New Precision Measurement of the $\pi^+ \to e^+ \nu_e$ Branching Ratio

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For PIENU Collaborator
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Discrete 2014 at King's College

Outline

- $\pi^+ \to e^+ \nu_e$ Decay
- Measurement Method
- Detector
- Analysis
- Status and Errors
- Summary

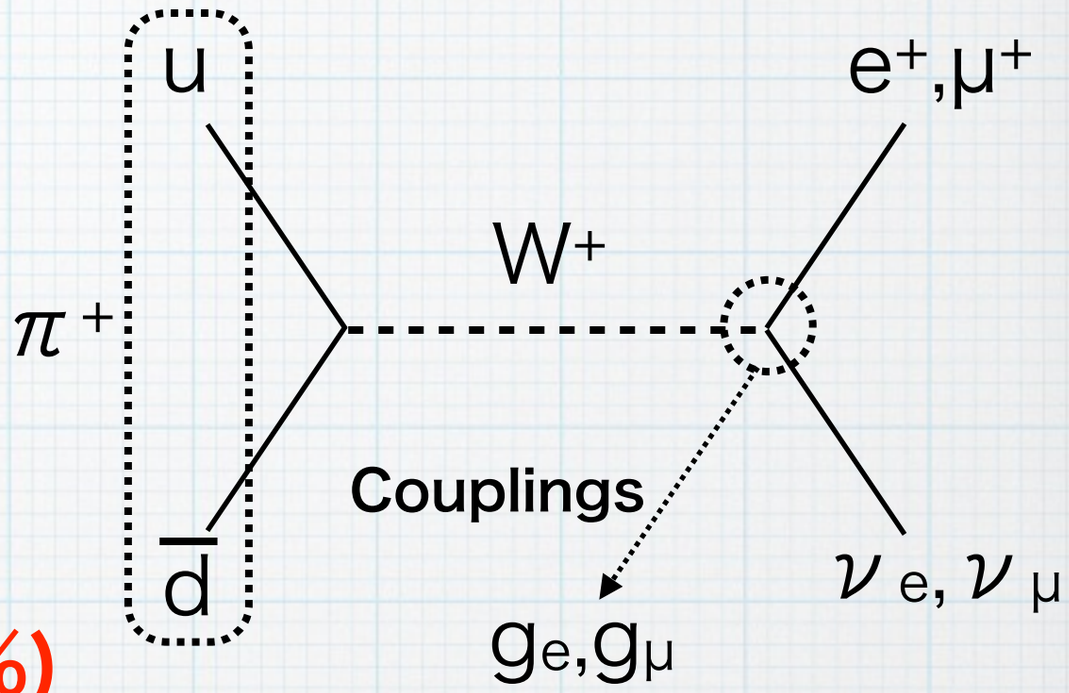
$\pi^+ \to e^+ \nu_e$ Decay

- π^+ branching ratio R in SM

$$R_{SM} = \frac{\Gamma(\pi \to e\,\nu + \pi \to e\,\nu\,\gamma)}{\Gamma(\pi \to \mu\,\nu + \pi \to \mu\,\nu\,\gamma)} = \frac{g_e^2}{g_\mu^2}\frac{m_e^2(m_\pi^2-m_e^2)^2}{m_\mu^2(m_\pi^2-m_\mu^2)^2}(1+\delta)(1+\varepsilon)$$

Radiative Correction

$$= (1.2352 \pm 0.0001) \times 10^{-4}$$ **(0.01%)**



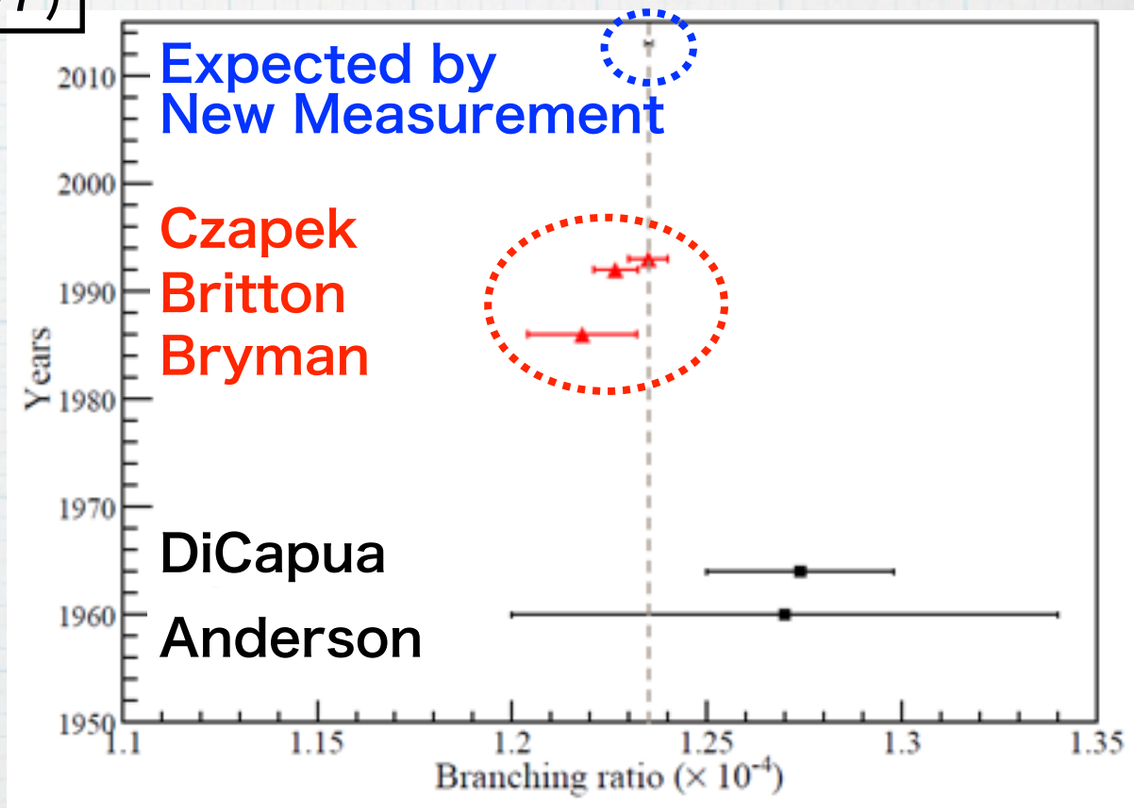
V.Cirigliano, I.Rosell, PRL 99 231801 (2007)

- $g_e = g_\mu$: **lepton universality.**
- $\pi^+ \to e^+ \nu_e$ is disfavored (V-A).

➡ **Helicity suppression.**

- Experimental result

$$R_{Exp} = (1.231 \pm 0.004) \times 10^{-4}$$ **(0.3%)**



History of R measurement.

Universality Test & Beyond SM

- Lepton universality violation.
  - π^+ R is one of the most precise measurement.
  - Improve R measurement.

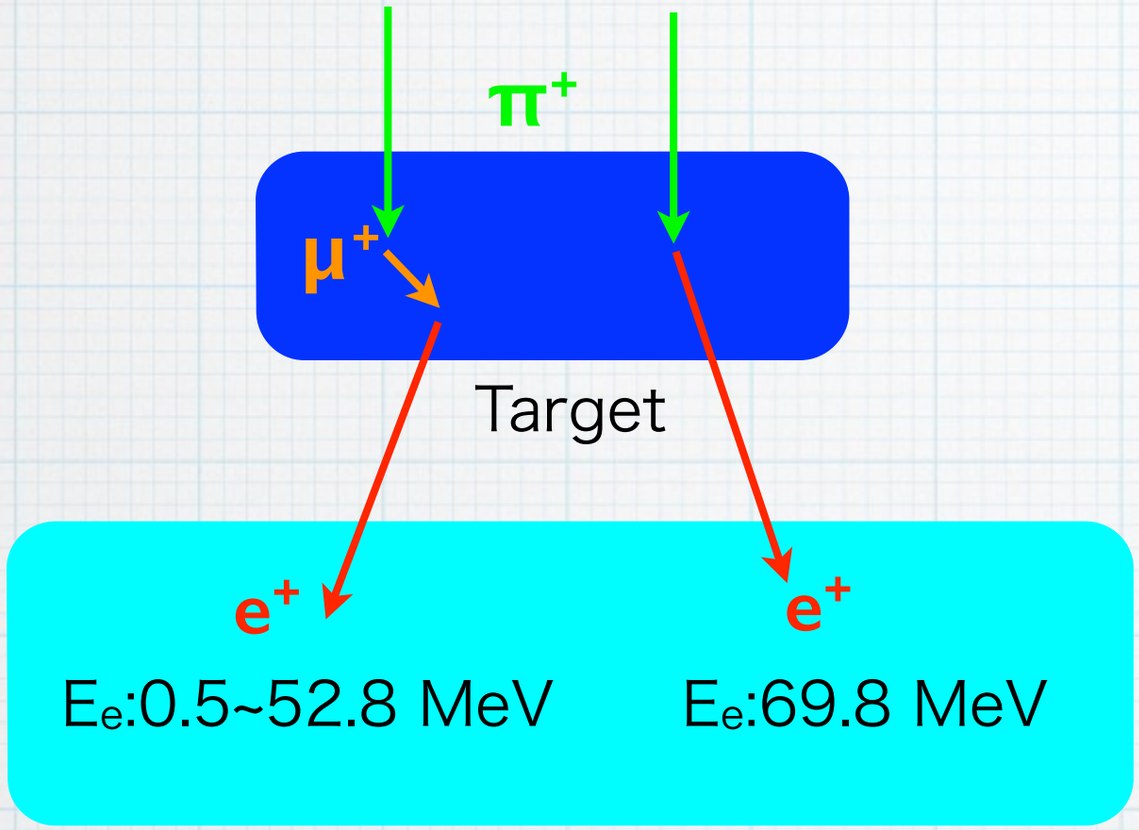
    ➡0.05% in g_μ/g_e.

Current experimental results of g_μ/g_e

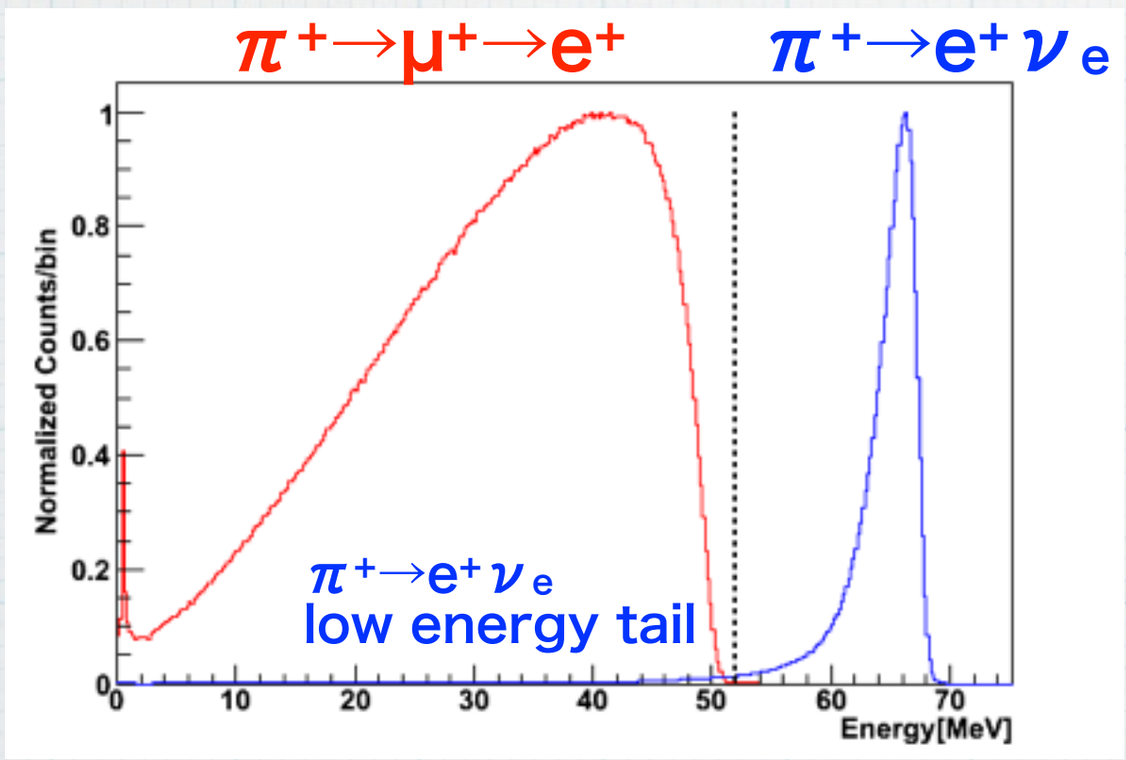
Decay Mode	g_μ/g_e	Year
$\tau\to\mu/\tau\to e$	1.0018±0.0014	2010
$\pi\to\mu/\pi\to e$	1.0021±0.0016	1994
$K\to\mu/K\to e$	0.996±0.005	2011
$K\to\pi\mu/K\to\pi e$	1.002±0.002	2007
$W\to\mu/W\to e$	0.997±0.010	2008

- New pseudo-scalar interaction without helicity suppression.
  - **0.1% level allows to access new physics up to 1000 TeV/c^2.**
  - R-parity violation SUSY, leptoquarks, charged Higgs, etc...
- Massive neutrino search→ M.Aoki et al. PRD 84 052002 (2011)
- PIENU experiment at TRIUMF → **aims at <0.1% level.**

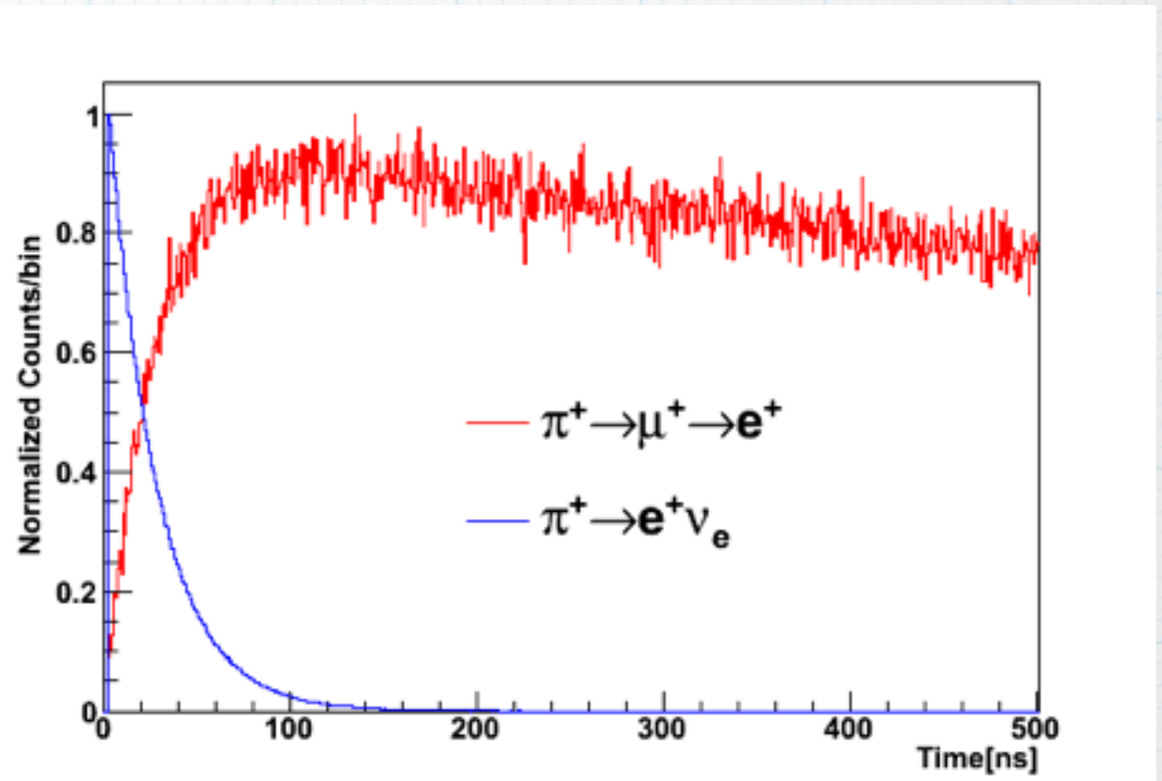
Measurement Method



Calorimeter



Decay positron energy (MC)



Positron decay time (MC)

$\pi^+ \to \mu^+ \to e^+$

$N_{PIMU}(1/(\tau_\mu - \tau_e))$

$\times(\exp(-t/\tau_\mu) - \exp(-t/\tau_\pi))$

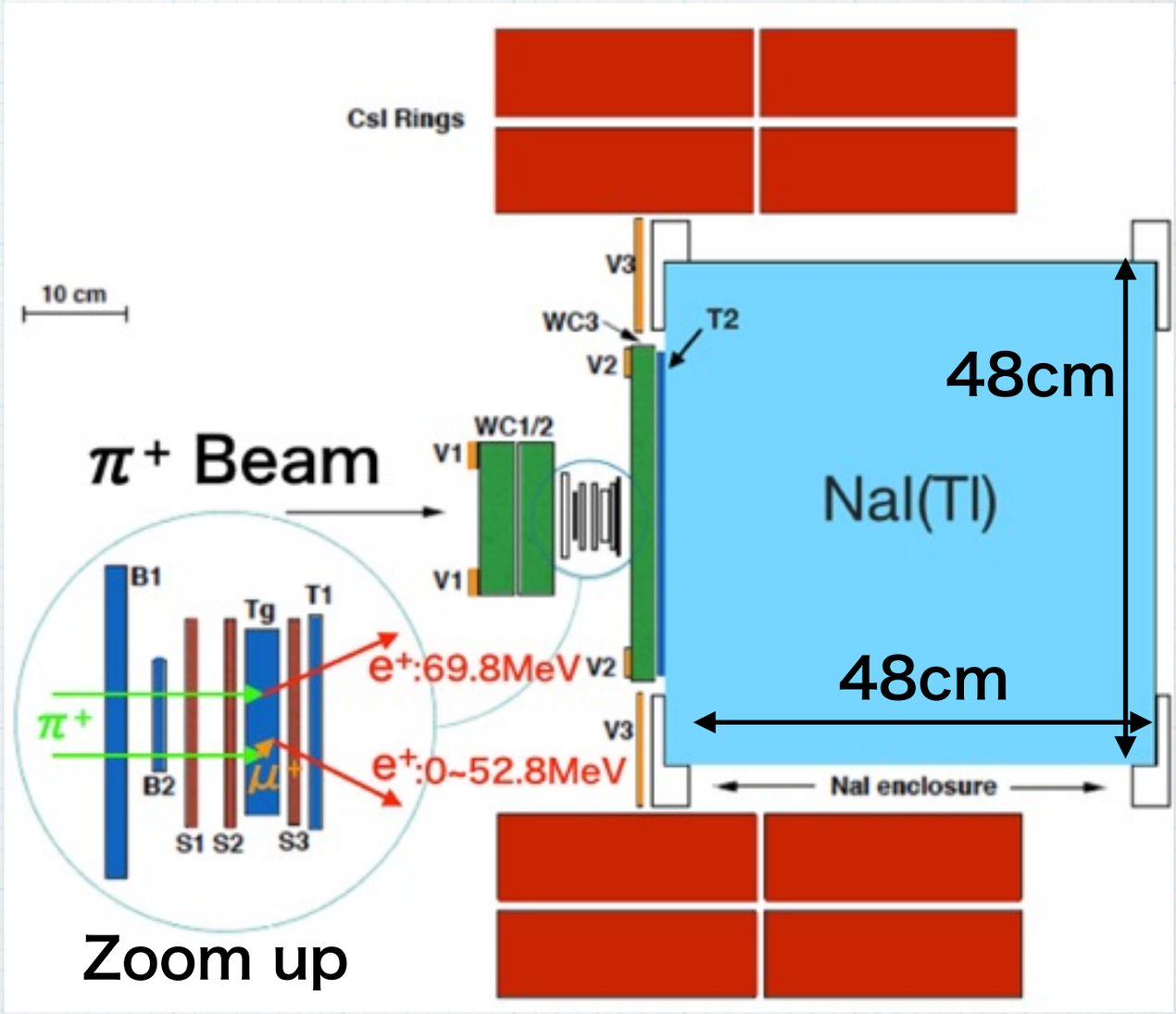
$\pi^+ \to e^+ \nu_e$

$(N_{PIE}/\tau_\pi)\exp(-t/\tau_\pi)$

$$R = \underbrace{N_{PIE}/N_{PIMU}}_{\text{Raw branching ratio R'}} \times \underbrace{(1+\varepsilon)}_{\text{Corrections (e.g: low energy tail)}}$$

PIENU Detector

- Detector acceptance:20%
- High energy resolution NaI(Tl)
  - ➡ σ=1% at 70 MeV.
- Pure CsI rings for shower leakage.
- Wire chamber & silicon strip for π^+ beam tracking.
  - ➡Detect π-DIF events.



PIENU detector

TRIUMF M13 Beam line

Beam rate:~70 kHz

Beam momentum:75±1 MeV/c

π^+:μ^+:e^+=85:14:1

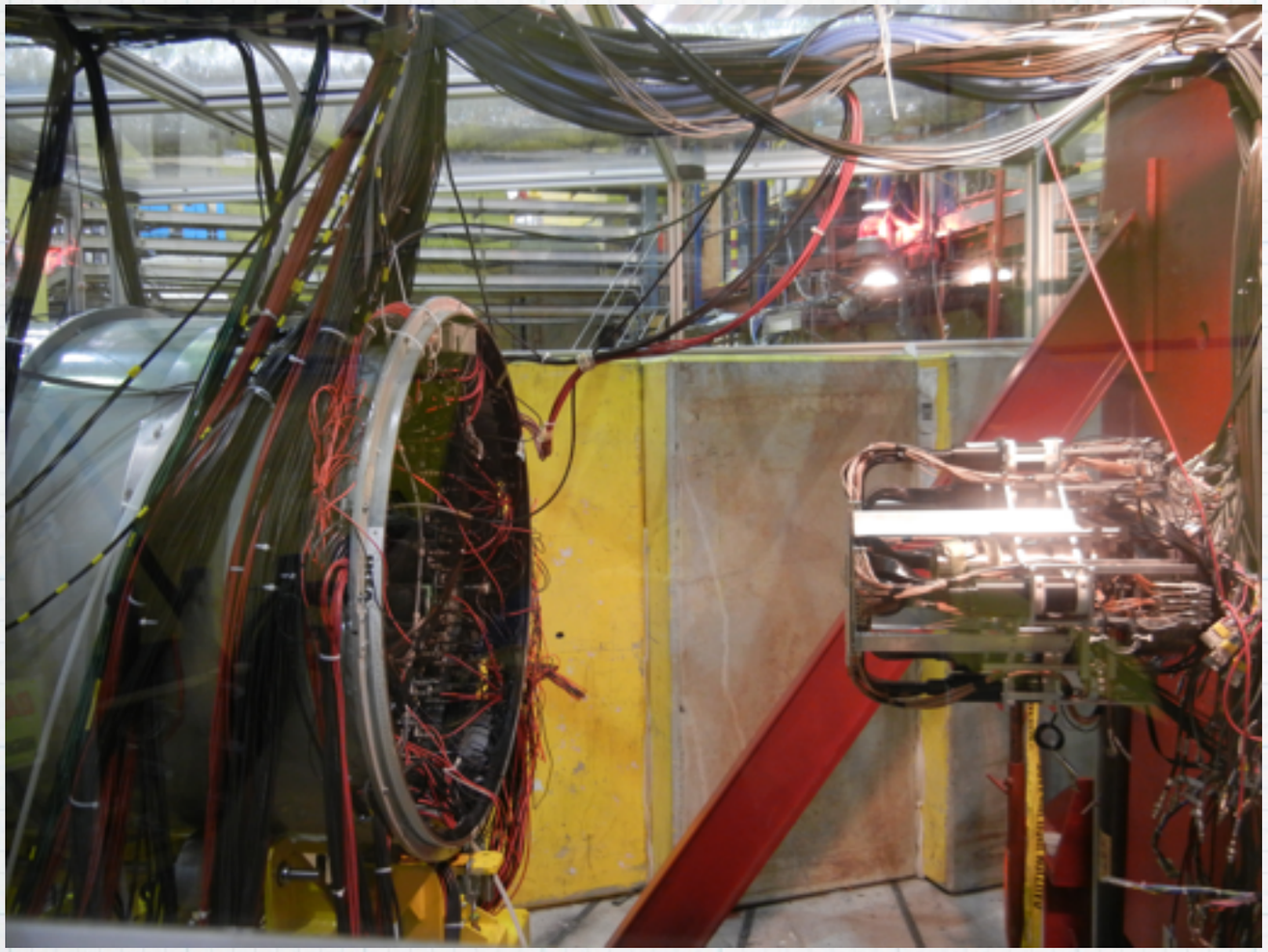
Data taking: 2009~2012

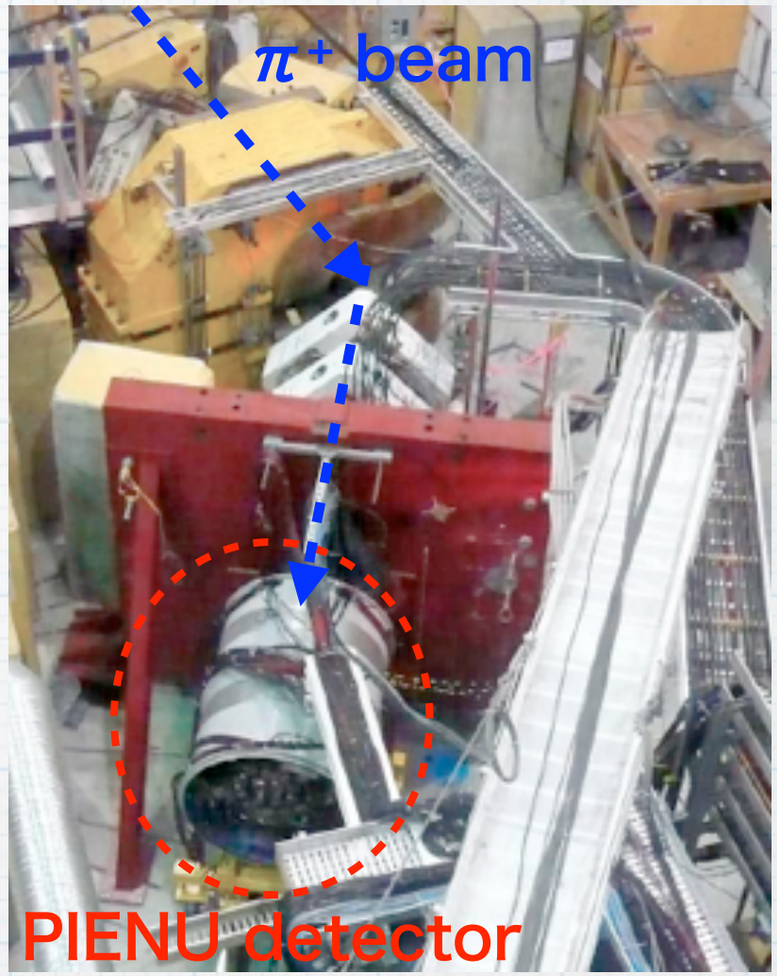
WC:Wire Chamber

S:Silicon Strips

B1,B2,Tg,T1,T2:Plastic scintillator

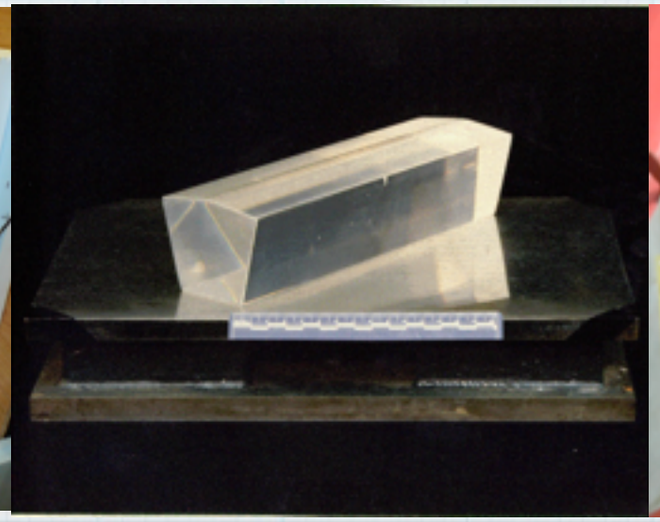
PIENU Detectors & Beam Line





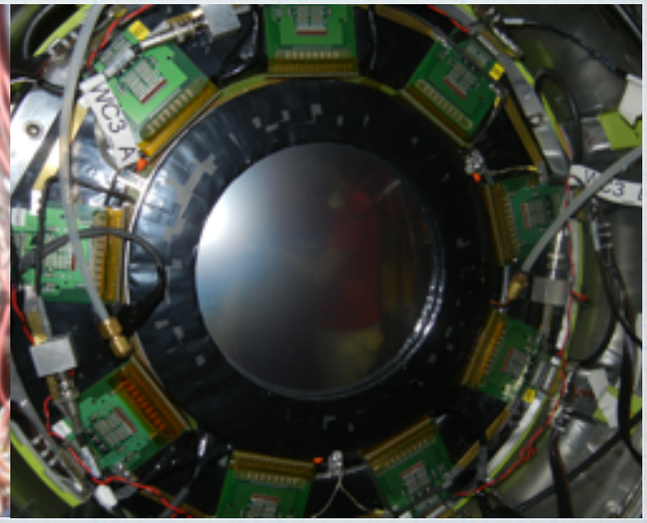
NaI

1 CsI crystal



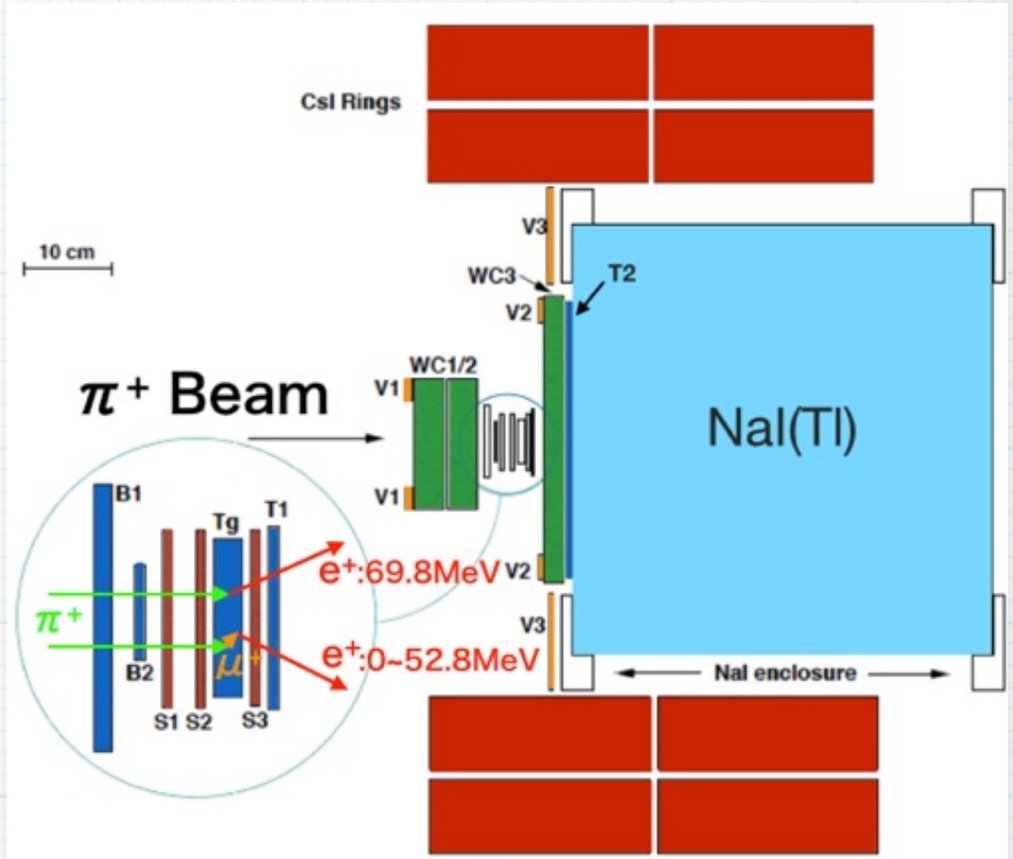
Scint + Si Strip

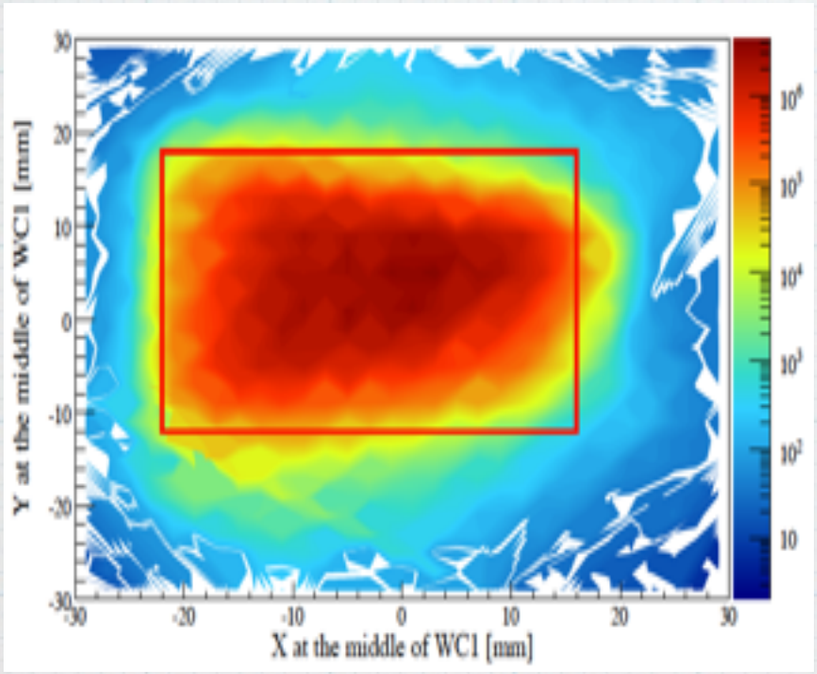
WC3



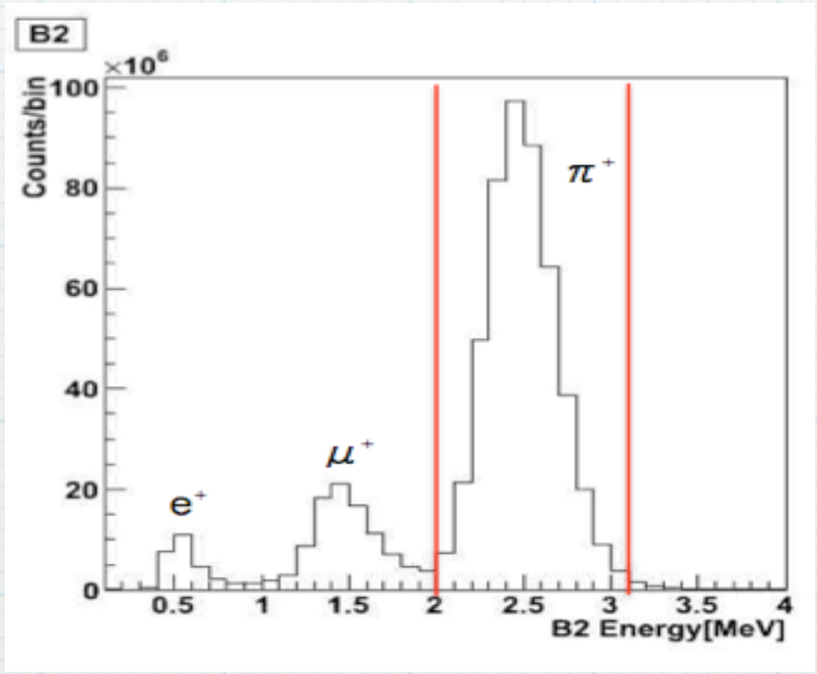
Analysis: Event Selection Cuts

- Data set: taken in Oct~Dec 2010.
  - ➡~5% of full data.
- Event selection cuts.
  - Beam profile by WC1,2.
  - Pion selection by dE/dx in B1,B2.
  - Single hit requirement.
  - Acceptance cut.

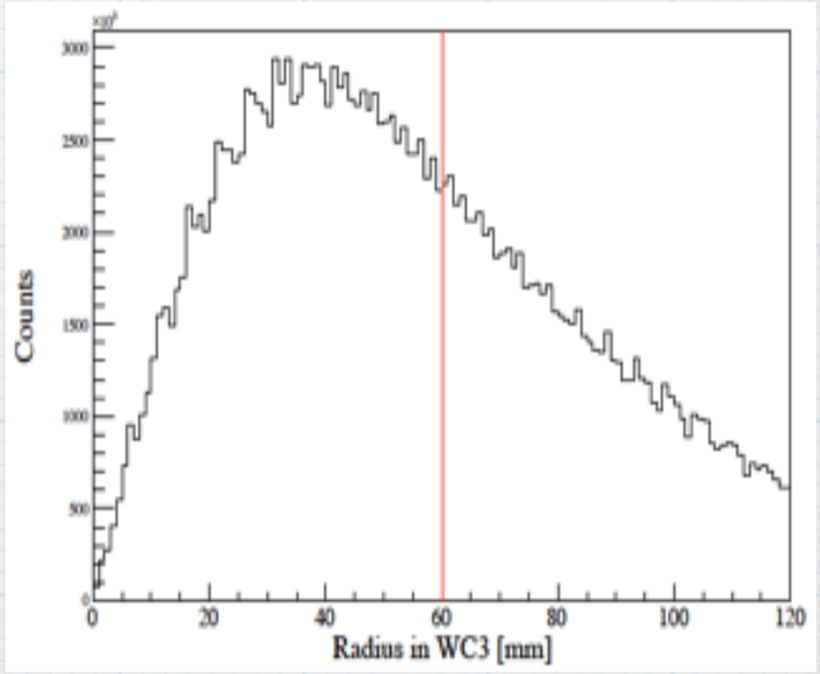




Beam profile by WC1

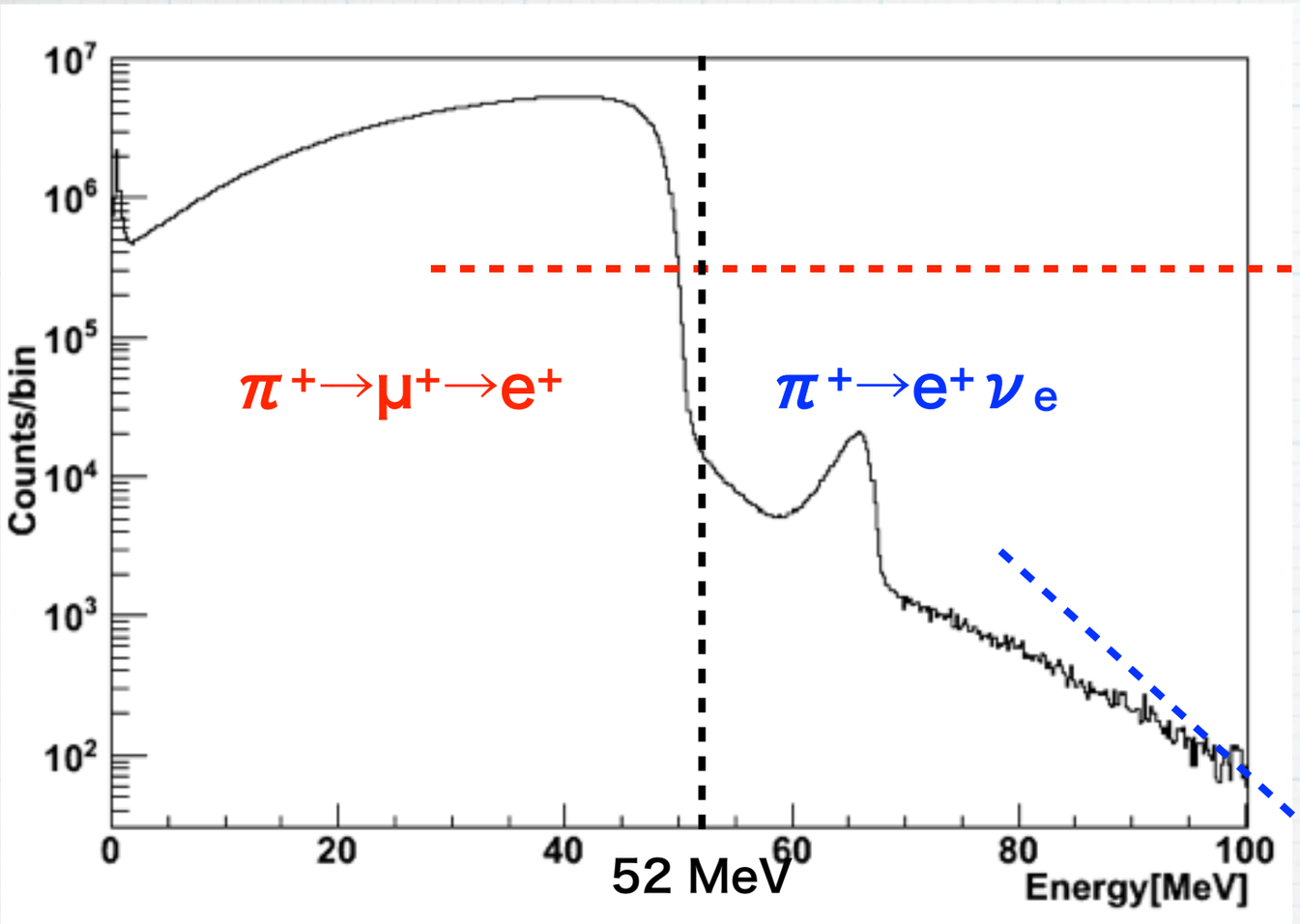


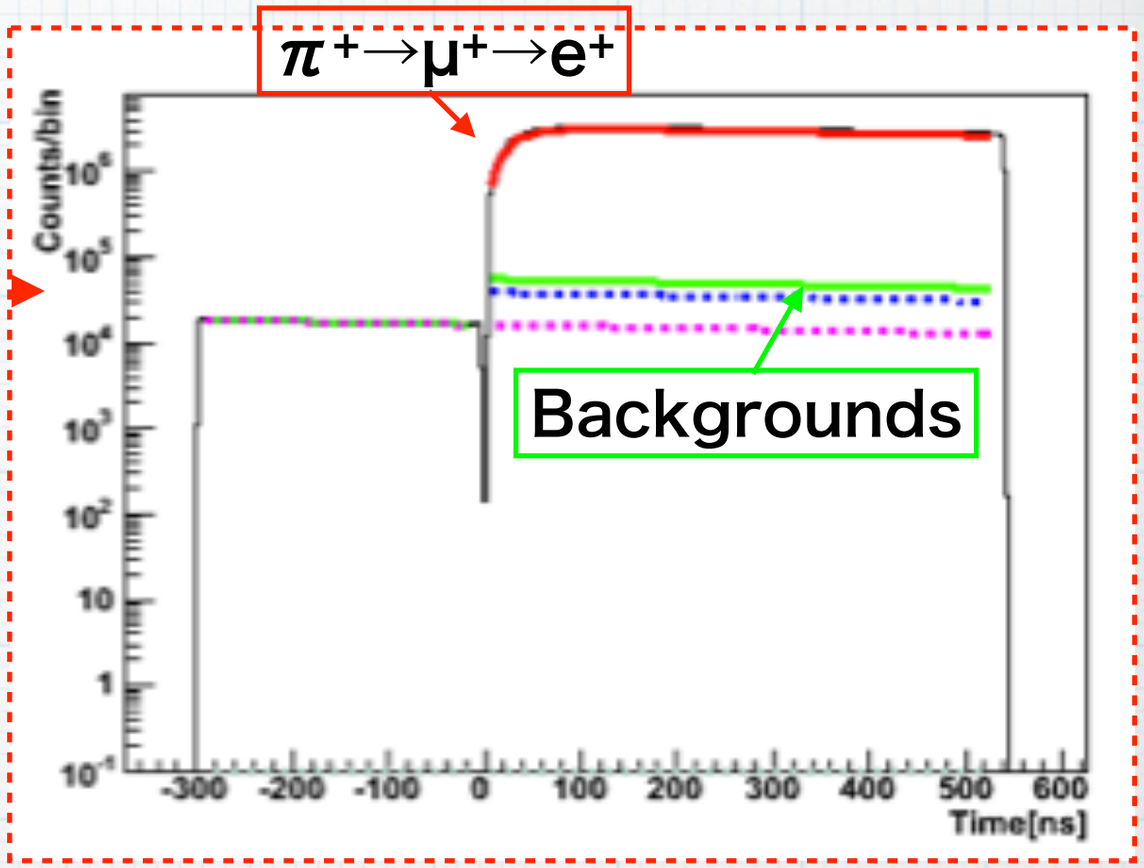
dE/dx in B2

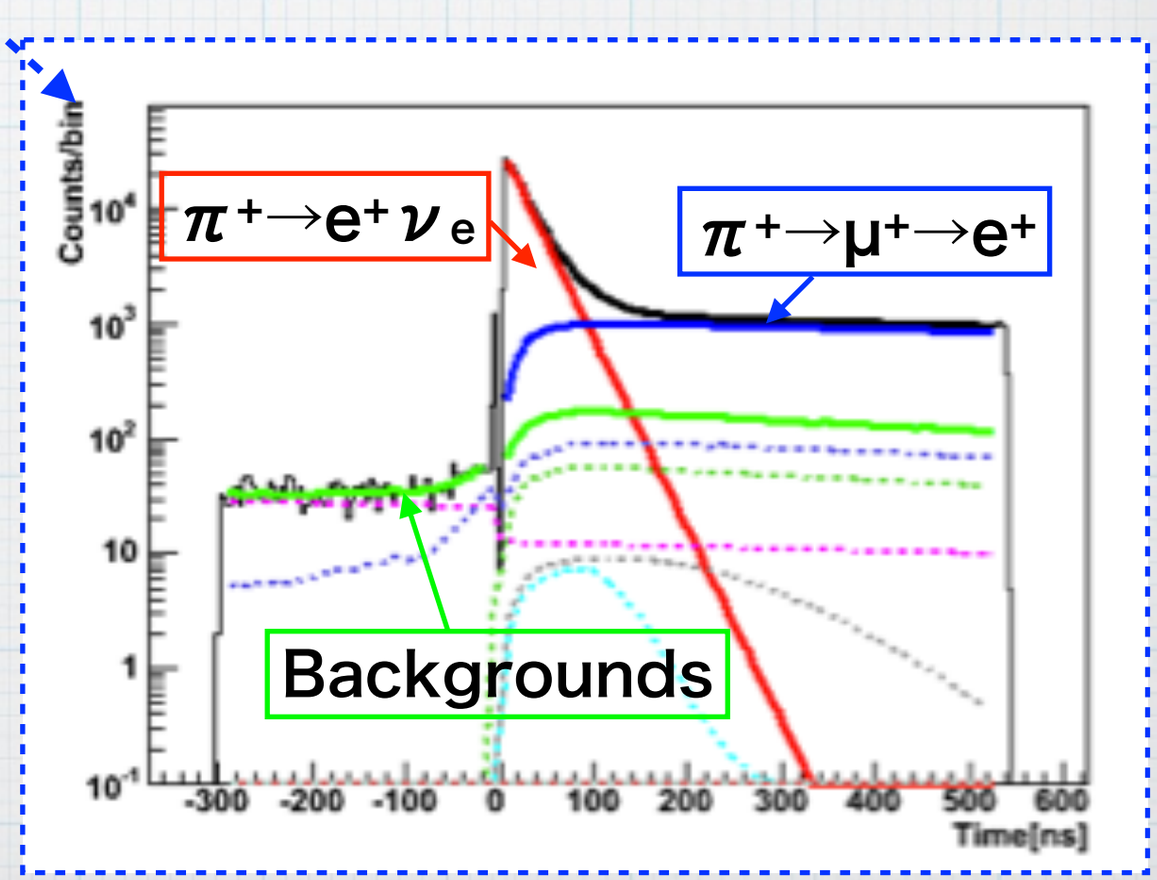


Reconstructed radius at WC3.

Analysis: Raw Branching Ratio Extraction







- 4.5×10^5 $\pi^+ \to e^+ \nu_e$ events.
- **Fit both spectra simultaneously.**

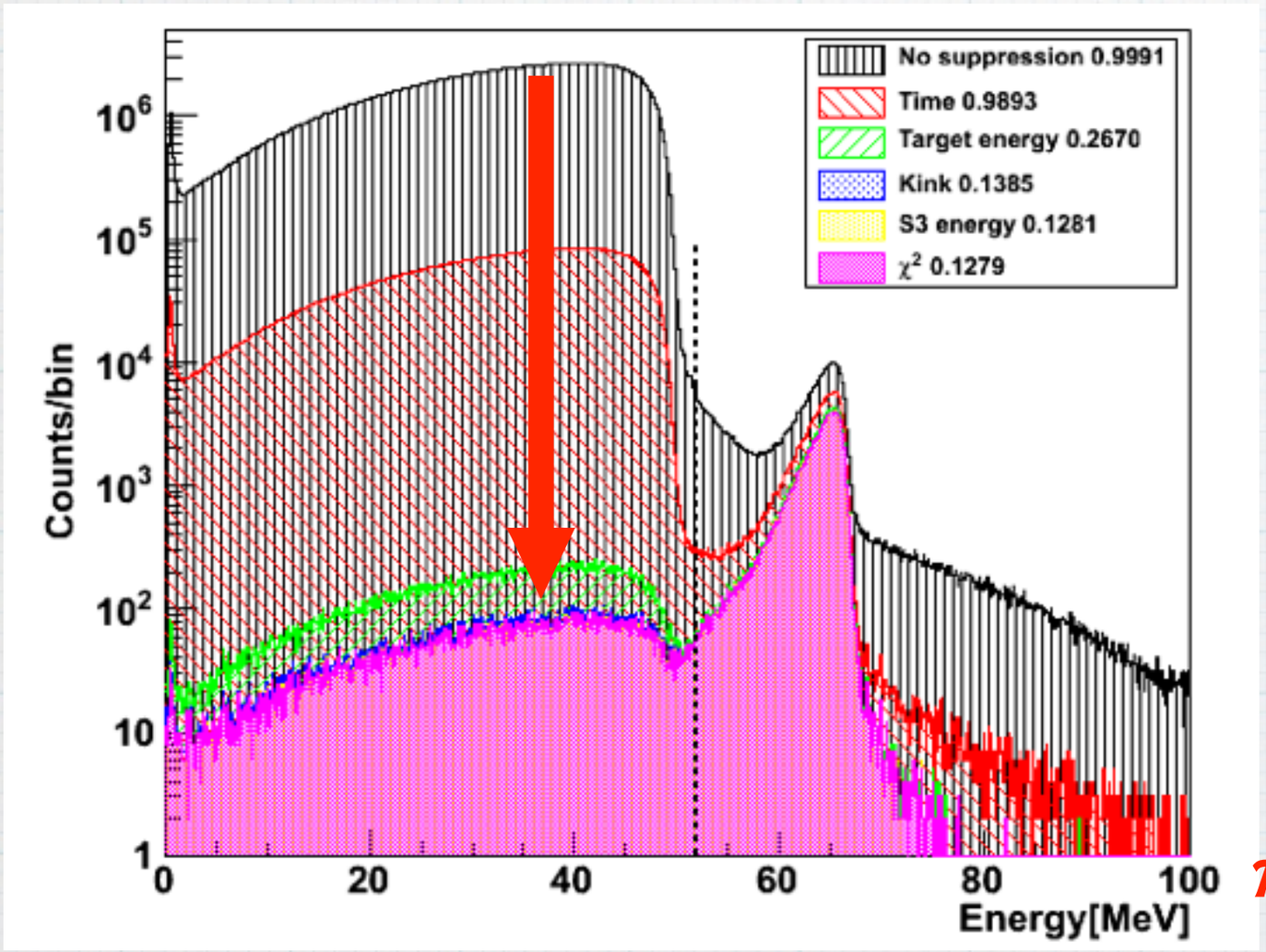
$R'_{Blind} = (1.2XXX \pm 0.0021)\times10^{-4}$

$\chi^2/ndf = 1.06 \to$ **Syst:0.04%**

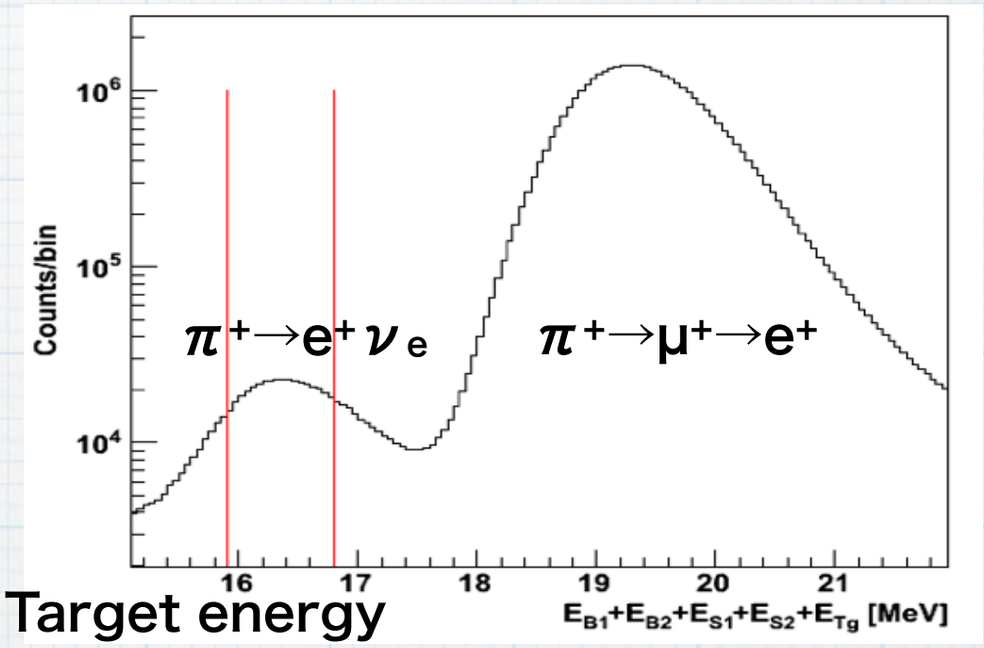
Analysis: Tail Correction

- $\pi^+ \to e^+ \nu_e$ low energy tail buried under $\pi^+ \to \mu^+ \to e^+$.
- Need to suppress $\pi^+ \to \mu^+ \to e^+$ by target energy, beam angle, etc

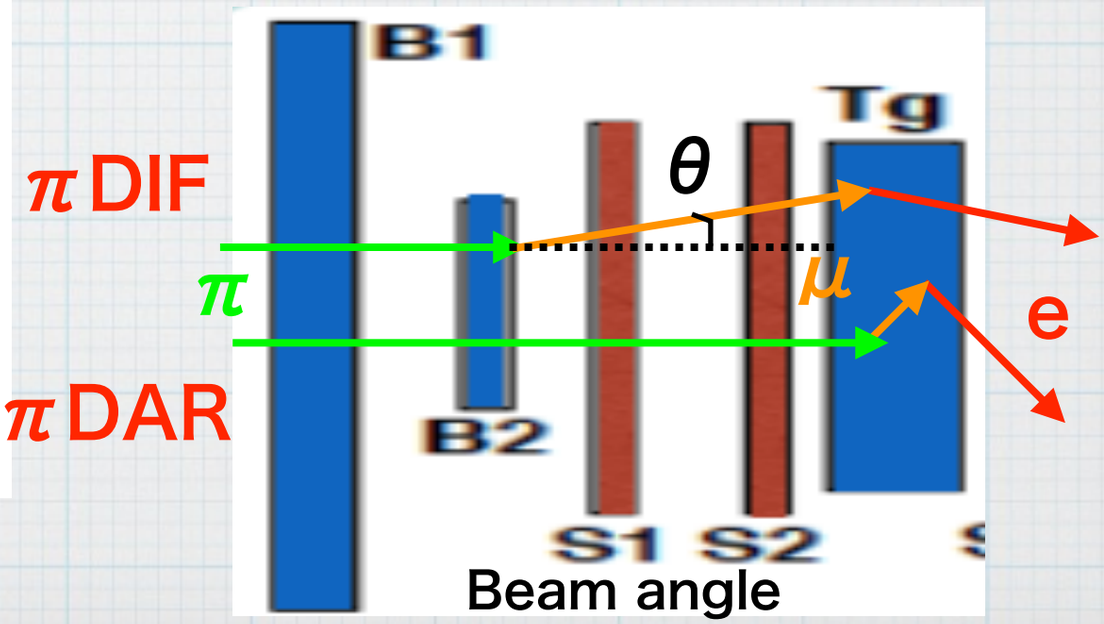
  ➡ $\pi^+ \to \mu^+ \to e^+$ are suppressed by a factor of ~10^5.



$\pi^+ \to \mu^+ \to e^+$ suppression



Target energy



Beam angle

Analysis: Tail Correction

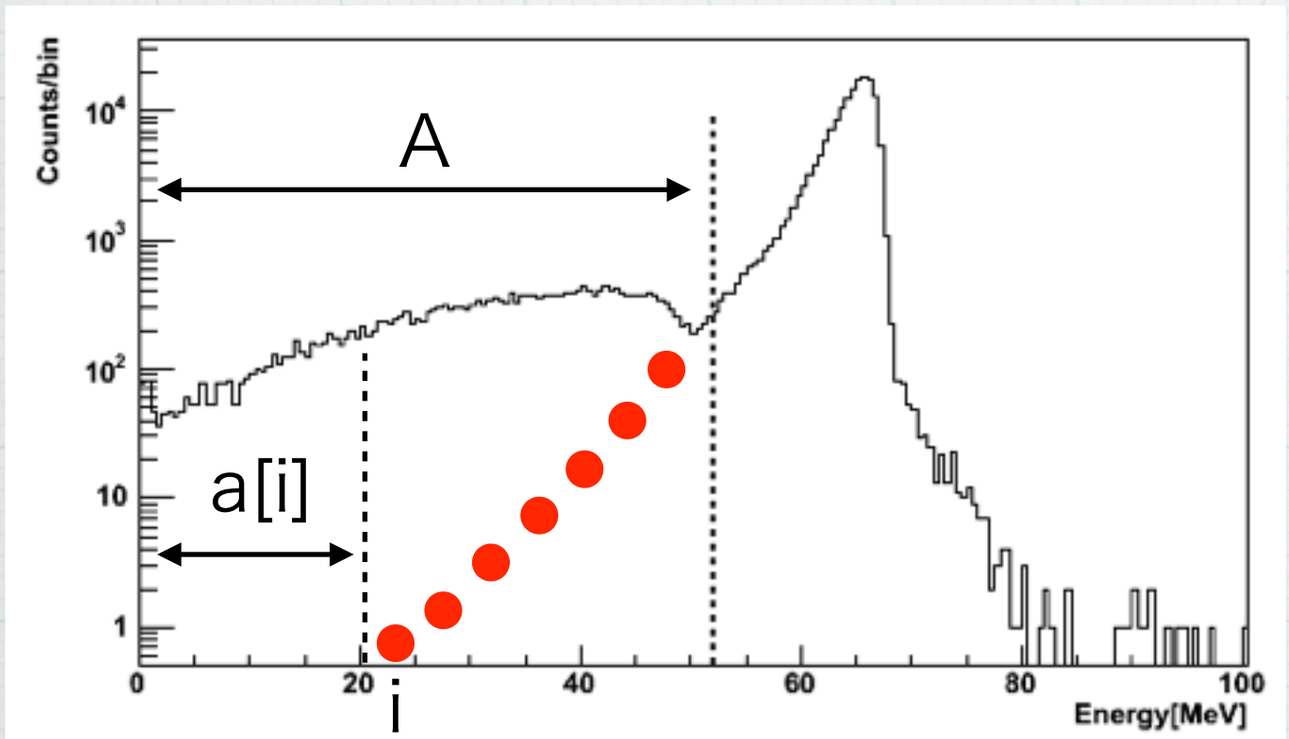
- Assume that all events below i(0~52 MeV) are coming from remaining unsuppressed $\pi^+ \to \mu^+ \to e^+$ backgrounds.
- The amount of tail is estimated by shapes of suppressed spectrum and Michel spectrum from data.

The amount of $\pi^+ \to e^+ \nu_e$ tail = A - a[i]×B/b[i]

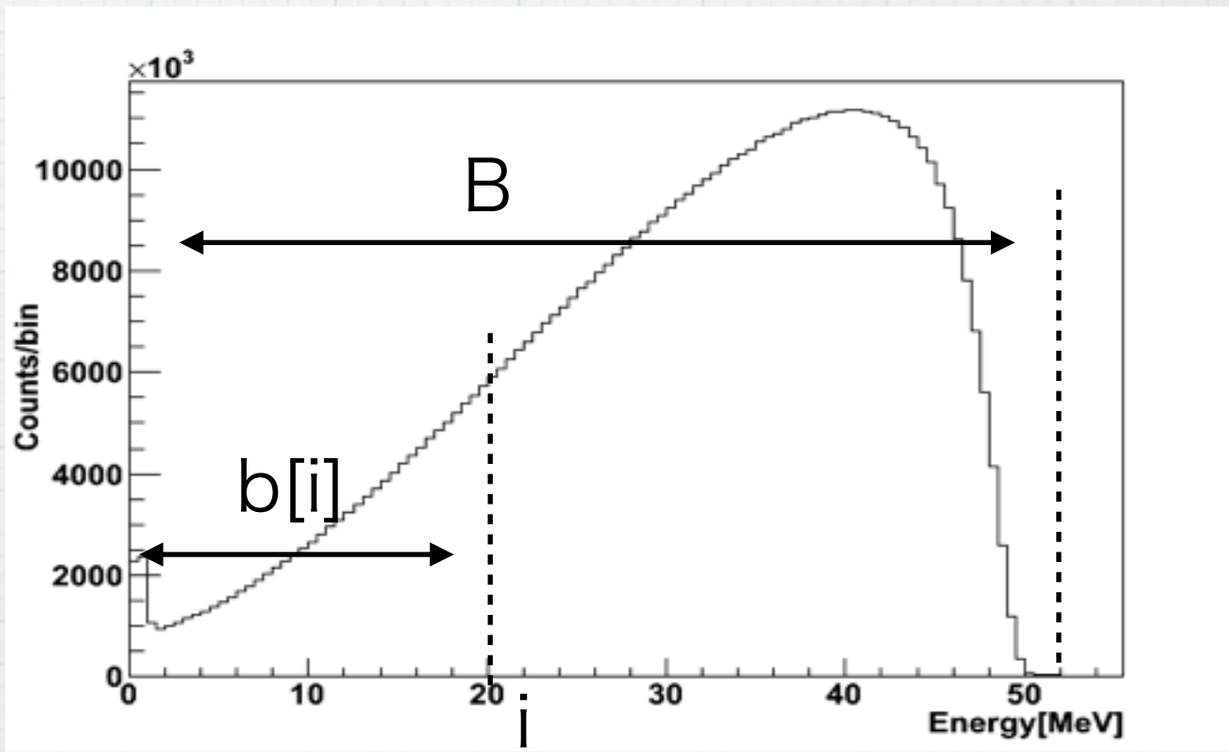
- It might be underestimation of tail

➡ **Decide only lower bound (preliminary)**

$N_{<52MeV}/N_{All}$ = (2.98 ± 0.10)%



$\pi^+ \to \mu^+ \to e^+$ suppressed spectrum



Michel spectrum from data

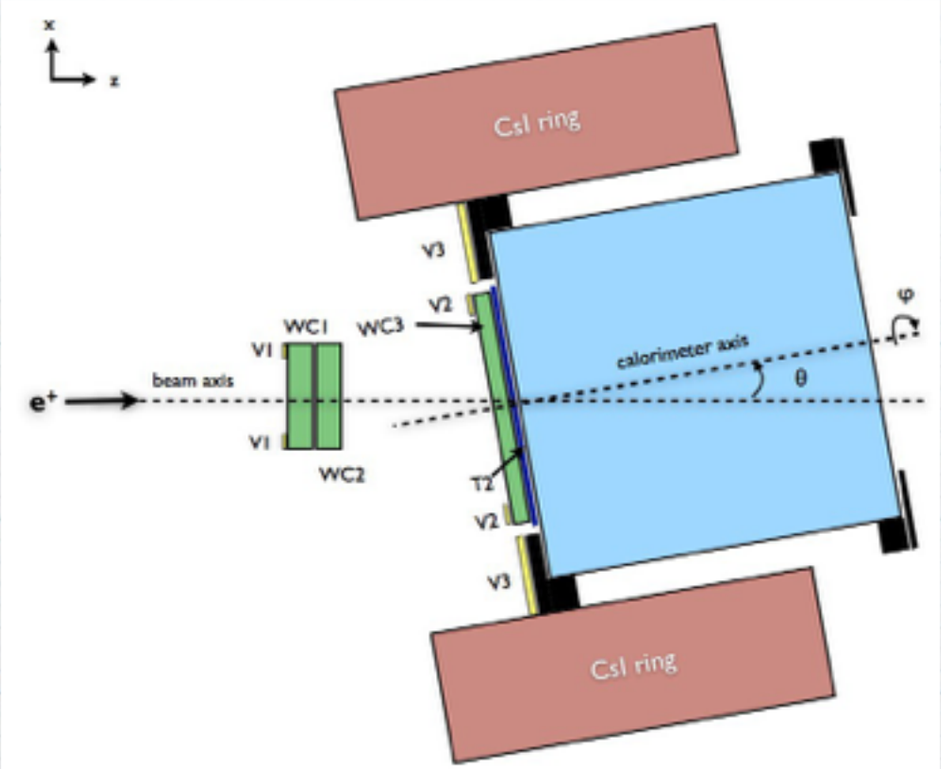
Analysis: Tail Correction

- Tail measurement by using mono-energetic positron beam.
- Rotate the crystals for different entrance angle measurement.
- Possibility of beam momentum spread and might make wider tail.

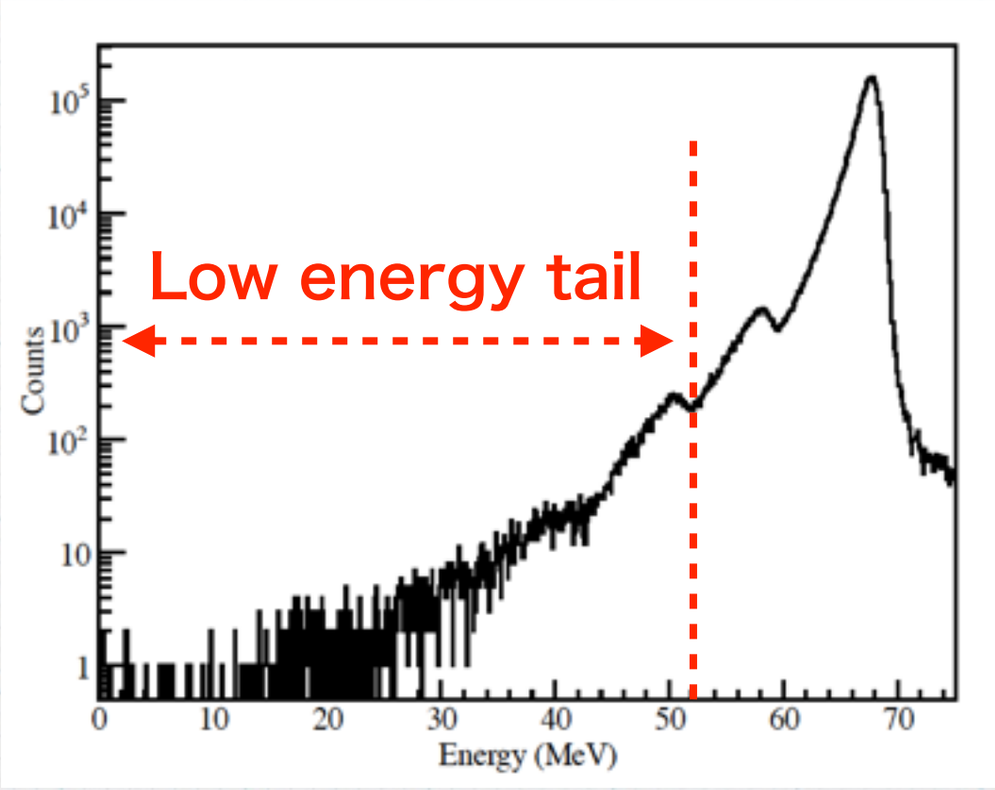
➡**Decide only upper bound (preliminary)**

$$N_{<52MeV}/N_{All} = (3.03 \pm 0.06)\%$$

➡Combine lower and upper bound to become correction value.



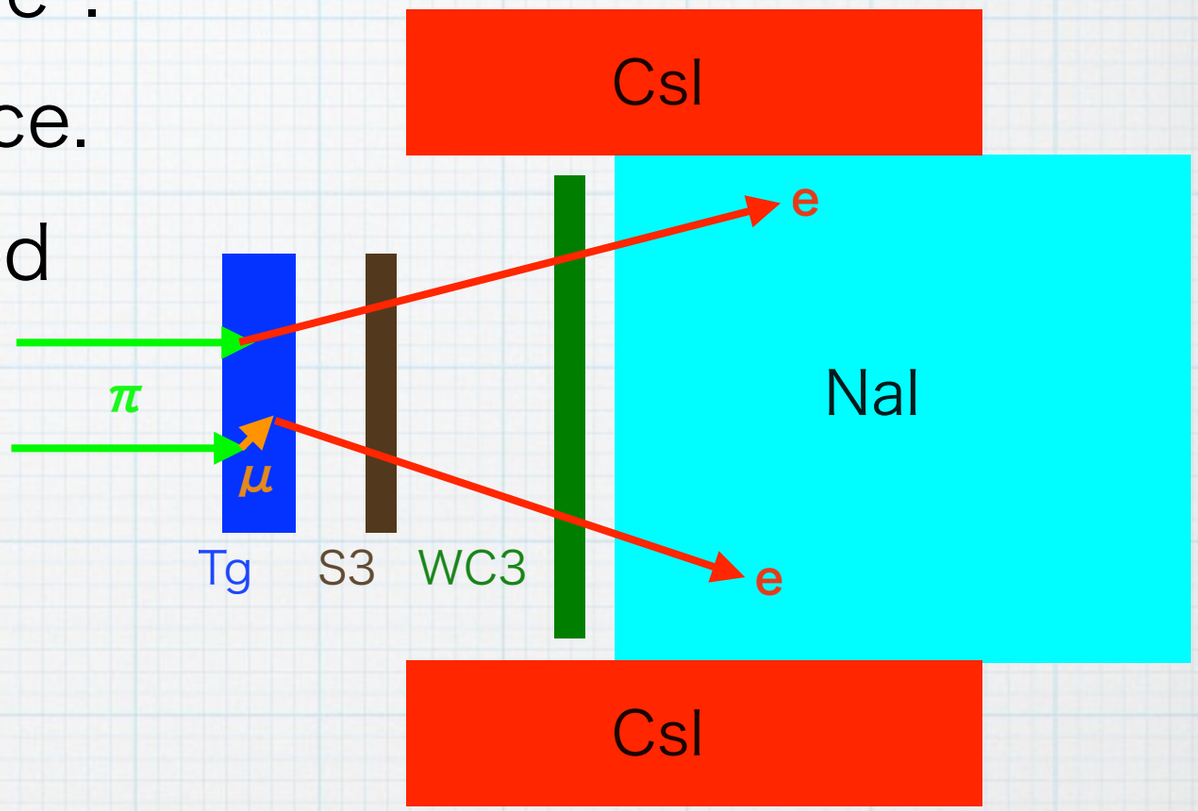
Positron beam measurement.
Rotation of crystals



Tail measurement at 0 degree.

Analysis: Acceptance Correction

- The correction of acceptance difference between $\pi^+ \to e^+ \nu_e$ and $\pi^+ \to \mu^+ \to e^+$.
  - ➡ Positrons energy dependence.
- Track of positron is reconstructed by S3,WC3.
- Rely on MC to study various systematic effects.
  - π stopping position.
  - Displacement of detectors.
  - Thickness, etc...

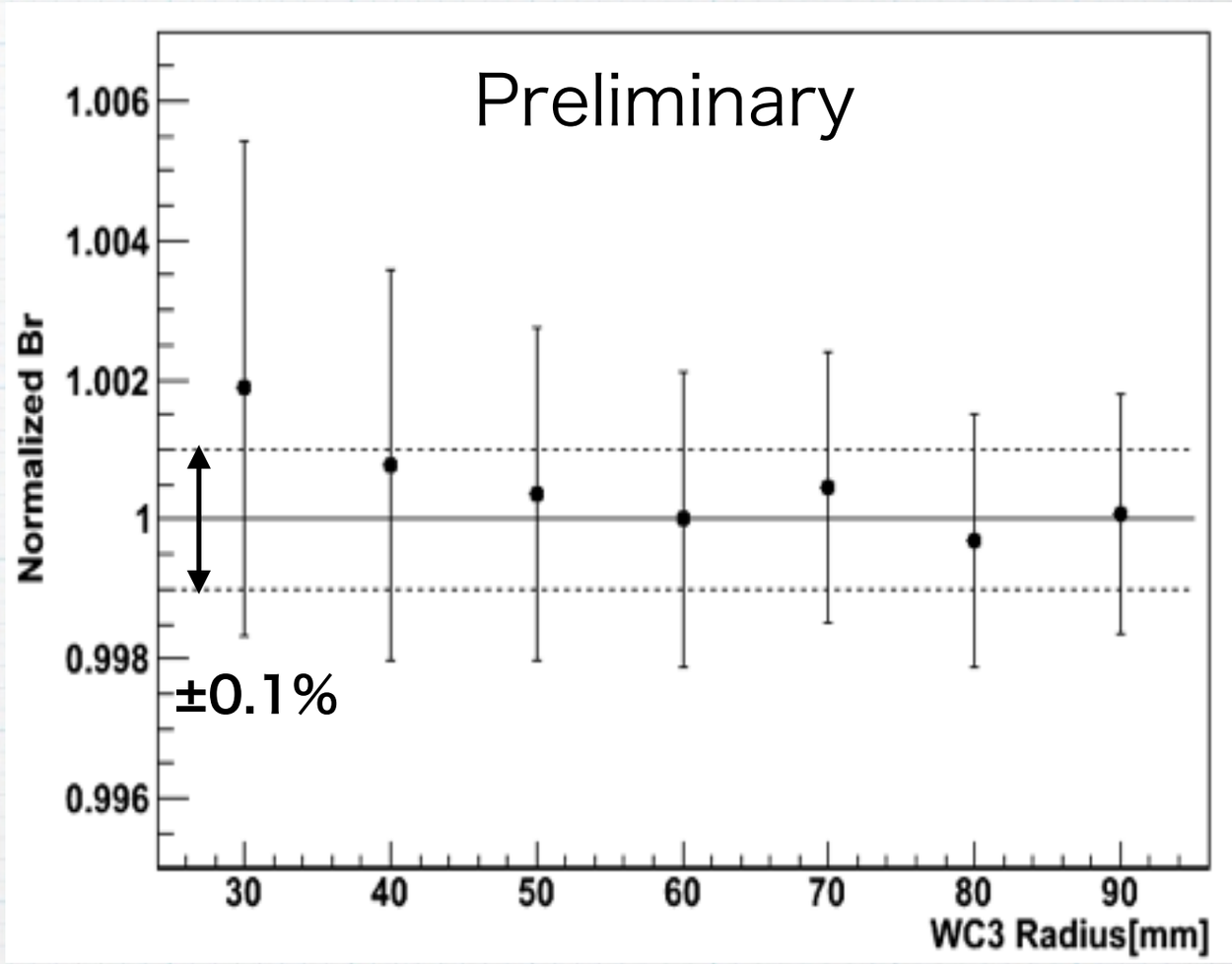


Downstream trackers.

Acceptance correction: 0.9994 ± 0.0007

Analysis Status

- Blind analysis is underway.
  - Finish all systematic studies.
  - Stability check of R.
    - ➡ Cuts or threshold etc...
  - Unblind for final result.
- Full data set analysis: >×10 statistics than presented data.
  - Systematic uncertainties depend on statistics.
  - We collected systematic study data in 2011,2012.



Branching ratio stability check against WC3 radius cut.

➡ **Systematic uncertainties will be improved.**

Errors

Error	Previous TRIUMF Expt	PIENU Preliminary	PIENU Goal
Statistical	0.28%	0.19%	0.05%
Time Spectrum	0.19%	0.04%	0.03%
Tail Correction	0.25%	0.06%	0.03%
Acceptance Correction	0.11%	0.07%	0.03%
Others	0.11%	0.05%	0.03%
Total	0.47%	0.2?%	<0.1%

Result will be coming soon.

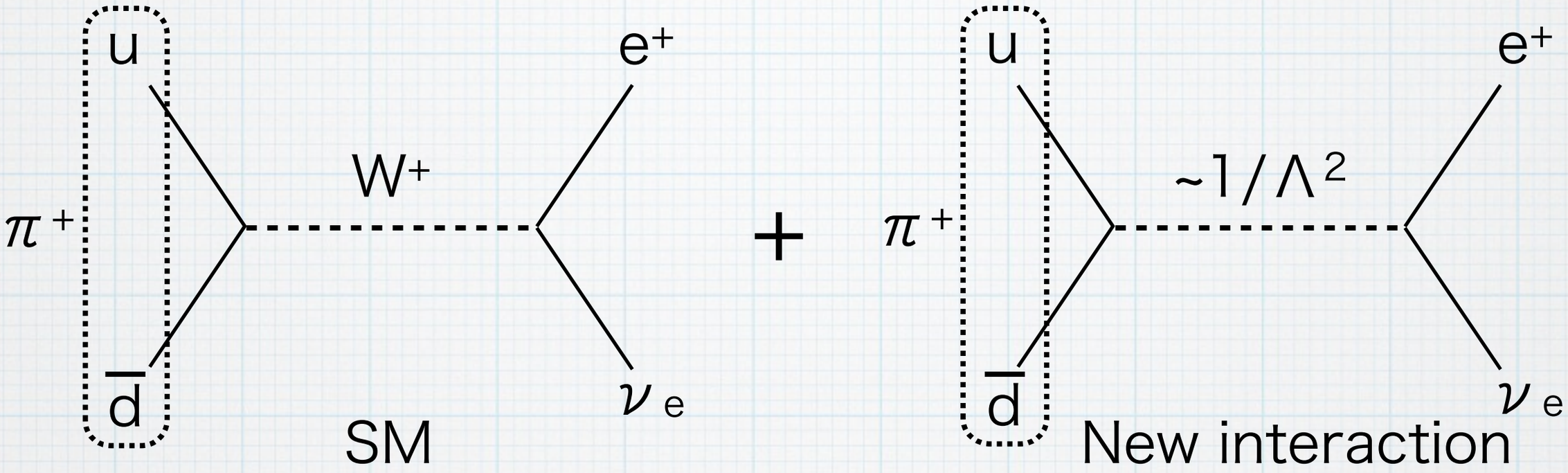
Summary

- Precise π^+ branching ratio measurement is sensitive to new physics beyond the SM.
- PIENU aims to measure π^+ branching ratio to <0.1% level.
- Finished data taking in 2012 and blind analysis is ongoing.
- Unblinded result of 2010 data set is coming soon.
- We hope full statistics analysis will finish by 2016.

Thank you for your attention!!

Backup

Pseudo Scalar Interaction



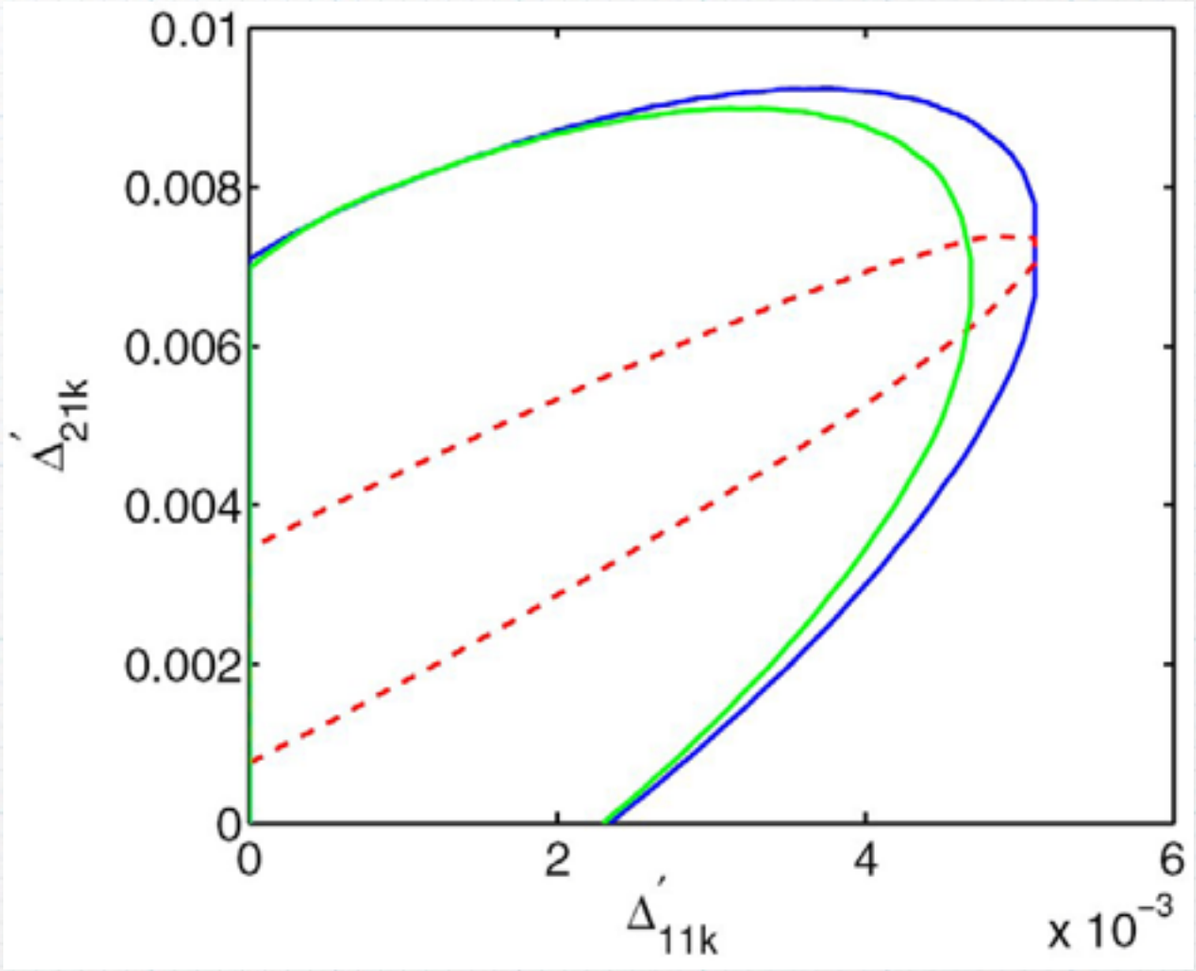
$$1 - \frac{R_{Exp}}{R_{SM}} \sim \frac{\sqrt{2}\pi}{G} \frac{1}{\Lambda^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \times 10^3$$

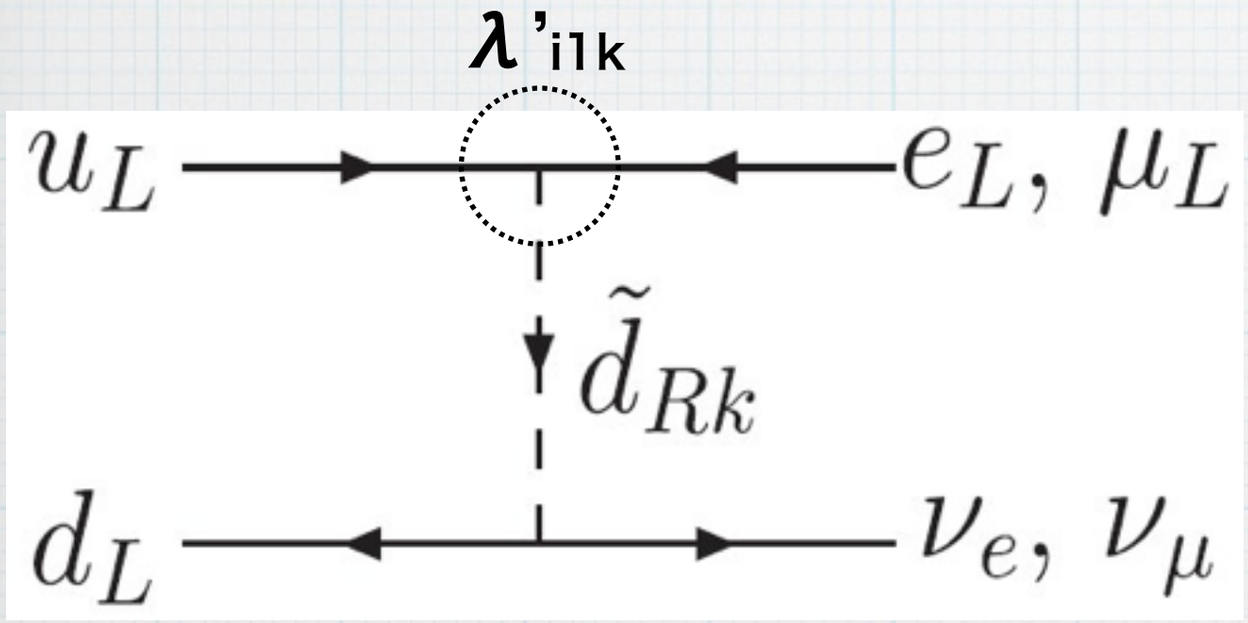
$$R_{Exp} = R_{SM} + R_{New}$$

R-Parity Violation SUSY

$$\frac{\Delta R_\pi^{RPV}}{R_\pi^{SM}} = 2(\Delta'_{11k} - \Delta'_{21k})$$

$$\Delta'_{i1k}(\tilde{f}) = \frac{\lambda'_{i1k}}{4\sqrt{2}Gm^2_{\tilde{f}}} \qquad i = 1, 2$$





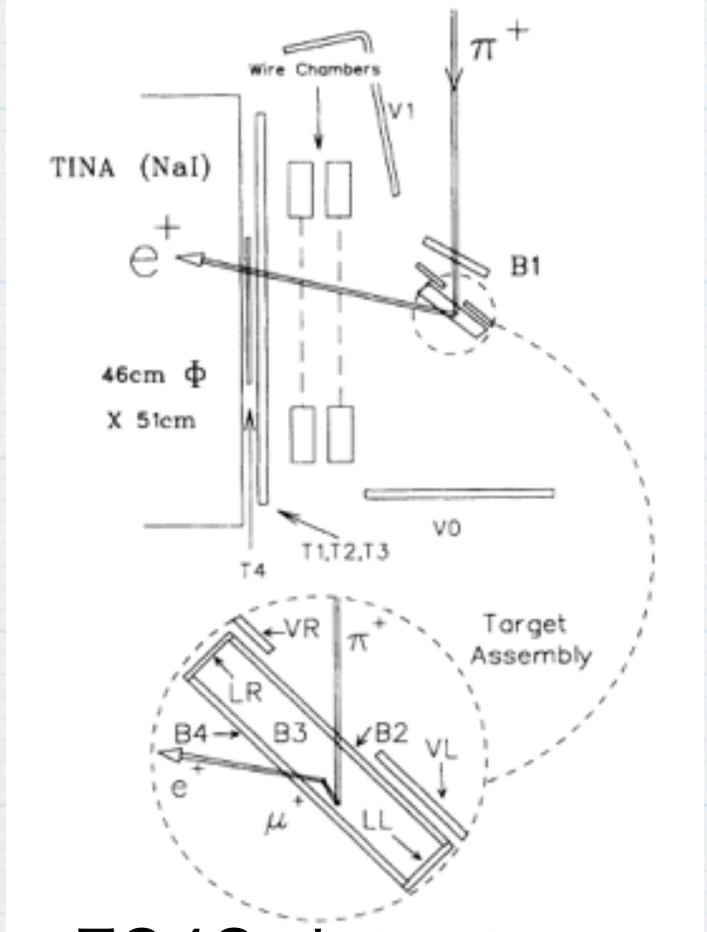
M.J.Ramsey-Musolf, S.Su & S.Tulin, PRD 76 095017 (2007).

Current constraints

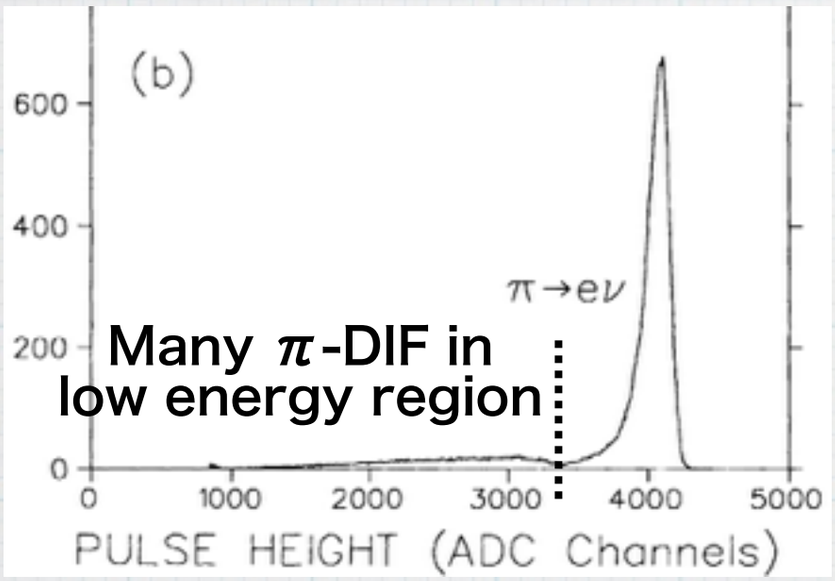
Future measurement of proton weak charge.

Expected by PIENU

Previous TRIUMF Experiment



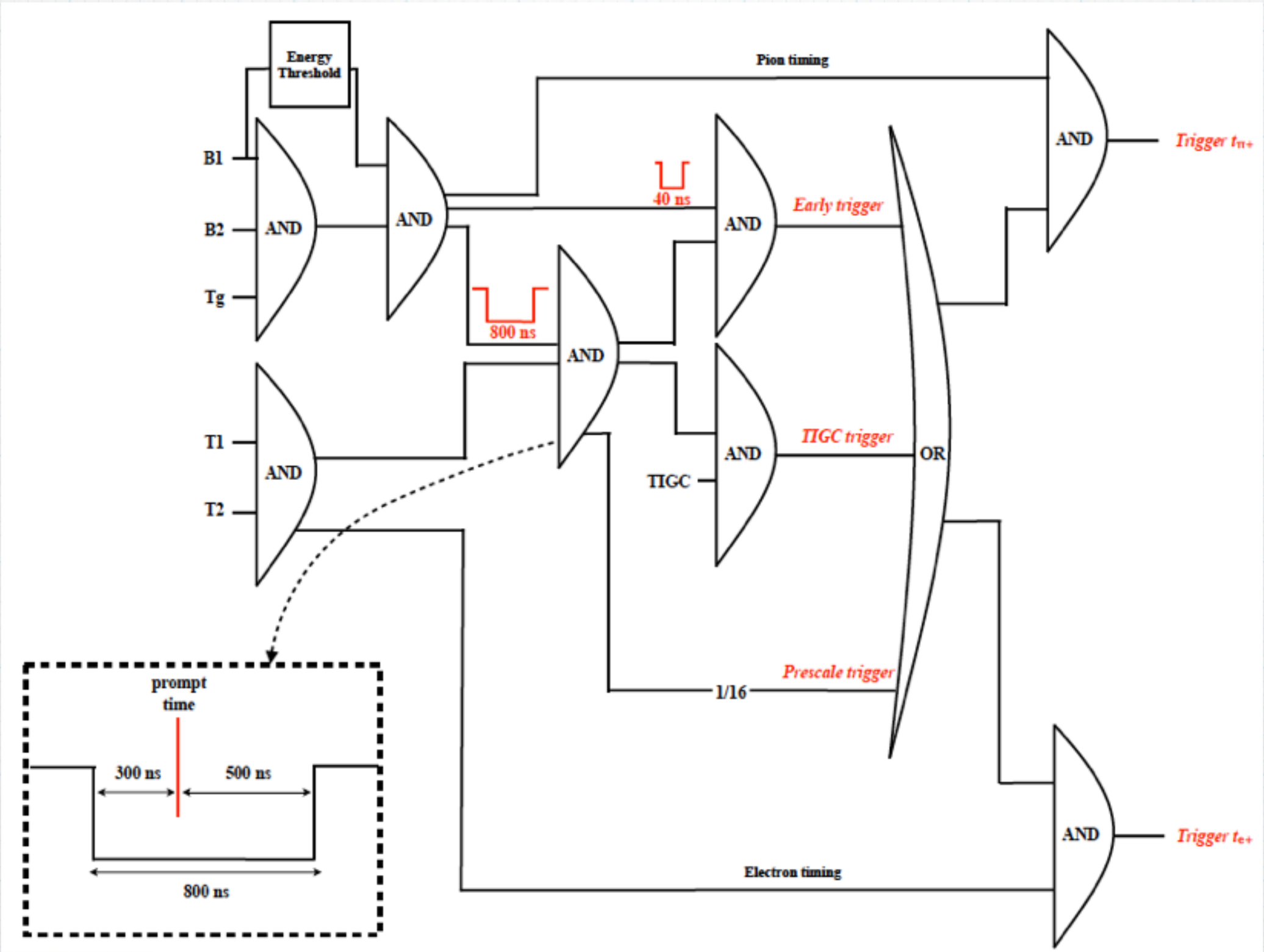
E248 detector



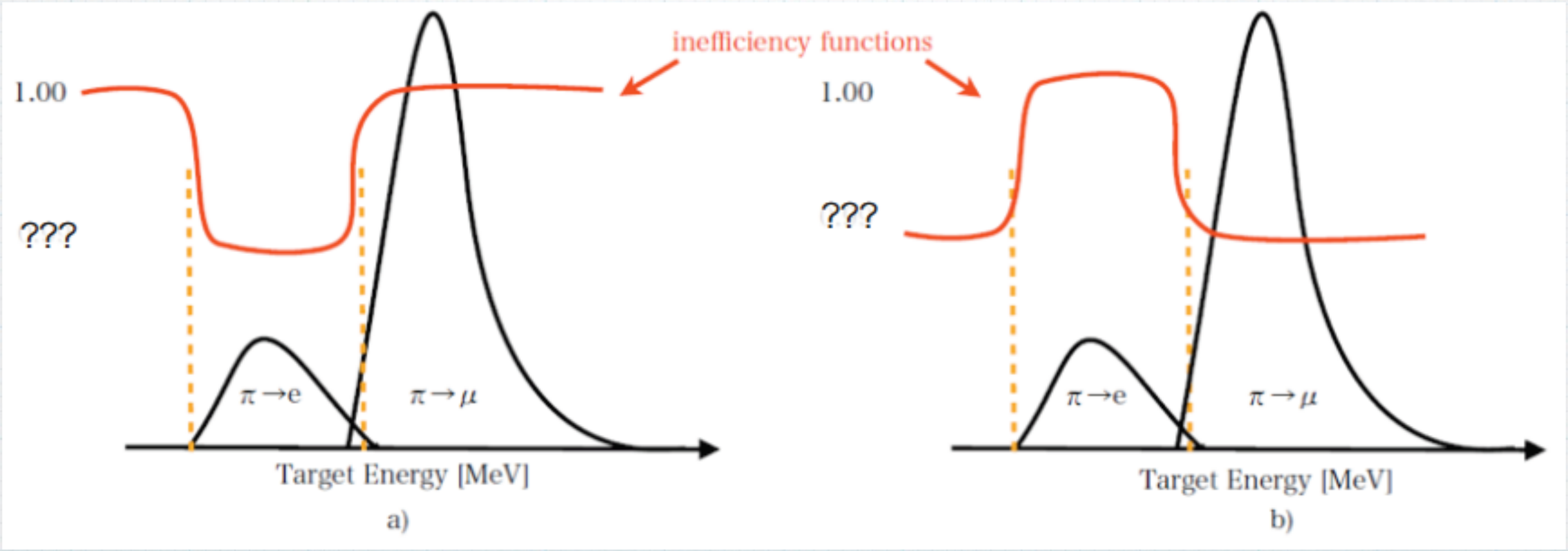
Energy spectrum
after $\pi^+ \to \mu^+ \to e^+$ suppression

- E248 experiment at TRIUMF in 80's.
- $R=(1.2265 \pm 0.0034_{\text{(stat)}} \pm 0.0044_{\text{(syst)}}) \times 10^{-4}$
- 1.5×10^5 $\pi^+ \to e^+ \nu_e$ events.
- Dominant sources
  - Small acceptance: ~2%
    - ➡ Low statistics.
  - Many unsuppressed π-DIF in low energy region : ~20%
    - ➡ Largest systematic uncertainty.

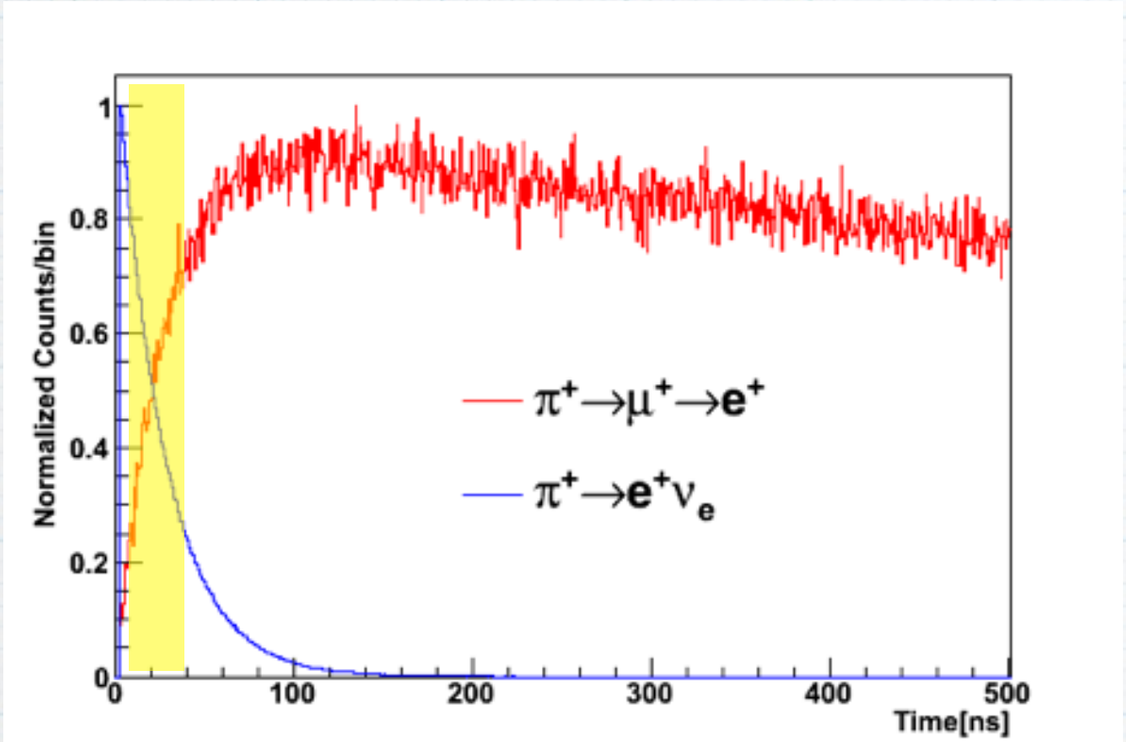
Trigger Logic

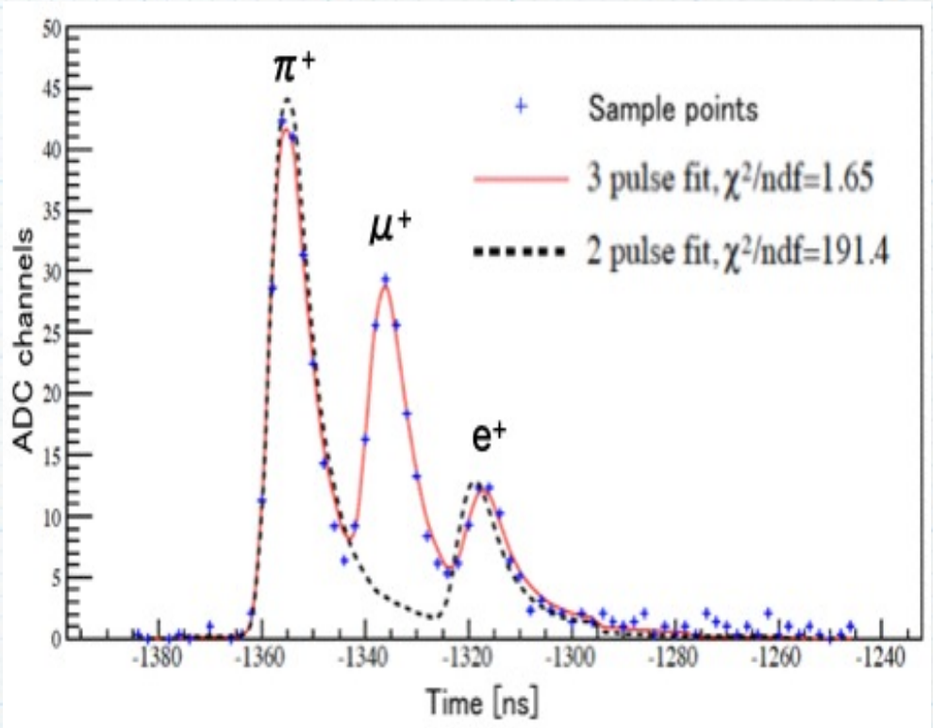


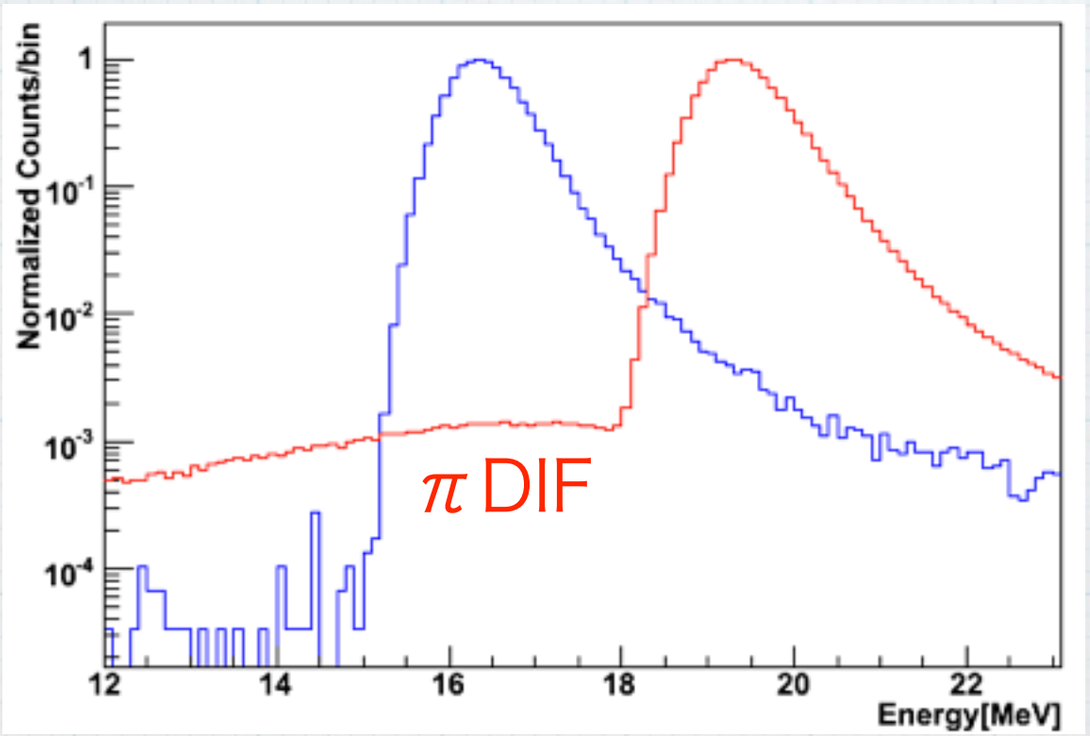
Blind Analysis

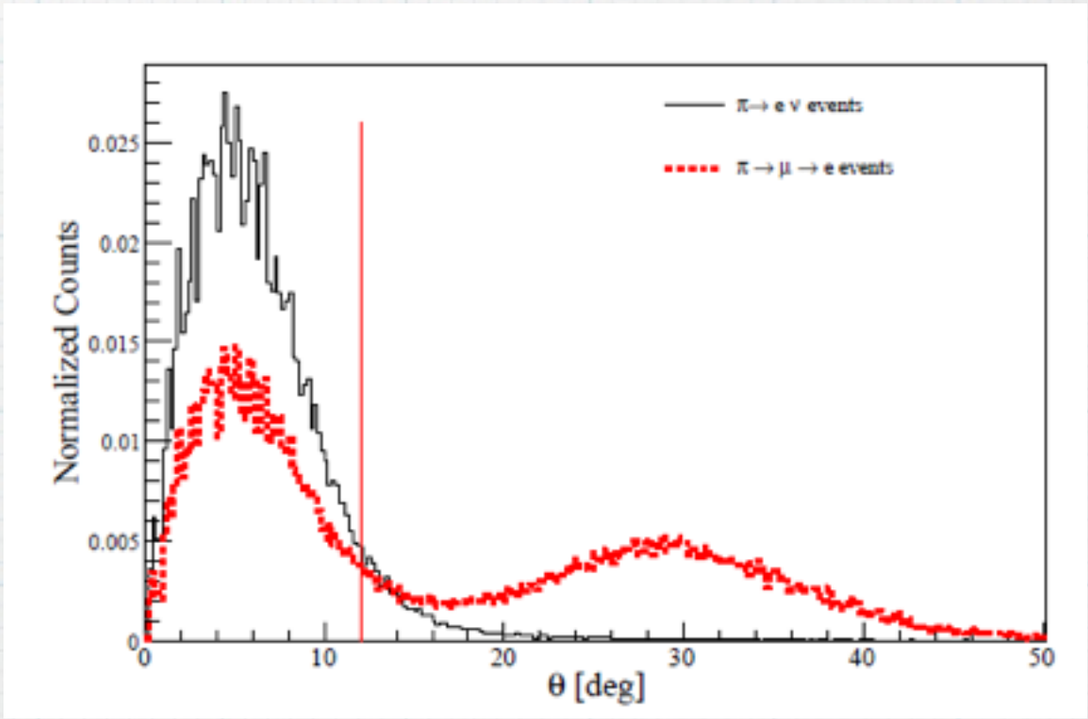


Tail Analysis

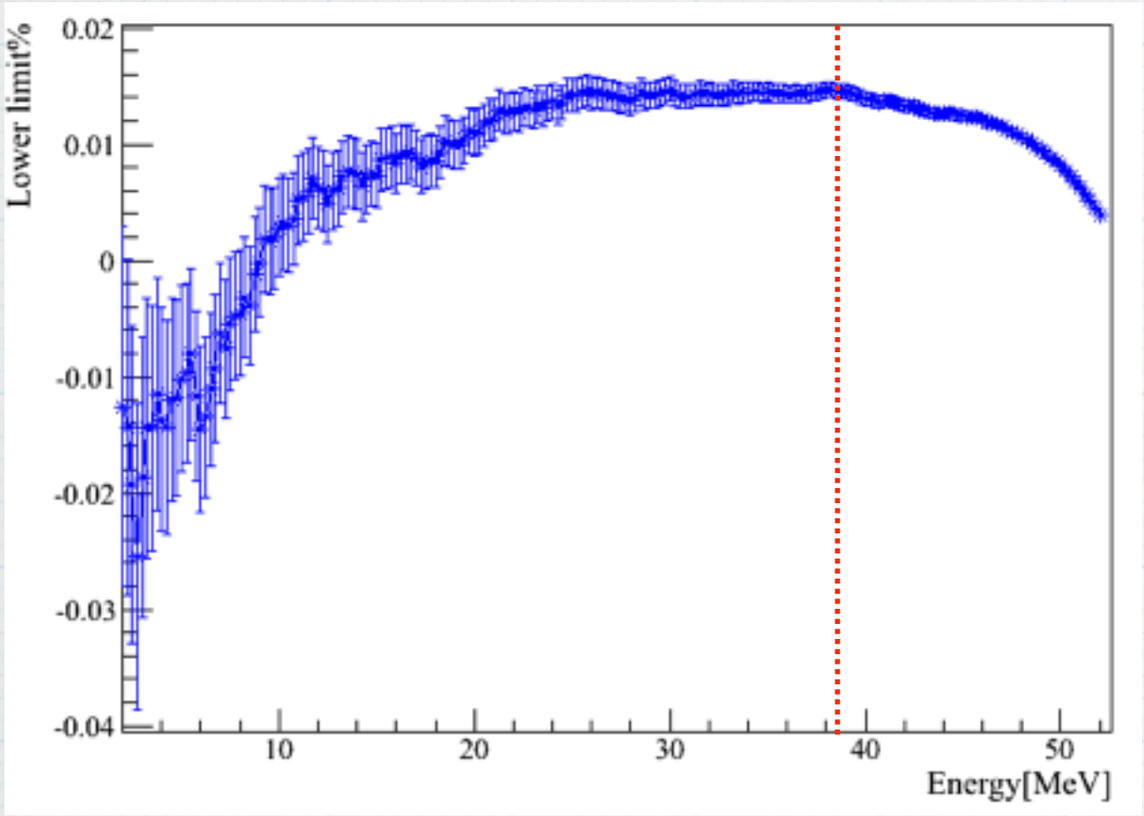




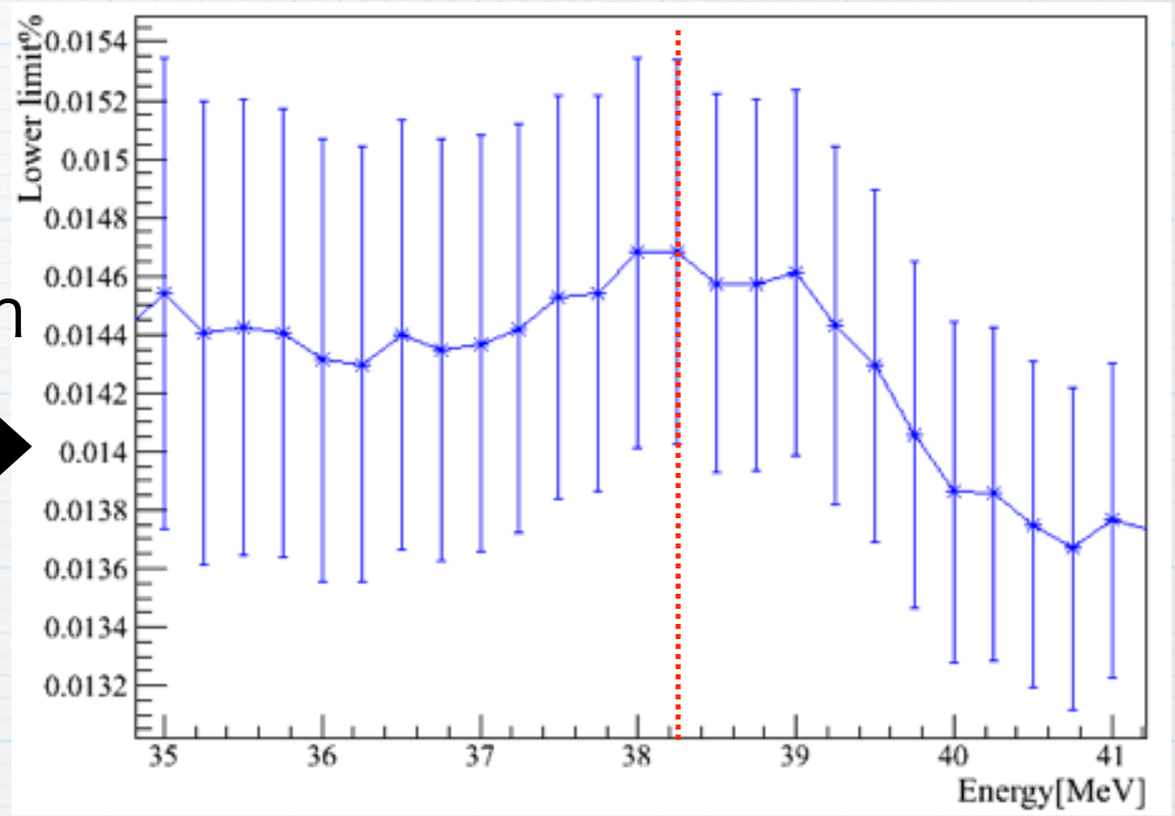




Tail Analysis



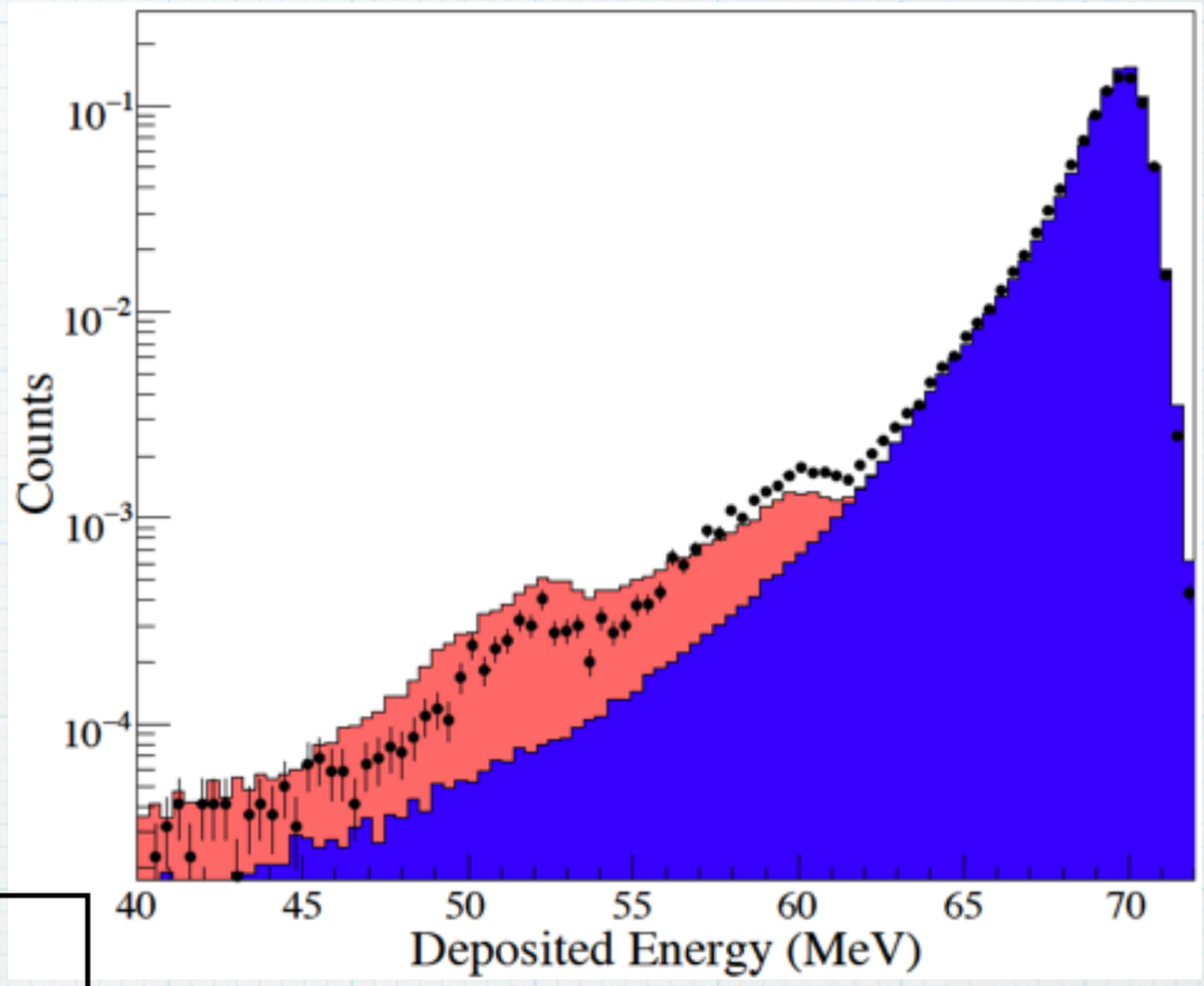
Zoom



Tail Analysis -NaI Response-

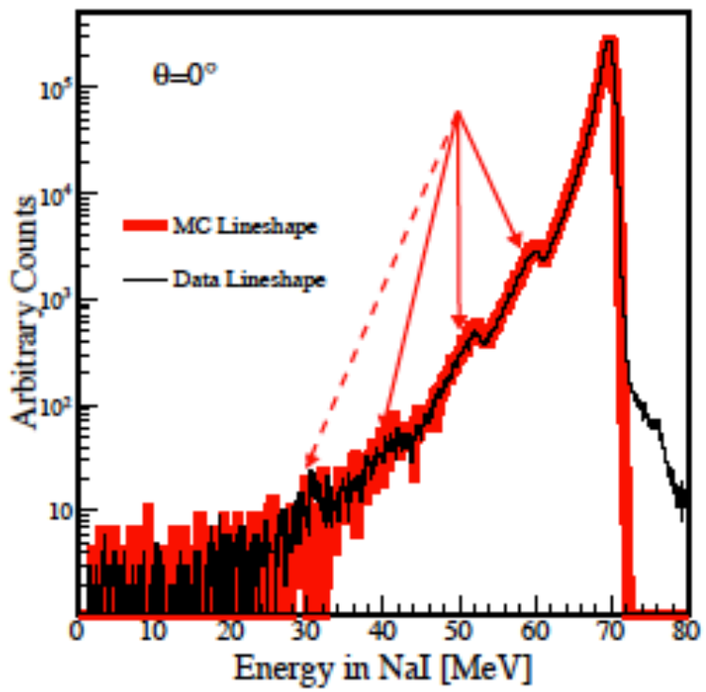
- First observation of photo-nuclear effect.
- Peaks are consistent with neutrons escaping.
- Well agreement between data and MC

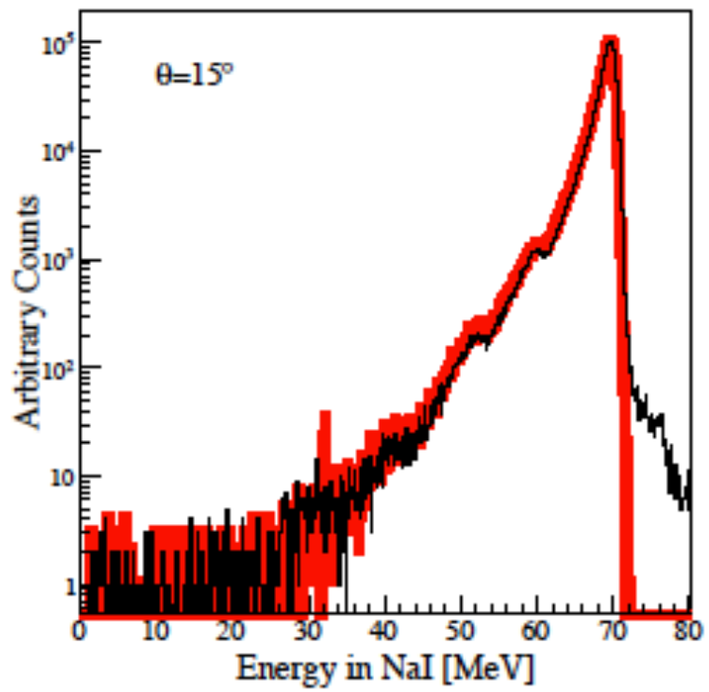
A.Aguilar-Arevalo et al
Nucl. Inst. and Methods A (2010)

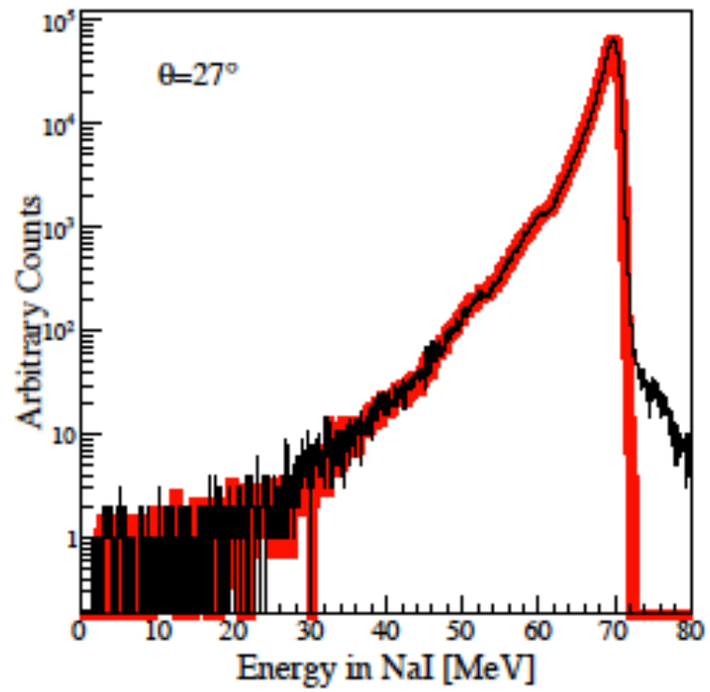


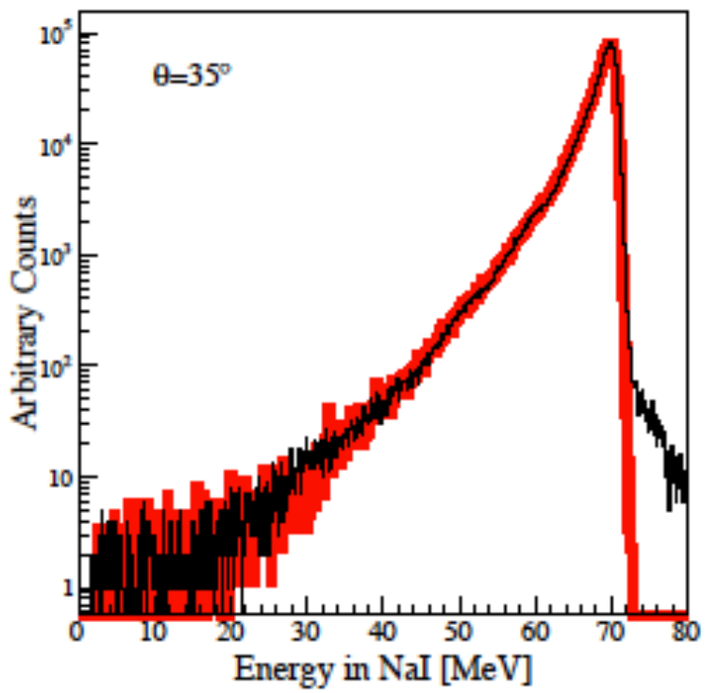
Data
MC with hadronic interaction
MC without hadronic interaction

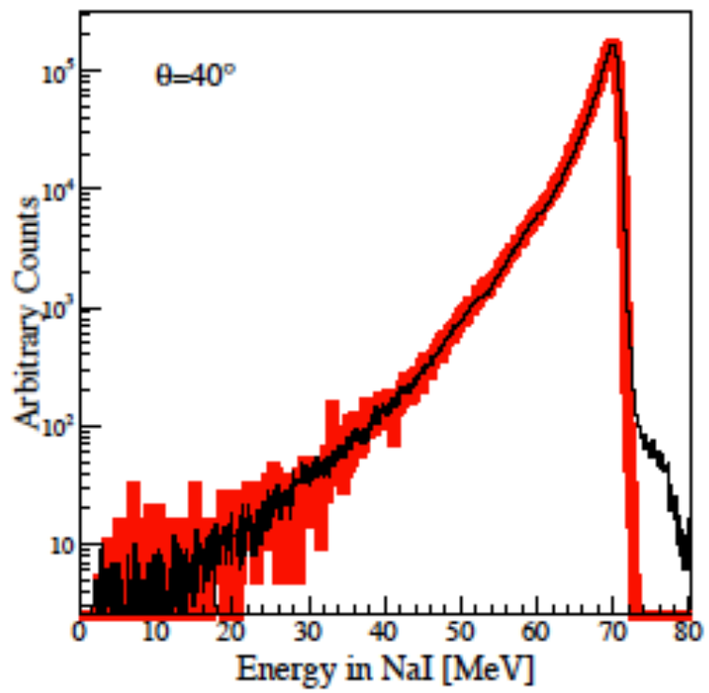
Tail Analysis

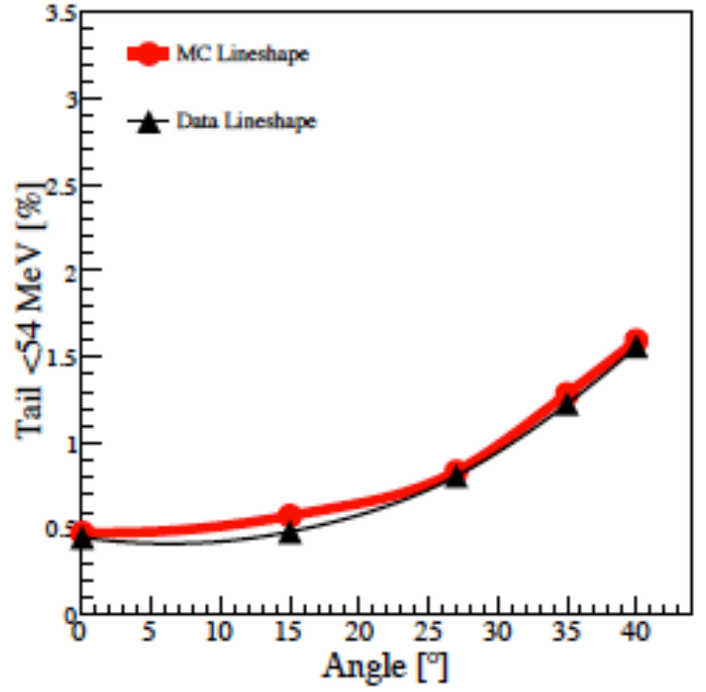




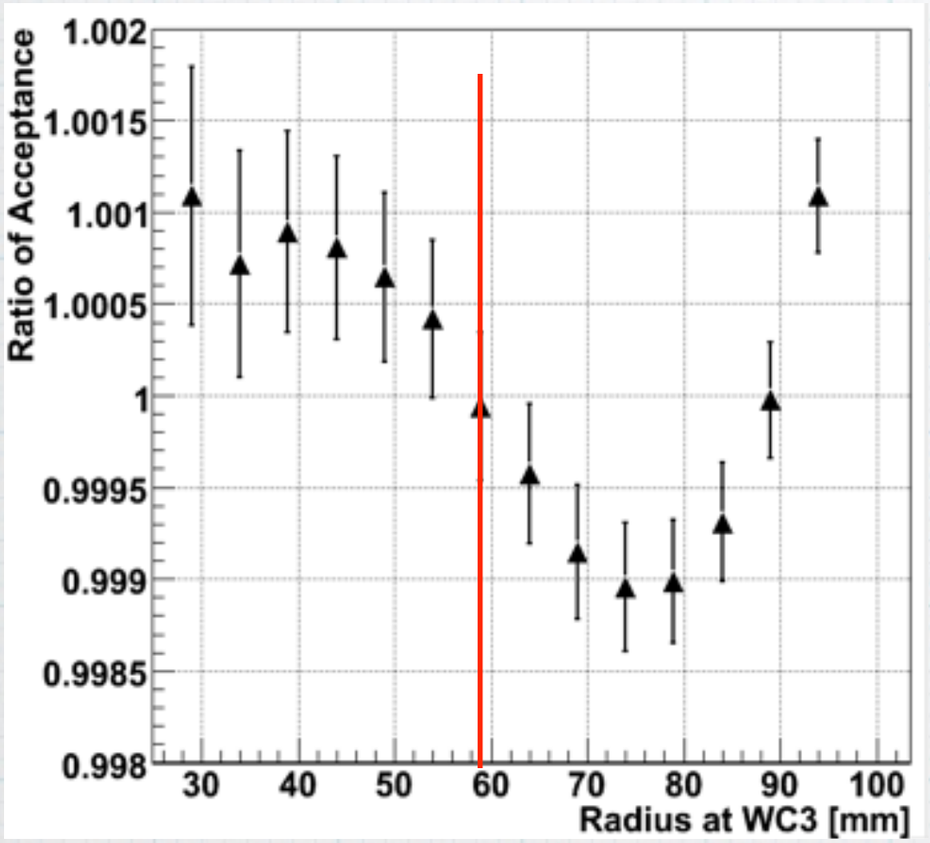








Acceptance Correction



Case	Description	Ratio of acceptances at R=60 mm	Stat. Errors
π stop in Tg	[mm]		[%]
I.a)	z = 0.08 (nominal)	0.9994	0.04
I.b)	z =+1	0.9997	0.04
I.c)	z =-1	0.9993	0.04
I.d)	σ=1%	0.9996	0.04
Displacement	[mm]		[%]
II.a)	z WC3 =+2	1.0000	0.04
II.b)	z WC3 =-2	0.9999	0.04
II.c)	z S3 =+0.2	0.9995	0.04
II.d)	z S3 =-0.2	0.9992	0.04
III.a)	x WC3 =+0.2	0.9988	0.04
III.b)	x WC3 =-0.2	0.9996	0.04
III.c)	y WC3 =+0.2	0.9997	0.04
III.d)	y WC3 =-0.2	0.9997	0.04
III.e)	x S3 =+0.02	0.9996	0.04
III.f)	x S3 =-0.02	0.9998	0.04
III.g)	y S3 =+0.02	1.0002	0.04
III.h)	y S3 =-0.02	0.9999	0.04