Interference in Ultra Peripheral Collisions (UPCs)

An overview

Daniel Torres Valladares, Summer 2023

Heavy Ions UPCs

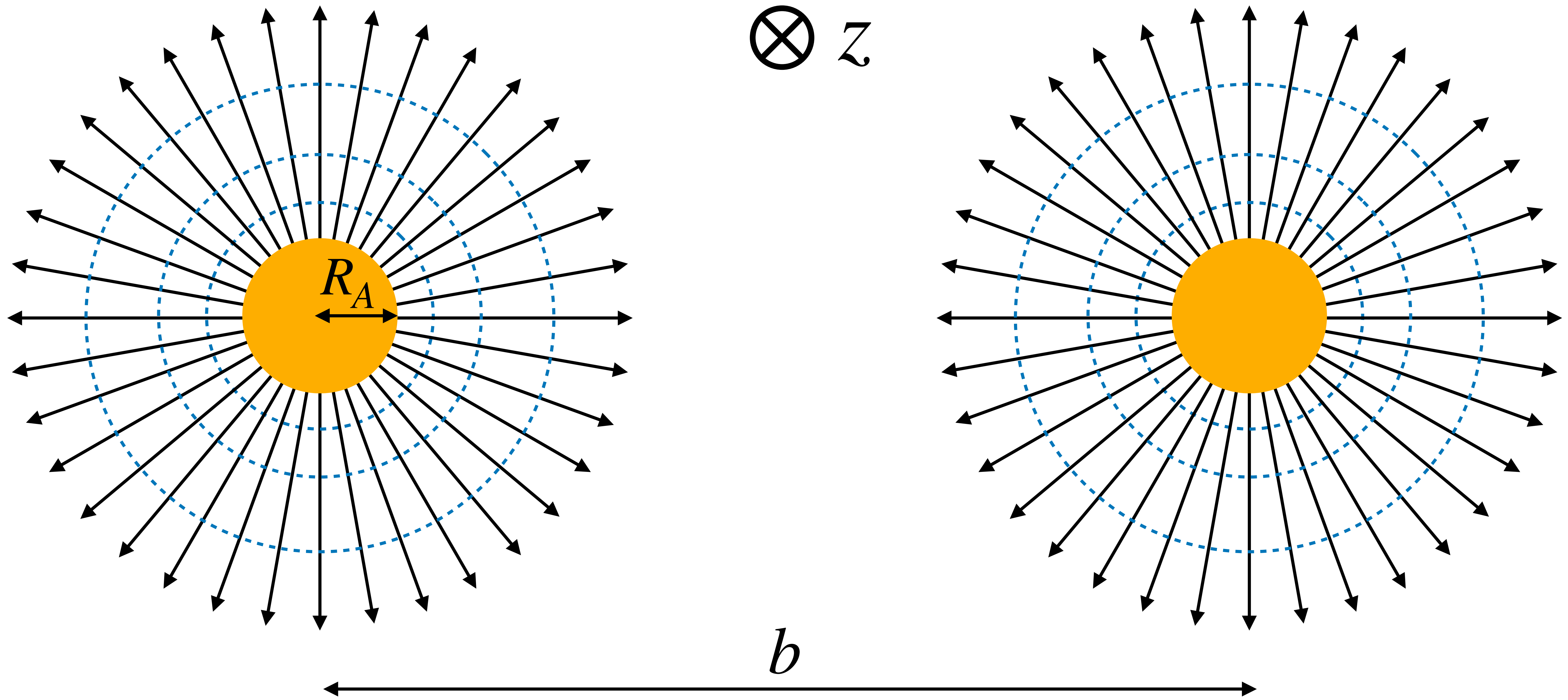
What is a UPC?

- Relativistic particle fields can be treated as a sea of quasi-real photons.

- Photons can either

    1. Interact with the nucleus and break it producing hadronic matter

    2. Produce a virtual meson that elastically scatter with a gluons/quarks producing a real vector mesons.



$b > 2R_A$

$$\mathbf{B} \propto \frac{Zq\beta}{(1-\beta^2)^{1/2}} \frac{\hat{\varphi}}{b^2}$$

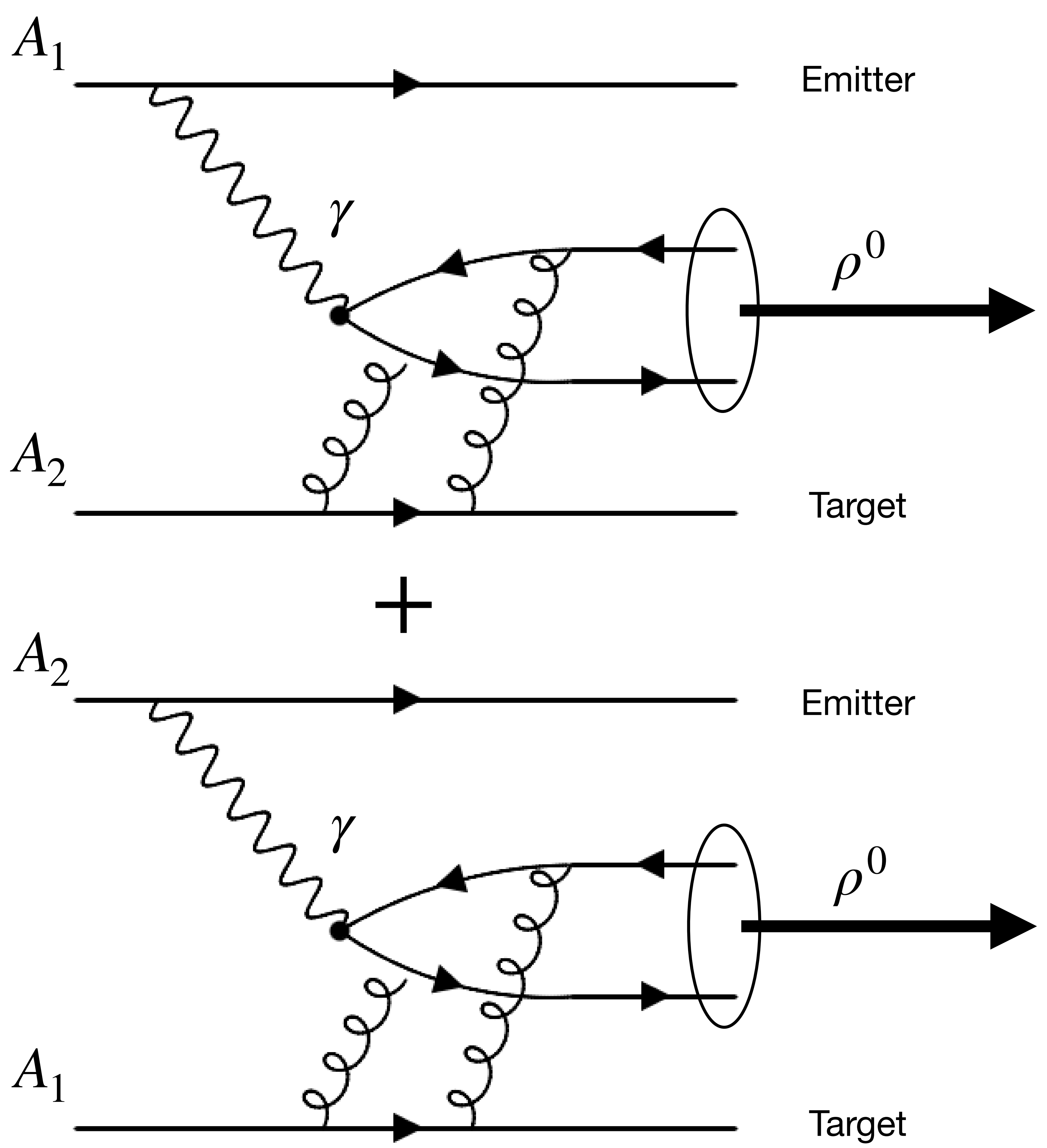
$$\mathbf{E} \propto \frac{Zq\beta}{(1-\beta^2)^{1/2}} \frac{\hat{R}}{b^2}$$

at $z = 0$

Heavy Ions UPCs

Vector meson production

- Virtual photons fluctuate to virtual vector mesons.
- This virtual mesons elastically scatter from the target nucleus and become a real meson.
- It is not necessary a ρ^0 it could be any neutral vector meson $(\omega, \phi, J/\psi)$. However, the ρ^0 has the biggest branching ratio.



Interference in UPC

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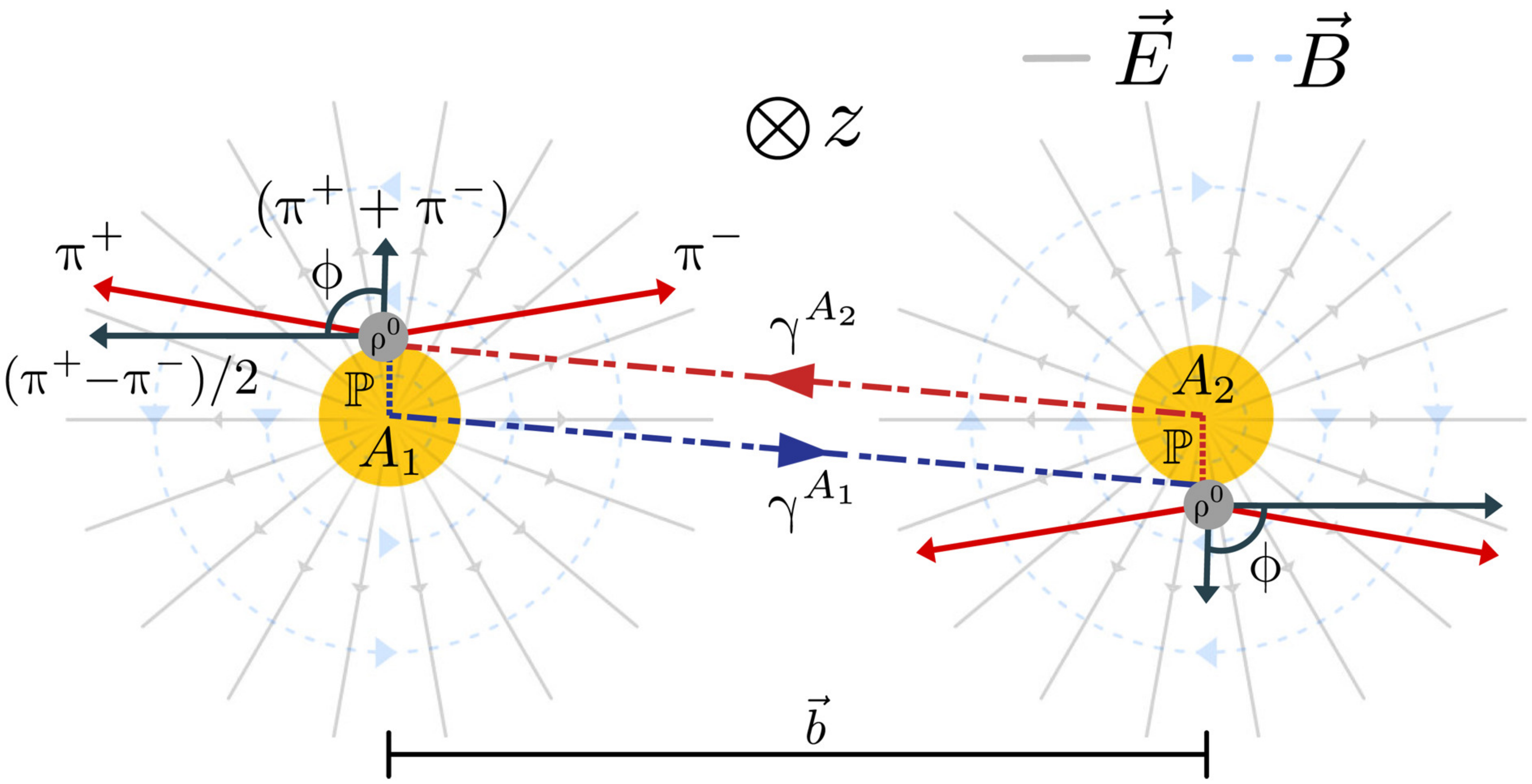


Brandenberg D. et. al. (2023)

- Emitter and target can switch places and give the final state.

- The system invariance under parity, but due to the vector nature of the emitted meson the amplitude of the two processes must have different sign.

- Decay products remain in a entangled stat until detection.

Interference in UPCs

Amplitude of the decay

The amplitude of the vector meson production is given by the sum of the amplitudes of both processes.

$p_\perp$: transverse momentum of the vector meson.

y: rapidity

$\phi(y)$: Phase at rapidity y

$$A_0(x_0, \vec{p}, b) = A(p_\perp, y, b)\exp i[\phi(y) + \vec{p}\cdot\vec{b}/2] - A(p_\perp, -y, b)\exp i[\phi(-y) + \vec{p}\cdot\vec{b}/2]$$

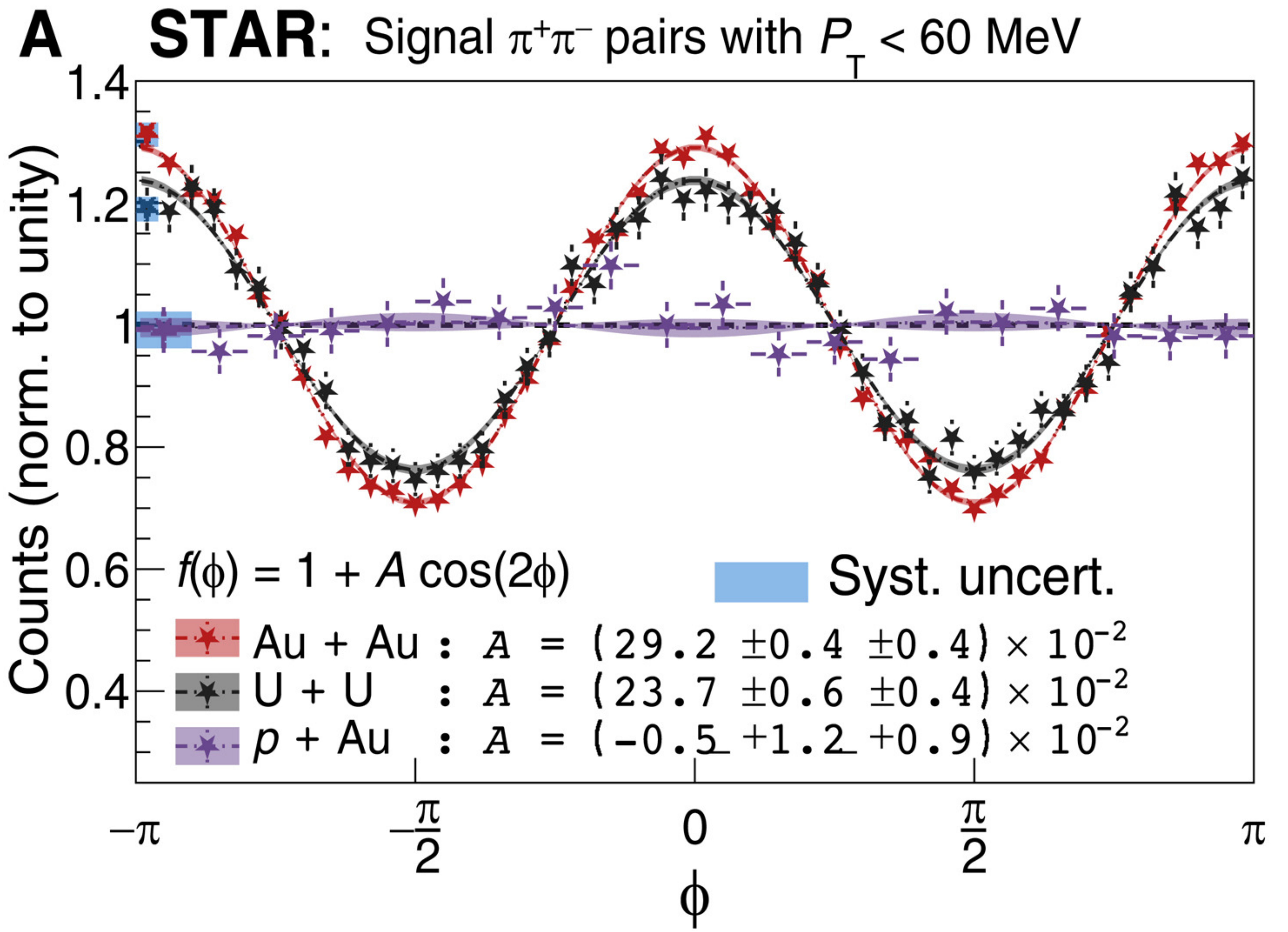
$$\sigma(p_\perp, y, b) = A^2(p_\perp, y, b) + A^2(p_\perp, -y, b) - 2A(p_\perp, y, b)A(p_\perp, -y, b)\cos[\phi(y) + \vec{p}\cdot\vec{b}]$$

At $y = 0$, we get:

$$\boxed{\sigma(p_\perp, y=0, b) = 2A^2(p_\perp, y=0, b)[1 - \cos(\vec{p}\cdot\vec{b})]}$$

Observed interference effect

Here, we observe three types of UPC. Au + Au, U + U, which present parity invariance, and p + Au, that breaks the symmetry. This symmetry breaking vanish the interference effect. In p + Au collisions it is more like that the Au ion acts as the emitter and the proton as the target



Remaining questions

- Why do we say this phenomena is due to entanglement?
- Why do we see ρ^0 and not as many ω?
- Following to Frank's question on Wilczek's talk, what is the cross section of axions at UPC events? Is this a viable way of detecting them?

- It is not completely clear to me why ϕ is the relevant parameter.
- How robust are the theoretical models for vector meson production?
- What are EMC suppression effects? The EMC suppression effects refer to the observed reduction in the parton distribution functions (PDFs) inside the nucleons when they are part of a nucleus.

Why do we see ρ^0 and not as many ω?

Rates in the low energy regime

$M_{\rho^0} = 770$ MeV $\quad \rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

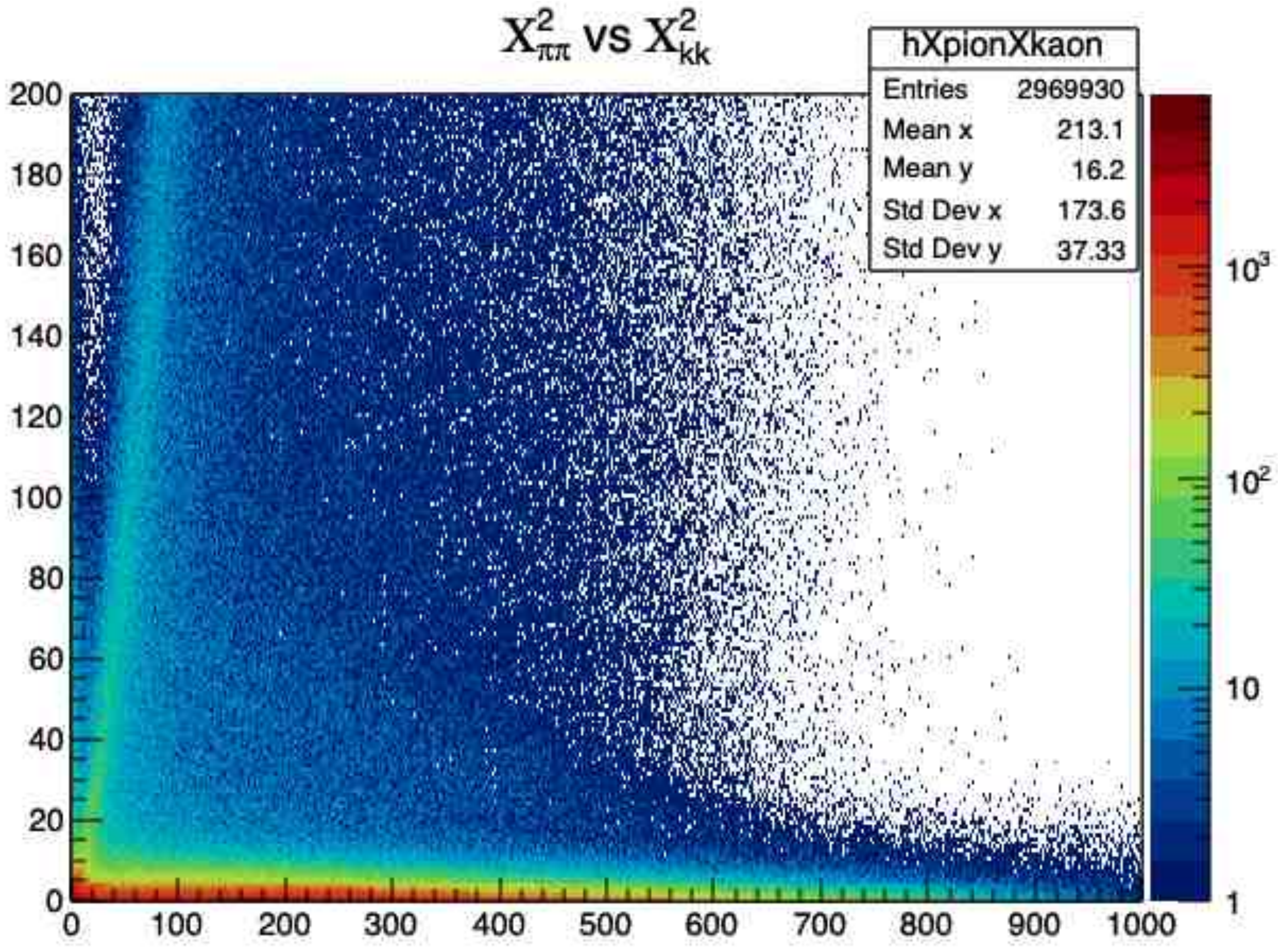
$M_{\omega} = 782$ MeV $\quad \omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$

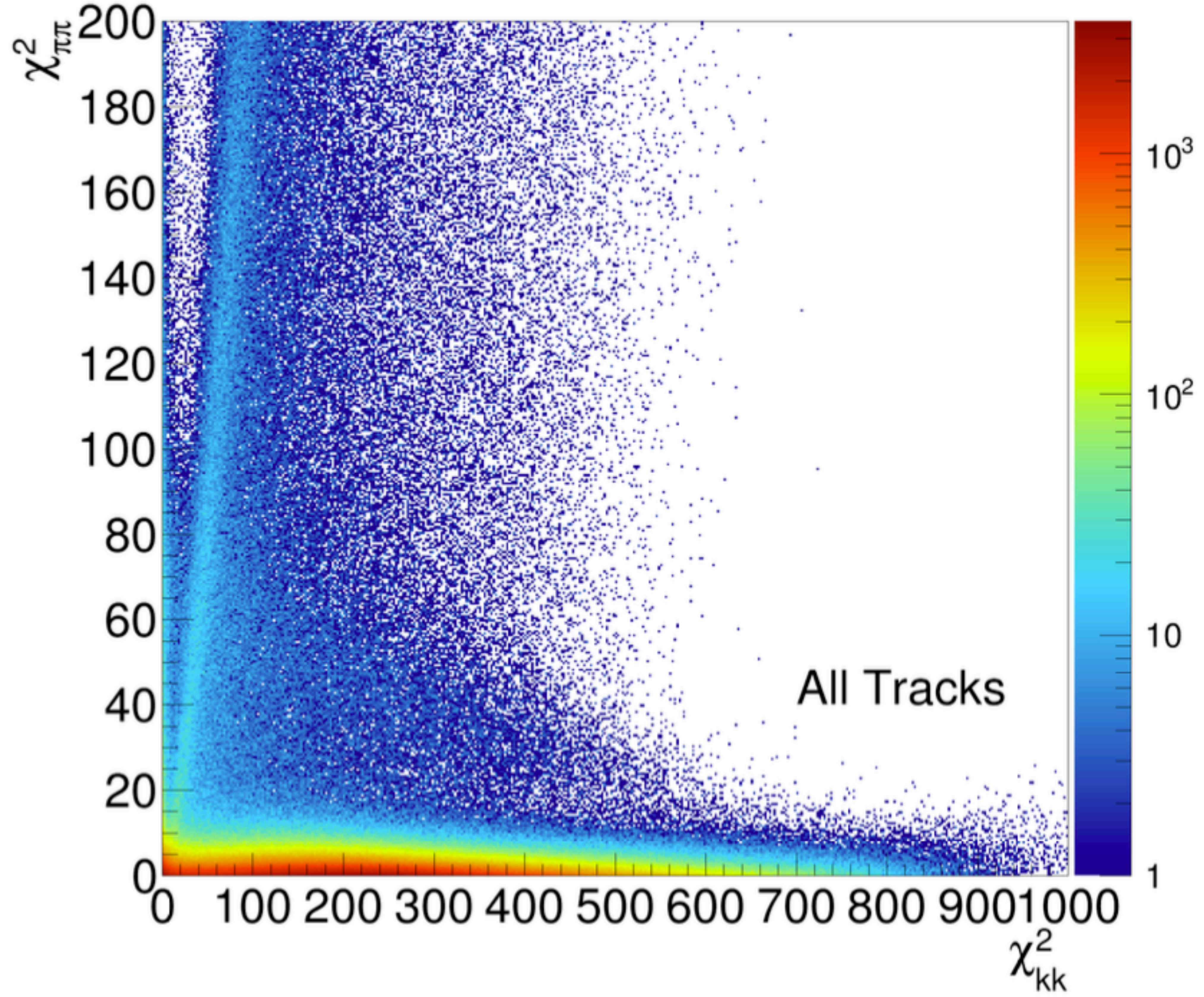
$$\mathscr{L}_{int} = -2M_V f_\pi e A_\mu \left(\frac{\rho^\mu}{\sqrt{2}} + \frac{\omega^\mu}{3\sqrt{2}} + \frac{\phi^\mu}{3} \right)$$

Dias et. al. (2018)

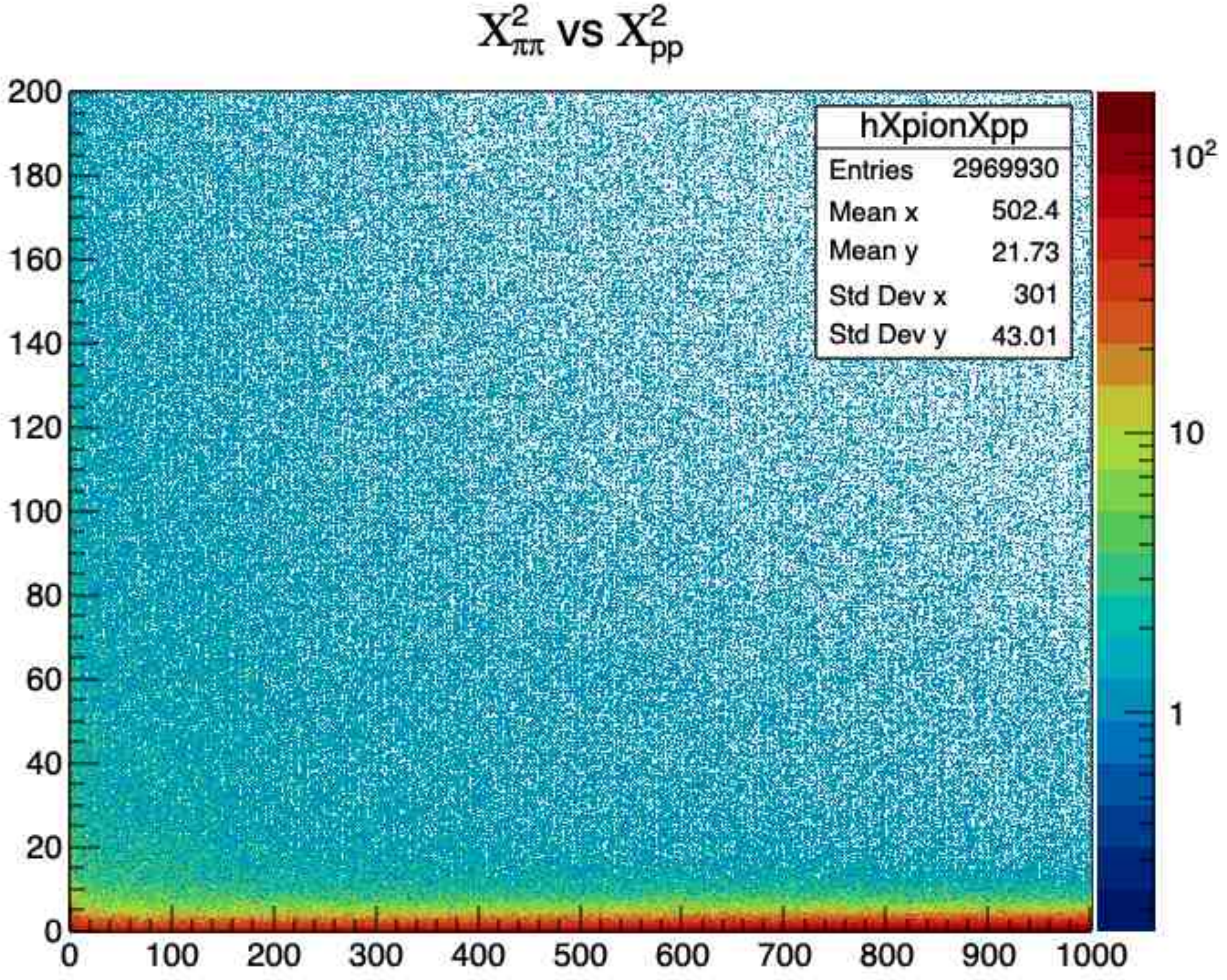
"Exclusive ρ^0 production was about 10 % of the hadronic cross section for gold on gold collisions at a per nucleon center of mas energy $\sqrt{S_{NN}} = 200$ GeV […], rising to 30% for the $\sqrt{S_{NN}} = 5.5$ TeV lead on lead collisions […]. The ω and ϕ are about an order of magnitud smaller, […]" Klein S. Nystrand J. (1999)

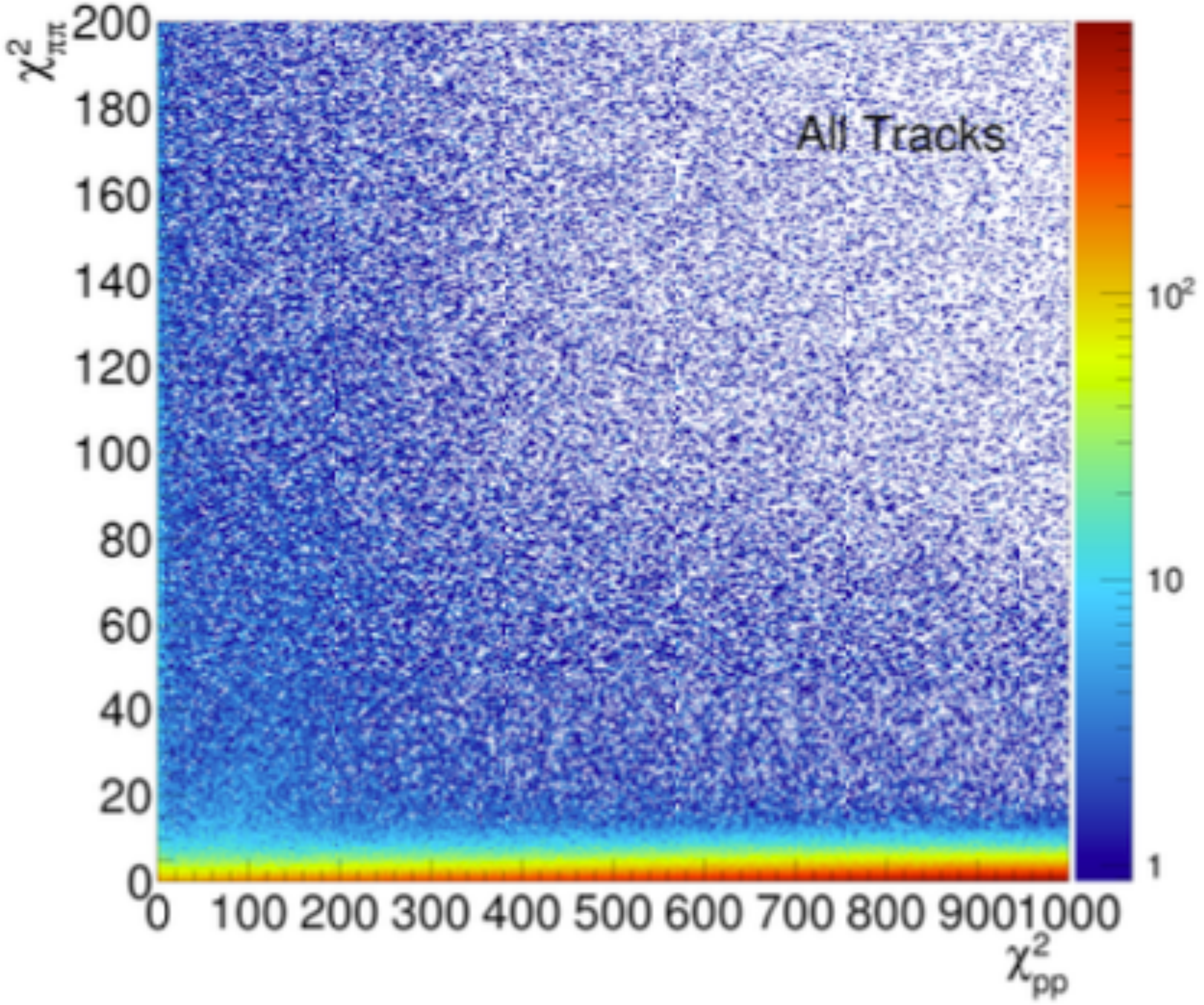
$\chi_{\pi\pi}$ vs χ_{kk}



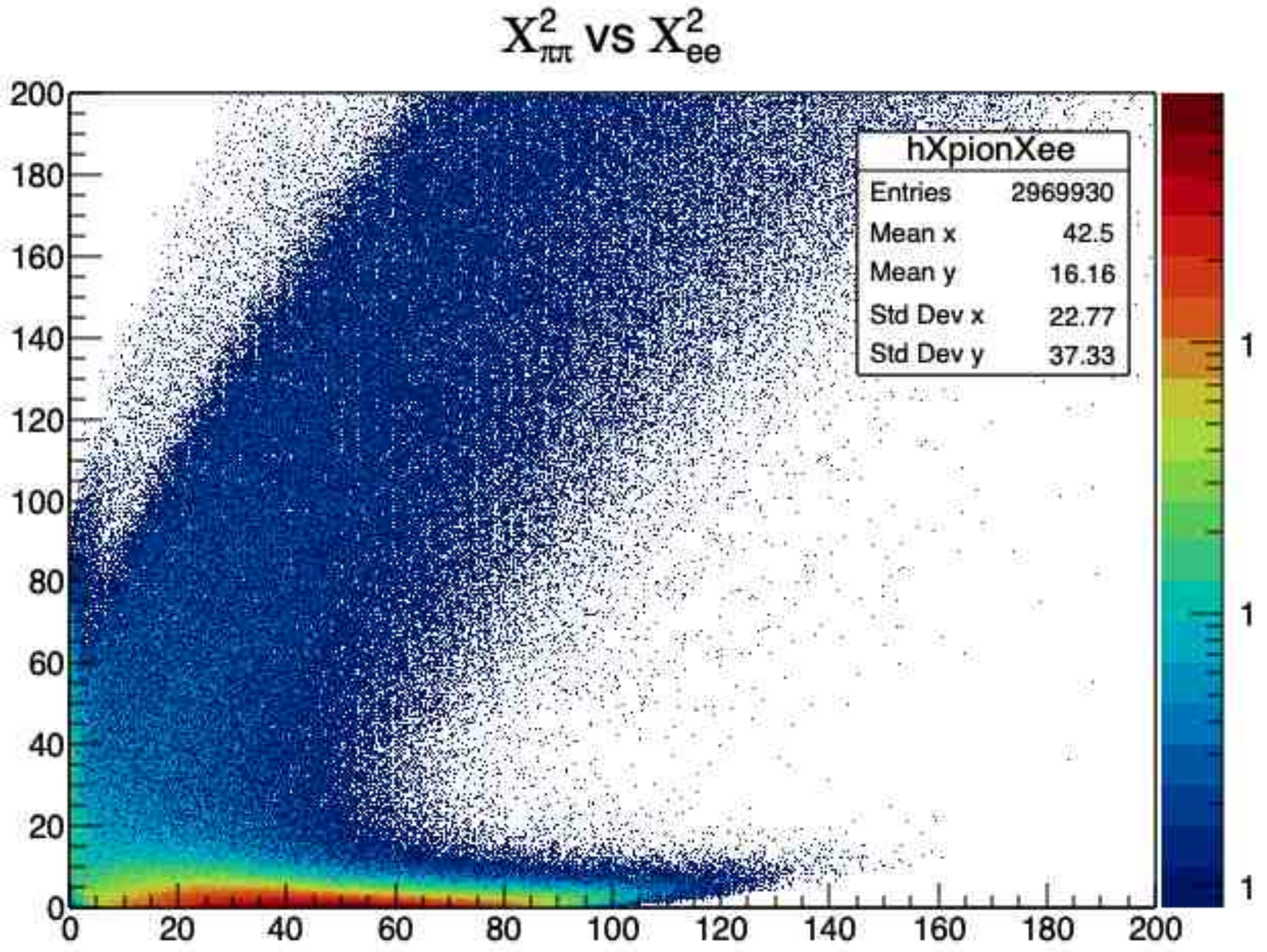


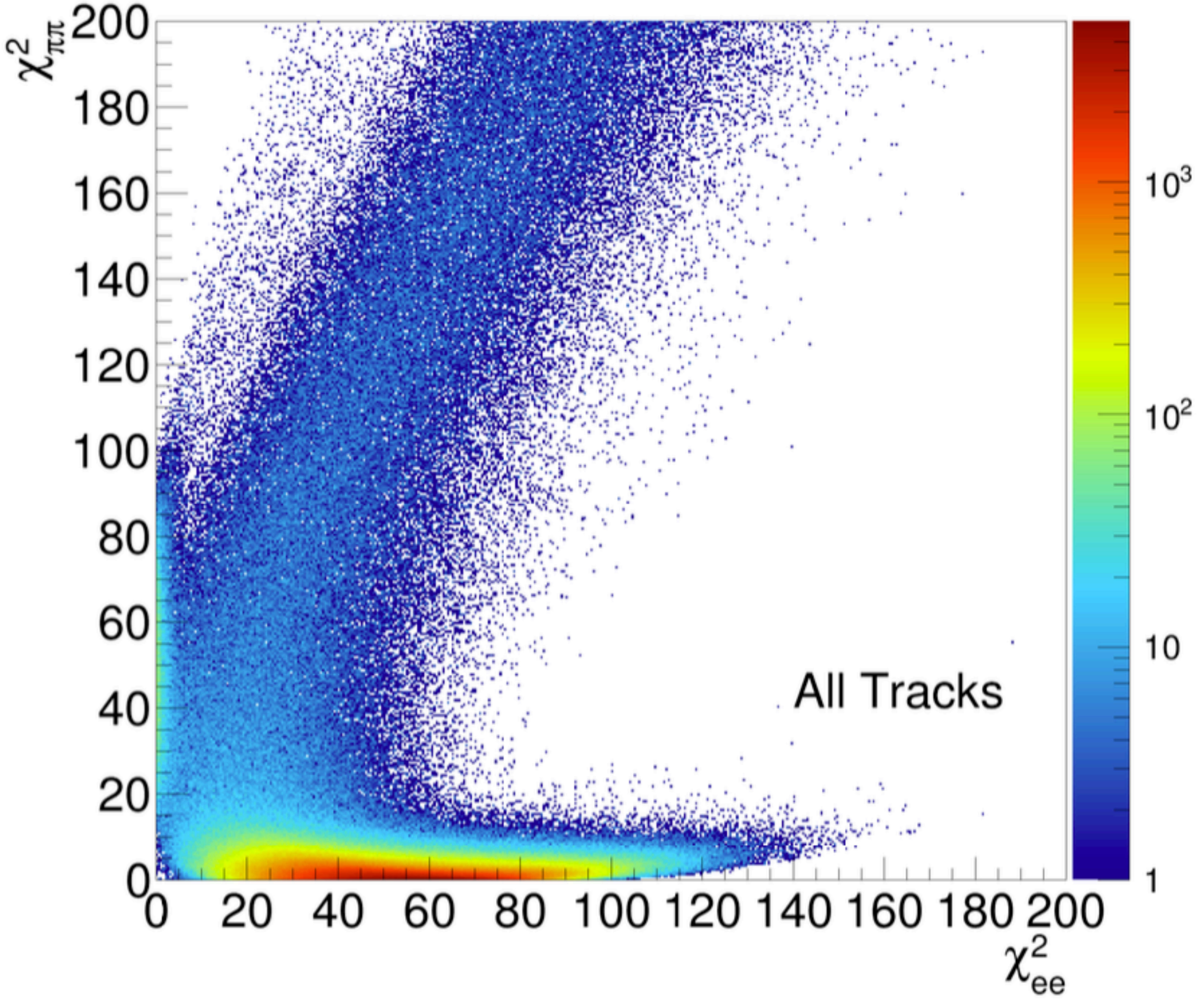
$\chi_{\pi\pi}$ vs χ_{pp}





$\chi_{\pi\pi}$ vs χ_{ee}





ρ_0 peak

$$t_{\text{calc}} = \frac{\Delta s}{c}\sqrt{1 + \frac{m_\pi^2}{p^2}}$$

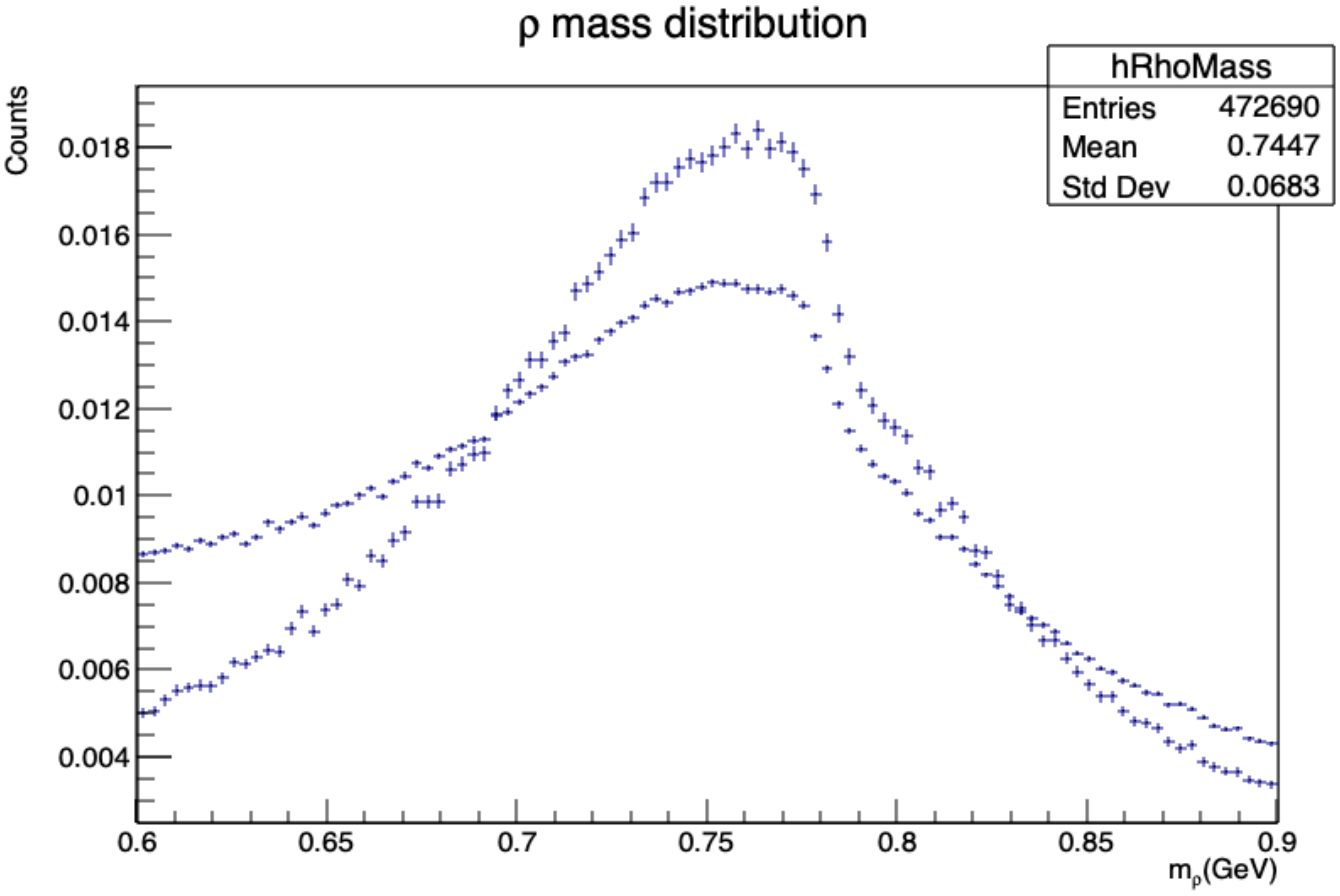
$$\Delta TOF = t^{(2)} - t^{(1)}$$

$$\Delta\Delta TOF = \left|\Delta TOF_{\text{obs}} - \Delta TOF_{\text{calc}}\right|$$

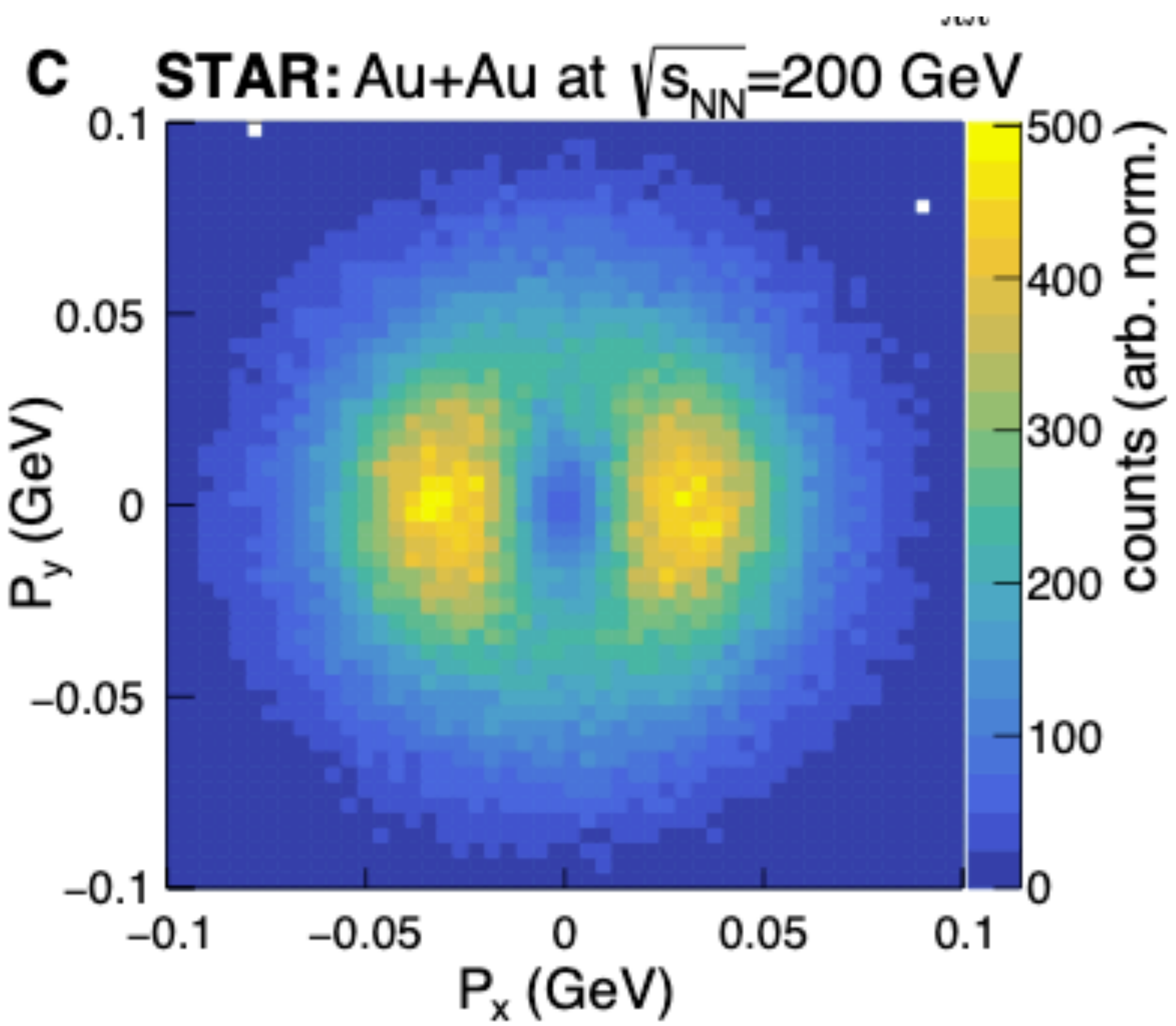
$$\chi^2_{\pi\pi} = n\sigma^2_{\pi^1} + n\sigma^2_{\pi^2}$$

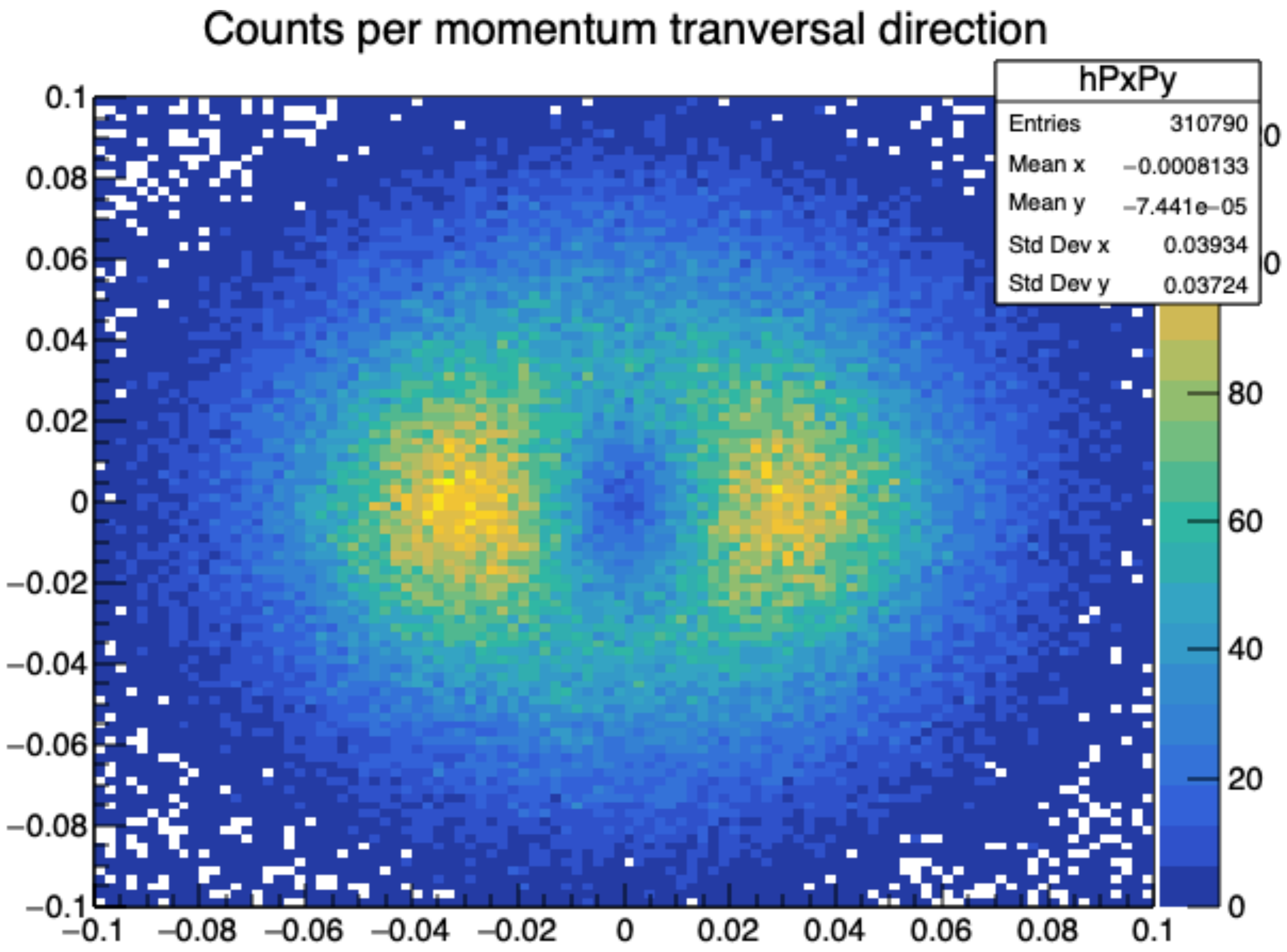
$$\Delta\Delta TOF < 750 \text{ ps}$$

$$\chi_{\pi\pi} < 8$$

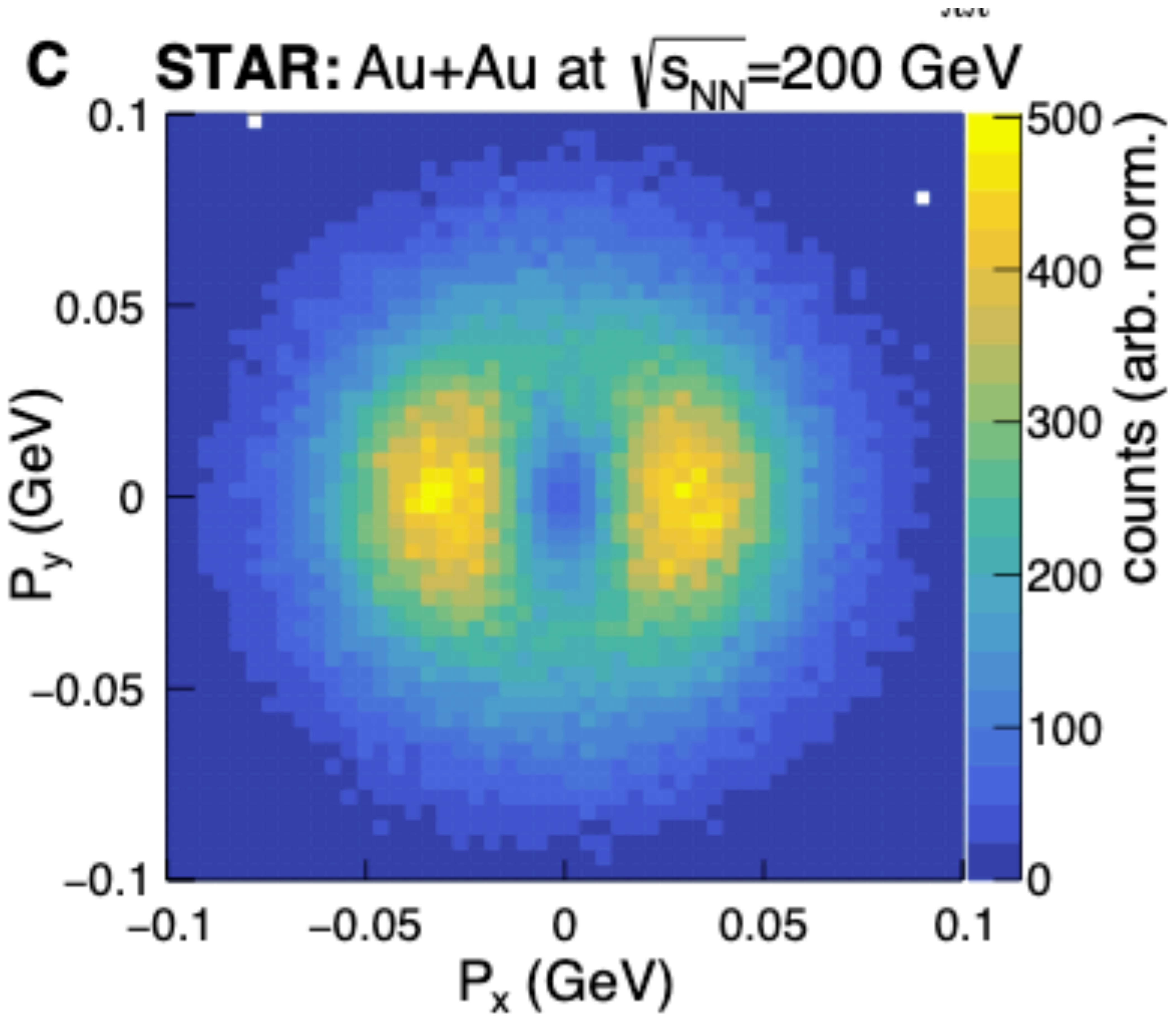


p_x vs. p_y

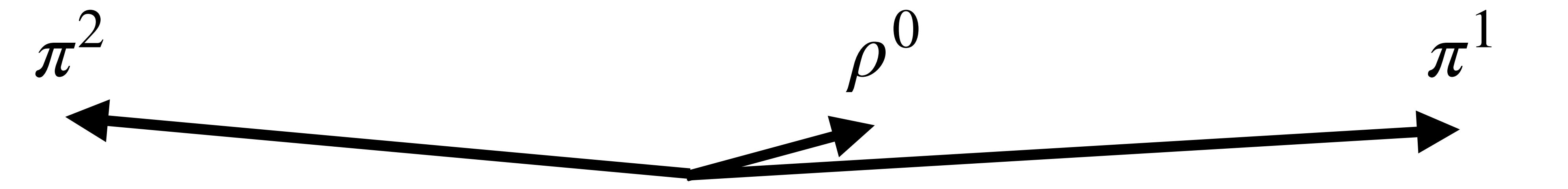

C
STAR: Au+Au at $\sqrt{s_{NN}}$=200 GeV
P_y (GeV)
P_x (GeV)
counts (arb. norm.)
0.1
0.05
0
−0.05
−0.1
500
400
300
200
100
0


Counts per momentum tranversal direction
hPxPy
Entries 310790
Mean x −0.0008133
Mean y −7.441e−05
Std Dev x 0.03934
Std Dev y 0.03724
80
60
40
20
0

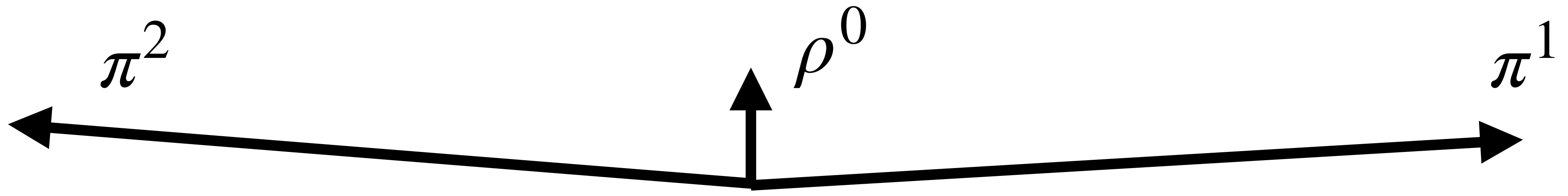
What does this mean?



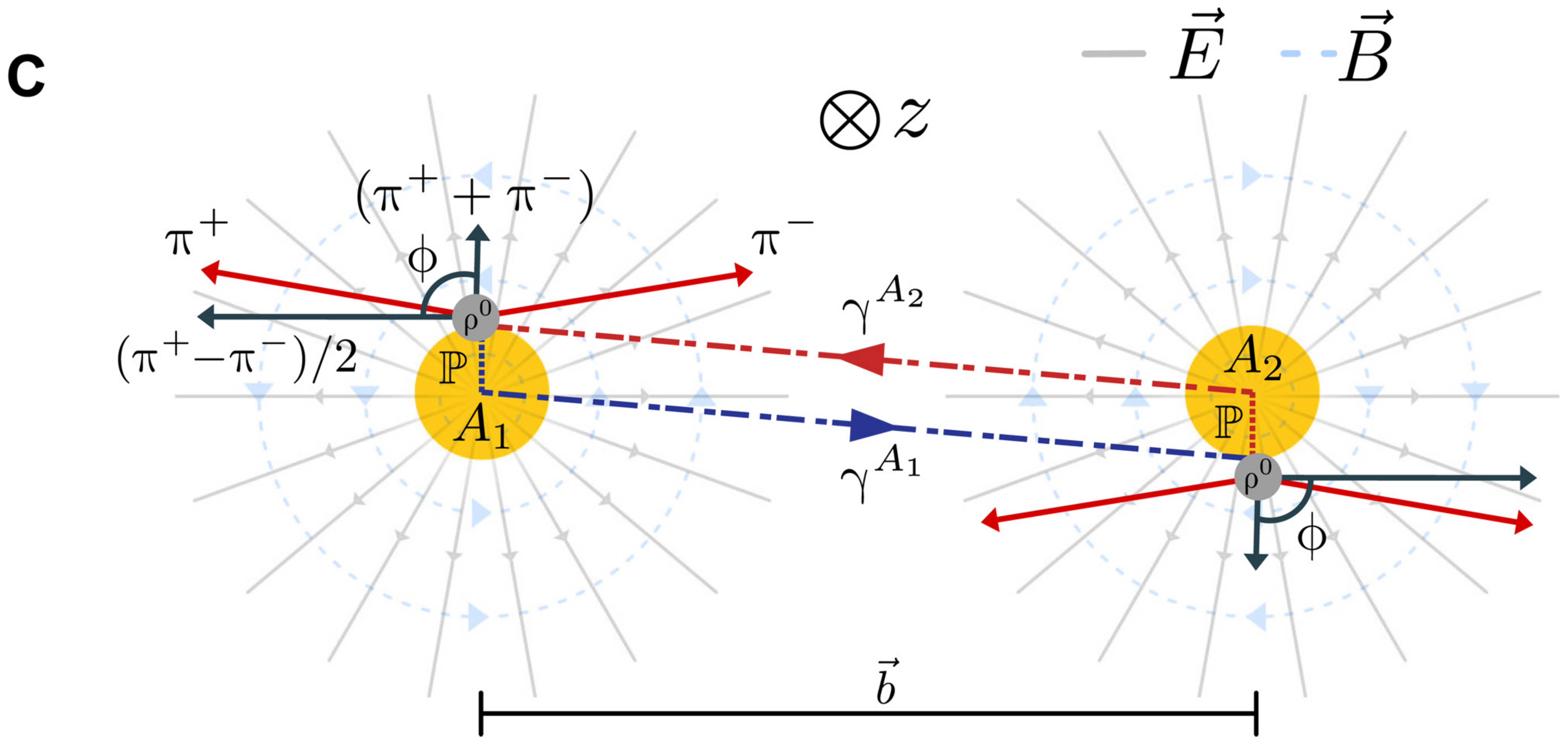
This process is enhanced



This process is suppressed



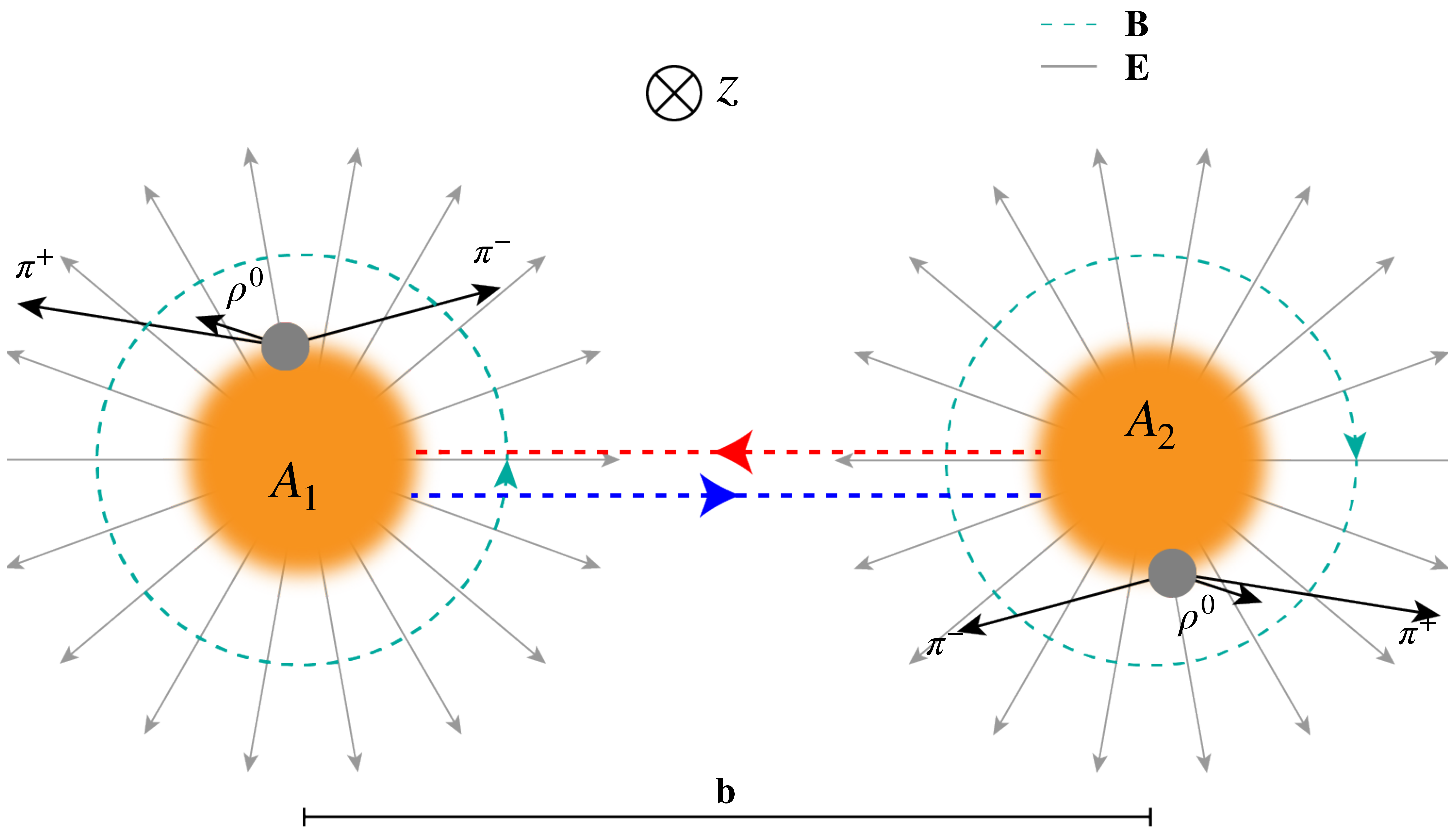
This image is misleading



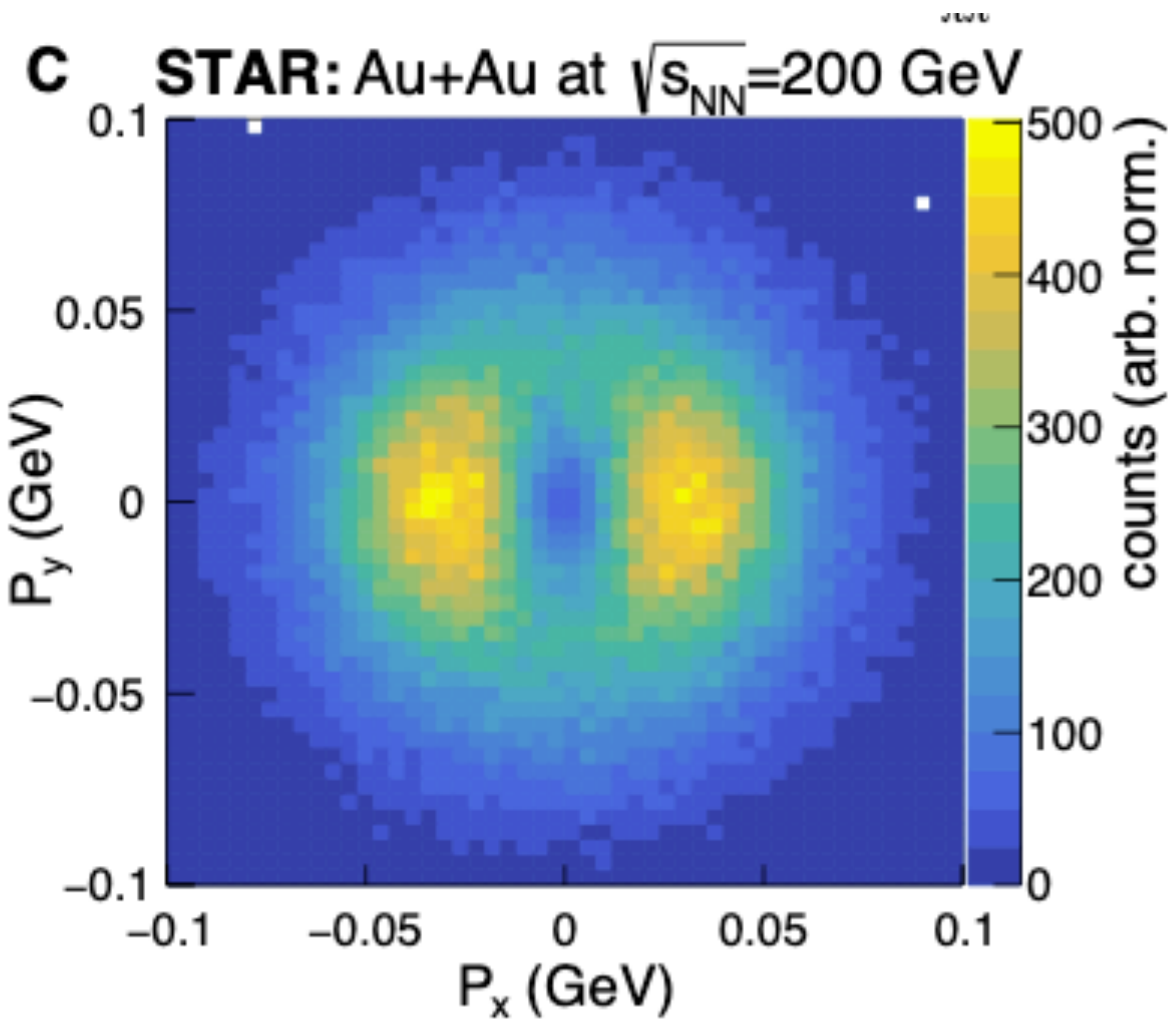
$$P_x = (P_{\pi^+} + P_{\pi^-})\cos\phi \approx 0$$

Not what the previous plot shows

A small change



What does this mean?



"At ϕ = 90○, all the effects from photon momentum, polarization and interference should be at a minimum or completely disappear."

Last time we said this is not interference, this is just an effect of the decay of the ρ^0 which has spin 1.

However, if this was true everything said in the article in the article will meaningless ϕ is used a way of measuring the interference effect

$$P \sim A^2(1 - \cos(\mathbf{b} \cdot \mathbf{P}_{\perp}^{\rho^0}))$$

More Questions

- “The recent measurements of lepton pair production from photon collisions in UPC events at RHIC (*23–26*) and LHC (*27–30*) have shown that the **photons behave as real photons in all observables.**”

- “[…] since the **photon polarization, oriented with the nucleus-nucleus impact parameter** […]”

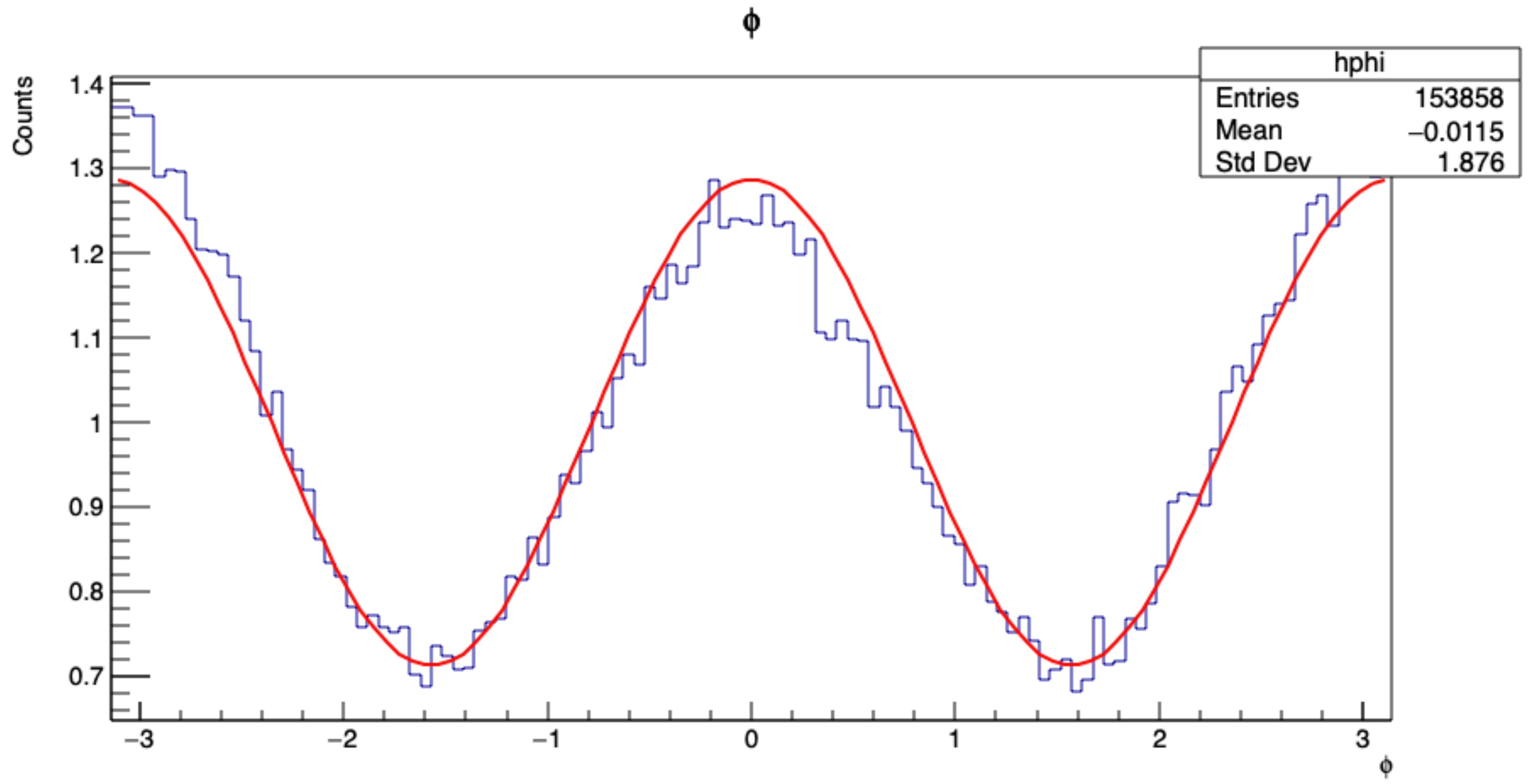
- “For a real (as opposed to virtual) photon, the polarization vector is always transverse to the direction of motion.” Thompson (2013)

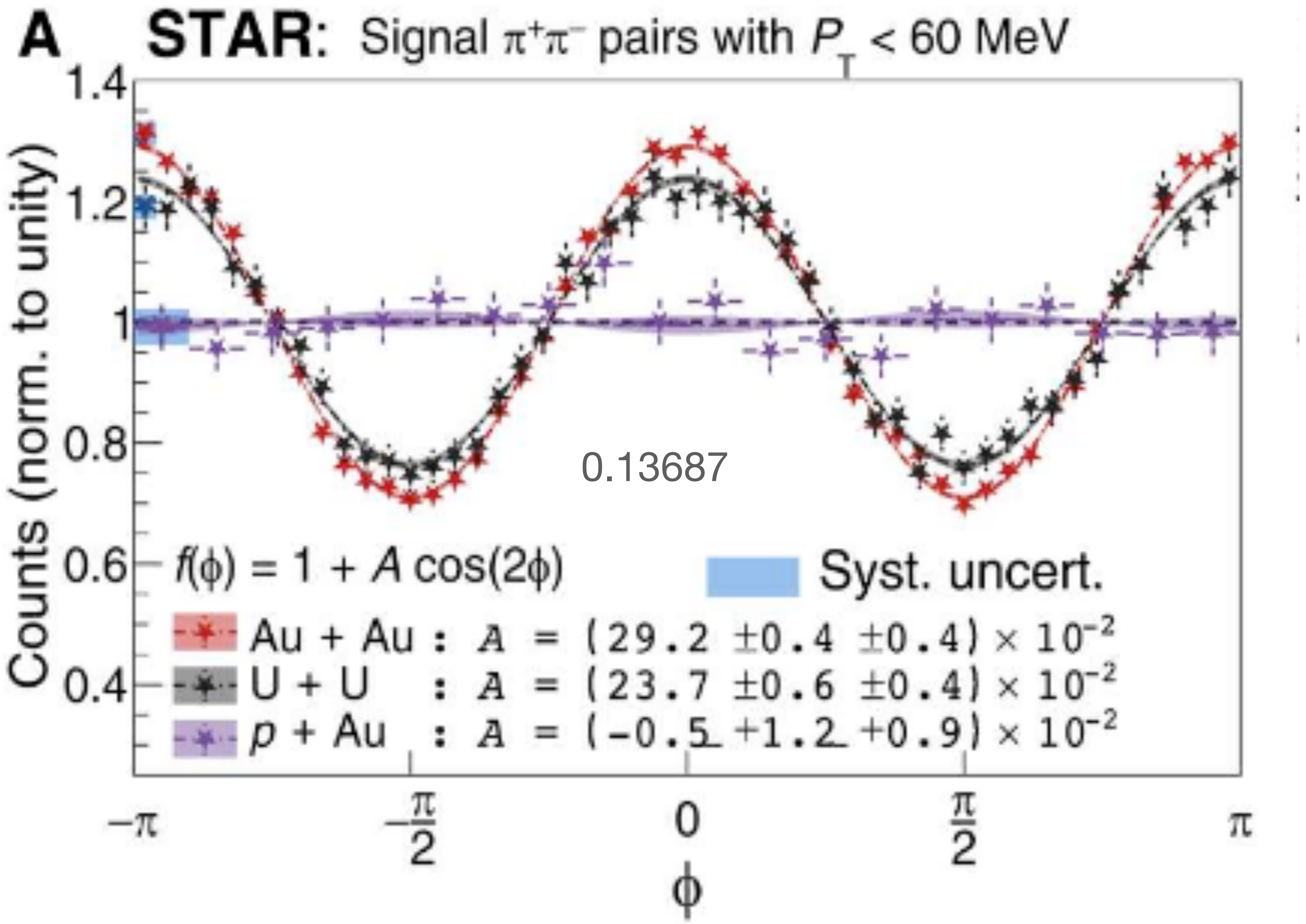
$$\Psi(\rho^0) = \eta_{space}\chi_{spin}\phi_{flavor}\psi_{color}$$

$$\Psi(\pi^+\pi^-) = \eta_{space}\chi_{spin}\phi_{flavor}\psi_{color}$$

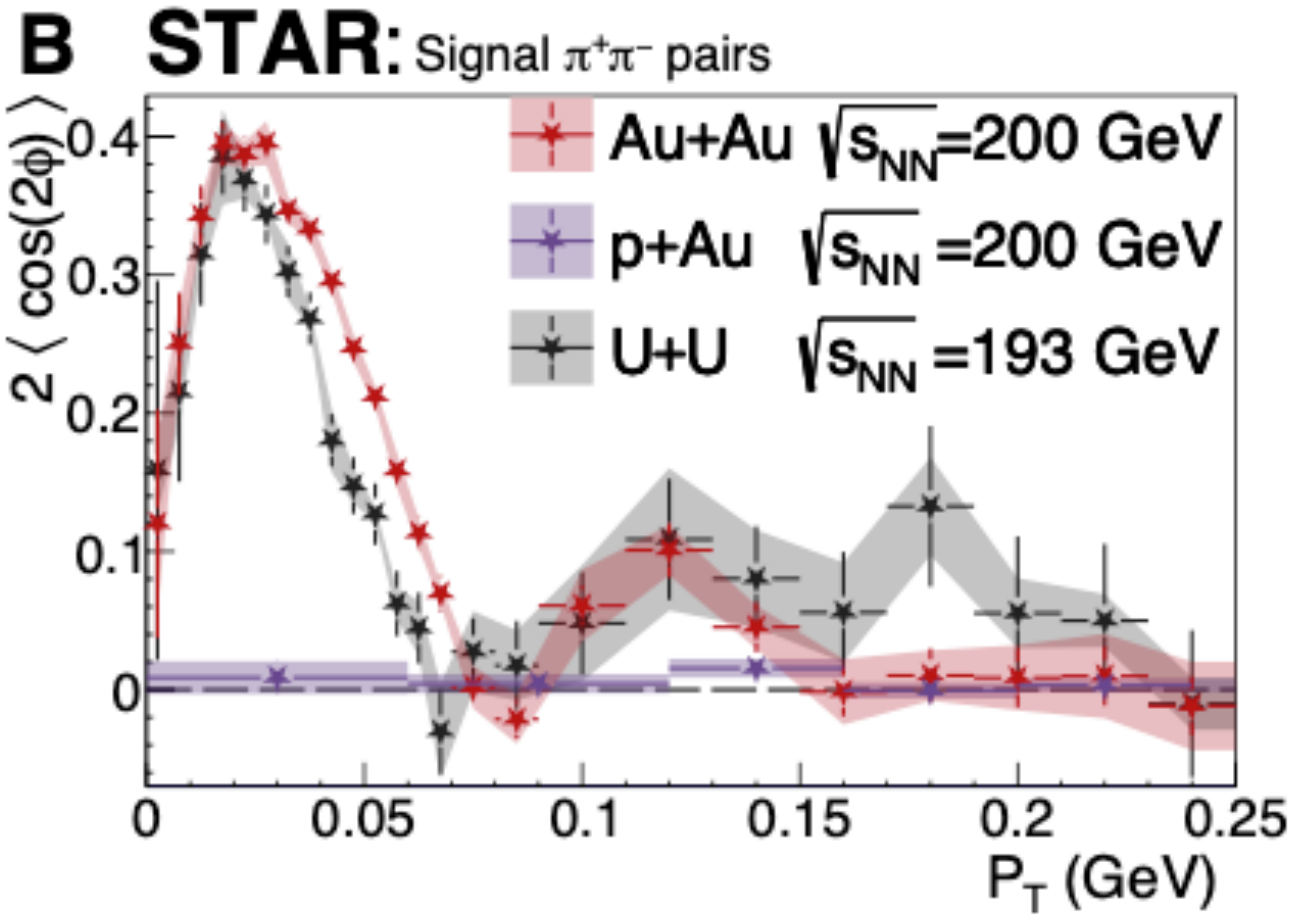
Answer: Almost all photons’ momentum goes in the z direction

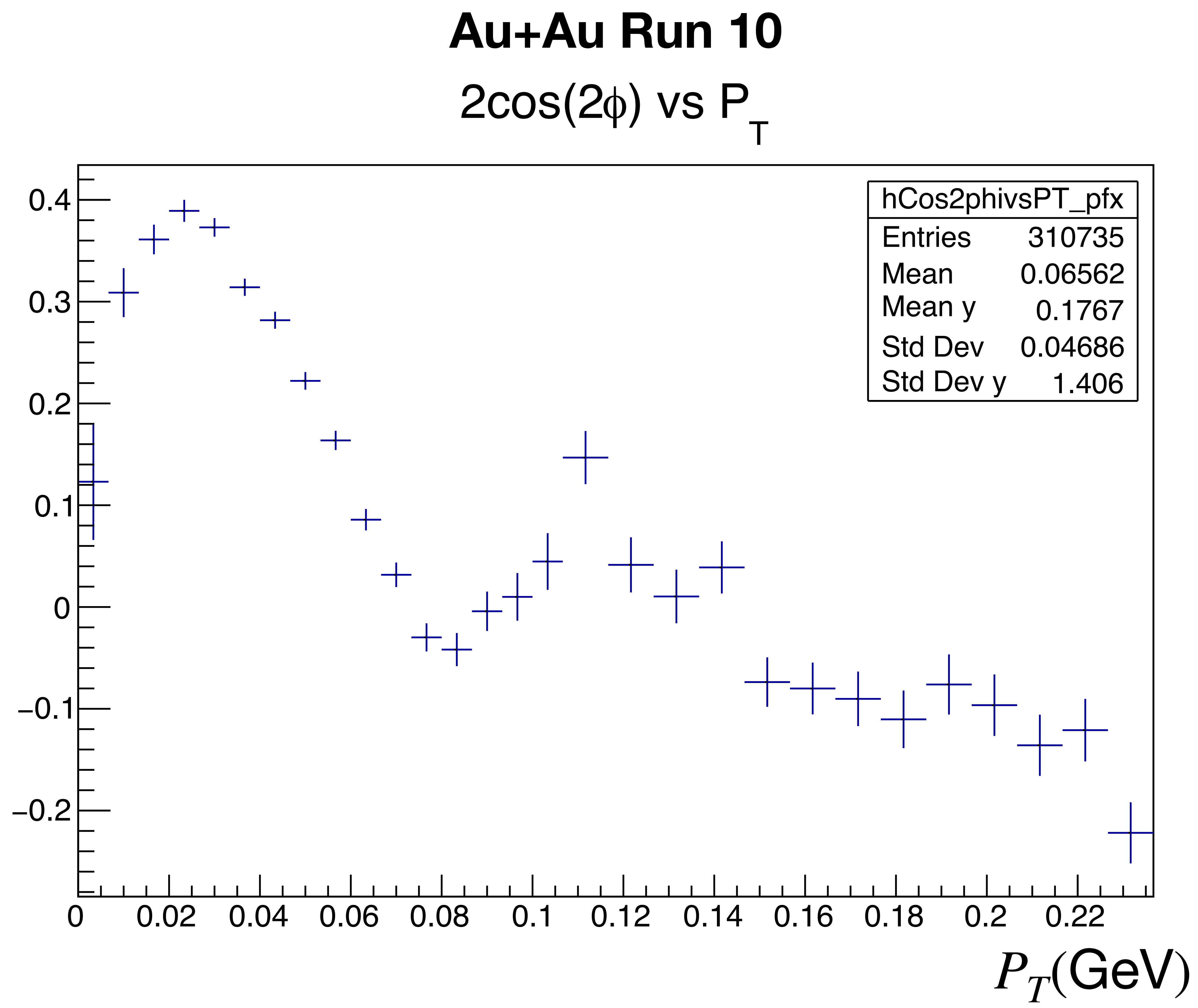
Experimental observation of interference in π signal



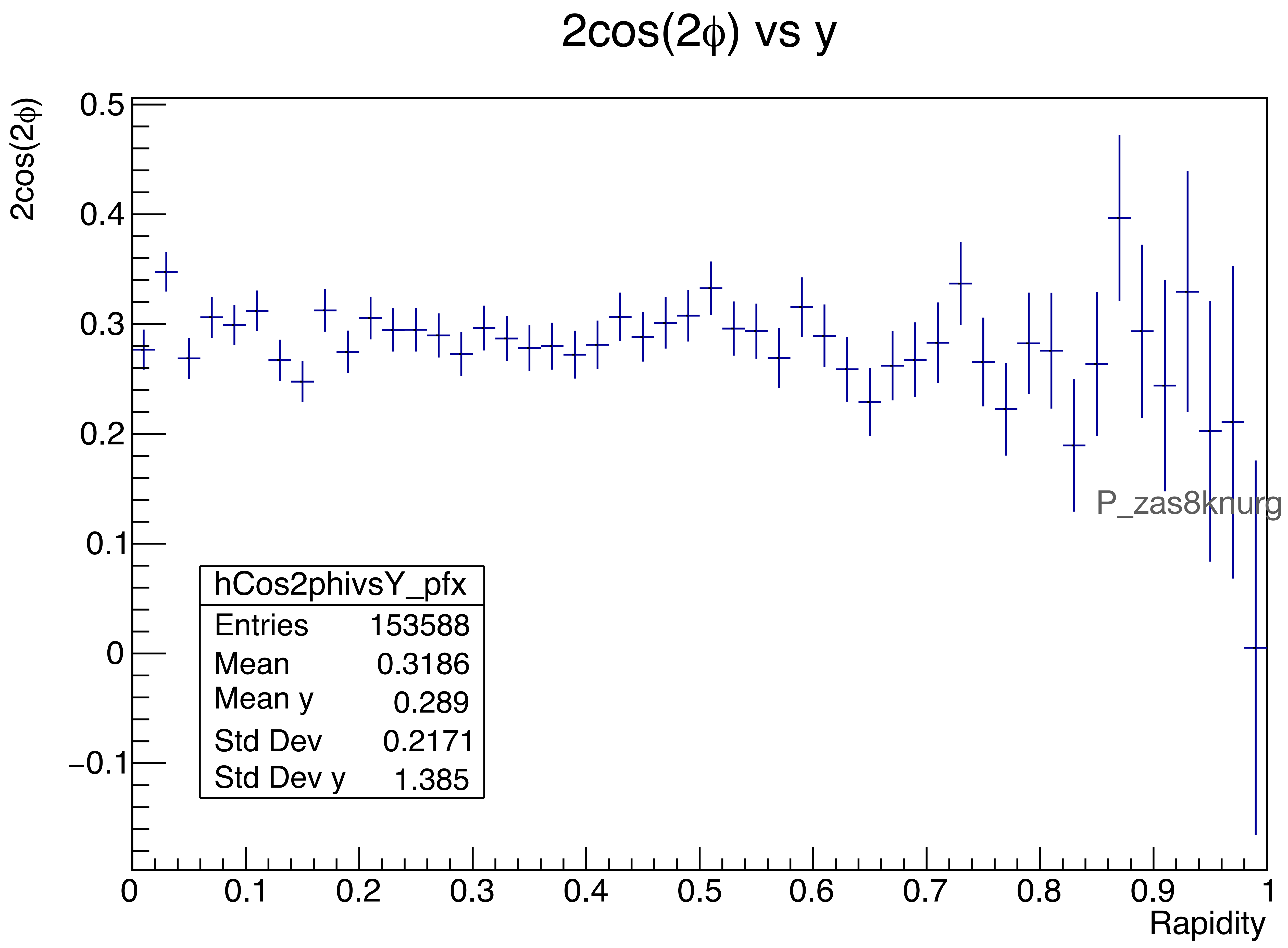


2 cos(2ϕ) vs P_T

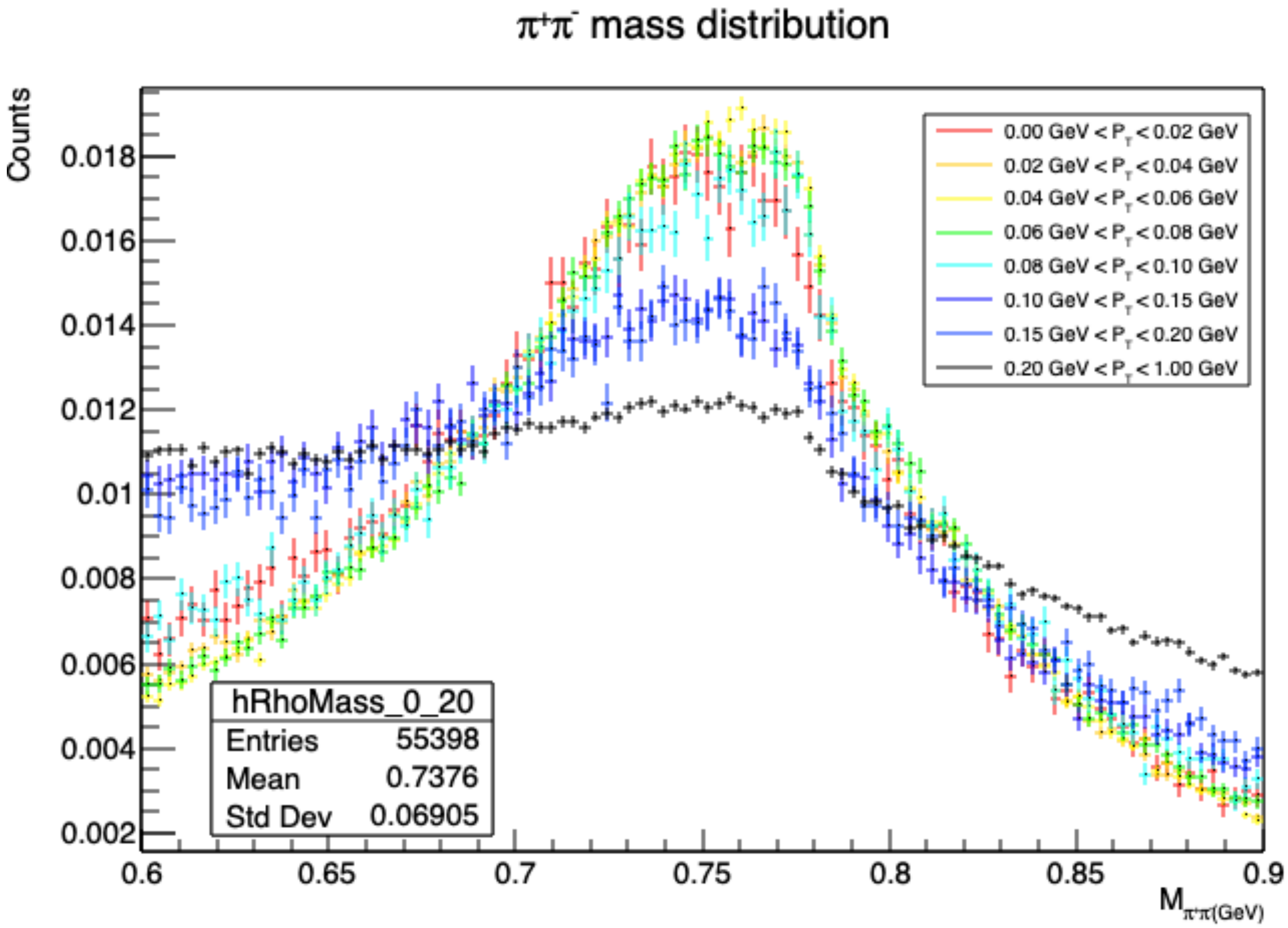




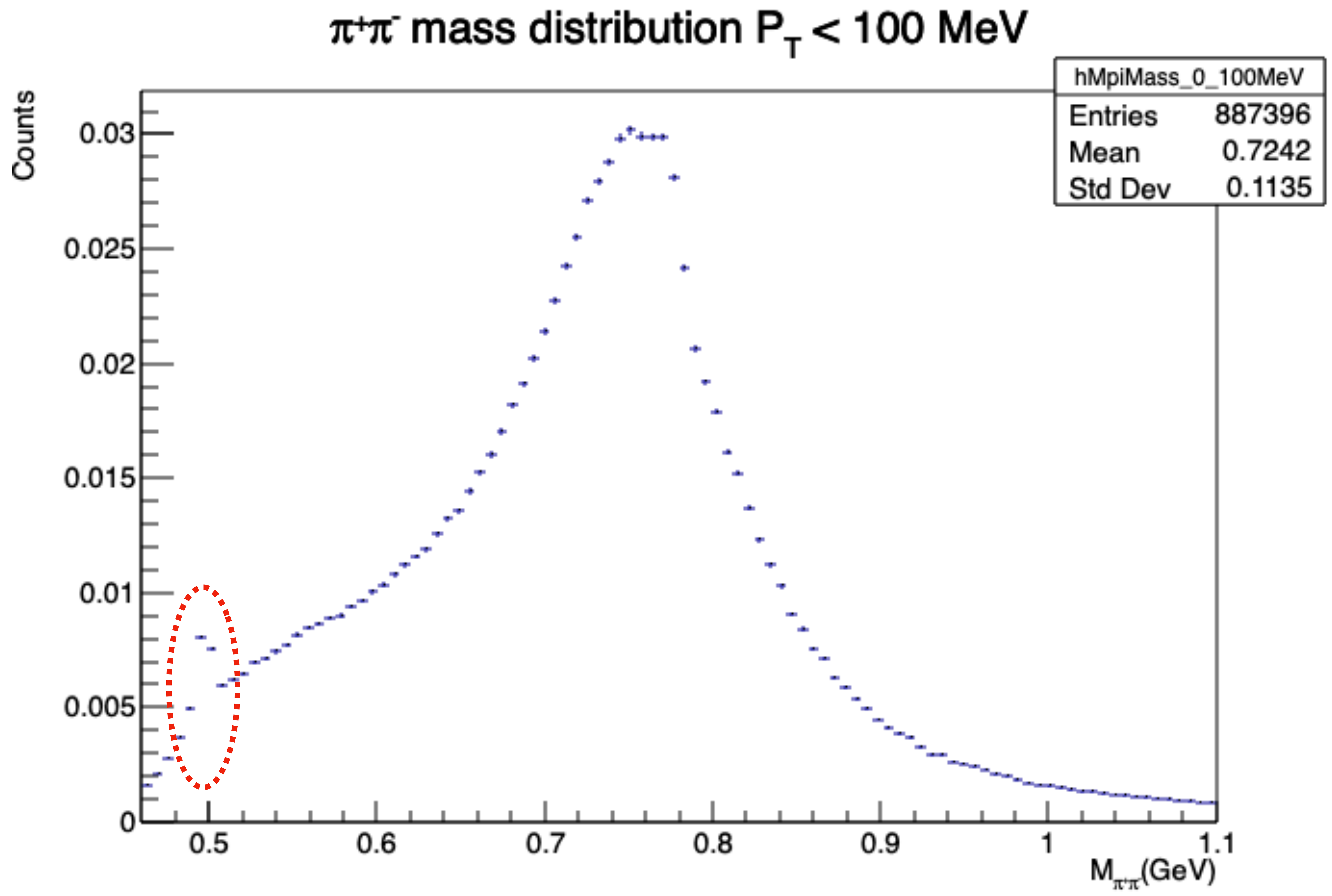
2 cos(2ϕ) vs y



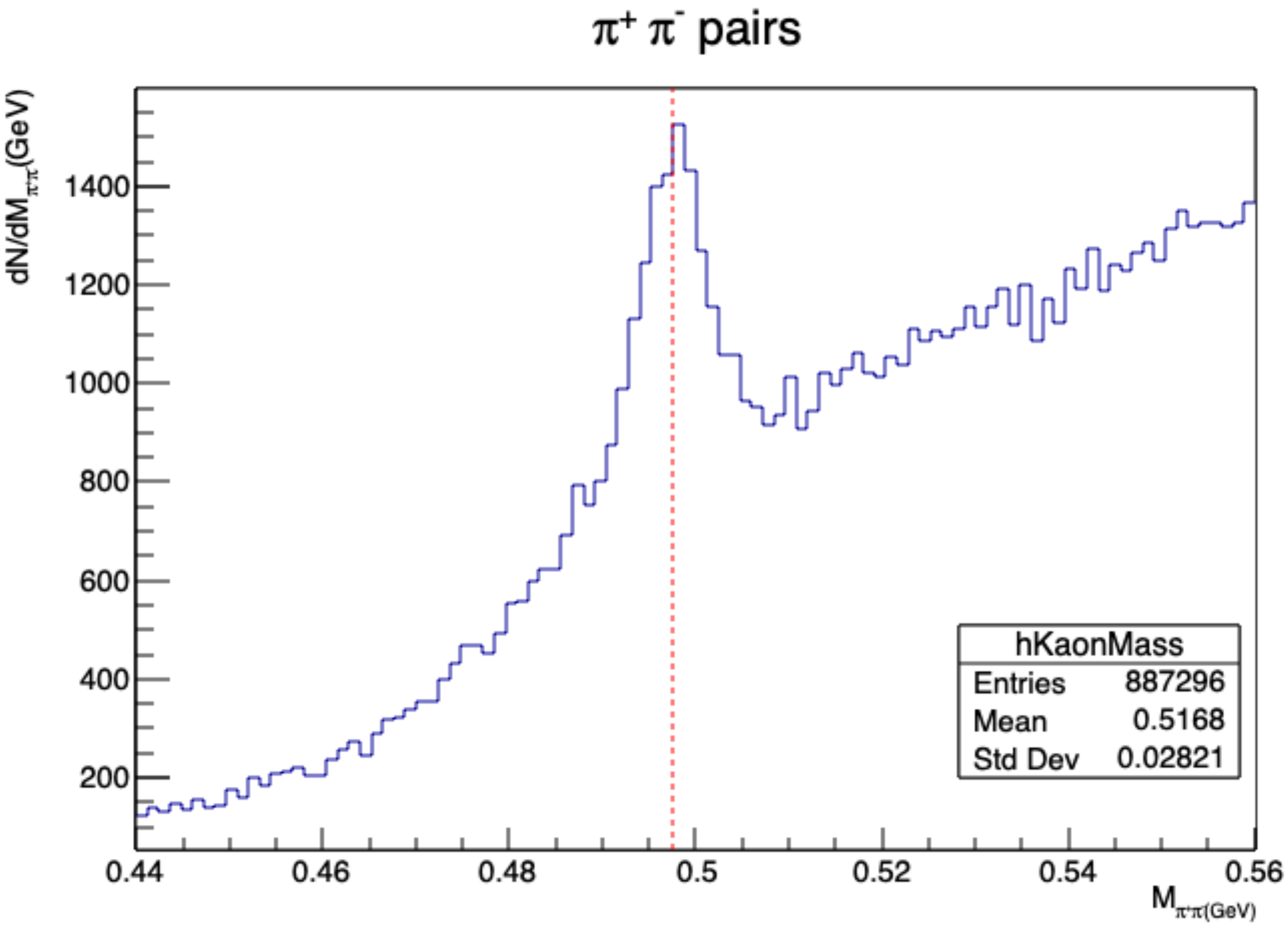
Normalized mass distribution $\pi^+\pi^-$ pairs



Kaon-short signal?



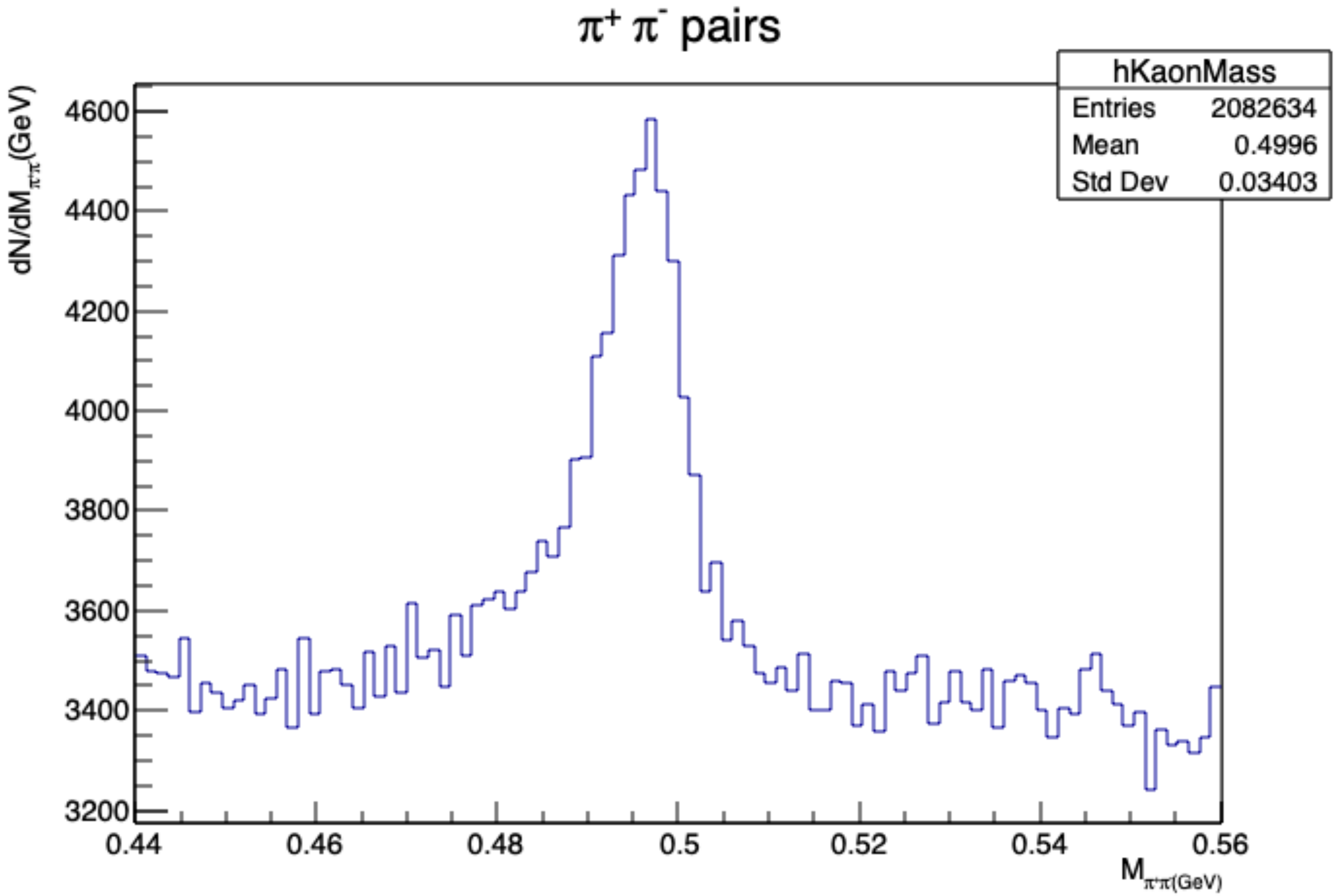
Kaon-short signal?



$$K_S^0 \rightarrow \pi^+ + \pi^- \quad \sim 70\,\%$$

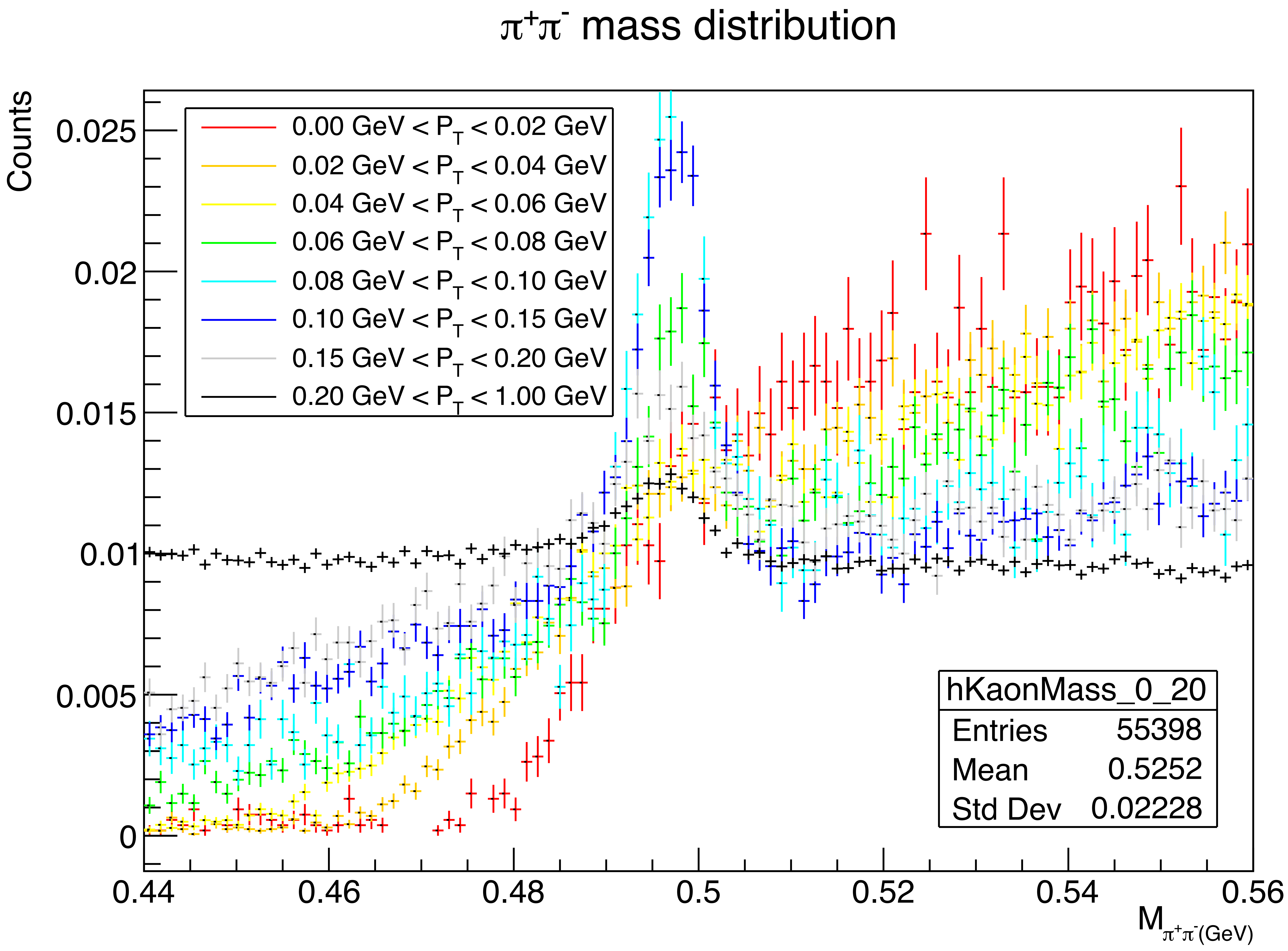
$$M_{K_S^0} = 497 \text{ MeV}$$

Kaon-short signal



$P_T > 150$ MeV

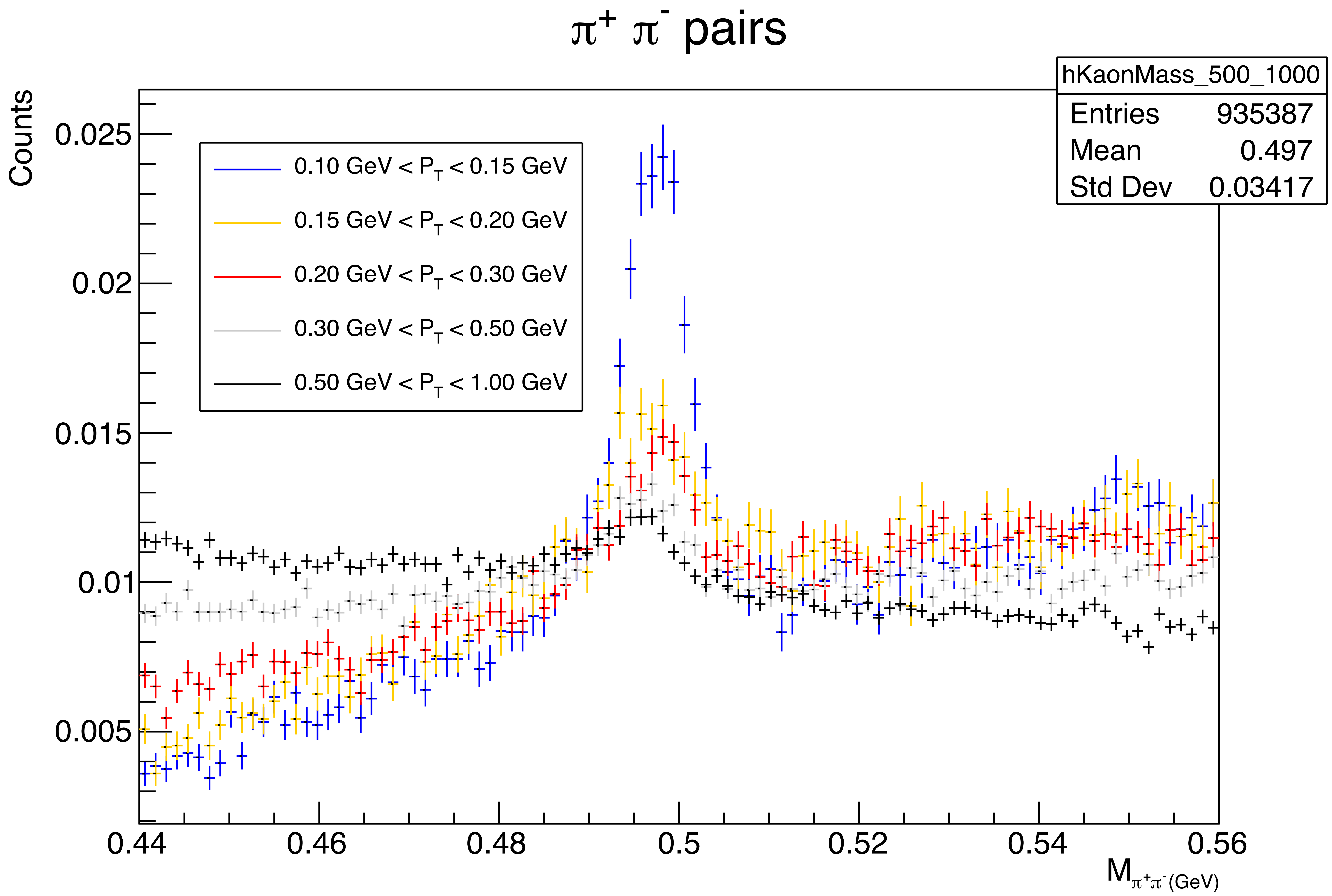
Kaon-short signal

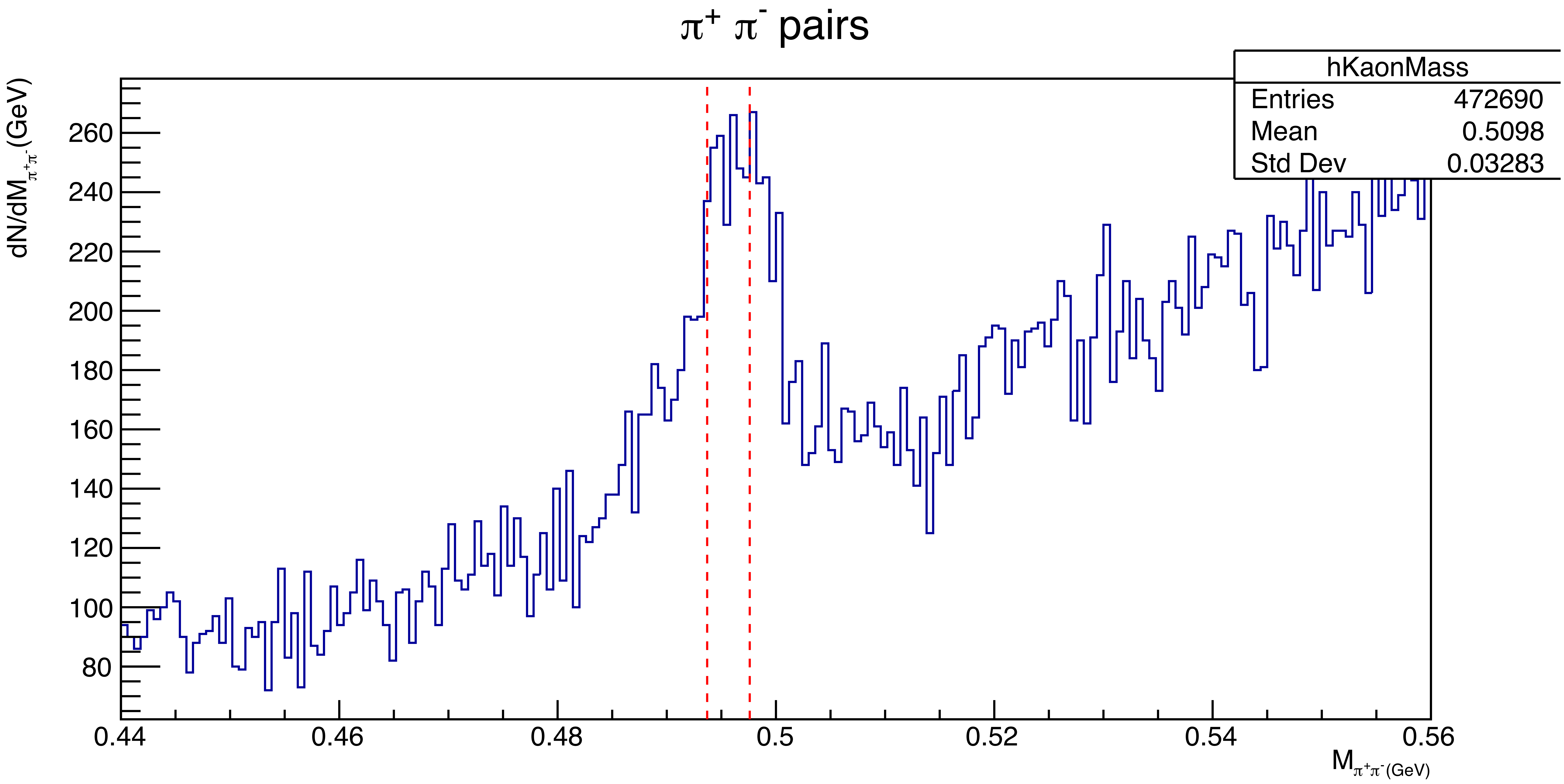


Enhancement in the range

80 MeV $< P_T <$ 150 MeV

Kaon-short signal





$\pi^+ \pi^-$ pairs
hKaonMass
Entries 472690
Mean 0.5098
Std Dev 0.03283
$dN/dM_{\pi^+\pi^-}$(GeV)
$M_{\pi^+\pi^-}$(GeV)
260
240
220
200
180
160
140
120
100
80
0.44
0.46
0.48
0.5
0.52
0.54
0.56

Weizsäcker–Williams method

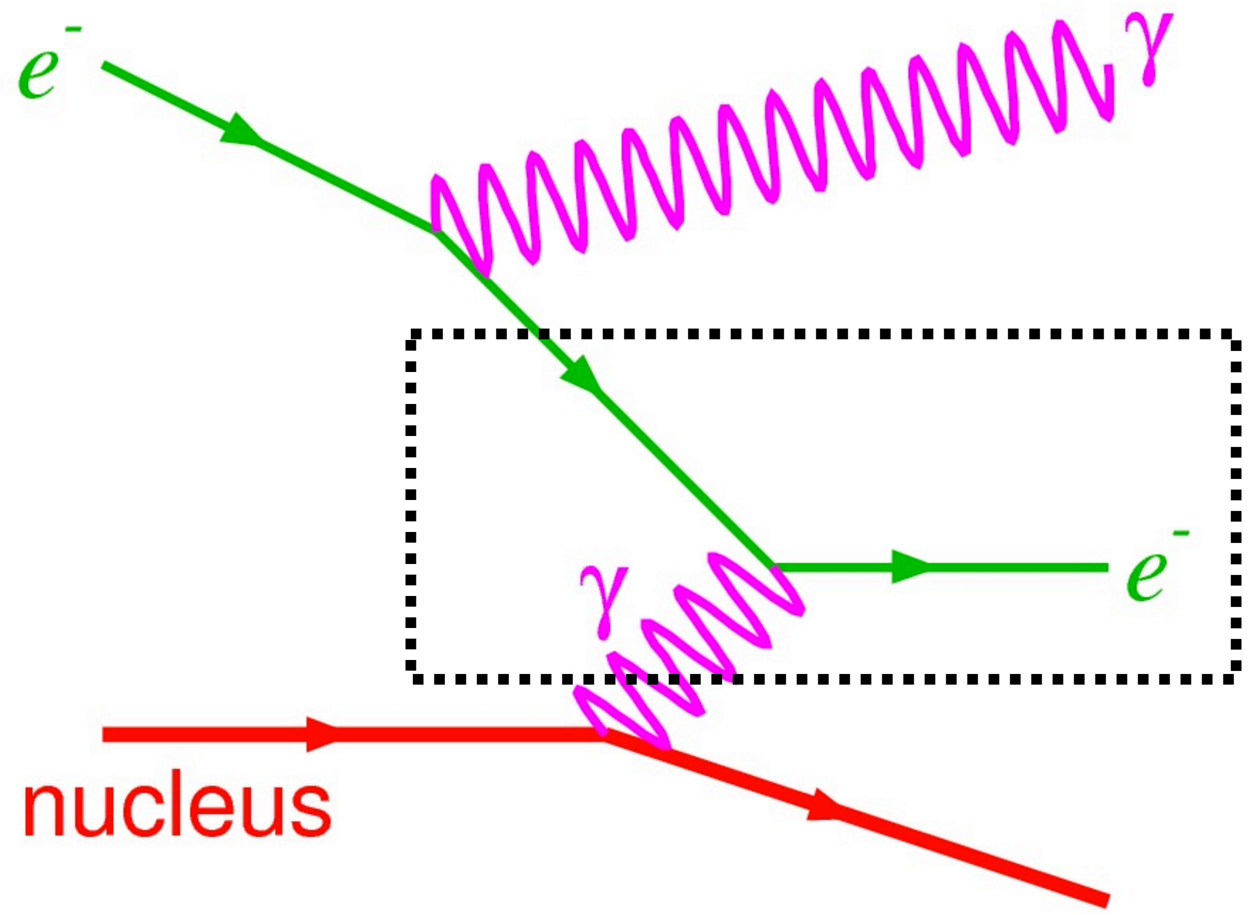
An overview

The Weizsäcker–Williams (WW) method is an approximation to estimate cross sections of charged particles interacting with a Coulombic fields.
Two main assumption are done in the WW approximation:

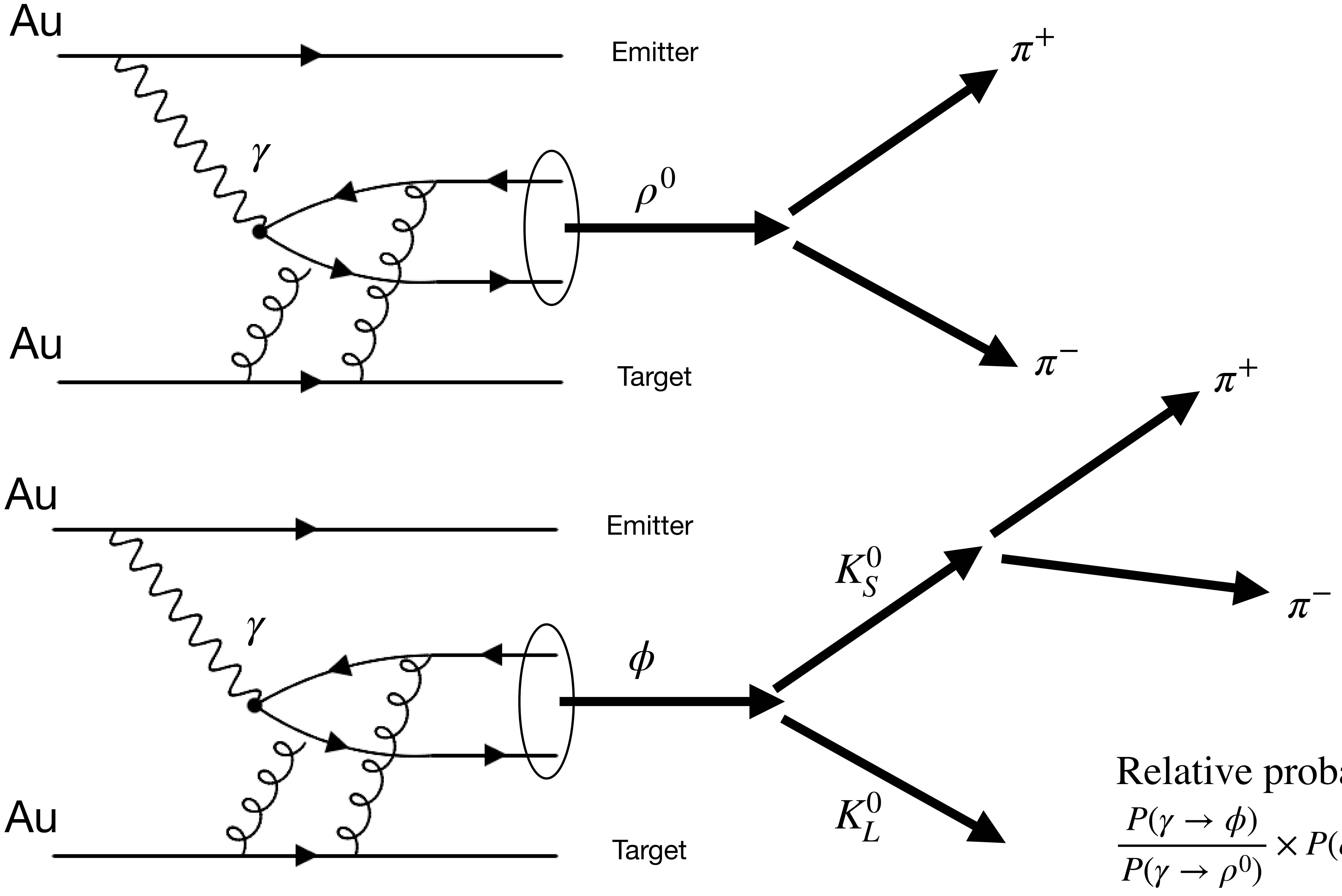
- The path of the emitter remains practically string during the collision. So the energy of the virtual photon is much smaller than that of the emitter itself.
- The effects of different Fourier amplitudes in the virtual photon can be considerer independent. In oder words higher order radiative corrections are neglected. No photon-photon interaction within the field.

$$\gamma(k) + X(p) \to X(p') + Y(k')$$

$$\text{Coulombic Field} + X(p) \to X(p') + Y(k')$$



Two sources for pions



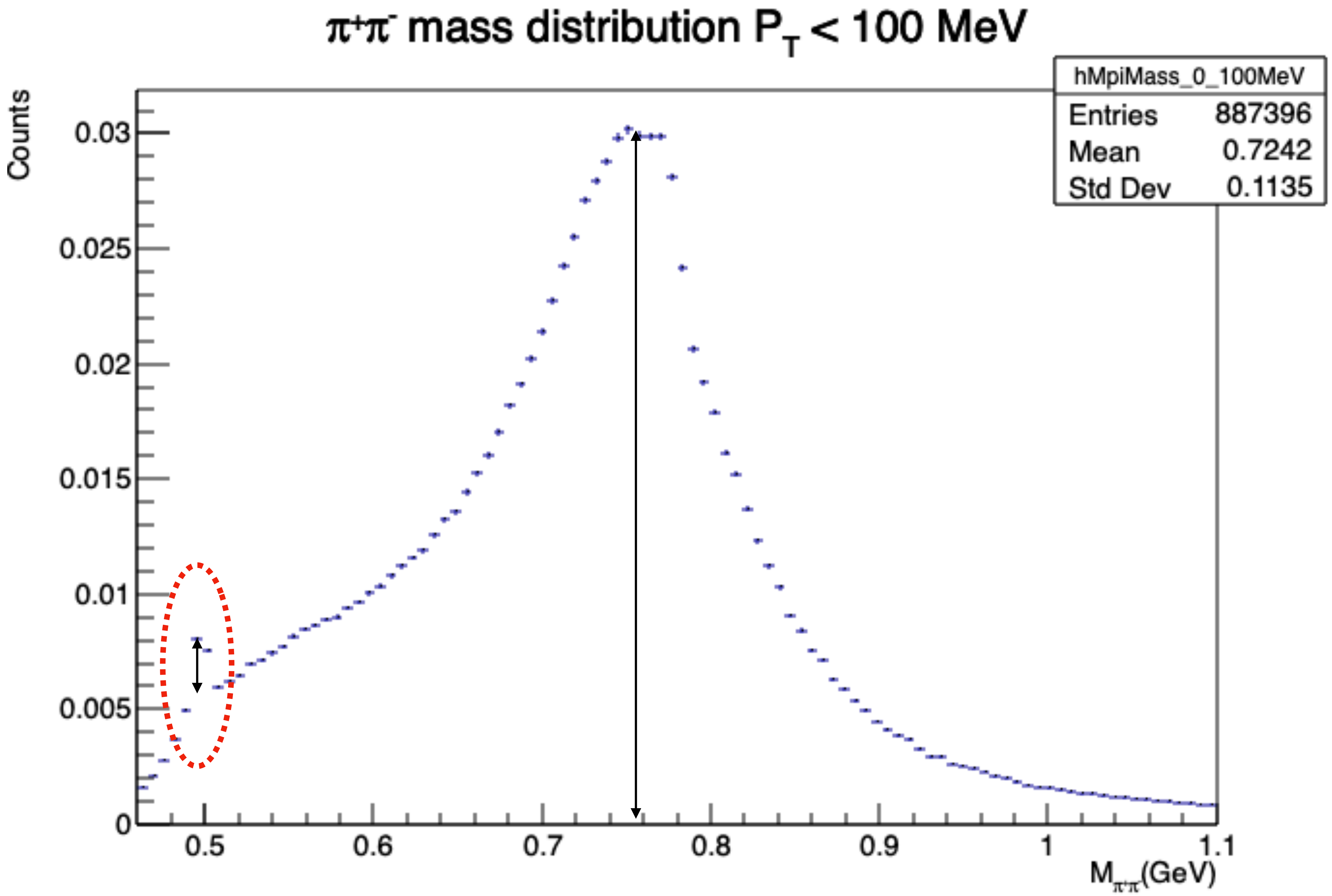
Weizsacker-Williams Approximation (Maybe) +

Vector Meson Dominance

Relative probability of both scenarios

$$\frac{P(\gamma \to \phi)}{P(\gamma \to \rho^0)} \times P(\phi \to K_S^0 + K_L^0) \times P(K_S^0 \to \pi^+\pi^-) \sim 0.05$$

Kaon-short signal?



Relative height of both peaks

$$\frac{0.03}{0.002} \sim 0.0666$$

Fitting functions

$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A\frac{\sqrt{M_{\pi\pi}M_\rho\Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + M_\rho\Gamma_\rho} + B \right|^2 + f_p$$

Modified Soding Parametrization

$$\frac{d\sigma}{dM_{\pi\pi}} = f_\rho\frac{M_{\pi\pi}M_\rho\Gamma_\rho}{(M_\rho^2 - M_{\pi\pi})^2 + M_\rho^2\Gamma_\rho^2} + f_I\frac{M_\rho^2 - M_{\pi\pi}^2}{(M_\rho^2 - M_{\pi\pi})^2 + M_\rho^2\Gamma_\rho^2} + f_p$$

Relativistic BW

$$\frac{d\sigma}{dM_{\pi\pi}} = f_\rho\frac{M_{\pi\pi}M_\rho\Gamma_\rho}{(M_\rho^2 - M_{\pi\pi})^2 + M_\rho^2\Gamma_\rho^2}\left(\frac{M_\rho}{M_{\pi\pi}}\right)^n + f_p$$

Ross-Stodolsky Parametrization

Fitting functions

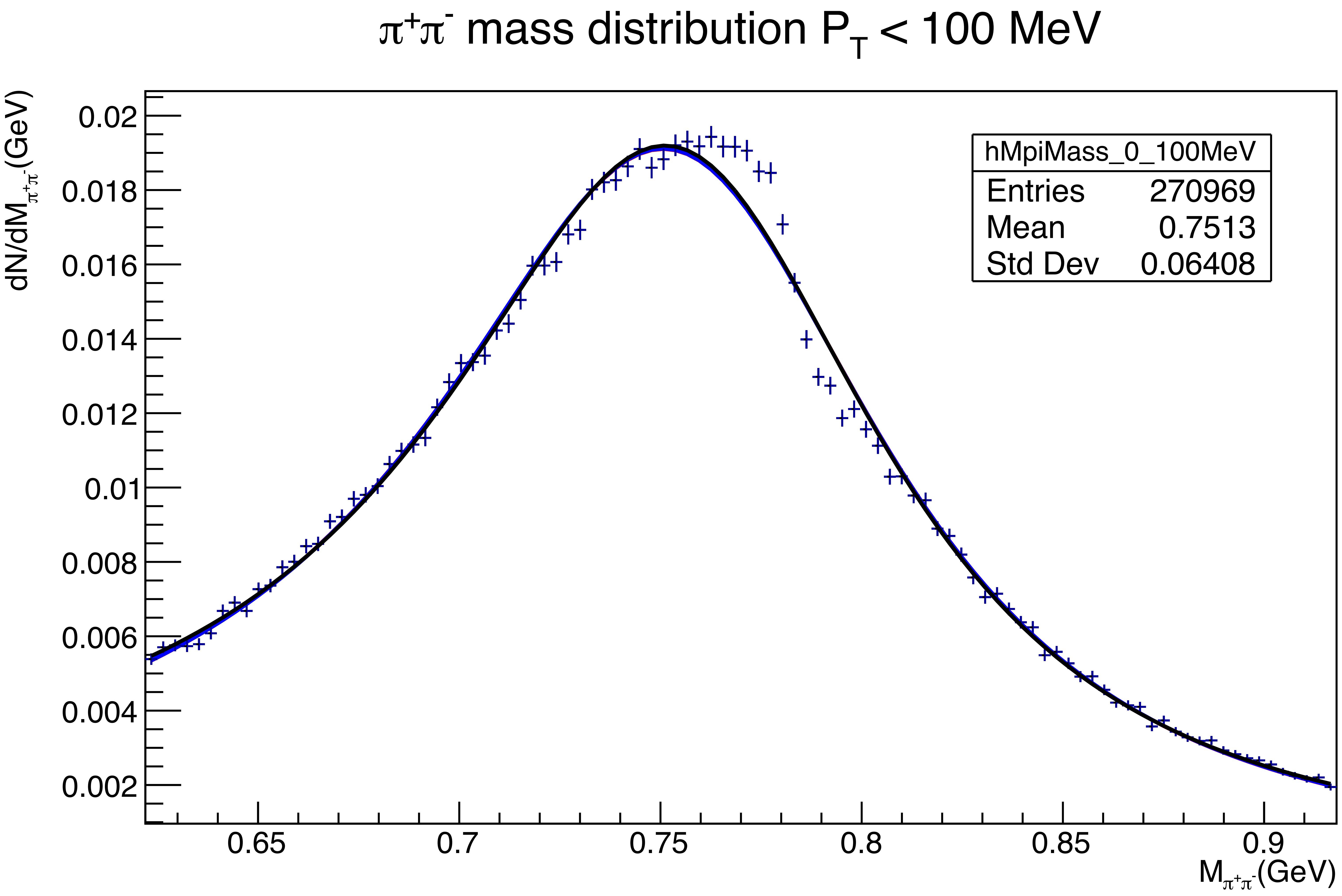
Eq.	M_ρ (MeV/c^2)	Γ_ρ (MeV/c^2)	
Modified Soding Parametrization	753.5 ± 0.3	151.5 ± 0.4	$\lvert B/A \rvert = 0.2794 + 0.0047$
Relativistic BW	752.6 ± 0.3	151.5 ± 0.4	$\lvert f_I/f_\rho \rvert = 0.1563 \pm 0.0027$
Ross-Stodolsky Parametrization	754.5 ± 0.3	145.4 ± 0.4	$n = 2.342 \pm 0.036$

Fitting functions

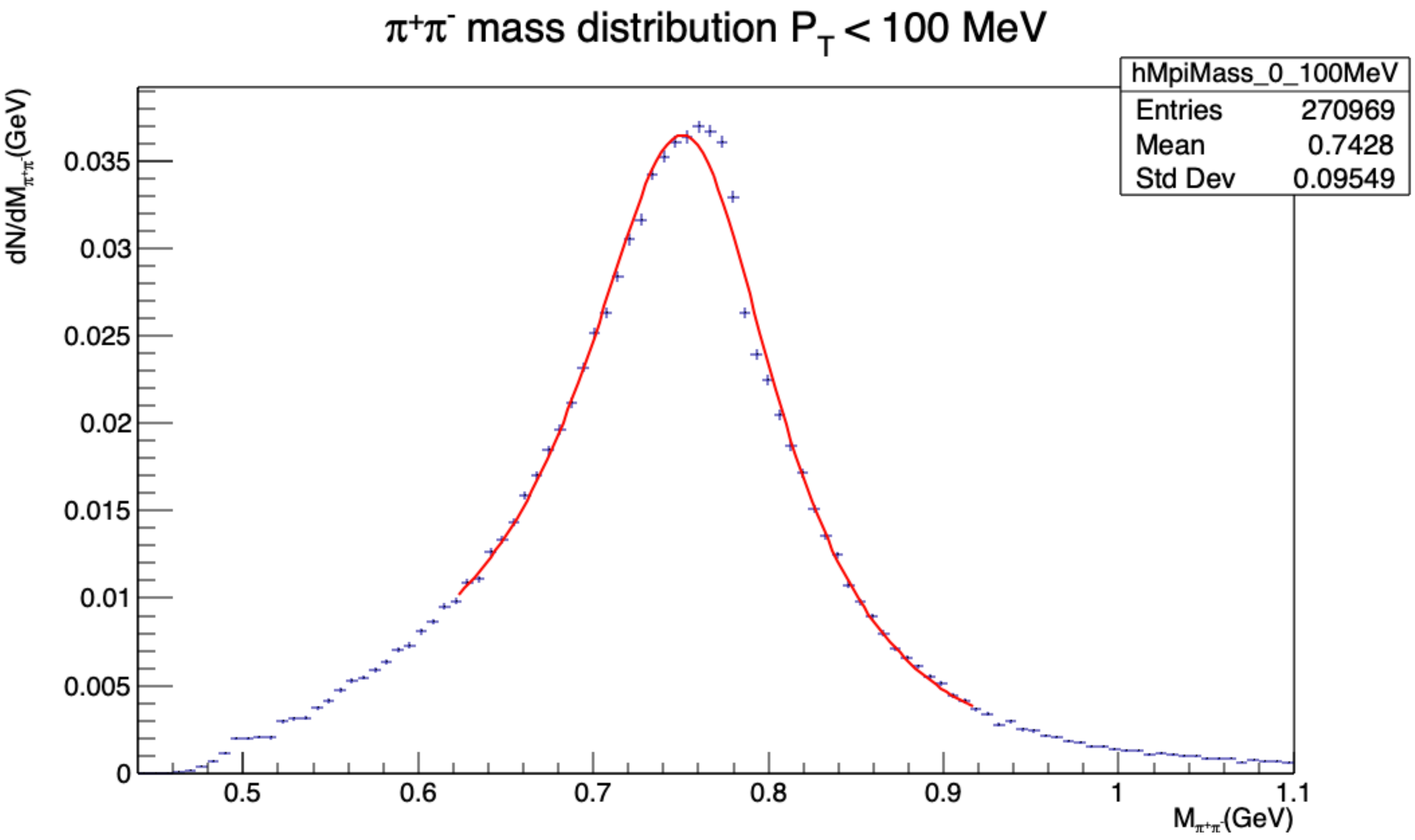
$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A\frac{\sqrt{M_{\pi\pi}M_\rho\Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + M_\rho\Gamma_\rho} + B \right|^2 + f_p$$

$$\frac{d\sigma}{dM_{\pi\pi}} = f_\rho \frac{M_{\pi\pi}M_\rho\Gamma_\rho}{(M_\rho^2 - M_{\pi\pi})^2 + M_\rho^2\Gamma_\rho^2} + f_I \frac{M_\rho^2 - M_{\pi\pi}^2}{(M_\rho^2 - M_{\pi\pi})^2 + M_\rho^2\Gamma_\rho^2} + f_p$$

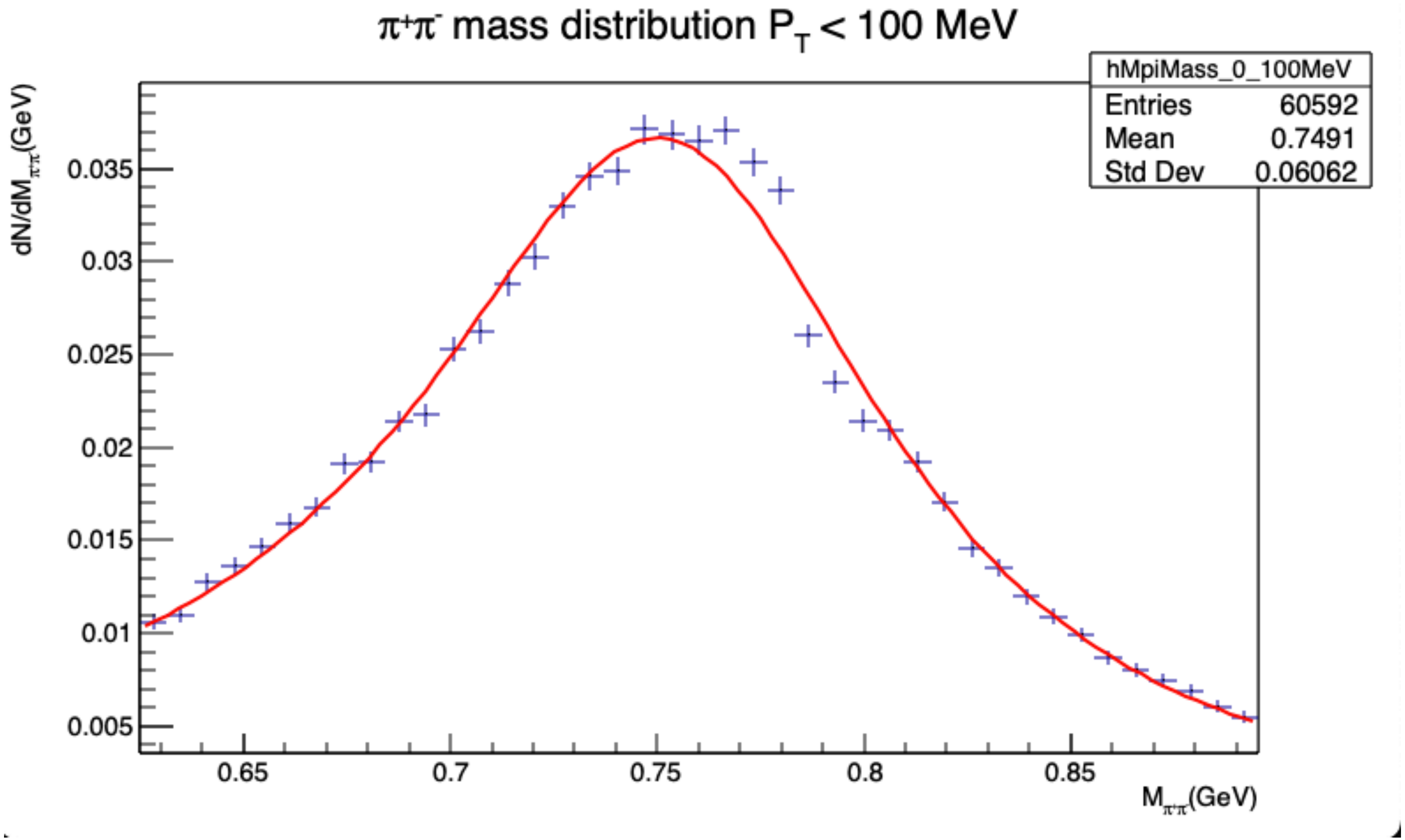
$$\frac{d\sigma}{dM_{\pi\pi}} = f_\rho \frac{M_{\pi\pi}M_\rho\Gamma_\rho}{(M_\rho^2 - M_{\pi\pi})^2 + M_\rho^2\Gamma_\rho^2} \left(\frac{M_\rho}{M_{\pi\pi}}\right)^n + f_p$$

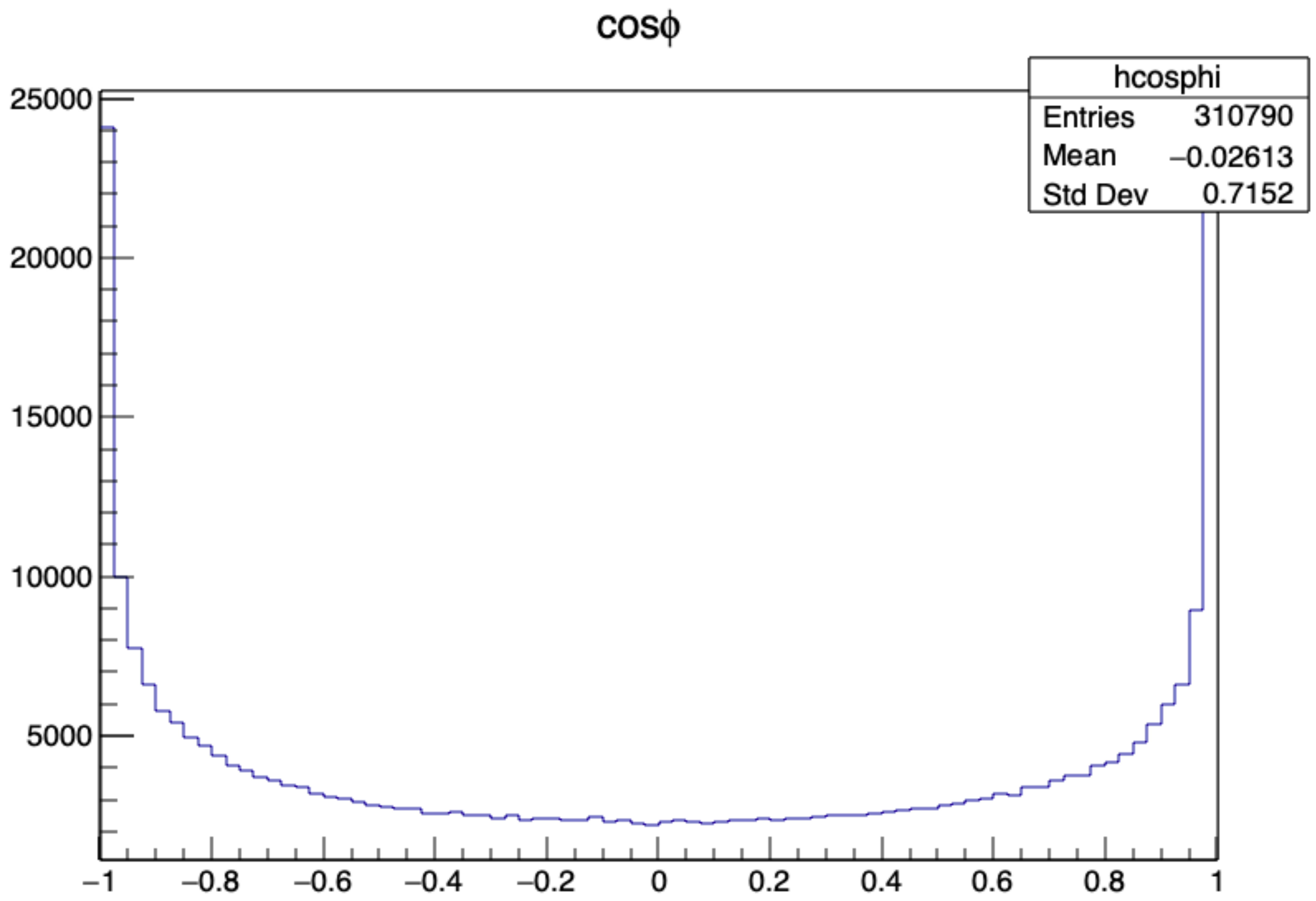


First, I made a mistake



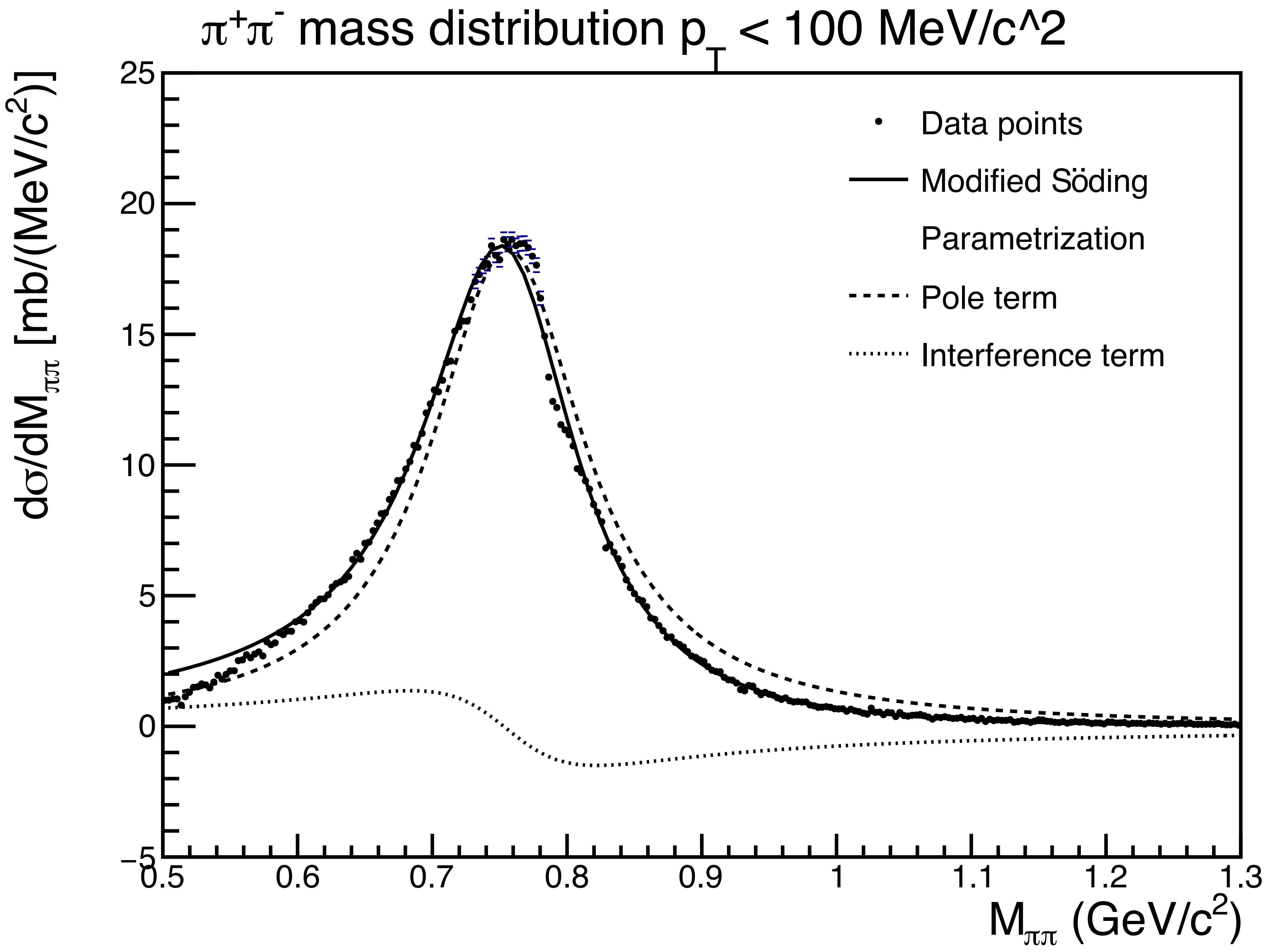
Fitting functions, with ZDC cut





$$\cos\phi = \frac{P_T^{\rho} \cdot (p_{T1} - p_{T1})}{|\, P_T^{\rho} \cdot (p_{T1} - p_{T1})\,|}$$

Breit-Weigner + Soding Term



Parameter	My Value	Paper Value
|B/A|	0.211 ± 0.0066 GeV^(-1/2)	0.81 ± 0.20 GeV^(-1/2)
M_ρ	753 ± 0.41 MeV/c^2	777 ± 7 MeV/c^2
Γ_ρ	139 ± 0.56 MeV/c^2	139 ± 13 MeV/c^2

$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + M_\rho \Gamma_\rho} + B \right|^2 + f_p$$

$\rho^0 + \omega$ Breit-Wigner