Emission shape evolution in the Monte Carlo models of heavy-ion collisions

Mátyás Molnár, Eötvös Loránd University

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ACHT, Budapest

Outline

- Phenomenology
  - Correlation functions in femtoscopy
  - Lévy-type source function
- Monte Carlo models
  - EPOS4 and UrQMD comparison
- $D(\rho)$ analysis
  - Results
    - EPOS4, UrQMD at STAR energies
    - Other

CORRELATION FUNCTIONS IN FEMTOSCOPY

- Correlation function for bosons with the invariant momentum distributions N_1, N_2:

  ↪ in this analysis: $\pi^+\pi^+$ and $\pi^-\pi^-$

$$C_2(p_1,p_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_2(p_2)} \Longrightarrow C_2(q,K) \approx 1 + \left|\frac{\tilde{S}(q,K)}{\tilde{S}\,(0,K}\right|^2,$$

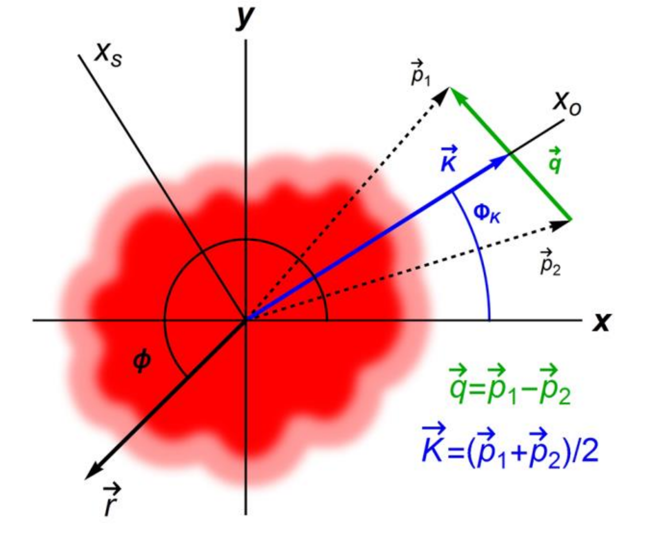
  where

$$N_2(p_1,p_2) = \int S(x_2,p_2)|\Psi_2(x_1,x_2)|^2 \mathrm{d}^4x_2\mathrm{d}^4x_1,$$
$$\tilde{S} = \int S(x,k)e^{iqx}\mathrm{d}^4x,$$
$$K = \frac{k_1+k_2}{2} \text{ (or } p_1,p_2),$$
$$q = k_1 - k_2.$$

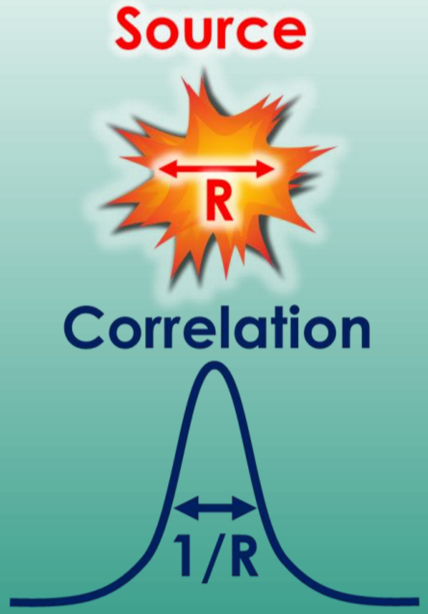
- **Event shape**: $D(r,K) = \int S(x_1,K)S(x_2,K)\mathrm{d}^4\rho = \int S\left(\rho+\frac{r}{2},K\right)S\left(\rho-\frac{r}{2},K\right)\mathrm{d}^4\rho$ with average $\rho = \frac{x_1+x_2}{2}$ and relative $r = x_1 - x_2$
- With this, $C(q,K) = 1 + \int D(r,K)e^{-iqr}\mathrm{d}^4r$

The Lévy-type source function

- Lévy-stable distribution can be assumed and tested for the source function [Csörgő, Hegyi, Zajc *Eur. Phys. J. C* 36 (2004)], [Csörgő et al. *AIP Conf. Proc.* 828 (2006)]:
$$S := L(\boldsymbol{x}, \alpha, R),$$
where
$$L = \frac{1}{(2\pi)^2} \int \mathrm{d}^3 q e^{iqr} e^{-\frac{1}{2}|\mathrm{qR}|^\alpha}$$
- Thus, the 2-particle correlation function
$$C_2(|k|) = 1 + \lambda e^{-(2R|k|)^\alpha},$$
(note: $|k| = \frac{|q|}{2}$)
- The spatial distribution
$$D(\boldsymbol{r}) = L(\boldsymbol{r}, \alpha, 2^{\frac{1}{\alpha}} R)$$
- In LCMS frame already K-independent:
$$D(r_{LCMS}) = \int \mathrm{d}\Omega_{LCMS} \mathrm{d}t D(\boldsymbol{r}_{LCMS})$$
(note: $\boldsymbol{r}_{LCMS}$ is the pair-separation vector in the lab frame)



[Plumberg & Heinz, Phys. Rev. C 98, 034910]

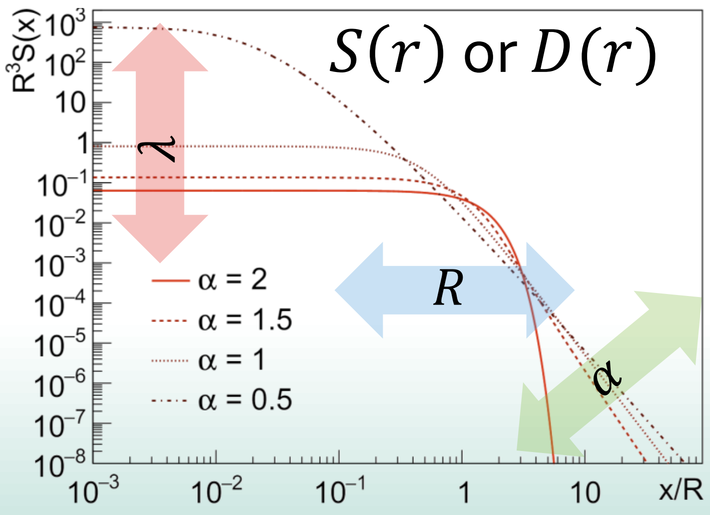


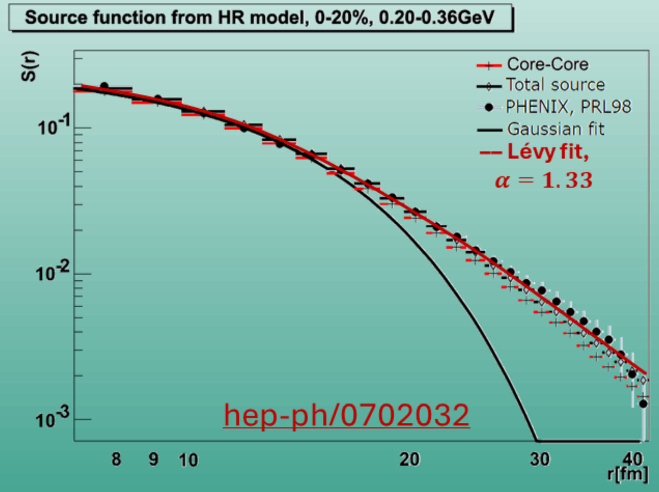
[CsM]

Gaussian or Lévy source?

- Either assumption needs to be *tested*
- Gaussian: corresponds to $\alpha = 2$
- Experimental results in 1D: indicate non-Gaussian ($\alpha \neq 2$) behaviour, Lévy distribution describes the data better.[Kincses, Nagy, Csanád *Communications Physics vol. 8* (55)], [Pórfy *arXiv:2410.13975v2 [nucl-ex]* 22 Apr 2025].

...as it will also appear in the simulations (?)





MONTE CARLO EVENT GENERATORS USED IN THIS ANALYSIS

EPOS

- Monte Carlo tool for simulating high-energy scatterings
- uses traditional S-matrix theory and modern concepts of perturbative QCD and saturation

K. Werner: *Revealing a deep connection between factorization and saturation: New insight into modeling high-energy proton-proton and nucleus-nucleus scattering in the EPOS4 framework*, Phys. Rev. C 108, 064903 – Published 6 December, 2023

K. Werner and B. Guiot *Perturbative QCD concerning light and heavy flavor in the EPOS4 framework*, Phys. Rev. C 108, 034904 (2023)

K. Werner *Parallel scattering, saturation, and generalized Abramovskii-Gribov-Kancheli (AGK) theorem in the EPOS4 framework, with applications for heavy-ion collisions at $\sqrt{s_{NN}}$ of 5.02 TeV and 200 GeV*, Phys. Rev. C 109, 034918 (2024)

K. Werner *Core-corona procedure and microcanonical hadronization to understand strangeness enhancement in proton-proton and heavy ion collisions in the EPOS4 framework*, Phys. Rev. C 109, 014910 (2024)

MONTE CARLO EVENT GENERATORS USED IN THIS ANALYSIS

EPOS4

In the latest version EPOS4:

- treatment of parton ladders completely redone
- saturation scales fixed by a prescription
- high precision applied in parallel scattering

K. Werner: *Revealing a deep connection between factorization and saturation: New insight into modeling high-energy proton-proton and nucleus-nucleus scattering in the EPOS4 framework*, Phys. Rev. C 108, 064903 – Published 6 December, 2023

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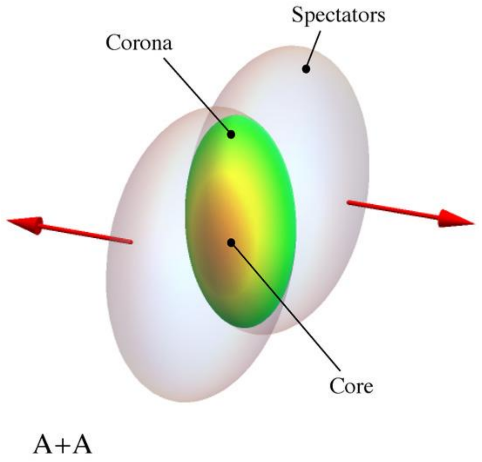
MONTE CARLO EVENT GENERATORS USED IN THIS ANALYSIS

EPOS4

UrQMD

[no ambiguous acronym here]



QUICK COMPARISON

EPOS4

[K. Werner *Phys. Rev. C 109*, 014910 (2024)], [Ayala et al. *MDPI Particles vol. 6. (1)*]

- Gribov—Regge-based + hydrodynamics
- Core-corona approach, viscous hydrodynamics, jet quenching
- QGP phase included
- Not a transport model per se
- Slower (hydro evolution)

UrQMD

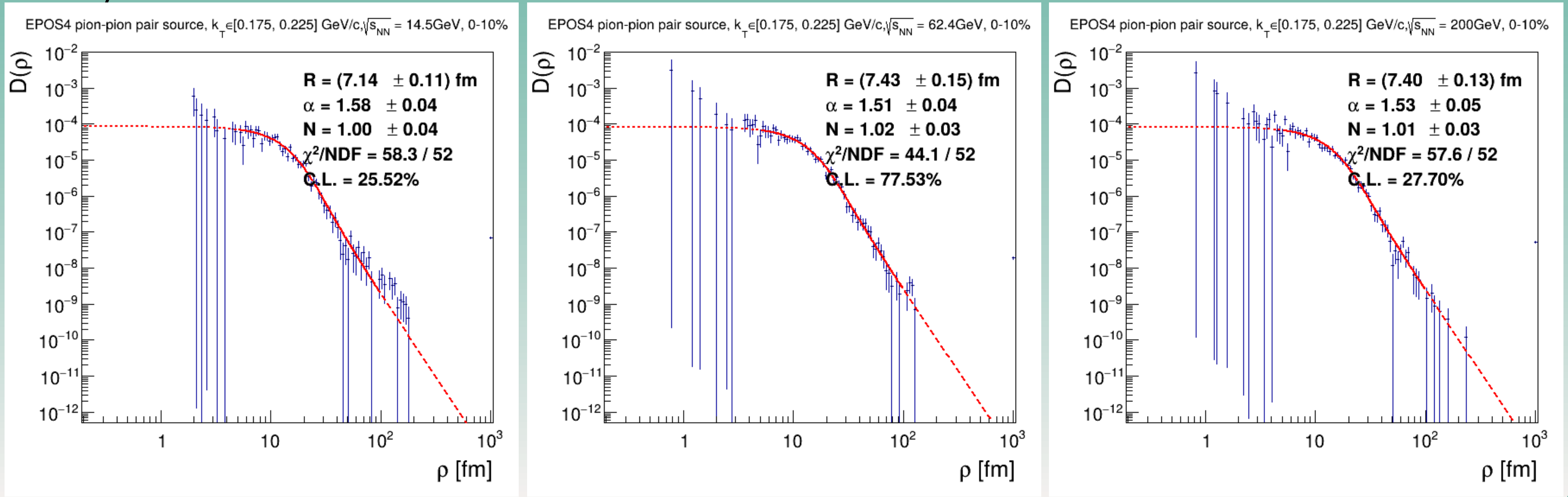
[Petersen, Hannah et al. *arXiv:0805.0567* (2008).]

- Microscopic transport model
- Binary hadronic and string interactions
- No explicit QGP/hydro
- Excellent for studying hadronic transport and rescattering
- Faster (no hydro)

$D(\rho)$ ANALYSIS METHOD

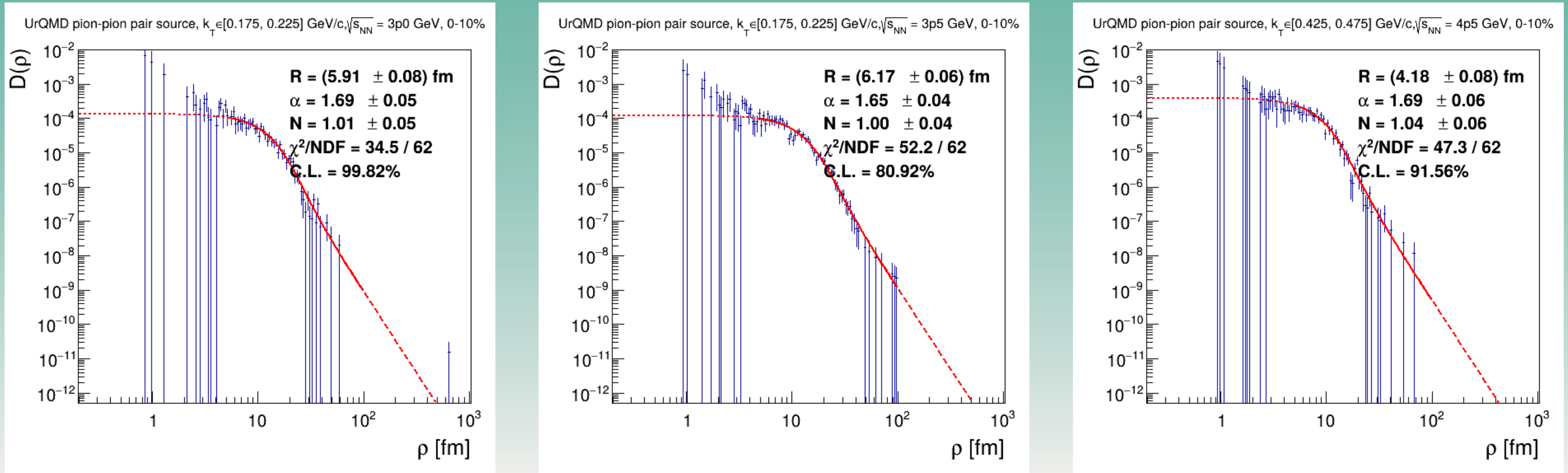
Pion pair event-by-event distribution

- Au+Au collisions simulated
- Separated into 10 $K_T = \frac{1}{2}\sqrt{K_x^2 + K_y^2}$ bins
- 1-dimensional projection along Bertsch—Pratt coordinates, cuts in η, p_T, q_{LCMS}
- Lévy-distribution fitted

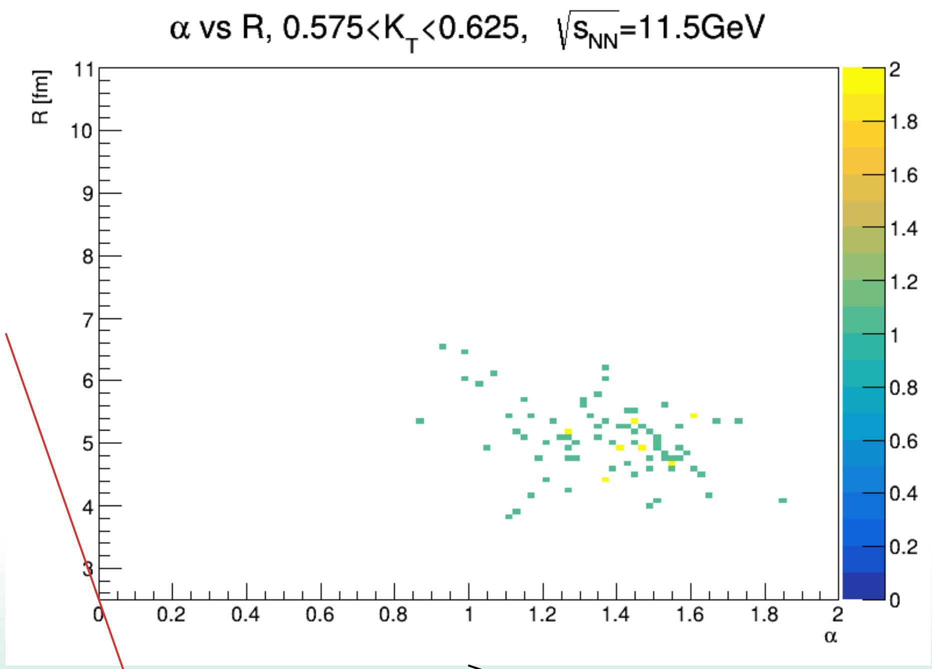


PION PAIR EVENT-BY-EVENT DISTRIBUTION

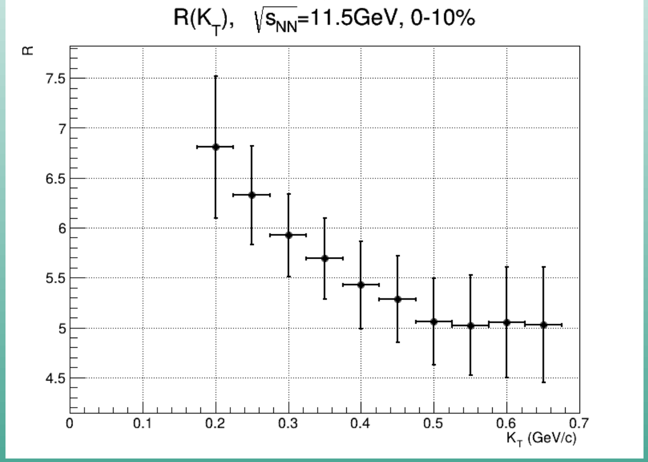
- Lower energies (UrQMD): **event averaging needed** (low statistics)
- Averaging 100 events' $D(r_{LCMS})$ distributions before fitting

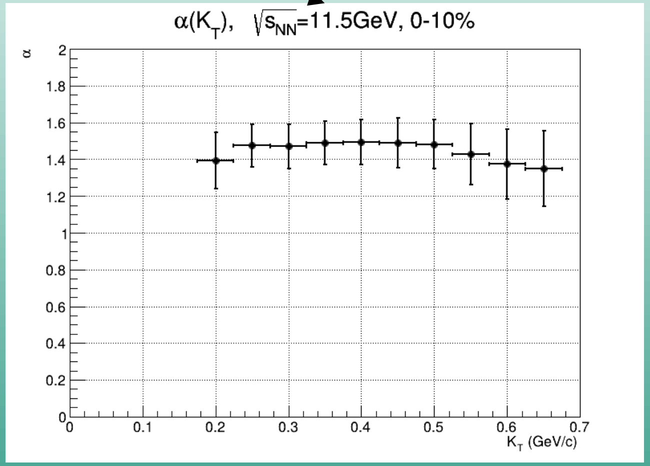


Fit parameter avg. & std. dev.



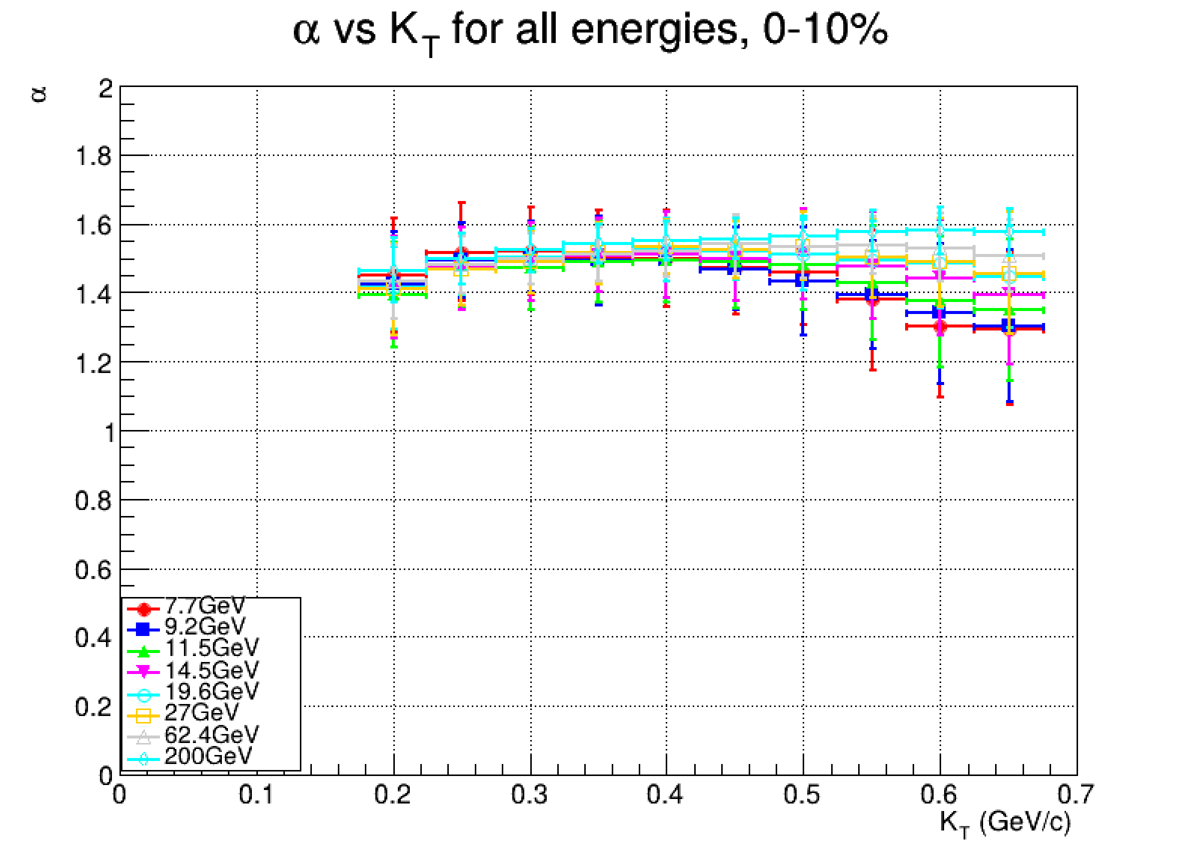
- Histograms of fit parameters (α, R)
- Fit parameter mean and standard deviation obtained
- As a function of K_T:
  - **α consistent with constant within uncertainty**
  - **R decreasing with K_T**

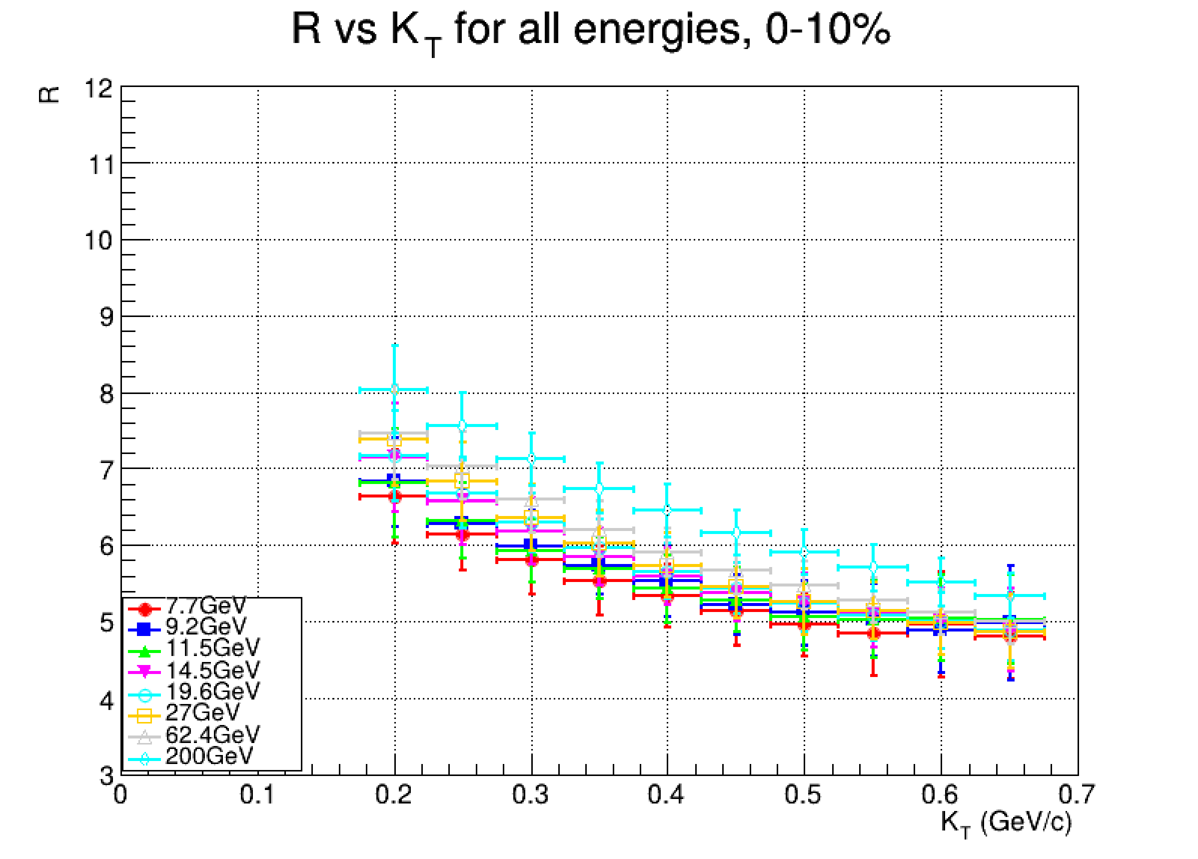




EPOS4 $\alpha(K_T), R(K_T)$

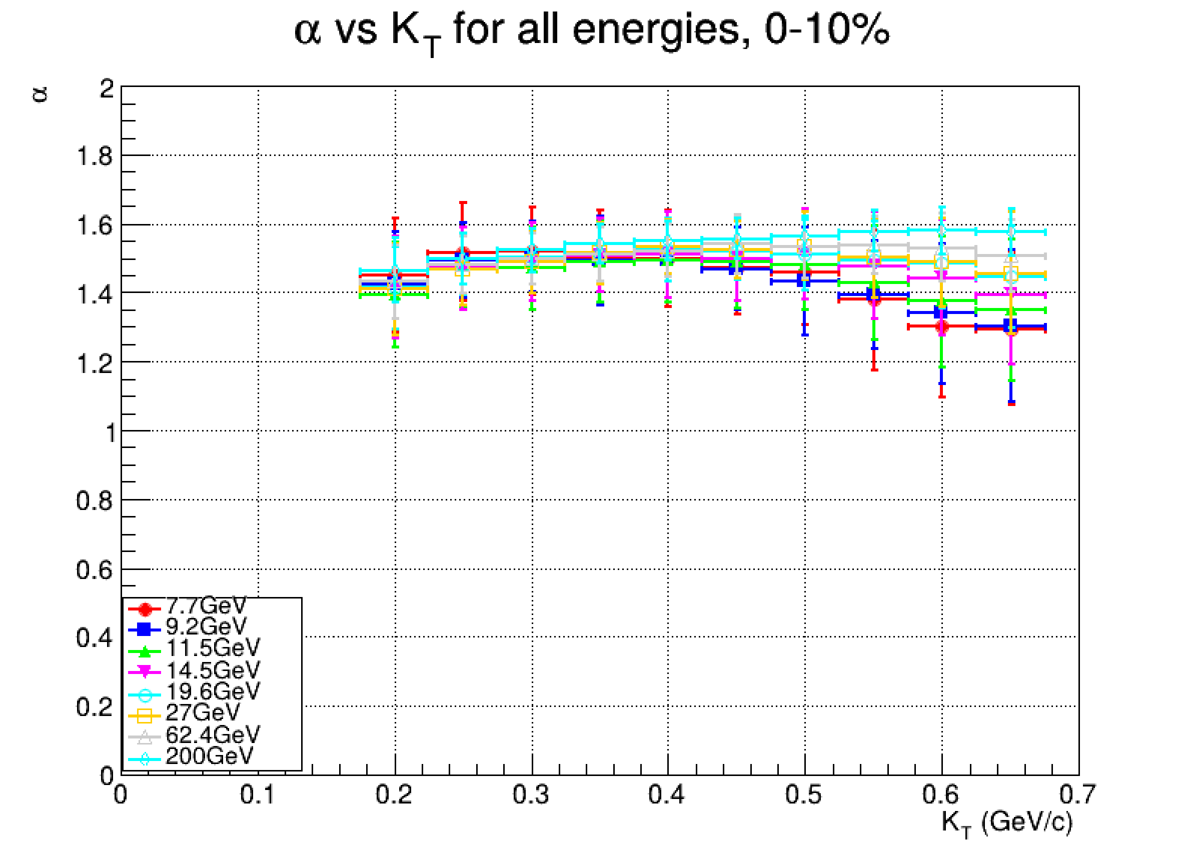
- In all analysed energies: **α consistent with constant within uncertainty**, **R decreasing with K_T**

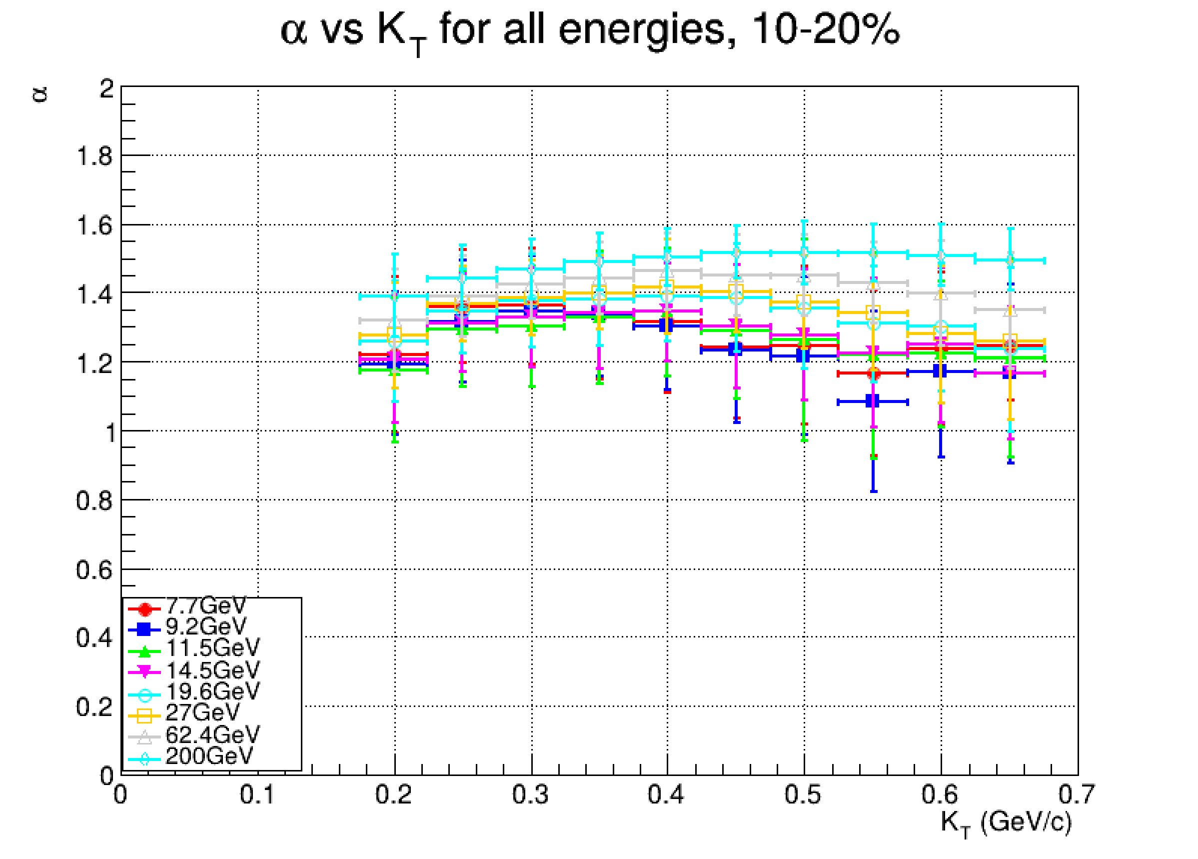




EPOS4 $\alpha(K_T)$ CENTRALITY DEPENDENCE

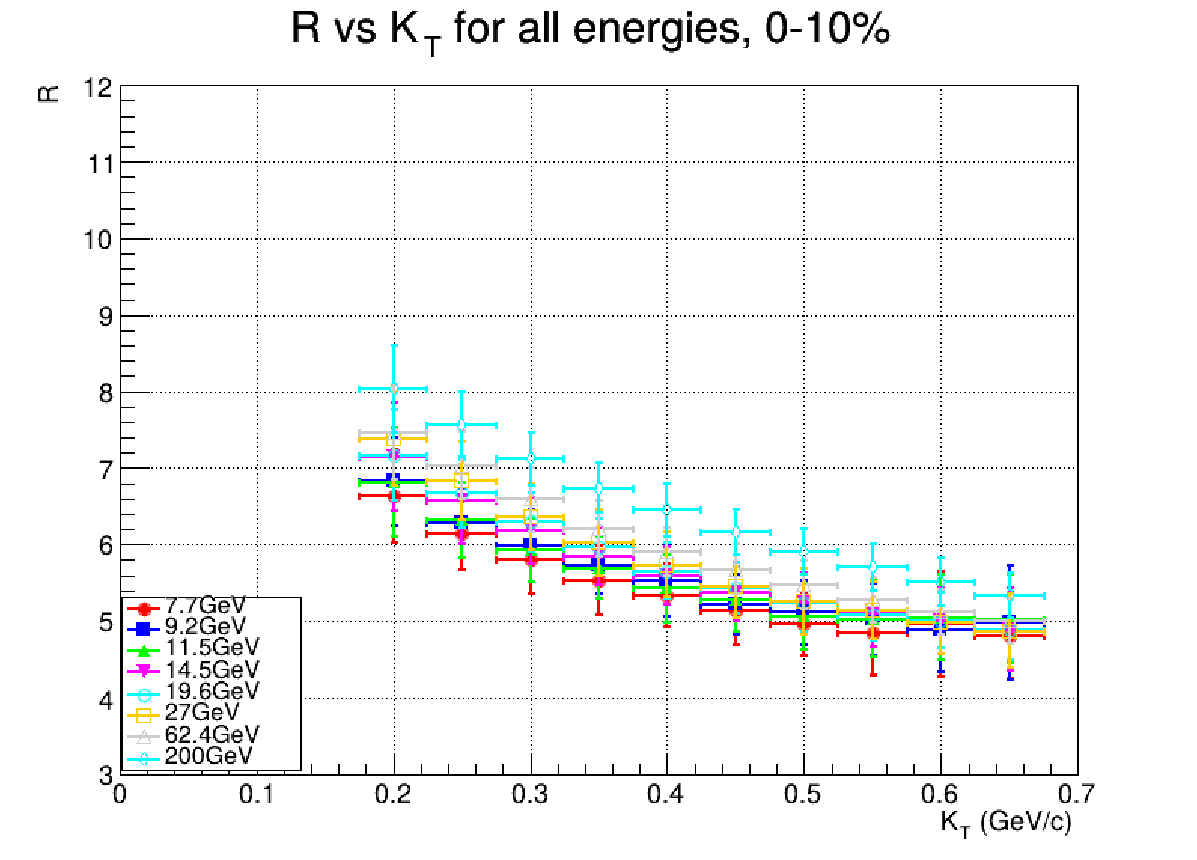
- Generally, a decreasing trend in parameter values with more peripheral collisions

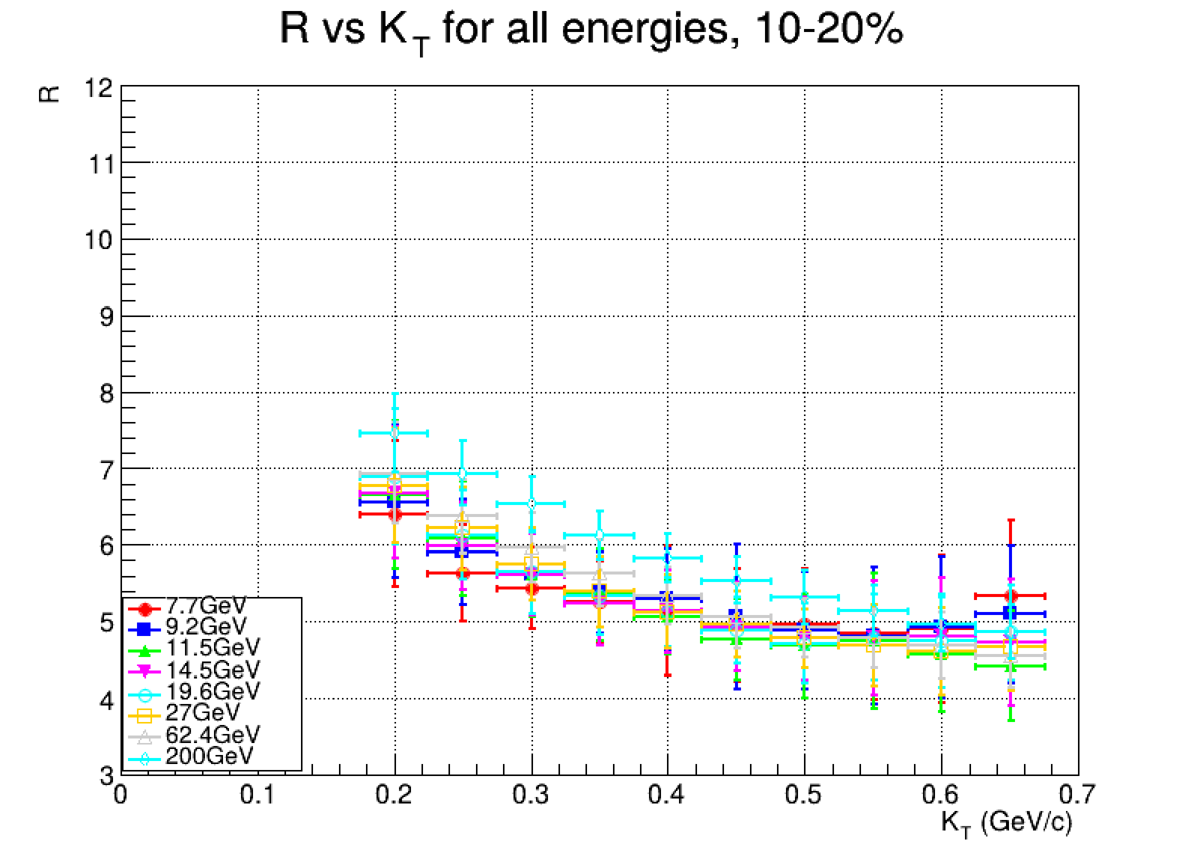




EPOS4 $R(K_T)$ CENTRALITY DEPENDENCE

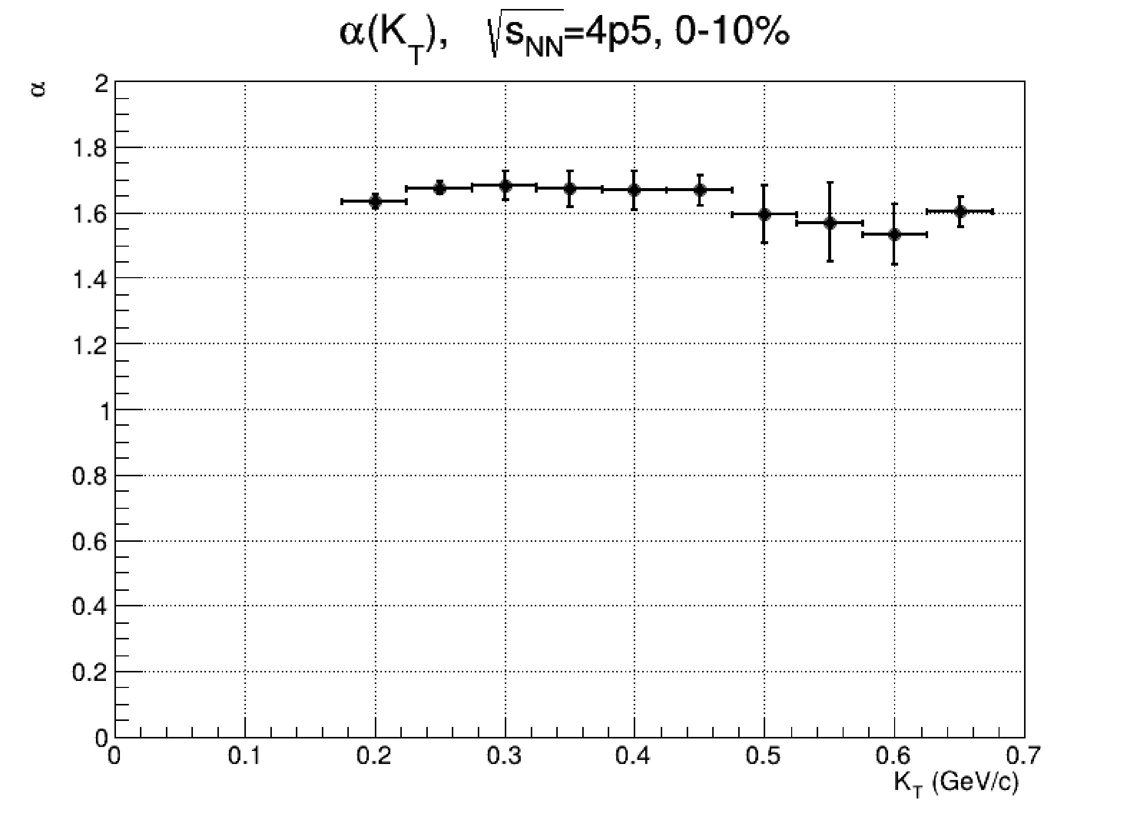
- Generally, a decreasing trend in parameter values with more peripheral collisions
- Fits for both parameters tends to be less reliable towards higher centralities & higher K_T bins (lack of statistics without event averaging)

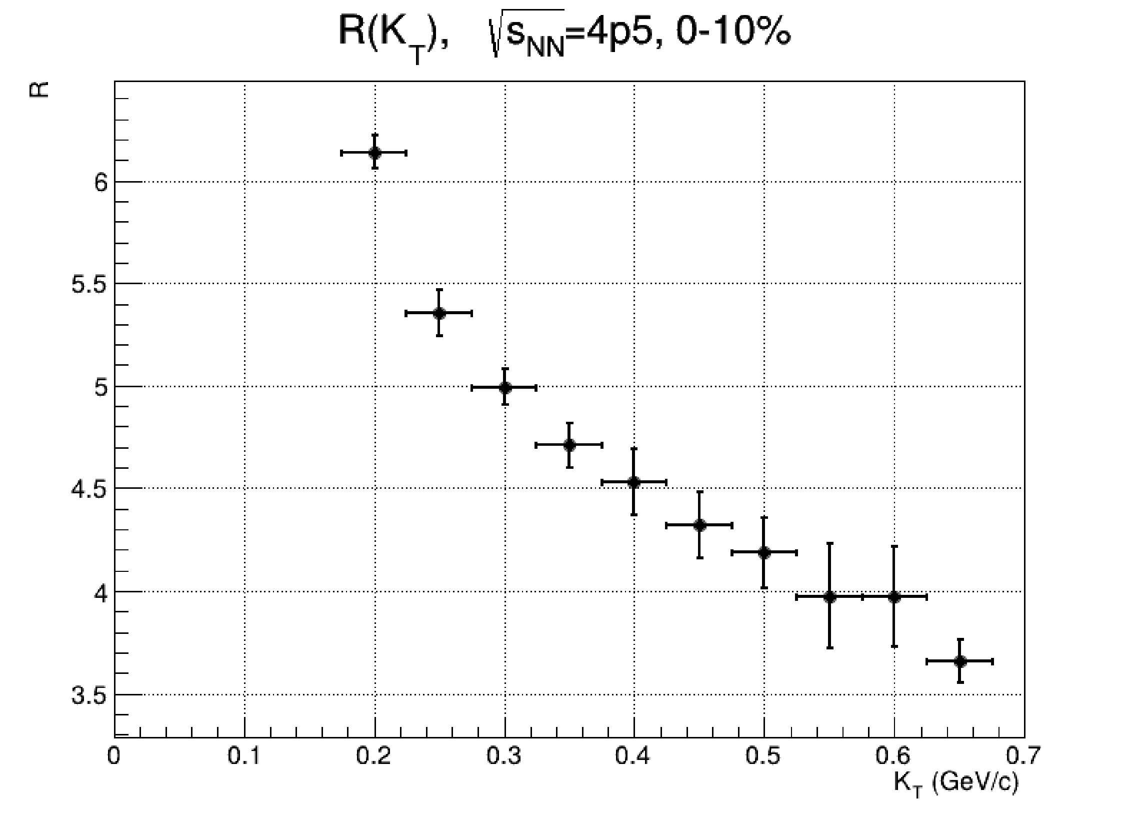




UrQMD $\alpha(K_T), R(K_T)$

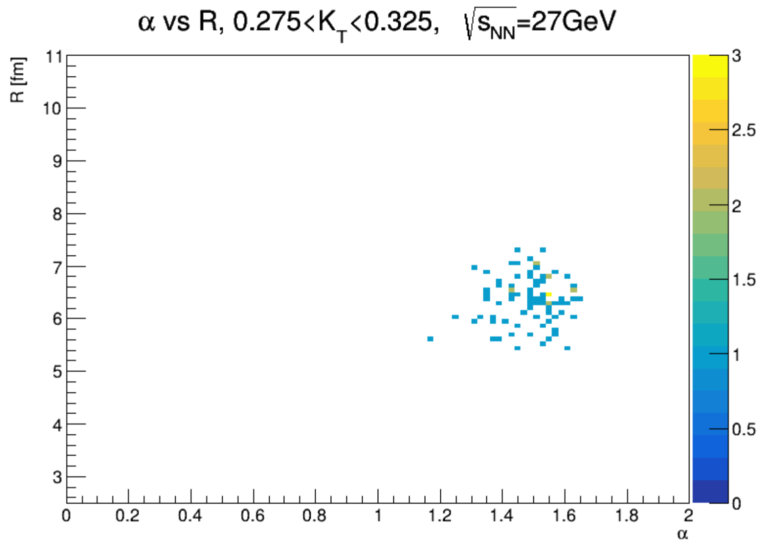
- Same trend with UrQMD analysis
- Event averaging applied ($D(r)$ fitted from 100-100 events)
- Still mostly too low statistics towards higher K_T bins



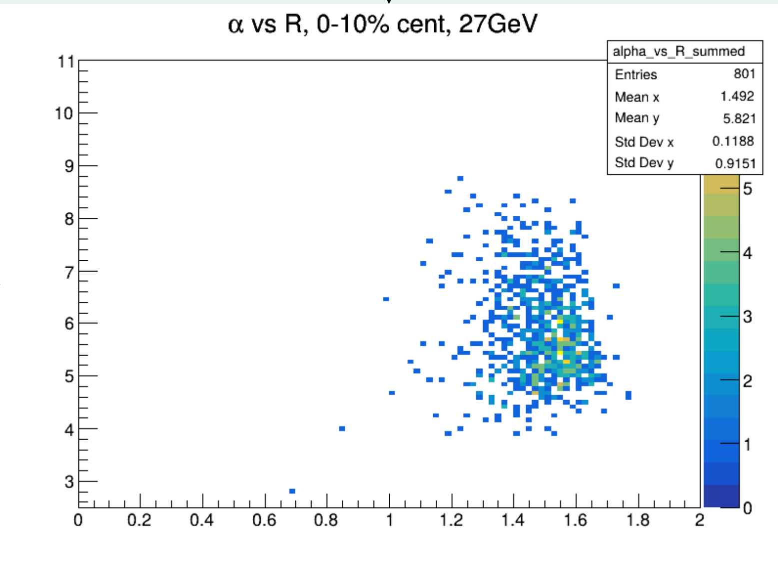


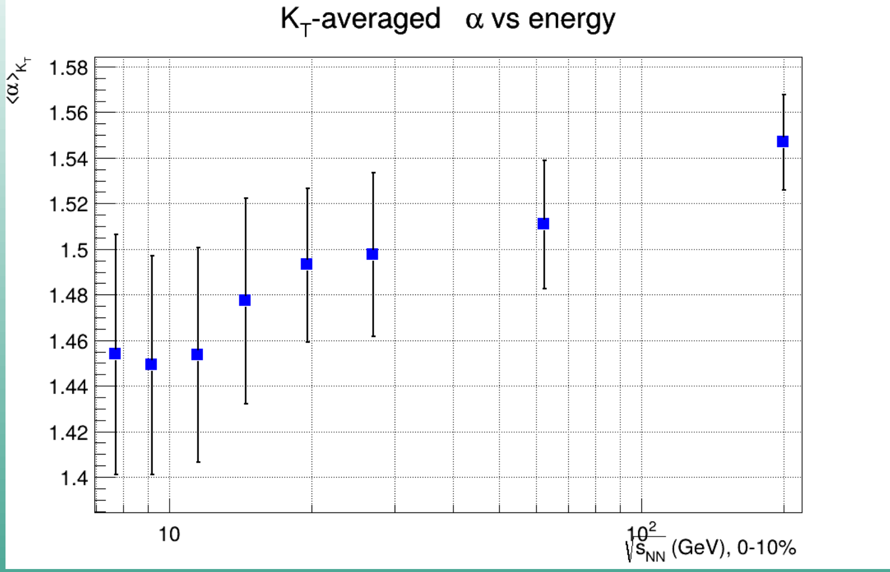
K_T-AVERAGED RESULTS

- Histograms of fit parameters averaged (summed)
- Mean and standard deviation (~uncertainty) obtained

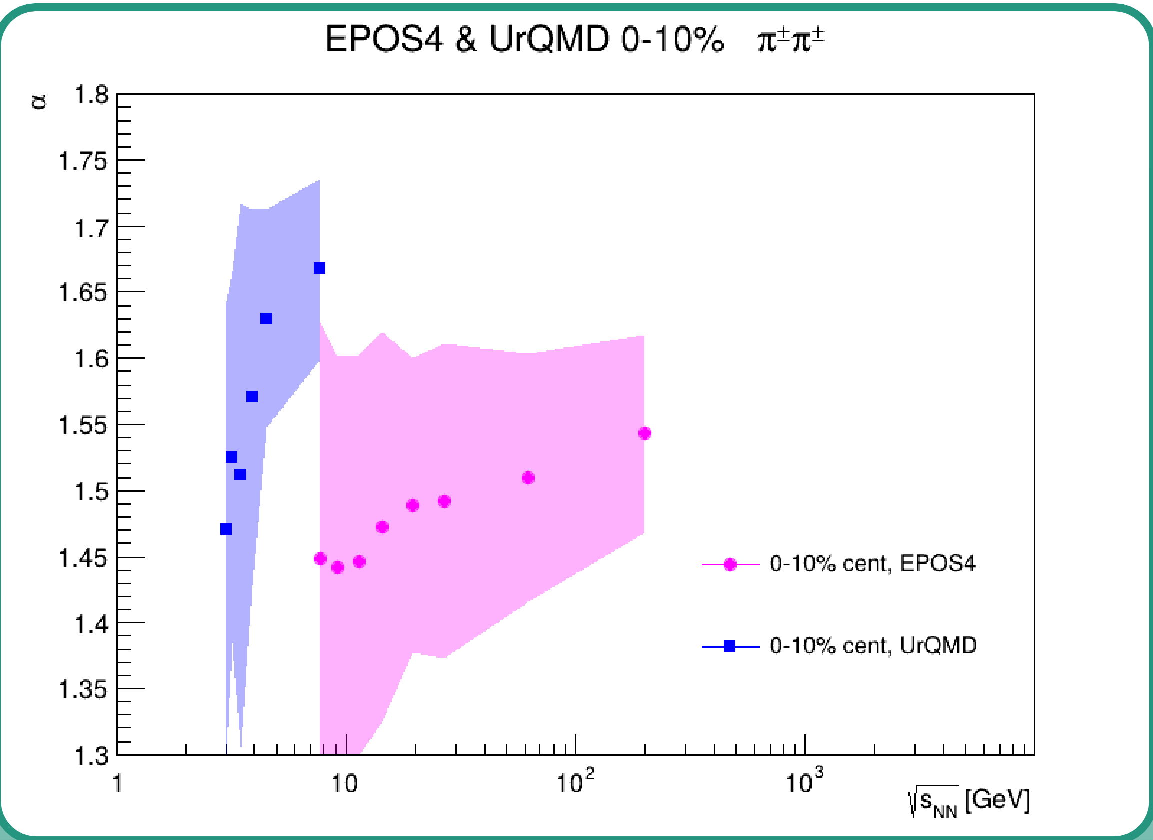


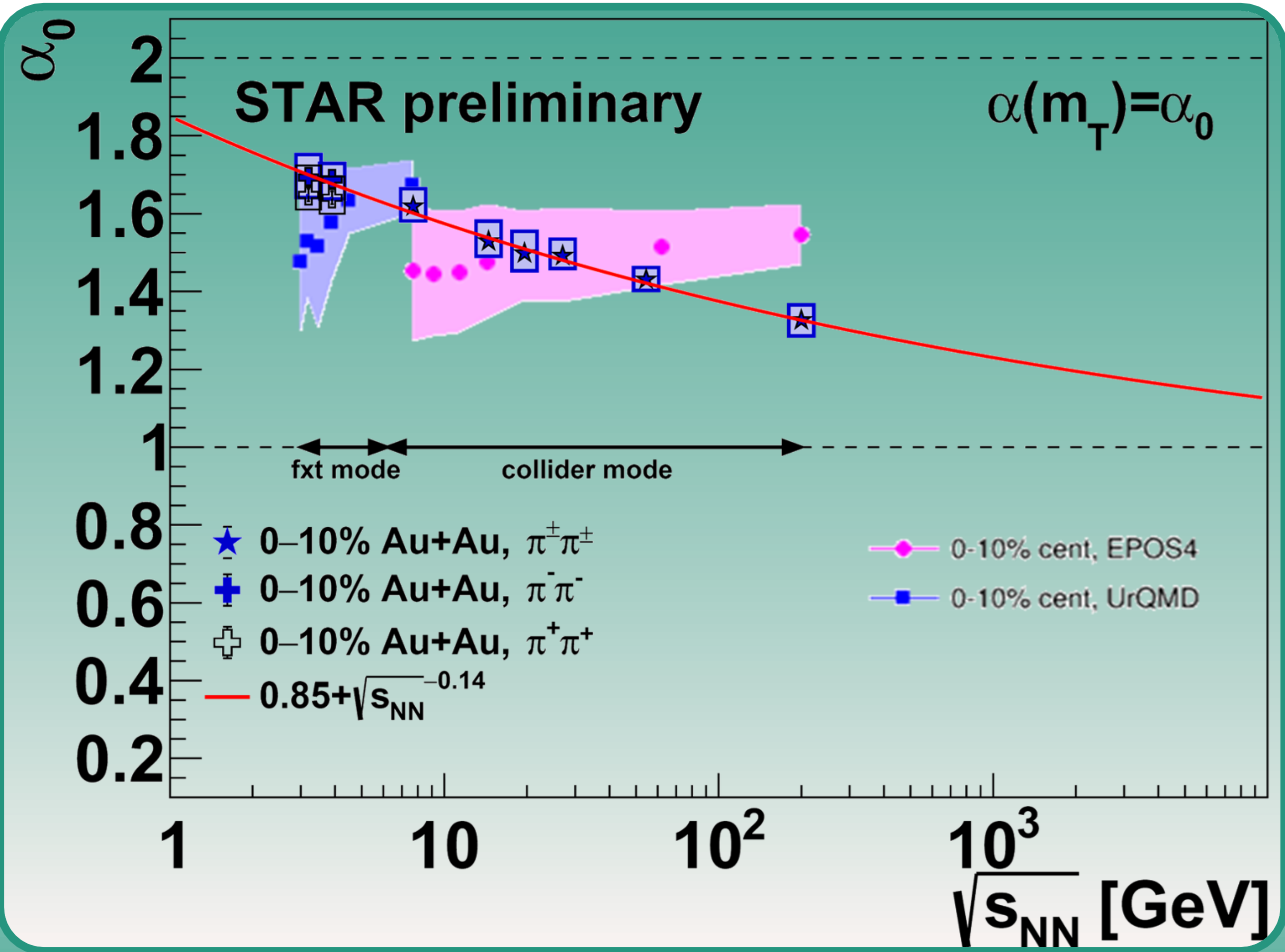
summing all K_T ranges





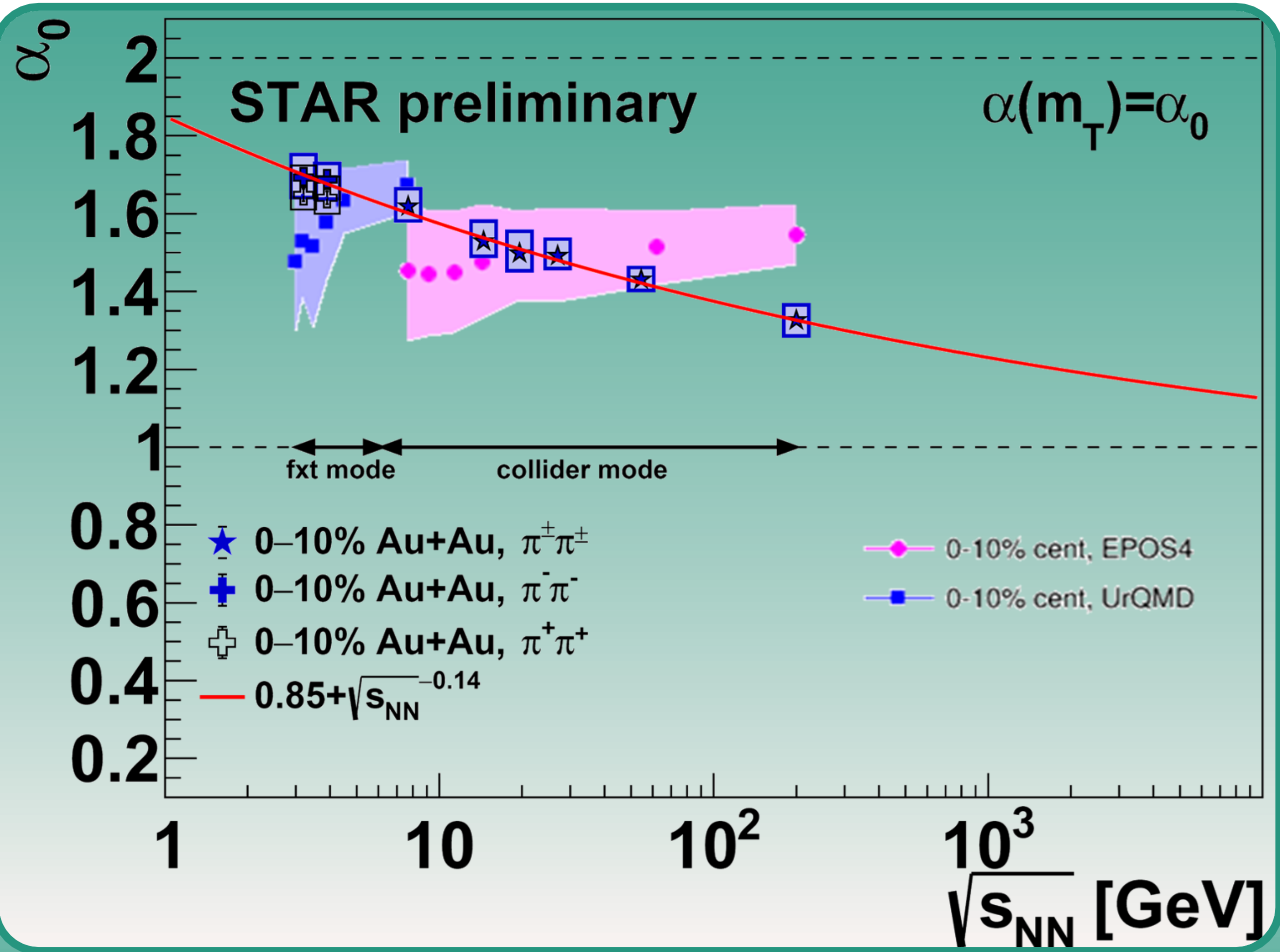
RESULT: EPOS4 & URQMD AT RHIC ENERGIES





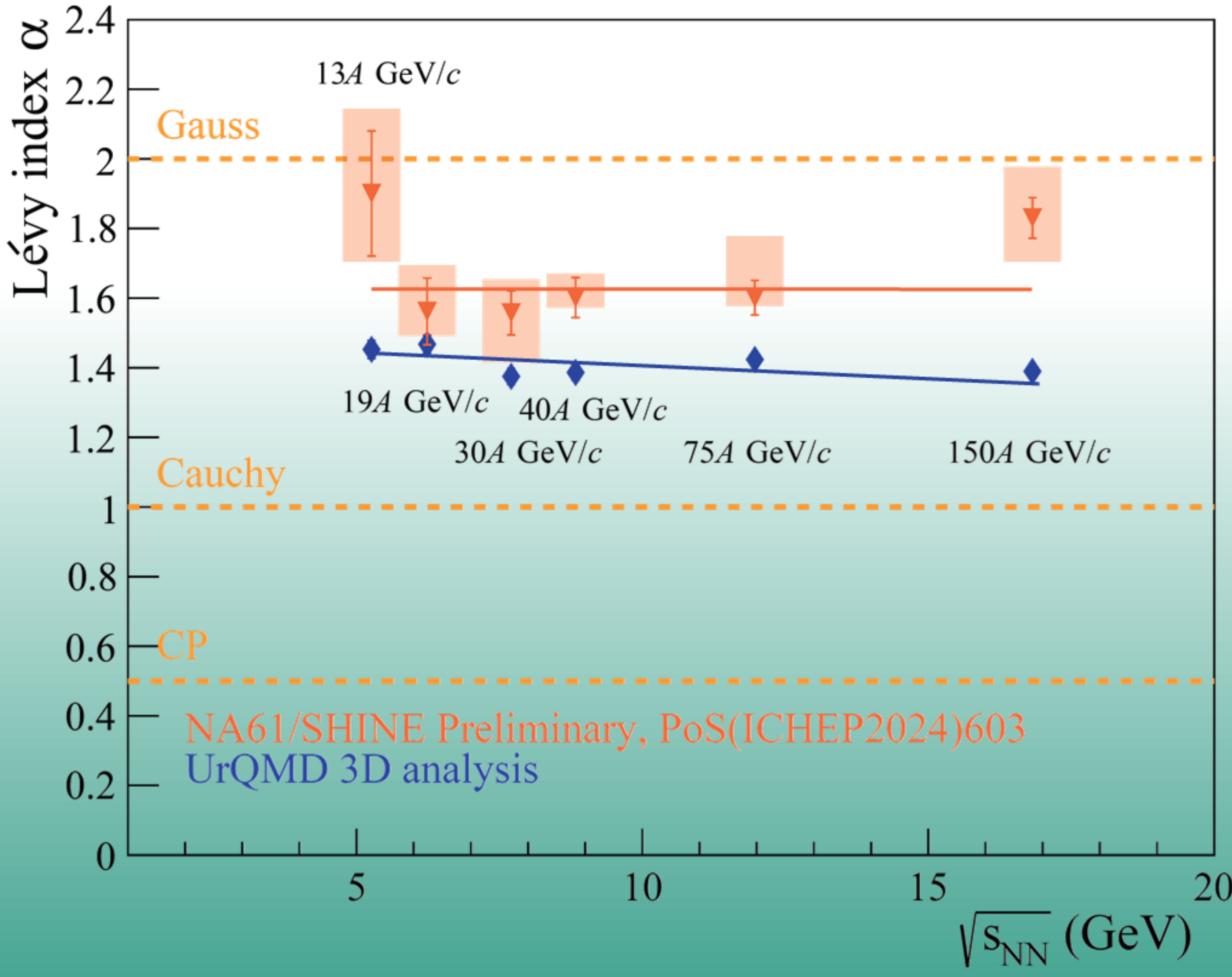
Result: EPOS4 & UrQMD at RHIC energies

- Au+Au
- Quantitatively (mostly within the "std. dev. uncertainty") not far from the $\sqrt{s_{NN}}$ = 3 to 60 GeV data
- Larger differences toward larger energies of collider mode & smallest energies of fixed-target mode
- **Different trend from the data** both in UrQMD & EPOS4 results



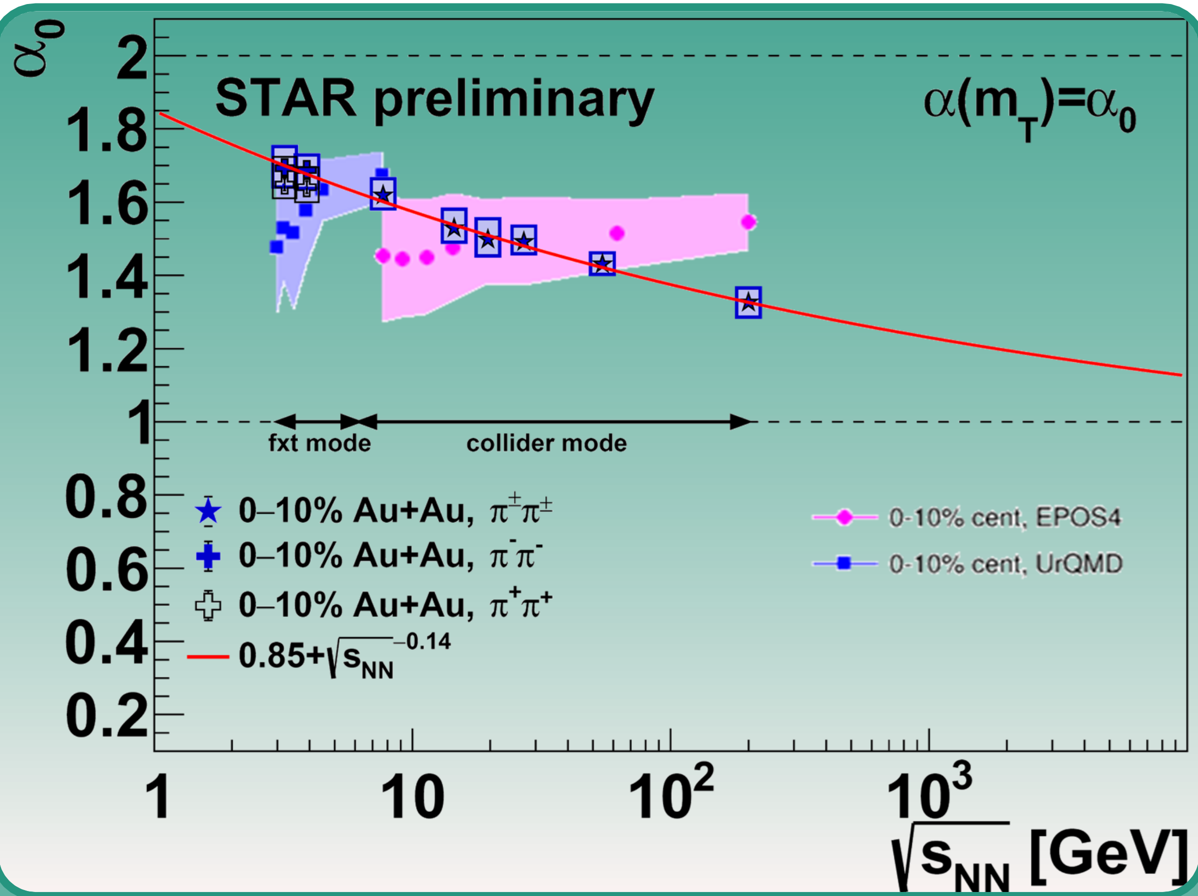
Another result: UrQMD at NA61 energies

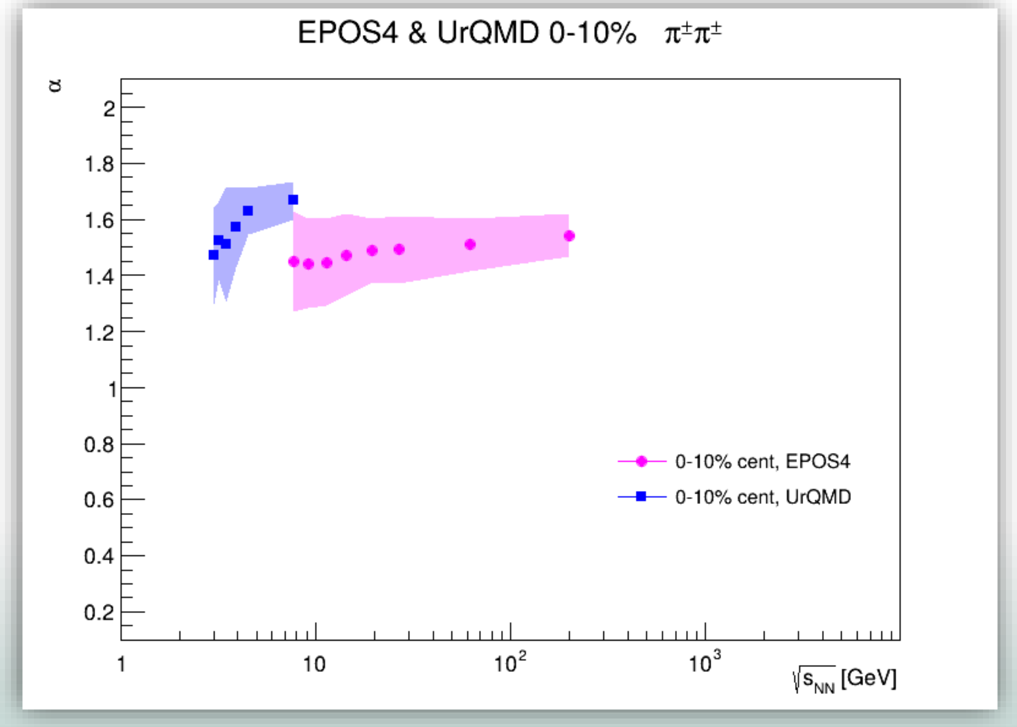
- Collisions 13*A* to 150*A* GeV/c energy (Ar+Sc)
  [The NA61/SHINE Collaboration, *arXiv:2503.22484v2 [nucl-ex]* 31 Mar 2025]
- UrQMD 3D analysis done by B. Pórfy
- Quantitatively, UrQMD close to experimental data for $\sqrt{s_{NN}} =$ 6 to 10 GeV
- Different trend compared to data



SUMMARY

- Au+Au simulations done at RHIC energies
- Source functions obtained from EPOS4 and UrQMD
- Lévy-fits performed
- Results quantitatively close to experimental data but seemingly different trend
- Next steps: correlation afterburner, higher statistics



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export MYDIR=$PWD/
export EPO=${MYDIR}epos${EPOSVSN}/
#export LIBDIR=${EPO}bin
#export OPT=./
#export HTO=./
#export CHK=./
wget https://box.in2p3.fr/s/g8aNMit2fKXLHYP/download/epos${EPOSVSN}.tgz # 4.0.3
#wget https://box.in2p3.fr/s/Hrm4wKaCQemGECk/download/epos${EPOSVSN}.tgz # 4.0.0
tar -xzvf epos${EPOSVSN}.tgz

#export path=$ROOTSYS/bin:$FASTSYS/bin:$path
export PATH=$ROOTSYS/bin:$FASTSYS/bin:$PATH
#export COP=BASIC
#export LD_LIBRARY_PATH=$ROOTSYS/lib:$ROOTSYS/lib/root:/usr/local/lib:$LD_LIBRARY_PATH
export LD_LIBRARY_PATH=$HEPMC3_DIR/lib:$FASTSYS/lib:$ROOTSYS/lib:$ROOTSYS/lib/root:/usr/local/lib:$LD_LIBRARY_PATH

#cd $EPO # worked with epos 4.0.0
#rm -Rf $LIBDIR && cmake -B$LIBDIR -DHepMC3_DIR=$HEPMC3_DIR/share/HepMC3/cmake && make -C$LIBDIR -j3
#cd ..
#rm epos${EPOSVSN}.tgz
#chmod -R a=rwx epos${EPOSVSN}
# run it:
#${EPO}scripts/epos -root optnsfile


# EPOS 4.0.3
mkdir epos_build && export BUILD_DIR=${MYDIR}epos_build
mkdir epos_install && export BIN_DIR=${MYDIR}epos_install

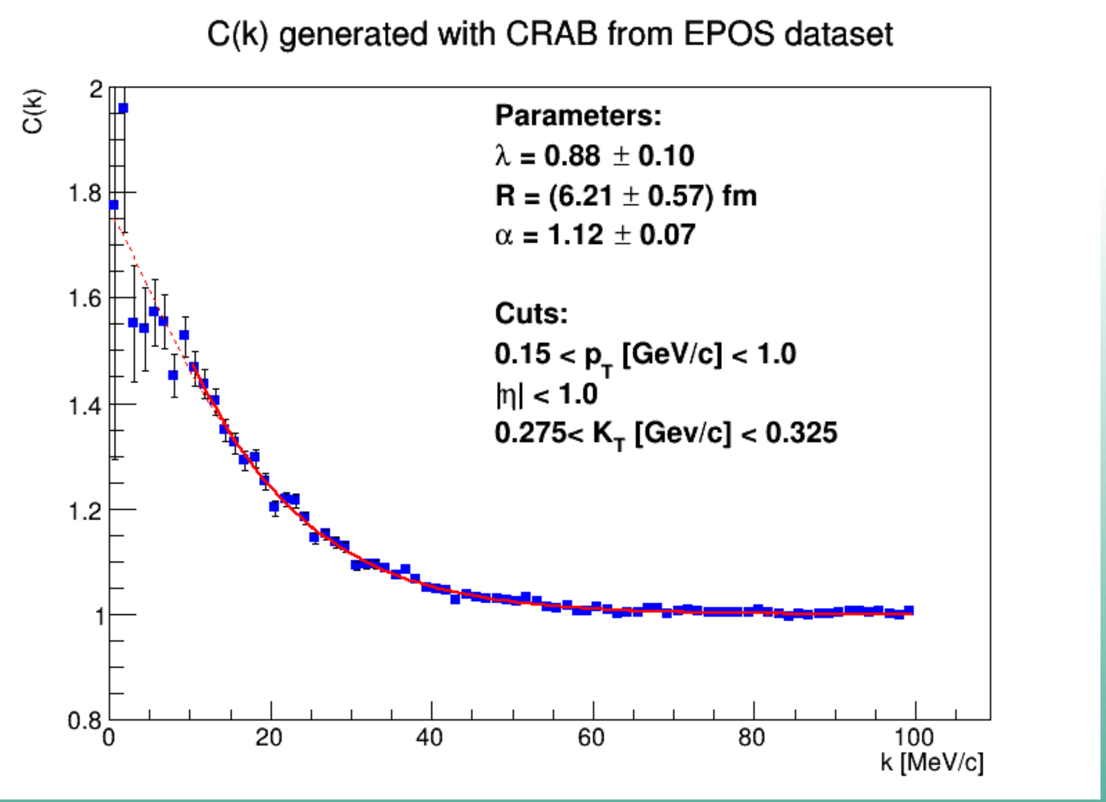
cmake -S $EPO -B $BUILD_DIR -DCMAKE_INSTALL_PREFIX=$BIN_DIR -DCOMPILE_OPTION=BASIC -DCMAKE_BUILD_TYPE=Release -DFAST
cmake --build $BUILD_DIR -j8
cmake --install $BUILD_DIR
ctest --test-dir $BUILD_DIR --verbose
# You run the code via
# $BIN_DIR/bin/epos -root myfile
# or
# $MYDIR/epos_install/bin/epos -root prueba_EOS2
```

THANK YOU FOR YOUR ATTENTION!

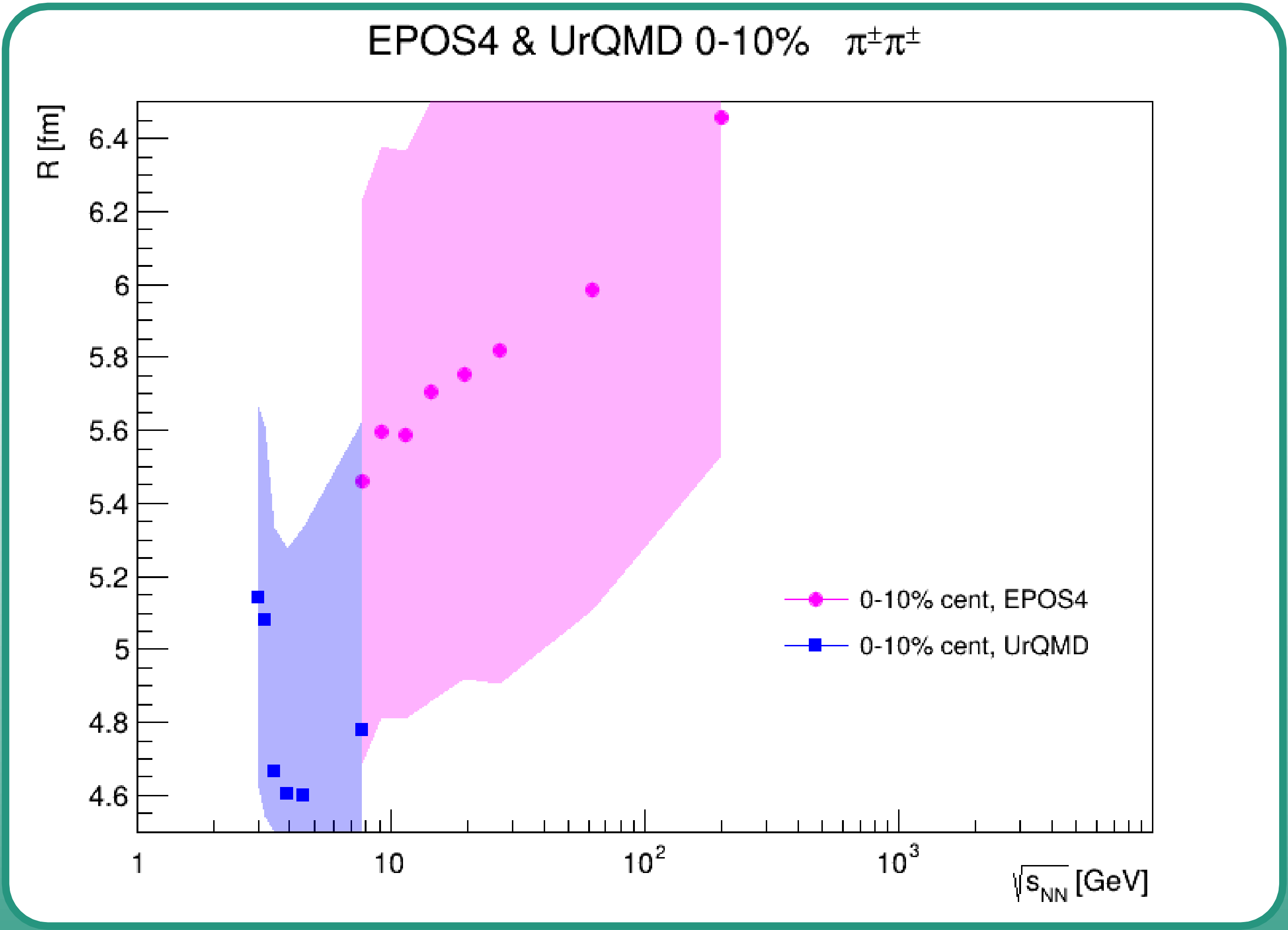
BACKUP SLIDES

TODO: Correlation afterburner

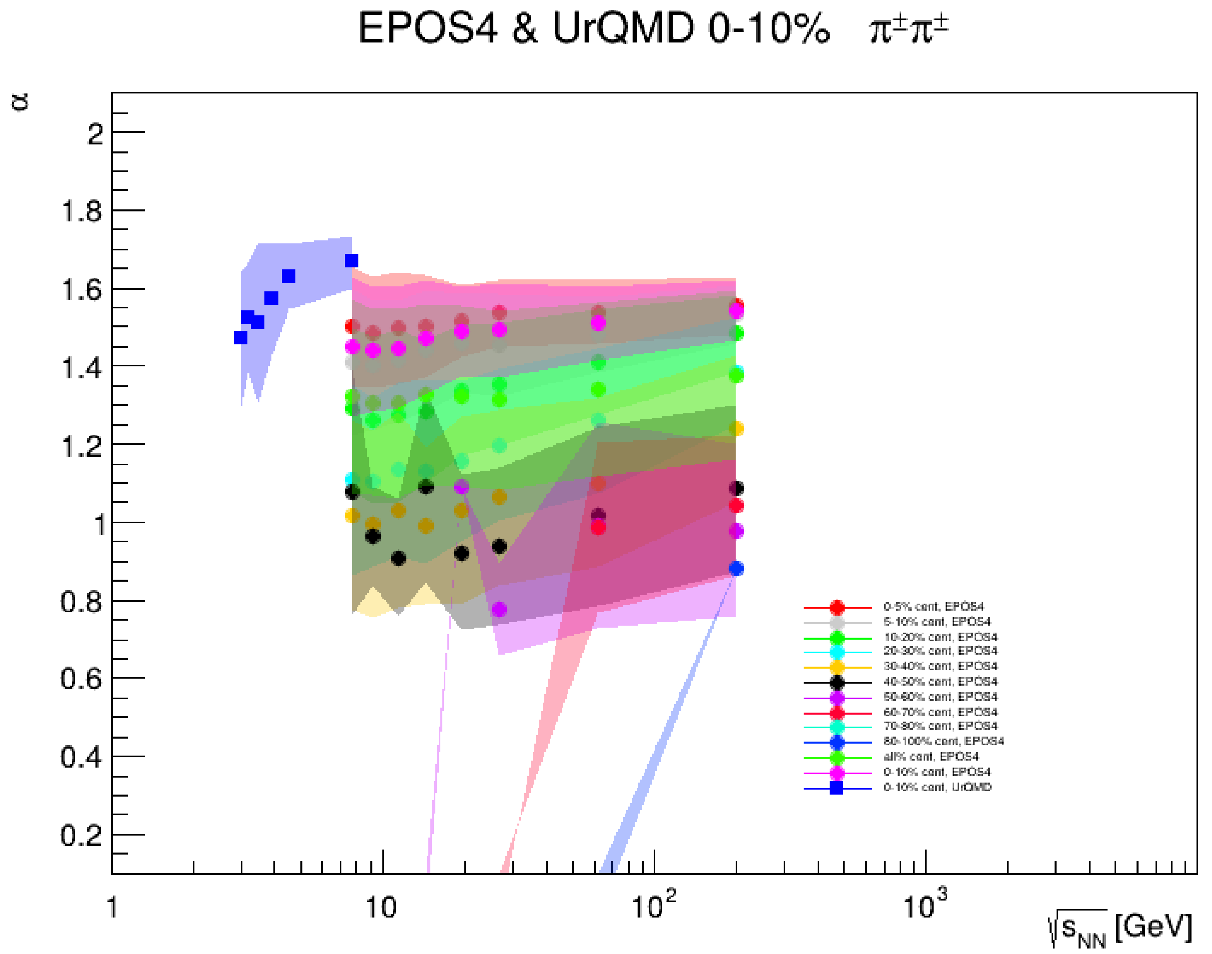
- CRAB: Correlation After Burner
  - Generate correlation functions from semi-classical transport codes
  - with impact-parameter averaging, experimental acceptances, experimental resolution, kinematic cuts
  - Input: files of phase space points (final momentum & point of last interaction of generated particles e.g. in EPOS4), impact parameters
  - Efficient 3D processing possible
  - Work-in-progress



EPOS4 $R(\langle K_T \rangle)$

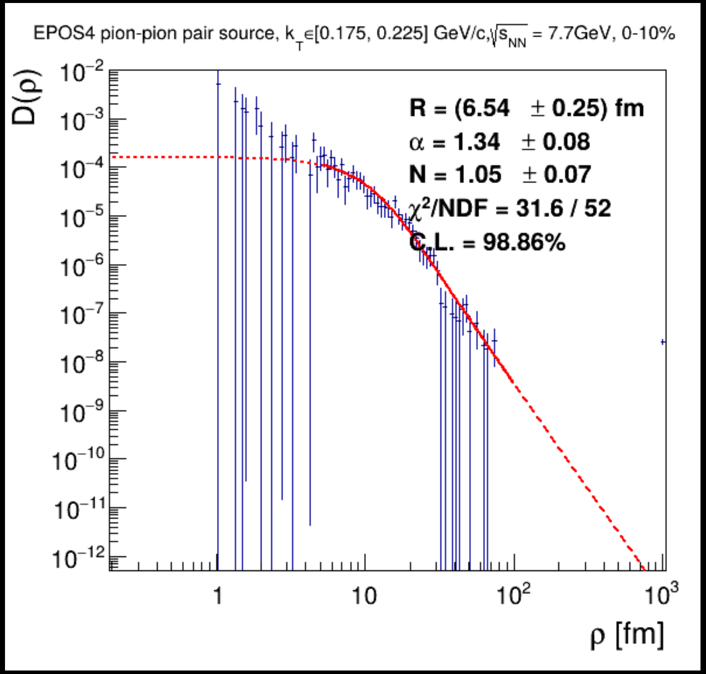


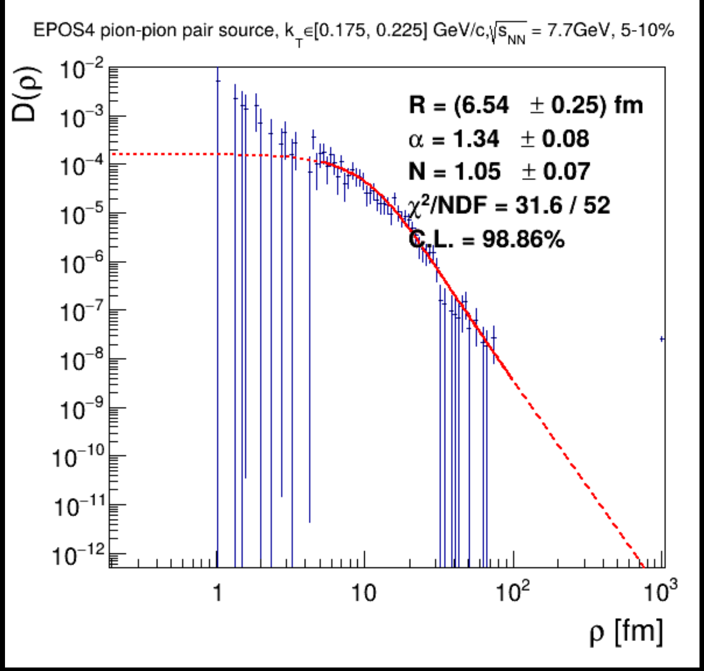
EPOS4 $\alpha(\langle K_T \rangle)$

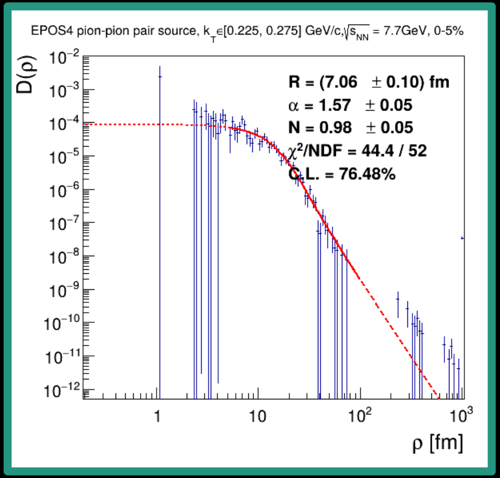


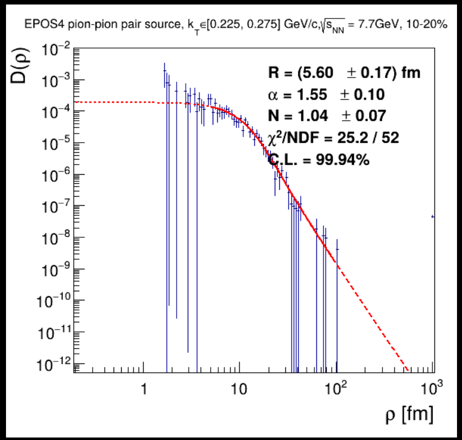
EVENT-BY-EVENT PION SOURCE FUNCTION LÉVY FITS

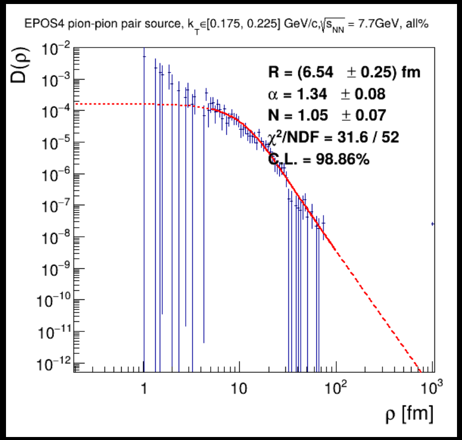
$\sqrt{s_{NN}} = 7.7$ GeV





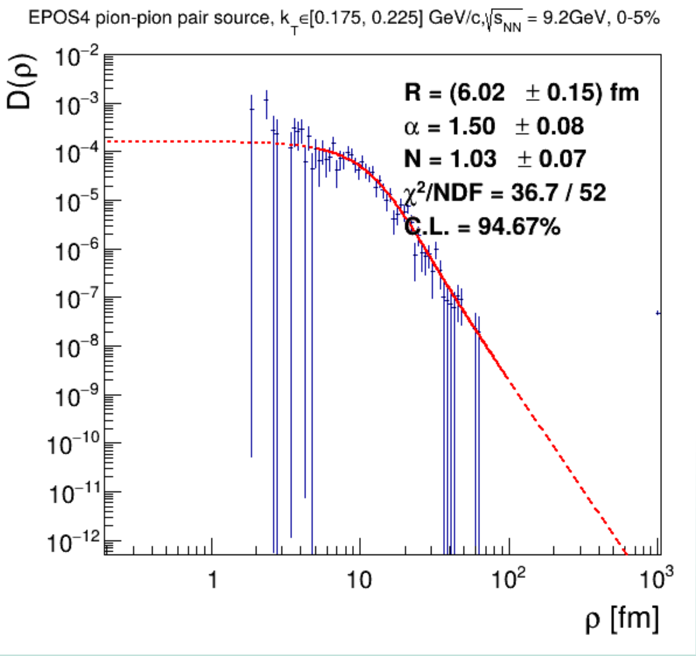


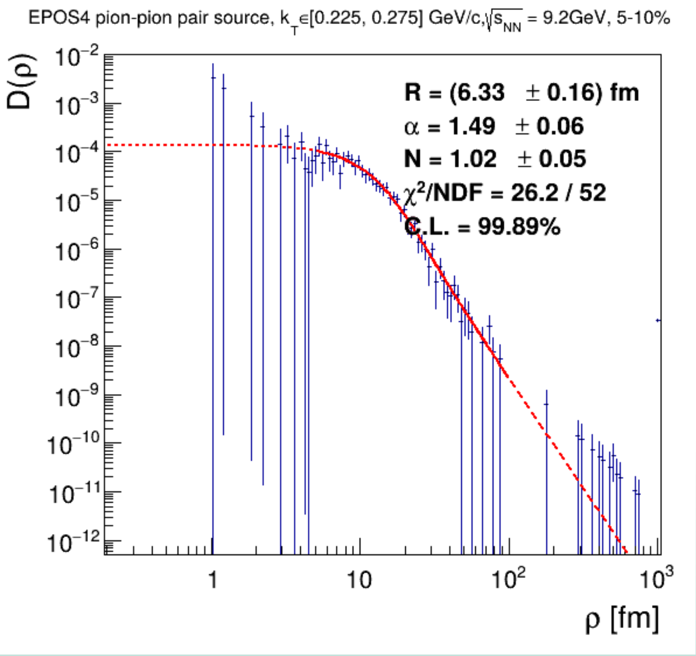


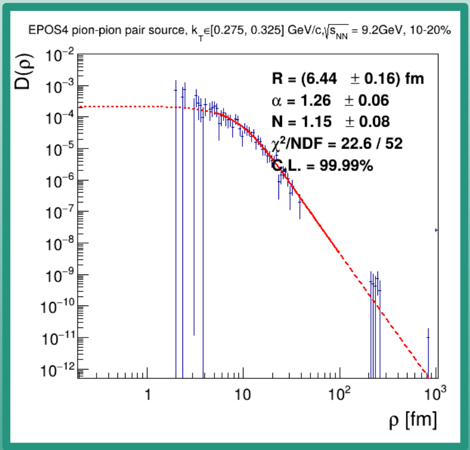


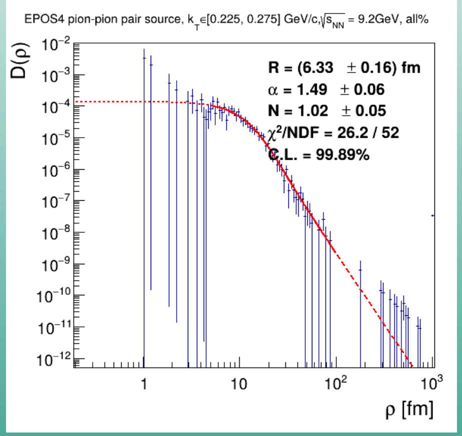
EVENT-BY-EVENT PION SOURCE FUNCTION LÉVY FITS

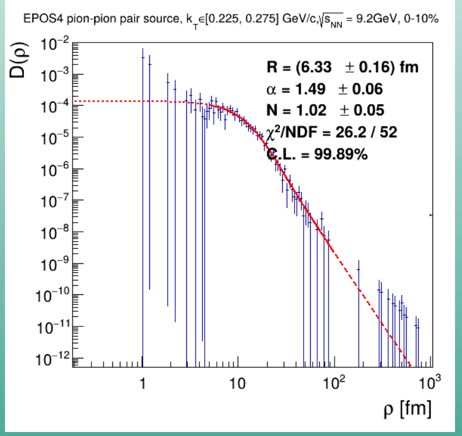
$\sqrt{s_{NN}} = 9.2$ GeV





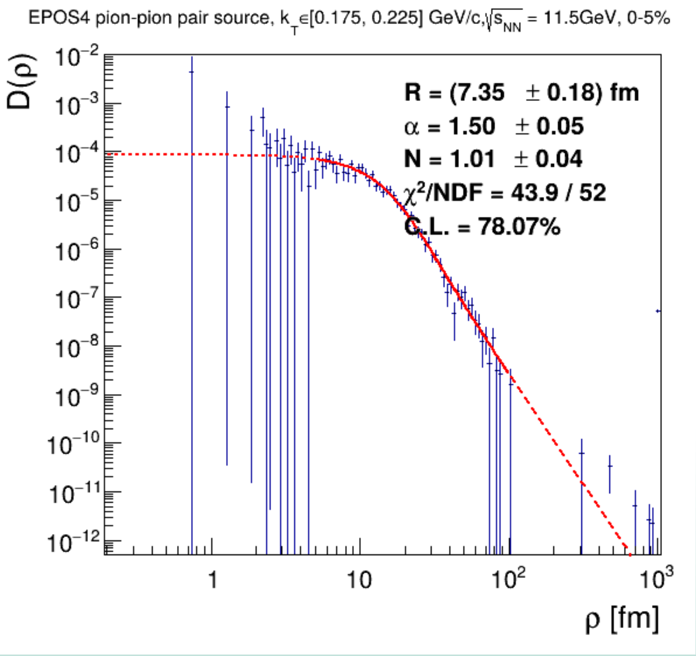


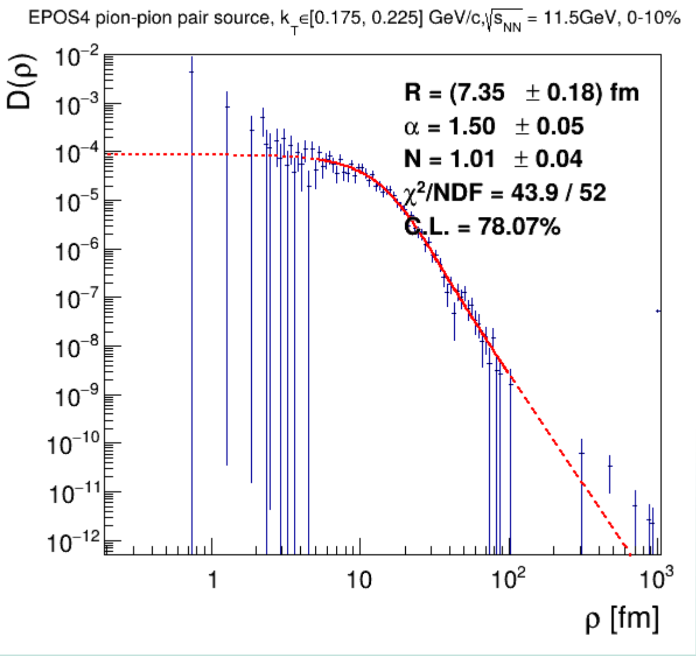


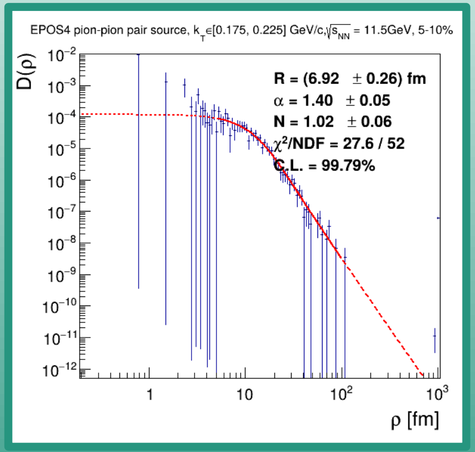


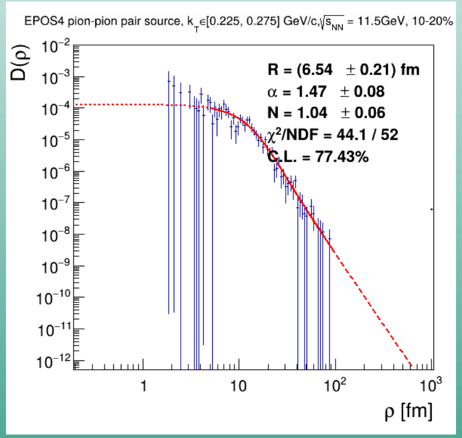
Event-by-event pion source function Lévy fits

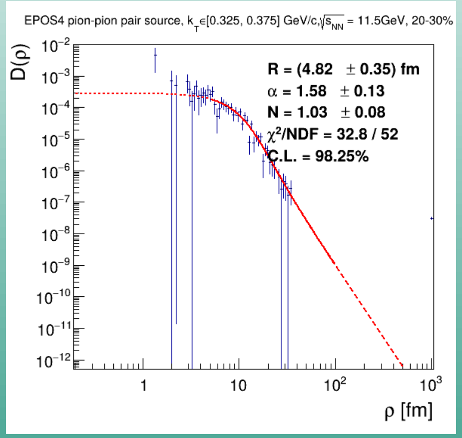
$$\sqrt{s_{NN}} = 11.5\text{ GeV}$$





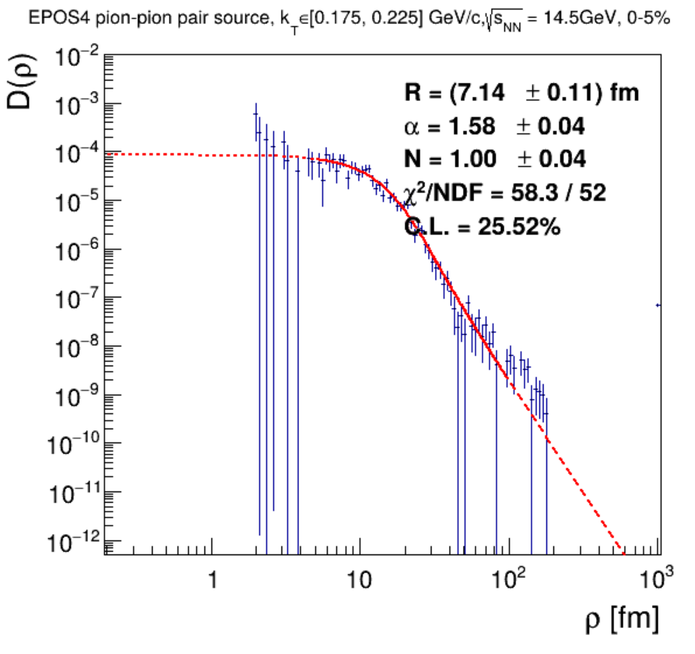


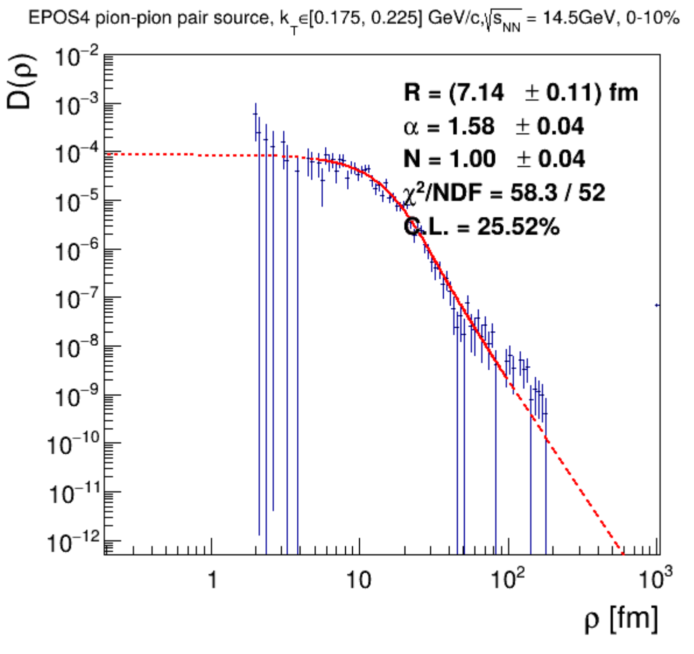


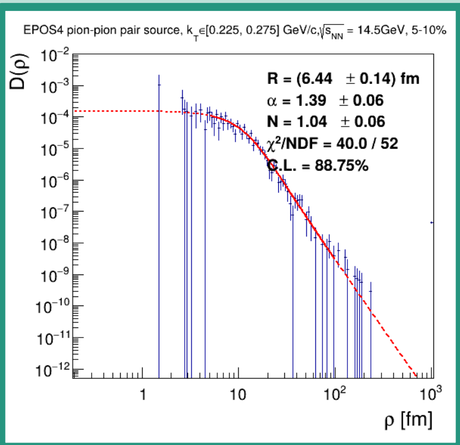


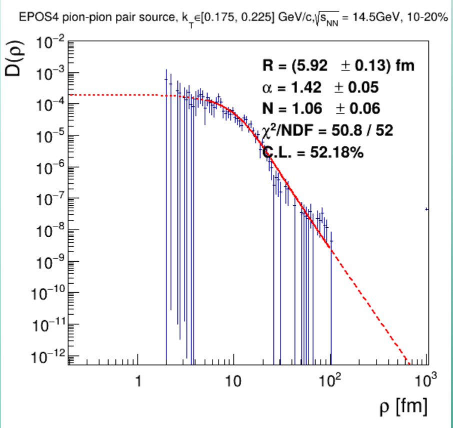
EVENT-BY-EVENT PION SOURCE FUNCTION LÉVY FITS

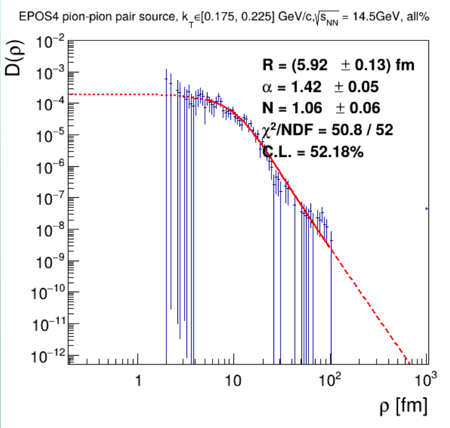
$\sqrt{s_{NN}} = 14.5$ GeV





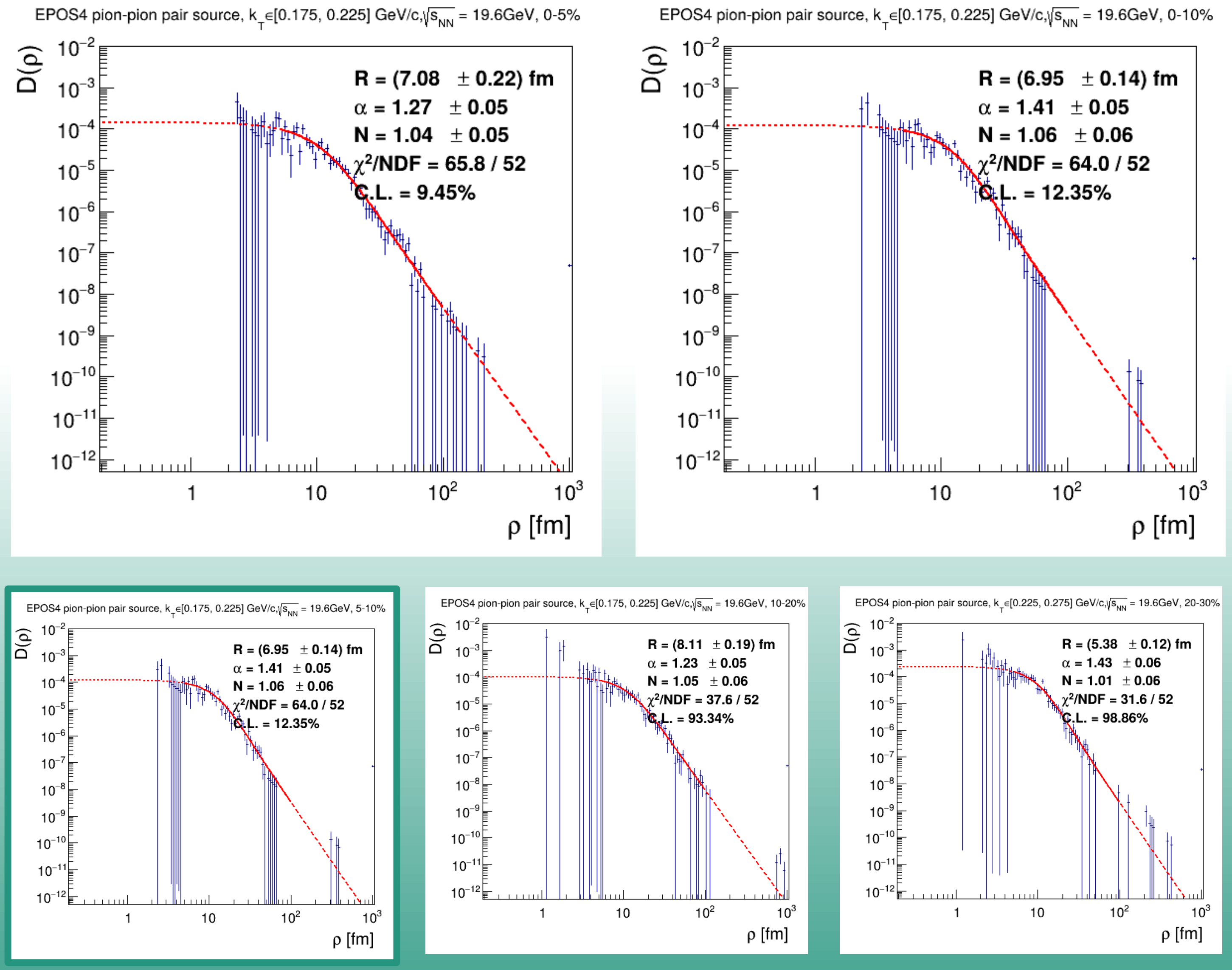






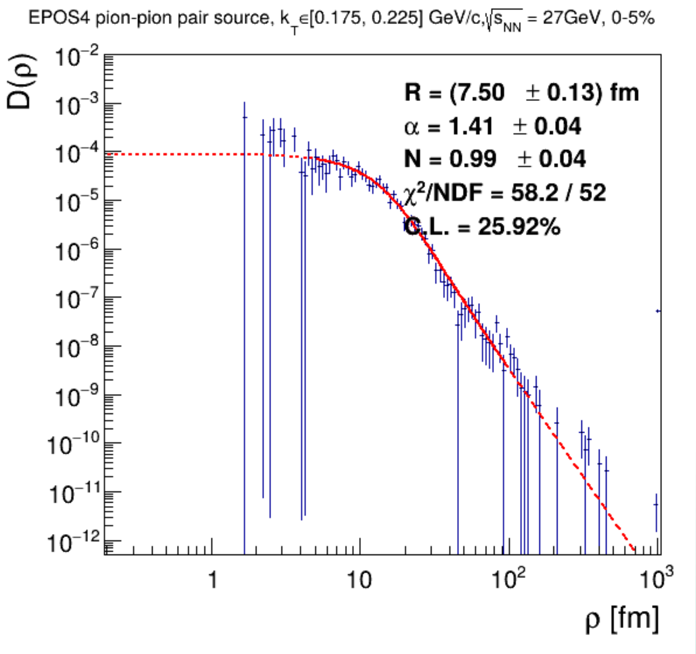
EVENT-BY-EVENT PION SOURCE FUNCTION LÉVY FITS

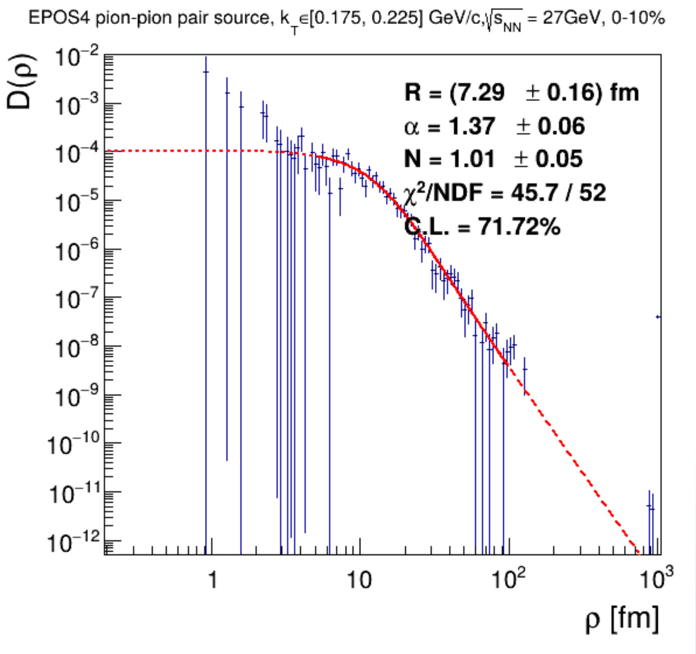
$\sqrt{s_{NN}} = 19.6\ \mathrm{GeV}$

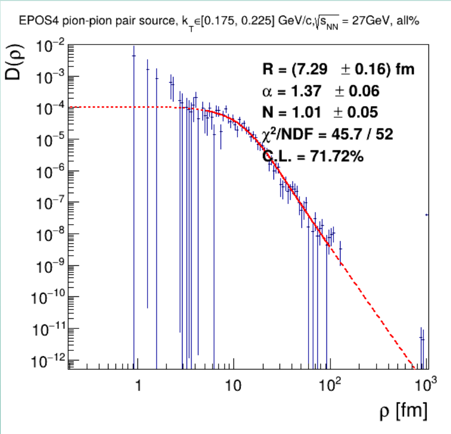


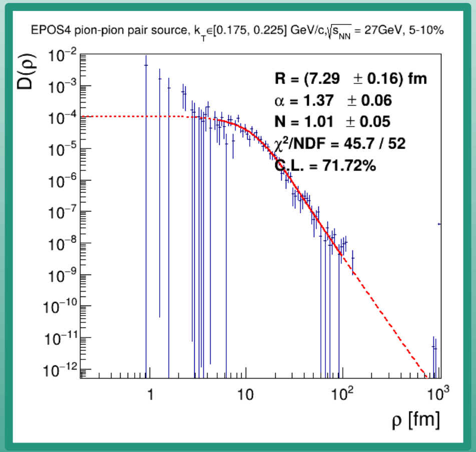
Event-by-event pion source function Lévy fits

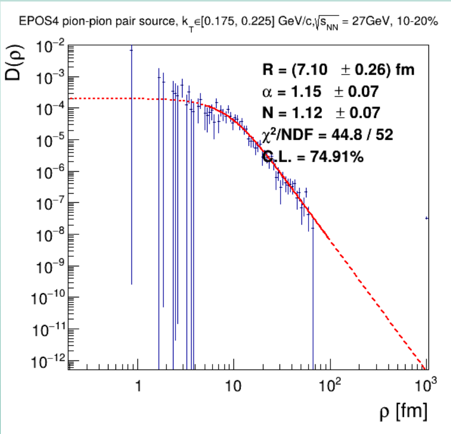
$\sqrt{s_{NN}} = 27$ GeV

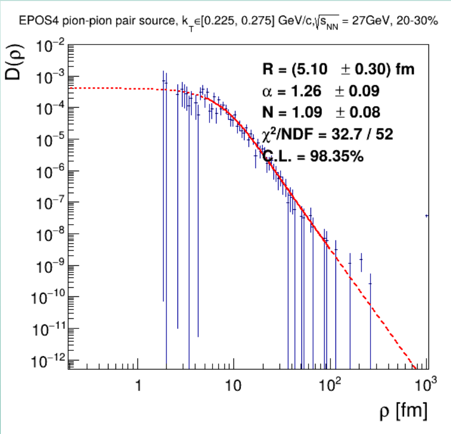




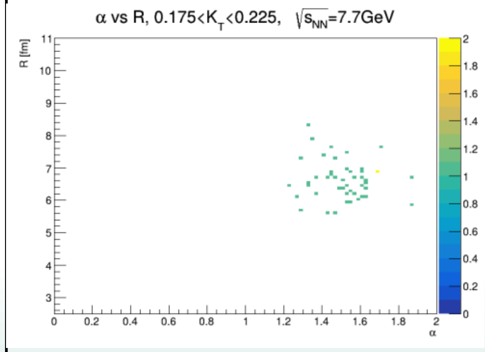


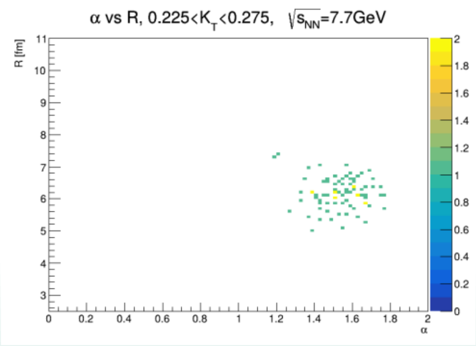


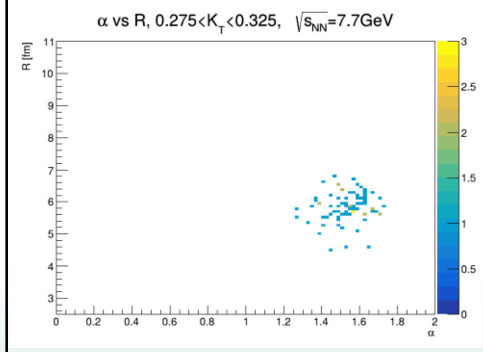


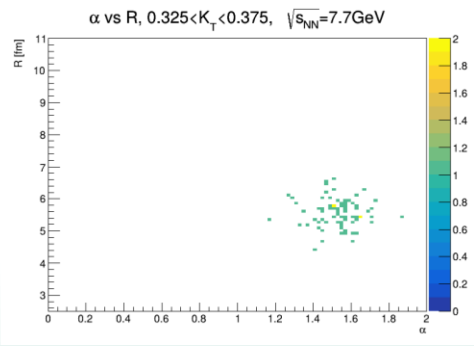


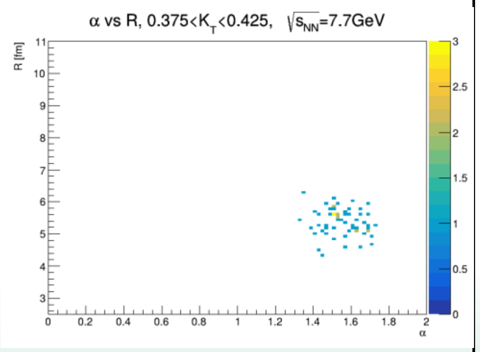
α vs R $\sqrt{s_{NN}} = 7.7$ GeV

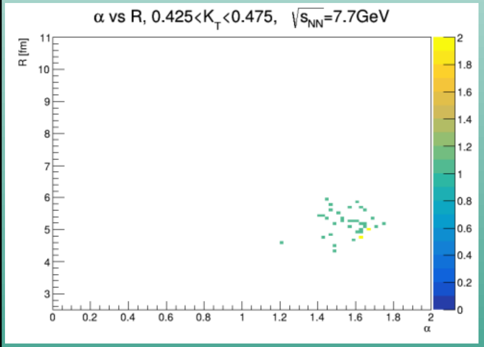


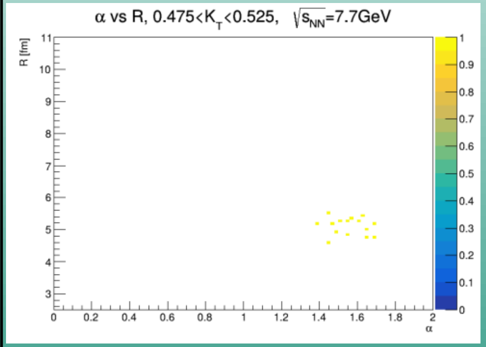


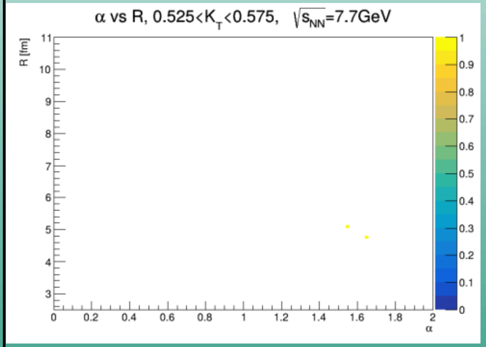


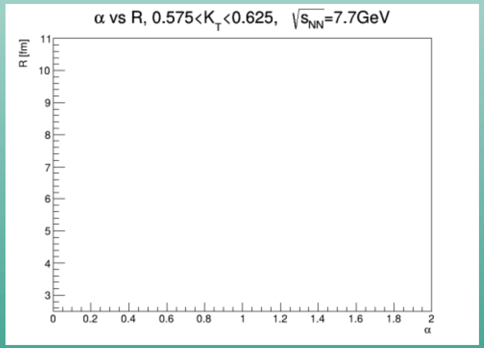


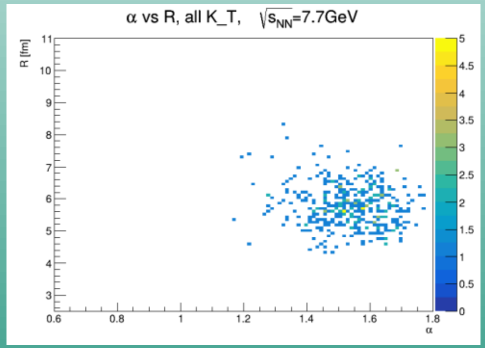




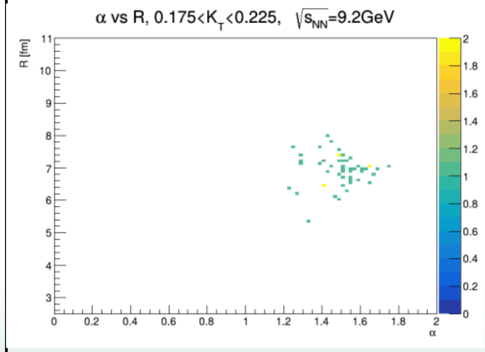


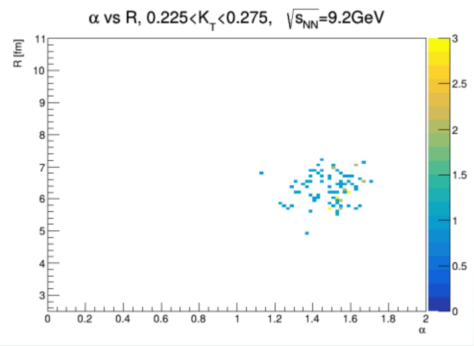


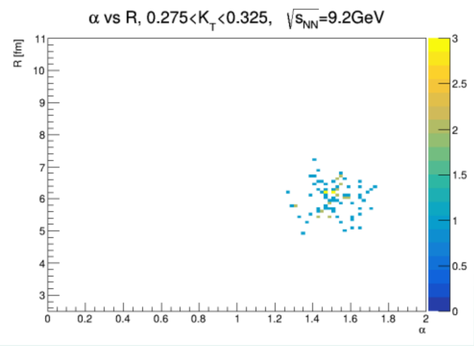


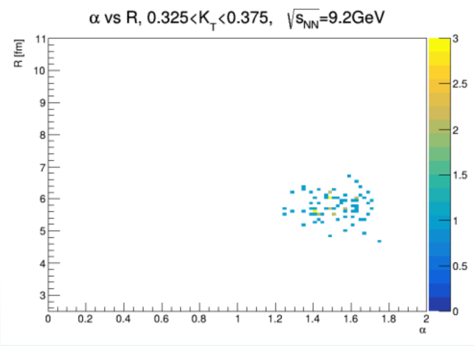


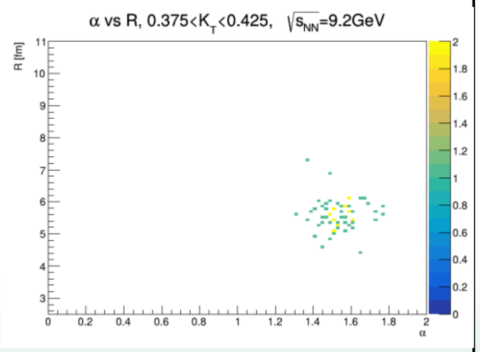
α vs R $\sqrt{s_{NN}} = 9.2$ GeV

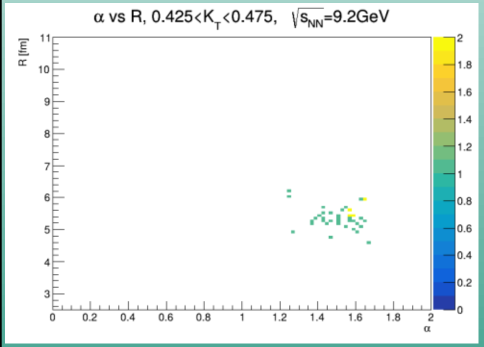


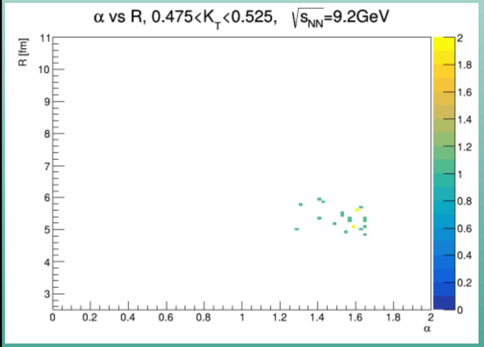


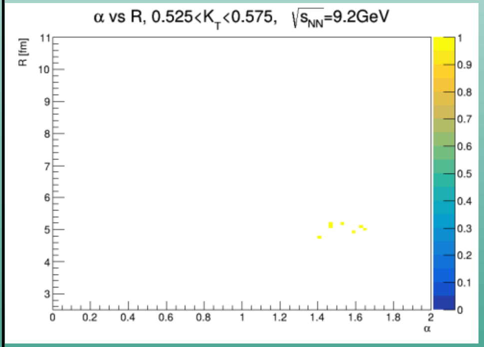


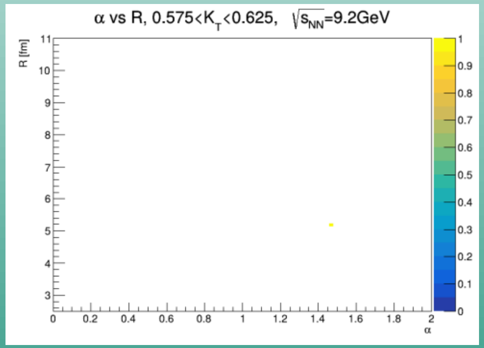


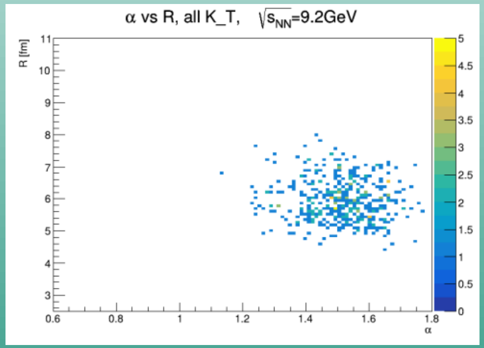




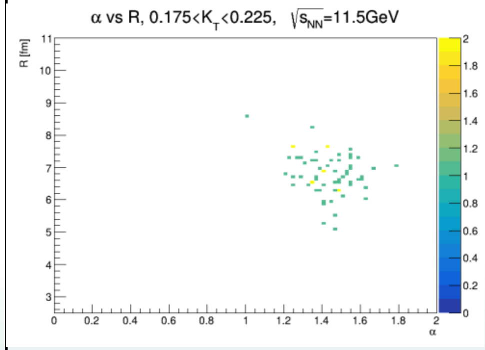


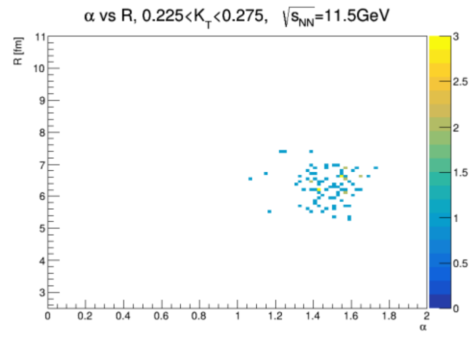


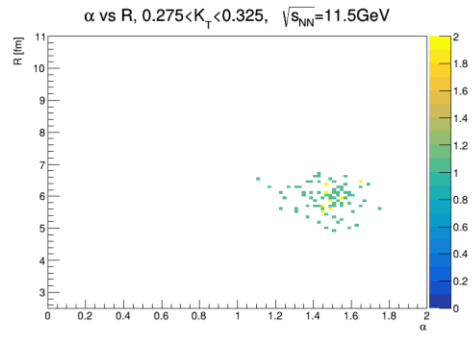


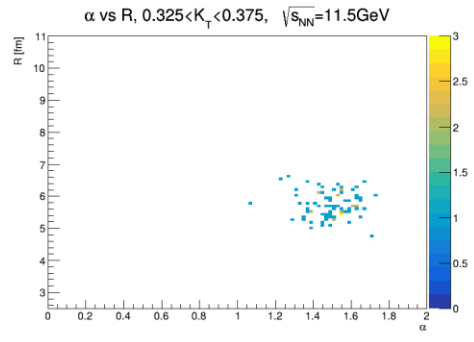


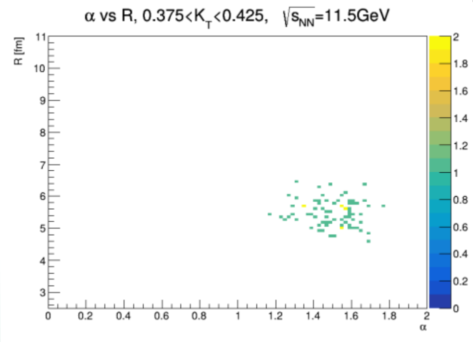
α vs R $\sqrt{s_{NN}} = 11.5$ GeV

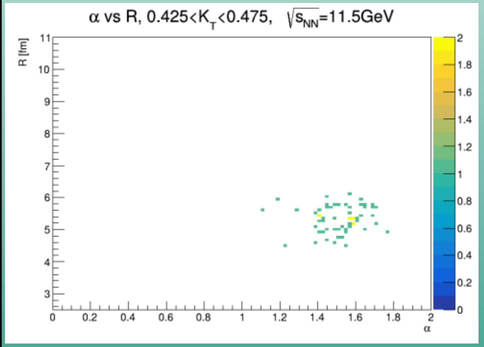


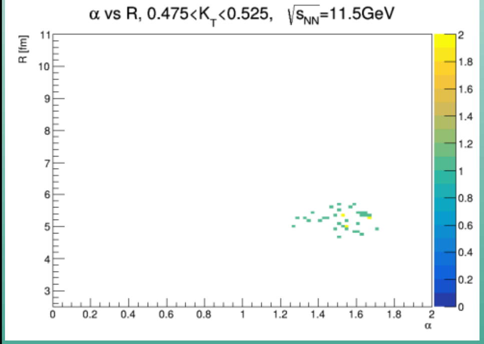


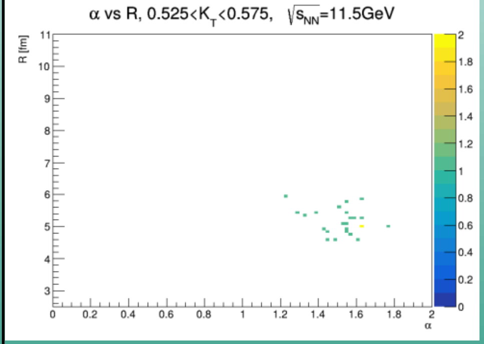


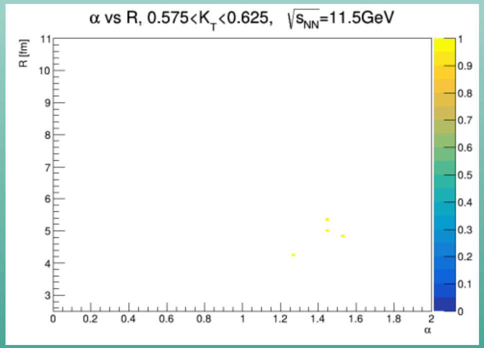


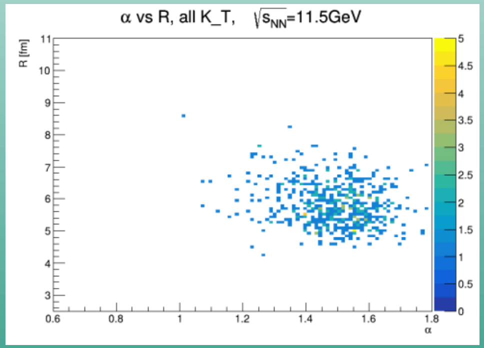




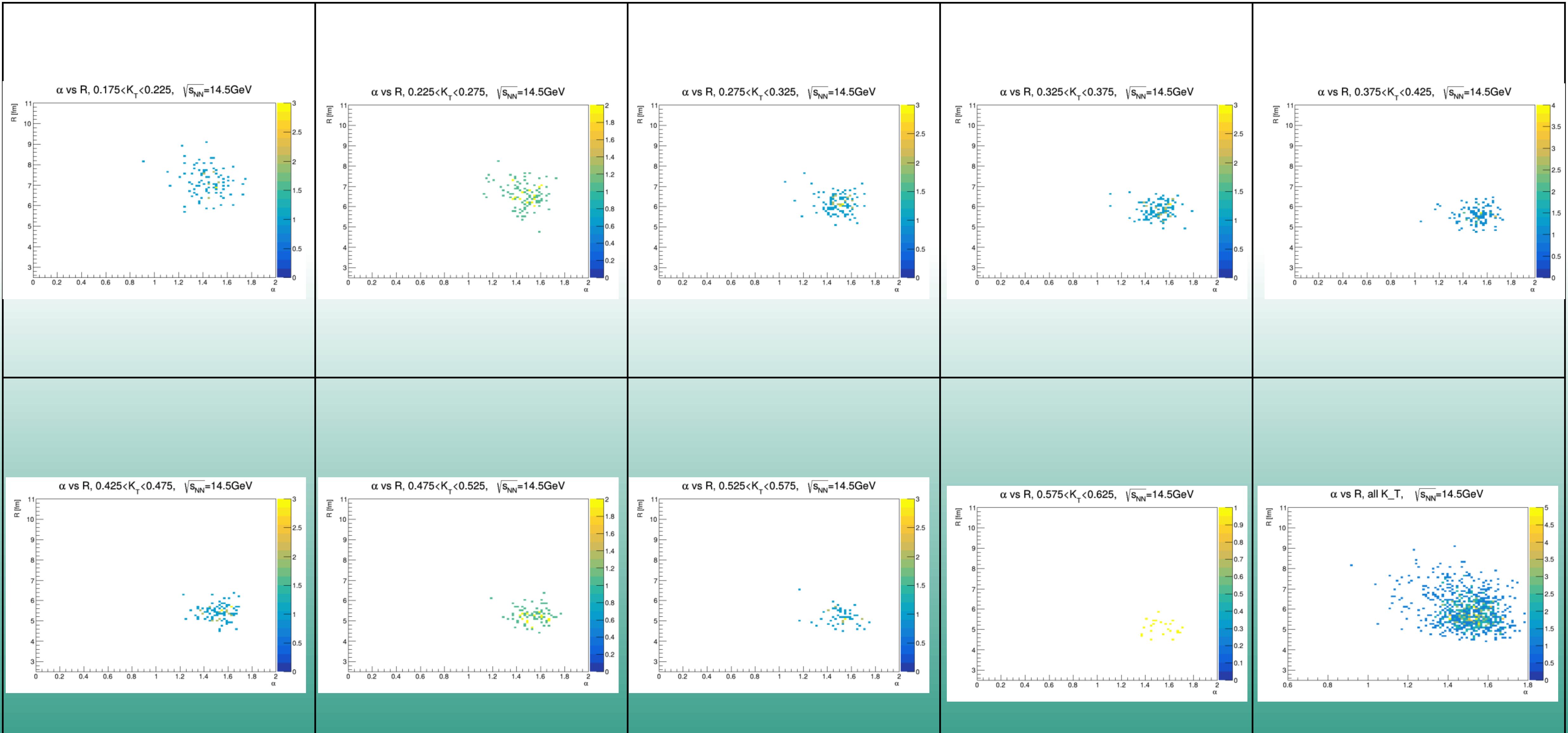




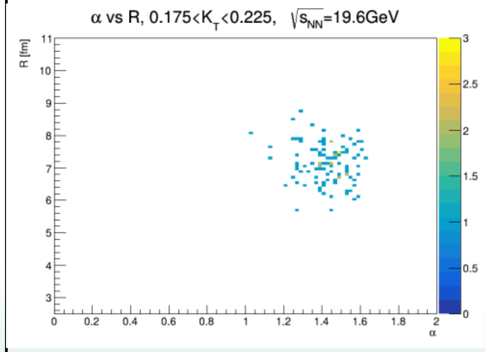


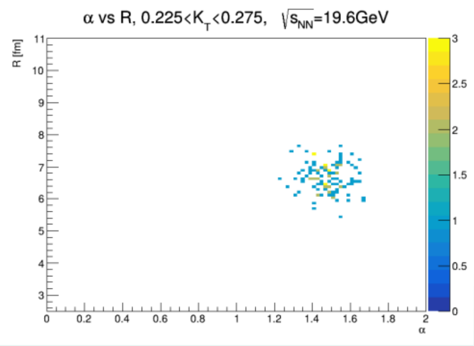


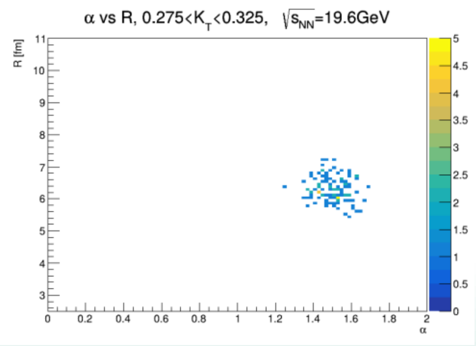
α vs R $\sqrt{s_{NN}} = 14.5$ GeV

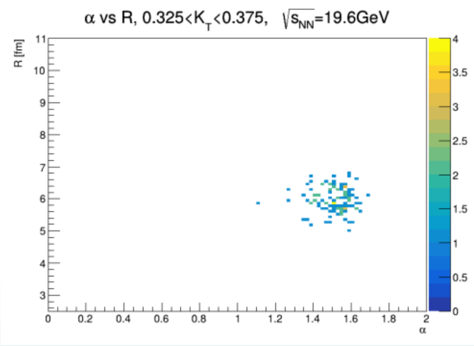


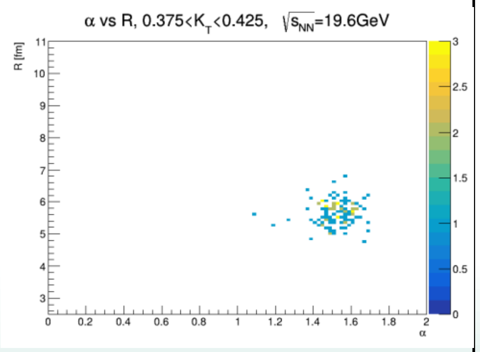
α vs R $\sqrt{s_{NN}} = 19.6$ GeV

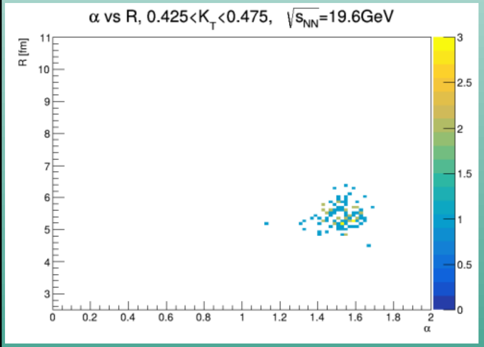


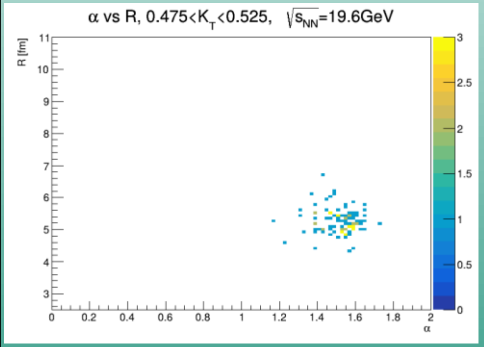


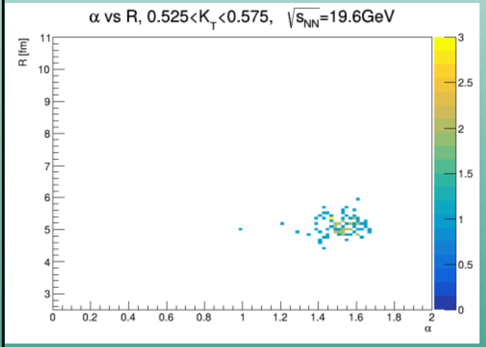


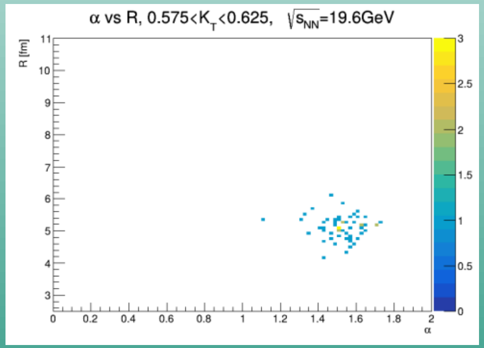


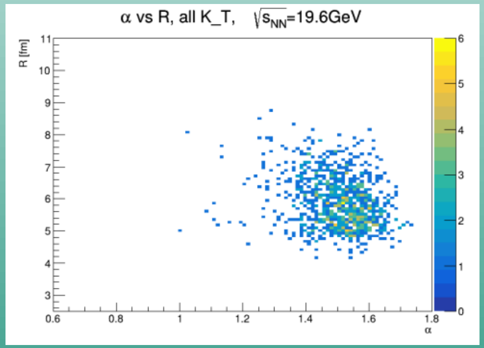




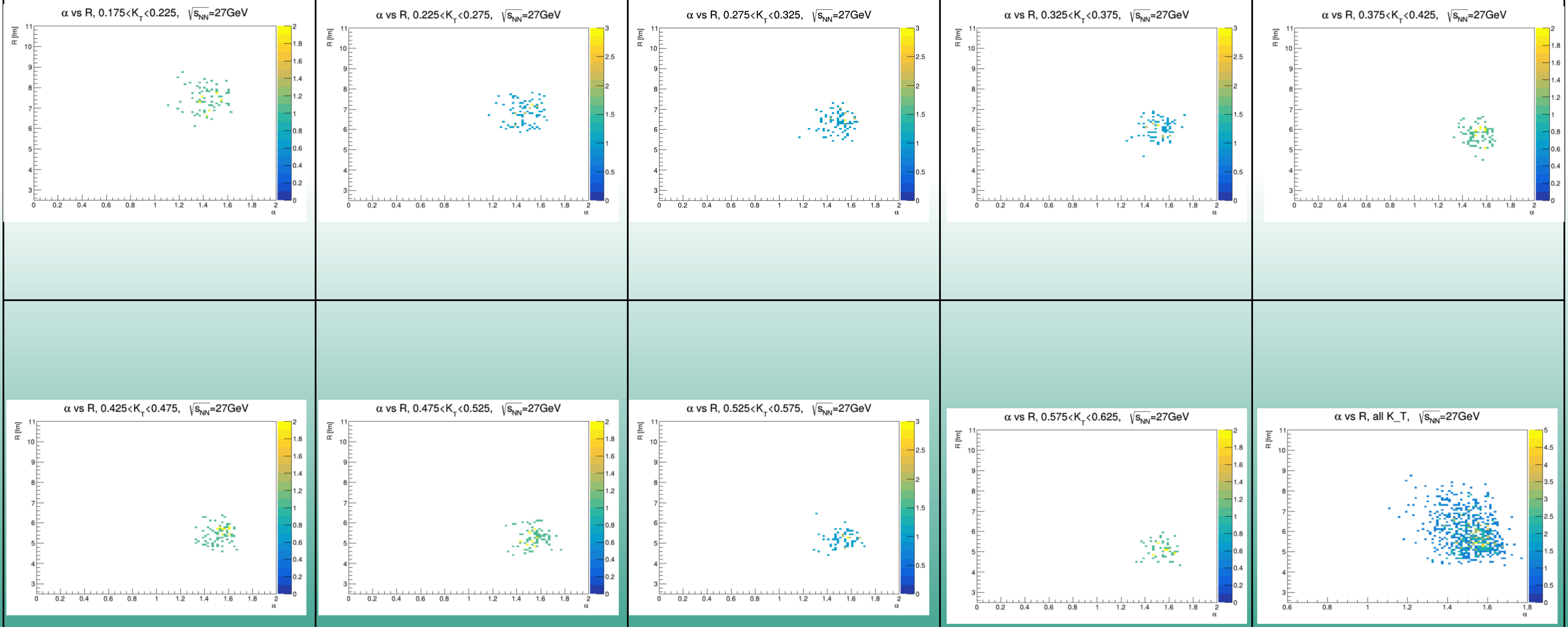




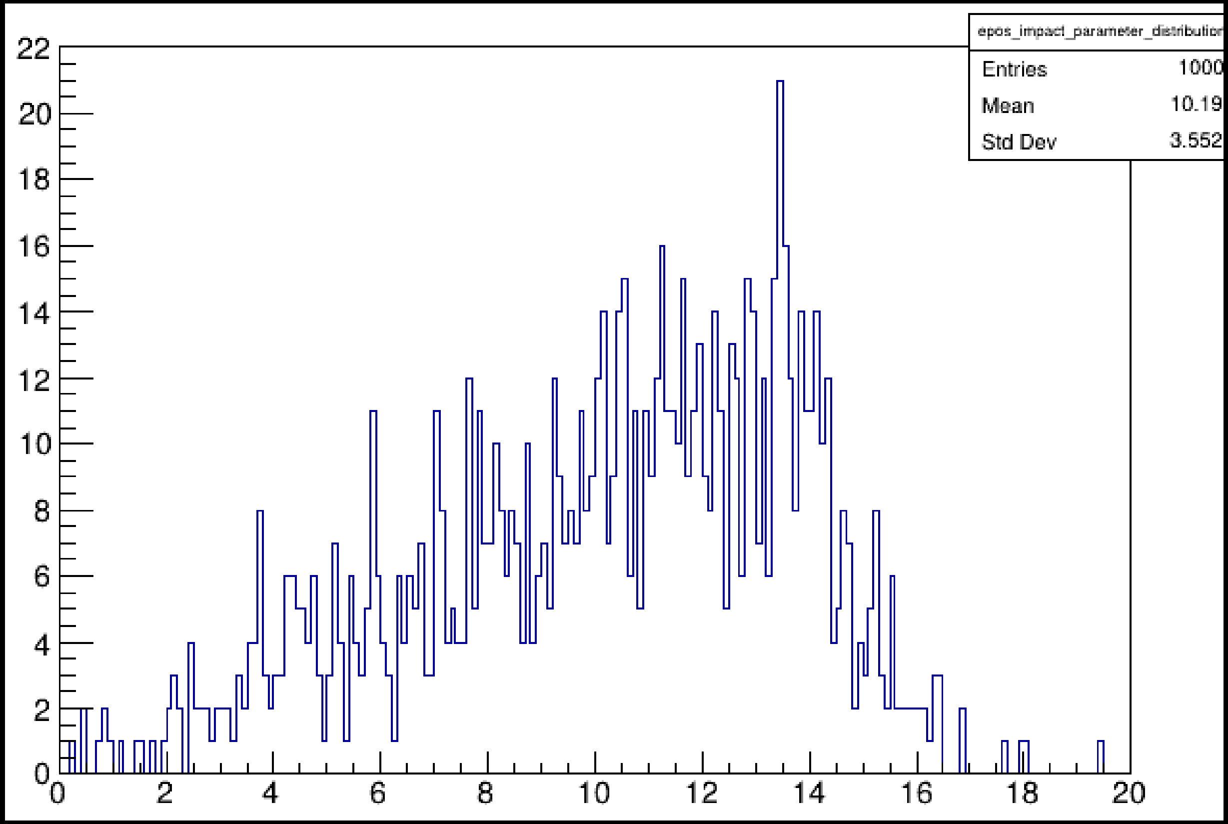


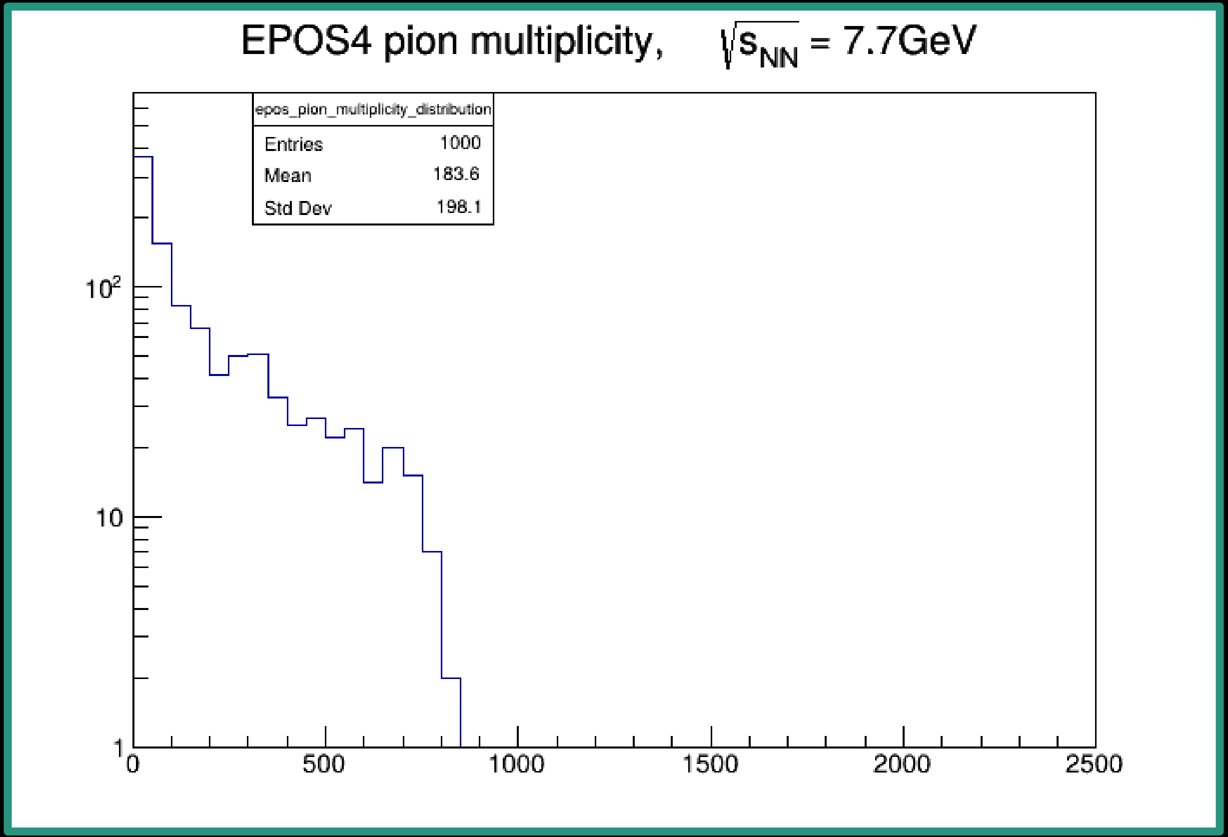


α vs R $\sqrt{s_{NN}} = 27$ GeV

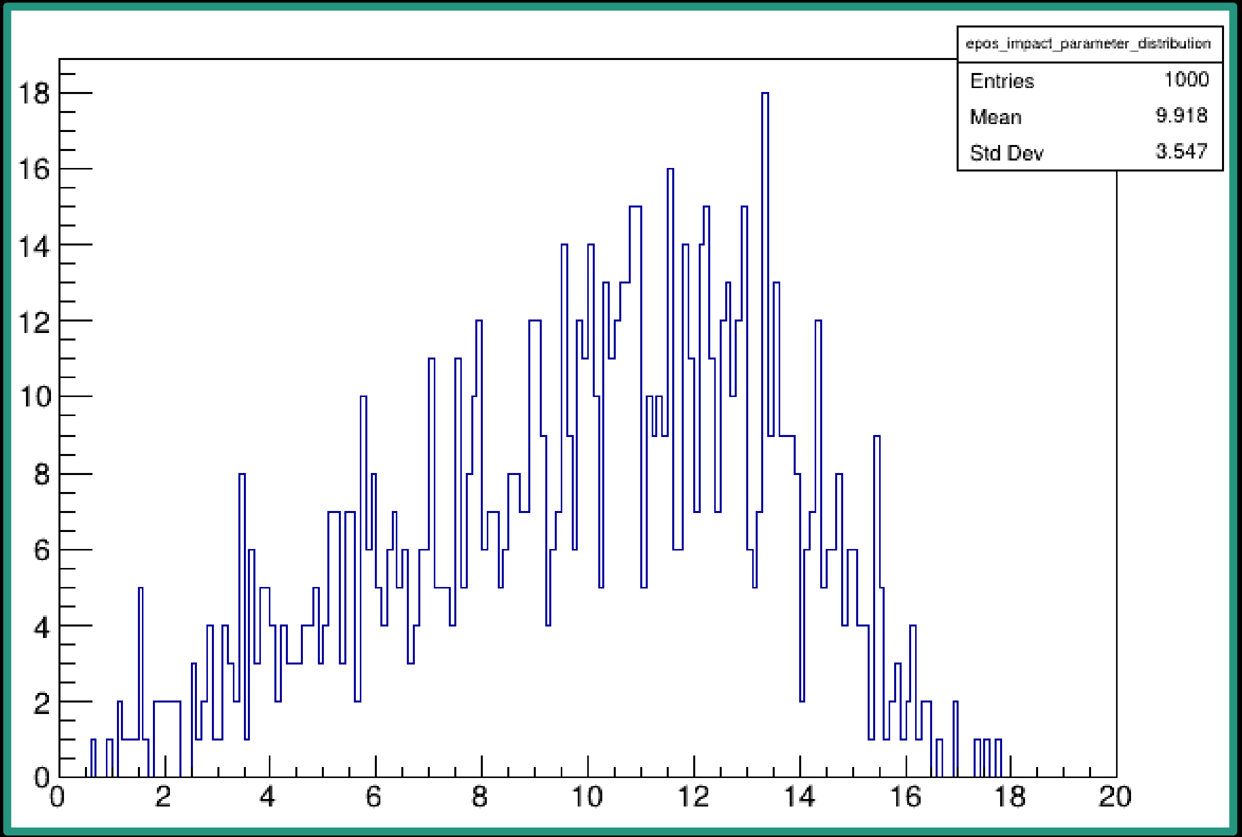


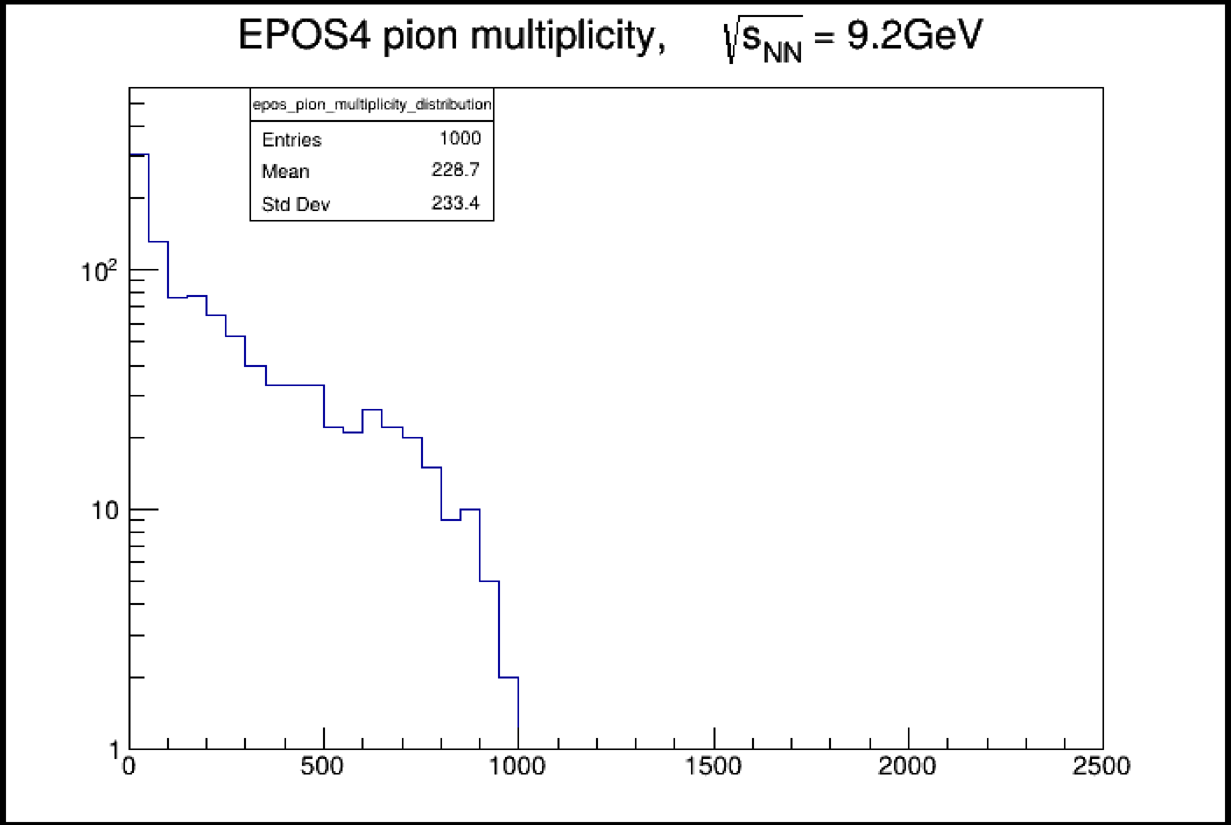
Impact parameter (bim) and npart distributions, $\sqrt{s_{NN}} = 7.7$ GeV



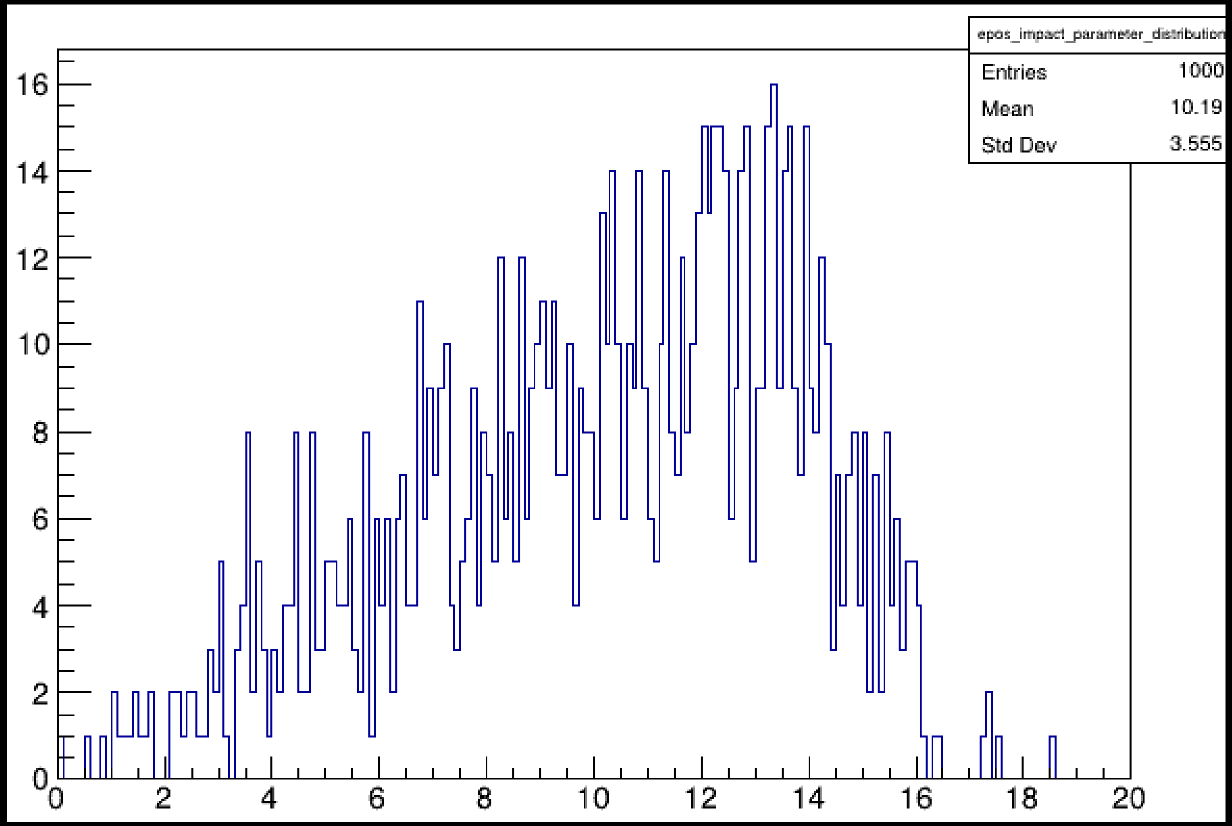


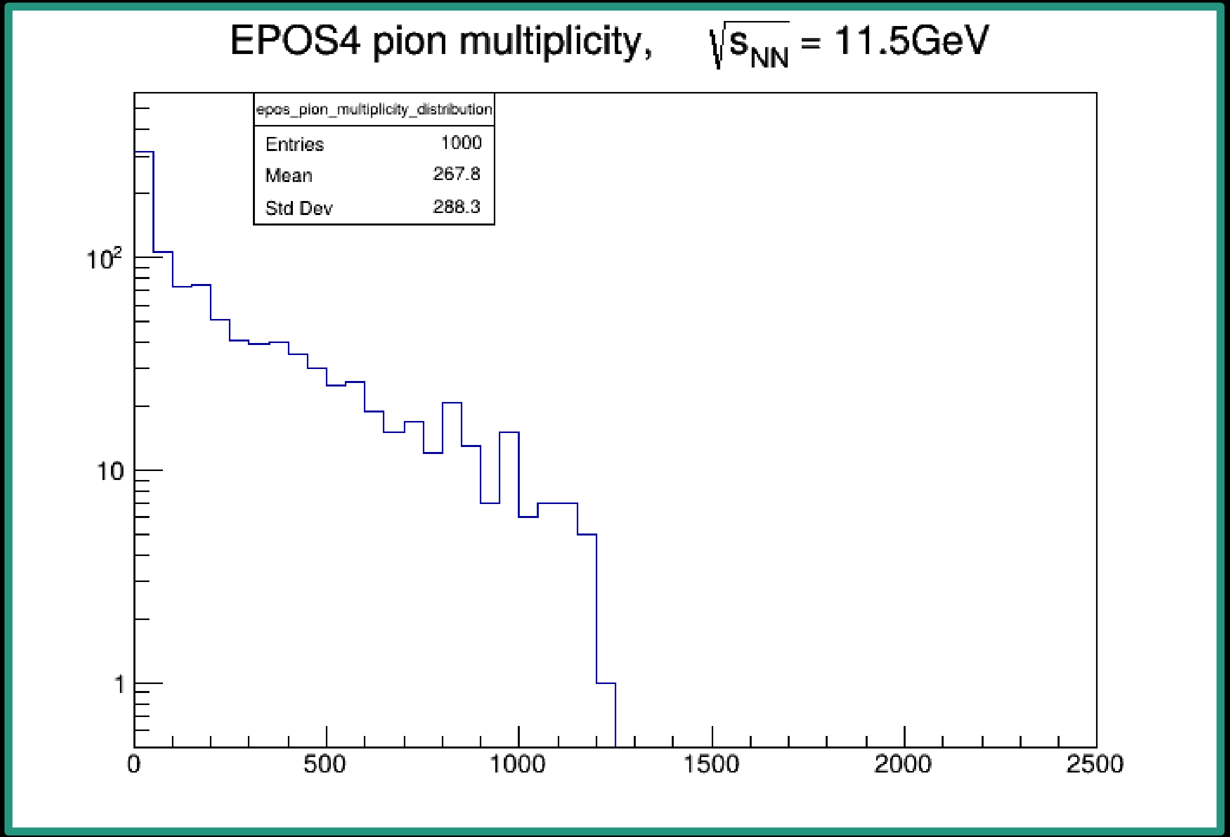
IMPACT PARAMETER (BIM) AND NPART DISTRIBUTIONS, $\sqrt{s_{NN}} = 9.2$ GEV



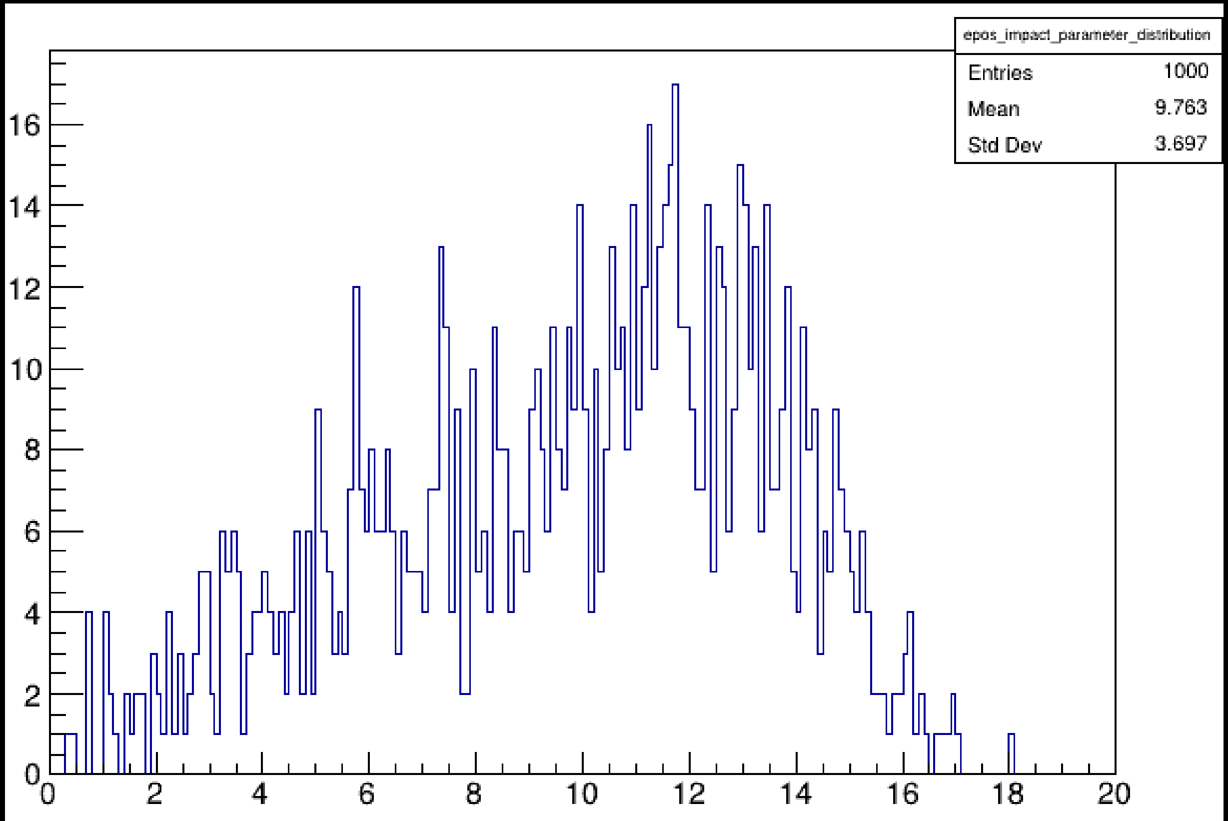


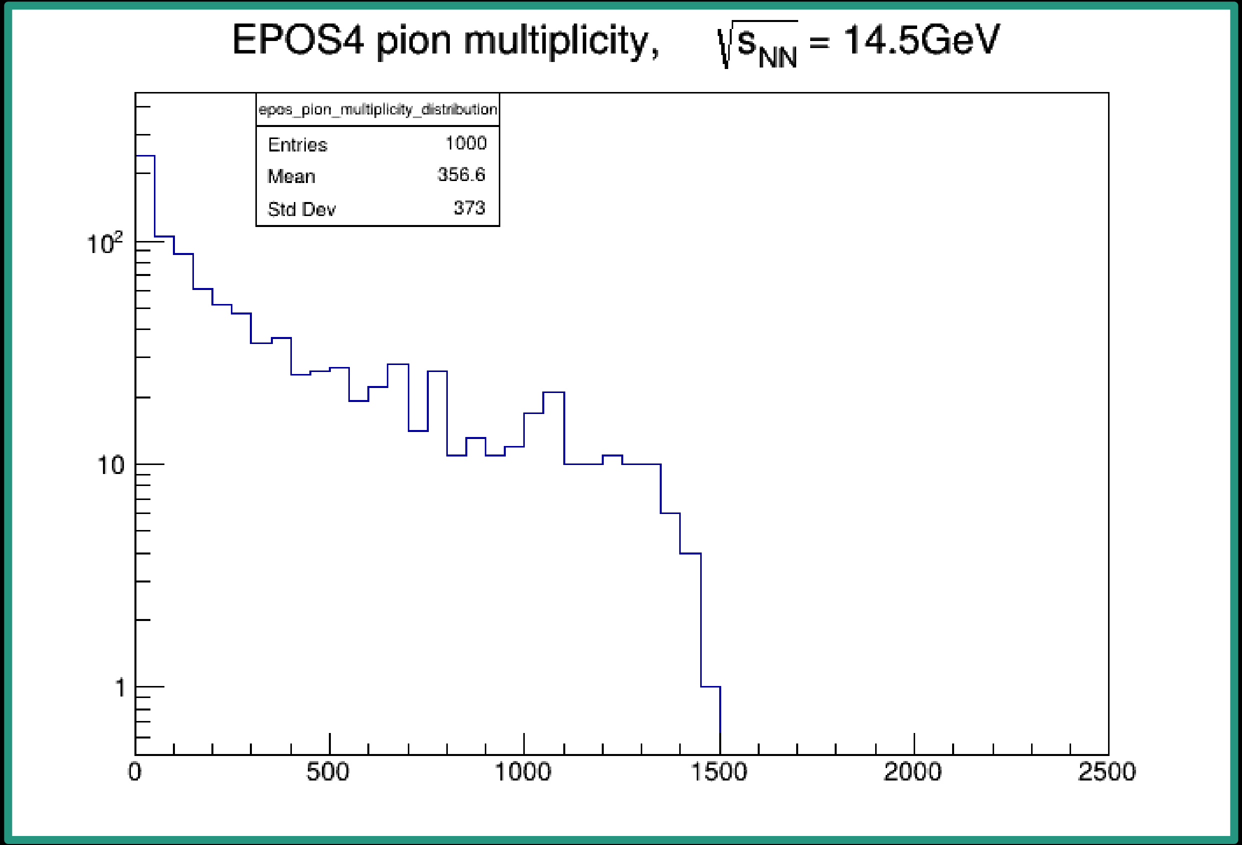
IMPACT PARAMETER (BIM) AND NPART DISTRIBUTIONS, $\sqrt{s_{NN}} = 11.5$ GEV



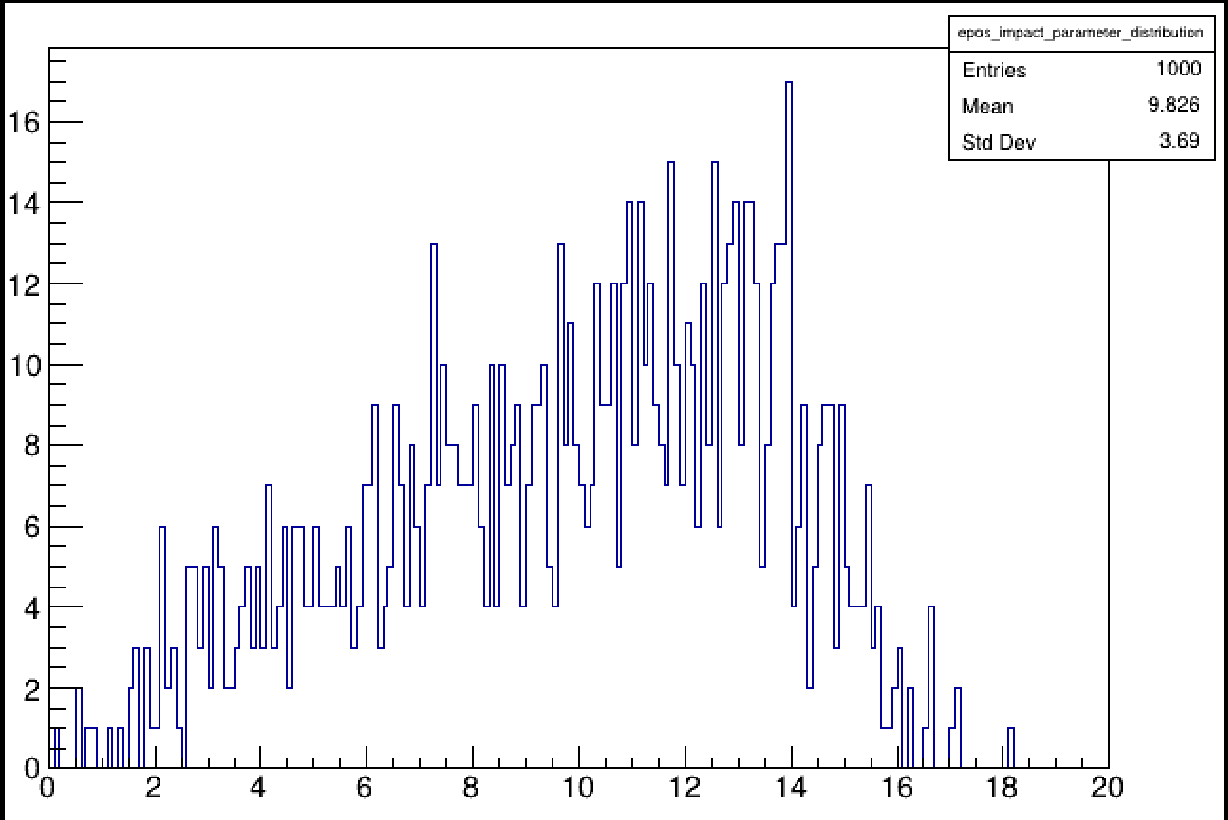


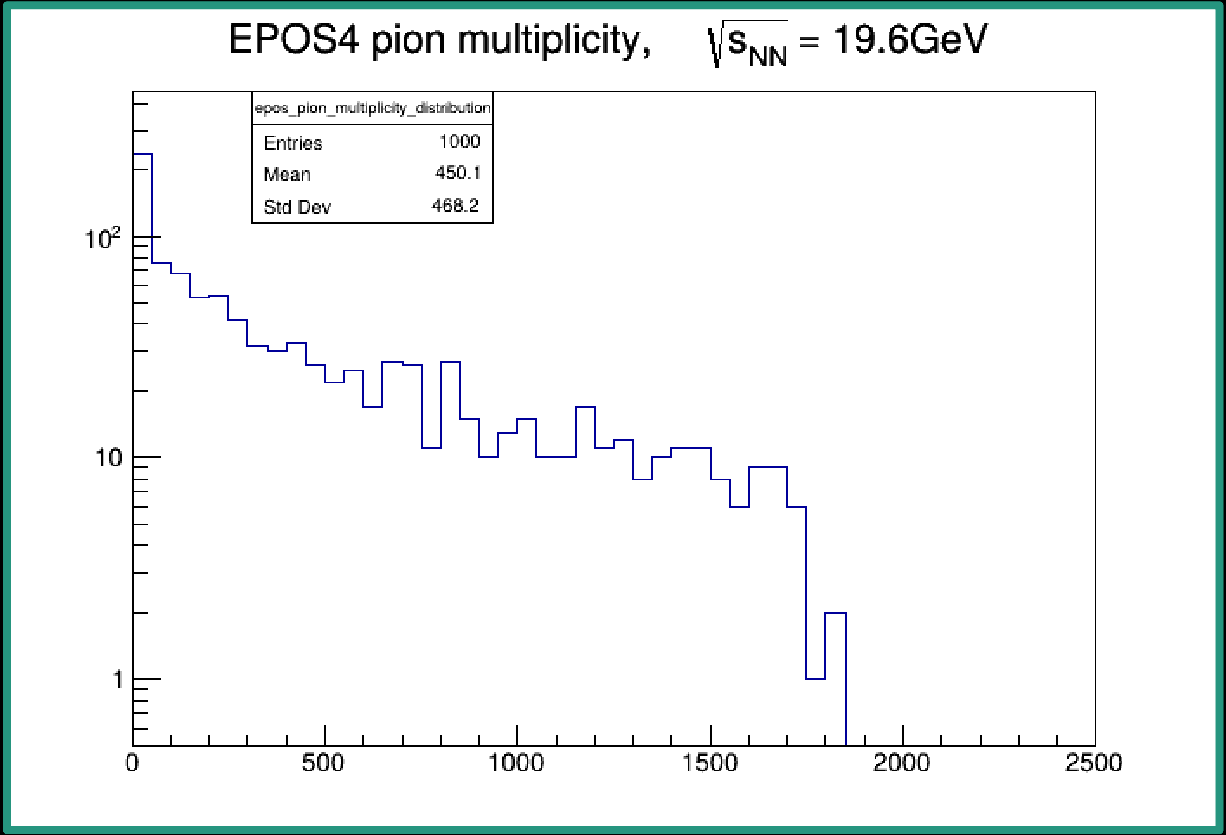
Impact parameter (bim) and npart distributions, $\sqrt{s_{NN}} = 14.5$ GeV





Impact parameter (bim) and npart distributions, $\sqrt{s_{NN}} = 19.6$ GeV





IMPACT PARAMETER (BIM) AND NPART DISTRIBUTIONS, $\sqrt{s_{NN}} = 27$ GeV