The cross section measurement of $e^+e^- \to p\bar{p}$ near threshold at $\sqrt{s}$ from 1.840 to 1.970 GeV

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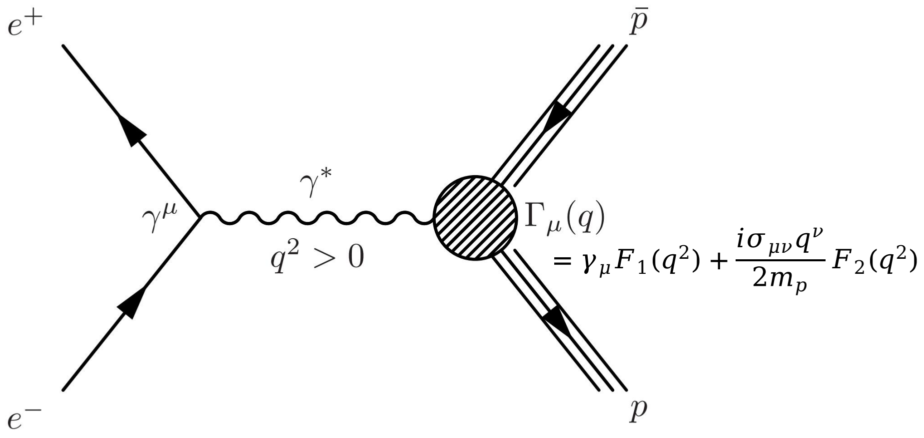
τ-QCD Group Meeting
24th Sep. 2025

Outline

- **Motivation**
- **Data and MC Samples**
- **Analysis Strategy**
- $\boldsymbol{e^+e^- \to p\bar{p}}$ **at** $\sqrt{\boldsymbol{s}} < \mathbf{1.940}$ **GeV**
- $\boldsymbol{e^+e^- \to p\bar{p}}$ **at** $\sqrt{\boldsymbol{s}} \geq \mathbf{1.940}$ **GeV**
- **Cross Section**
- **Summary**
- **Back Up**

Motivation

- Nucleons' internal structure can be described by electromagnetic form factors, electric $\boldsymbol{G_E}$ and magnetic $\boldsymbol{G_M}$, which are complex functions of the momentum transfer squared(q^2).
  - Connected to nucleons' internal charge, current distribution.
  - Crucial testing ground for models of the nucleon internal structure.



$$\frac{d\sigma_{p\bar{p}}}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2(1+\cos\theta^2) + \frac{1}{\tau}|G_E(s)|^2 \sin\theta^2\right],$$
$$\tau = \frac{s}{4m_p^2}, C = \frac{y}{1-e^{-y}}, \quad y = \pi\alpha/\beta$$

Integrated cross section:

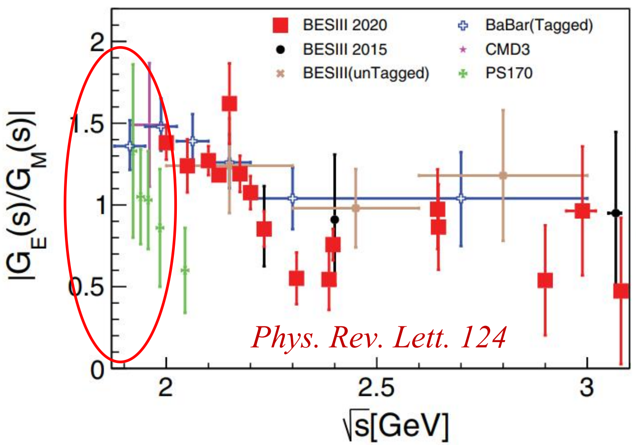
$$\sigma(s) = \frac{4\pi\alpha^2\beta C}{3s}\left(1+\frac{1}{2\tau}\right)|G_{\text{eff}}|^2, \quad |G_{\text{eff}}|^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau+1}$$

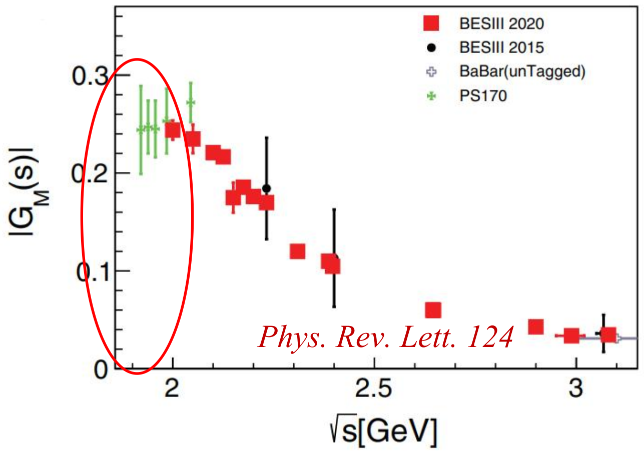
Sachs FFs:
$G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$,
$G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

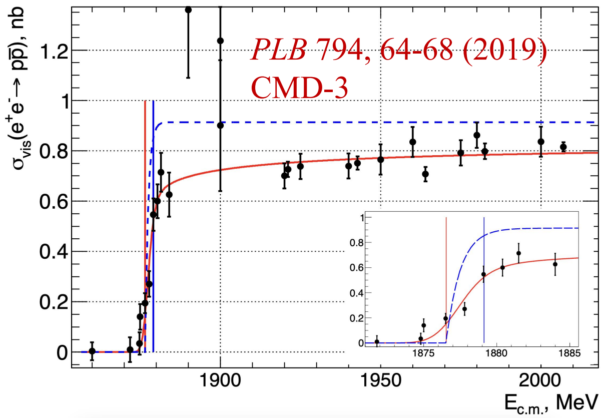
Motivation

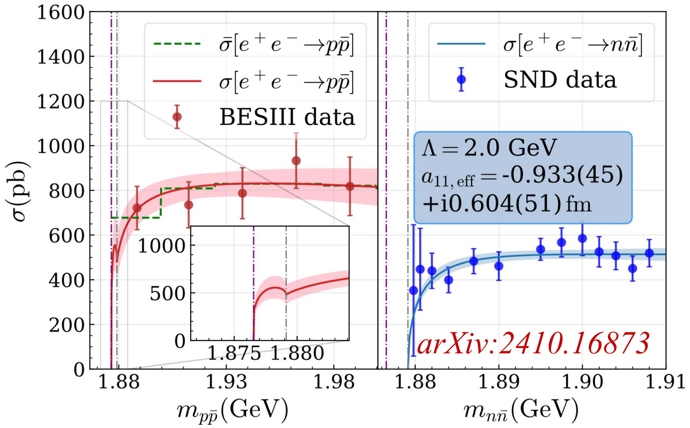
- Various theoretical models describe time-like form factors in non-perturbative region:
  - ChEFT, VMD, Relativistic CQM, parton model, pQCD etc.
  - Experimental data near the threshold are **very scarce**.

- Anomaly production cross section:
  - Cross section of $e^+e^- \to p\bar{p}$ near threshold shows **very sharp step-like behavior.**
  - The plateau indicates **anomaly threshold effect.**
  - **Fine structures** near the $N\bar{N}$ threshold.
  - More experimental results are needed.









Data and MC samples

- Data: Boss 7.1.3

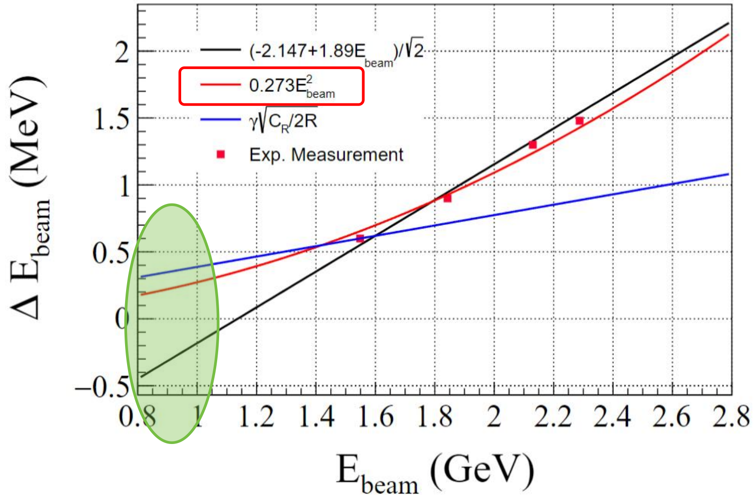
Requested $\sqrt{s}$(GeV)	Updated[1] $\sqrt{s}$ (GeV)	Online Lumi.(pb^{-1})	Run No.
1.840	1.8441	1.502	81849-81970
1.870	1.8741	2.003	81971-82104
1.872	1.8760	2.014	82543-82656
1.874	1.8780	2.019	82657-82783
1.875	1.8791	1.485	82835-82909
1.876	1.8801	2.035	82105-82203
1.877	1.8809	1.341	82784-82834
1.878	1.8822	2.021	82204-82261
1.882	1.8860	2.033	82262-82310
1.886	1.8902	2.031	82311-82358
1.900	1.9038	2.022	82359-82404
1.940	1.9437	2.040	82405-82462
1.970	1.9735	2.229	82463-82530

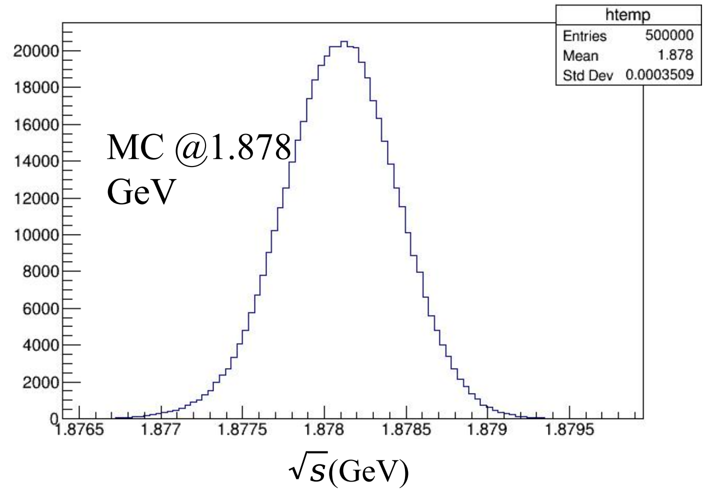
[1]:See Mi Wang's report

- MC:
  - Signal MC:
    - ✓ $e^+e^- \to p\bar{p}$: 0.5M for each energy point; generated by Phokhara.
  - Background MC:
    - ✓ $e^+e^- \to n\bar{n}$: 0.5M for each energy point; generated by Phokhara.
    - ✓ $e^+e^- \to e^+e^-$: $\times$ 1, Babayaga
    - ✓ $e^+e^- \to \mu^+\mu^-$: $\times$ 10, Babayaga
    - ✓ $e^+e^- \to hardons$: $\times$ 4, Hybird
  - Control sample:
    - ✓ $J/\psi \to p\bar{p}\pi^+\pi^-$: 2.5M for $P_{\bar{p}} < 0.3$ GeV; PHSP MC weighted according to the amplitude of data. (for $\bar{p}$ control sample selection).
    - ✓ $J/\psi \to p\bar{n}\pi^-$: 4.0M for $P_{\bar{n}} < 0.5$ GeV with amplitude from PWA results.

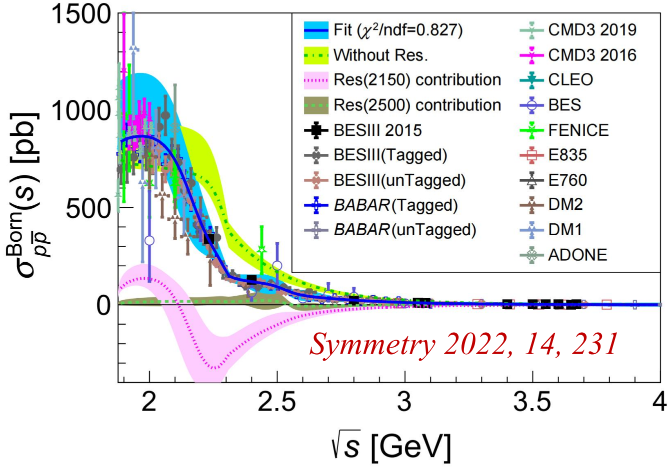
Data and MC samples

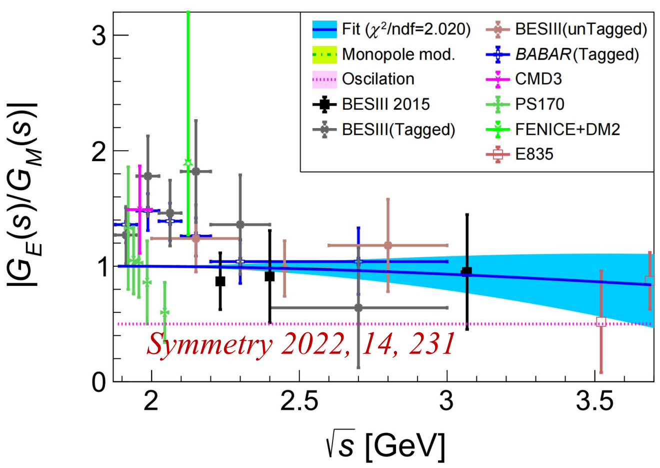
- Consider energy spread in Phokhara.





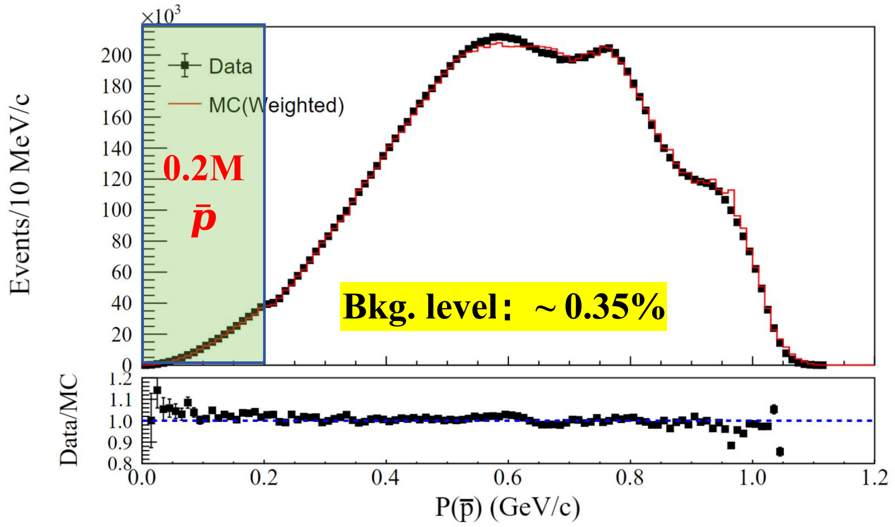
- MC lineshape input to Phokhara:

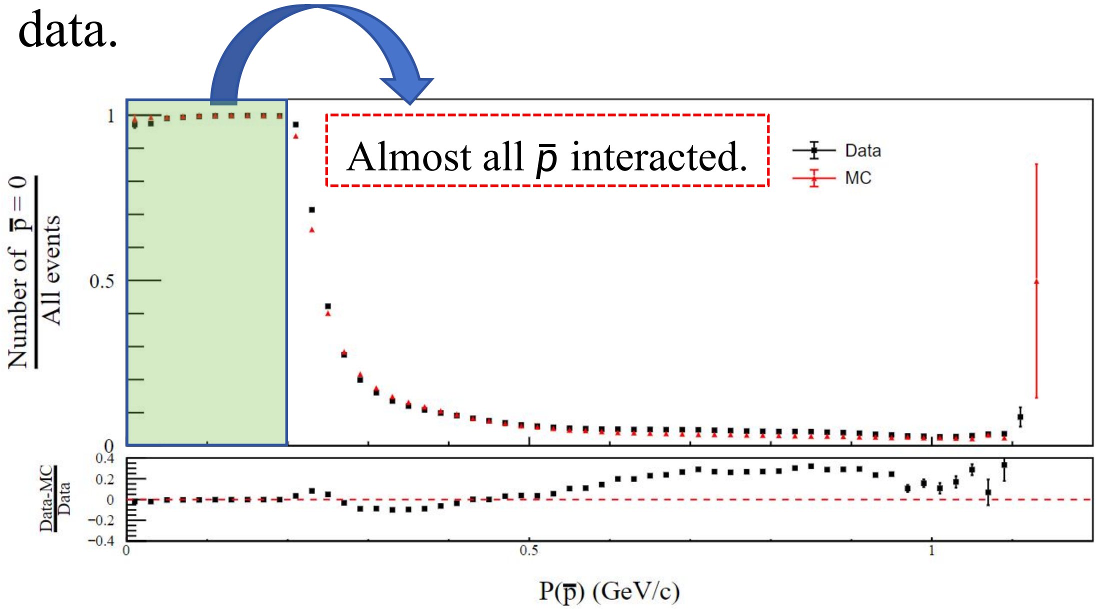


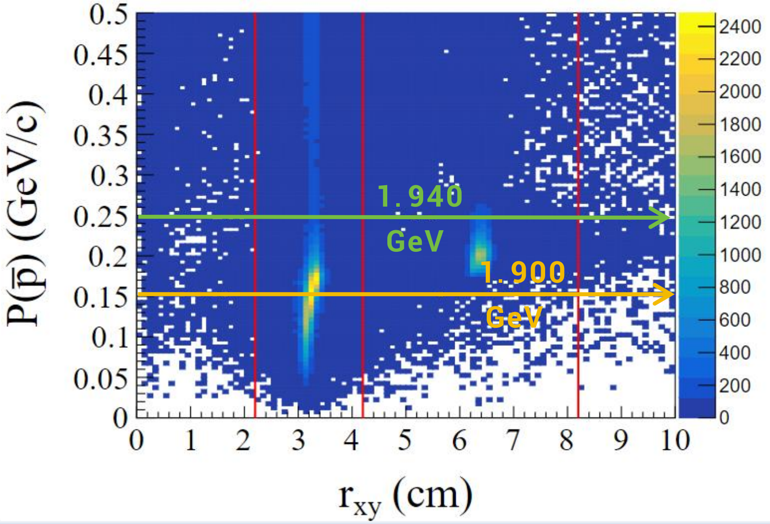


Control Sample of $\bar{p}$

- $\bar{p}$ samples are selected from $J/\psi \to p\bar{p}\pi^+\pi^-$ data.







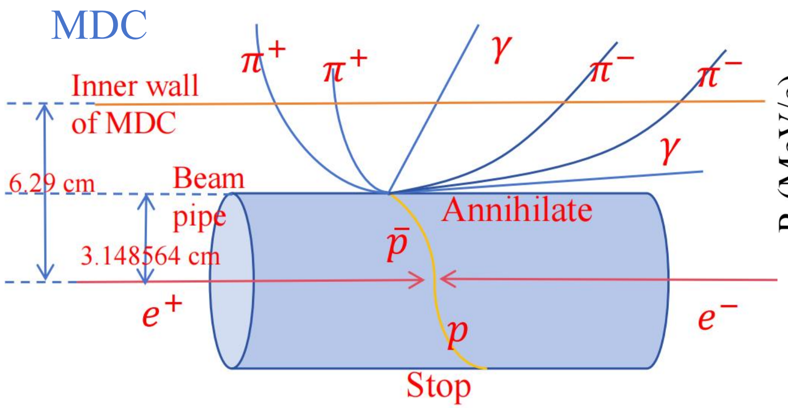
- ✓ Select the remain tracks after removing the $p\pi^+\pi^-$ tracks.
- ✓ These remain tracks should come from $\bar{p}N$ interaction.
- ✓ Vertex fit is performed to obtain the **interaction points**.

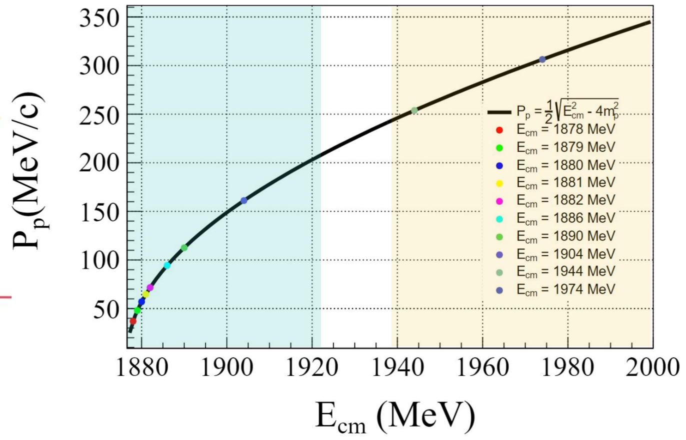
Analysis Strategy

- Case 1 ($\sqrt{s}$ <1.940 GeV):
  - $p\bar{p}$ are ionized to rest before MDC due to **high ionozation energy loss**.
  - Reconstruct the **$\bar{p}N$ annihilation point** (R_{xy},R_z) by these secondary particles.
  - Extract signal yields from the R_{xy} distribution.
- Case 2 ($\sqrt{s}$ ≥1.940 GeV):
  - Most protons and antiprotons **can reach MDC** to be detected.
  - Only reconstruct $\bar{p}$ directly to improve efficiency.
  - Extract signal yields from the momentum distribution of antiproton.

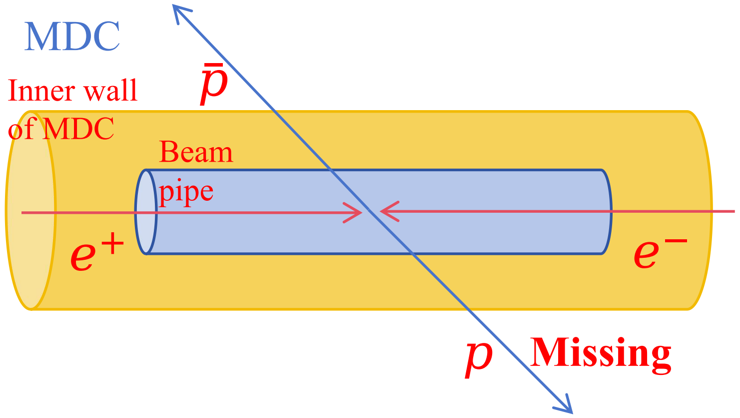
◆ Energy point @1.874 GeV which is below $p\bar{p}$ threshold, can be used to estimate the beam-induced background.

Typical process for case1





Typical process for case2



$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Event Selection

Decay Chain:

$e^+e^- \to p\bar{p}$

$\bar{p}N \to anything$

- **Good Charged Track:**

  $|\cos\theta| \le 0.93$; $2 \le N_{\text{charged}} \le 9$;

- **Good Photon:**

  $E_{\text{barrel}} \ge 25$ MeV ($|\cos\theta| < 0.80$); $E_{\text{endcap}} \ge 50$ MeV ($0.86 < |\cos\theta| < 0.92$); $0 \le TDC \le 700$ ns.

- **PID: Only use dedx**

  p: prob(p)>0.001 and prob(p)>prob(π, K, e)

  π: prob(π)>0.001 and prob(π)>prob(p, K, e)

  K: prob(K)>0.001 and prob(K)>prob(p, π, e)

  e: prob(e)>0.001 and prob(e)>prob(p, π, K)

  Require: $N_{\pi^+} \ge 1$ and $N_{\pi^-} \ge 1$

- **Further Selection:**
  - $\chi^2_{\text{vtx}} < 200$
  - $2.2 < R_{xy} < 4.2$ cm
  - $|R_z| < 10$ cm
  - $Ang_{\pi^+\pi^-} < 175°$
  - ML cut

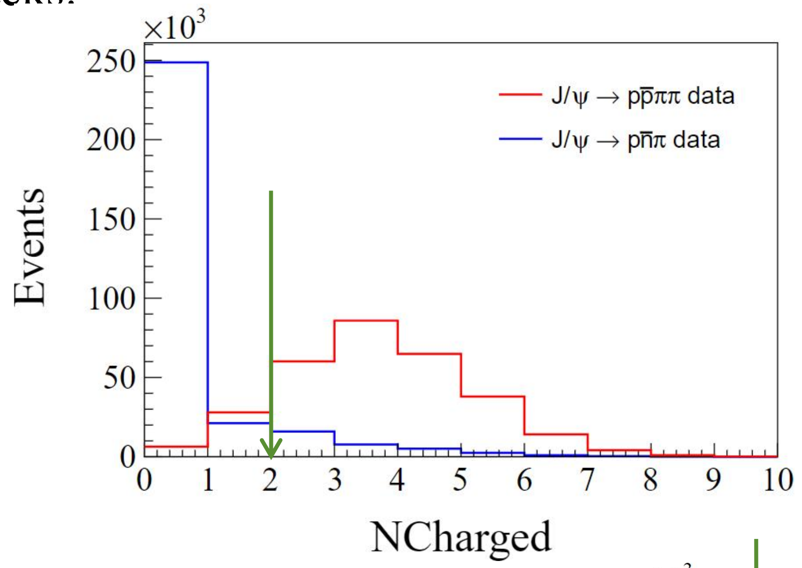
- **Vertexfit:**

  A vertex fit is performed to all the selected charged tracks, and need to be successful. Interacion points(R_{xy}, R_z) are obtained from vertex fit.

Exact signal events from R_{xy} distribution.

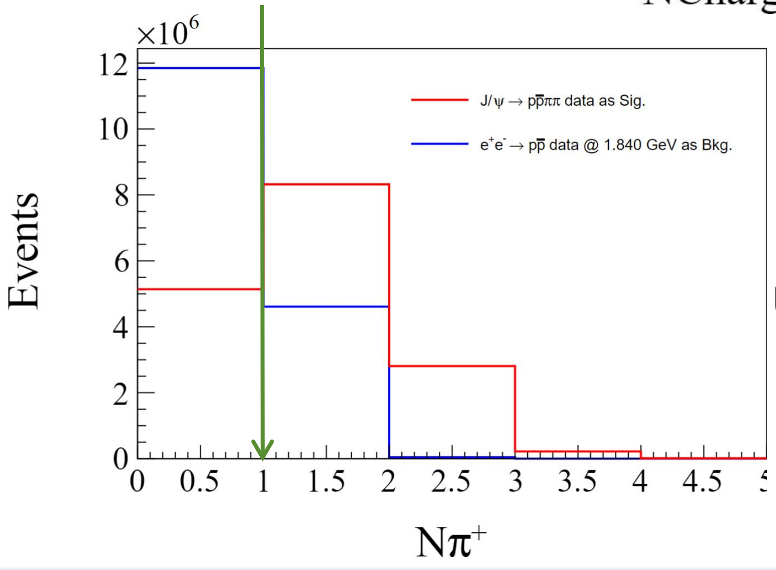
$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Event Selection

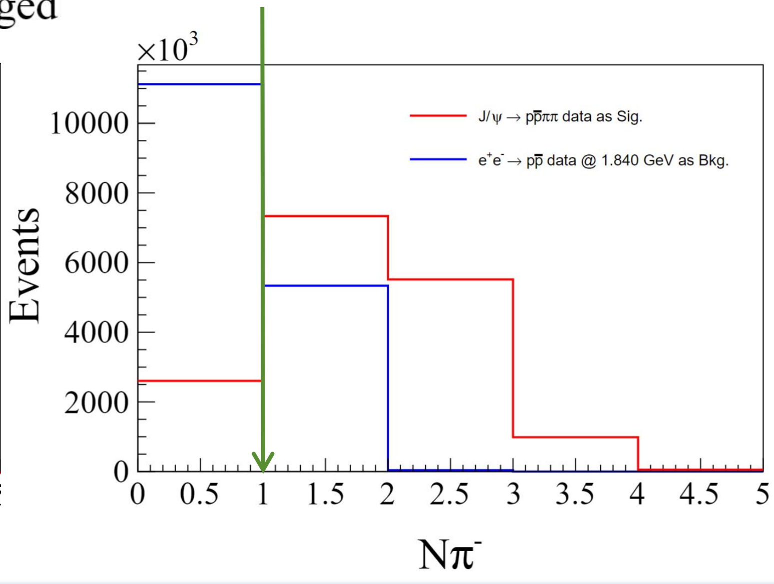
- Charged tracks:



$2 \le N_{charged} \le 9$:

✓ Veto $e^+e^- \to n\bar{n}$ whose reaction rate with beam pipe is less than 10%.

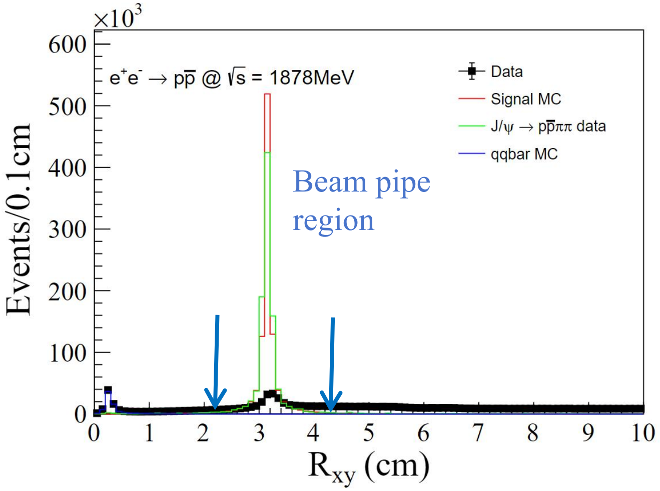


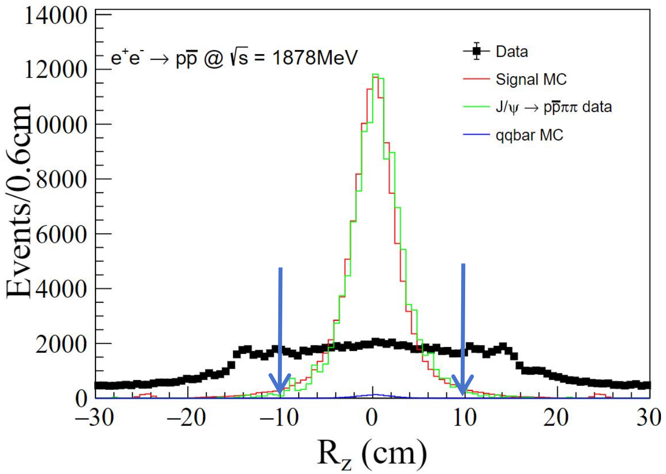


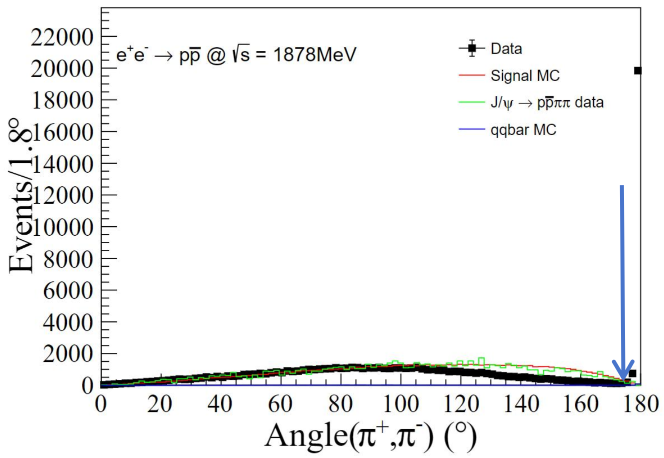
$N_{\pi^+} \ge 1$ and $N_{\pi^-} \ge 1$:

✓ Veto beam-induced background.

$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Event Selection







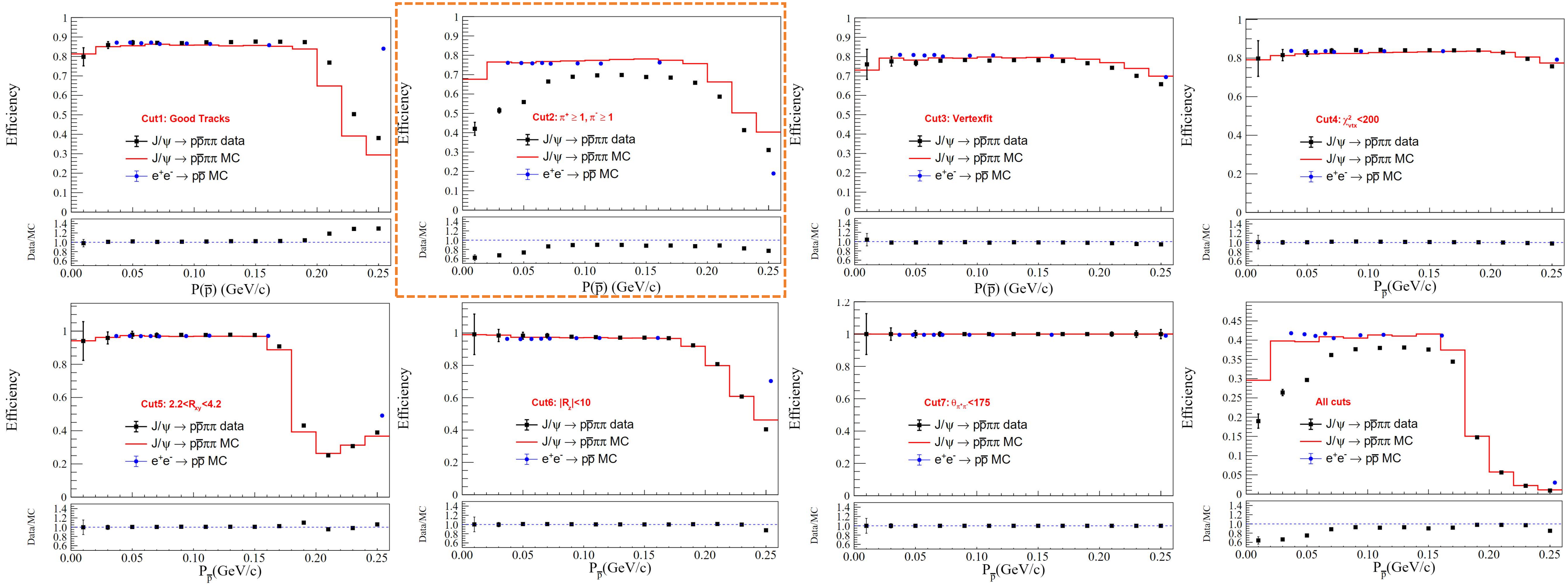
- R_{xy}, R_z: The distance between the vertexfit point and the original point in xy, z direction.
- $Ang_{\pi^+\pi^-}$: The angle between the two most energetic charged pions.

- The signal region is determined to be $2.2 < R_{xy} < 4.2$ cm and $|R_z| < 10$ cm for energy points lower than 1.940 GeV.
- Require $Ang_{\pi^+\pi^-} < 175°$ to supress cosmic-ray background.

The remain background is beam-induced background, and nnbar background.

$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: MC Efficiency

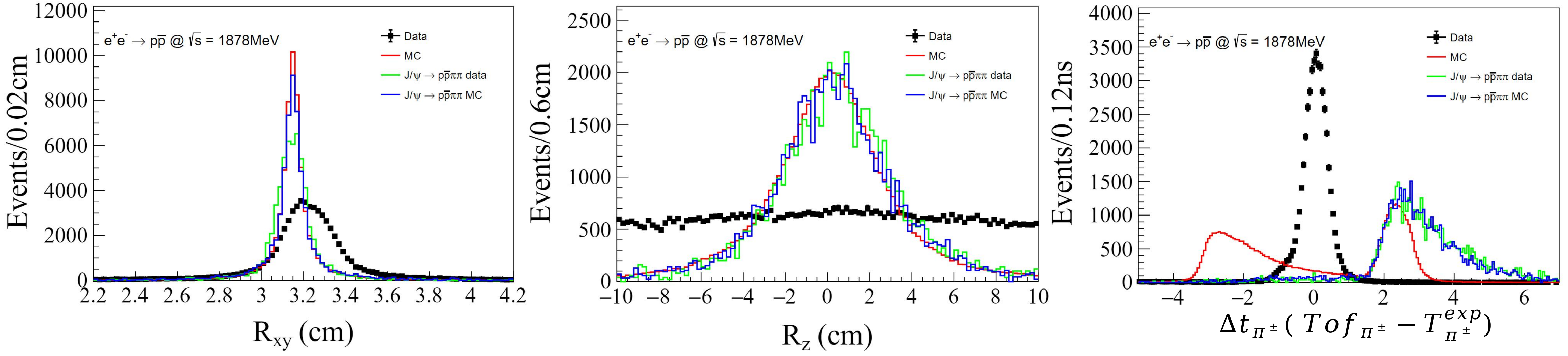
- Compare the efficiencies from $p\bar{p}$ MC and $\bar{p}$ control sample:



- There are significant differences between data and MC in some selection conditions, mainly in the low momentum region (Especially for the selection of $N_{\pi^+} \geq 1, N_{\pi^-} \geq 1$).

$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Distribution after previous selection criteria

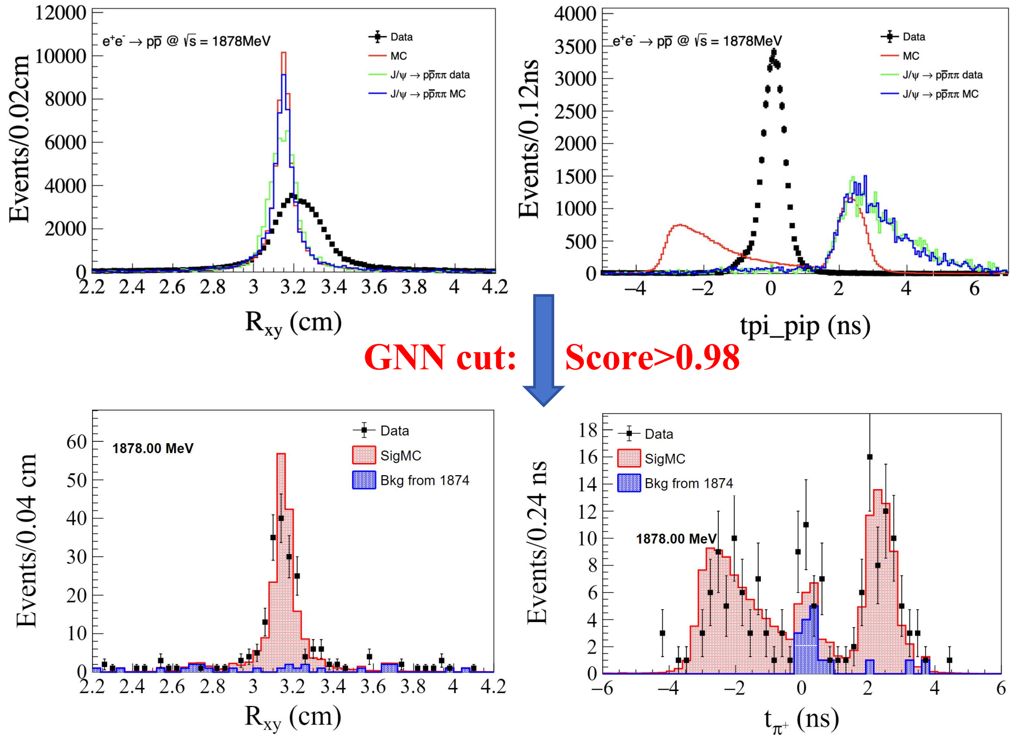
- Some distributions after previous selection criteria (take 1.878 GeV as example):



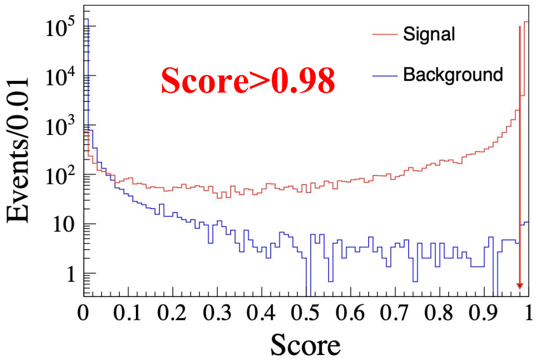
The background currently exceeds signals by over two orders of magnitude (~60000:400), mainly from the beam-induced background. Stronger methods for background removal are needed.

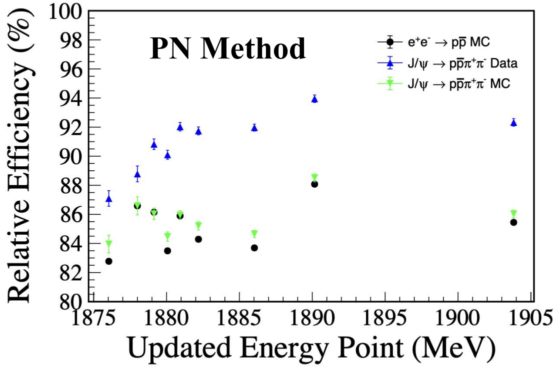
$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Machine Learning Method

- Use a GNN model (**Particle Net**) to supress the background. (BDT method as a cross check)
- Low level variables are used for training:
  - ✓ Use data below the $p\bar{p}$ threshold as background (@1.8441, 1.8741 GeV).
  - ✓ Use $\bar{p}$ data control sample as signal.
  - ✓ The trained models were applied to all energy points' data and MC.



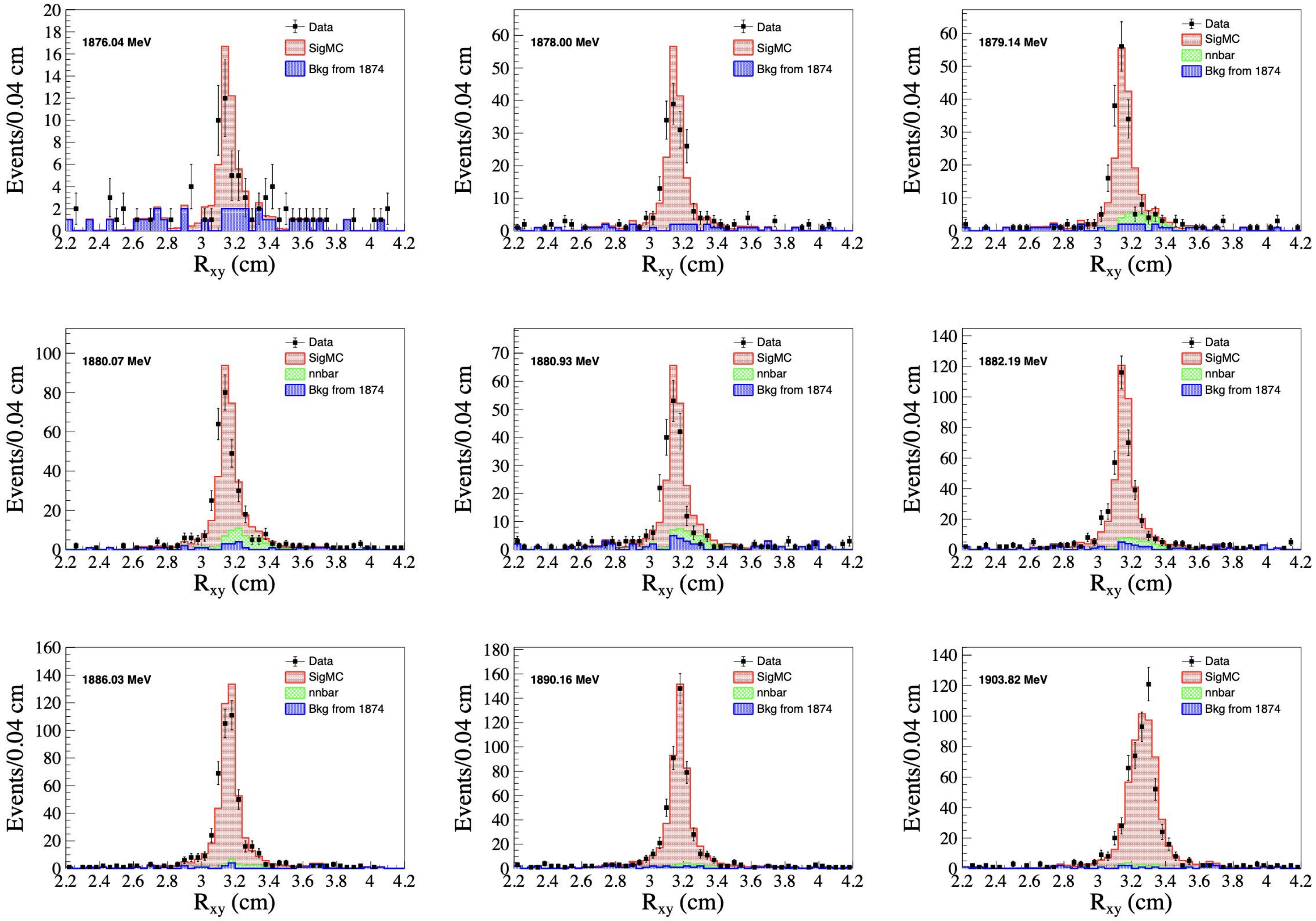
Approximately 90% signal efficiency has been achieved with a background rejection rate more than 99.98%.





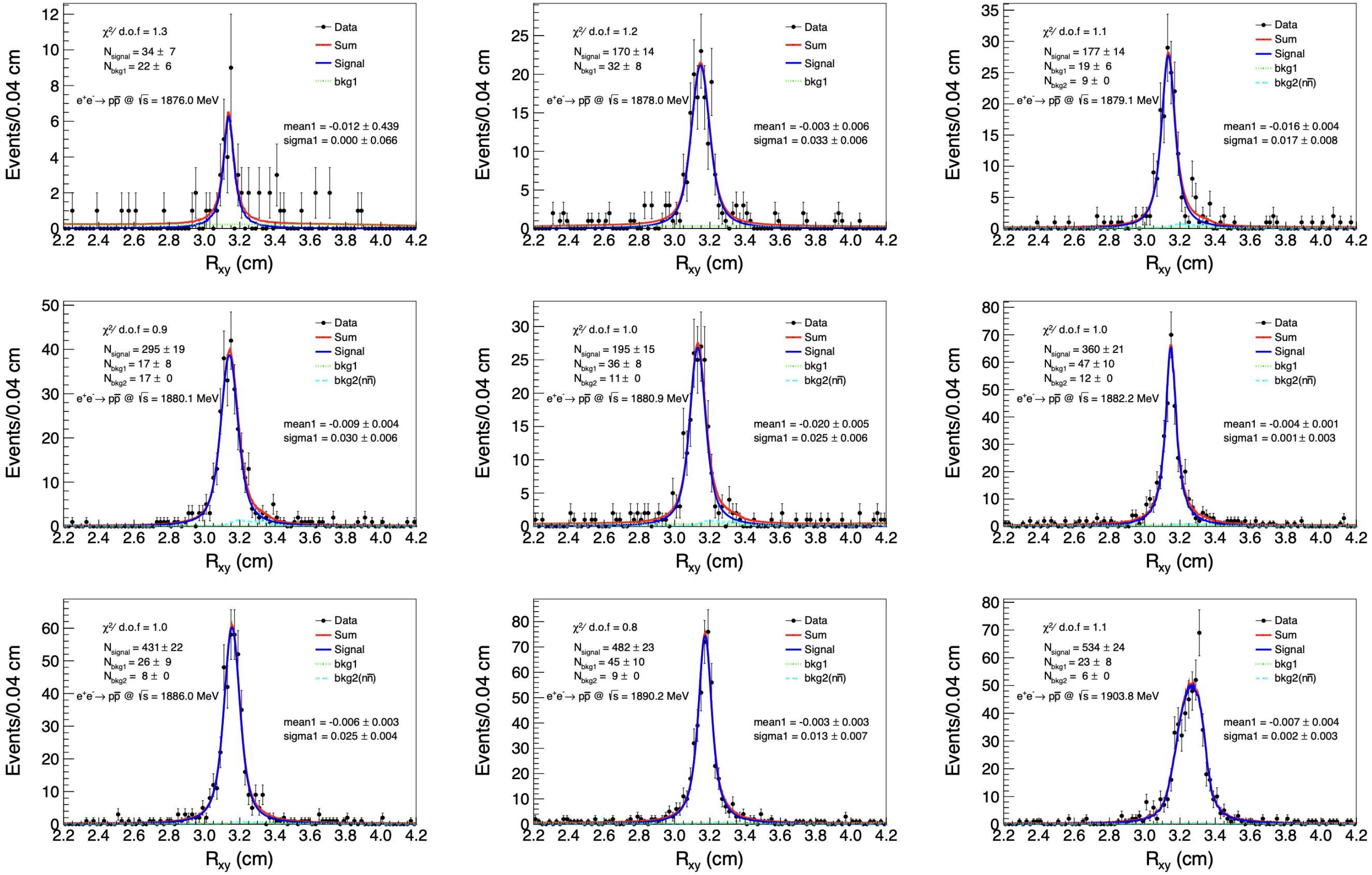
$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Rxy Distribution

- After GNN cut:



$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Fit Method

- Model: Unbinned fit
  - ✓ MC shape ⊗ GS for signal, 2nd Cheby.for flat background.
  - ✓ For energy points above $n\bar{n}$ threshold, use $n\bar{n}$ MC shape for $n\bar{n}$ background, and fix the $n\bar{n}$ events.



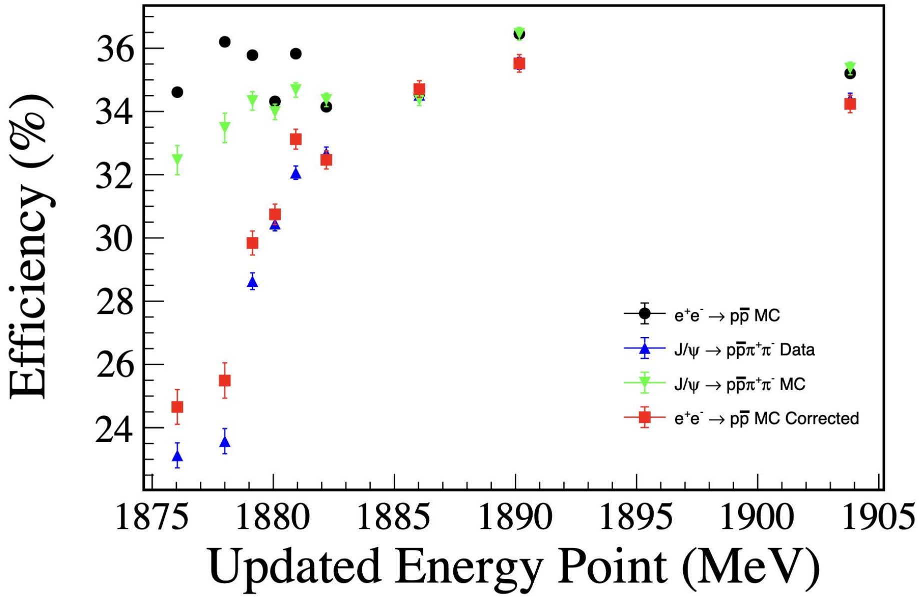
$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: MC Efficiency Correction

- Due to the particularity of this process, which involves the complex interaction between antiprotons and the detector, the MC efficiency will be corrected by $\bar{p}$ control sample.

$$\varepsilon_{e^+e^-\to p\bar{p}\ \mathrm{Corr}} = \varepsilon_{e^+e^-\to p\bar{p}\ \mathrm{MC}} \frac{\varepsilon_{J/\psi\to p\bar{p}\pi\pi\ \mathrm{data}}}{\varepsilon_{J/\psi\to p\bar{p}\pi\pi\ \mathrm{MC}}}$$

Updated $\sqrt{s}$ (GeV)	$P_{\bar{p}}$ (MeV/c)	$\bar{p}$ CS Mom. Interval(MeV/c)
1.8760	-	(0, 50)
1.8780	37	(0, 50)
1.8791	48	(30,70)
1.8801	57	(40, 80)
1.8809	65	(45, 85)
1.8822	72	(50, 90)
1.8860	94	(80, 110)
1.8902	113	(100, 120)
1.9038	161	(155, 165)

✓ For control sample, we use the efficiencies from specific $\bar{p}$ momentum intervals to match with the discrete momentum in signal MC.

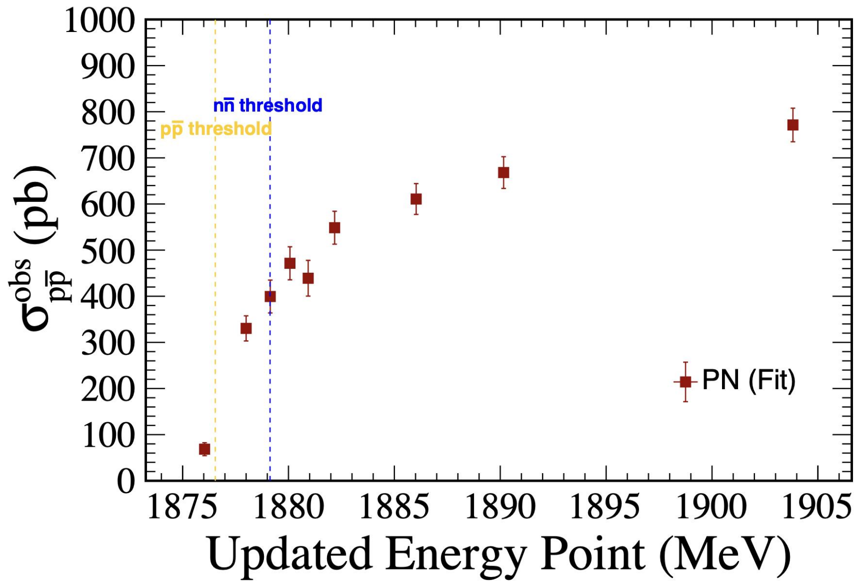


$e^+e^- \rightarrow p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Preliminary cross section results

- The observed cross section of $e^+e^- \rightarrow p\bar{p}$ can be calculated by:

$$\sigma_{p\bar{p}}^{obs} = \frac{N_{obs} - N_{n\bar{n}} - N_{bkg}}{L \bullet \varepsilon_{cor}}$$

  - Background estimation:
    - ✓ $N_{n\bar{n}}$: Estimate with MC simulation.
    - ✓ N_{bkg}: Estimate with survived events from 1.870 GeV data.
  - ε_{cor} is the corrected MC efficiency by control sample.



- **Particle Net results:**

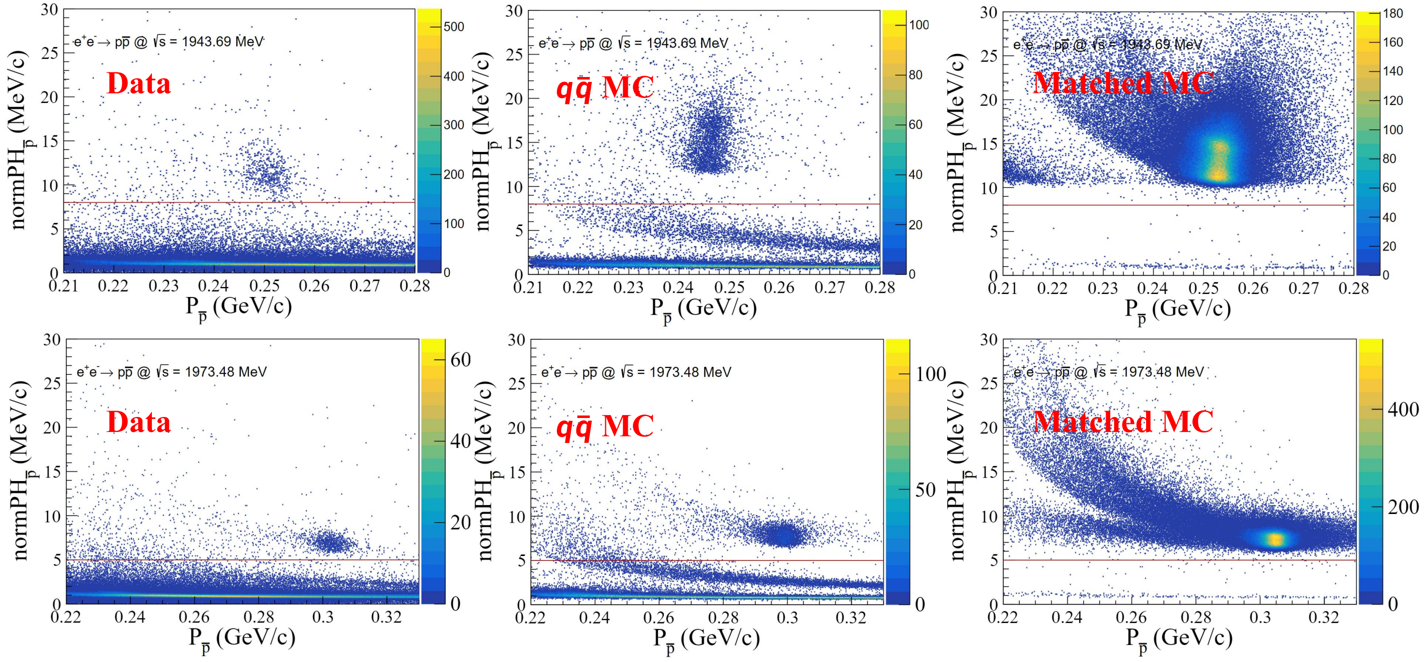
Updated $\sqrt{s}$ (GeV)	1.8760	1.8780	1.8791	1.8801	1.8809	1.8822	1.8860	1.8902	1.9038
ε_{cor}(%)	24.7	25.5	29.8	30.8	33.1	32.5	34.7	35.5	34.2
N_{sig}	34±7	170±14	177±14	295±19	195±15	360±21	431±22	482±23	534±24
$\sigma_{p\bar{p}}^{obs}$(pb)	68±14	330±27	399±36	471±36	439±39	549±36	611±33	668±34	771±36

$e^+e^- \to p\bar{p}$ at $\sqrt{s} \geq 1.940$ GeV: Event Selection

- Reconstruct $\bar{p}$ only:
  - **Good Charged Track:**
    $|\cos\theta| \leq 0.93$, $|V_{xy}| < 1$ cm, $|V_z| < 10$ cm; $N_{charged} \geq 1$;
  - **PID: use normPH**
    $\bar{p}$: normPH>(5, 8) for 1.9437 and 1.9735 GeV
    Require: $N_{\bar{p}} = 1$.
  - **Further Selection:**
    Momentum window for $\bar{p}$:
    $0.21 < P_{\bar{p}} < 0.28$ GeV/c for 1.9437 GeV
    $0.26 < P_{\bar{p}} < 0.33$ GeV/c for 1.9735 GeV

Decay Chain:
$e^+e^- \to p\bar{p}$

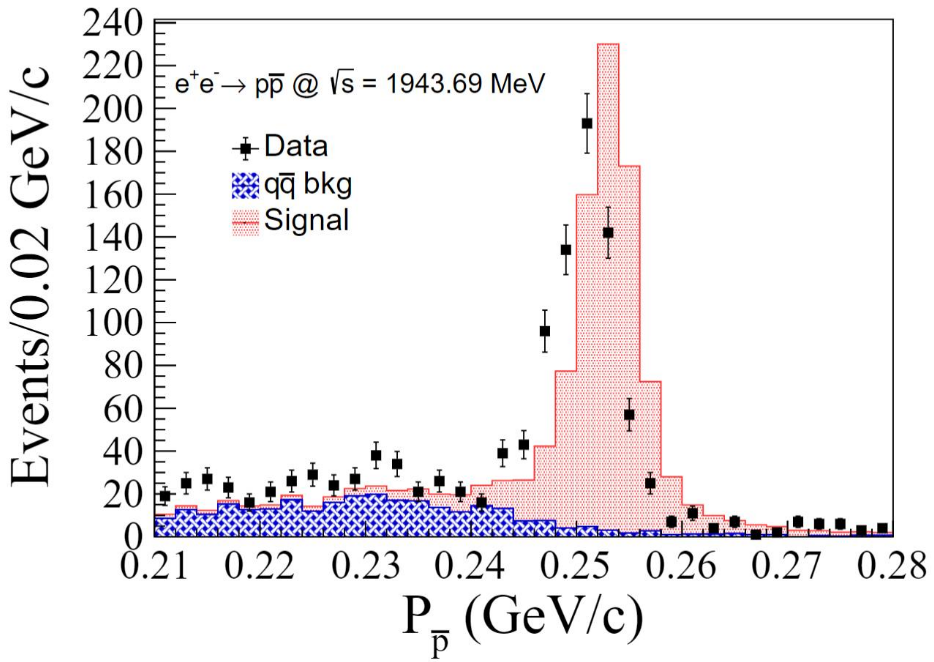
Exact signal events from momentum distribution.

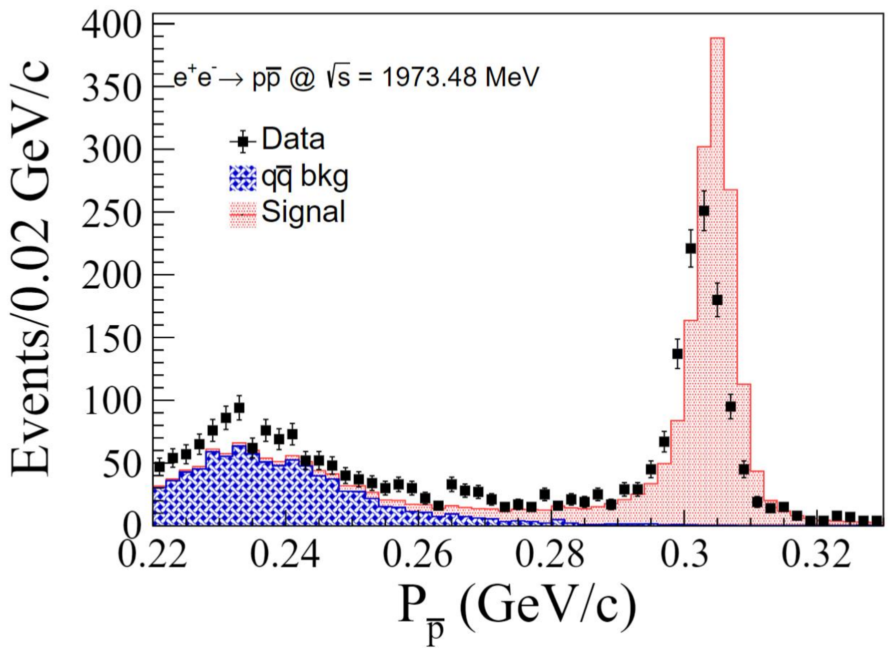


$e^+e^- \to p\bar{p}$ at $\sqrt{s} \geq 1.940$ GeV: Background Analysis

- After all the event selections:

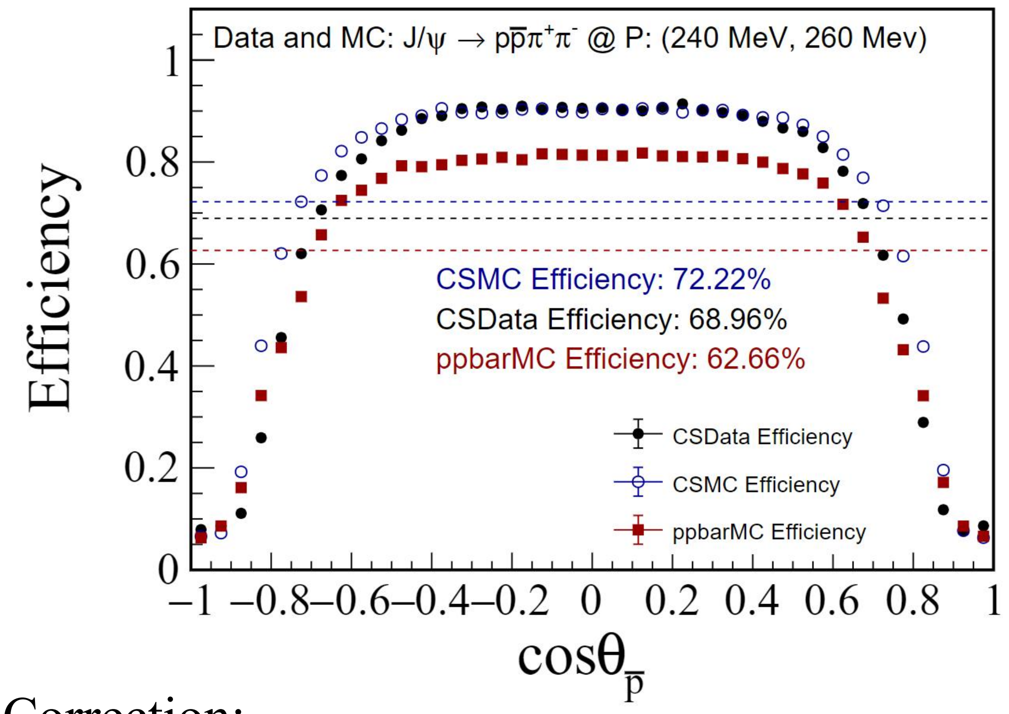
ECM (GeV)	data	MC Efficiency	$q\bar{q}$ MC	Bhabha MC	dimu MC
1.9437	1180	56.2%	3522/4642	0	0
1.9735	1933	69.3%	5348/6497	0	0

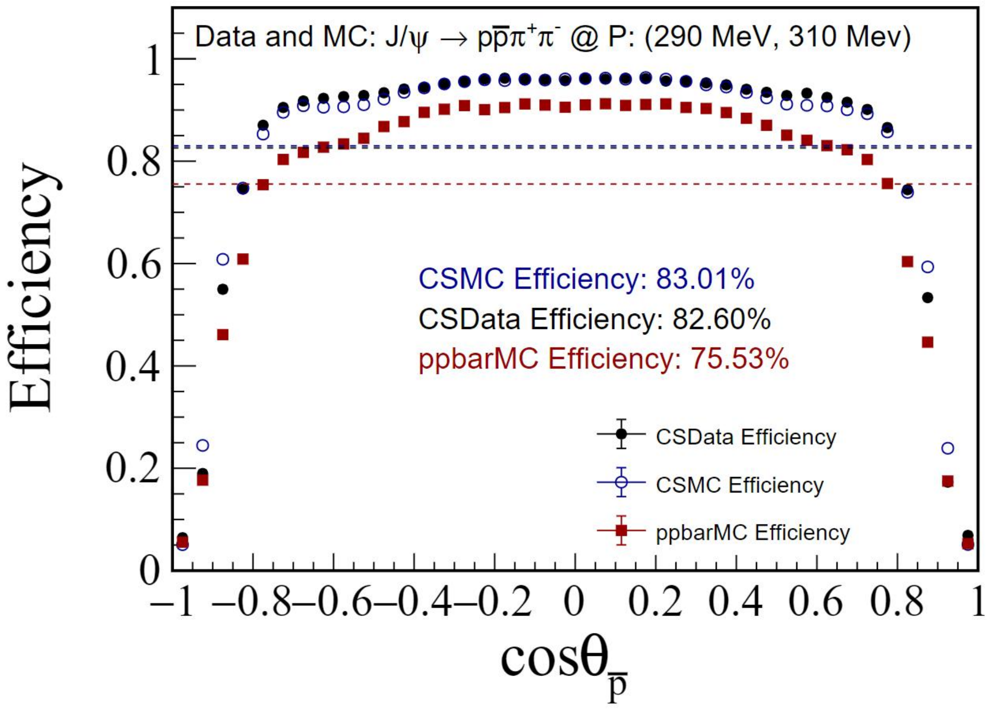




$e^+e^- \to p\bar{p}$ at $\sqrt{s} \geq 1.940$ GeV: Tracking Efficiency

- For $\bar{p}$ control sample: $\varepsilon_{trk} = {N^-=1}/{N_{\mathrm{recoil}}}$
- For $p\bar{p}$ MC: $\varepsilon_{trk} = {N^-=1}/{N_{\mathrm{gen}}}$



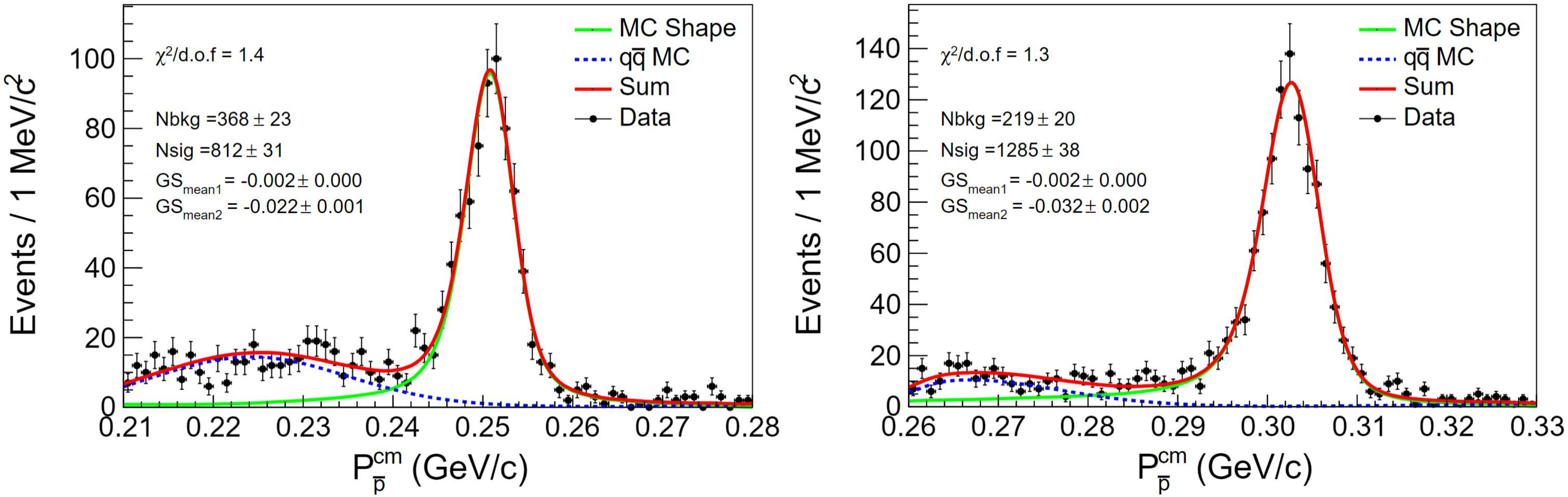


✓ Correction:

$$\varepsilon_{e^+e^-\to p\bar{p}\ \mathrm{Corr}} = \varepsilon_{e^+e^-\to p\bar{p}\ \mathrm{MC}} \frac{\varepsilon^{trk}_{J/\psi\to p\bar{p}\pi\pi\ \mathrm{data}}}{\varepsilon^{trk}_{J/\psi\to p\bar{p}\pi\pi\ \mathrm{MC}}}$$

$e^+e^- \to p\bar{p}$ at $\sqrt{s} \geq 1.940$ GeV: Signal Extraction

- MC shape $\otimes$ GS for signal, $q\bar{q}$ MC shape $\otimes$ GS for background.



✓ Cross section:

$$\sigma_{p\bar{p}}^{obs} = \frac{N_{obs}}{L \bullet \varepsilon_{cor}}$$

Updated $\sqrt{s}$ (GeV)	1.9437	1.9735
Signal Events	812 ± 31	1285 ± 38
ε_{cor} (%)	53.6	69.0
$\sigma_{p\bar{p}}^{obs}$(pb)	742 ± 28	836 ± 25

$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Systematic Uncertainty

- **Efficiency Correction:** Corrected by $\bar{p}$ control sample.

$$f_{cor} = \frac{\varepsilon_{trk}(\text{data})}{\varepsilon_{trk}(\text{MC})}, \qquad \sigma_\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}}, \qquad \sigma_{f_{\text{cor}}} = f_{\text{cor}}\sqrt{\frac{\sigma_\varepsilon^2(MC)}{\varepsilon^2(MC)} + \frac{\sigma_\varepsilon^2(data)}{\varepsilon^2(data)}},$$

- **The selection range of $\bar{p}$ control sample:** Change the momentum match range, and obtain the new correction factors. The differences between nominal results are assigned to the uncertainties.

- **Energy shift:** Generate signal MC with $\sqrt{s}$ shift ($\pm 1\sigma$), the efficiency differences from nominal's are assigned to the uncertainties.

- **MC model:** Generate PHSP signal MC as an alternative, and the efficiency differences from nominal's are assigned to the uncertainties.

- **MC statistics:** $\sigma_\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}}$,

$e^+e^- \to p\bar{p}$ at $\sqrt{s} < 1.940$ GeV: Systematic Uncertainty

- **ML related uncertainty [BAM-632]:**
  - Still an ongoing research field.
  - Consider two primary sources.

➢ Model uncertainty:

✓ Caused by shortcomings of the model.

✓ Training for 30 times to obtain different models.

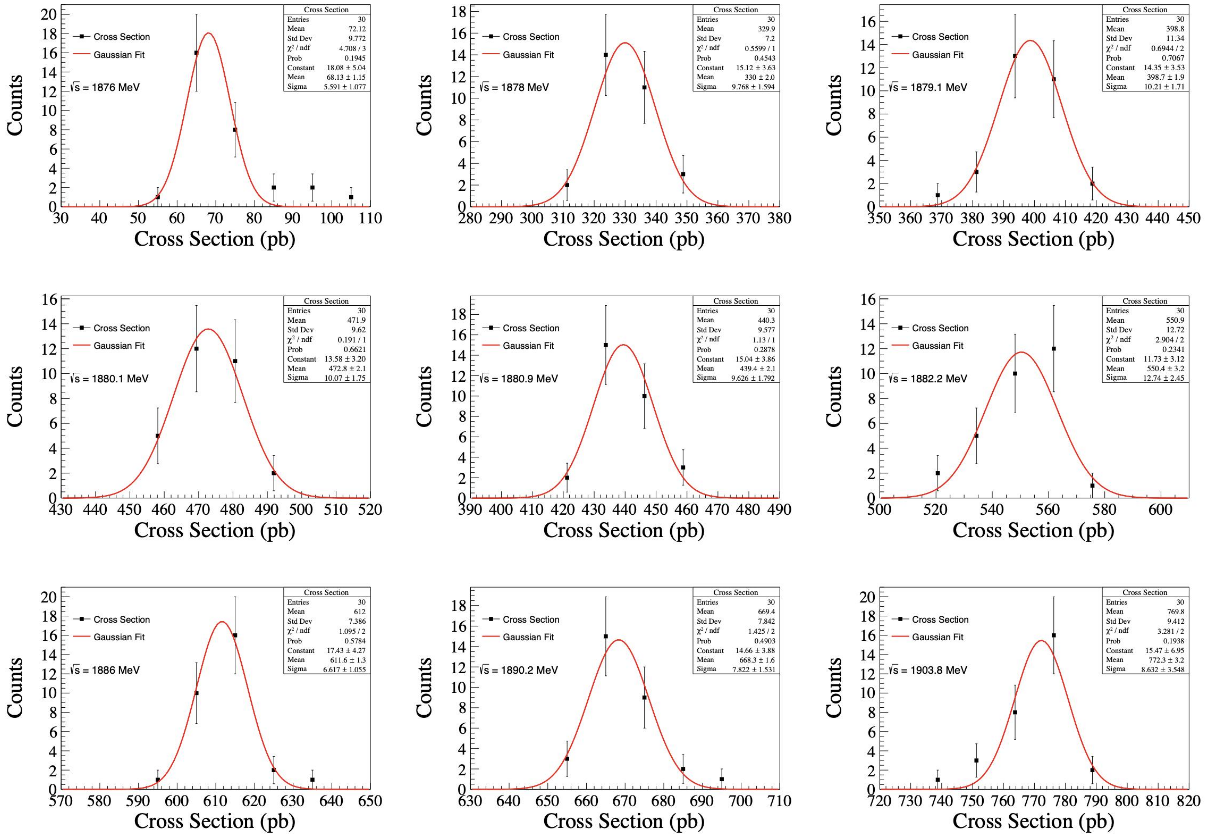
✓ Take the GNN models with colsest output to the fitted mean values as nominal results.

✓ Assign **sigma/mean** as systematic uncertainty.

➢ Domain shift:

✓ Mismatch between training and applied datasets, i.e., data-MC discrepancy.

✓ Change the training datasets for signal (from $\bar{p}$ data sample to $p\bar{p}$ MC).



$e^+e^- \to p\bar{p}$ at $\sqrt{s} \geq 1.940$ GeV: Systematic Uncertainty

- **Tracking efficiency:** Corrected by $\bar{p}$ control sample.

$$f_{cor} = \frac{\varepsilon_{trk}(\text{data})}{\varepsilon_{trk}(\text{MC})}, \qquad \sigma_\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}}, \qquad \sigma_{f_{cor}} = f_{cor}\sqrt{\frac{\sigma_\varepsilon^2(MC)}{\varepsilon^2(MC)} + \frac{\sigma_\varepsilon^2(data)}{\varepsilon^2(data)}},$$

- **PID efficiency:** Change normPH cut values (minus or plus 0.5), and perform the same analysis. The differences between nominal results are assigned to uncertainties.

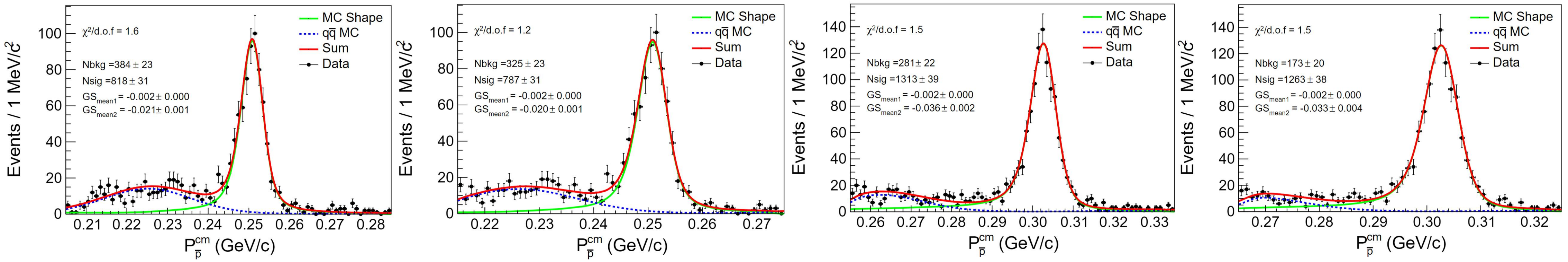
- **Energy shift:** Generate signal MC with ECM shift $\pm 1\sigma$, the efficiency differences from nominal's are assigned to uncertainties.

- **MC model:** Generate PHSP signal MC as an alternative, and the efficiency differences from nominal's are assigned to uncertainties.

- **MC statistics:** $\sigma_\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}}$,

$e^+e^- \to p\bar{p}$ at $\sqrt{s} \geq 1.940$ GeV: Systematic Uncertainty

- **Fitting range:**
  - ✓ Adjust the fitting range by expanding or contracting it.



Updated $\sqrt{s}$ (GeV) Fitting Range	1.9437 [0.210,0.280]	[0.205,0.285]	[0.215,0.275]	1.9735 [0.260,0.330]	[0.255,0.335]	[0.265,0.325]
Signal Events	812 ± 31	818 ± 31	787 ± 31	1285 ± 38	1313 ± 39	1263 ± 38
ε_{cor} (%)	53.6	54.1	53.1	69.0	69.8	68.1
$\sigma^{obs}_{p\bar{p}}$(pb)	742 ± 28	742 ± 28	726 ± 29	836 ± 25	844 ± 25	833 ± 25

Systematic Uncertainty

- Summary of systematic uncertainty:

✓ Case I:

Updated $\sqrt{s}$ (GeV)	1.8760	1.8780	1.8791	1.8801	1.8809	1.8822	1.8860	1.8902	1.9038
ε correction[%]	2.2	2.2	1.3	1.0	0.9	0.9	0.7	0.8	0.8
Energy shift [%]	3.5	3.5	3.7	1.1	0.6	0.2	0.4	0.4	0.1
MC model[%]	0.2	0.2	0.1	0.5	0.1	0.1	0.2	0.4	0.3
GNN model [%]	8.2	3.0	2.6	2.1	2.2	2.3	1.1	1.2	1.1
Domain shift [%]	0.8	1.9	1.4	1.0	2.5	1.2	0.9	2.0	2.5
MC statistics [%]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Luminosity [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total [%]	9.3	5.6	5.0	3.0	3.7	2.9	1.9	3.1	4.1

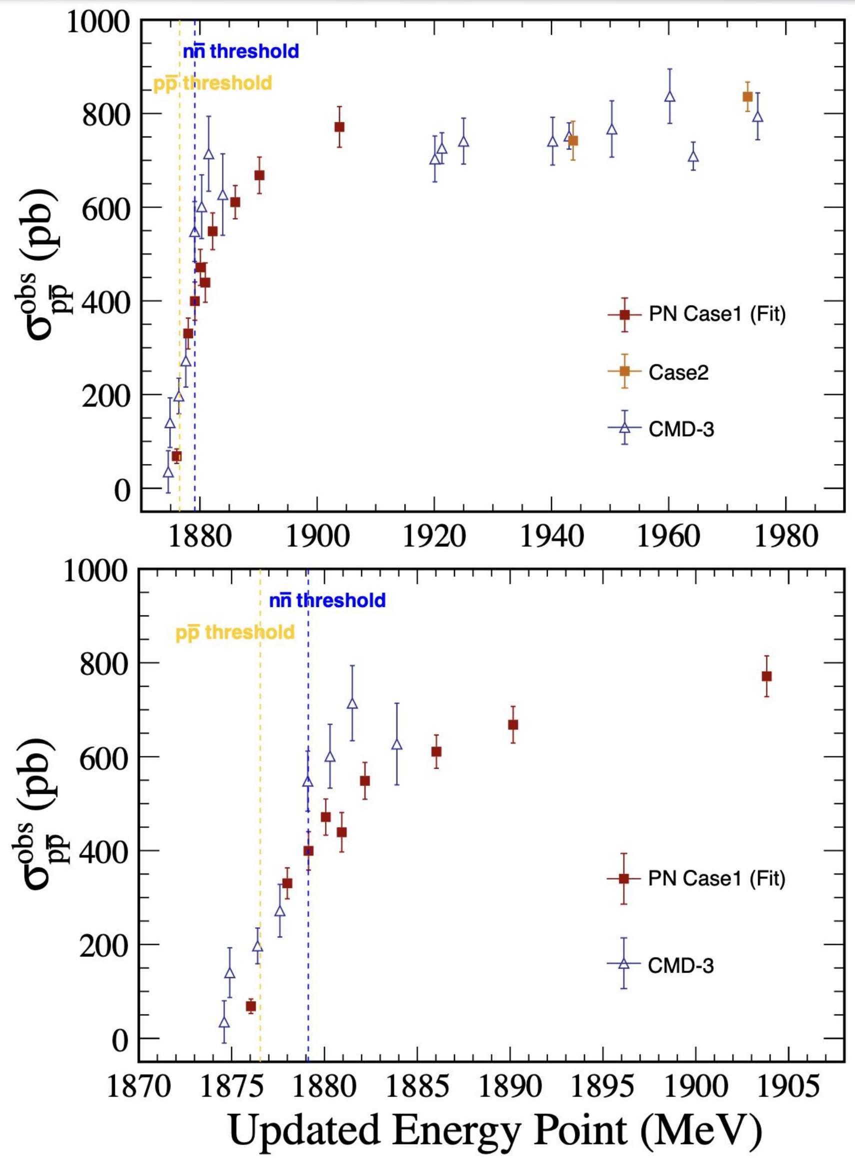
✓ Case II:

Updated $\sqrt{s}$ (GeV)	1.9437	1.9735
ε correction[%]	0.2	0.1
Energy shift [%]	0.7	0.2
MC model[%]	0.8	0.8
normPH cut [%]	3.1	1.6
Fitting Range [%]	2.2	1.0
MC statistics [%]	0.1	0.1
Luminosity [%]	1.0	1.0
Total [%]	4.1	2.3

Cross Section Results

- The observed cross section has been measured.
  - ✓ The threshold effect is observed similar to CMD-3 results.

Updated $\sqrt{s}$(GeV)	$N_{\rm sig}$	$\sigma^{obs}_{p\bar{p}}$(pb)
1.8760	34 ± 7	$68 \pm 15_{tot.}(\pm 14_{stat.} \pm 6_{sys.})$
1.8780	170 ± 14	$330 \pm 33_{tot.}(\pm 27_{stat.} \pm 19_{sys.})$
1.8791	177 ± 14	$399 \pm 41_{tot.}(\pm 36_{stat.} \pm 20_{sys.})$
1.8801	295 ± 19	$471 \pm 38_{tot.}(\pm 36_{stat.} \pm 14_{sys.})$
1.8809	195 ± 15	$439 \pm 42_{tot.}(\pm 39_{stat.} \pm 16_{sys.})$
1.8822	360 ± 21	$549 \pm 39_{tot.}(\pm 37_{stat.} \pm 16_{sys.})$
1.8860	431 ± 22	$611 \pm 35_{tot.}(\pm 33_{stat.} \pm 12_{sys.})$
1.8902	482 ± 23	$668 \pm 39_{tot.}(\pm 34_{stat.} \pm 18_{sys.})$
1.9038	534 ± 24	$771 \pm 43_{tot.}(\pm 36_{stat.} \pm 24_{sys.})$
1.9437	812 ± 31	$742 \pm 41_{tot.}(\pm 28_{stat.} \pm 30_{sys.})$
1.9735	1285 ± 38	$836 \pm 31_{tot.}(\pm 25_{stat.} \pm 19_{sys.})$

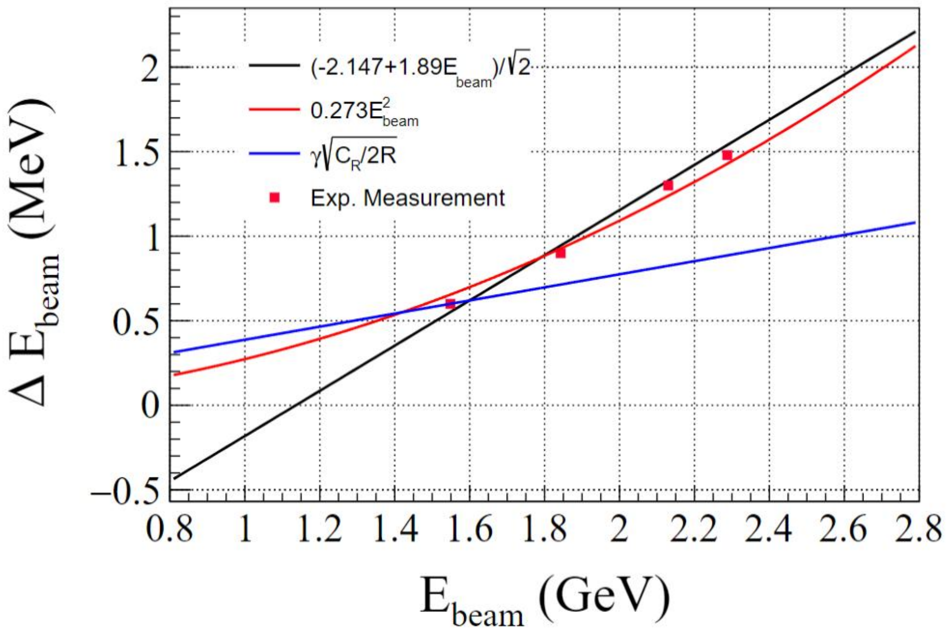


Line Shape Fit

- The cross section changes drastically at the threshold, the effect of energy spread should be taken into account.
- The **energy spread**, **ISR** and **vacuum polarization(VP)** effect are considered together by convolved with the Born cross section to obtain the observed cross section.

$$\sigma_{p\bar{p}}^{obs}(W, m_{\bar{p}}, \Delta) = \frac{1}{\sqrt{2\pi}\Delta}\int_{2m_{\bar{p}}}^{\infty} dW' e^{\frac{-(W-W')^2}{2\Delta^2}} \int_0^{1-\frac{4m^2}{w'^2}} dx F(x, W') \frac{\sigma_{p\bar{p}}^{Born}(W'\sqrt{1-x}, m_{\bar{p}})}{|1-\prod(W)|^2}$$

- Model:
  - ✓ **Energy Spread:** $a \cdot \sqrt{2} \cdot E_{beam}^2$
  - ✓ **ISR:** from Sov.J.Nucl.Phys. 41 (1985) 466-472
  - ✓ **VP:** from Phys.Lett.B 63 (1976) 432-434
  - ◆ Try different $\sigma_{p\bar{p}}^{Born}$ models?

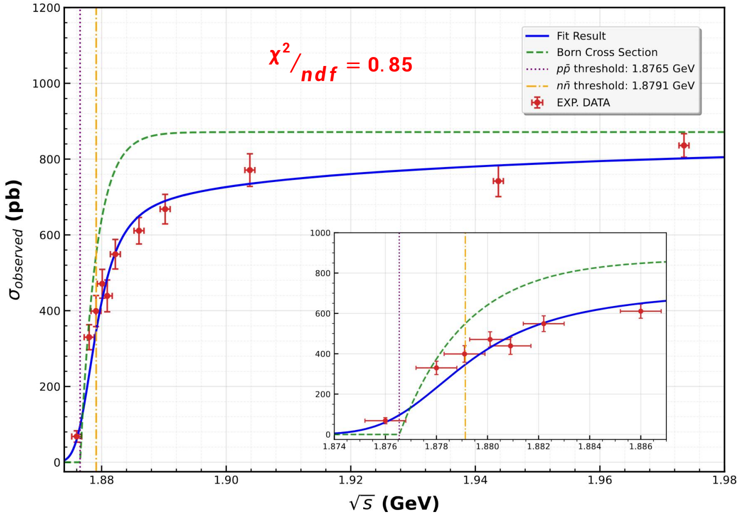


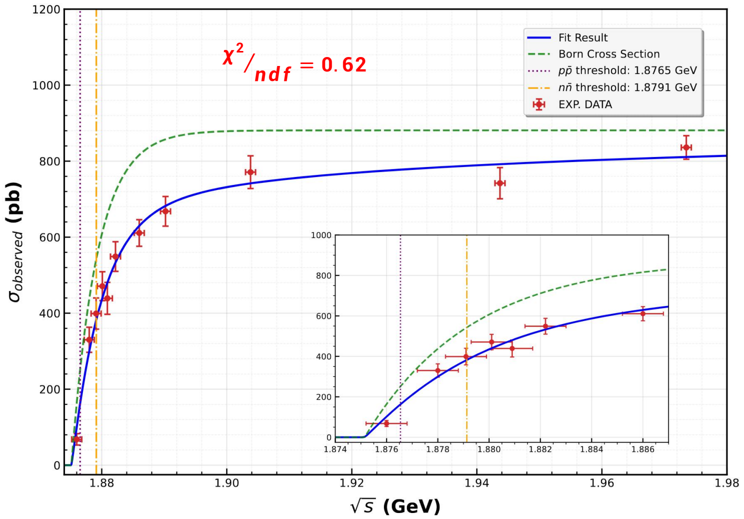
- χ^2 fit:
  - ✓ $\chi_{fit}^2 = \sum_{i=1}^{N} \frac{(\sigma_{exp.}^{obs}(W_i) - \sigma_{th.}^{obs}(W_i))^2}{(\Delta\sigma_{exp.}^{obs}(W_i))^2 + (\frac{d\sigma_{th.}^{obs}}{dW}(W_i) \cdot \Delta W_i)^2}$

Line Shape Fit

✓ Described with an exponentially saturated function:

$$\sigma_{p\bar{p}}^{Born}(W) = A + B[1 - exp(-\frac{(W - E_{th})}{\sigma_{th}})]$$





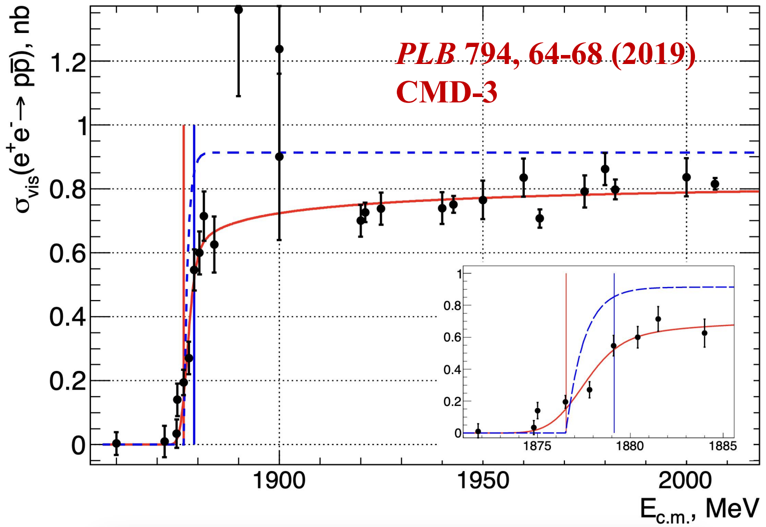


Table 1
Results of the fit to the exponentially rising function. Only statistical uncertainties are shown.

Reac.	A, nb	B, nb	E_{thr}, MeV	σ_{thr}, MeV	χ^2/ndf
$p\bar{p}$	0 – fxd	0.91±0.02	1877.1±0.2	0.18±0.27	29/26
$p\bar{p}$	0 – fxd	0.91±0.02	1876.54-fxd	0.76±0.28	31/27
6π	1.55±0.02	−0.42±0.03	1875.8±0.2	0.18±0.67	17/20
6π	1.54±0.02	−0.41±0.03	1876.54–fxd	0.0±2.5	18/21
$2K2\pi$	4.69±0.08	−0.44±0.12	1878.8±0.2	0.35±2.69	7/10
$2K2\pi$	4.70±0.08	−0.45±0.12	1876.54–fxd	2.36±2.01	8/11

Reaction	B, fb	Beam Energy Spread(a), MeV	E_{thr}, MeV	σ_{thr}, MeV	χ^2/ndf
$e^+e^- \to p\bar{p}$	871±22	1.22±0.73	1876.544-fxd	2.59±0.54	6.8/8
$e^+e^- \to p\bar{p}$	881±23	0.04±2.51	1875.14±0.38	4.16±0.89	4.3/7

✓ The threshold effect is observed similar to CMD-3 results, but increased more gradually.

Summary and Future Plan

Summary

- Two reconstruction method:
  - For $\sqrt{s} < 1.94$ GeV, we reconstruct signal process by secondary particles from $\bar{p}N$ annilation.
  - For $\sqrt{s} \geq 1.94$ GeV, we only reconstruct $\bar{p}$ directly.
- Based the 25 fb^{-1} Rscan data bellow 2 GeV, the observed cross section of $e^+e^- \to p\bar{p}$ near threshold from 1.840 to 1.970 GeV has been measured.
- The total uncertainties for energy points near threshold are about 15%, while for higher energy points are less than 10%.
- The threshold effect is observed similar to CMD-3 results, but increased more gradually.
- Memo is ready.

Future Plan

- ☐ Try more theoretical model for lineshape fit.

Thank you for attention!!!

$\bar{p}N \rightarrow Anything$

$\bar{p}p \rightarrow Anything$

Pionic multiplicity distribution	From Table 7	From [263]
2 pions	$0.38 \pm 0.03\%$	$0.38 \pm 0.03\%$
3 pions	$7.4 \pm 0.3\%$	$7.8 \pm 0.4\%$
4 pions	$18.1 \pm 1.8\%$	$17.5 \pm 3.0\%$
5 pions	$35.2 \pm 3.7\%$	$45.8 \pm 3.0\%$
6 pions	$23.3 \pm 2.8\%$	$22.1 \pm 1.5\%$
7 pions	$3.3 \pm 0.3\%$	$6.1 \pm 1.0\%$
8 pions		$0.3 \pm 0.1\%$

10^{-3}

Final state	BNL	CERN
K^+K^-	1.10 ± 0.10	0.96 ± 0.08
$K_sK_s + K_lK_l$	$0.010^{+0.012}_{-0.010}$	0.008 ± 0.008
K_sK_l	0.71 ± 0.10	0.80 ± 0.05
$(K_sK_s + K_lK_l)\pi^0$	1.46 ± 0.20	1.56 ± 0.12
$K_sK_l\pi^0$	0.67 ± 0.07	0.67 ± 0.07
$(K_sK_s + K_lK_l)MM$	1.28 ± 0.16	1.42 ± 0.26
$K_sK^\pm\pi^\mp$	4.25 ± 0.55	4.25 ± 0.20
$(K_sK_s + K_lK_l)\pi^-\pi^+$	4.02 ± 0.52	3.90 ± 0.46
$K_sK_l\pi^-\pi^+$	2.41 ± 0.36	2.26 ± 0.45
$K^0K^\pm\pi^\mp\pi^0$	8.94 ± 1.06	9.38 ± 1.10
$(K_sK_s + K_lK_l)\pi^-\pi^+\pi^0$	2.98 ± 0.44	2.20 ± 0.28
$K^0K^\pm\pi^\mp\pi^-\pi^+$	0.59 ± 0.08	0.71 ± 0.07
$K^0K^\pm 4\pi$	~ 0	~ 0
Sum	28.4 ± 1.5	28.1 ± 1.4

Physics Reports 413 (2005) 197 – 317

$\bar{p}n \rightarrow Anything$

Final state	Frequency (in %)
$\pi^- n\pi^0$	16.4 ± 0.5
$\pi^-\pi^0$	0.40 ± 0.04
$\pi^- 2\pi^0$	0.68 ± 0.07
$\pi^- 4\pi^0$	1.32 ± 0.20
$2\pi^-\pi^+ n\pi^0$	59.7 ± 1.2
$2\pi^-\pi^+$	1.57 ± 0.21
$2\pi^-\pi^+\pi^0$	21.8 ± 2.2
$2\pi^-\pi^+ 2\pi^0$	6.3 ± 1.1
$3\pi^- 2\pi^+ n\pi^0$	23.4 ± 0.7
$3\pi^- 2\pi^+$	5.15 ± 0.47
$3\pi^- 2\pi^+\pi^0$	15.1 ± 1.0
$4\pi^- 3\pi^+ n\pi^0$	0.39 ± 0.07
Sum	$95.5 \pm 1.5\%$

Final state	Frequency (in 10^{-4})
K^0K^-	14.7 ± 2.1
$K^0K^+\pi^-\pi^-$	36.0 ± 4.2
$K_sK_s\pi^-$	14.7 ± 2.0
$K_sK_l\pi^-$	21.2 ± 3.6
$K^0K^+\pi^-\pi^-$	24.8 ± 2.6
$K^0K^-\pi^+\pi^-$	34.2 ± 3.5
$K_sK_s\pi^-\pi^0$	25.6 ± 2.8
$K^0K^+\pi^-\pi^-\pi^0$	1.6 ± 0.9
$K_sK^-\pi^+\pi^-\pi^0$	33.6 ± 3.8
$K_sK^-\omega$	35.0 ± 5.2
$K_sK_s\pi^+\pi^-\pi^-$	2.8 ± 1.2
$K_sK_l\pi^+\pi^-\pi^-$	1.9 ± 1.2
Sum	$2.5 \pm 0.1\%$

Appendix:

$\bar{p}$ sample: Event Selection

- Anti-proton control sample is selected from $J/\psi \to p\bar{p}\pi^+\pi^-$ data, and here is the event selection:
  - **Good Charged Track:**

    $|\cos\theta| \leq 0.93$; $|V_{xy}| < 0.5$ cm; $|V_z| < 5.0$ cm; $3 \leq N_{charged} \leq 12$;
  - **PID**: use dE/dx and TOF information

    p: prob(p)>prob(π, K)

    π: prob(π)>prob(p, K)

    K: prob(K)>prob(π, p)

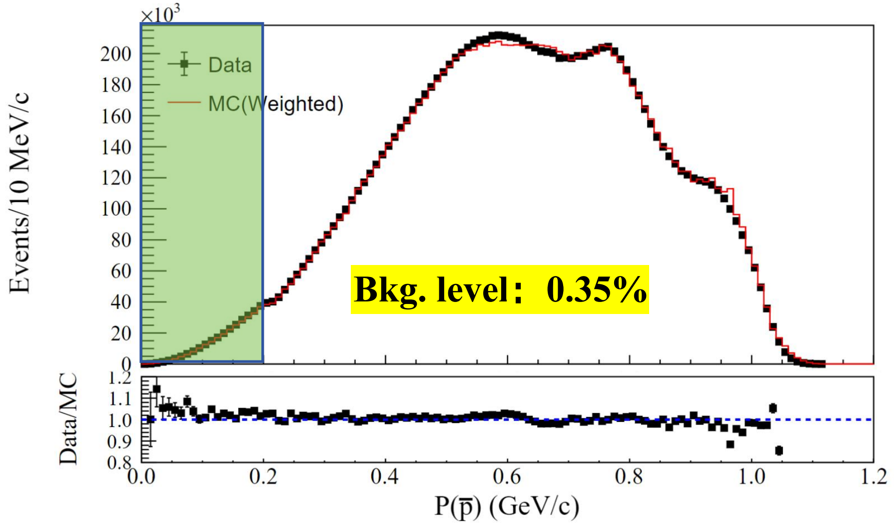
    $N_p \geq 1$ and $N_{\pi^+} \geq 1$ and $N_{\pi^-} \geq 1$
  - **Vertex fit:**

    Loop all the $p\pi^+\pi^-$ tracks, and select the combination with minimum χ^2_{VF}
  - **Kinematic fit:**

    Missing 3-momentu of $\bar{p}$, do 1C kinematic fit, χ^2_{KF}
  - **Recoil $\bar{p}$:**

    $P_{\bar{p}} = P_{cms} - P_p - P_{\pi^+} - P_{\pi^-}$ with 4-mom before Kinematic fit
  - **Further Selection:**

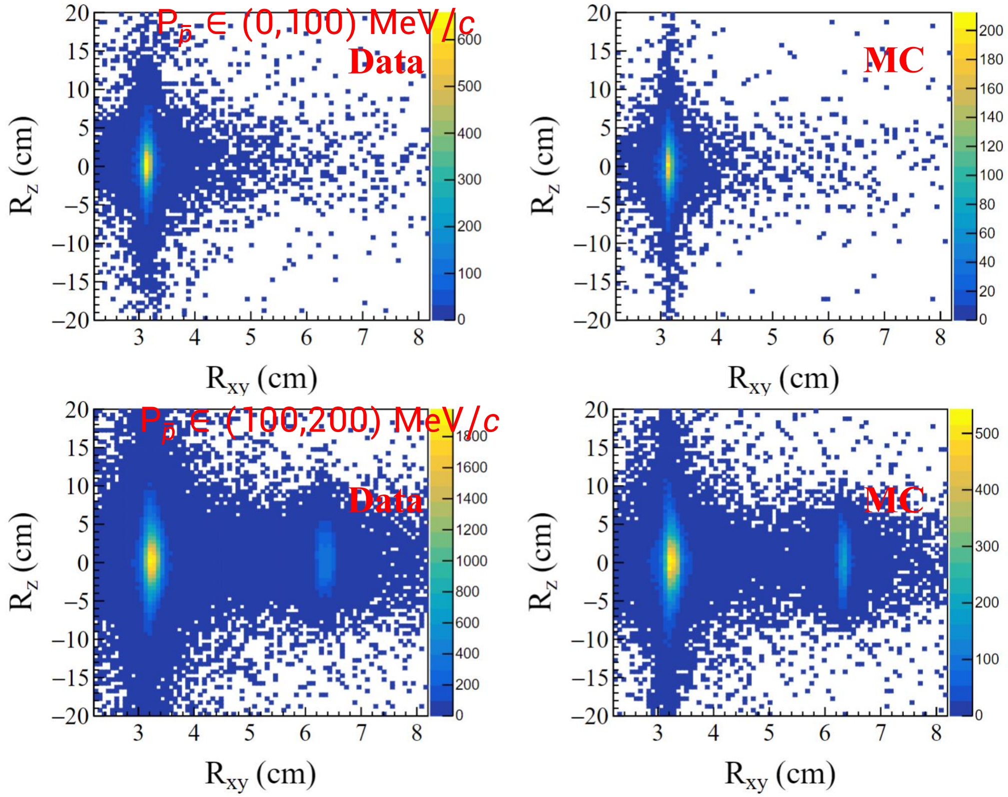
    $0.92 < M_{\bar{p}} < 0.96$ GeV/c^2, $\chi^2_{VF} < 20$, $\chi^2_{KF} < 10$,
    $M(p\pi^-) > 1.12$ GeV/c^2 or $M(p\pi^-) < 1.11$ GeV/c^2.

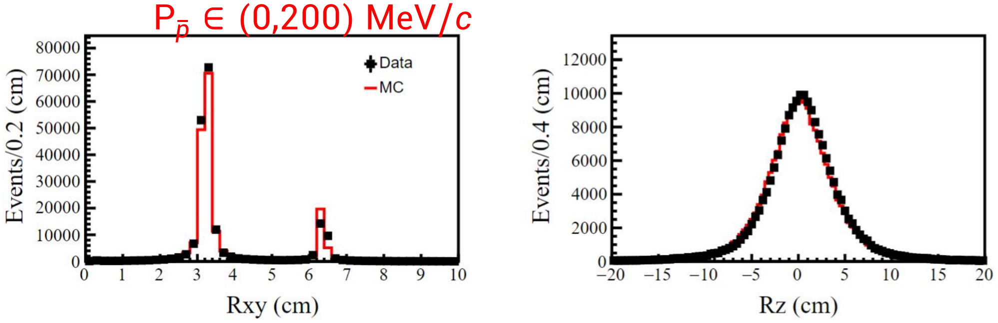


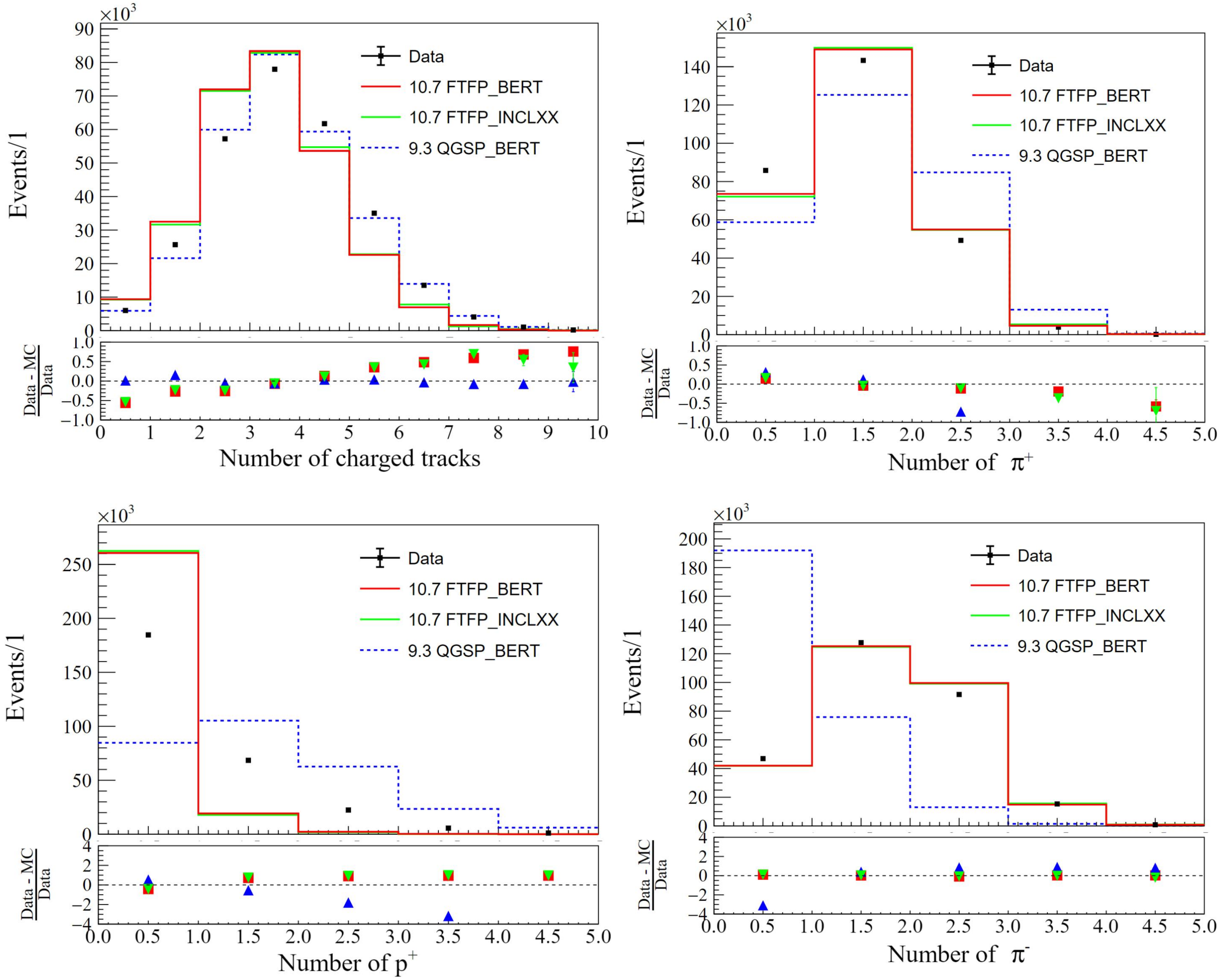
Almost 0.2 million antiproton with momentum less than 200 MeV/c obtained

Appendix:

$\bar{p}$ sample

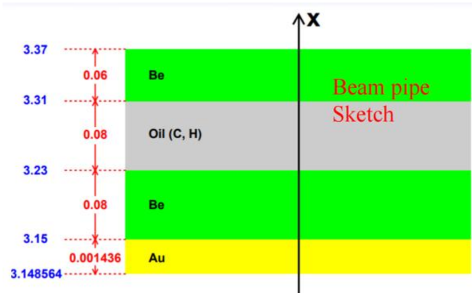


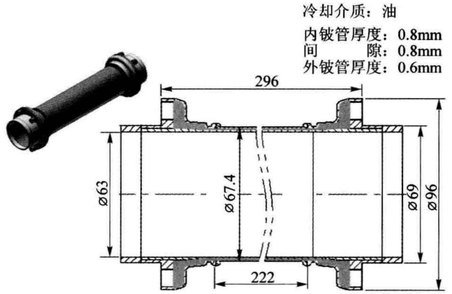


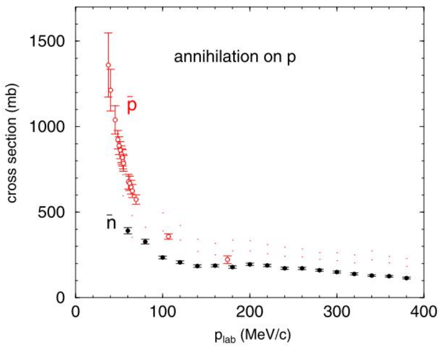


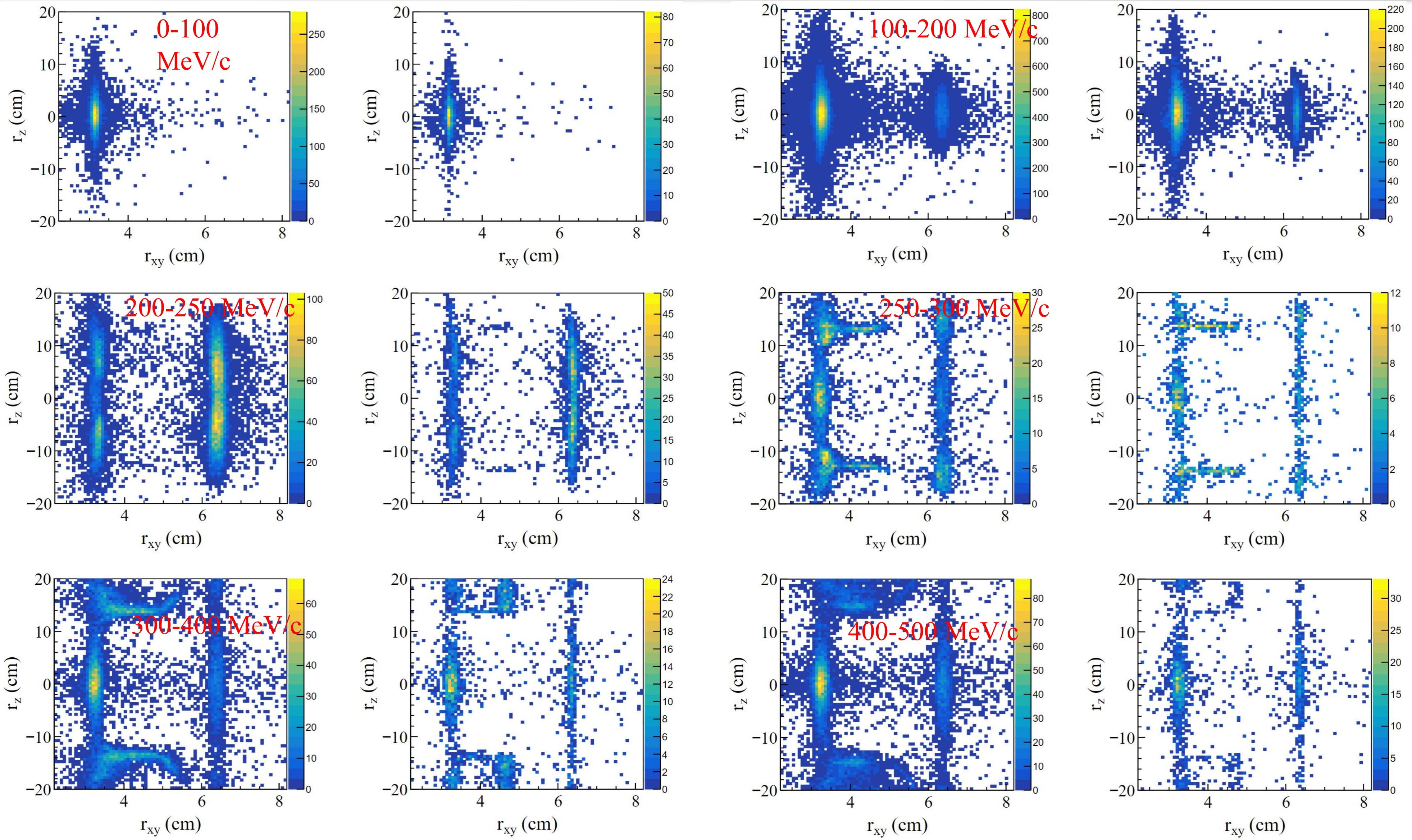
Appendix:

$\bar{p}$ sample



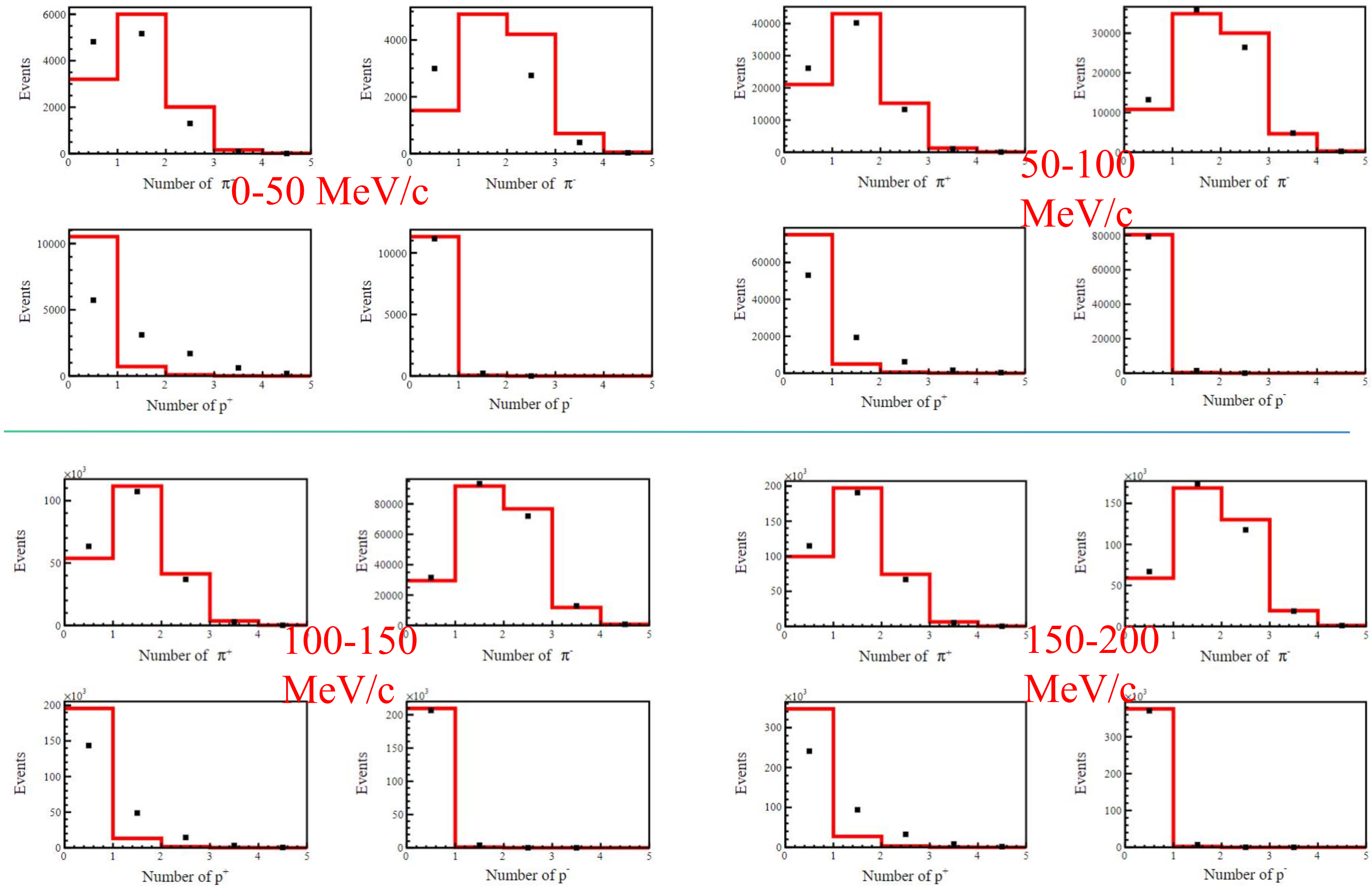






Appendix:

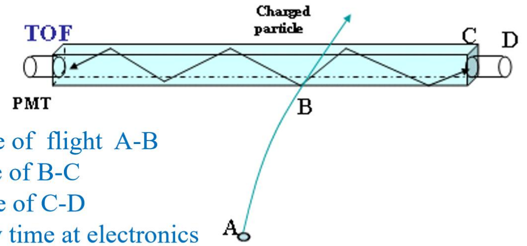
$\bar{p}$ sample



Appendix:

T0 mismatch: case1

Use TOF to calculate T_{est}



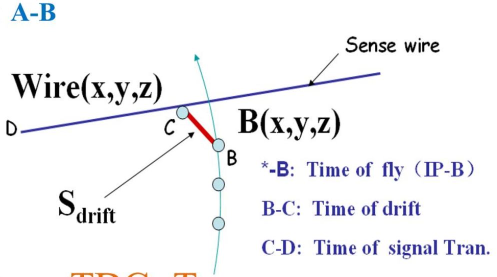
T_{tof}: Time of flight A-B
T_{pro}: Time of B-C
T_{pmt}: Time of C-D
T_{elc}: delay time at electronics

T_{est} = TDC - T_{ev}

$T_{ev} = T_{tof} + T_{pro} + T_{pmt} + T_{elc}$

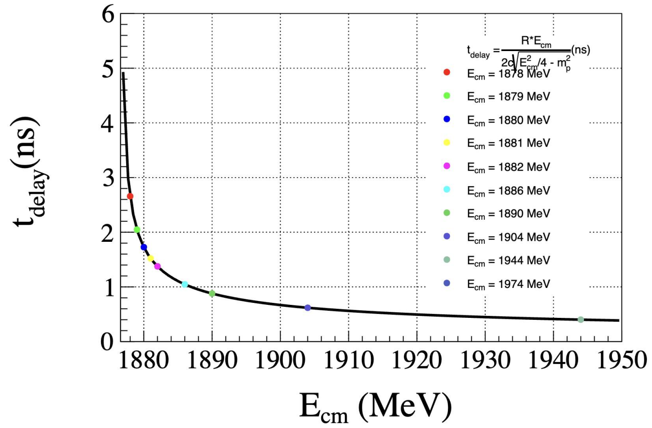
Use MDC to calculate T_{est}

T_f: Time of flight A-B
T_{drift}: Time of B-C
T_{wp}: Time of C-D
T_{elc}: delay time at electronics



T_{est} = TDC - T_{ev}

$T_{ev} = T_f + T_{drift} + T_{wp} + T_{elc}$

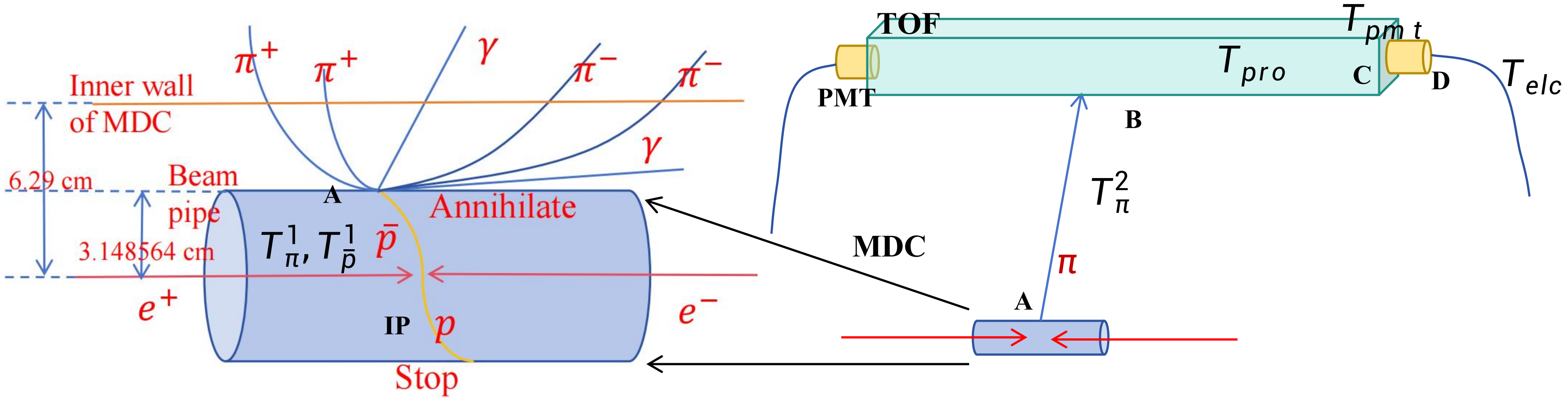


True case: $T_{tof} = T^1_{\bar{p}}$(before annihilation) + T^2_{π}

But in Alg: T_{tof} = ~~T^1_{π}(before annihilation)~~ + T^2_{π}

T_{ev} is underestimated, T_{est} is overestimated.

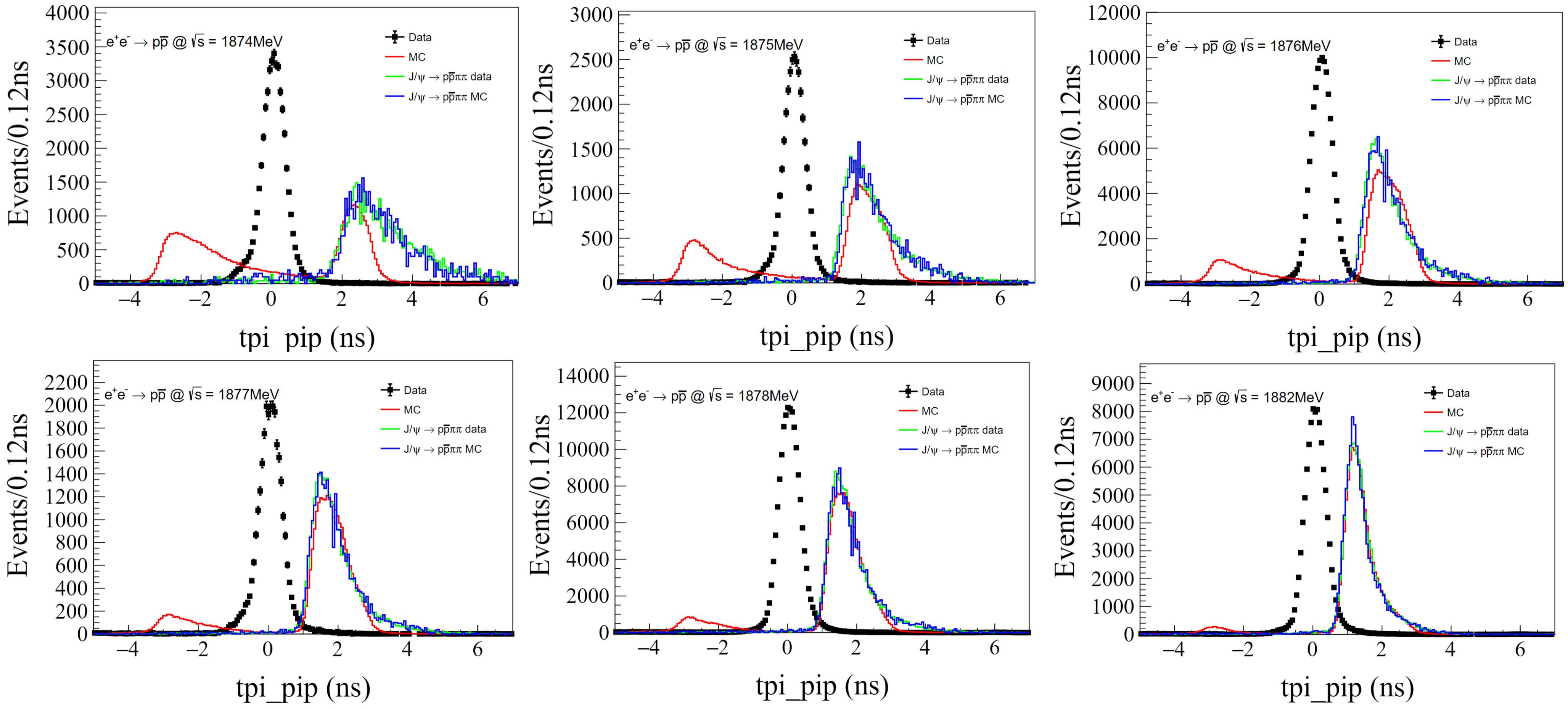
If $T_{\bar{p}}$ large than 3ns, T_0 will mismatch.



Appendix:

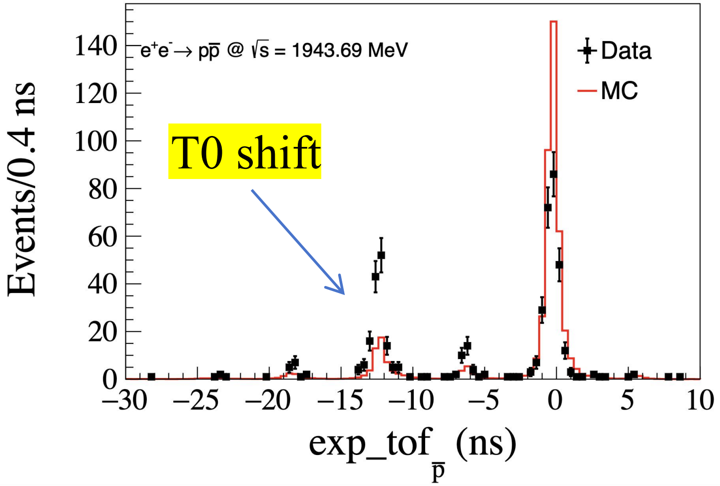
T0 mismatch: case1

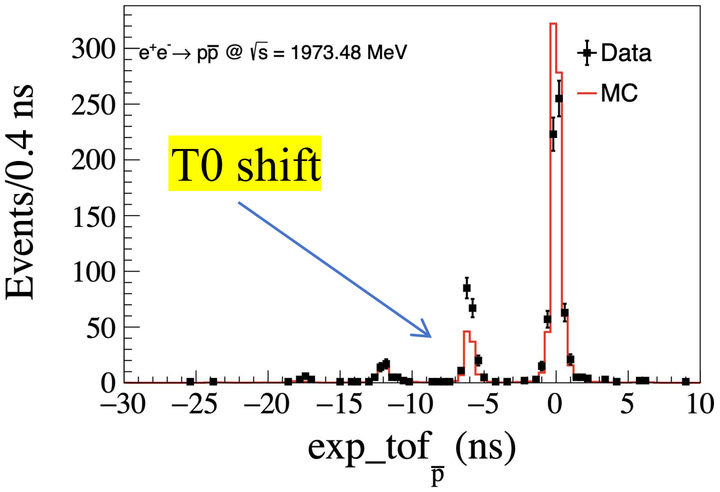
- $t_{\pi^{\pm}}$: $Tof_{\pi^{\pm}} - T_{\pi^{\pm}}^{exp}$



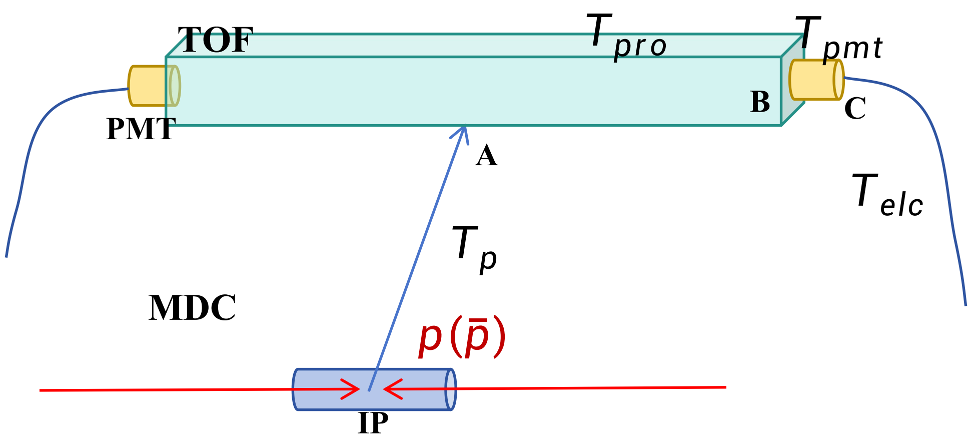
Appendix:

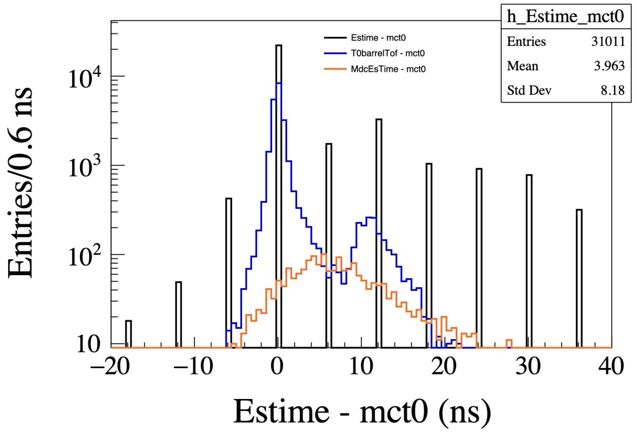
T0 mismatch: case2

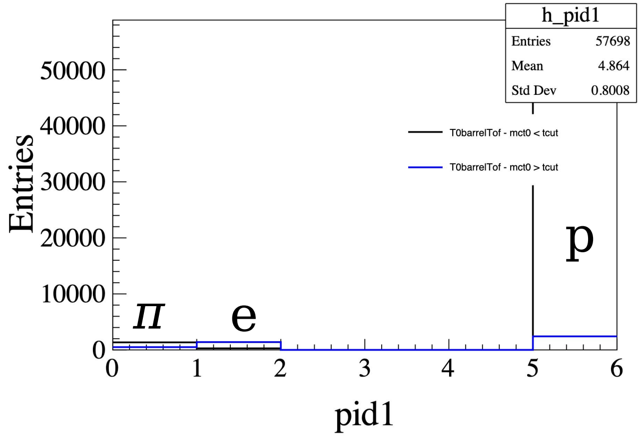




$$T_{ev} = T_{tof} + T_{pro} + T_{pmt} + T_{elc}; \quad T_{tof} = T_p$$







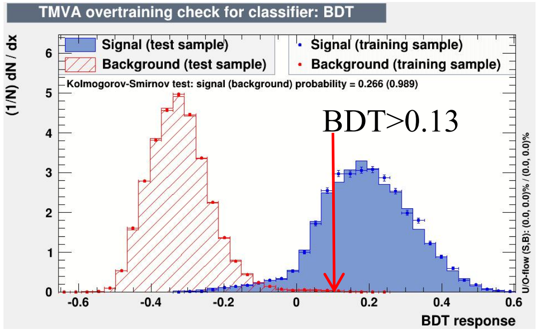
$$t_e = \frac{81cm}{30\ cm/ns} \cong 2.7ns$$

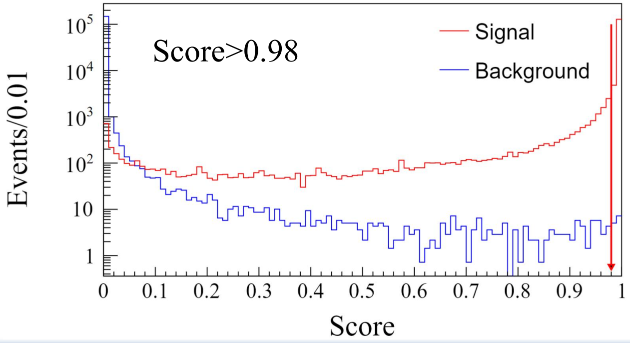
$$t_p = \frac{81cm}{0.2 * 30\ cm/ns} \cong 13.5ns$$

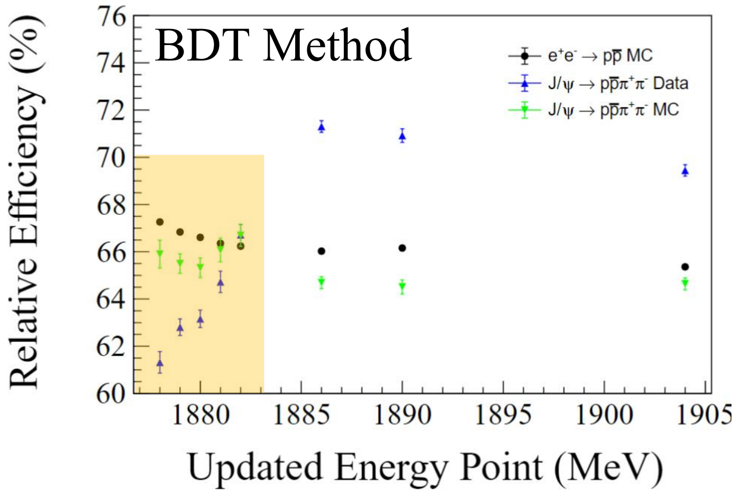
Appendix:

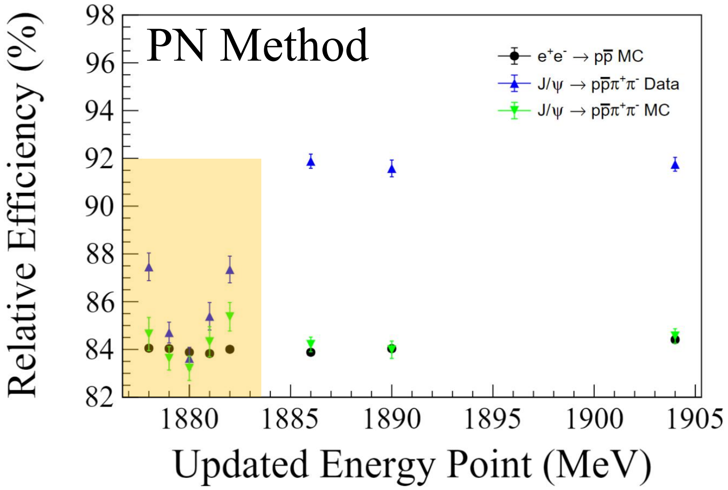
Machine Learning Method

- Some ML methods are used to supress the backgrounds: MVA(BDT), GNN(Particle Net).
  - ➢ Training was conducted using data below the threshold (as background, @1.840, 1.870 GeV) and control sample data (as signal, with $P_{\bar{p}} < 0.1$ GeV), and the trained model was applied to all energy point data and MC.
  - ➢ Simply using the 1.870 GeV data and nnbar MC to estimate background events.
- Compare the ML relative efficiency given by $p\bar{p}$ MC and $J/\psi \to p\bar{p}\pi^+\pi^-$ control sample:









✓ Take GNN method as the nominal one, and BDT as a cross-check.

Machine Learning Method

Features of Changed Tracks:

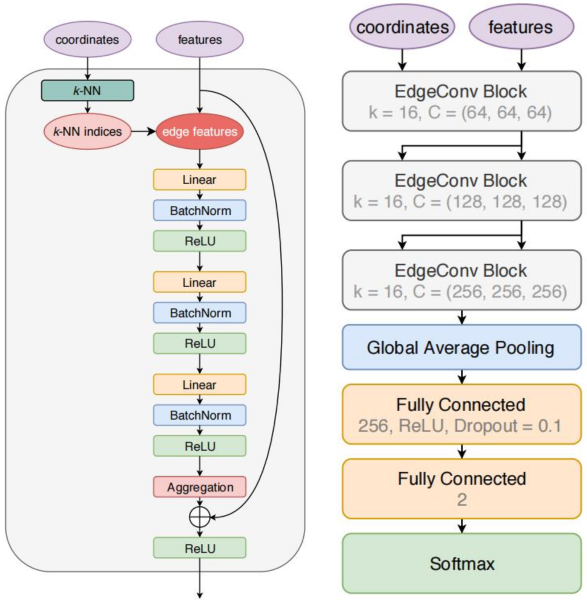
- **Azimuth angle:** ϕ and θ in lab frame.
- **Charge:** the charge of track.
- **Momentum:** the momentum of track. To achieve better resolution, this feature is obtained from `RecMdcKalTrack` after Kalman filter.
- **Helix parameters:** the five helix parameters $\left(d_\rho,\ d_z,\ \kappa,\ \phi_0,\ \lambda\right)$ describing the spatial trajectory of track.
- $\chi_{\mathbf{d}E/\mathbf{d}x}$**:** the four variables describing the divergence of $\mathrm{d}E/\mathrm{d}x$ measurement from its expected values under electron, pion, kaon and proton hypotheses, respectively.

Points of Tracks:

- (θ, ϕ) as the position of particles.

$$\boldsymbol{x}_i' = \mathop{\square}_{j=1}^{k} \boldsymbol{h}_{\Theta}(\boldsymbol{x}_i, \boldsymbol{x}_{i_j}),$$

$$\boldsymbol{h}_{\Theta}(\boldsymbol{x}_i, \boldsymbol{x}_{i_j}) = \bar{\boldsymbol{h}}_{\Theta}(\boldsymbol{x}_i, \boldsymbol{x}_{i_j} - \boldsymbol{x}_i),$$



Features of Neutral Tracks:

- **Azimuth angle:** ϕ and θ in lab frame.
- **Energy:** the energy of this shower.
- **Hit Number:** the number of hitting crystals in EMC.
- **Time:** the time information of shower.
- $\boldsymbol{E_{III}}$ **and** $\boldsymbol{E_V}$**:** the ratio of energy deposited in the 3×3 or 5×5 crystal around the center of the shower, respectively.
- $\boldsymbol{A_{20}}$ **moment and** $\boldsymbol{A_{42}}$ **moment:** the Zernike moment A_{nm} defined as

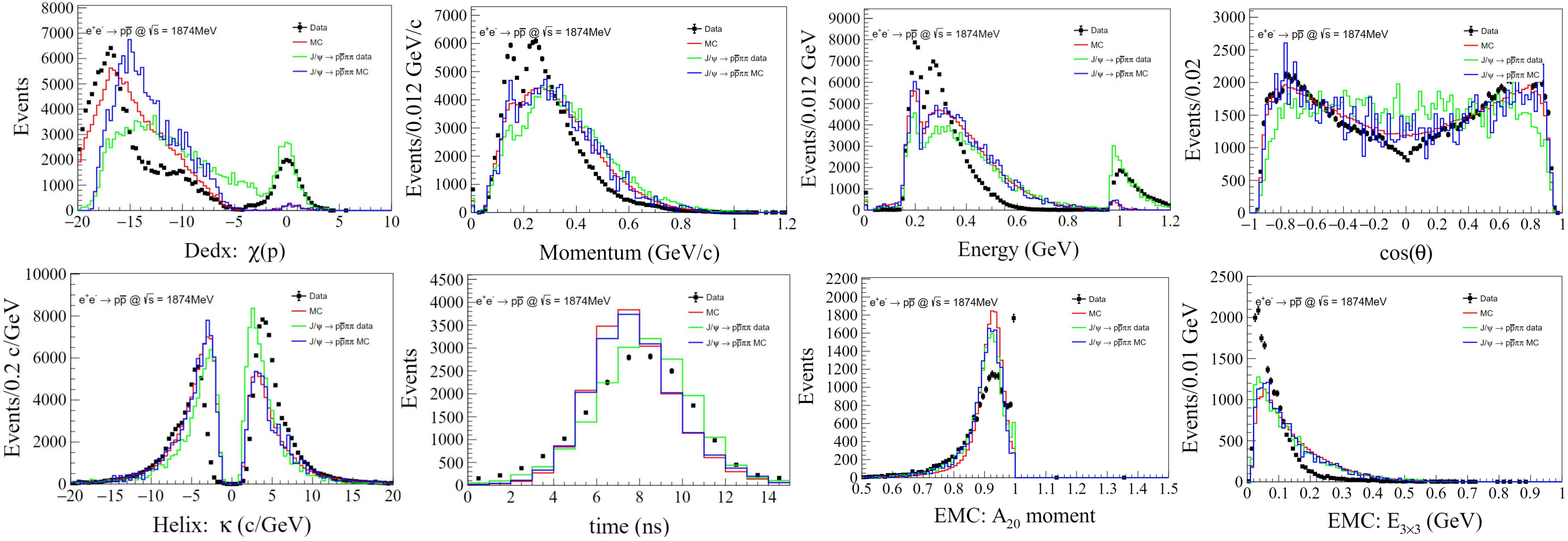
$$A_{n,m} = \left|\sum_i \frac{E_i}{E_{tot}} f_{n,m}(r_i/R_0) e^{im\phi}\right|, \tag{9}$$

with $f_{2,0}(x) = 2x^2 - 1$ and $f_{4,2} = 4x^4 - 3x^2$. Here i denotes the different crystals, E_i is the energy deposited in the crystal and r_i is its distance from the shower center.

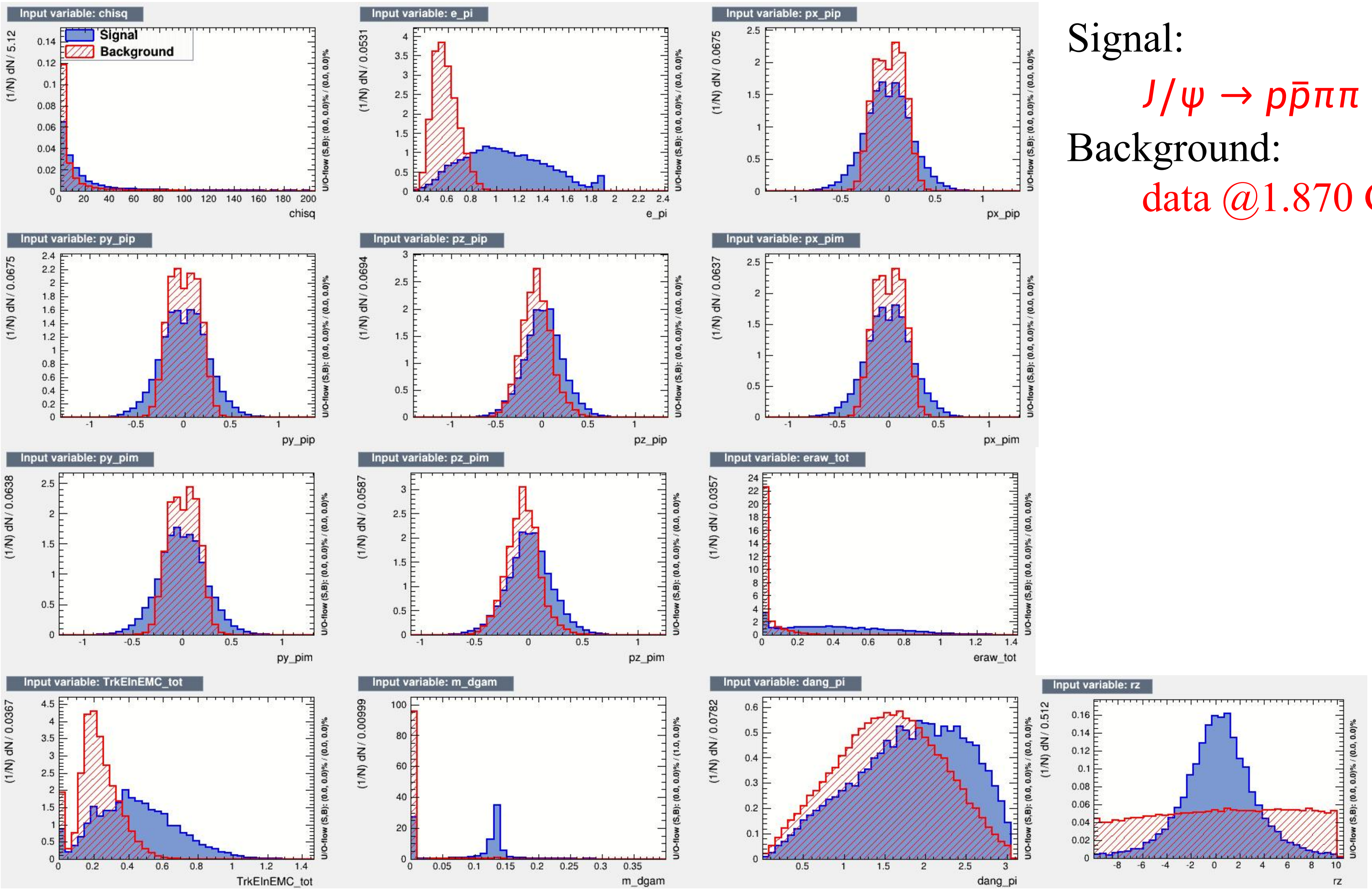
- **Secondary moment:** defined as $\sum_i E_i r_i^2 / \sum_i E_i$.
- **lateral moment:** defined as $\sum_{i=3}^{n} E_i r_i^2 / (E_1 r_0^2 + E_2 r_0^2 + \sum_{i=3}^{n} E_i r_i^2)$.

Appendix:

Machine Learning Method



Appendix:
BDT Method



Signal:

$J/\psi \to p\bar{p}\pi\pi$ data with $P_{\bar{p}} < 0.1$ GeV

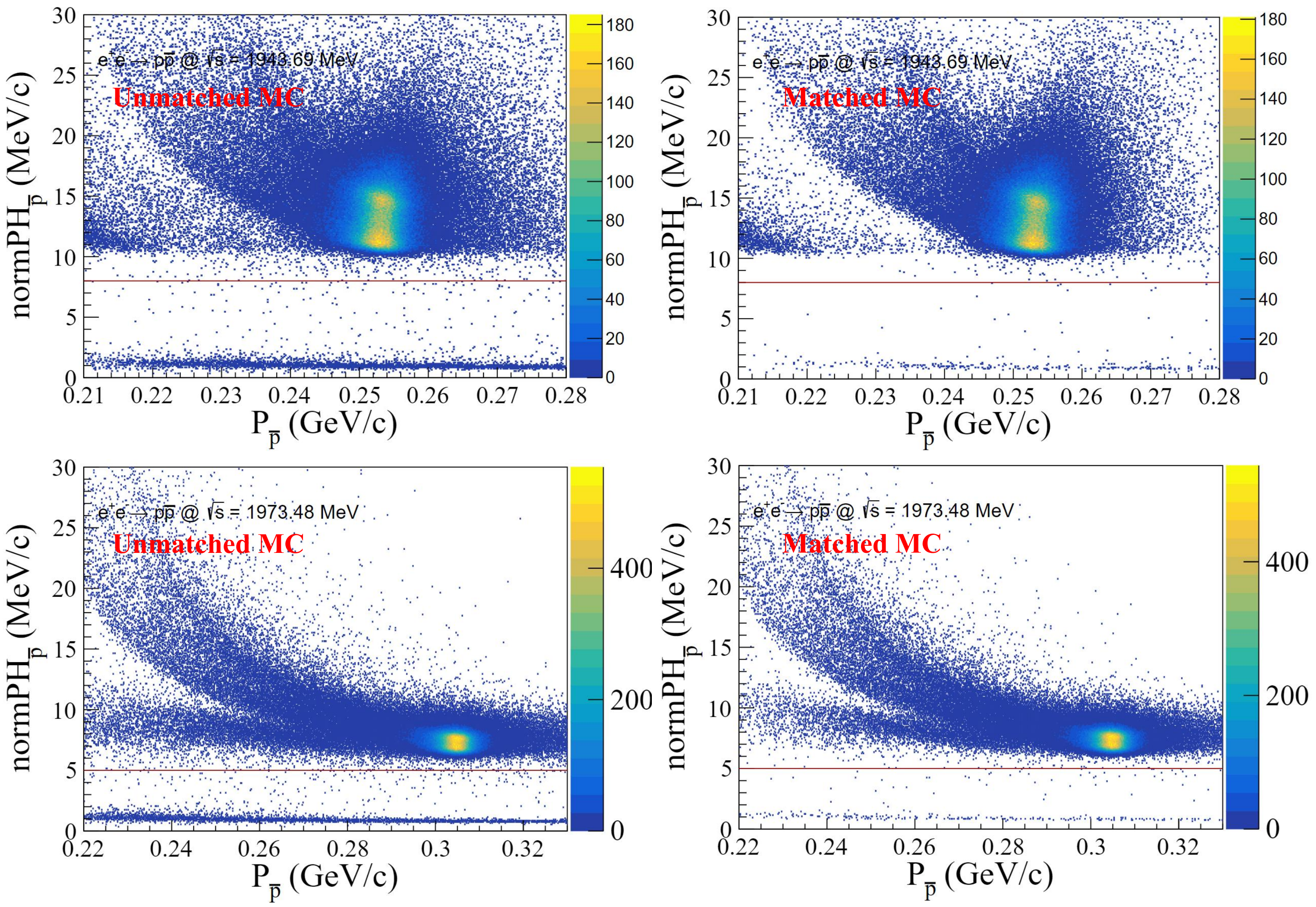
Background:

data @1.870 GeV and 1.840 GeV

Appendix:

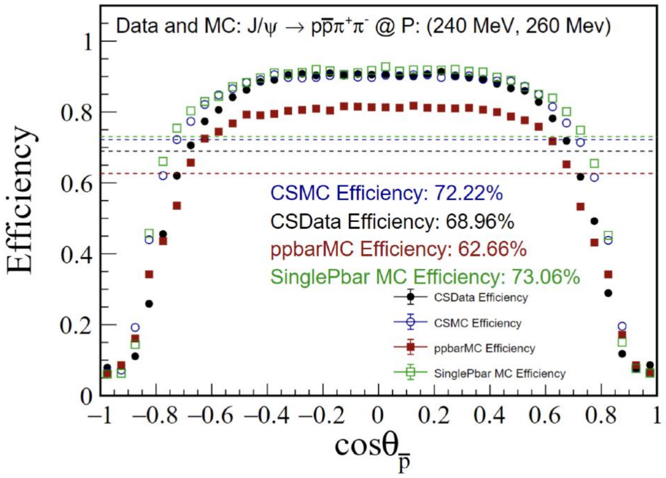
normPH cut

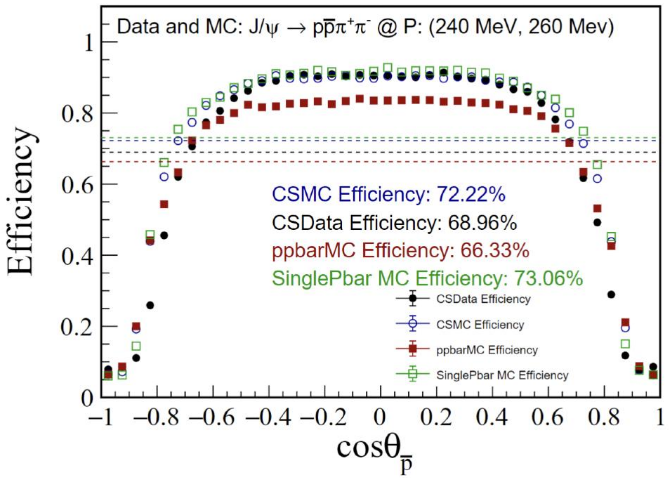
- ✓ $\Delta\theta_{\bar{p}}(\mathrm{Rec}-\mathrm{Truth}) < 5^{\circ}$

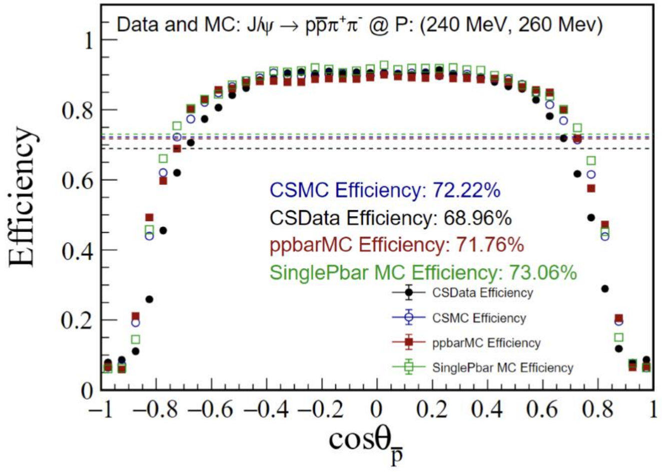


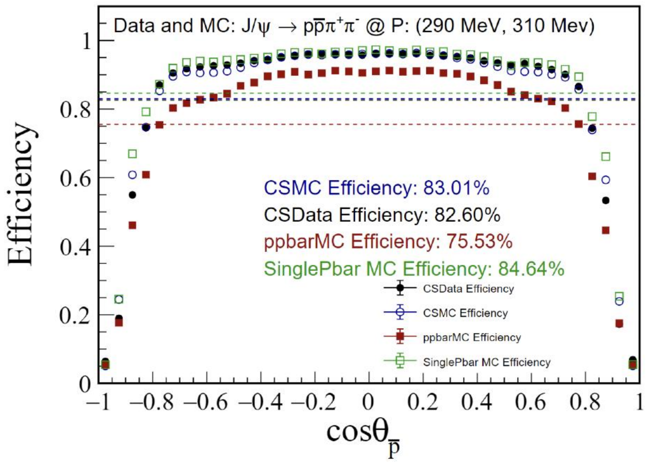
Appendix:

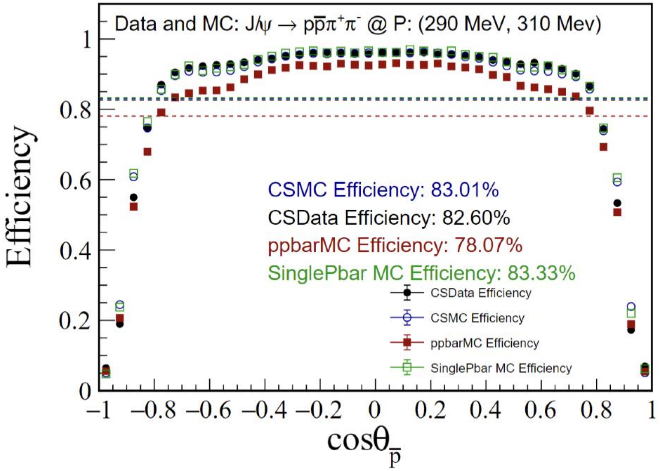
Tracking Efficiency

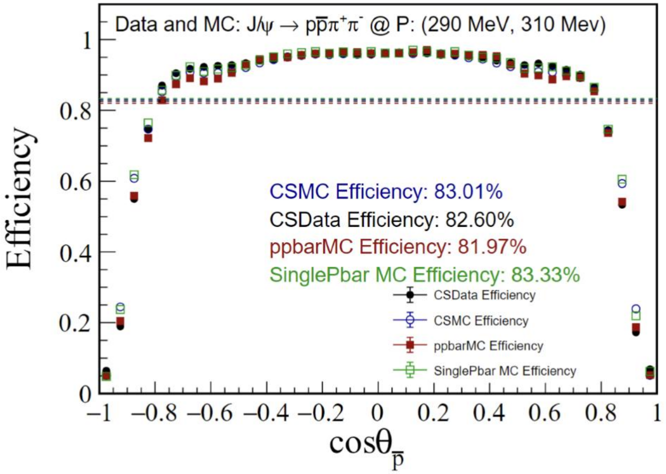












Appendix:

$e^+e^- \to n\bar{n}$ and other background

➢ **SND experiment: 0.5 ± 0.1 nb**

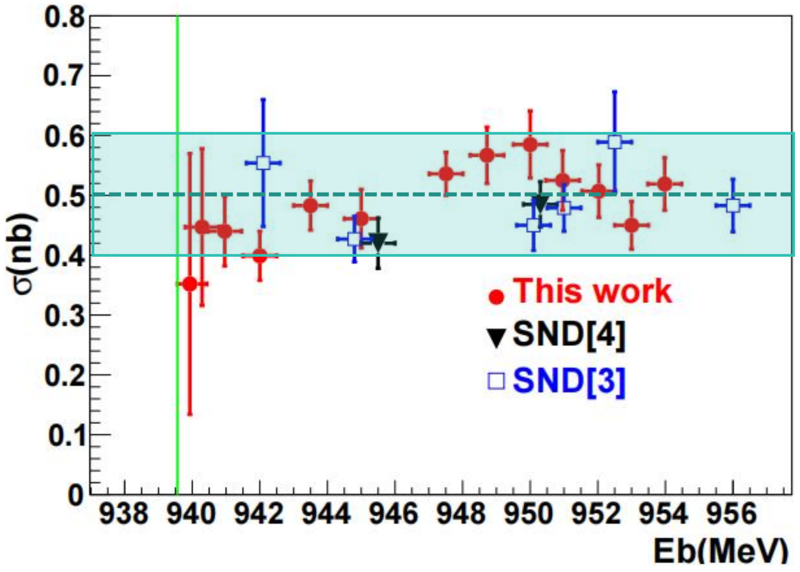
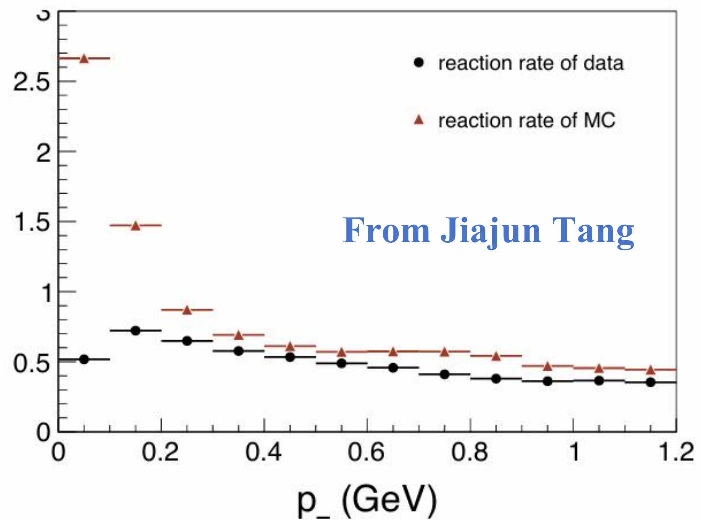


FIG. 12: The measured $e^+e^- \to n\bar{n}$ cross section in the vicinity of the nucleon threshold. The vertical line is the $n\bar{n}$ threshold.



➢ **Background estimation:**

$$\sigma_{other\ bkg} = \frac{\sqrt{N_{other\ bkg}}}{N_{obs} - N_{other\ bkg} - N_{n\bar{n}}}$$

$$\sigma_{n\bar{n}\ bkg} = \frac{N_{n\bar{n}\ bkg} * 20\%}{N_{obs} - N_{other\ bkg} - N_{n\bar{n}}}$$

Appendix: