Search for Lepton and Baryon Number Violating τ^- Decays into $\bar{p}\gamma$, $\bar{p}\pi^0$, $\bar{\Lambda}\pi^-$ and $\Lambda\pi^-$

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

Introduction

- We have searched for LFV τ decay modes:
  $\tau \to \mu/e + \gamma, \quad \tau \to \mu/e + \eta/\pi^0/\eta', \quad \tau \to 3\ell.$
- 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 $\tau^- \to \bar{\Lambda}\pi^-, \bar{p}K_S$, from right-handed 4-fermi interaction
- We report here our searches for L and B violating τ decay modes:

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

  - $\tau^- \to \bar{p}\,\gamma$(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):
    $\mathcal{B}(\tau^- \to \bar{p}\gamma) < 35 \times 10^{-7}, \quad \mathcal{B}(\tau^- \to \bar{p}\pi^0) < 150 \times 10^{-7}.$
  - $\tau^- \to \bar{\Lambda}/\Lambda + \pi^-$ (153.8 fb^{-1} data):
    These modes have never been studied before.

Experimental Signature

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

$$\Big\{\underbrace{\tau^- \to \bar{p} + n_\gamma^{\rm SIG}}_{\text{(signal-side)}}\Big\} + \Big\{\underbrace{\tau^+ \to (\text{one trk})^+ + n_\gamma^{\rm TAG} + X(\text{missing})}_{\text{(tag-side)}}\Big\}$$

  - 1–1 prong topology
  - Main BG: $\tau^+\tau^-(\tau \to \rho\nu)$ and $q\bar{q}$ continuum (including true p)

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

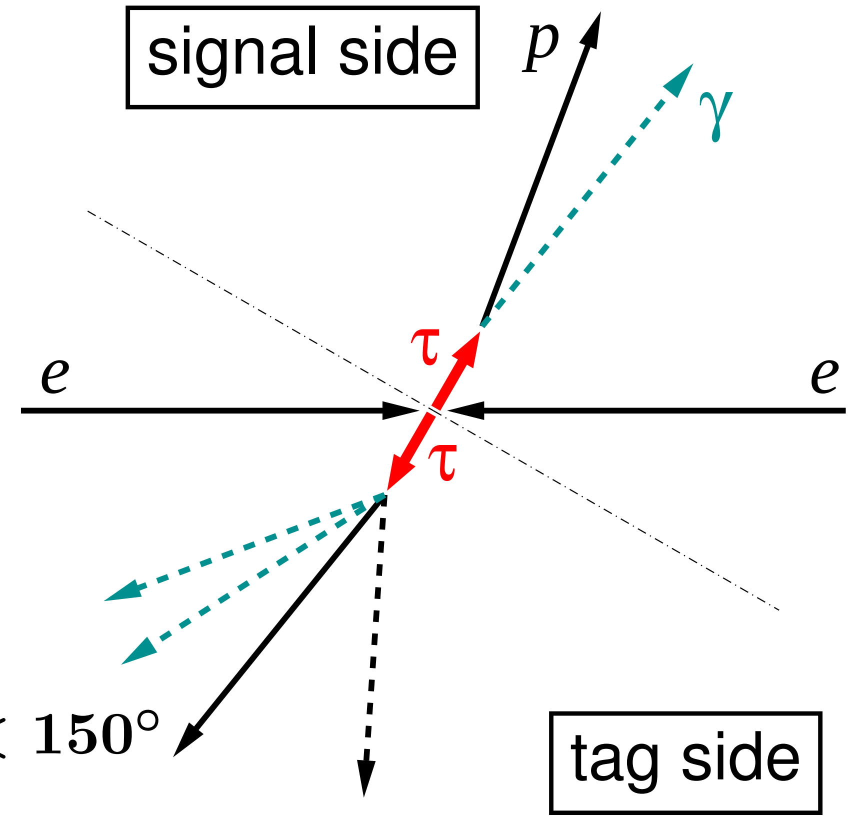
$$\Big\{\underbrace{\tau^- \to (\bar{p}\pi^+) + \pi^-}_{\text{(signal-side)}}\Big\} + \Big\{\underbrace{\tau^+ \to (\text{one trk})^+ + n_\gamma^{\rm TAG} + X(\text{missing})}_{\text{(tag-side)}}\Big\}$$

  - 1–3 prong topology
  - We reconstruct $\bar{\Lambda}$ from $\bar{\Lambda} \to \bar{p}\pi^+$ using vertex info. of Λ
  - Main BG: $\tau^+\tau^-(\tau \to a_1\nu)$ 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 $\tau^- \to \bar{p} + \gamma/\pi^0$ and $\tau^- \to \bar{\Lambda}/\Lambda + \pi^-$
$\Rightarrow$ We discuss these modes separately.

Selection Criteria $\tau \to p\gamma$

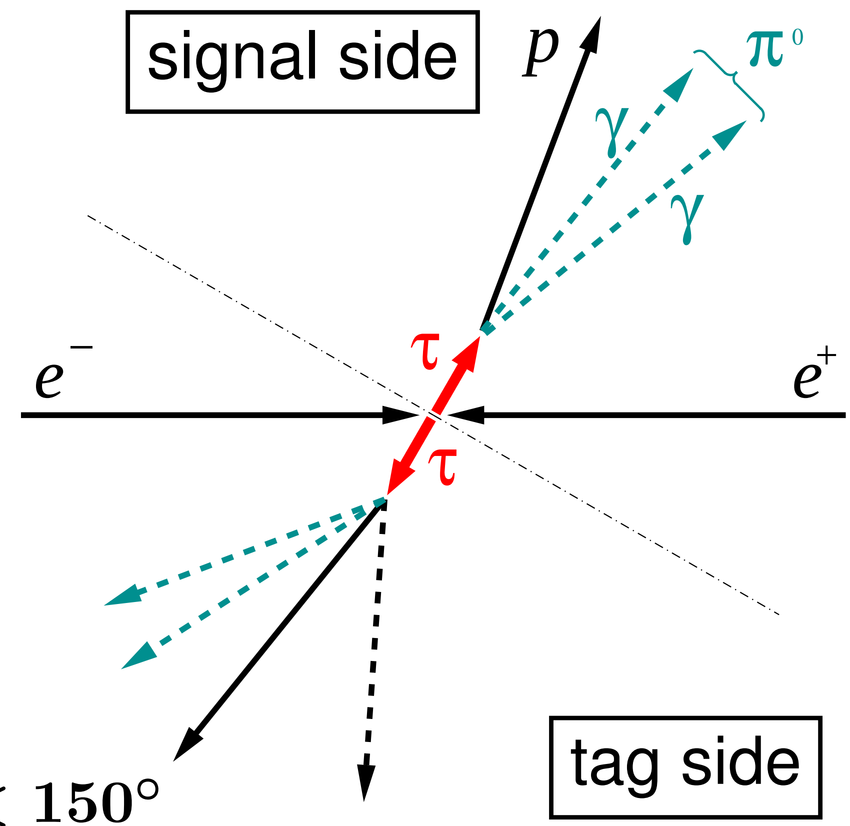
- 1-1 prong, $1 \le N_\gamma \le 3$
  $E_\gamma > 0.1$ GeV, net charge = 0
- $0.5 < E_{vis}^{CM}/\sqrt{s} < 0.92$
- signal side :
  proton-ID and $p_p > 1.0$ GeV/c
  $E_\gamma > 0.5$ GeV,
- $0.6 < \cos\theta_{p\gamma}^{CM} < 0.96$
- $p_{miss} > 0.6$ GeV/c, $17^\circ < \theta_{miss} < 150^\circ$
- $\cos\theta_{tag-miss}^{CM}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



Selection Criteria $\tau \to p\pi^0$

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

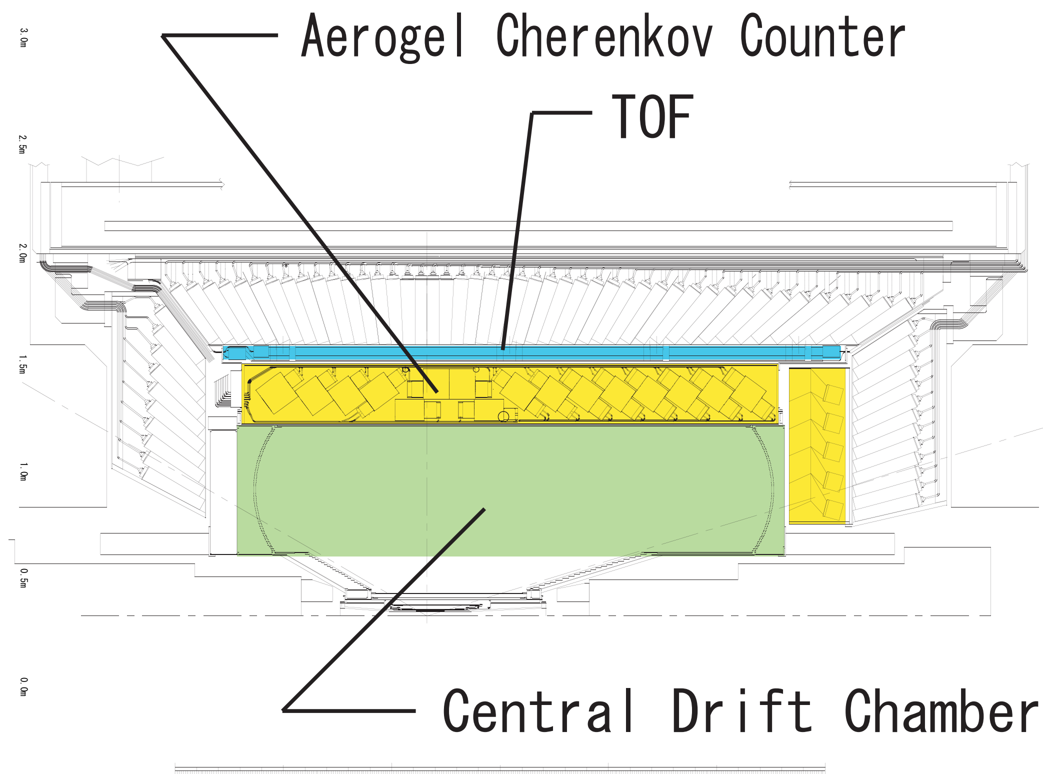
- 1-1 prong, $2 \le N_\gamma \le 4$
  $E_\gamma > 0.1$ GeV, net charge = 0
- $0.5 < E_{vis}^{CM} / \sqrt{s} < 0.92$
- signal side :
  proton-ID and $p_p > 1.0$ GeV/c
  One π^0 ($\left|\frac{M_{\gamma\gamma} - M_{\pi^0}}{\sigma_{\gamma\gamma}}\right| < 5$)
- $0.0 < \cos\theta_{p\pi^0}^{CM} < 0.95$
- $p_{miss}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



Hadron-ID in the Belle Detector

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,

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

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

Proton-ID

$\tau \rightarrow p\gamma/\pi^0$

BG events: mostly pions $\Rightarrow$ p/π 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.

	$P < P_{th}^{p}$	$P > P_{th}^{p}$
Fire	$\times$ Not Proton	$\triangle$ Any particle
Not Fire	○ Proton	$\times$ Not Proton

$\tau \rightarrow p\gamma$	$P < P_{th}^{p}$	$P > P_{th}^{p}$
sig eff	2.0%	0.47%
#data	6341 ev	86 ev
sig eff	11%	0.12%
#data	494 ev	4 ev

- The sig chgd trk: 1 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.

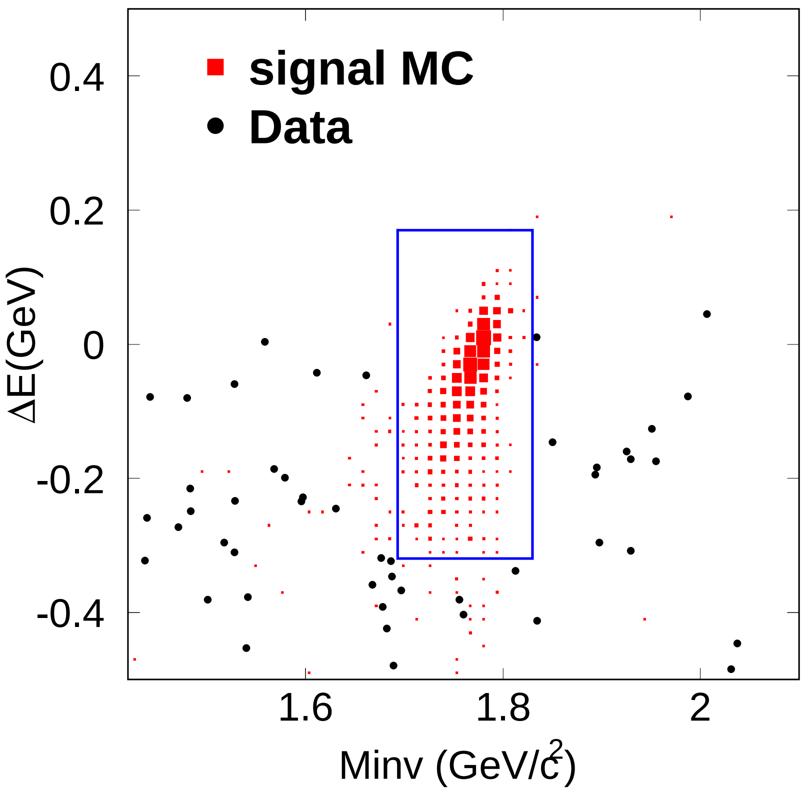
$\Rightarrow$ To further reduce the pion BG, we use $\mathcal{L}^{\text{TOF}}$ and $\mathcal{L}^{dE/dx}$.

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

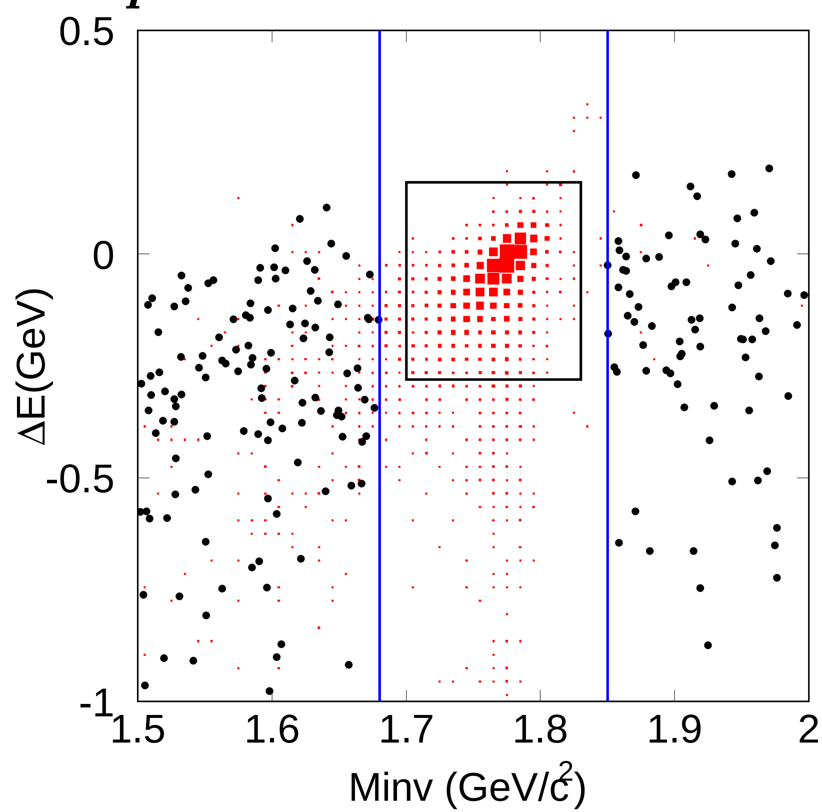
Blind Analysis $\tau \to p\gamma/\pi^0$

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

$\tau \to p\gamma$



$\tau \to p\pi^0$



Blind Region (denoted blue lines) :

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

-0.32 GeV $< \Delta E <$ 0.17 GeV

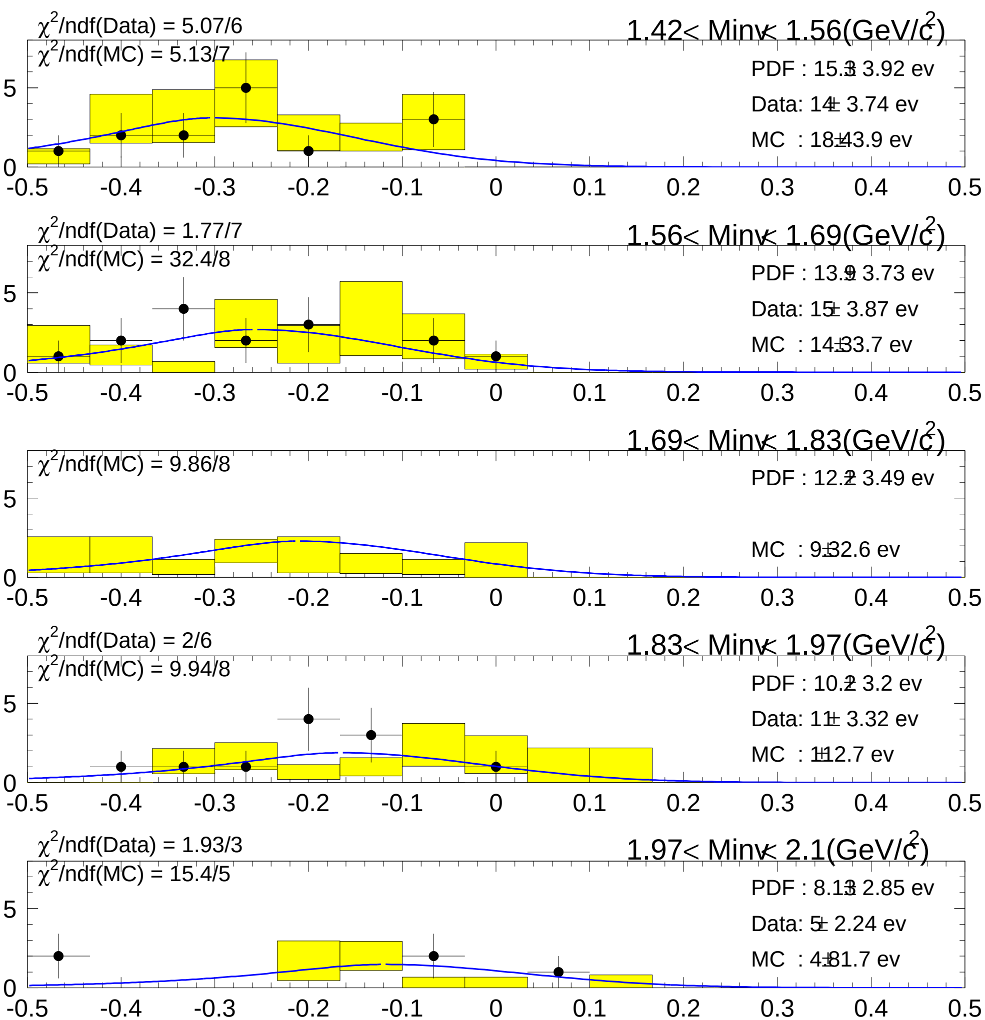
($\pm$5-σ Box region)

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

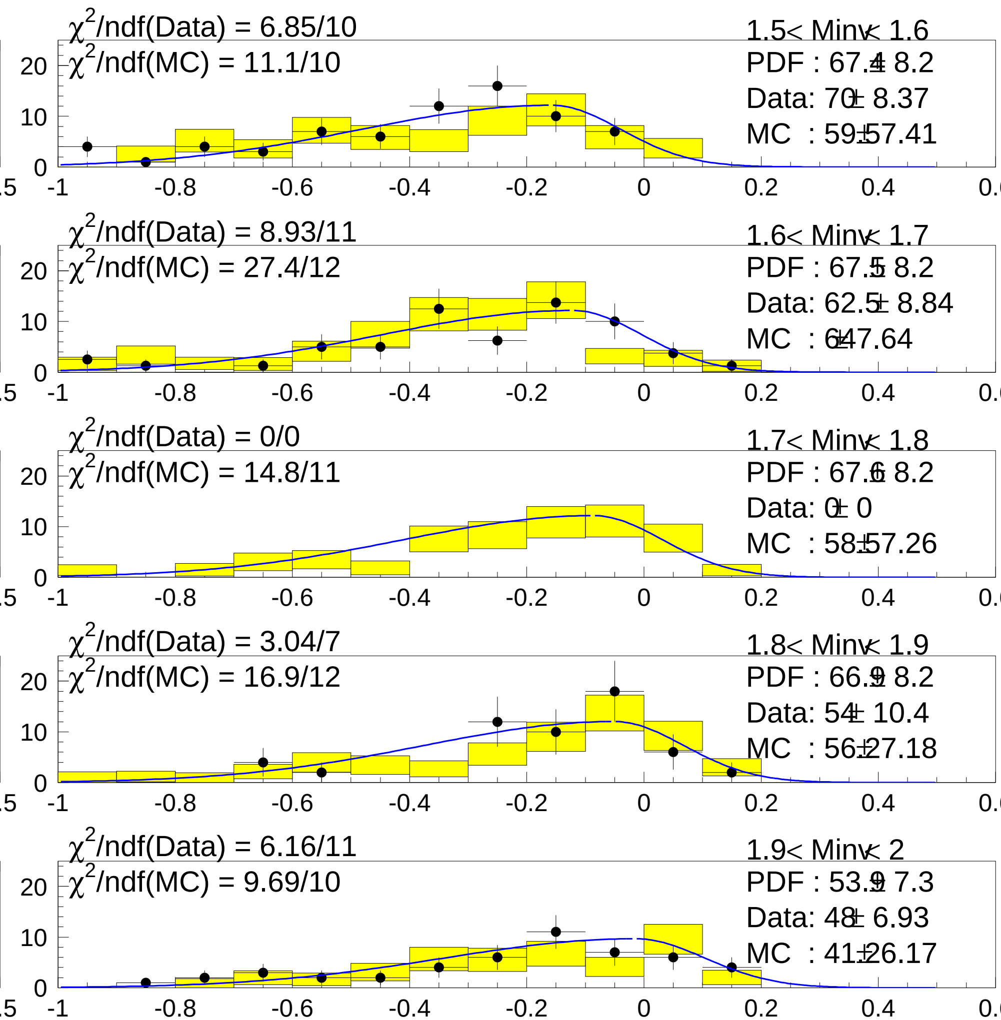
Background PDF $\tau \to p\gamma/\pi^0$

BELLE

$\tau \to p\gamma$



$\tau \to p\pi^0$



In the 5-σ Box:

Signal Eff = 9.4%

Expected BG = 9.1$\pm$1.7 ev

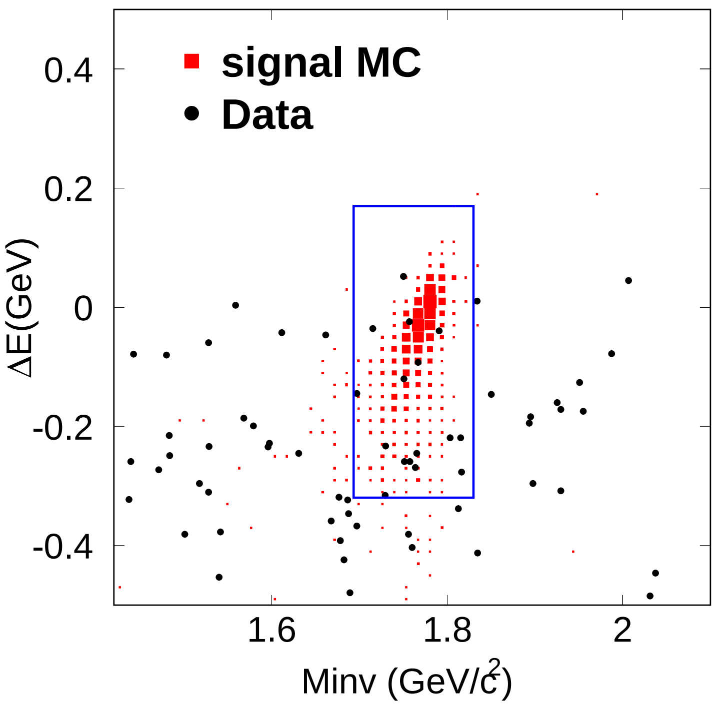
In the 5-σ Box:

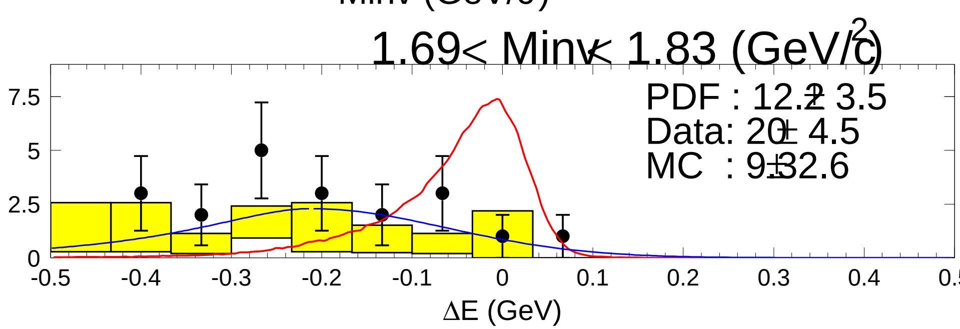
Signal Eff = 5.8%

Expected BG = 52.2$\pm$7.3 ev

Blind Opening $\tau \to p\gamma/\pi^0$

$\tau \to p\gamma$



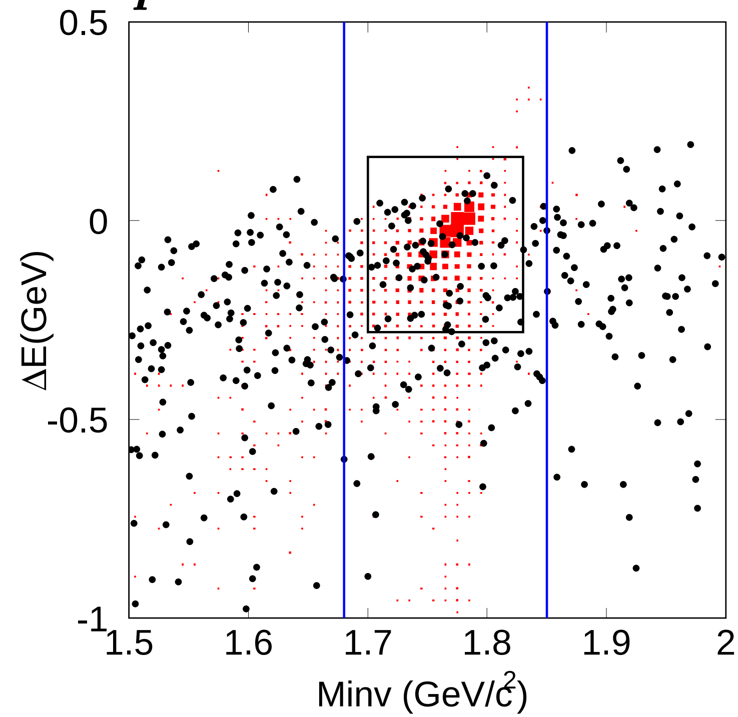


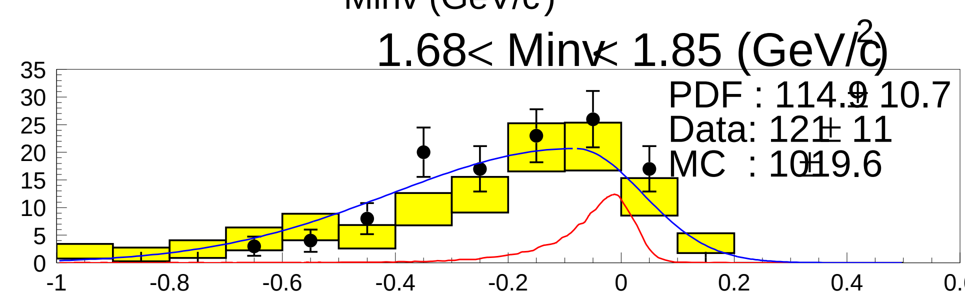
In the 5-σ Box:

Observed: 16 ev (9.1$\pm$1.7 expected)

diff: 6.9$\pm$4.3ev (1.6σ)

$\tau \to p\pi^0$





In the 5-σ Box:

Observed: 70 ev (52.2$\pm$7.3 expected)

diff: 17.8$\pm$11.1ev(1.6σ)

Evaluation of UL

$\tau \to p\gamma/\pi^0$

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 Max($\mathcal{L}(s,b)$):

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

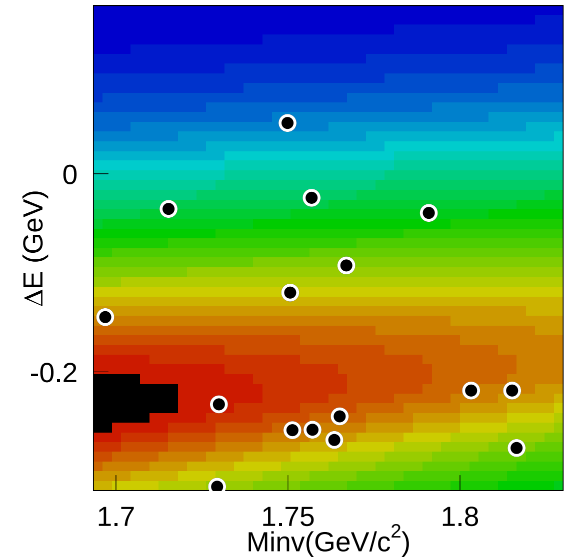
The UL of the sig ev @90% C.L. s_{90} are estimated by using TOY MC:

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

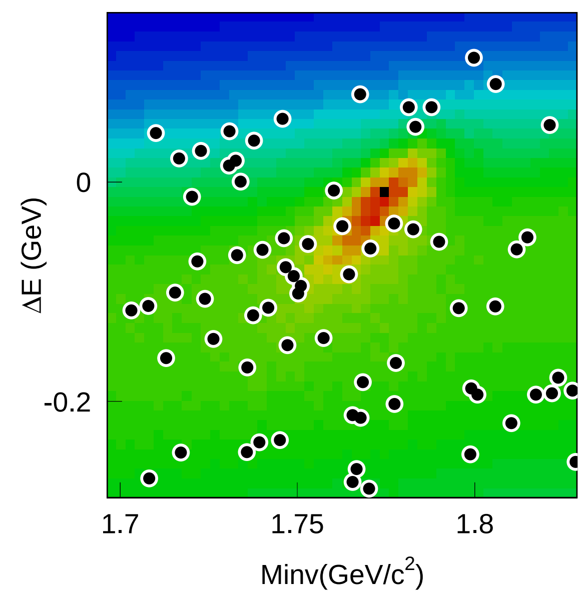
The UL of Br @90% C.L., $\mathcal{B} < s_{90}/2\epsilon N_{\tau\tau}$:

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

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

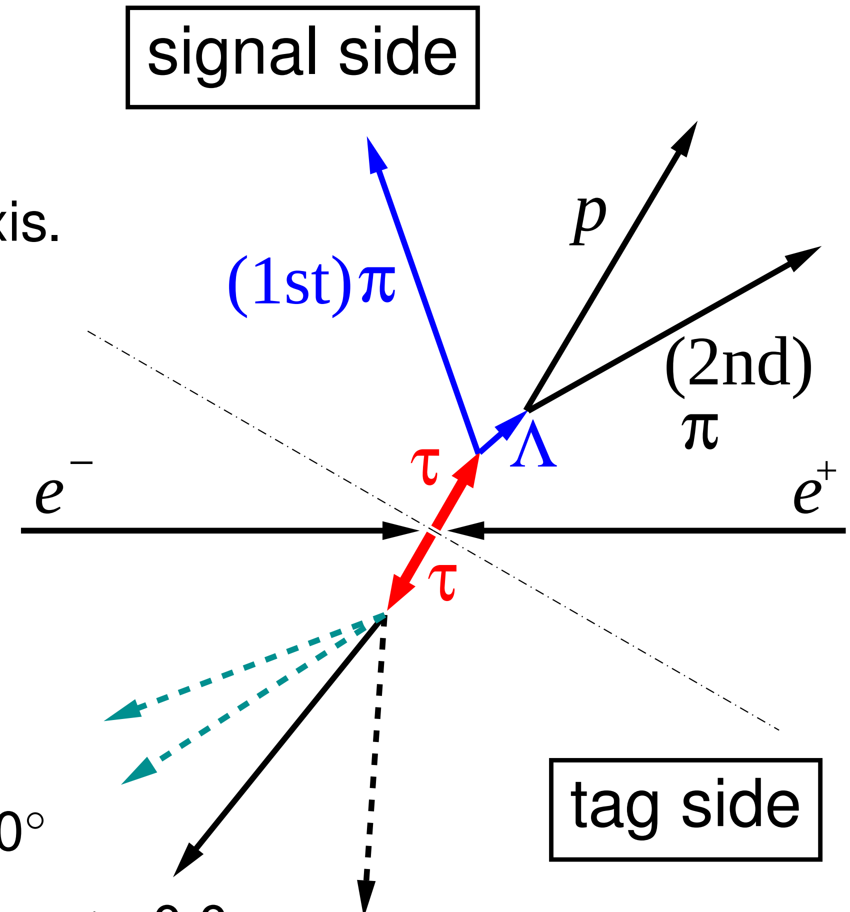


$sS_i + bB_i(\tau \to p\pi^0)$



Selection Criteria $\tau \to \Lambda\pi$

- 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)
  - $|M_\Lambda| < 5$ MeV/c^2
  - $p_\Lambda^{CM} > 1.75$ GeV/c
- $p_{miss} > 0.4$ GeV/c, $17^\circ < \theta_{miss} < 150^\circ$
- $5.29 < E_{vis}^{CM} < 10.5$ 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 $\mathcal{P}(K/p) < 0.6$
- $p_{miss} > 1.5\, m_{miss}^2 - 1$

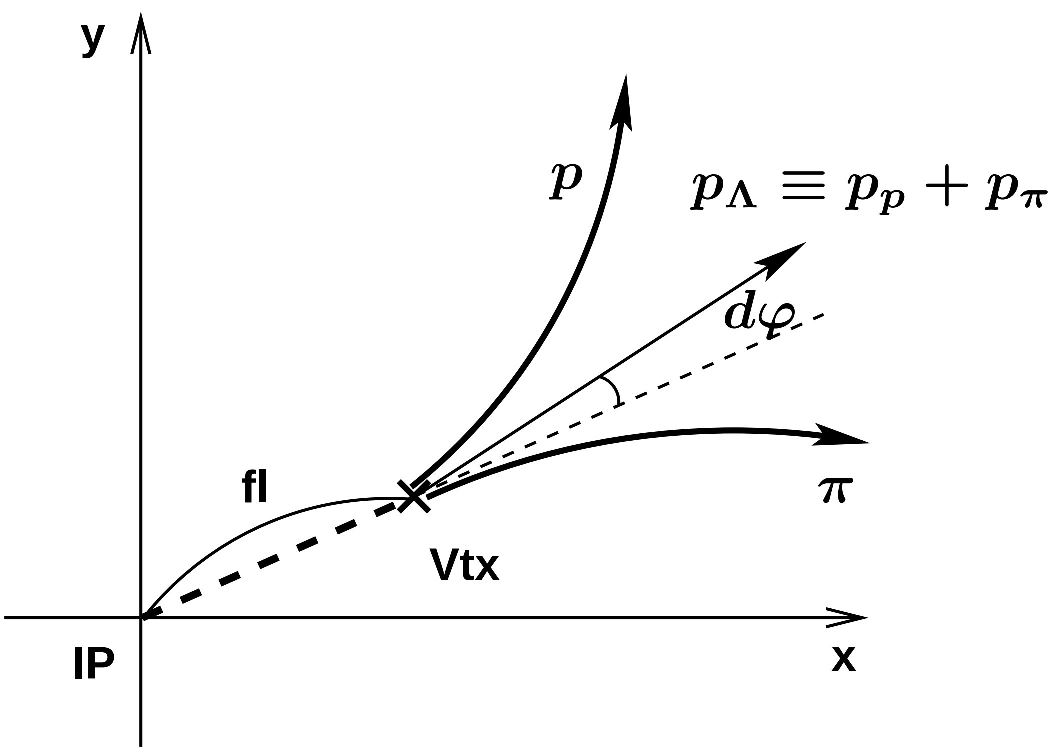


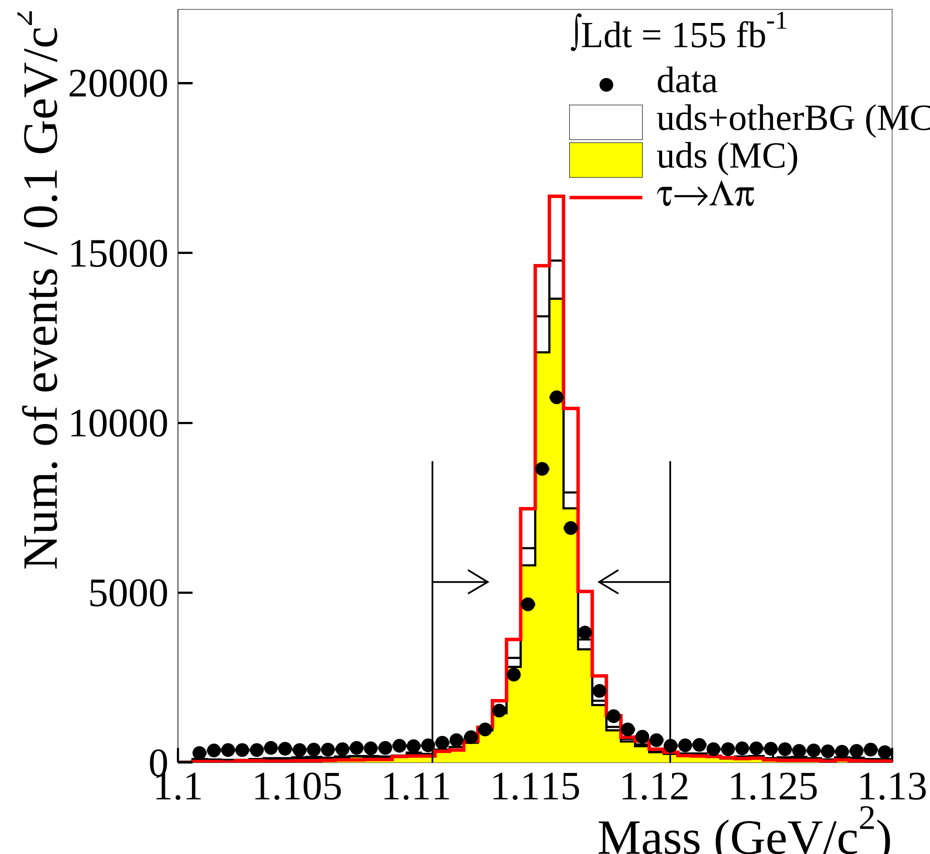
Λ Selection

$\tau \to \Lambda\pi$

"Good Λ" condition:

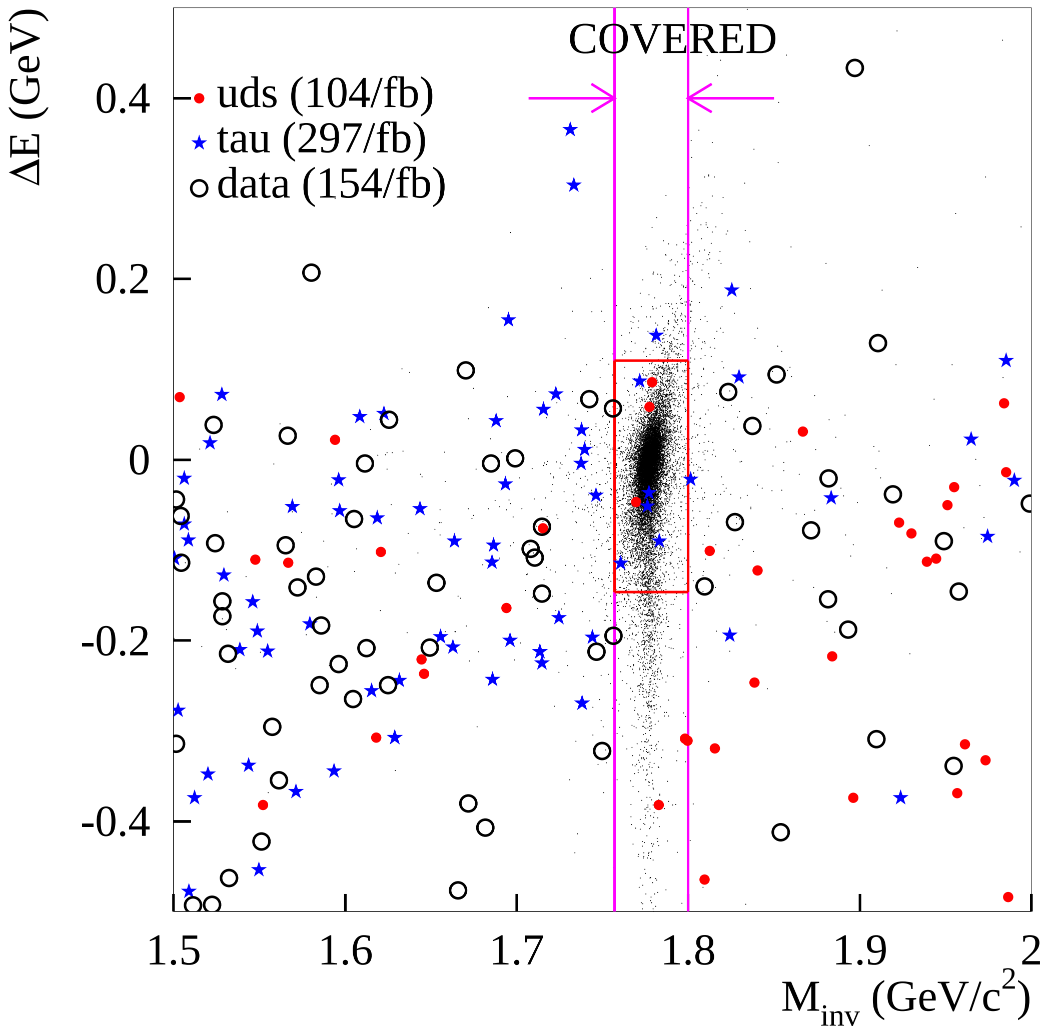
P_Λ (GeV)	fl (>) (cm)	dφ (<) (rad)	zdist (<) (cm)	dr (>) (cm)
0.45 – 0.5	0.5 (<15)	0.4	1.0	0.1
0.50 – 1.5	0.24	0.1	2.1	0.033
1.50 –	0.35	0.07	3.0	0.02





Blind Analysis

$\tau \rightarrow \Lambda\pi$



Blind Region:
$\pm\, 5\sigma$ of M_{inv}
$(1.76 < M_{inv} < 1.80$ GeV/c$^2)$
$-0.5 < \Delta E < 0.5$ GeV

Signal eff. = 13.1%

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

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

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

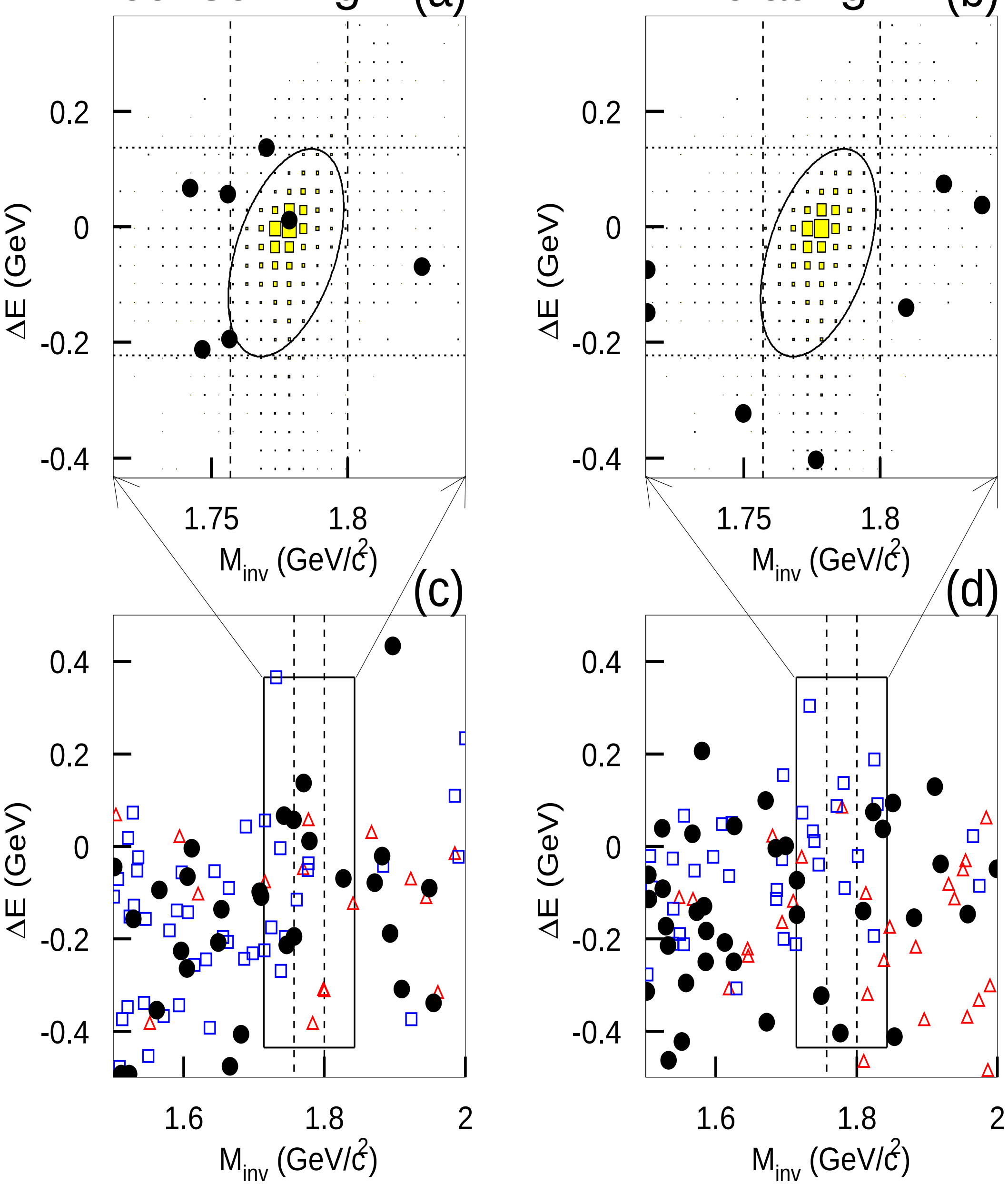
(and charge conjugations)

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.

Blind Opening & Results $\tau \to \Lambda\pi$

$B-L$ conserving: (a) $B-L$ violating: (b)



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

	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
$\mathcal{B}(\times 10^{-7})$	$< \mathbf{1.3}$	$< \mathbf{0.70}$

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

Summary

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

$$\mathcal{B}(\tau^- \to \overline{p}\gamma) < 3.0 \times 10^{-7} \text{ @ 90\% C.L. (87fb}^{-1}\text{ Data)}$$
$$\mathcal{B}(\tau^- \to \overline{p}\pi^0) < 6.5 \times 10^{-7} \text{ @ 90\% C.L. (154fb}^{-1}\text{ Data)}$$

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.

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

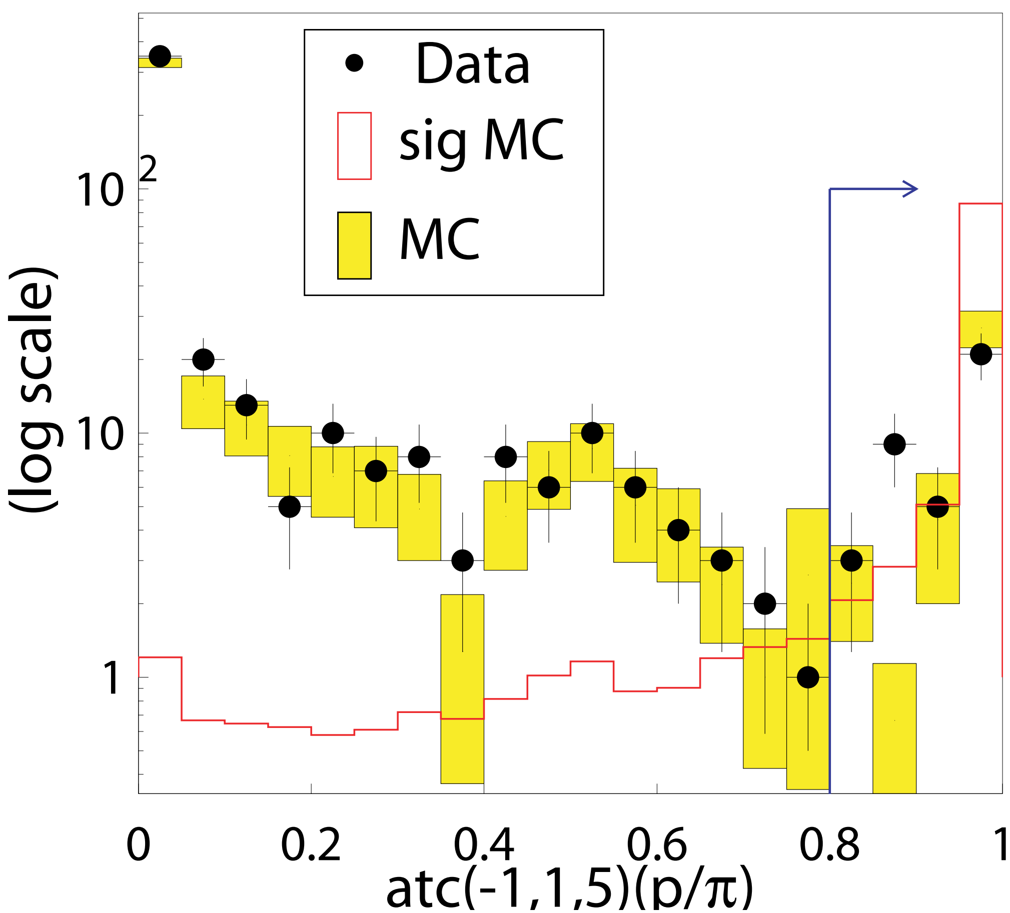
$$\mathcal{B}(\tau^- \to \overline{\Lambda}\pi^-) < 1.3 \times 10^{-7} \text{ @ 90\% C.L. (154fb}^{-1}\text{ Data, } B-L \text{ con.)}$$
$$\mathcal{B}(\tau^- \to \Lambda\pi^-) < 0.70 \times 10^{-7} \text{ @ 90\% C.L. (154fb}^{-1}\text{ Data, } B-L \text{ vio.)}$$

These results are the first measurement ever performed.

Backup Slides

TOF & dE/dx $\tau \to p\gamma/\pi^0$

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 $\mathcal{L}^{TC} = \mathcal{L}^{TOF} \times \mathcal{L}^{CDC}$.



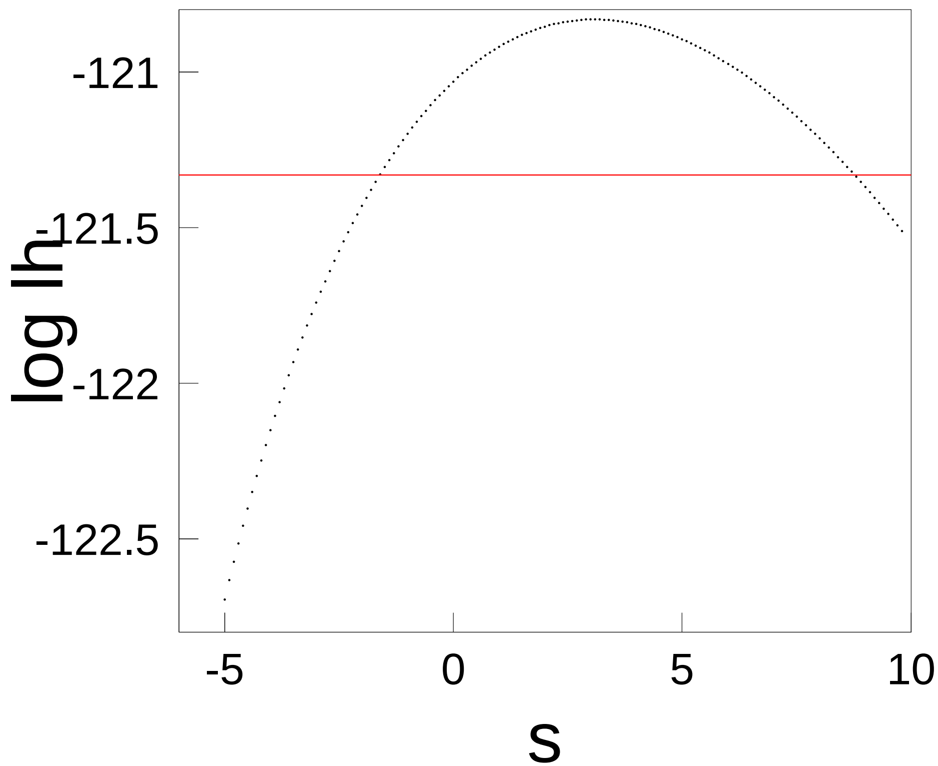
Our Proton-ID scheme:

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

Discussion of the Result $\tau \to p\pi^0$

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

log likelihood as a function of s:



Red line: Max($\ln \mathcal{L}$)$-$0.5.
$\Rightarrow \pm$ 1 σ 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.

Systematics

$\tau \to p\gamma/\pi^0$

Sources	Sys. related to detection sensitivity	
	$\tau \to p\gamma$	$\tau \to p\pi^0$
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%

Systematics

$\tau \longrightarrow \Lambda\pi$

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%