Search for BNV process at BESIII

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Introduction

- If baryon number is conserved, in the process of baryon generation and annihilation of baryon-antibaryon pairs, the baryon number should always be 0, which means there should not be more matter than antimatter. But it is observed to depart from the fact. So, Sakharov put forward three rules:
  (1) Baryon number violating (BNV).
  (2) C violation and CP violation.
  (3) Out of thermal equilibrium.
- As many theories have suggested, even a small amount of BNV processes can cause great influence on the universe and its evolution. Searching for BNV processes can help to learn the origin of matter and expend the standard model.

Results on BESIII Experiments

BNV:

$\overline{\Lambda} - \Lambda$ oscillations with $\Delta B = 2$(PRL 131, 121801 (2023))

(B-L)NV:

$D^{\pm} \to n(\overline{n})e^{\pm}$ (PRD 106, 112009 (2022))

$\Xi^0 \to K^{\pm}e^{\mp}$(PRD 108, 012006 (2023))

$D^0 \to pe^-(\overline{p}e^+)$(PRD 105, 032006 (2022))

$J/\psi \to pe^-/\overline{p}e^+$ Ongoing

Search for (B-L) NV $D^{\pm} \to n(\overline{n})e^{\pm}$

- Data samples: 2.93 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 3.773GeV$
- In most grand unified theories (GUTs) and some SM extension models, baryon-number and lepton-number violation (LNV) is allowed, but the difference of baryon and lepton is conserved ($\Delta|B-L| = 0$) Dimension-six operators
- $\Delta|B-L| = 2$ Dimension-seven operators

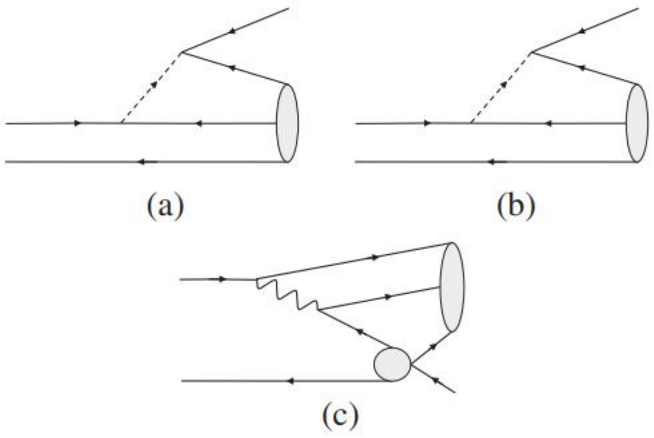


FIG. 1. Feynman diagrams for $D^+ \to \bar{n}e^+$ with heavy gauge bosons X (a) and Y (b), and $D^+ \to ne^+$ with elementary scalar fields ϕ (c).

PRD 106, 112009 (2022))

Search for (B-L) NV $D^{\pm} \to n(\overline{n})e^{\pm}$

- Method : $\psi(3773) \to D^+D^-, D^{\pm} \to n(\overline{n})e^{\pm}$
  - Double tag

ST modes	$N^i_{\mathrm{ST}}(\times 10^3)$	ϵ^i_{ST}	$\epsilon^{i,c1}_{\mathrm{DT}}$	$\epsilon^{i,c2}_{\mathrm{DT}}$
$D^+ \to K^-\pi^+\pi^+$	390.2 ± 1.1	50.22 ± 0.03	9.79	9.26
$D^+ \to K^-\pi^+\pi^+\pi^0$	124.0 ± 0.6	26.40 ± 0.05	5.51	5.21
$D^+ \to K^0_S\pi^+$	45.9 ± 0.2	50.58 ± 0.10	9.69	9.17
$D^+ \to K^0_S\pi^+\pi^0$	106.7 ± 0.6	27.07 ± 0.06	5.66	5.36
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	56.9 ± 0.4	28.16 ± 0.08	5.64	5.34
$D^+ \to K^+K^-\pi^+$	34.6 ± 0.3	41.13 ± 0.15	7.88	7.46
$D^- \to K^+\pi^-\pi^-$	392.4 ± 0.7	51.19 ± 0.03	9.21	9.72
$D^- \to K^+\pi^-\pi^-\pi^0$	127.7 ± 1.0	26.86 ± 0.06	5.19	5.47
$D^- \to K^0_S\pi^-$	45.5 ± 0.2	50.64 ± 0.09	9.12	9.62
$D^- \to K^0_S\pi^-\pi^0$	107.6 ± 0.6	27.21 ± 0.05	5.33	5.63
$D^- \to K^0_S\pi^-\pi^-\pi^+$	56.2 ± 0.4	27.87 ± 0.07	5.31	5.60
$D^- \to K^+K^-\pi^-$	34.6 ± 0.3	40.40 ± 0.12	7.42	7.83

$D^{+(-)} \to \overline{n}(n)e^{+(-)}$
$with\ \Delta|B-L| = 0$

$D^{+(-)} \to n(\overline{n})e^{+(-)}$
$with\ \Delta|B-L| = 2$

PRD 106, 112009 (2022))

Search for (B-L) NV $D^{\pm} \to n(\overline{n})e^{\pm}$

- In the fit, signal and background are modeled by the MC simulated shapes obtained from signal and inclusive MC samples, respectively.

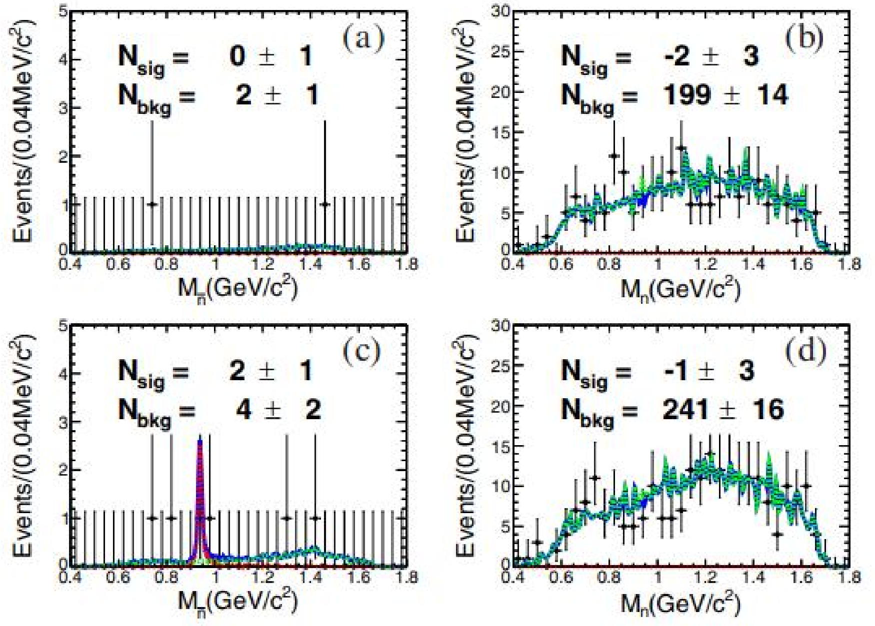


FIG. 4. Fit for $M_{n/\bar{n}}$ distributions for processes (a) $D^+ \to \bar{n}e^+$, (b) $D^- \to ne^-$, (c) $D^- \to \bar{n}e^-$, and (d) $D^+ \to ne^+$. The black dots with error bar are data. The red dotted, green dotted and blue solid lines are signal, background, and the sum of signal and background, respectively.

$D^{+(-)} \to \overline{n}(n)e^{+(-)}$:

$\mathcal{B}(D^{+(-)} \to \overline{n}(n)e^{+(-)}) < 1.43 \times 10^{-5}$

$D^{+(-)} \to \overline{n}(n)e^{+(-)}$:

$\mathcal{B}(D^{+(-)} \to n(\overline{n})e^{+(-)}) < 2.91 \times 10^{-5}$

PRD 106, 112009 (2022))

Search for B-L NVdecays $D^0 \to pe^-(\bar{p}e^+)$

- Data sample: 2.93 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 3.773GeV$. $e^+e^- \to D^0\bar{D}^0, D^0 \to pe^-(\bar{p}e^+)$
- In 2009, the CLEO Collaboration searched for the decays of $D^0(\bar{D}^0) \to pe^+$ and $D^0(\bar{D}^0) \to pe^-$ and set upper limits (ULs) on the BFs to be $\mathcal{B}(D^0(\bar{D}^0) \to pe^+) < 1.1 \times 10^{-5}$ and $\mathcal{B}(D^0(\bar{D}^0) \to pe^-) < 1.0 \times 10^{-5}$ at 90% confidence level (CL), respectively.
- $\Delta|B - L| = 0 \longleftarrow$ Dimension-six operators .These decays can be mediated by heavy gauge bosons X and Y which have electric charge $\frac{4}{3}$ e or $\frac{1}{3}$e and can couple a quark to a lepton.

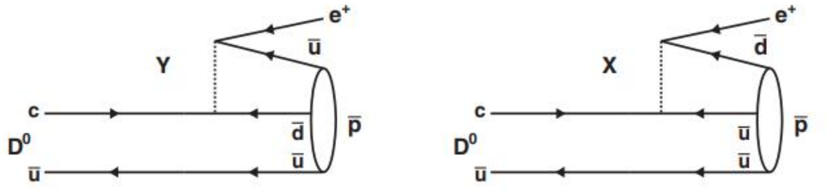


FIG. 1. Feynman diagrams of $D^0 \to \bar{p}e^+$ based on a leptoquark scenario.

PRD 105, 032006 (2022)

Search for B-L NVdecays $D^0 \to pe^-(\bar{p}e^+)$

- Method :
  - Double tag method
- Signal tag channel:
  - $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^0$, $\bar{D}^0 \to K^+\pi^+\pi^-\pi^-$

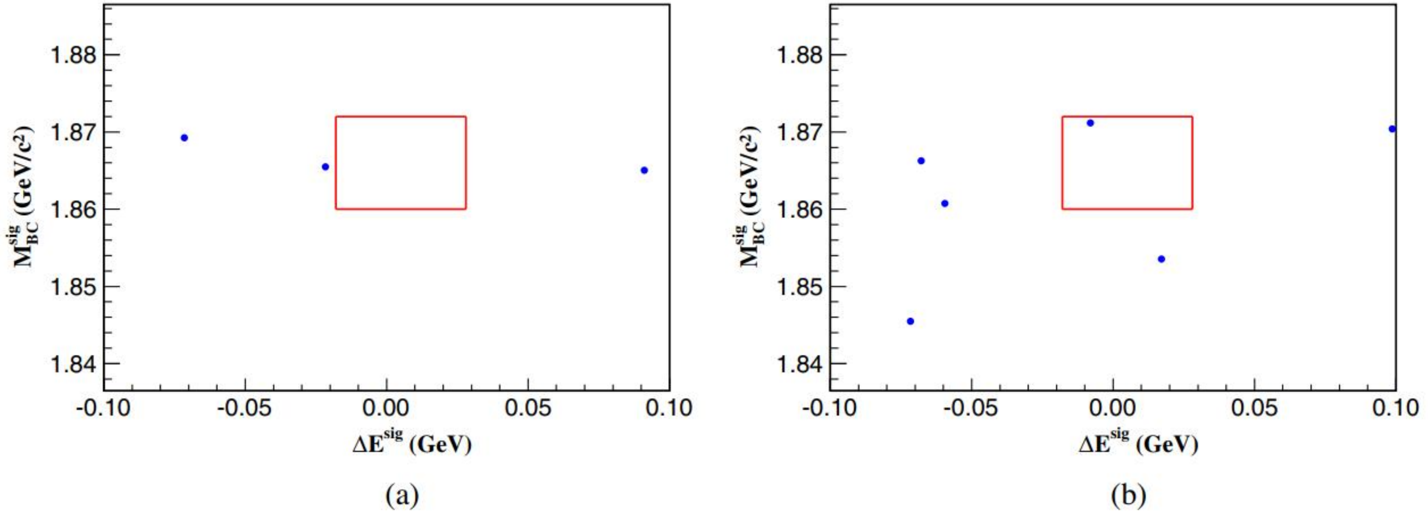


FIG. 3. Distributions of $M_{\rm BC}^{\rm sig}$ vs $\Delta E^{\rm sig}$ of the candidate events for (a) $D^0 \to \bar{p}e^+$ and (b) $D^0 \to pe^-$ in data. The red rectangles denote the signal region.

$D^0 \to \bar{p}e^+$:

$\mathcal{B}(D^0 \to \bar{p}e^+) < 1.2 \times 10^{-6}$

$D^0 \to pe^-$:

$\mathcal{B}(D^0 \to pe^-) < 2.2 \times 10^{-6}$

PRD 105, 032006 (2022)

Search for B-L NV decays of Ξ0 hyperons

- Data sample : $(1.0087 \pm 0.0044) \times 10^{10}\ J/\psi$
- Experimentally, potential BNV processes have been searched for in D decays, J/ψ decays, τ decays, B decays, top-quark decays and Λ hyperon decays. So far, no signal has been observed, and the upper limits on their branching fractions were set to be $10^{-3}{\sim}10^{-8}$ at the 90% (95% for top-quark decays) confidence level.
- The CLAS experiment has searched for Λ hyperon decays, imposing an upper limit on the branching fraction in the range of $10^{-5}{\sim}10^{-7}$ at the 90% confidence level.

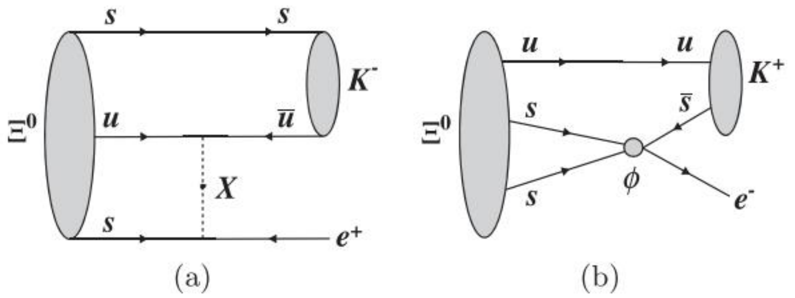


FIG. 1. Feynman diagrams for the BNV decays of (a) $\Xi^0 \to K^- e^+$ with $\Delta(B-L) = 0$ mediated by a gauge boson X and (b) $\Xi^0 \to K^+ e^-$ with $|\Delta(B-L)| = 2$ mediated by an elementary scalar field ϕ.

PRD 108, 012006 (2023)

Search for B-L NV decays of Ξ0 hyperons

- Process:
  - $J/\psi \to \Xi^0\overline{\Xi^0}$, $\overline{\Xi^0} \to \overline{\Lambda}(\to \bar{p}\pi^+)\pi^0(\to \gamma\gamma)$, $\Xi^0 \to K^\pm e^\mp$.
- Method: Tag method

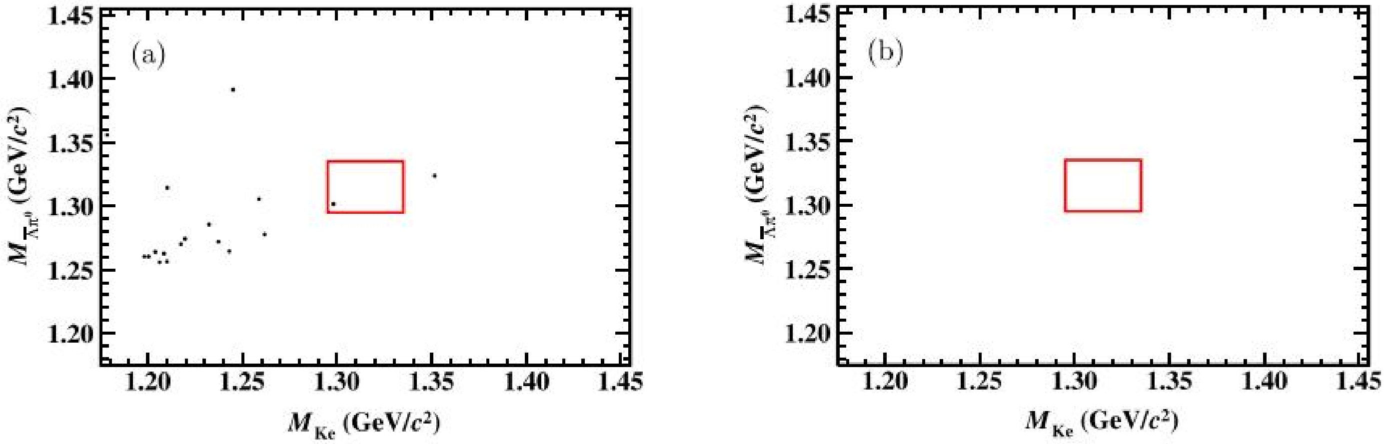


FIG. 3. Distributions of M_{Ke} versus $M_{\bar{\Lambda}\pi^0}$ of the accepted candidates for (a) $\Xi^0 \to K^- e^+$ and (b) $\Xi^0 \to K^+ e^-$ in data, respectively. The red box indicates the signal region.

$\Xi^0 \to K^- e^+$:

$\mathcal{B}(\Xi^0 \to K^- e^+) < 3.6 \times 10^{-6}$

$\Xi^0 \to K^+ e^-$:

$\mathcal{B}(\Xi^0 \to K^+ e^-) < 1.9 \times 10^{-6}$

PRD 108, 012006 (2023)

$J/\psi \to pe^- / \bar{p}e^+$

- Inclusive MC: 2748M (2009, 2012 and 2021)
- Semi-blind data: 270M (10% of full $\psi(2S)$ data)
- BOSS version: 7.0.9
- Generator:

```
Decay psi(2S)
1.0 J/psi  pi+ pi-                     JPIPI;
Enddecay

Decay J/psi
1.0   anti-p-   e+                    PHSP;
Enddecay


End
```

```
Decay psi(2S)
1.0 J/psi  pi+ pi-                     JPIPI;
Enddecay

Decay J/psi
1.0   p+   e-                     PHSP;
Enddecay


End
```

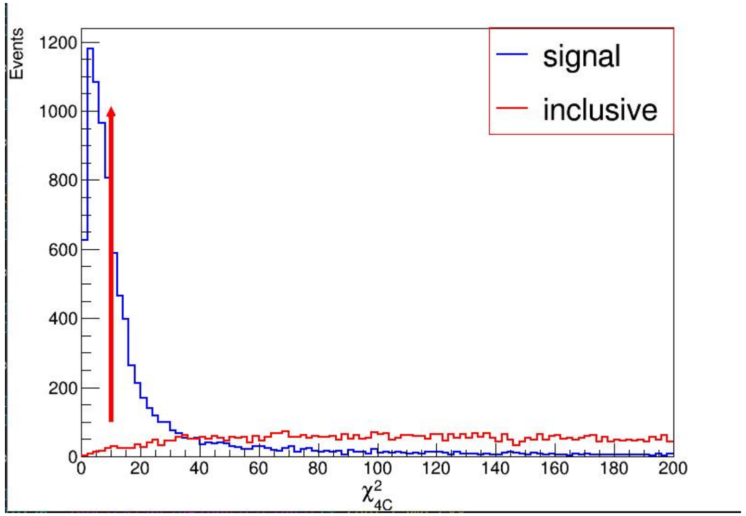
Event Selection

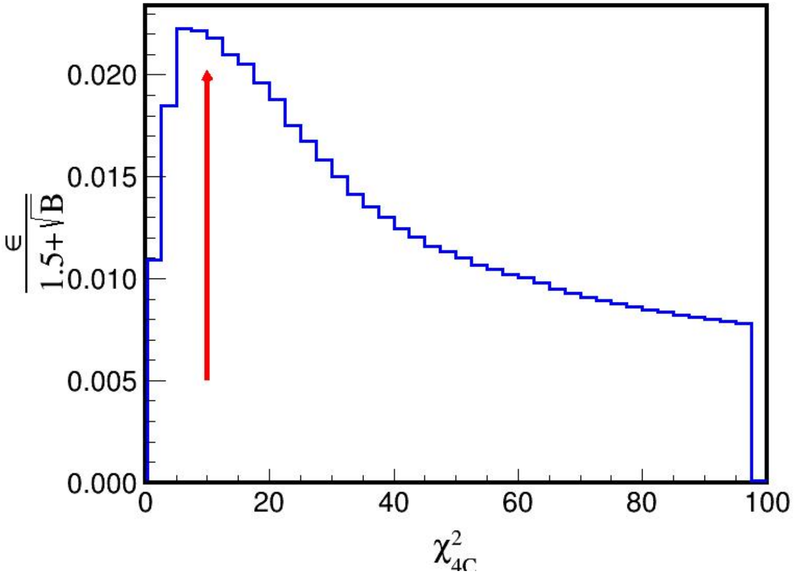
1. Total tracks ≥ 3
2. 4 good charged tracks, Total charge = 0
   $|V_z|$ < 5 cm
   V_r < 1 cm
   $|\cos\theta|$ < 0.93
3. PID (Combine dE/dx and TOF)
   pion: $|p_\pi| < 0.45\ \mathrm{GeV}/c^2$
   electron: $\frac{CL_e}{CL_e+CL_\pi+CL_K} > 0.8$, $CL_e > 0.001$, $0.8 < E/p\ ratio$
   proton: $CL_p > CL_K, CL_p > CL_\pi,\ CL_p > CL_e, CL_p > 0.001$

4. 4c kinematic fit: $\chi^2(\pi^+\pi^-pe^-) < \chi^2(\pi^+\pi^-e^+e^-)$,
   $\chi^2(\pi^+\pi^-pe^-) < \chi^2(\pi^+\pi^-\pi^+\pi^-)$,
   $\chi^2(\pi^+\pi^-pe^-) < \chi^2(\pi^+\pi^-\mu^+\mu^-)$,
   $\chi^2(\pi^+\pi^-pe^-) < \chi^2(\pi^+\pi^-K^+K^-)$,
   $\chi^2(\pi^+\pi^-pe^-) < \chi^2(\pi^+\pi^-p\,\bar{p})$;

Event Selection

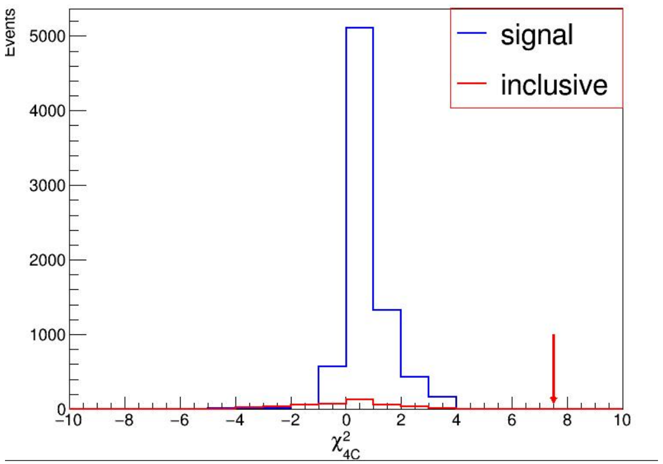
5. $\chi^2(\pi^+\pi^-\bar{p}e^+) \leq 10$ (determined by Punzi significance method)

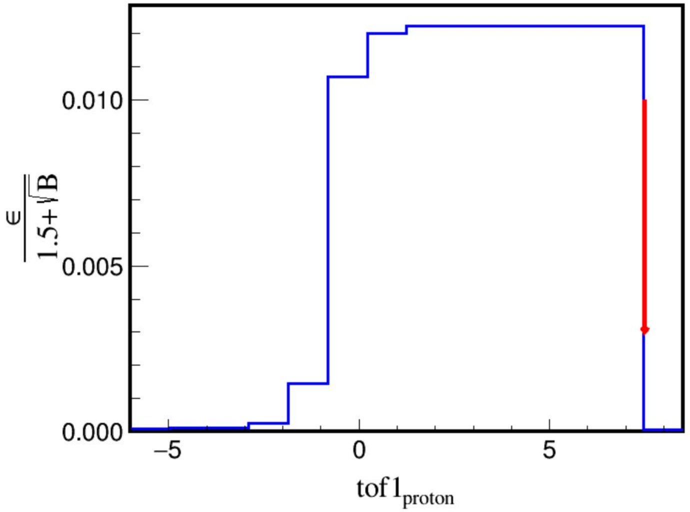


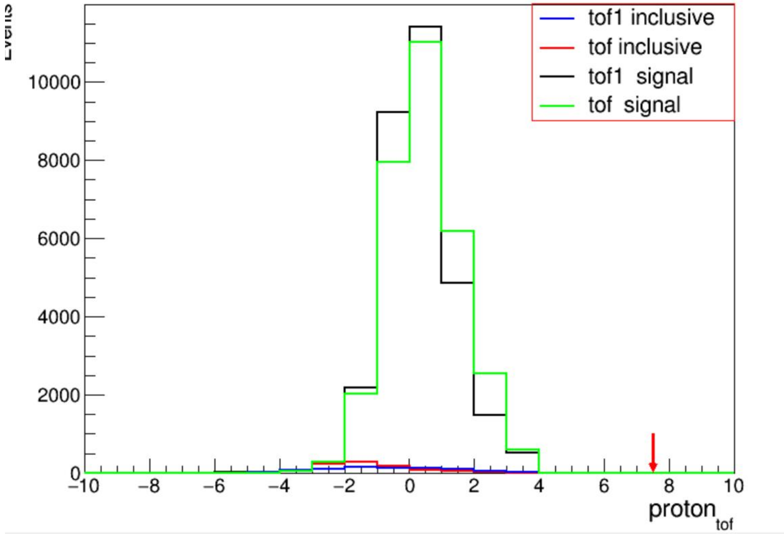


Event Selection

6. $\chi^{tof1}_{proton} < 7.5$

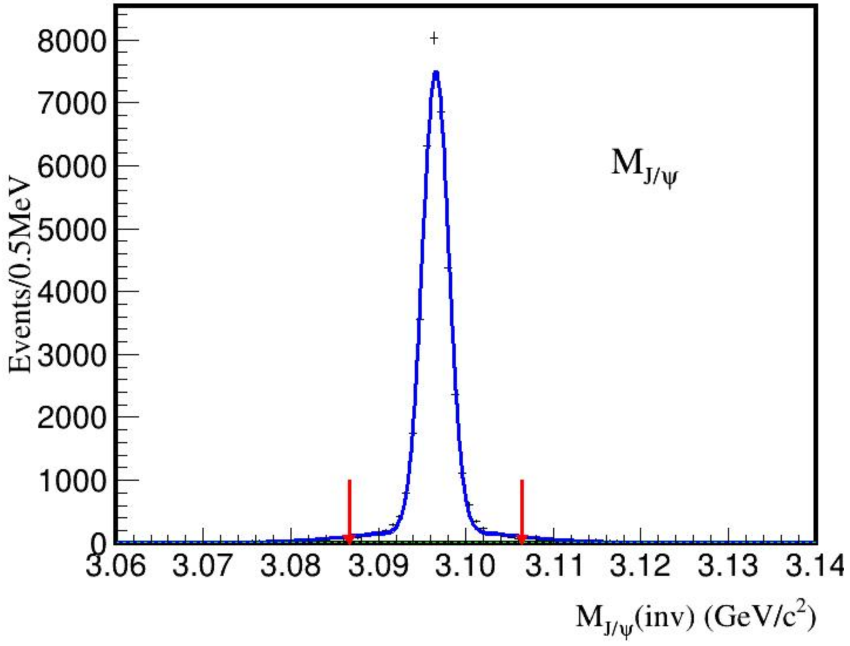


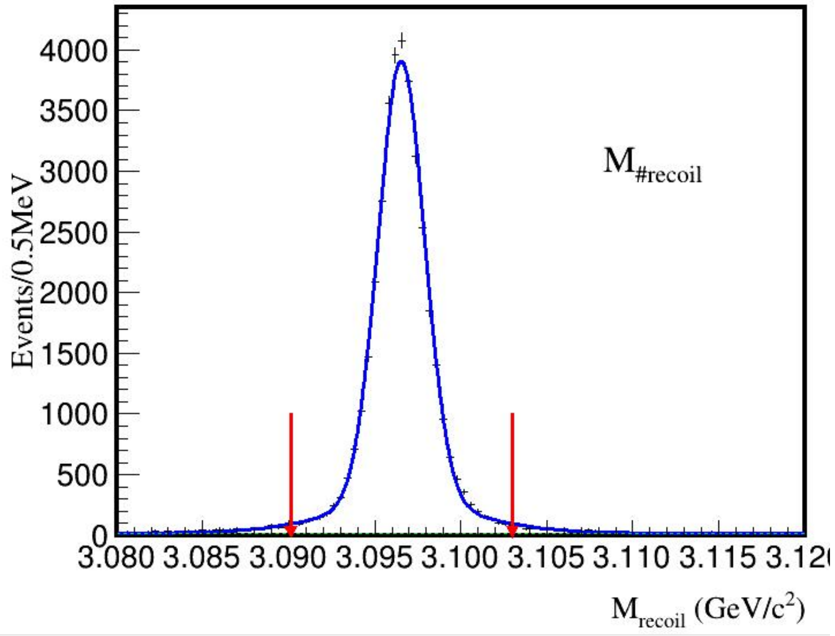




Event Selection: Signal region

Signal shape model:
Double Gaussian function
Background shape model:
second-order Chebychev function

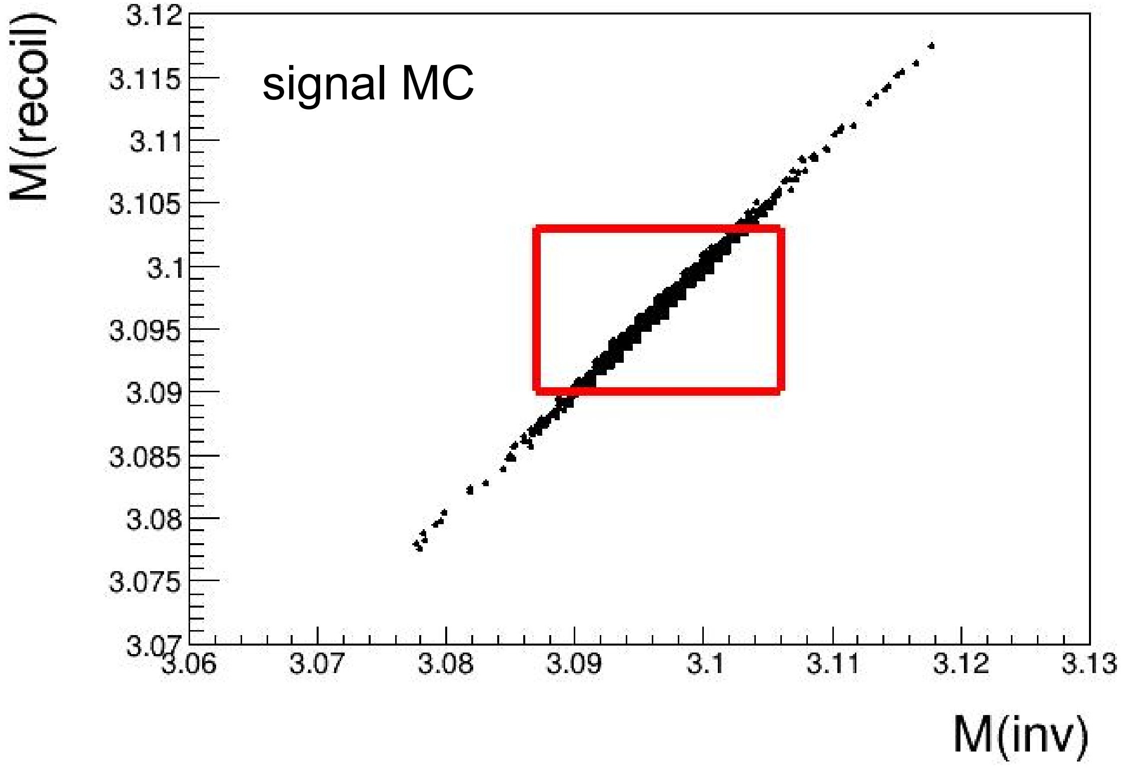


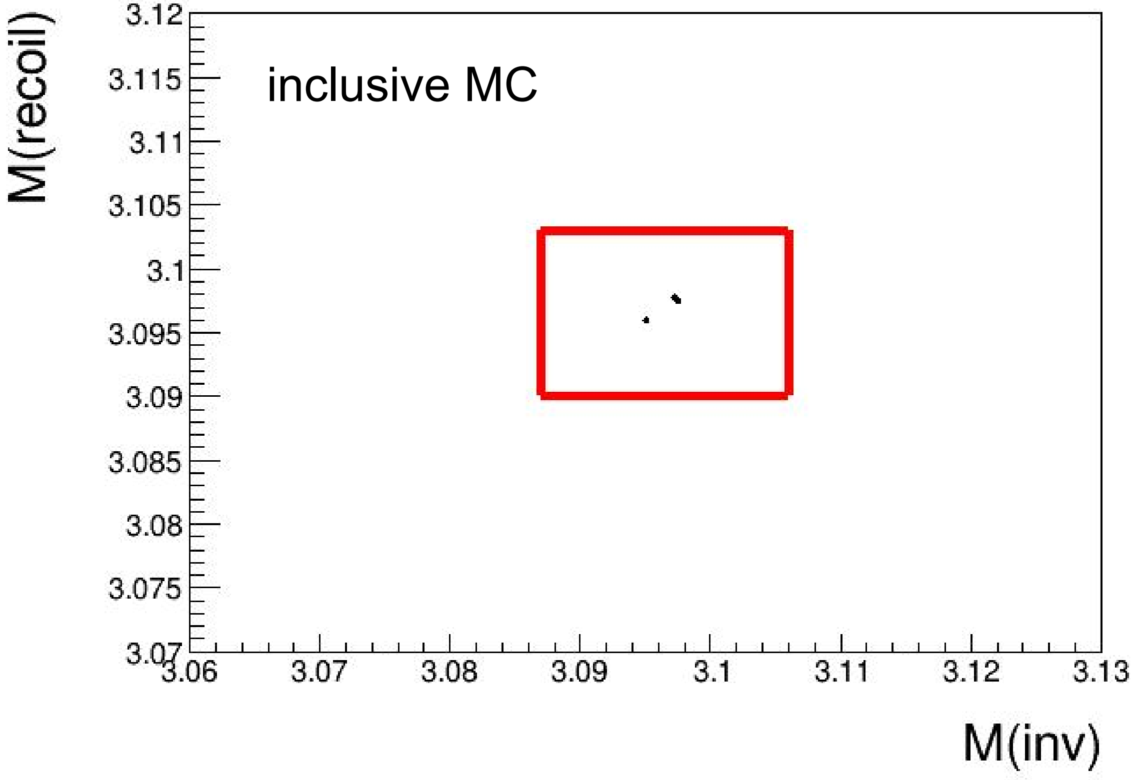


μ = 3.097 GeV
σ = 0.003GeV
[μ -3σ,μ +3σ] = [3.087, 3.106]

μ = 3.097 GeV
σ = 0.002 GeV
[μ -3σ,μ +3σ] = [3.090, 3.103]

Event Selection: 2D distribution





signal region = $[\mu\ -3\sigma,\ \mu\ +3\sigma]$
x-axis region = $[\mu\ -10\sigma,\ \mu\ +10\sigma]$
y-axis region = $[\mu\ -10\sigma,\ \mu\ +10\sigma]$

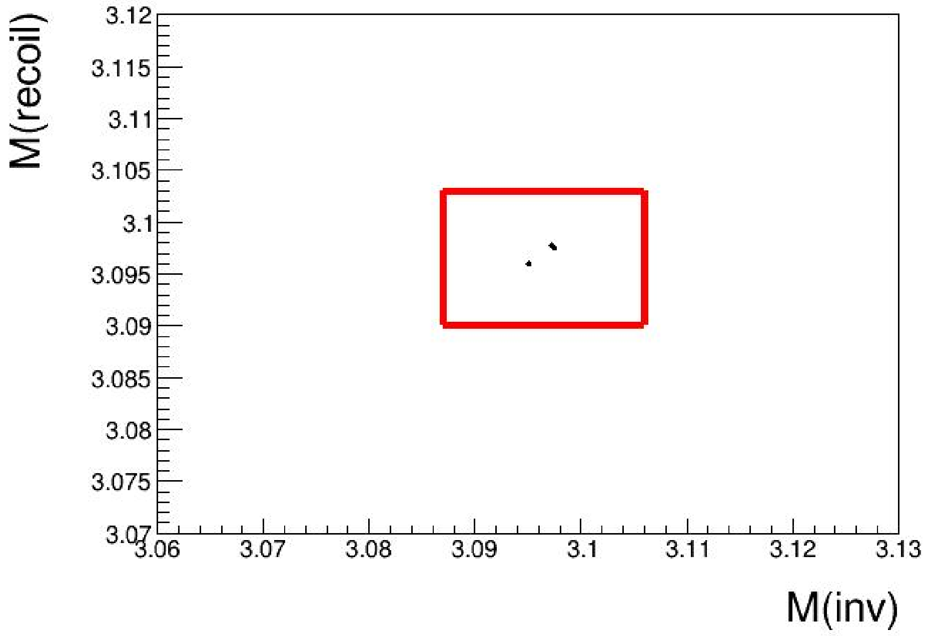
Event Selection: Cut flow

	pe^-efficiency (%)	$\bar{p}e^+$ efficiency (%)	inclusiveMC Absolute efficiency (%)
Total number	100000 (100, 100)	100000 (100, 100)	2748000000 (100, 100)
Charged tracks >= 4	77603 (77.60, 77.60)	78602 (78.60, 78.60)	1918480114 (69.81, 69.81)
Good charged tracks = 4	63859 (63.86, 82.29)	63543 (63.54, 80.84)	670439126 (24.40, 34.95)
After particle ID	52828 (52.83, 82.73)	51658 (51.66, 81.30)	2623404 (0.10, 0.39)
After 4c kinematic fit	42102 (42.1, 79.70)	40422 (40.42, 78.25)	89949 (3.27E-03, 3.43)
χ^2min	41803 (41.80, 99.29)	40132 (40.13, 99.28)	9994 (3.64e-04, 11.11)
χ^2<10	22011 (22.01, 52.65)	21051 (21.1, 52.45)	119 (4.33e-06, 1.20)
tof1_proton<7.5	20530 (20.53, 93.27)	19345 (19.35, 91.90)	8 (2.91e-07, 6.72)
signal region	20327 (20.33, 99.01)	19160 (19.16, 99.04)	3 (1.09e-07, 37.5)

Background Estimation

- After applying all cuts to inclusive MC (2748M from 2009, 2012 and 2021), there are 3 events left in the signal region (red box).

rowNo	decay tree	decay final state	iDcyTr	nEtr	nCEtr
1	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-\gamma^f\gamma^f$	$e^+e^-\pi^+\pi^-\gamma^f\gamma^f$	0	2	2
2	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-\gamma^f$	$e^+e^-\pi^+\pi^-\gamma^f$	1	1	3

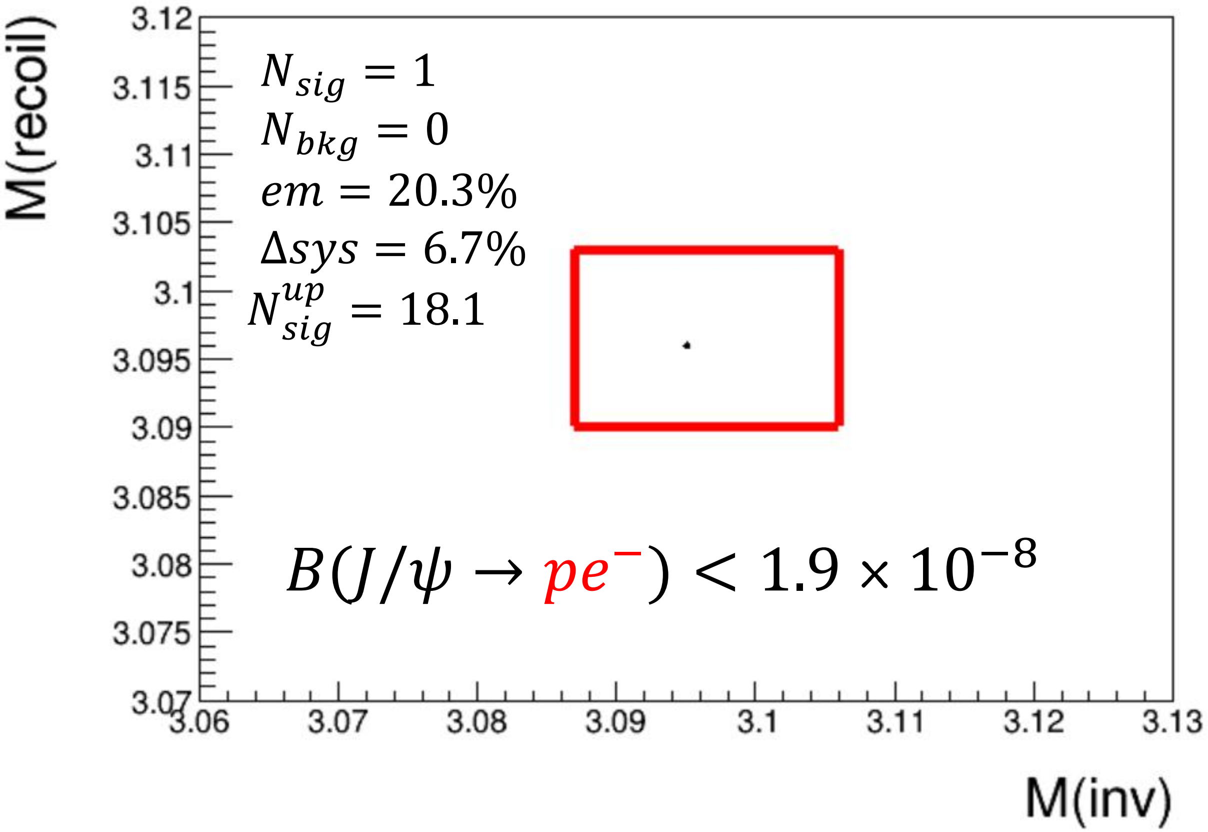


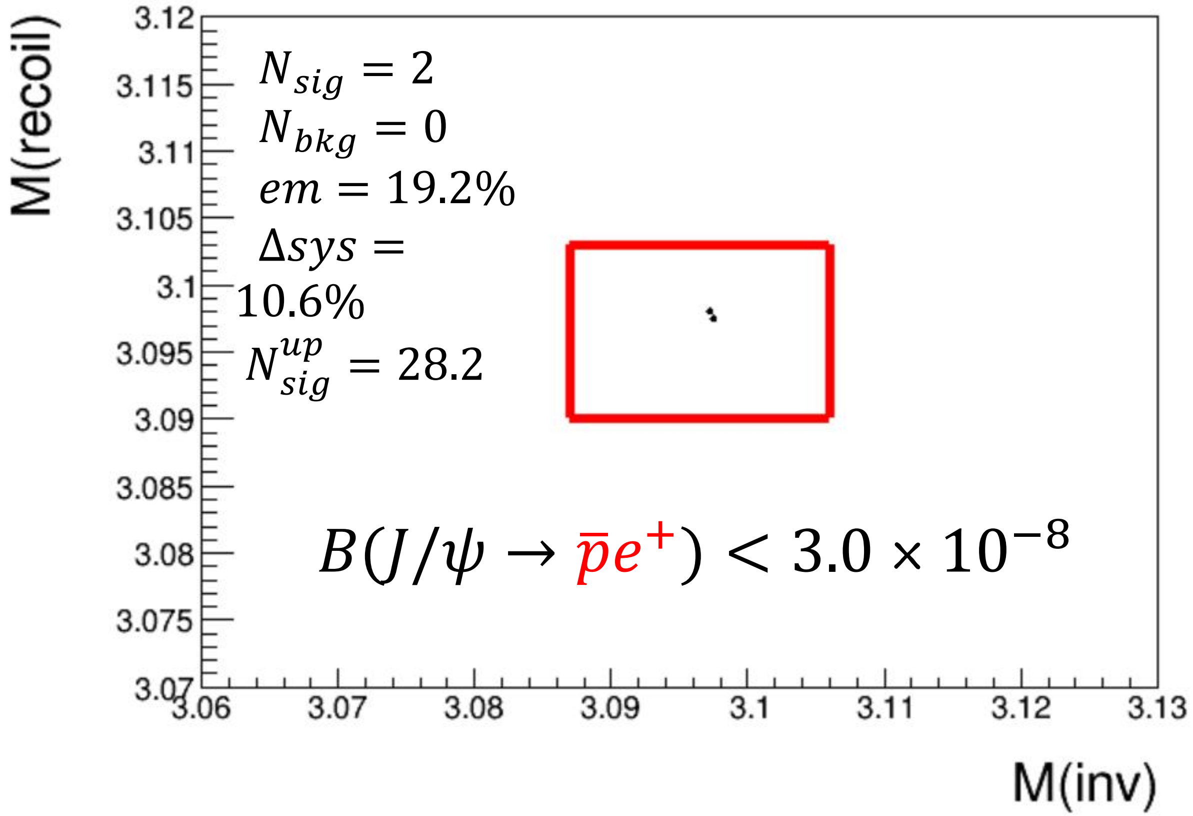
Summary of Systematic uncertainties

Sources	pe^-	$\bar{p}e^+$	Citation
$N_{\psi(3686)}$	0.6%	0.6%	[1]
Br($\psi(3686) \to \pi^+\pi^- J/\psi$)	negligible	negligible	[2]
Tracking	1.8%	1.8%	[2,3]
PID	3.1%	3.1%	-
4C Kinematic Fit	2.7%	4.0%	-
χ_{proton}^{tof1}	4.9%	9.1%	-
Mass Window	0.3%	0.3%	-
Total	6.7%	10.6%	

[1] C.liu et al. (BESIII Collaboration), Report on Collaboration Meeting in Summer 2022
[2] M.Ablikim er al.,Phys.Rev. D 88(2013) 3, 032007
[3] M.Ablikim er al.,Phys.Rev. D 99 (2019) , 112010

The Upper Limit $N^{up}_{J/\psi\to pe}$ with Full blind data

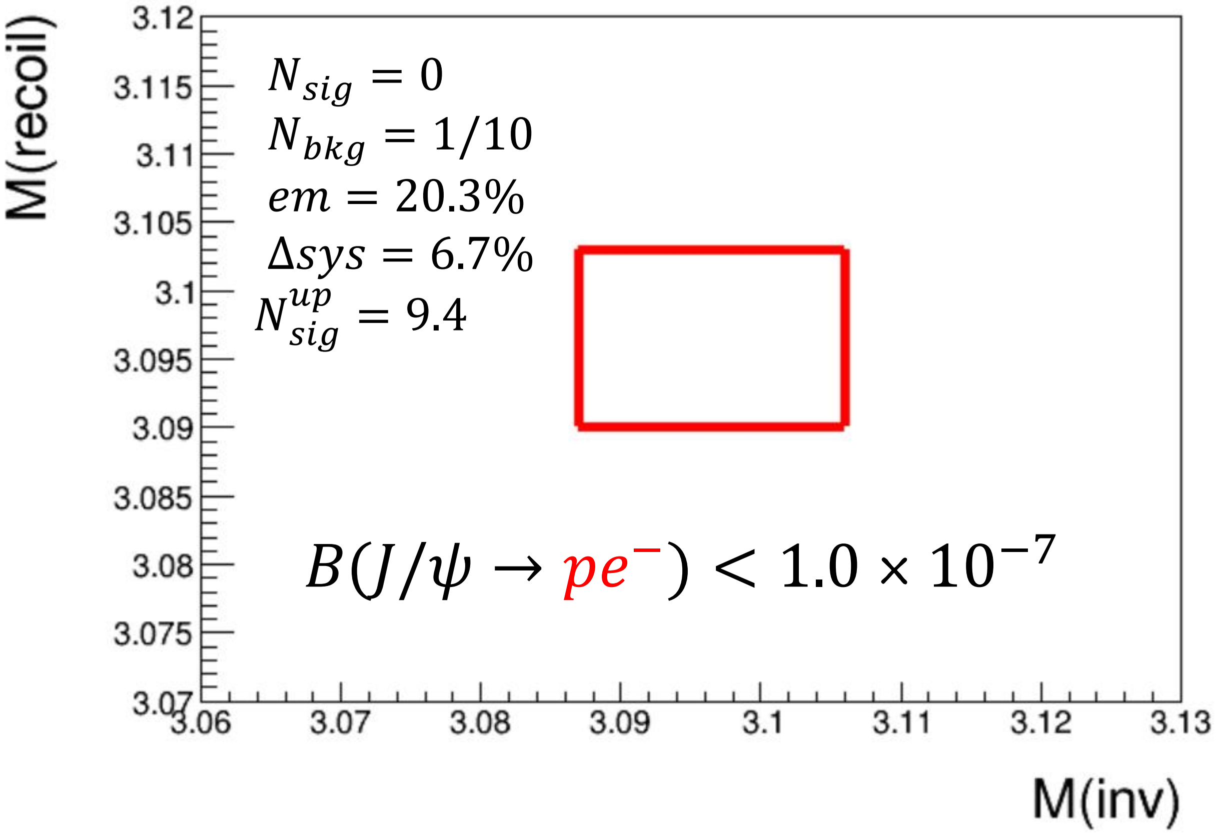


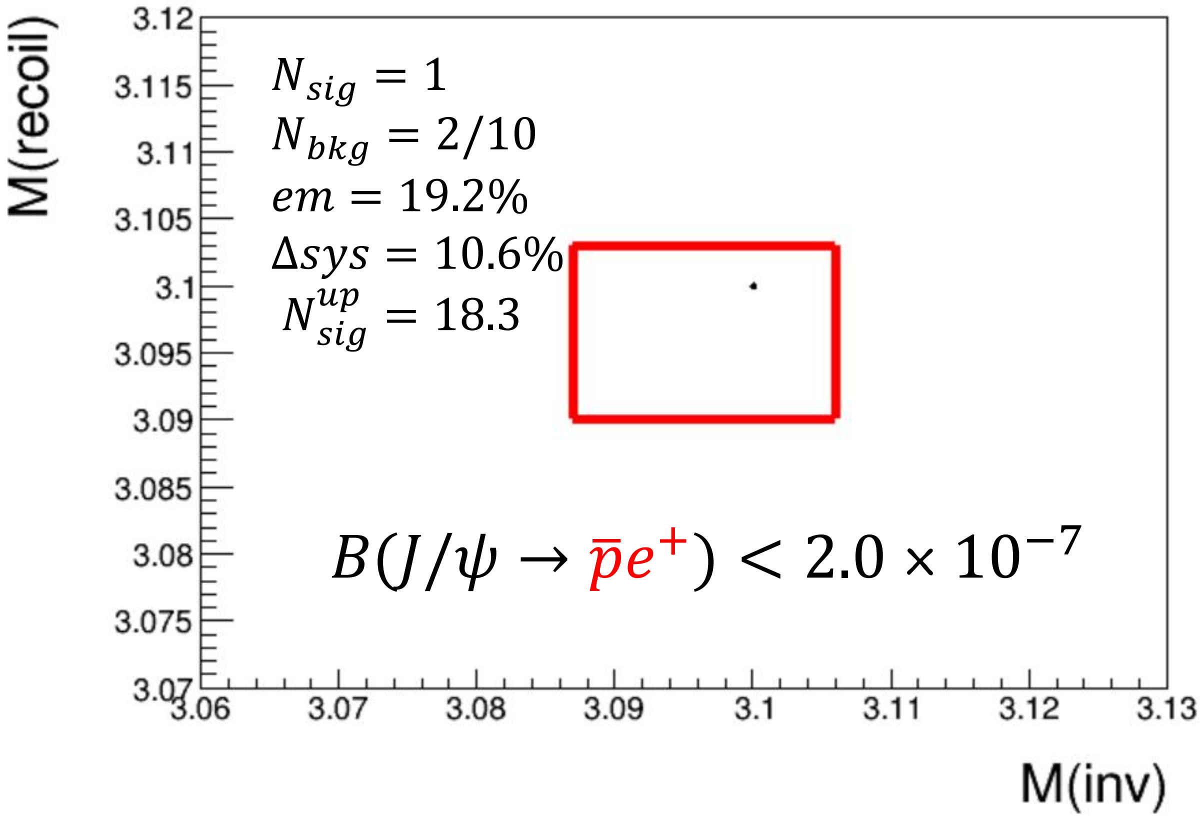


- N^{up} 90% C.L. is estimated by using the TROLKE program, where the number of the signal and background events are assumed to follow a Poisson distribution, the detection efficiency is assumed to follow a Gaussian distribution.

The Upper Limit $N^{up}_{J/\psi\to pe}$ with semi-blind data

- In semi-blind analysis, the Nsig is obtained from semi-blind data, the Nbkg is estimated from inclusive MC sample whose size if 10 times of semi-blind data.





Summary

- Searching BNV from experiment plays key role to reveal the nature of neutrino and revolution of the universe. Present limits are still above SM predictions, no BNV have been found.

- In the future, more data on BESIII will collected, new result and more strict constraint can be expected.

THANKS