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Transverse flow of strange hadrons in heavy-ion collisions at a beam kinetic energy of a few GeV measured in HADES

27th of February 2025
Nuclear Physics Seminar
Nuclear Physics Department, University of Warsaw

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

HADES

NATIONAL SCIENCE CENTRE
POLAND

This work is part of a project co-financed by the N.S.C.
under reference number 2024/53/N/ST2/02107

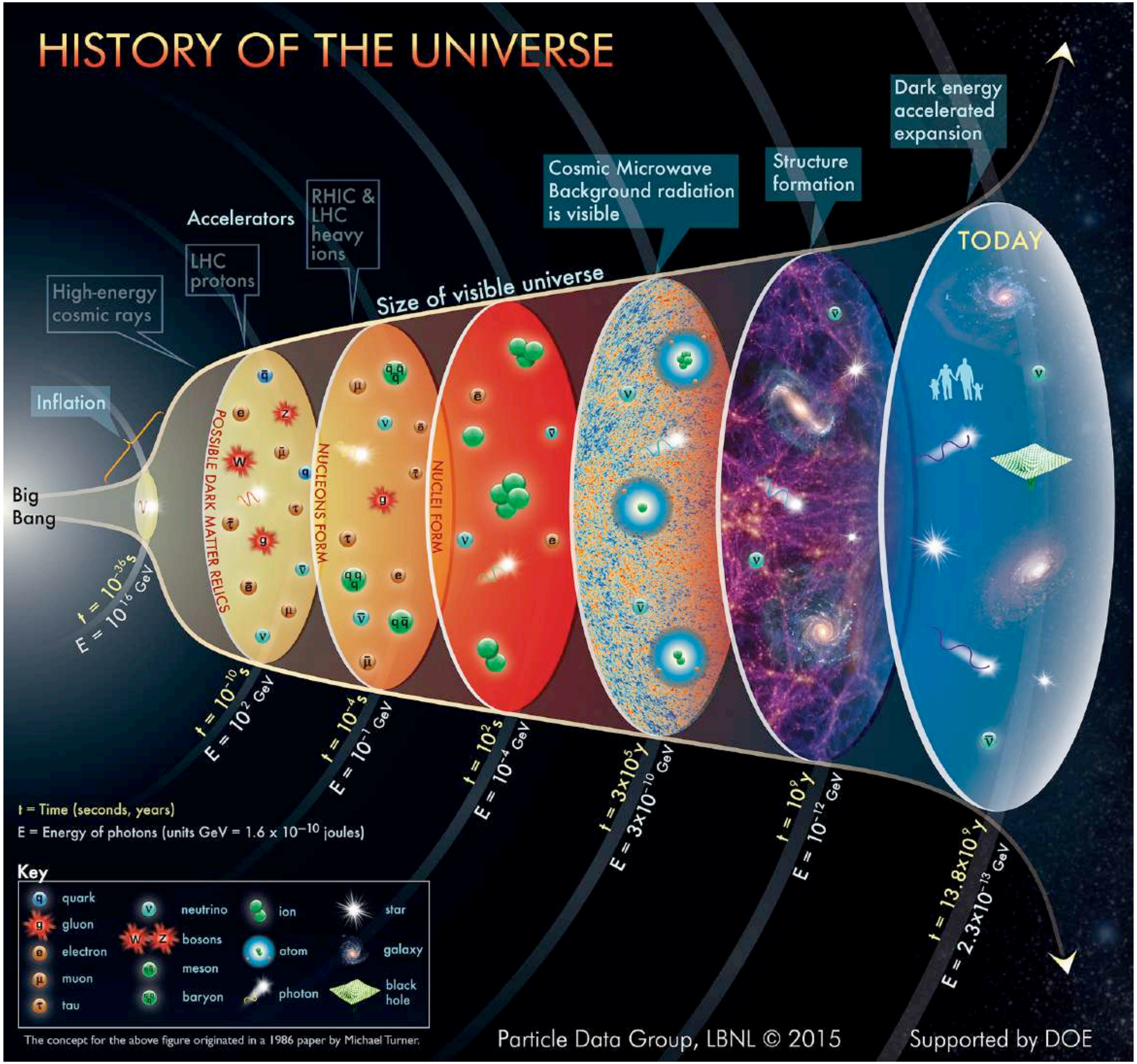
Introduction

- Goal of the talk: introduction to transverse flow analysis, review of status and current study;
- Particles selected for analysis are strange hadrons: K^+, K^- and Λ^0;
- The issue of Kaon-Nuclear Matter potential and the role of Λ^0 baryons in astrophysics are discussed;
- Ongoing analysis of data collected by the HADES experiment in March 2019 — Ag+Ag collisions at 1.6 GeV/nucleon

Physical motivation

History of the Universe

- Heavy-ion collisions allow the study of matter in extreme conditions;
- The few-GeV energy regime is located between free quarks and the formation of hadrons;
- Our understanding of Quantum Chromo-Dynamics in this area is still limited



Nuclear matter

➠ Starting point: liquid-drop model of the nucleus:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \delta(N, Z)$$

➠ To obtain "nuclear matter" we extend the nucleus into infinite volume;

Nuclear matter

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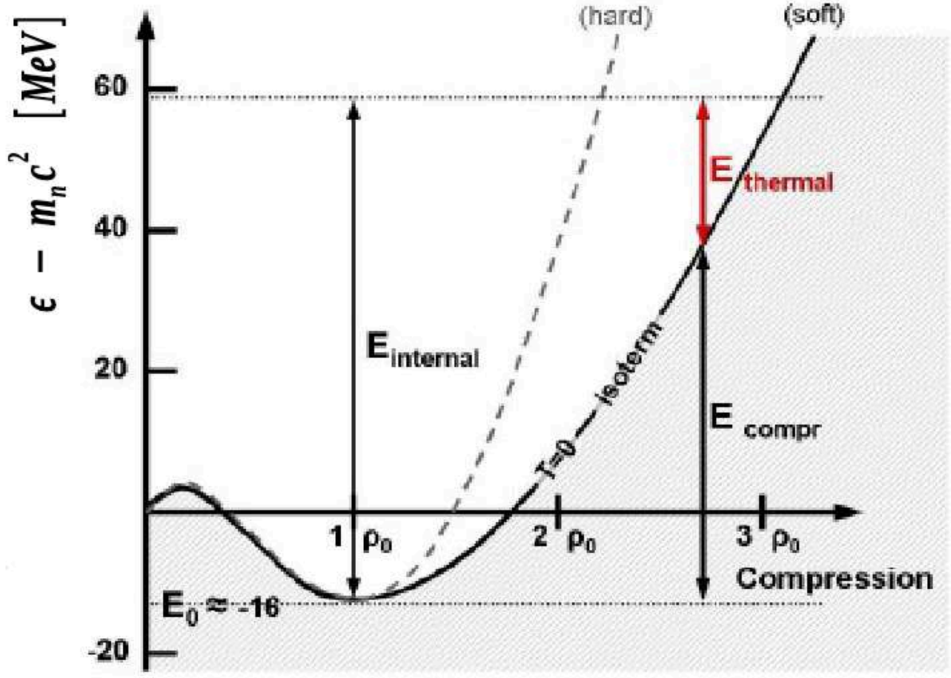
- To obtain "nuclear matter" we extend the nucleus into infinite volume;
- The surface and Coulomb contributions can be canceled $a_S = a_C = 0$;
- The pairing contribution can be omitted;
- We assume infinite A and V, but well defined concentration $\rho = \left\langle \frac{A}{V} \right\rangle$

Equation of State of nuclear matter

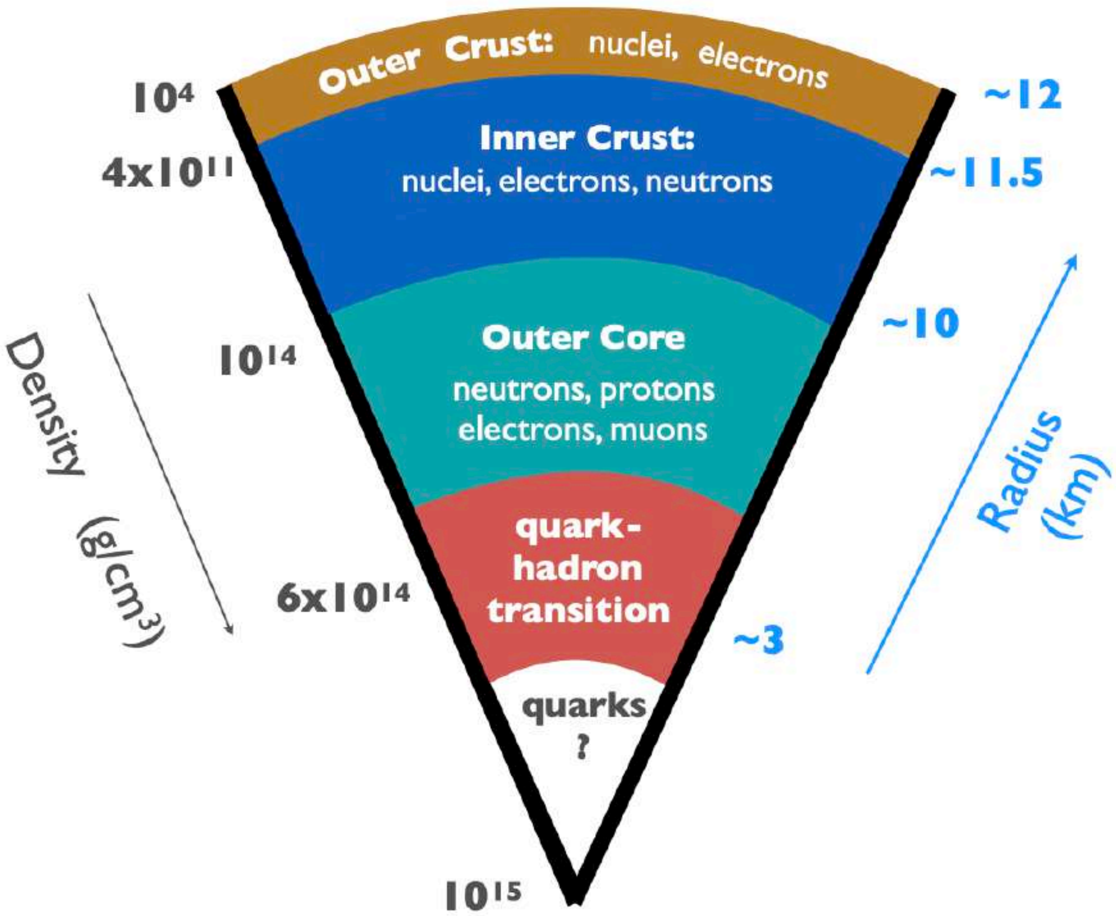
- Nuclear matter can be described in thermodynamic terms ($\rho, T, \mu, p, \epsilon$, etc…);
- These variables are related by the Equation of State (EoS);
- The EoS describes, among others, the resistance of nuclear matter against compression;



A. Le Fèvre et al., Nucl. Phys. A 945 112 (2016)

- Method of study: transverse flow of protons in HIC;
- Soft (hard) EoS is more (less) susceptible to compression because if a slower (faster) increase of energy with growing matter density

Neutron Stars (NS)



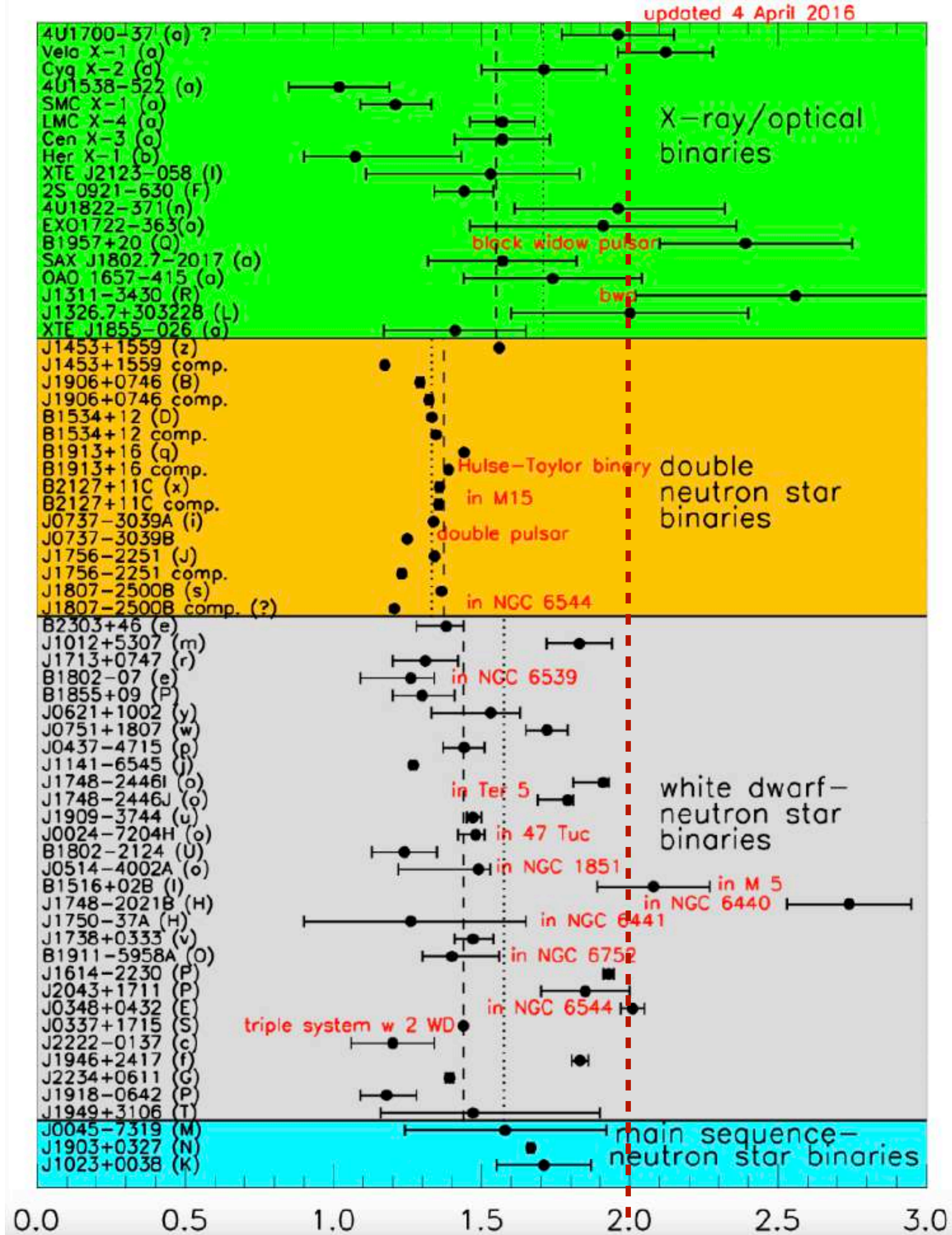
V. Kalogera *et al.*, arXiv 2111.06990v1

- There is a deep crossover between matter in NS's and atomic nuclei;
- NS's partly described with the EoS of nuclear matter;
- Matter at densities $\leq \rho_0$ forms the crust of the NS (with nuclei);
- Deeper we find Nuclear Matter at extreme conditions:
  - Free and stable neutrons
  - At highest ρ: free quarks?
- If and when does this transition happen?

The Hyperon Puzzle

- Currently observed masses of NS's are roughly in the range of 1-2$M_\odot$;
- Some observed masses are $\geq 2M_\odot$ and **strongly constrain theory**;
- Theories assuming the presence of hyperons in NS core do not reproduce this range of masses;
- Simultaneously, the thermodynamic conditions inside strongly suggest production of strangeness…
- How to reconcile this tension?

J. Lattinger, https://stellarcollapse.org/nsmasses



Modification of K properties

- Hadronic density and temperature affect the mean value of the quark-antiquark condensate;

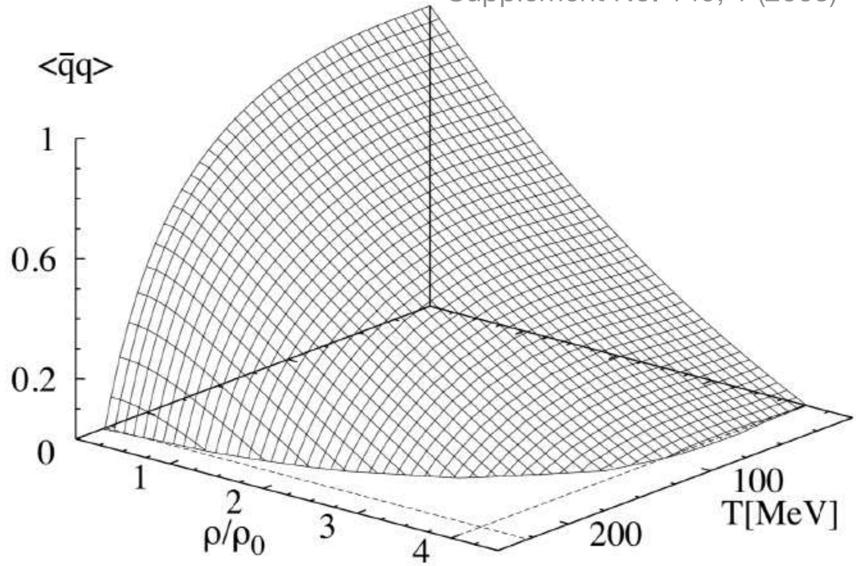
- In consequence, fundamental properties of particles are modified

- Gell-Mann—Oakes—Renner:

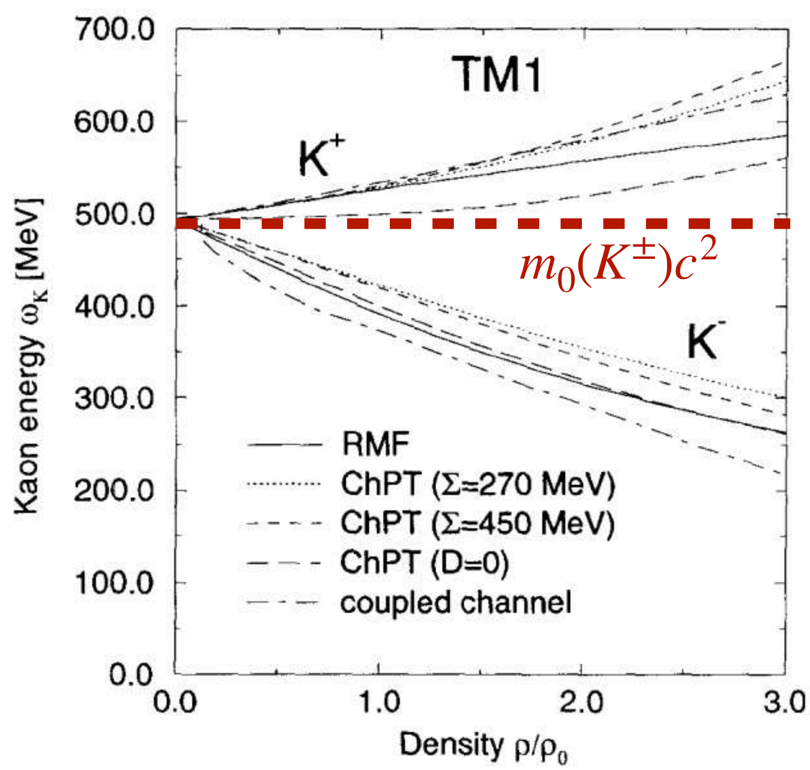
$$m_K^{*2} f_K^{*2} = -\frac{m_u + m_s}{2}\langle \mathrm{u\bar{u}} + \mathrm{s\bar{s}} \rangle + \Theta(m_s^2)$$

- Significant effect predicted for the transverse flow of charged K mesons: K^+N repulsion and K^-N attraction

W. Weise, Prog. Theor. Phys. Supplement No. 149, 1 (2003)



J. Schaffner-Bielich et al. / Nuclear Physics A 625 (1997) 325–346



Transverse flow

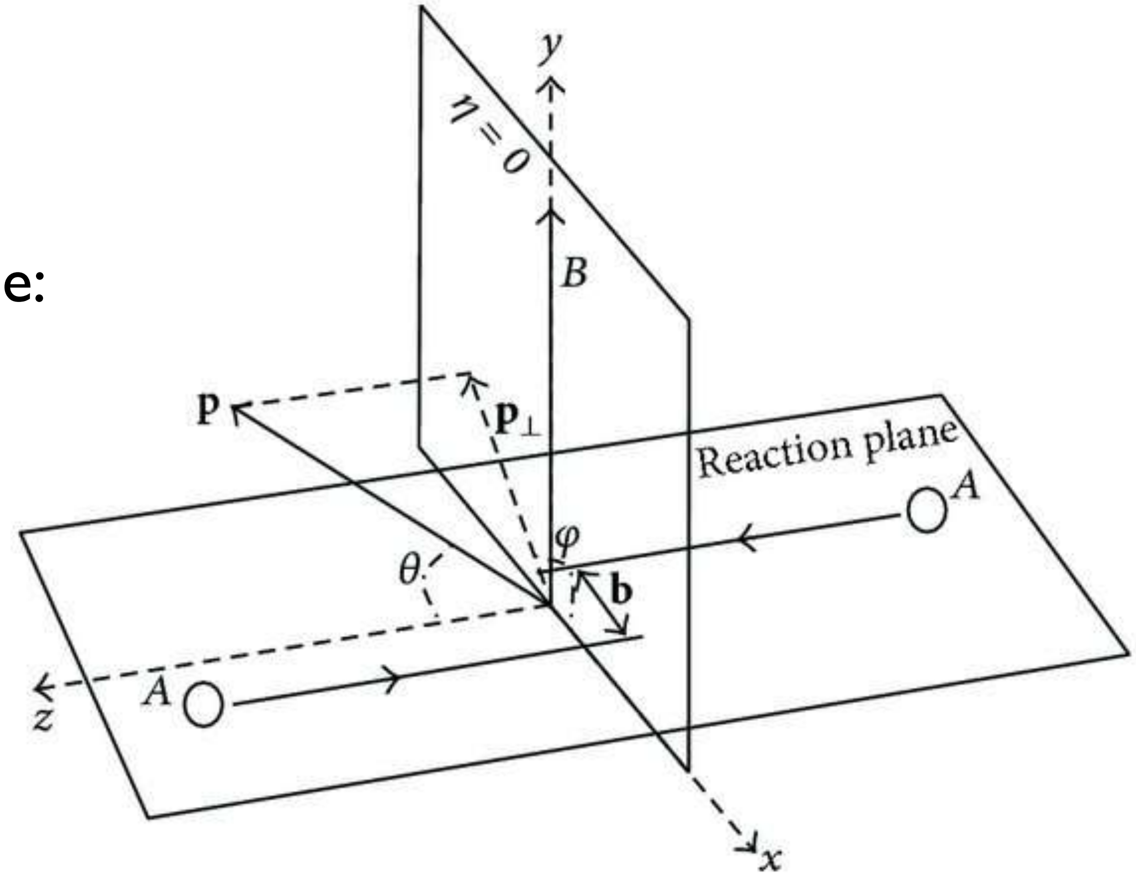
Geometry of a heavy ion collision

- By definition, $\vec{p}_{beam} = p_{beam}\hat{e}_z$
- Relativistic momentum phase-space:

$$p_t = \sqrt{p_x^2 + p_y^2} \ ,$$

$$y = \tanh^{-1} \beta_z$$

$$y_0 = \frac{y - y_{CM}}{y_{CM}}$$



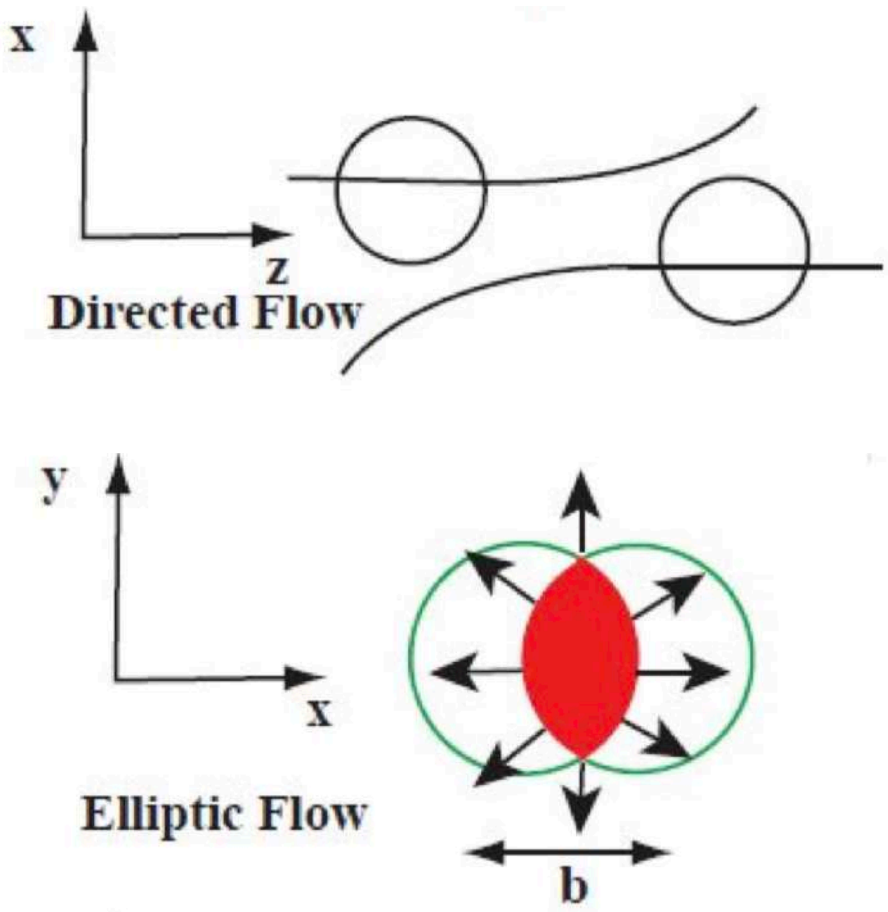
- Polar angle θ, azimuthal angle ϕ
- Centrality determined by collision parameter b (not available in exp)

Non-central heavy ion collision

➠ Non-central heavy-ion collisions preselect certain azimuthal angles;

➠ The final kinematic distribution of particles is a composition of multiple factors:

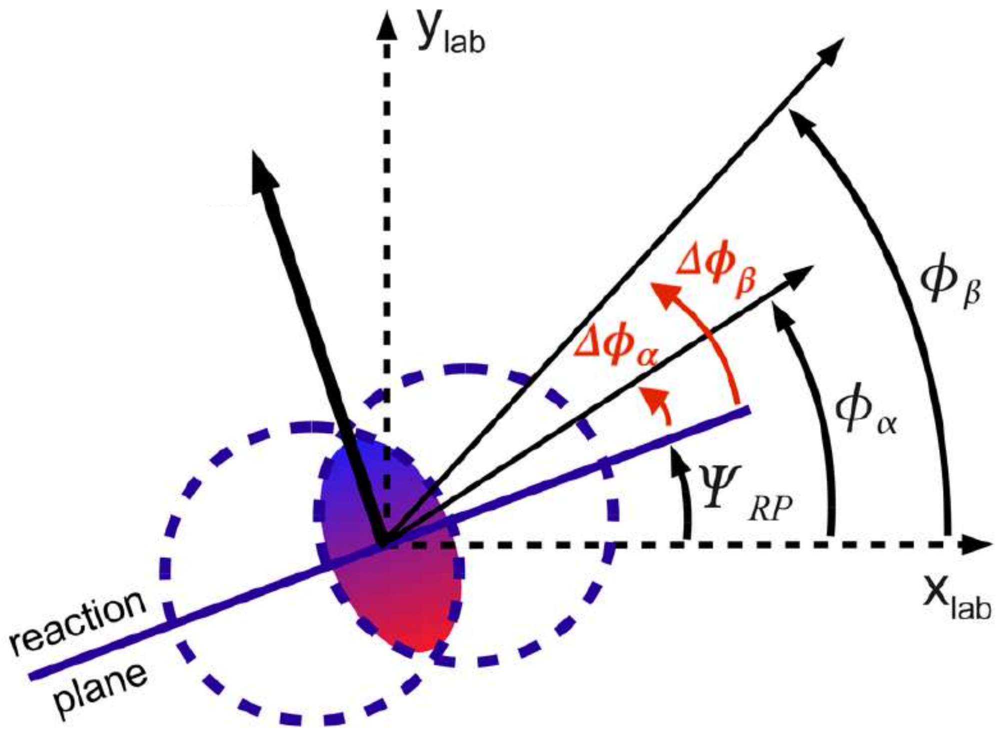
- non-isotropic collision zone,
- pressure gradients,
- in-medium effects,
- Coulomb interaction.



A. Poskanzer et al., arXiv:08090409 [nucl-ex] (2002)

Fourier decomposition

- If the orientation of the collision is known (**this is not trivial!**), we can measure relative azimuthal angle of emitted particles;



Adapted from:
B. I. Abelev et al. (STAR Collaboration), Phys. Rev. Lett. 103(25):251601 (2009)

- Reaction Plane: defined as the plane containing the collision vector $\vec{b}$ and the beam momentum ($\hat{e}_z$);

- We define $\Delta\phi$ as the azimuthal angle with respect to the Event plane

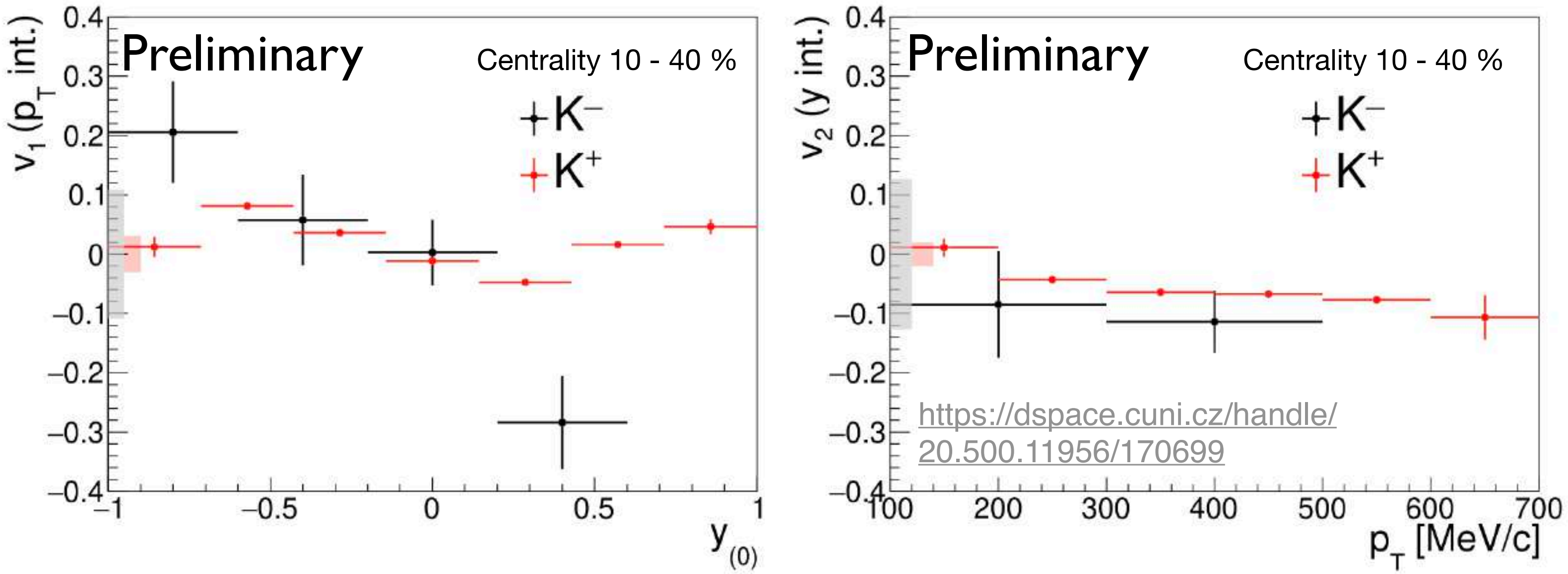
- Then, the $\Delta\phi$ distribution: $\dfrac{dN}{d\Delta\phi} = \mathcal{N}\left(1 + 2\sum_n v_n \cos(n\Delta\phi)\right)$

Some flow predictions

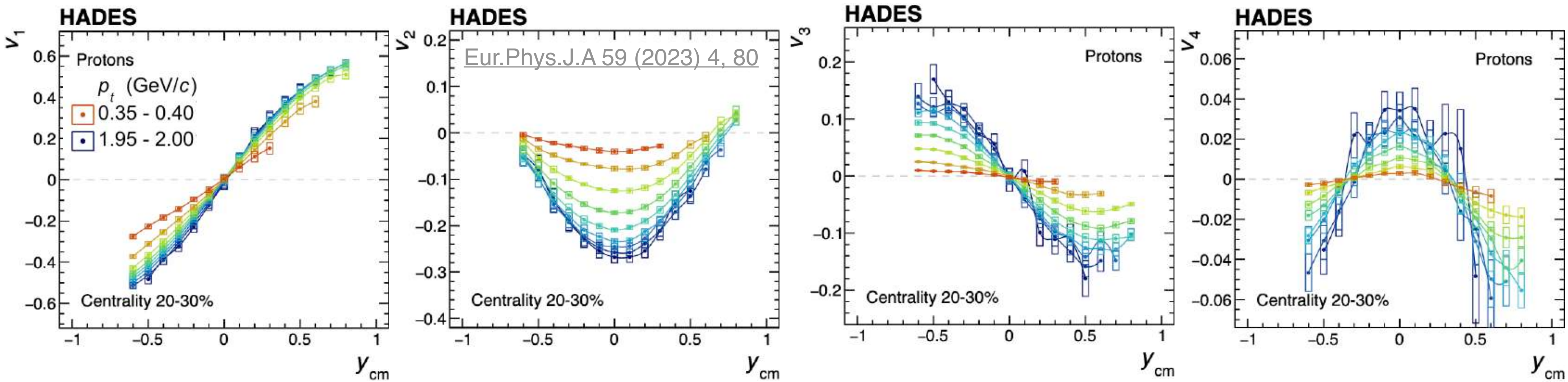
- In this work, main harmonic coefficients are studied: directed flow (v_1) and elliptic flow (v_2);
- In the Center-of-Mass frame, we expect $v_1(y)$ to be an odd function (for a symmetrical collision system);
- From this follows $v_1(y = 0) = 0$;
- Asymmetry of directed flow is a benchmark of measurement quality;
- Flow is used to draw physical conclusions by comparing experimental results to transport model calculations.

Previous flow reports from HADES

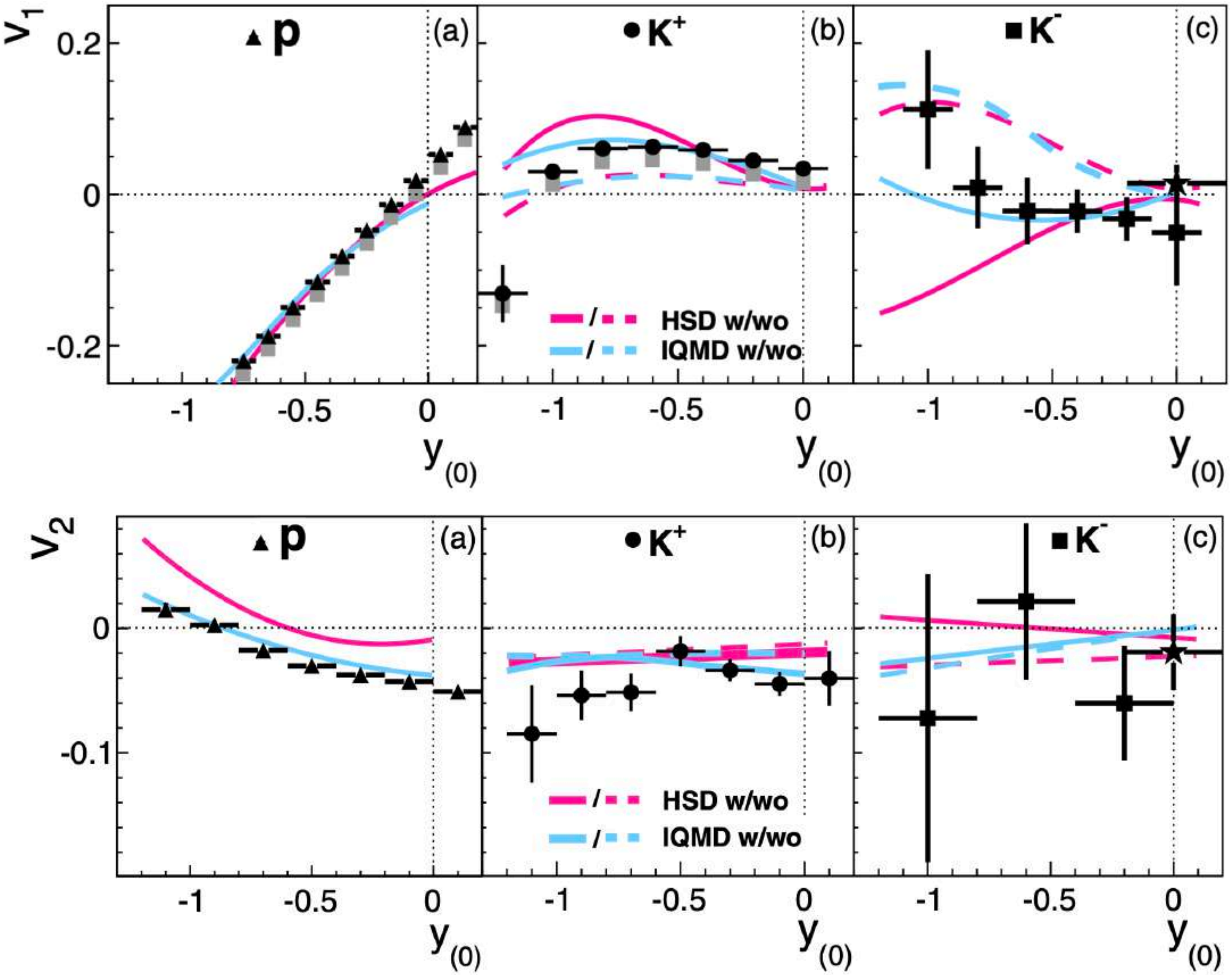
$v_{1,2}$ of charged kaons
in Au+Au @ 1.23*A* GeV ↘



v_{1-4} of protons
in Au+Au @ 1.23*A* GeV ↓



Charged kaon flow in FOPI



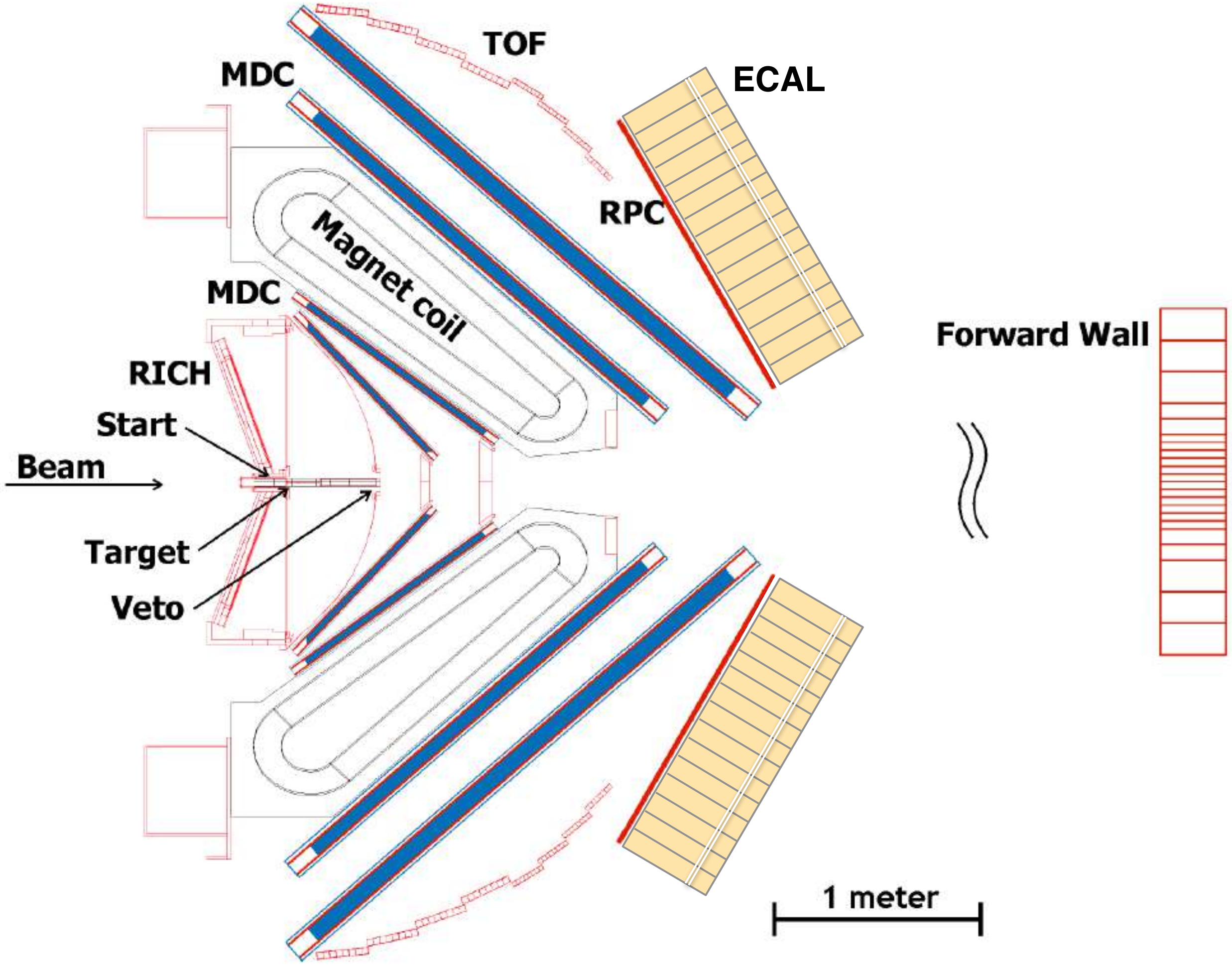
V. Zinyuk et al. (FOPI)
Phys. Rev. C 90, 025210 (2014)

➟ Note: $v_{1,2}(p_t, y)$ maps were never published for Λ baryons in this energy range!

The **H A D E S**

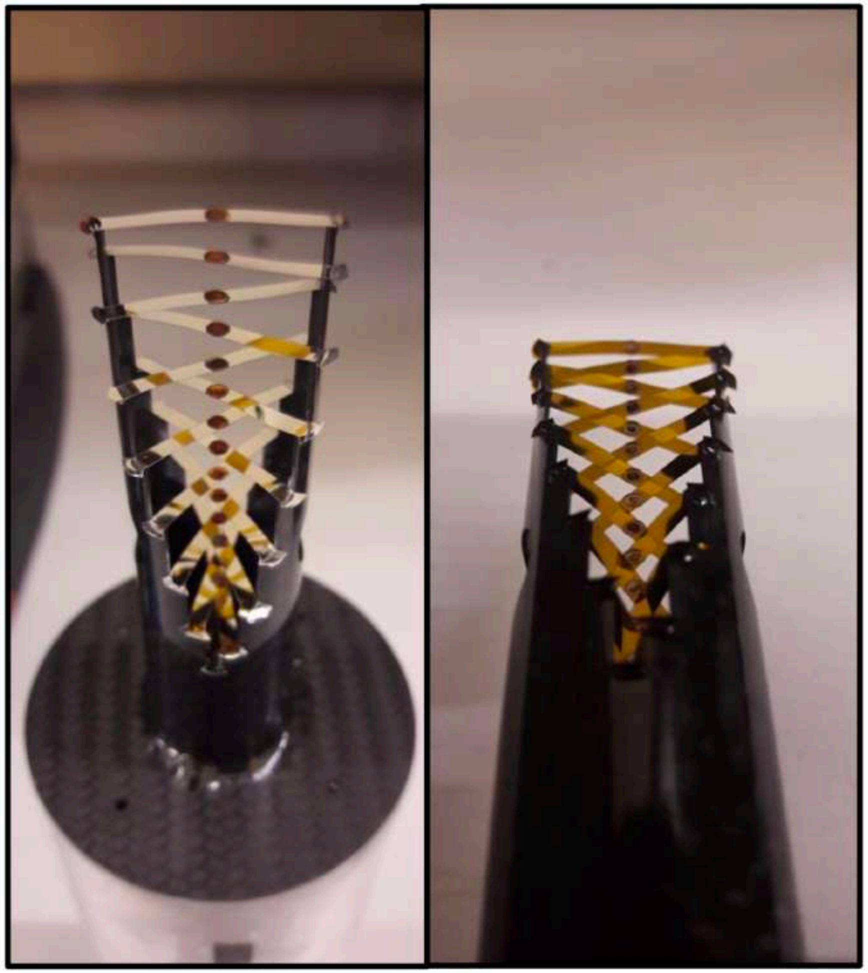
The
High
Acceptance
Di-
Electron
Spectrometer

Layout of the Spectrometer

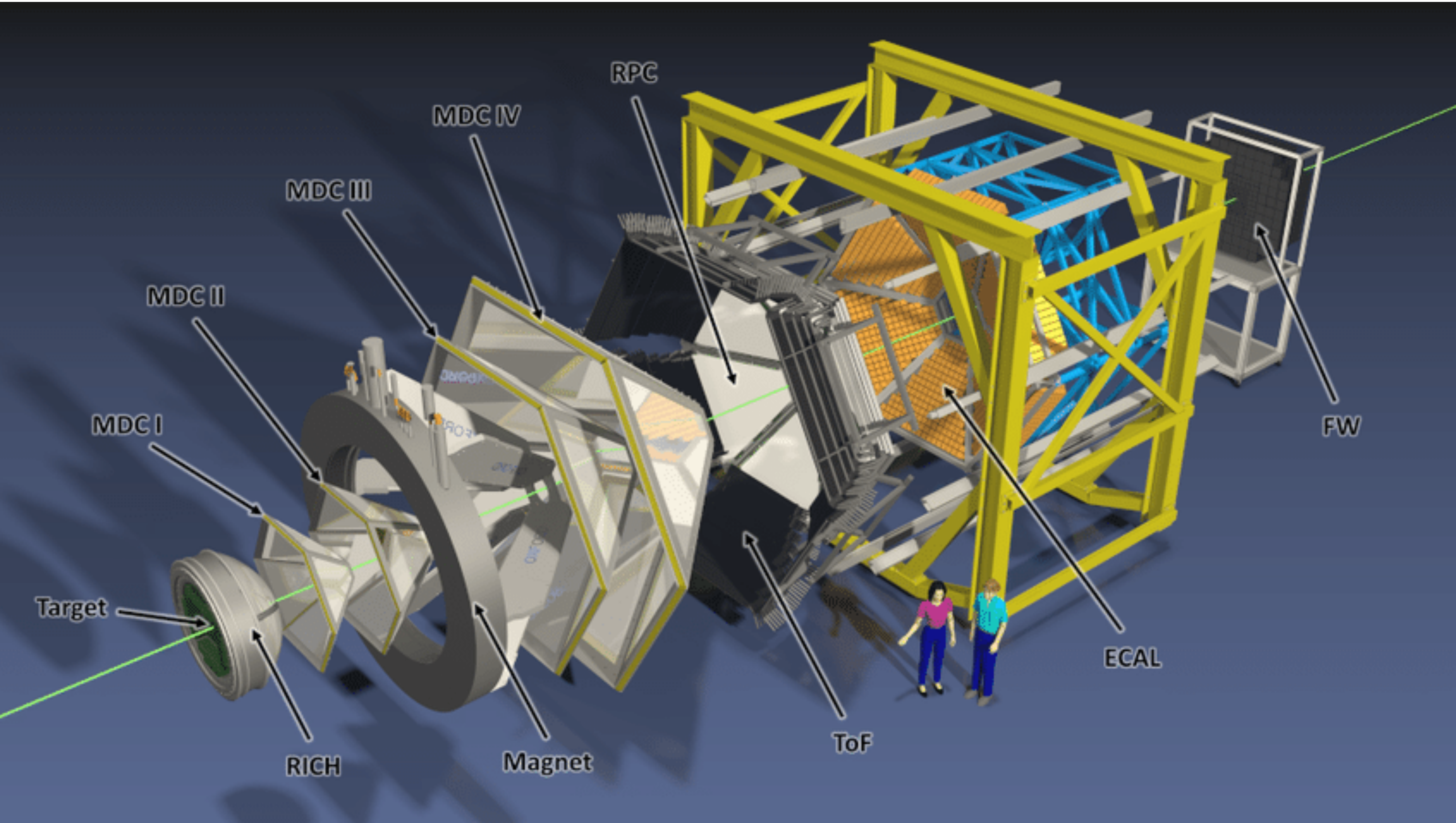


G. Agakichiev et al. (HADES Collaboration),
Eur. Phys. J. A 41, 243 (2009)

The Ag segmented target

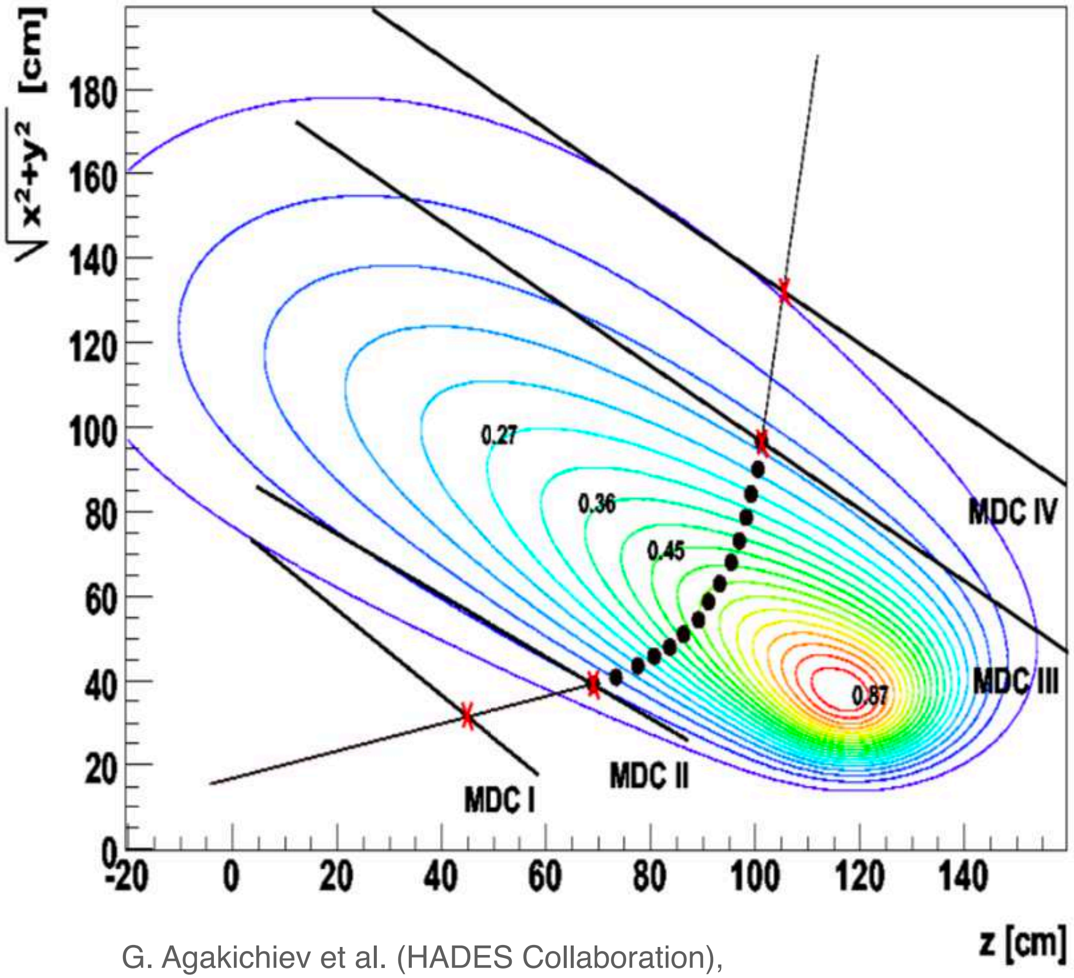


Layout of the Spectrometer



Momentum reconstruction (MDC)

- Solving differential equations of motion in a known magnetic field allows the reconstruction of $\vec{p}$
- Superconducting toroidal magnet with field up to 0.9 T.
- Resolution within a few %
- Momentum reconstruction only possible for charged particles!



G. Agakichiev et al. (HADES Collaboration), Eur. Phys. J. A 41, 243 (2009)

Mass reconstruction

➠ From known trajectory, the particle's path length (l) can be calculated;

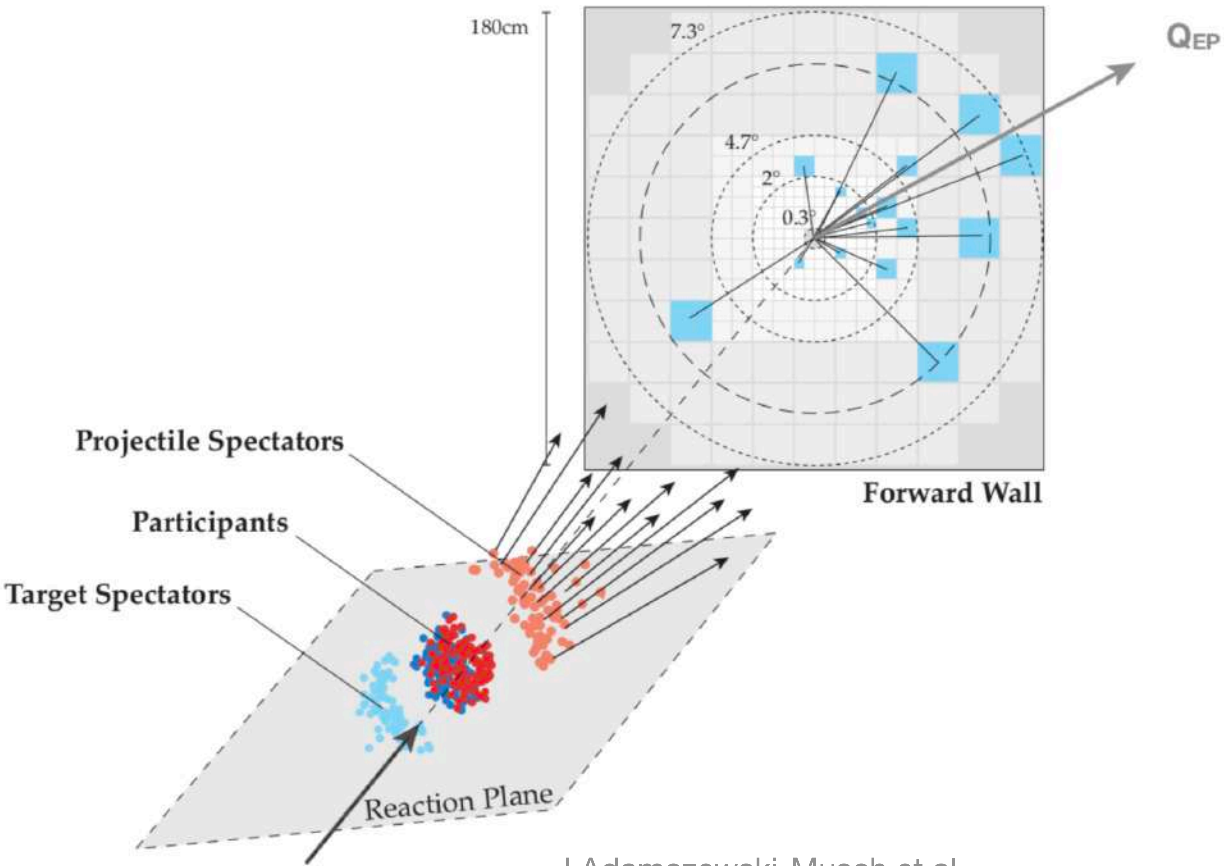
➠ We can use timestamps from the first (START) and last (ToF or RPC) detectors (Δt) to calculate average velocity $v = \beta c = l \,/\, \Delta t$;

➠ Mass can be then calculated from $p = \gamma m v$.

➠ The final resolution of mass reconstruction is a combination of:

- momentum reconstruction resolution
- accuracy of path reconstruction
- timing resolution of the START detector
- timing resolution of the ToF/RPC detectors

Event-plane reconstruction

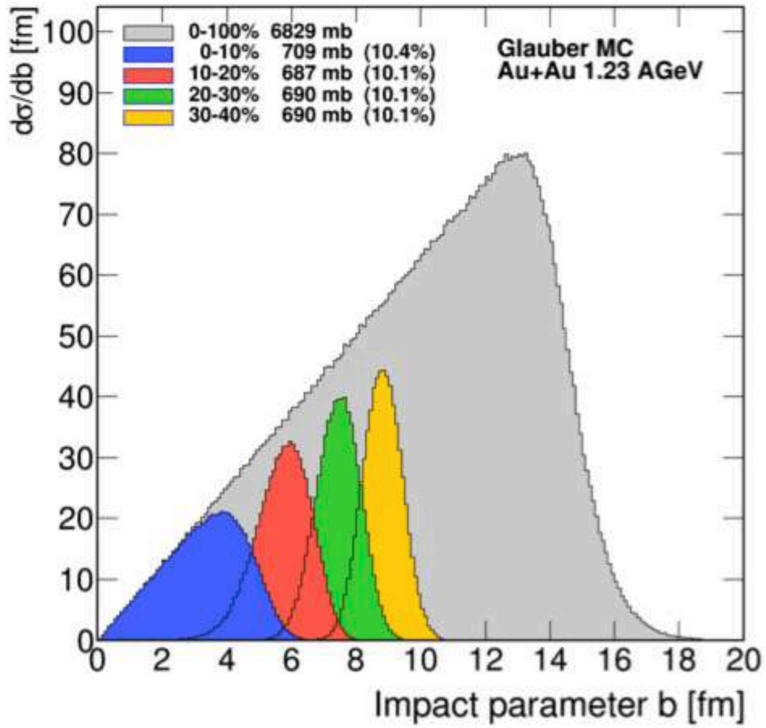


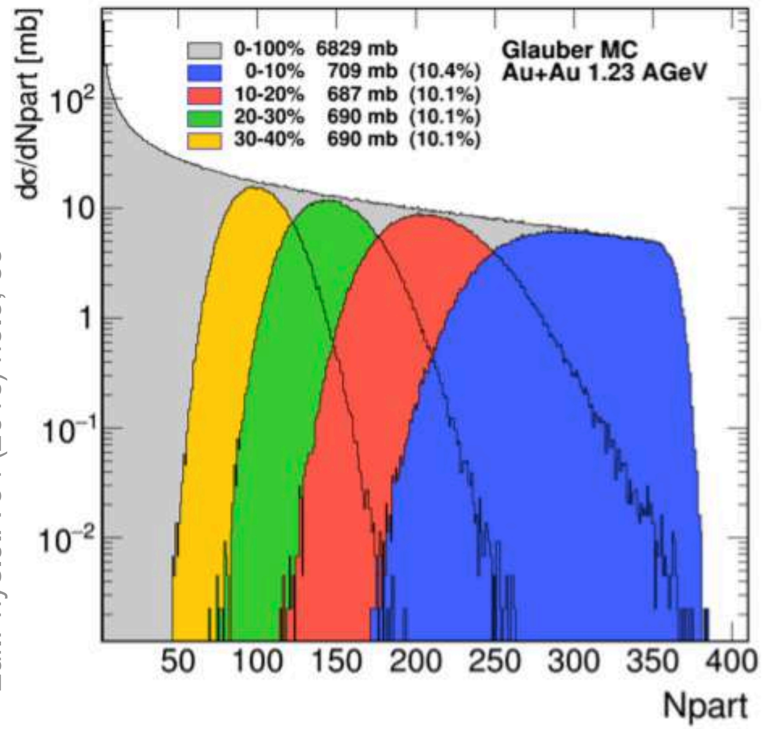
J.Adamczewski-Musch et al.
Eur.Phys.J.A 59 (2023) 4, 80

- Event Plane: experimental estimation of the RP
- EP orientation in HADES calculated from the distribution of projectile spectators in the FWall;
- Q-vector method based on charge-weighted average direction of hits;
- Limited spectator hits → finite resolution of reconstructed orientation

Centrality in HADES

- Impact parameter translated to experimental observables via Glauber MC
- In HADES centrality selected based on $N_{ToF+RPC}$
- Glauber MC model is applied to convert $N_{ToF+RPC}$ to $\langle b \rangle$ or $\left\langle A_{part} \right\rangle$;
- All flow results in this talk will be presented for the 10-40 % most central collisions;
- The selected centrality must:
  - have a well-defined Event Plane
  - have high multiplicity of strange hadrons
  - provide a large statistical sample



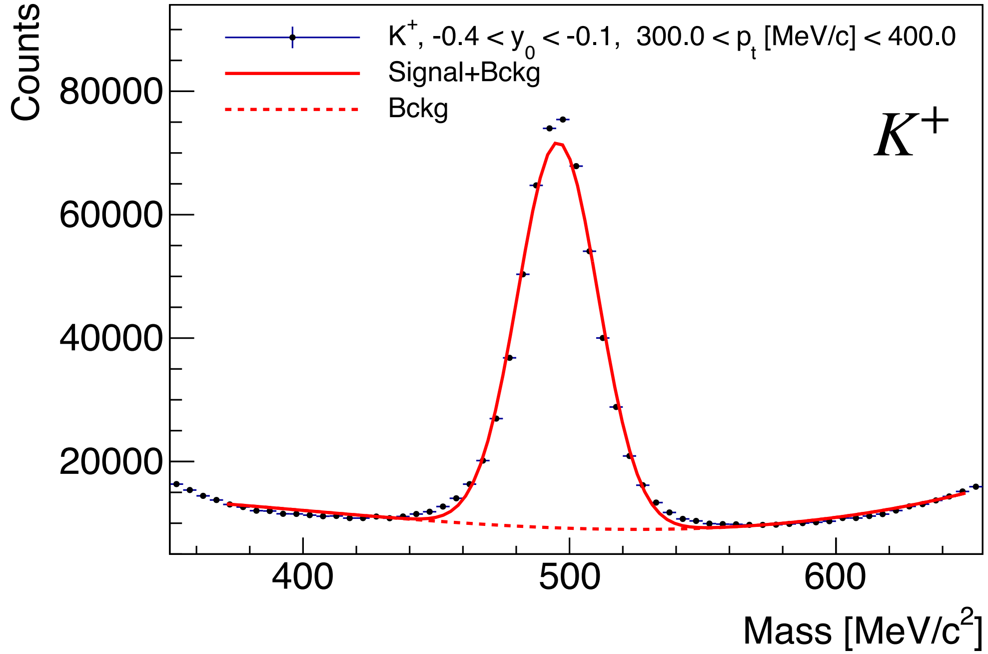


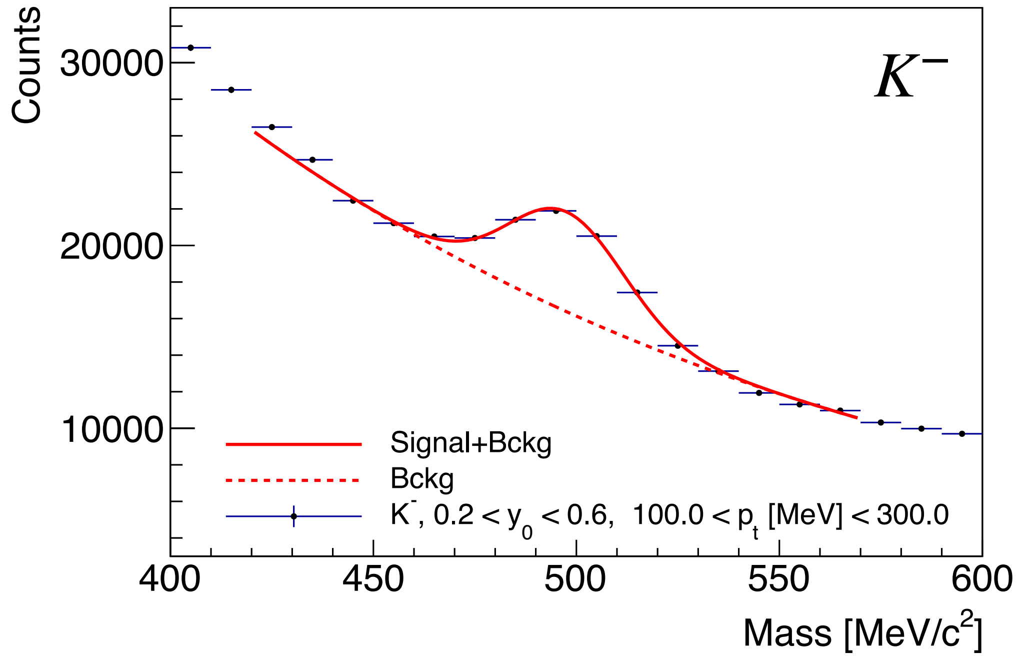
J. Adamczewski-Musch et al.
Eur.Phys.J.A 54 (2018) no.5, 85

$K^{\pm}$ analysis

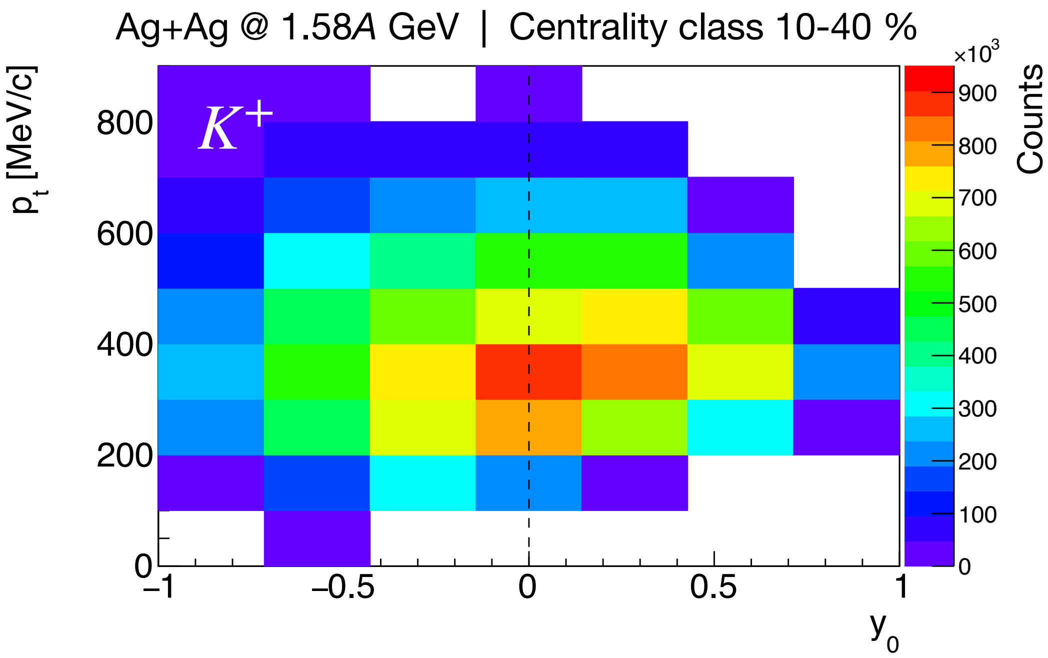
Identification of $K^{\pm}$

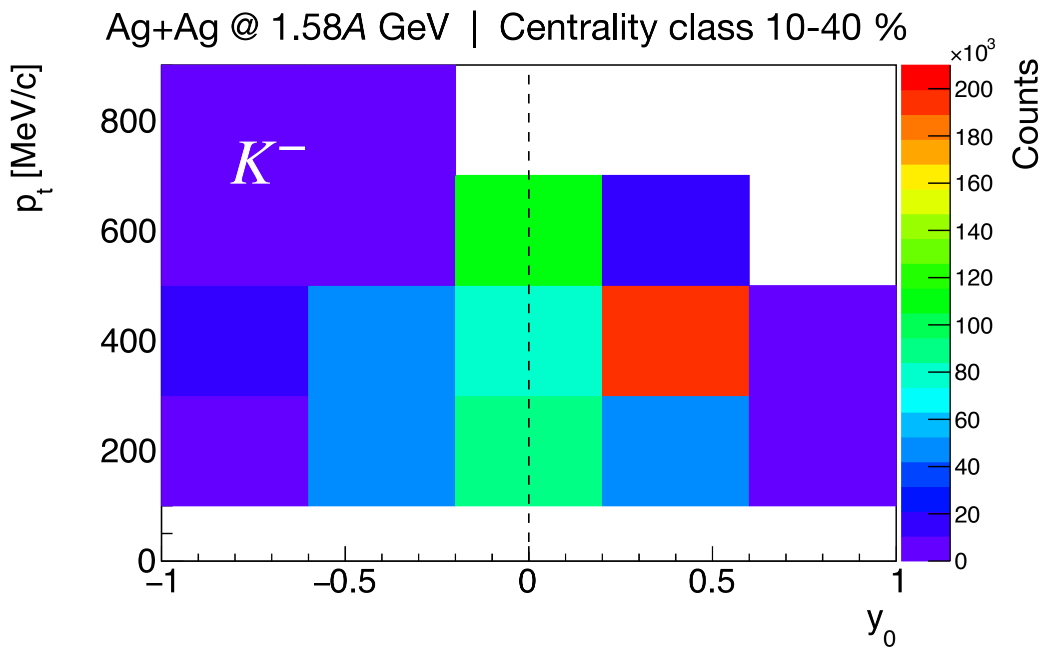
- Mass spectrum from time-of-flight measurement shows Gaussian peak around $K^{\pm}$ mass
- Background modelled with polynomial of 3rd degree (K^{+}) or exponential (K^{-})
- Independent fits in p_T , y_0 and $\Delta\phi$ bins yield a 3D distribution of K^{+} mesons
- **Signal measurement must be sensitive to small variations in kaon signal!**





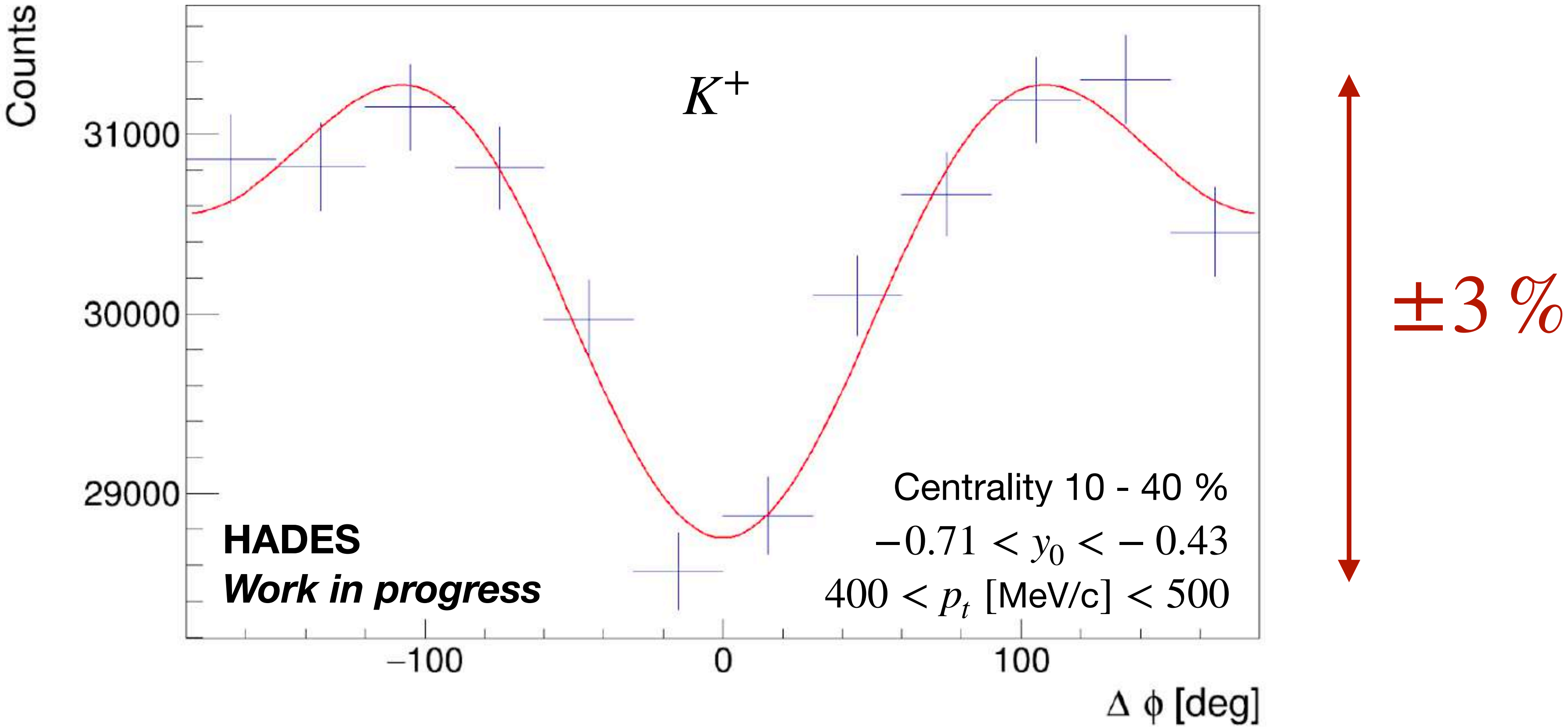
Raw $p_t : y$ distributions of $K^{\pm}$ mesons





- Raw reconstructed yields (no efficiency correction):
  - $8.6 \cdot 10^6$ of K^+
  - $6.7 \cdot 10^5$ of K^-
- HADES provides a very wide acceptance for both particles

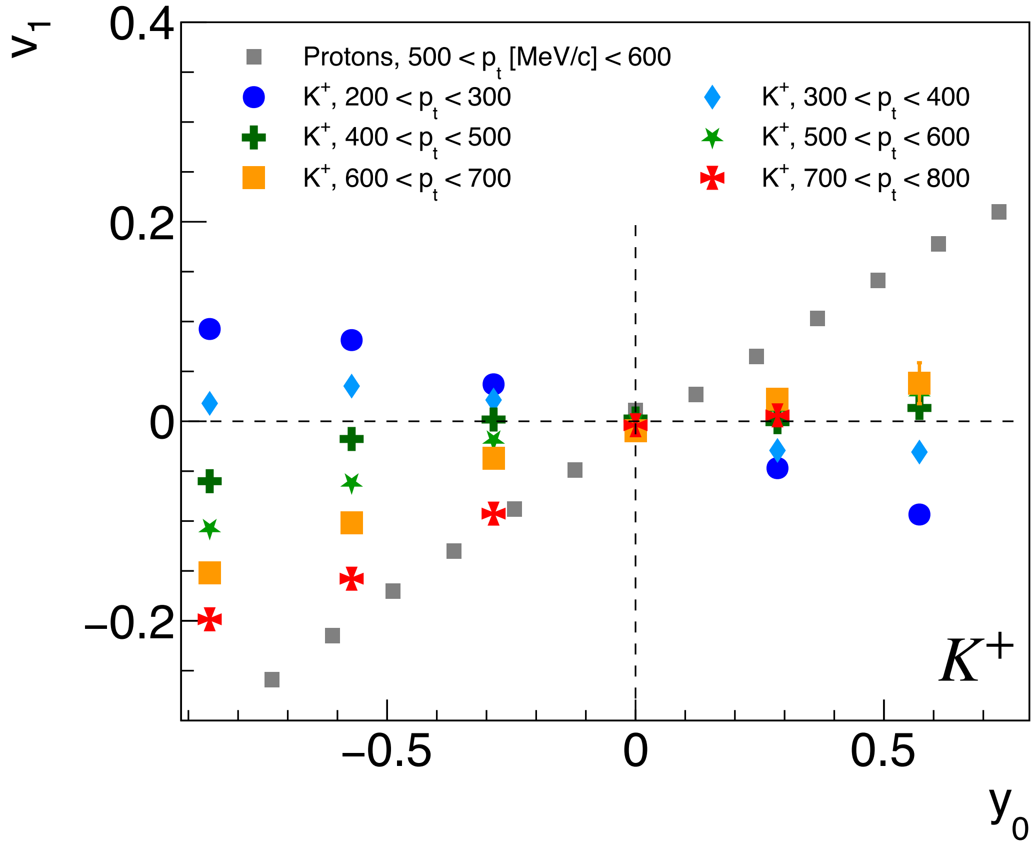
Fourier analysis

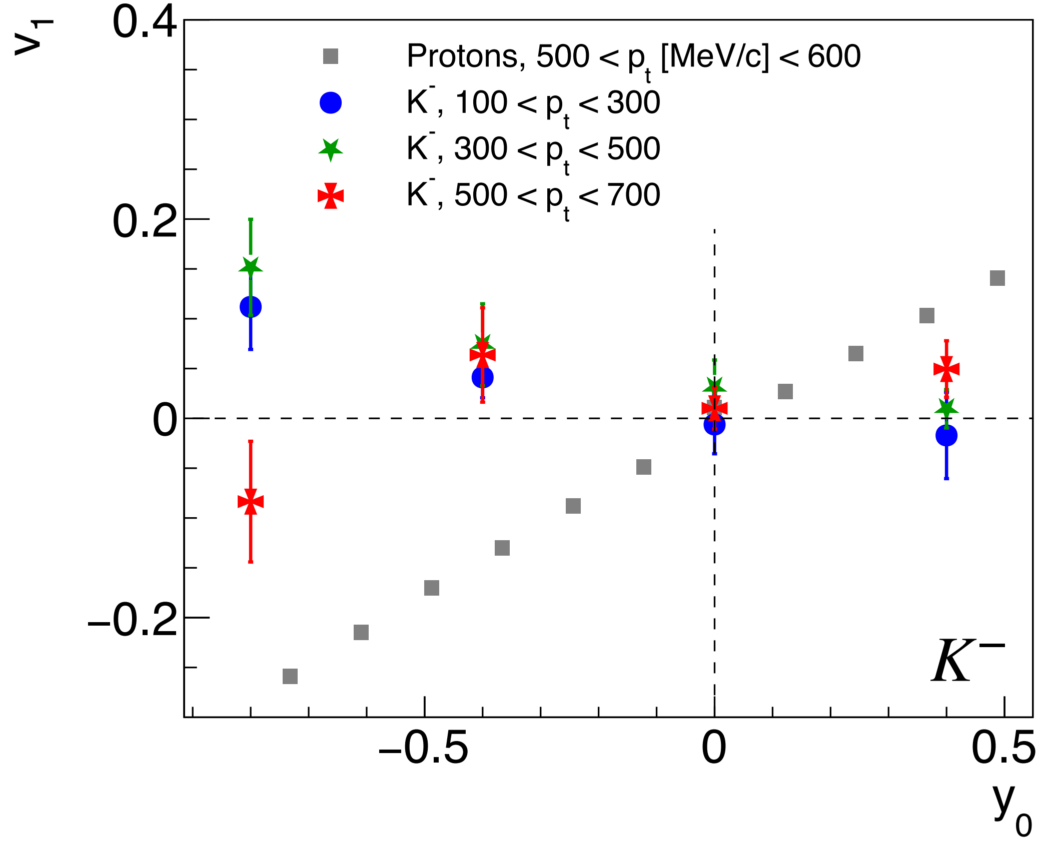


➠ The $\Delta\phi$ distribution for given p_t and y_0 is used to obtain flow coefficients

➠ For this cell, $v_1 = -0.0149 \pm 0.0015$ and $v_2 = -0.0122 \pm 0.0016$.

Directed flow (v_1) of $K^{\pm}$ as function of y_0

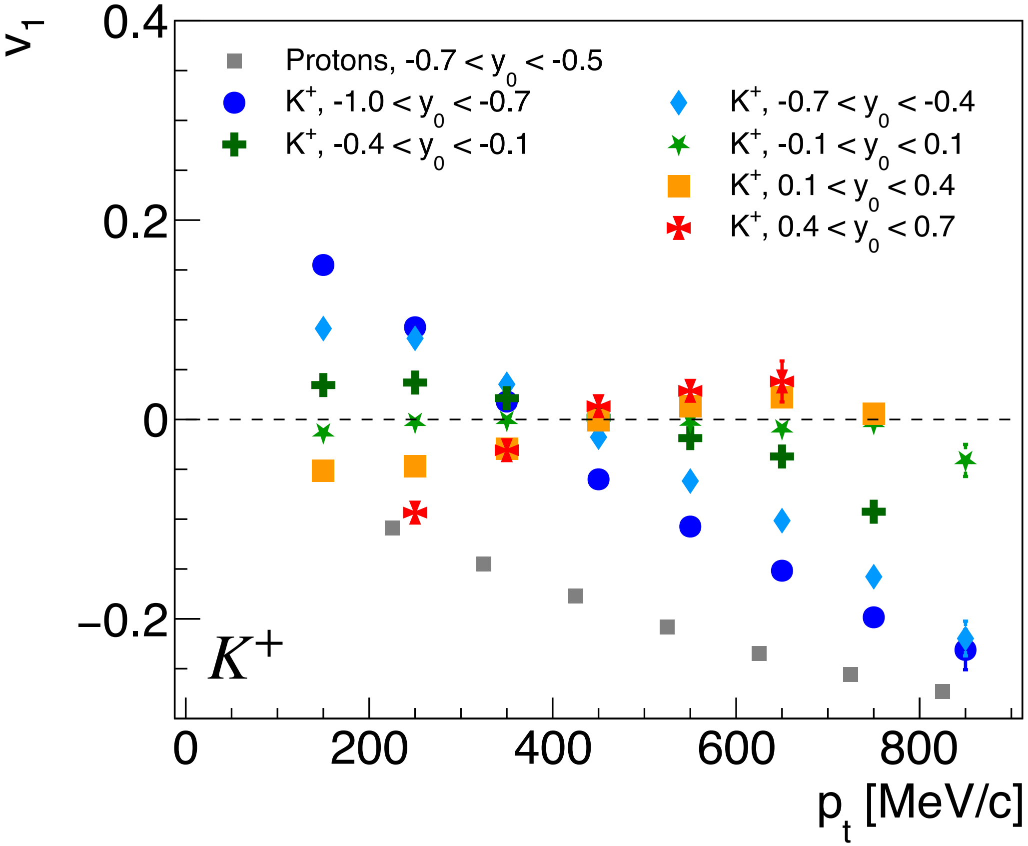


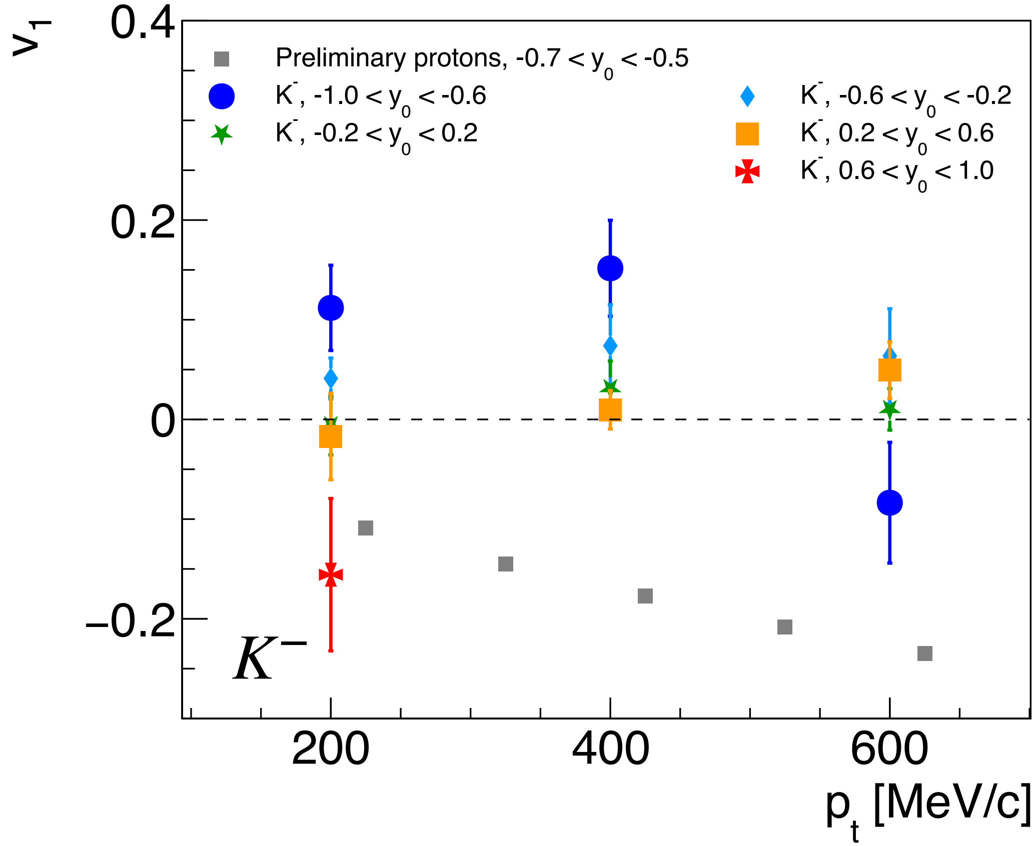


- All shown results are corrected for the finite EP reconstruction resolution
- No other efficiency effects considered

- Fast K^+ mesons flow "with" the protons, slow K^+ — oppositely…
- Suggests a repulsive K^+N potential?

Directed flow (v_1) of $K^{\pm}$ as function of p_T





- All shown results are corrected for the finite EP reconstruction resolution
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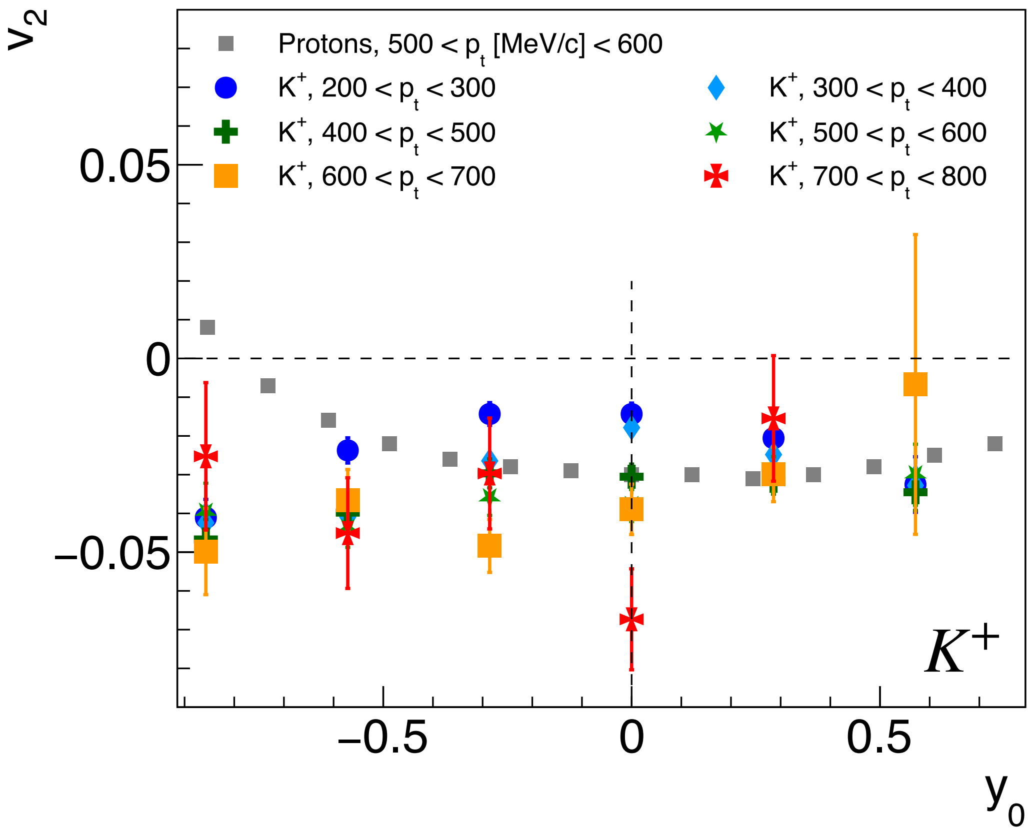
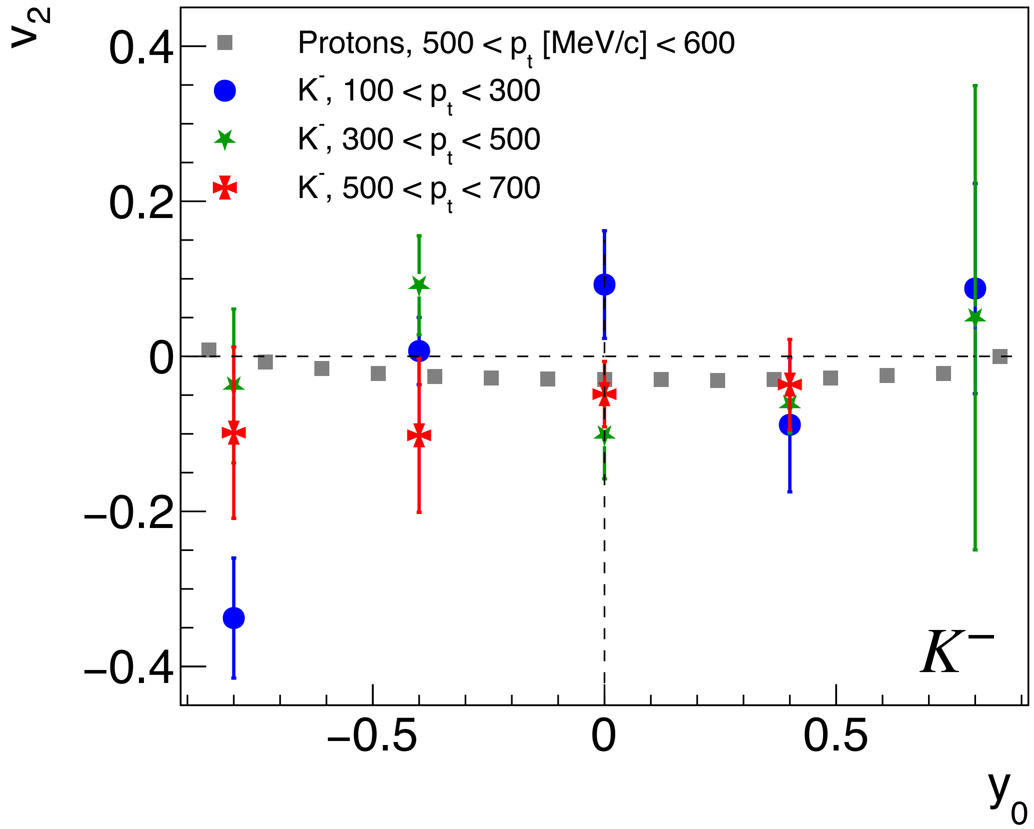
Elliptic flow (v_2) of $K^{\pm}$ as function of y_0

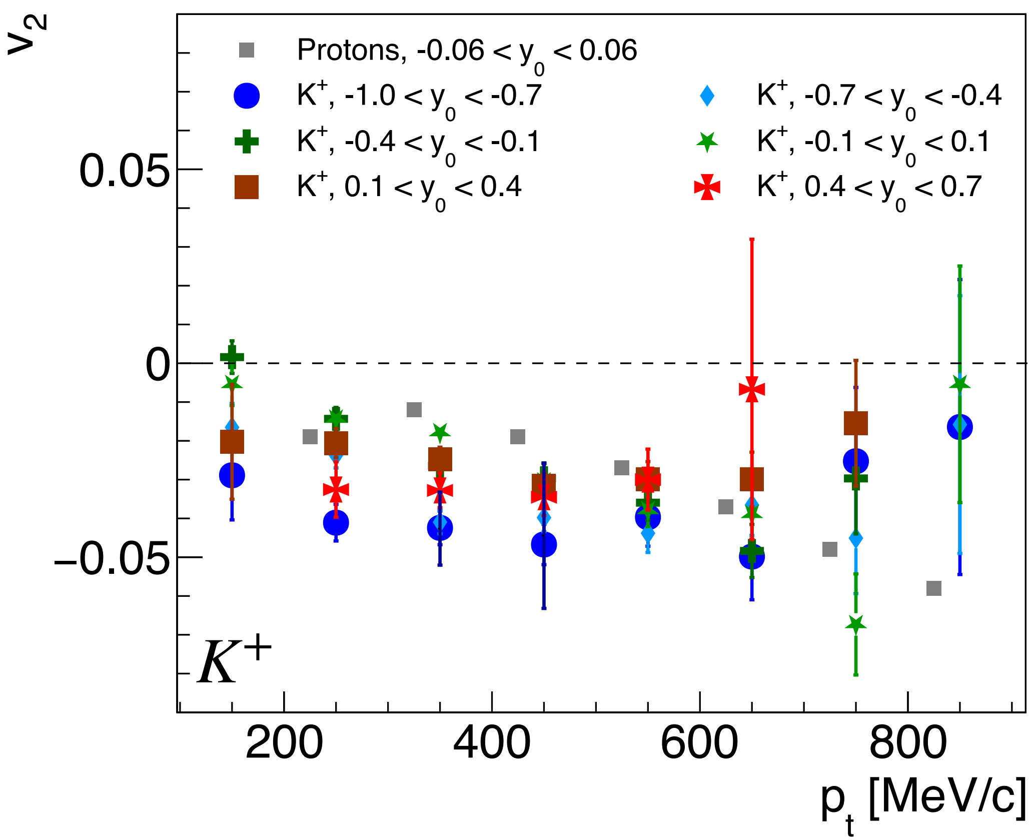


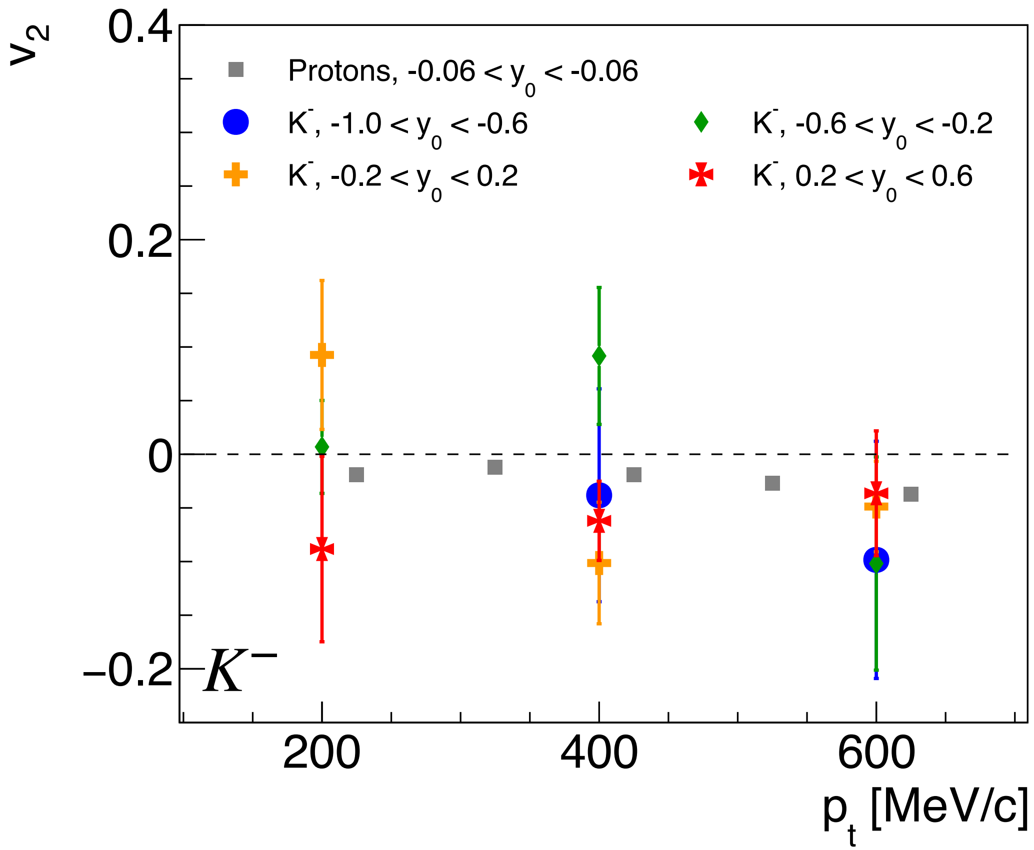


- All shown results are corrected for the finite EP reconstruction resolution
- No other efficiency effects considered

- K^+ exhibits negative v_2, like the protons!

Elliptic flow (v_2) of $K^{\pm}$ as function of p_T





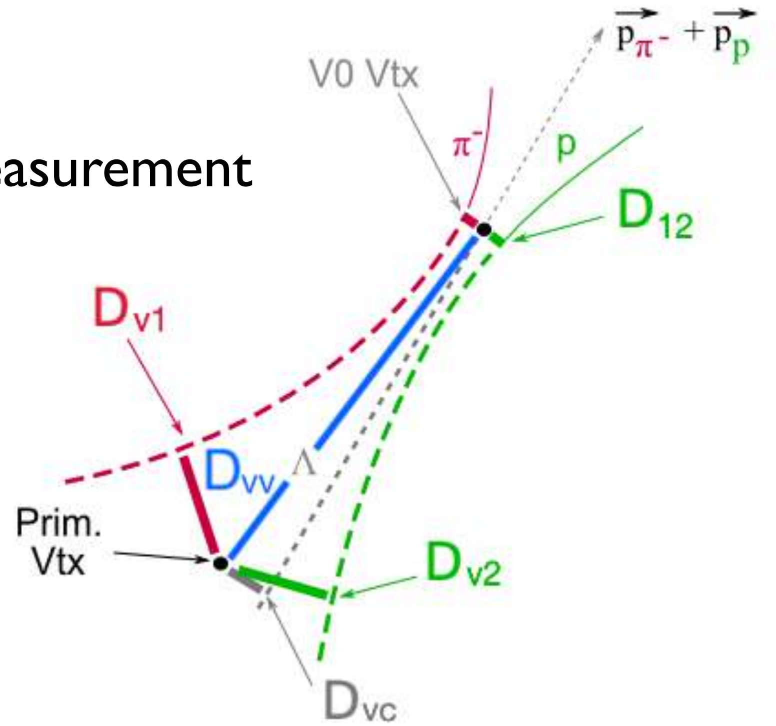
- All shown results are corrected for the finite EP reconstruction resolution
- No other efficiency effects considered

Λ analysis

Lambda reconstruction

- The Λ^0 baryon is electrically neutral $\Rightarrow$ no direct measurement main decay channel: $\Lambda \rightarrow p\pi^-$ (BR=64%).

- Invariant mass of daughters = rest mass of mother.



pi-

$Q = -1$

$\chi^2_{RK} \leq 200$

proton

$Q = +1$

$600 < M[\mathtt{MeV}] < 1300$

$p[\mathtt{MeV}] < 2500$

Λ candidates initial cuts [mm]:

$D_{v1} \geq 12$
$D_{v2} \geq 5$
$D_{vc} \leq 12$
$D_{12} \leq 20$
$D_{vv} \geq 30,\ D^Z_{vv} \geq 30$

410 million accepted

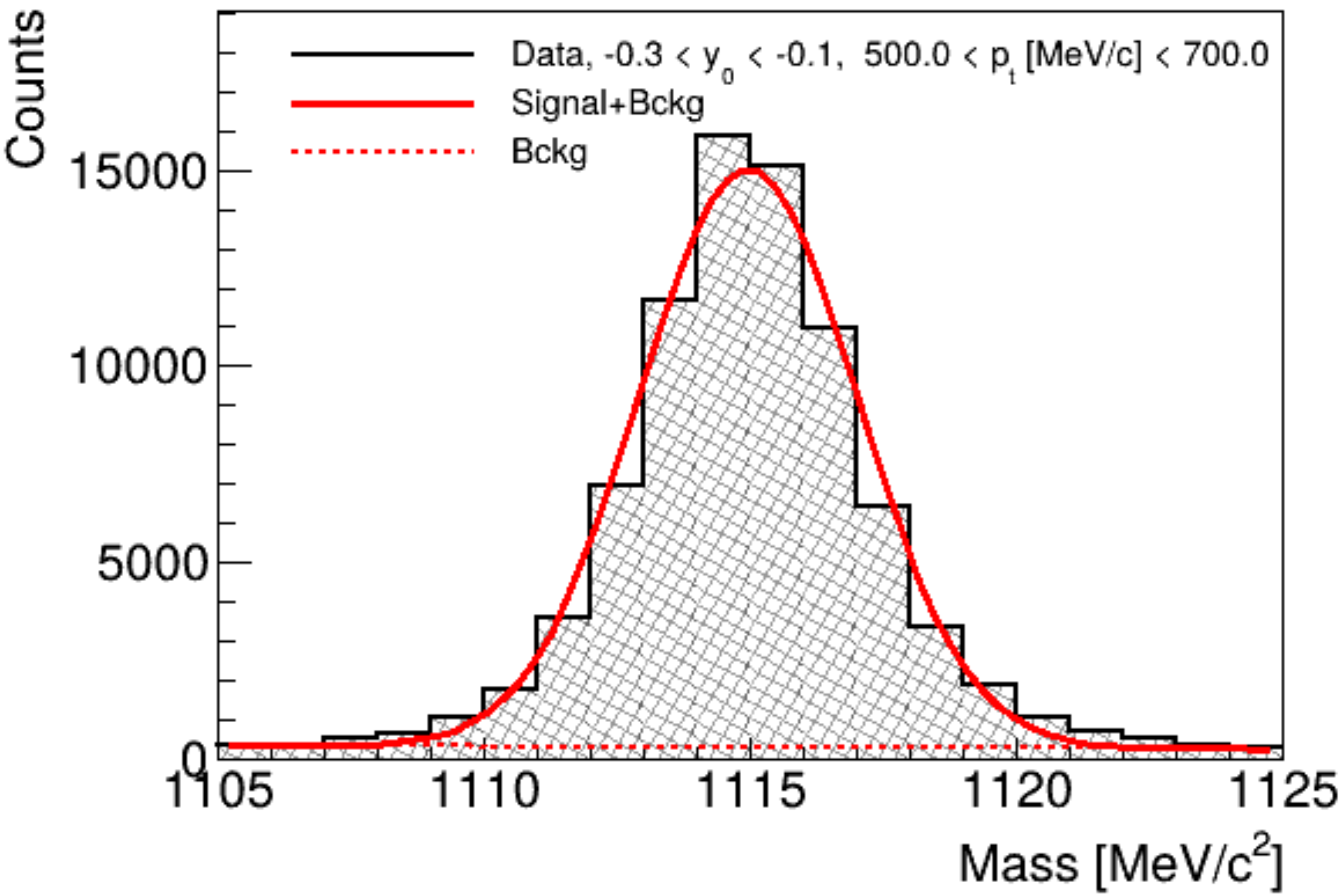
S/B optimization

Λ candidates final cuts [mm]:

$D_{v1} \geq 22$
$D_{v2} \geq 8.5$
$D_{vc} \leq 5.5$
$D_{12} \leq 9$
$D_{vv} \geq 78,\ D^Z_{vv} \geq 29$

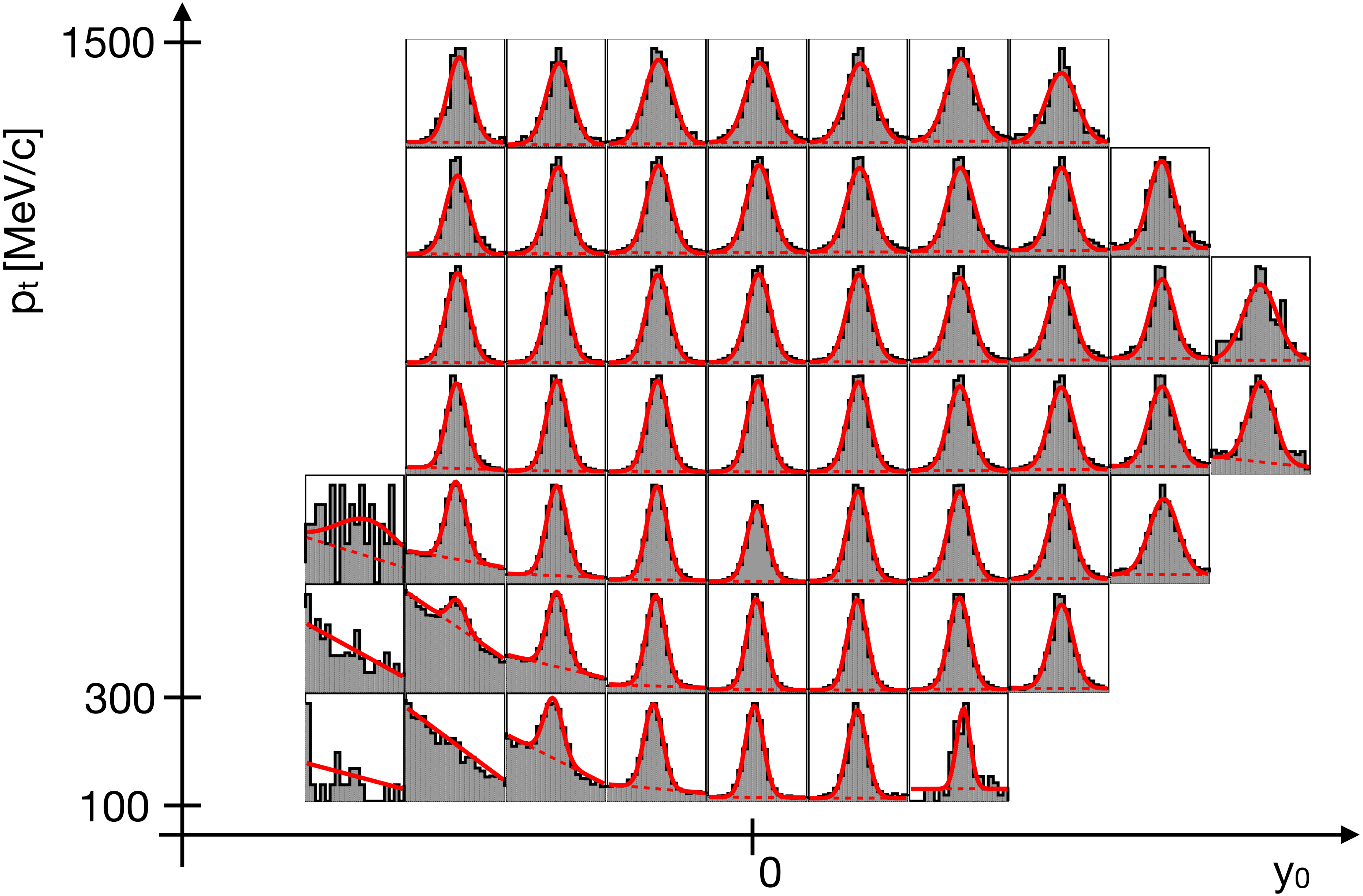
3.1 million accepted

Lambda mass fit example

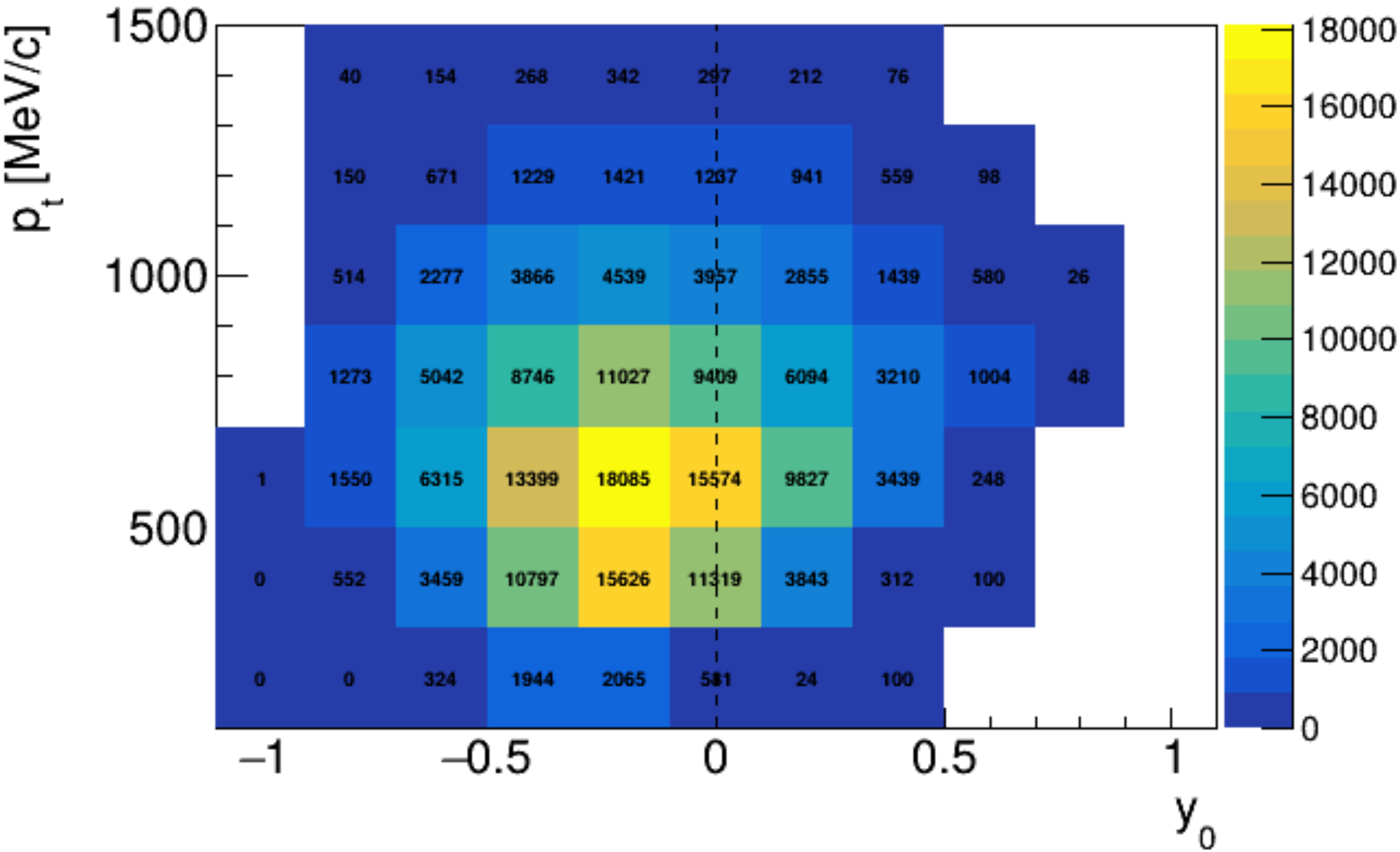


- Signal is reconstructed by fitting linear bckg and Gaussian signal
- More sophisticated methods of bckg estimation can be used
- So far, the fitting method is satisfactory

Fitting the $p_t : y_0$ phase space...



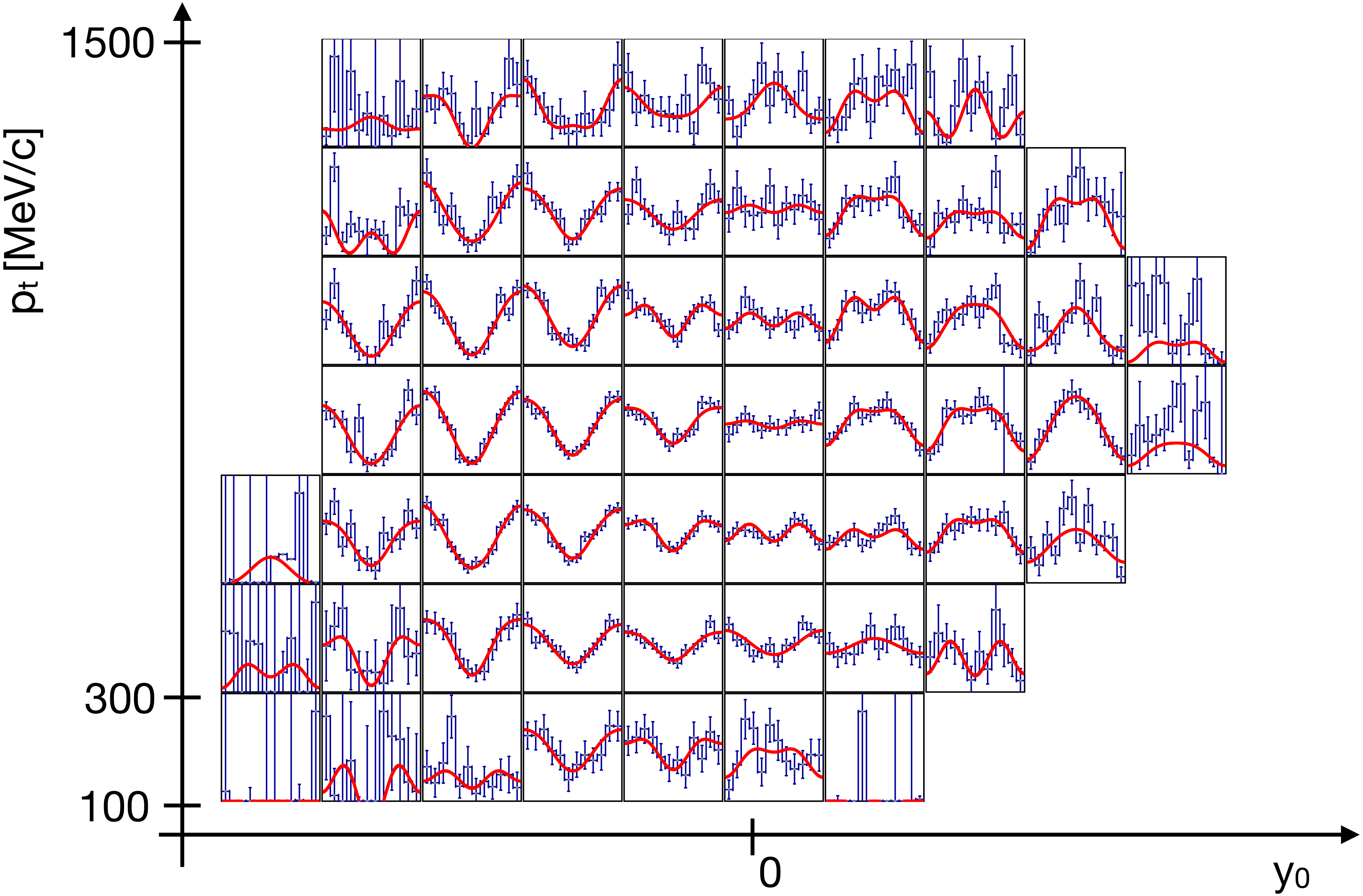
Lambda $p_t : y_0$ distribution



Jan Orlinski
Faculty of Physics, University of Warsaw

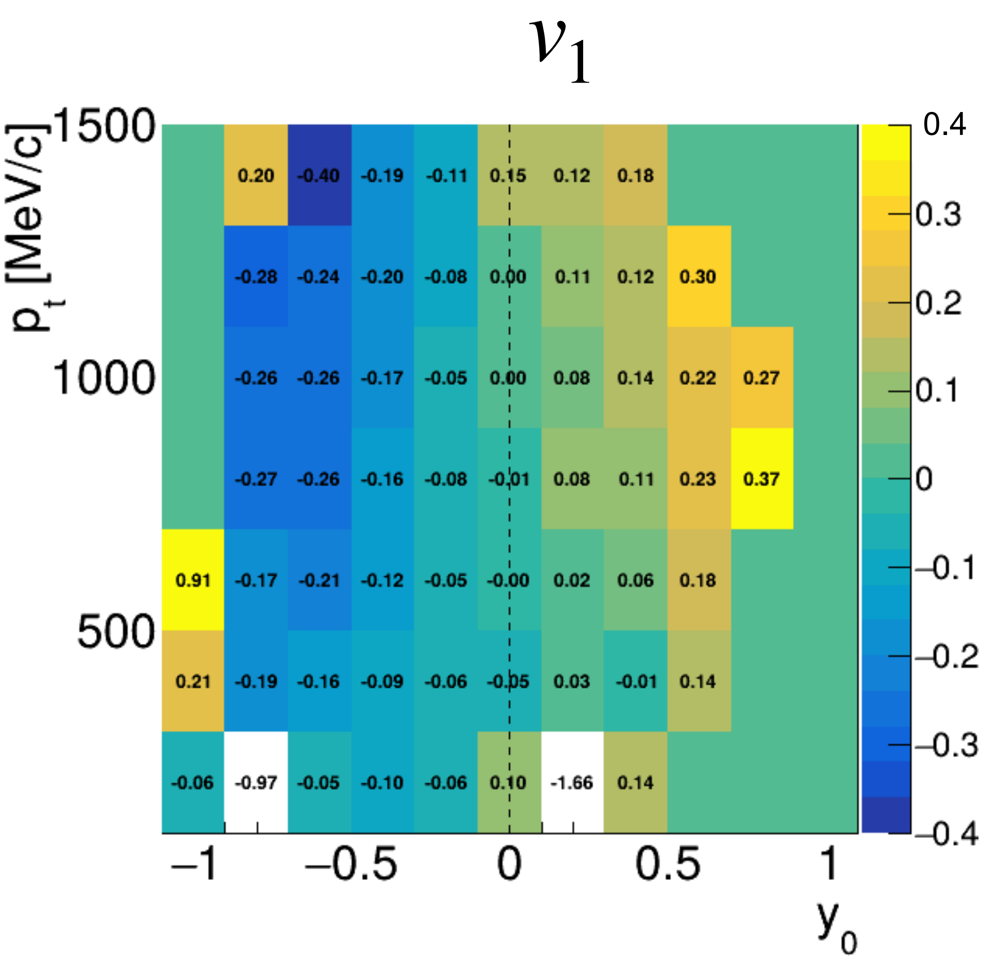
Nuclear Physics Seminar, UW
27.02.2025

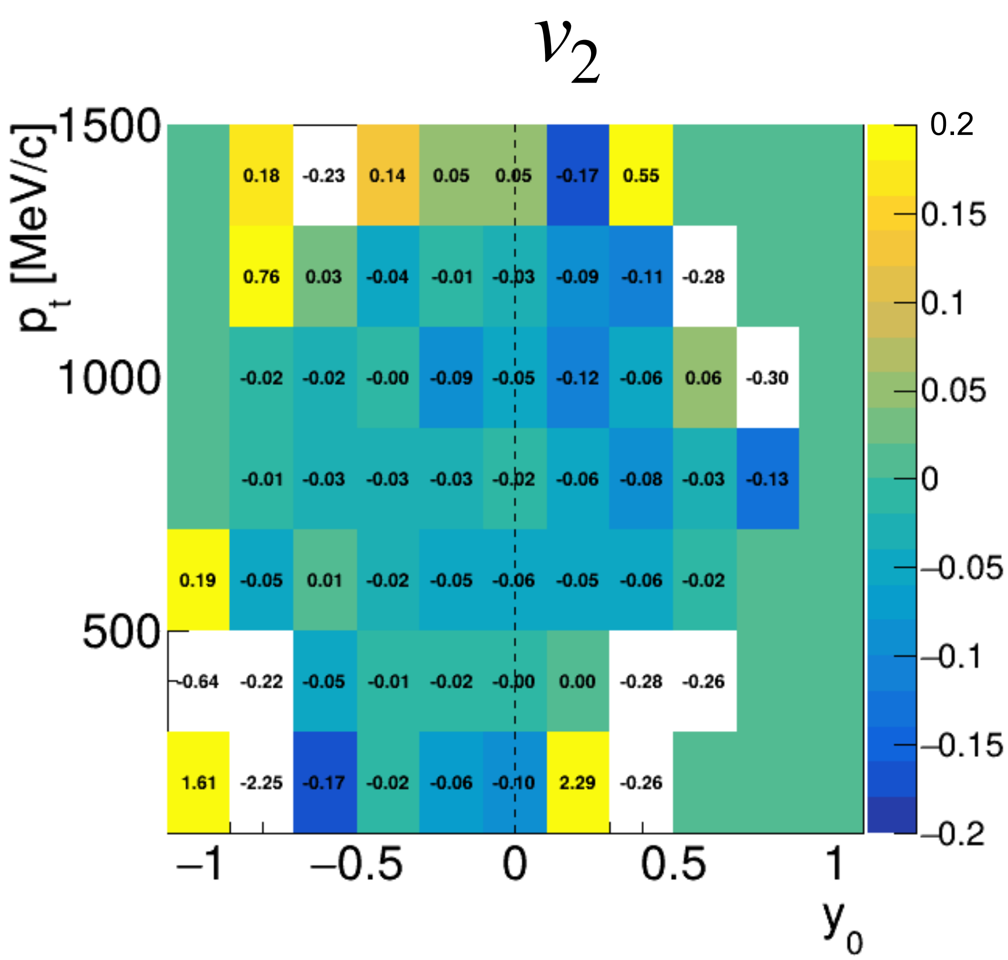
Fitting the $p_t : y_0 : \Delta\phi$ phase space...



Distribution of $v_{1,2}$ coefficients

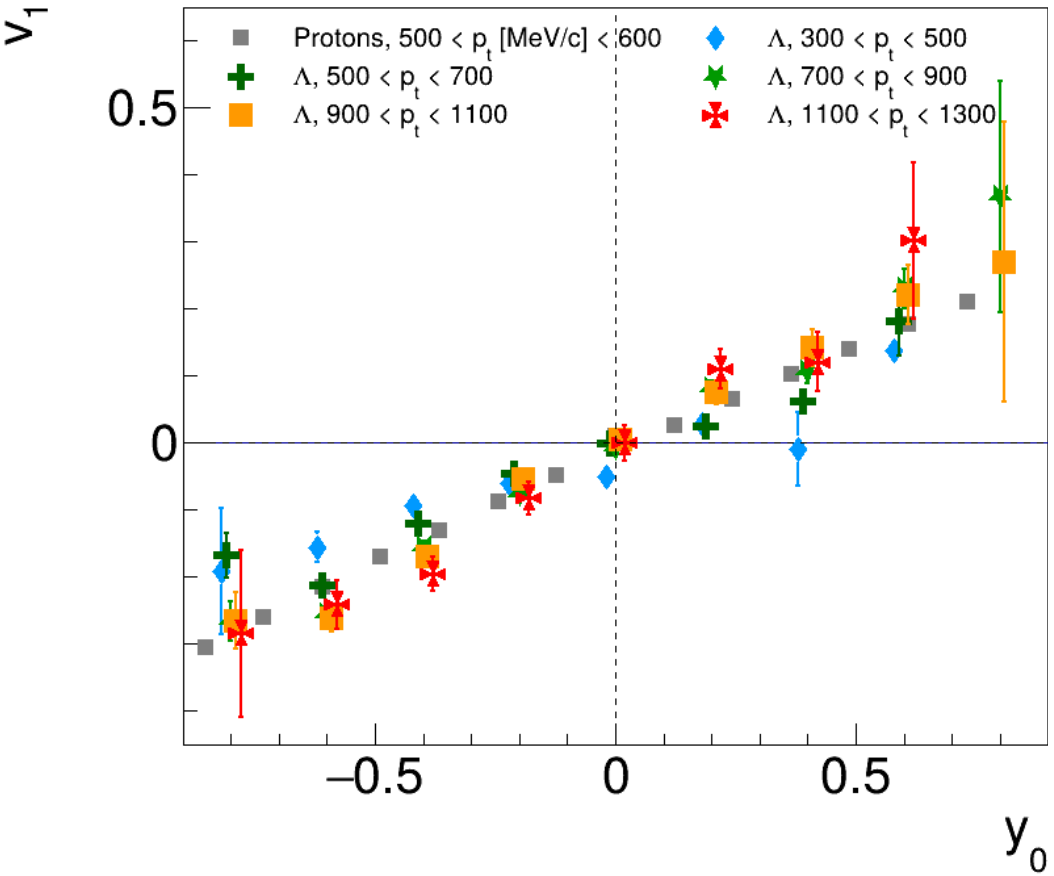
- All shown results are corrected for the finite Event Plane reconstruction resolution
- No other efficiency effects were considered

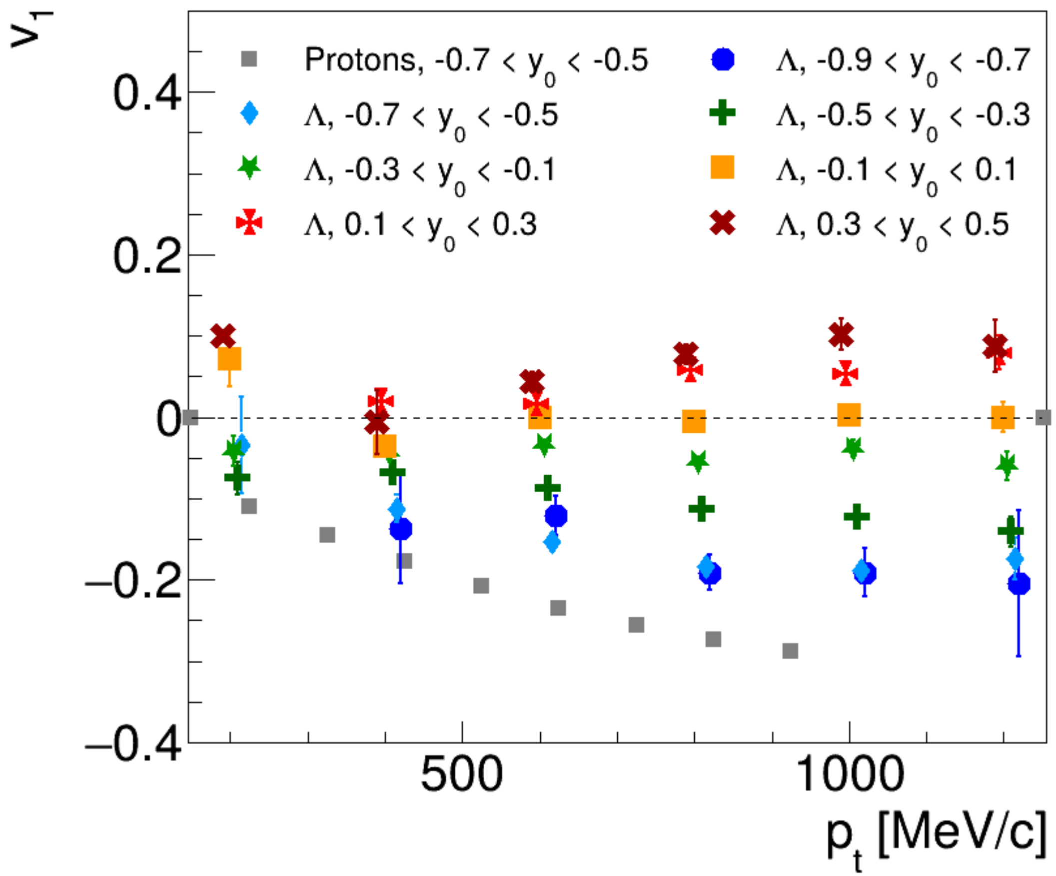




Differential v_1 distributions

- Caution: small horizontal shifts for readability only

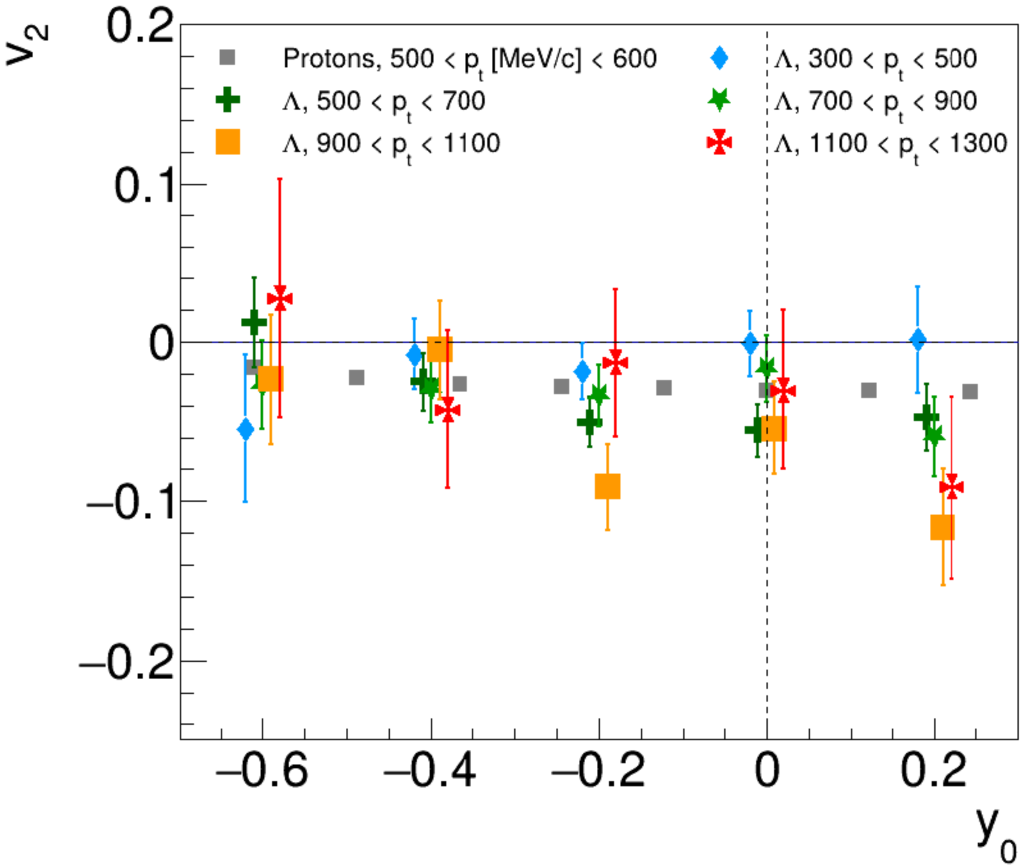


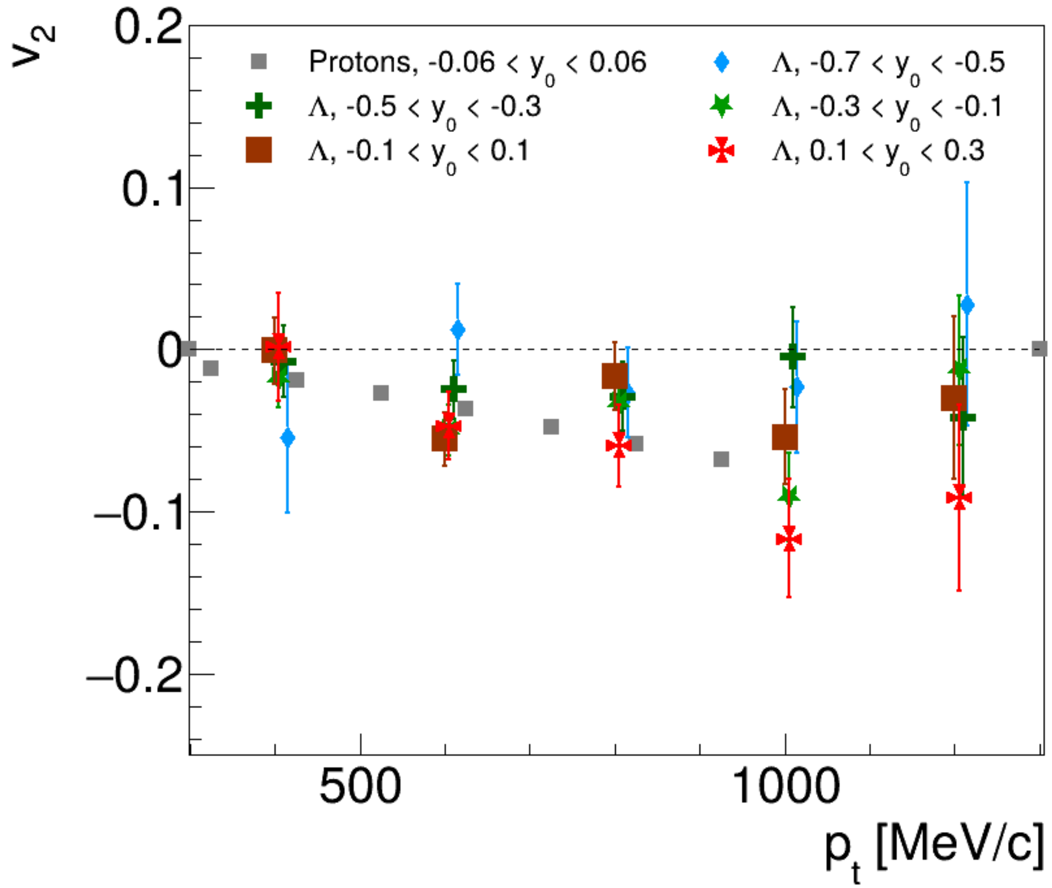


- The v_1 of Λ^0 baryons exhibits only small variations with p_t (if any),
- Qualitative difference between K^+ mesons and Λ baryons.

Differential v_2 distributions

- Caution: small horizontal shifts for readability only





- Negative v_2 of Λ^0 baryons corresponds with that of the K^+ and protons.

Summary

- The transverse flow of strange hadrons $K^{\pm}$ and Λ^0 emitted from Ag+Ag collisions at 1.58 GeV/nucleon is being analysed;

- The preliminary maps of $v_{1,2}$ in the momentum phase-space were obtained;

- Steps to the finalization of the results:
  - optimization of signal extraction,
  - study of the occupancy-related efficiency effects,
  - evaluation of systematic uncertainties;

- This may provide new insight into the interaction between these strange hadrons and the nuclear matter;

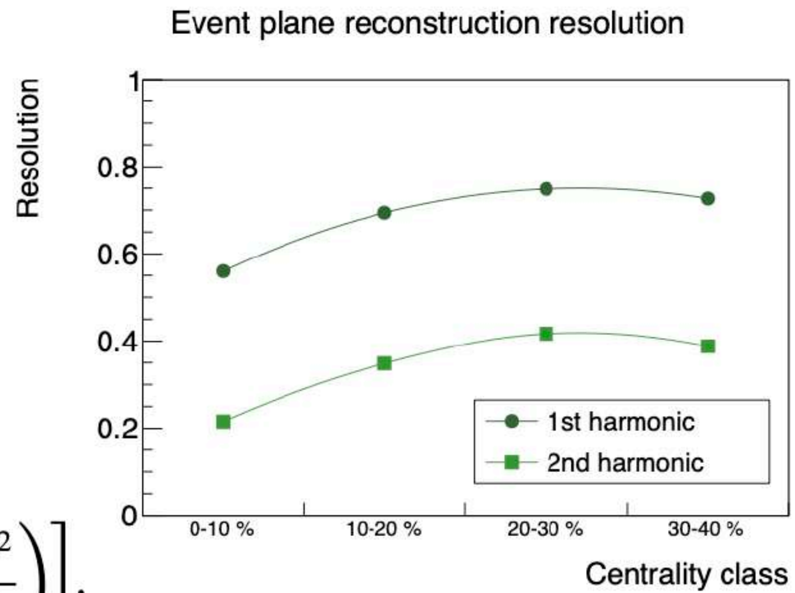
- Published results in this energy range is very limited, with the $v_{1,2}$ of Λ^0 never published before!


THANK YOU!
HADES XLVII Collaboration Meeting, 26-30 August 2024, Warsaw

BACKUP SLIDES:

Event-plane reconstruction resolution

- Standard method by J.-Y. Ollitrault was used to correct for the finite resolution of event plane reconstruction (J.-Y. Ollitrault, arXiv:9711003 [nucl-ex])



- Divide the spectators into two random sub-events (A and B) and evaluate $\Delta\Psi_{AB} = \Psi_A - \Psi_B$

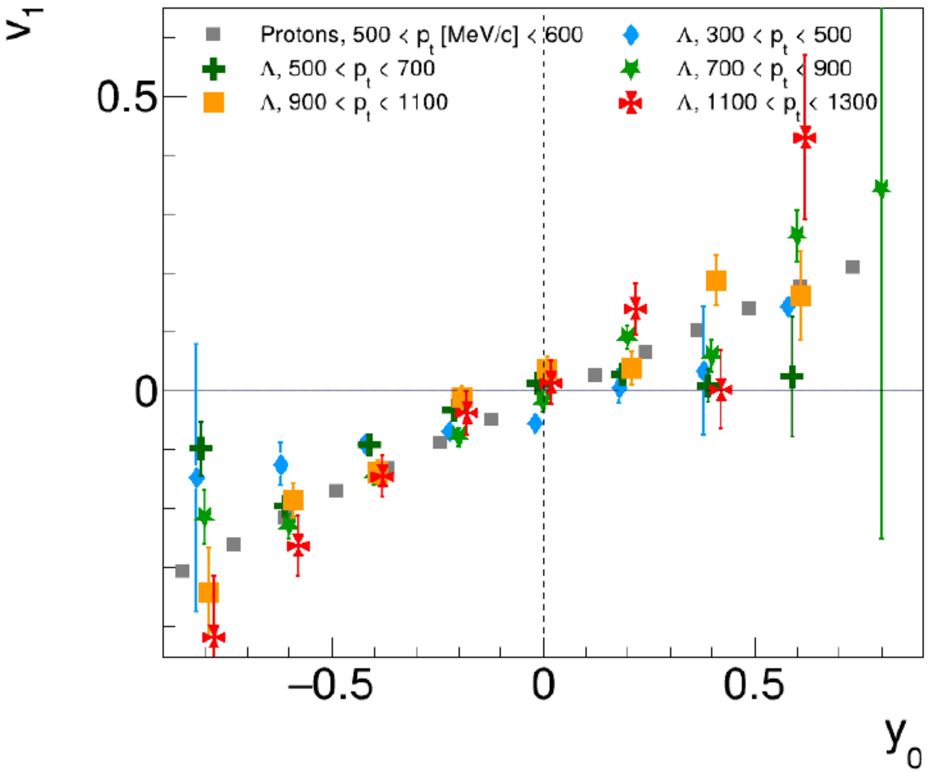
- Resolution can be calculated as:

$$\mathscr{R} = \frac{\sqrt{\pi}}{2} \cdot \chi \cdot \exp\left(-\frac{\chi^2}{2}\right) \cdot \left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right],$$

where $I_k(x)$ is the modified Bessel function of 1° kind and $\chi^2 = -2\ln\left(\frac{2 \cdot \Delta\Psi_{AB}(90^\circ - 180^\circ)}{\Delta\Psi_{AB}(0^\circ - 180^\circ)}\right)$

Differential $v_1(y_0)$ distributions

Ag+Ag @ 1.58*A* GeV
10-20 % centrality



Ag+Ag @ 1.58*A* GeV
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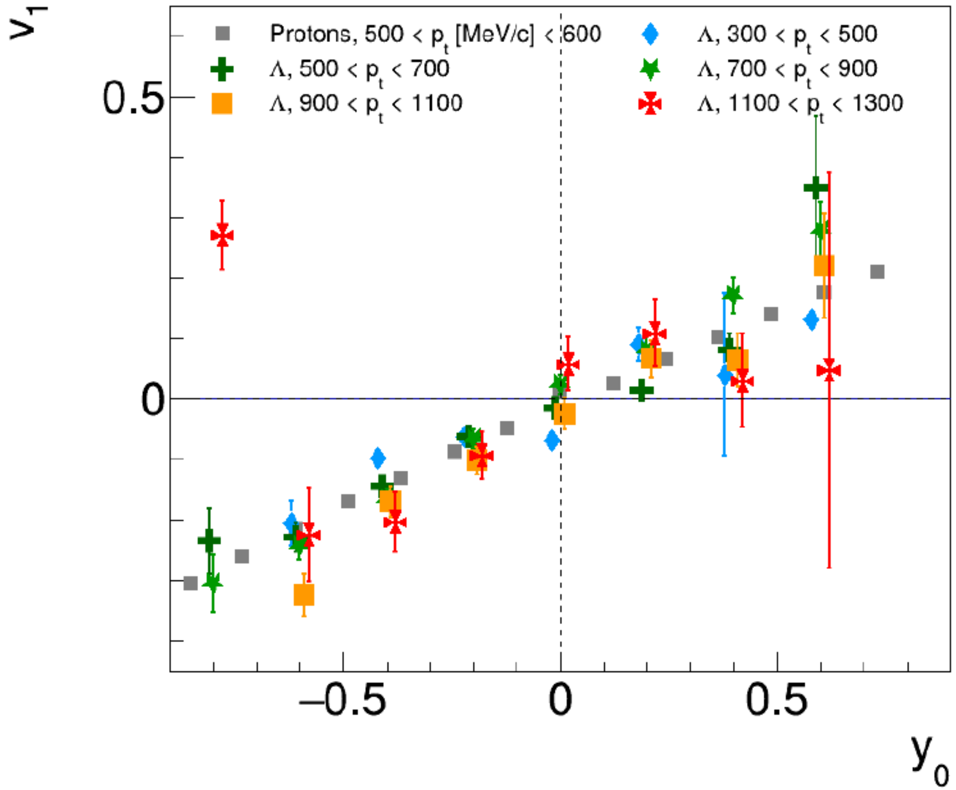

Proton distributions from 10-40 % centrality

Differential $v_1(p_t)$ distributions

Ag+Ag @ 1.58*A* GeV
10-20 % centrality

Ag+Ag @ 1.58*A* GeV
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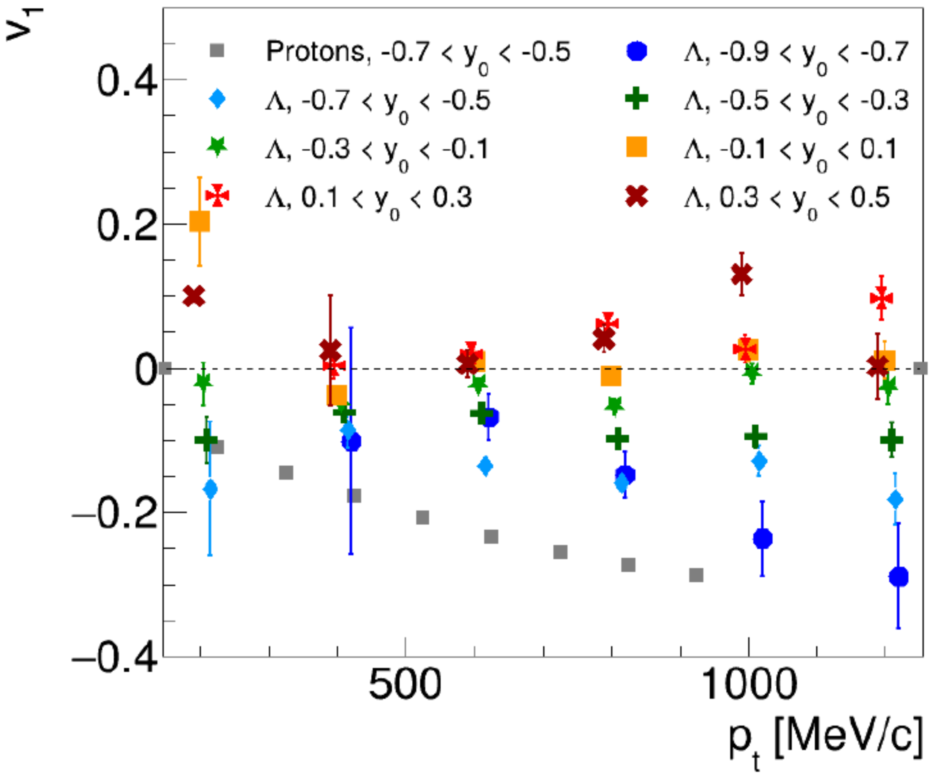
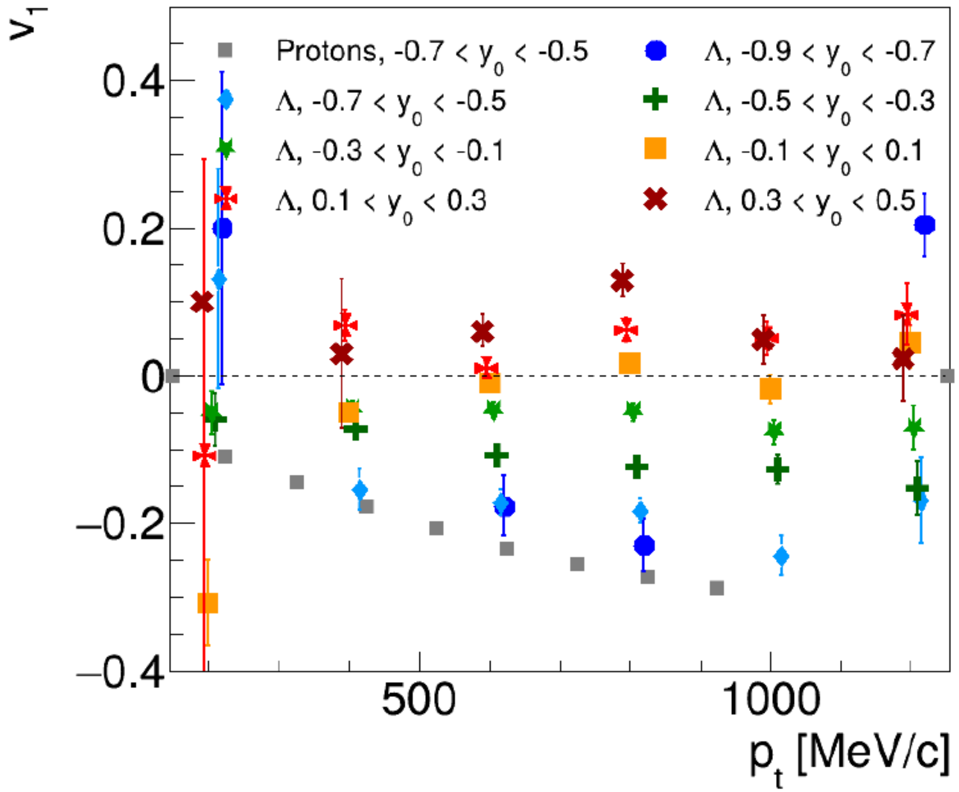
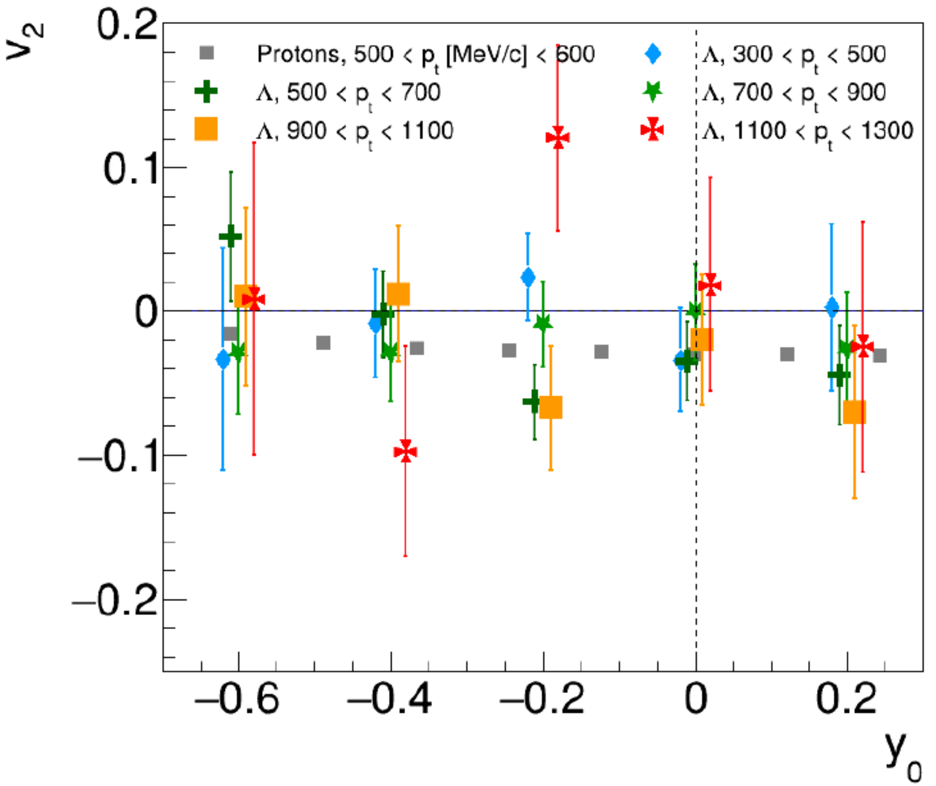




Proton distributions from 10-40 % centrality

Differential $v_2(y_0)$ distributions

Ag+Ag @ 1.58*A* GeV
10-20 % centrality



Ag+Ag @ 1.58*A* GeV
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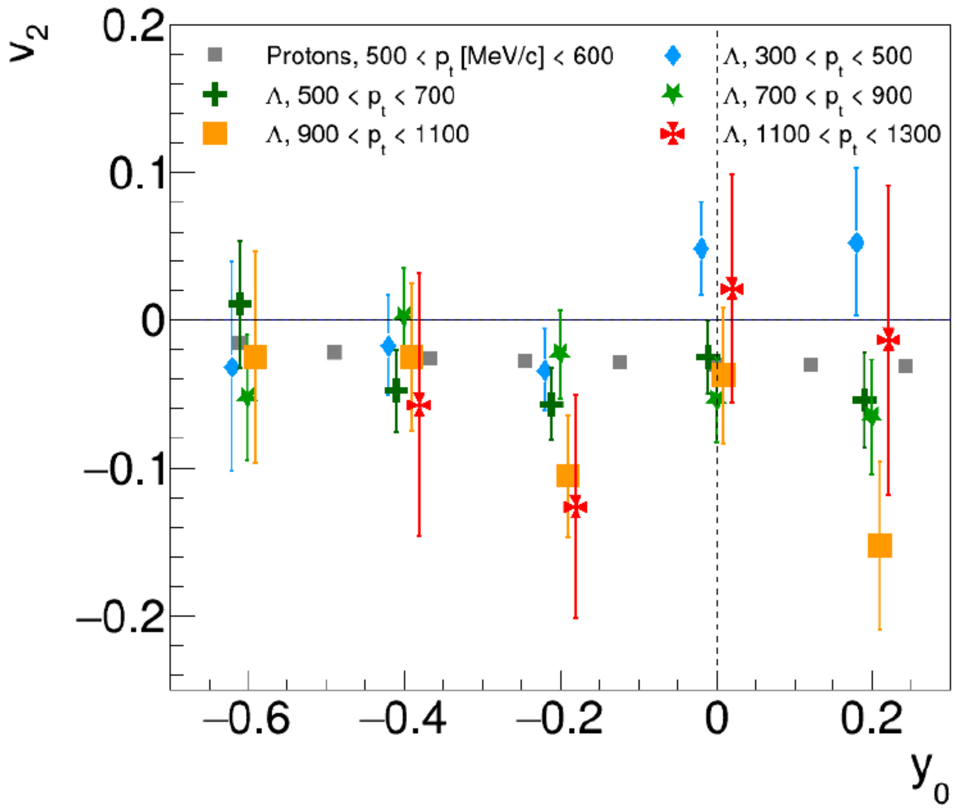

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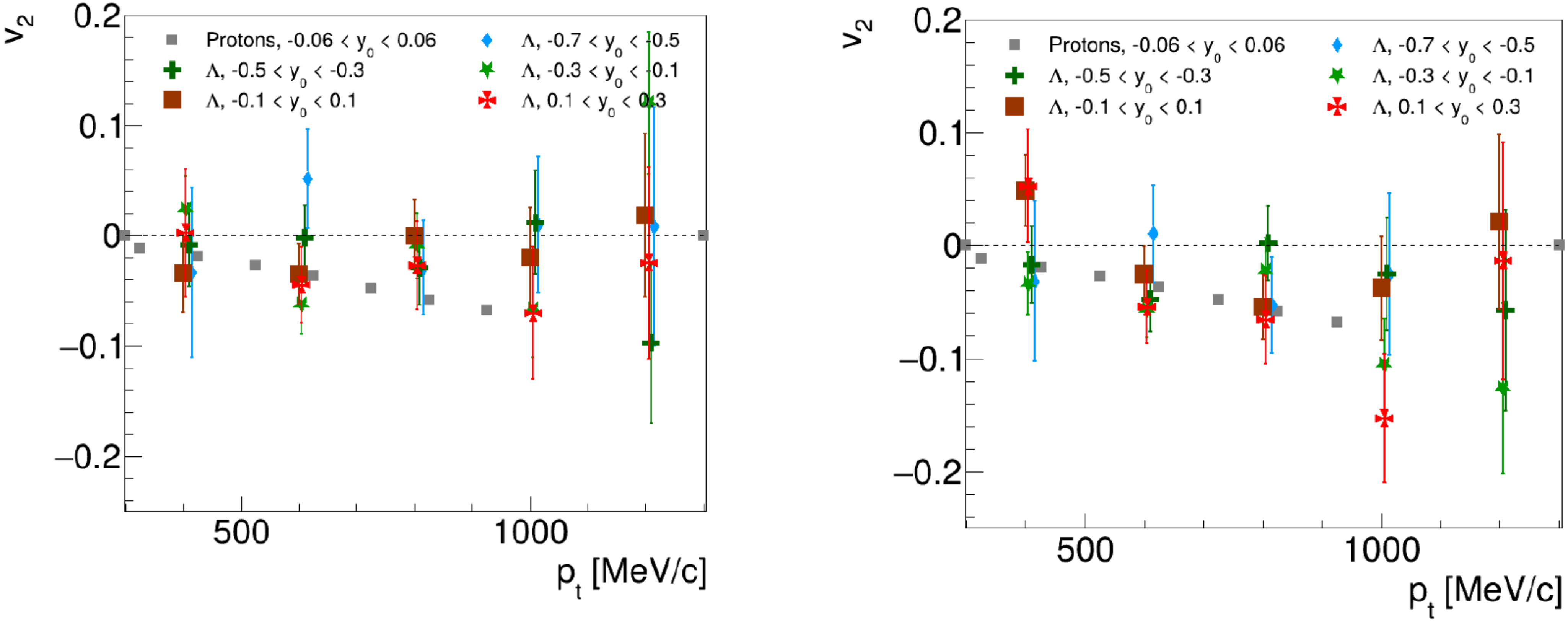

Proton distributions from 10-40 % centrality