

Search For Pentaquark And Study on p-K Correlation in Au+Au Collisions

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Pentaquark

Motivation:

- Exotic particles
- Study of subatomic structure (e.g. Quark Model, QCD...)

Background:

- Fourquark $Z_c(3900)$, $Z_c(4020)$
 - BESIII, 2013 (1303.5949, 1309.1896)
- Pentaquark $P_c^+(4380)$, $P_c^+(4450)$
 - LHCb, 2015... (arXiv: 1507.03414)

Pentaquark

• Particle to search: $\Theta^{++}(uuud\bar{s})$

Decay mode: $\Theta^{++} \rightarrow K^+ + p$

Method: Rotational BG & Mixed Event

• p/K Selection:

Proton:

- DCA ≤ 1 cm
- $0.2 \leq Pt \leq 2.8$ GeV/c
- $|\text{Eta}| \leq 0.5$
- $0 < \text{Flag} \leq 1000$
- TOFflag ≥ 1 && $|\text{TofYLocal}| \leq 1.8$ && $0.8 \leq \text{TofM}^2 \leq 1$
- ndEdx ≥ 10
- $|\text{n}\sigma_p| \leq 2$

Kaon:

- TOFflag ≥ 1
- $|\text{Eta}| \leq 0.5$
- DCA ≤ 1 cm
- $0 < \text{Flag} \leq 1000$
- $P \leq 1.6$ GeV/c && $|\text{TofYLocal}| \leq 1.8$ && $0.2 \leq \text{TofM}^2 \leq 0.35$

Pentaquark—Mass Distribution

MB1 (~50% data) cen=60~70%

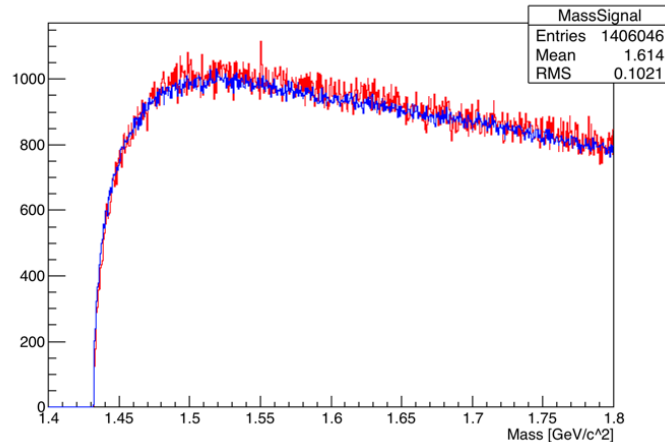
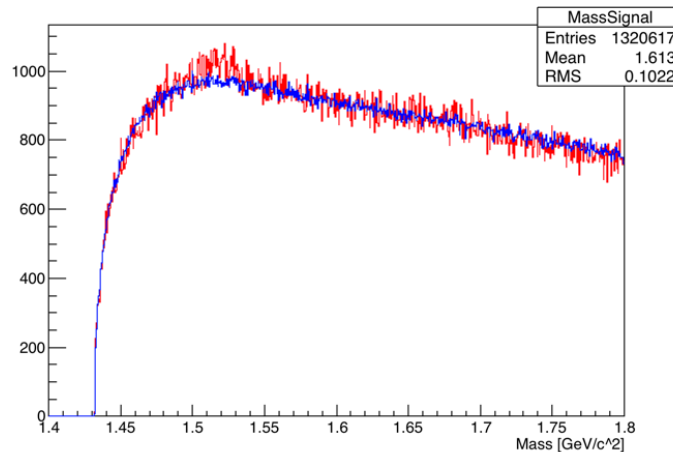
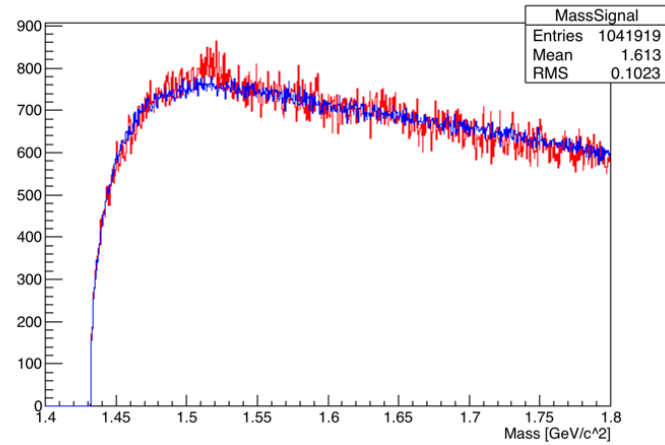
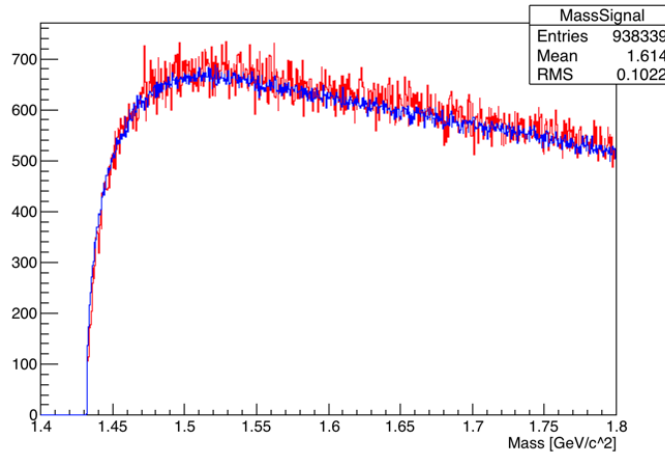
Red: FG Blue: BG

Mixed Event

Rotational BG

K^-

K^+



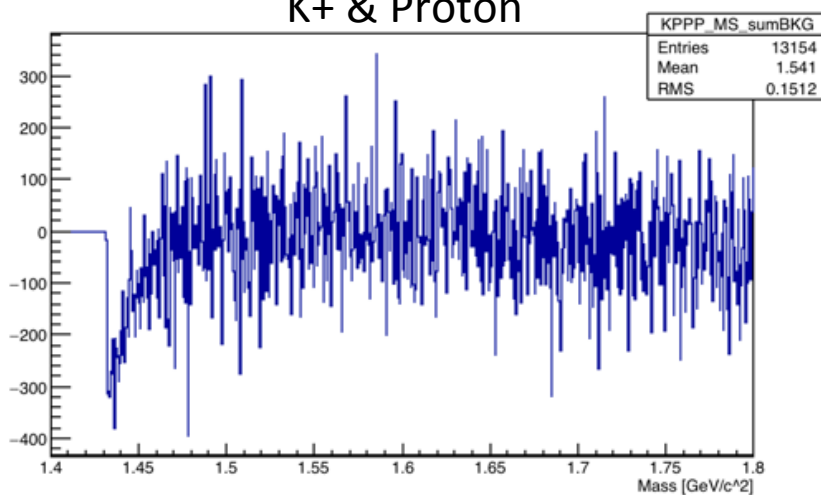
$E_k = \frac{1}{2} m v^2$
 $-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi = E\psi$
 $U_{ef} = U_m$
 $\vec{B} = \mu \frac{NI\sqrt{2}}{2\pi r}$
 $k = \frac{p^2}{2m} m_0 = \frac{M_0}{N_0}$
 $\lambda = \frac{h}{p}$
 $\sqrt{2eUm}$
 $f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{e}} \psi(x) = \sqrt{2/L}$
 $\oint \vec{B} \cdot d\vec{l} = \mu \int \vec{J} \cdot d\vec{S}$
 $C(s)$
 $v_k = \sqrt{\frac{3kT}{m_0}} = \sqrt{\frac{3kTN}{M_m}} = \sqrt{\frac{3R}{M}}$
 $\lambda = \frac{\ln 2}{T} F_h = P$
 $\left(\frac{E_t}{E_0}\right)_{\parallel} = \frac{2 \cos \vartheta_1 \cos \vartheta_2}{\cos(\vartheta_1 - \vartheta_2) \sin \vartheta_2}$
 $E_y = E_0 \sin(k_x - \omega t)$
 $S = \frac{1}{A} \frac{d\omega}{dt}$

Pentaquark—Mass Distribution

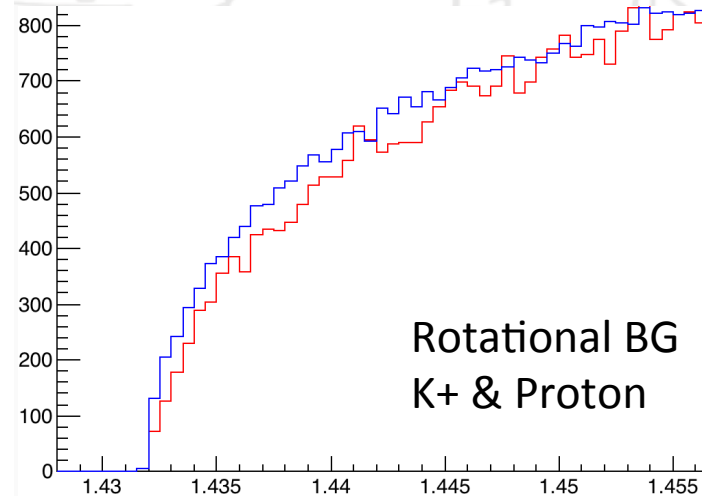
MB1/5/6 cen60~70% Both Rotational and Mixed Event BG

Same Sign :

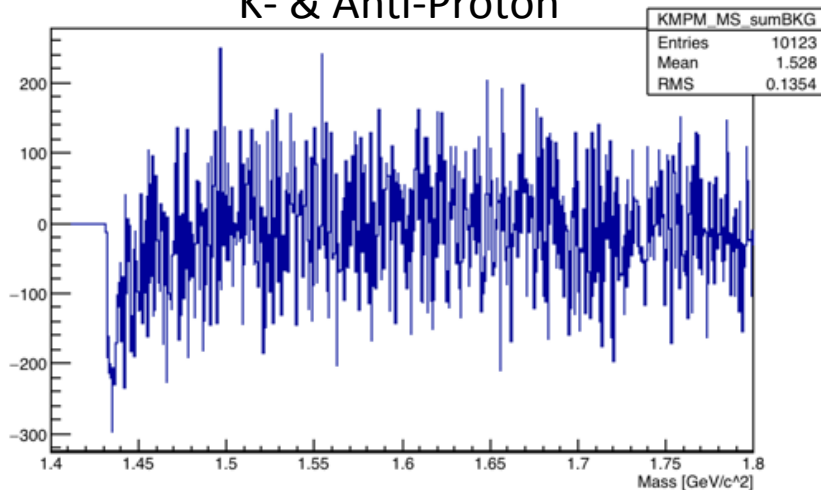
K+ & Proton



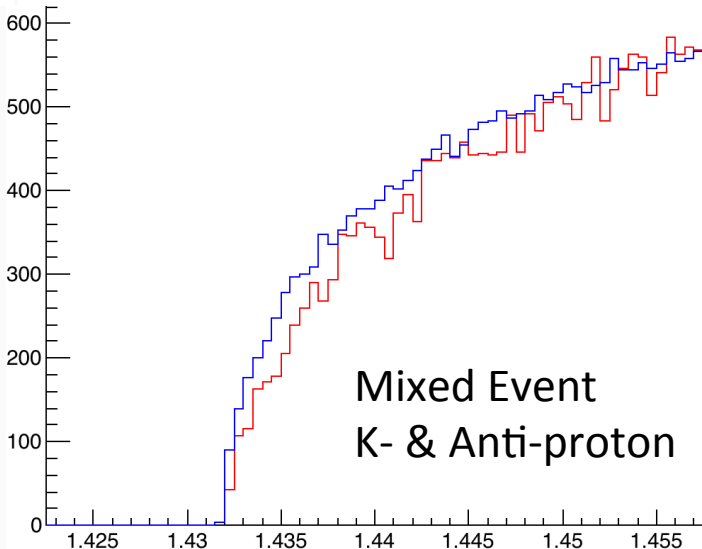
Rotational BG
K+ & Proton



K- & Anti-Proton



Mixed Event
K- & Anti-proton



$$E_k = \frac{1}{2} m v^2$$
$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi = E\psi$$
$$U_{ef} = U_m$$
$$\vec{B} = \mu_0 \frac{NI\sqrt{2}}{r}$$
$$k = \frac{p^2}{2m} = \frac{m_0 v^2}{2}$$
$$\lambda = \frac{h}{p}$$
$$V_{2eU} = \sqrt{2eU}$$
$$f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{l}}$$
$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$
$$C(s)$$
$$v_k = \sqrt{\frac{3kT}{m_0}} = \sqrt{\frac{3kTN}{Mm}}$$
$$\lambda = \frac{\ln 2}{T} F_h$$
$$\left(\frac{E_t}{E_0}\right)_{\parallel} = \frac{2 \cos \theta_1}{\cos(\theta_1)}$$
$$E_y = E_0 \sin(kx - \omega t)$$
$$S = \frac{1}{A} \frac{dW}{dt}$$

Pentaquark—Mass Distribution

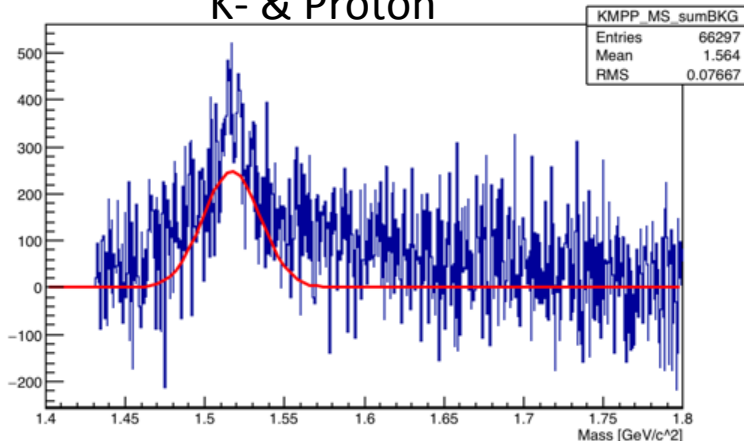
MB1/5/6 cen60~70% Both Rotational and Mixed Event BG

Opposite Sign: $\Lambda(1520) \rightarrow K^- + P$

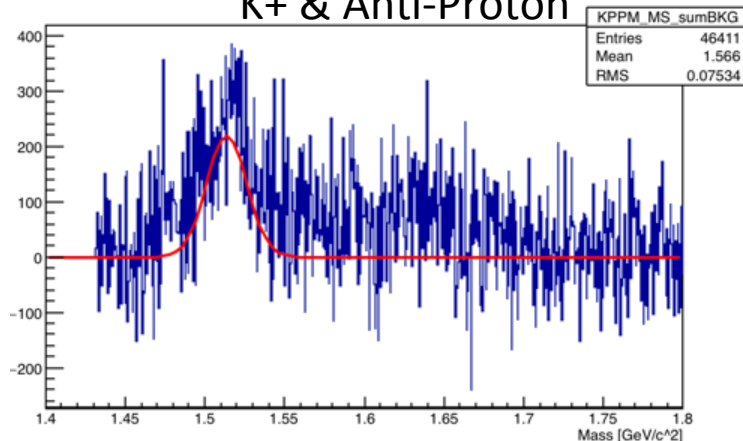
K⁻ & Proton

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Constant	2.46475e+02	3.60199e+00	2.08732e-01	2.27622e-06
2	Mean	1.51690e+00	1.61252e-04	1.60560e-05	-9.54244e-02
3	Sigma	1.79697e-02	2.60803e-04	1.22167e-04	1.08990e-03

K⁻ & Proton



K⁺ & Anti-Proton



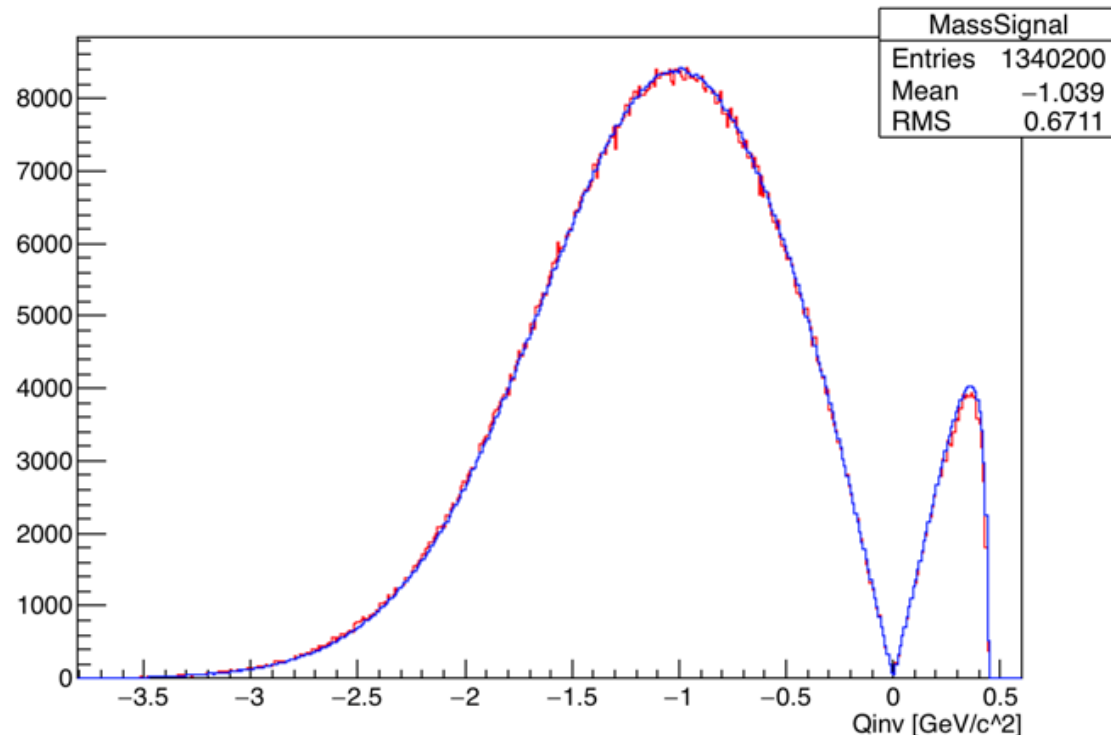
K⁺ & Anti-proton

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Constant	2.19258e+02	2.92751e+00	2.17101e-01	-1.24284e-04
2	Mean	1.51370e+00	1.32916e-04	1.34788e-05	6.95243e-01
3	Sigma	1.25410e-02	1.50243e-04	1.08384e-04	1.33239e-01

Correlation Function—Kaon & Proton

- Q_{inv}
 - Equation: $Q_{inv}^2 = \Delta E^2 - \Delta P^2$
 - Function in code: m() from StLorentzVectorD.h
 - Mixed Event BG & Same KP Selection
 - MB5 (~25% data) cen60~70% K– Anti-Proton

Red: FG
Blue: BG



Correlation Function—Kaon & Proton

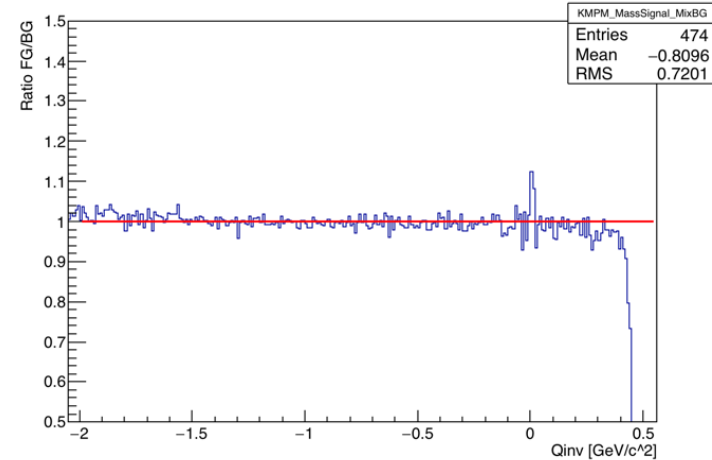
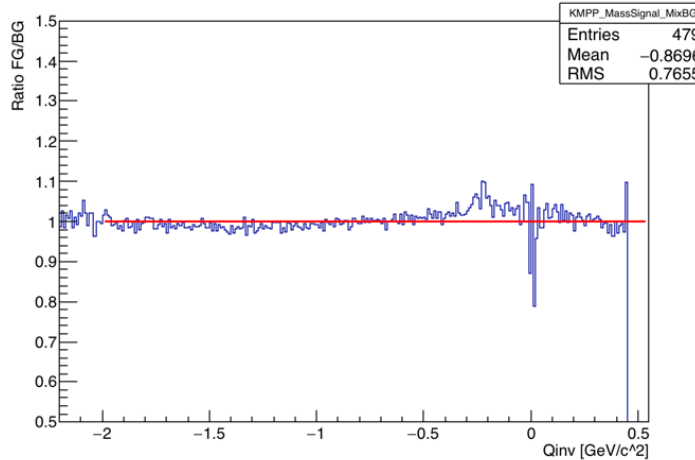
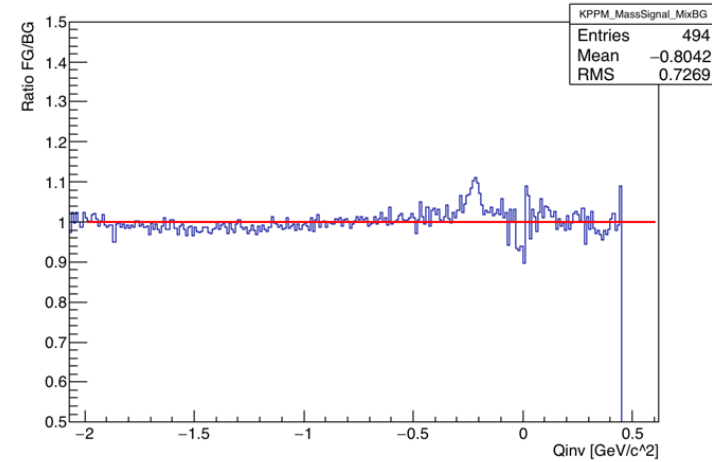
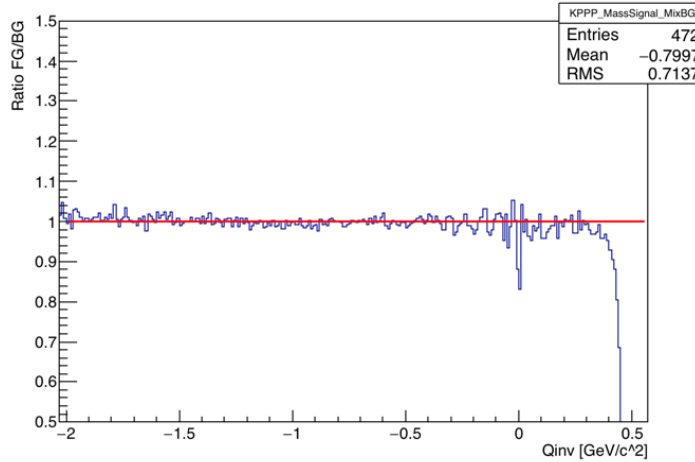
MB5 (~25% data) cen60~70%

$$P \quad \text{Ratio} = \frac{\text{Foreground}}{\text{Background}} \quad \bar{P}$$

$E_k = \frac{1}{2} m v^2$
 $-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi = E\psi$
 $U_{ef} = U_m$
 $\vec{B} = \mu \frac{NI\sqrt{2}}{r}$
 $k = \frac{p^2}{2m} m_0 = \frac{M_p}{M_n}$
 $\lambda = \frac{h}{mv}$
 $\sqrt{2eU_m}$
 $f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{l}}$
 $\oint \vec{B} \cdot d\vec{l} = \mu \int \vec{J} \cdot d\vec{s}$
 $C(s)$
 $v_k = \sqrt{\frac{3kT}{m_0}} = \sqrt{\frac{3kTN}{M_m}}$
 $\lambda = \frac{\ln 2}{T} F_h$
 $\left(\frac{E_t}{E_0}\right)_{\parallel} = \frac{2\cos\theta_1\cos\theta_2}{\cos(\theta_1-\theta_2)}$
 $E_y = E_0 \sin(k_x - \omega t)$
 $S = \frac{1}{A} \frac{d\omega}{dt}$

K^+

K^-



Correlation Function—Kaon & Proton

- Momentum in Center of Mass Frame $|k^*$

– Mixed Event BG & Same KP Selection

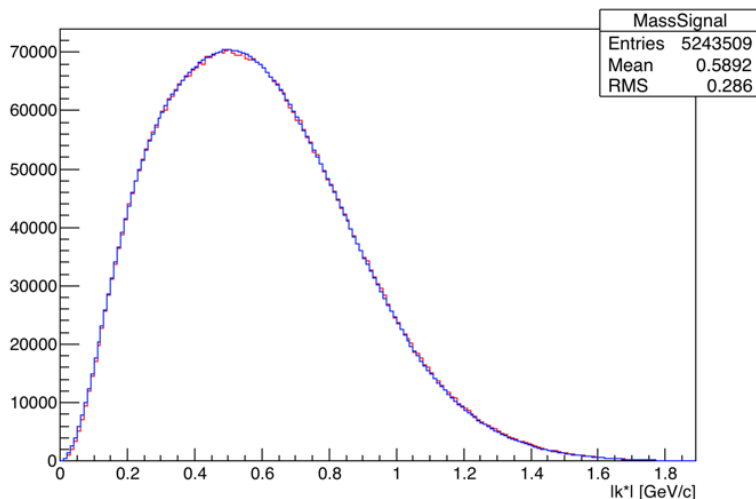
– Code:

```
double P_CoM(const StLorentzVectorD P1, const StLorentzVectorD P2)
{
    StLorentzVectorD Dau1 = P1, Dau2 = P2;
    StLorentzVectorD Par = Dau1 + Dau2;
    StLorentzVectorD Boo = -Par;
    Dau1 = Dau1.boost(Boo); Dau2 = Dau2.boost(Boo); Par = Par.boost(Boo);
    double px1 = Dau1.px(), py1 = Dau1.py(), pz1 = Dau1.pz();
    double px2 = Dau2.px(), py2 = Dau2.py(), pz2 = Dau2.pz();
    double px0 = Par.px(), py0 = Par.py(), pz0 = Par.pz();
    double p02 = px0*px0 + py0*py0 + pz0*pz0;
    double px = px1 + px2, py = py1 + py2, pz = pz1 + pz2;
    double p12 = px1*px1 + py1*py1 + pz1*pz1, p22 = px2*px2 + py2*py2 +
        pz2*pz2;
    return sqrt(p12);
}
```

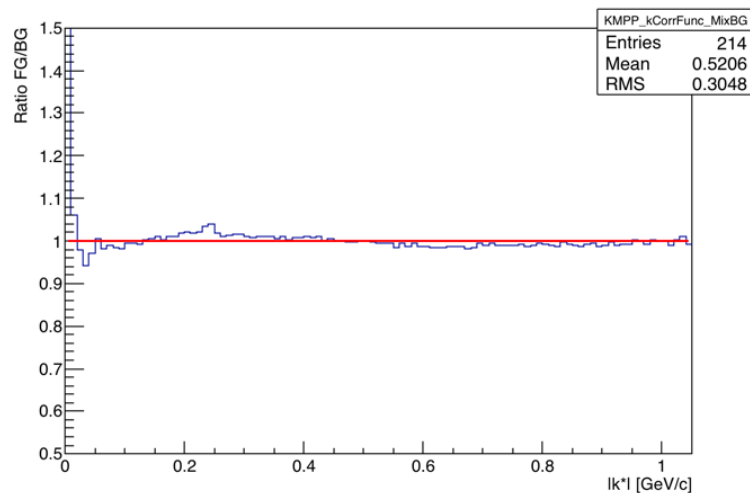
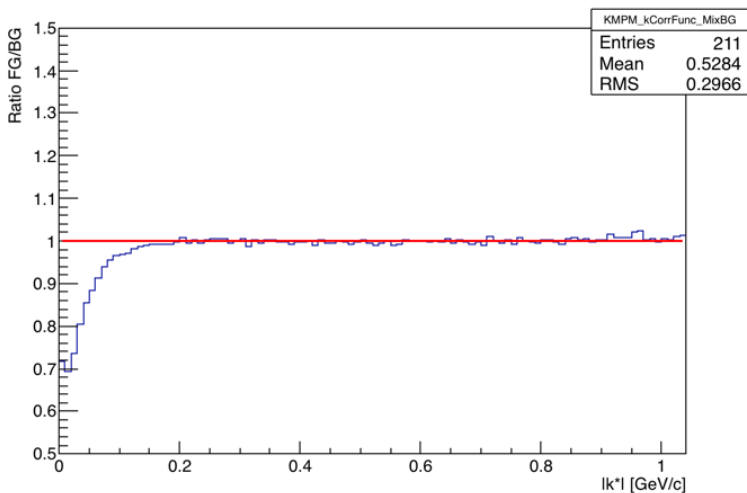
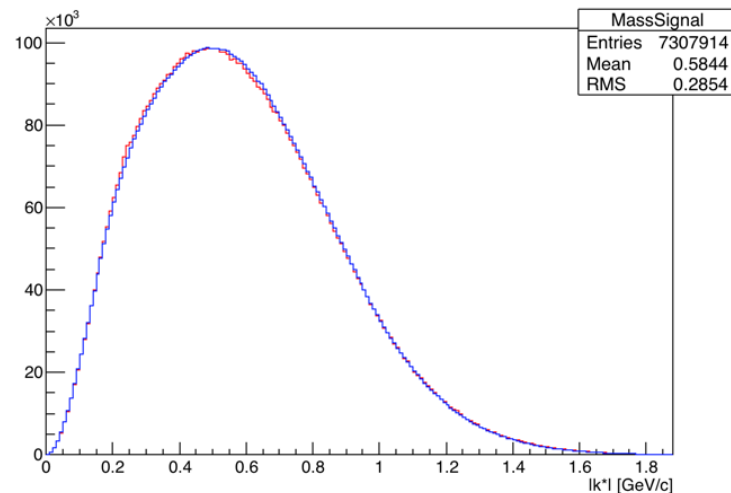
Correlation Function—Kaon & Proton

MB5 (~25% data) cen50~60%

K- & Anti-Proton



K- & Proton



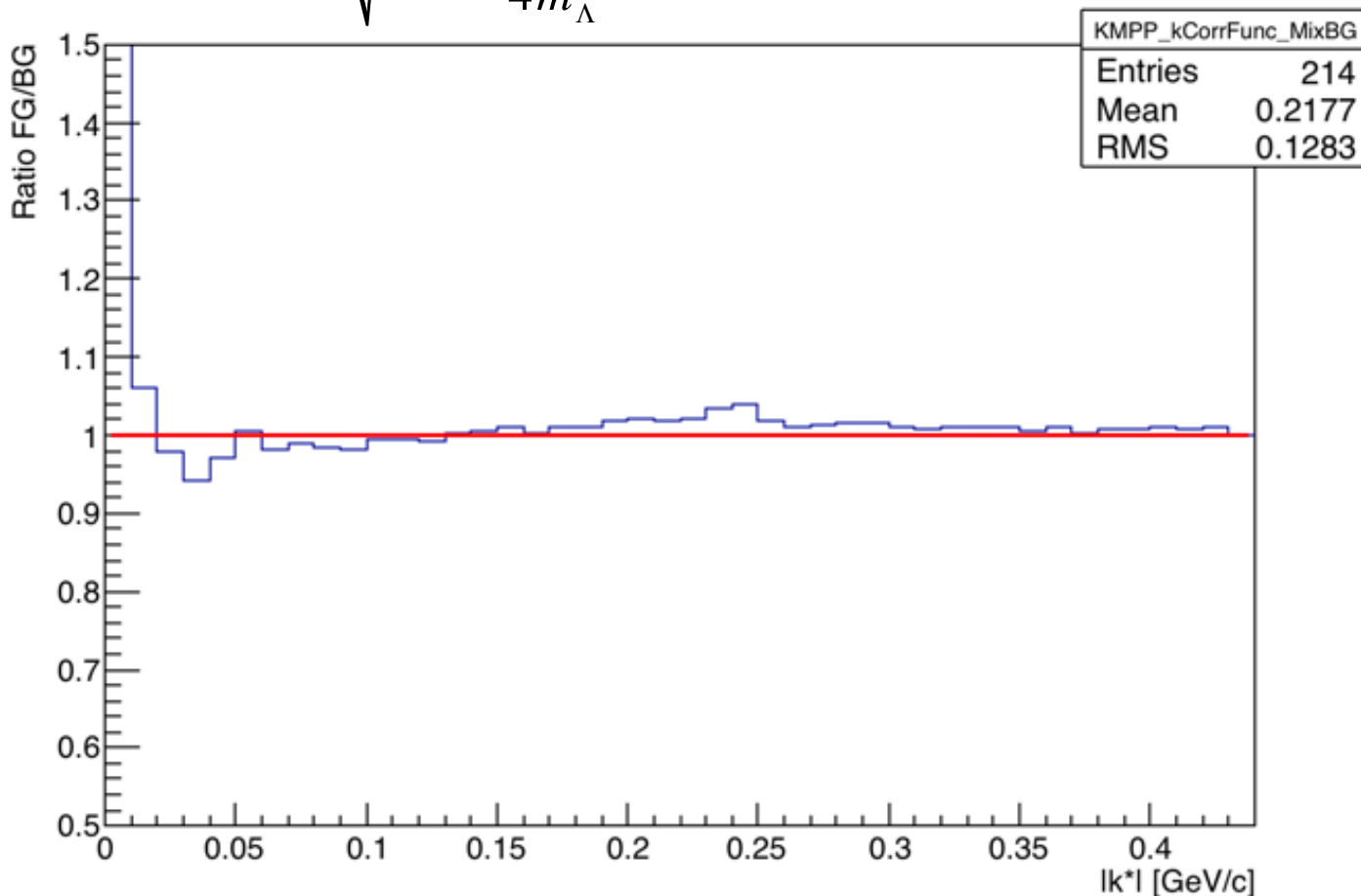
$E_k = \frac{1}{2} m v^2$
 $-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi = E\psi$
 $U_{ef} = U_m$
 $\vec{B} = \mu_0 \frac{NI\sqrt{2}}{r}$
 $k = \frac{p^2}{2m} m_0 = \frac{M}{N}$
 $\lambda = \frac{h}{mv}$
 $\sqrt{2eU}$
 $f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{e}} \psi_0$
 $\oint \vec{B} d\vec{l} = \mu_0 I$
 $C(s)$
 $v_k = \sqrt{\frac{3kT}{m_0}} = \sqrt{\frac{3kTN}{Mm}}$
 $\lambda = \frac{\ln 2}{T} F_h$
 $\left(\frac{E_t}{E_0}\right)_{||} = \frac{2\cos\theta_1}{\cos(\theta_1)}$
 $E_y = E_0 \sin(k_x - \omega t)$
 $S = \frac{1}{A} \frac{d\omega}{dt}$

Correlation Function—Kaon & Proton

MB5 (~25% data) cen50~60%

$\Lambda(1520) \rightarrow K^- (0.493667) + P (0.938272)$

$$|k^*| = \sqrt{\frac{(m_\Lambda^2 + m_K^2 - m_P^2)^2}{4m_\Lambda^2} - m_K^2} \approx 0.243$$



$E_k = \frac{1}{2} m v^2$
 $-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi = E\psi$
 $U_{ef} = \frac{U_m}{N}$
 $\vec{B} = \mu_0 \frac{NI\sqrt{2}}{r}$
 $k = \frac{p^2}{2m} m_0 = \frac{M_p}{N}$
 $\lambda = \frac{h}{m v}$
 $\sqrt{2eUm}$
 $f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{e}} \psi(\alpha)$
 $\oint \vec{B} d\vec{l} = \mu_0 \int \vec{J} dV$
 $C(s)$
 $v_k = \sqrt{\frac{3kT}{m_0}} = \sqrt{\frac{3kTN}{M_m}}$
 $\lambda = \frac{\ln 2}{T} F_h$
 $\left(\frac{E_t}{E_0}\right)_\parallel = \frac{2 \cos \theta_1 \cos \theta_2}{\cos(\theta_1 - \theta_2)}$
 $E_y = E_0 \sin(k_x - \omega t)$
 $S = \frac{1}{A} \frac{d\omega}{dt}$

Summary

- No signal of pentaquark particle
- Further study on P-K Correlation Functions
- Send an abstract to undergraduate conference (CEU):

Study of proton-kaon correlations in heavy-ion collisions

The proton-kaon (pK^+ , pK^- and their anti-particles) correlations can be sensitive to several physics topics in heavy-ion collisions. The pK^+ correlation could be sensitive to a possible formation of penta-quark candidates with quark contents (uudu-sbar). The pK^- correlation measurement could be sensitive to the formation of Lambda (1520) and Lambda(1405). In particular, the Lambda (1405) is below the pK^- threshold and a bound state of Lambda (1405), as a molecular state of proton-kaon suggested by recent Lattice QCD calculation^[1], could deplete the pK^- correlation at small Q_{inv} due to coalescence formation of Lambda(1405) from pK^- . We will present the status and further physics implications of our pK correlations from Au+Au collisions at 200 GeV at the STAR experiment.

[1]: PhysRevLett.114.132002

$$E_k = \frac{1}{2} m v^2$$

$$-\frac{\hbar^2}{2m} \frac{d^2 \psi}{dx^2} + V \psi = E \psi$$

$$U_{ef} = \frac{U_m}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\vec{B} = \mu_0 \frac{NI \sqrt{2}}{2r}$$

$$k = \frac{p^2}{2m} m_0 = \frac{M_m}{N_A}$$

$$\lambda = \frac{h}{m v}$$

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{l}}$$

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \int_S \vec{J} \cdot d\vec{S}$$

$$v_k = \sqrt{\frac{3kT}{m_0}} = \sqrt{\frac{3kTN_A}{M_m}}$$

$$\lambda = \frac{h \nu_2}{T}$$

$$\left(\frac{E_t}{E_0} \right)_{\parallel} = \frac{2 \cos \theta_1 \cos \theta_2}{\cos(\theta_1 - \theta_2) \sin(\theta_1 + \theta_2)}$$

$$S = \frac{1}{A} \frac{d\omega}{dt}$$

$$2 \tan \theta_B = \frac{m_2}{m_1} = m_{21}$$

$$Me = \sigma T^4$$

$$\phi_e = \frac{L}{4\pi r^2}$$

$$U = \frac{W_{AB}}{q} = \frac{|E_{PA} - E_{PB}|}{q} = \frac{|\varphi_A - \varphi_B|}{q}$$

$$\varphi_E = \frac{E_e}{q_0} = k \frac{Q}{r}$$

$$m = N \cdot m_0 = \frac{Q}{N_A} \frac{M_m}{e}$$

$$l_t = l_0 (1 + \alpha \Delta t)$$

$$R = \rho \frac{l}{S}$$

$$E = \frac{1}{2} \hbar \sqrt{k/m}$$

$$\vec{S} = \frac{1}{\mu_0} (\vec{E} \times \vec{B})$$

$$E = \hbar k^2 \frac{1}{2m}$$

$$f_0 = \frac{1}{2\pi \sqrt{CL}}$$

$$\int \vec{E} \cdot d\vec{l} = - \int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$$

$$R = R_0 \sqrt[3]{A}$$

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

$$u = U_m \sin \omega(t - \tau) = U_m \sin 2\pi \left(\frac{t}{T} - \frac{x}{\lambda} \right)$$

$$\rho V = nRT$$

$$\Psi = \iint \vec{D} \cdot d\vec{S} = AD$$

$$H_\lambda = \frac{\Delta Me}{\Delta \lambda}$$

$$\frac{\Delta \varphi}{2\pi} = \frac{\Delta x}{\lambda} = \frac{x_2 - x_1}{\lambda}$$

$$V = c/\lambda$$

$$\Phi = NBS$$

$$k = \frac{2\pi}{\lambda}$$

$$v = \sqrt{\frac{M_2}{R_2}}$$

$$\vec{F}_m = \vec{B} I l = \frac{\mu_0 I_1 I_2}{2\pi d} l$$

$$X_L = \frac{U_m}{I_m} = \omega L = 2\pi f L$$

$$F_g = \frac{m_1 m_2}{r^2}$$

$$R_m = \frac{c}{T}$$

$$k = \pm \sqrt{\frac{2m}{\hbar^2} (E - V_0)}$$

$$E = \frac{E_c}{q} \int_{-a/L}^{+a/L} \sin(\omega t + \phi) dy$$

$$\tan \tau = \frac{d}{f}$$

$$\omega = 2\pi f$$

$$v_1 = \frac{v_2}{n_1}$$

$$v = \frac{1}{\sqrt{\epsilon \cdot \mu}} = \frac{c}{\sqrt{\epsilon + \mu}}$$

$$F_x = \frac{1}{2} C_x \rho \omega^2$$

$$\frac{\Delta I_B}{X} + \frac{\Delta I_C}{X'} = \frac{\omega_2 - \omega_1}{v}$$

$$\oint \vec{D} \cdot d\vec{S} = Q^*$$

$$R = \frac{U}{I}$$

$$F_v = \int \frac{F_n}{R}$$

$$M = \int F d \cos \alpha$$

$$S I_m^2 = U_m^2 \left[\frac{1}{R^2} + \left(\frac{1}{X_C} - \frac{1}{X_L} \right)^2 \right]$$

$$\lambda^* T = b$$

Thanks