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Strangeness enhancement in PHQMD model

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विज्ञान एवं प्रौद्योगिकी विभाग
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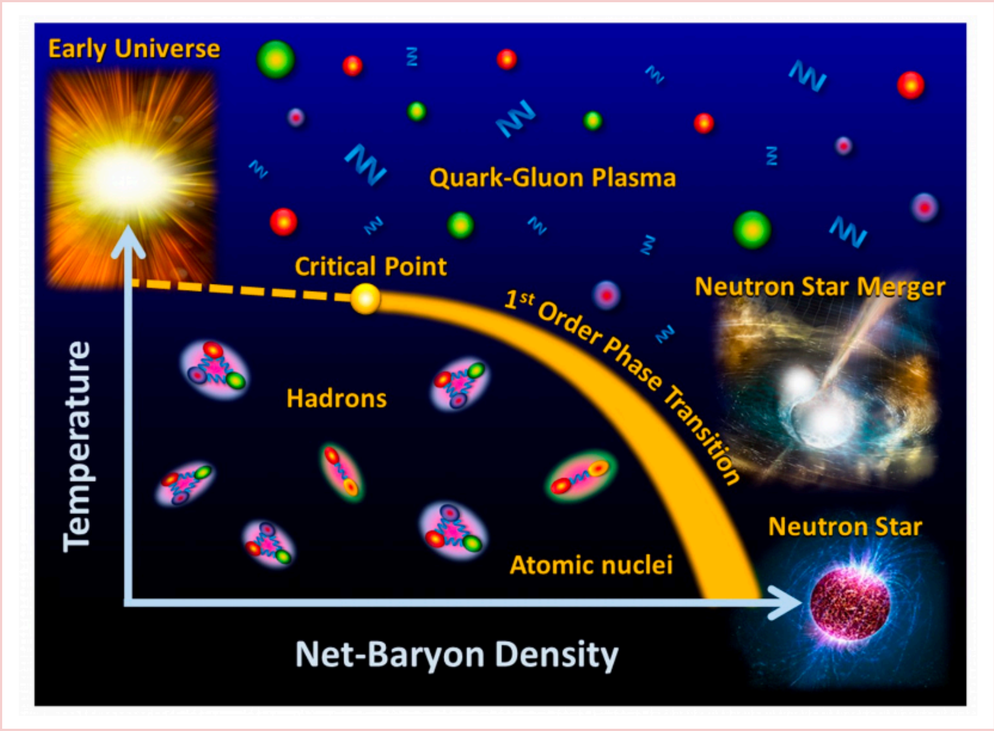
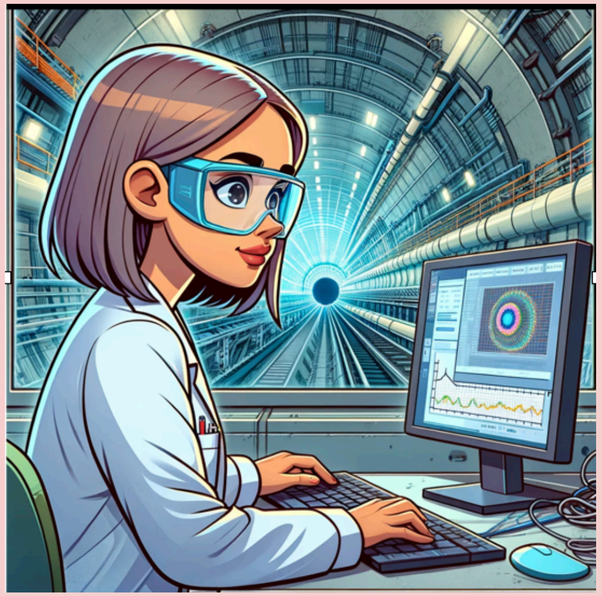
Outline

- Motivation
- Experimental Overview of strangeness measurements
- PHQMD model
- Results
- Summary



Theory

Simulation



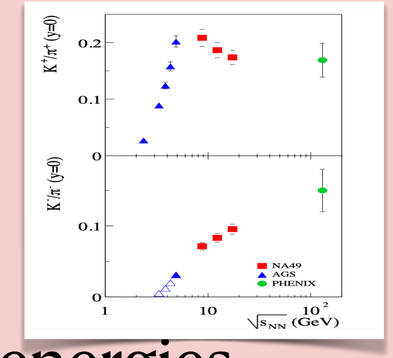
Experiment

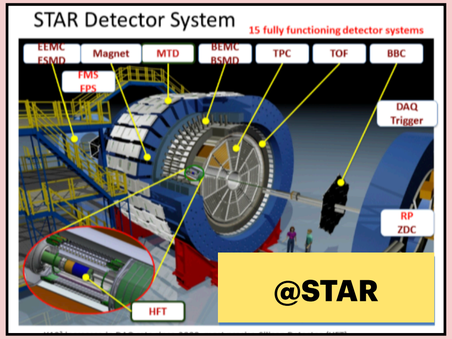
Motivation

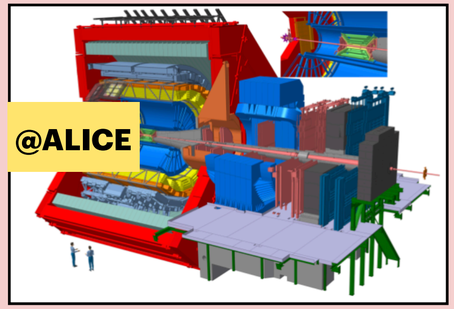
- Strange particle production is enhanced in heavy-ion collisions → *key QGP signal*
- Strange quarks are abundantly produced in the QGP medium
- Enhanced strangeness production has been observed in nucleus-nucleus collisions and small systems
- Ratios such as K^+/π^+ and $(\Lambda + \Sigma^0)/\pi^-$ serve as sensitive QGP observables.

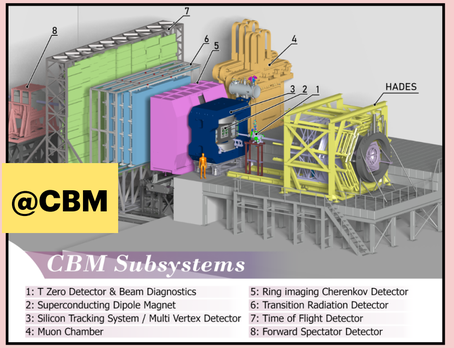
Overview of strangeness measurements (Experiments)

- **SPS (CERN)**: First observation of strangeness enhancement (NA49)
- **STAR (RHIC) :** Observe particle ratio at all BES energies
- **ALICE (LHC)**: Enhancement seen even in small systems
- **NICA (JINR)**: Future high-baryon density program
- **CBM (FAIR):** High-precision strangeness & dilepton measurements









Ref: NA49 Collab., Phys. Rev. C 66, 054902 (2002)
STAR Collab., Phys. Rev. C 96, 044904 (2017)
ALICE Collab., Nature Phys. 13, 535–539 (2017)
CBM Collab., CBM Physics Book (Springer, 2021)

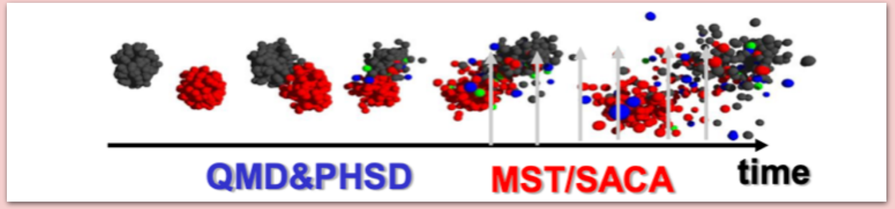
Parton-Hadron-Quantum-Molecular Dynamics (PHQMD)

A unified n-body microscopic transport approach for the description of heavy-ion collisions and dynamical cluster formation from low to ultra-relativistic energies!!

1. Initialization (QMD)
- Propagation of baryons
- Quantum-Molecular Dynamics

2. Propagation & Interactions (PHSD)
- Partons (quarks, gluons), mesons, hadrons
- Collision integral → QGP dynamics

3. Cluster Recognition (MST / SACA)
- Minimum Spanning Tree (MST)
- Simulated Annealing Clusterization Algorithm (SACA)



Ref: J. Aichelin et al., PRC 101 (2020) 044905, arXiv:1907.03860

MST & SACA

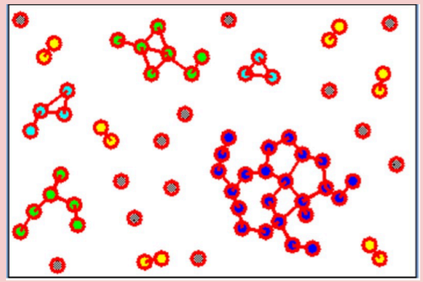
Minimum Spanning Tree (MST)

- Cluster recognition method for final states.
- Searches for accumulations of particles in coordinate space.

Criteria:

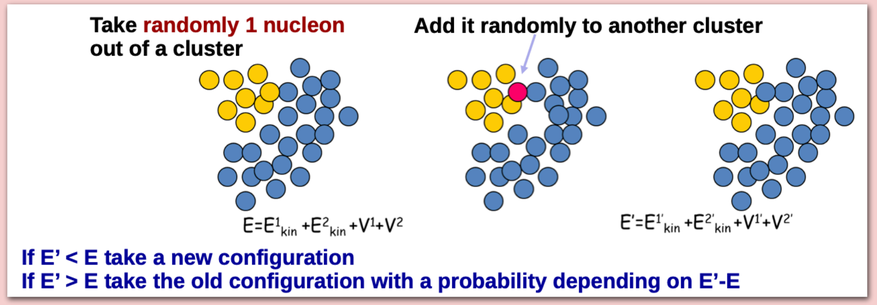
1. Two particles are bound if $|r_i - r_j| \leq 4$ fm.

2. A particle belongs to a cluster if it binds with at least one particle.



Simulated Annealing Clusterization Algorithm (SACA)

- Uses positions and momenta of nucleons at time t.
- Considers all possible partitions into clusters or single nucleons.
- Neglects interactions among clusters.
- Chooses configuration with maximum binding energy.
- Iterative procedure leads to most bound cluster configuration.



Credit:V. Kireyeu

Ref: R. K. Puri, J. Aichelin, J. Comp. Phys. 162 (2000) 245–266,
P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

Simulation details

- Event generator: PHQMD
- Number of events: 2 million minimum bias
- $\sqrt{s_{NN}}$ = 3.5 - 14.5 GeV
- Cluster algorithm: MST

QGP ON: QGP phase when local energy density exceeds 0.5 GeV/fm³.

QGP OFF: If above threshold is not reached, the system remains in the hadronic phase (no QGP).

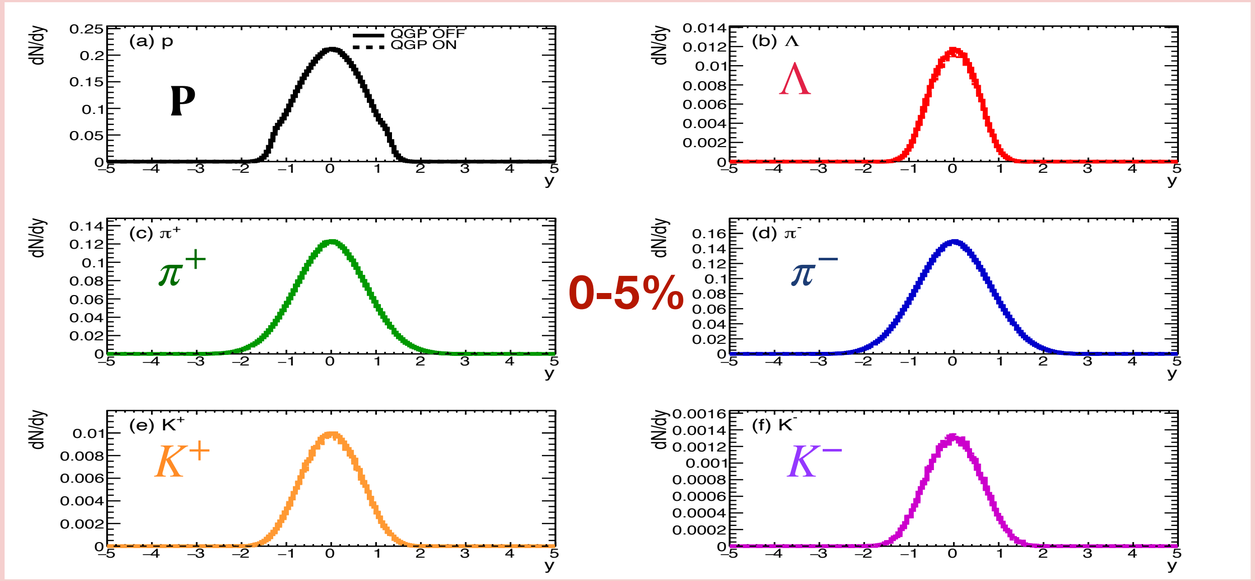
Three analysis cases

1. No cuts

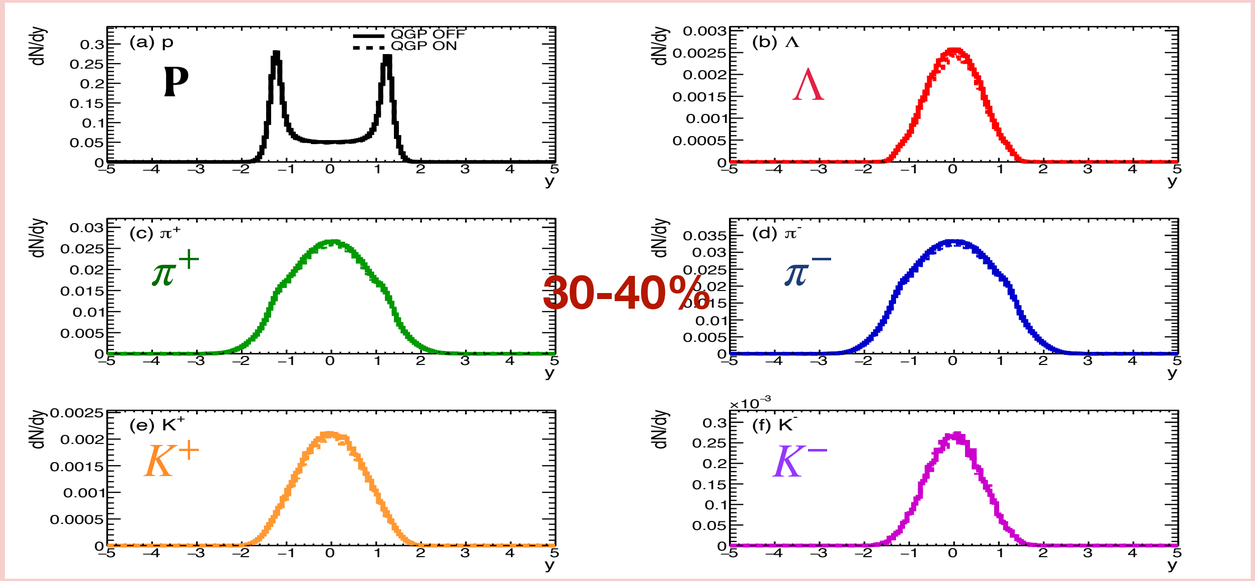
2. Mid-rapidity (|y| < 0.5)

3. Mid-rapidity |y| < 0.5 & transverse momentum range 0.4 < p_T < 2.0 GeV/c.

Rapidity spectra for 3.5 GeV



0-5%



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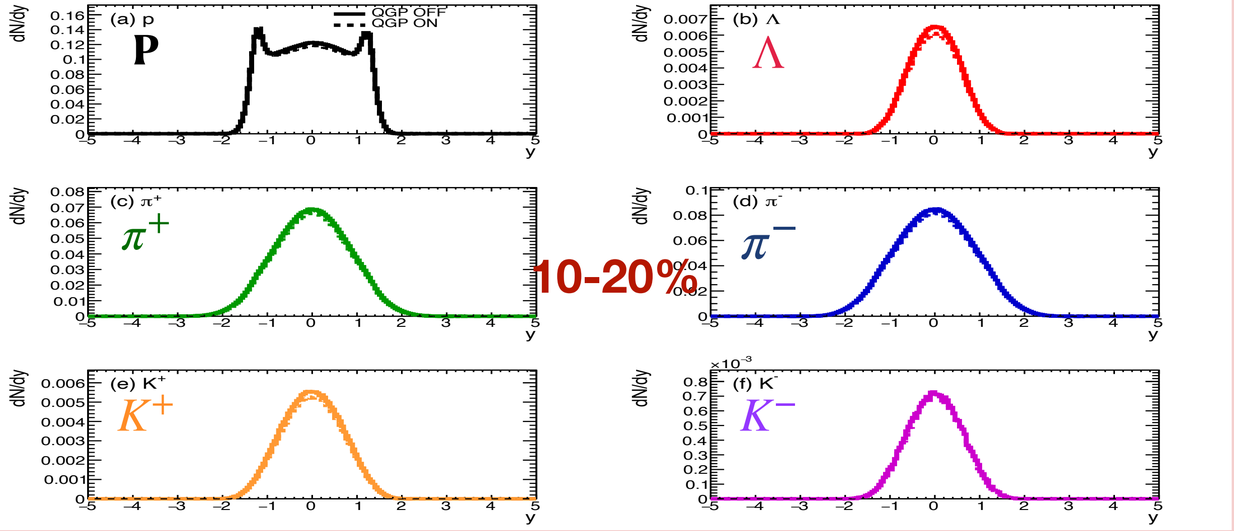

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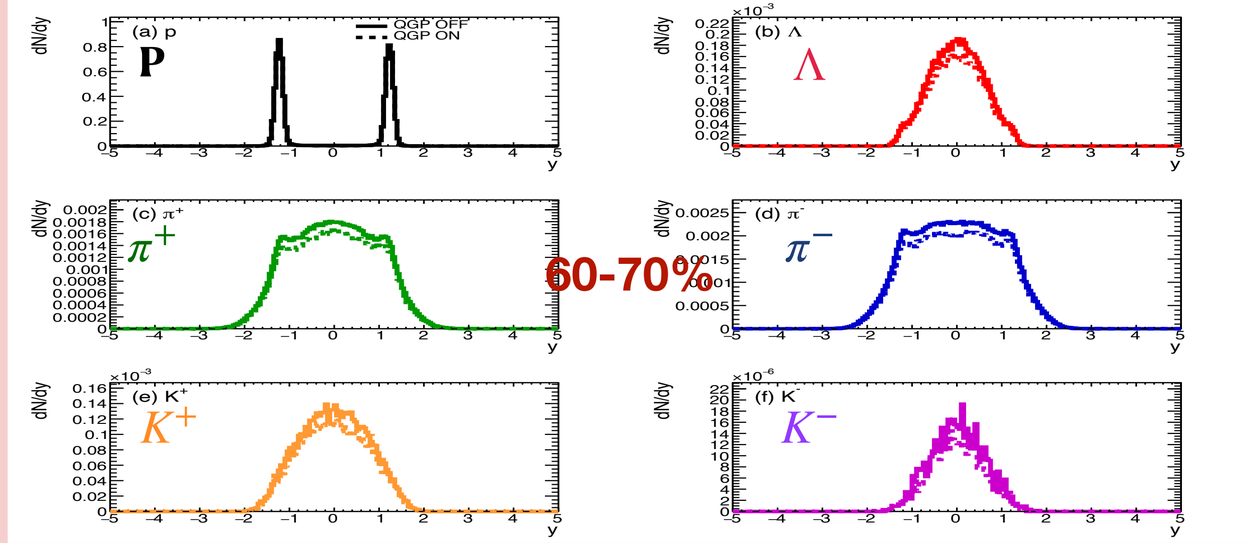
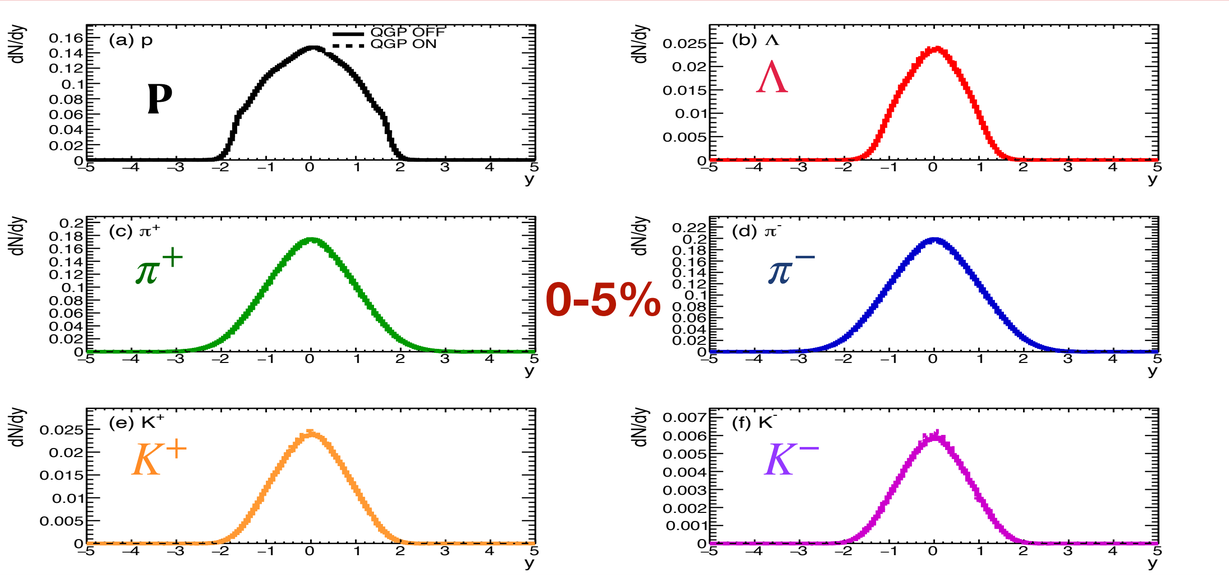
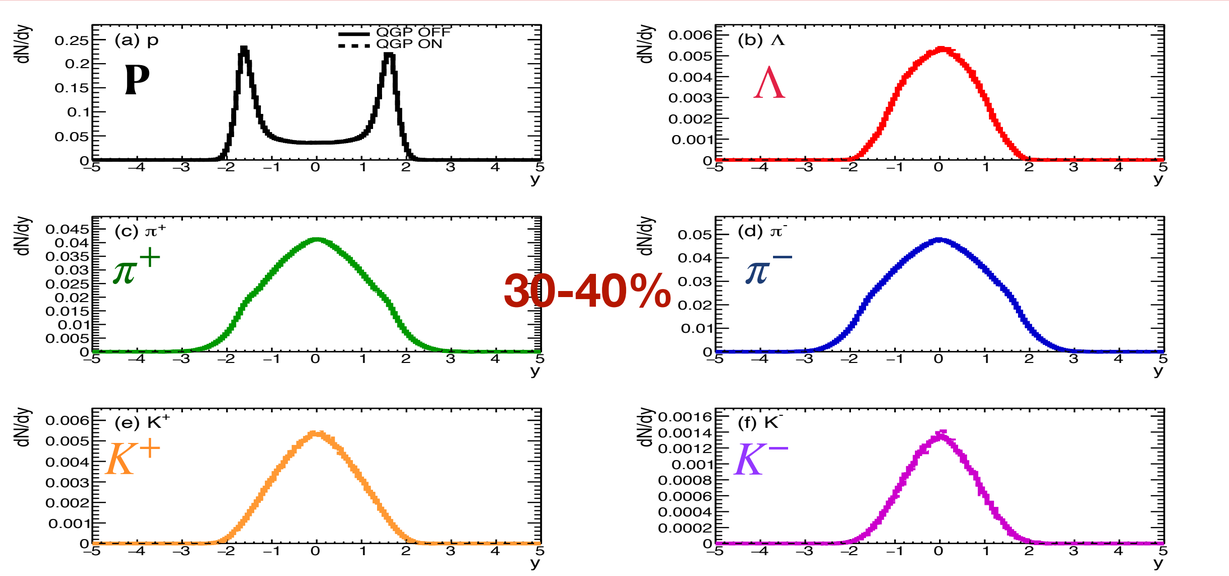
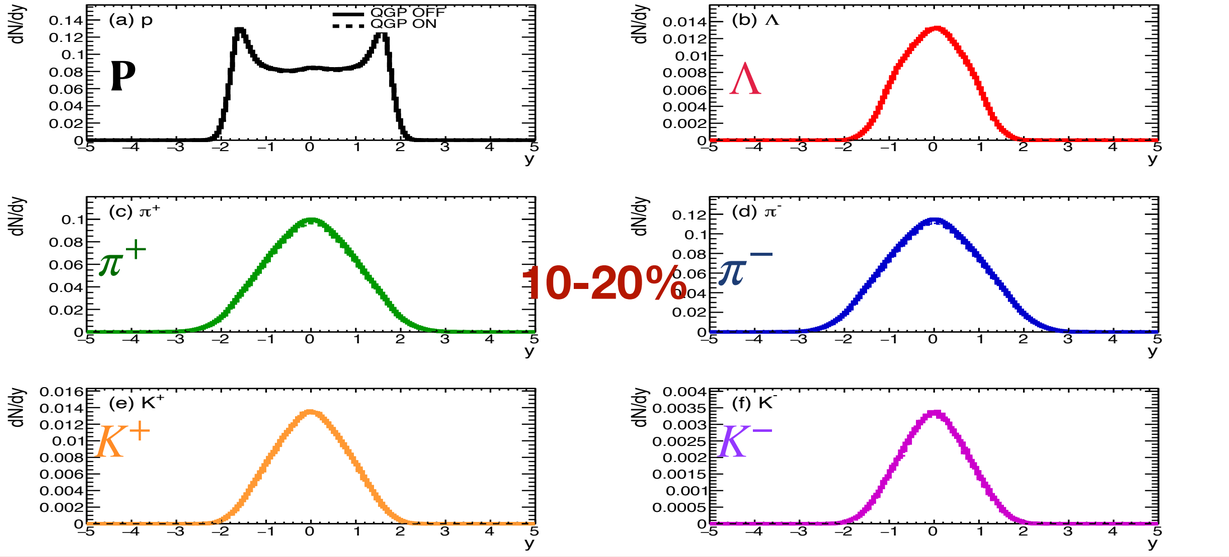


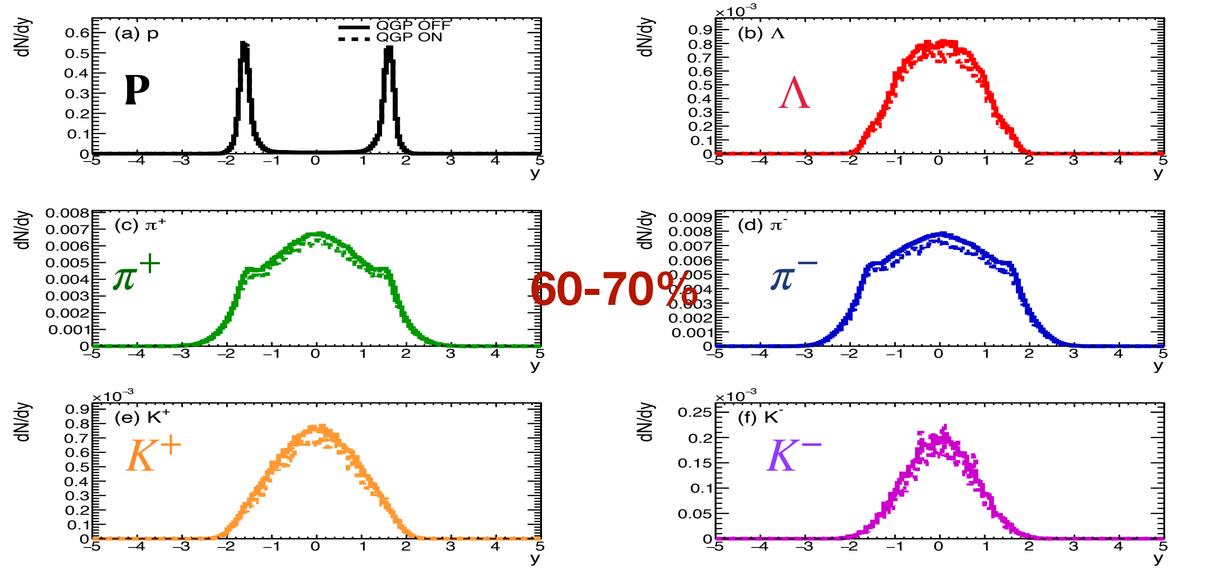
60-70%

Rapidity spectra for 4.9 GeV

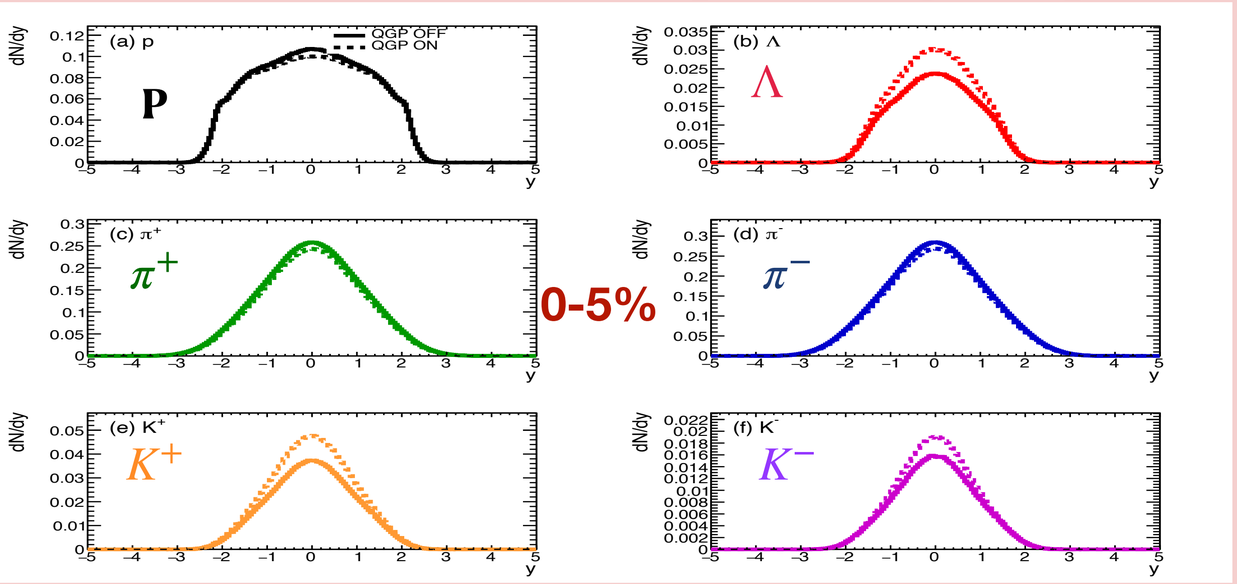








Rapidity spectra for 7.7 GeV



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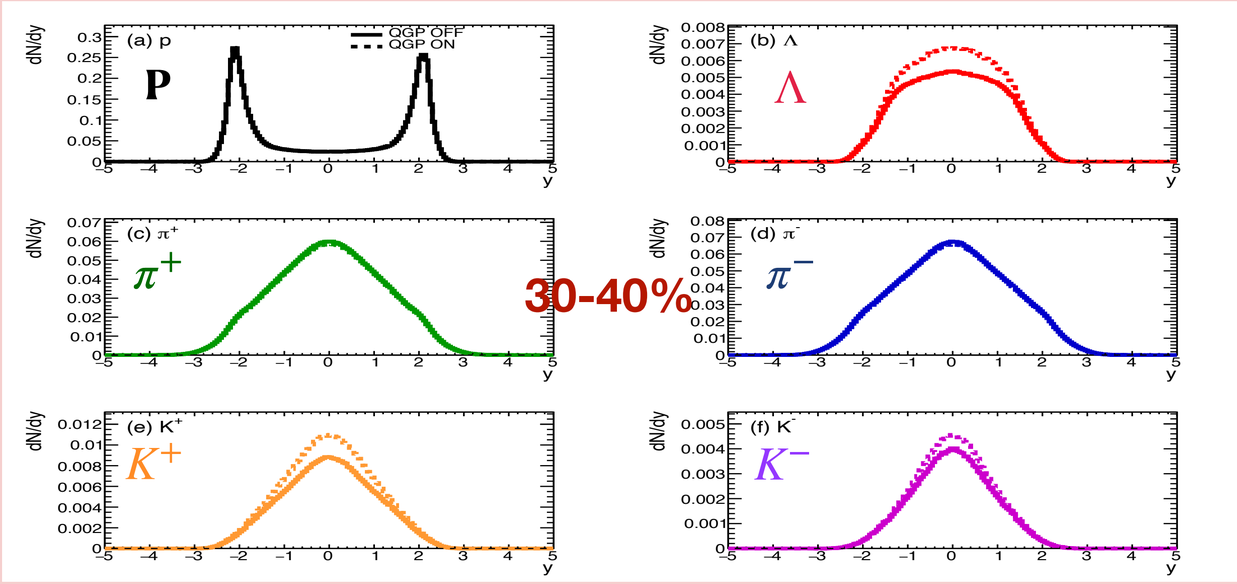

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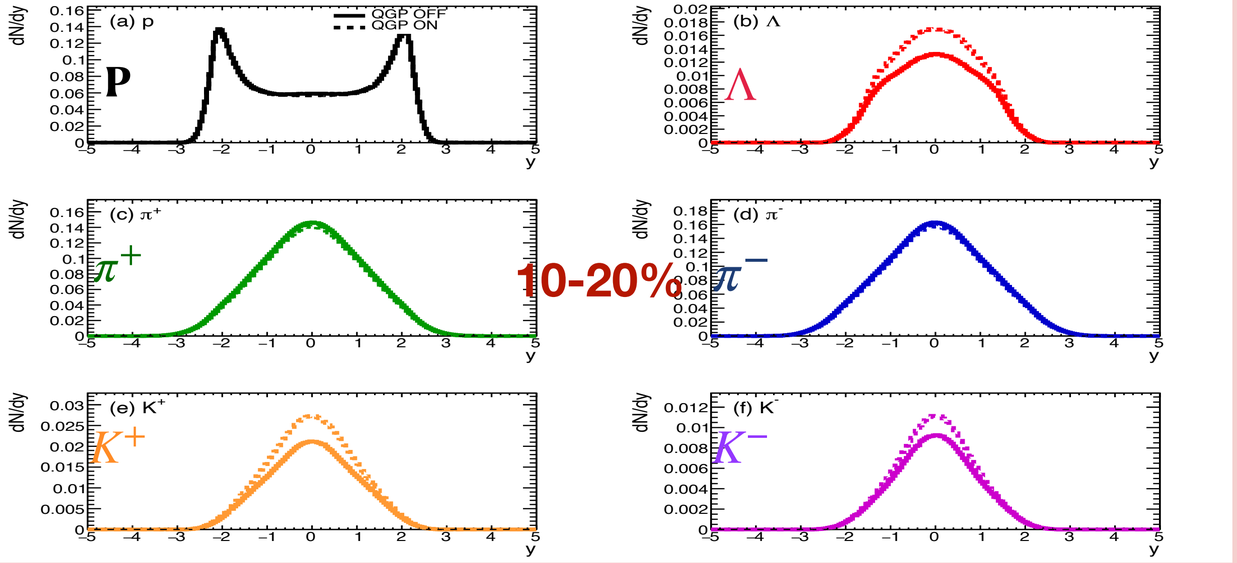

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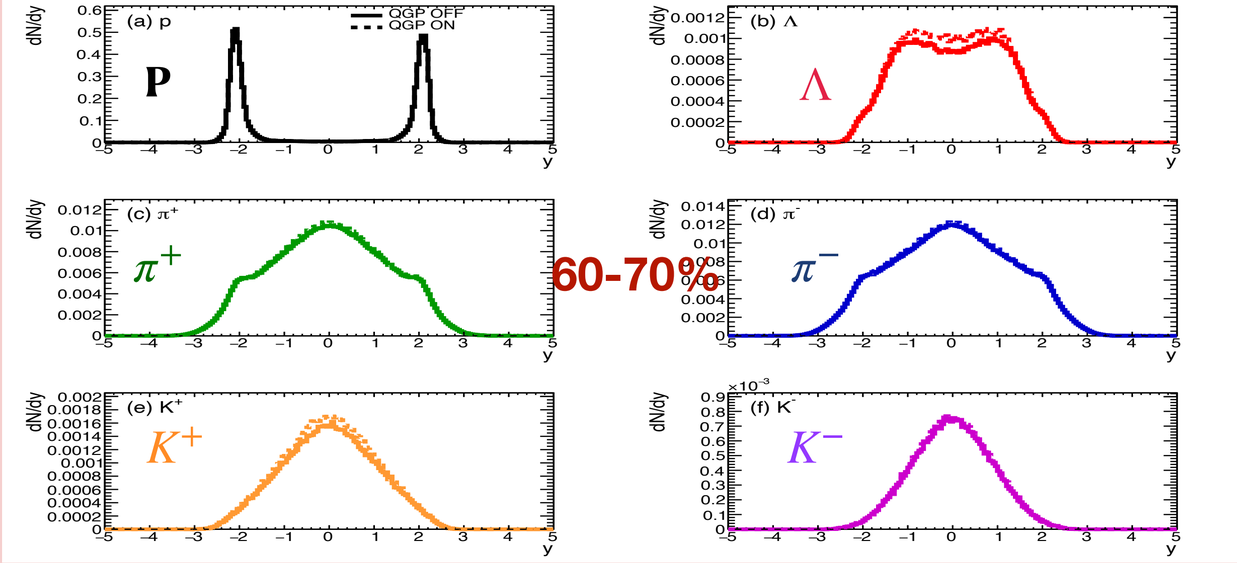
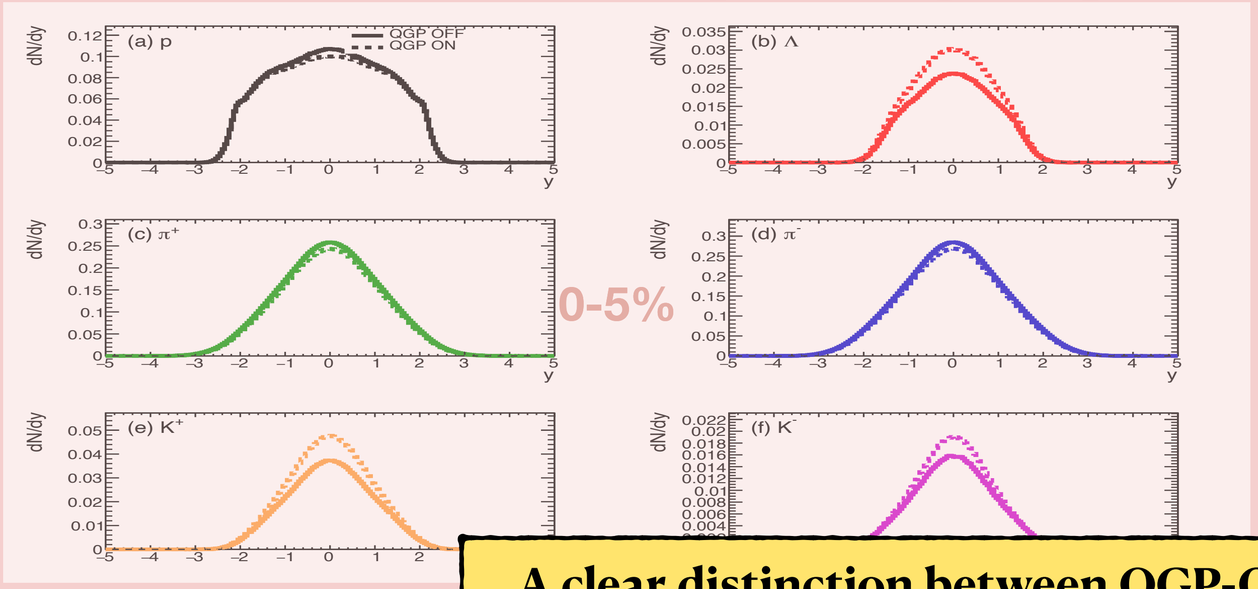


60-70%

Rapidity spectra for 7.7 GeV



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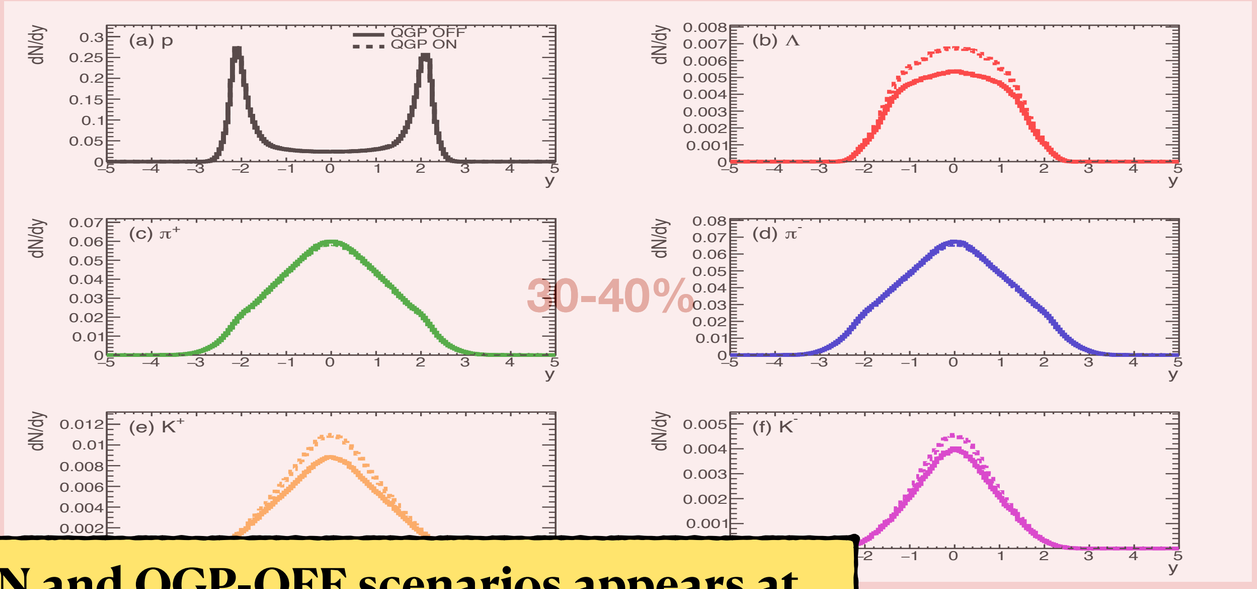
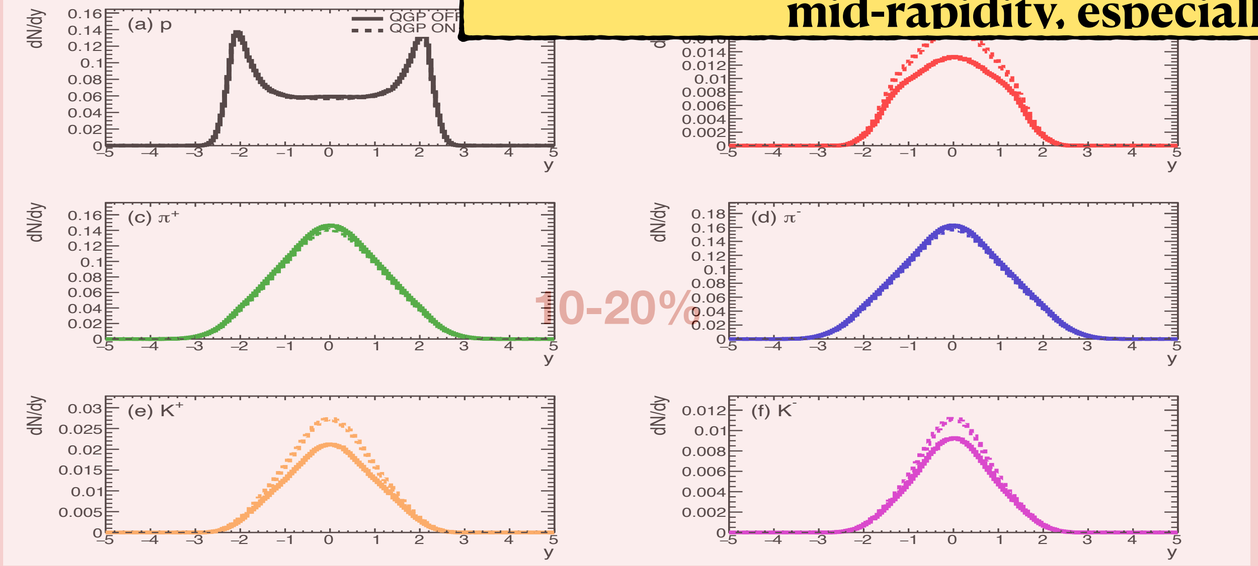


30-40%

A clear distinction between QGP-ON and QGP-OFF scenarios appears at mid-rapidity, especially for Lambda and kaons!!



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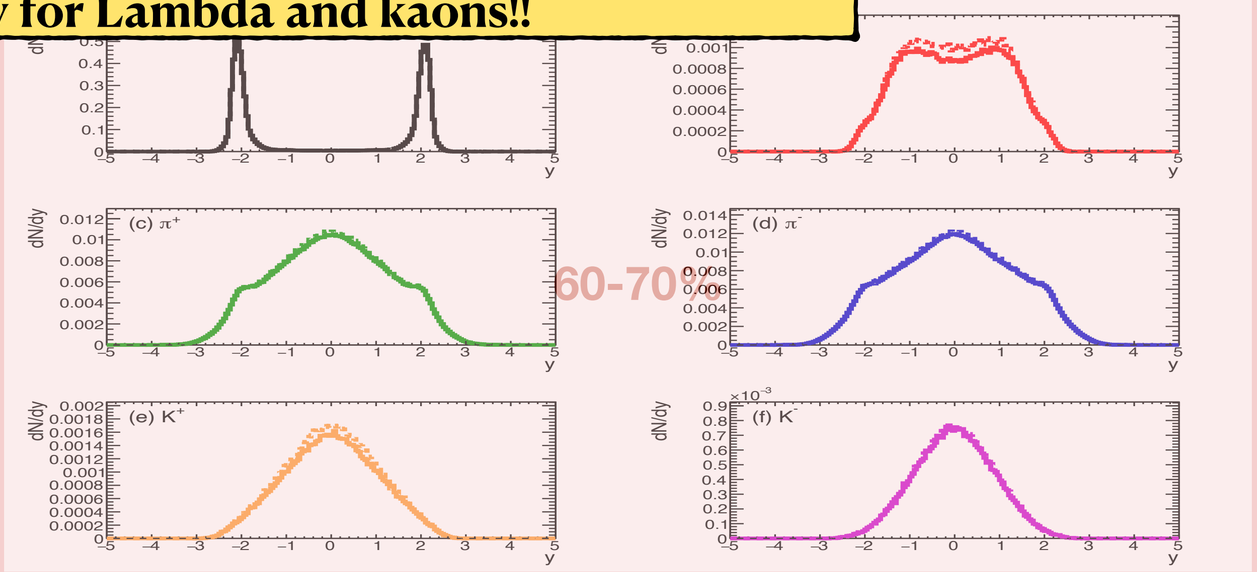
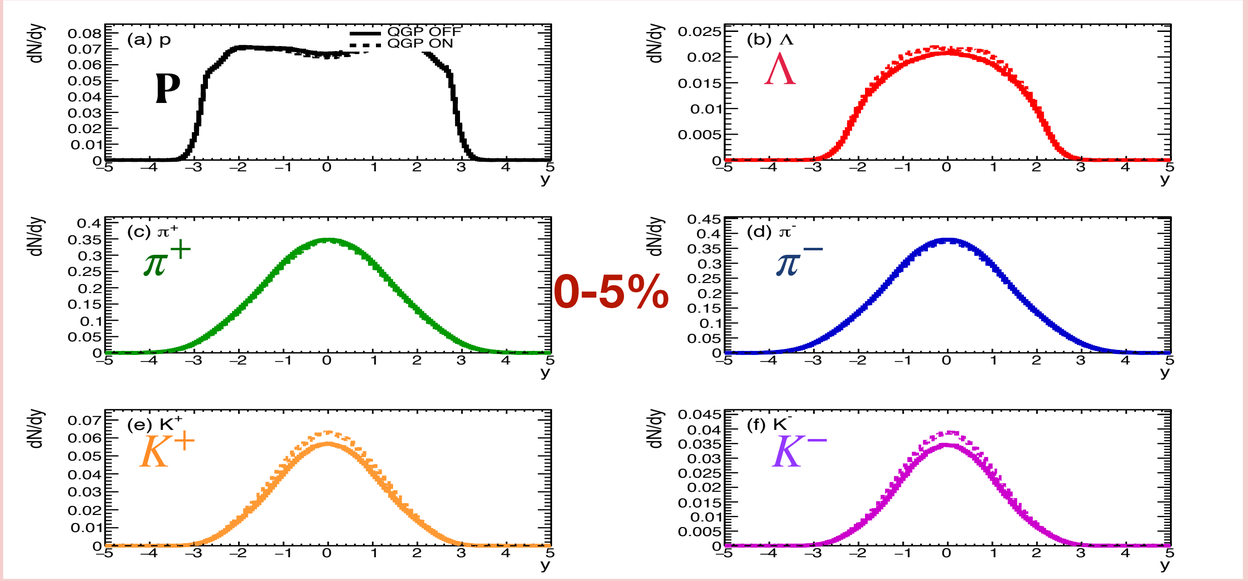


60-70%

Rapidity spectra for 14.5 GeV



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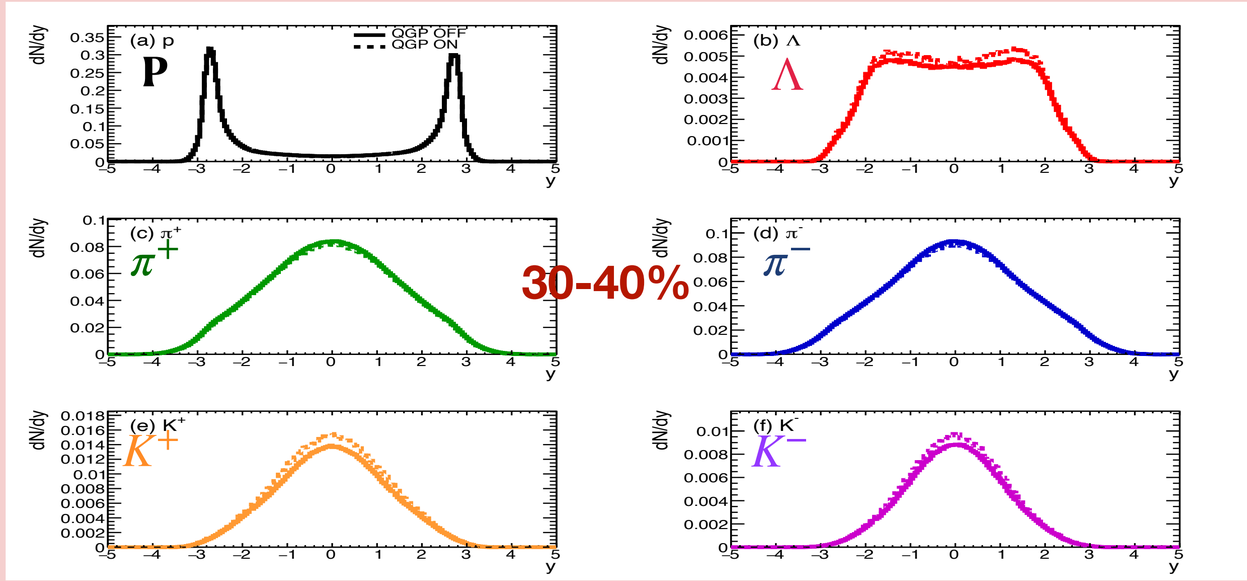

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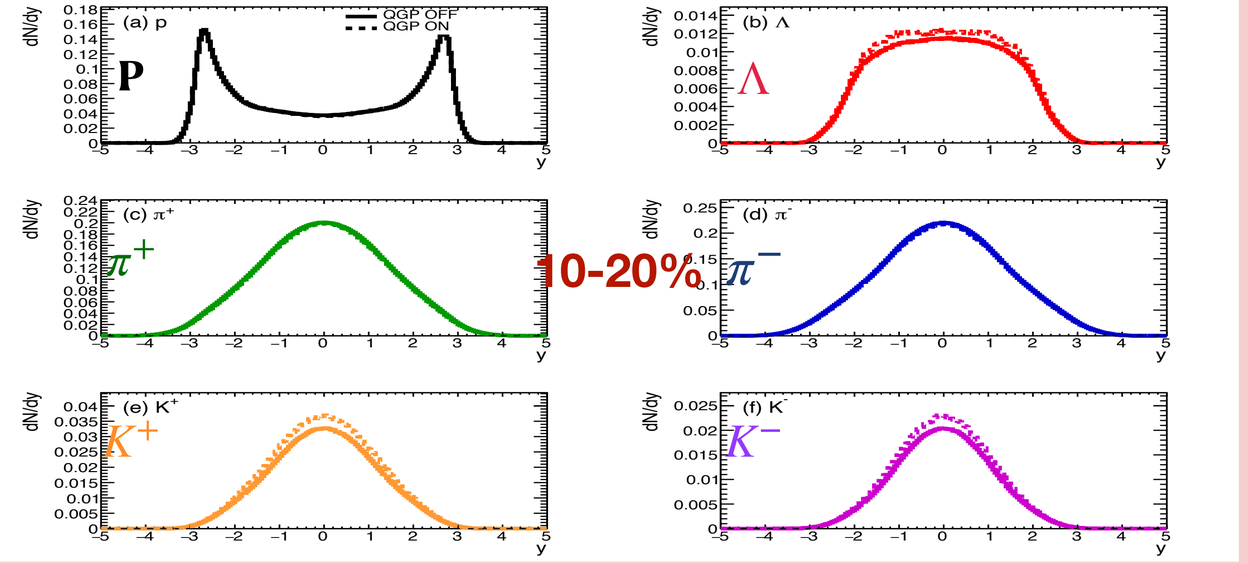

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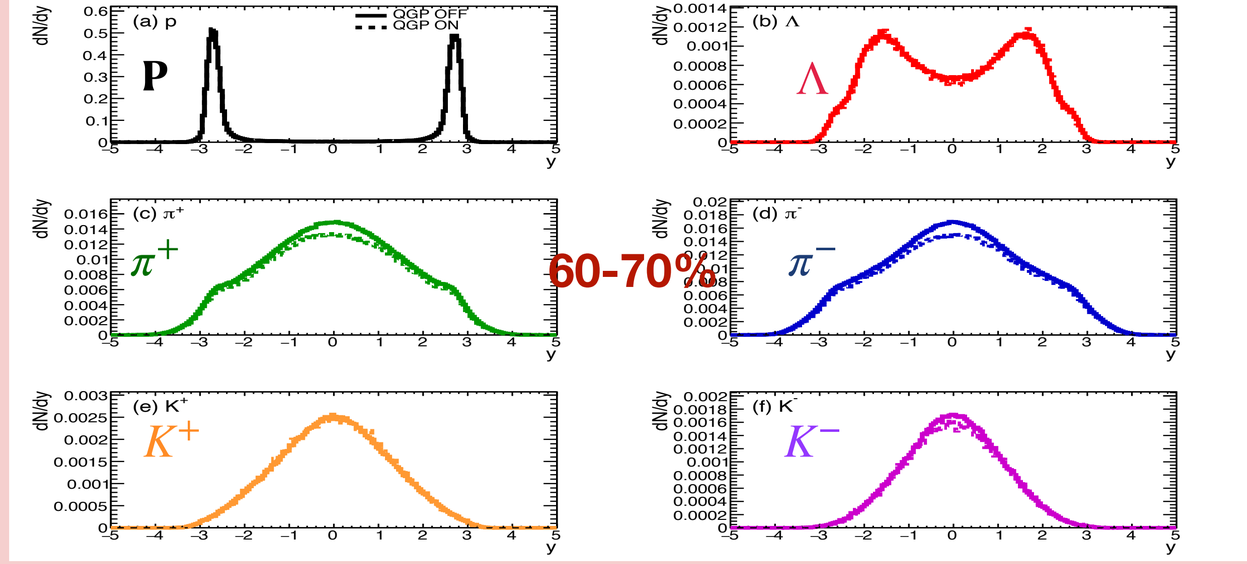
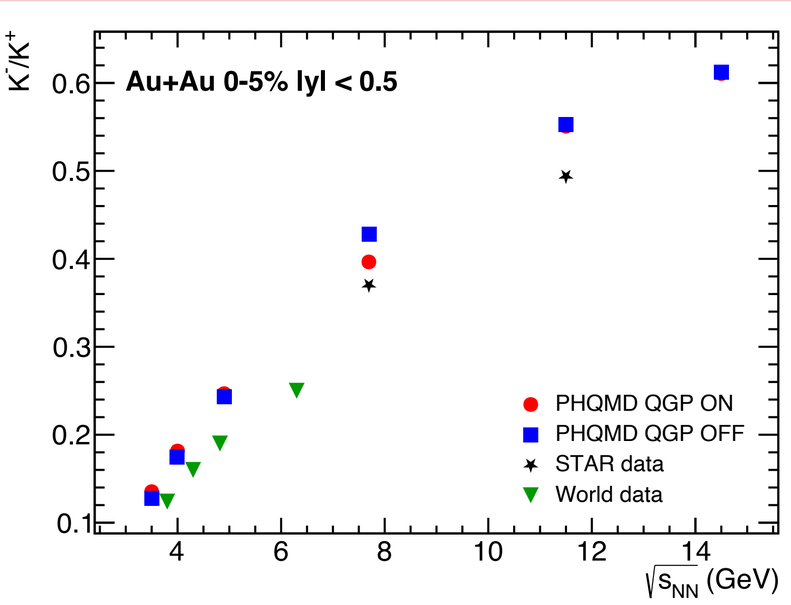
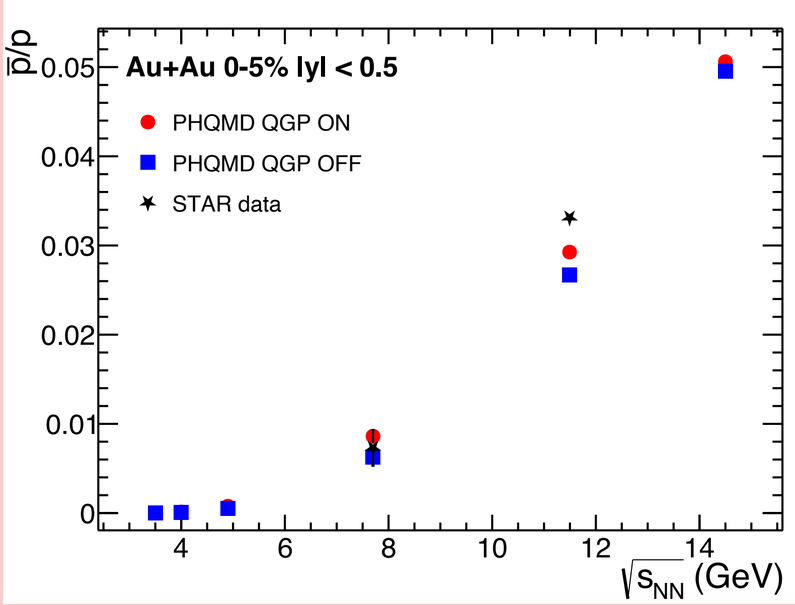
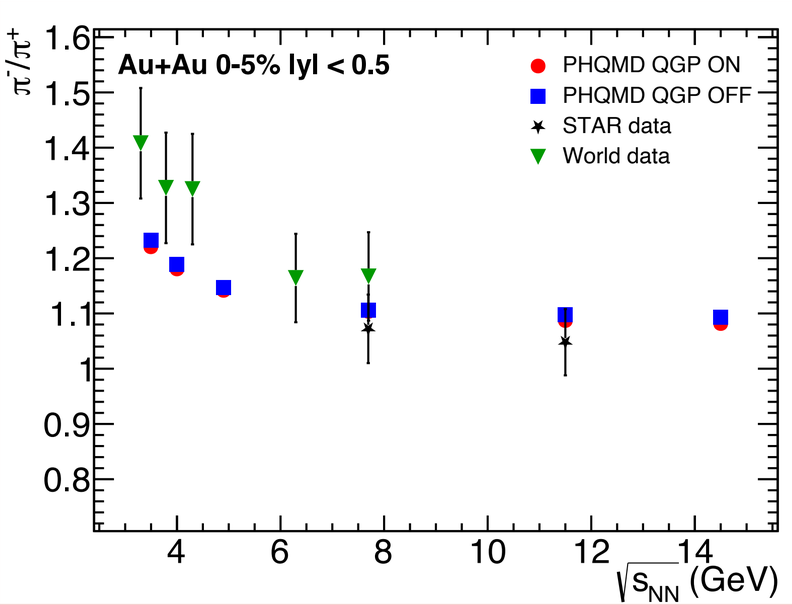


60-70%

Particle Ratio vs Energy







World data: NA49, AGS, SPS

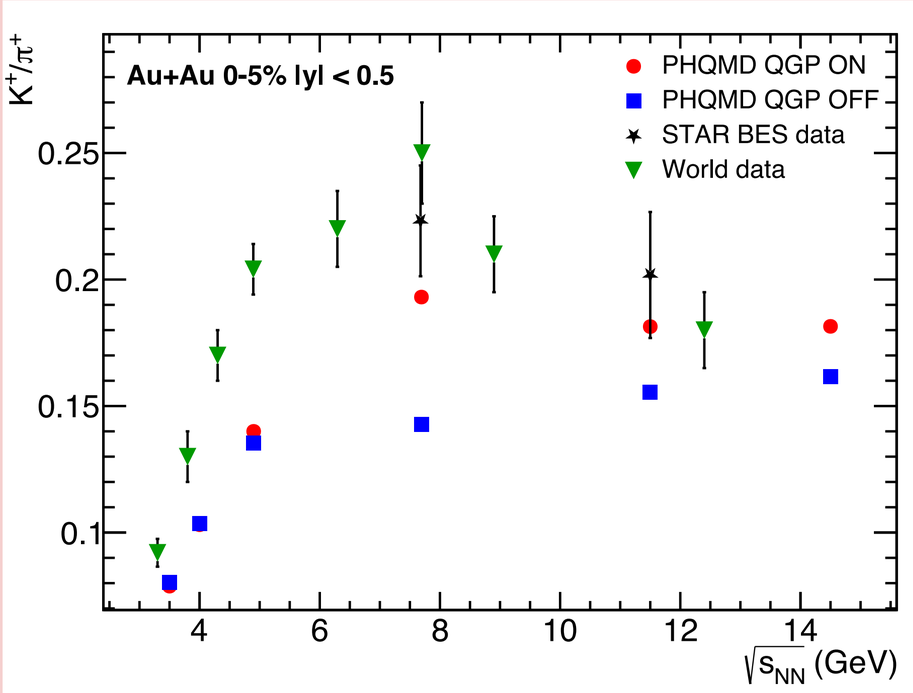
K^-/K^+ , $\bar{p}/p$ & π^-/π^+ ratio of PHQMD model at mid-rapidity for 0-5% central and compared with experimental data

- K^-/K^+ is significantly less than unity.
- Suppression of K^- occurs due to associated production with hyperons like Λ.
- Strangeness is conserved, but s quarks favor anti-kaons and hyperons, while $\bar{s}$ quarks primarily form kaons.

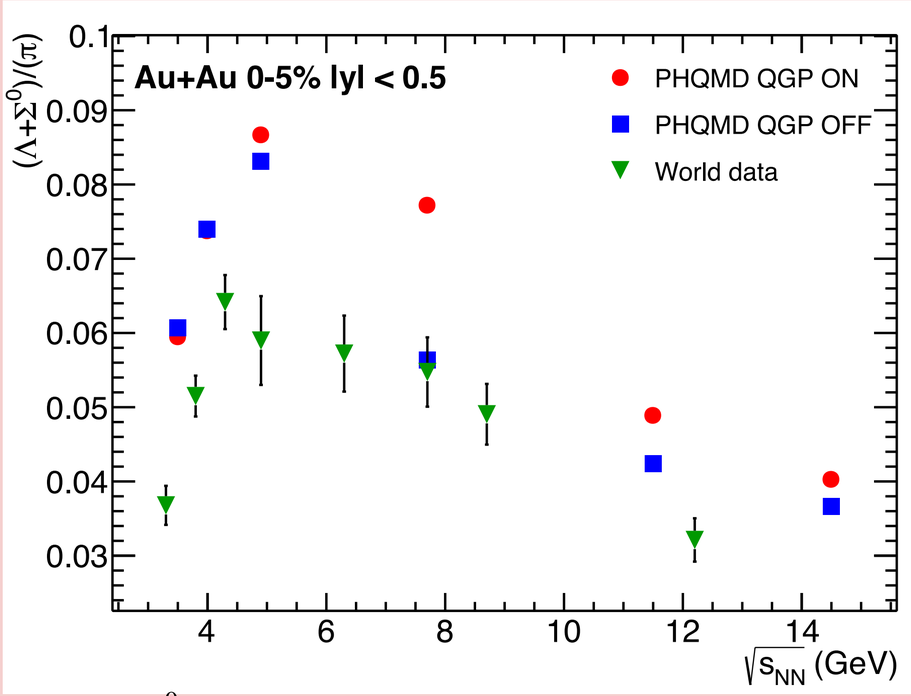
- With increasing $\sqrt{s_{NN}}$, the $\bar{p}/p$ ratio rises, nearing unity at top RHIC energies. Higher beam energies lead to greater collision transparency, with mid-rapidity proton and antiproton production mainly from pair production.
- The ratio of π^-/π^+ follows the trend of experimental data for both QGP ON and OFF scenarios.

Ref: L. Adamczyk, et al., Phys. Rev. C, 96, 044904 (2017)

Strangeness enhancement



K^+/π^+ ratio of PHQMD model at mid-rapidity for 0-5% central and compared with experimental data



$(\Lambda + \Sigma^0)/\pi$ ratio of PHQMD model at mid-rapidity for 0-5% central and compared with experimental data

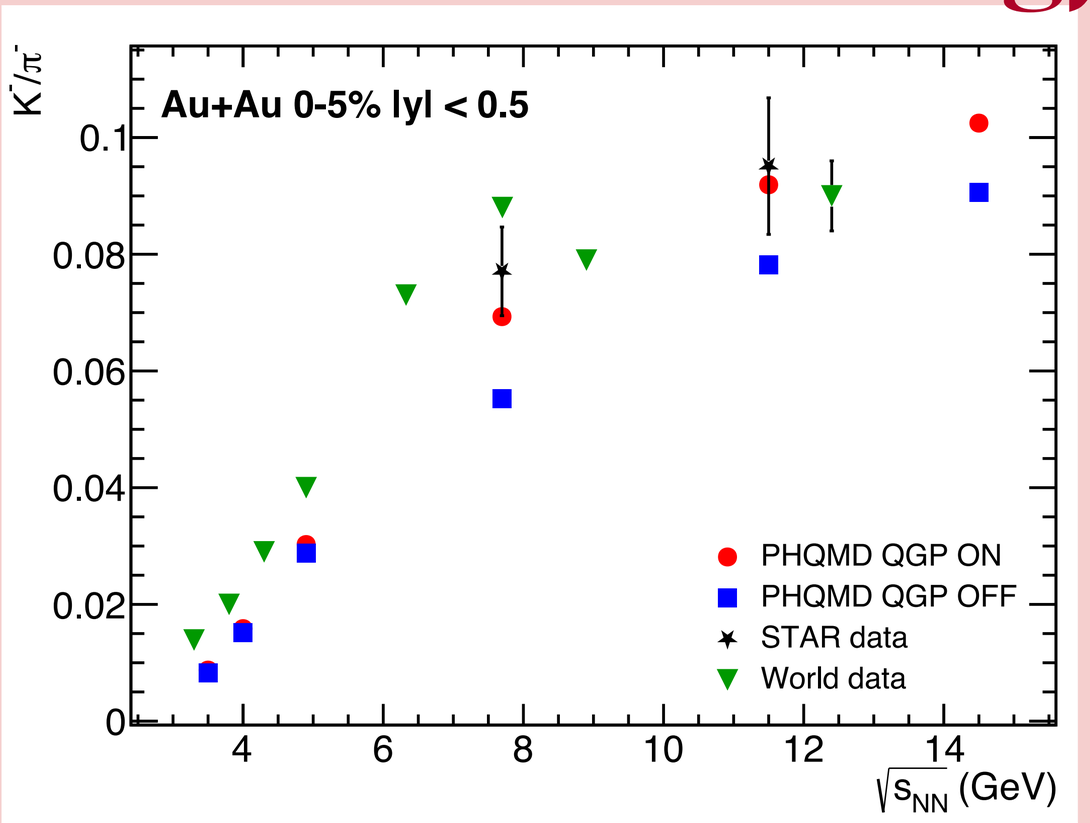
A clear distinction is observed between QGP ON and OFF states in the ratios around 7.7 GeV.

- **QGP ON scenario: K^+/π^+ ratio is closer to experimental data.**
- **QGP OFF scenario: No "horn" structure observed, highlighting the impact of QGP on particle ratios.**

- **PHQMD overestimates the data in $(\Lambda + \Sigma^0)/\pi$ ratio, especially for QGP ON scenario.**

Ref: L. Adamczyk, et al., Phys. Rev. C, 96, 044904 (2017)

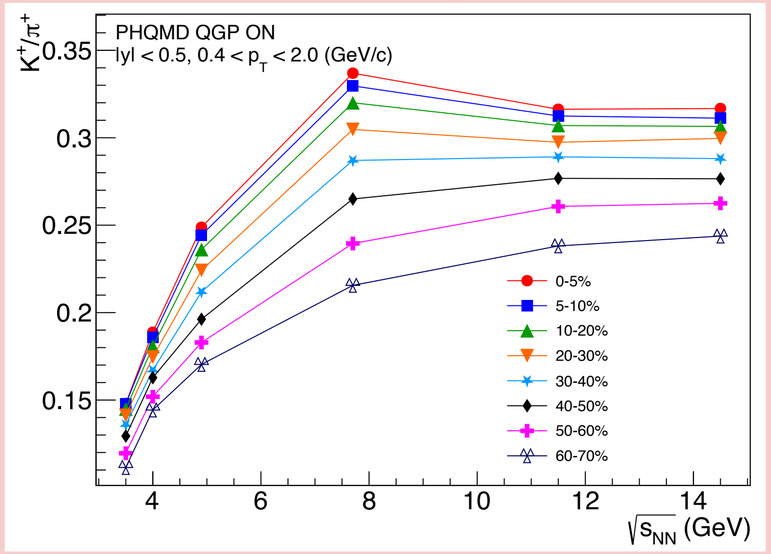
K^-/π^- Ratio vs Energy



- **No peak is observed in the excitation function of the K^-/π^- ratio, which instead rises monotonically with $\sqrt{s}_{NN}$**
- **Both the QGP ON and OFF scenarios show the consistent result with the experimental data for K^-/π^- ratio**

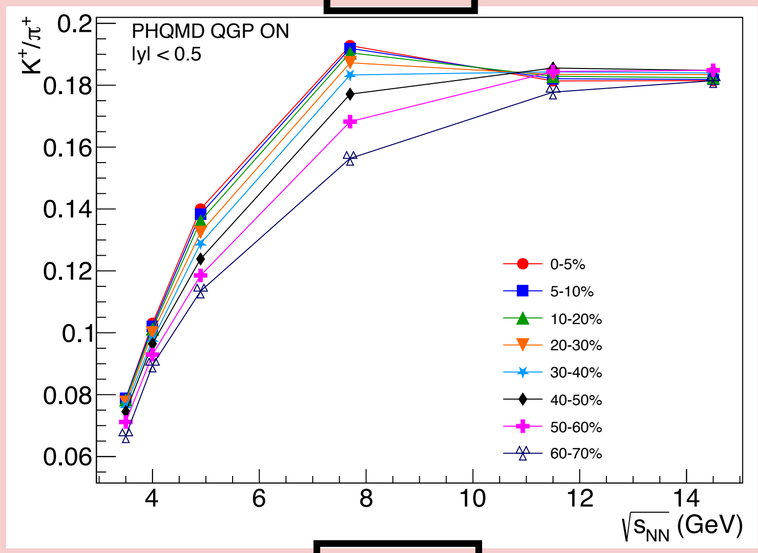
Centrality and energy dependence of K^+/π^+

|y| < 0.5, 0.4 < p_T < 2.0

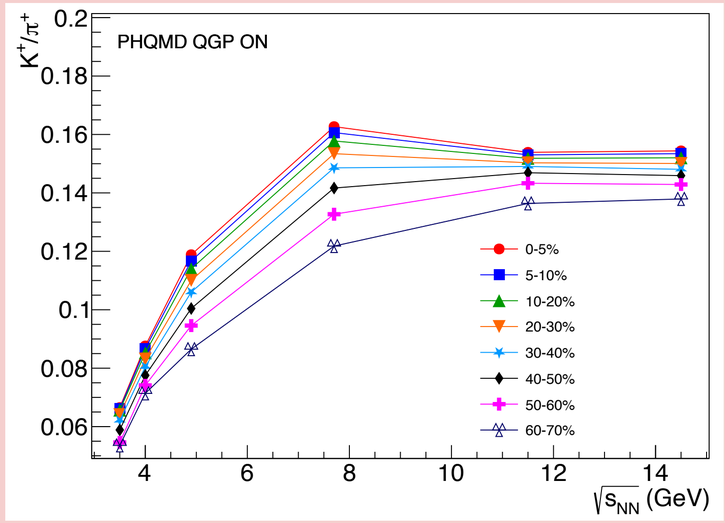


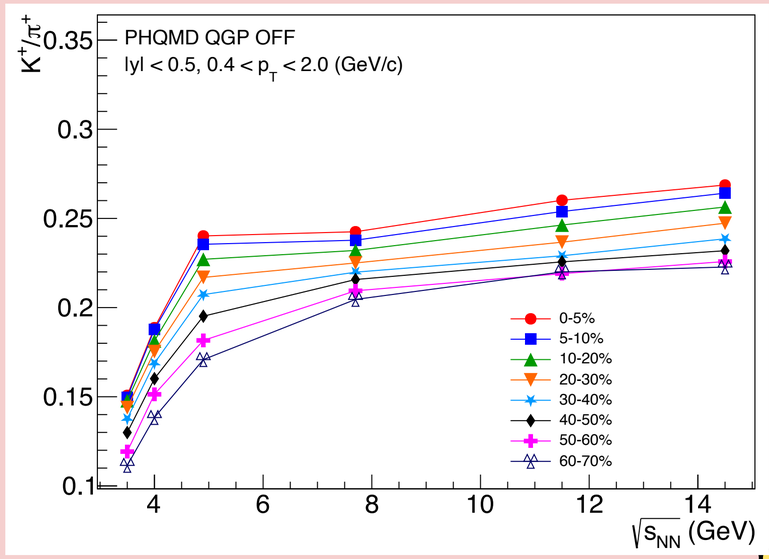
|y| <0.5

QGP ON

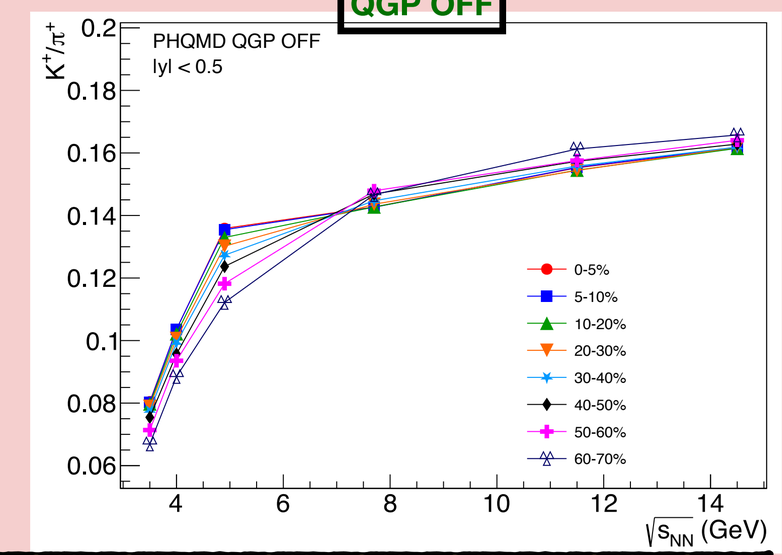


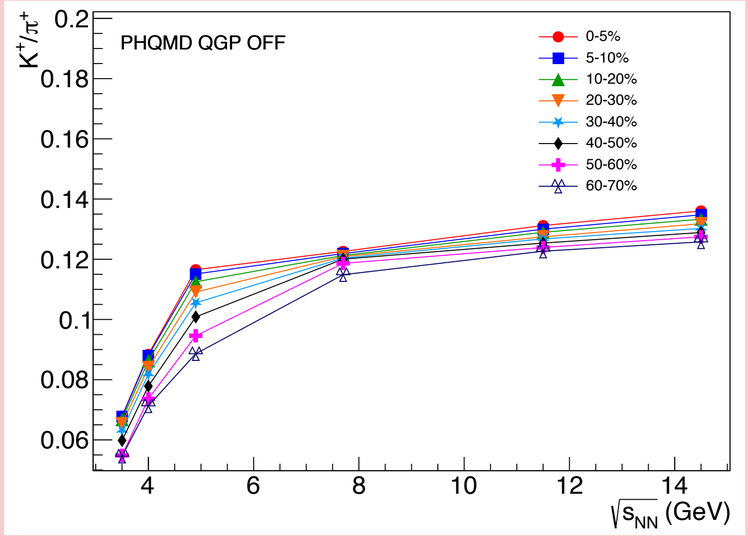
No y-p_T cut





QGP OFF





Horn structure is visible for PHQMD QGP ON

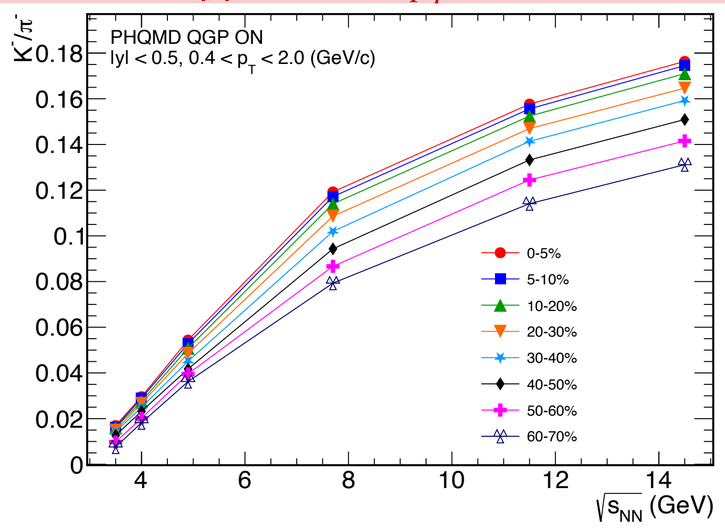
Centrality and energy dependence of K^-/π^-

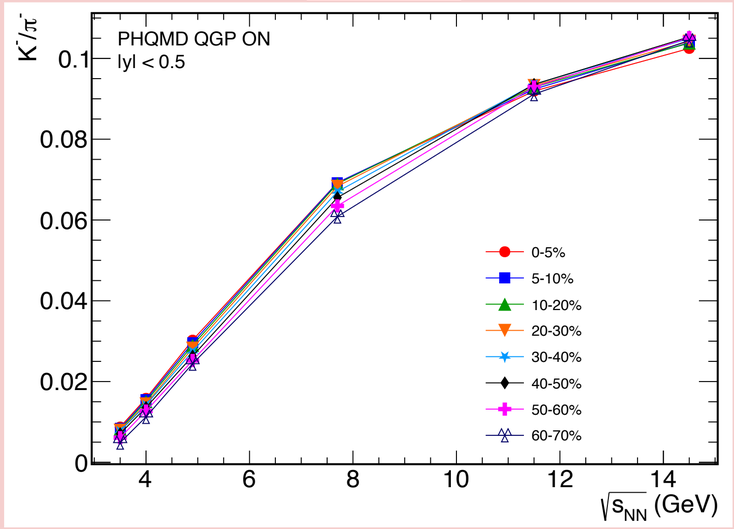
|y| < 0.5, 0.4 < p_T < 2.0

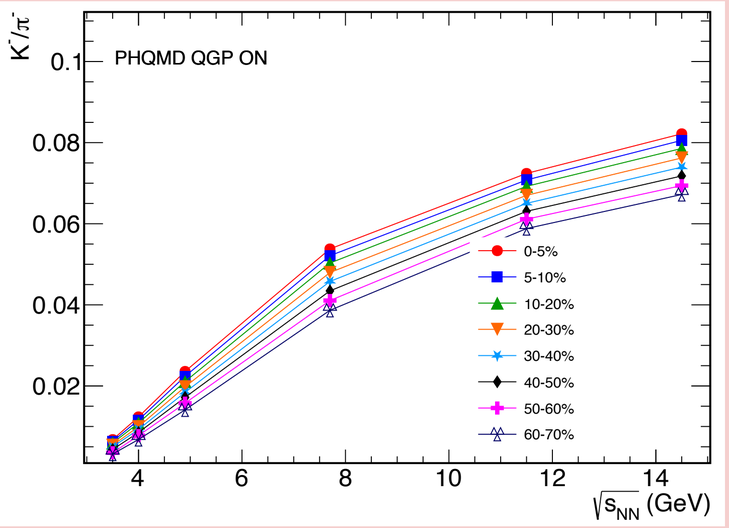
|y| <0.5

QGP ON

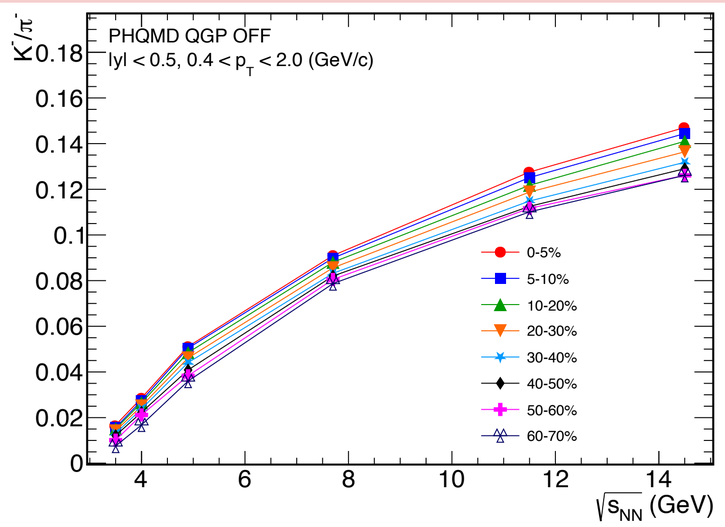
No y-p_T cut

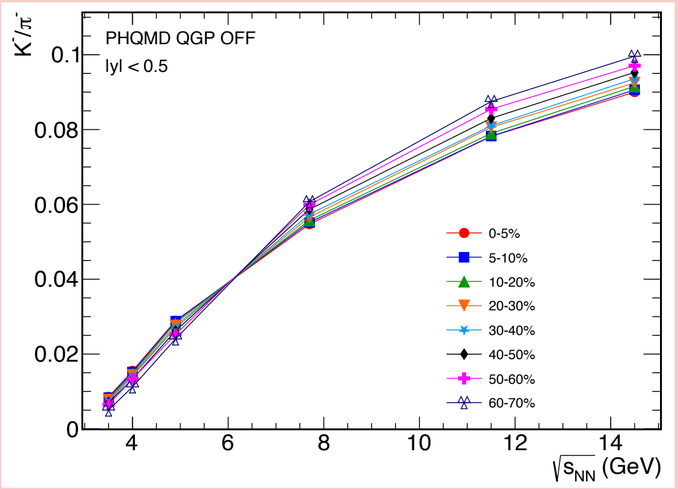


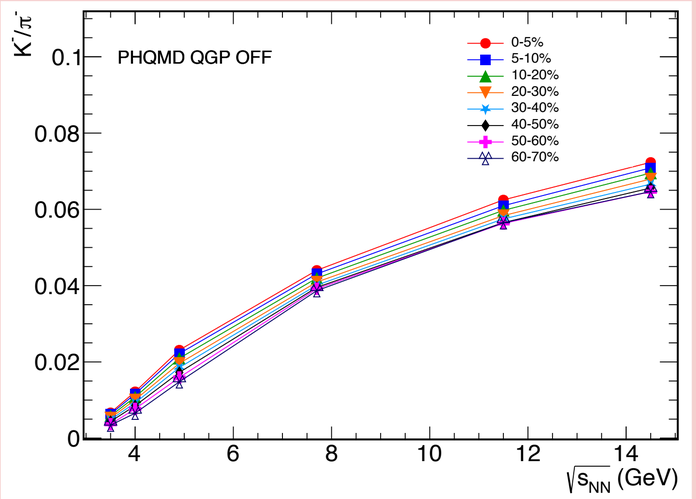




QGP OFF







No peak is observed in the excitation function, monotonic rise with $\sqrt{s_{NN}}$

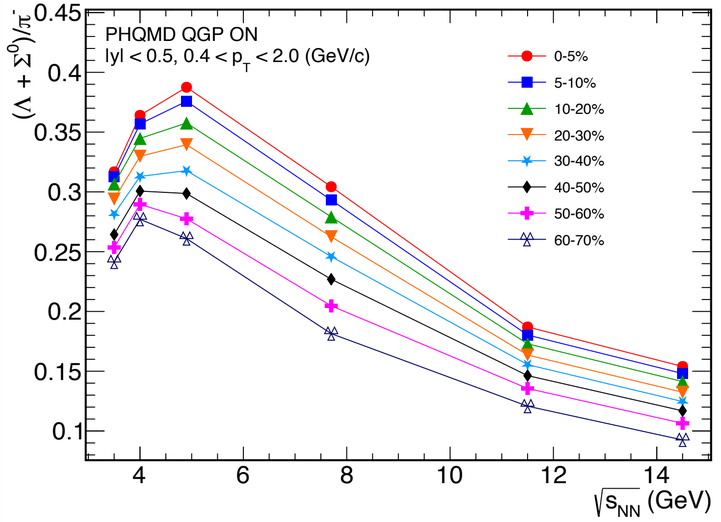
Centrality and energy dependence of $(\Lambda + \Sigma^0)/\pi^-$

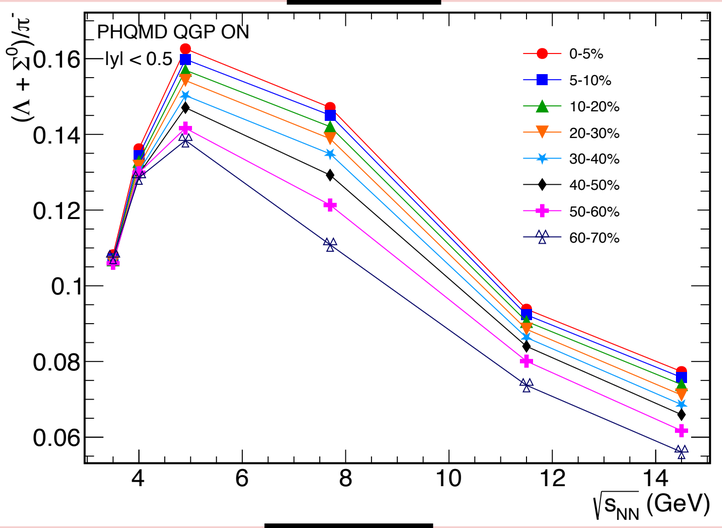
|y| < 0.5, 0.4 < p_T < 2.0

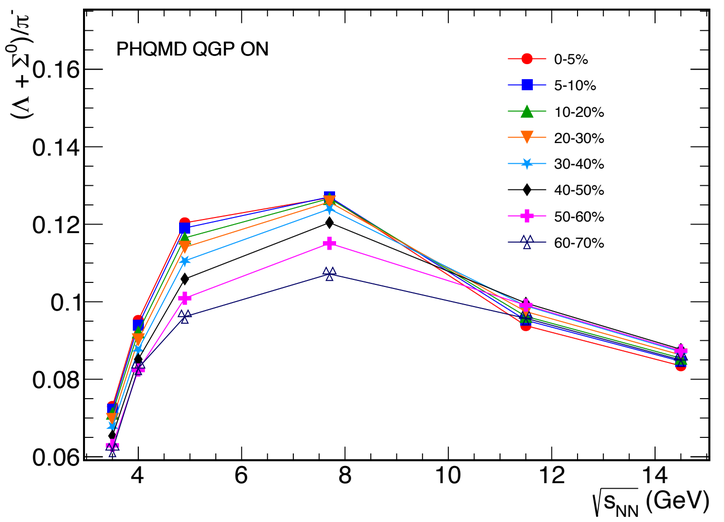
|y| <0.5

QGP ON

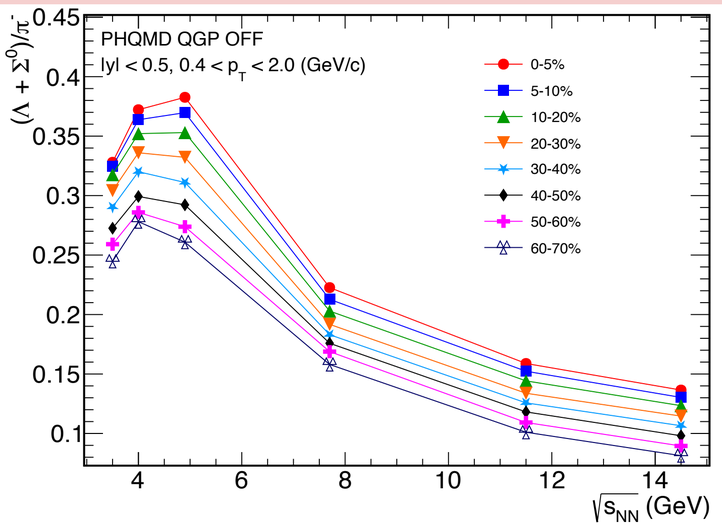
No y-p_T cut

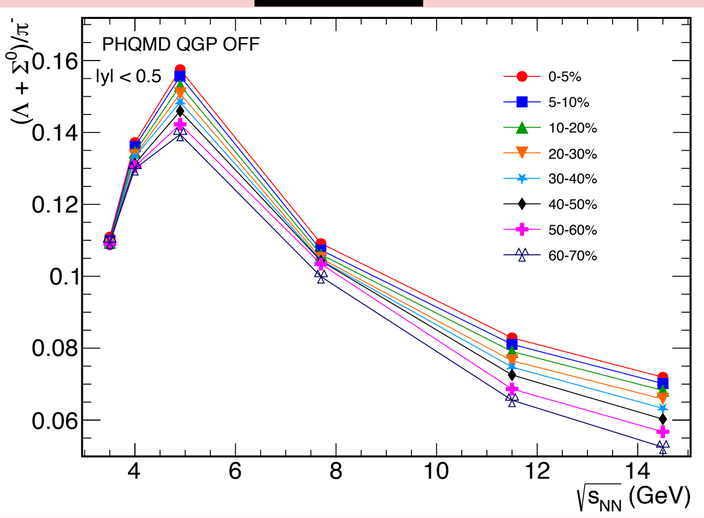


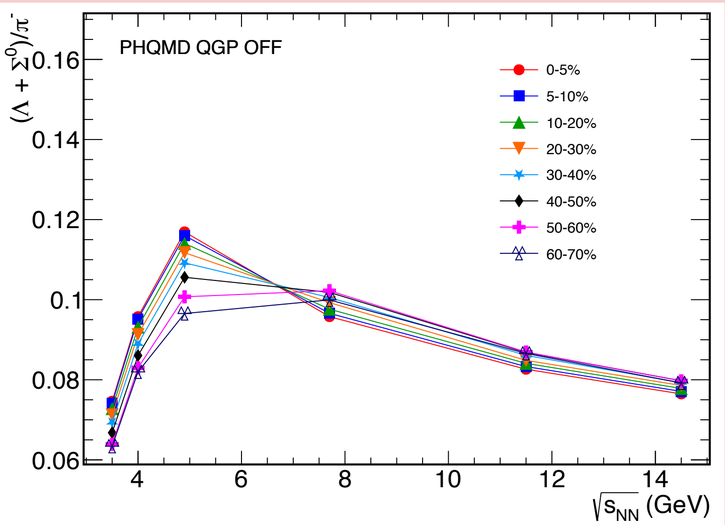




QGP OFF







Summary

✓ **Energy & centrality dependence of particle ratios studied in Au+Au collisions from FAIR/ AGS to SPS energies.**

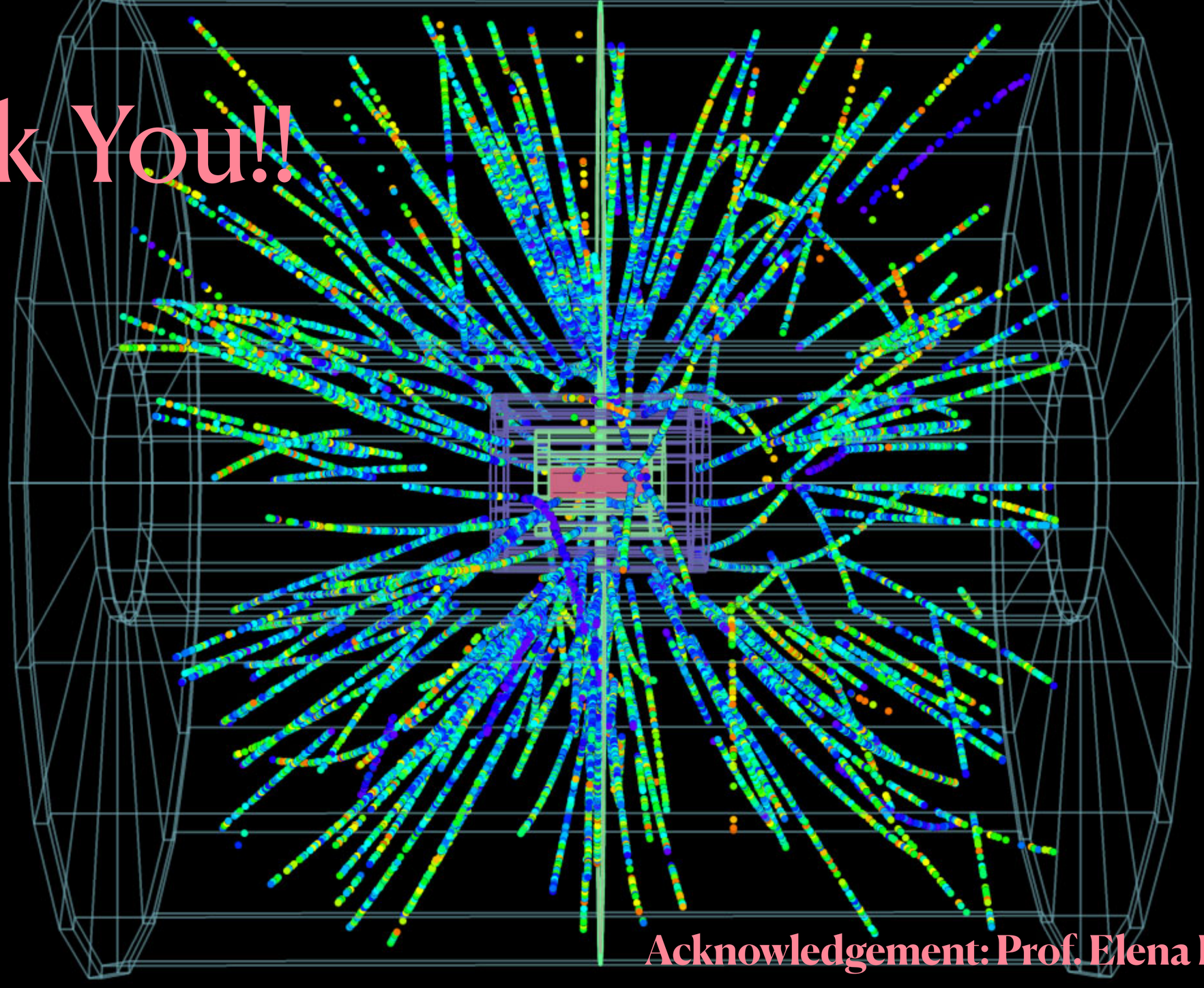
✓ **Different acceptances, with/without QGP phase.**

✓ **Rapidity spectra: Clear QGP ON vs OFF differences at $\sqrt{s}_{NN}$=7.7 GeV (most pronounced for Λ, K at midrapidity). At $\sqrt{s}_{NN}$=11.5, 14.5 GeV → differences persist but weaker.**

✓ **Horn structure in K^+/π^+ ratio reproduced in PHQMD (QGP ON), consistent with experimental data.**

Results indicate: Strangeness enhancement well described. Supports chiral symmetry restoration (CSR) before deconfinement.

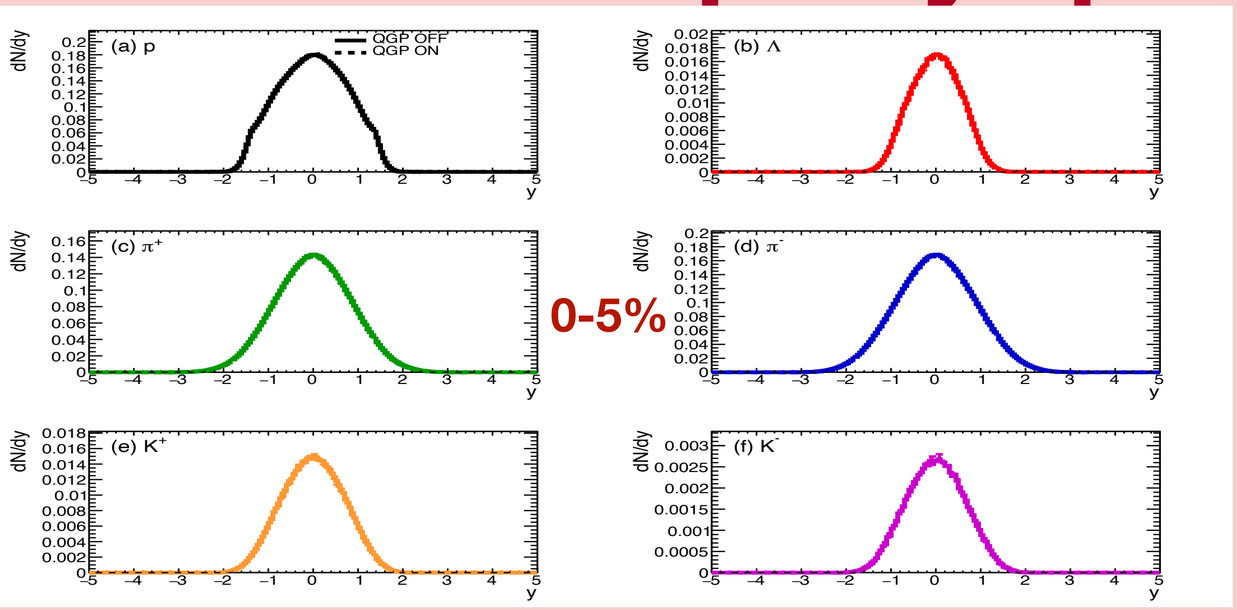
Thank You!!



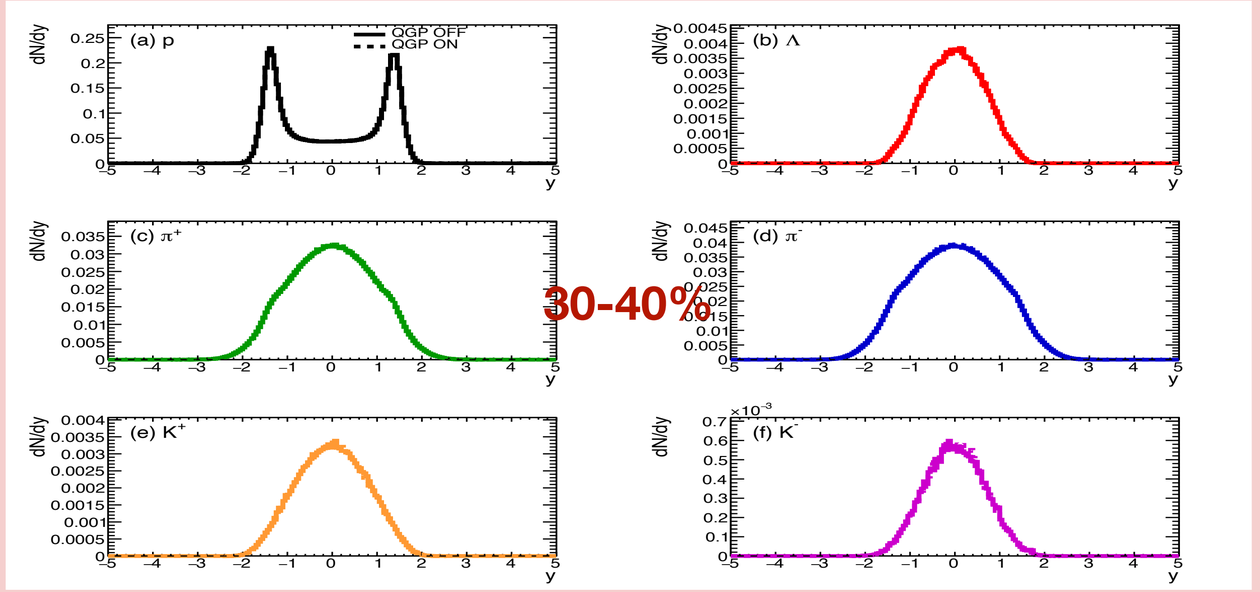
Acknowledgement: Prof. Elena Bratkovskaya

Backup

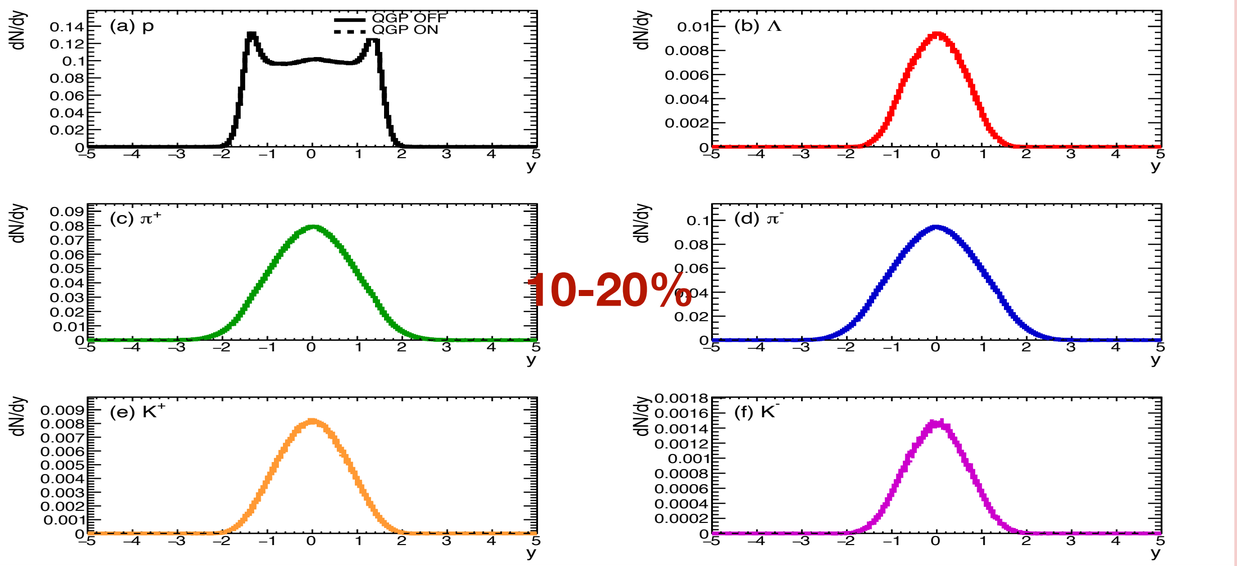
Rapidity spectra for 4.0 GeV



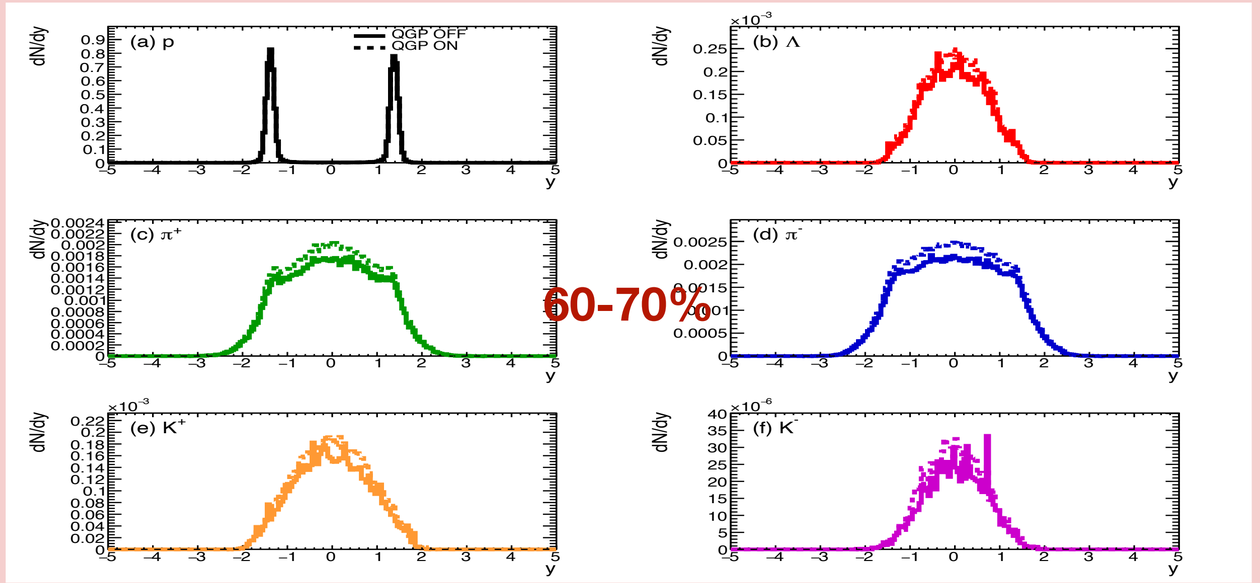
0-5%



30-40%

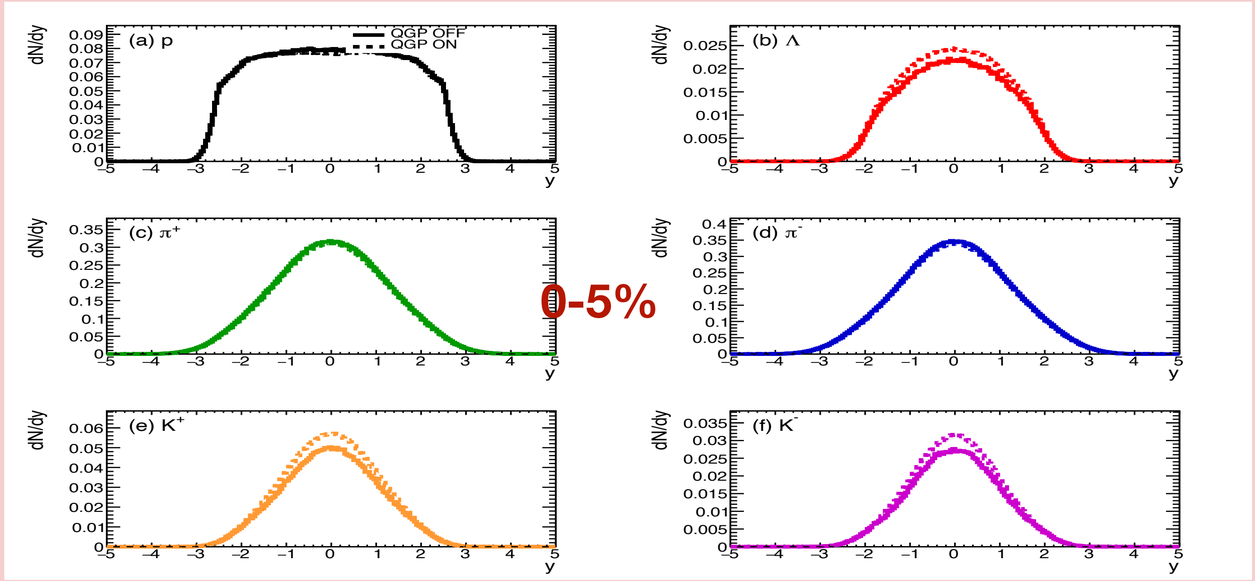


10-20%

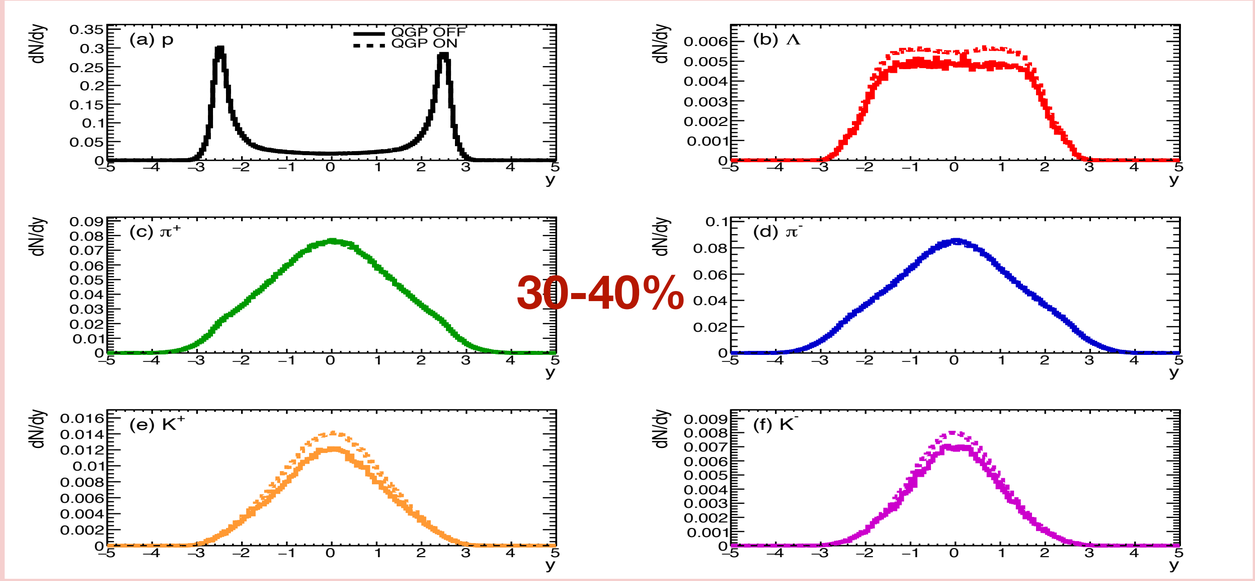


60-70%

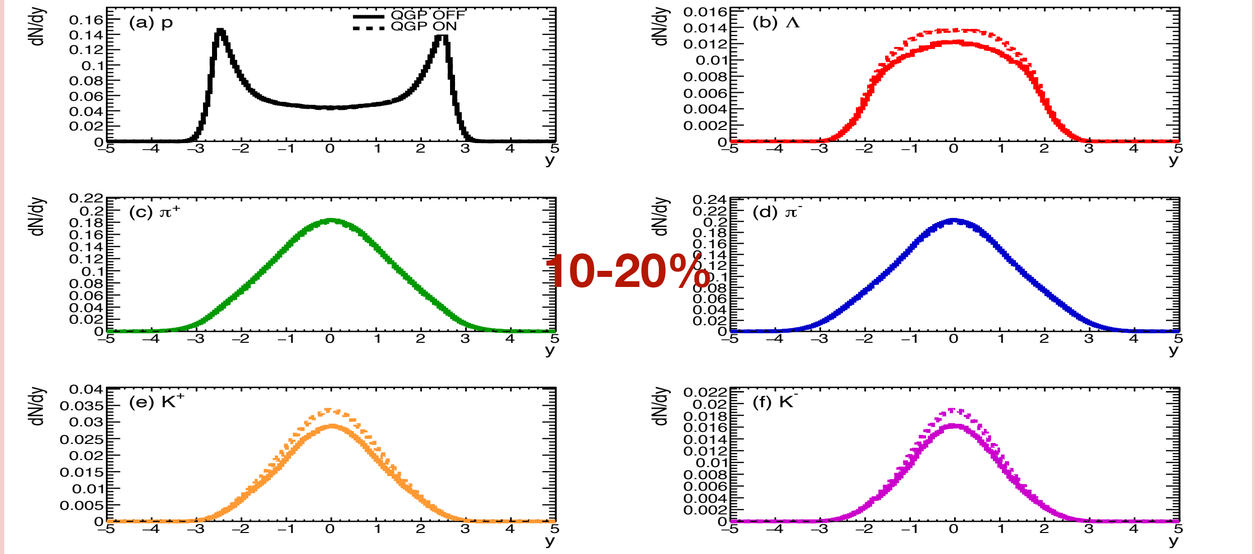
Rapidity spectra for 11.5 GeV



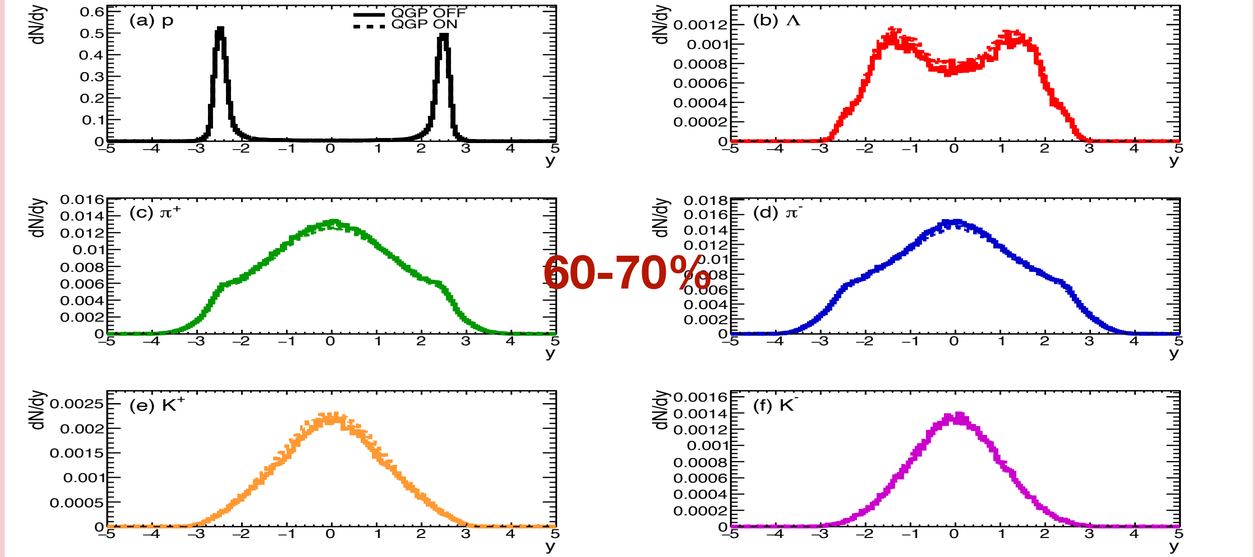
0-5%



30-40%

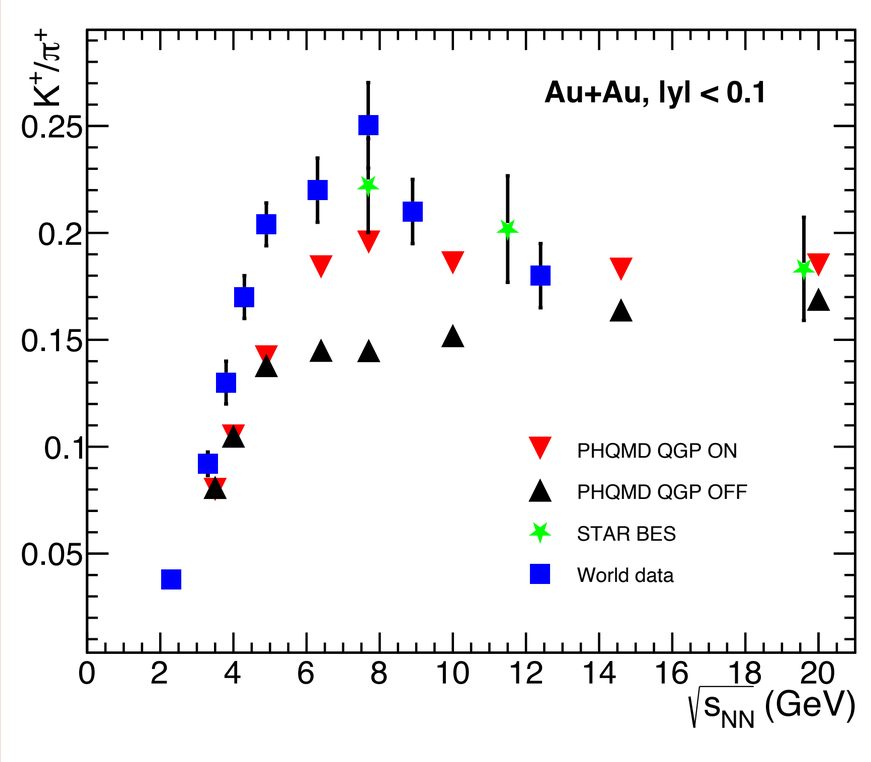


10-20%



60-70%

Strangeness enhancement



K^+/π^+ ratio of PHQMD model at mid-rapidity considering b_{max}=3.2 fm and compared with 0-5% central mid-rapidity data

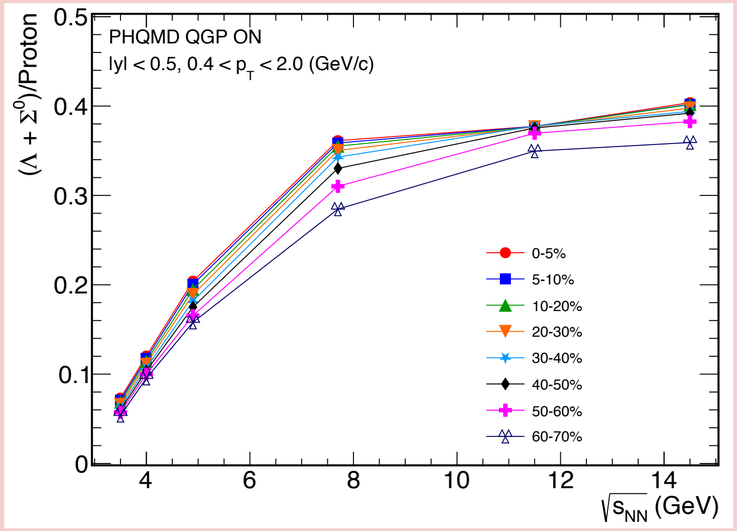
- **A clear distinction is observed between QGP ON and OFF states in the K^+/π^+ ratio within 6-10 GeV.**

Ref: L. Adamczyk, et al., Phys. Rev. C, 96, 044904 (2017)

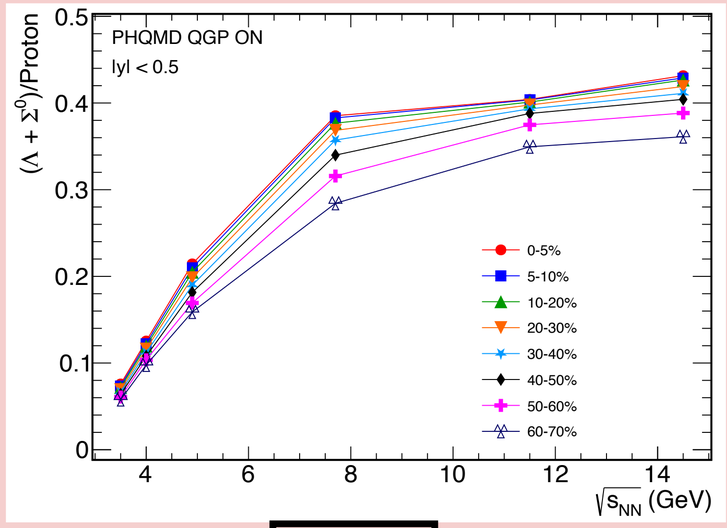
$(\Lambda + \Sigma^0)/p$

QGP ON

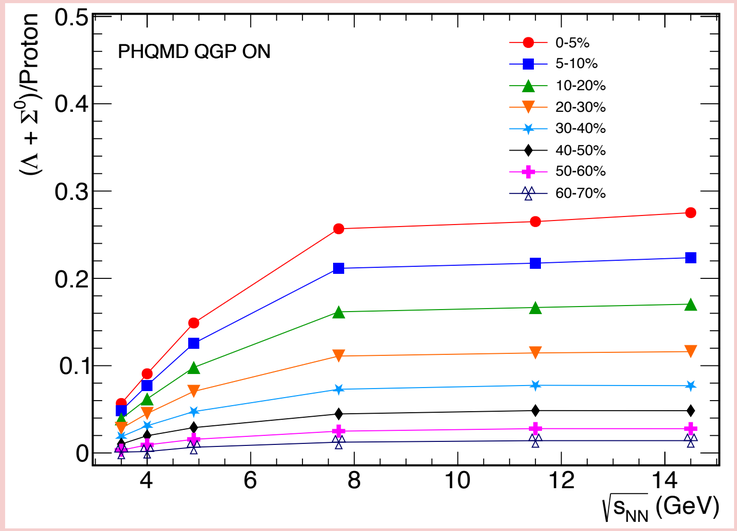
|y| < 0.5, 0.4 < p_T < 2.0



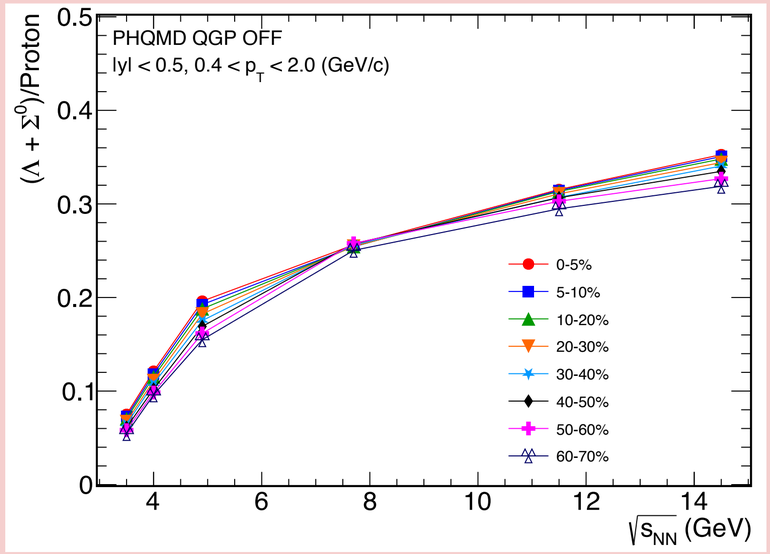
|y| <0.5

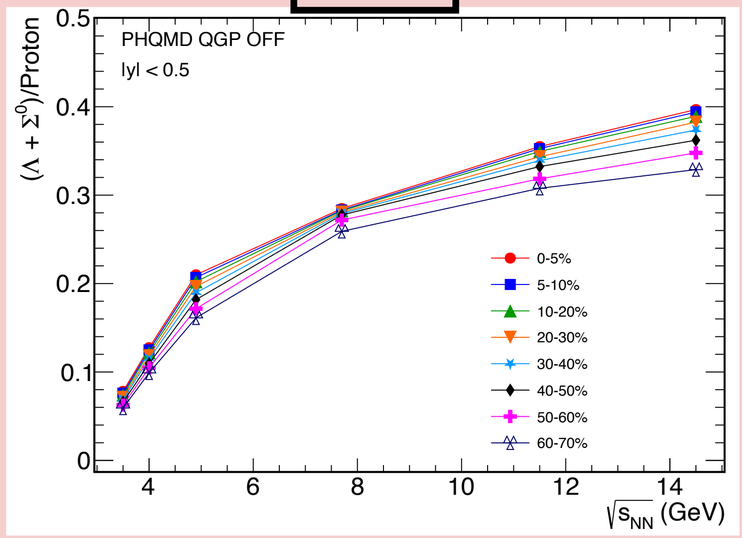


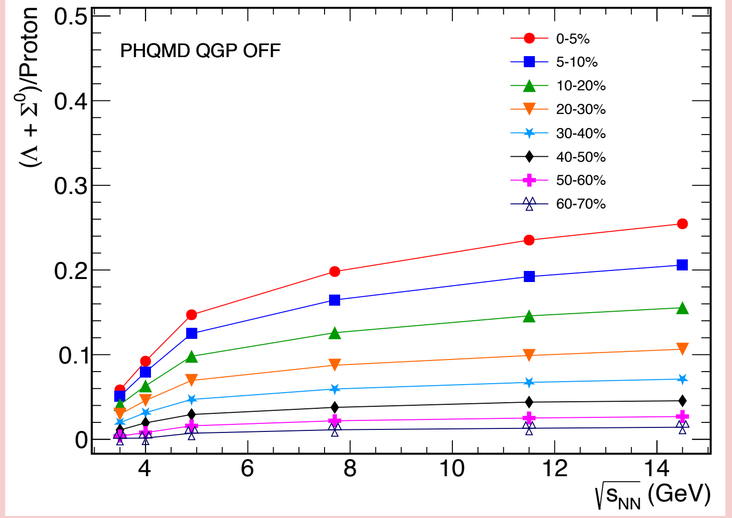
No y-p_T cut



QGP OFF





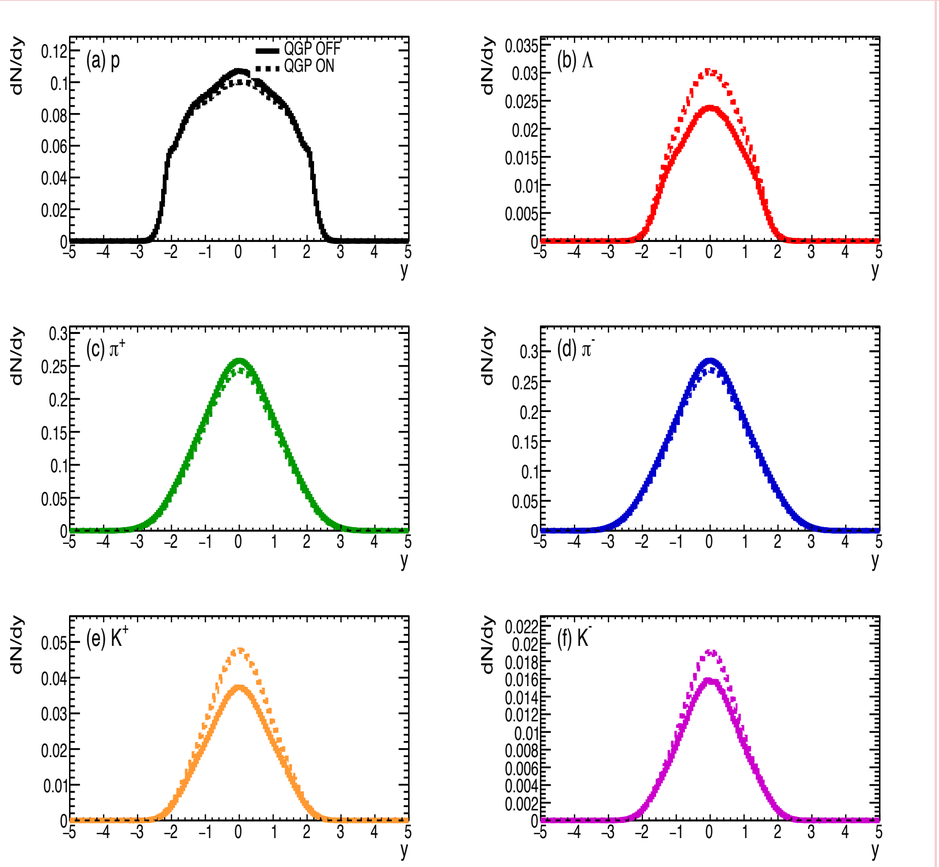


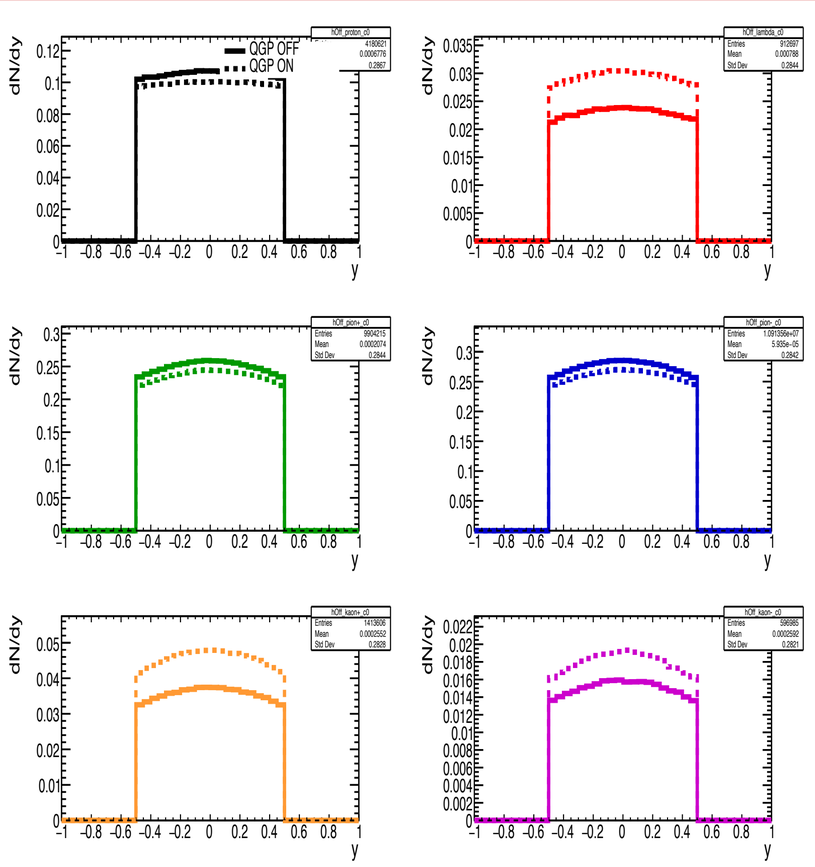
dN/dy comparison for 7.7 GeV (0-5%)

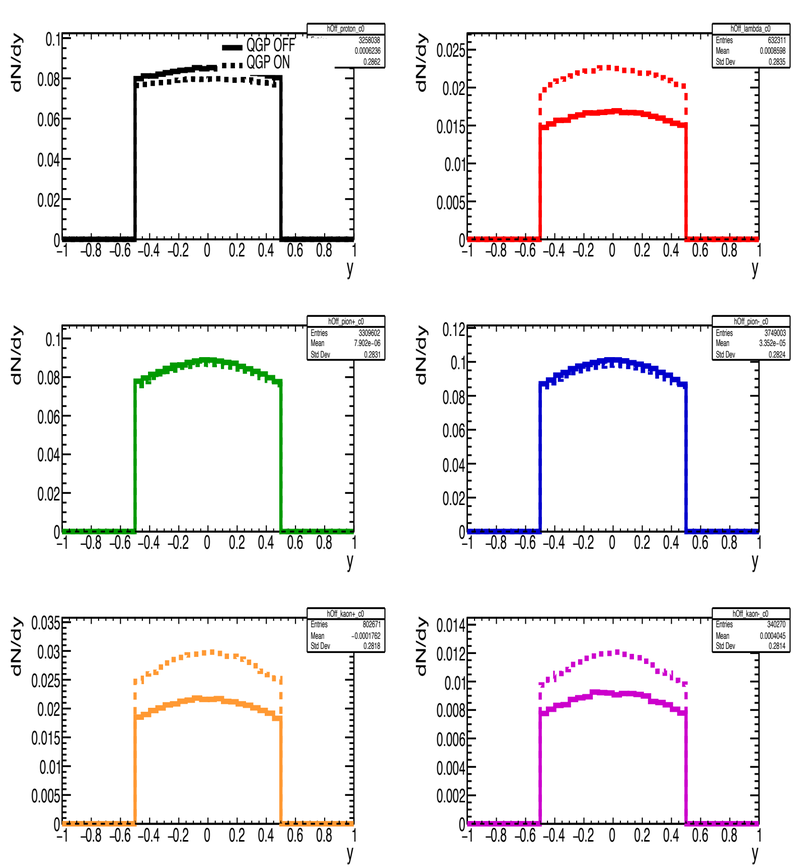
No y-p_T cut

|y| <0.5

|y| < 0.5, 0.4 < p_T < 2.0







dN/dy comparison for 7.7 GeV (60-70%)

No y-p_T cut

|y| <0.5

|y| < 0.5, 0.4 < p_T < 2.0