

Search for Lepton and Baryon Number

Violating τ^- Decays into $\bar{p}\gamma$, $\bar{p}\pi^0$, $\bar{\Lambda}\pi^-$ and $\Lambda\pi^-$

N. Sato, Y. Miyazaki and Belle Collaboration

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- Introduction
- $\tau^- \rightarrow \bar{p}\gamma, \bar{p}\pi^0$
- $\tau^- \rightarrow \bar{\Lambda}\pi^-, \Lambda\pi^-$
- Summary

- We have searched for LFV τ decay modes:
 $\tau \rightarrow \mu/e + \gamma, \quad \tau \rightarrow \mu/e + \eta/\pi^0/\eta', \quad \tau \rightarrow 3\ell.$
- As a next step, we search for both lepton number (L) and baryon number (B) violating τ decays, which are expected in some models, such as Grand Unified Theories(GUTs).
 - hep-ph/0404002, W.S.Hou et al.
 B and L violating τ decays, such as $\tau^- \rightarrow \bar{\Lambda}\pi^-, \bar{p}K_S$, from right-handed 4-fermi interaction

- We report here our searches for L and B violating τ decay modes:

$$\tau^- \rightarrow \bar{p}\gamma, \tau^- \rightarrow \bar{p}\pi^0, \tau^- \rightarrow \bar{\Lambda}\pi^- \text{ and } \tau^- \rightarrow \Lambda\pi^- \text{ (& chg conj.)}$$

- $\tau^- \rightarrow \bar{p}\gamma$ (86.7fb⁻¹ data) and $\bar{p}\pi^0$ (153.8 fb⁻¹ data):
 Current UL of Br. fraction \mathcal{B} by CLEO (4.7fb⁻¹ data):
 $\mathcal{B}(\tau^- \rightarrow \bar{p}\gamma) < 35 \times 10^{-7}, \quad \mathcal{B}(\tau^- \rightarrow \bar{p}\pi^0) < 150 \times 10^{-7}.$

- $\tau^- \rightarrow \bar{\Lambda}/\Lambda + \pi^-$ (153.8 fb⁻¹ data):

These modes have never been studied before.

- $\tau^- \rightarrow \bar{p} + \gamma/\pi^0$

$$\left\{ \frac{\tau^- \rightarrow \bar{p} + n_\gamma^{\text{SIG}}}{\text{(signal-side)}} \right\} + \left\{ \frac{\tau^+ \rightarrow (\text{one trk})^+ + n_\gamma^{\text{TAG}} + X(\text{missing})}{\text{(tag-side)}} \right\}$$

- 1-1 prong topology

- Main BG: $\tau^+ \tau^- (\tau \rightarrow \rho \nu)$ and $q\bar{q}$ continuum (including true p)

- $\tau^- \rightarrow \bar{\Lambda}/\Lambda + \pi^-$

$$\left\{ \frac{\tau^- \rightarrow (\bar{p}\pi^+) + \pi^-}{\text{(signal-side)}} \right\} + \left\{ \frac{\tau^+ \rightarrow (\text{one trk})^+ + n_\gamma^{\text{TAG}} + X(\text{missing})}{\text{(tag-side)}} \right\}$$

- 1-3 prong topology

- We reconstruct $\bar{\Lambda}$ from $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ using vertex info. of Λ

- Main BG: $\tau^+ \tau^- (\tau \rightarrow a_1 \nu)$ and $q\bar{q}$ continuum (including true Λ)

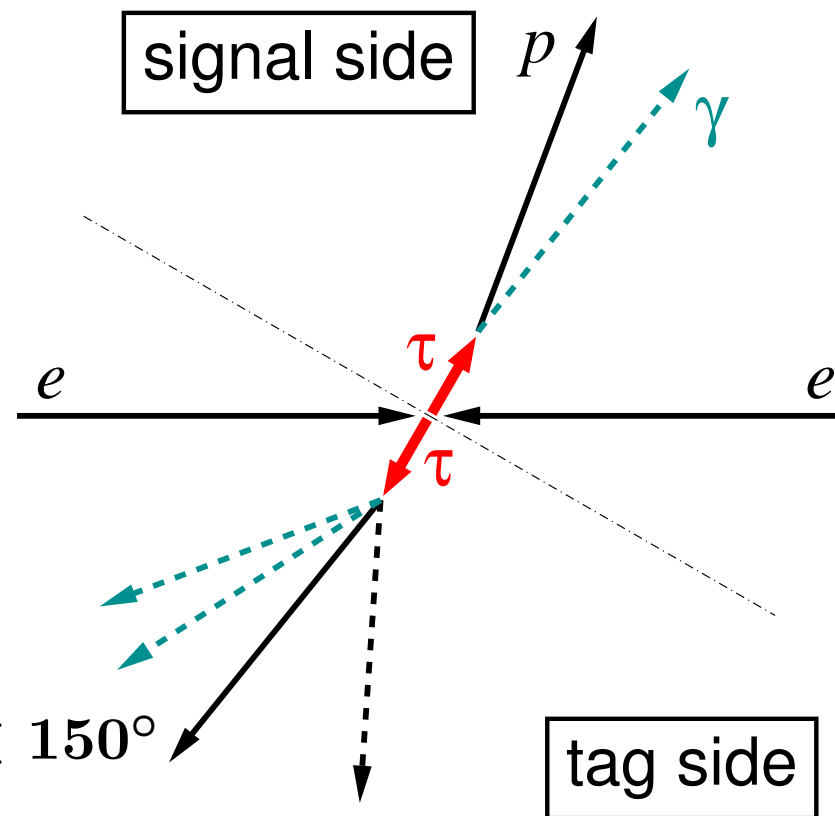
- Very clean mode due to the constraint from Λ

The experimental signatures and analysis methods are different for

$$\tau^- \rightarrow \bar{p} + \gamma/\pi^0 \text{ and } \tau^- \rightarrow \bar{\Lambda}/\Lambda + \pi^-$$

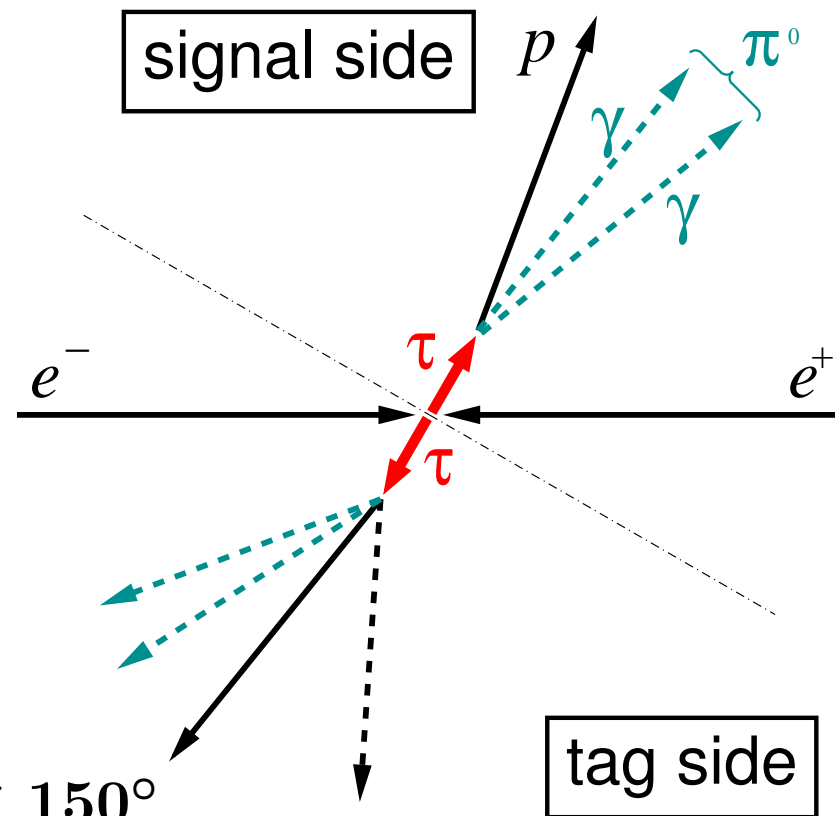
⇒ We discuss these modes separately.

- 1-1 prong, $1 \leq N_\gamma \leq 3$
 $E_\gamma > 0.1 \text{ GeV}$, net charge = 0
- $0.5 < E_{vis}^{CM} / \sqrt{s} < 0.92$
- signal side :
proton-ID and $p_p > 1.0 \text{ GeV}/c$
 $E_\gamma > 0.5 \text{ GeV}$,
- $0.6 < \cos \theta_{p\gamma}^{CM} < 0.96$
- $p_{miss} > 0.6 \text{ GeV}/c$, $17^\circ < \theta_{miss} < 150^\circ$
- $\cos \theta_{tag-miss}^{CM} > 0.3$
- $p_{miss} > -3m_{miss}^2 - 1$ & $p_{miss} > 1.2m_{miss}^2 - 1$
- $\theta_{2trk}^{CM} > 90^\circ$
- **$M_{tag} \leq 1.2 \text{ GeV}/c^2$, π^0 veto & EM shower-like for signal γ**



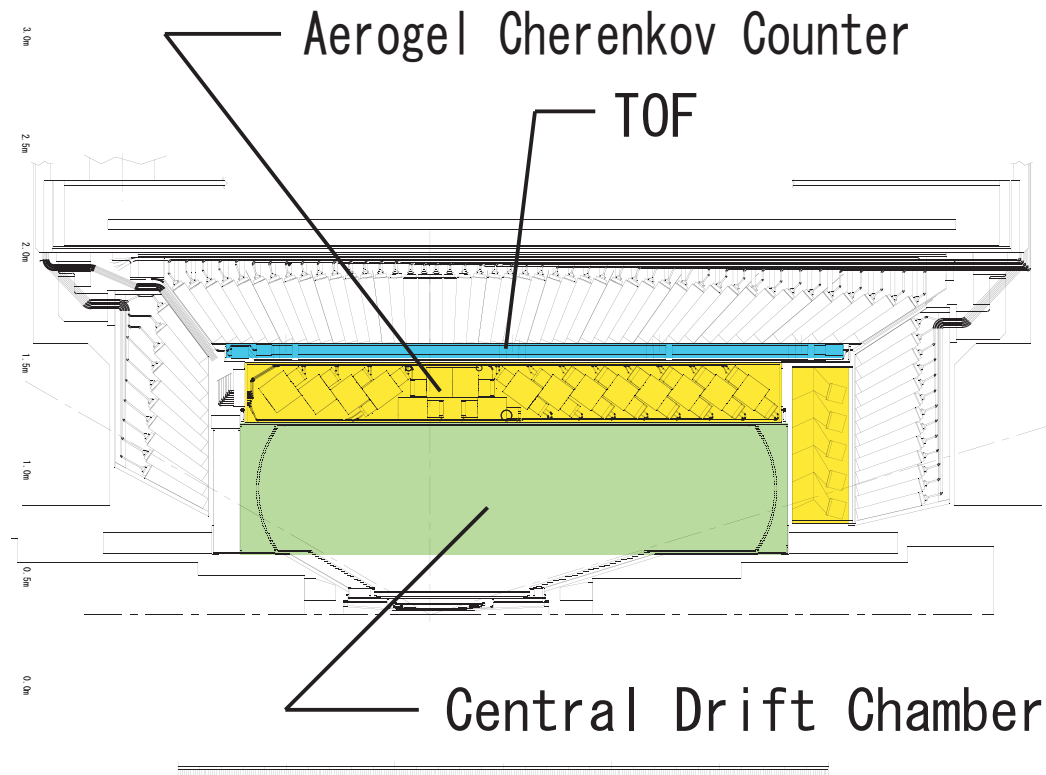
Almost same as $\tau \rightarrow p\gamma$

- 1-1 prong, $2 \leq N_\gamma \leq 4$
 $E_\gamma > 0.1 \text{ GeV}$, net charge = 0
- $0.5 < E_{vis}^{CM} / \sqrt{s} < 0.92$
- signal side :
 proton-ID and $p_p > 1.0 \text{ GeV}/c$
 One π^0 ($\left| \frac{M_{\gamma\gamma} - M_{\pi^0}}{\sigma_{\gamma\gamma}} \right| < 5$)
- $0.0 < \cos \theta_{p\pi^0}^{CM} < 0.95$
- $p_{miss} > 0.5 \text{ GeV}/c$, $17^\circ < \theta_{miss} < 150^\circ$
- $\cos \theta_{tag-miss}^{CM} > 0.0$
- $p_{miss} > -0.8m_{miss}^2 + 0.3$, & $p_{miss} > 1.6m_{miss}^2 - 1$
- $\theta_{2trk}^{CM} > 90^\circ$, $M_{tag} \leq m_\tau$



Hadron-ID in the Belle detector is based on the responses of sub-detectors:

- Threshold type ACC (Aerogel Cherenkov Cnt.)
- Time-of-flight from TOF cnt.
- dE/dx in CDC (Central Drift Chamber)



Basically we use likelihood ratios to distinguish hadron species,

$$\text{for instance, } \mathcal{P}(p/\pi) = \frac{\mathcal{L}_p}{\mathcal{L}_p + \mathcal{L}_\pi},$$

where \mathcal{L}_i is likelihood for the detector response to the trk with flavour hypothesis i .

BG events: mostly pions $\Rightarrow p/\pi$ separation is important.

\Rightarrow ACC is a useful detector in this case;

Threshold mom. of π : $P_{th}^\pi < 1$ GeV/c \Rightarrow All pions should FIRE ACC

Threshold mom. of p : $P_{th}^p = 4 \sim 6$ GeV/c

\Rightarrow Most of protons should NOT FIRE ACC.

	$P < P_{th}^p$	$P > P_{th}^p$	$\tau \rightarrow p\gamma$	$P < P_{th}^p$	$P > P_{th}^p$
Fire	× Not Proton	△ Any particle	sig eff #data	2.0% 6341 ev	0.47% 86 ev
Not Fire	○ Proton	× Not Proton	sig eff #data	11% 494 ev	0.12% 4 ev

• The sig chgd trk: $1 \text{ GeV/c} < P < P_{th}^p$ & ACC Not Fired

\Rightarrow Retaining 85% of the signal eff, 90% of BG ev are rejected.

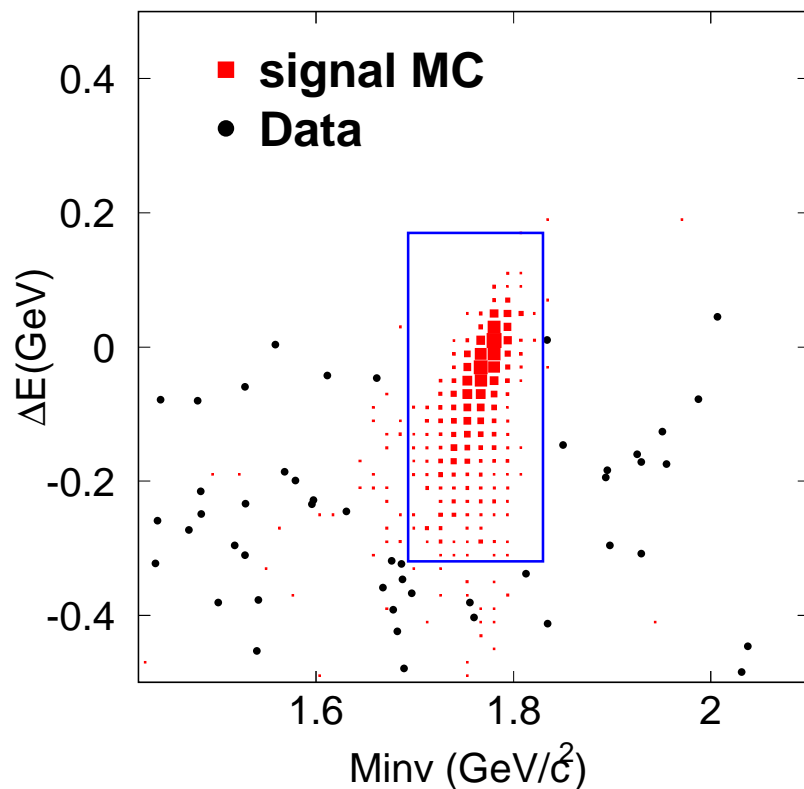
• Applying this cut, 90% of BG are still pions.

\Rightarrow To further reduce the pion BG, we use \mathcal{L}^{TOF} and $\mathcal{L}^{dE/dx}$.

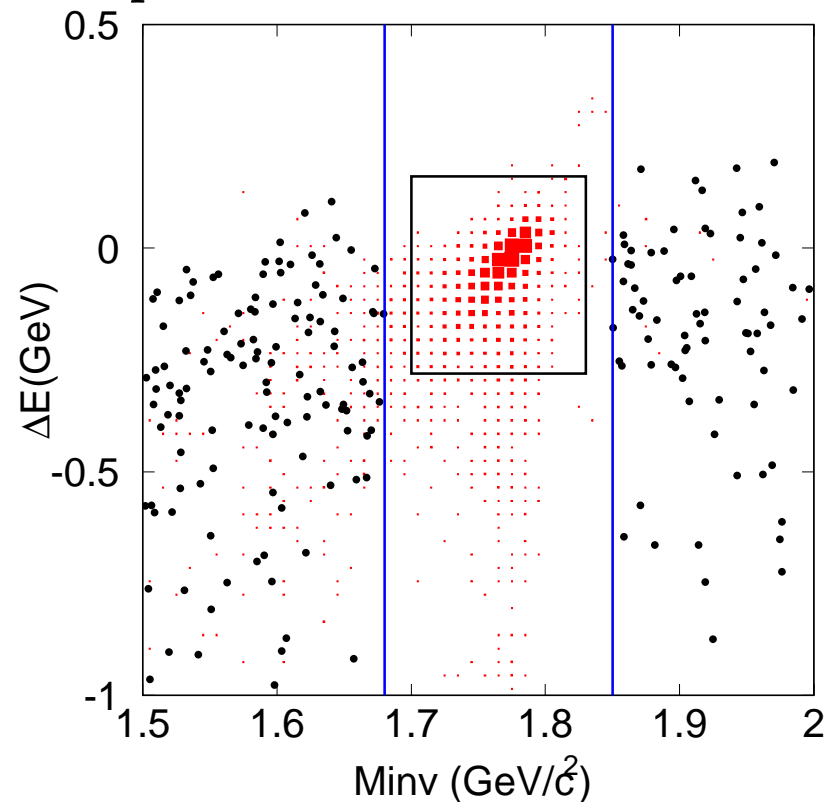
• p eff and π fake rate are calibrated by using Λ and K_S samples, respectively.

We used a blind analysis method similar to that used in Belle's search for LFV τ decays.

$\tau \rightarrow p\gamma$



$\tau \rightarrow p\pi^0$



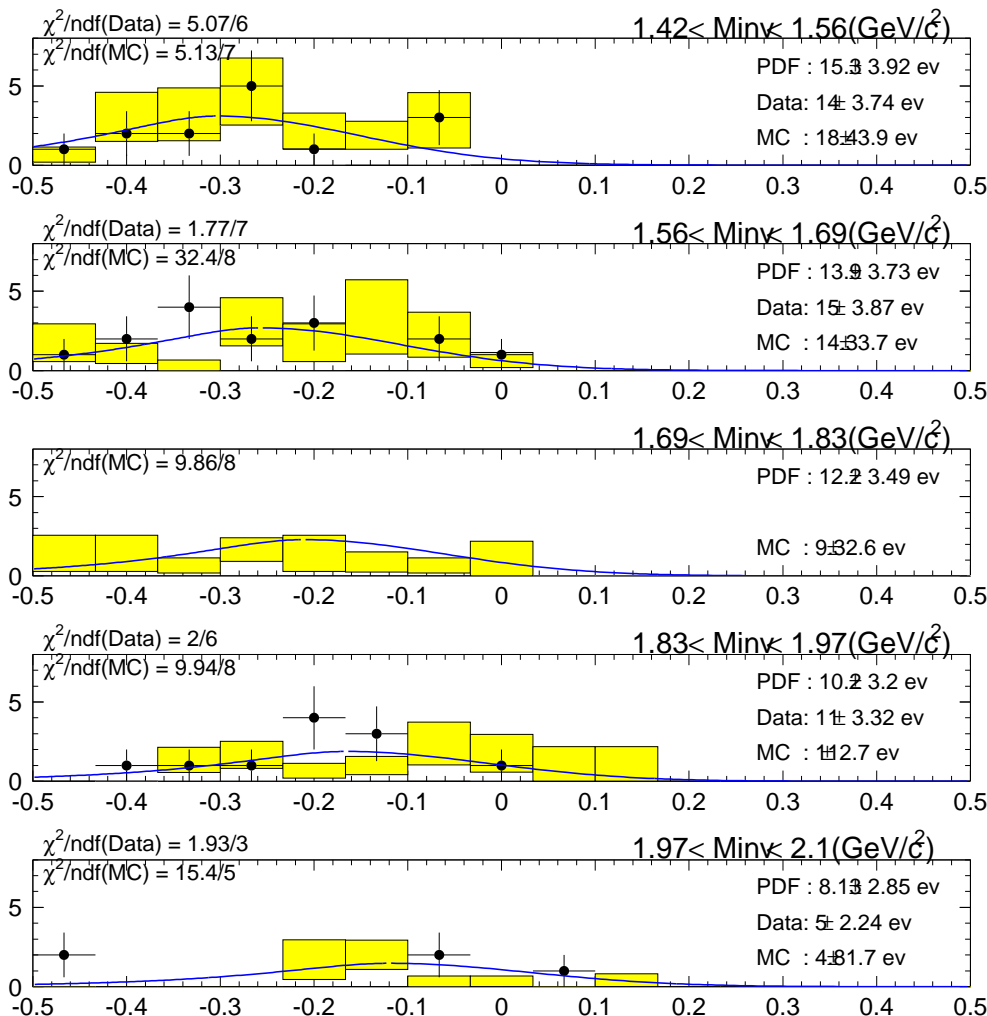
Blind Region (denoted blue lines) :

$$1.69 \text{ GeV}/c^2 < M_{inv} < 1.83 \text{ GeV}/c^2$$

$$-0.32 \text{ GeV} < \Delta E < 0.17 \text{ GeV}$$

($\pm 5\text{-}\sigma$ Box region)

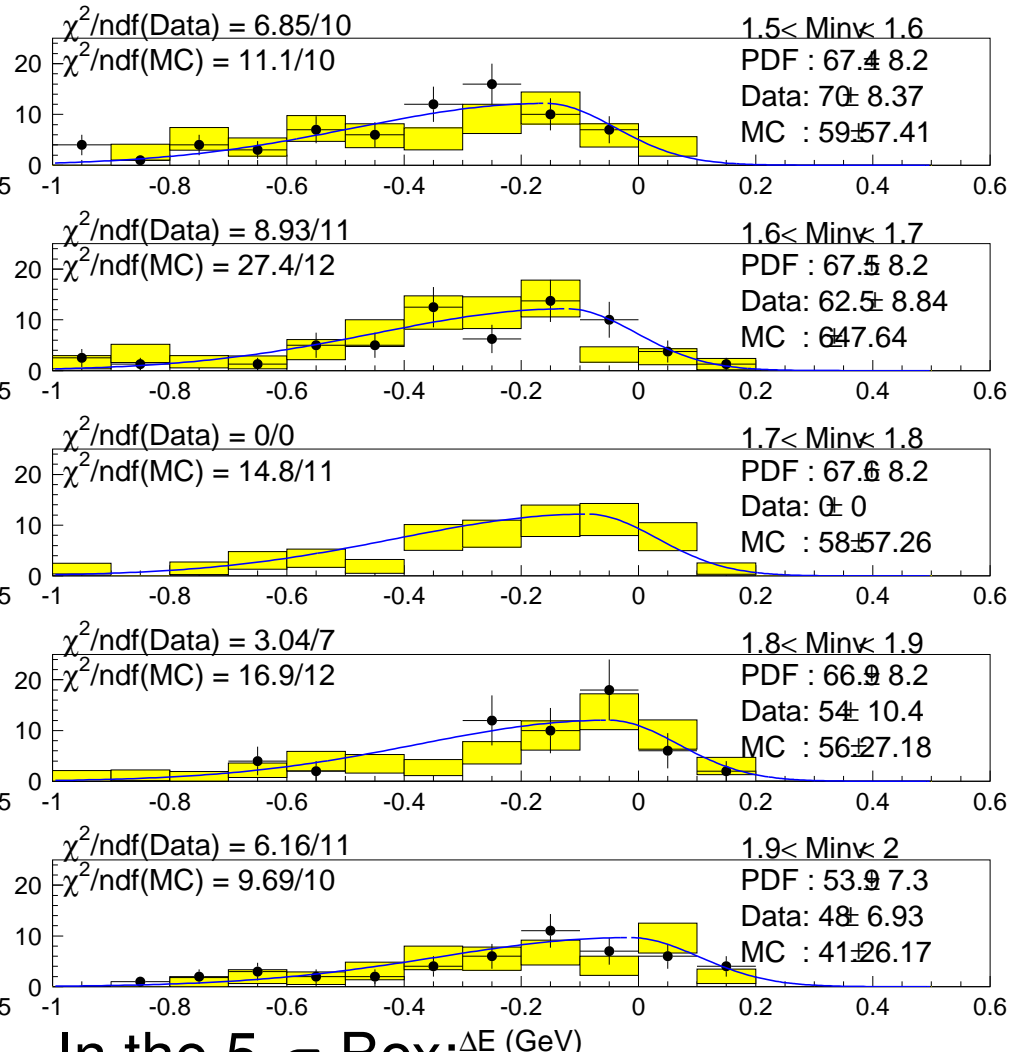
$$1.7 \text{ GeV}/c^2 < M_{inv} < 1.85 \text{ GeV}/c^2$$

$\tau \rightarrow p\gamma$


In the 5- σ Box:

Signal Eff = 9.4%

Expected BG = 9.1 ± 1.7 ev

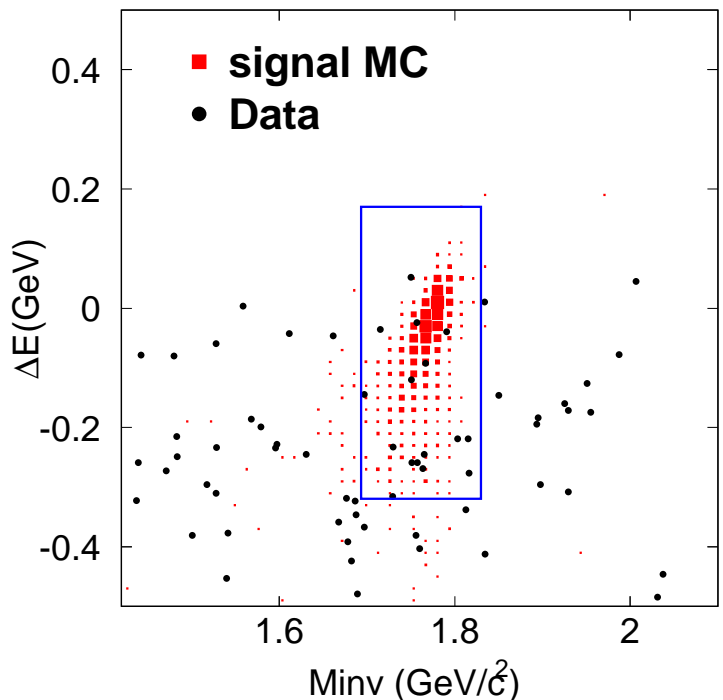
 $\tau \rightarrow p\pi^0$


In the 5- σ Box:

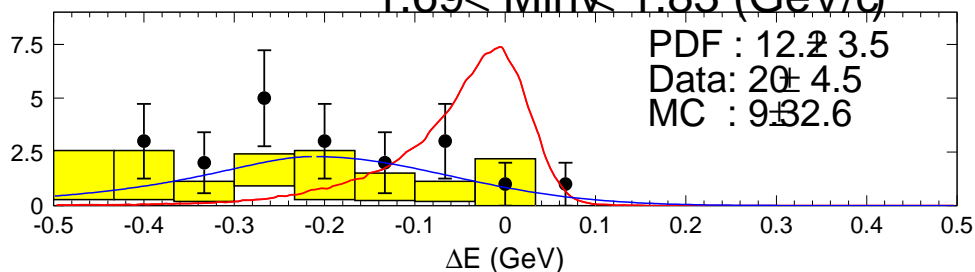
Signal Eff = 5.8%

Expected BG = 52.2 ± 7.3 ev

$\tau \rightarrow p\gamma$



$1.69 < \text{Minv} < 1.83 \text{ (GeV}/c^2\text{)}$

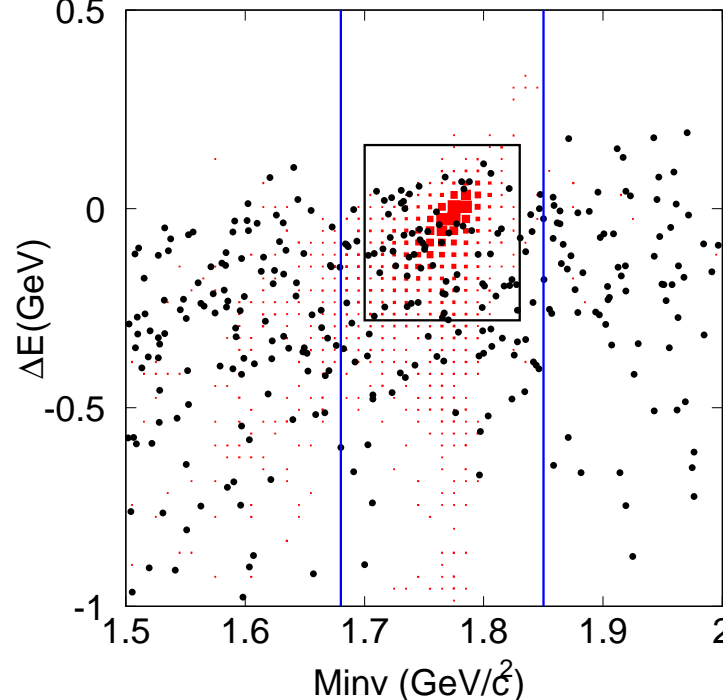


In the 5- σ Box:

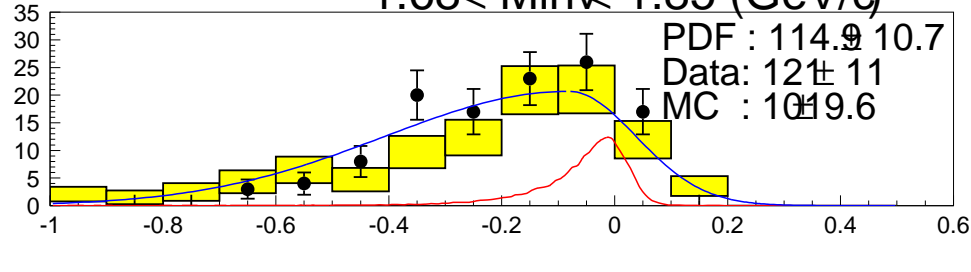
Observed: 16 ev (9.1 ± 1.7 expected)

diff: 6.9 ± 4.3 ev (1.6σ)

$\tau \rightarrow p\pi^0$



$1.68 < \text{Minv} < 1.85 \text{ (GeV}/c^2\text{)}$



In the 5- σ Box:

Observed: 70 ev (52.2 ± 7.3 expected)

diff: 17.8 ± 11.1 ev (1.6σ)

The likelihood function of the UEML method:

$$\mathcal{L}(s, b) = \frac{e^{-(s+b)}}{N!} \prod_{i=1}^N (sS_i + bB_i)$$

where N : #(obs. ev), s : #(sig ev), b : #(BG ev),
 S_i : PDF of the signal, B_i : BG PDF

The s and b are determined to give the $\text{Max}(\mathcal{L}(s, b))$:

$$\begin{cases} \tau^- \rightarrow \bar{p}\gamma & s = 0.16 \text{ ev}, \quad b = 15.8 \text{ ev} \\ \tau^- \rightarrow \bar{p}\pi^0 & s = 3.1 \text{ ev}, \quad b = 66.9 \text{ ev} \end{cases}$$

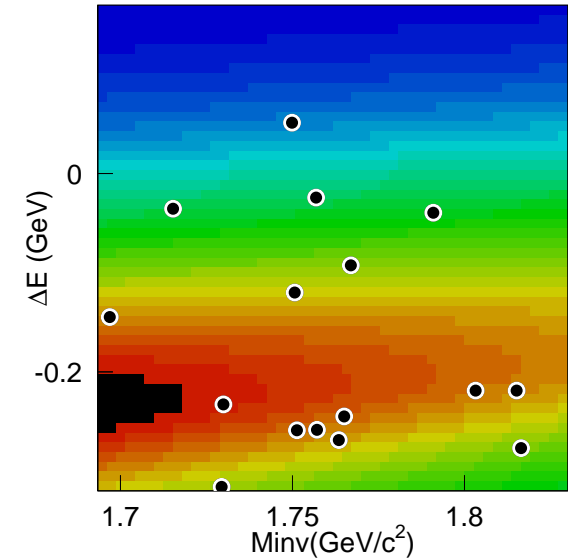
The UL of the sig ev @90% C.L. s_{90} are estimated by using TOY MC:

$$\begin{cases} \tau^- \rightarrow \bar{p}\gamma & s_{90} = 3.7 \text{ ev} \quad (+0.77 \text{ sys.}) \\ \tau^- \rightarrow \bar{p}\pi^0 & s_{90} = 9.8 \text{ ev} \quad (+0.75 \text{ sys.}) \end{cases}$$

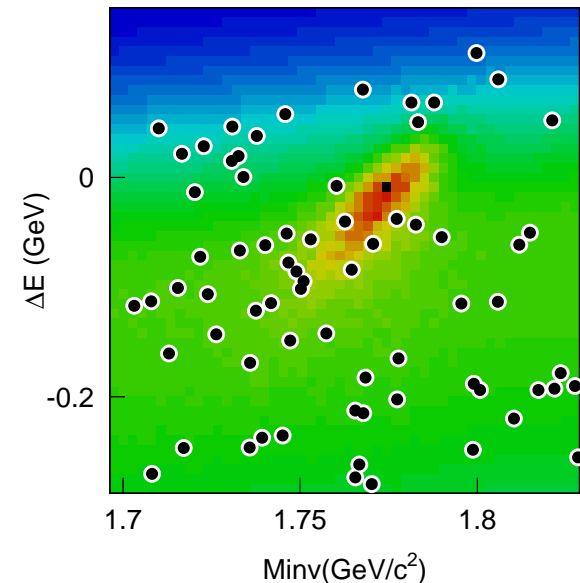
The UL of Br @90% C.L., $\mathcal{B} < s_{90}/2\epsilon N_{\tau\tau}$:

$$\begin{cases} \mathcal{B}(\tau^- \rightarrow \bar{p}\gamma) < 3.0 \times 10^{-7} \\ \mathcal{B}(\tau^- \rightarrow \bar{p}\pi^0) < 6.5 \times 10^{-7} \end{cases}$$

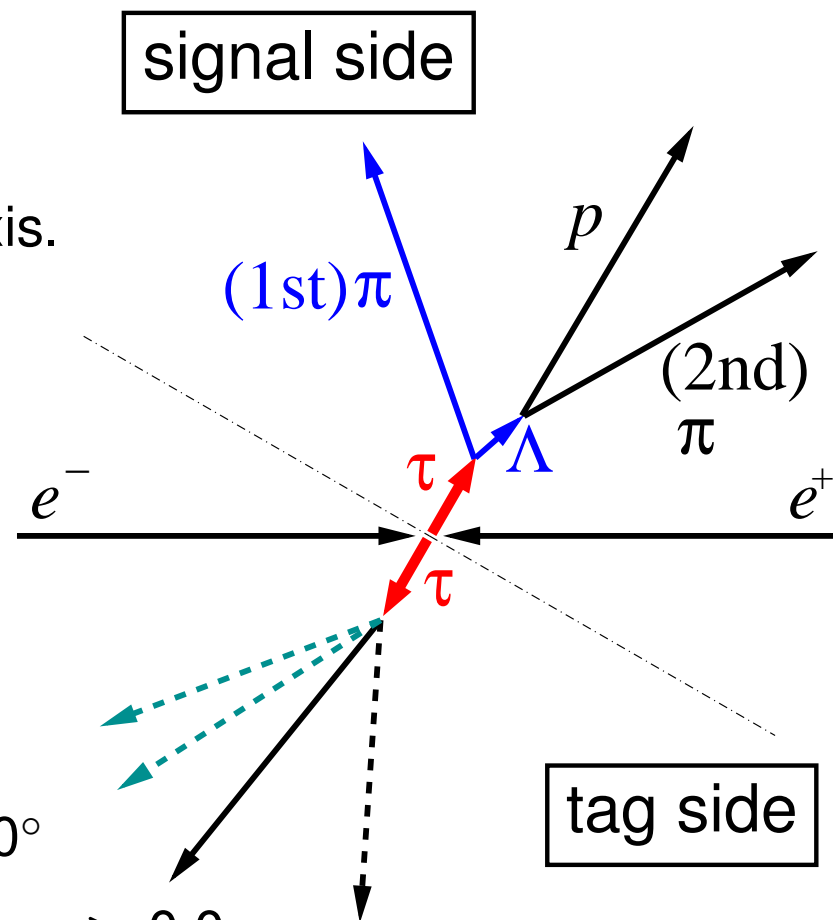
$sS_i + bB_i(\tau \rightarrow p\gamma)$



$sS_i + bB_i(\tau \rightarrow p\pi^0)$

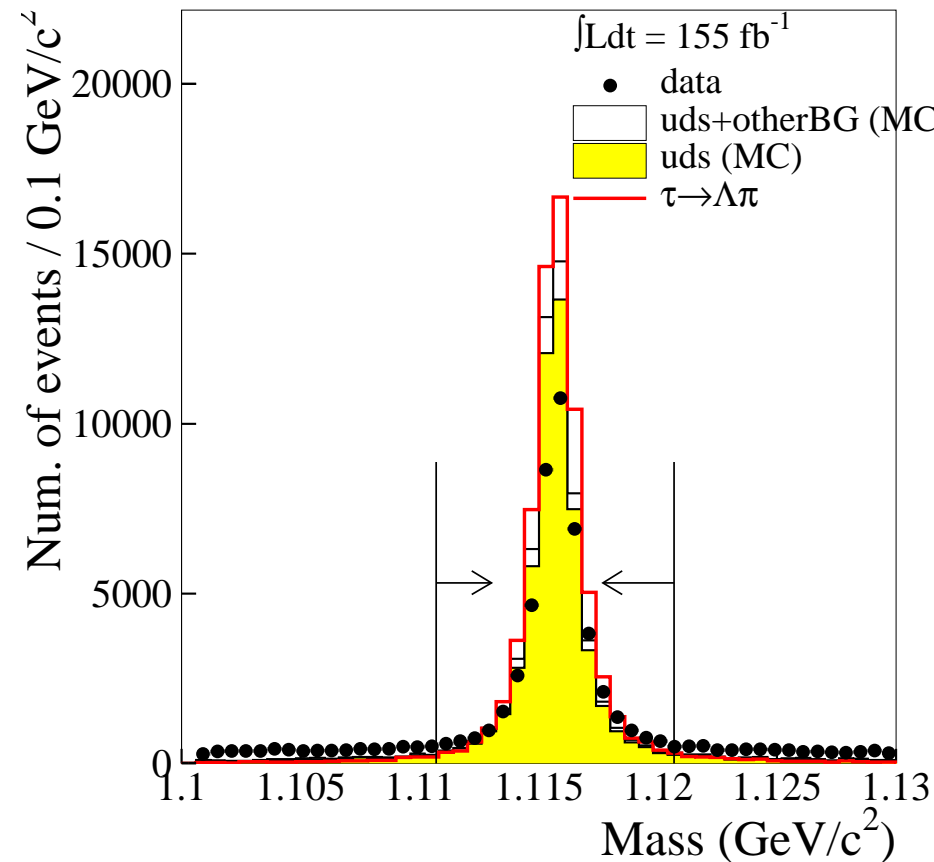
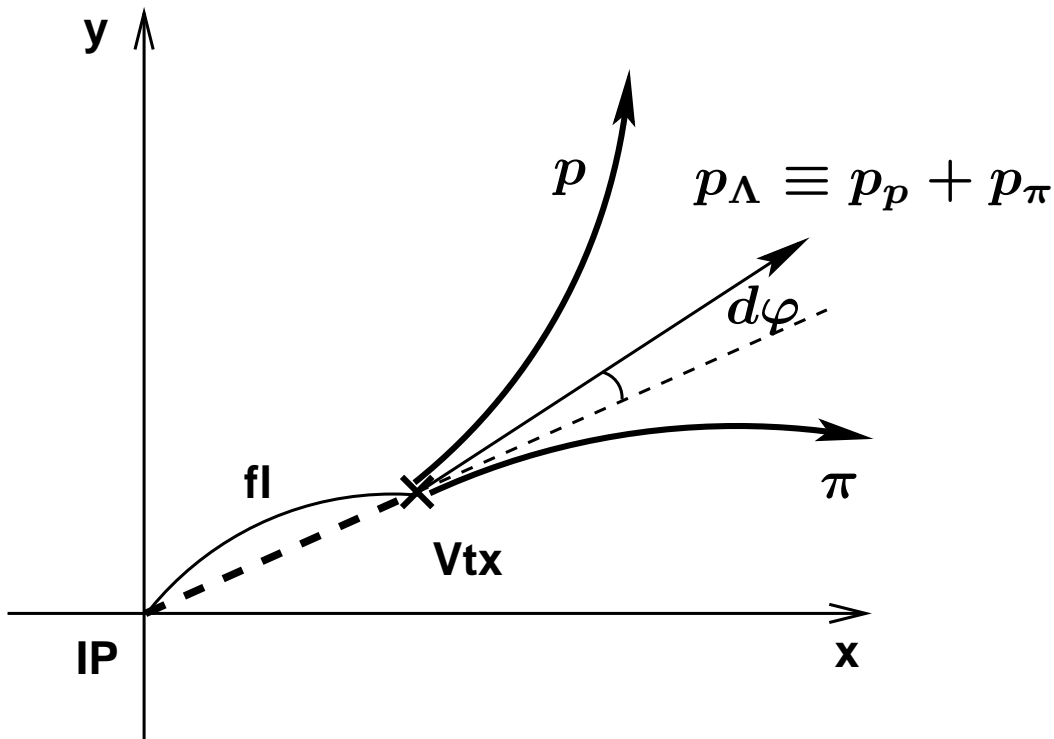


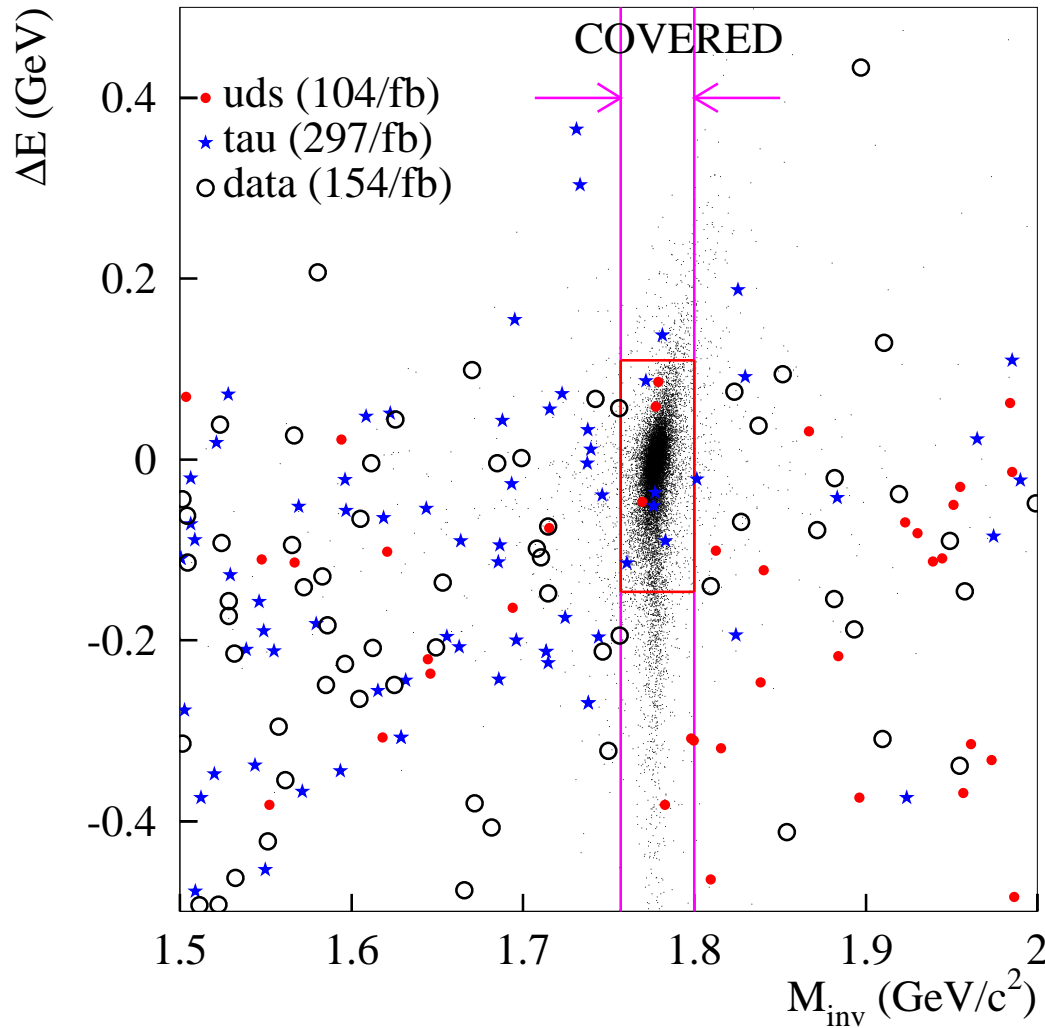
- 1-3 prong with net charge = 0
- Thrust magnitude > 0.9
- Divide into two hemispheres by thrust axis.
- Λ selection:
 - Proton-ID: $\mathcal{P}(p/\pi) > 0.6$
 - Λ fake veto by e -ID < 0.1
 - Select "Good Λ " (Explain later)
 - $|M_\Lambda| < 5 \text{ MeV}/c^2$
 - $p_\Lambda^{CM} > 1.75 \text{ GeV}/c$
- $p_{miss} > 0.4 \text{ GeV}/c$, $17^\circ < \theta_{miss} < 150^\circ$
- $5.29 < E_{vis}^{CM} < 10.5 \text{ GeV}$, $\cos \theta_{miss-tag}^{CM} > 0.0$
- $N_\gamma^{sig} \leq 1$, $N_\gamma^{tag} \leq 2$
- Proton and Kaon veto for tag side trk and 1st π :
 $\mathcal{P}(p/\pi) < 0.6$ and $\mathcal{P}(K/p) < 0.6$
- $p_{miss} > 1.5 m_{miss}^2 - 1$



“Good Λ ” condition:

P_Λ (GeV)	fl ($>$) (cm)	$d\varphi$ ($<$) (rad)	zdist ($<$) (cm)	dr ($>$) (cm)
0.45 – 0.5	0.5 (<15)	0.4	1.0	0.1
0.50 – 1.5	0.24	0.1	2.1	0.033
1.50 –	0.35	0.07	3.0	0.02





Blind Region:

$\pm 5\sigma$ of M_{inv}

$(1.76 < M_{inv} < 1.80 \text{ GeV}/c^2)$

$-0.5 < \Delta E < 0.5 \text{ GeV}$

Signal eff. = 13.1%



$B - L$ con. & vio. mode $\tau \rightarrow \Lambda\pi$

Differently from the $\tau \rightarrow p\gamma/\pi^0$ case, we consider two $\tau \rightarrow \Lambda\pi$ decay modes:

1. $B - L$ conserving mode: $\tau^- \rightarrow \bar{\Lambda}\pi^-$ ($\bar{\Lambda} \rightarrow \bar{p}\pi^+$)
2. $B - L$ violating mode : $\tau^- \rightarrow \Lambda\pi^-$ ($\Lambda \rightarrow p\pi^-$)

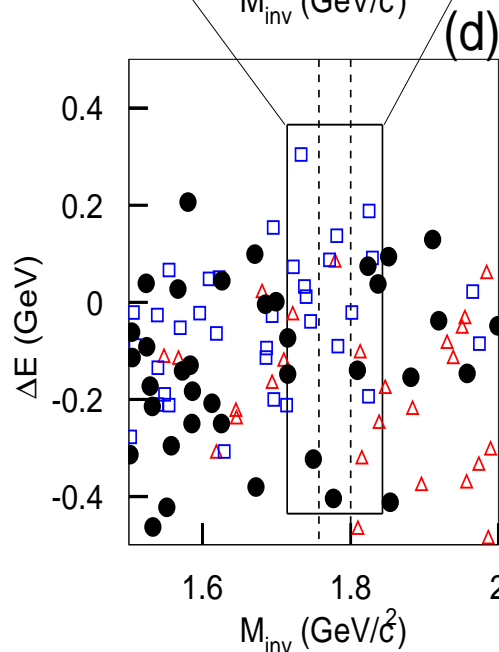
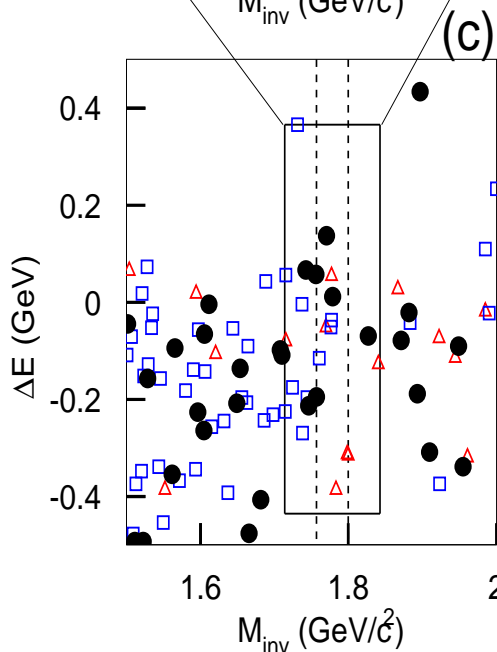
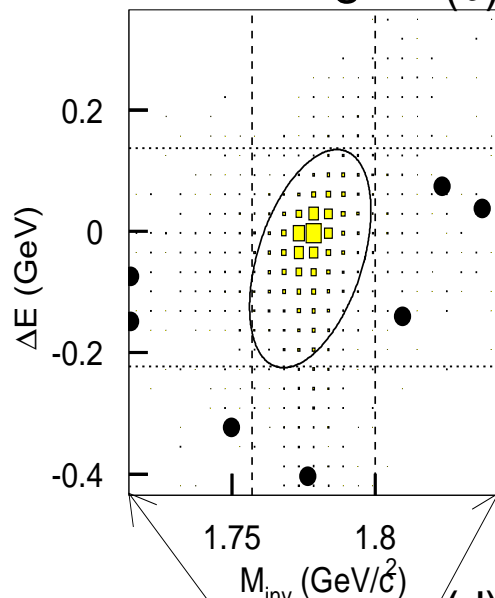
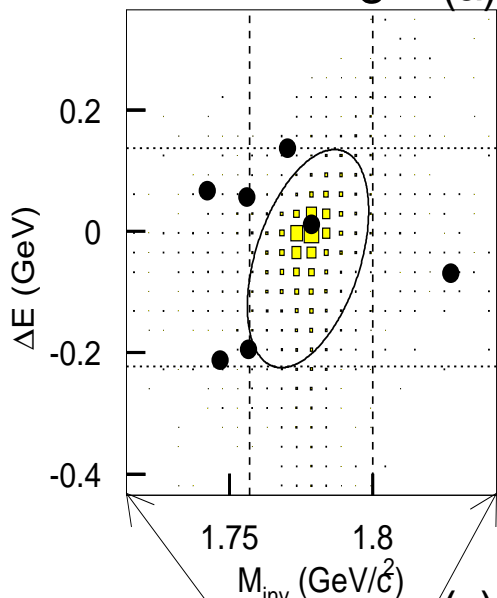
(and charge conjugations)

We can simply distinguish between these two modes by the chgs of two pions:

1. $B - L$ conserving mode: the two pions have **opposite charges**.
2. $B - L$ violating mode : the two pions have **the same charge**.

$B - L$ conserving: (a)

$B - L$ violating: (b)



We evaluate UL of Br in the 90% elliptical region. Assuming linear BG distribution:

	con.	vio.
Eff(%)	11.8	11.7
#(ev) in side-band	5	5
Expected	1.7 ± 0.8	1.7 ± 0.8
Observed	1	0
s_{90}	2.77	1.47
$\mathcal{B}(\times 10^{-7})$	< 1.3	< 0.70

s_{90} : Feldman-Cousins UL of sig @90% C.L. including systematic errs evaluated by POLE program

- $\tau^- \rightarrow \bar{p} \gamma / \pi^0$: We obtained new BR UL's (Preliminary)

$$\mathcal{B}(\tau^- \rightarrow \bar{p} \gamma) < 3.0 \times 10^{-7} \text{ @ 90\% C.L. (87fb}^{-1} \text{ Data)}$$

$$\mathcal{B}(\tau^- \rightarrow \bar{p} \pi^0) < 6.5 \times 10^{-7} \text{ @ 90\% C.L. (154fb}^{-1} \text{ Data)}$$

Comp. btw Belle & CLEO (in the 90% ellipse)	Belle		CLEO		Ratio $\left(\frac{\text{Belle}}{\text{CLEO}}\right)$	
	$p\gamma$	$p\pi^0$	$p\gamma$	$p\pi^0$	$p\gamma$	$p\pi^0$
Eff.(%)	8.7	5.7	10.7	8.4	0.8	0.7
Lum.(fb ⁻¹)	86.7	153.8	4.7	4.7	19	33
Observed Ev	6	41	1	14	6.0	2.9
Obs. Ev/Lum	0.057	0.27	0.21	3.0	1/3.7	1/11
$\mathcal{B}(\times 10^{-7})$	3.0	6.5	35	150	1/ 12	1/ 23

We succeed to reduce large BG due to the effective proton-ID.

- $\tau^- \rightarrow \bar{\Lambda} / \Lambda \pi^-$: We obtained BR UL's (Preliminary)

$$\mathcal{B}(\tau^- \rightarrow \bar{\Lambda} \pi^-) < 1.3 \times 10^{-7} \text{ @ 90\% C.L. (154fb}^{-1} \text{ Data, } B - L \text{ con.)}$$

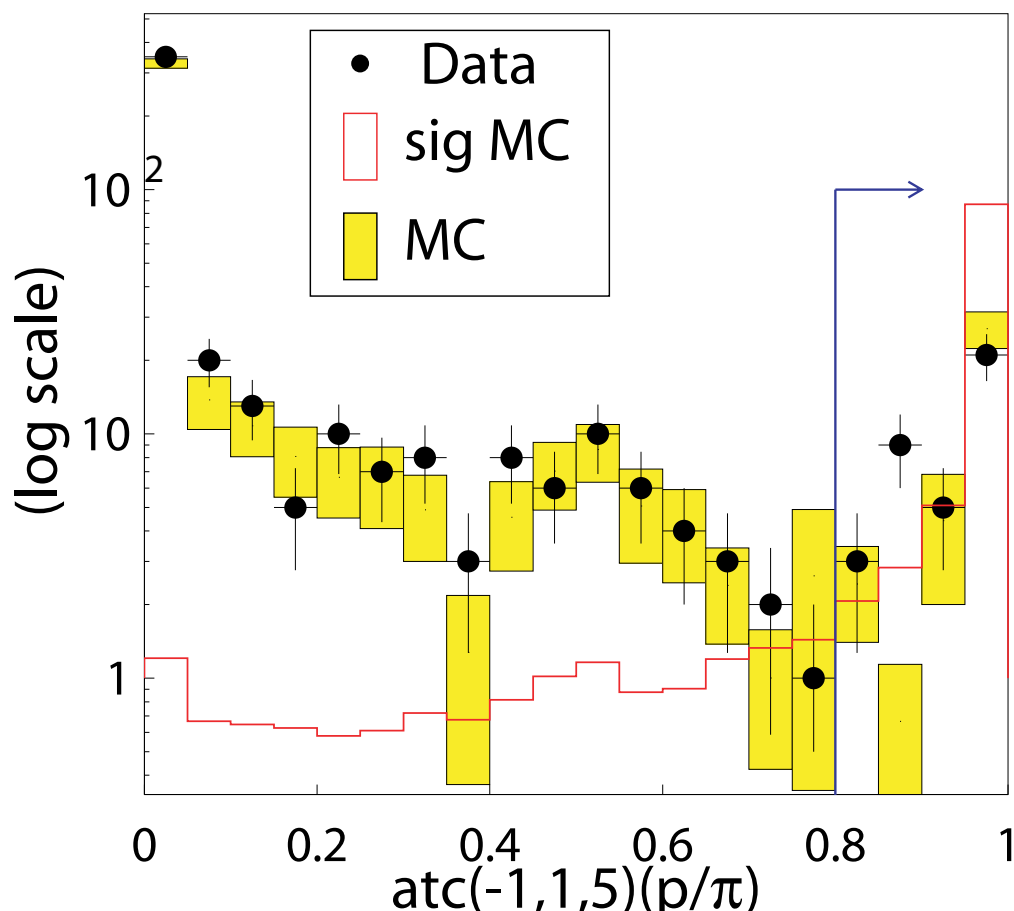
$$\mathcal{B}(\tau^- \rightarrow \Lambda \pi^-) < 0.70 \times 10^{-7} \text{ @ 90\% C.L. (154fb}^{-1} \text{ Data, } B - L \text{ vio.)}$$

These results are the first measurement ever performed.



Backup Slides

To further reduce pion BG, we used dE/dx in Central Drift Chamber and TOF information, $\mathcal{P}^{TC}(p/\pi) = \mathcal{L}_p^{TC} / (\mathcal{L}_p^{TC} + \mathcal{L}_\pi^{TC})$, where $\mathcal{L}^{TC} = \mathcal{L}^{TOF} \times \mathcal{L}^{CDC}$.

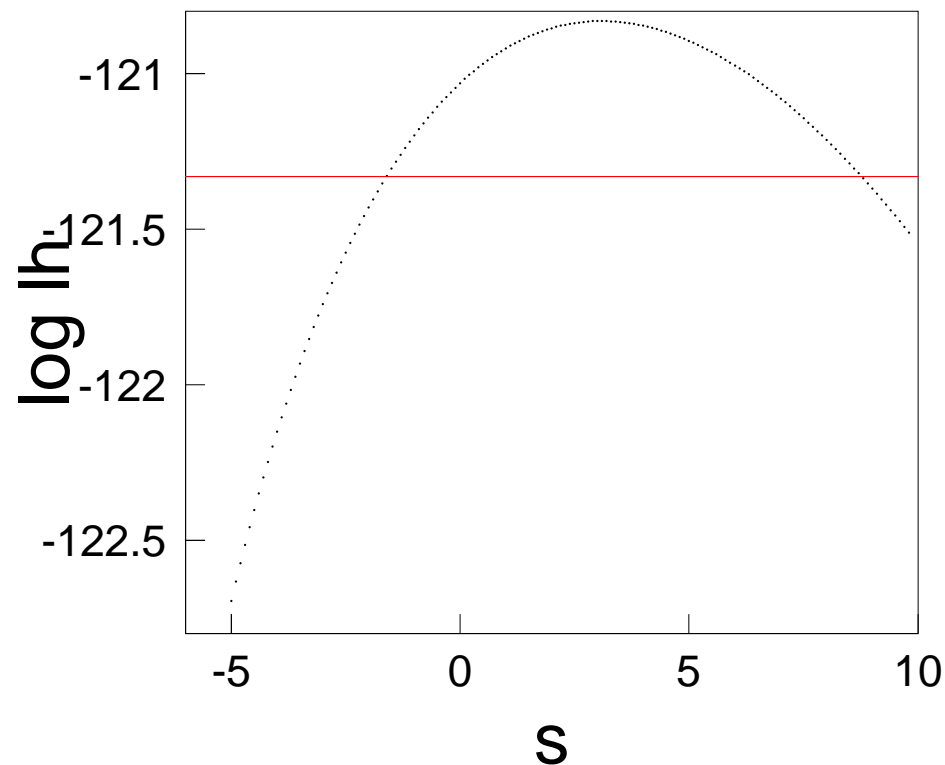


Our Proton-ID scheme:

0. lepton rejection
($e\text{-ID} < 0.8$, $\mu\text{-ID} < 0.8$)
1. $1\text{GeV} < P < P_{th}^p$
and ACC Not Fired
2. $\mathcal{P}^{TC}(p/\pi) > 0.8$
3. $\mathcal{P}(p/K) > 0.8$ for $\tau \rightarrow p\pi^0$
(to reduce BG from $\tau \rightarrow K^*\nu$)

Short discussion of the signal like excess of $\tau \rightarrow p\pi^0$.

log likelihood as a function of s :



Red line: $\text{Max}(\ln \mathcal{L}) - 0.5$.
 $\Rightarrow \pm 1 \sigma$ of s is $-1.6 \sim 8.8$.

$s = 0$ within one σ

Thus the signal like excess is possibly due to the statistical fluctuation.

Sources	Sys. related to detection sensitivity	
	$\tau \rightarrow p\gamma$	$\tau \rightarrow p\pi^0$
Tracking eff.	2.0%	2.0%
Photon reconst. eff	3.0%	6.0%
Selection criteria	2.0%	4.0%
Trigger eff.	3.0%	3.0%
Proton-ID	2.5%	3.0%
MC statistics	0.2%	0.3%
Luminosity	1.4%	1.4%
$\tau\tau$ cross-section	0.03%	0.03%
Total	5.9%	8.7%

Sources	Sys. related to detection sensitivity
Λ selection	6.0%
Proton-ID	3.0%
$\mathcal{B}(\Lambda \rightarrow p\pi)$	0.8%
Tracking eff.	4.2%
Trigger eff.	0.5%
Selection criteria	4.0%
MC statistics	0.7%
Luminosity	1.4%
$\tau\tau$ cross-section	0.03%
Total	9.1%