第20届全国中高能核物理大会

Observation of proton-antiproton pairs from QED vacuum excitation in Relativistic heavy-ion collisions

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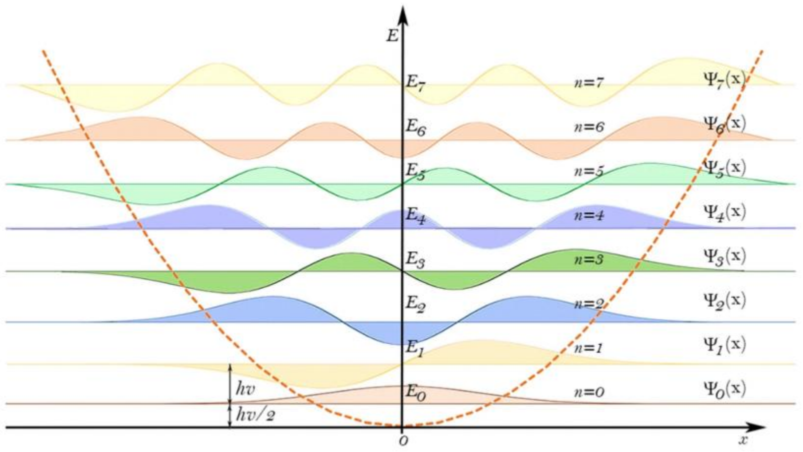
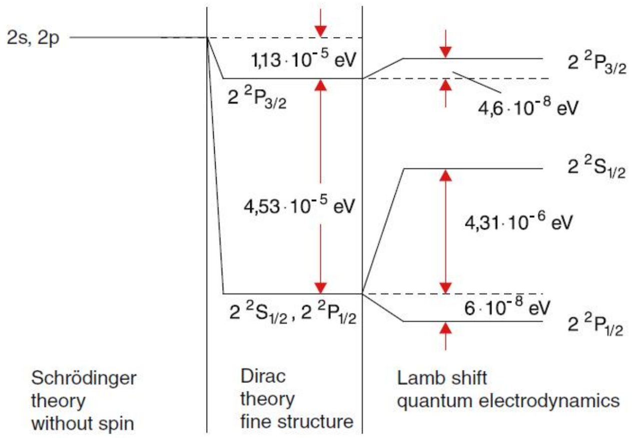
2025.4.26

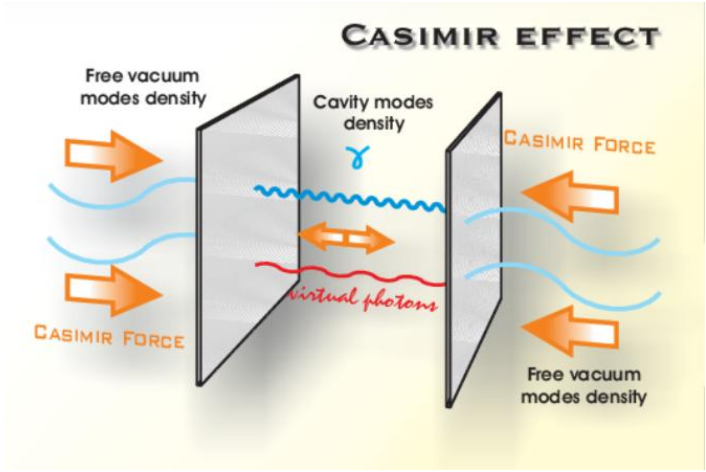
QED vacuum state



Zero point motion



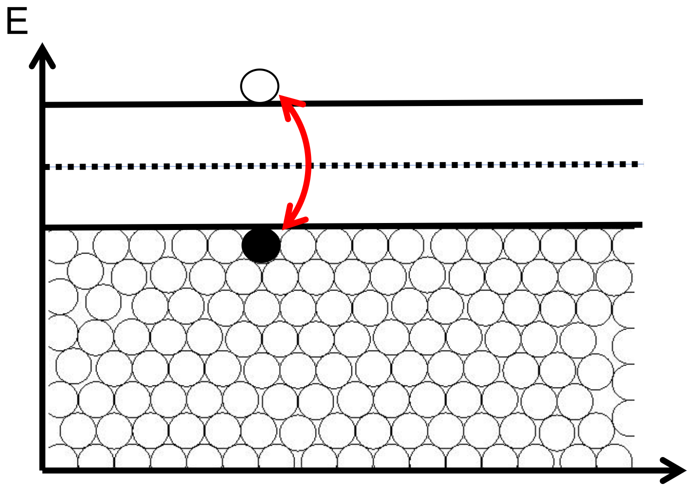
Lamb shift

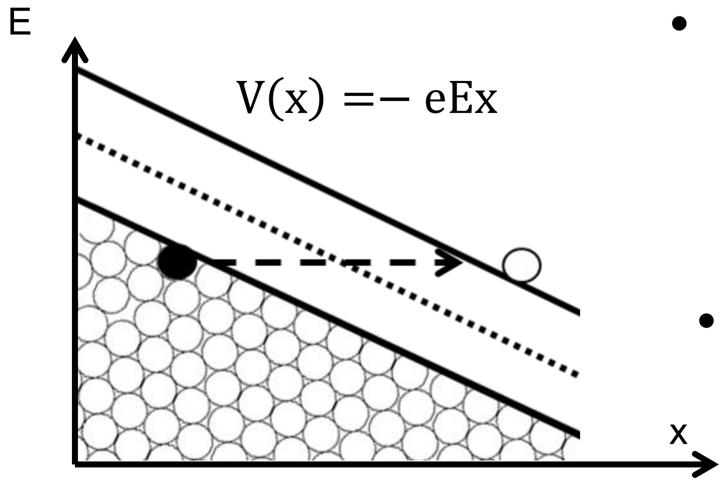


Casimir effect

- The ground state of quantum systems is characterized by zero-point motion.
- Related phenomenon have been observed: Lamb shift, Casimir effect, Electric field fluctuations in vacuum...
- Can we directly “see” the vacuum quantum fluctuation?

Schwinger effect



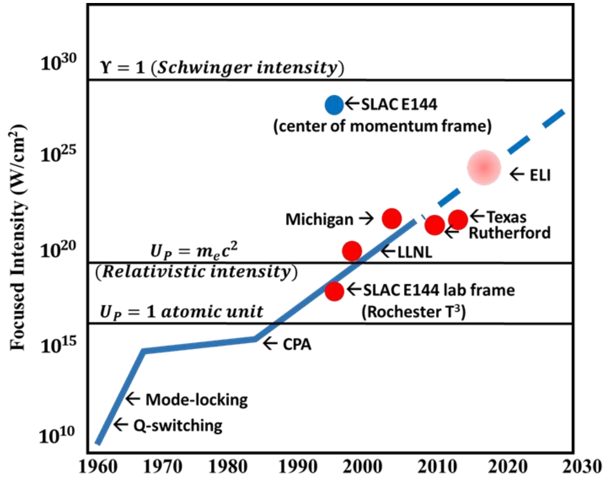


- The production rate of an e^+e^- pair in a static field:

$$\Gamma = \frac{(eE)^2}{4\pi^3\hbar^2 c}\Sigma_{n=1}^{\infty}\frac{1}{n^2}\exp\{-\frac{\pi m^2 c^3 n}{\hbar e E}\}$$

- If an extremely strong external field is applied, the vacuum could spark.

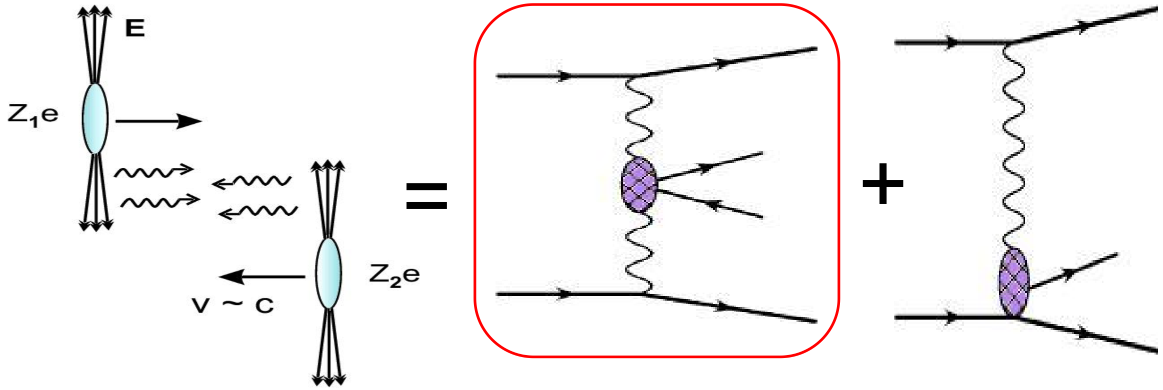
$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{16}\ \mathrm{V/cm}$$

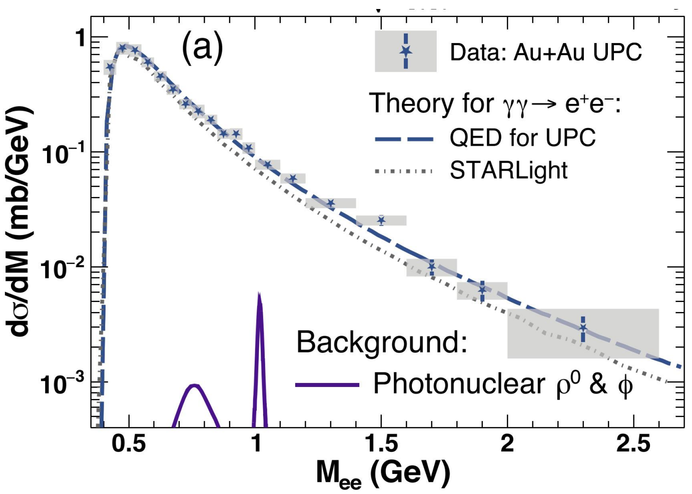


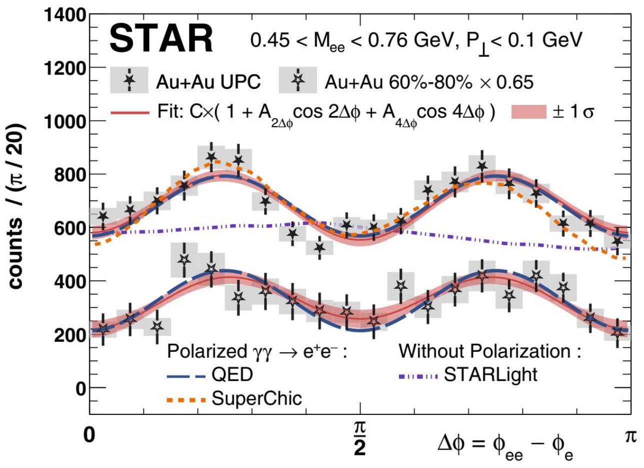
- The highest laser intensity currently can't achieve the Schwinger limit.

- Relativistic heavy-ion collisions provide ideal environment for studying the QED vacuum properties.

Observation of Breit- Wheeler process

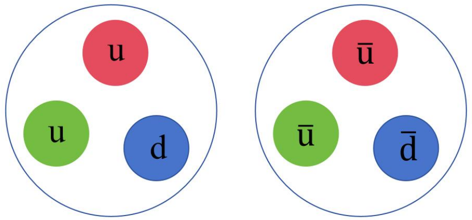




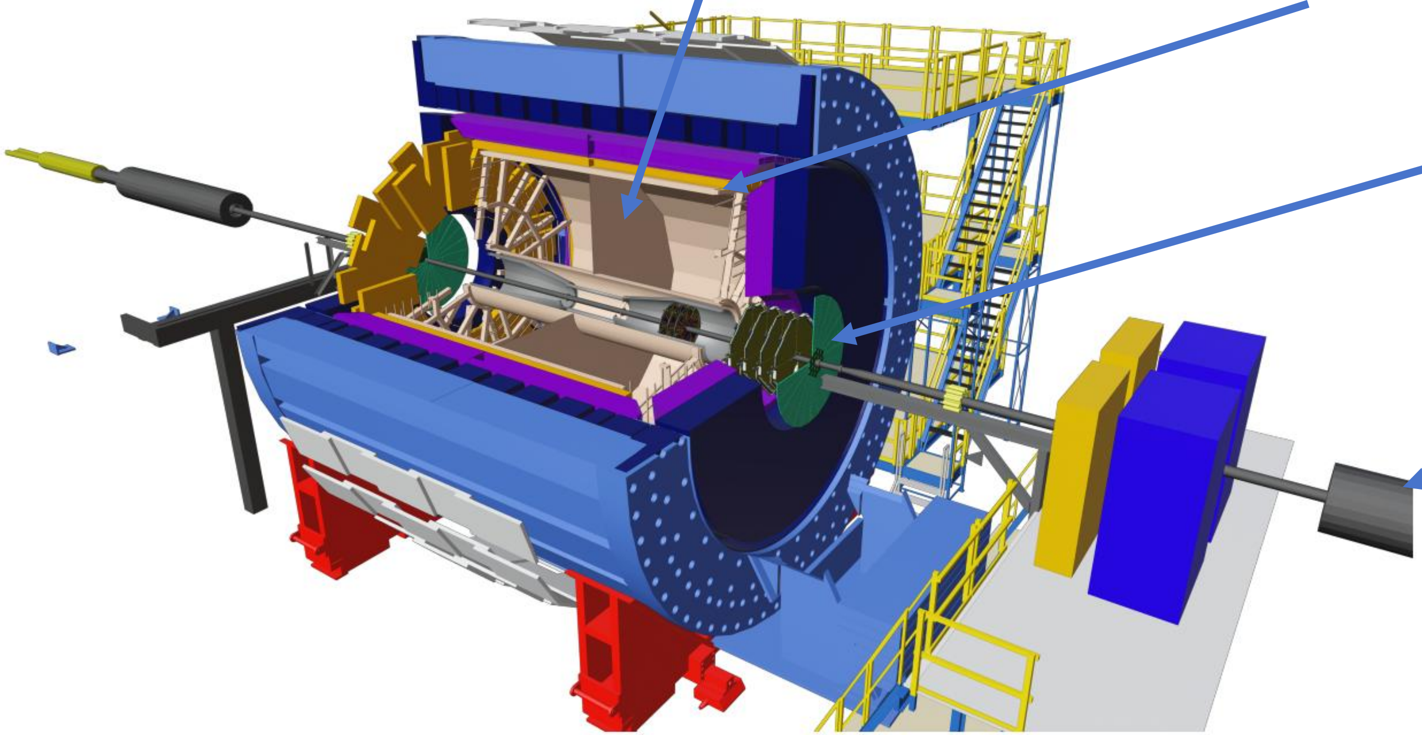


STAR, Phys. Rev. Lett. 127 (2021) 5, 052302

- The strongest electromagnetic field on Earth.
- QED vacuum excitation can be regarded as γγ interaction process.
- Motivation: More complex system, such as proton-antiproton pairs, can they be produced through QED vacuum excitation?

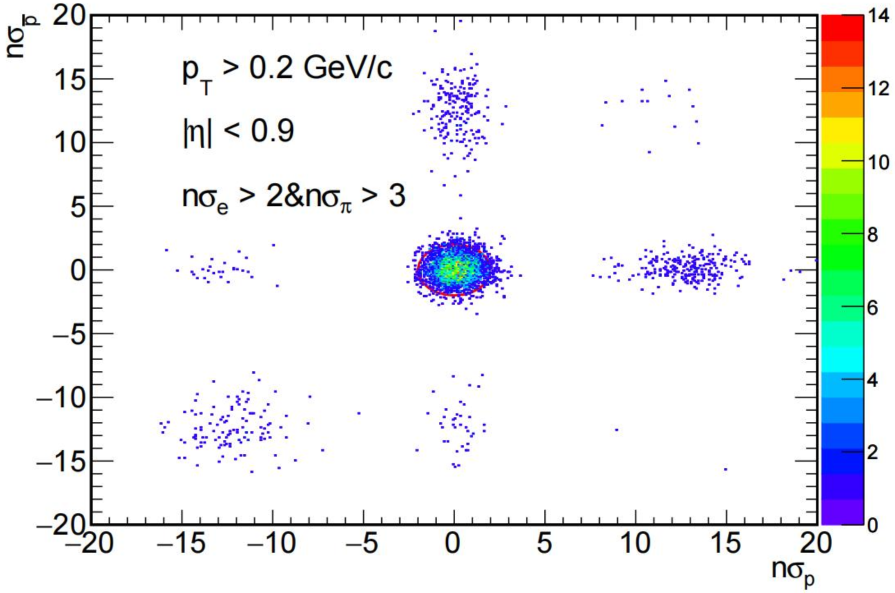


The Solenoidal Tracker At RHIC (STAR)



Dataset and selection criteria

- Dataset: Au+Au ultra-peripheral collisions (UPCs) at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV taken in 2010, 2011 and 2014



$$n\sigma_x = \frac{1}{\sigma}\log\frac{\langle \mathrm{dE/dx}\rangle^{Measured}}{\langle \mathrm{dE/dx}\rangle_x^{Theory}}$$

$$\chi^2_{p\bar{p}} = n\sigma_p{}^2 + n\sigma_{\bar{p}}{}^2 < 4$$

- BBC veto, TOFMulti, Coincidence between two ZDCs
- Events with only two charged tracks
- Protons and antiprotons identified by Time Projection Chamber

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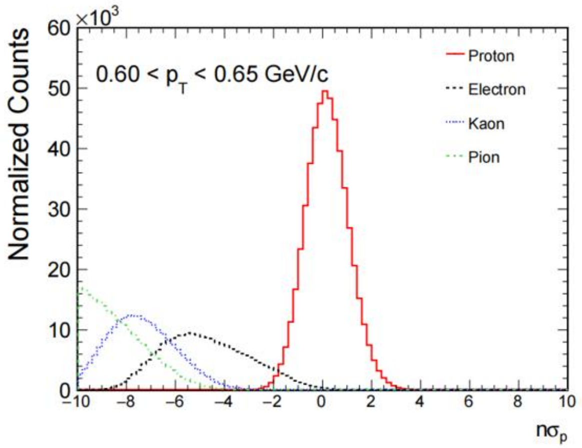

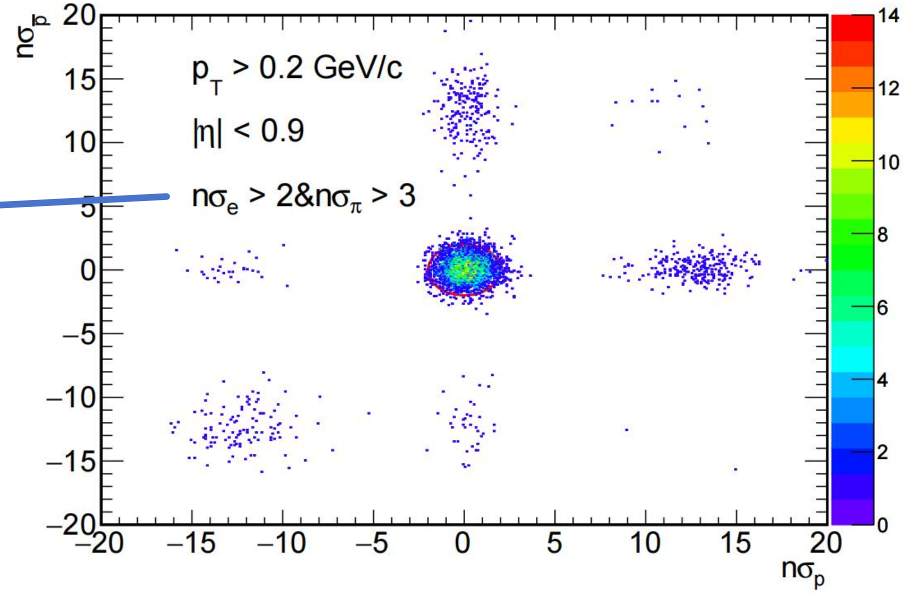

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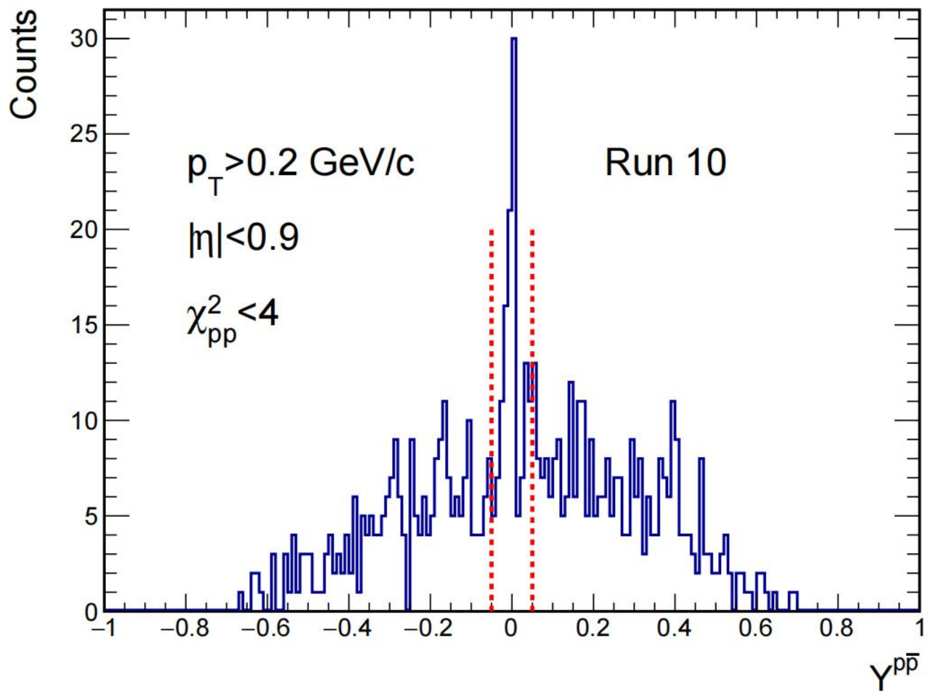
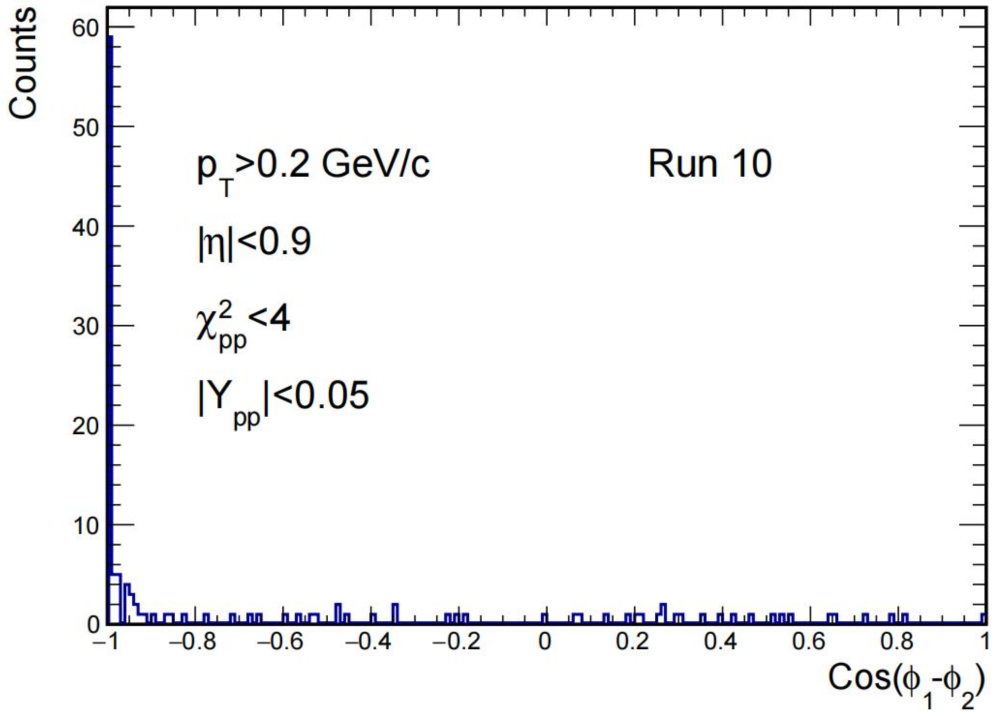
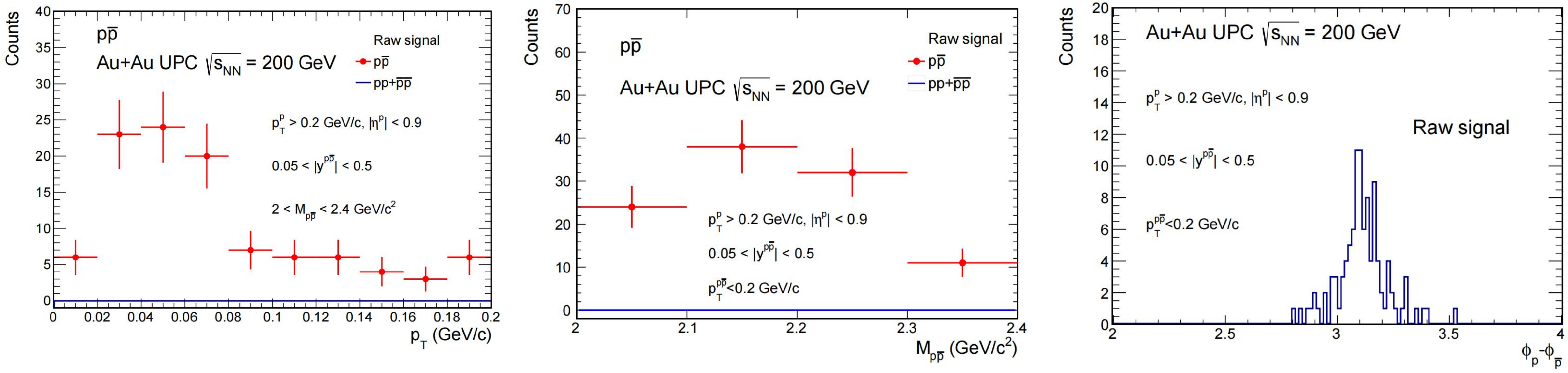
Cosmic ray background

- The cosmic ray located at mid rapidity. → $0.05 < |Y^{p\bar{p}}| < 0.5$





Raw signal



- $p\bar{p}$ pairs are predominantly located within $p_T < 0.1\ \mathrm{GeV}/c$ region.
- At the lowest mass bin, the raw counts are lower mainly due to the efficiency.
- The p and $\bar{p}$ are almost back-to-back.

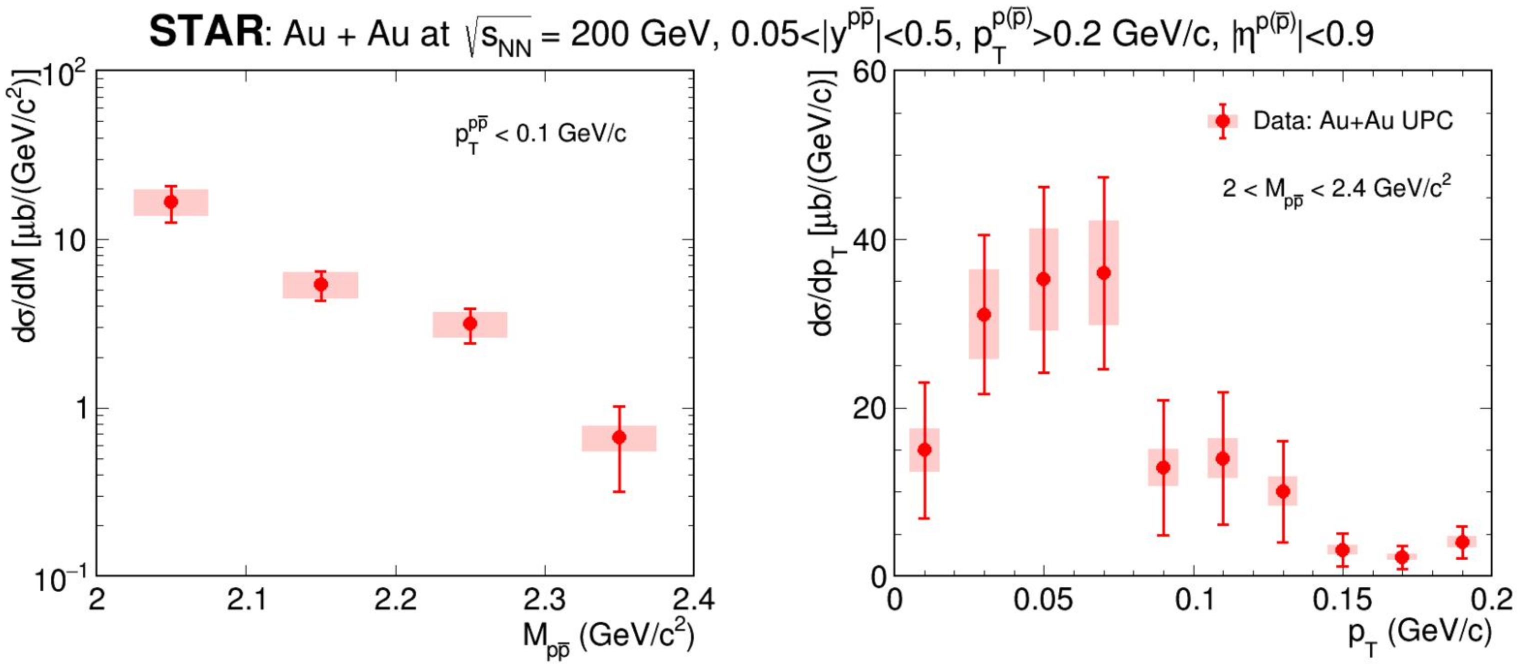
Cross section calculation

$$\frac{d\sigma}{dp_T} = \frac{N_{counts}(p_T)}{\Delta p_T \times Lumi \times f_{analy} \times \epsilon_{Trigger} \times \epsilon_{TPC} \times \epsilon_{TOF} \times \epsilon_{PID} \times \epsilon_{V_Z}^{TPC}}$$

$$\frac{d\sigma}{dM_{p\bar{p}}} = \frac{N_{counts}(M_{p\bar{p}})}{\Delta M_{p\bar{p}} \times Lumi \times f_{analy} \times \epsilon_{Trigger} \times \epsilon_{TPC} \times \epsilon_{TOF} \times \epsilon_{PID} \times \epsilon_{V_Z}^{TPC}}$$

- The luminosity and the analyzed ratio is from the official webpage.
- The efficiency was determined through a data-driven approach.

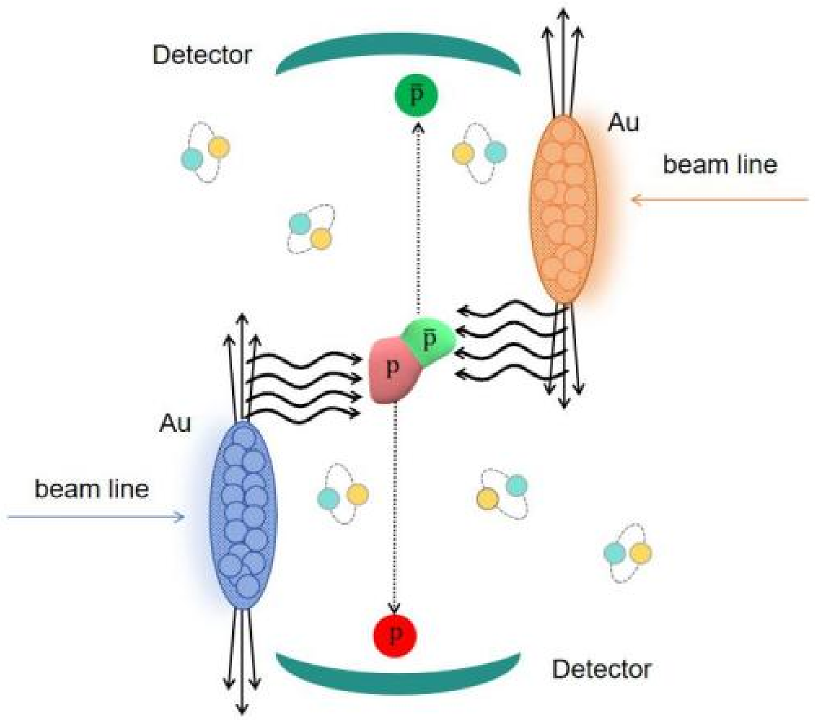
The combined cross section



- $\sigma = 2.6 \pm 0.4(stat) \pm 0.5(sys)\ \mu\text{b}$
- The invariant mass spectrum is continuous and the pairs are mainly located at very low p_T.
- The first time measurement of the $p\bar{p}$ pairs produced in UPCs.

Low-p_T $p\bar{p}$ Production Mechanism

- Vacuum Excitation



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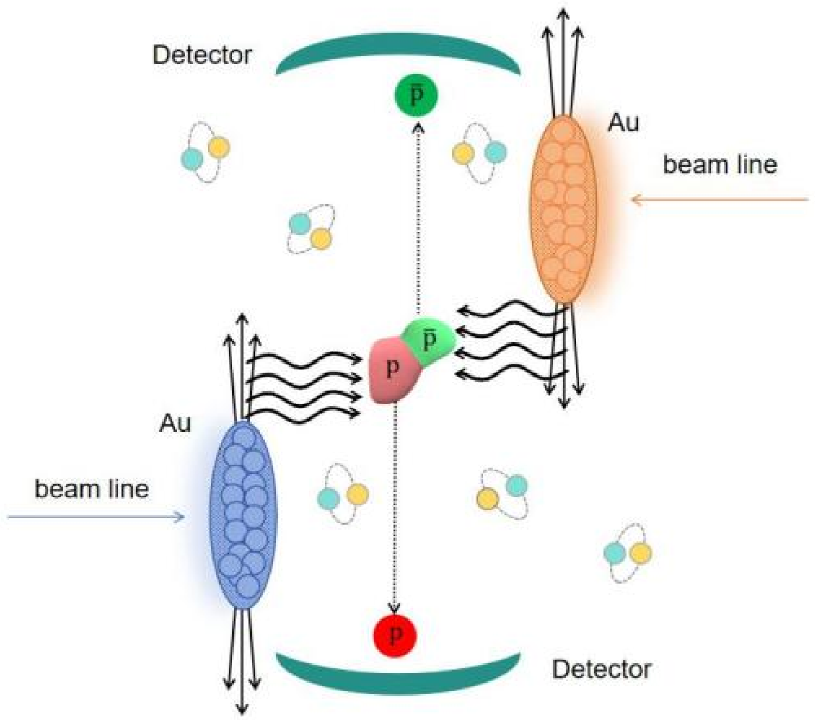
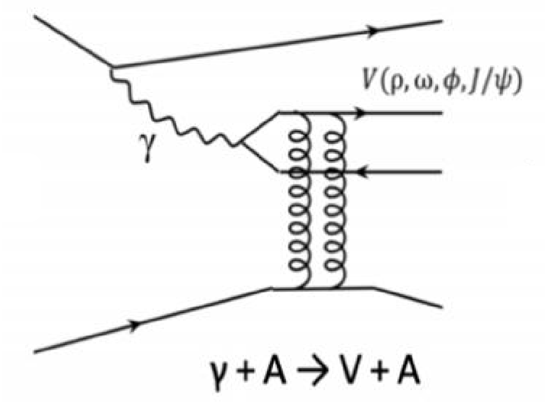
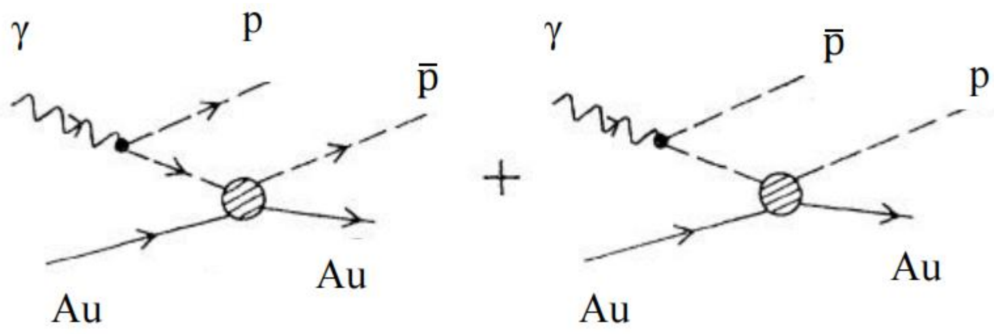


- Background: γA interaction



S. Klein, ARNPS55 (2005) 271

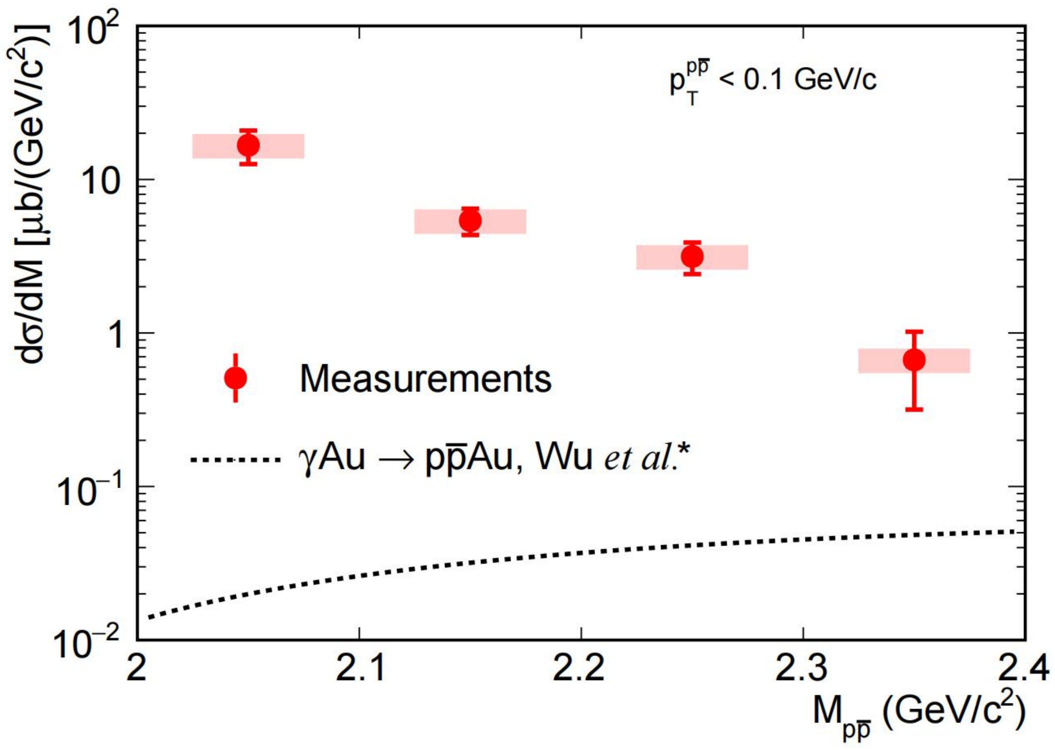
Vector mesons: J/Ψ...



P. Sodding, PLB19 (1966) 702

Drell-Södding Process

Comparision with model calculation

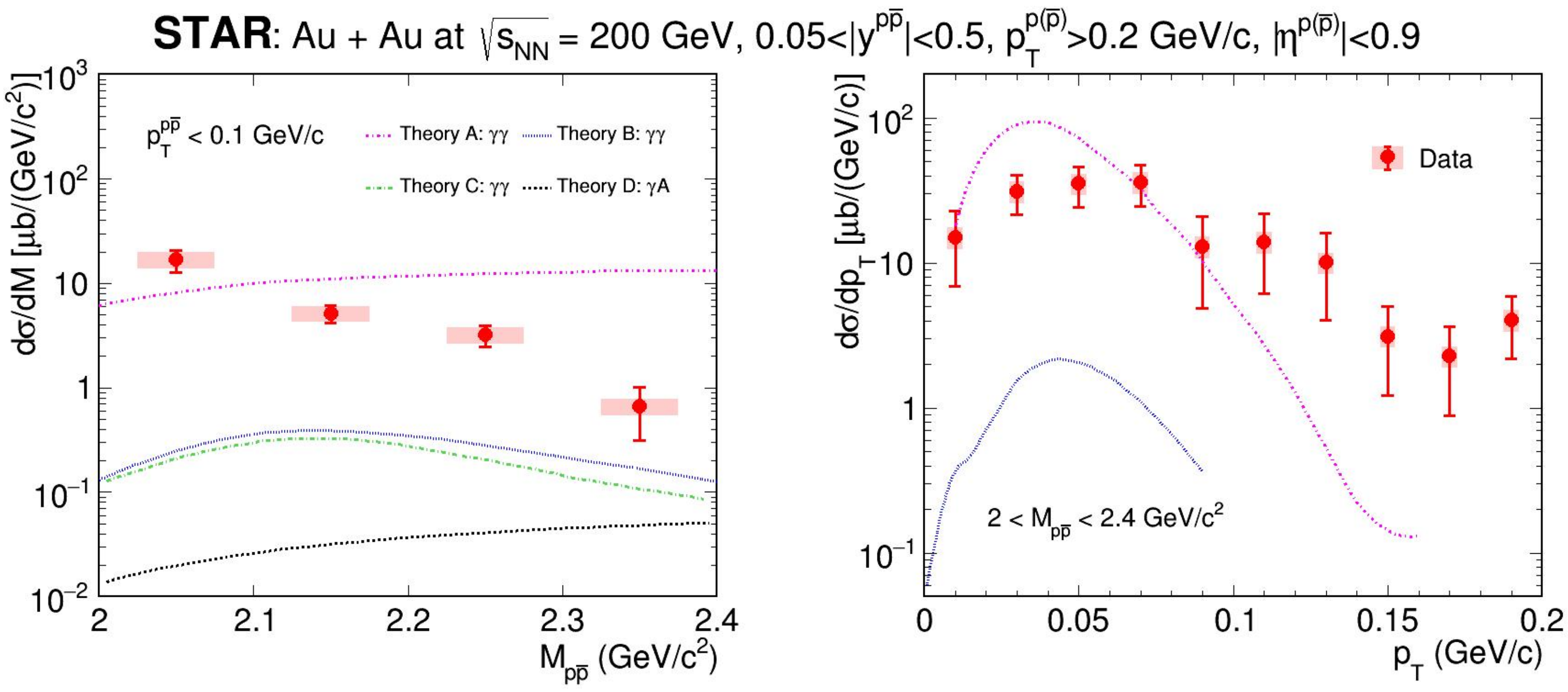


- Drell-Soding process significantly lower than the measurement

Comparision with model calculation

Theory A: Pu et al.*, arXiv:2407.06091

Theory B: Shao et al.*, arXiv:2406.05618



- Provide deeper insight into QED processes in extreme electromagnetic environments and non-perturbative QCD processes.

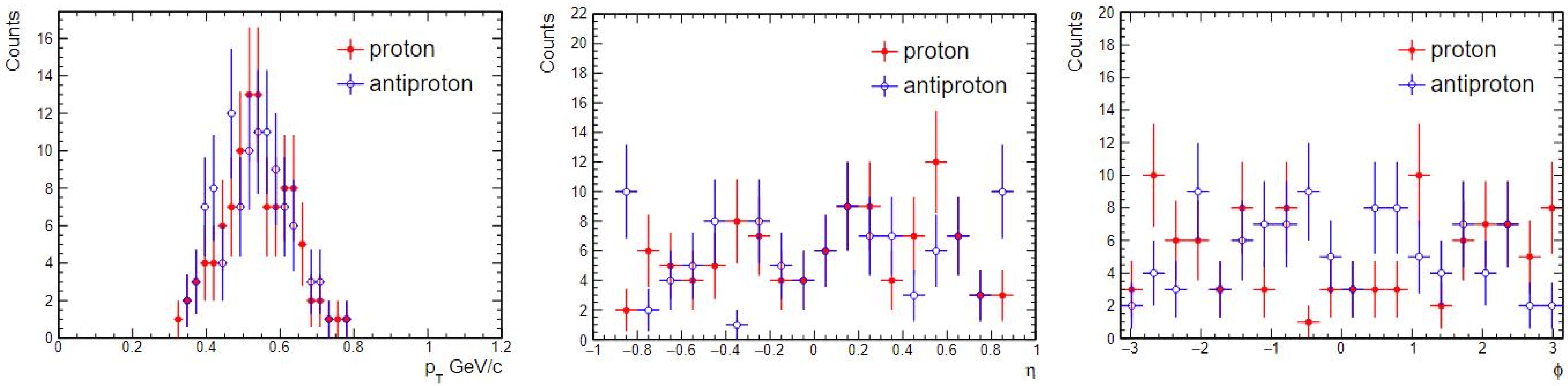
Summary

- The mass spectrum is continuous within the range of 2 GeV/c^2 to 2.4 GeV/ c^2, while the p_T distribution is concentrated below 0.1 GeV/c .
- The contribution from photonuclear interactions is negligible, strongly suggesting these proton-antiproton pairs arise from $\gamma\gamma$ interaction process.
- Provide deeper insight into QED processes in extreme electromagnetic environments and non-perturbative QCD processes.

Thank you !

Back up

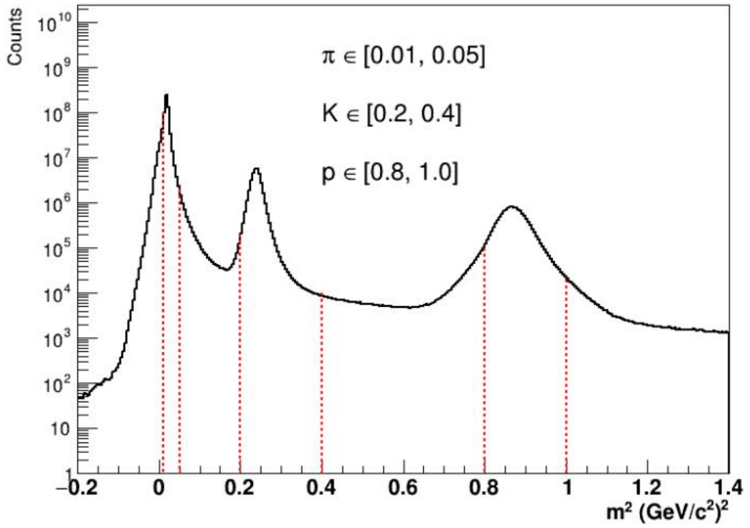
Raw signal

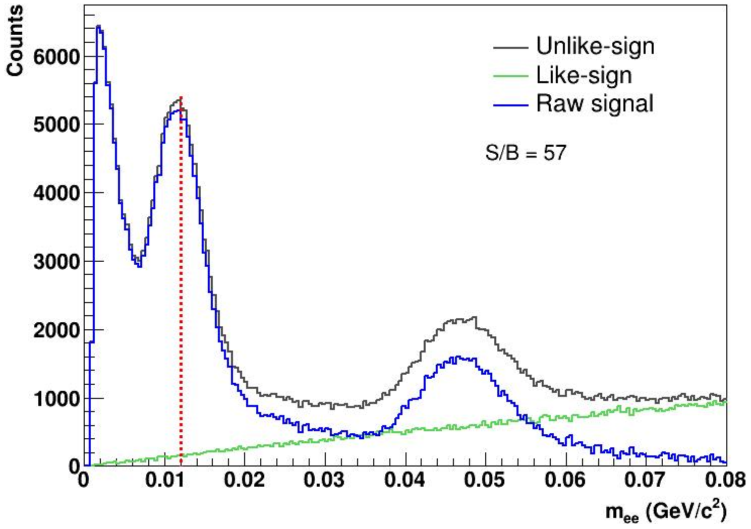


- No significant difference appeared between proton and antiproton.
- The p_T shape is used to assess the quality of the dynamics in embedding.

Pure sample extraction

- A substantial pure p, π, K, and e sample is needed (purity, efficiency).
- Pure sample is taken from Au+Au collisions with minimum-bias trigger.
- For purity test, the p, π, and K sample is selected using the mass information from TOF.
- The electron sample is selected from photon conversion.

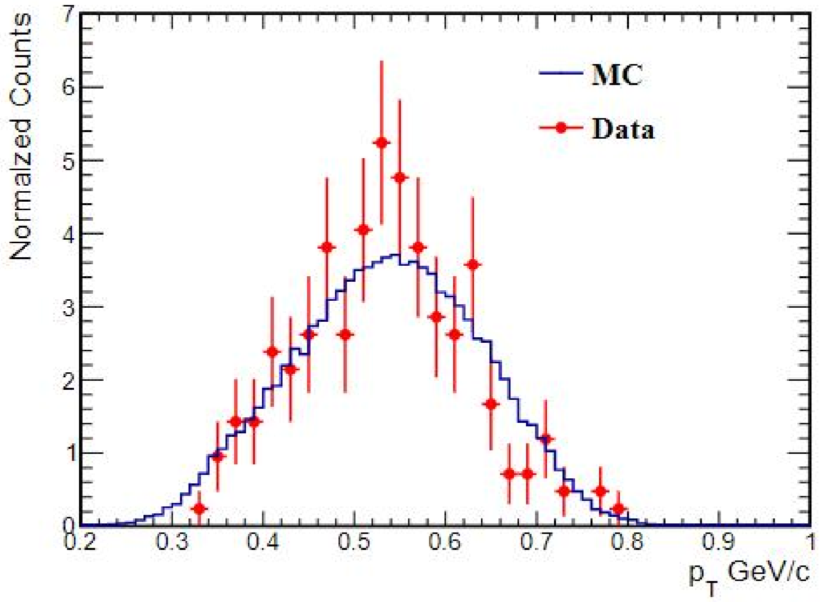




Purity estimation

- Generate a Monte Carlo sample with a flat distribution in proton-antiproton pair transverse momentum, mass, and rapidity. Use the two-body decay kinematics to generate the polar angle distribtuion of the single particles.

$$G(M_{p\bar{p}}, \theta_p) = 2 + 4\left(1 - \frac{m_p^2}{M_{p\bar{p}}^2}\right)\frac{1 - 4m_p^2/M_{p\bar{p}}^2 \sin^2\theta_p \cos^2\theta_p + 4m_p^2/M_{p\bar{p}}^2}{\left[1 - \left(1 - m_p^2/4M_{p\bar{p}}^2\right)\cos^2\theta_p\right]^2}$$



MC can discribe data very well.

Purity estimation

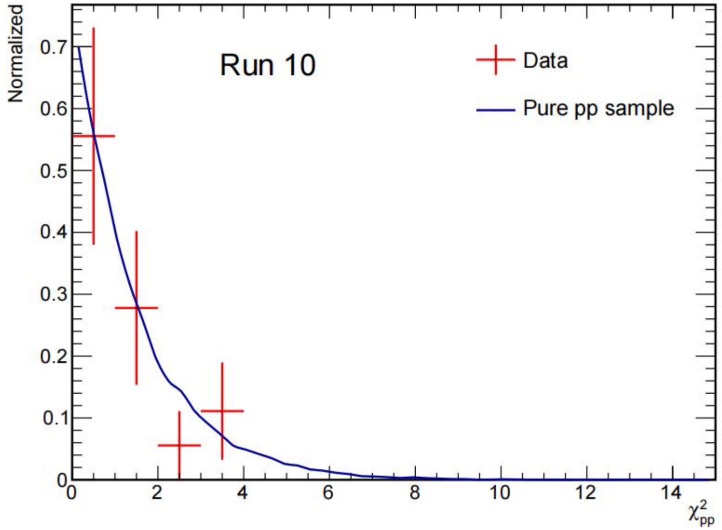
- The pure sample was used to estimate the purity of $p\bar{p}$ pairs.

- The purity of the proton is extracted as:

  ✓ Sampling the pair p_T, rapidity and invariant mass from the UPC-data

$$G(M_{p\bar{p}}, \theta_p) = 2 + 4\left(1 - \frac{m_p^2}{M_{p\bar{p}}^2}\right)\frac{1 - 4m_p^2/M_{p\bar{p}}^2 \sin^2\theta_p \cos^2\theta_p + 4m_p^2/M_{p\bar{p}}^2}{\left[1 - \left(1 - m_p^2/4M_{p\bar{p}}^2\right)\cos^2\theta_p\right]^2}$$

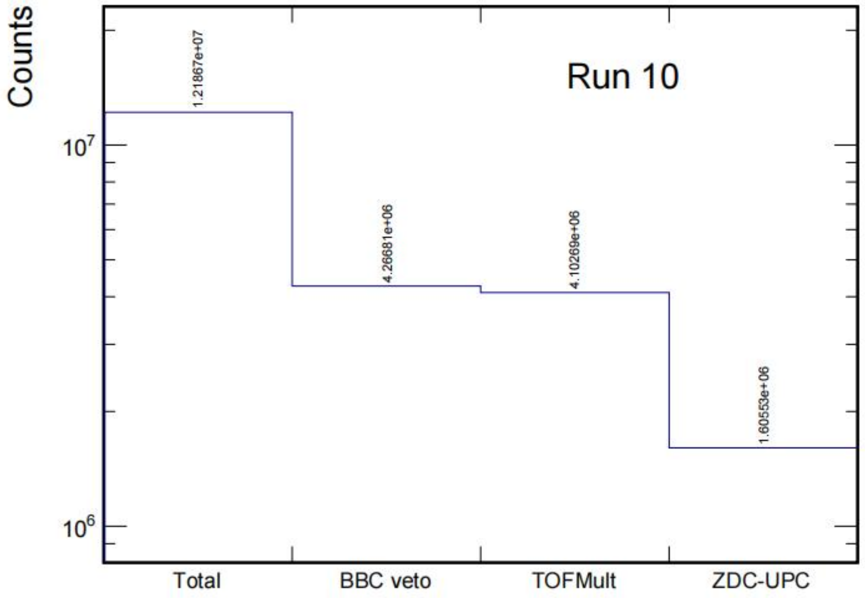
  ✓ Sampling the $n\sigma_p$, $n\sigma_e$ and $n\sigma_\pi$ with the given momentum to produce the MC pair, then calculate the $\chi^2_{p\bar{p}}$ of this pair.



Trigger efficiency correction - ZDC coincidence

- Use the ZDC-mon trigger (ZDC-ADC > 50) to calculate the ZDC-ADC upper cut efficiency.
- To estimate the correction factor, the remaining UPC-main trigger conditions need to be taken into account.

$$\epsilon_{ZDC-ADC_{upper}} = N_{Events}^{East<1200\&West<1200}/N_{Events}$$

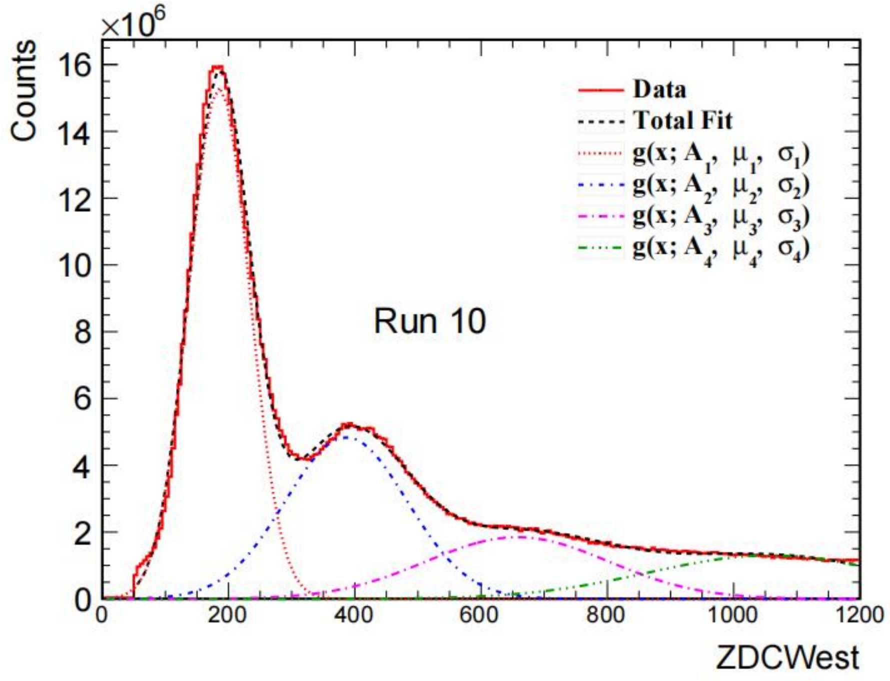


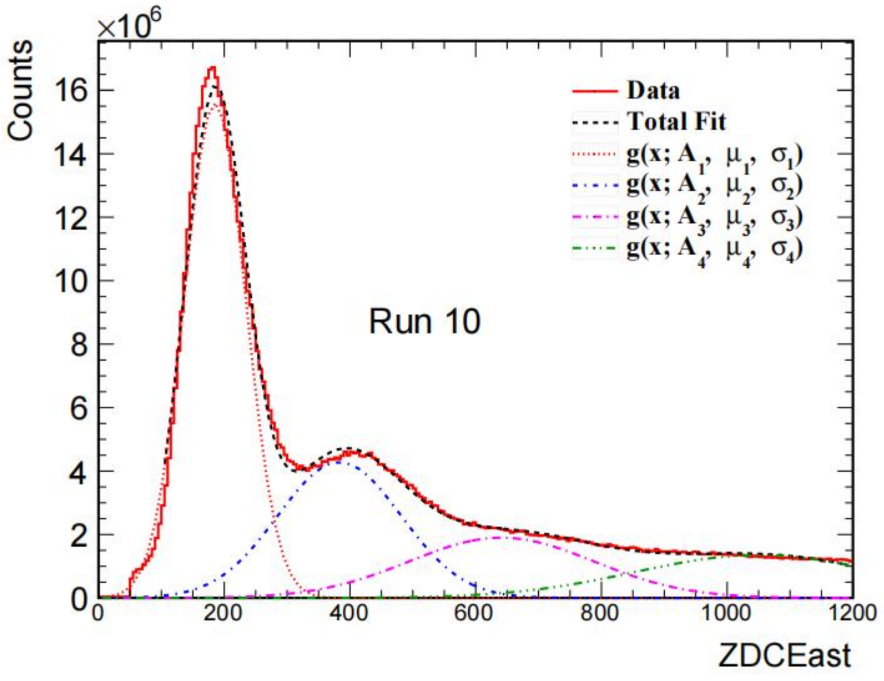
	Run10	Run11	Run14
$\epsilon_{ZDC-ADC_{upper}}$	39%	37%	57%

Trigger efficiency correction - ZDC coincidence

- The efficiency for ZDC-ADC less than 50 is extracted from the multi-Gaussian fit.

$$f(x) = g(x; A_1, \mu_1, \sigma_1) + g(x; A_2, \mu_2, \sigma_2) + g(x; A_3, \mu_3, \sigma_3) + g(x; A_4, \mu_4, \sigma_4) \qquad g(x; A, \mu, \sigma) = \frac{A}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$$



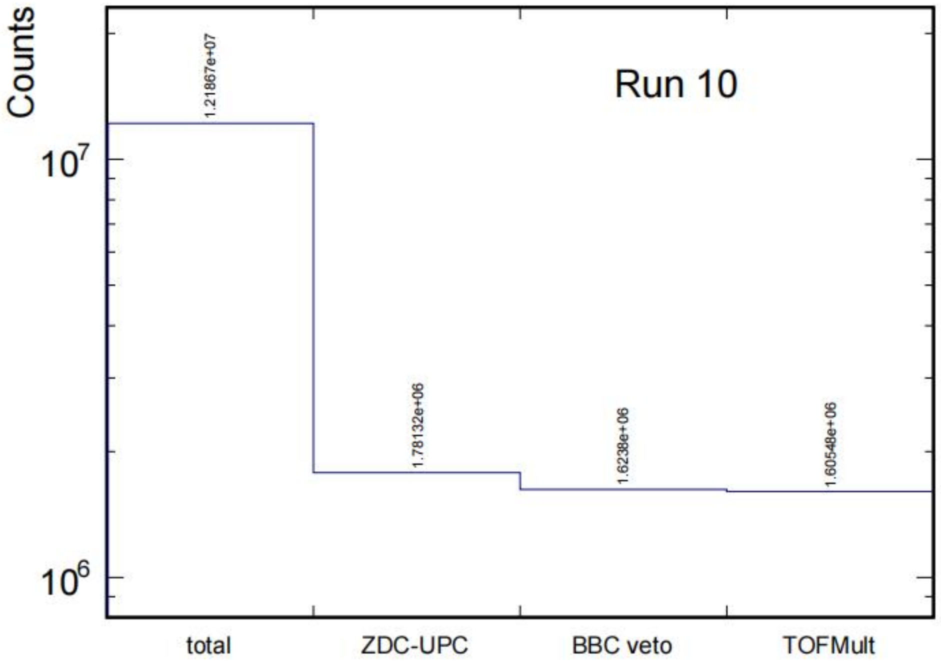


$$\epsilon_{ZDC-ADC_{lower}} < 1\%$$

Trigger efficiency correction –BBC veto and TOFMult

- 2 signal TOF trigger hits. → Inefficient if signal+background > 6 TOF trigger hits.
- The efficiency is calculated as:

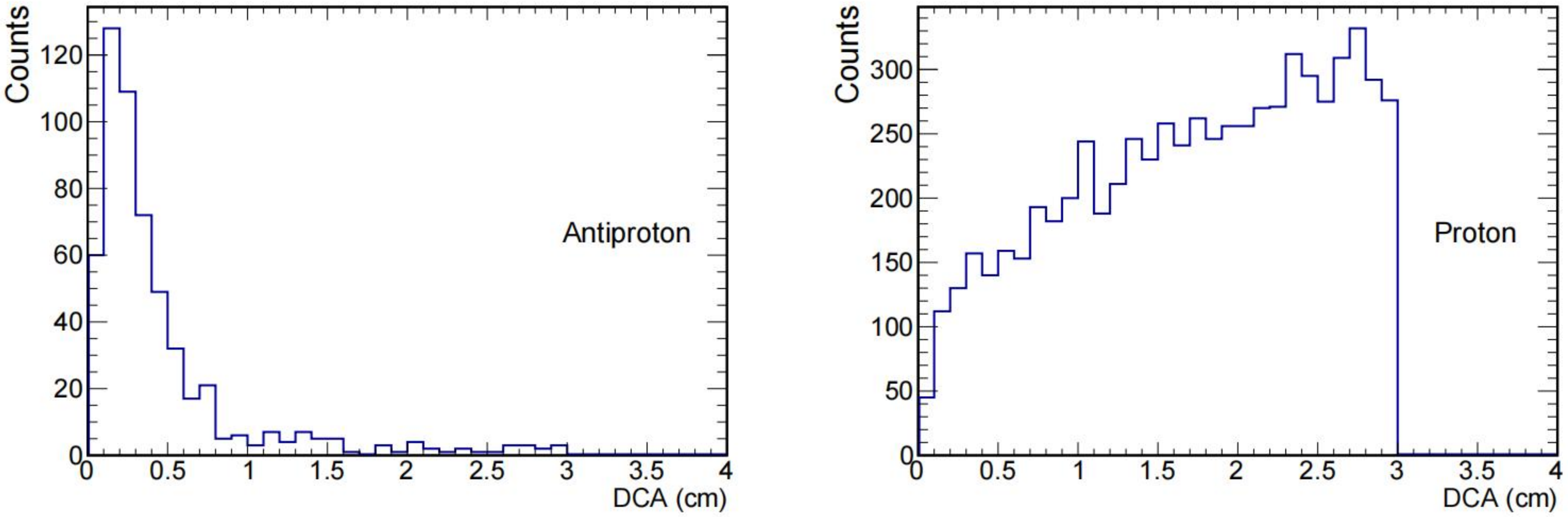
$$\epsilon_{BBCveto\&TOFMult} = N_{Events}^{BBCveto\&TOFMult\leq 4}/N_{Events}$$



	Run10	Run11	Run14
$\epsilon_{BBCveto\&TOFMult}$	90	91%	79%

Knock-out proton background

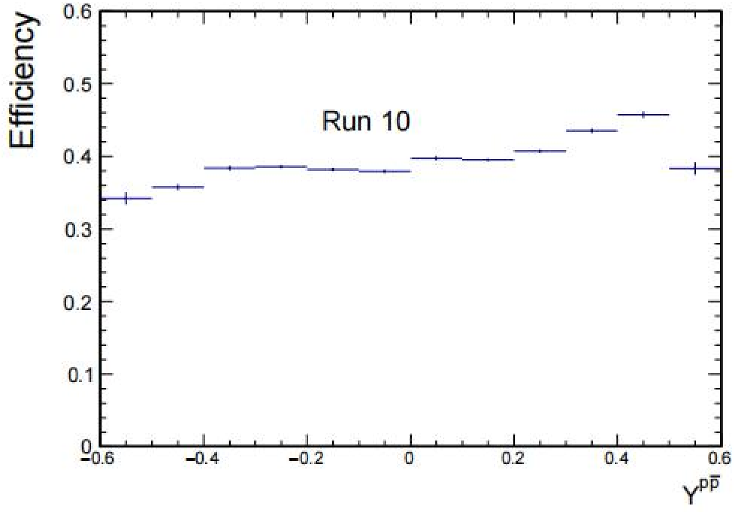
- Beam pipe could knock the proton out from the materials.

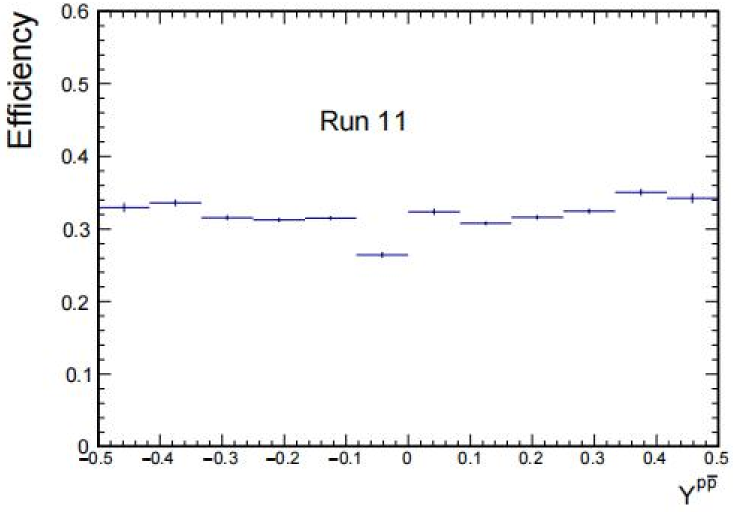


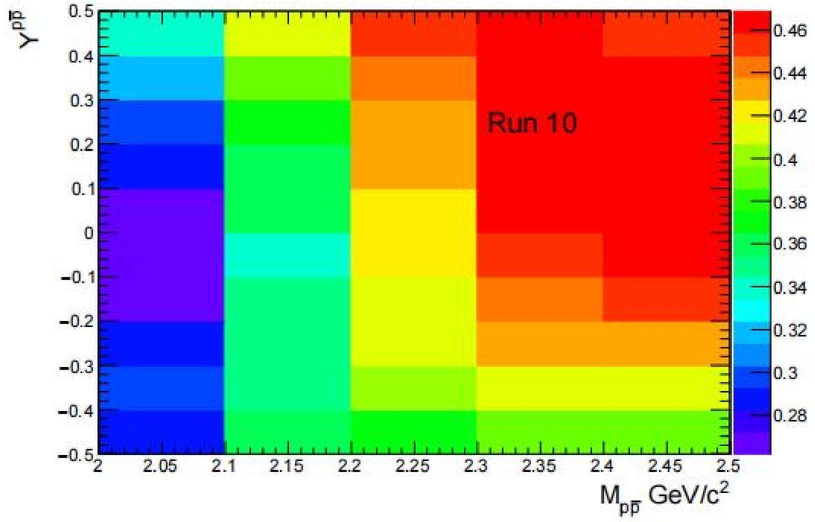
TPC efficiency extraction

- The TPC efficiency is calculated as:

$$\epsilon_{TPC} = N_{RC}^{with\ measured\ acceptance} / N_{MC}^{with\ measured\ acceptance}$$





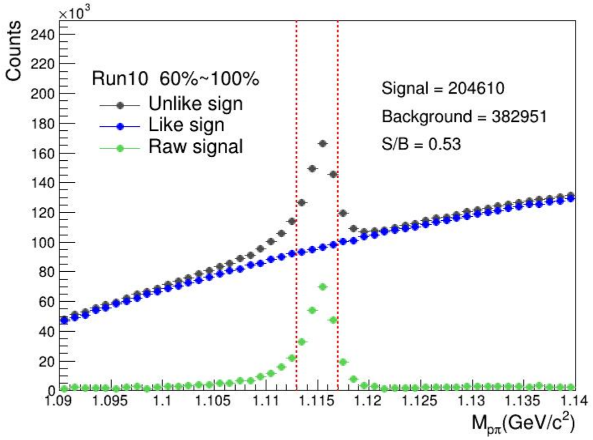


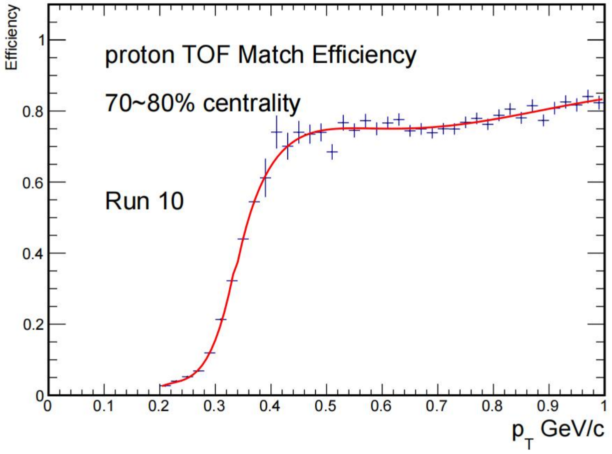
- For run10, a sector on the left side was malfunctioning.

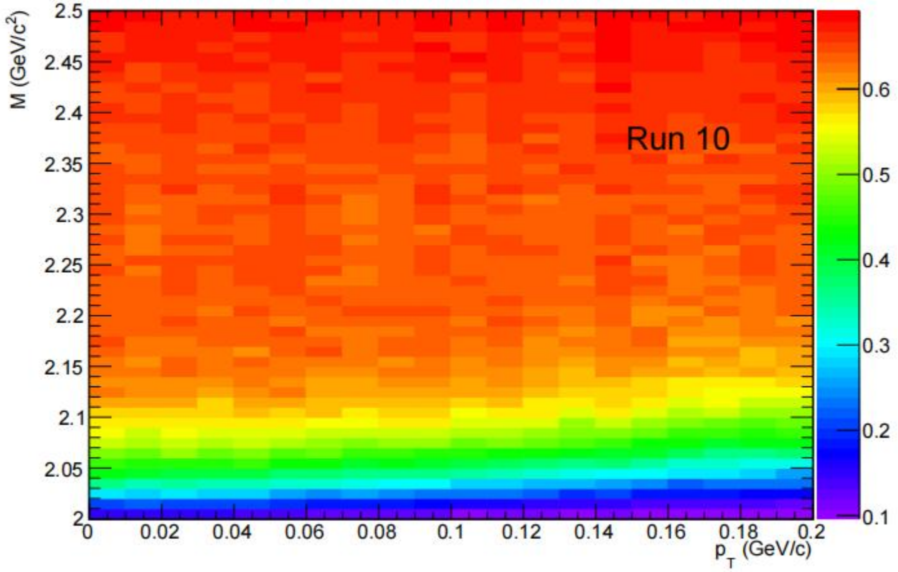
- For midrapidity, the TPC has the membrane structure.

TOF matching efficiency

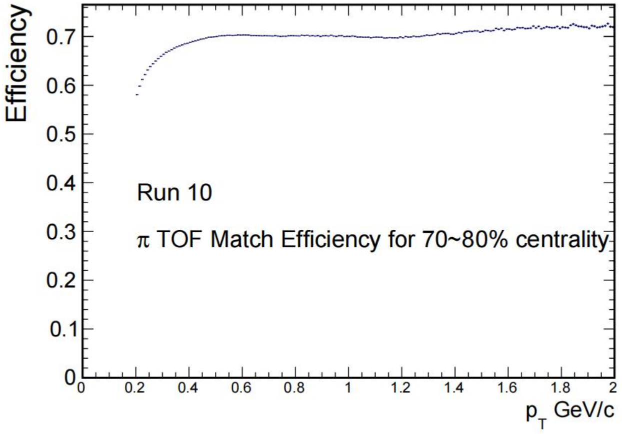
- The pure proton sample for TOF matching efficiency is obtained from Λ decay.

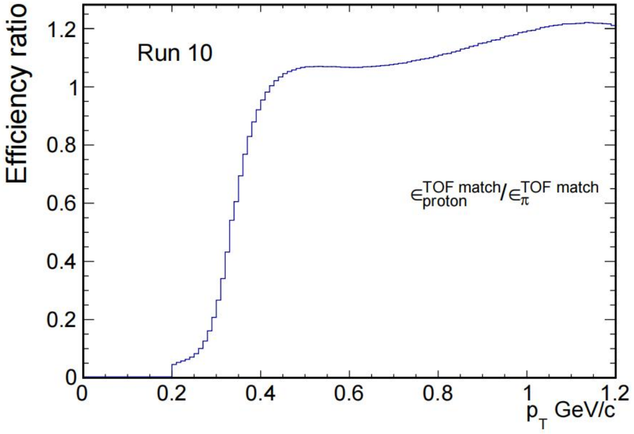






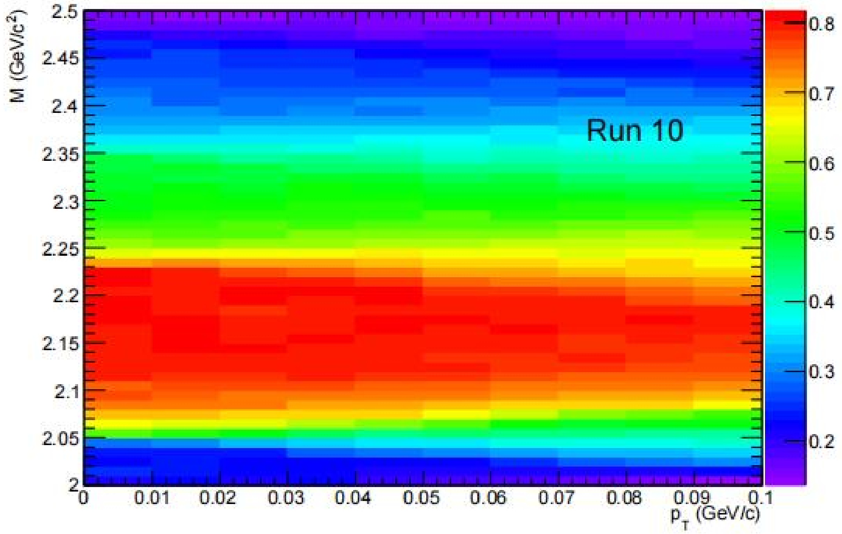
2D TOF matching efficiency





PID efficiency

- For a $p\bar{p}$ pair with determined dynamic quantities, generate the single $p/\bar{p}$ angle distribution in $p\bar{p}$ rest frame.
- In the $p_T - n\sigma_p - n\sigma_e - n\sigma_\pi$ 4D distribution, fix the p_T and sample the $n\sigma_p$, $n\sigma_e$ and $n\sigma_\pi$ simultaneously for both proton and antiproton.
- Calculate the PID efficiency: $\epsilon_{PID} = N_{events}^{passPIDcut} / N_{events}^{total}$.

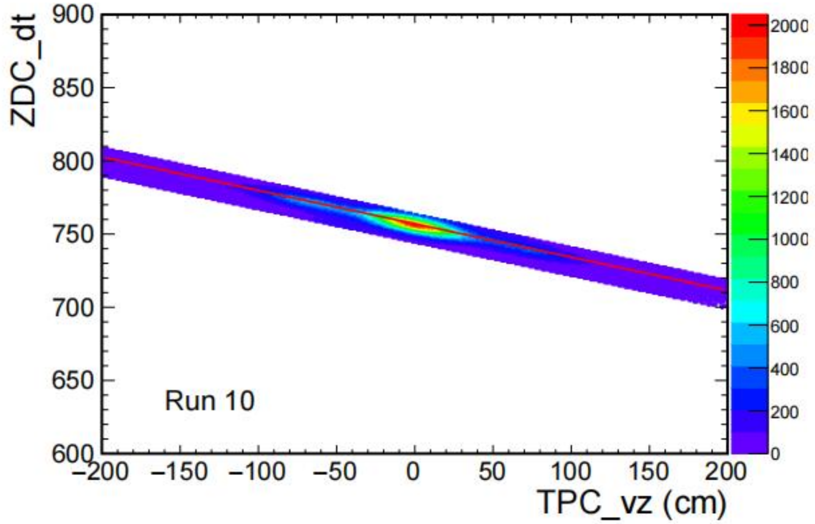


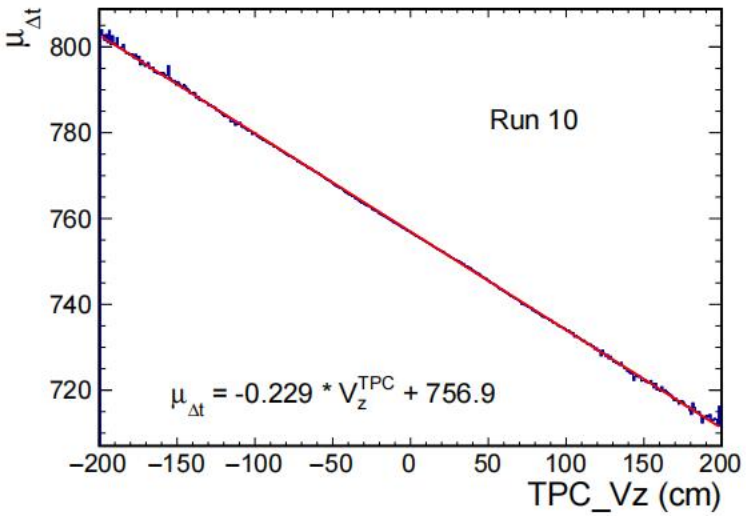
- Low mass: rising due to the acceptance.
- High mass: higher single track p_T degrade the TPC's resolution.

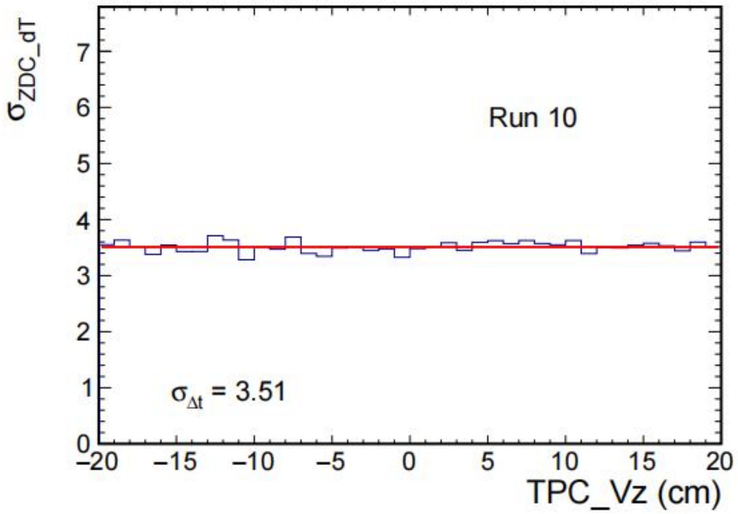
Relationship extraction

- To minimize the influence of background, the band cut was required.
- For each V_z^{TPC}, a Gassuian function was used to fit the ZDC_{dt} to extract the mean ZDC_{dt} and its variance.

$$\mu_{ZDC_{dt}} = a * V_z^{TPC} + b$$

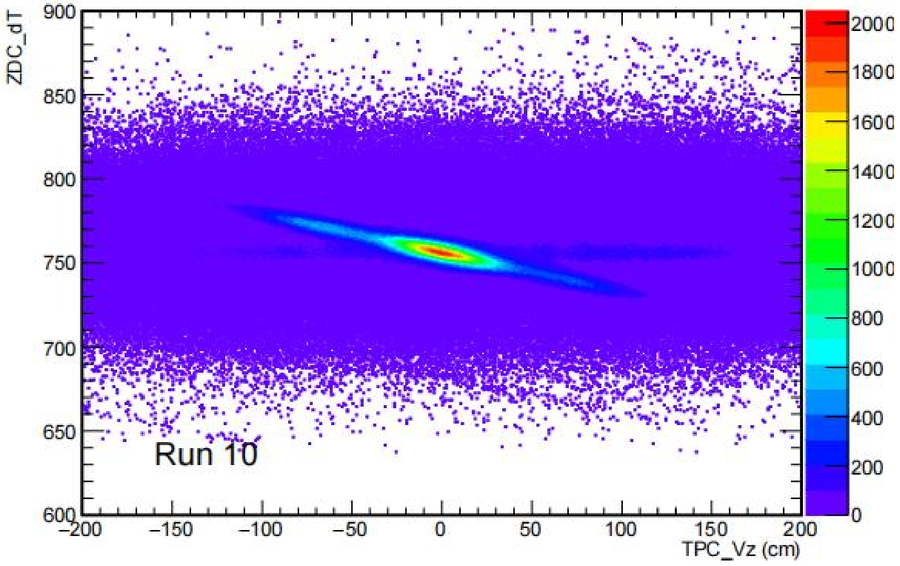


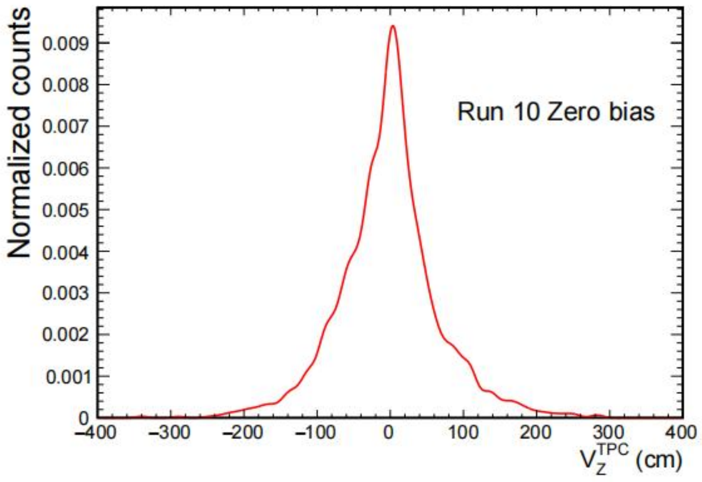


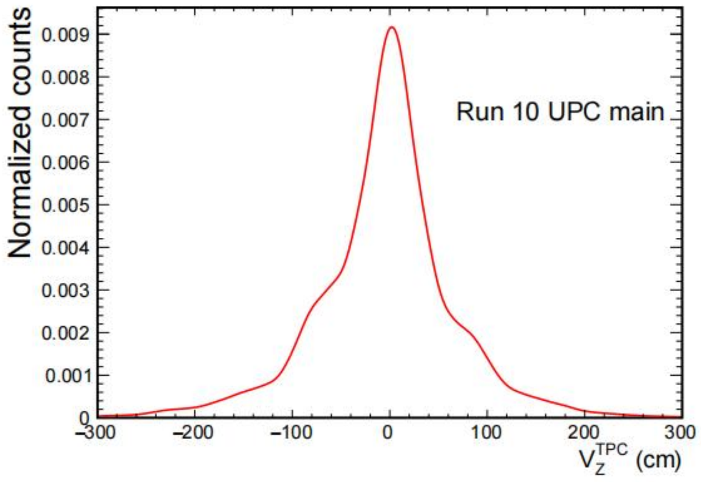


V_z cut efficiency

- The full length in z is beyond the acceptance of the central STAR detector.
- Pile-up events will cause the V_z^{TPC} to be inaccurate in high luminosity situations.
- Using ZDC information to reproduce the full z shape.

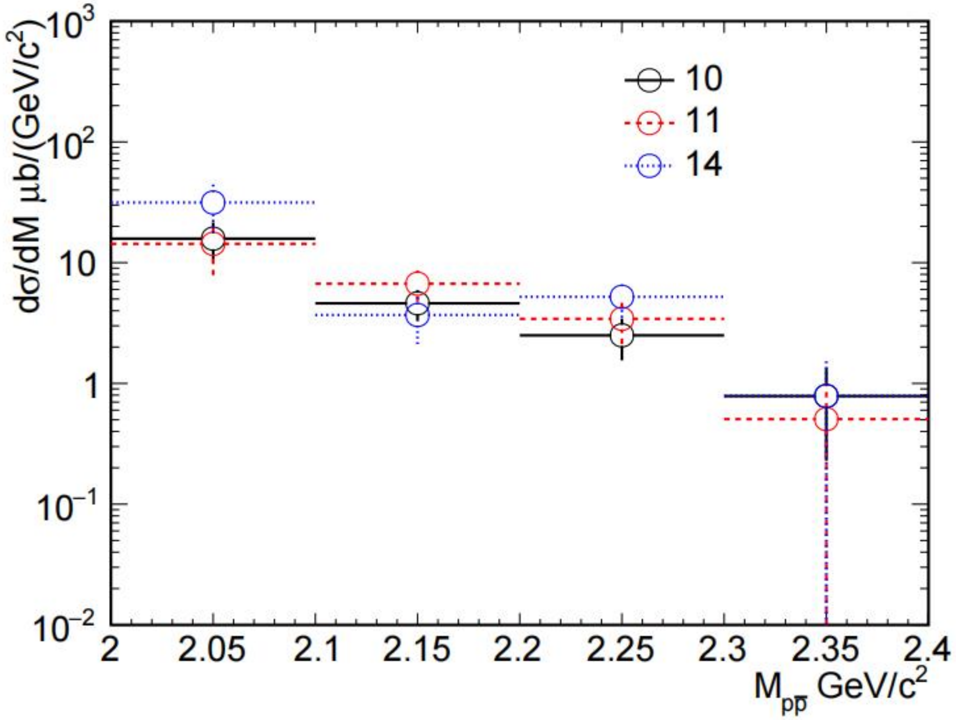


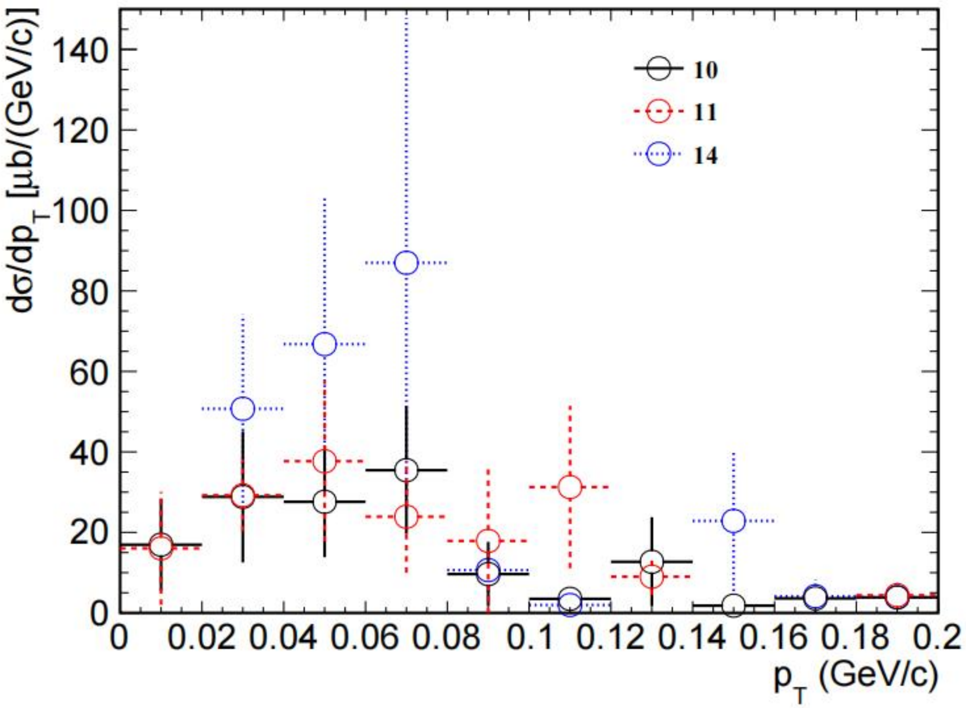




Cross sections for each year

- The final cross sections after efficiency correction is:





- Each run can match with each other.

Systematic uncertainties summary

- Luminosity: Common uncertainty for each run.
- TPC efficiency: Extracted from the difference between the embedding and data.
- TOF efficiency: Extracted from the difference between the calculated from the Λ decay proton and the TPC proton.
- PID efficiency: Extracted from different centralities.
- V_z cut efficiency: Extracted from the calculated difference between UPC data and zerobias data.

	Run 10	Run 11	Run14
Luminosity	10%	10%	10%
nHitsDedx	5%	3%	2%
nHitsFit	1%	1%	2%
DCA	6%	7%	14%
TOF	10%	9%	3%
PID	7%	7%	2%
V_z	1%	2%	2%
Total	18%	17%	18%

Combine the cross section from different years

- For different years, the results were combined using the following formula:

$$mDen = \Sigma \frac{1}{E_{stat}^2}$$

$$W_{Run} = \frac{1}{E_{stat\,Run}^2 \times mDen}$$

$$\sigma_{combined} = \Sigma W_{\mathrm{Run}} \times \sigma_{Run}$$

$$E_{combined}^{stat} = \sqrt{\Sigma (W_{Run} \times E_{stat})^2}$$

$$E_{combined}^{sys} = \Sigma W_{\mathrm{Run}} \times E_{sys}$$