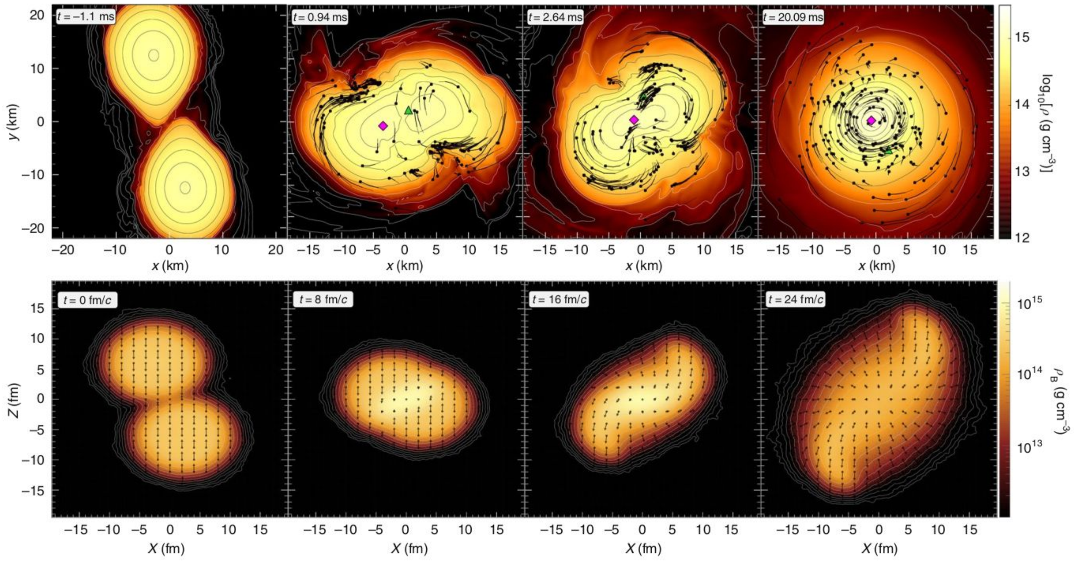
Charged Kaon and $\phi(1020)$ Production

In Ag+Ag Collisions at $\sqrt{s_{NN}} = 2.55\,\mathrm{GeV}$ Measured with HADES

Physics Motivation

- Ag+Ag at $\sqrt{s_{NN}} = 2.55\,\mathrm{GeV}$ with large stopping (Baryon dominance)
- Similar conditions as in merging Neutron Stars
  - $T < 70\,MeV$
  - $\rho \approx 3\rho_0$



Nature Phys. 15 (2019) 10, 1040-1045

- *E. R. Most, L. J. Papenfort, V. Dexheimer, M. Hanauske, S. Schramm, H. Stöcker, L. Rezzolla, Phys. Rev. Lett.* ***122*** *(2019) no.6, 061101*
- *S. A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, M. Hofmann, S. Hofmann and J. Konopka, et al., Prog. Part. Nucl. Phys.* ***41*** *(1998), 255-369*
- *HADES Collaboration - J. Adamczewski-Musch et al., Nature Phys.* ***15*** *(2019) 10, 1040-1045*

Motivation for this Work

- In-medium strangeness production mechanisms at/below energetic binary NN collision threshold

$$NN \rightarrow NK^+\Lambda \qquad (\sqrt{s_{NN}} = 2.55\,\mathrm{GeV})$$
$$NN \rightarrow NNK^+K^- \qquad (\sqrt{s_{NN}} = 2.86\,\mathrm{GeV})$$
$$NN \rightarrow NN\phi \qquad (\sqrt{s_{NN}} = 2.90\,\mathrm{GeV})$$

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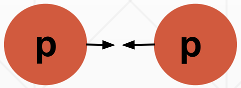
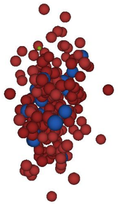


VS



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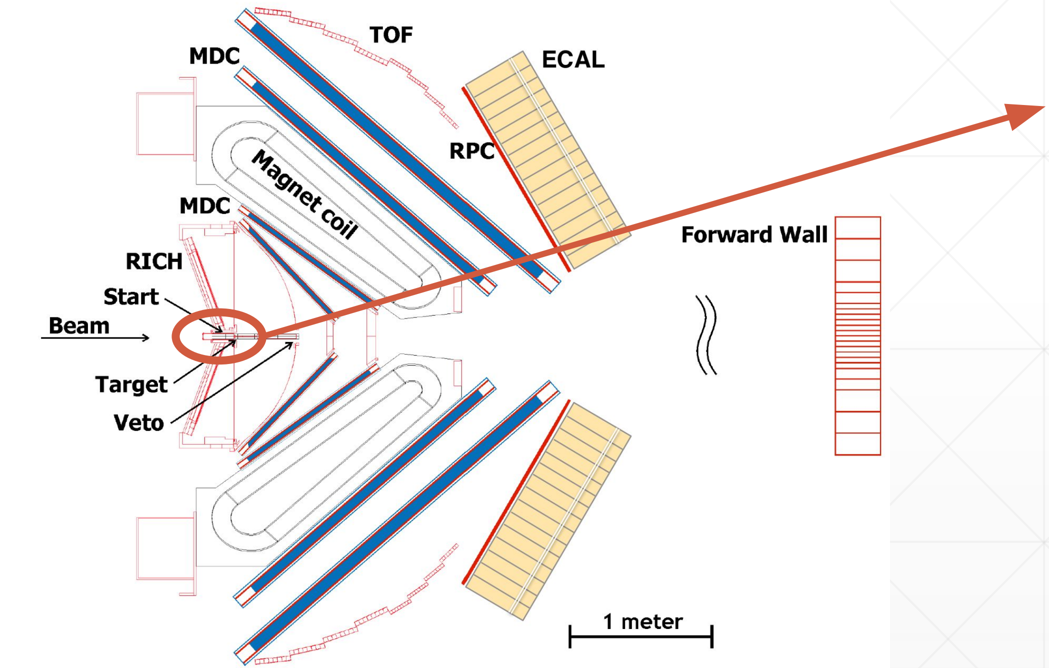
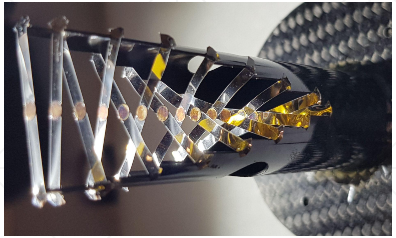
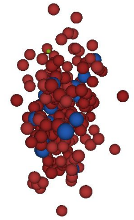
$$NN \rightarrow NN\phi \qquad (\sqrt{s_{NN}} = 2.90\,\mathrm{GeV})$$

  - **How is strangeness produced inside the medium?**
    - Production via decay of baryonic resonances?
      - *J. Steinheimer et al., DOI: 10.1088/0954-3899/43/1/015104*
      - *J. Steinheimer et al., DOI: 10.1103/PhysRevC.93.064908*
  - **Can strangeness yields be explained by thermal models?**
      - *A. Motornenko et al., arXiv:2104.06036 [hep-ph]*
      - *S. Harabasz et al., DOI: 10.1103/PhysRevC.102.054903*
      - *J. Cleymans, H. Oeschler and K. Redlich, DOI: 10.1103/PhysRevC.59.1663*
      - *HADES Collaboration - G. Agakishiev et al., DOI: 10.1140/epja/i2016-16178-x*
      - *J. Stachel, A. Andronic, P. Braun-Munzinger, K. Redlich, DOI: 10.1088/1742-6596/509/1/012019*

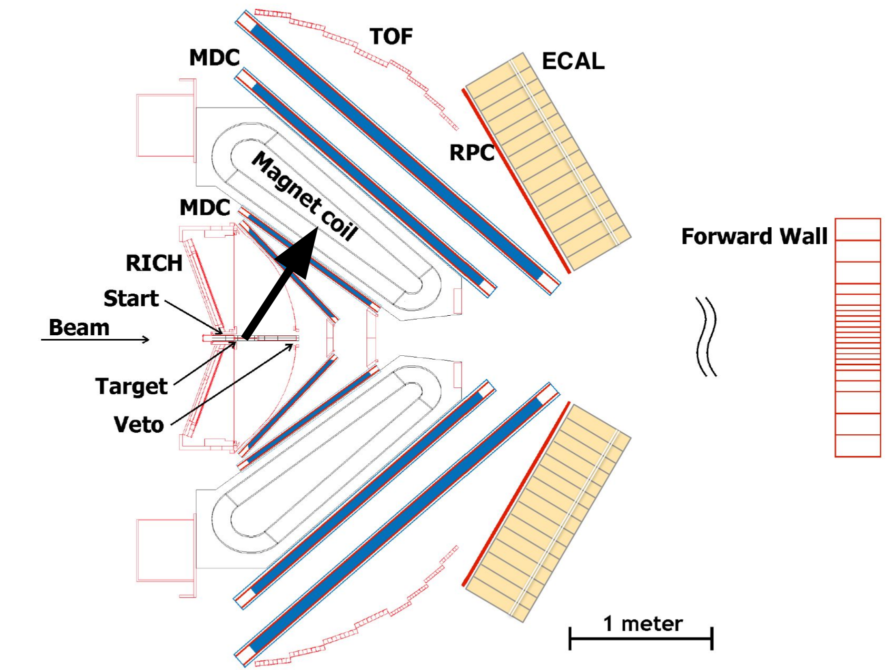
Phase Space Reconstruction



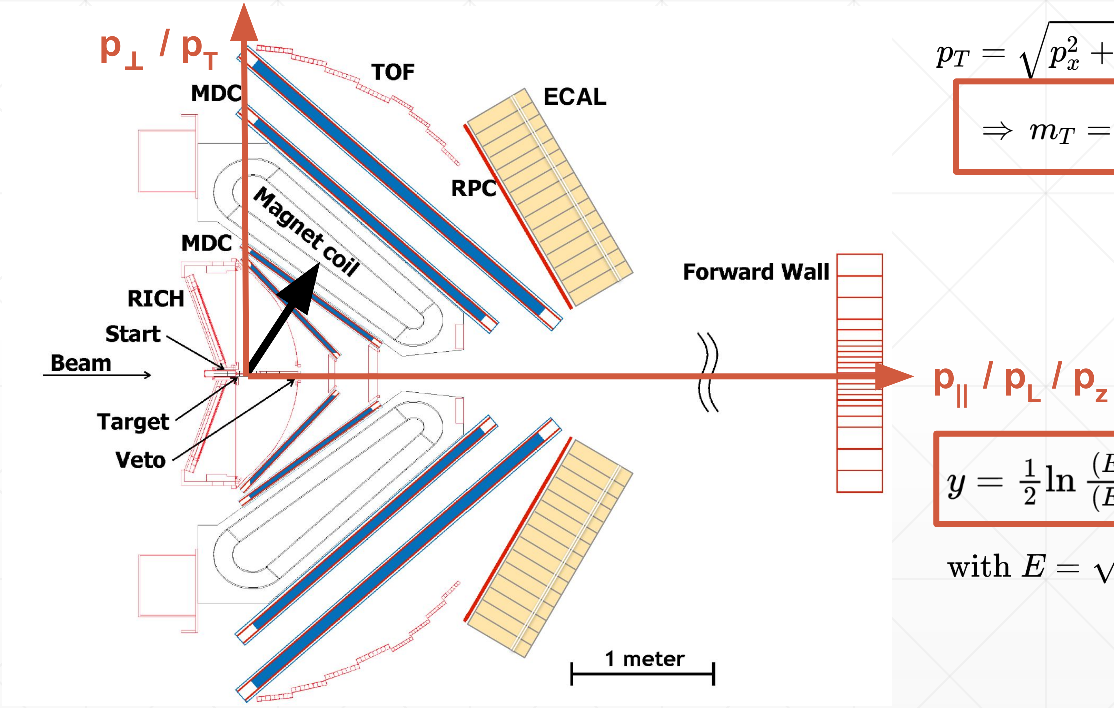




Phase Space Reconstruction



Phase Space Reconstruction

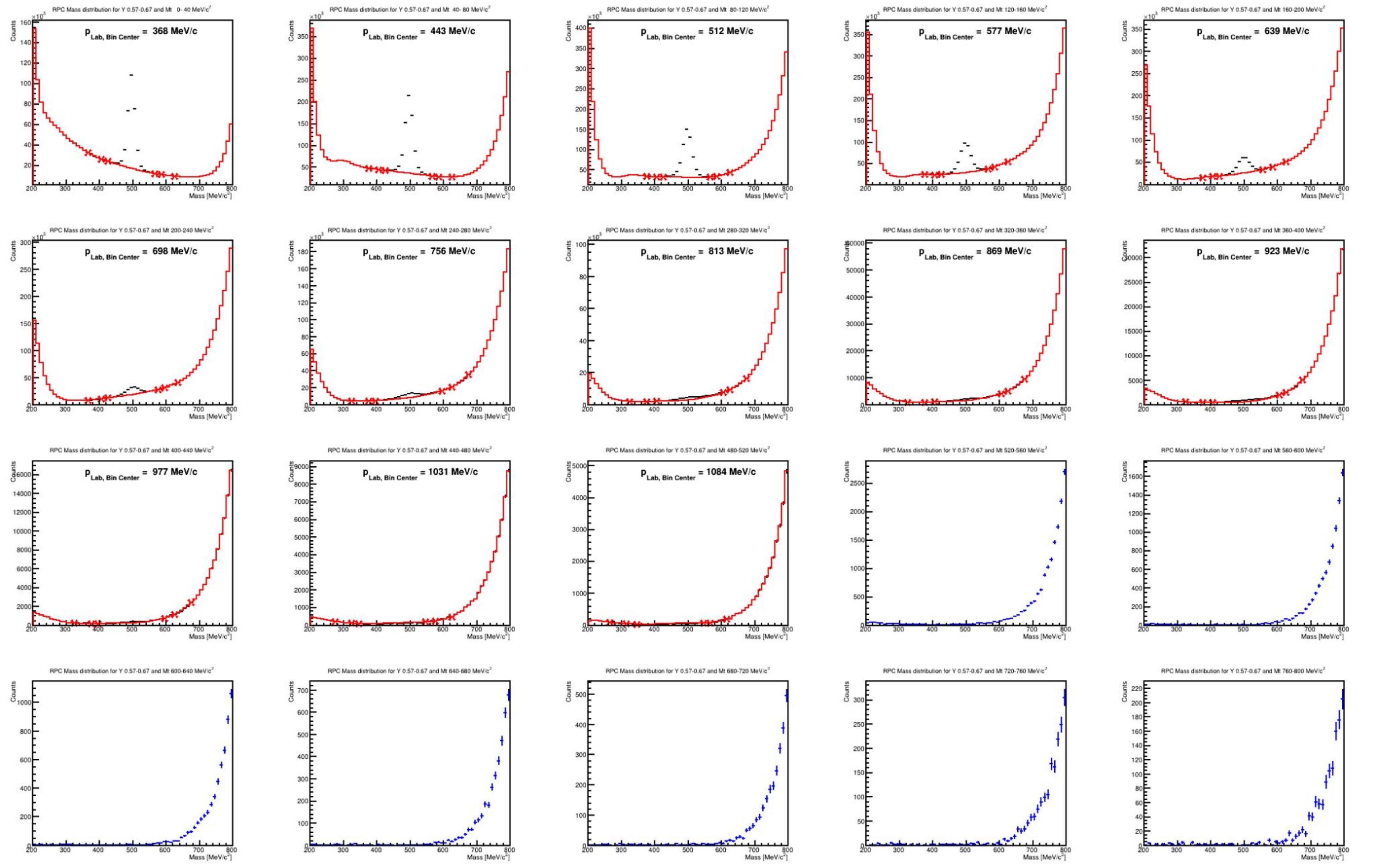


$$p_T = \sqrt{p_x^2 + p_y^2}$$

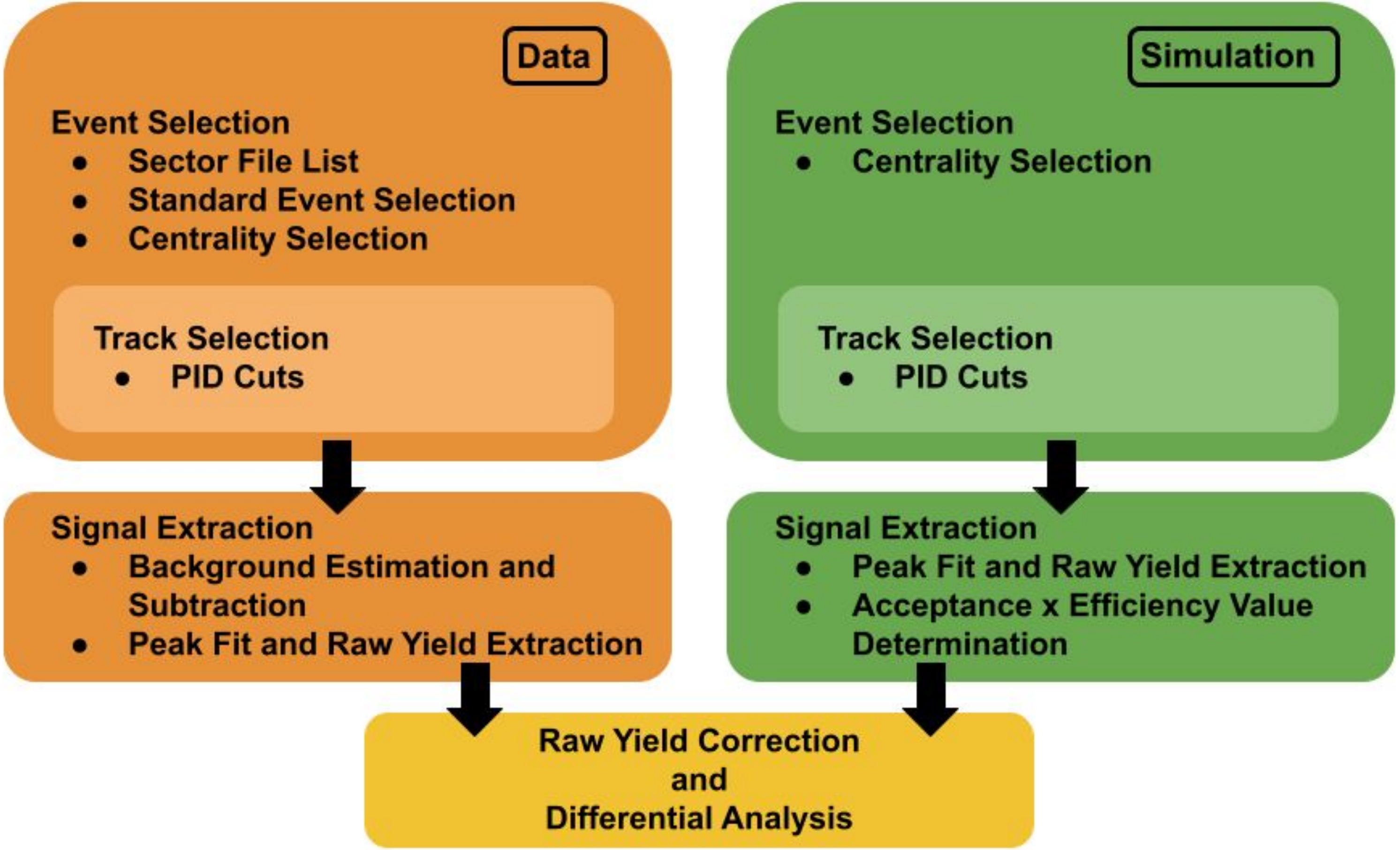
$$\Rightarrow m_T = \sqrt{m^2 + p_T^2}$$

$$y = \frac{1}{2}\ln\frac{(E+p_L)}{(E-p_L)} = \operatorname{arctanh}\left(\frac{p_L}{E}\right) = \operatorname{arctanh}(v_L)$$

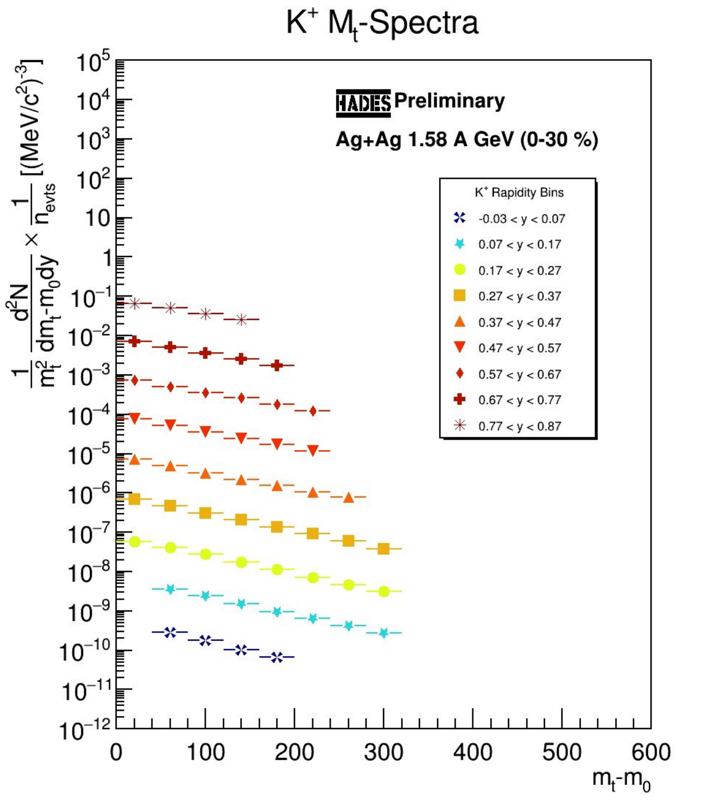
with $E = \sqrt{m^2 + \mathbf{p}^2}$ and $v_L = \dfrac{p_L}{E}$

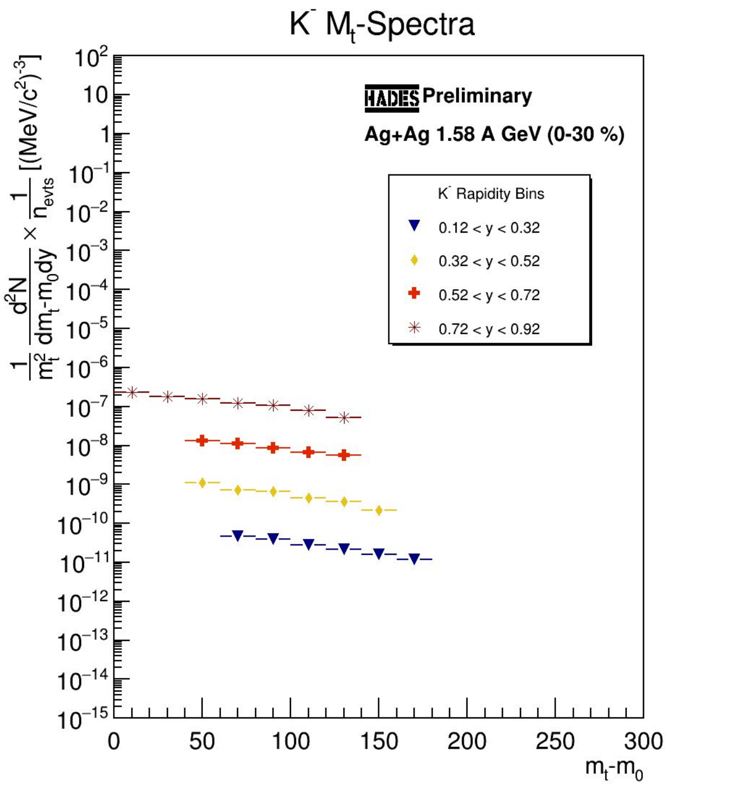


pLab, Bin Center = 368 MeV/c
pLab, Bin Center = 443 MeV/c
pLab, Bin Center = 512 MeV/c
pLab, Bin Center = 577 MeV/c
pLab, Bin Center = 639 MeV/c
pLab, Bin Center = 698 MeV/c
pLab, Bin Center = 756 MeV/c
pLab, Bin Center = 813 MeV/c
pLab, Bin Center = 869 MeV/c
pLab, Bin Center = 923 MeV/c
pLab, Bin Center = 977 MeV/c
pLab, Bin Center = 1031 MeV/c
pLab, Bin Center = 1084 MeV/c
Counts
Mass [MeV/c²]

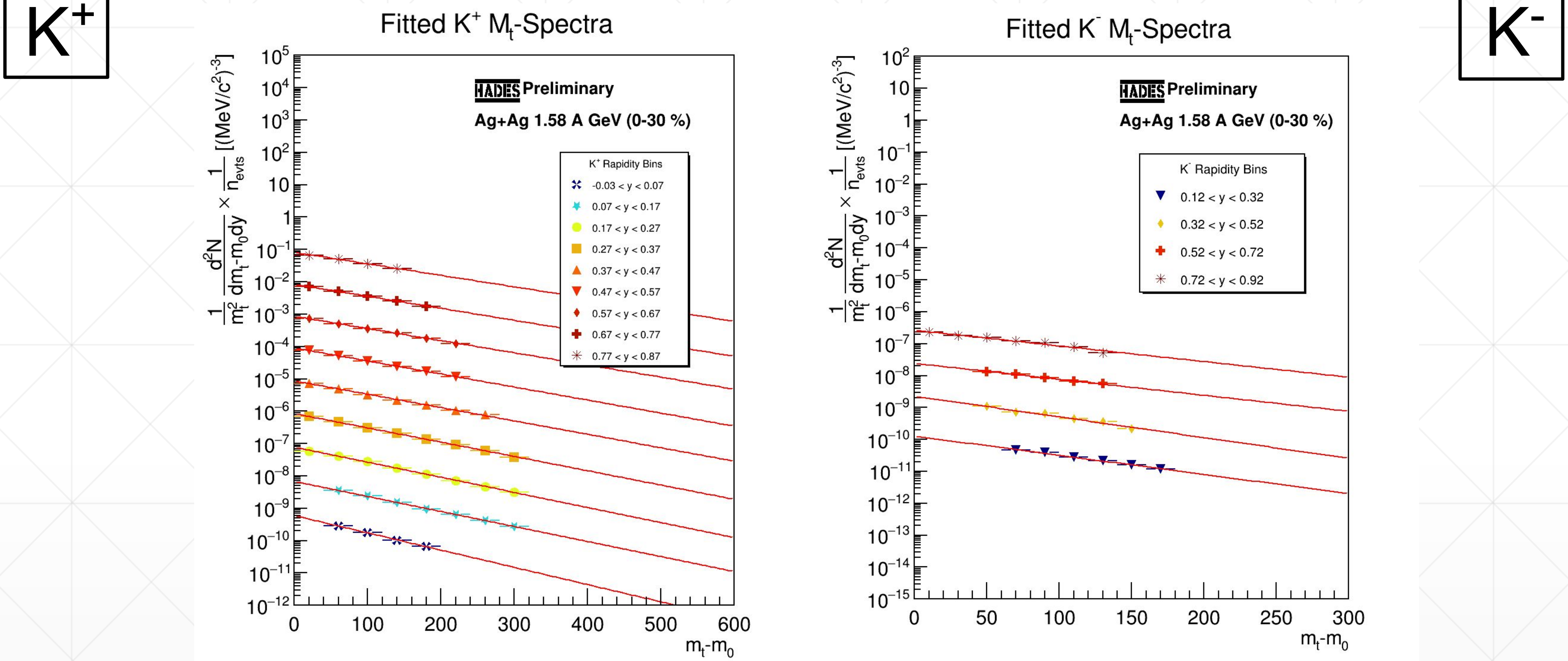

Data
Event Selection
Sector File List
Standard Event Selection
Centrality Selection
Track Selection
PID Cuts
Signal Extraction
Background Estimation and Subtraction
Peak Fit and Raw Yield Extraction
Simulation
Event Selection
Centrality Selection
Track Selection
PID Cuts
Signal Extraction
Peak Fit and Raw Yield Extraction
Acceptance x Efficiency Value Determination
Raw Yield Correction and Differential Analysis

K+


K+ Mt-Spectra
HADES Preliminary
Ag+Ag 1.58 A GeV (0-30 %)
K+ Rapidity Bins
-0.03 < y < 0.07
0.07 < y < 0.17
0.17 < y < 0.27
0.27 < y < 0.37
0.37 < y < 0.47
0.47 < y < 0.57
0.57 < y < 0.67
0.67 < y < 0.77
0.77 < y < 0.87
mt-m0


K- Mt-Spectra
HADES Preliminary
Ag+Ag 1.58 A GeV (0-30 %)
K- Rapidity Bins
0.12 < y < 0.32
0.32 < y < 0.52
0.52 < y < 0.72
0.72 < y < 0.92
mt-m0

K-



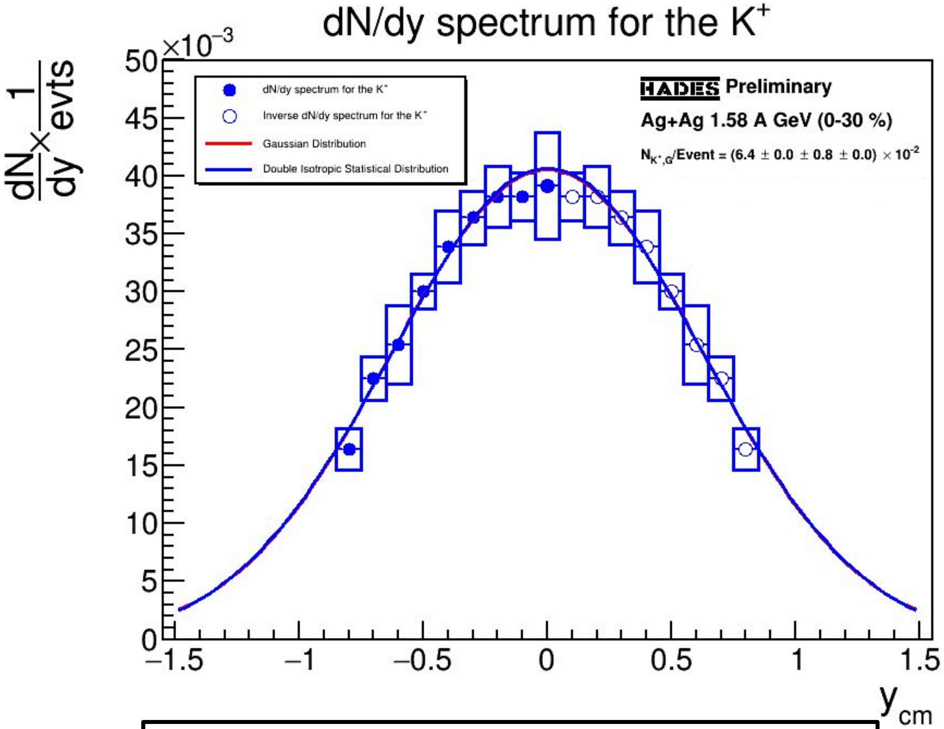
$$\left(\frac{d^2N}{dm_t dy}\right)_{DIS} = \left(\frac{d^2N}{dm_t dy}\right)_{IS}(m_t, y-\eta) + \left(\frac{d^2N}{dm_t dy}\right)_{IS}(m_t, y+\eta)$$

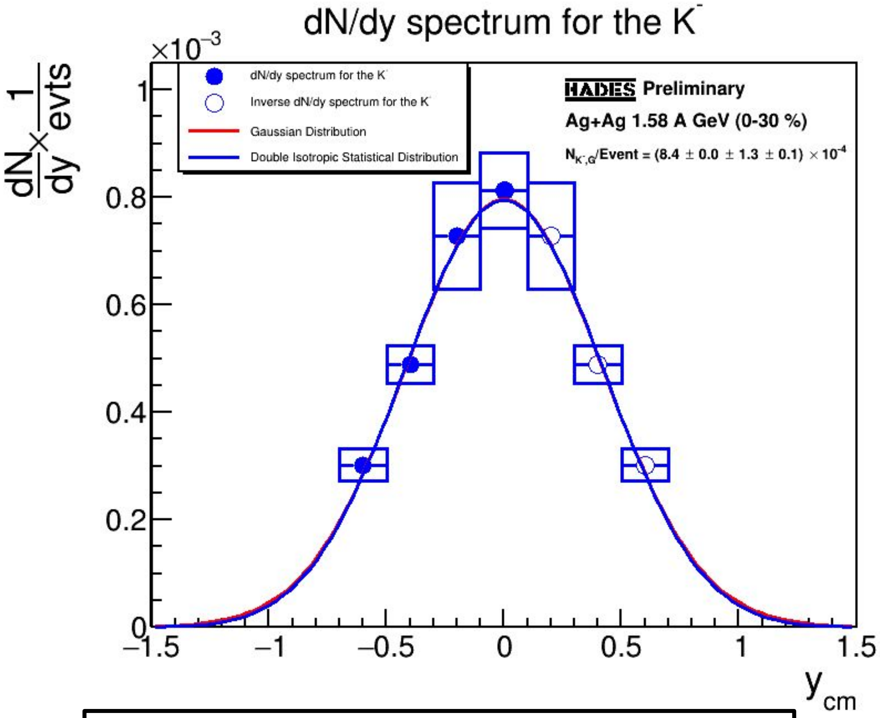
T_{eff} = (120.5 ± 0.1 ± 8.9) MeV

T_{eff} = (84.9 ± 0.1 ± 9.4) MeV

→ Smaller inverse slope parameter for K^-

K^+ | K^-

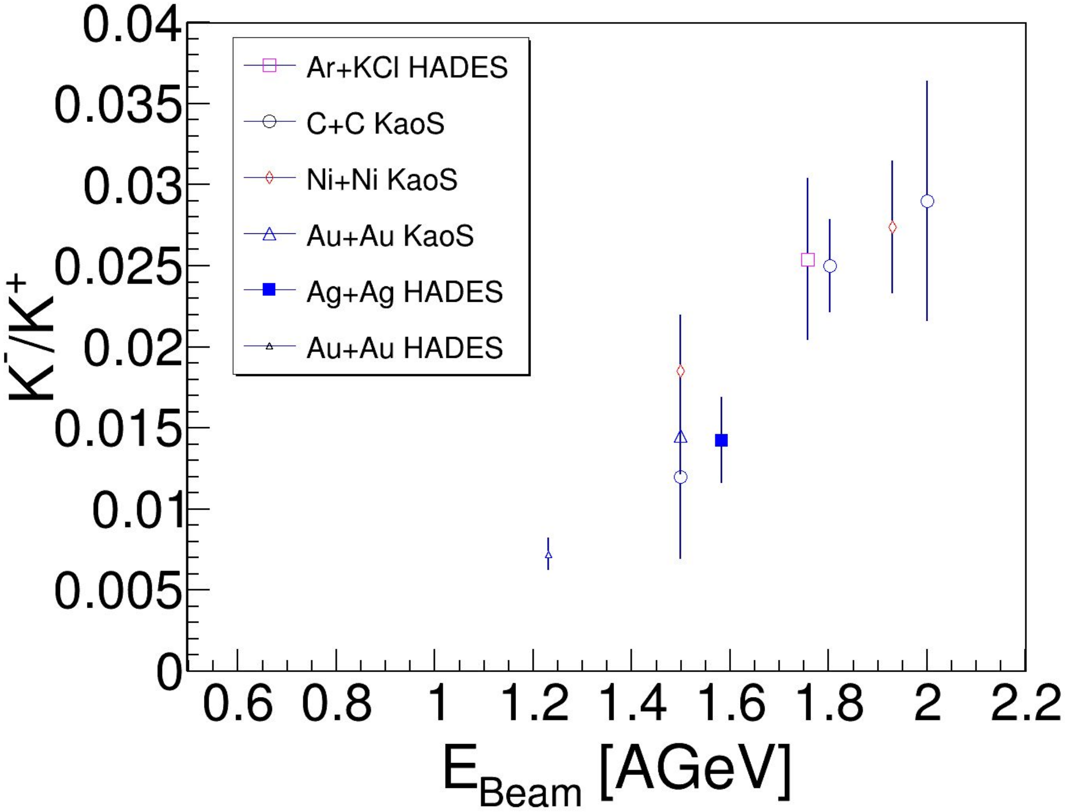




N_{K+} /Event = (6.4 ± 0.0 ± 0.8 ± 0.0) x 10^{-2}

N_{K-} /Event = (8.4 ± 0.0 ± 1.3 ± 0.1) x 10^{-4}

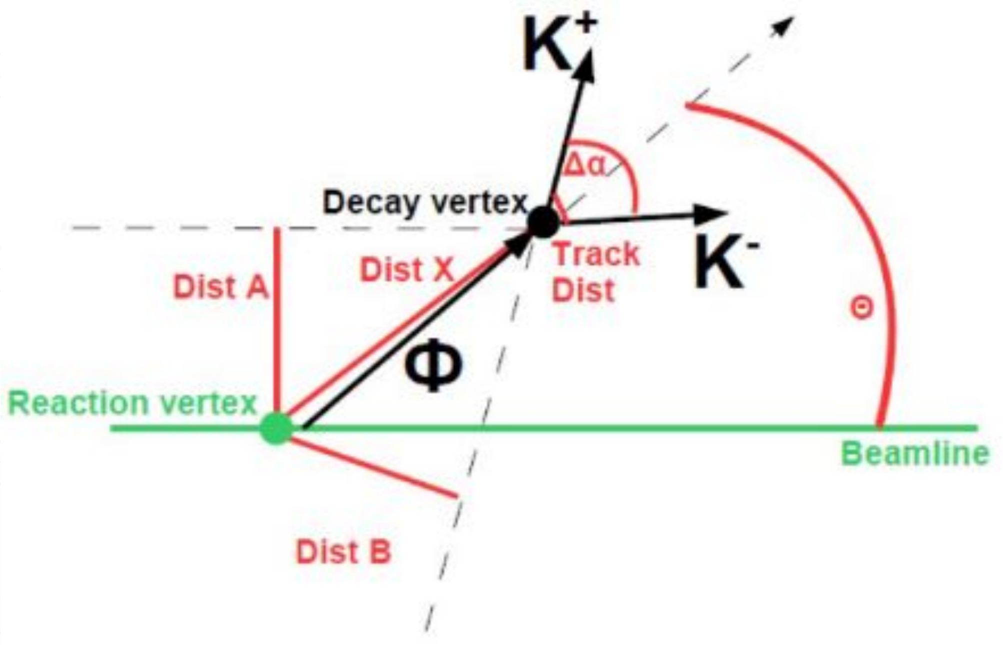
Errors: yield ± stat. err. ± sys. err. ± extrapol. err.



- K^-/K^+ ratio in accordance with world data

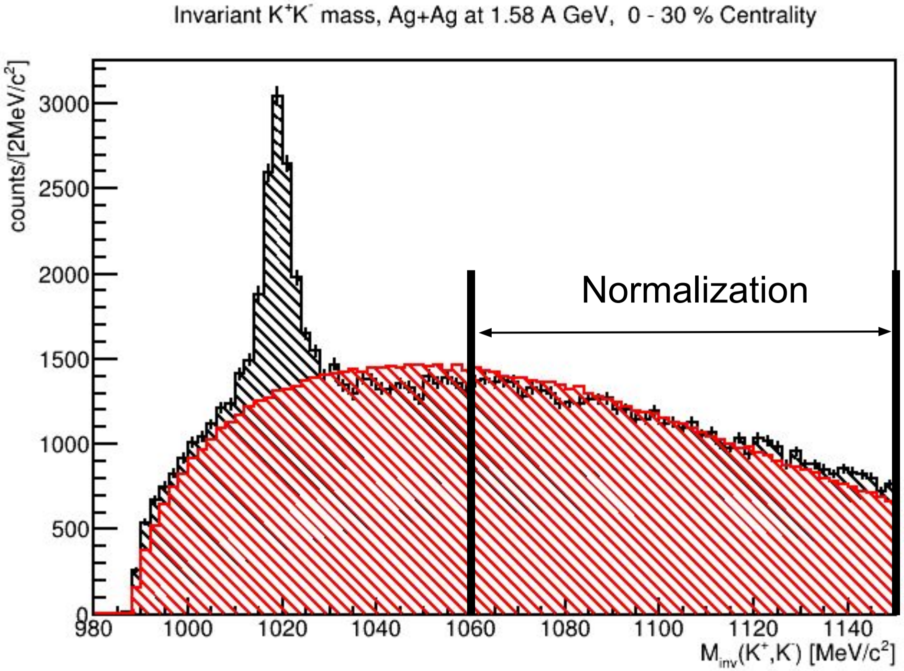
- *A. Forster, F. Uhlig, I. Bottcher, D. Brill, M. Debowski, F. Dohrmann, E. Grosse, P. Koczon, B. Kohlmeyer and S. Lang, et al., Phys. Rev. C* ***75*** *(2007), 024906*
- *HADES Collaboration - G. Agakishiev, et al., Phys. Rev. C* ***80*** *(2009), 025209*
- *HADES Collaboration - H. Schuldes, Nucl. Phys. A* ***967*** *(2017), 804-807*

ϕ

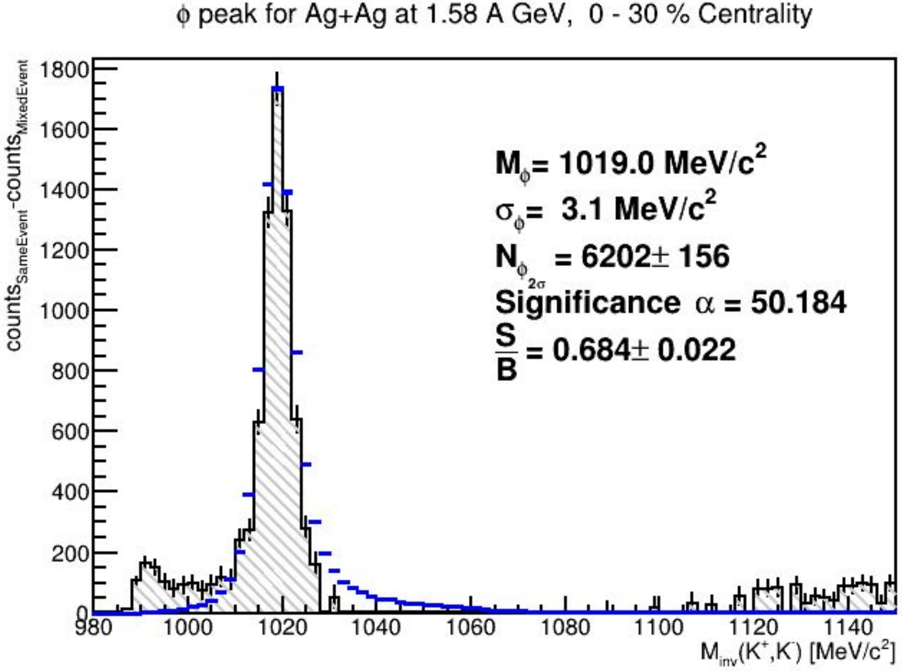


K+
Δα
Decay vertex
K-
Track Dist
Dist X
Dist A
Φ
Θ
Reaction vertex
Beamline
Dist B

ϕ

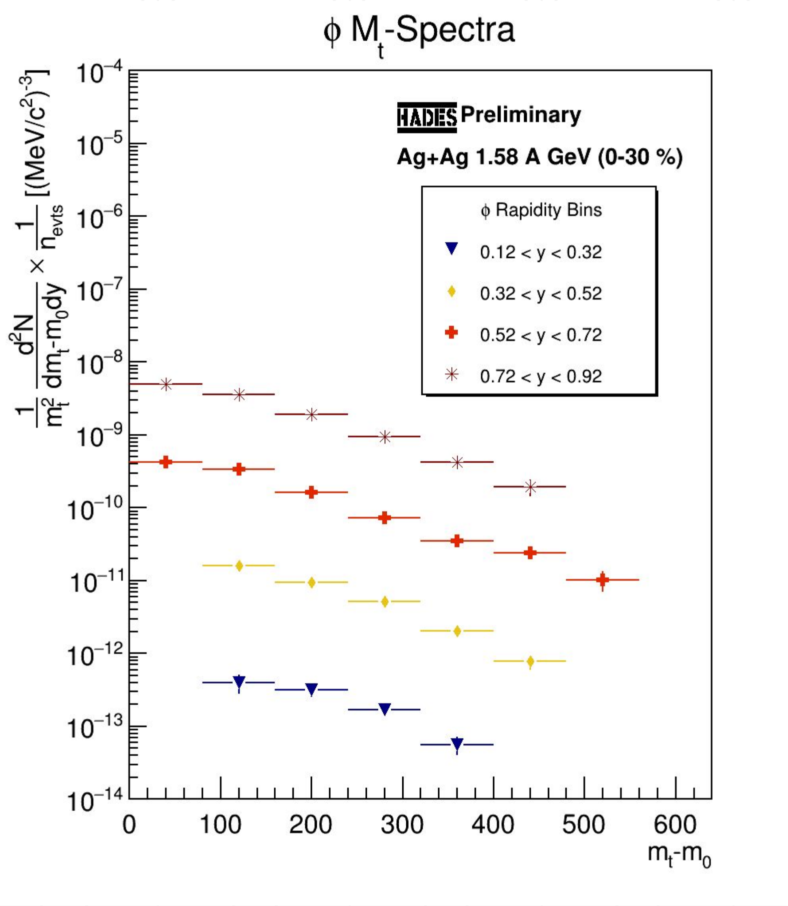


Invariant K⁺K⁻ mass, Ag+Ag at 1.58 A GeV, 0 - 30 % Centrality
counts/[2MeV/c²]
Normalization
M_inv(K⁺,K⁻) [MeV/c²]



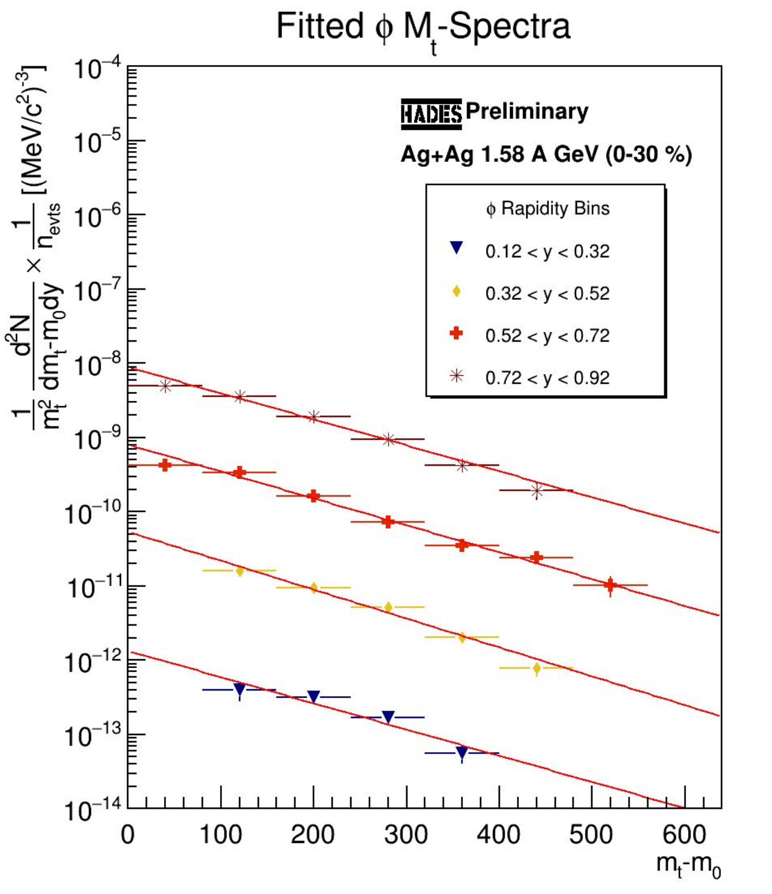
ϕ peak for Ag+Ag at 1.58 A GeV, 0 - 30 % Centrality
counts_SameEvent - counts_MixedEvent
M_ϕ = 1019.0 MeV/c²
σ_ϕ = 3.1 MeV/c²
N_ϕ_2σ = 6202± 156
Significance α = 50.184
S/B = 0.684± 0.022
M_inv(K⁺,K⁻) [MeV/c²]

ϕ

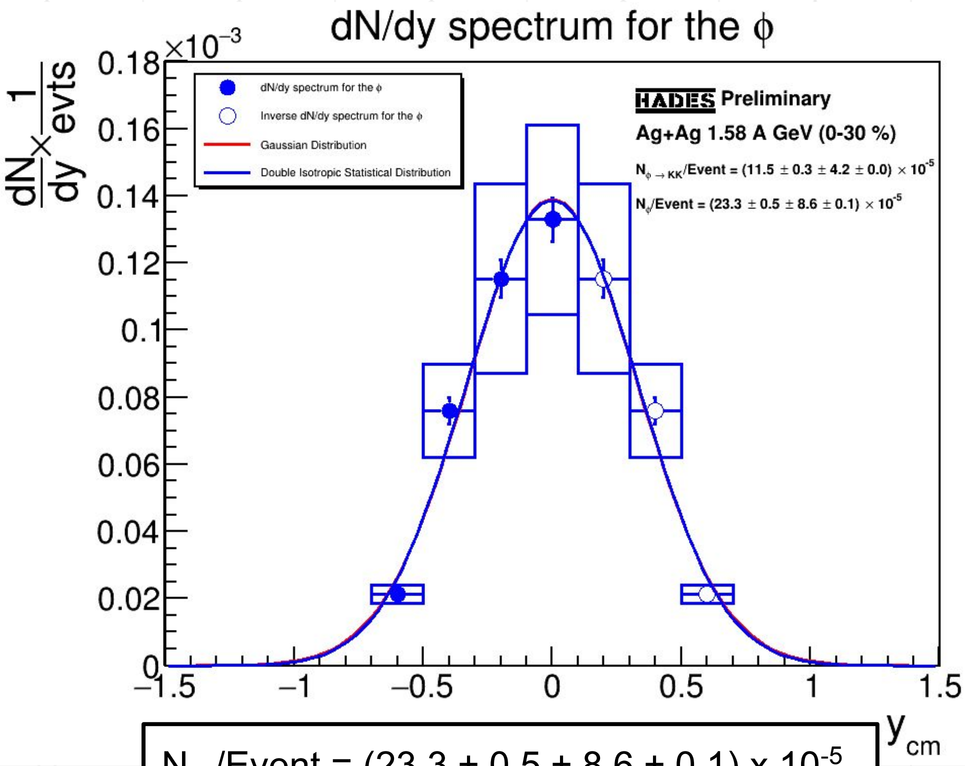


φ M_t-Spectra
HADES Preliminary
Ag+Ag 1.58 A GeV (0-30 %)
φ Rapidity Bins
0.12 < y < 0.32
0.32 < y < 0.52
0.52 < y < 0.72
0.72 < y < 0.92
m_t-m_0

ϕ



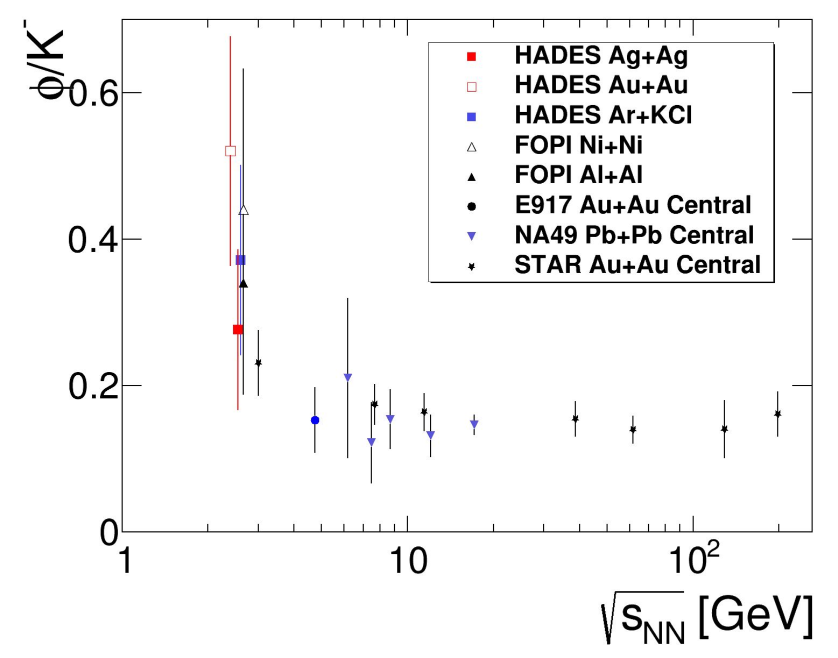
T_{eff} = (122.9 ± 2.9 ± 1.0) MeV

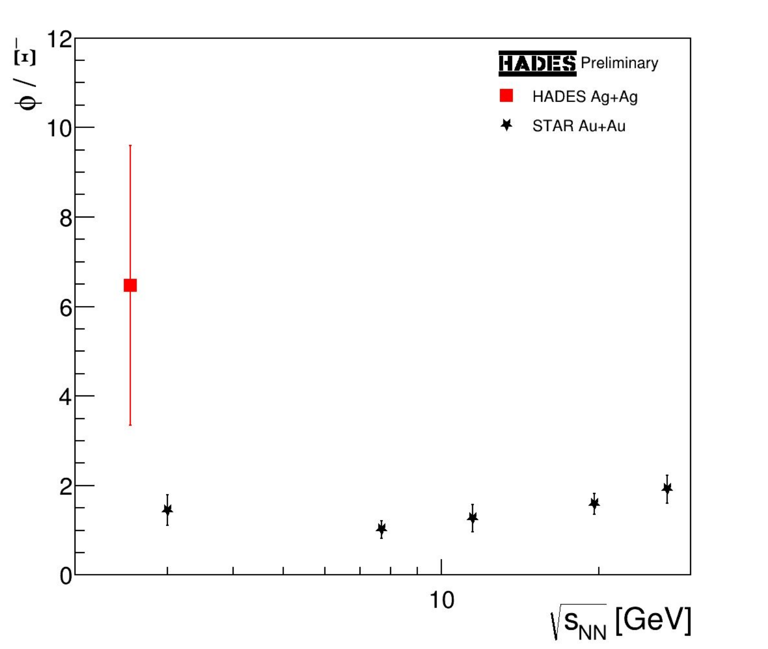


N_{ϕ} /Event = (23.3 ± 0.5 ± 8.6 ± 0.1) x 10^{-5}

Errors: yield ± stat. err. ± sys. err. ± extrapol. err.

ϕ to K⁻ and ϕ to Ξ^- Ratios

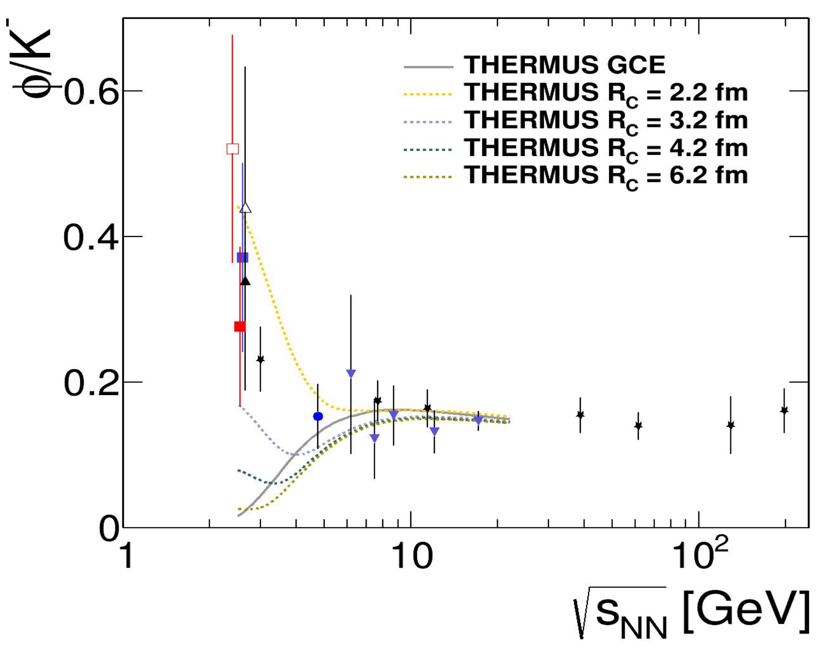


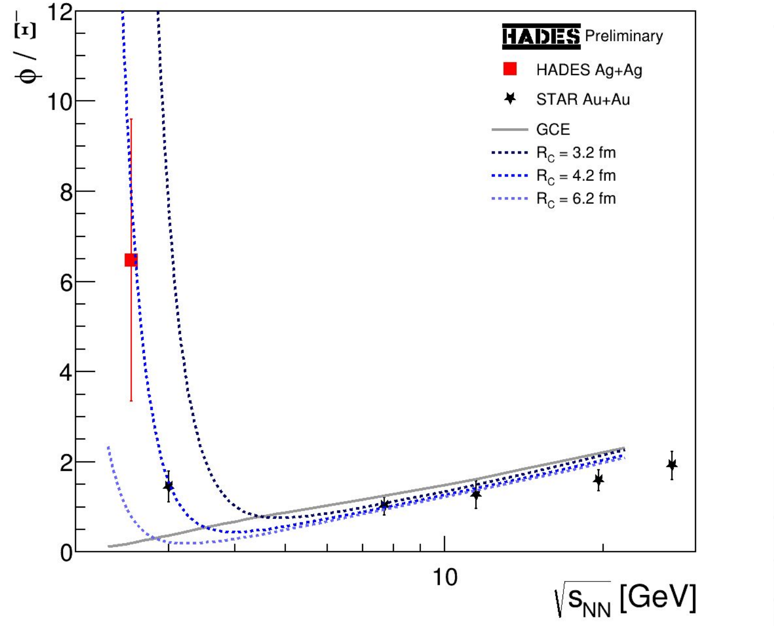


[1] *G. Agakishiev et al. , DOI: 10.1103/PhysRevC.80.025209*

[2] *M.S. Abdallah et al., arXiv:2108.00924v4*

Comparison to Statistical Hadronization Model [2]





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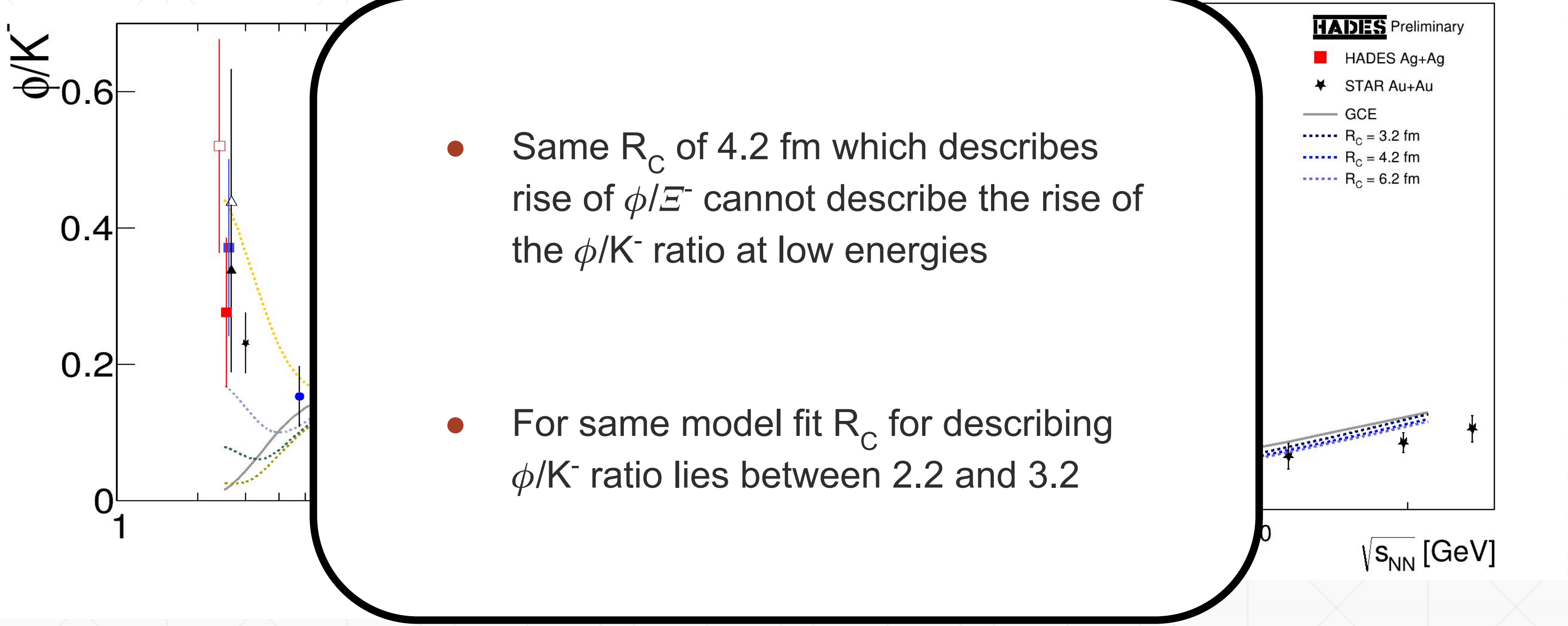
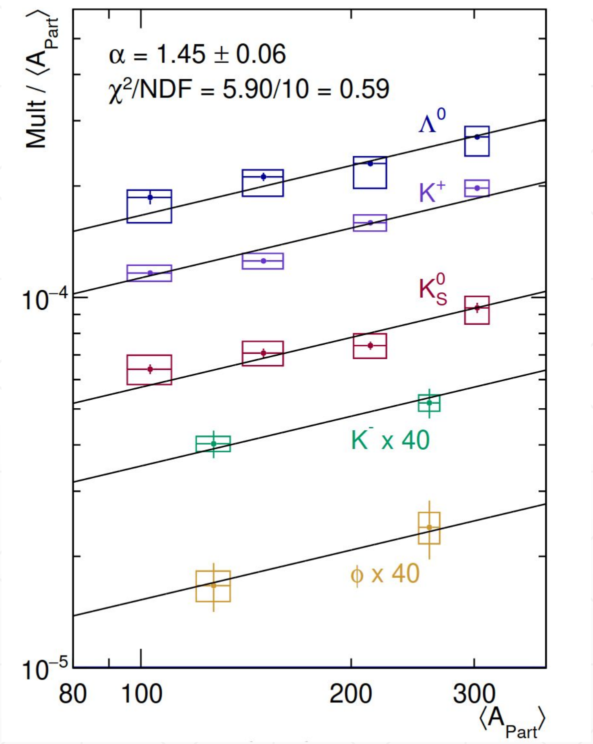


- Same R_C of 4.2 fm which describes rise of ϕ/Ξ^- cannot describe the rise of the ϕ/K^- ratio at low energies
- For same model fit R_C for describing ϕ/K^- ratio lies between 2.2 and 3.2

[1] *G. Agakishiev et al. , DOI:* 10.1103/PhysRevC.80.025209

[2] *M.S. Abdallah et al.,* arXiv:2108.00924v4

Au+Au @ 1.23 A GeV



HADES Collaboration - S. Spies,
DOI: 10.1088/1742-6596/1667/1/012041

- Different production thresholds

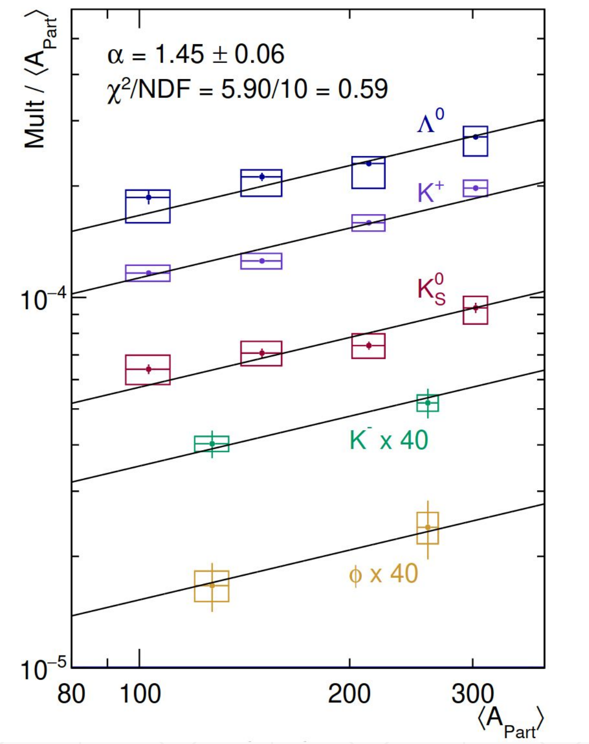
  but

  universal scaling with participant number

- χ^2 derived only from statistical errors

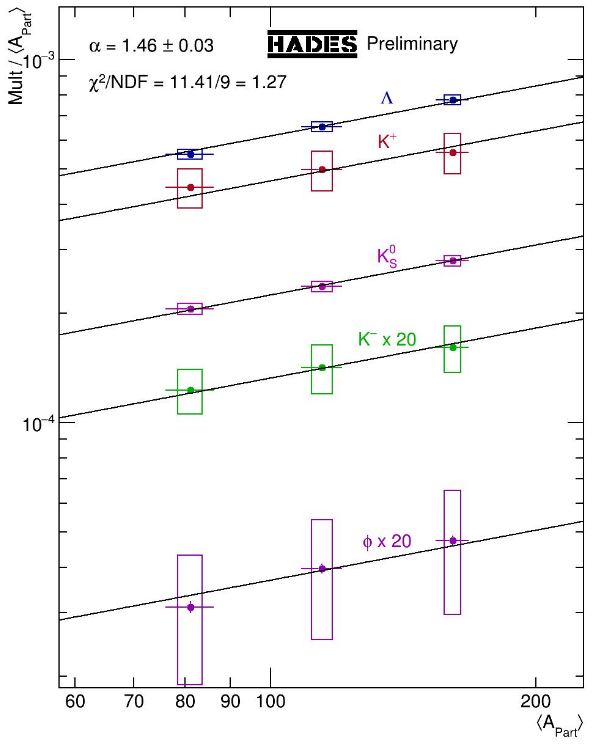
$$NN \rightarrow NK^+\Lambda \qquad (\sqrt{s_{NN}} = 2.55\,\mathrm{GeV})$$
$$NN \rightarrow NNK^+K^- \qquad (\sqrt{s_{NN}} = 2.86\,\mathrm{GeV})$$
$$NN \rightarrow NN\phi \qquad (\sqrt{s_{NN}} = 2.90\,\mathrm{GeV})$$

Au+Au @ 1.23 A GeV



HADES Collaboration - S. Spies,
DOI: 10.1088/1742-6596/1667/1/012041

Ag+Ag @ 1.58 A GeV



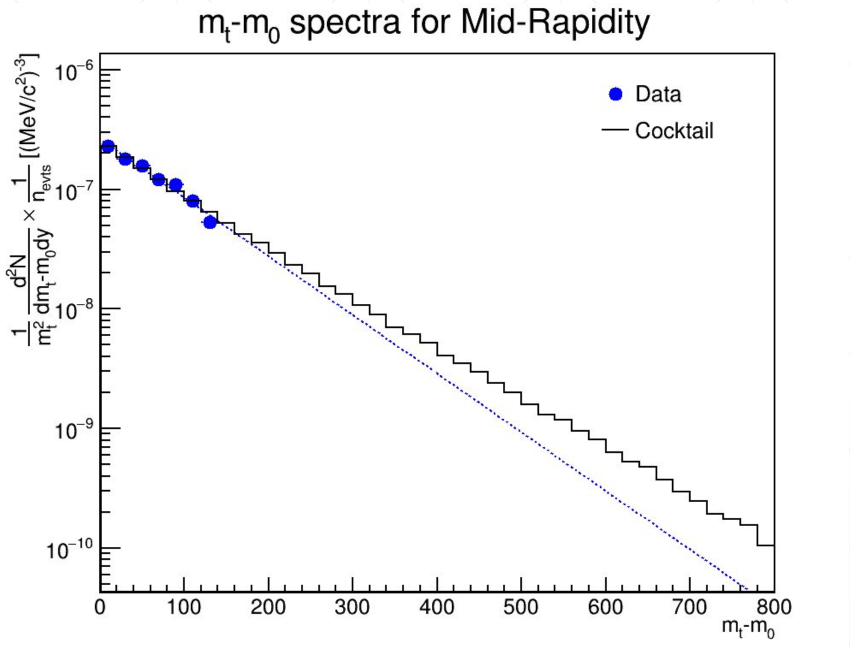
- Different production thresholds

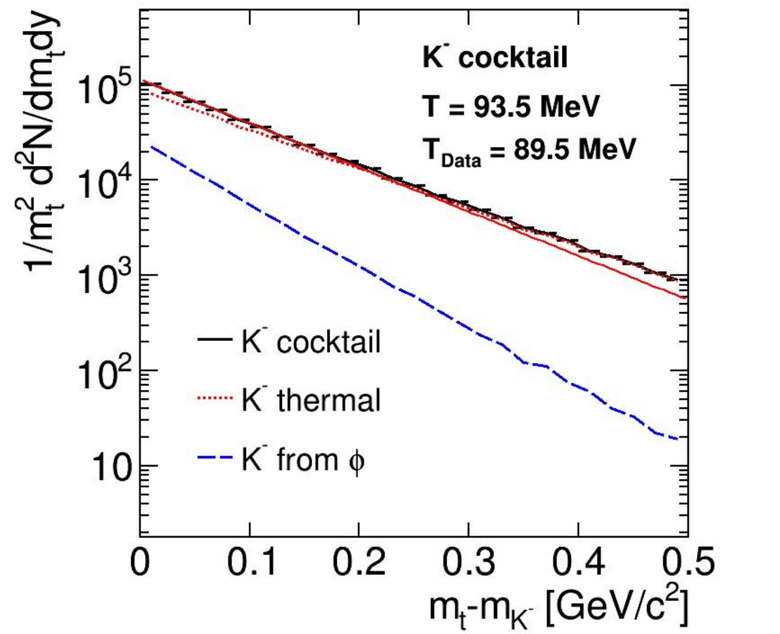
  but

  universal scaling with participant number
- χ^2 derived only from statistical errors
- Both cases consistent with slope of 1.45 ± 0.06 (stat.)

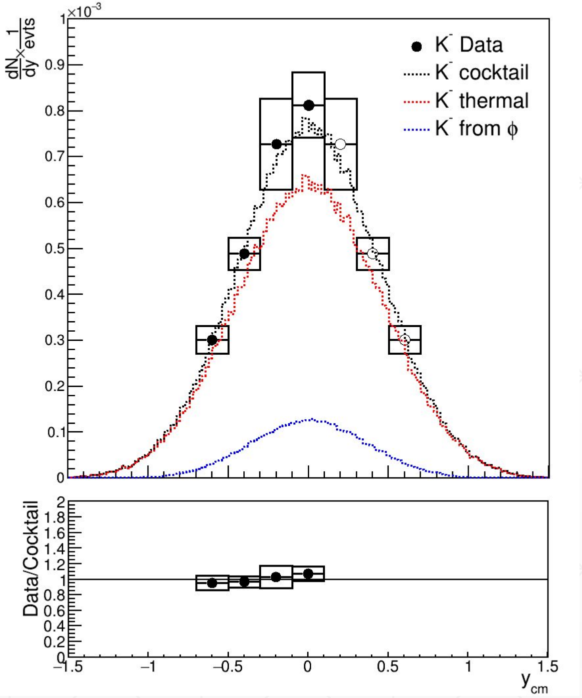
$$NN \to NK^+\Lambda \qquad (\sqrt{s_{NN}} = 2.55\,\text{GeV})$$
$$NN \to NNK^+K^- \qquad (\sqrt{s_{NN}} = 2.86\,\text{GeV})$$
$$NN \to NN\phi \qquad (\sqrt{s_{NN}} = 2.90\,\text{GeV})$$

How to understand the K⁻ slope?





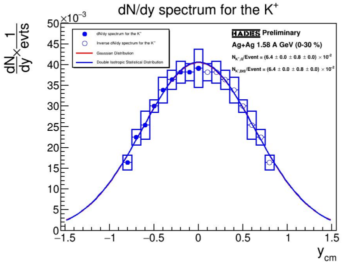
How to understand the K^- slope?

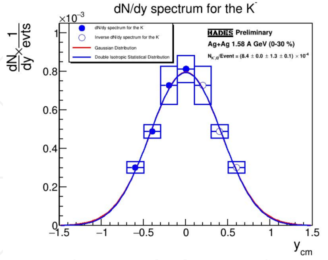


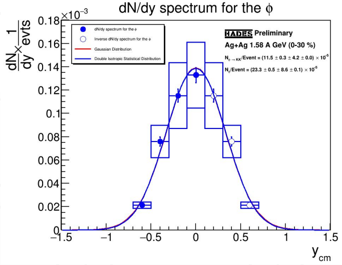
- ➢ Not related to different coupling of K^+ and K^- to baryons

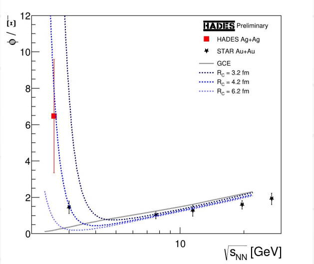
Summary

- Preliminary results on charged Kaons and $\phi(1020) \rightarrow K^{+}K^{-}$ from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55\,\mathrm{GeV}$ presented
- Particle ratio trends in low energy regime consistent with STAR BES data
- Observation by STAR confirmed: ϕ/K^{-} and ϕ/Ξ^{-} cannot be described simultaneously by the same R_C
- Investigation of $\phi(1020)$ feed-down effect on K^{-} spectra (PLUTO K^{-} from ϕ vs thermal K^{-})





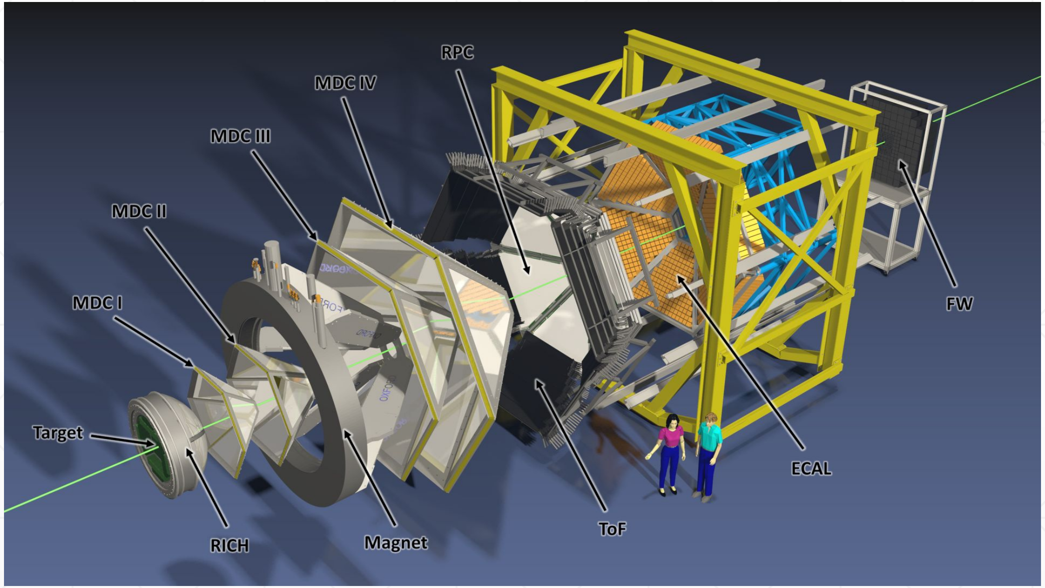


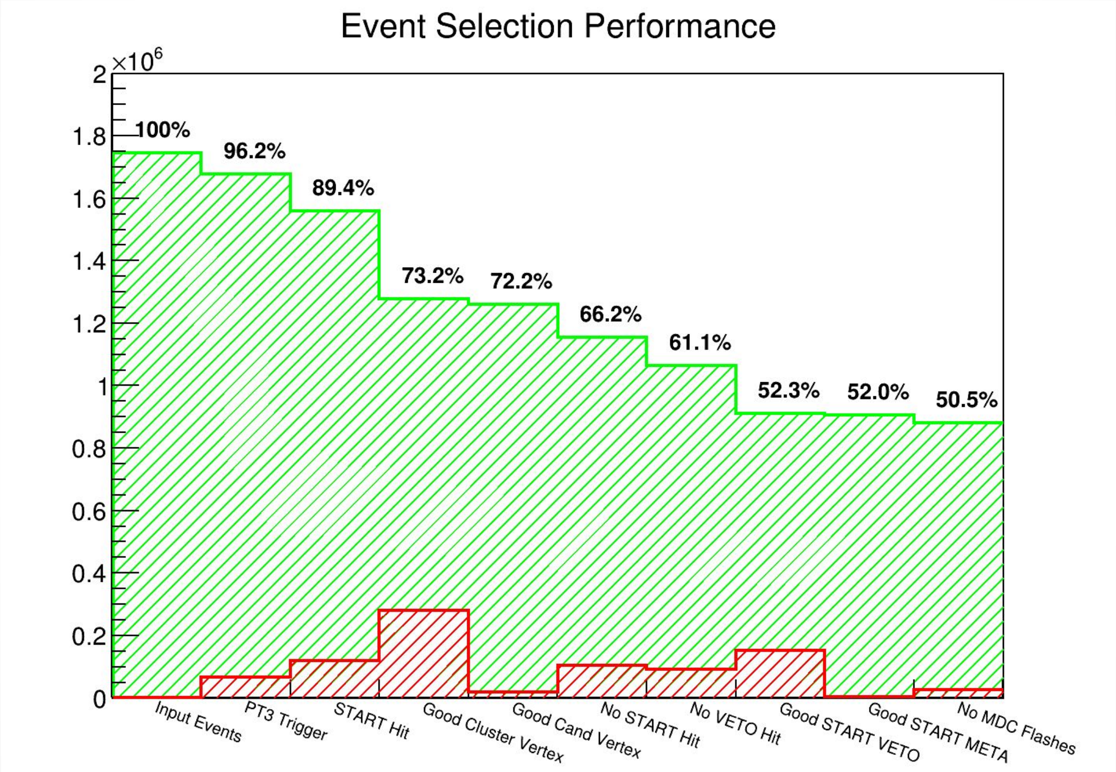


Backup

Experimental Setup

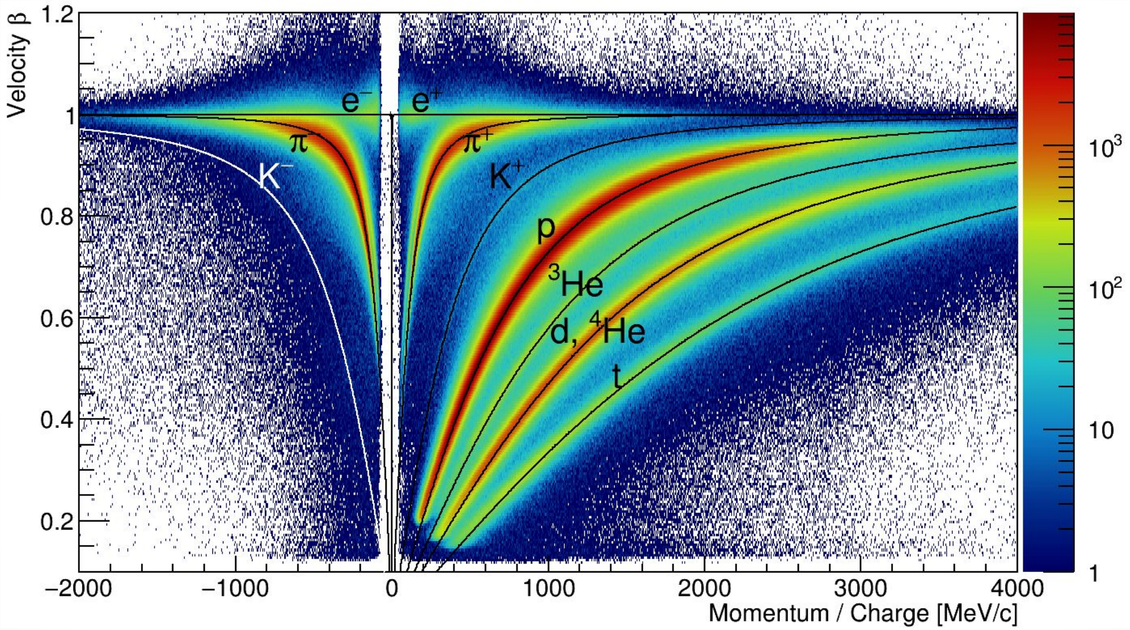
- Fixed target experiment at SIS18 (GSI)
- Magnet spectrometer
- Mini-Drift-Chambers (MDCs) and time of flight walls (RPC and TOF) for tracking of charged hadrons
- Forward hodoscope for spectator detection
- Azimuthal and polar coverage between 18° and 85°





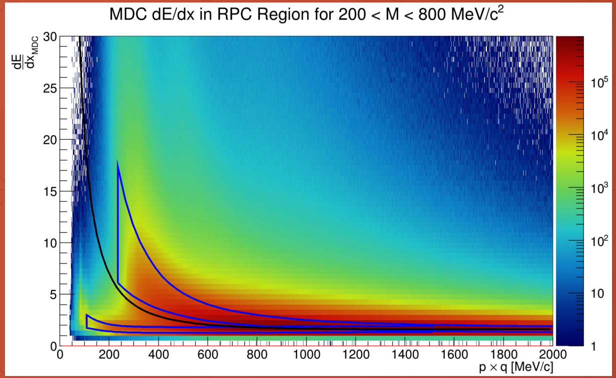
Event Cleaning

- Removing contaminations from overlapping Ag+Ag or from Ag+C events
- Events with systematic track reconstruction problems removed



PID

- Primarily via momentum and velocity
- Additional selection via energy-loss



Fitting - Double Isotropic Statistical Model (M_t)

- Isotropic Statistical Model assumes particle emission from thermalized, spherically symmetric source and has direct physical interpretation

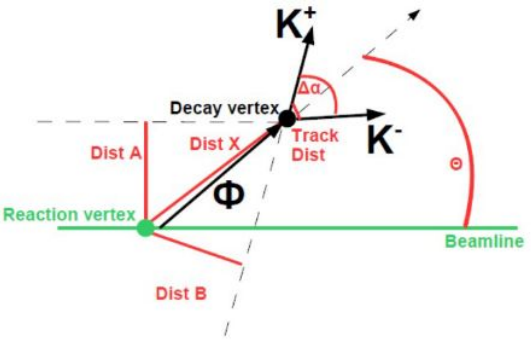
$$\left(\frac{d^2N}{dm_t dy}\right)_{IS} = 2\pi \cdot C \cdot m_t^2 \cdot \cosh(y) \cdot e^{-\frac{m_t \cosh(y)}{T_{Eff}}}$$

- As the beam ions possess an initial momentum, the spherical symmetry in longitudinal direction is not a sufficient description
  - Two isotropic statistical sources are placed at $\pm\eta$ around the center of mass origin (hence Double Isotropic Statistical Model)

$$\left(\frac{d^2N}{dm_t dy}\right)_{DIS} = \left(\frac{d^2N}{dm_t dy}\right)_{IS}(m_t, y-\eta) + \left(\frac{d^2N}{dm_t dy}\right)_{IS}(m_t, y+\eta)$$

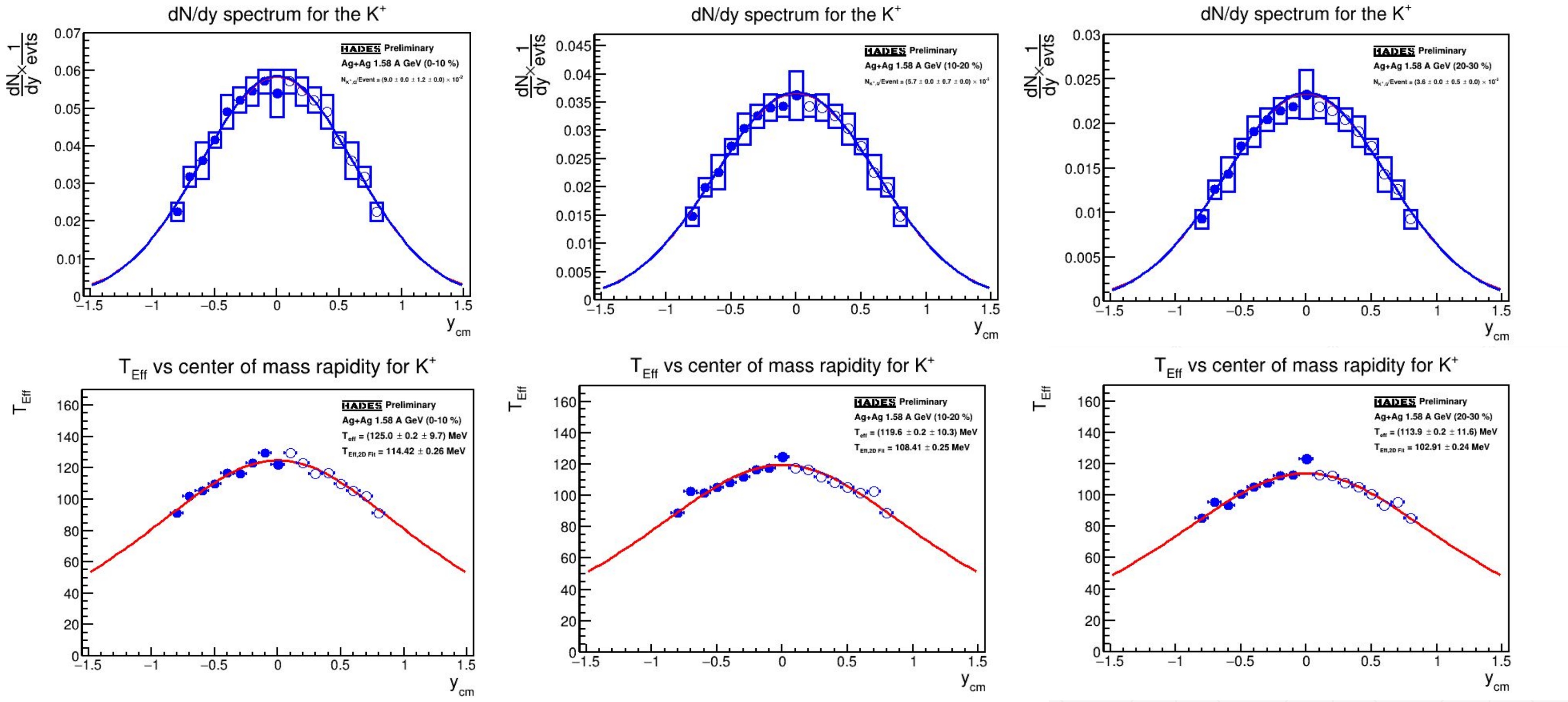
Cuts for single particle analysis	K^+	K^-
Dataset	gen5	
MetaQA	< 3.	
χ^2_{RK}	< 200.	
TOF dE/dx	yes	
MDC dE/dx	yes	
Acc x Eff Correction	UrQMD + PLUTO	
Acc x Eff Correction Cut-Off	1 %	
Maximum (M_t-M_0) [MeV/c^2]	800	
(M_t-M_0) Bin-Width [MeV/c^2]	40	20
y-Range	-0.03-1.97	-0.08-1.92
y Bin-Width	0.1	0.2
Lower Momentum Cut [MeV/c]	200	
Sectors	1-6	1-4

Cuts for ϕ analysis	$\boldsymbol{\phi}$
VerDistA/B/X	< 10 [mm]
Opening Angle Daughters	5° < α < 70°
(M_t-M_0) Maximum [MeV/c^2]	800
(M_t-M_0) Bin-Width [MeV/c^2]	20
y-Range	-0.08 - 1.92
y Bin-Width	0.2
Acc x Eff Correction	UrQMD + PLUTO

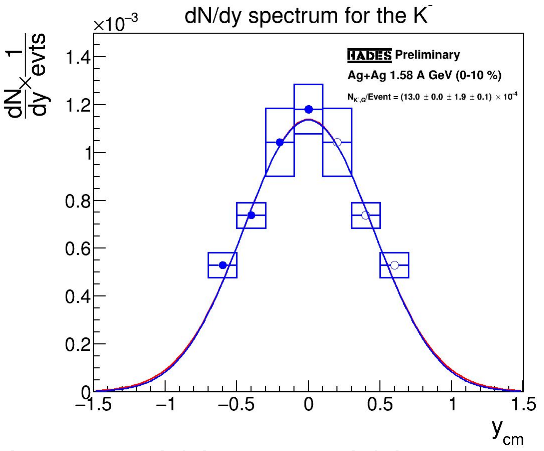


Cuts for ϕ analysis (daughters)	**K^+**	**K^-**
Dataset	gen5	
MetaQA	< 3.	
Mass Cut	430-540 MeV/c^2	
Charge	+1	-1
χ^2_{RK}	< 200.	
TOF upper momentum cut	800 MeV/c	
RPC upper momentum cut	1000 MeV/c	800 MeV/c
Lower momentum cut	150 MeV/c	
TOF dE/dx	yes	
MDC dE/dx	**no (only for syst. error estimation)**	
Acc x Eff Correction Cut-Off	1 %	

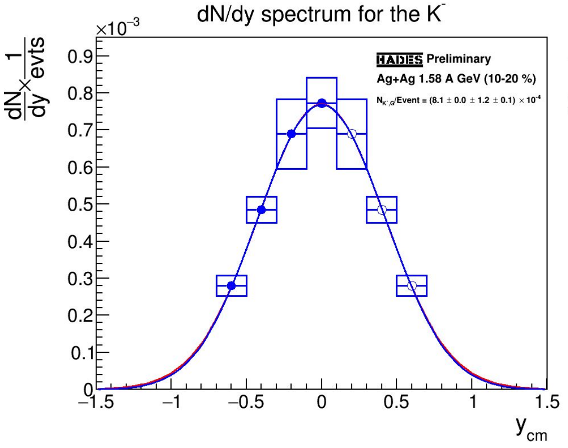
K+


dN/dy spectrum for the K+
dN/dy × 1/evts
y_cm
HADES Preliminary
Ag+Ag 1.58 A GeV (0-10 %)
N_K+,G/Event = (9.0 ± 0.0 ± 1.2 ± 0.0) × 10^-2
Ag+Ag 1.58 A GeV (10-20 %)
N_K+,G/Event = (5.7 ± 0.0 ± 0.7 ± 0.0) × 10^-2
Ag+Ag 1.58 A GeV (20-30 %)
N_K+,G/Event = (3.6 ± 0.0 ± 0.5 ± 0.0) × 10^-2
T_Eff vs center of mass rapidity for K+
T_Eff
T_eff = (125.0 ± 0.2 ± 9.7) MeV
T_Eff,2D Fit = 114.42 ± 0.26 MeV
T_eff = (119.6 ± 0.2 ± 10.3) MeV
T_Eff,2D Fit = 108.41 ± 0.25 MeV
T_eff = (113.9 ± 0.2 ± 11.6) MeV
T_Eff,2D Fit = 102.91 ± 0.24 MeV

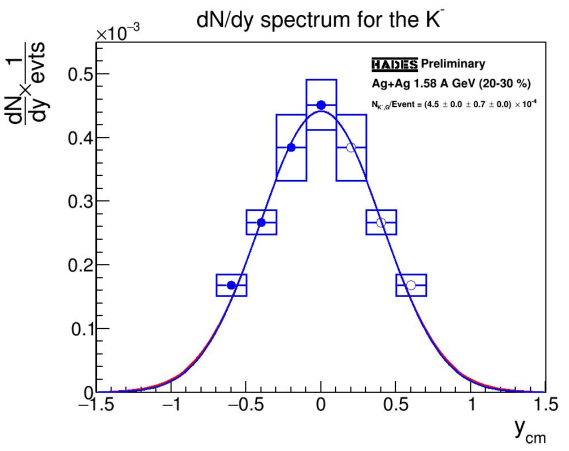
K^-



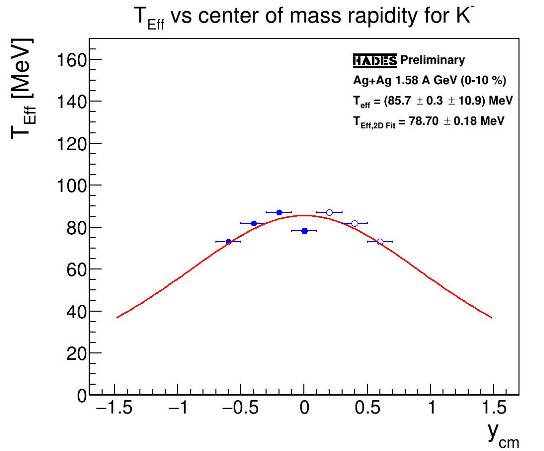
dN/dy spectrum for the K-
HADES Preliminary
Ag+Ag 1.58 A GeV (0-10 %)
N_K-,0/Event = (13.0 ± 0.0 ± 1.9 ± 0.1) × 10^-4
dN/dy × 1/evts
y_cm



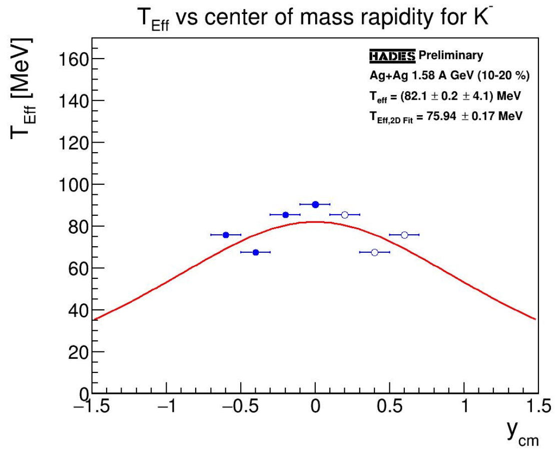
dN/dy spectrum for the K-
HADES Preliminary
Ag+Ag 1.58 A GeV (10-20 %)
N_K-,0/Event = (8.1 ± 0.0 ± 1.2 ± 0.1) × 10^-4
dN/dy × 1/evts
y_cm



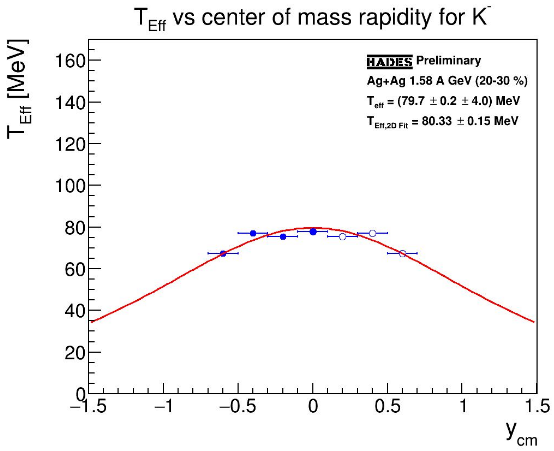
dN/dy spectrum for the K-
HADES Preliminary
Ag+Ag 1.58 A GeV (20-30 %)
N_K-,0/Event = (4.5 ± 0.0 ± 0.7 ± 0.0) × 10^-4
dN/dy × 1/evts
y_cm



T_Eff vs center of mass rapidity for K-
HADES Preliminary
Ag+Ag 1.58 A GeV (0-10 %)
T_eff = (85.7 ± 0.3 ± 10.9) MeV
T_Eff,2D Fit = 78.70 ± 0.18 MeV
T_Eff [MeV]
y_cm

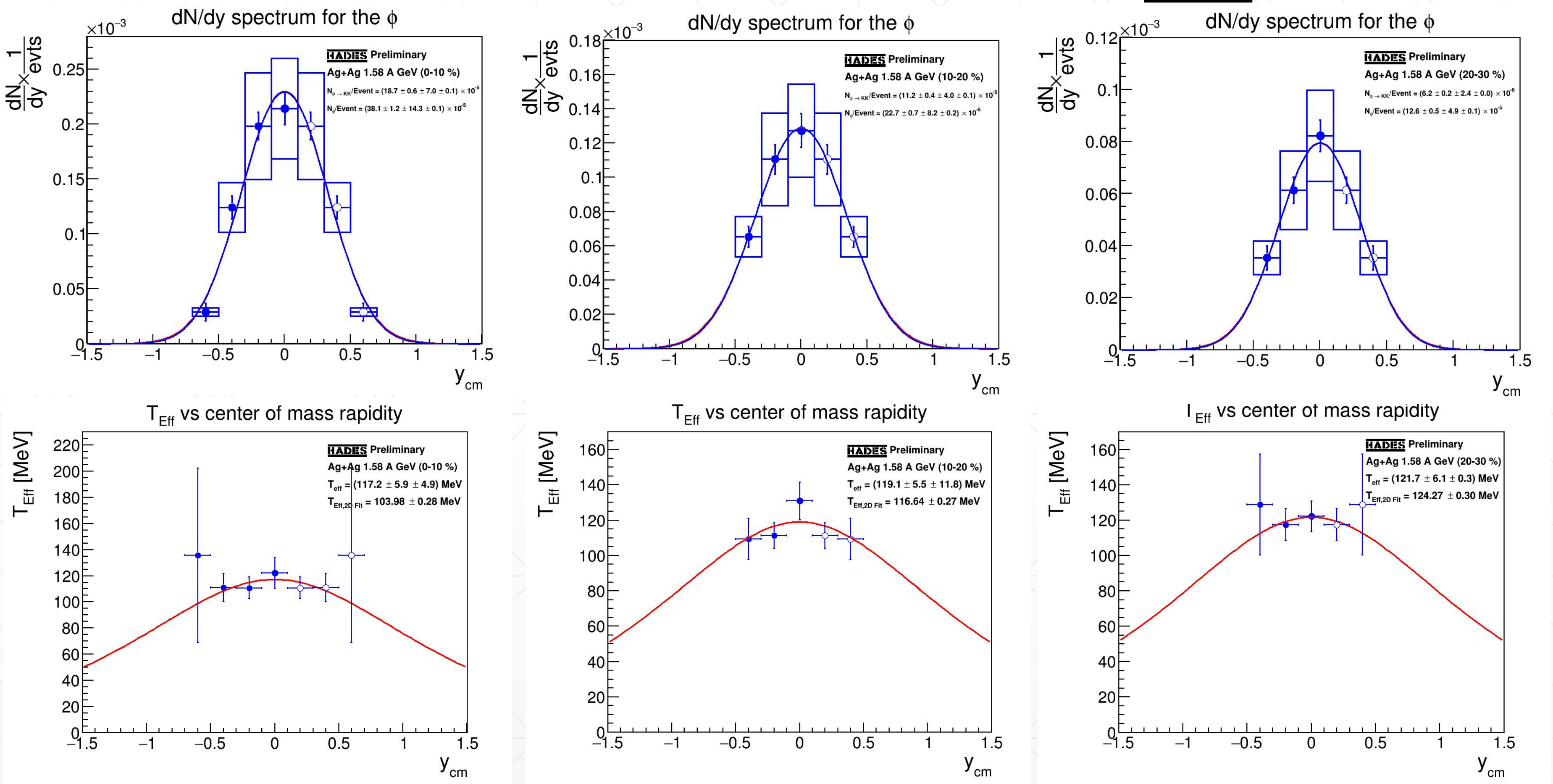


T_Eff vs center of mass rapidity for K-
HADES Preliminary
Ag+Ag 1.58 A GeV (10-20 %)
T_eff = (82.1 ± 0.2 ± 4.1) MeV
T_Eff,2D Fit = 75.94 ± 0.17 MeV
T_Eff [MeV]
y_cm

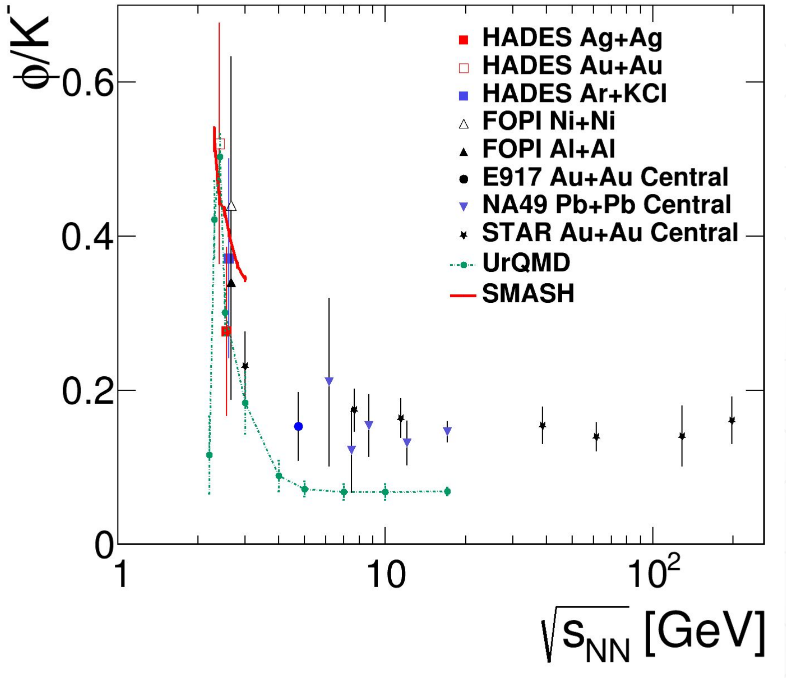


T_Eff vs center of mass rapidity for K-
HADES Preliminary
Ag+Ag 1.58 A GeV (20-30 %)
T_eff = (79.7 ± 0.2 ± 4.0) MeV
T_Eff,2D Fit = 80.33 ± 0.15 MeV
T_Eff [MeV]
y_cm

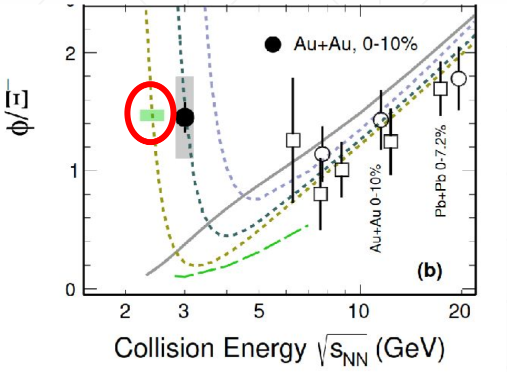
ϕ


dN/dy spectrum for the φ
HADES Preliminary
Ag+Ag 1.58 A GeV (0-10 %)
N_φ→KK/Event = (18.7 ± 0.6 ± 7.0 ± 0.1) × 10^-5
N_φ/Event = (38.1 ± 1.2 ± 14.3 ± 0.1) × 10^-5
dN/dy × 1/evts
×10^-3
y_cm
dN/dy spectrum for the φ
HADES Preliminary
Ag+Ag 1.58 A GeV (10-20 %)
N_φ→KK/Event = (11.2 ± 0.4 ± 4.0 ± 0.1) × 10^-5
N_φ/Event = (22.7 ± 0.7 ± 8.2 ± 0.2) × 10^-5
dN/dy spectrum for the φ
HADES Preliminary
Ag+Ag 1.58 A GeV (20-30 %)
N_φ→KK/Event = (6.2 ± 0.2 ± 2.4 ± 0.0) × 10^-5
N_φ/Event = (12.6 ± 0.5 ± 4.9 ± 0.1) × 10^-5
T_Eff vs center of mass rapidity
T_Eff [MeV]
HADES Preliminary
Ag+Ag 1.58 A GeV (0-10 %)
T_eff = (117.2 ± 5.9 ± 4.9) MeV
T_Eff,2D Fit = 103.98 ± 0.28 MeV
T_Eff vs center of mass rapidity
HADES Preliminary
Ag+Ag 1.58 A GeV (10-20 %)
T_eff = (119.1 ± 5.5 ± 11.8) MeV
T_Eff,2D Fit = 116.64 ± 0.27 MeV
T_Eff vs center of mass rapidity
HADES Preliminary
Ag+Ag 1.58 A GeV (20-30 %)
T_eff = (121.7 ± 6.1 ± 0.3) MeV
T_Eff,2D Fit = 124.27 ± 0.30 MeV

Comparison to Transport Models



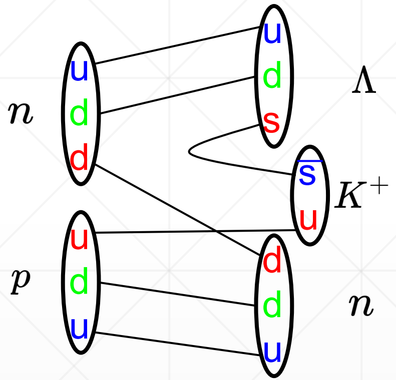
- UrQMD with higher resonance feed-down [1] describes trend of low-energy regime of ϕ/K^- ratio, SMASH [2] lies too high
- ϕ/Ξ^- in UrQMD [1] follows global trend [2]:

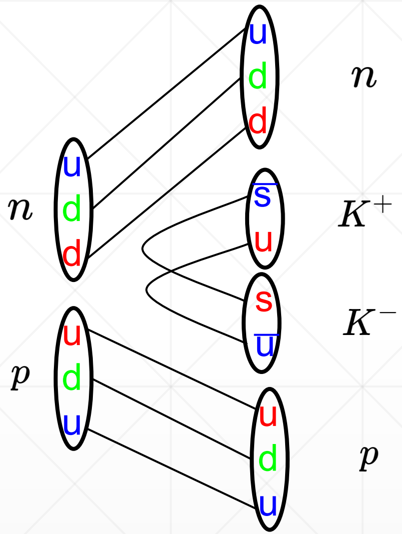


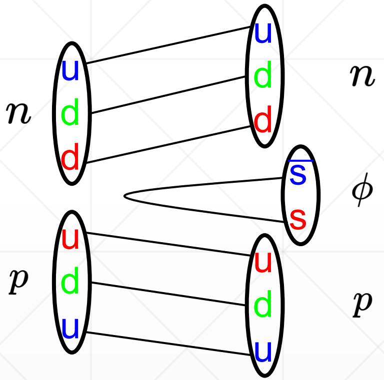
[1] *J. Steinheimer, M. Bleicher, DOI:* [10.1088/0954-3899/43/1/015104](10.1088/0954-3899/43/1/015104)

[2] *M.S. Abdallah et al.,* arXiv:2108.00924v4

Strangeness Production





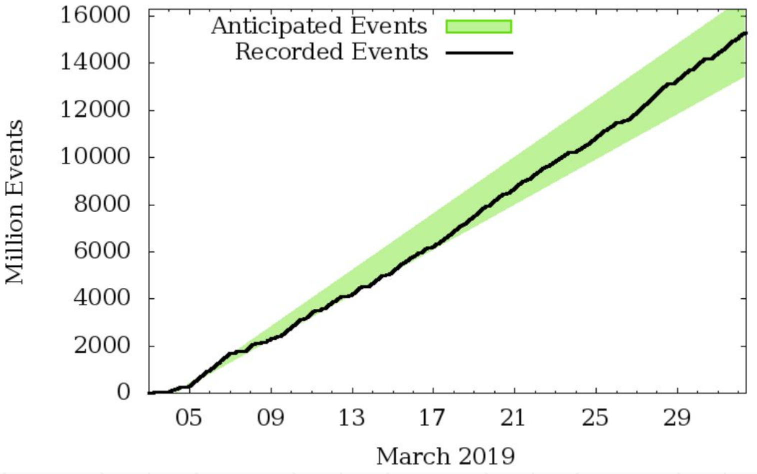


ϕ(1020) mass higher than $K^+ K^-$, as it is Vectormeson (both quarks spin up) - spin spin interaction shifts mass up $M_{q\bar{q}} = m_q + m_{\bar{q}} + \Delta M_{ss}$

where $\Delta M_{ss} > 0$ for Vectormeson and $\Delta M_{ss} < 0$ for pseudoscalar Meson

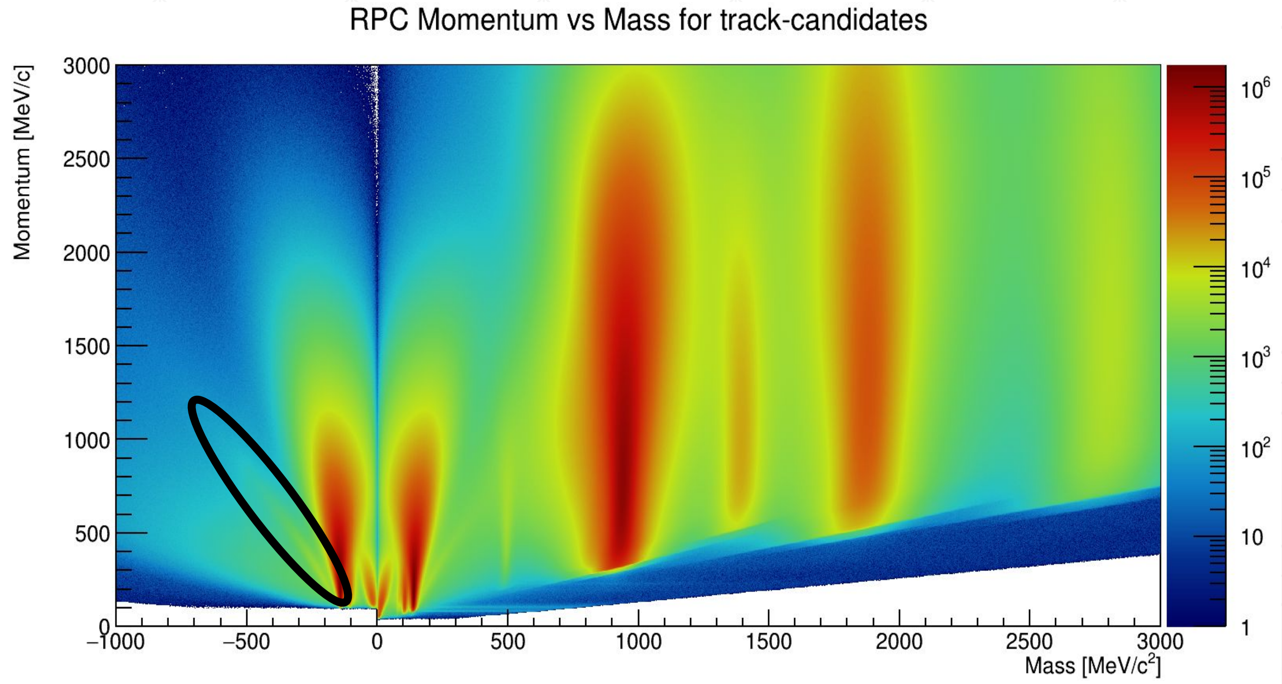
Ag+Ag Beamtime 2019

- One month of beamtime in march 2019
- About 15 billion events recorded
- Several phases with different physics motivations



	Phase 1	Phase 2	Phase 3
$\sqrt{s_{NN}}$	2.55 GeV	2.4 GeV	2.4 GeV
Magnet Current	3200 A	2500 A	200 A
Events	13.68×10^9	1.32×10^9	0.26×10^9
Total File Size	334.52 TB	29.31 TB	5.75 TB
Duration	441.7 h	39.1 h	6.76 h
Event Rate	8.6 kHz	9.4 kHz	10.5 kHz

Momentum vs Mass x Polarity



Differential K^- Analysis (RPC Polar Angle Region)