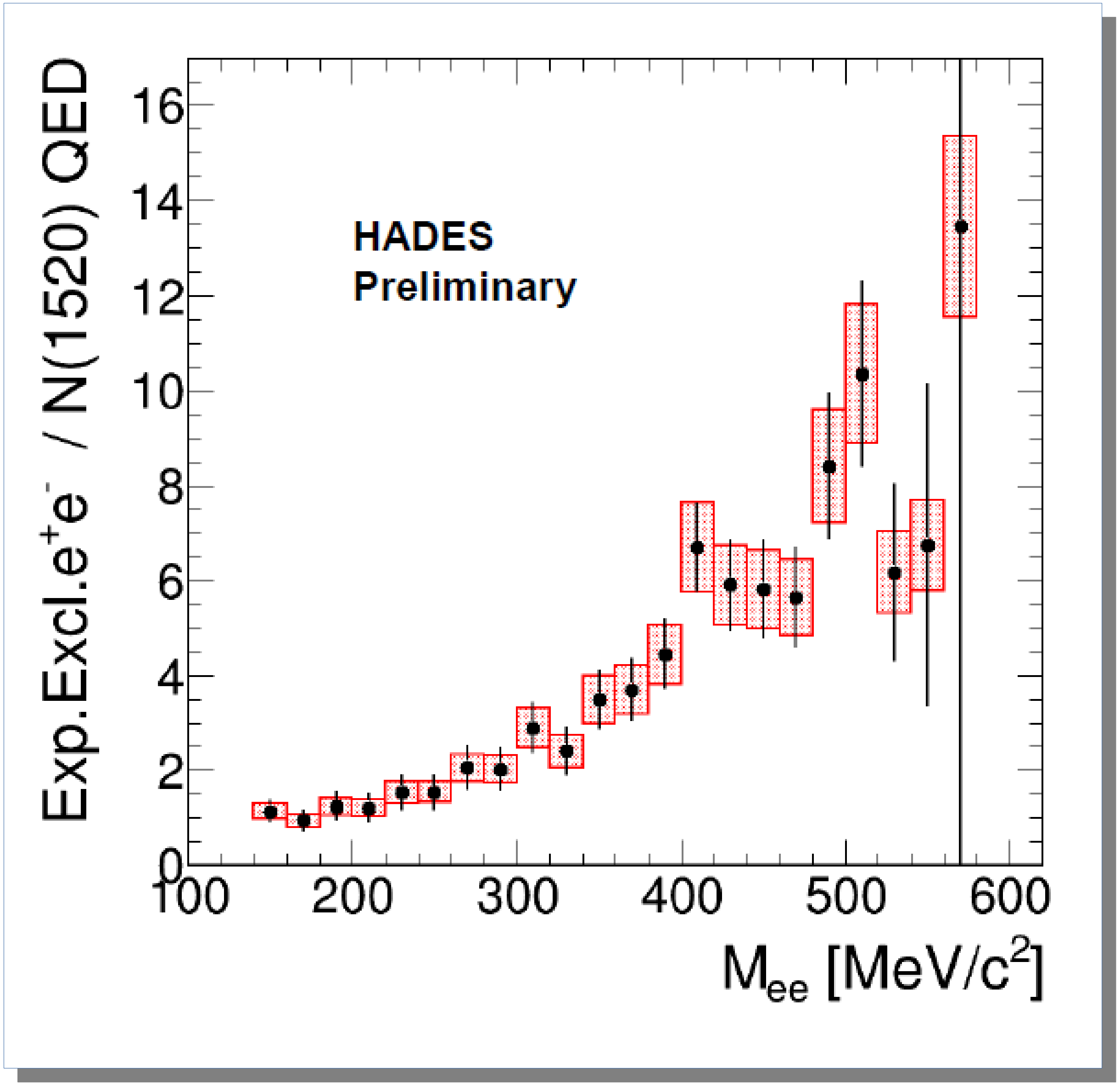


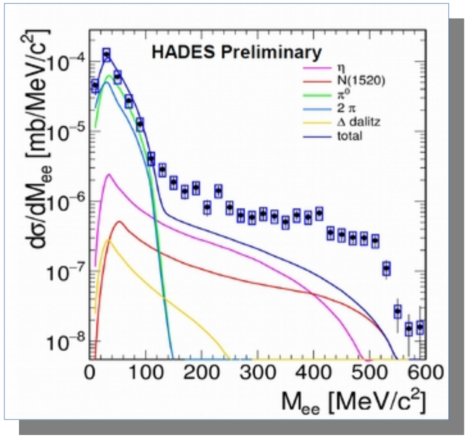
900 < Miss.Mass < 1020 MeV/c²

Good description using a cocktail of point-like baryons+ρ contribution

ρ contribution from PWA (partial wave analysis) of $\pi^+\pi^-$ HADES data and using the **Strict Vector Dominance Model (VDM)**

$$\frac{d\sigma}{dM_{ee}} = \frac{d\sigma}{dM_{\pi\pi}} c_p \left(\frac{m_\rho}{m_{ee}}\right)^3 \quad C_p = 4.7\text{x}10^{-5}$$



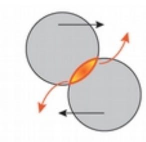


- Ratio between:
  - Efficiency corrected exclusive e+e- spectra
  - N(1520) QED calculation, filtered through the HADES acceptance
- **Clear deviation from unity in the high mass region!**
- **Indication for VDM like form factors**

Collective properities: flow of pions

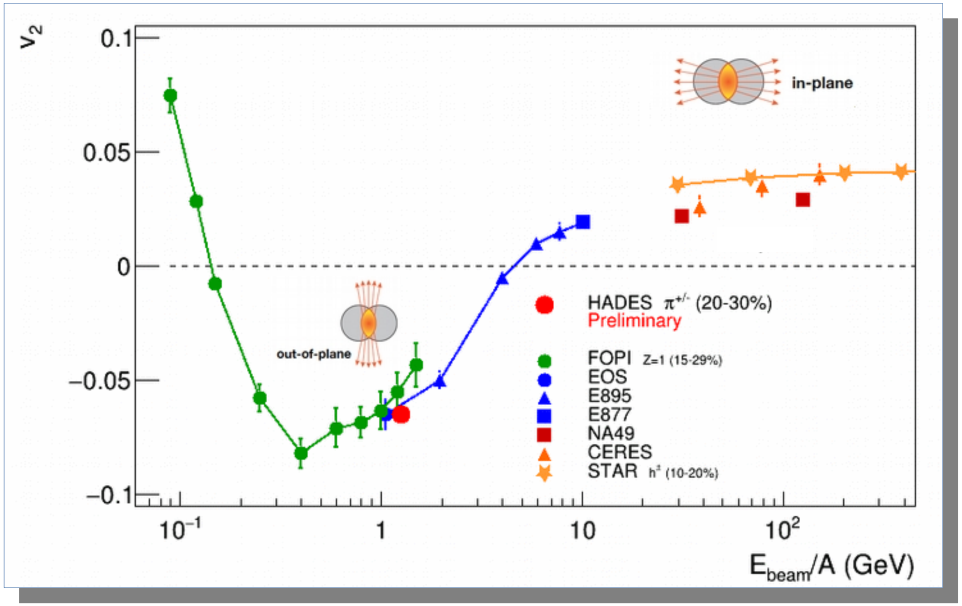
FOPI: Phys.Lett. B612 (2005) 173-180
STAR: Phys. Rev. C 86, 054908
EOS, E895: Phys. Rev. Lett. 83 (1999) 1295
E877: Nucl. Phys. A 638 (1998) 3
CERES: Nucl. Phys. A 698 (2002) 253
NA49: Phys. Rev. C 68 (2003) 034903

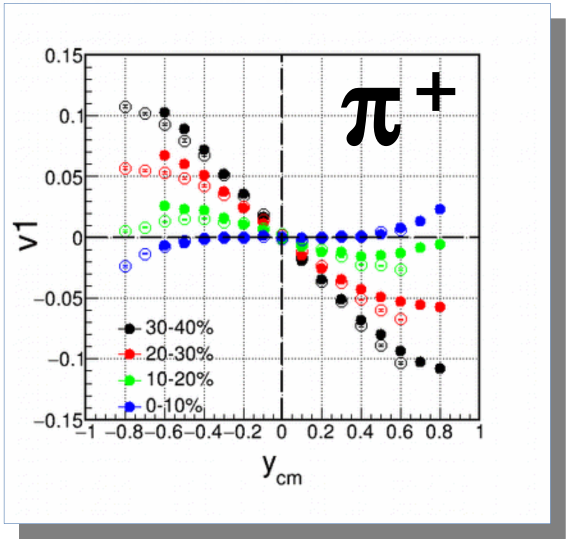
Agreement with world data

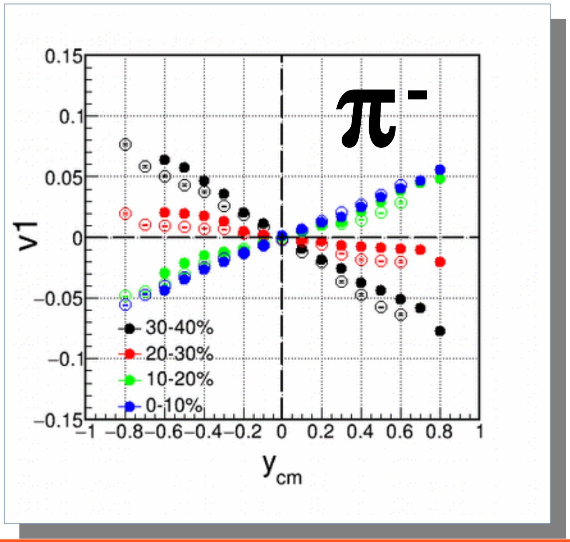


directed flow

$$v_1 = \langle \cos(\phi) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$







The directed flow of pions of opposite charge is not the same

$$E_f = E_i \pm \boxed{V_C}$$

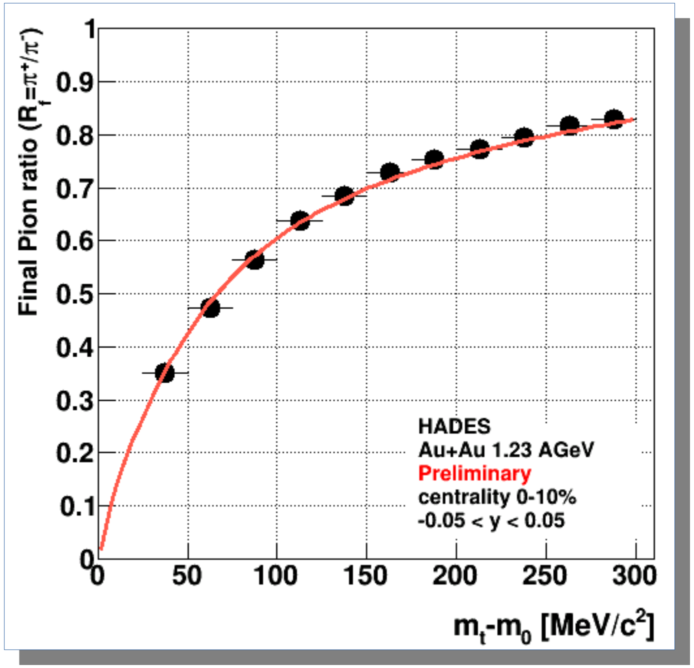
Coulomb Potential

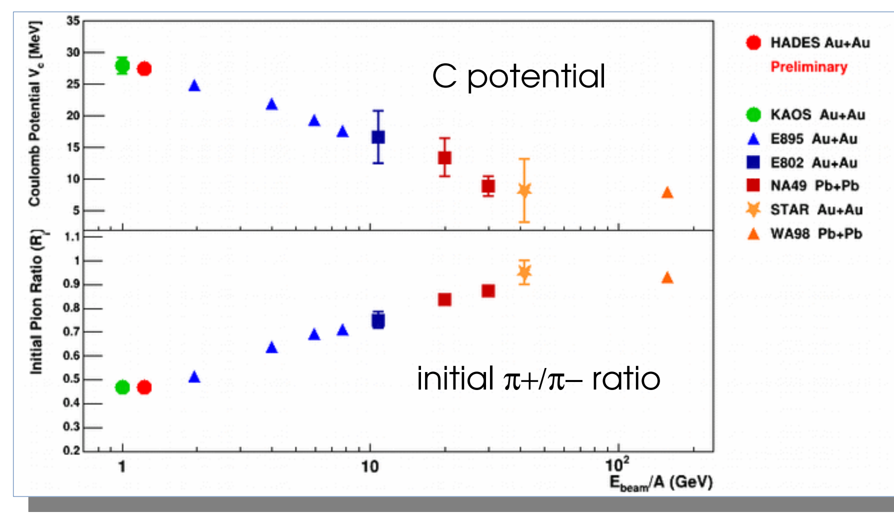
$$R_f(E_f) = \boxed{\frac{E_f - V_C\sqrt{(E_f - V_C)^2 - m^2}}{E_f - V_C\sqrt{(E_f + V_C)^2 - m^2}}}\boxed{\frac{A^+(e^{(E_f+V_C)/T_\pi} - 1)}{A^-(e^{(E_f-V_C)/T_\pi} - 1)}}$$

Jacobian **Bose-Einstein Formula**

$$V_{eff} = V_C(1 - e^{-E_{\max}/T_p})$$

Formalized described in arXiv:1408.1369v1



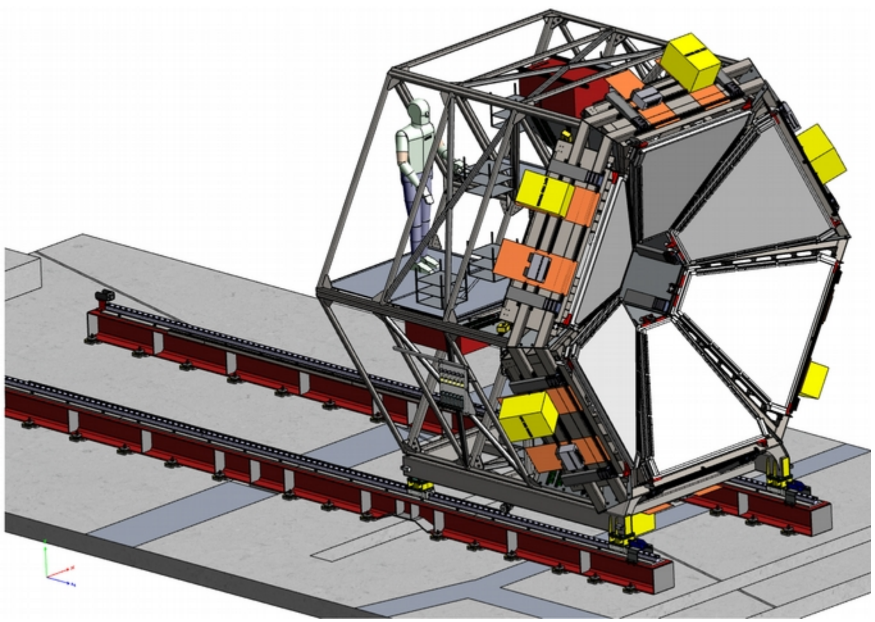


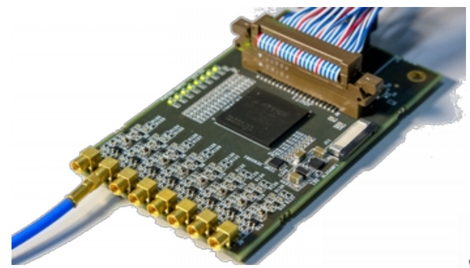
- Coulomb potential (V_c) of the source modifies momentum distribution
  - **Greater effect for low-momentum π**
- Net positive charge in the collision zone
  - **Expanding spherical source**
  - **Effective potential**

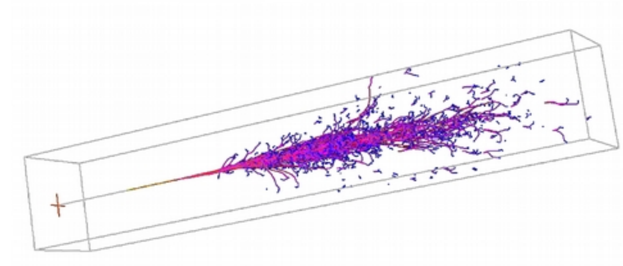
HADES data in line with previous measurements

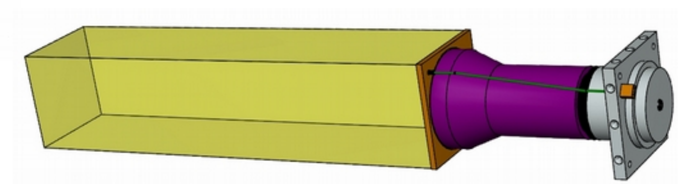
Electromagnetic calorimeter ECAL

2017 - 2018



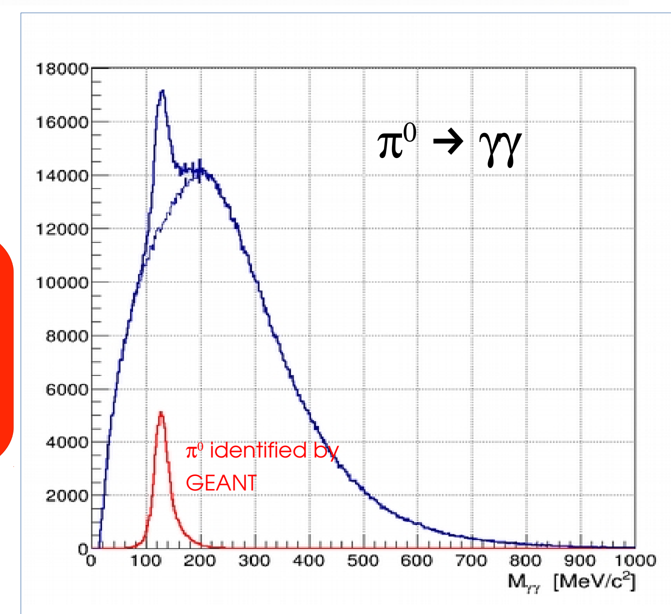






- 978 lead glas modules
- 4,7x4,7*3 m
- Total weight 15 T
- 10 x 10 x 30 cm each module

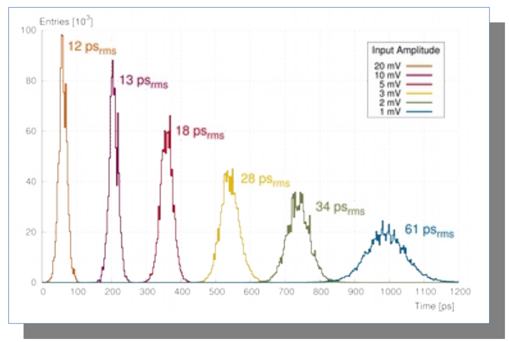
- Access to decays with neutral particles in the final state.
- Access to direct photons.

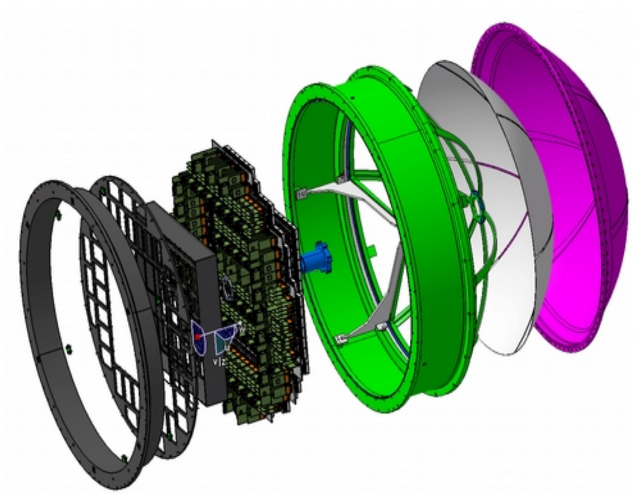


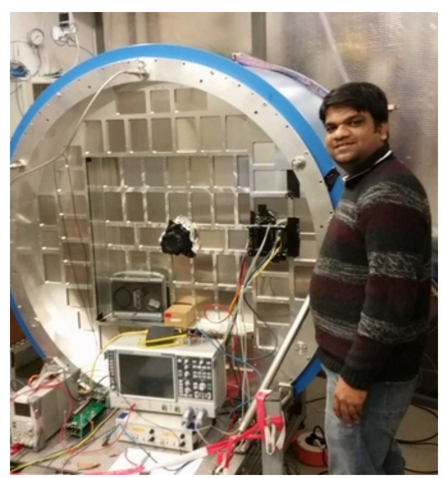
RICH MAPMT UV Upgrade (together with CMB)

2017 - 2018

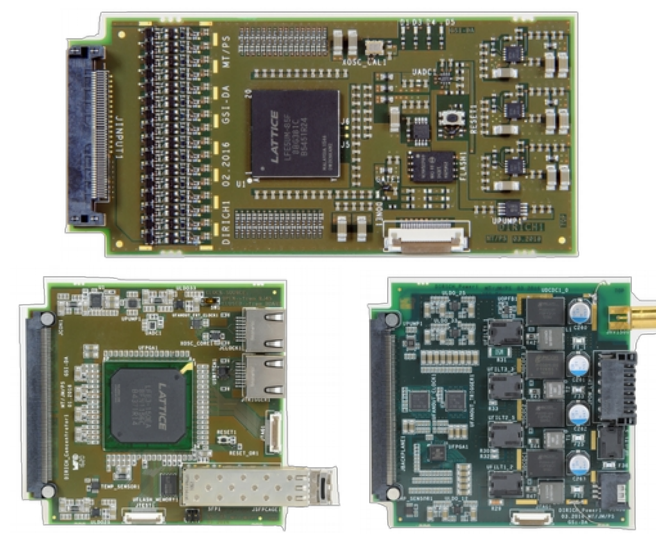
- Replaces aging CsI photo detector
- Improvement of efficiency
- Accurate time measurement: reduced background







- MAPMT (Hamamatsu) based detector modules
- Joint design and realization effort
- Design compatible for use in HADES and CBM RICH

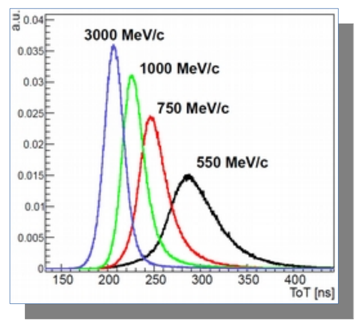


Forward Detector (together with PANDA)

2017 - 2018

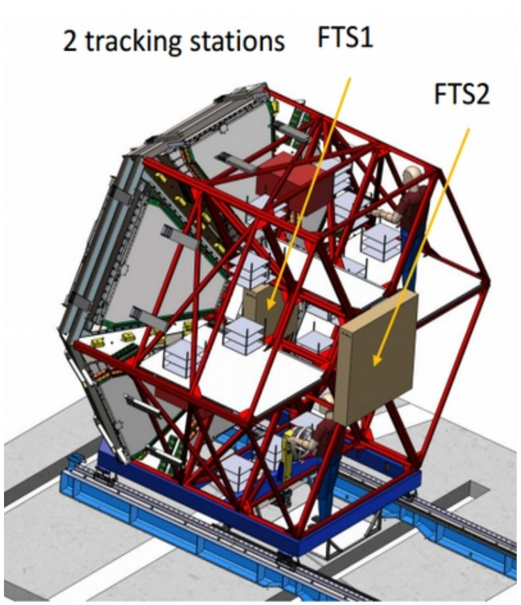
- **Tracking stations** (FTS1, FTS2) based
  on PANDA Straw technology
- **Forward TOF** based on RPC prototypes developed for neuLAND.

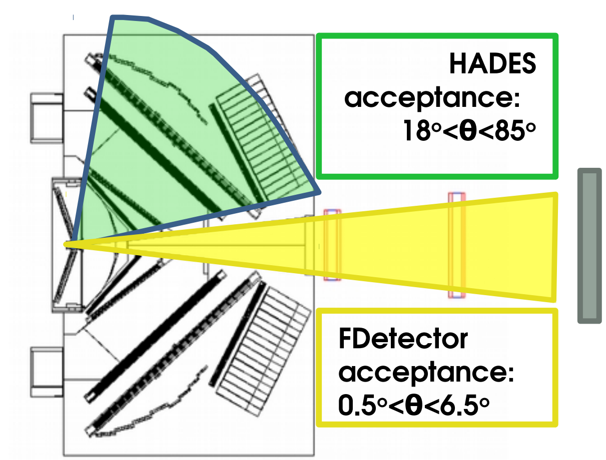
dE/dx via ToT



Significant increase in acceptance for elementary reacitons.

Not suitable for AA runs





straws

RPC

Before SIS100....

HADES Phase 0 physics program

- Electromagnetic structure of baryons in the time-like region.
- Strangeness in (baryonic, non-strange) resonances.
- Excitation spectrum of strange resonances.
- Microscopic structure of dense & hot matter and cold matter (SRC).
- Signatures for exotic properties of dense baryonic matter.

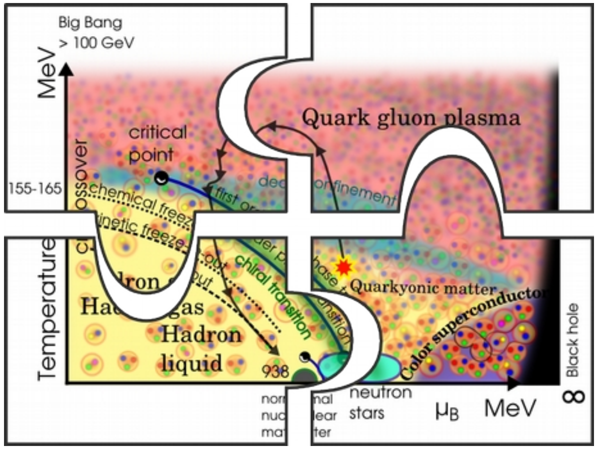
SIS18

π,p → PE

π,p → A

A → A

Program will be optimized w.r.t. beam time available, accelerator performance, spectrometer upgrade



- HADES is the heavy ion experiment that measures the densest region of the QCD phase diagram.
- Au + Au collisions show properties of a thermalized medium: universal participant number scaling.
- Rising ϕ/K^- ratio with lower energies modifies the effective temperature of K^-.
- The differential analysis of meson and baryon resonances show similarities with theoretical predictions as a strong modification of their shapes and pole position..
- Extraction of the medium di-lepton radiation by subtracting the freeze-out and the first chance collisions. Exponential slope points to the melting of the chiral condensate.
- The true temperature of the fireball measured with di-leptons is 72 MeV.
- The upgraded HADES will be able to provide data on neutral particles with ECAL, more dilepton pairs due to the higher RICH efficiency and an inreased acceptance for elementary reaction with the Forward Detector.

Thank you for your attention!