Strangeness Production at SIS: Au+Au at 1.23A GeV with HADES & Microscopic Description by Transport Models

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

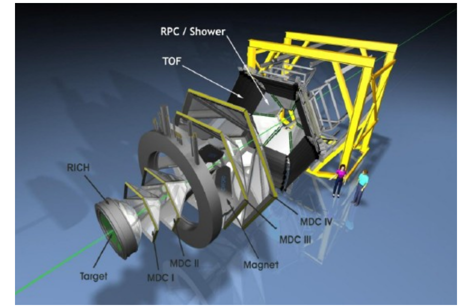
H-QM Helmholtz Research School Quark Matter Studies

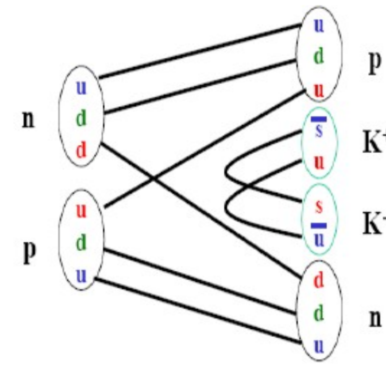
HADES

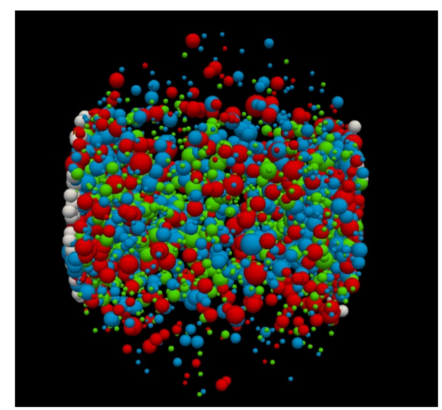
HIC for FAIR
Helmholtz International Center

// Outline

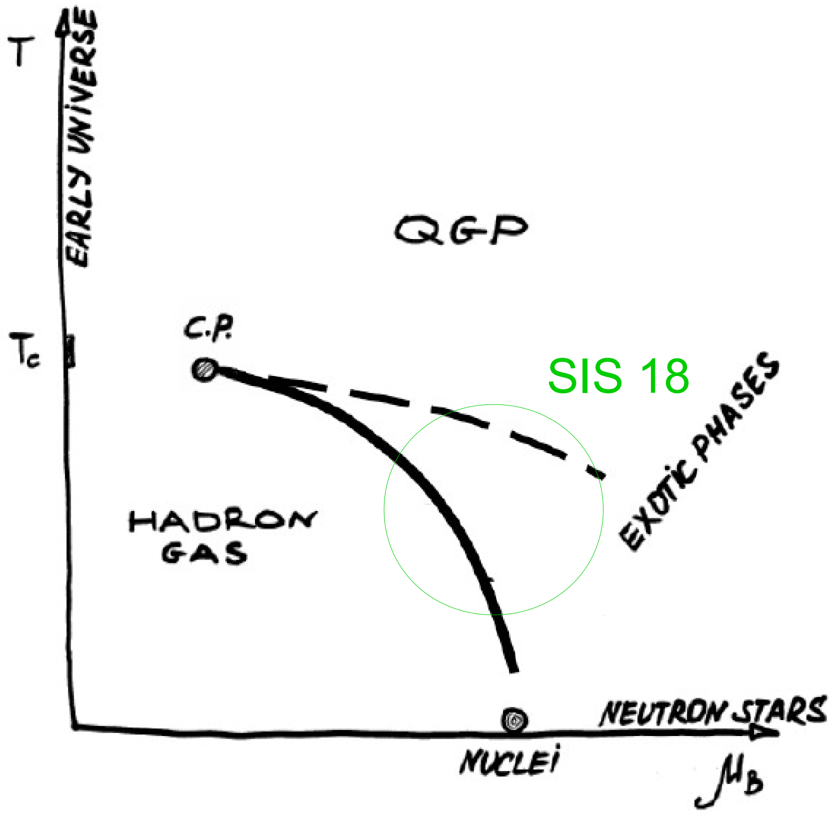
- HADES at SIS
- Strangeness Production below NN threshold: Au+Au @ 1.23A GeV
  - Charged kaon production
  - The role of the φ meson
  - Completing the strange picture: long-living Λ and K^0_s
  - Microscopic modelling of HIC dynamics: comparison to transport
- Summary

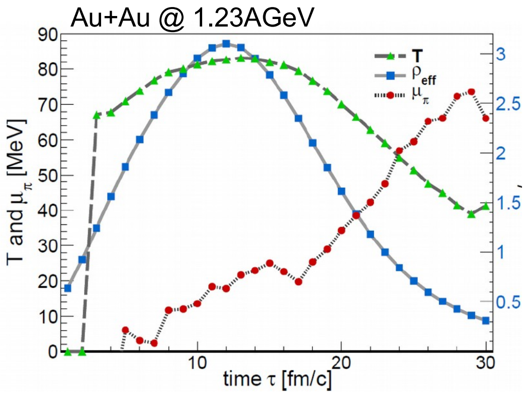






// Heavy-Ion Collisions at SIS Energies with HADES





Coarse-Graining Approach: T. Galatyuk *et al.*: Eur. Phys. J. A **52** (2016) 131

- SIS18: beam energies 1-2A GeV (HIC)
- Freeze-out at high μ_B (moderate T)
- Baryon dominated matter
- Rather long-living system

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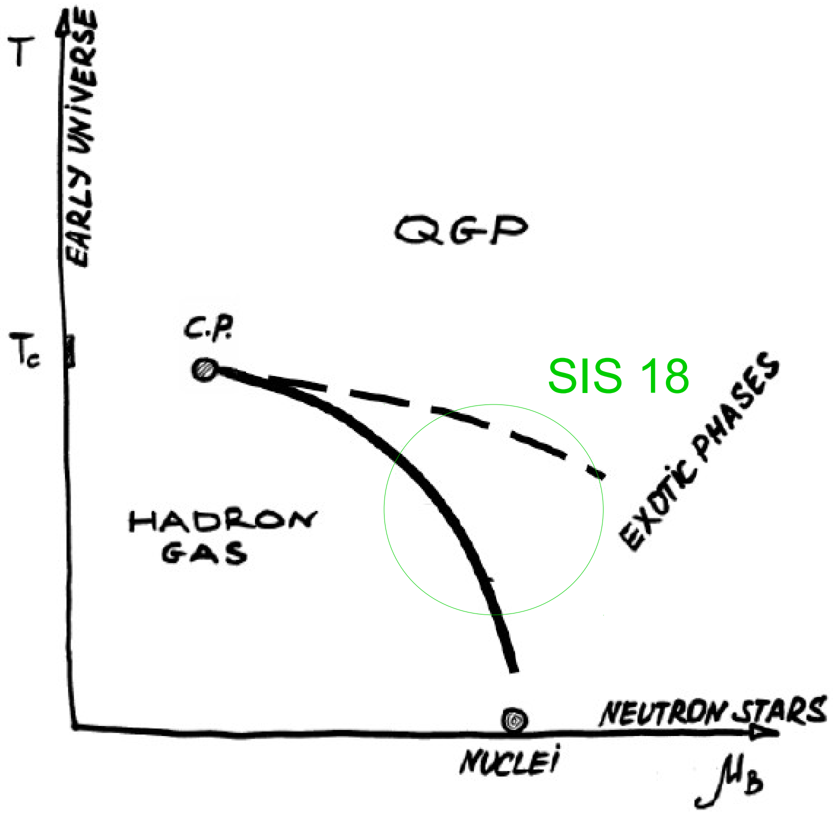

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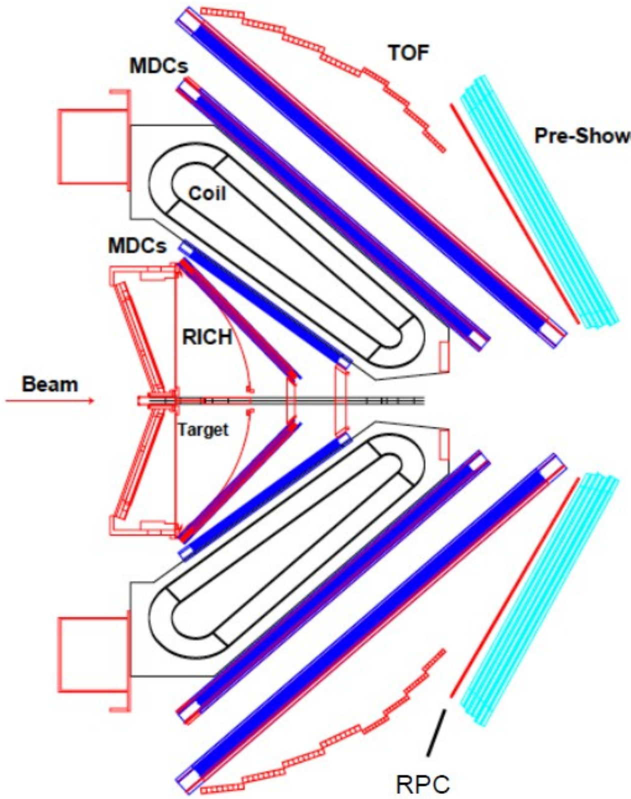
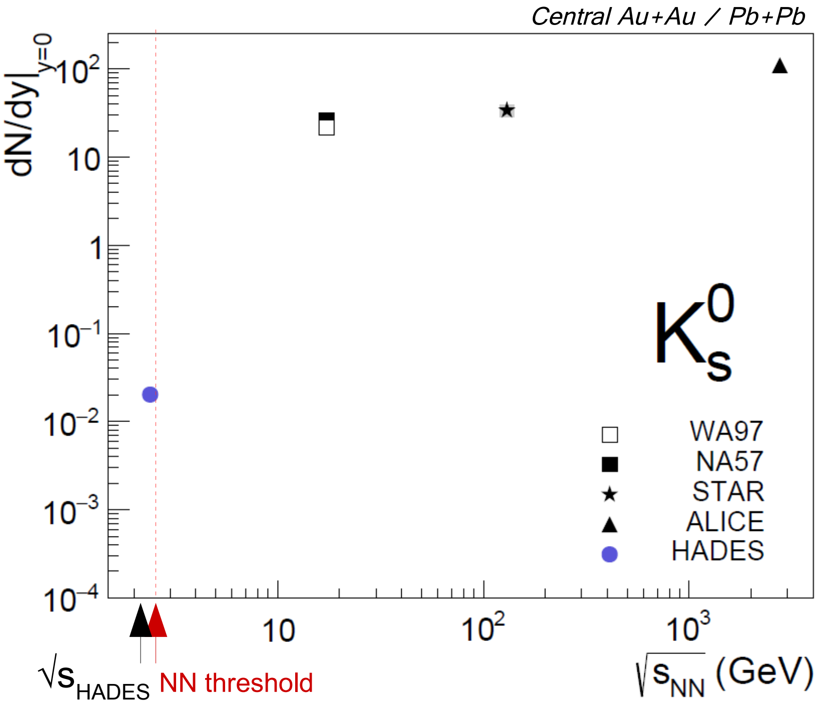
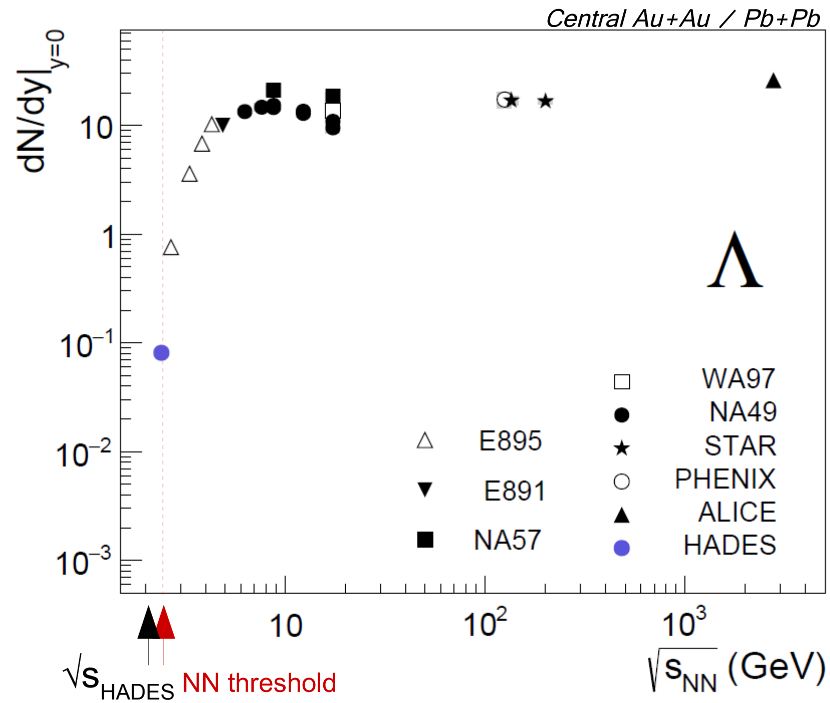


HADES schematic view

- Trigger rates: up to 50kHz
- Acceptance: θ = 18-85° polar angles; full azimuthal coverage

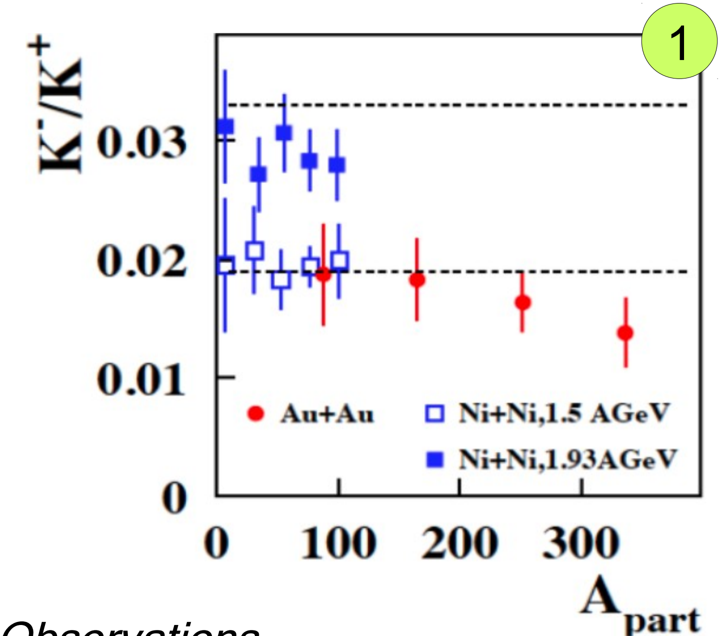
// Strange Particles in Au-Au Collisions at 1.23 A GeV

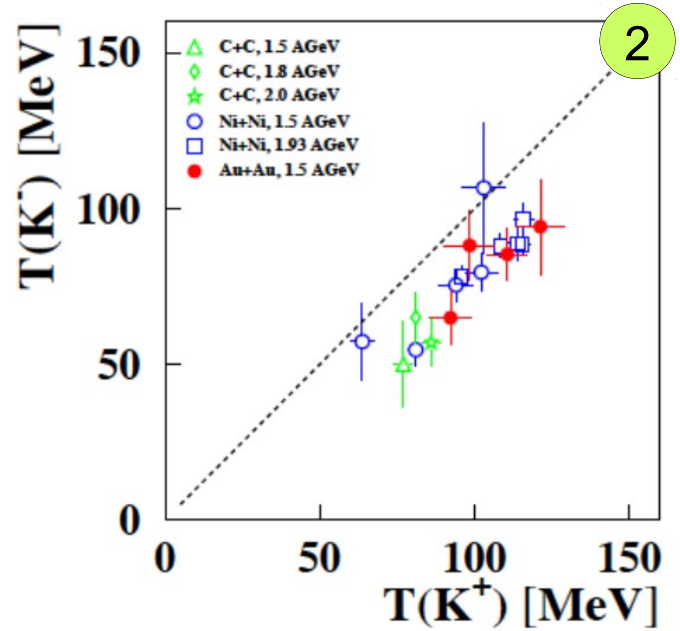




Production channel	$\sqrt{s_{AuAu}} - \sqrt{s_{thr}}$ [GeV]
$NN \rightarrow NK^+\Lambda$	-0.14
$NN \rightarrow NNK^+K^-$	-0.45
$NN \rightarrow NN\phi$	-0.49

- **All** strange particles produced below NN threshold !!!
  - ► High sensitivity to medium effects / multi-particle processes
- Steep excitation function at low energies





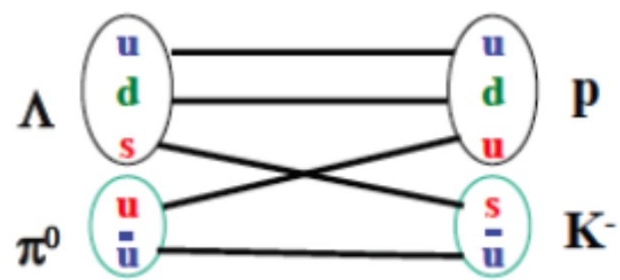
Förster et. Al (KaoS)
PHYSICAL REVIEW C **75**, 024906 (2007)

Observations

1. Centrality-invariant ratio of charged kaon yield: **coupled** K^+-K^- production
2. **Later freeze-out** for negative kaons

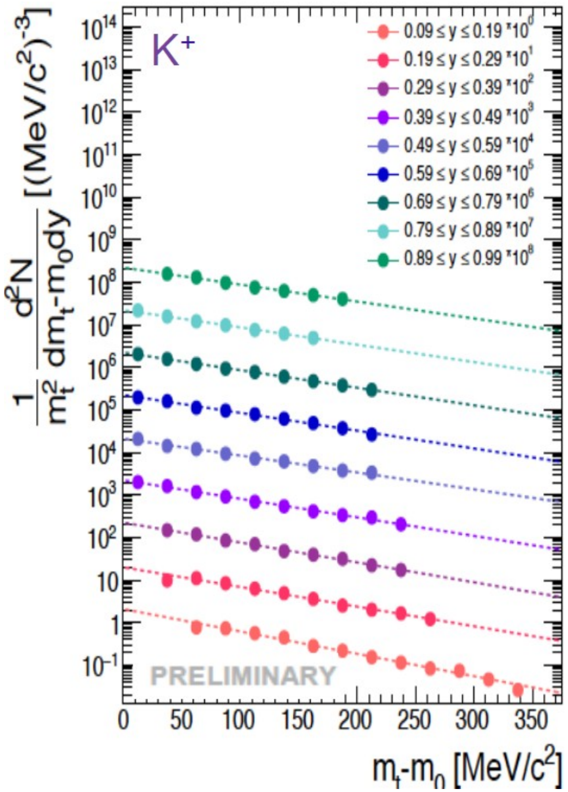
Conclusion

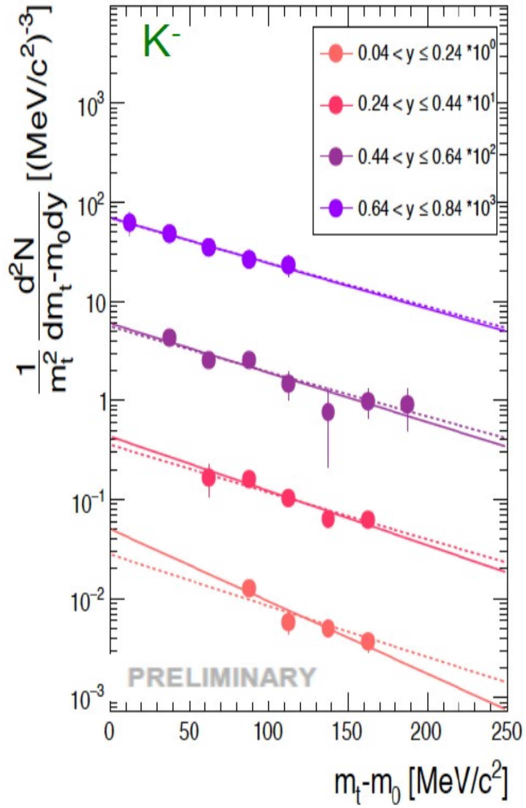
Strangeness Exchange (SE) reactions dominant source for K^-

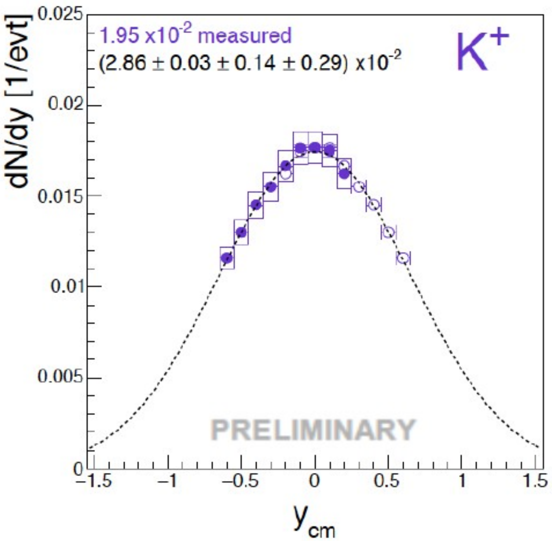


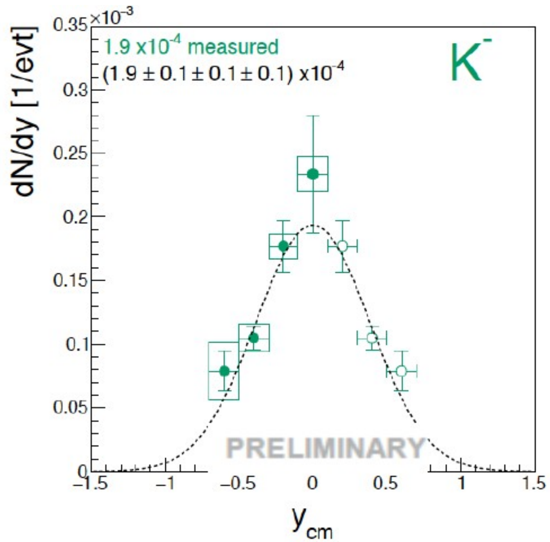
Strangeness Exchange

// HADES Data: Charged Kaon Results from Au+Au





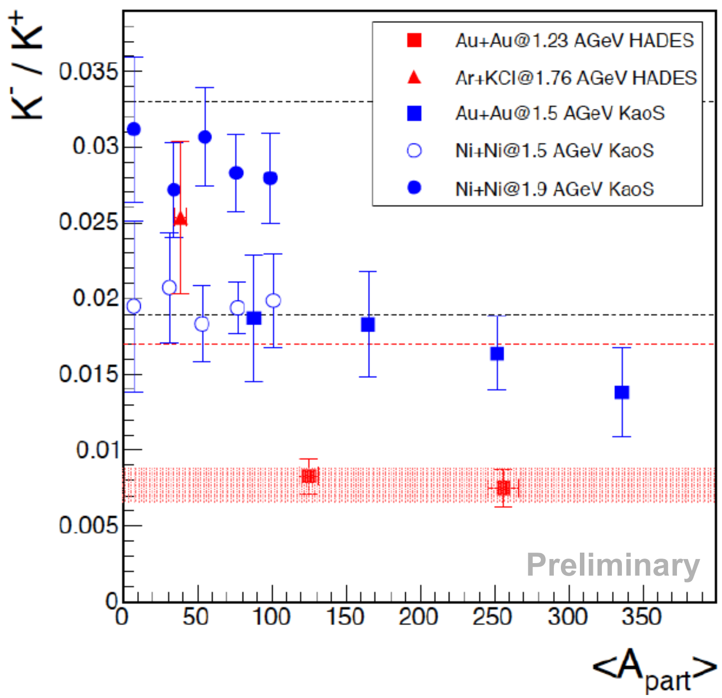


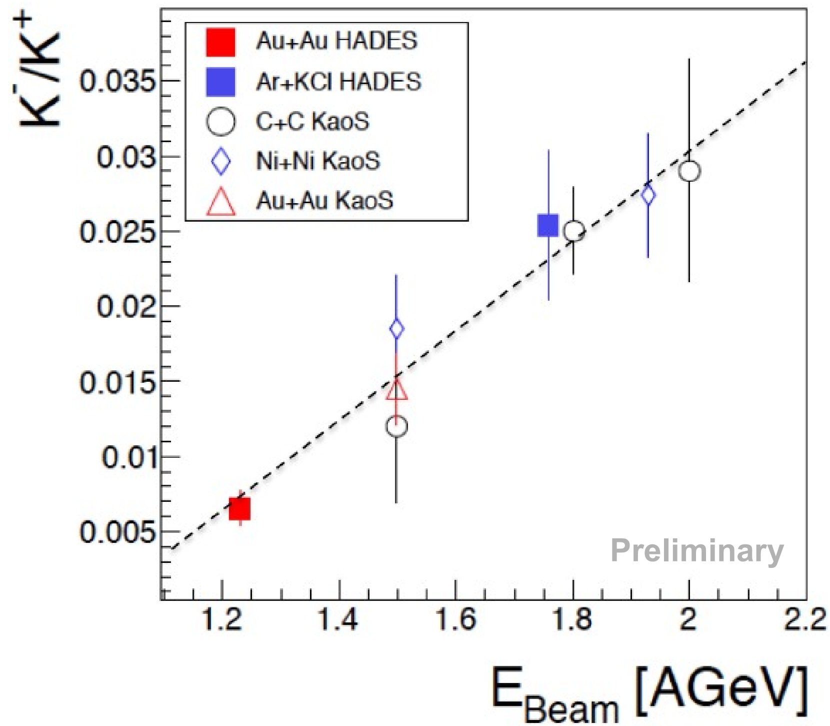


- **Inverse Slopes** at y_{cm}: $T_{eff}(K^+) = 105 \pm 4$ MeV
  $T_{eff}(K^-) = 82 \pm 9$ MeV

- Agreement with previous results from KaoS, FOPI, HADES

// HADES Data: Charged Kaon Results from Au+Au



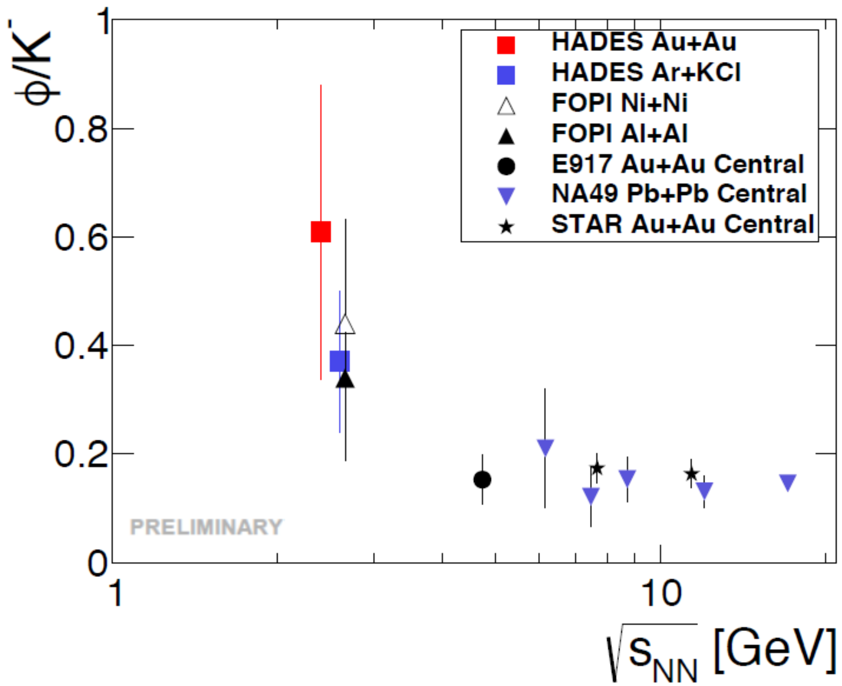


K^- / K^+ ratio:

- **constant** with **centrality**
- grows **linearly** with beam energy (confirming KaoS data)

PhD Schuldes

// The role of the φ-Meson I: Enhancement at SIS energies



- Sizeable increase of φ meson to **K⁻** ratio around production threshold

► **30%** of negative kaons K^- originate from φ-decay ($\varphi \rightarrow K^+K^-$; BR~50%)

PhD Schuldes

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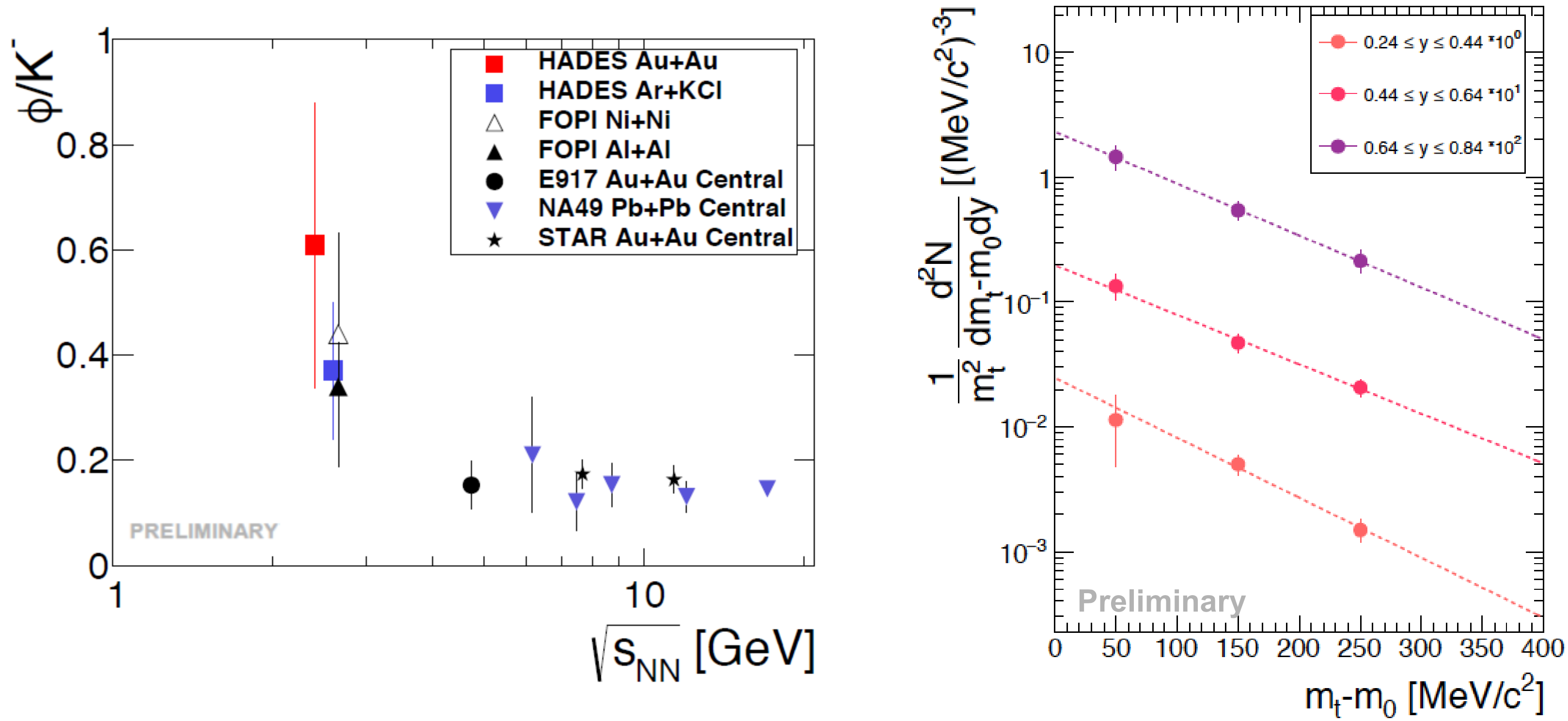


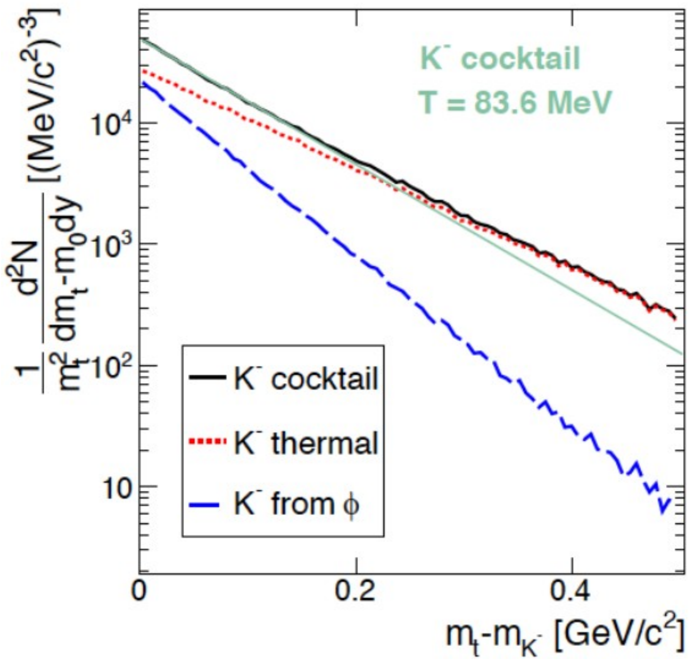
- Sizeable increase of φ meson to **K⁻** ratio around production threshold

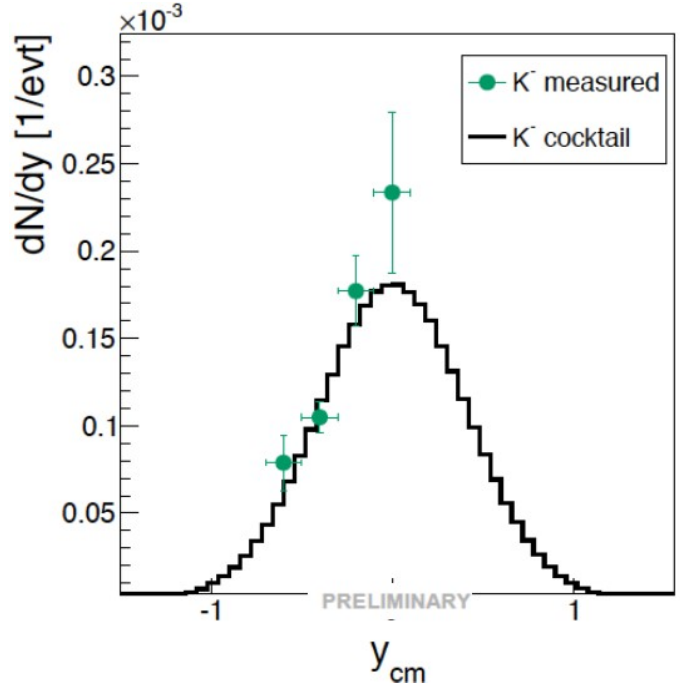
  ► **30%** of negative kaons K^- originate from φ-decay ($\varphi \rightarrow K^+K^-$; BR~50%)

- Sufficient statistics to perform multi-differential analysis for φ meson

PhD Schuldes

// The role of the φ-Meson II: Effect on Inverse Slope of K^-





Different inverse slopes for K^+ vs K^- can be corrected for φ feed-down:

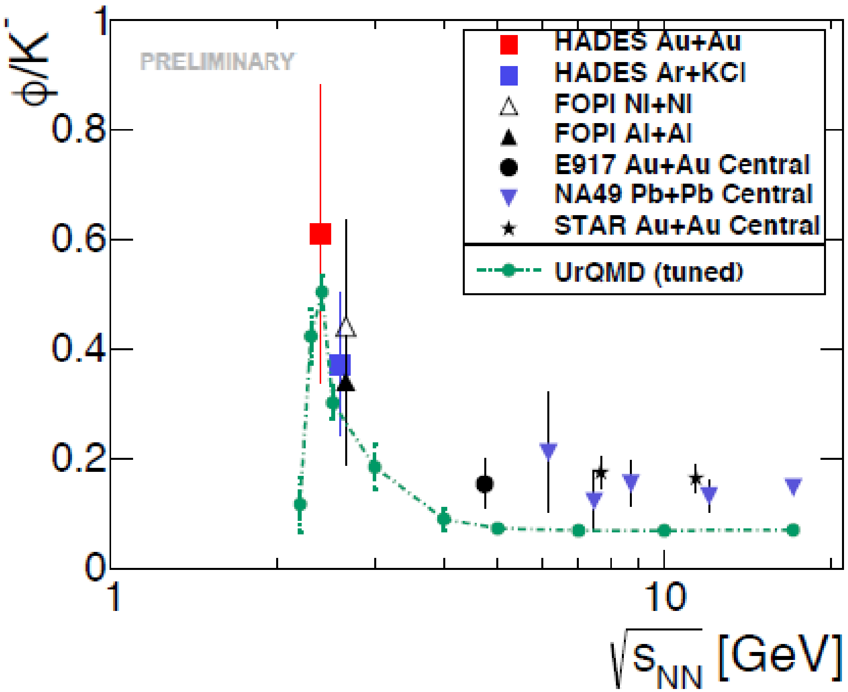
- Monte Carlo:
  - φ decay into K^+K^- with $T_{eff}(\varphi)$ = 103 MeV
  - 'Thermal' K^- with $T_{eff}(K^-) = T_{eff}(K^+)$ = 105 MeV
  - Taking measured φ/K^- ratio (~30%) into account

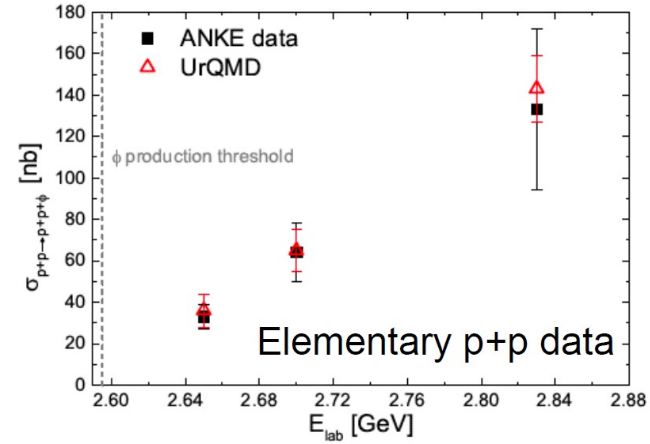
measured

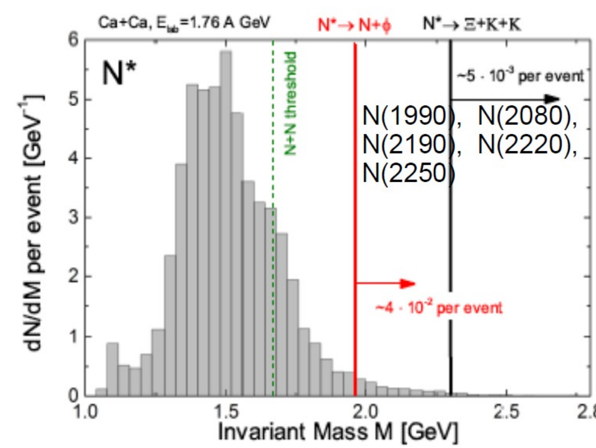
► Measured K^- rapidity distribution can be reproduced by cocktail

PhD Schuldes

// The role of the φ-Meson III: UrQMD Model Comparison



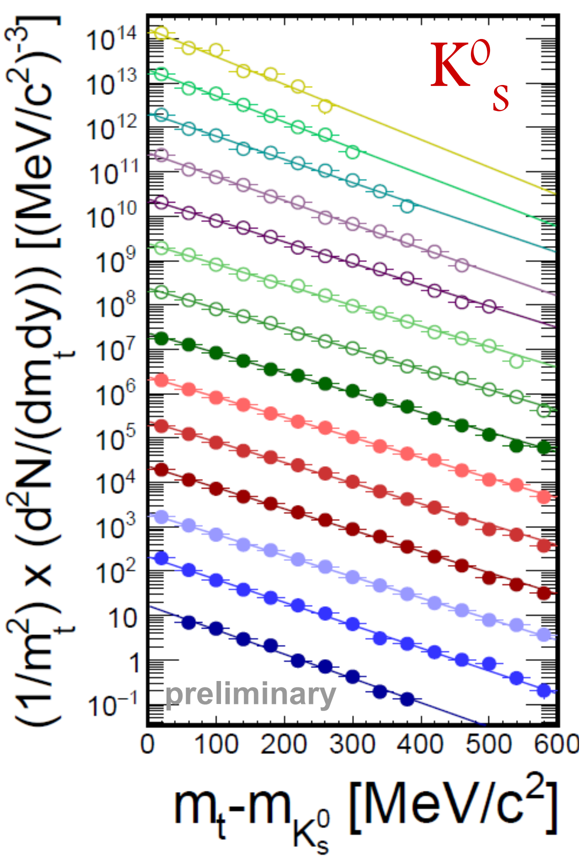


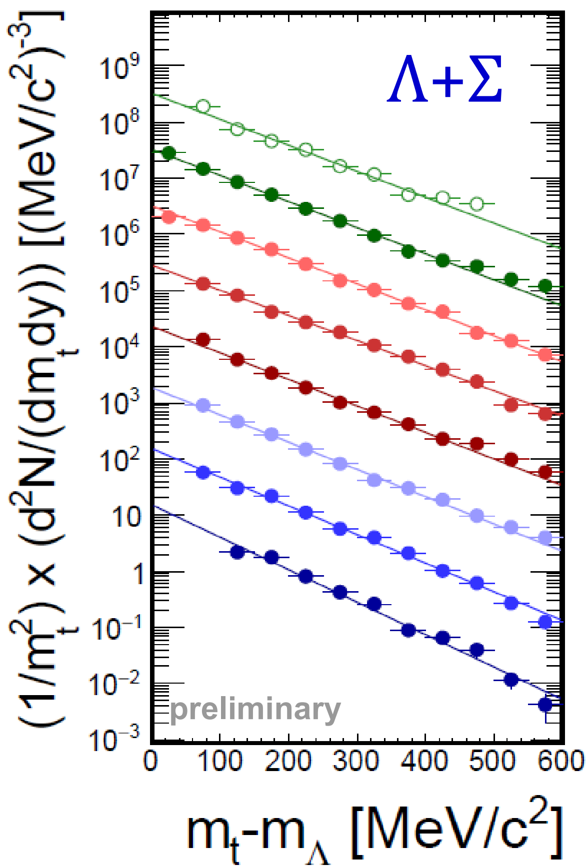


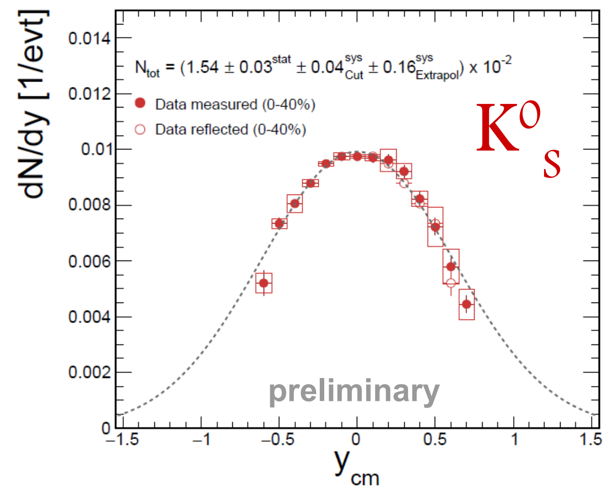
- Tuned UrQMD to match elementary data (ANKE) by increased BR for N* (needed in tails of resonances, consistent with OZI rule)

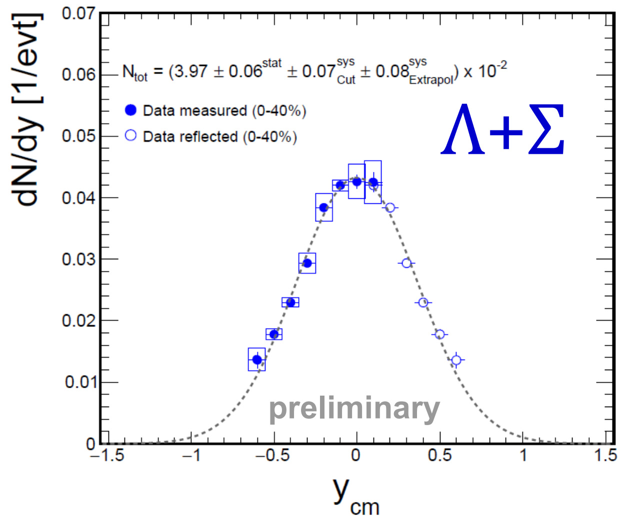
J. Steinheimer, M. Bleicher, J.Phys. G43 (2016) no.1, 015104

// Complete Strangeness Recipe: Add Neutral Hadrons Λ and K^0_s

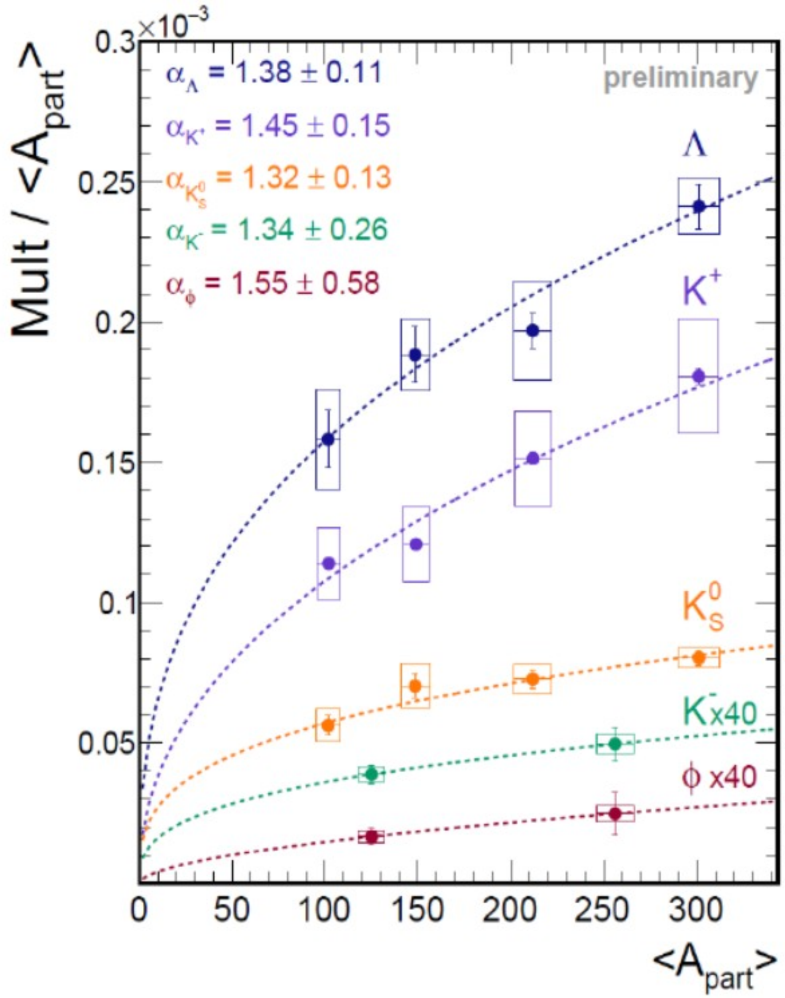






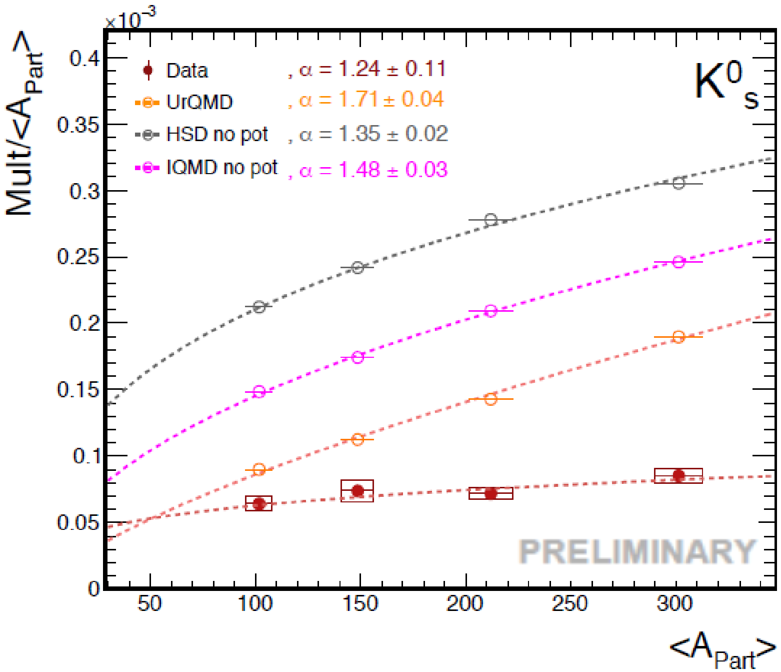


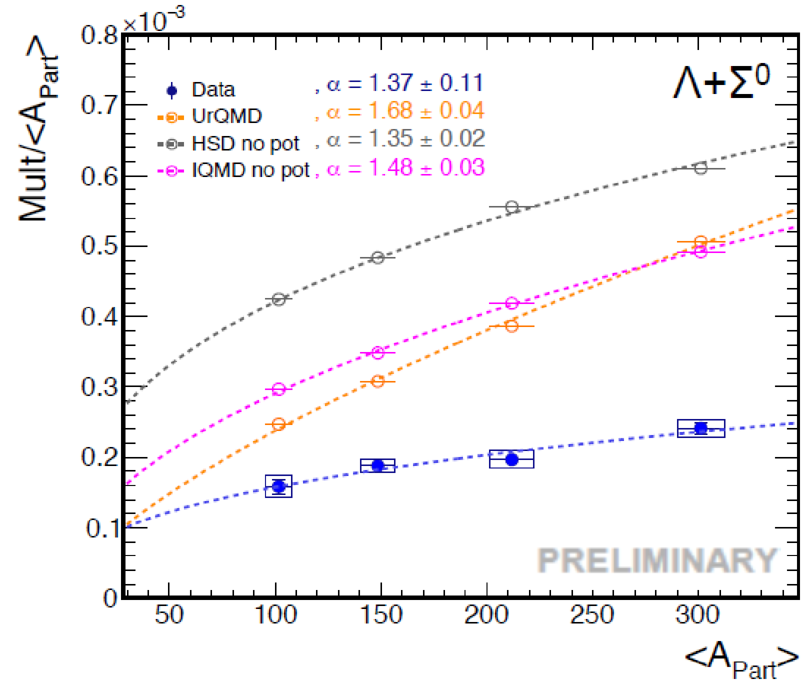
// Complete Strangeness



- Particle yields rise more than linear with centrality ($M/A_{part} \sim A_{part}^{\alpha}$)
- Within errors same trend as measured by KaoS and FOPI at higher energies (α_{K+}= 1.34 ± 0.16, α_{K-}= 1.22 ± 0.27, α_φ= 1.7 ± 0.5, $\alpha_{K°}$= 1.20 ± 0.25 α_Λ=1.34 ± 0.16)
- Similar trend for all strange particles!
  - ► hierarchy of production thresholds?
- Sensitive to multi-particle interactions
  - ► comparison to transport

// Dynamical Evolution: Comparison to Transport



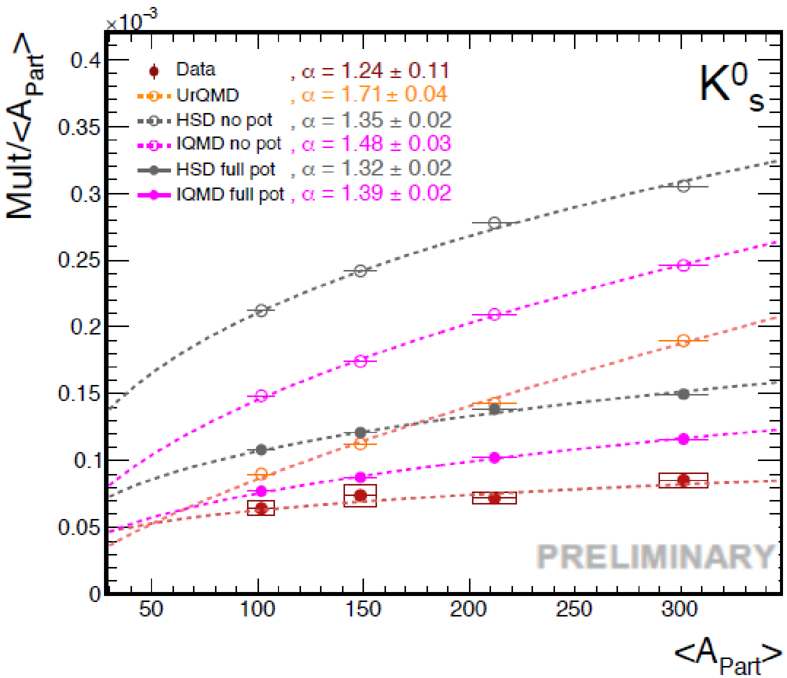


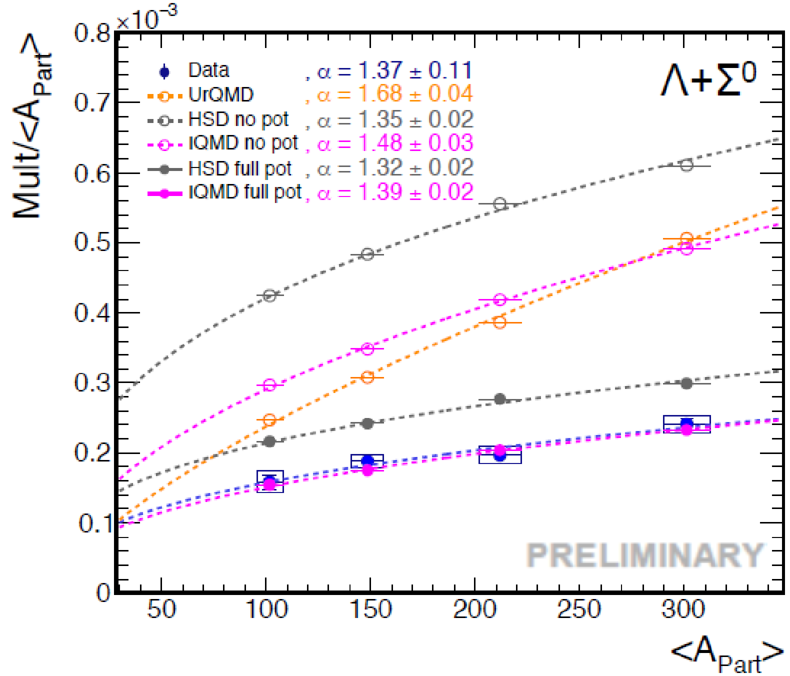
Models: HSD 711n, IQMD c8, UrQMD v3.4

- Similar rise predicted by HSD and IQMD ► multi-particle interactions under control
- Overestimation of rise by UrQMD ► due to resonance production?
- All models overshoot yield ► overall uncertainty in yield

Thanks to Y. Leifels, E. Bratkovskaya, C. Hartnack, J. Aichelin, J. Steinheimer, M. Bleicher

// Dynamical Evolution: Transport – Effect of Potentials



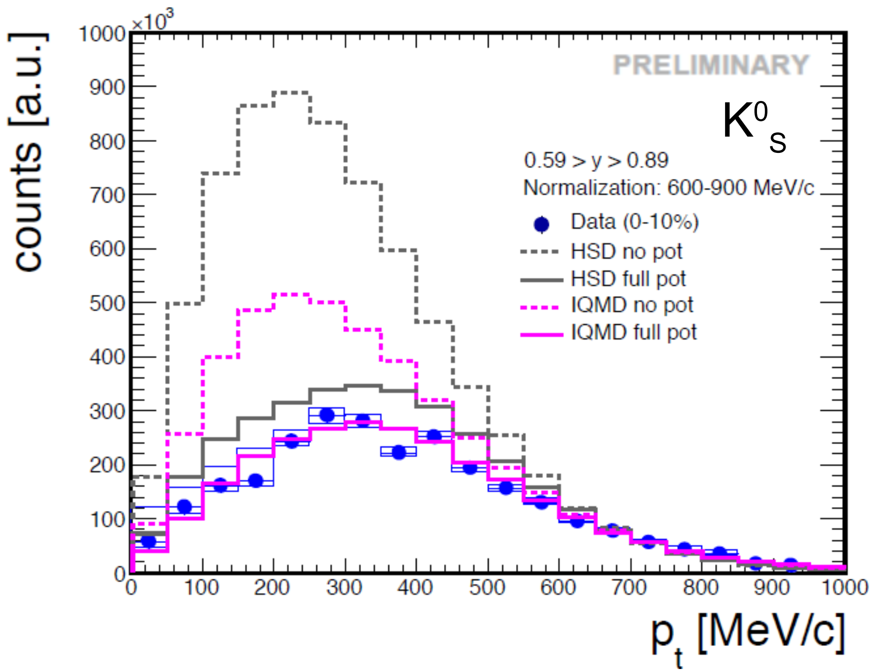


Models: HSD 711n, IQMD c8 (both full pot. 40 MeV), UrQMD v3.4

- Similar rise predicted by HSD and IQMD ► multi-particle interactions under control
- Overestimation of rise by UrQMD ► due to resonance production?
- All models overshoot yield ► overall uncertainty in yield
- Repulsive KN potential reduces yield ► compare shape of p_T spectra

Thanks to Y. Leifels, E. Bratkovskaya, C. Hartnack, J. Aichelin, J. Steinheimer, M. Bleicher

// Kaon Nucleon Potential: Comparison of p_T Shape



Models: HSD 711n, IQMD c8 (both full pot. 40 MeV), UrQMD v3.4

- KN potential (blue-)shift of p_T ► spectra normalized at high p_T
- Potential affects low p_T similarly in HSD and IQMD ► data favors incl. potential

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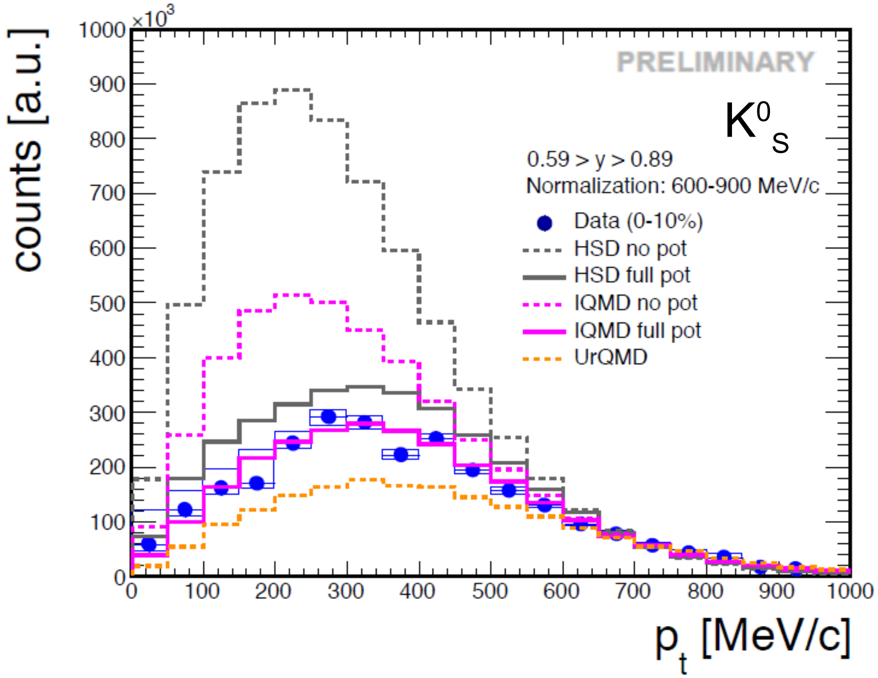
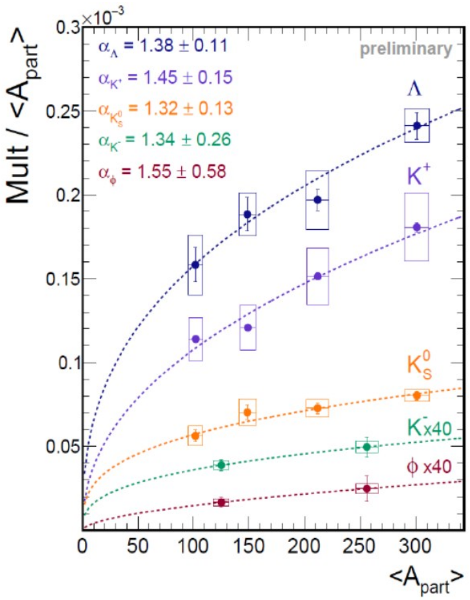


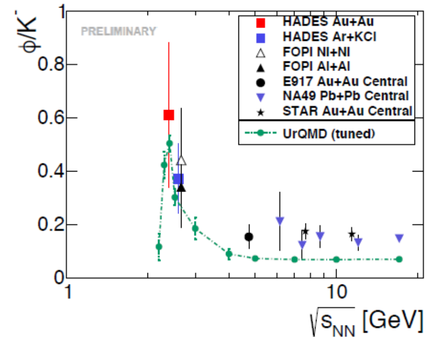
Models: HSD 711n, IQMD c8 (both full pot. 40 MeV), UrQMD v3.4

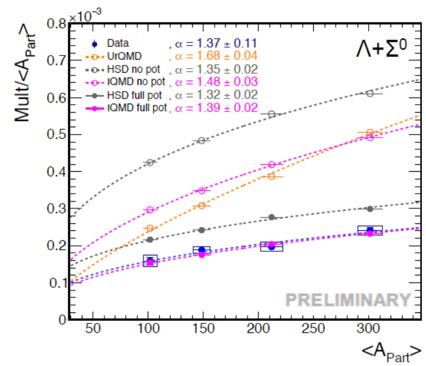
- KN potential (blue-)shift of p_T ► spectra normalized at high p_T
- Potential affects low p_T similarly in HSD and IQMD ► data favors incl. potential
- UrQMD: low p_T even lower yield (no pot.) ► shape modified by production via baryonic resonances

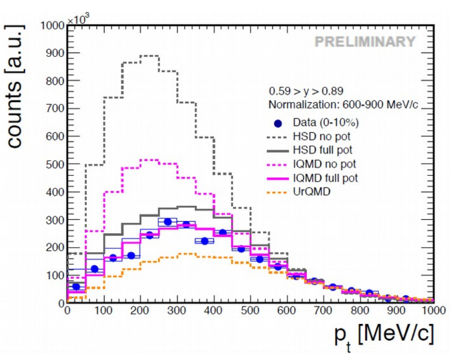
// Summary

- Complete set of strange particles vs. m_T, y and centrality
- Similar rise for all strange particle yields despite distinct hierarchy of production thresholds
- Lower effective temperature of K^- can be explained by φ feed-down
- Microscopic Description: Comparison to Transport
  - UrQMD predicts rise of φ/K^- towards lower energies
  - Multi-particle interactions predict rise of yields with centrality (HSD, IQMD)
  - Inclusion of potential reduces yield significantly and low p_T shape(HSD, IQMD)
  - Shape of p_T spectra strongly influenced already by introduction of more resonances (UrQMD)



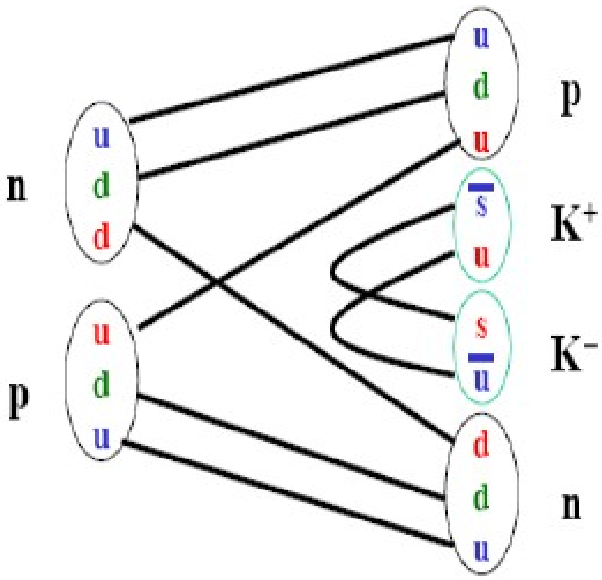






// Backup...

// Strange Particle Production in Elementary Collisions



$$NN \rightarrow NK^+\Lambda \quad (E_{thr} = 1.58\,GeV)$$

$$NN \rightarrow NNK^+K^- \quad (E_{thr} = 2.49\,GeV)$$

$$NN \rightarrow NN\varphi \quad (E_{thr} = 2.59\,GeV)$$

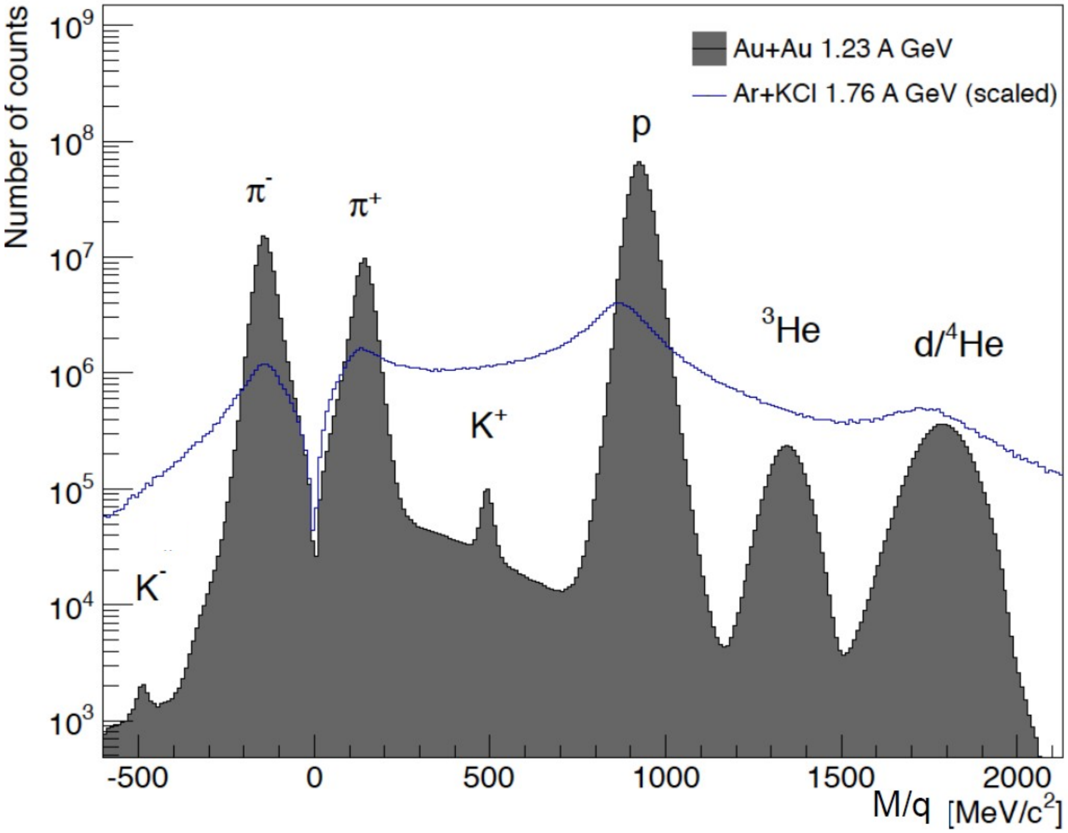
- **Strange** particles produced in **pairs** due to strangeness conservation

  ► relatively **high thresholds**

- Negative kaons: even higher due to additional baryon in final state

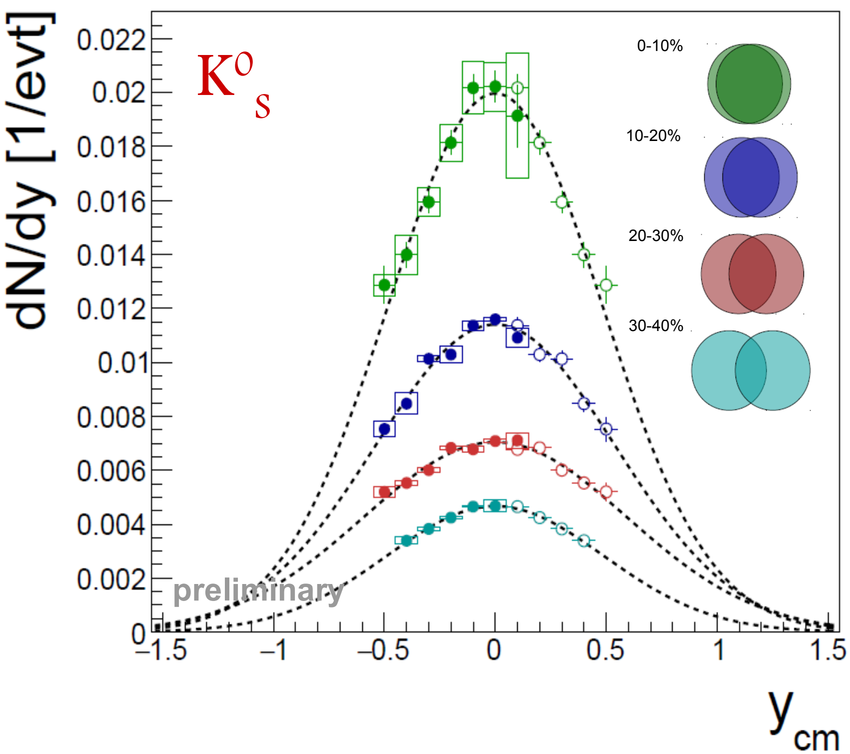
- Beam energy below NN threshold: **no direct NN production** possible

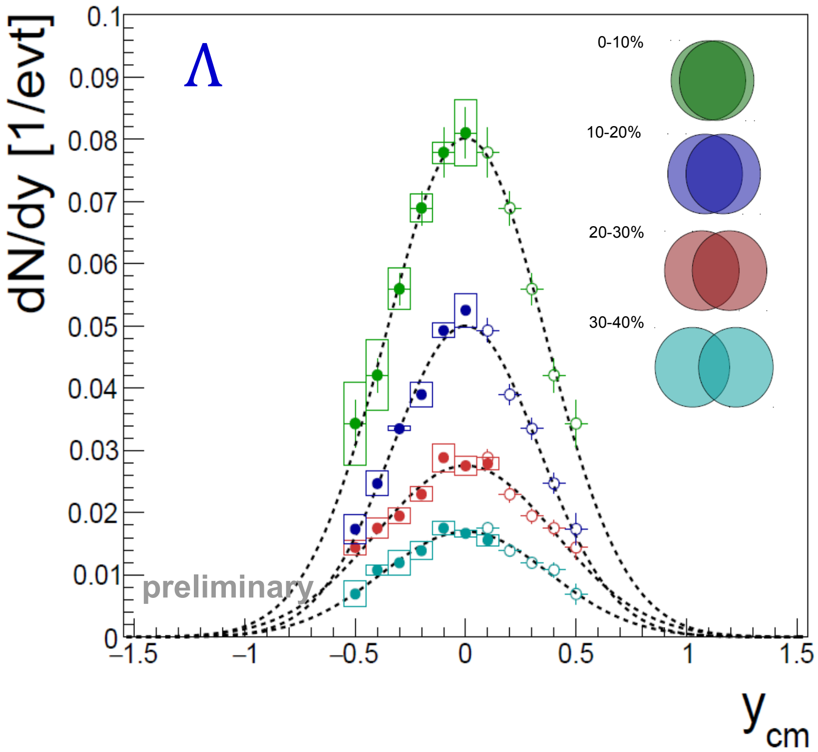
// Mass Spectrum: HADES Performance



- HADES upgrades: sizeable improvement in PID
- Pronounced charged Kaon signals

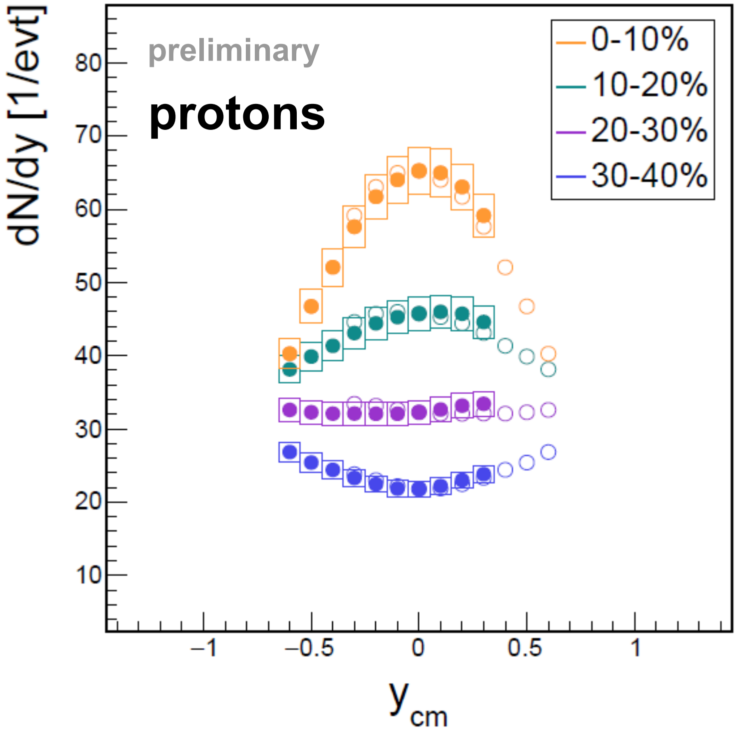
// Centrality Dependence

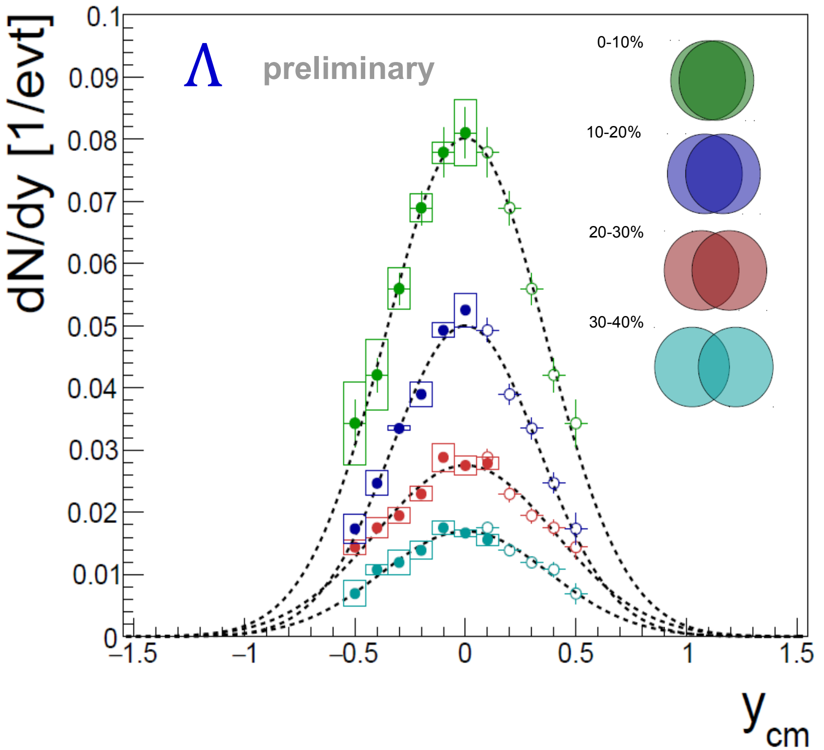




- Same analysis for centrality bins in 10% steps from 0% to 40%
- First centrality dependent measurement of K^0_S and Λ below NN threshold!
- Rising yield towards more central collisions

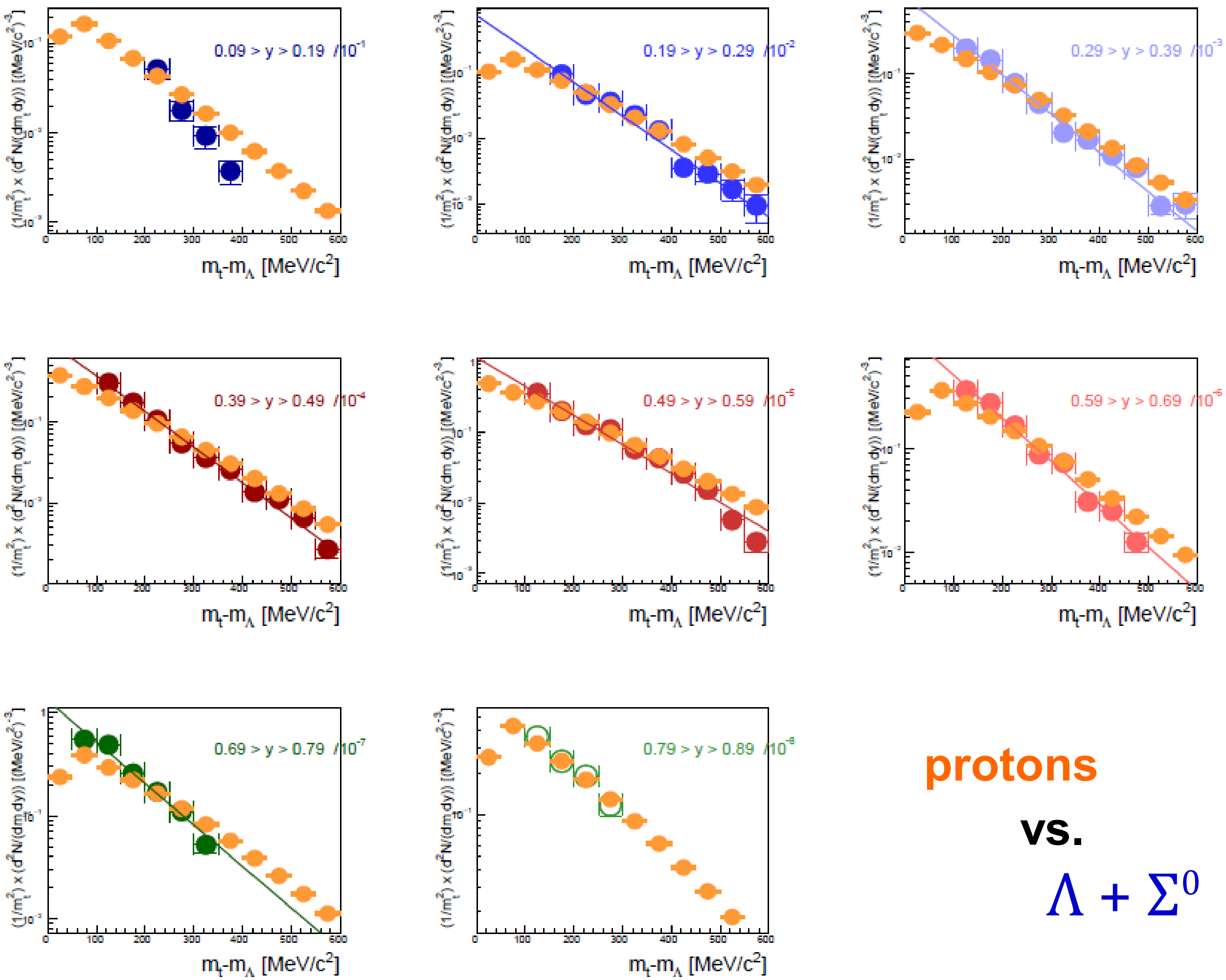
// Centrality Dependence

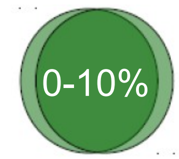




- Rising yield towards more central collisions
- No broadening of spectra for Lambda towards peripheral collisions
- Spectator-like distributions for protons going to peripheral collisions

// Comparison M_T Spectra: Most Central



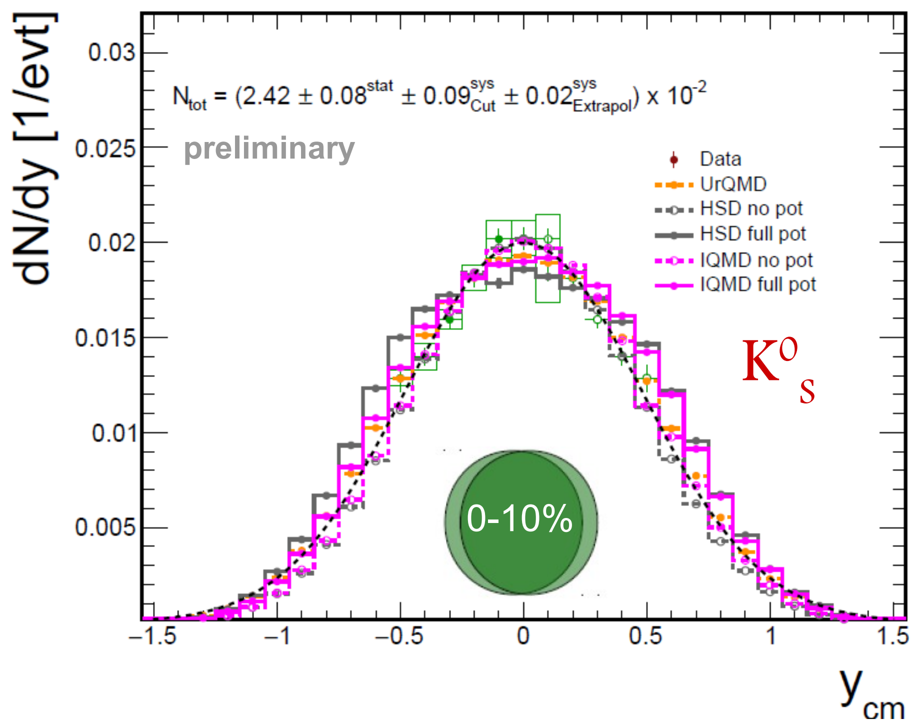


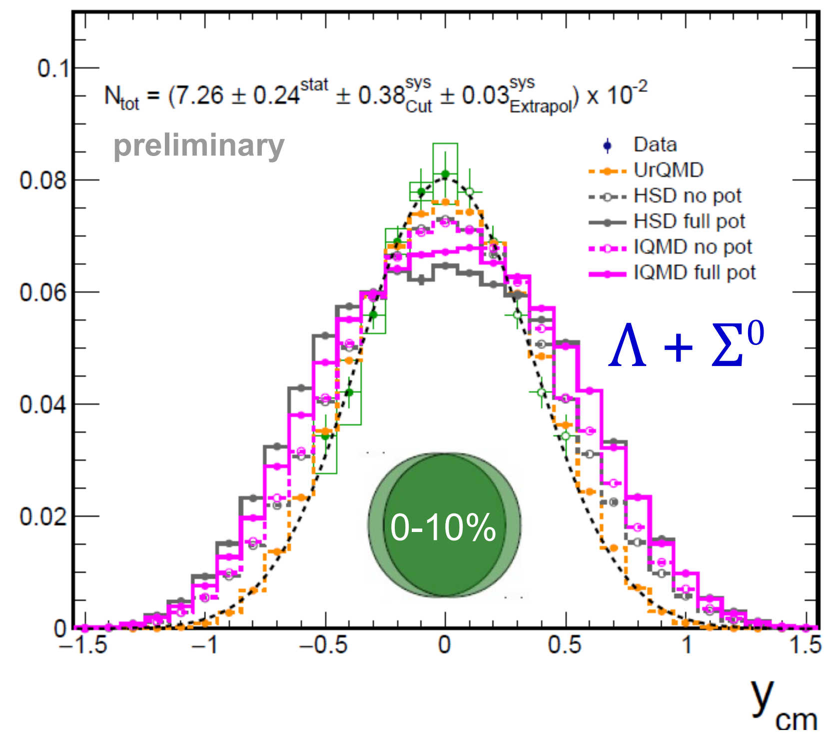
protons

vs.

$\Lambda + \Sigma^0$

// dN/dy Spectra: Comparison to Transport (Most Central)

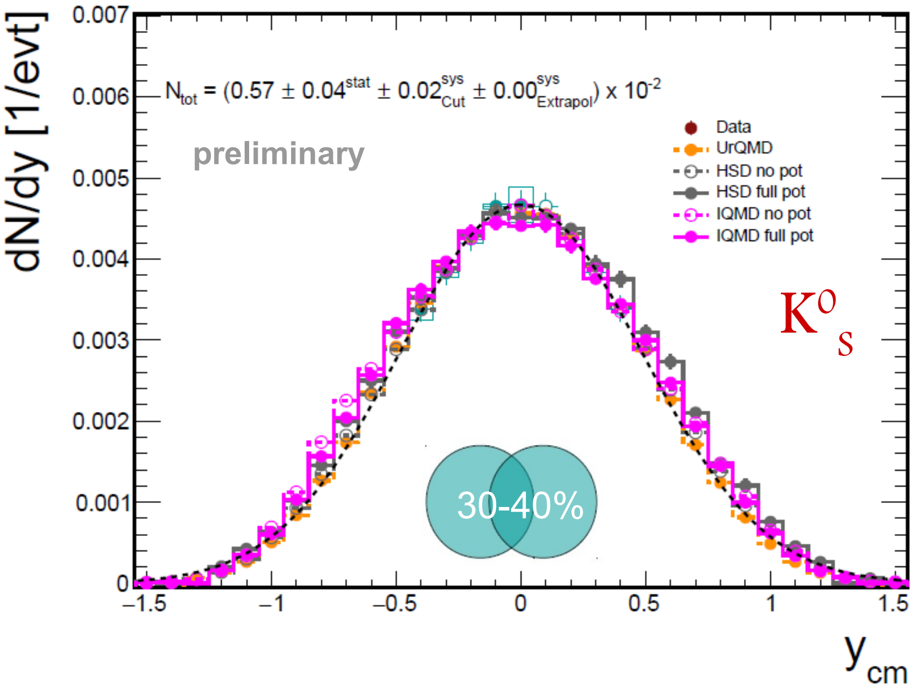


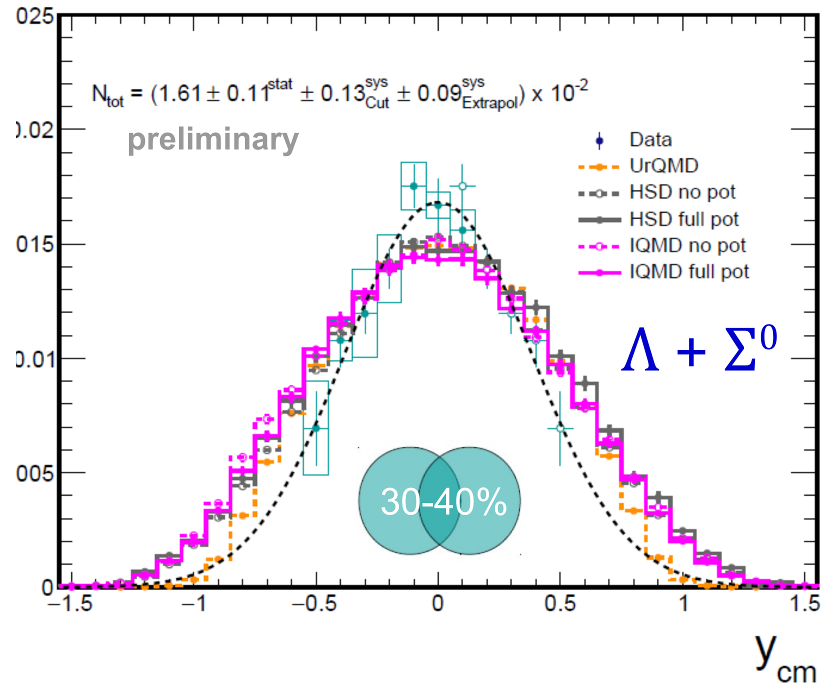


- Spectra from Transport **normalized** to integral of data
- Kaon Shape well reproduced by all models, better matching without potential
- Lambda Shape reproduced by UrQMD; HSD and IQMD broader

Thanks to Y. Leifels for providing model spectra

// dN/dy Spectra: Comparison to Transport (Peripheral)

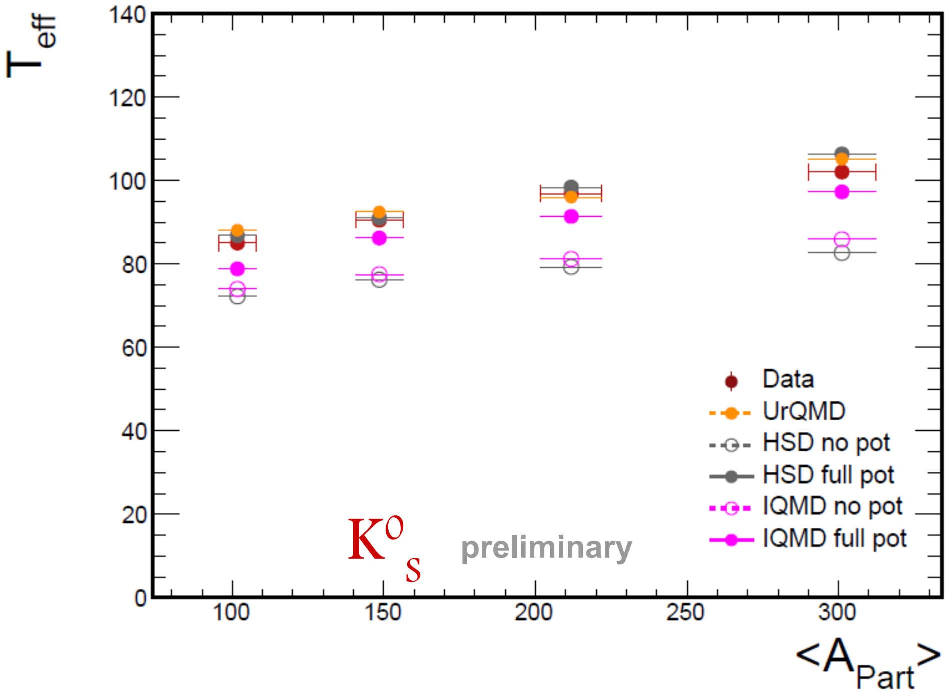


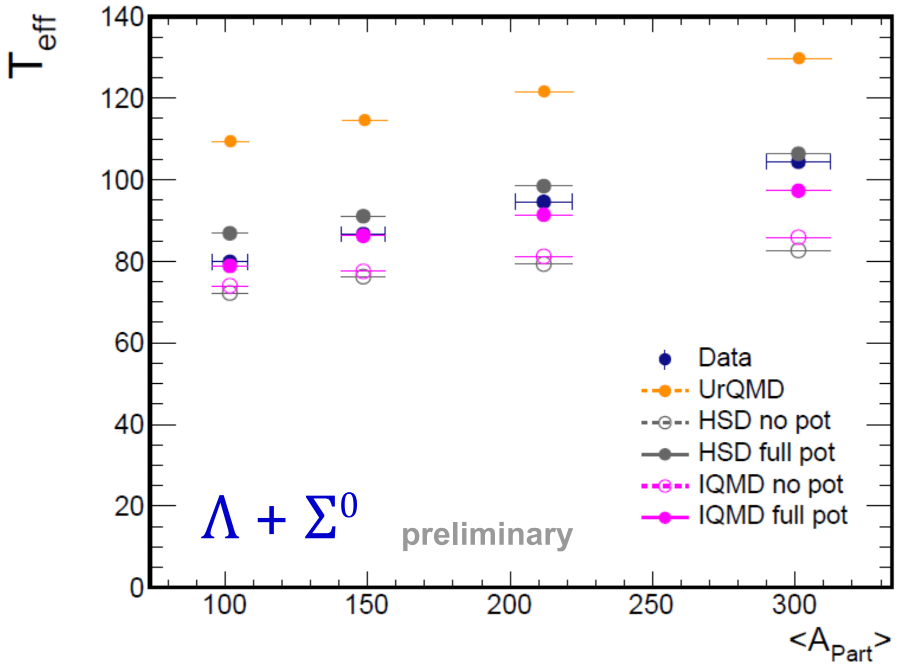


- Spectra from Transport normalized to integral of data
- Kaon Shape well reproduced by **all** models, slightly better matching with potential
- Lambda Models broader

Thanks to Y. Leifels for providing model spectra

// Inverse Slope vs Number of Participants





Lifetime Measurements

Measure and compare well-known mean lifetime τ of K^0_s and Λ

Exponential Decay

$$N(\Delta t) = N_0 \cdot exp^{\frac{-\Delta t}{\tau}}$$

Time-of flight of relativistic particle P in lab frame:

(I) $\Delta t_{lab} = \Delta t'_P \cdot \gamma$ ($\Delta t'_P$: Eigentime)

Time-of flight can be calculated from observables:

(II) $\Delta t_{lab} = \frac{\Delta l}{\beta \cdot c}$ (Δl : Dist. Prim. – Seco. Vertex, β : Velocity)

(I) = (II)

$$\Longrightarrow \Delta t'_P = \frac{\Delta l}{\beta \gamma c}$$

$\beta\gamma c = |p|/m$

$$\Longrightarrow \Delta t'_P = \frac{\Delta l \cdot m}{|p|}$$

(m : mass, p : momentum)