Study of quantum interference effects using ρ^0 photoproduction

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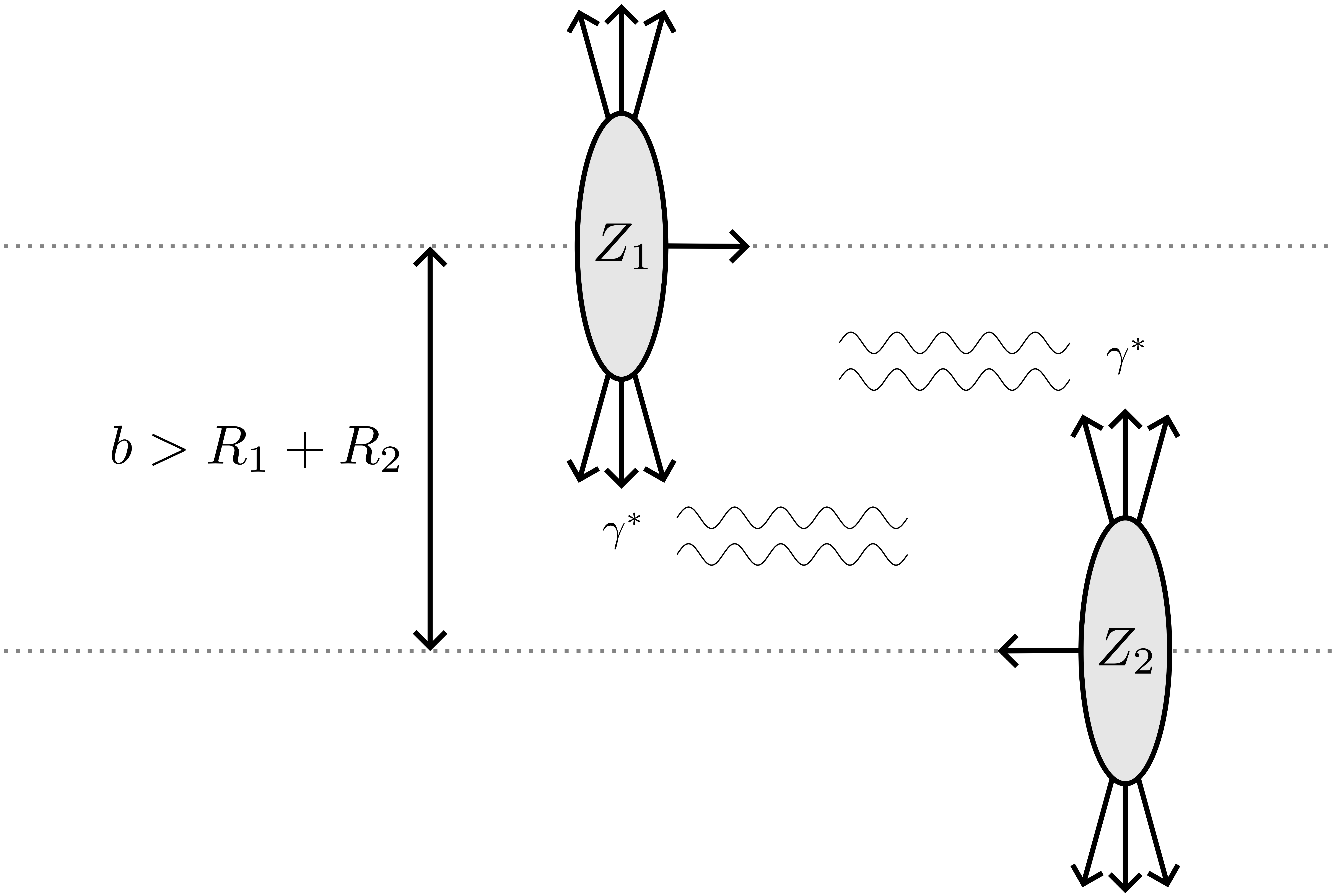
16/9/2025

Ultraperipheral collisions (UPCs)

brief intro



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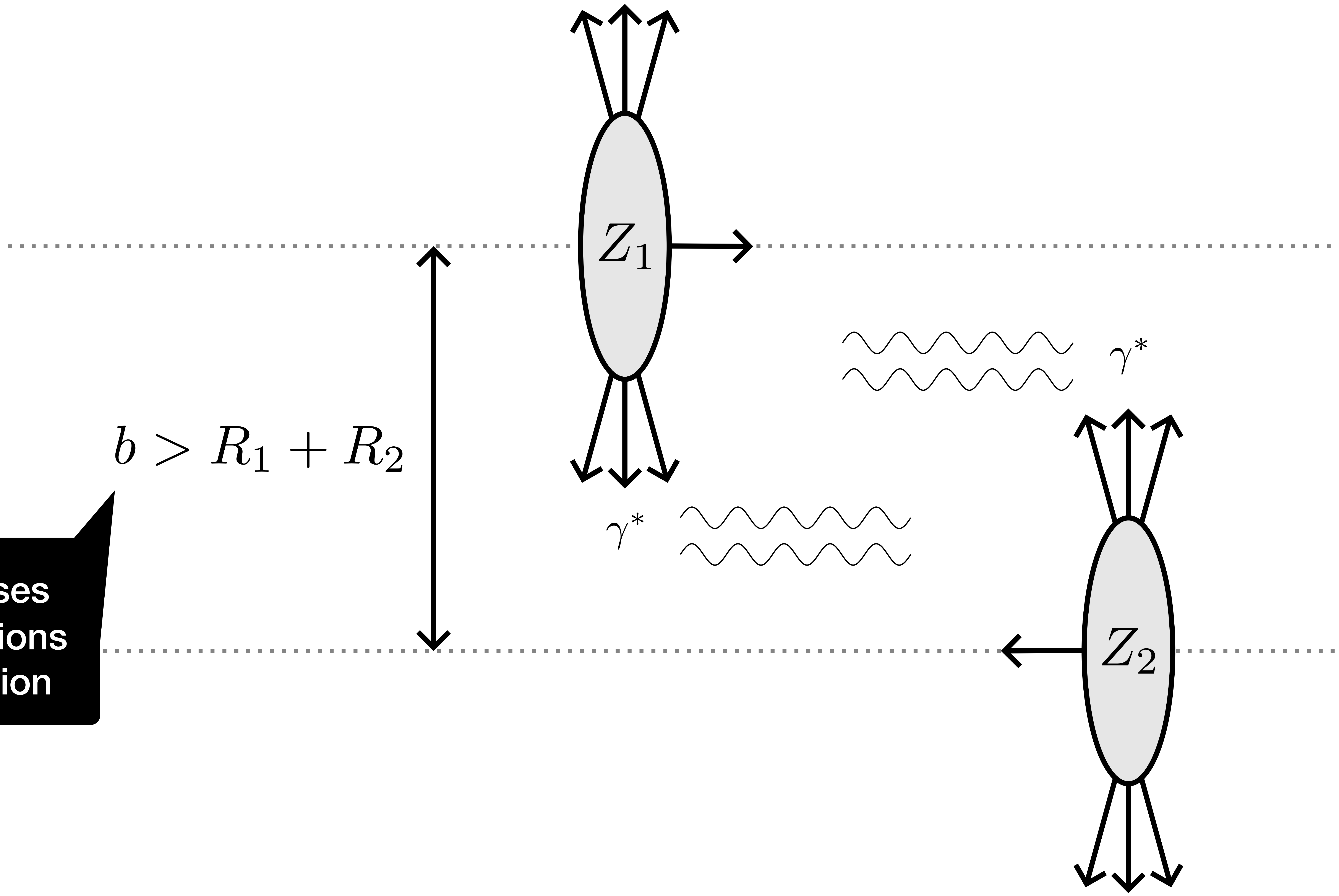

large b suppresses hadronic interactions and QGP formation

Ultraperipheral collisions (UPCs)
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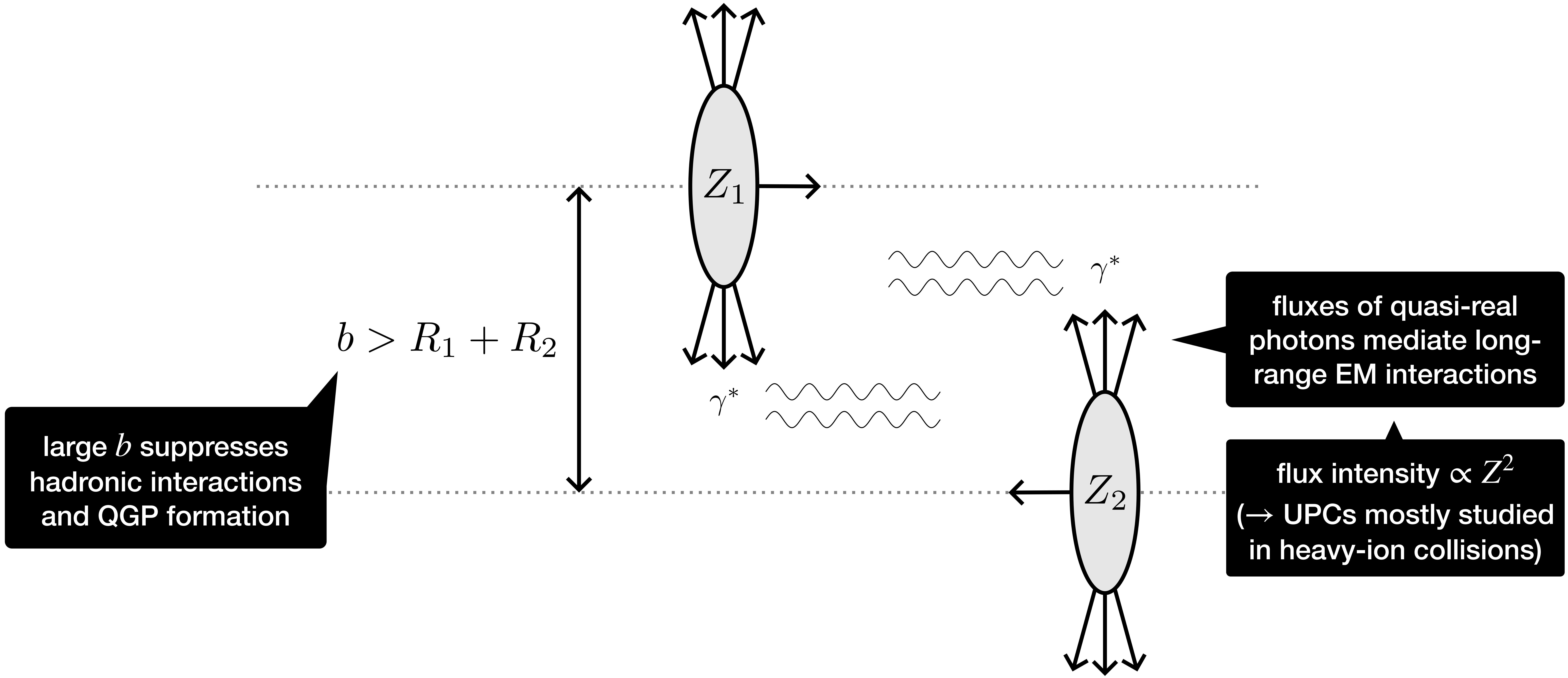
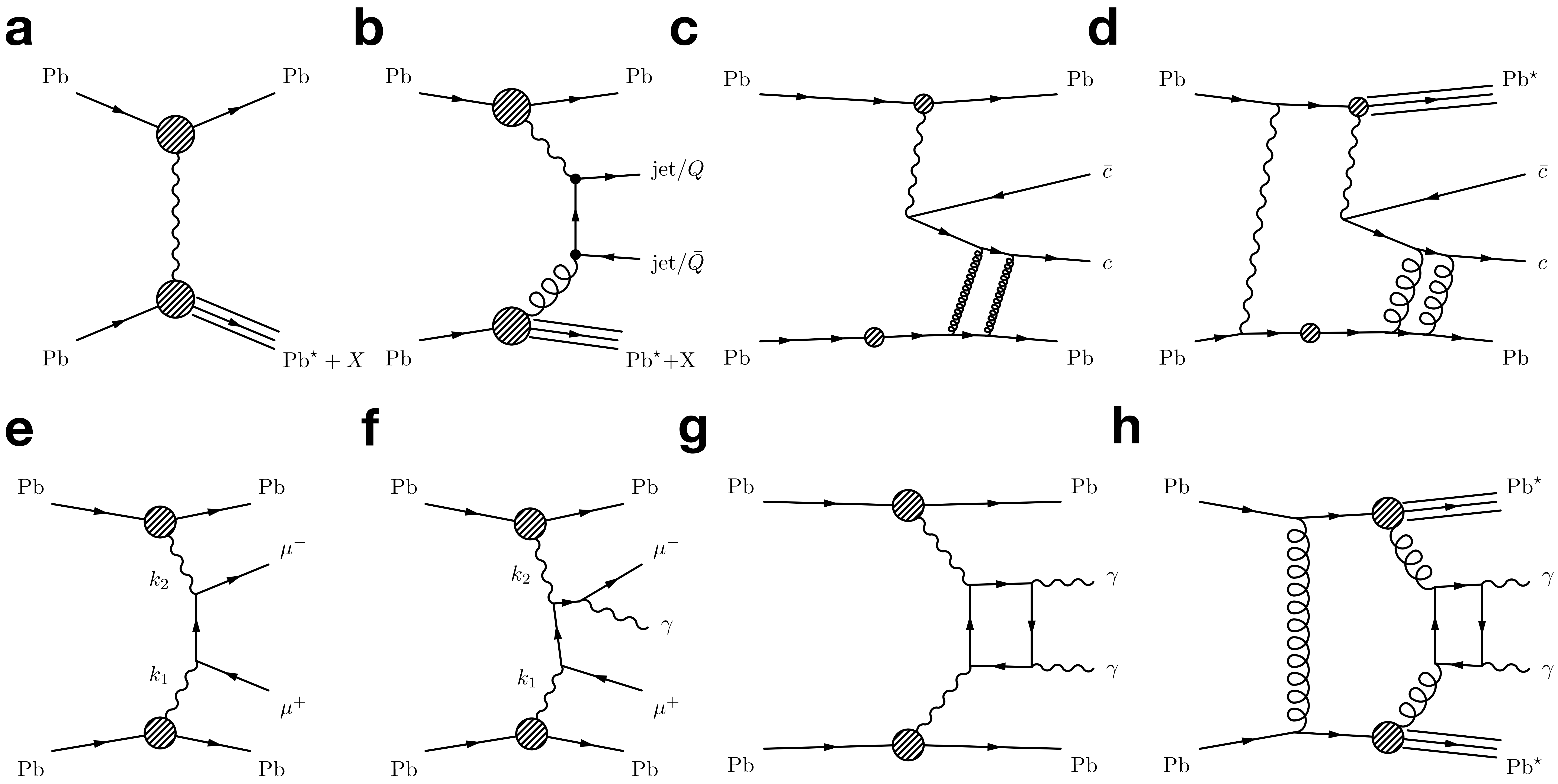


Ultraperipheral collisions (UPCs)

a selection of possible processes

c and d of most interest for this analysis…



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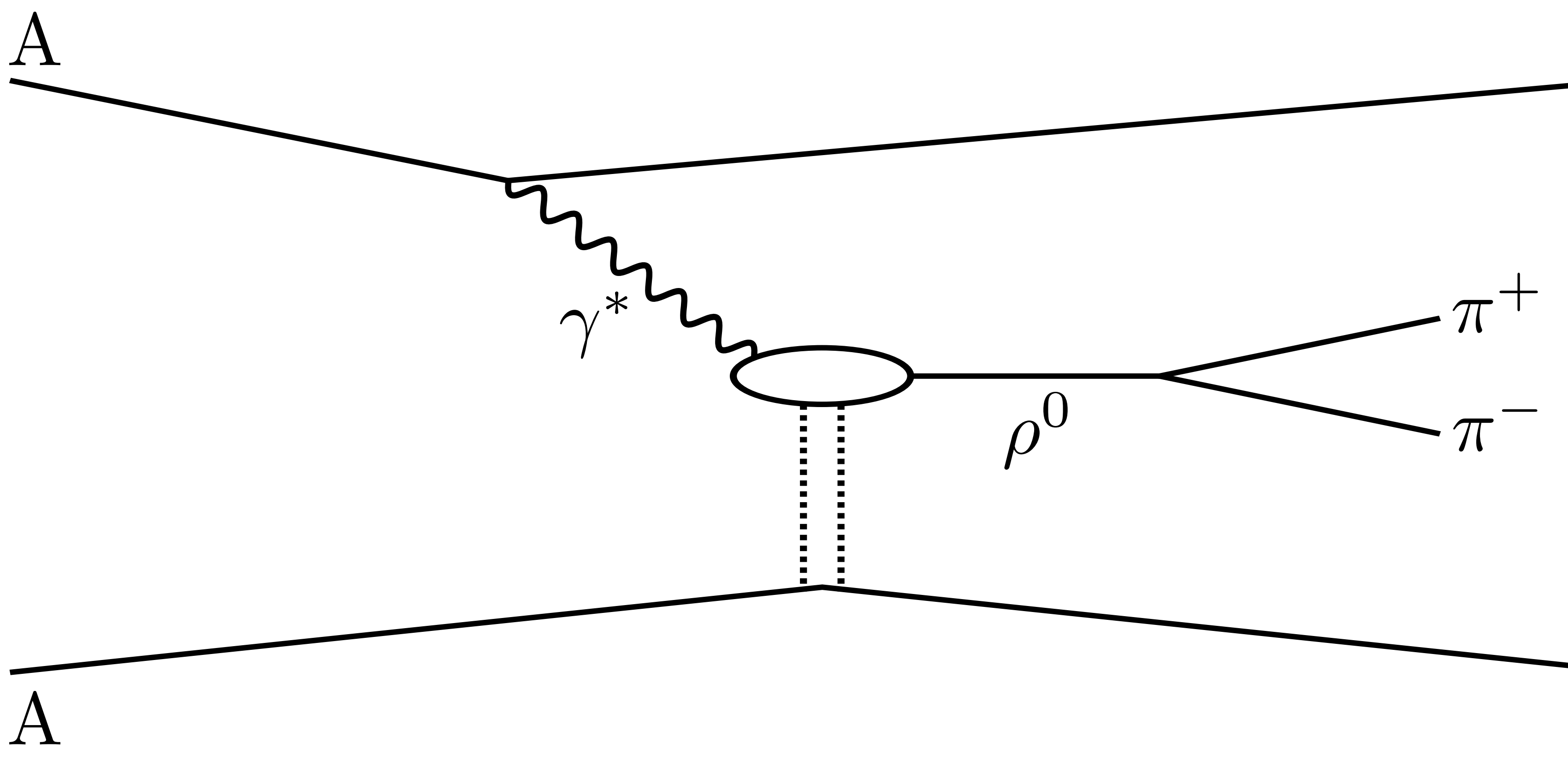
Vector meson photoproduction

- limited hadronic interactions → clean environments for measurements of exclusive events with rapidity gaps (e.g. photoproduction)
- cross sections sensitive to nuclear gluon distributions and quantum interference at sub-fermi scales



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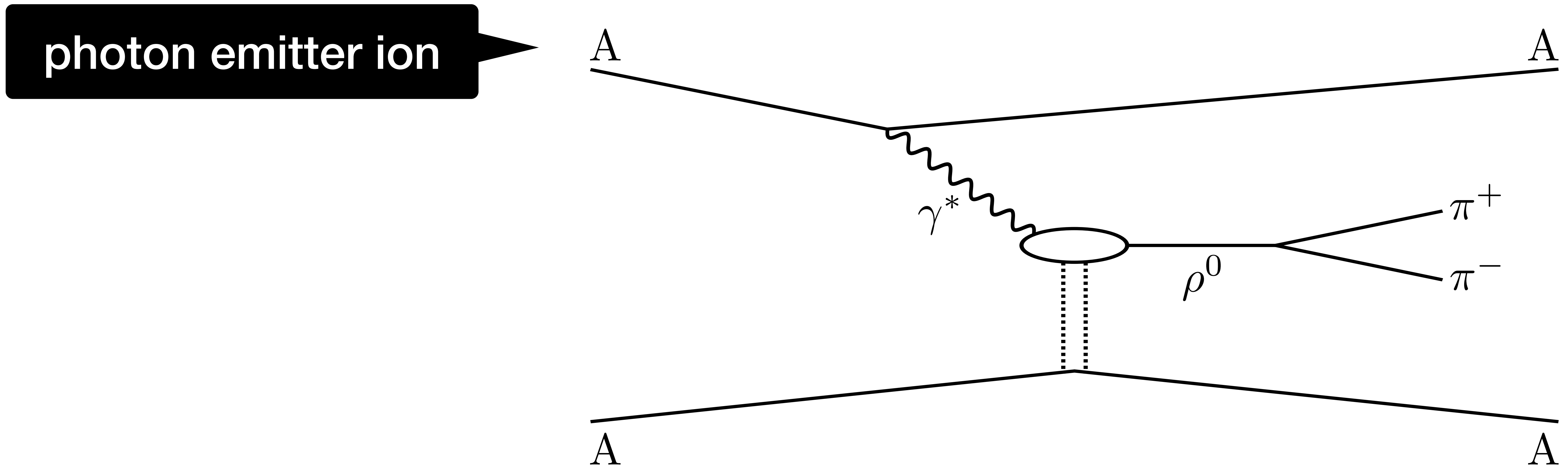

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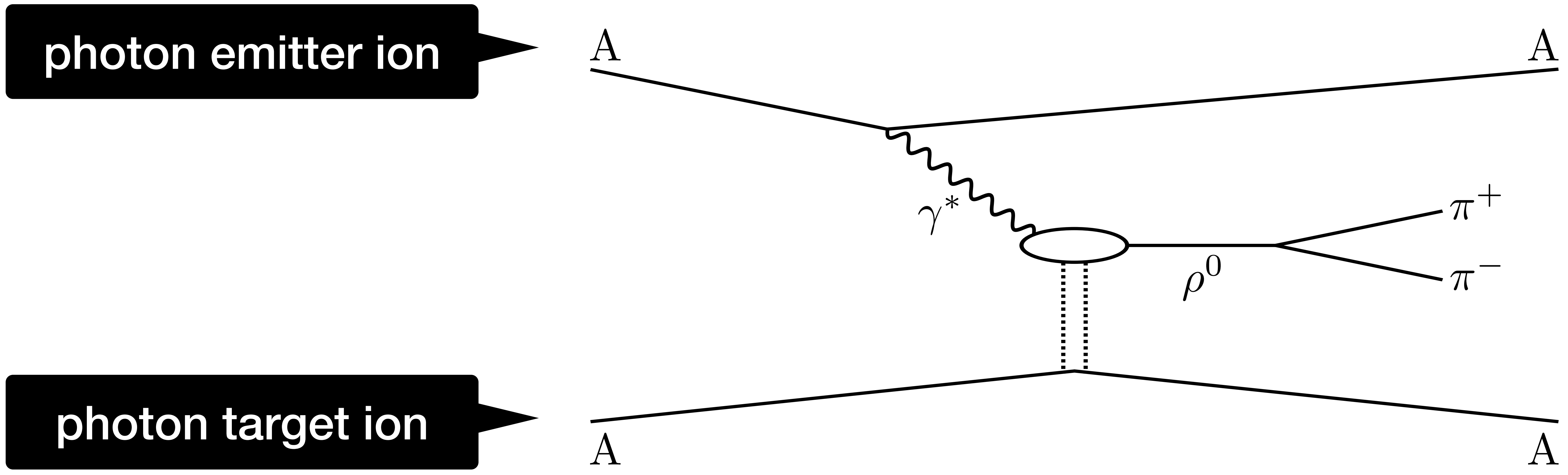

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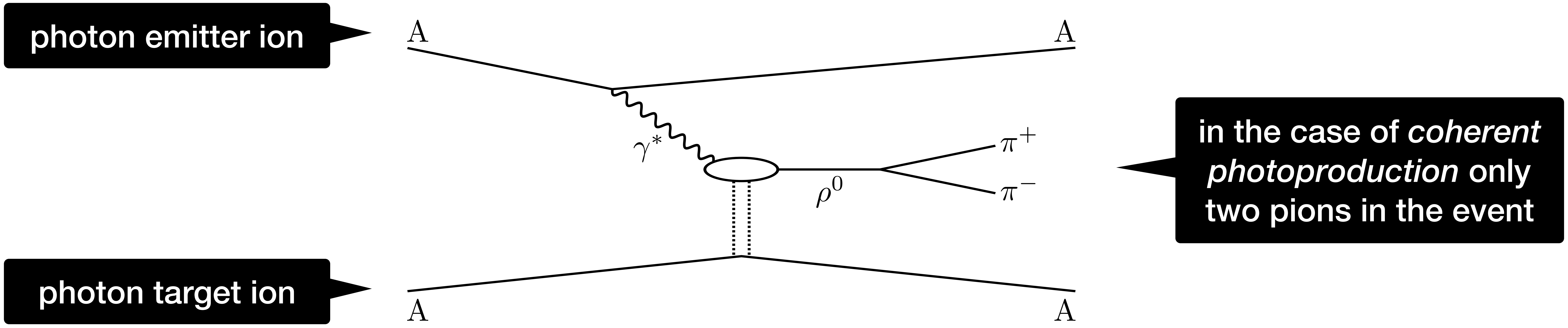

Interference in photoproduction processes

- the emitter/target roles of ions in the reaction are indistinguishable in symmetric collision systems
  - the produced vector meson behaves as a wave propagating from two spatially separated point sources

adapted from *Sci. Adv. 9, eabq3903 (2023)*

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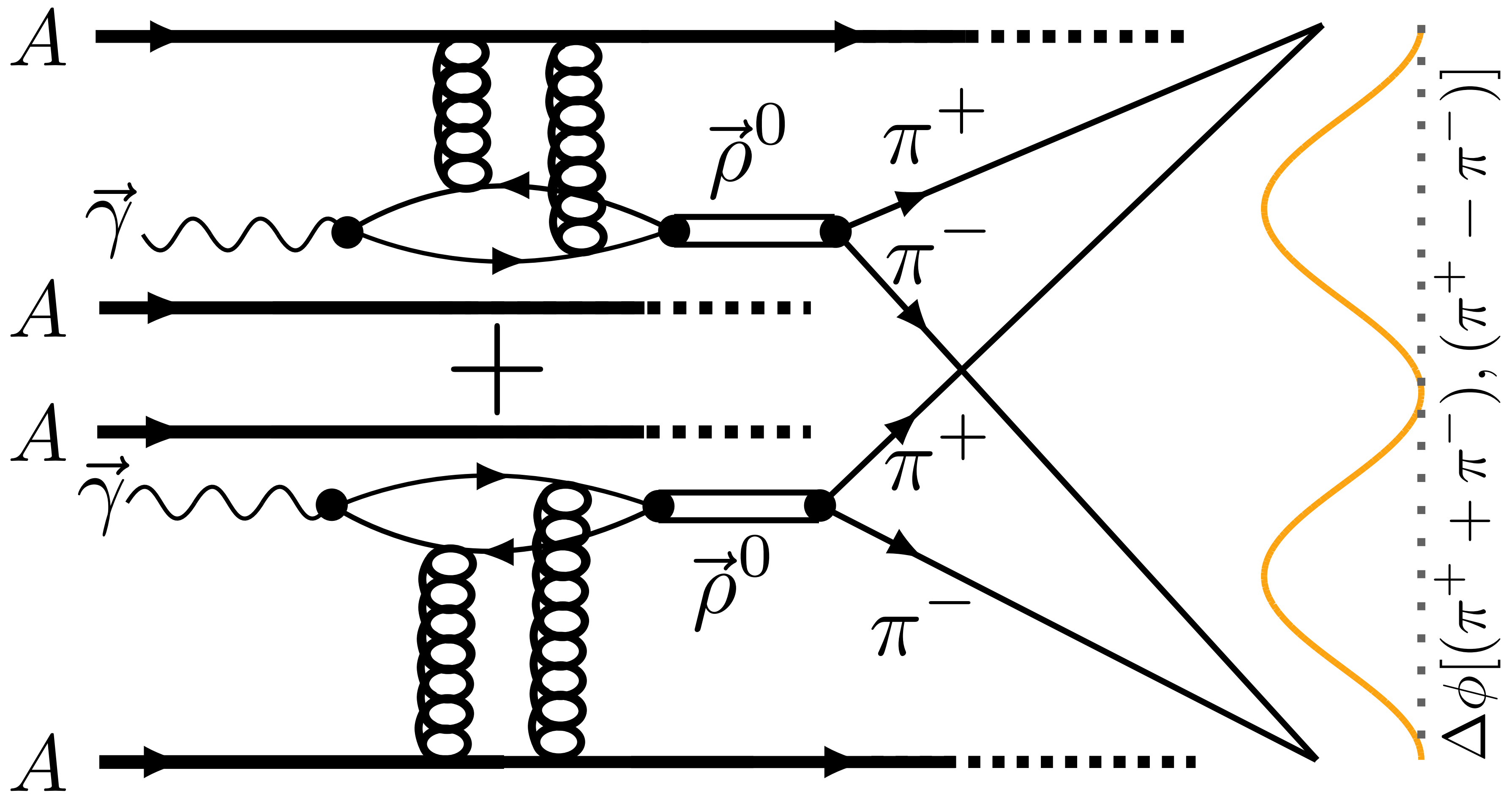


destructive quantum interference in the photoproduction cross section

adapted from *Sci. Adv. 9, eabq3903 (2023)*

$\Delta\phi$ anisotropy
in theory

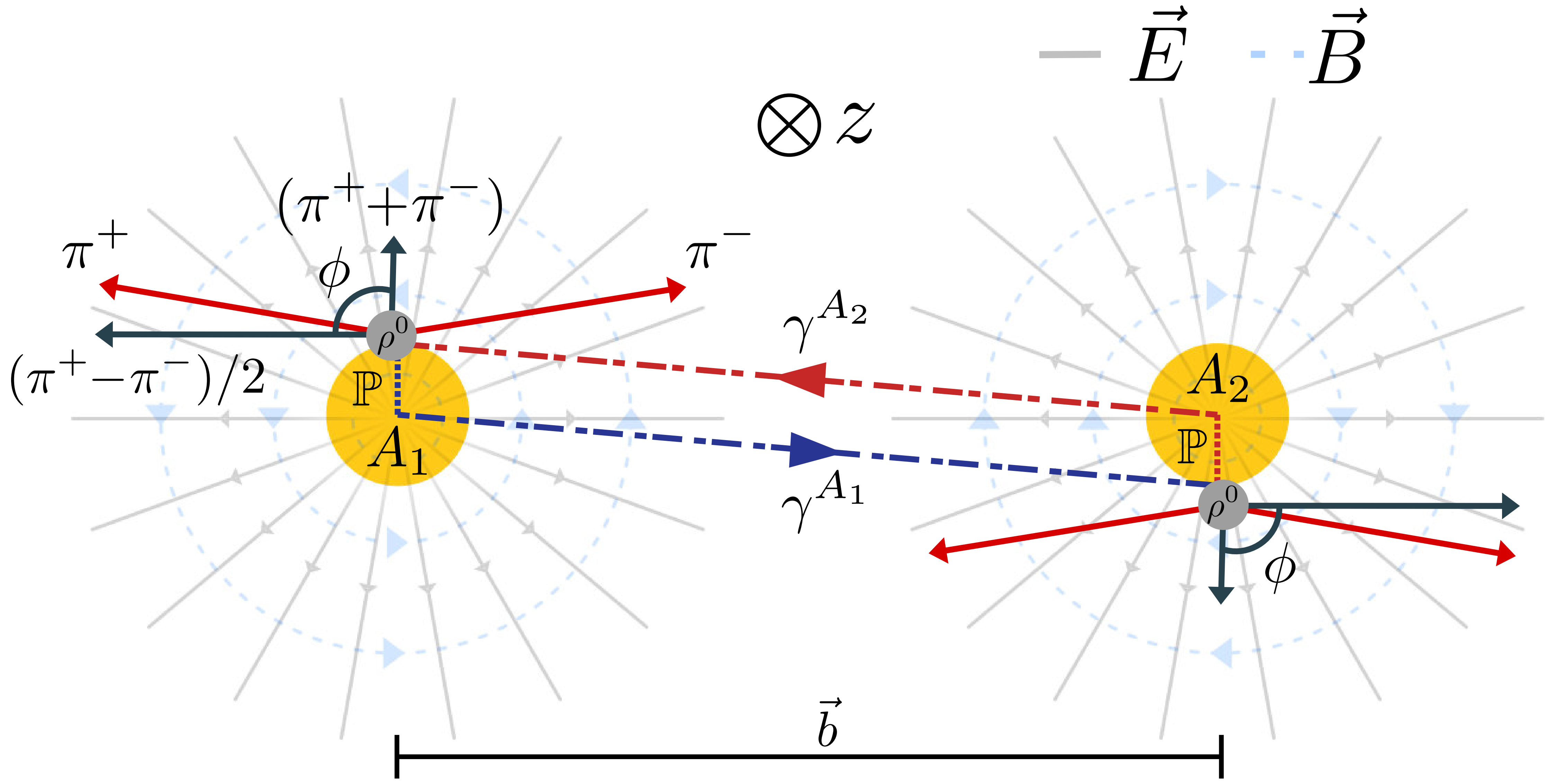
- photons participating in photoproduction reactions are linearly polarised
  - angular momentum conservation causes the initial polarisation vector to be transferred into the vector meson and eventually its decay products
    - for $\rho^0 \to \pi^+\pi^-$ manifests as a $\cos(2\phi)$ modulation in their azimuthal distribution
- several other processes induce modulations of other orders
  - e.g. direct pion production leads to 'Coulomb-nuclear interference' and induces $\cos(\phi)$ and $\cos(3\phi)$ modulations

$\Delta\phi$ anisotropy

in practice

- proxy for the effect of such anisotropies is $\Delta\phi$
    - azimuthal angle between the vector meson p_{T} and the 'relative' p_{T} of its decay products

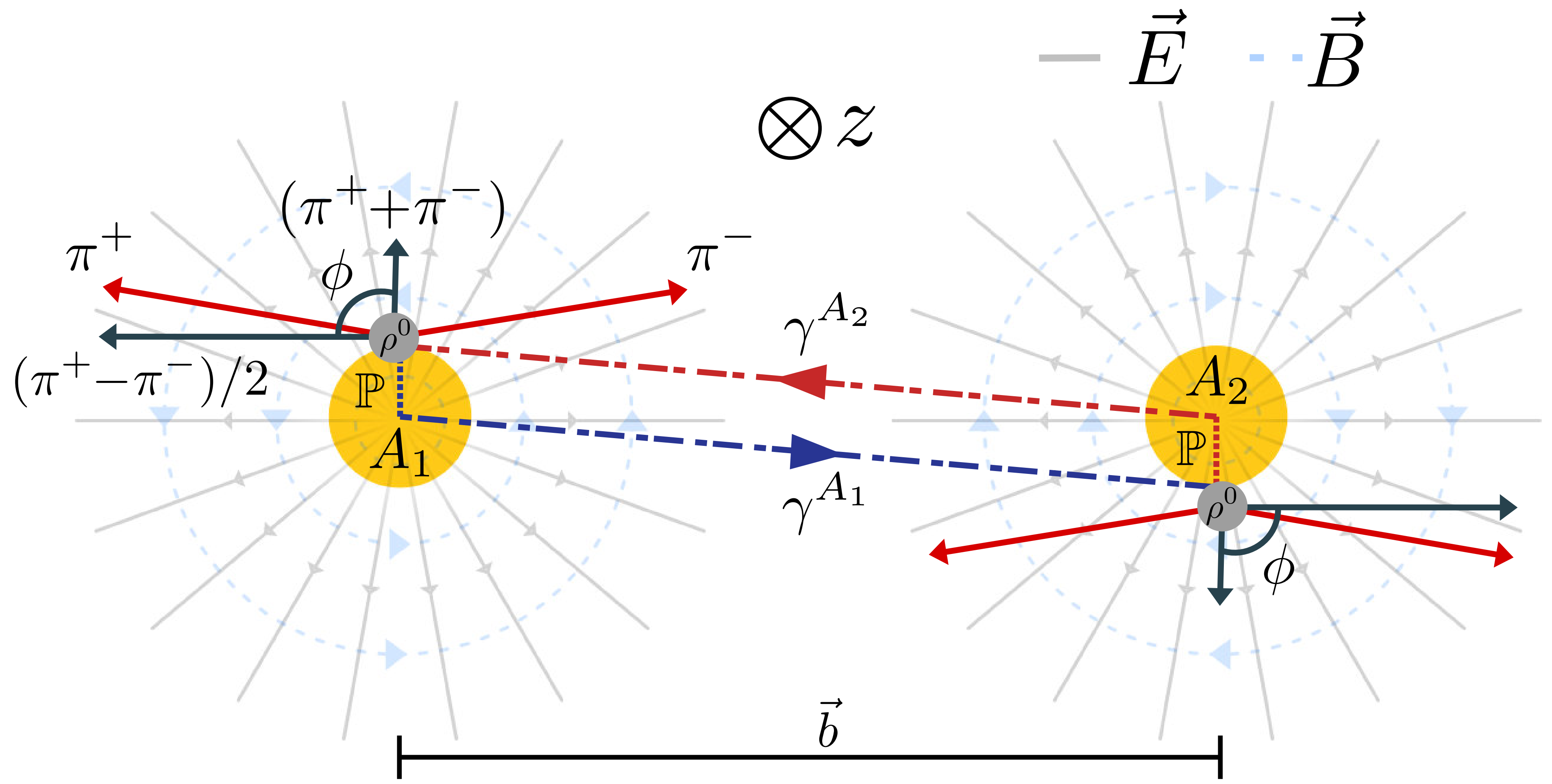
$$\cos(\Delta\phi) = \frac{(\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2}) \cdot (\vec{p}_{\mathrm{T}1} - \vec{p}_{\mathrm{T}2})}{|\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2}| \times |\vec{p}_{\mathrm{T}1} - \vec{p}_{\mathrm{T}2}|}$$



Sci. Adv. 9, eabq3903 (2023)

$\Delta\phi$ definitions

$$\cos(\Delta\phi) = \frac{(\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2}) \cdot (\vec{p}_{\mathrm{T}1} - \vec{p}_{\mathrm{T}2})}{|\vec{p}_{\mathrm{T}1} + \vec{p}_{\mathrm{T}2}| \times |\vec{p}_{\mathrm{T}1} - \vec{p}_{\mathrm{T}2}|}$$



- tracks can be assigned in several ways
  - $\Delta\phi_{\mathrm{random}}$ — randomised assignment with a time-based seed
    - this potentially avoids non-uniform detector responses to tracks of different charge, but also eliminates any odd-numbered harmonics
  - $\Delta\phi_{\mathrm{charge}}$ — ‘track 1’ always positive, ‘track 2’ always negative

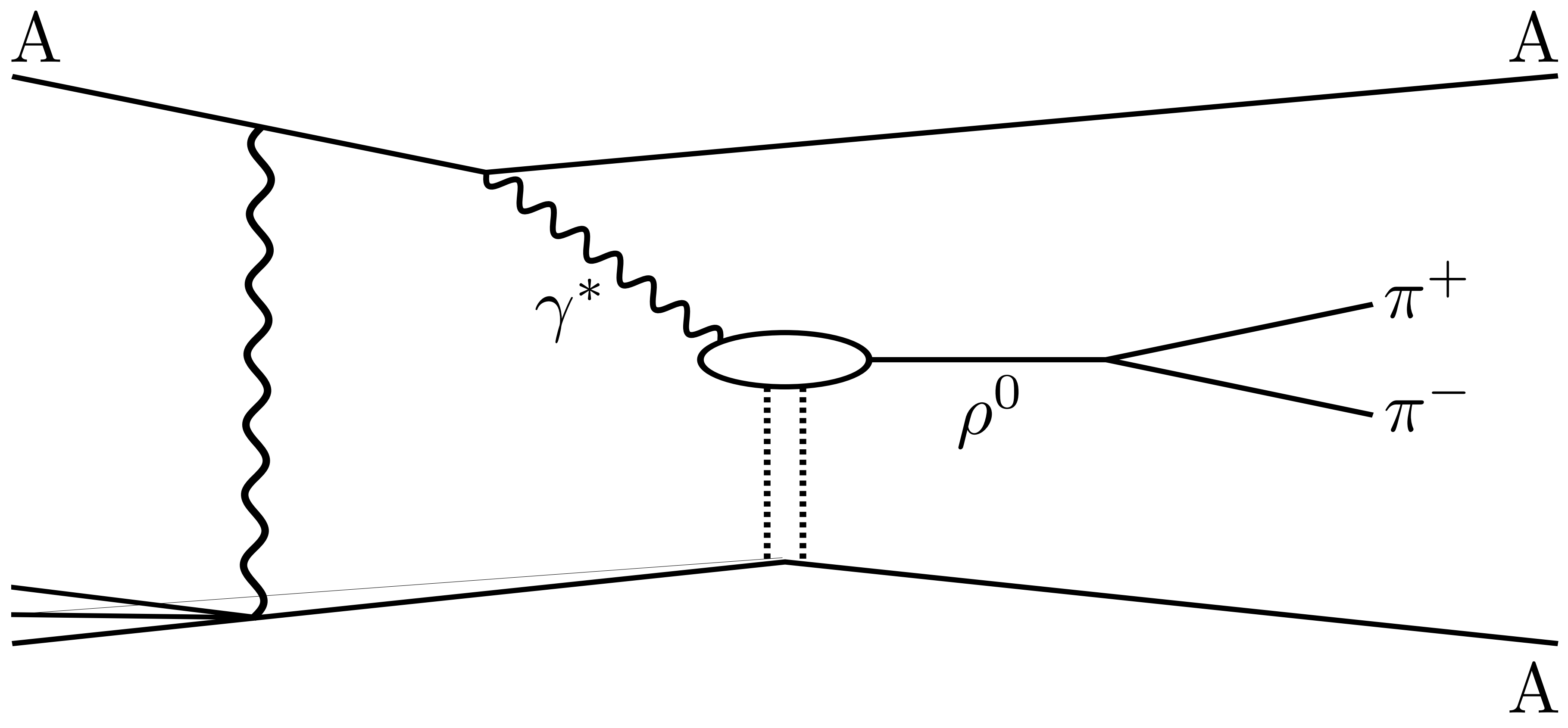
Sci. Adv. 9, eabq3903 (2023)

Utilised dataset

- apass4 data from Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV recorded by ALICE in 2023
  - pre-filtered with the Single Gap Candidate producer
    → *UD_LHC23_pass4_SingleGap*
  - STARLight MC productions
    - *kCohRhoToPiWithCont* ($\rho^0 \rightarrow \pi^+\pi^-$ + direct pion continuum)
    - *kTwoGammaToMuLow* ($\gamma\gamma \rightarrow \mu^+\mu^-$)

Neutron classes

- independent neutron emission may be used to tag events into *neutron classes*
  - distinguish 0n0n, 0nXn, Xn0n, XnXn from ZN Common Energy and ZN Time measured by the ZDC detectors
  - proxy for collision impact parameter



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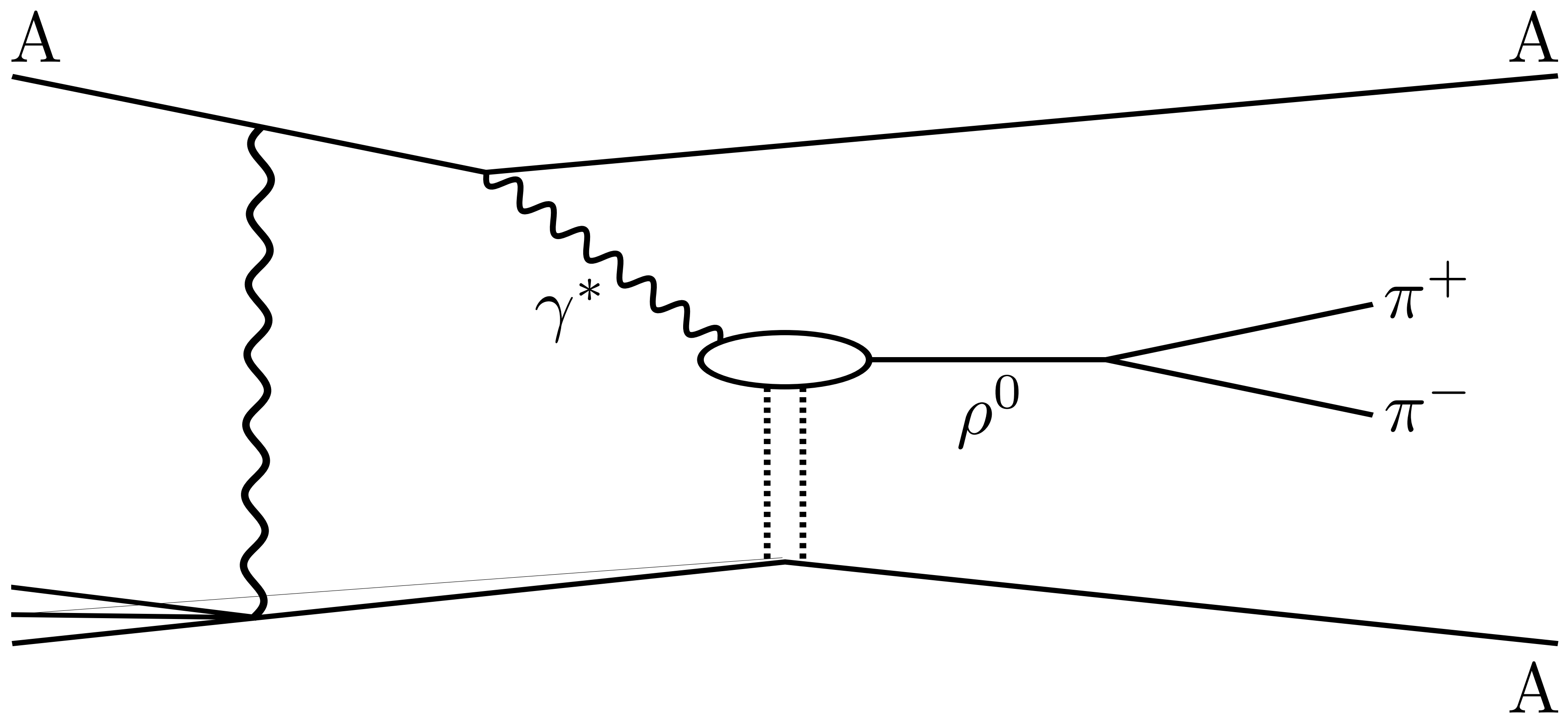
“Xn” event tagged for arbitrary positive value of ZN Common Energy and ZN Time within 2 ns



Utilised event selections

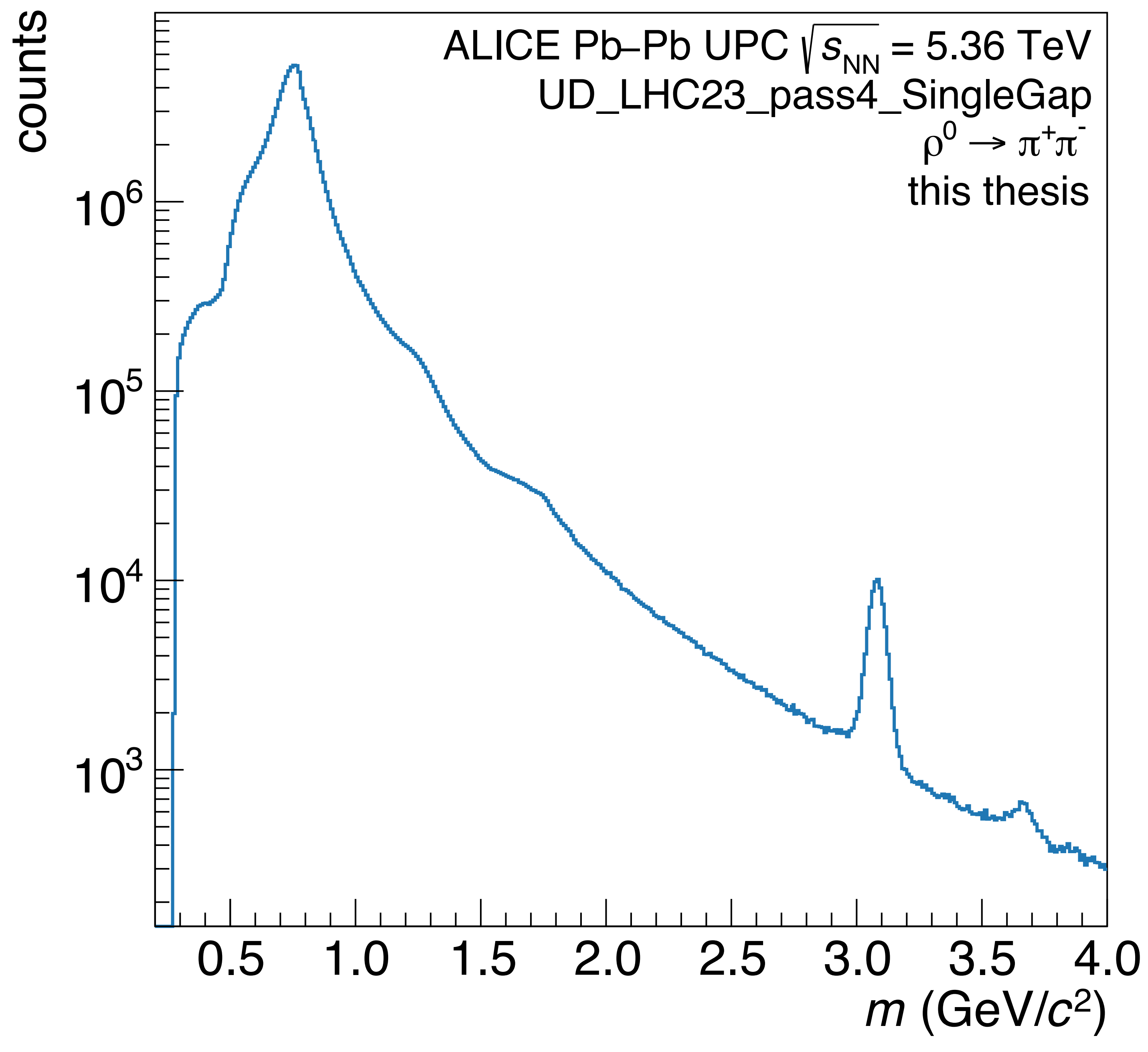
track level

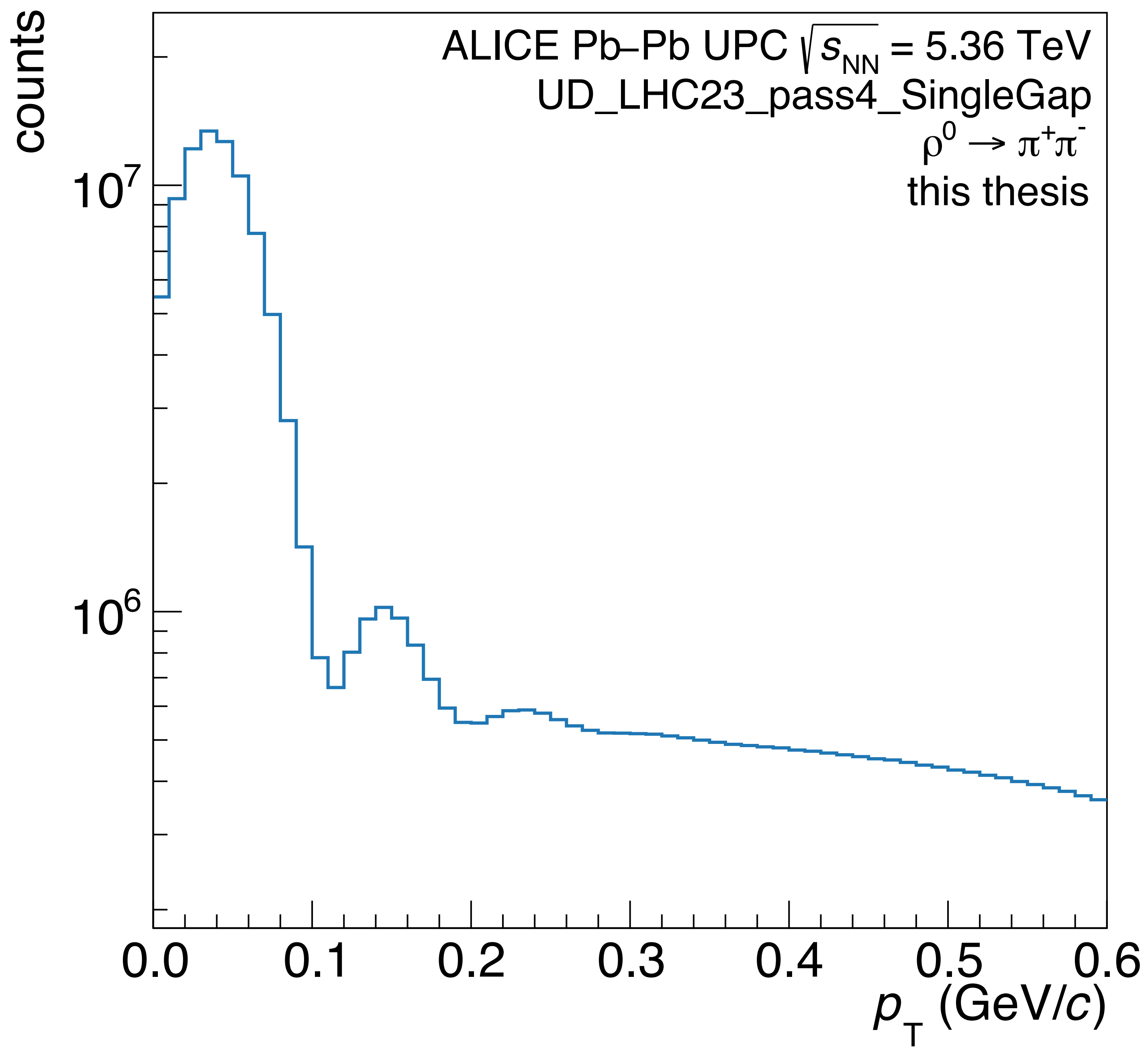
- PV contributor requirement
- hit in ITS
- minimum 4 ITS clusters and hit in the innermost ITS layer
- ITS χ^2/ndf < 3.0
- hit in TPC
- minimum 120 found TPC clusters
- TPC χ^2/ndf $\in$ [1.0, 3.0]

- at least 130 TPC rows
- tpcNClsCrossedRows/tpcNClsFindable ≥ 1.0
- $p_{\rm T}$ ≥ 0.1 GeV/*c*
- $DCA_Z \leq 1$ cm,
  $DCA_{XY} \leq 0.0105 + 0.0350/p_T^{1.01}$
- $|\eta| \leq 0.9$
- exactly 2 good tracks in event
- 2-dimensional PID selection within $3\sigma_\pi$

Event selections

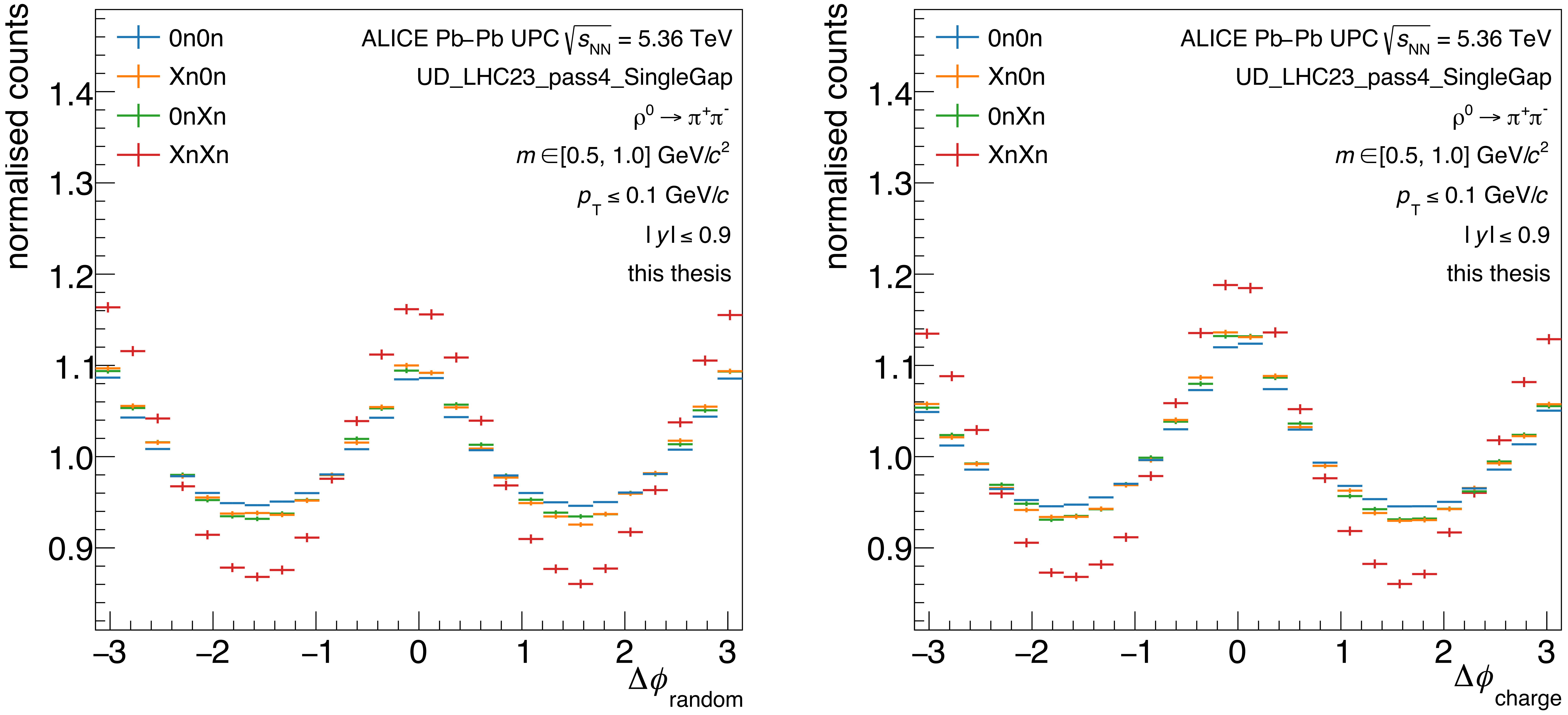
pion-pair level





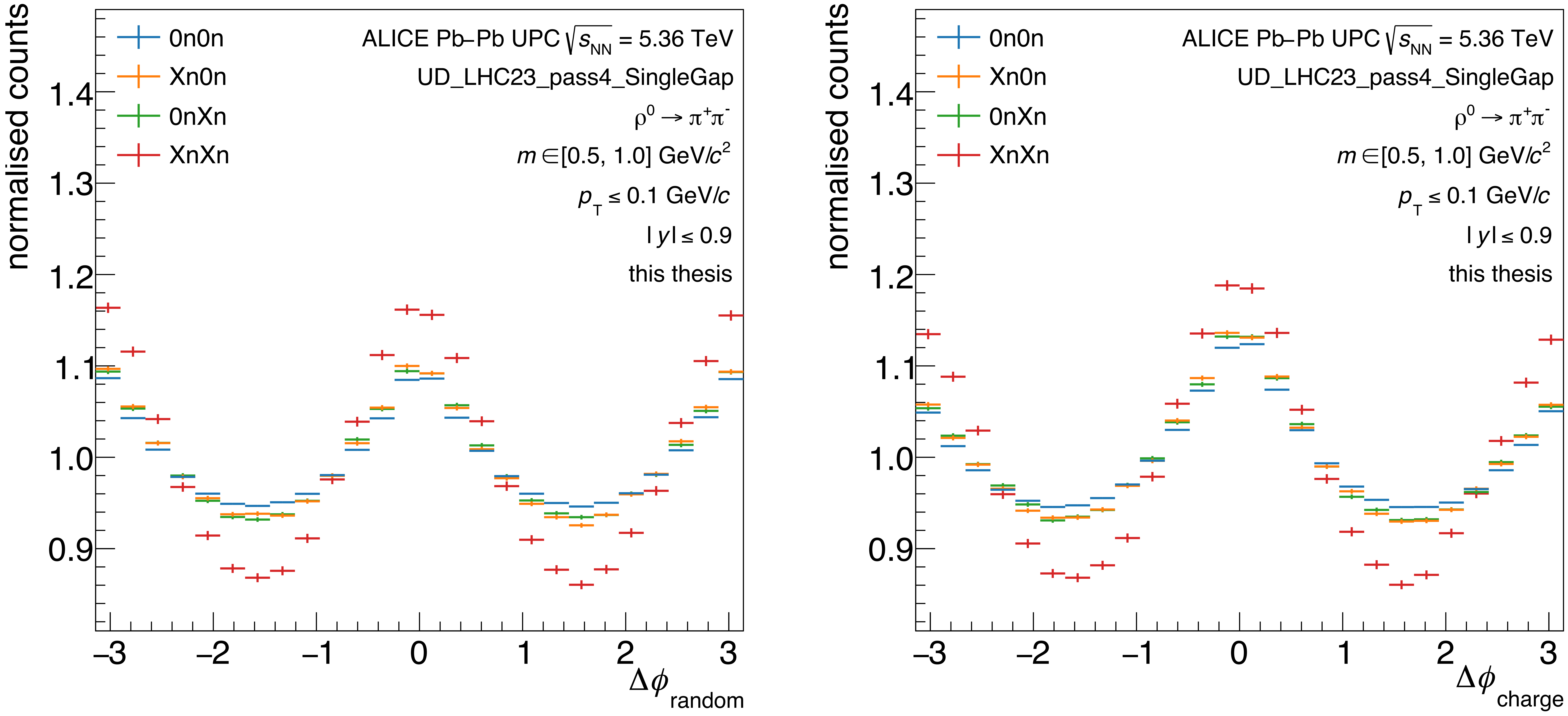
- further select $m \in [0.5, 1.0]$ GeV/c^2, $p_T \leq 0.1$ GeV/c, and $|y| \leq 0.9$ to extract coherent ρ^0 around the primary peak (~770 MeV/c^2)

Raw $\Delta\phi$ distributions



Raw $\Delta\phi$ distributions

further corrections should be made



Corrections

- events are divided into 14 bins in $\Delta\phi$ for all neutron classes
  - all subsets handled separately
- combinatorial background subtraction with $B = 4\sqrt{N_{++}N_{--}}$
- $A \times \varepsilon$ corrections calculated from *kCohRhoToPiWithCont* MC

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distributions of like-signed pion pairs

- combinatorial background subtraction with $B = 4\sqrt{N_{++}N_{--}}$
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Yield extraction

invariant mass fits

- invariant mass spectra fit using the Söding model

$$\frac{\mathrm{d}N}{\mathrm{d}m_{\pi\pi}} \propto \left| A_\rho \cdot \frac{\sqrt{m_{\pi\pi} m_\rho \Gamma_\rho}}{m_{\pi\pi}^2 - m_\rho^2 + \mathrm{i} m_\rho \Gamma_\rho} + B_{\pi\pi} + C_\omega \cdot \mathrm{e}^{\mathrm{i}\phi_\omega} \cdot \frac{\sqrt{m_{\pi\pi} m_\omega \Gamma_{\omega\to\pi\pi}}}{m_{\pi\pi}^2 - m_\omega^2 + \mathrm{i} m_\omega \Gamma_\omega} \right|^2 + c_\mu \cdot N_{\mu\mu}$$

with $\Gamma_\rho = \Gamma_0 \frac{m_\rho}{m_{\pi\pi}} \left(\frac{m_{\pi\pi}^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2} \right)^{3/2}$, $\Gamma_{\omega\to\pi\pi} = \mathrm{Br}(\omega \to \pi\pi)\Gamma_0 \frac{m_\omega}{m_{\pi\pi}} \left(\frac{m_{\pi\pi}^2 - 4m_\pi^2}{m_\omega^2 - 4m_\pi^2} \right)^{3/2}$, and $N_{\mu\mu} = a_\mu m_{\mu\mu}^{-b_\mu}$

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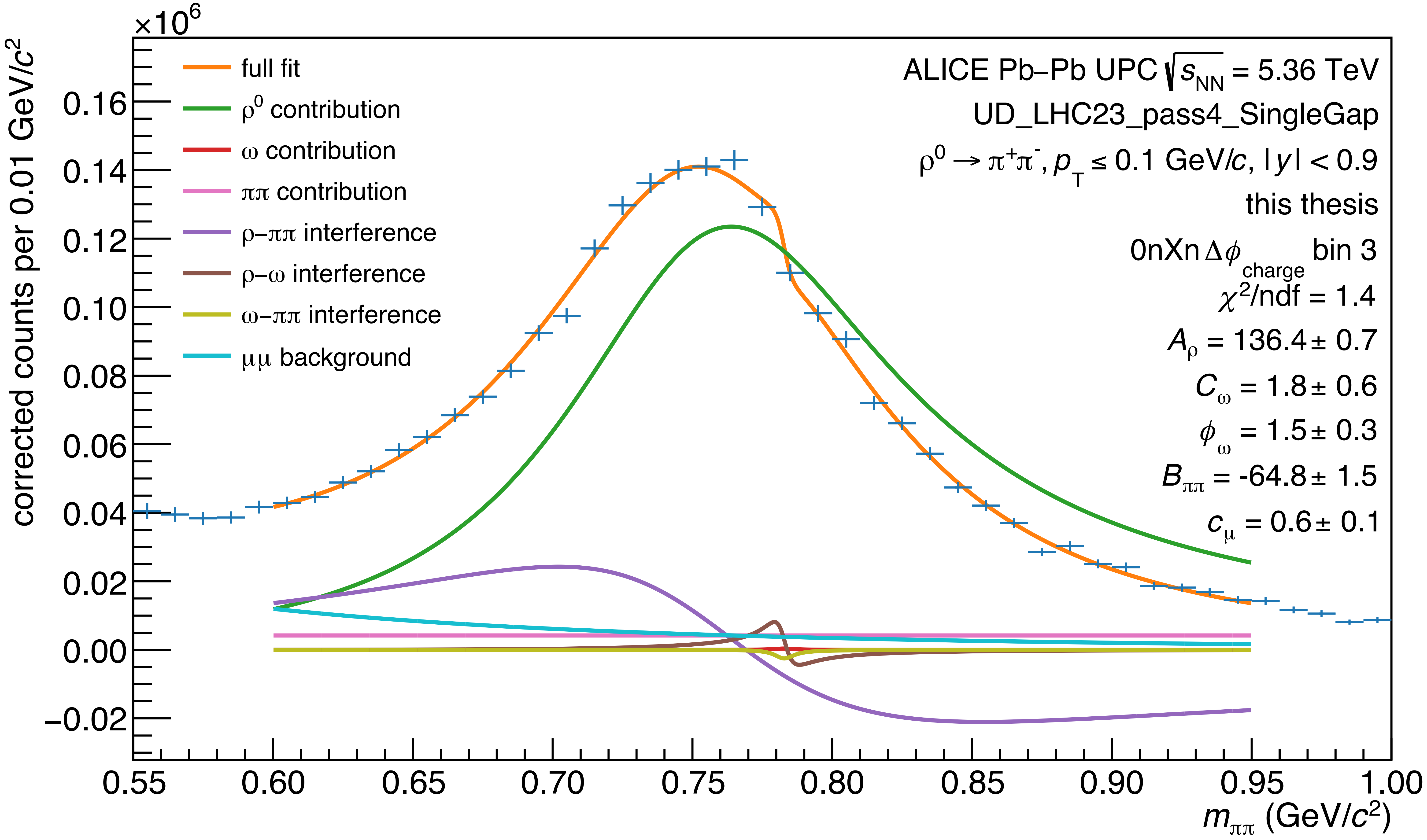
determined from *kTwoGammaToMuLow* MC

Yield extraction

example of an invariant mass fit



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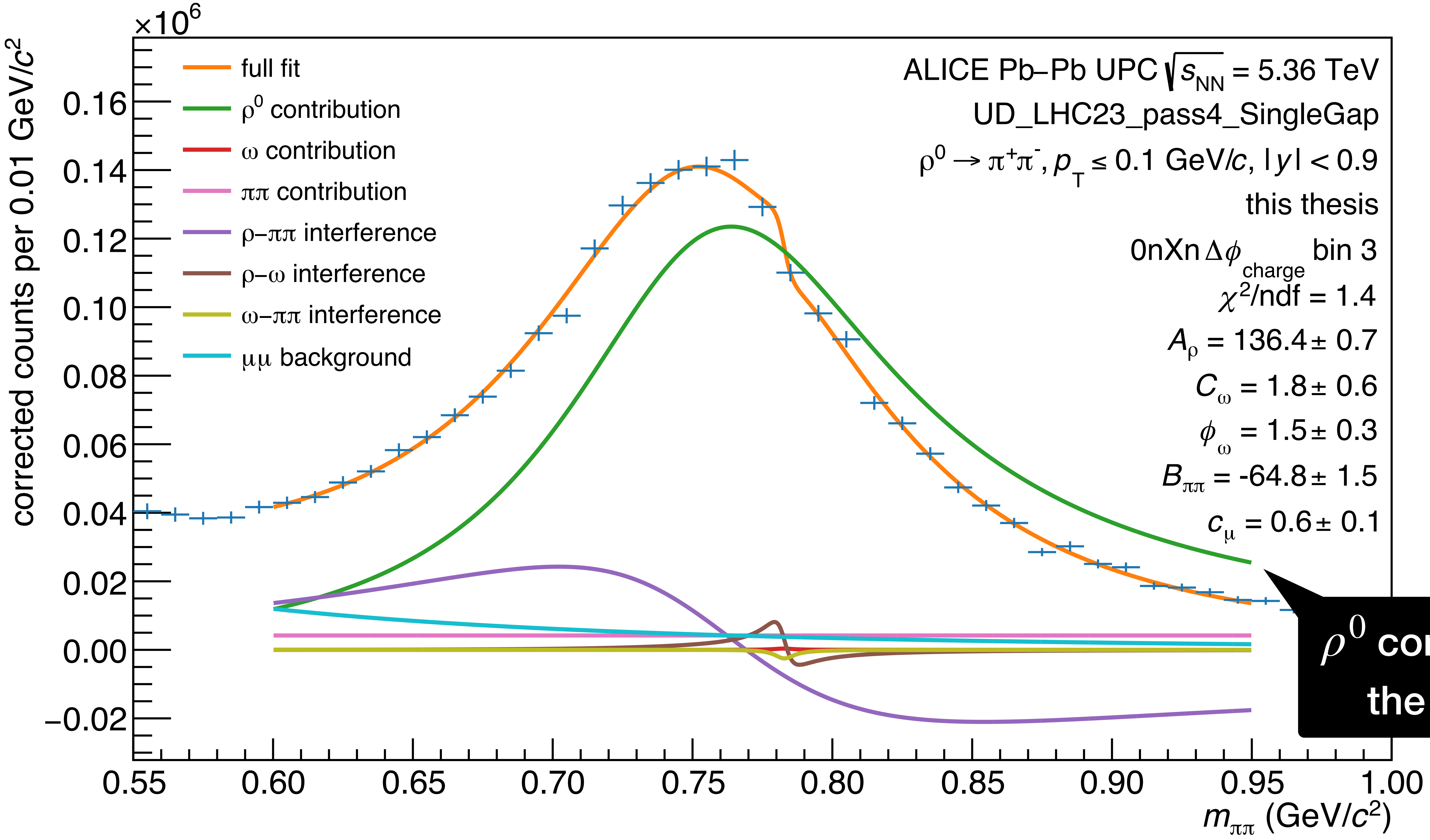


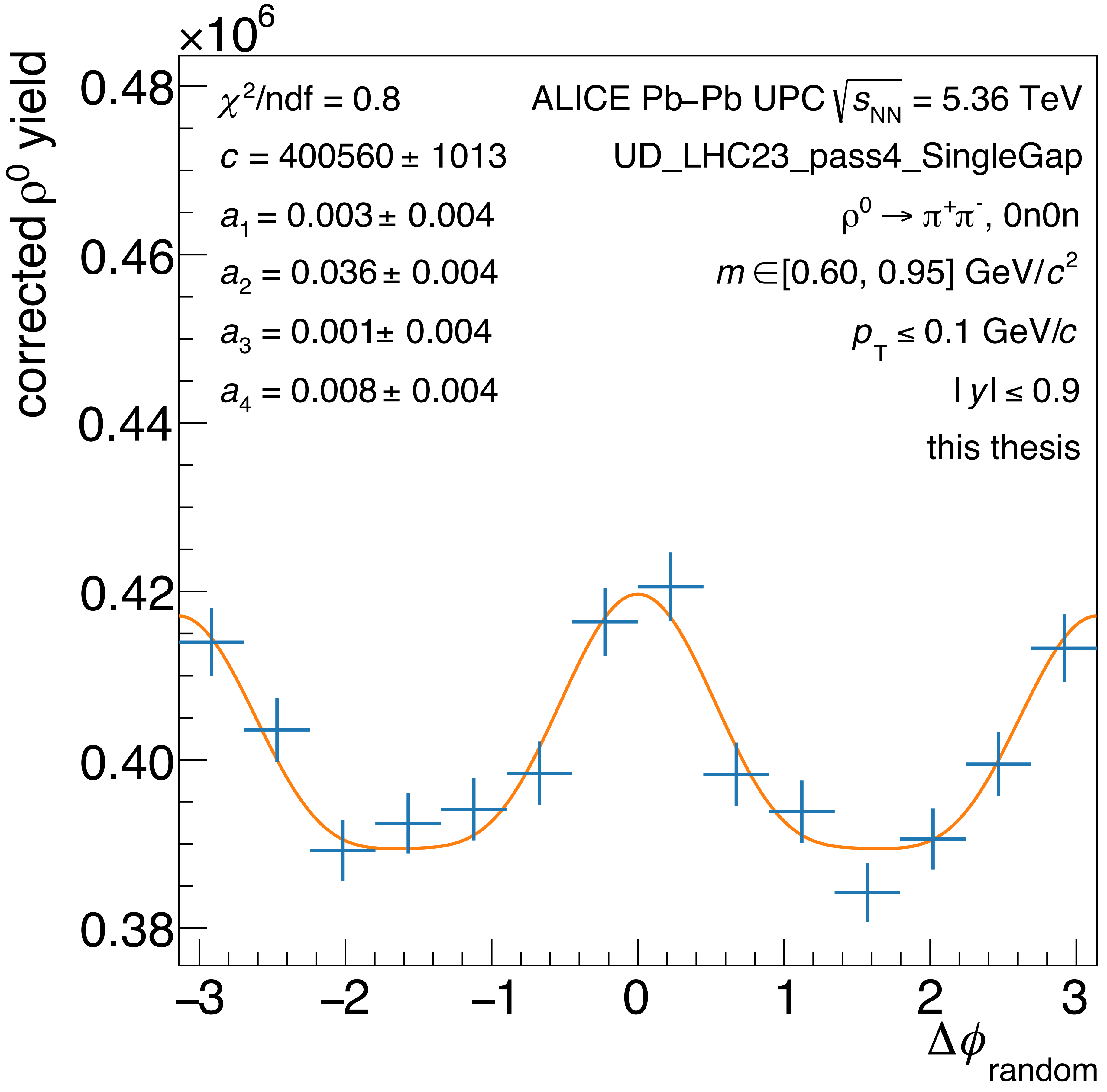
ρ^0 contribution integrated to get the yield for a given $\Delta\phi$ bin

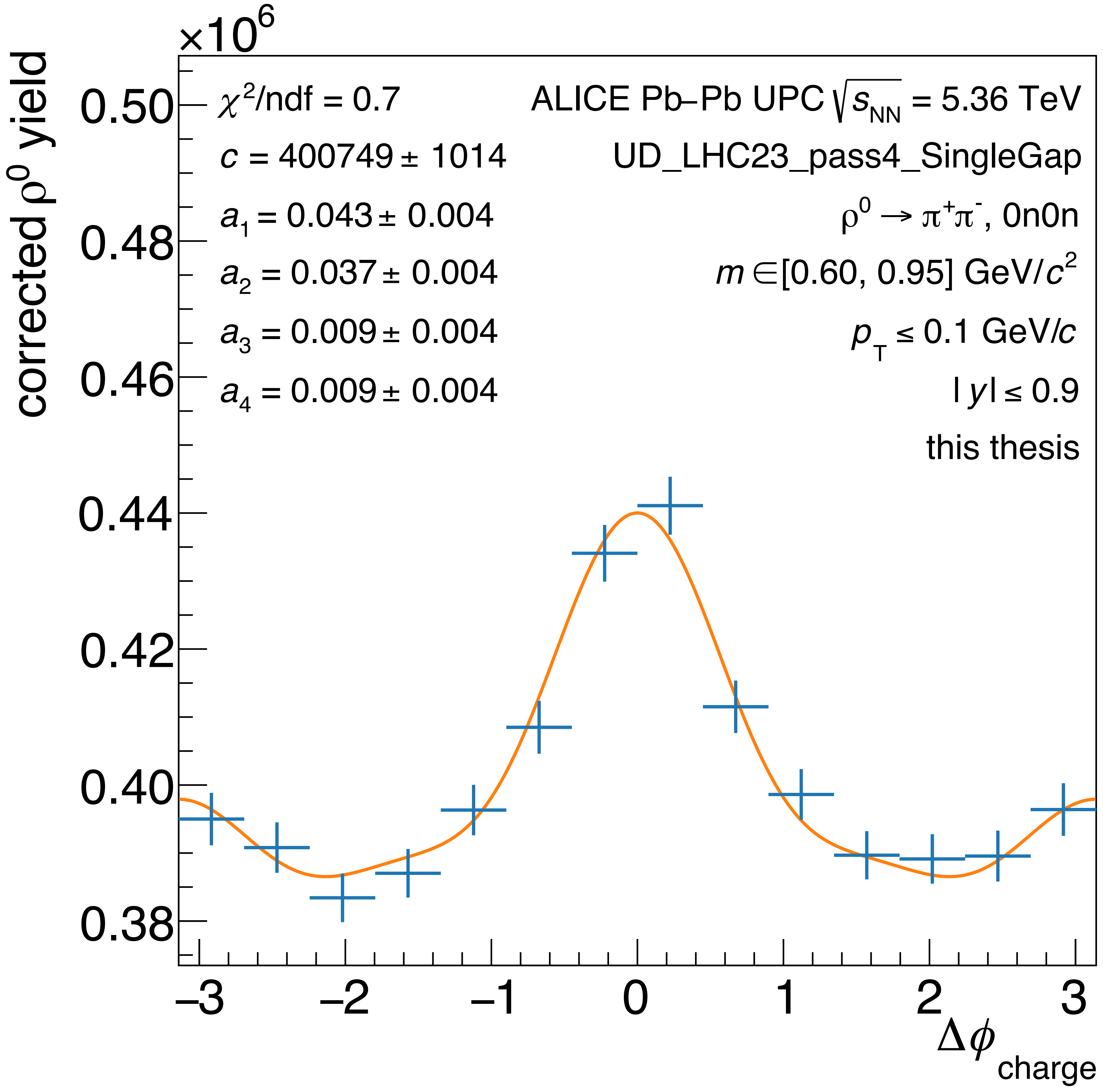
Modulation amplitude extraction

- corrected integrated ρ^0 yields in $\Delta\phi$ bins fit with a Fourier decomposition $N_{\rho^0}(\Delta\phi) = c\left(1 + \sum_{i=1}^{4} a_i \cos(i\Delta\phi)\right)$ to extract the modulation amplitudes

Modulation amplitudes

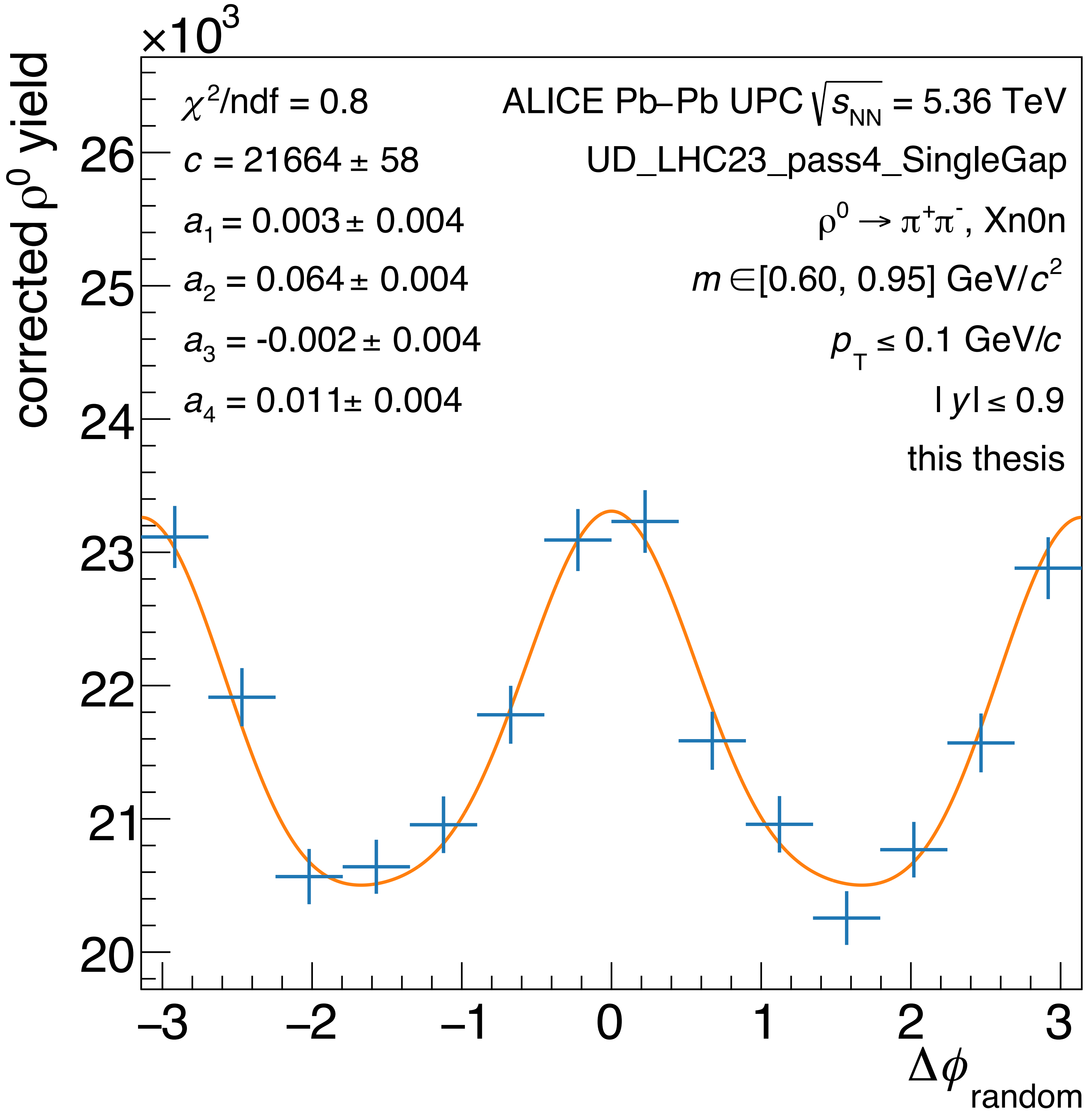
0n0n

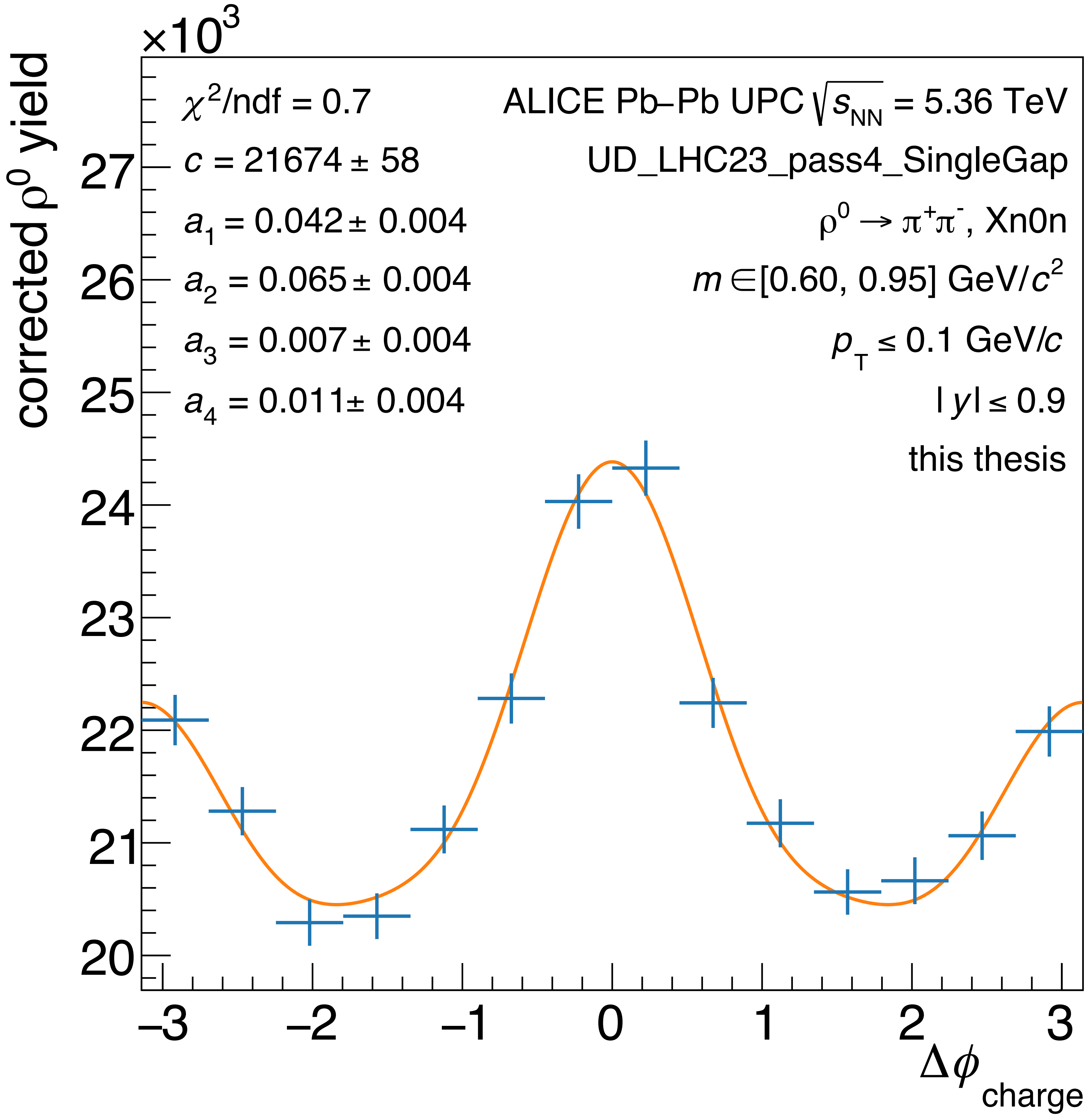




Modulation amplitudes

Xn0n





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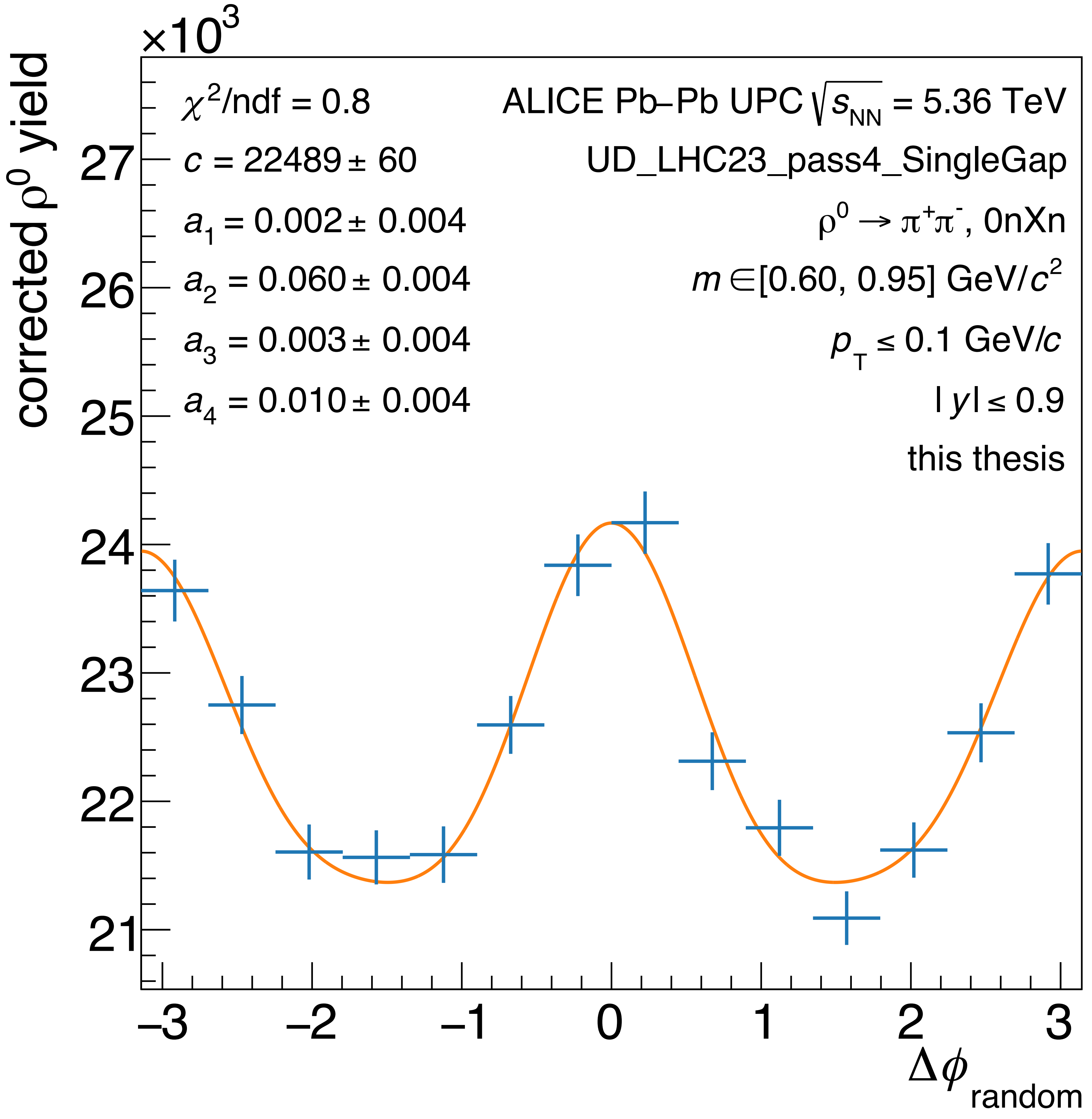

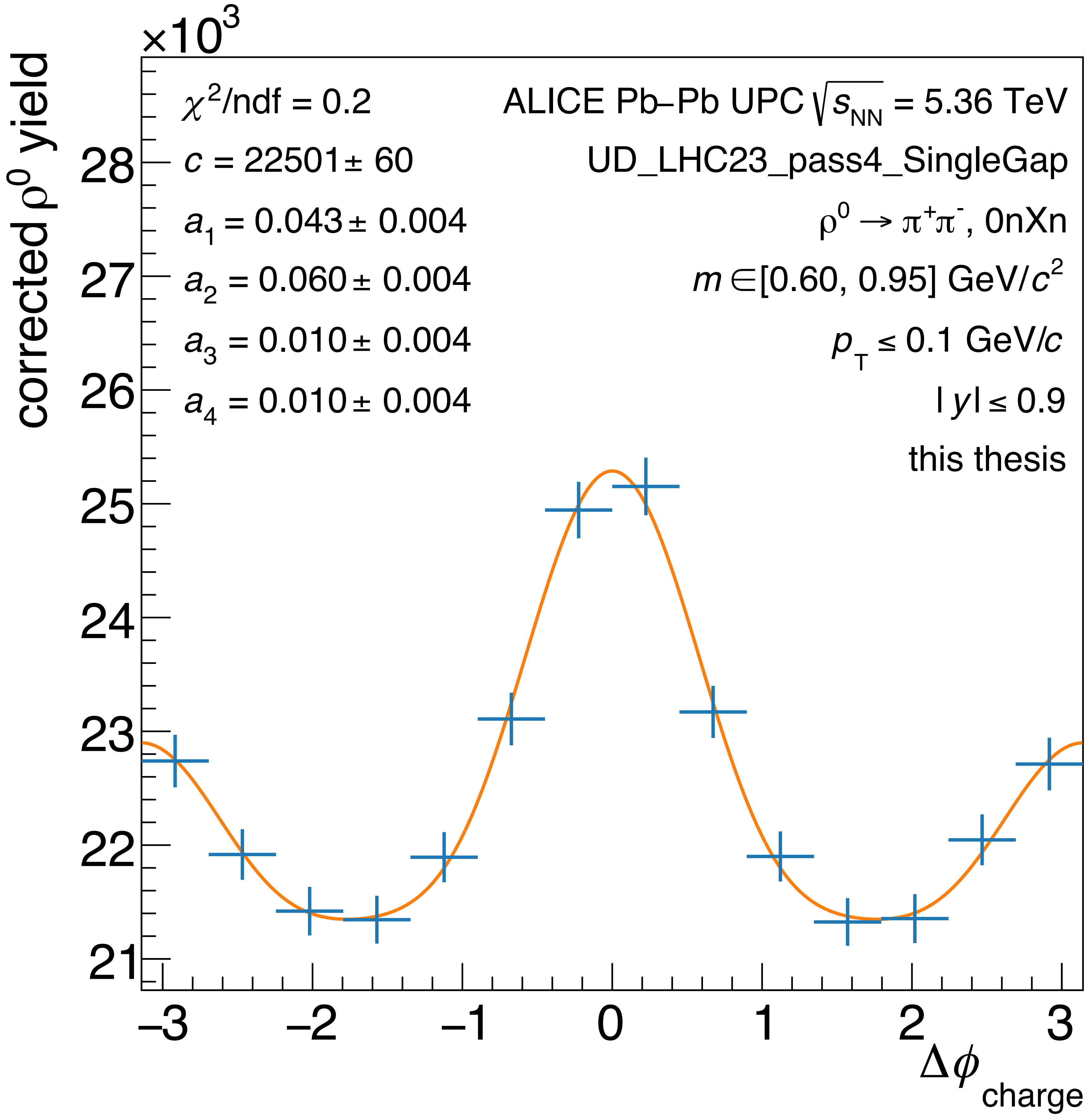

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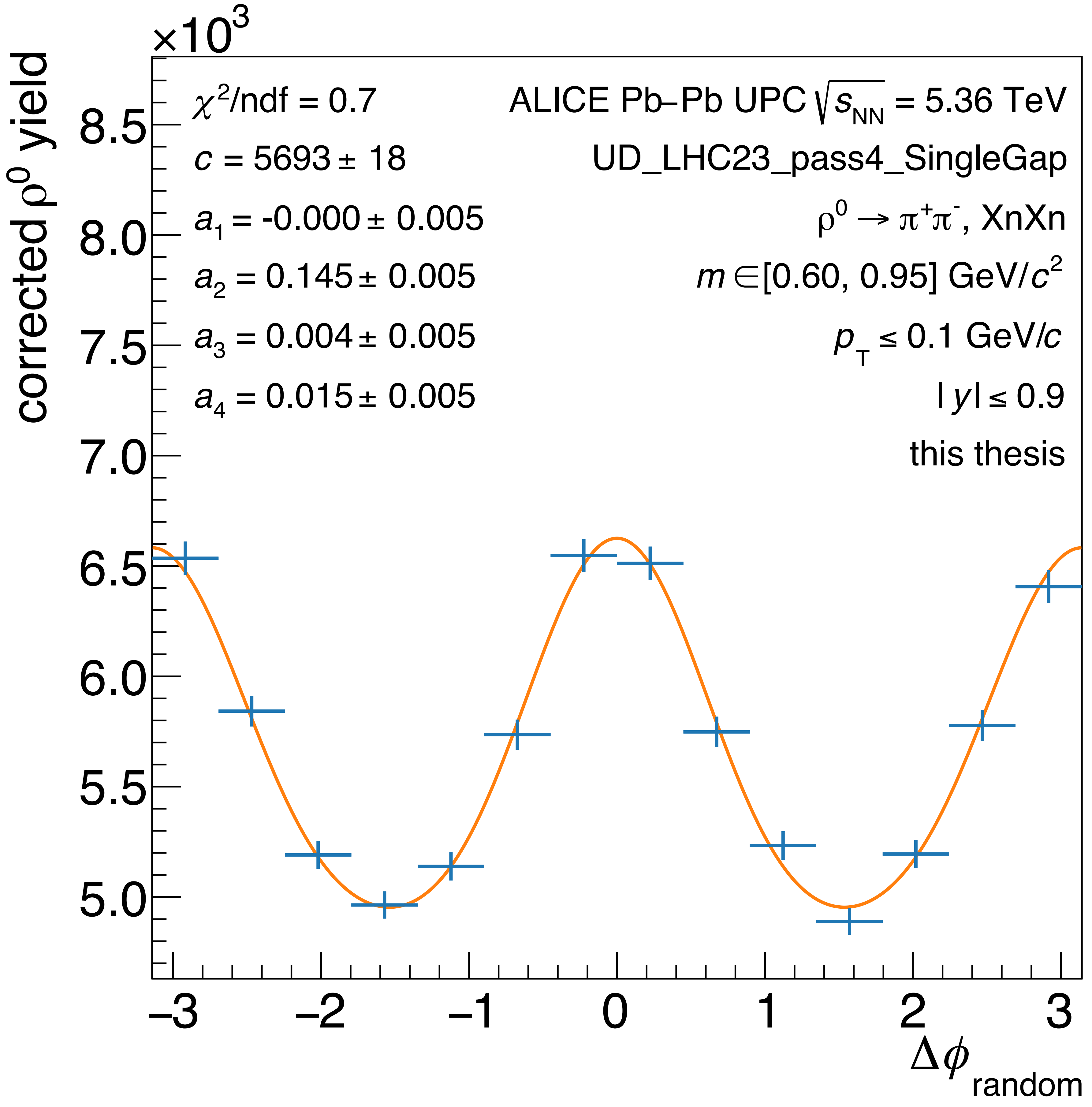
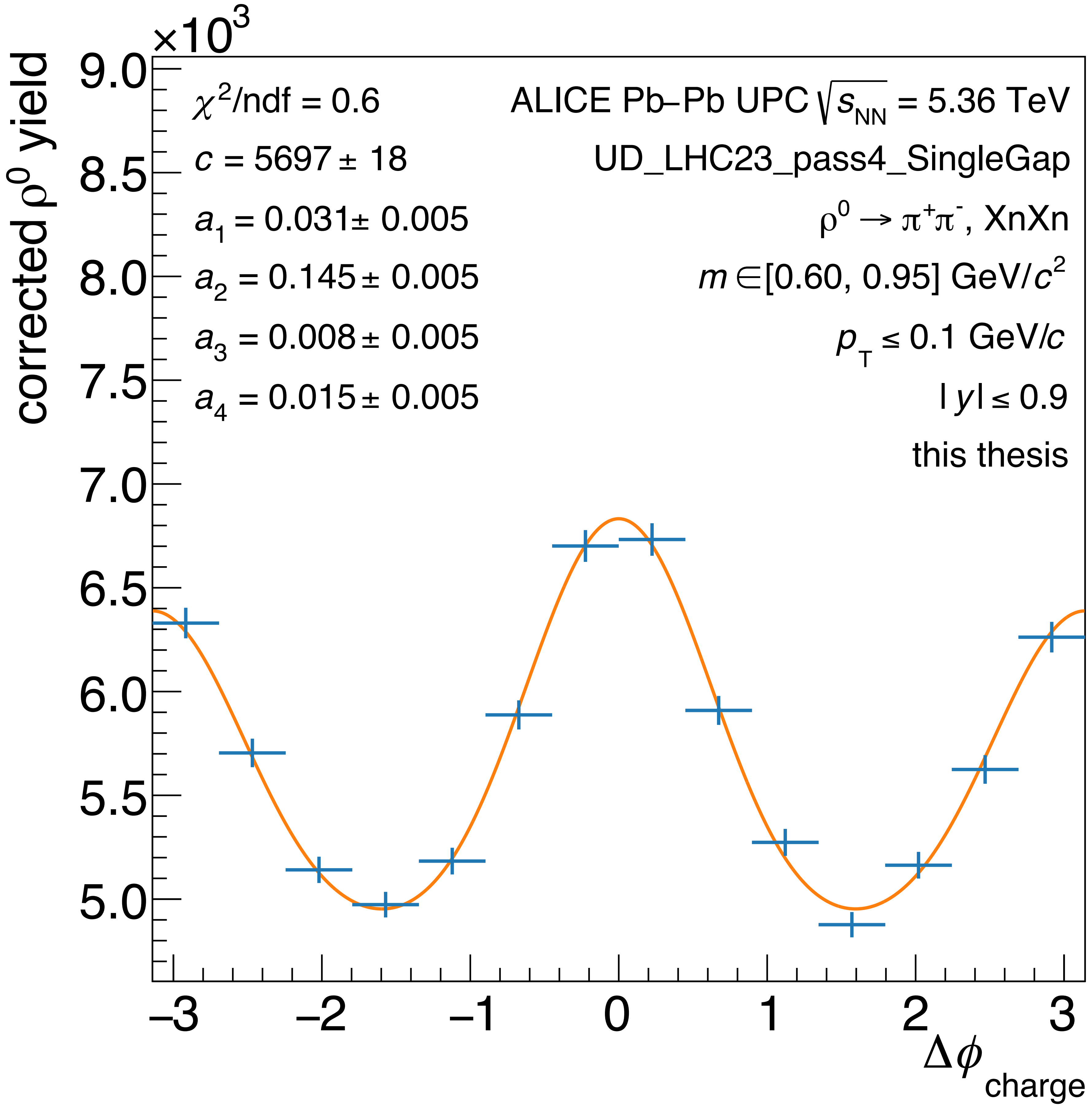




Summary and outlook

- first measurement of such asymmetries using LHC Run 3 data
  - investigates impact-parameter dependence through neutron class differentiation
  - results preliminary; working on improvements to fitting procedure, estimation of systematic uncertainties, and understanding of differences with respect to Run 2 results
- for the future
  - move analysis to apass5 data + new anchored MC when available
  - additional studies on a_2 p_{T}-dependence, …
  - explore photoproduction and anisotropy effects in O—O and Ne—Ne collisions
  - publish

Backup

Results comparison

Run 3 vs Run 2

- this analysis
  - 0n0n: $a_2 = 0.036 \pm 0.004$
  - Xn0n: $a_2 = 0.064 \pm 0.004$
  - 0nXn: $a_2 = 0.060 \pm 0.004$
  - XnXn: $a_2 = 0.145 \pm 0.005$
- Physics Letters B 858, 139017 (2024)
  - 0n0n: $a_2 = 0.028 \pm 0.011$
  - Xn0n: $a_2 = 0.14 \pm 0.04$
  - 0nXn joined with Xn0n
  - XnXn: $a_2 = 0.25 \pm 0.06$

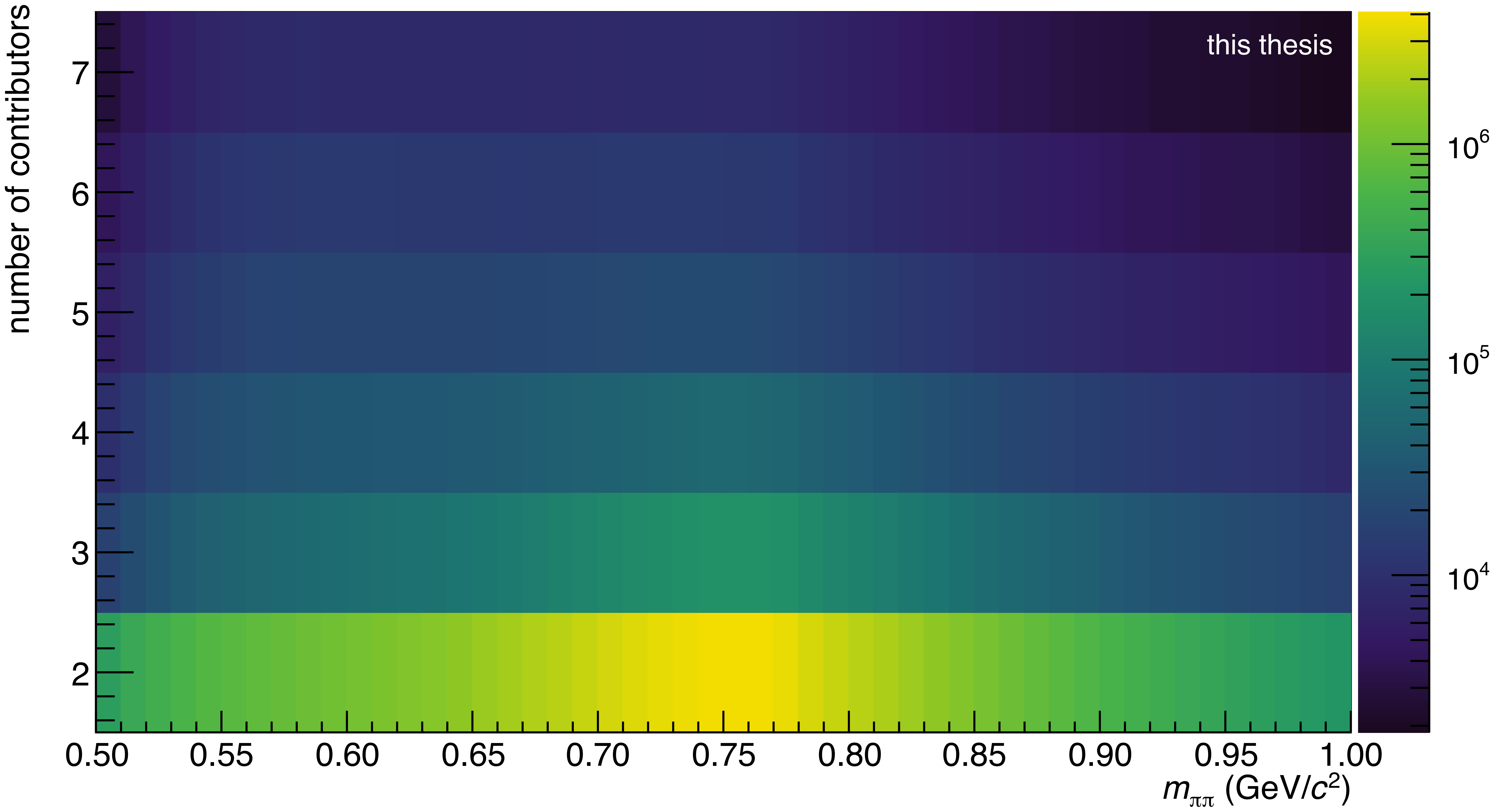
Utilised event selections

collision level

- select only double-gap events
- vertex *z* position ≤ 10 cm from IP
- events with exactly 2 contributors to the primary vertex
- event tagging into neutron classes (0n0n, 0nXn, Xn0n, XnXn) using the ZNA/C detectors
  - differentiated from ZN Common Energy and ZN Time
    "Xn" event tagged for arbitrary positive value of Common Energy and Time within 2 ns

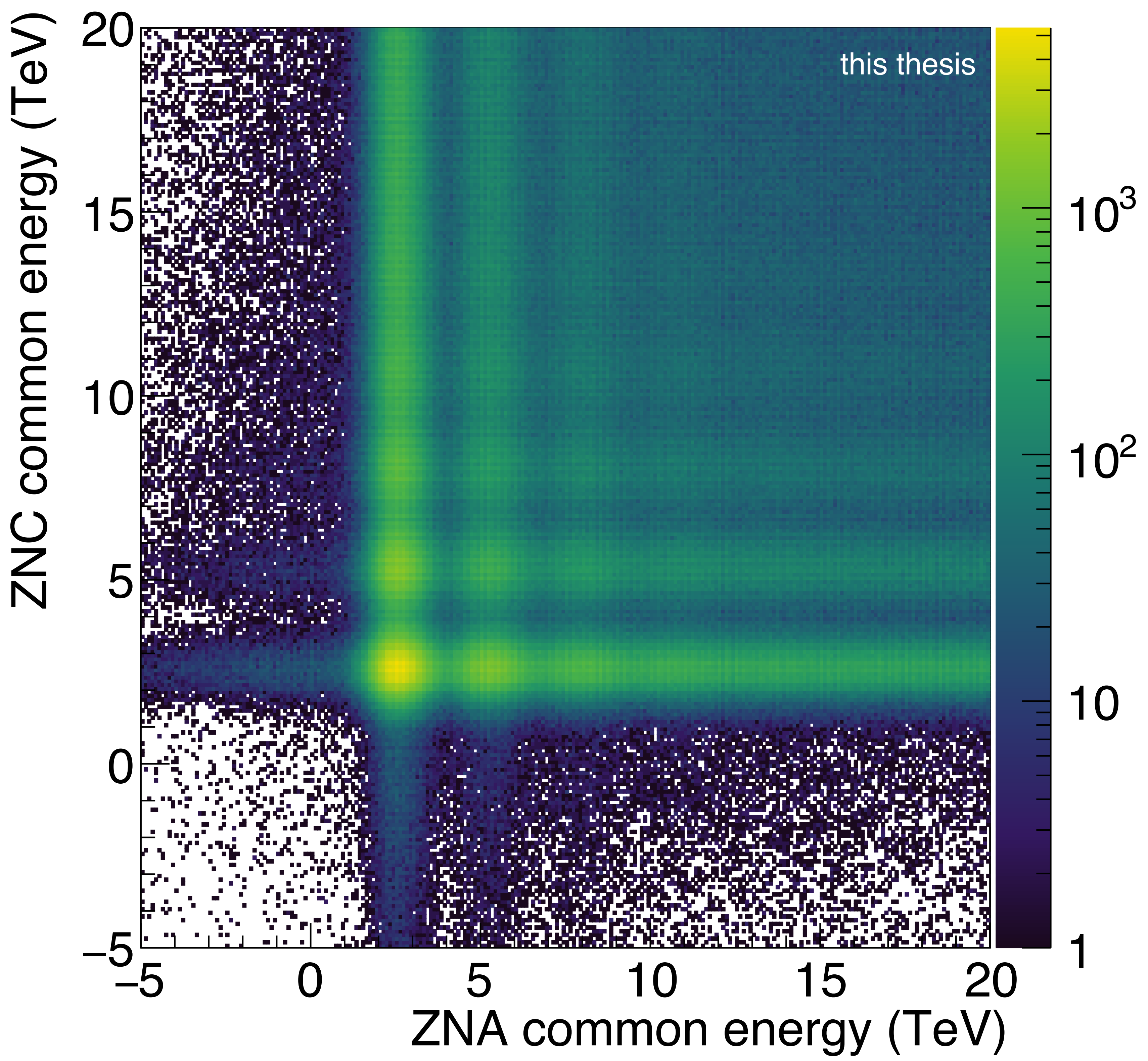
Utilised event selections

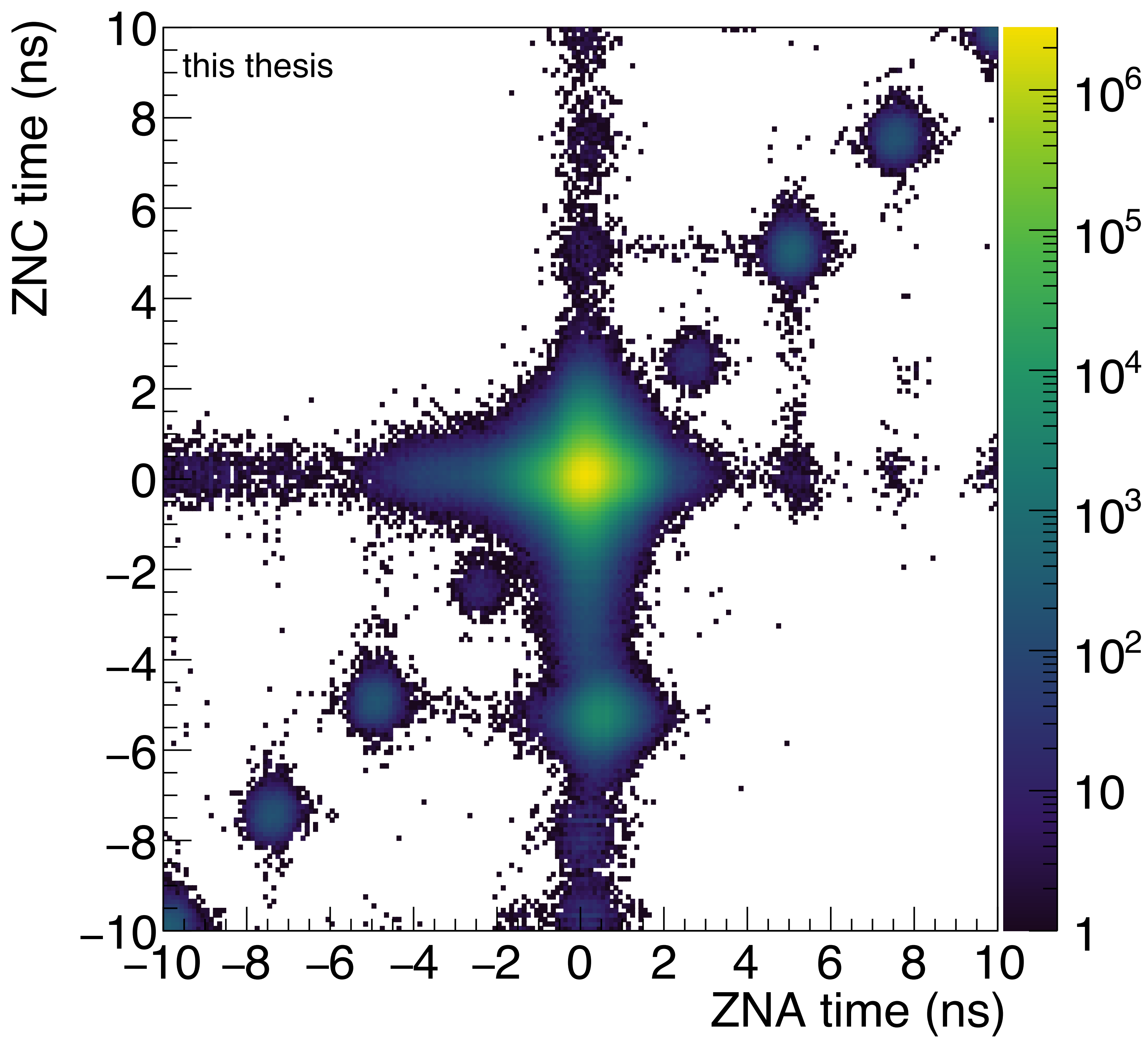
number of PV contributors limit



Utilised event selections

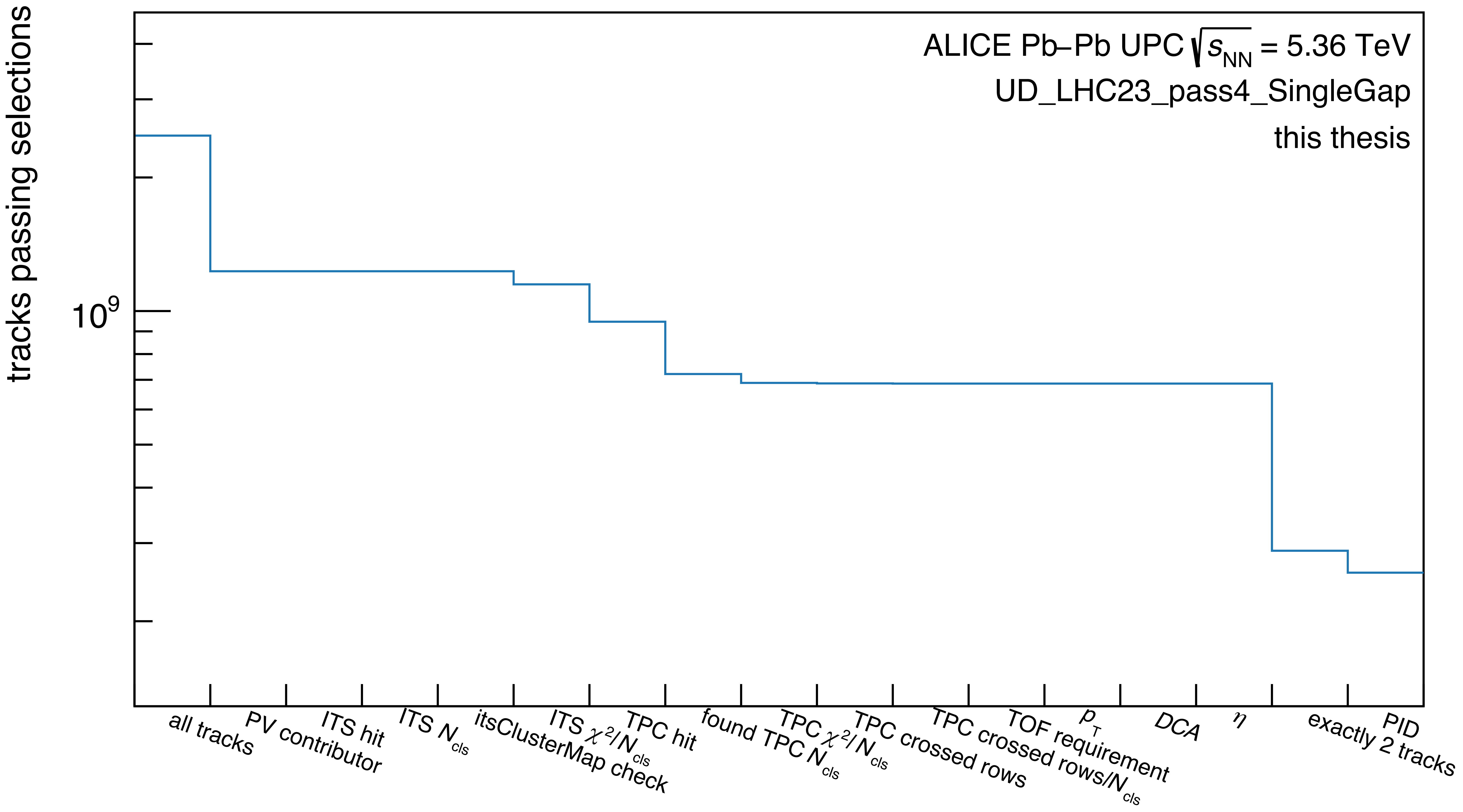
neutron class tagging





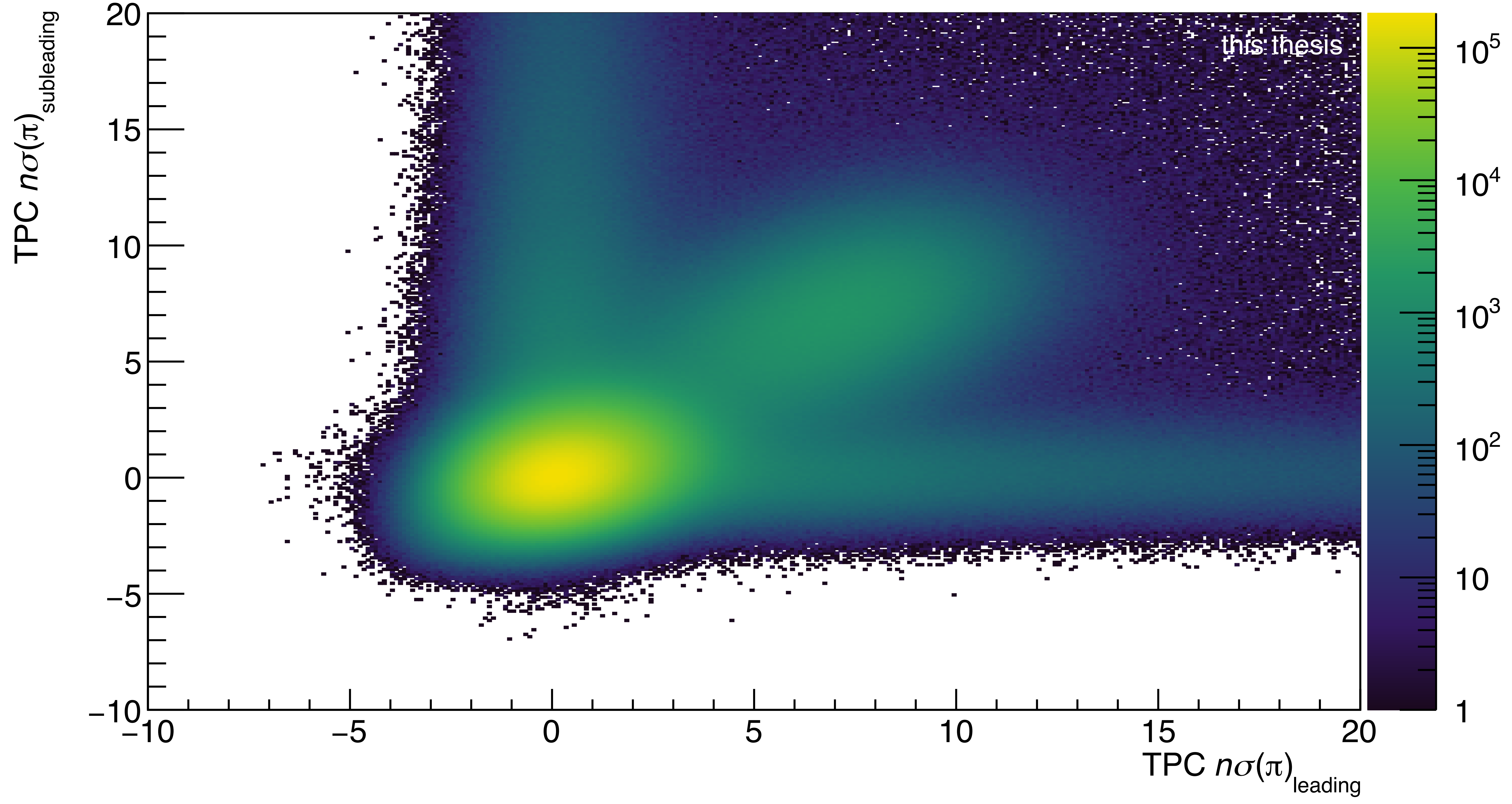
Utilised event selections

track level



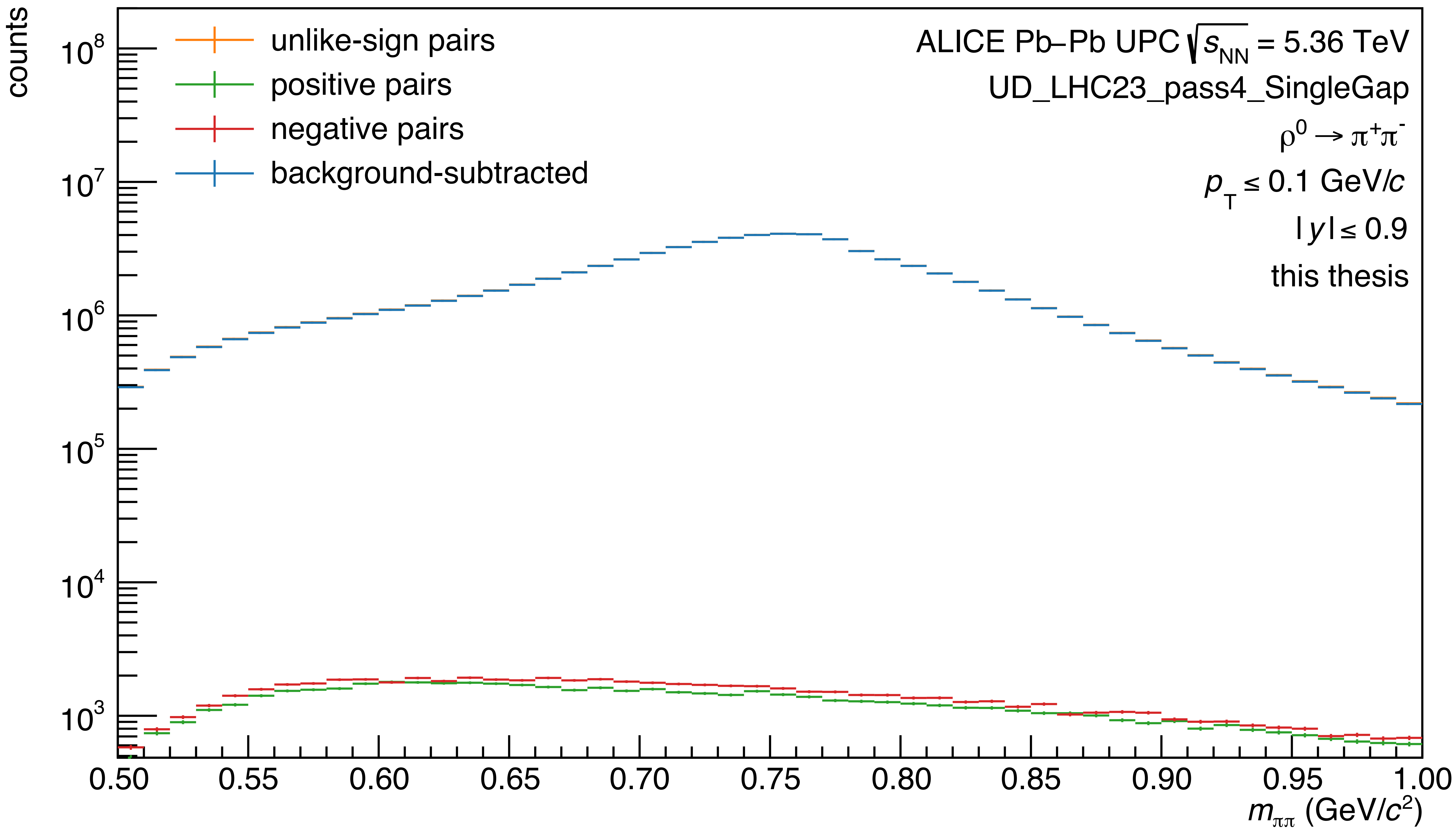
Utilised event selections

track level — PID



Corrections

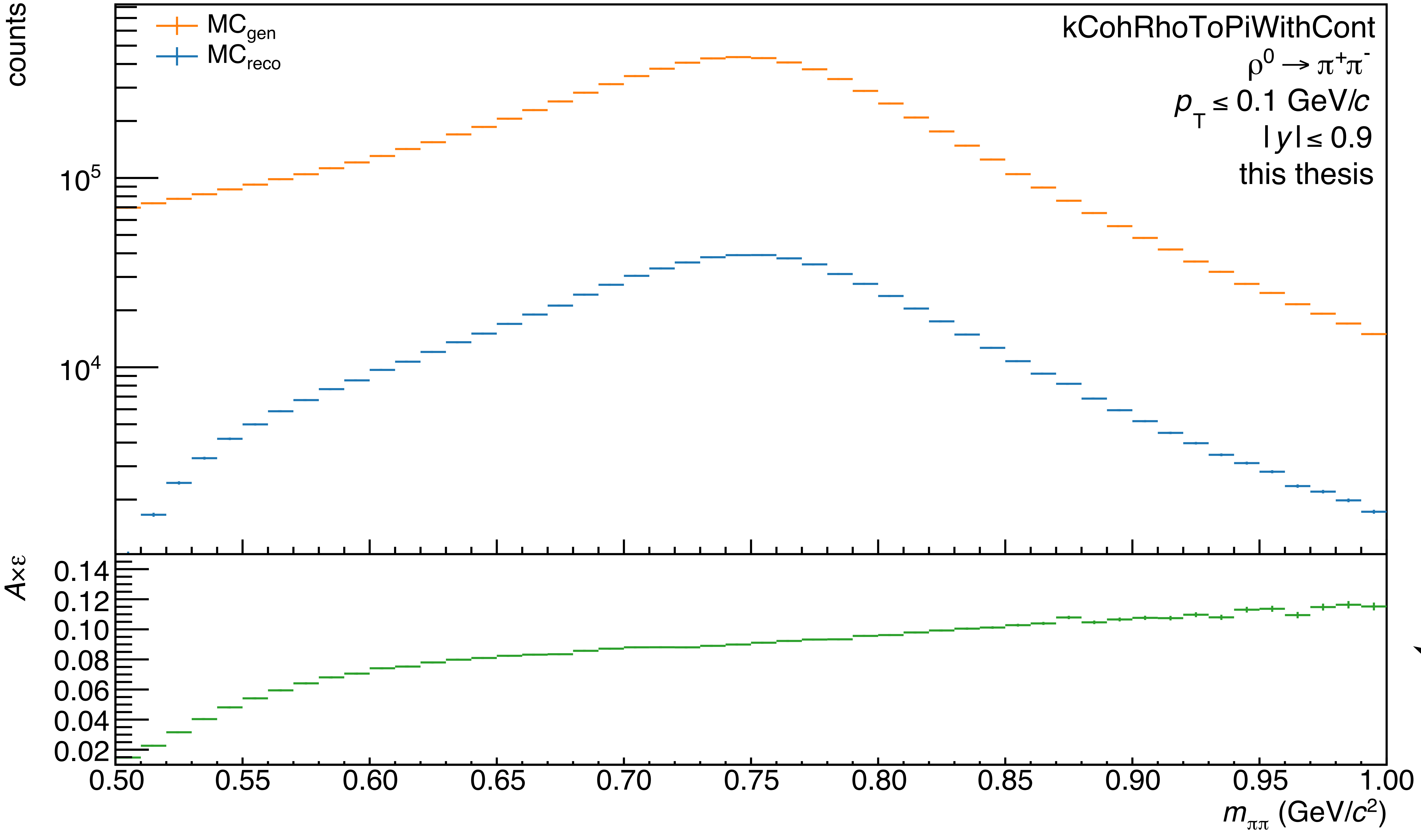
background subtraction



Corrections

$A \times \varepsilon$

example for the whole sample (integrated in $\Delta\phi$), $A \times \varepsilon$ very similar across all $\Delta\phi$ bins



mass fits performed in (0.60, 0.95) GeV/c^2