Constraining CP Violation in the CKM Matrix:

A Direct Search for $K_L \rightarrow \pi^0 \nu\nu$ at the KEK E391a Experiment & the J-PARC E14 Experiment

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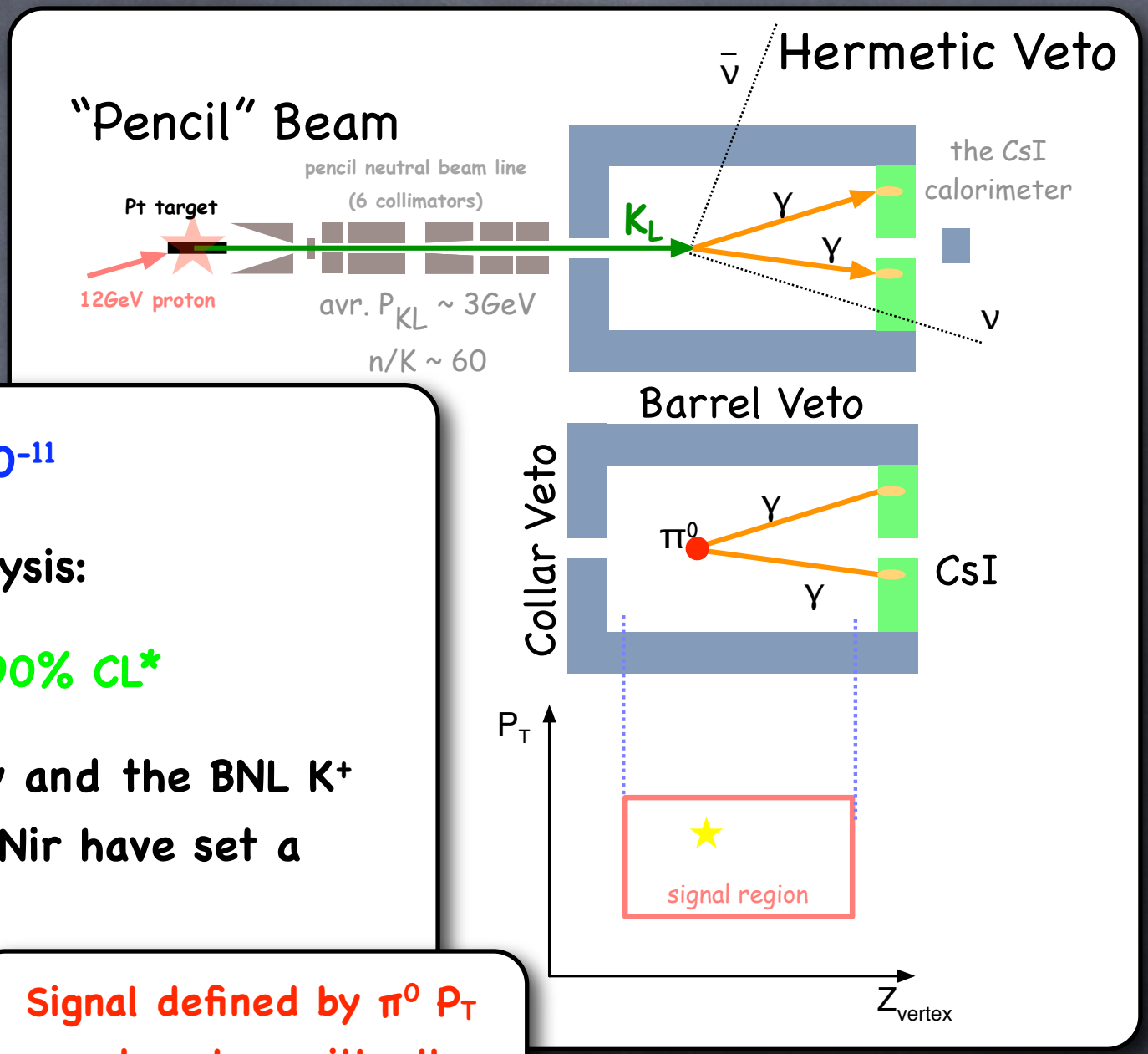
The University of Chicago

Project X Workshop, FNAL, January 2008

E391a

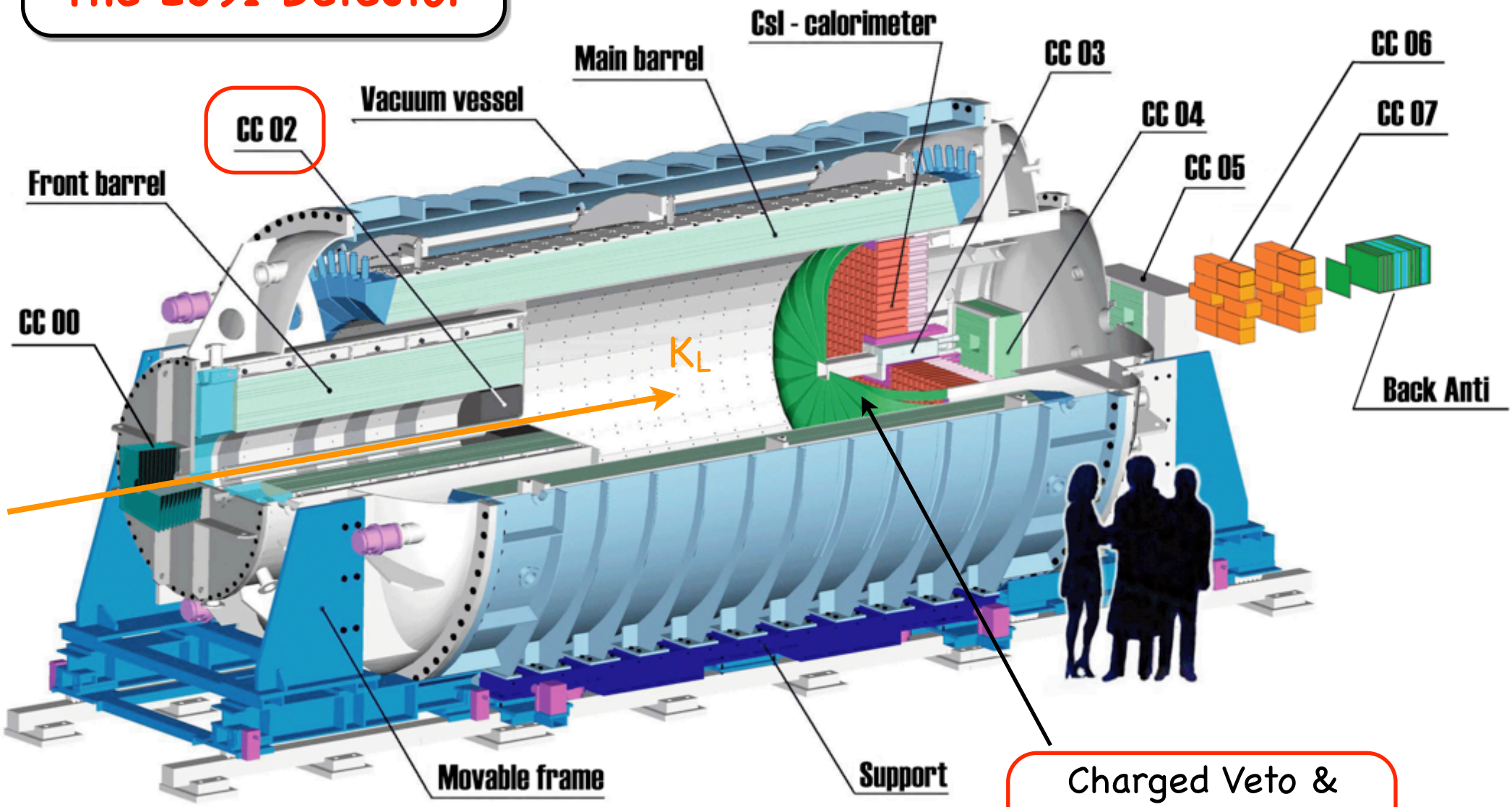


- $BR_{SM} = (2.5 \pm 0.4) \times 10^{-11}$
- Our Run-I partial analysis:
  - $BR < 2.1 \times 10^{-7}$ @ 90% CL*
- Using isospin symmetry and the BNL K^+ results, Grossman and Nir have set a tighter bound:
  - $BR < 1.4 \times 10^{-9}$

Signal defined by π^0 P_T and vertex, with all vetoes quiet... and the analysis is "Blind!"

*Ahn et al, Phys Rev D 74, 051105(R) (2006)

The E391 Detector

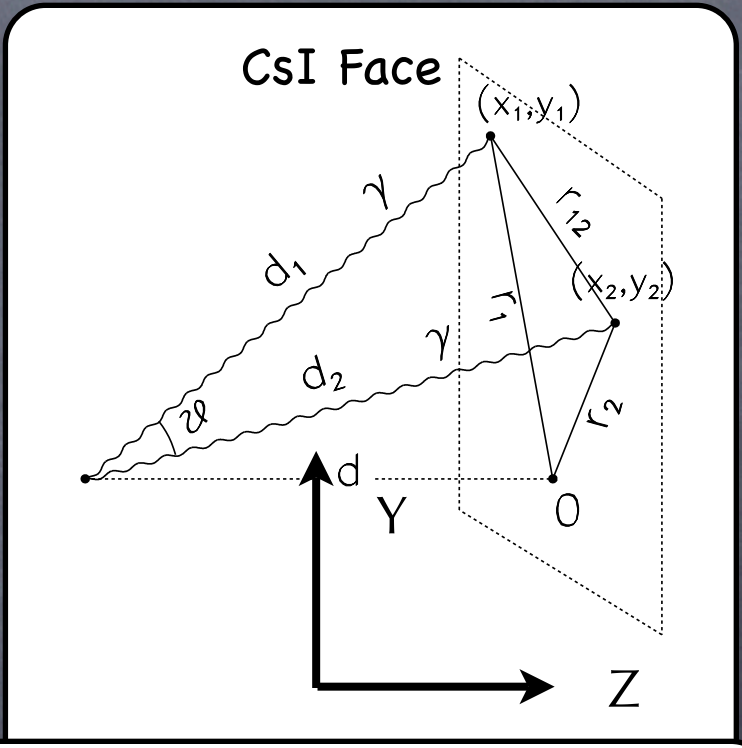


Charged Veto & Support Structure

Main fiducial volume is empty vacuum (10^{-5} Pa)!

Kaon and Pion Reconstruction and Cuts

- First we pair photons and reconstruct the (π^0/K) vertex by assuming the correct (PDG) mass and that the decay took place on the beam axis.
- In decays with multiple π^0's we group and sort them with pairing χ^2. We then shift the (x,y) vertex onto a center of energy projection from the target.
- We apply "photon vetoes" - @ O(1) MeV.
- Finally, we also impose kinematic (multi-particle) and photon reconstruction quality cuts.

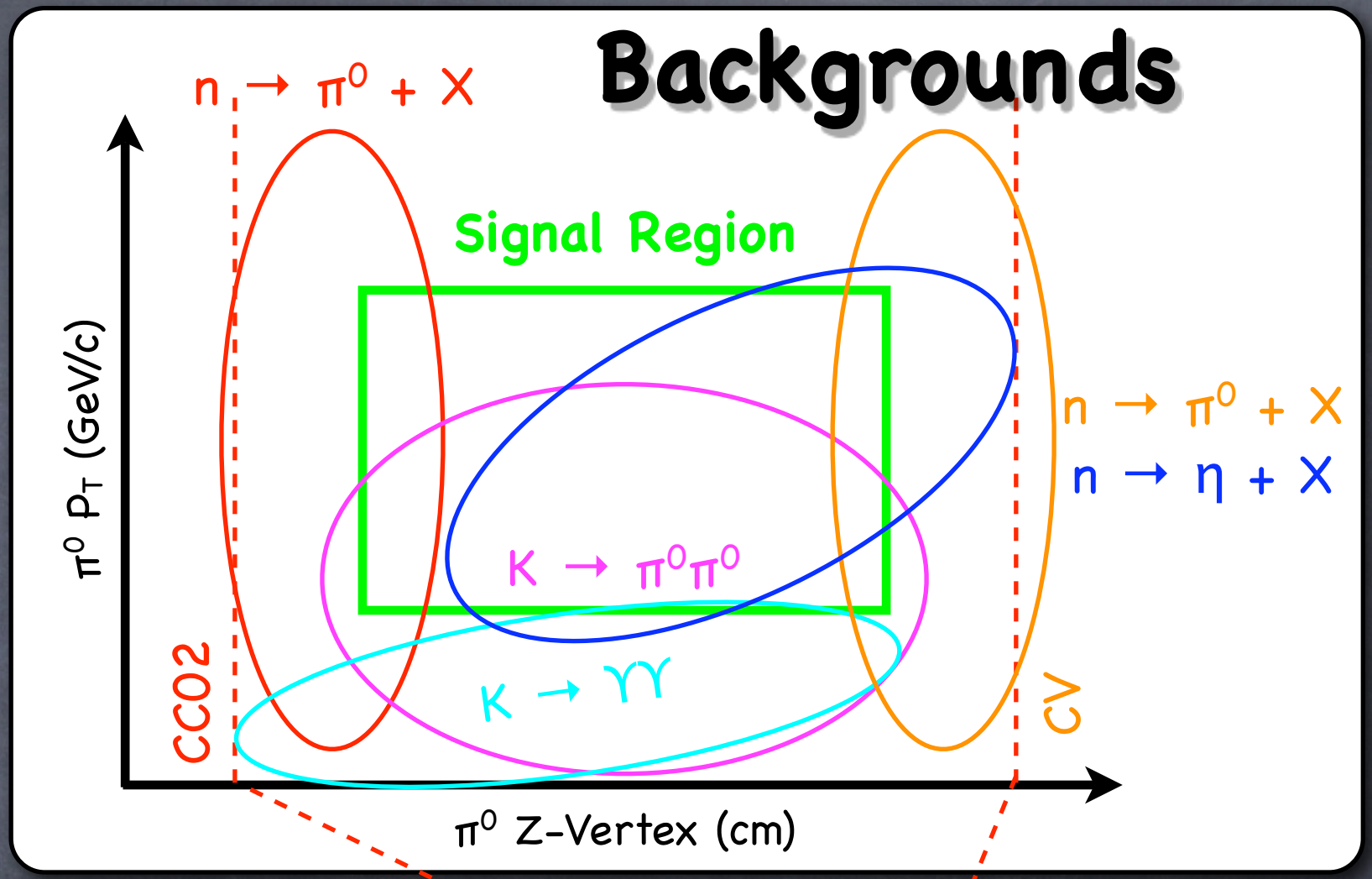


$$m_\pi^2 = (p_{\gamma_1} + p_{\gamma_2})^2 = 2\,E_1\,E_2 \times (1 - \cos\,\theta)$$

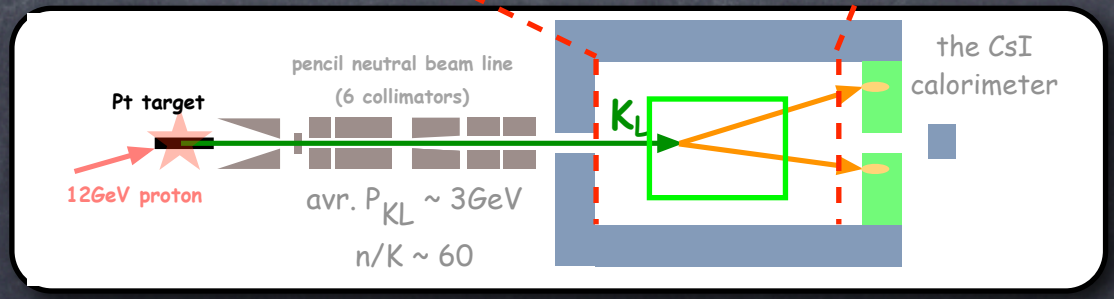
$$r_{12}^2 = d_1^2 + d_2^2 - 2\,d_1\,d_2 \cos\,\theta$$

(Low E $\Rightarrow$ Large ϑ)

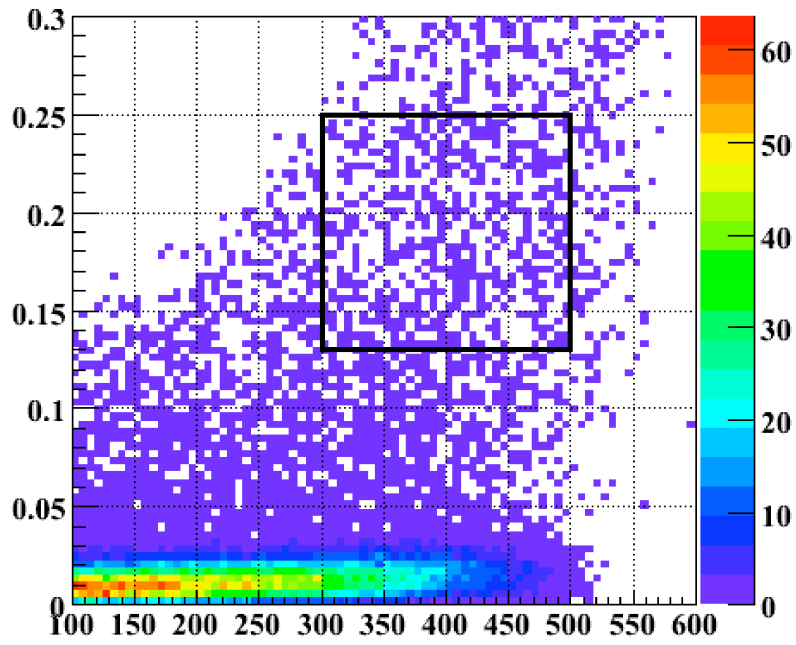
Backgrounds



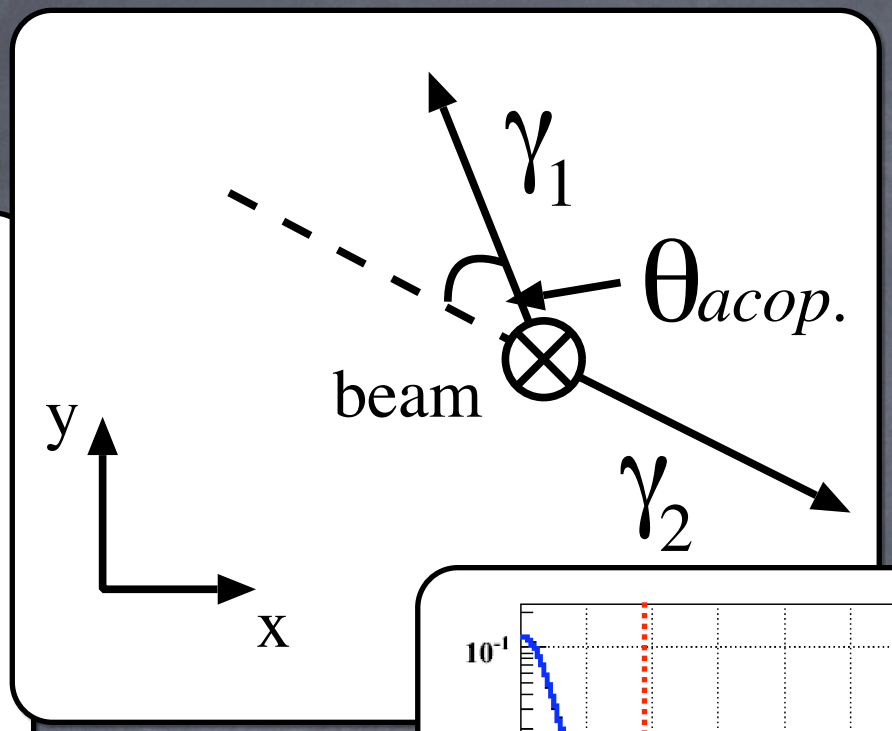
- Primary background sources:
  - Kaon decays
  - Halo neutrons

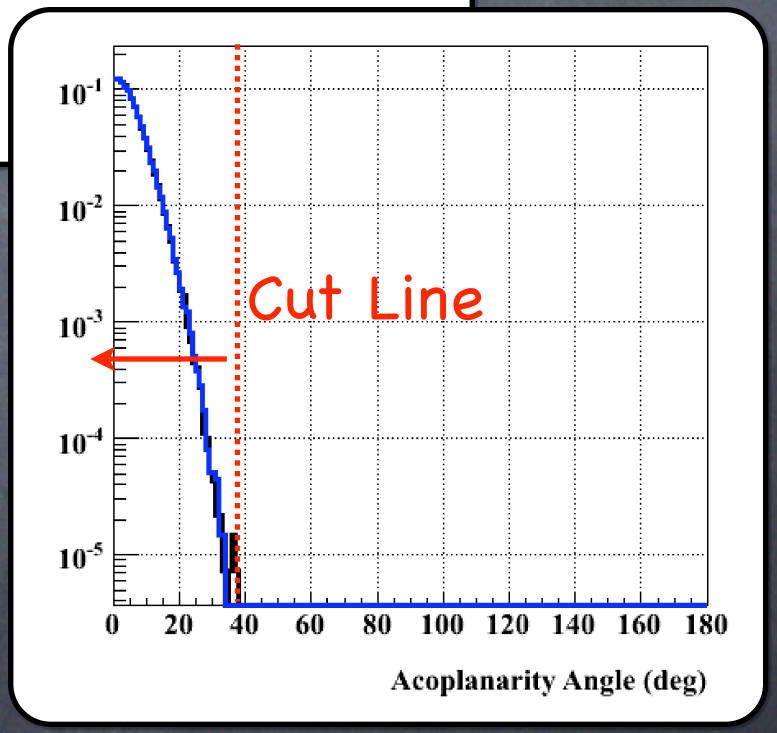


$K_L \rightarrow \gamma\gamma$ MC, No Cuts



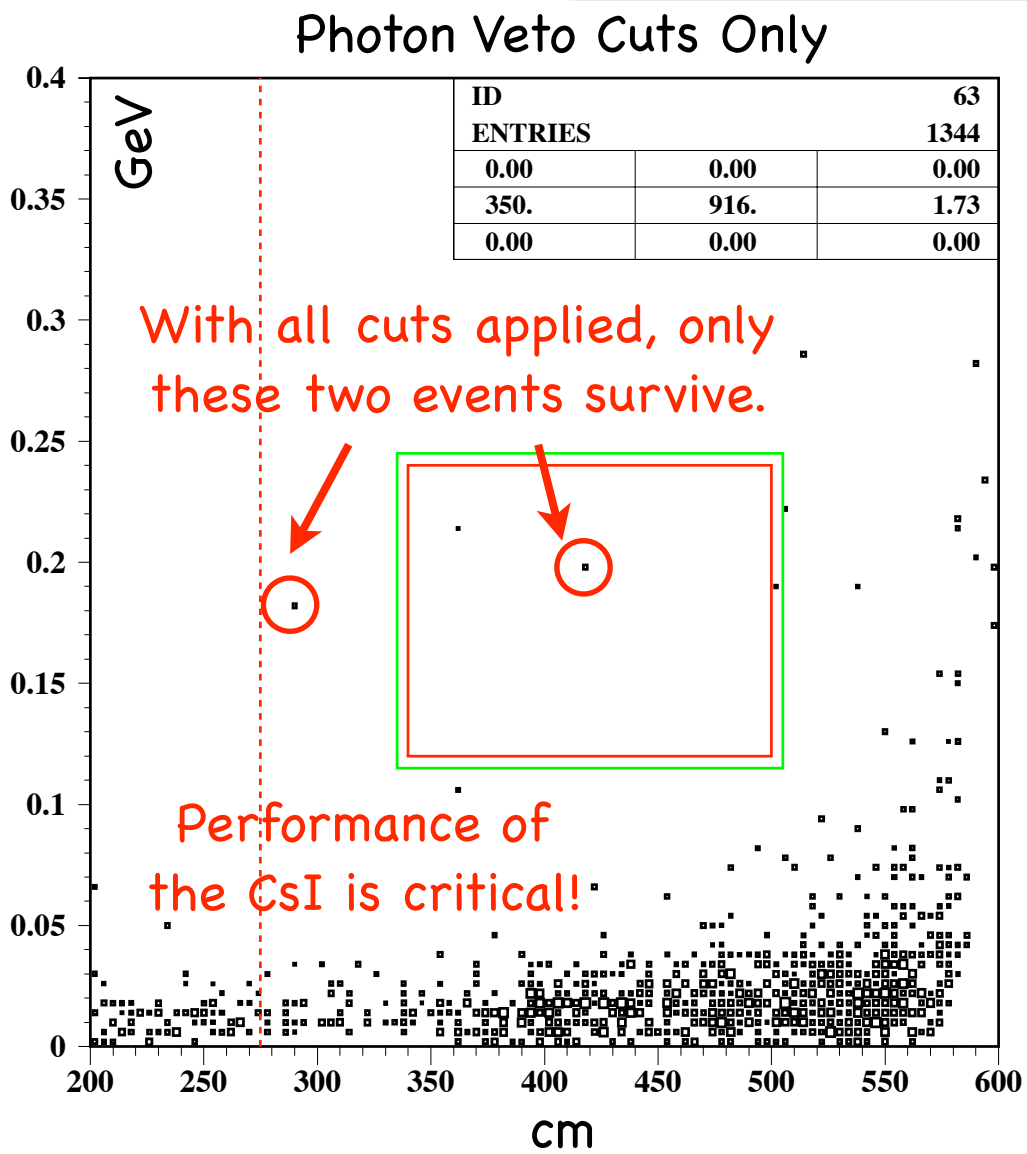
Plots courtesy of H. Nanjo.

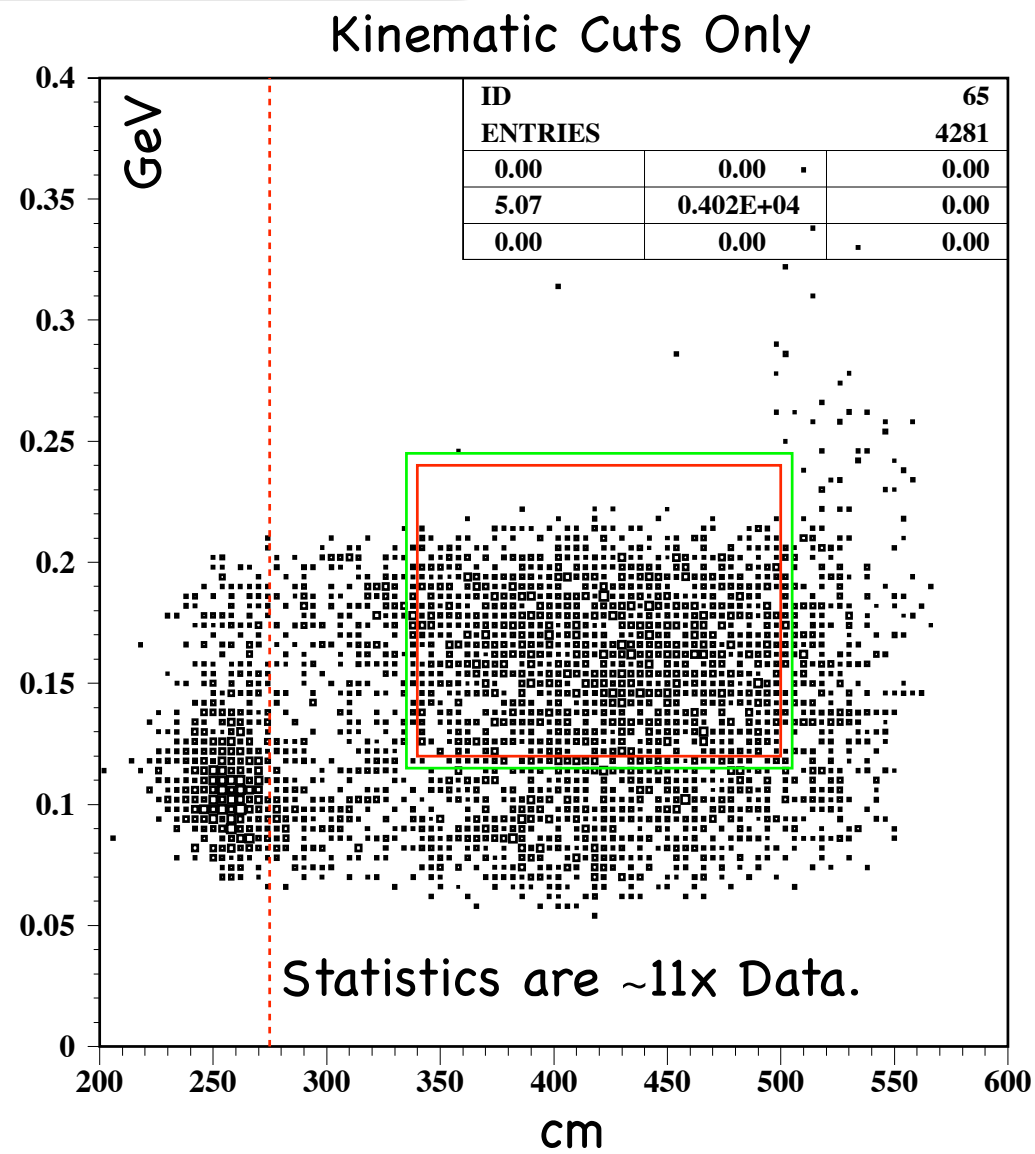




$K_L \rightarrow \gamma\gamma$ can become a threatening background only in cases where there is a significant measurement error in the photon energies - otherwise, the P_T is too low. This sort of "mis-measurement" background, however, is easily handled by an acoplanarity cut.

$2\pi^0$ MC, Single π^0 P_T vs. Z

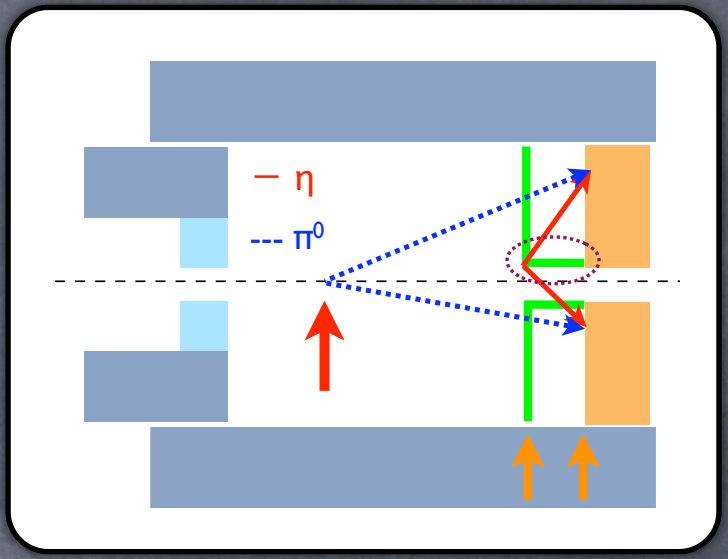




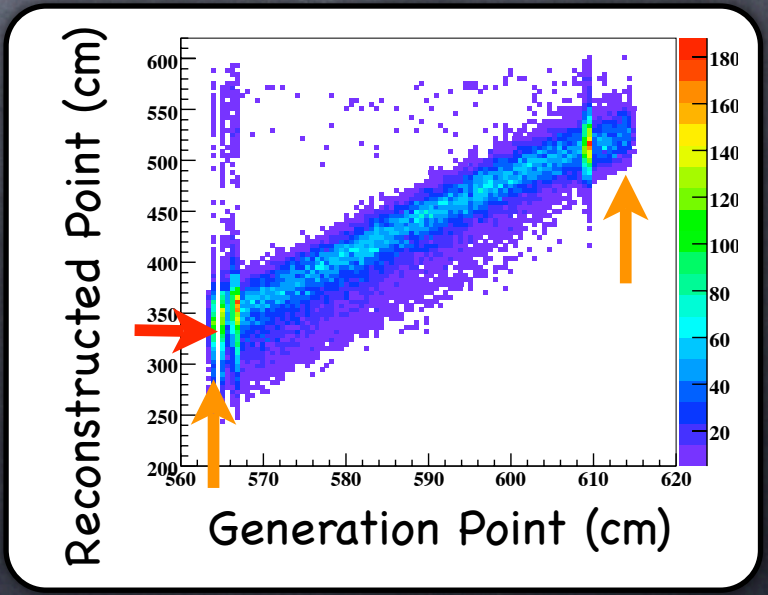
We use combinations of cuts (in addition to all the cuts at once) to estimate backgrounds from Kaon decays.

The "Charged Veto Background" - from halo particle interactions with the CV support structure.

- Two kinds of background events:
  - π^0 production:
    - Estimated with a GEANT3 MC.
  - η production:
    - Estimated with a GEANT4 MC (Binary Cascade Model).
      - Cross-check with FLUKA*

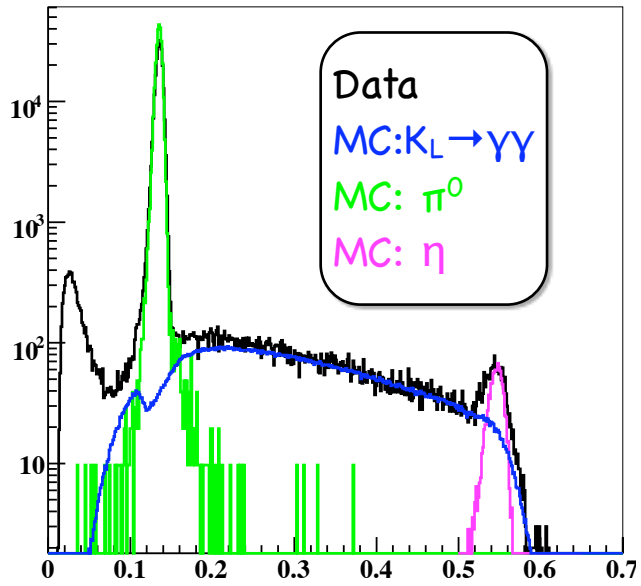


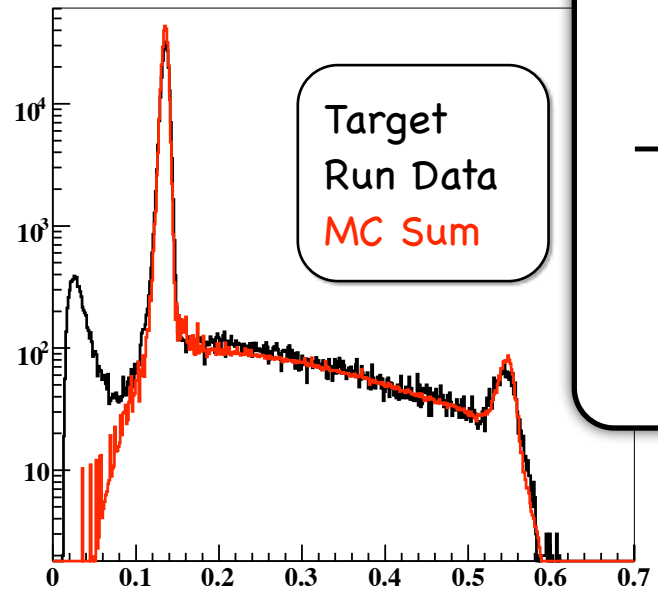
These sources are estimated with separate MC's for convenience and historical reasons (and because GEANT3 cannot produce η particles).



*Underway - this does not affect our Run-II analysis.

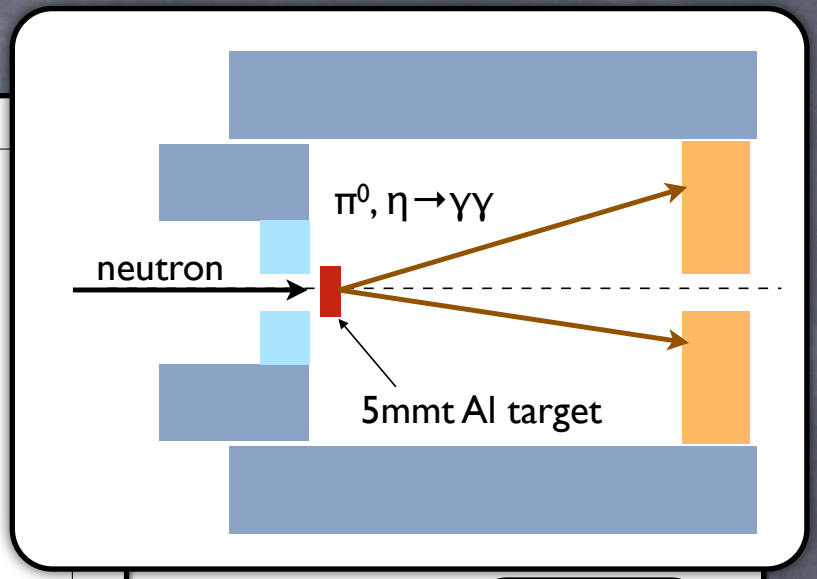
Can we trust our hadronic background MC's?

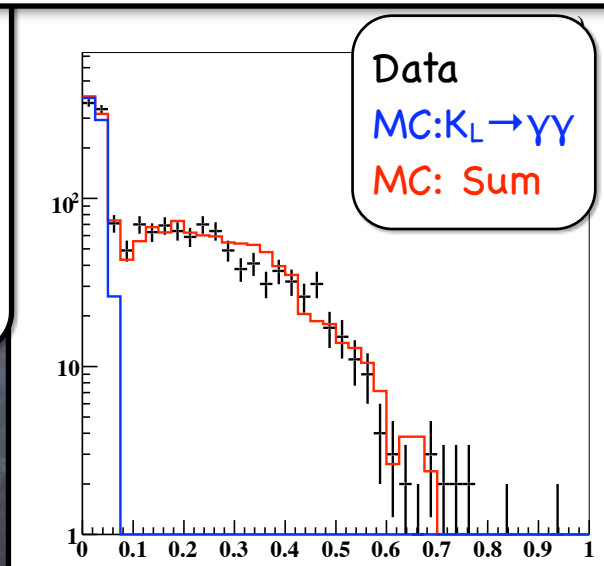




Invariant Mass (GeV/c^2)

Plots courtesy of T. Sumida.





P_T (GeV/c)

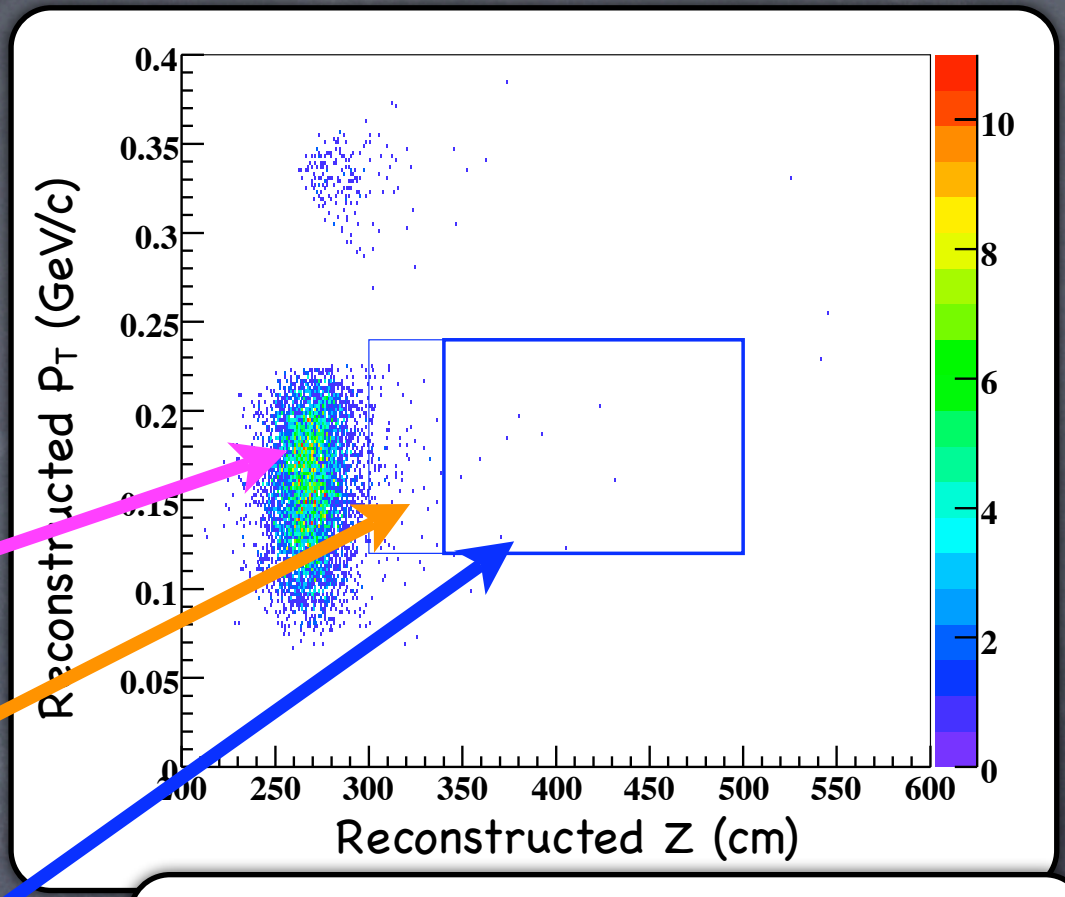
M > 0.52 GeV/c^2

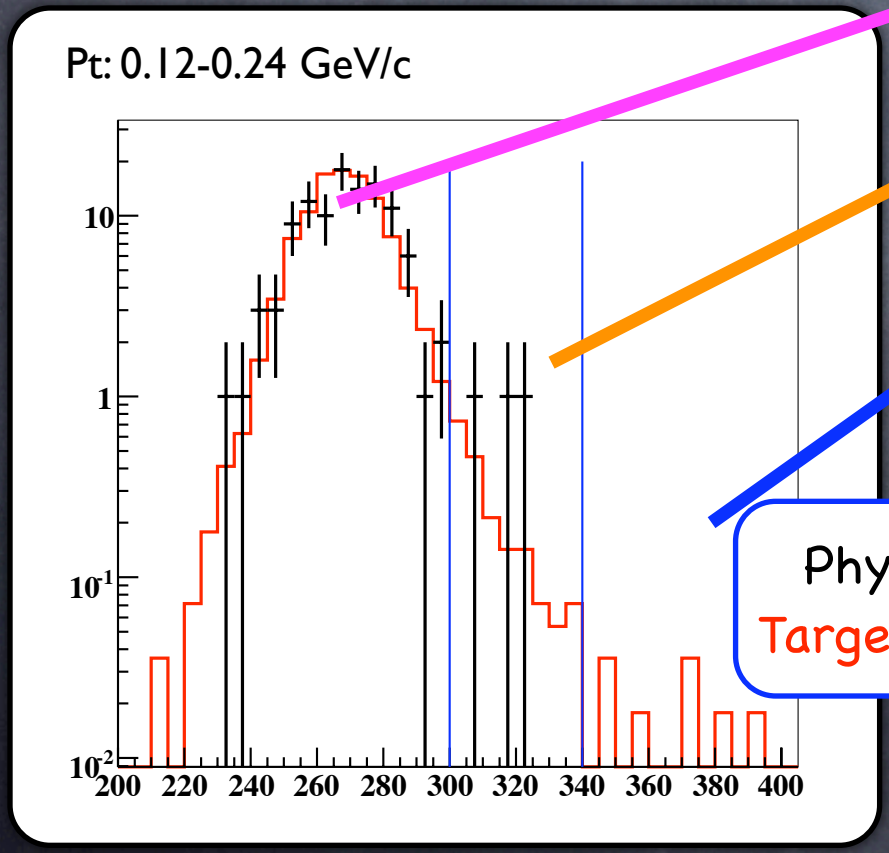
- We took special data with an aluminum target in our beam (@CC02) for calibration purposes.
- Our GEANT(3+4) MC is capable of reproducing the mass and momentum spectra using only P.O.T. normalization.

The target run also enables us to estimate the size of the "CCO2" background from data directly.

- Normalization Region
- Check Region
- Prediction Region

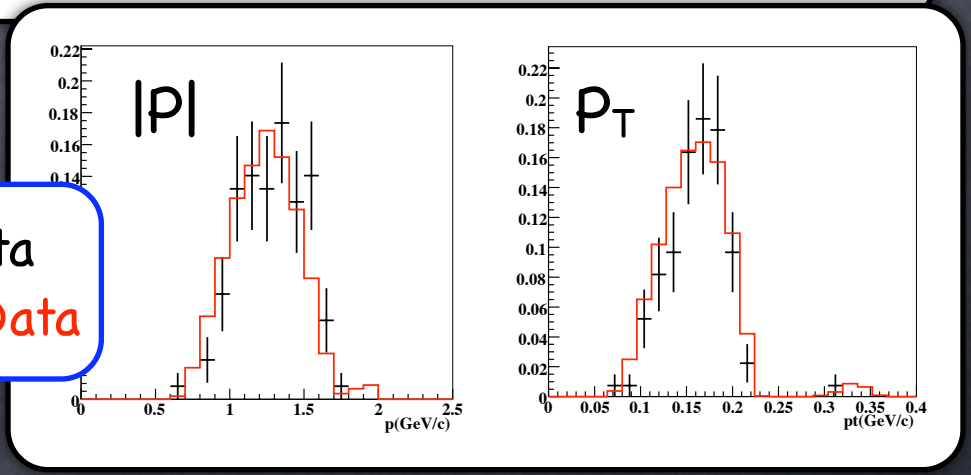
Target Run, All Cuts





Physics Data

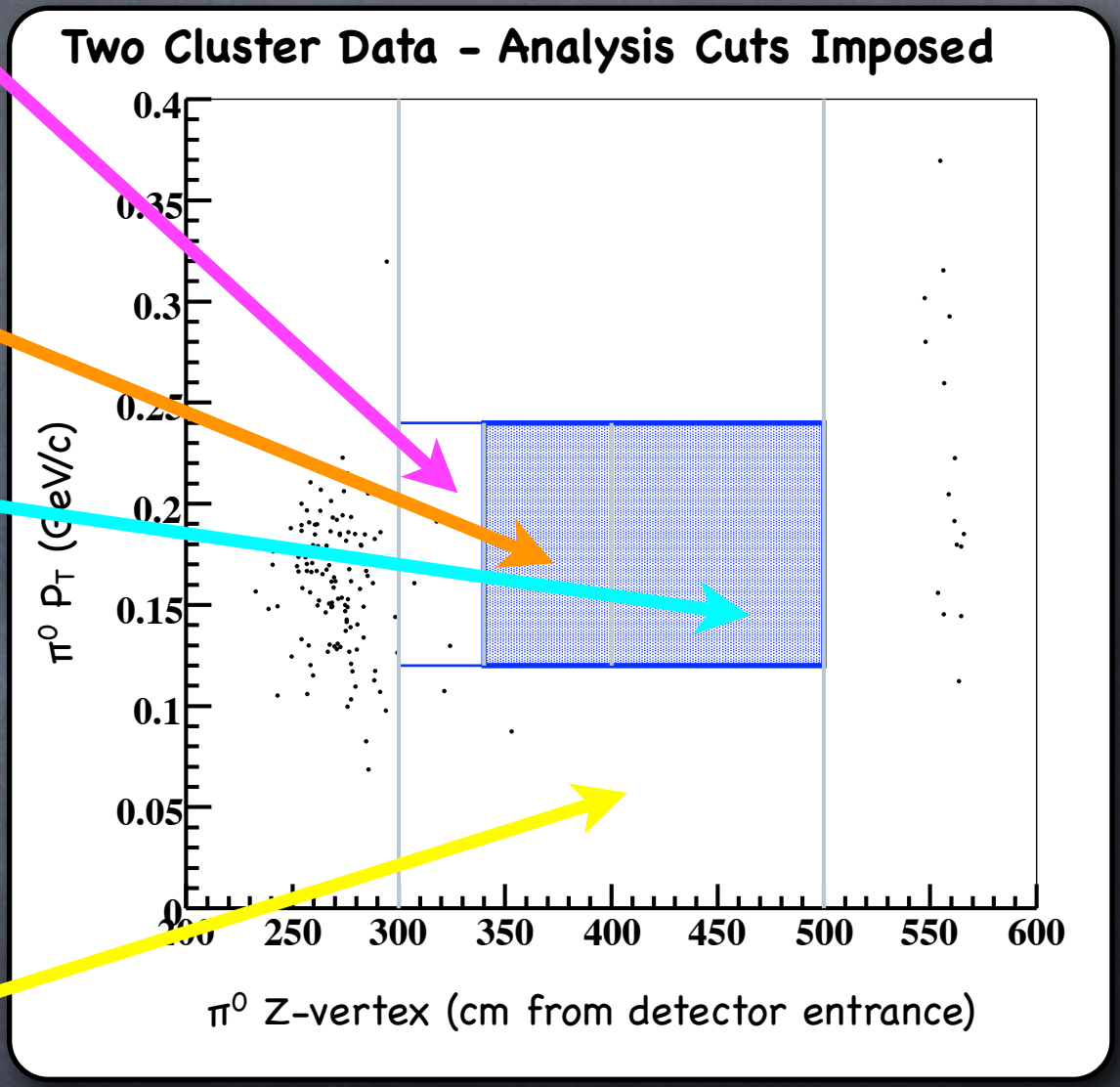
Target Run Data



Plot courtesy of T. Sumida.

- Region 1: 300-340 cm: 1.9 ± 0.2
  - CC02: 1.9 ± 0.2
  - CV-η: 0.02 ± 0.01
  - Observed: 3
- Region 2: 340-400 cm
  - CC02: 0.11 ± 0.04
  - CV-η: 0.04 ± 0.02
- Region 3: 400-500 cm
  - CC02: 0.05 ± 0.03
  - CV-π^0: 0.08 ± 0.04
  - CV-η: 0.02 ± 0.01
- Region 2+3:
  - $\pi^0\pi^0$: 0.11 ± 0.09
  - Ke3: 0.03 ± 0.007
  - **TOTAL: 0.44 ± 0.11**
- Region 4 (Low P_T): 0.39 ± 0.08
  - CC02: 0.26 ± 0.07
  - CV-π^0: 0.09 ± 0.04
  - CV-η: 0.04 ± 0.01
  - Observed: 2

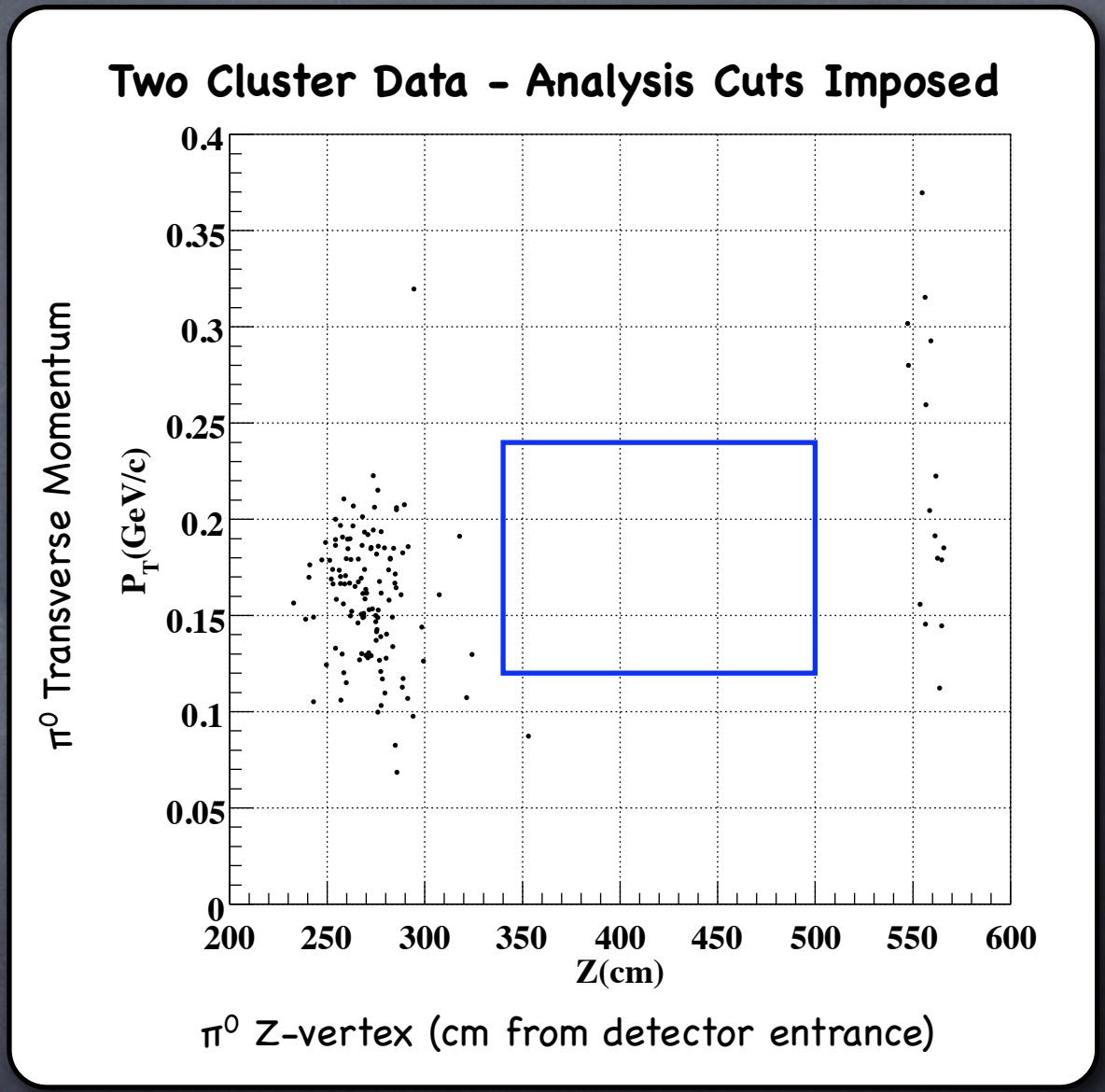
Background check before opening the box...



...statistically consistent!

Results

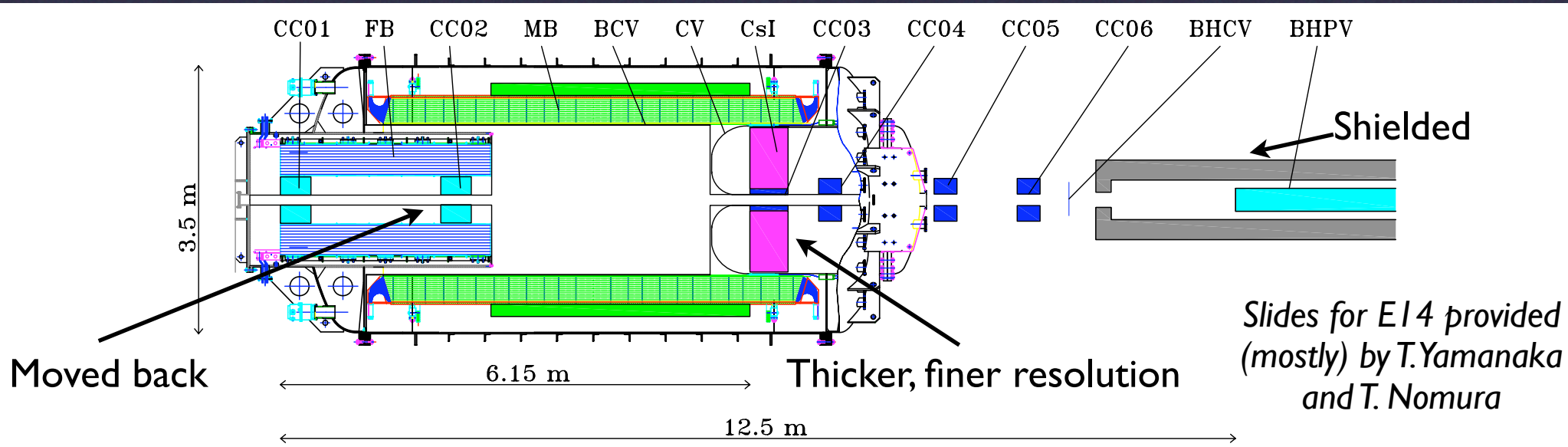
- Acceptance: 0.674%
- Single Event Sensitivity:
  - $1/(0.00674 \times 5.13 \times 10^9) = 2.89 \times 10^{-8}$
- **New Limit (Poisson):**
  - **6.7×10^{-8} (90% CL)**
- Comparison with Run-I:
  - Limit: 2.1×10^{-7}
  - Acceptance: 0.657%
  - BG estimate: 1.9 ± 1.0 (0 Observed)
  - S.E.S.: 9.11×10^{-8}
  - **S/N RunII/RunI ~ 15**



arXive: 0712.4164

J-Parc E14

- Improved beamline
- CsI: 7x7x30 ==> 2.5x2.5x50 cm^3
- Waveform digitization for rates and cost
- Upgraded veto counters



Slides for E14 provided (mostly) by T. Yamanaka and T. Nomura

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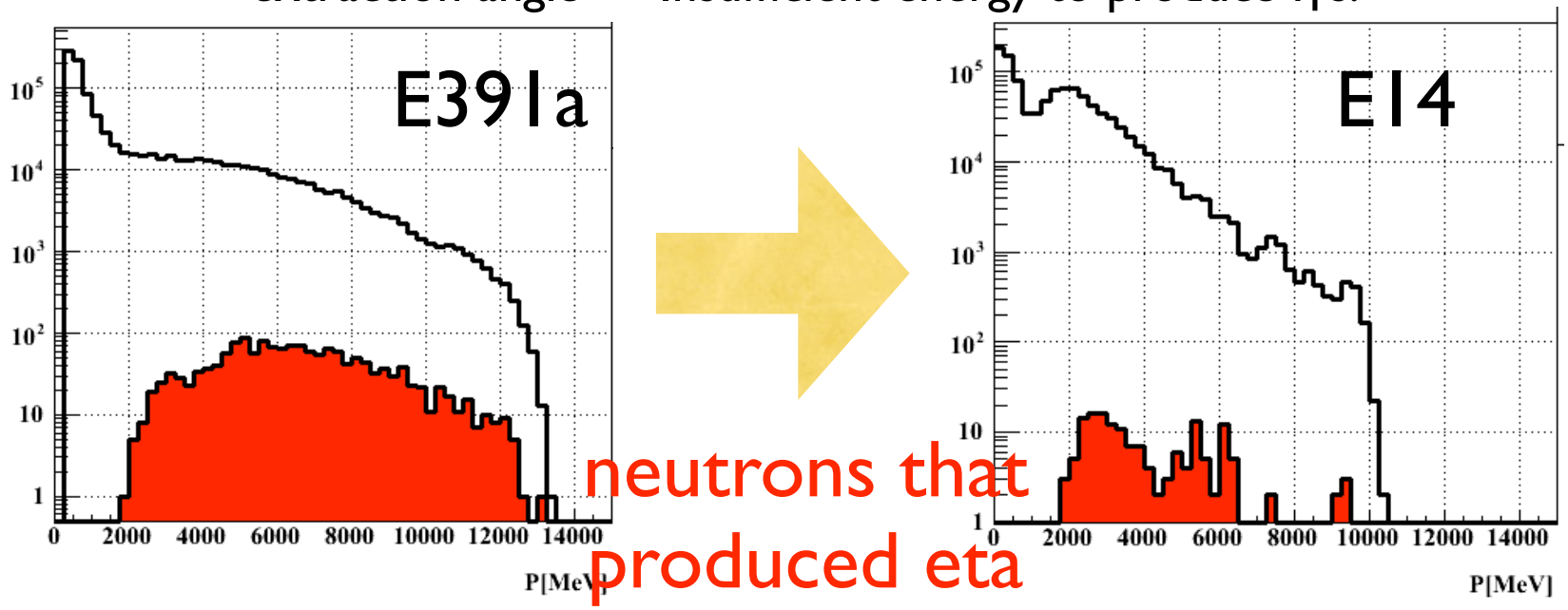
Suppress Halo Neutron Background

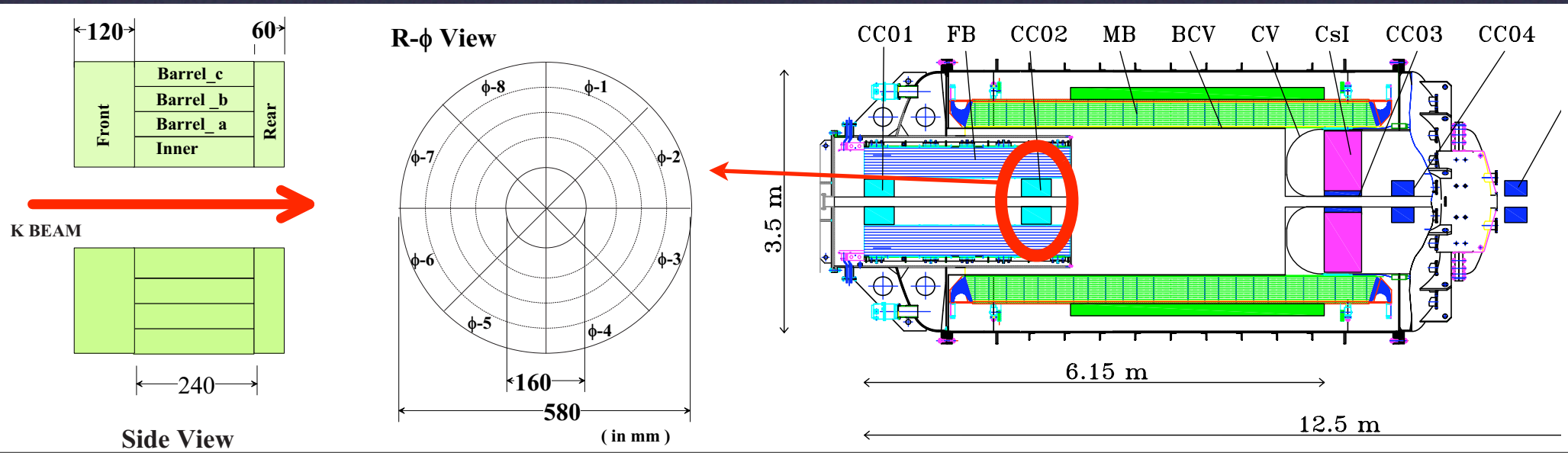
1. Reduce beam halo; halo/core < 10^{-5}
2. Reduce pi0 and eta production
   1. Lower neutron momentum

Neutron |P| spectrum is softer due to larger extraction angle → Insufficient energy to produce η's.



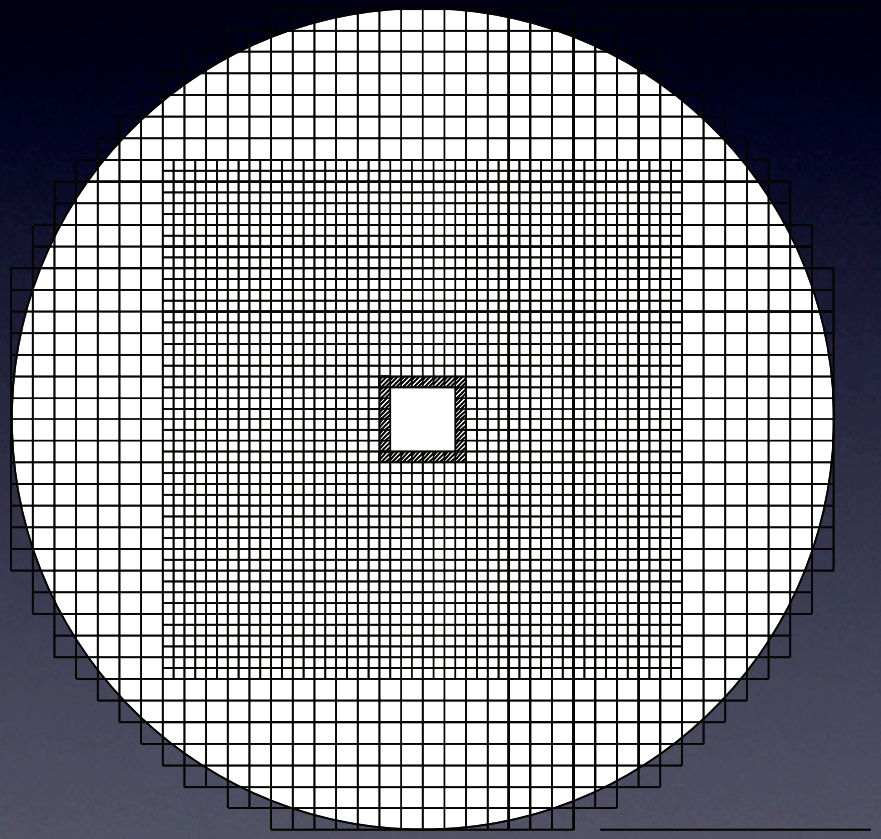
Suppress Halo Neutron Background

1. Reduce beam halo; halo/core < 10^{-5}
2. Reduce pi0 and eta production
3. Detect halo neutron interaction and veto
   1. Neutron Collar Counter (segmented CsI)



KTeV CsI

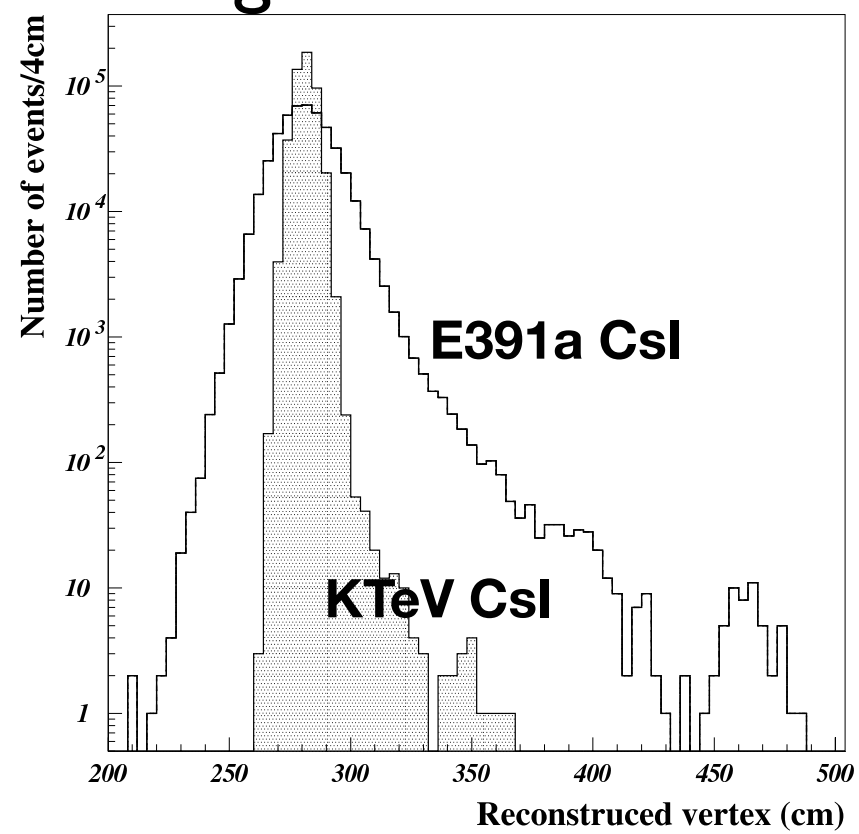
- Reduce fusion and photon punch-through
- Ownership is transferred from FNAL to Univ. Chicago
- Engineer+technician are preparing for unstacking
- Began disassembling / shipping in December 2007



KTeV CsI Calorimeter

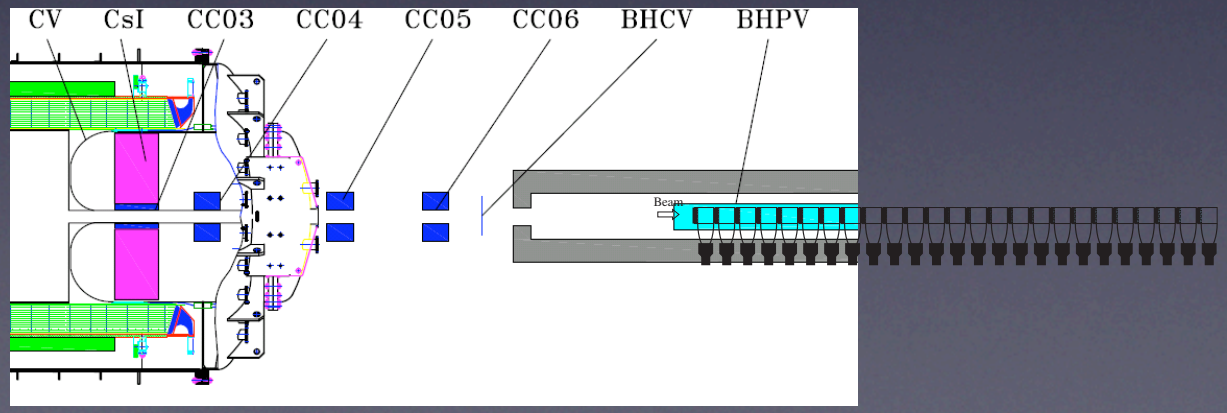
- 30cm -> 50cm (thick)
  - reduces energy response tail due to shower leakage
  - reduces punchthrough
- 7cm -> 2.5cm square
  - position resolution 5mm -->1mm
  - reduces photon fusion

Halo neutron background at CC02



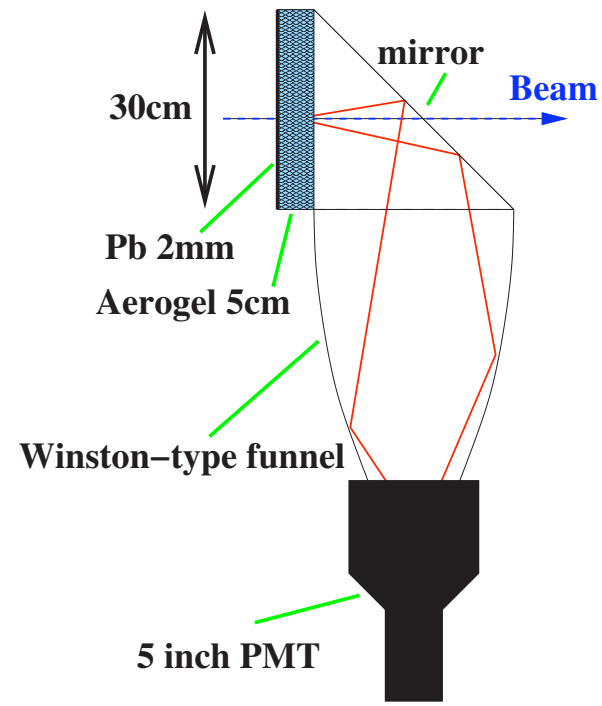
E14 Basic Strategies

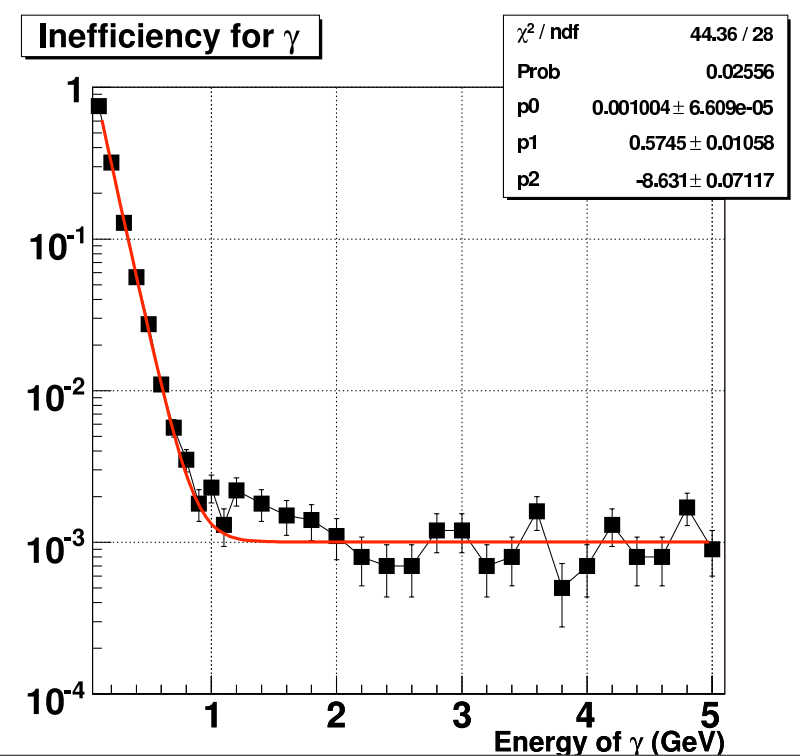
1. Suppress and control backgrounds based on the E391a experience
2. Need more Kaons... Make detector capable of handling high rates!
   - 2.1. BHPV in beam
   - 2.2. Waveform digitization



Beam Hole Photon Veto

- Originally designed and intensively studied for KOPIO
- Insensitive to neutrons: 0.2% @ 2GeV/c
- 10^{-3} photon detection inefficiency @>1GeV
- false hit rate : 2MHz
- Proven by prototype beam tests





Waveform digitization

- ~3000 (CsI) + ~1000 (others) channels
- Deadtime-less for 250kHz trigger
- Record waveform to isolate a pulse on earlier tail
- 0.3MeV ~ 2GeV, 14bit, <150 ps resolution
- Affordable
- Being designed by the US E14 team

Signal / Background Summary

MC largely validated by E391a *data!*

- 3 snowmass years
- "KL alone" beamline

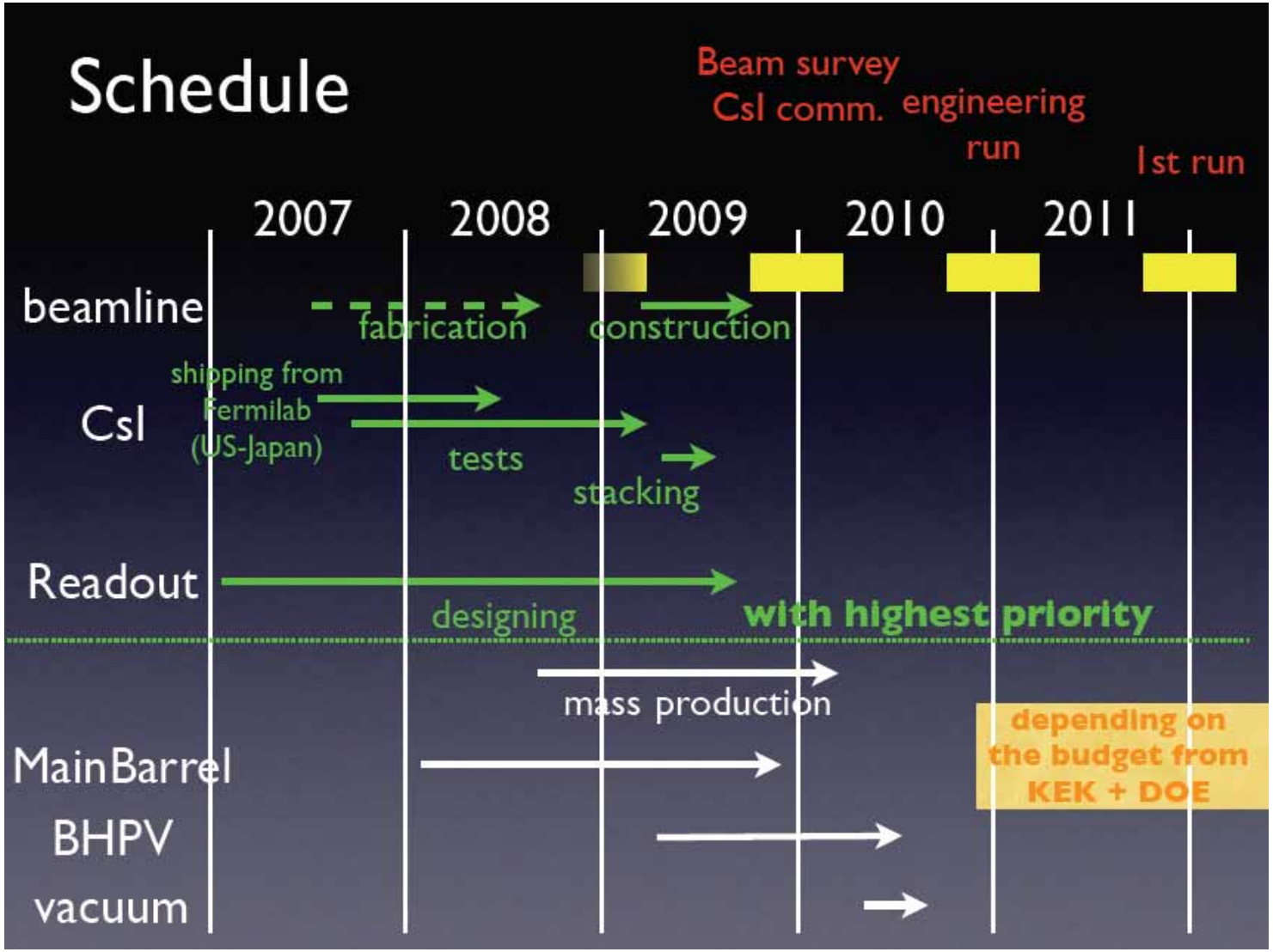
(KL yield based on GEANT4/QGSP)

		standard cuts	CsI cluster shape cut	acceptance loss (50%)
Signal	$K_L \to \pi^0 \nu \overline{\nu}$	6.0 ± 0.1	5.4 ± 0.1	2.70 ± 0.05
K_L BG	$K_L \to \pi^0 \pi^0$	3.7 ± 0.2	3.3 ± 0.2	1.7 ± 0.1
	$K_L \to \pi^+ \pi^- \pi^0$	0.18 ± 0.08	0.16 ± 0.07	0.08 ± 0.04
	$K_L \to \pi^- e^+ \nu_e$	0.13 ± 0.01	0.03 ± 0.003	0.02 ± 0.001
halo n BG	CV	—	—	0.08
	η	8.1	0.6	0.3

S/N ~ 2.7/1.7 ~1.6

Note:
Detailed simulation of CV/CC02 BG in progress

Schedule digest



Summary & Future

- E391a will improve the limit on $K_L \rightarrow \pi^0 \nu\nu$ by almost a full order. We are acceptance and statistics limited!
- Applying the lessons of E391a, we are going to attempt to improve our sensitivity by a factor of x1000 at the new J-PARC facility at Tokai in Japan in the E14 experiment.
  - Kaon flux will improve by a factor of x10.
  - Our running time will improve by a factor of x10.
  - A much improved CsI array and flash-ADC pipeline electronics will improve detector performance by a factor of x10.

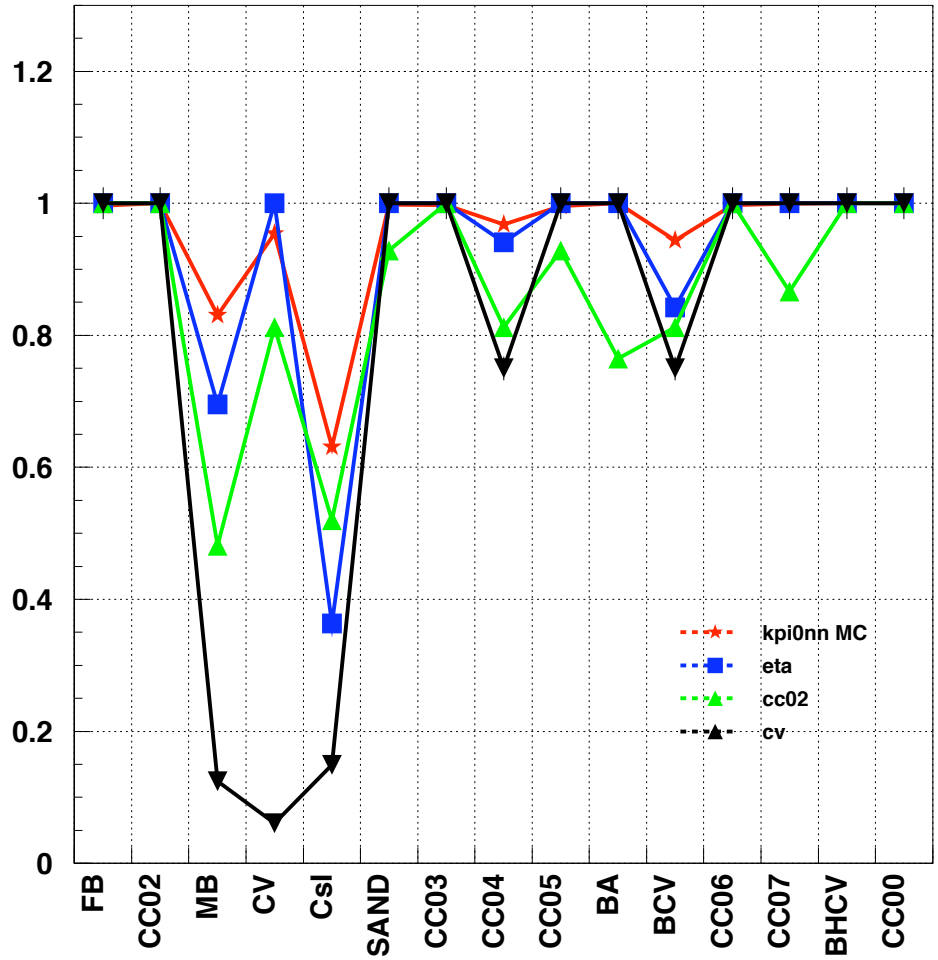
Thank You for Listening!

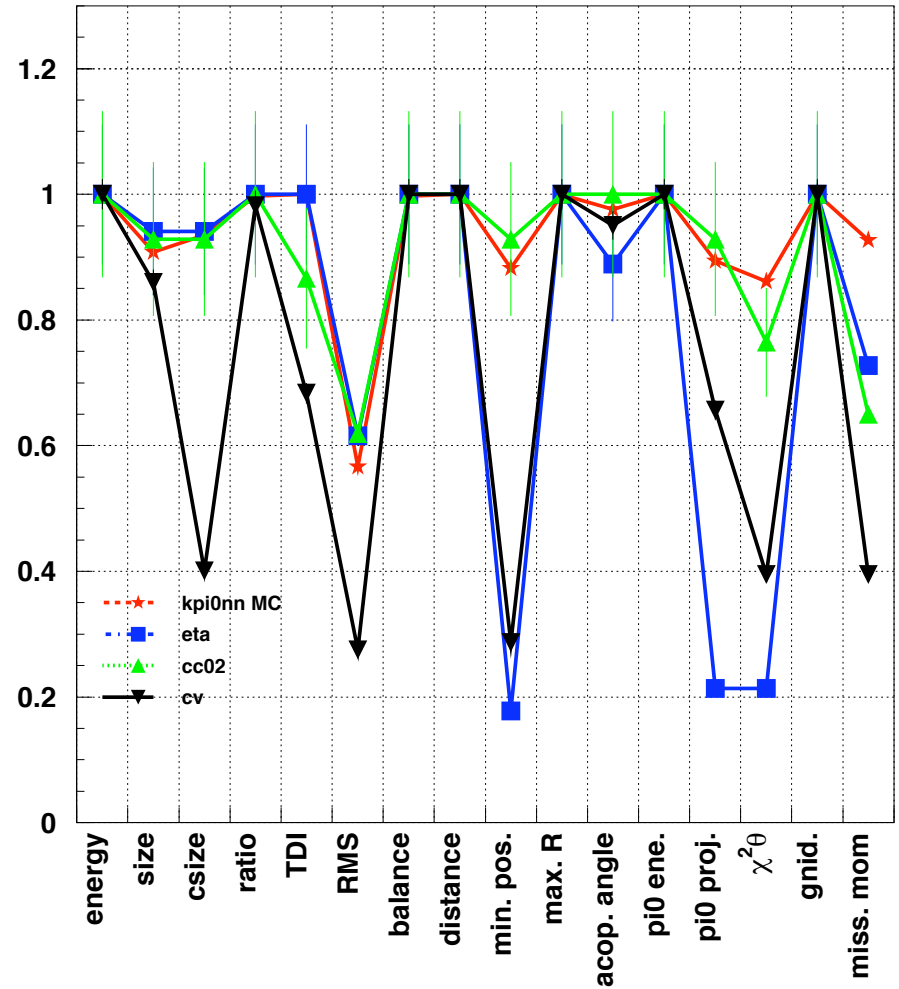
Back-Up Slides

Background Predictions

$K \rightarrow \pi^0\pi^0$	0.11 ± 0.09 Events
$K \rightarrow \pi^{\pm}e\upsilon$	0.03 ± 0.007 Events
$K \rightarrow \gamma\gamma$, $K \rightarrow \pi^{\pm}\mu\upsilon$, $K \rightarrow \pi^+\pi^-\pi^0$	Negligible
$n \rightarrow \pi^0 + X$ Upstream ("CC02")	0.16 ± 0.05 Events
$n \rightarrow \pi^0 + X$ Downstream ("CV")	0.08 ± 0.04 Events
$n \rightarrow \eta + X$ Downstream ("CV")	0.06 ± 0.02 Events
Total	0.44 ± 0.11 Events

Acceptance & Rejection

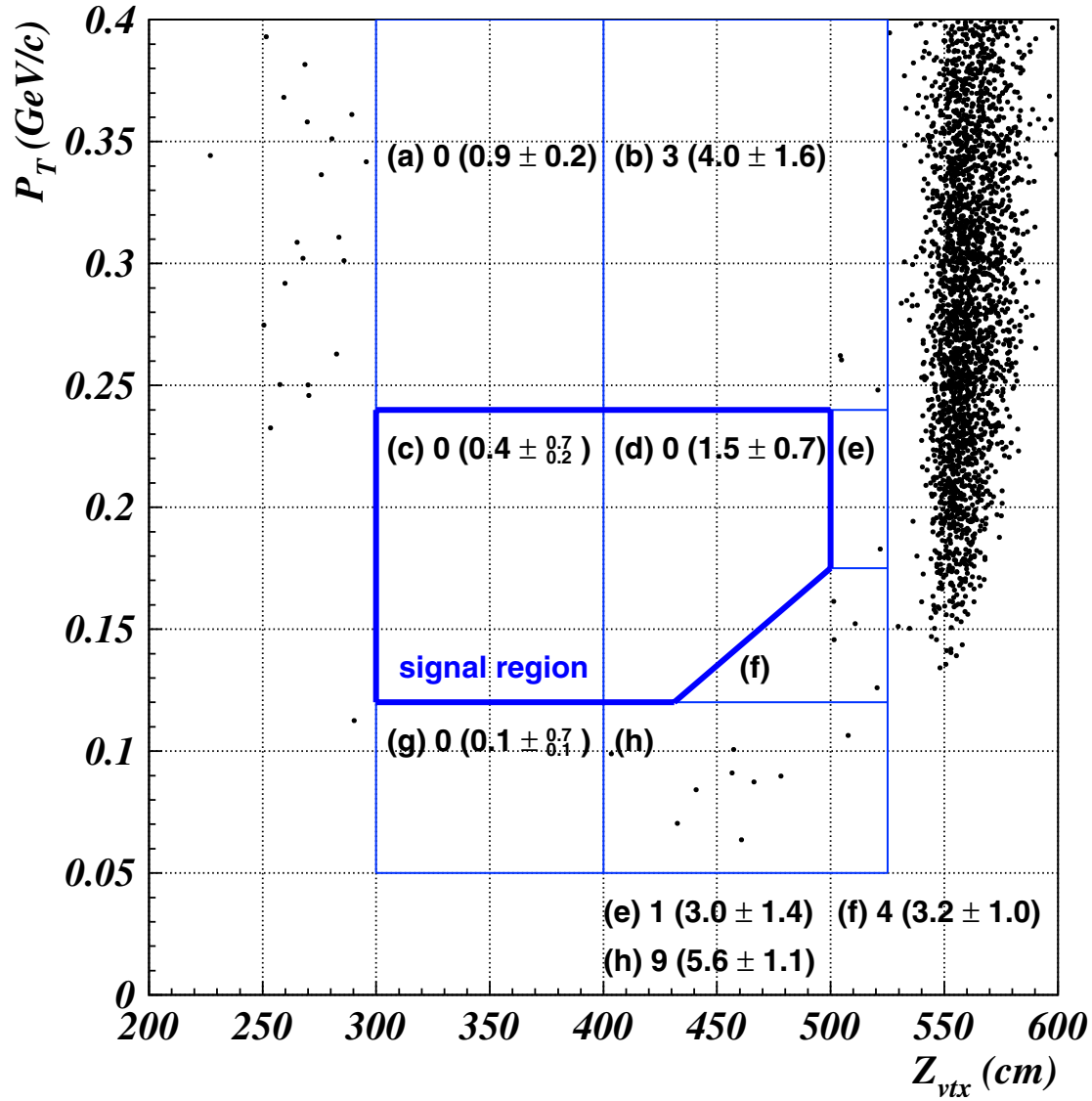




Review of the Run-I 1week and Upgrades in RunII

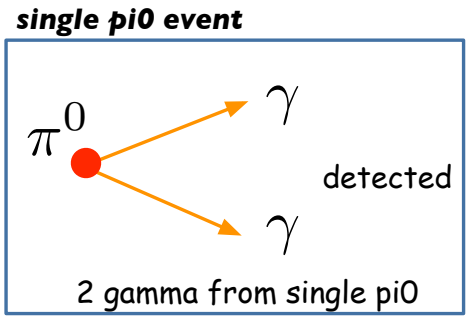
Result from Run-I 1week

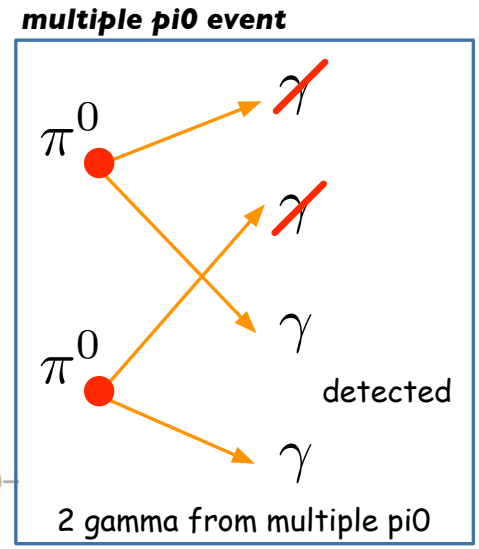
- Using 10% of Run-I data
- set new limit
  - Br < 2.1×10^{-7} (@90%C.L.) (PRD 74:051105, 2006)

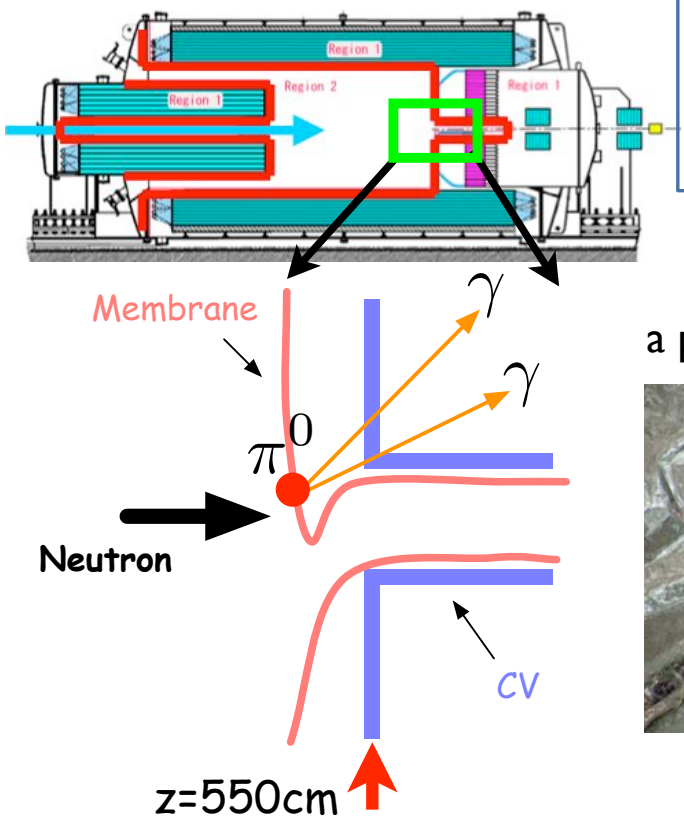


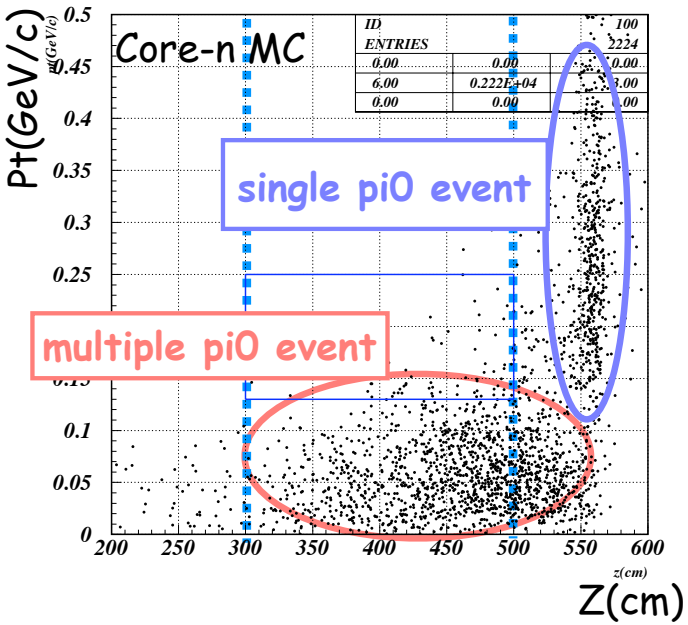
Problems in Run-I

- core neutron background
  - hitting on the membrane sagging into the beam-line

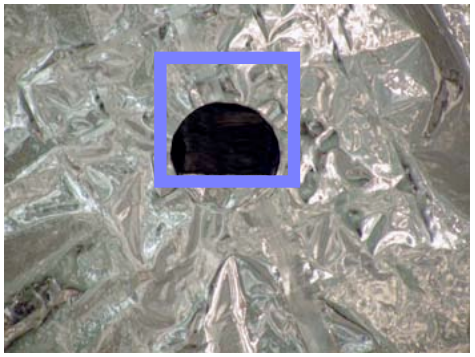






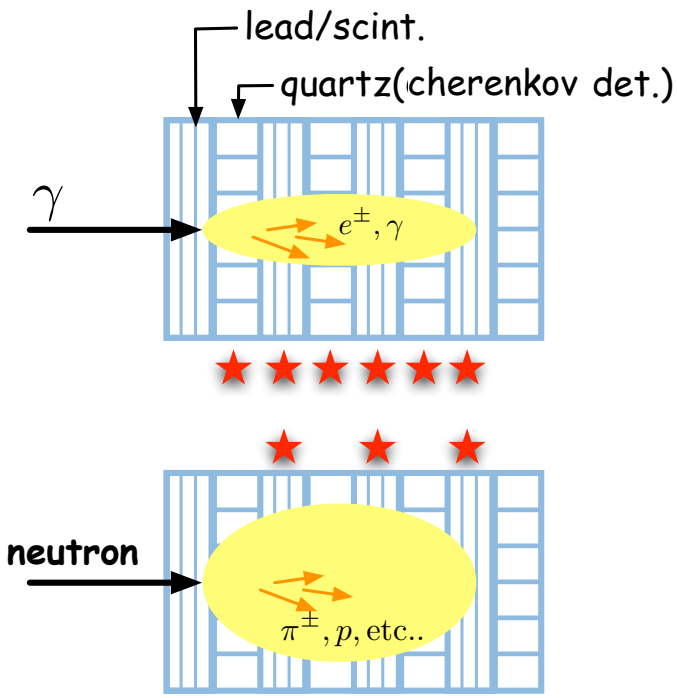


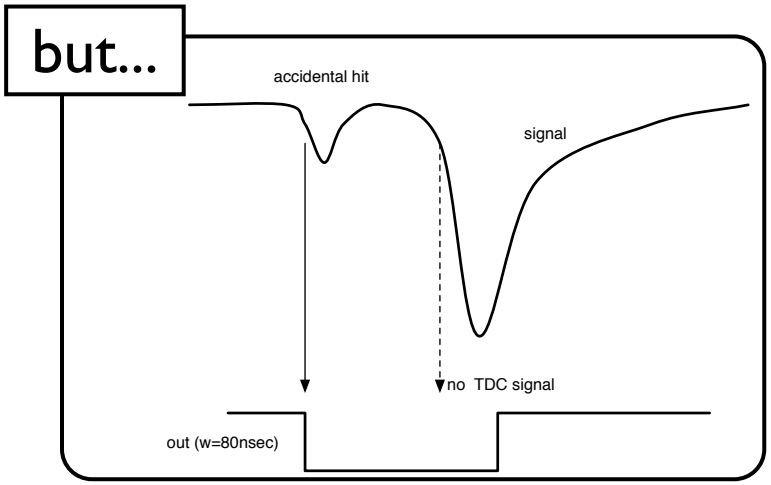
a photo of the membrane



Problems in Run-I

- Minimum pulse width for TDC: 80ns
  - Large acceptance loss in BeamAnti counter due to high accidental hit rate
    - To avoid the inefficiency with the masking effect

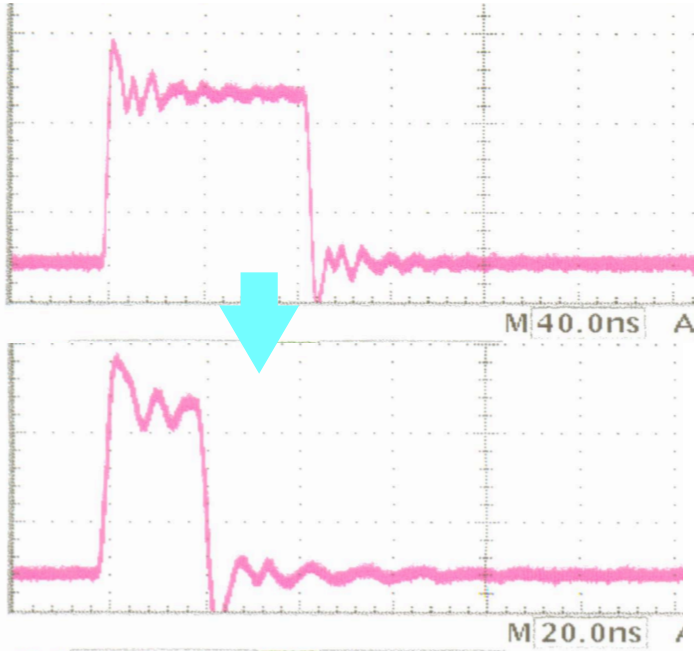


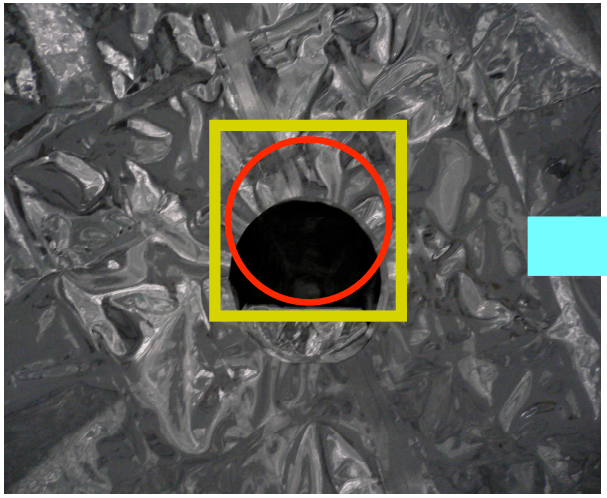


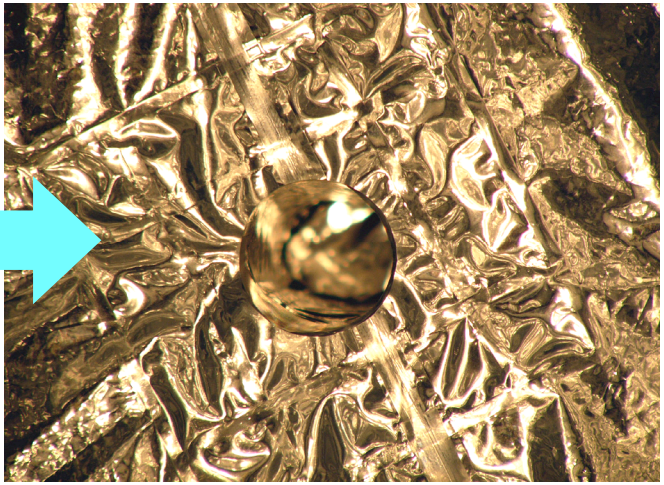
Improvements in Run-II

- The membrane trouble fixed

- Pulse width modified
  - 80ns → 25ns

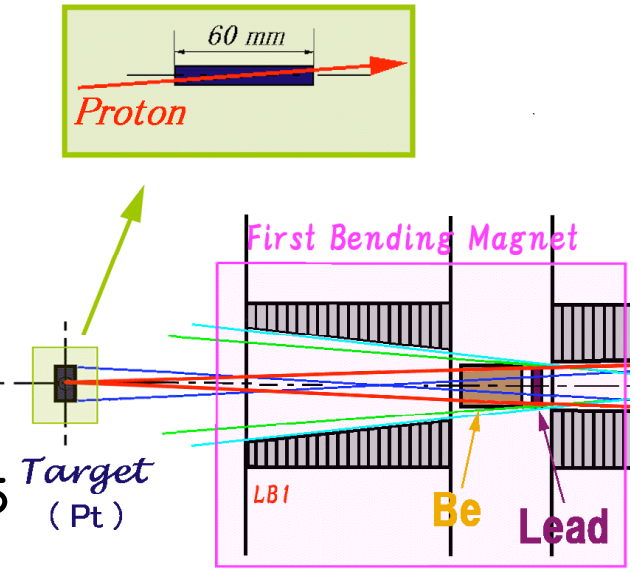




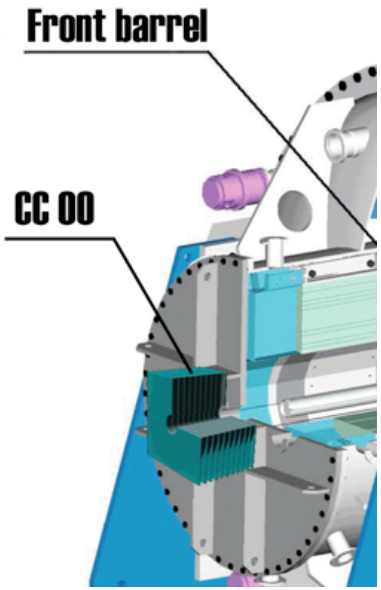


Improvements in Run-II

- Be absorber in the beam-line
  - merit, demerit
    - KL flux: x0.56
    - DAQ live time ratio: 0.90 (w/o 0.72)
    - Accidental loss: 0.83 (w/o 0.61)
    - Neutron flux: core: x0.34, halo: x0.40
  - Sensitivity
    - 0.56 * (0.90/0.72) * (0.83/0.61) = 0.95
  - S/N assuming the halo neutrons is all the source of BG
    - 0.95 / 0.40 = 2.4



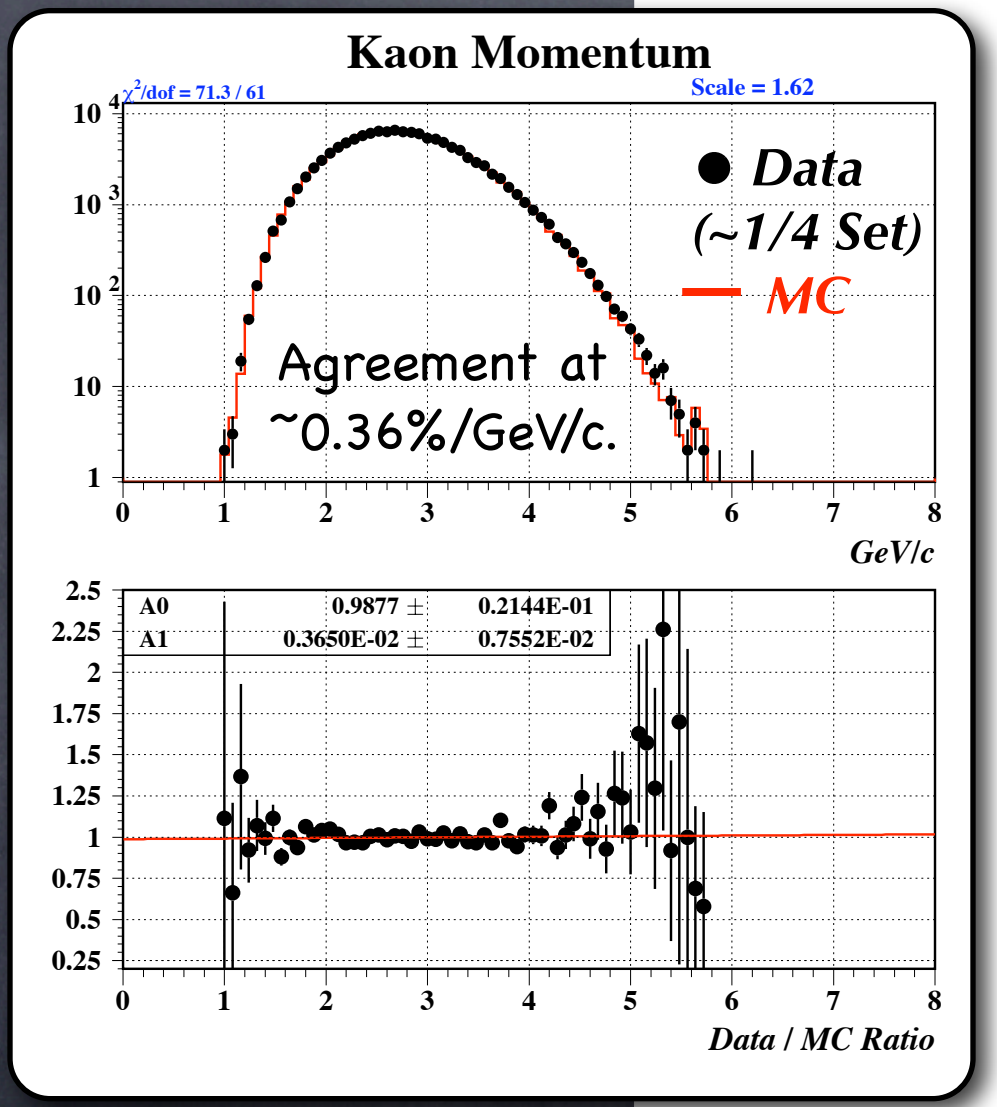
- Other upgrades
  - Beam Hole Charged Veto
    - 1mm thick → 3mm
    - 4ch → 8ch
  - Extra Collar Counter (CC00) installed
  - Data transfer speed from ADC
    - 100 Mbps → GbE

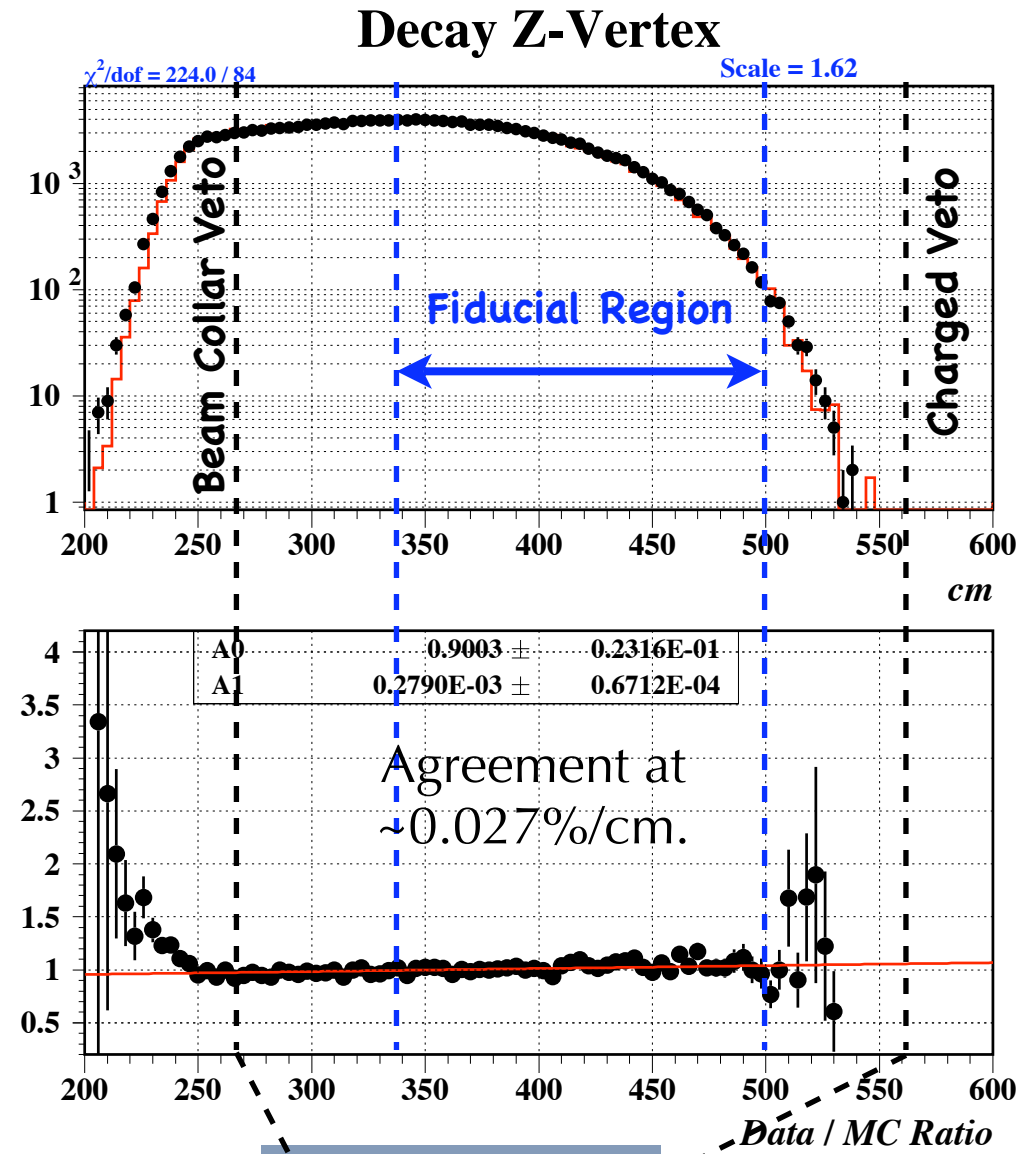


Normalization, Monte Carlo, & Systematics

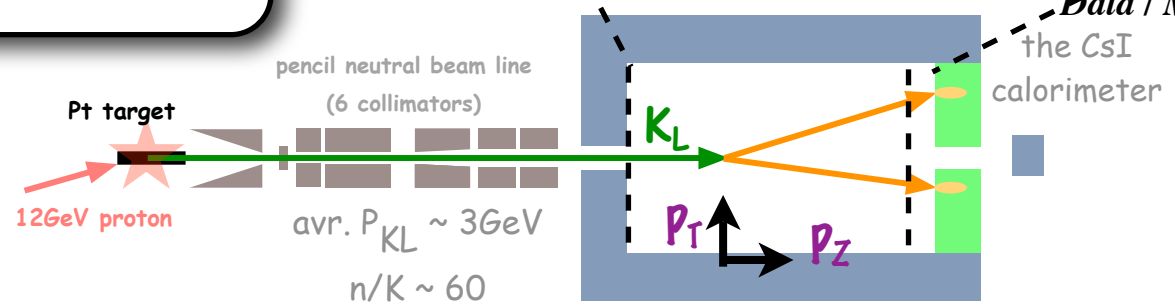
- The Run-II MC's performance is excellent with the exception of three geometrical bugs that we discovered in the process of data analysis.
- We use the MC to compute the acceptance, flux, and systematic error for our normalization mode; and to compute the acceptance for our flagship decay.

$K \rightarrow \pi^0\pi^0\pi^0$

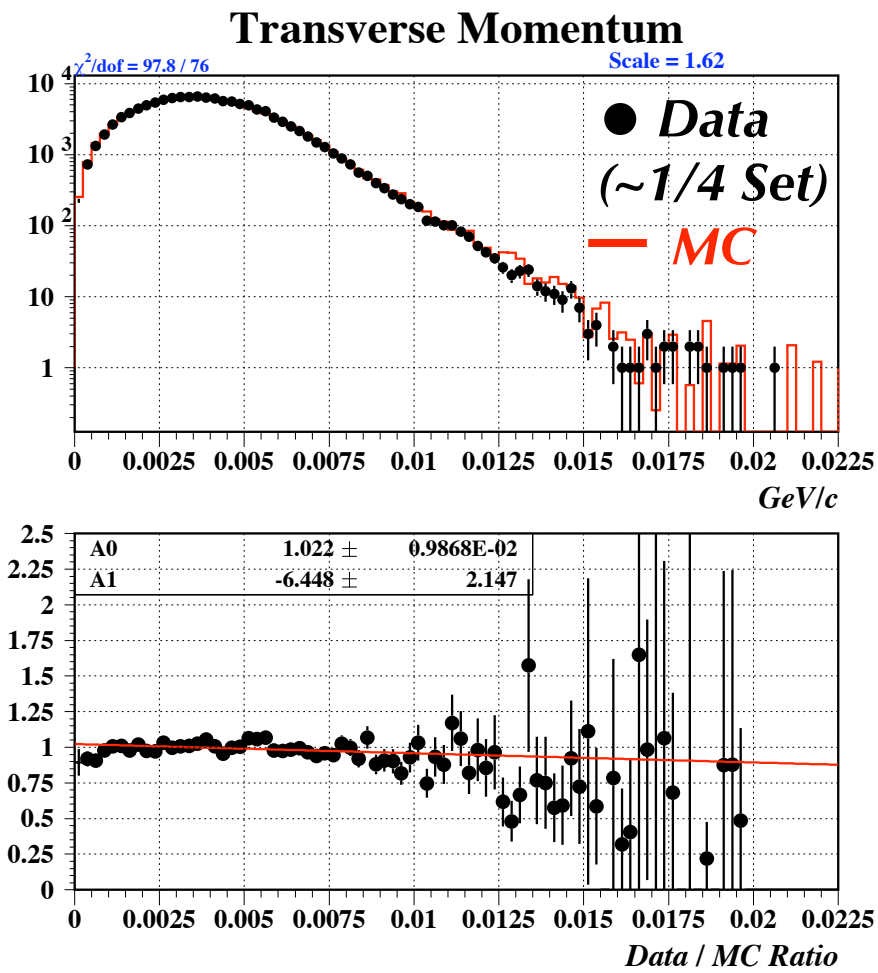


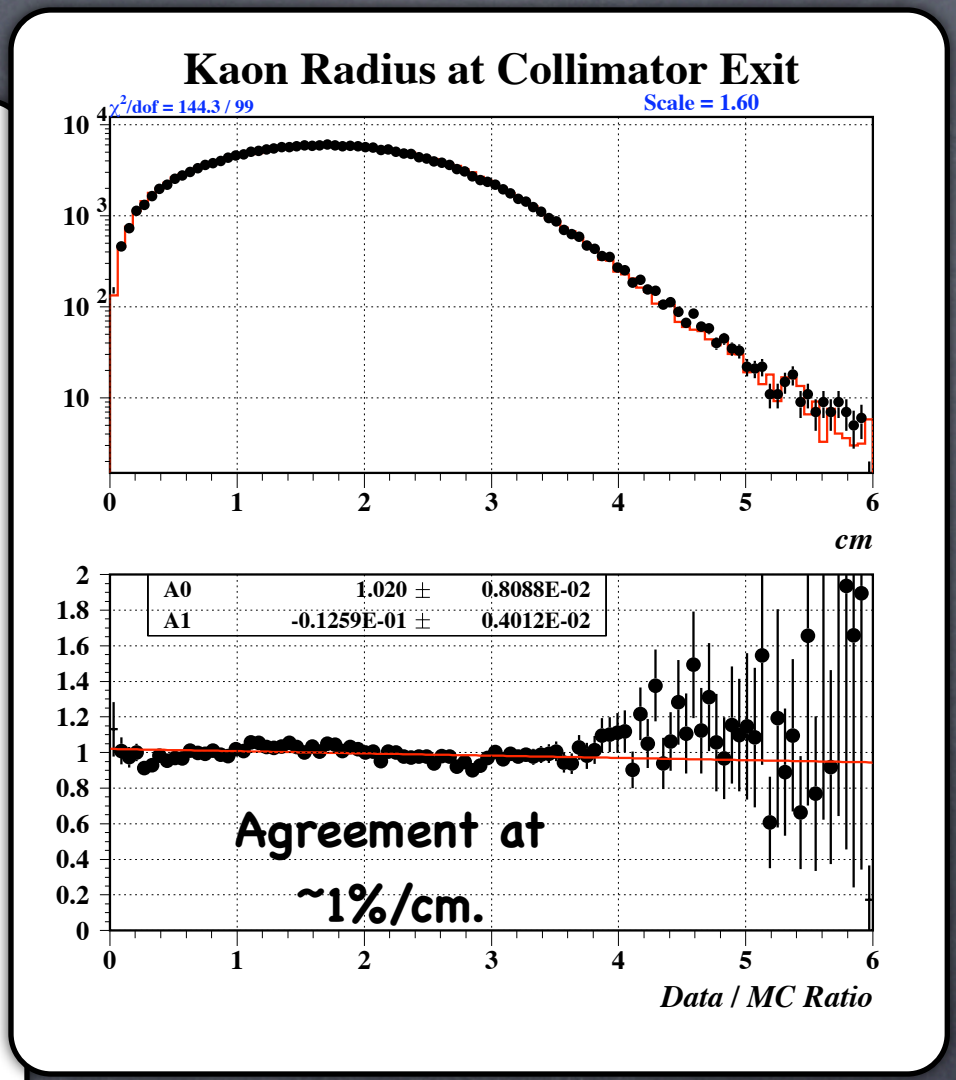


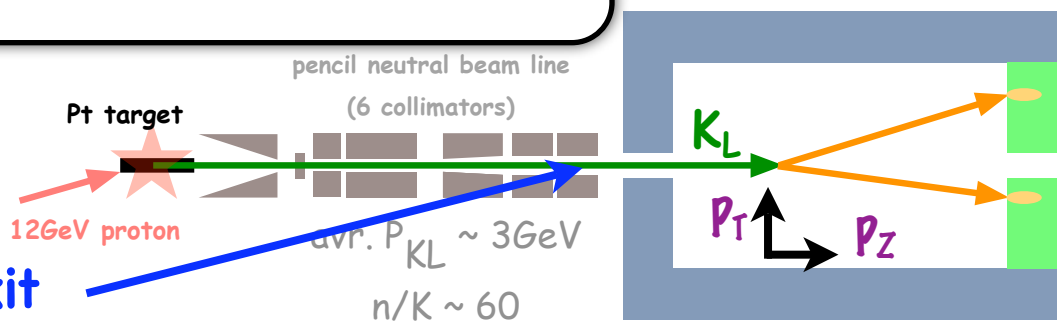
The photon vetoes are relaxed in order to boost statistics.



$K \rightarrow \pi^0\pi^0\pi^0$

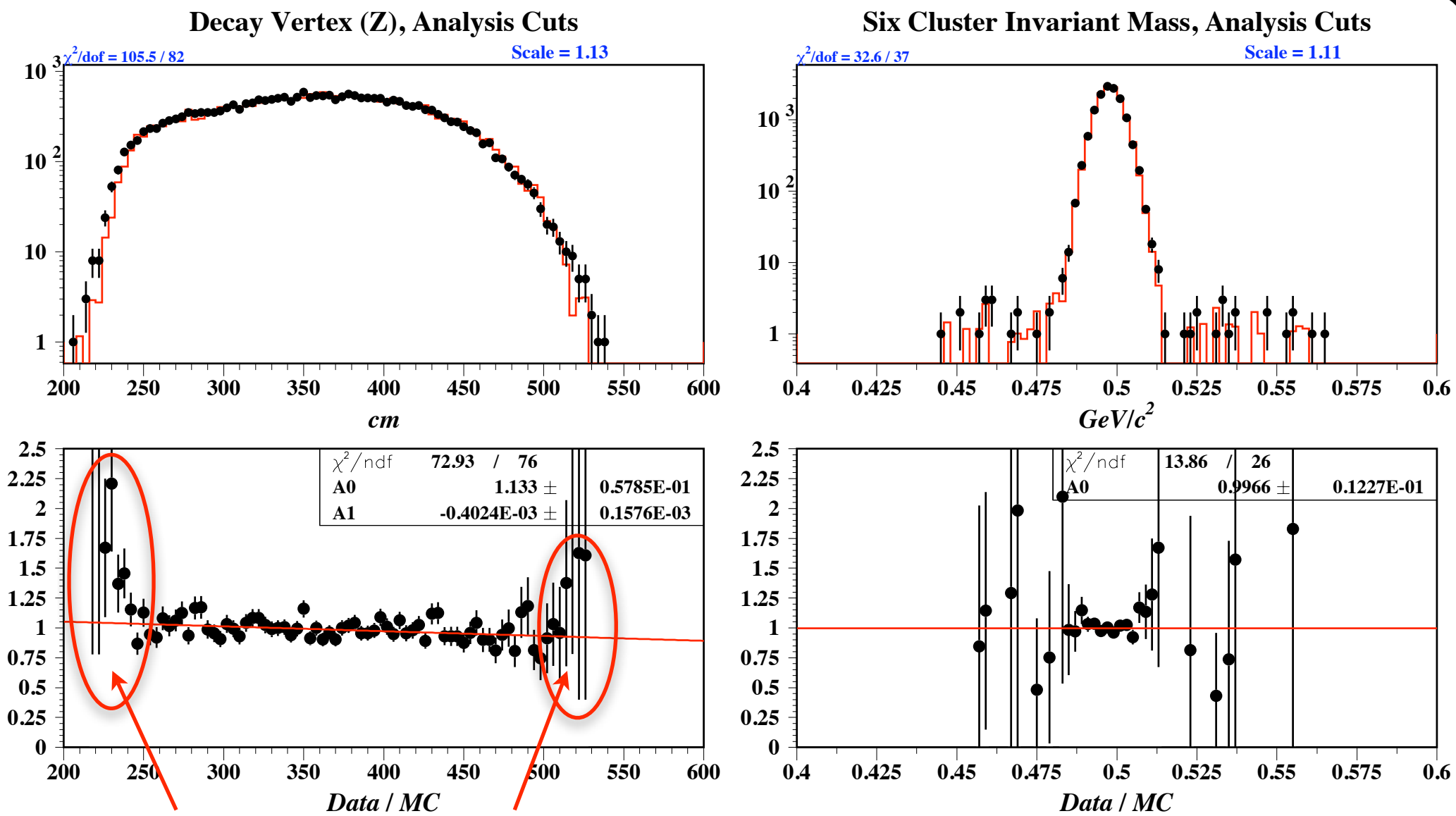






The photon vetoes are relaxed in order to boost statistics.

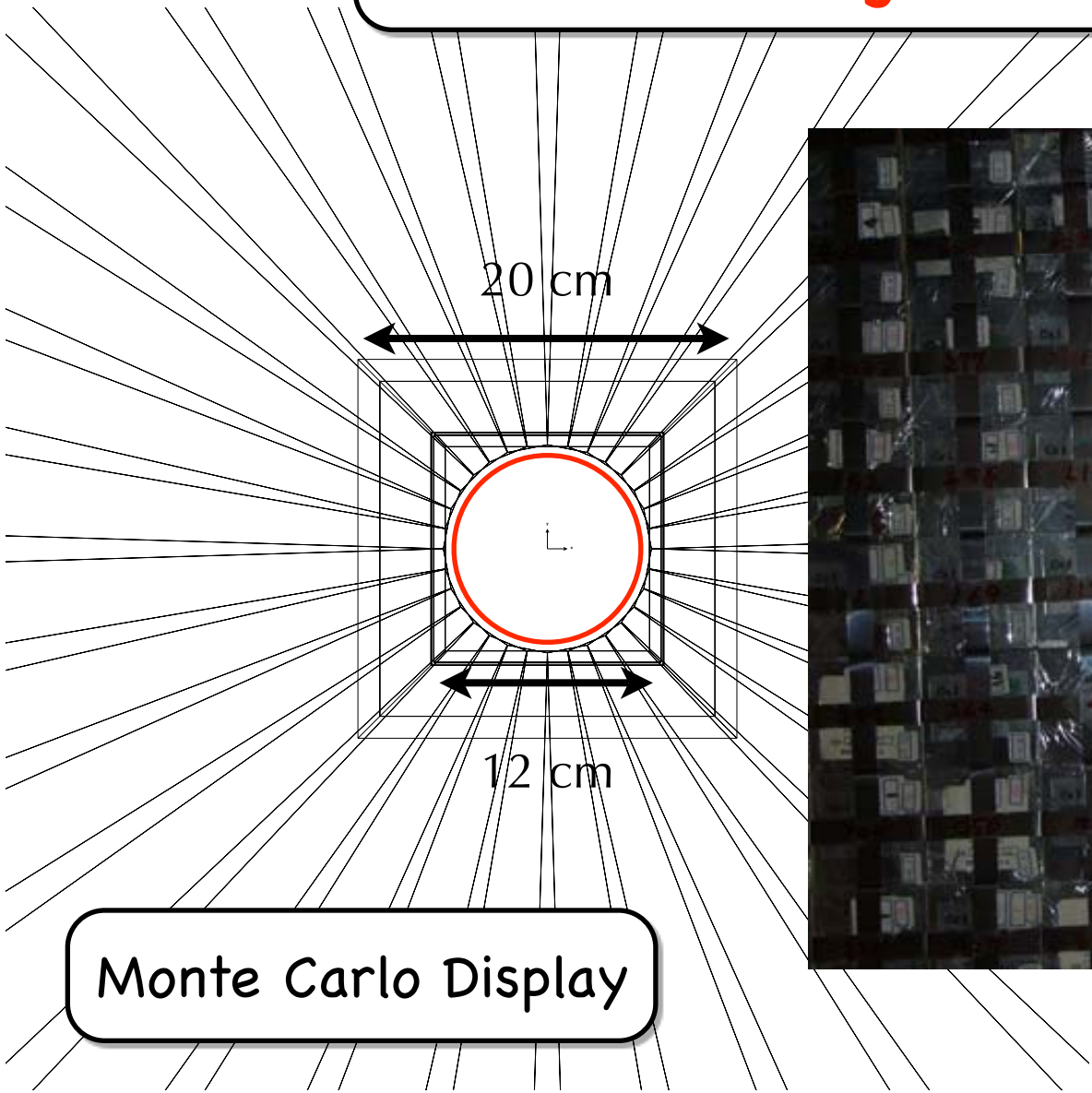
The CsI veto function introduces a 0.4%/cm slope in Z - this is our dominant systematic error.



Slight MC geometry mis-matches - we have to simply eat the associated systematics.

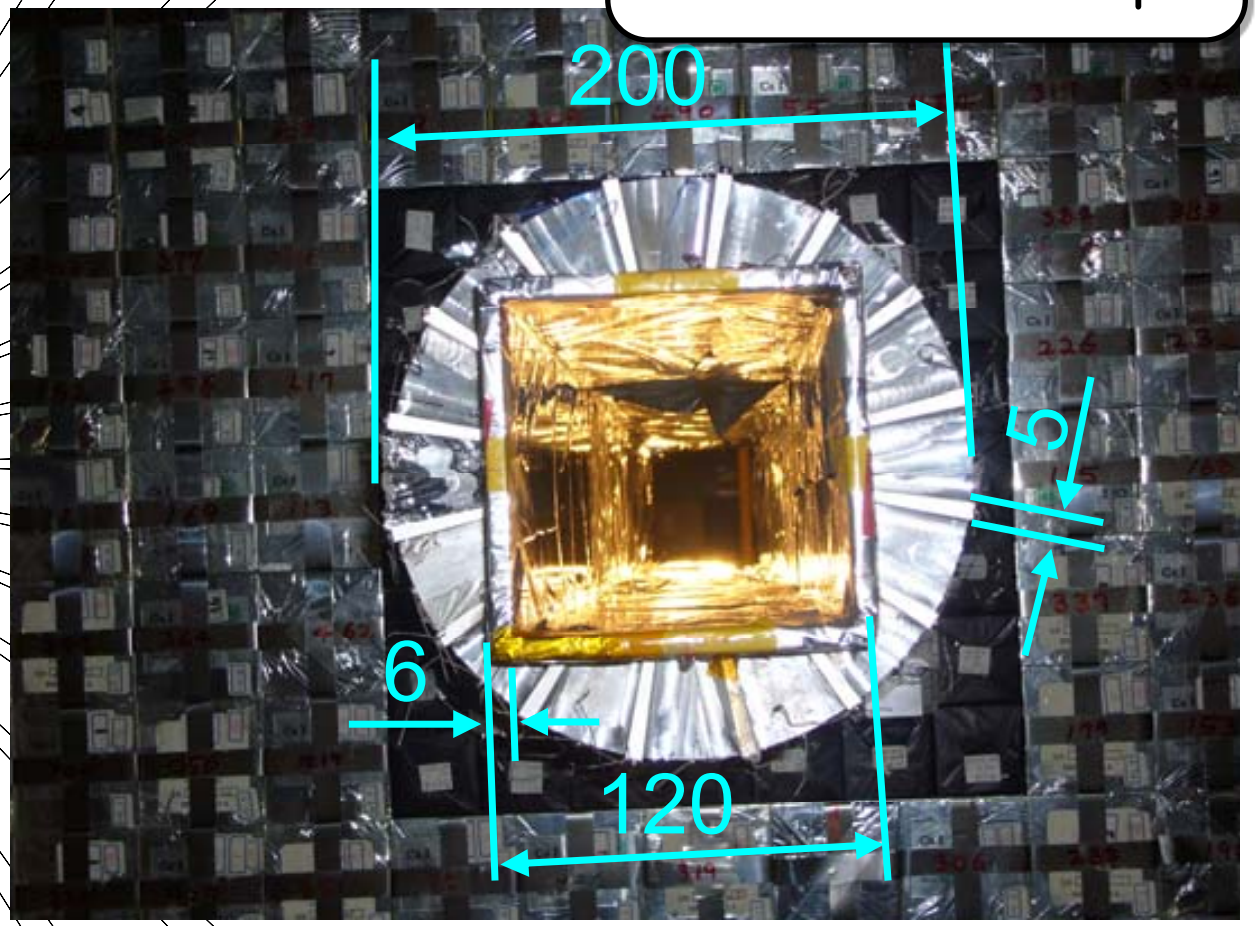
$\sigma_{Data}/\sigma_{MC} \approx 1.01$

The CV Beam-region Overlap



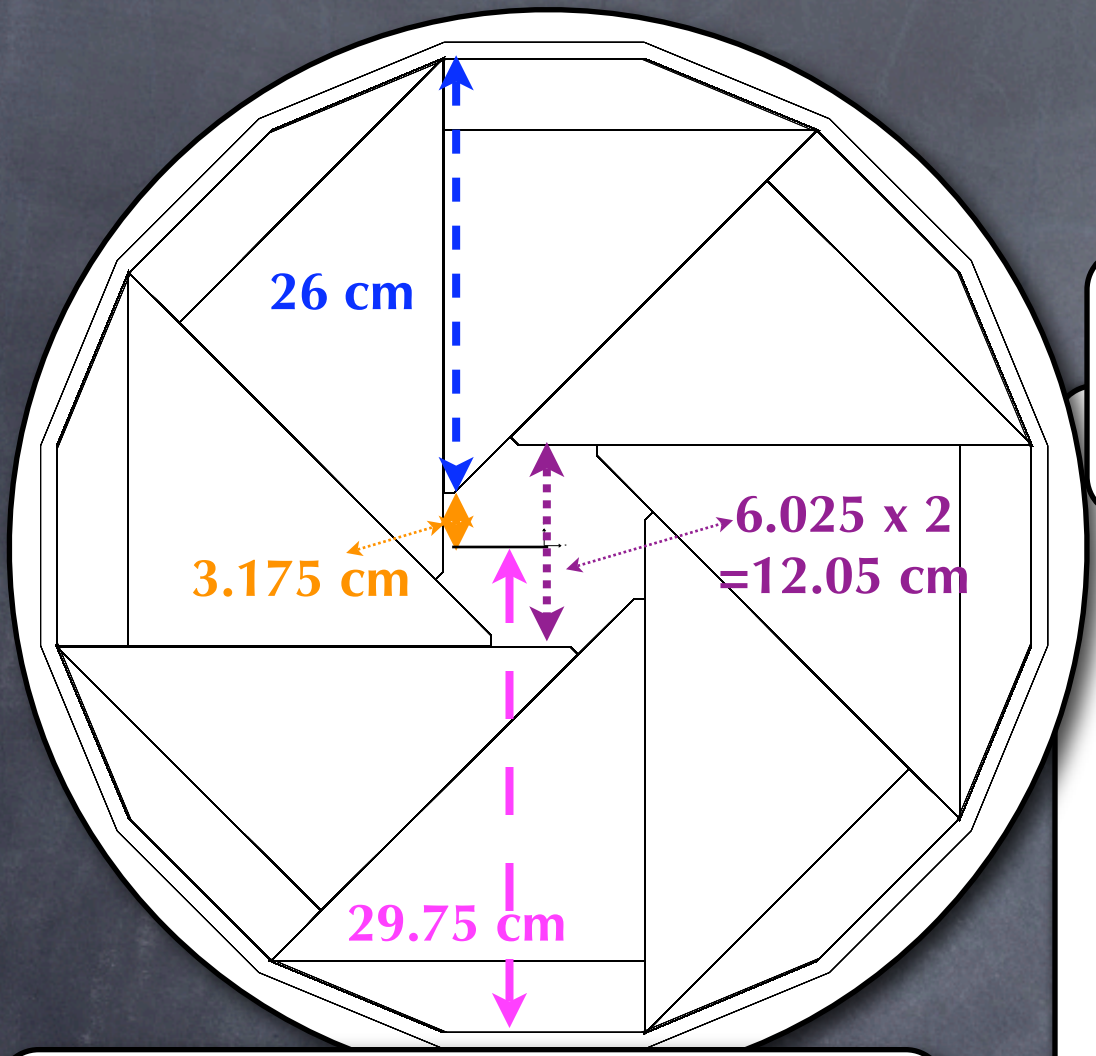
Monte Carlo Display

The CsI Beam Pipe

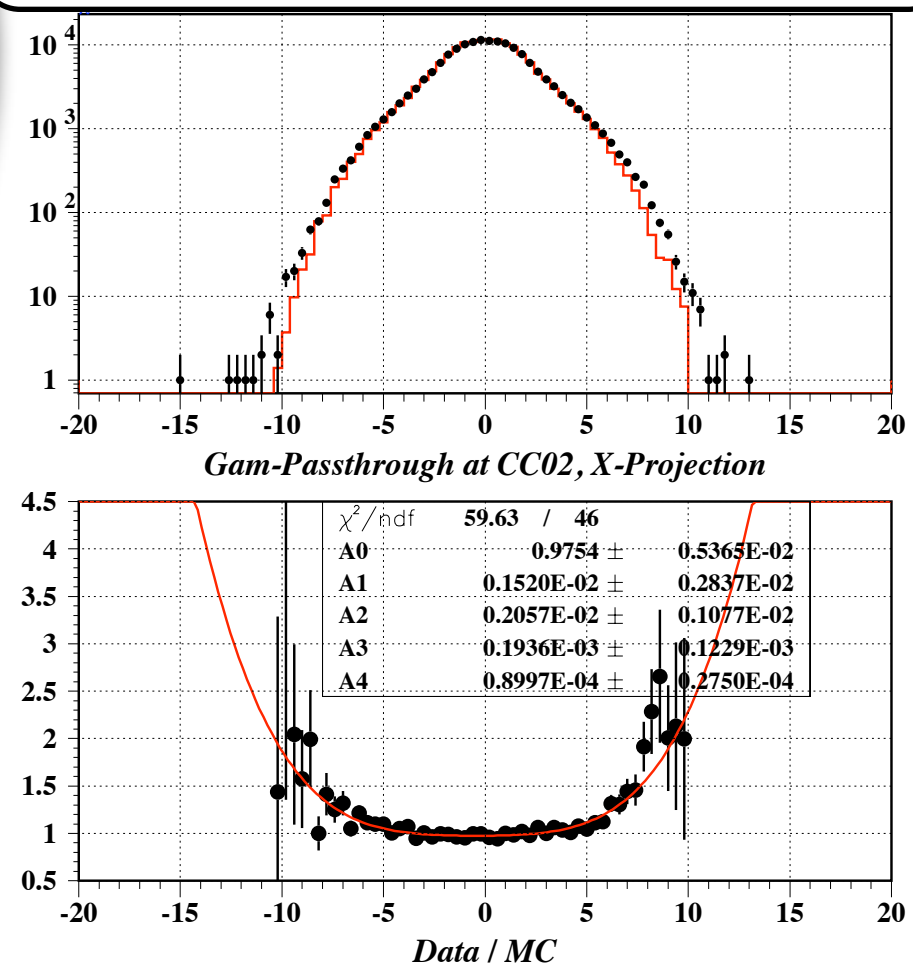


This overlap created an interaction point that lead to a peak in the MC.

Beam Collar Counter 2 "CC02"

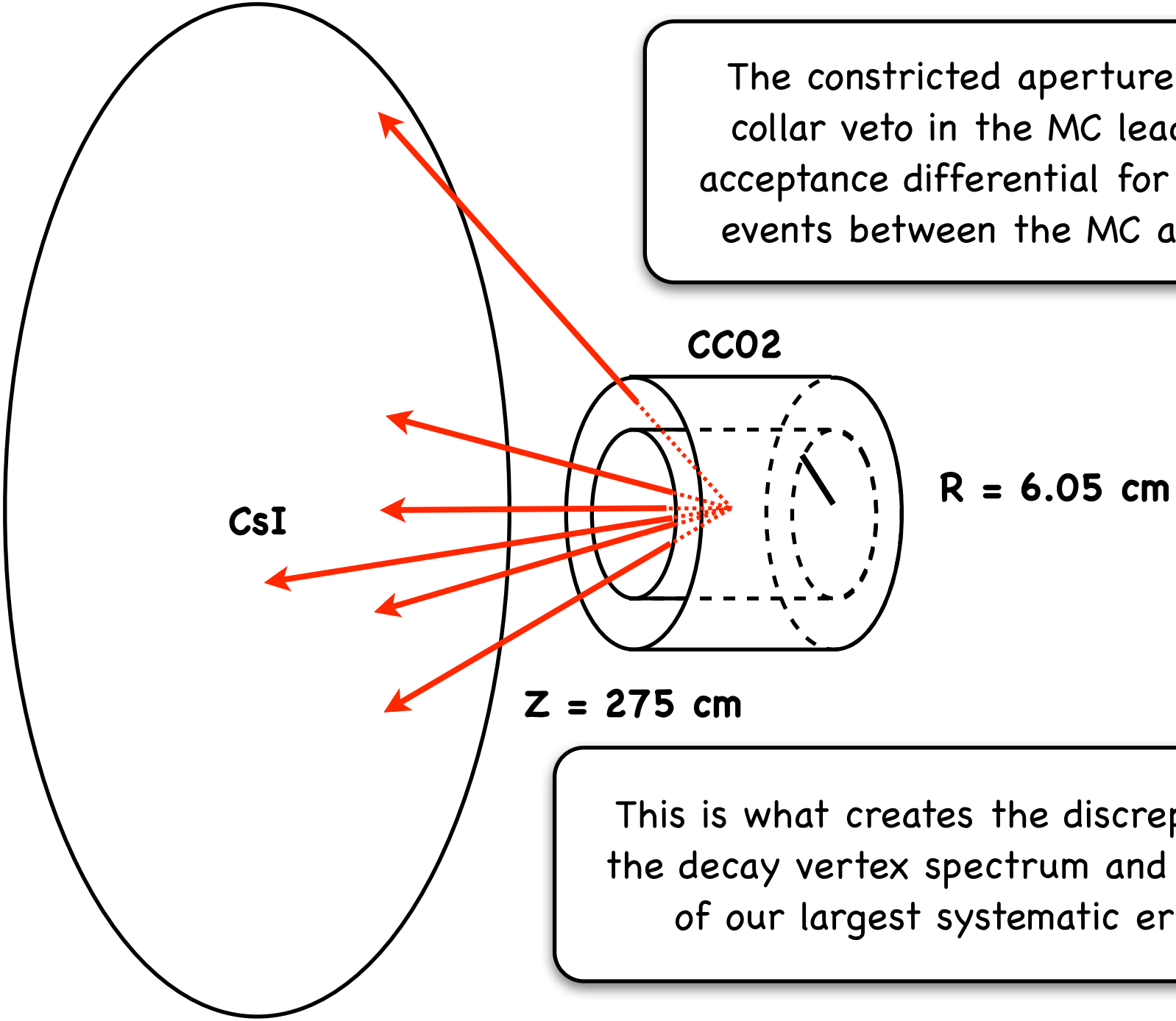


Six Cluster Data / ππ MC
Photon "Pass-through" Position @ CC02.
Kinematic cuts & K-Z < 275 cm.

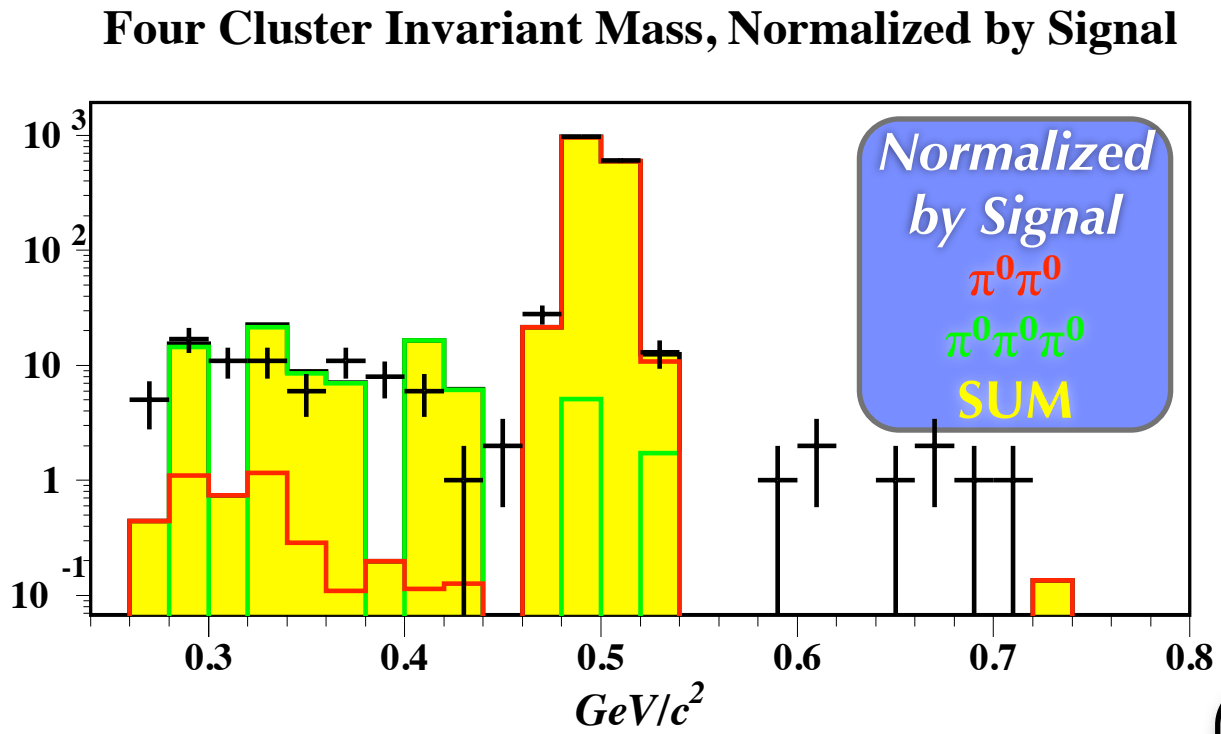


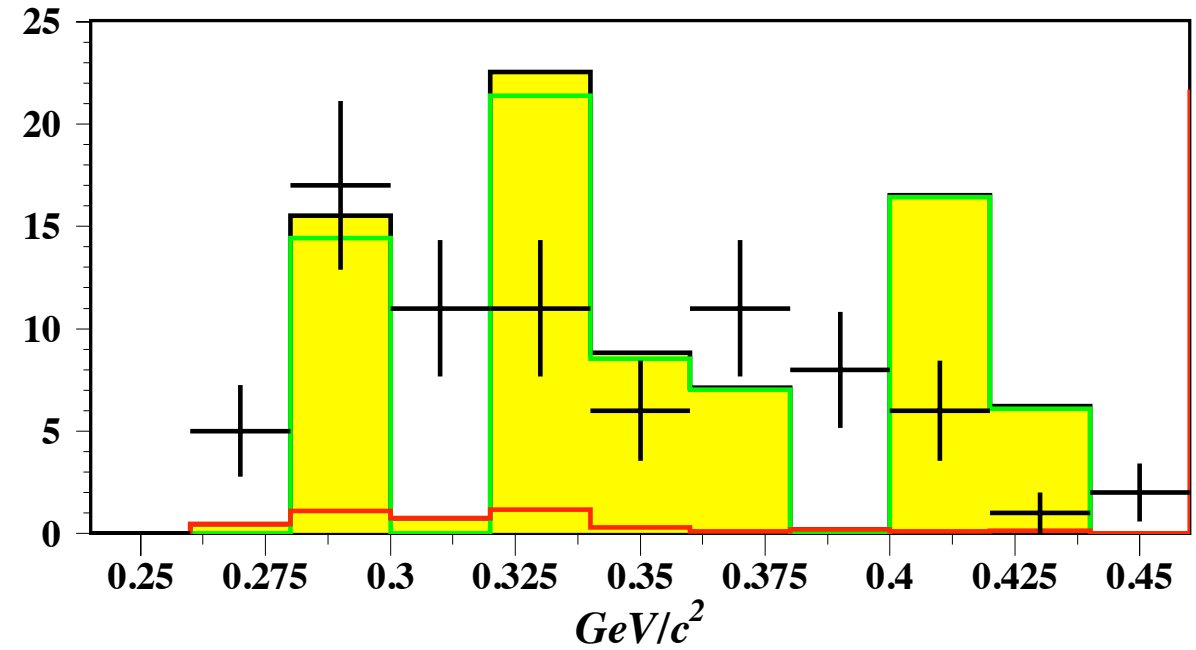
The diameter used for placement in the MC was 12.05 cm. It should have been 12.1 cm (true physical size), but may have been shrunk in order to minimize overlap with the can. The net change is about 1% in the total area.

The constricted aperture for the collar veto in the MC leads to an acceptance differential for upstream events between the MC and Data.



This is what creates the discrepancy in the decay vertex spectrum and it is one of our largest systematic errors.





The low-mass tail $\pi^0\pi^0\pi^0$ contribution is dominated by single-fusion + 1 "missing" photon events. Even though we suffer from low statistics for our $\pi^0\pi^0\pi^0$ MC, we are able to reproduce the numerical sum of events in the tail.

Low-Mass Region (Below 470 MeV)

3π Weight = 44.9711
Scale 2π = 0.104066
Scale 3π = 4.67996
Raw Data Sum = 79
Raw 2π Sum = 50.8574
Raw 3π Sum = 15.7862

Data: 79
2π: $(50.6 \pm 7.13)*0.1 = 5.29 \pm 0.74$
3π: $(15.8 \pm 3.97)*4.7 = 73.9 \pm 18.6$
$79 - 79.171 \approx 0$

Systematic Error

- Compute the fractional acceptance difference (F) between MC and Data. This is the exclusive acceptance of Data, minus the acceptance of the MC, divided by the acceptance of Data. It is a measure of the difference of the exclusive acceptance of the MC from Data as a fraction of the acceptance in Data.
- Weight the fractional acceptance by the acceptance in Data (A), then add all components in quadrature.
  - We weight by the acceptance in Data to keep less important cuts from skewing the results.
- Finally, normalize by the sum of the inverse squares of the acceptance in Data, and then take the square root.

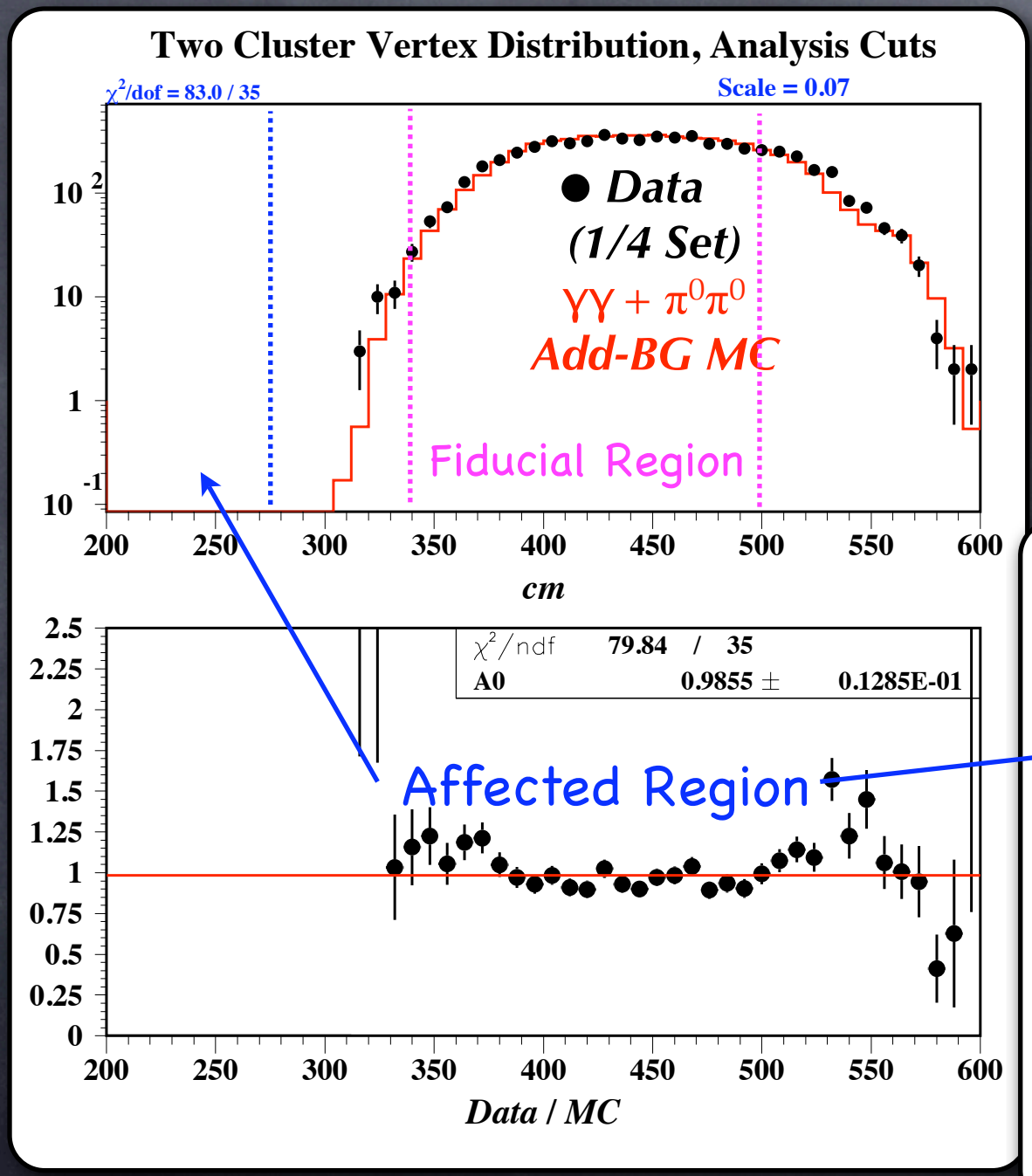
$$\text{Syst. Err.}^2 = \frac{\sum_{i=\text{All Cuts}} (F_i/A_i)^2}{\sum_{i=\text{All Cuts}} (1.0/A_i)^2}$$

Systematic Errors (Normalization Mode - $\pi^0\pi^0$)

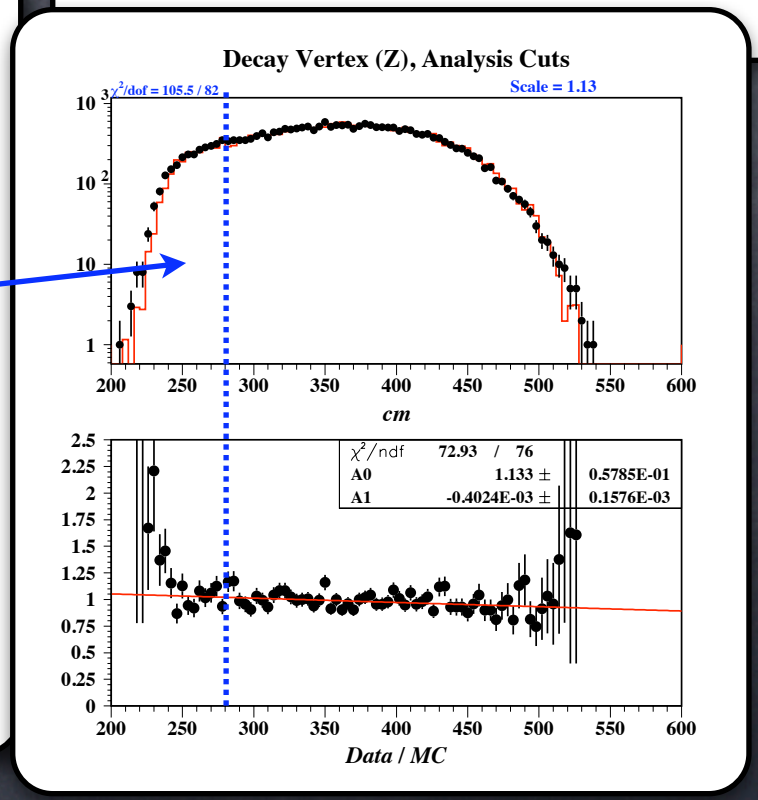
CsI Veto	6.1%
Decay Vertex (Z) Spectrum	2.3%
Decay Vertex (Radial) Spectrum	1.8%
Charged Veto	1.3%
Fusion Neural-Network	1.3%
Photon Hit Position (CsI Position)	1.2%
23 Others (Total)	2.9%
TOTAL (In Quadrature)	7.7%

Mode	Signal Events (Full Data Set)	Flux (w/ systematic errors)	Discrepancy $(X - \pi^0\pi^0)/\pi^0\pi^0$
$K \rightarrow \gamma\gamma$	20,685 (Signal: 340-500 Z) ($\pi^0\pi^0$ contamination is at the 10^{-4} level → Neglected.)	$(5.41 \pm 0.37) \times 10^9$	5.0%
$K \rightarrow \pi^0\pi^0$	1494.9 (1500 - 5.1) (Signal: 497-3x5.2 MeV to 497 + 3x5.2 MeV) ($\pi^0\pi^0\pi^0$ contribution ~5.1±4.8 events.)	$(5.13 \pm 0.40) \times 10^9$	0%
$K \rightarrow \pi^0\pi^0\pi^0$	70,054 (Signal: 497-3x5.2 MeV to 497 + 3x5.2 MeV) (Background contamination is at the 10^{-4} level → Neglected.)	$(5.02 \pm 0.35) \times 10^9$	-1.9%

Why is K→γγ so different?



The aperture mis-match at CC02 leads to an acceptance differential for data and MC for ππ and πππ modes that is understated for γγ.



core n / K_L

- n / K ~ 7 (T_n > 1GeV); << 40@E391a

  due to large targeting angle (16deg)

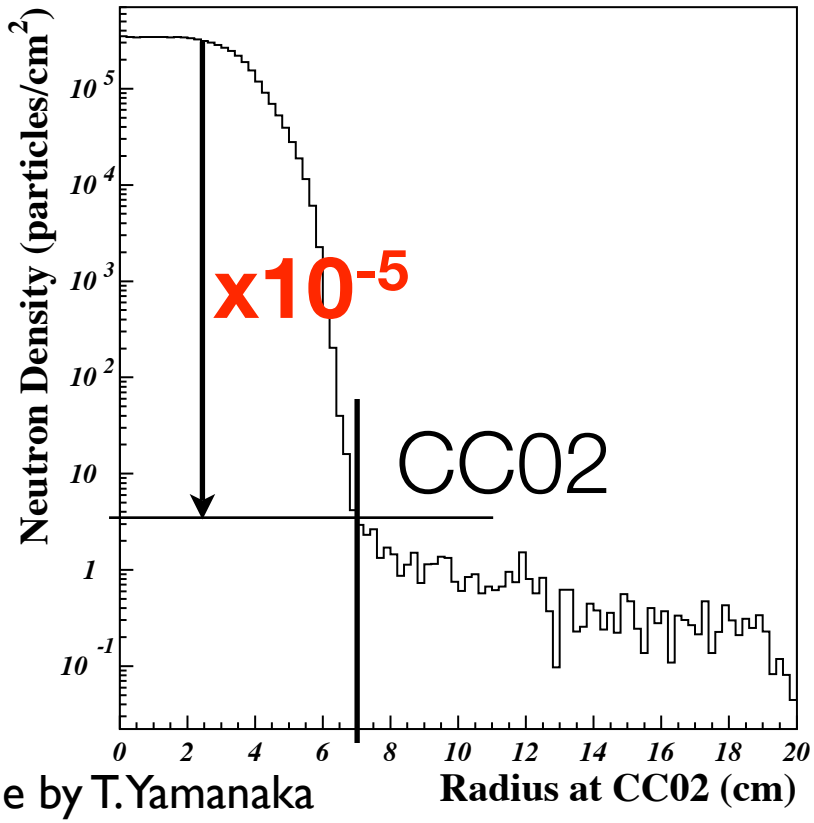
particles	detailed simulation	proposal [1]
K_L	4.6×10^6	8.1×10^6
n ($E_n > 0.1$GeV)	1.4×10^8	3.4×10^8
n ($E_n > 1.0$GeV)	3.0×10^7	6.9×10^7
γ (> 2MeV)	0.9×10^8	4.5×10^8
γ (> 10MeV)	1.3×10^7	6.1×10^7
γ (> 100MeV)	$< 10^6$	$< 10^6$

Slide by T. Yamanaka

Geant4 simulation for halo neutrons

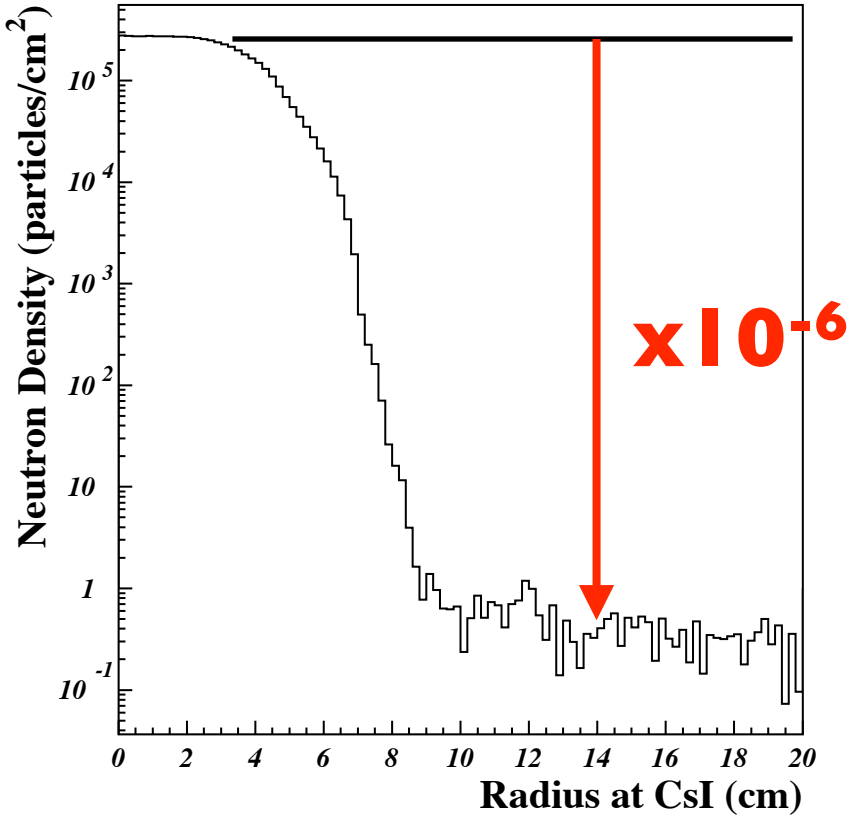
- 2×10^4 halo neutrons/pulse (2E14)

Neutron profile at CC02



Slide by T. Yamanaka

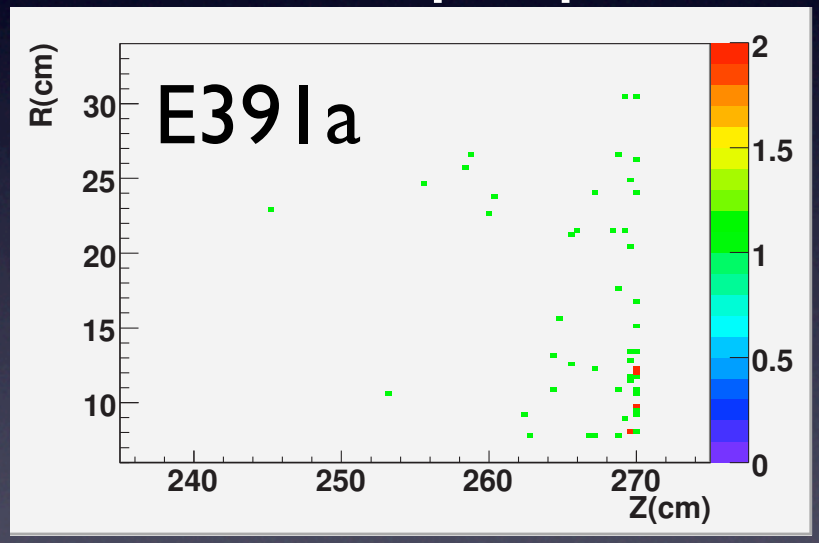
Neutron profile at the CsI

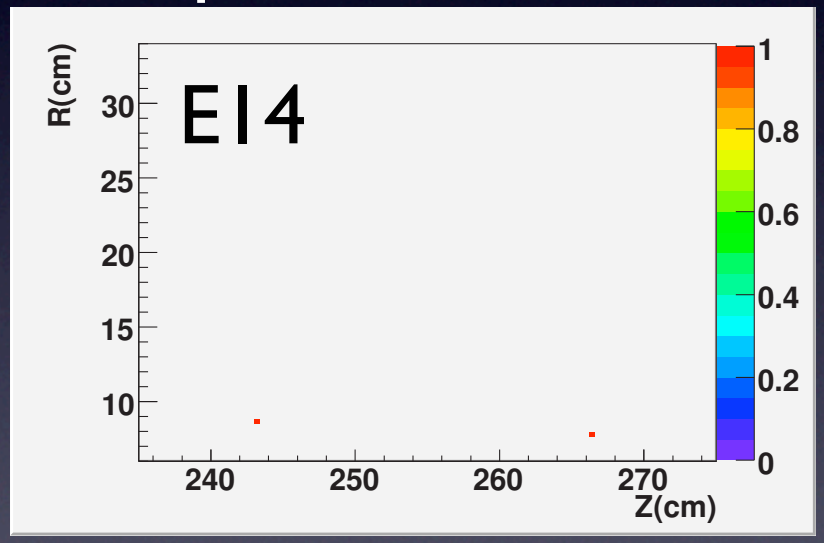


NCC

- Suppresses and vetoes pi0 bkg

pi0 prouduction points





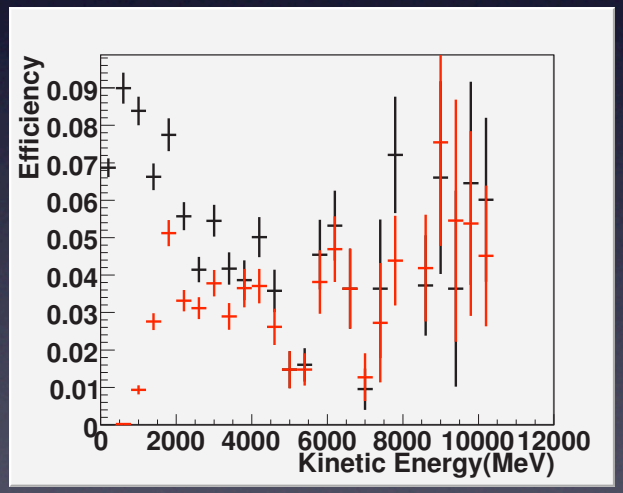
Counter	Generated	π^0 in CAL	After veto	In the signal box
CC02	10^8	6964	55	0.06
NCC2	10^8	869	2	0.001

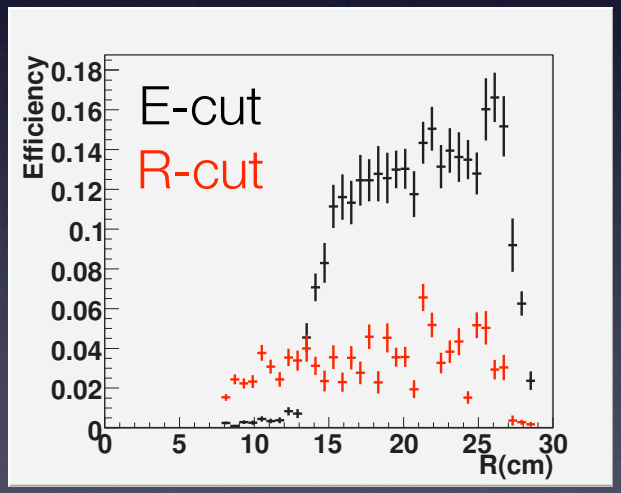
Slide by T. Yamanaka

NCC

- can measure halo neutron profile and energy spectrum

Neutron detection efficiency



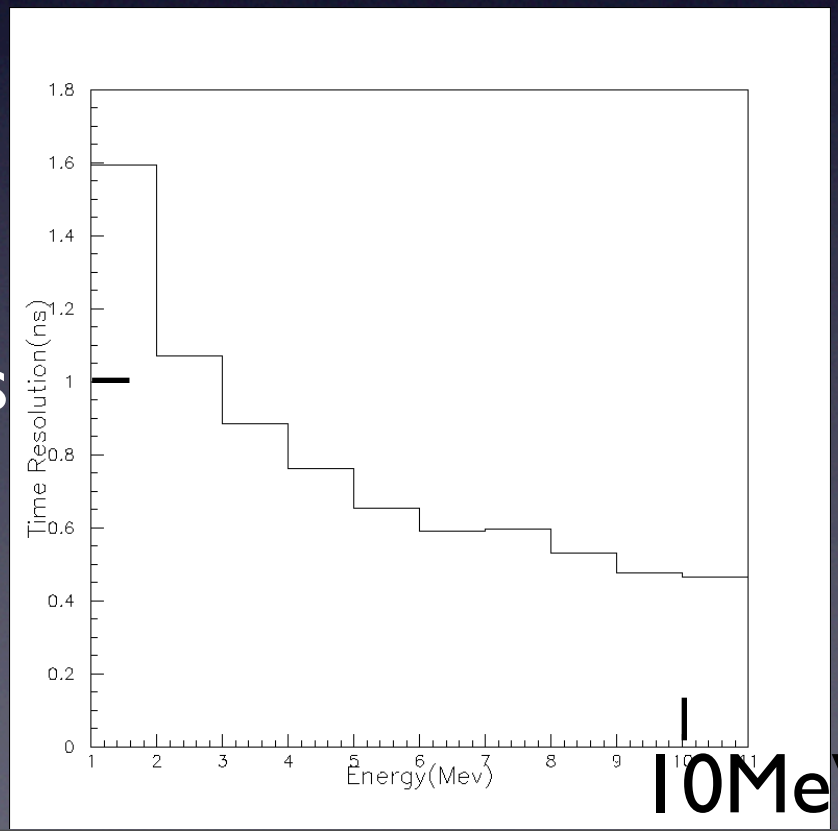


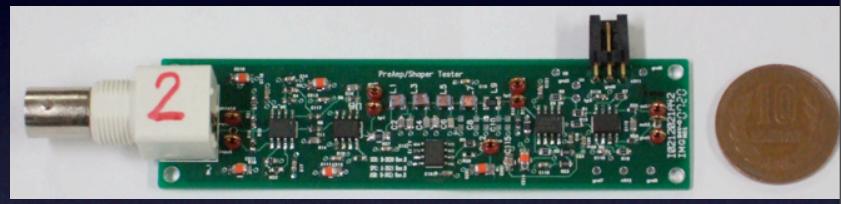
Cut set	ϵ_n	ϵ_K	Ratio (ϵ_n/ϵ_K)	K_L contamination
E-cut	6.3%	0.1%	63	5.4%
R-cut	2.9%	0.08%	37	9.2%

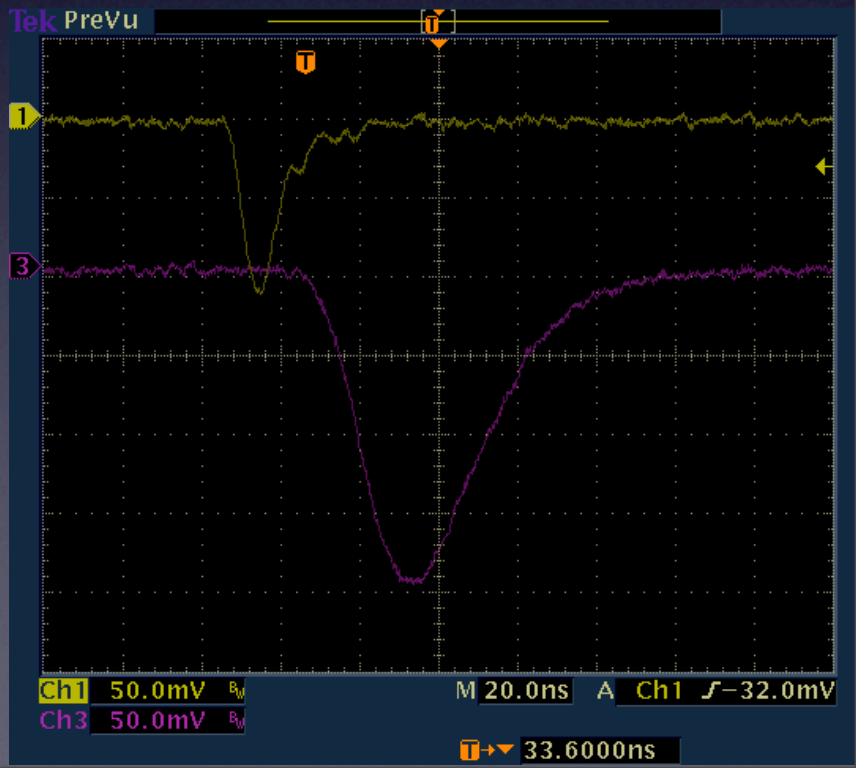
Slide by T. Yamanaka

solution = Gaussian filter + 125MHz 14bit FADC

- Δt <0.5ns for E>10MeV







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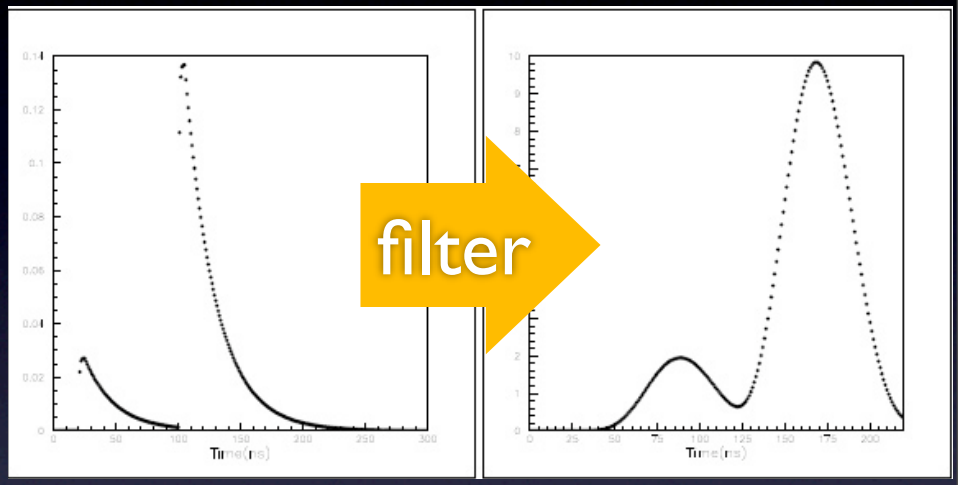
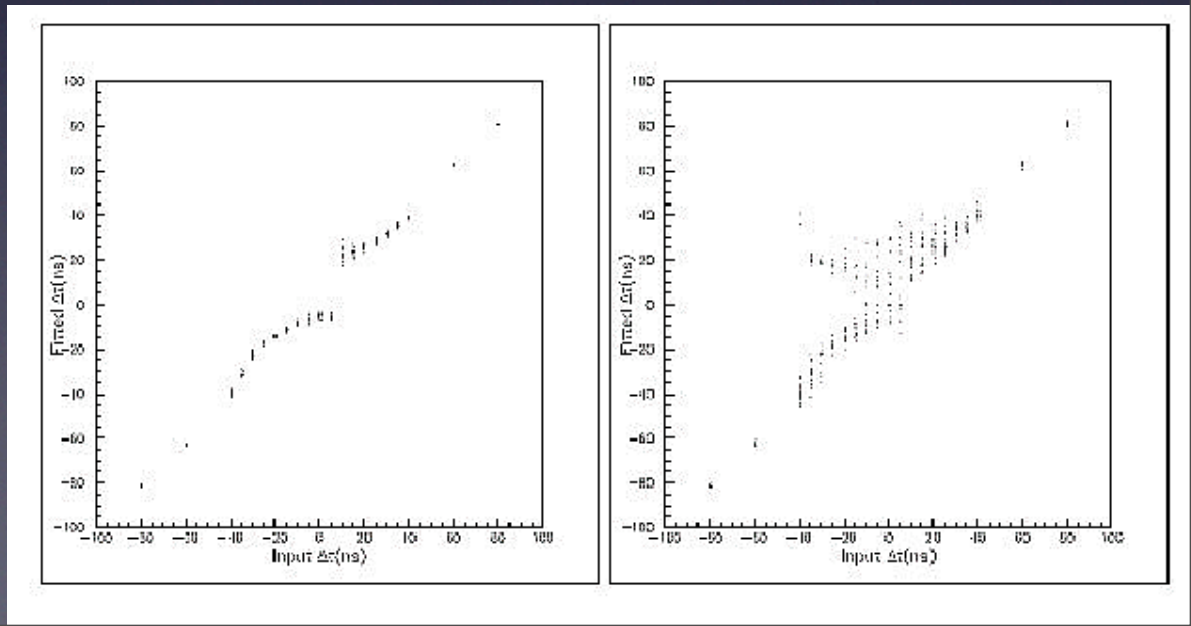
Double pulse resolution

- Can separate >20ns apart 5:1 pulses
- More studies underway



200MeV + 40MeV

10MeV + 2MeV



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