Search for the decay $K_L \to \pi^0 \nu\bar{\nu}$ at KEK-PS E391a

JPS 2007 Autumn meeting
Toshi SUMIDA

Physics motivations

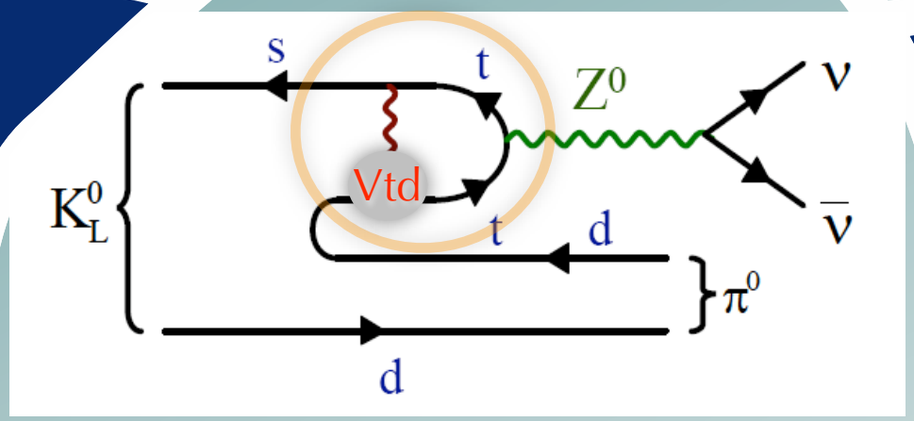
- $K_L \rightarrow \pi^0 \nu\nu$
  - FCNC process with $\Delta S = 1$
  - Direct CP violation
- Measurement of the branching ratio
  - $A(K_L \rightarrow \pi^0 \nu\nu) \propto Vtd^* Vts - Vts^* Vtd$

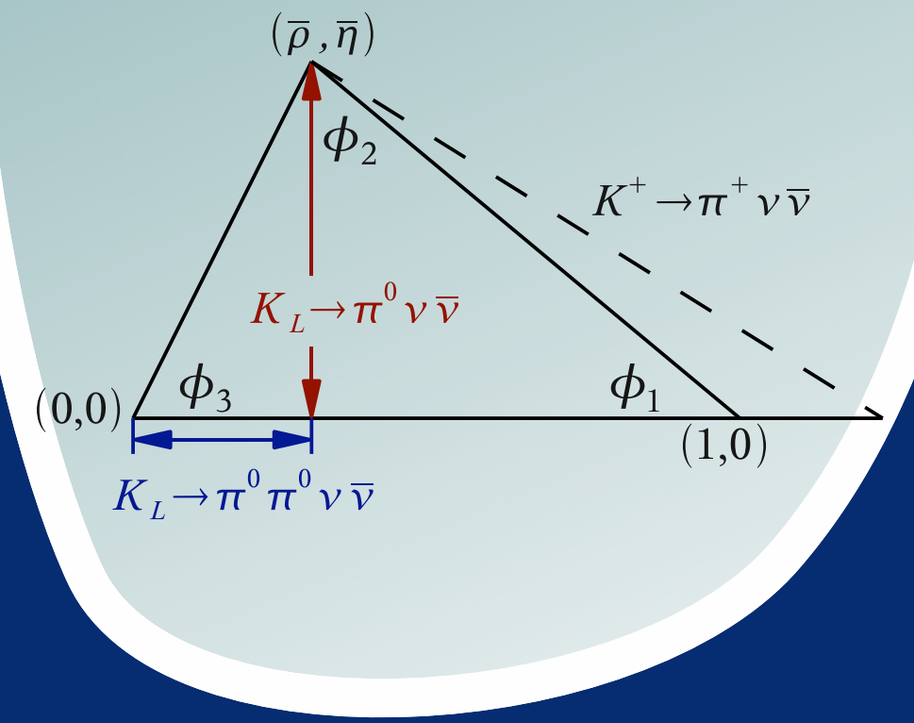
    $= 2 \times Vts \times Im(Vtd) \propto \eta$

    $\Rightarrow \; Br(K_L \rightarrow \pi^0 \nu\nu) \propto \eta^2$

    : Direct measurement of η
  - small theoretical uncertainty
    - $Br \rightarrow \eta$: σ ~1-2%
  - $Br(K_L \rightarrow \pi^0 \nu\nu)_{SM} \sim (2.8 \pm 0.4) \times 10^{-11}$

- Unitary triangle by Kaon
  - consistency between K^0 and K^+
  - comparison with B
- Loop in the diagram (EW penguin)
  - The probe for new physics





The E391a experiment

- 11 institutes, ~50 members
  - Dept. of Physics, Saga Univ.
  - Dept. of Physics, Pusan National Univ.
  - Joint Institute for Nuclear Research
  - Dept. of Physics, National Taiwan Univ.
  - Dept. of Physics, Osaka Univ.
  - High Energy Accelerator Research Organization (KEK)
  - Enrico Fermi Institute, Univ. of Chicago
  - National Defense Academy
  - Research Center for Nuclear Physics, Osaka Univ.
  - Dept. of Physics, Kyoto Univ.
  - Dept. of Physics, Yamagata Univ.
- At KEK 12GeV PS
- Run time
  - Run-I : Feb 2004 - Jul. 2004
    - new result published with 1week(10%) data
  - Run-II : Feb 2005 - Apr. 2005
  - Run-III : Nov. 2005 - Dec. 2005

Report the status of Run-II full data analysis

Principle of the experiment

- Detect 2γ from π^0 decay + no other particles

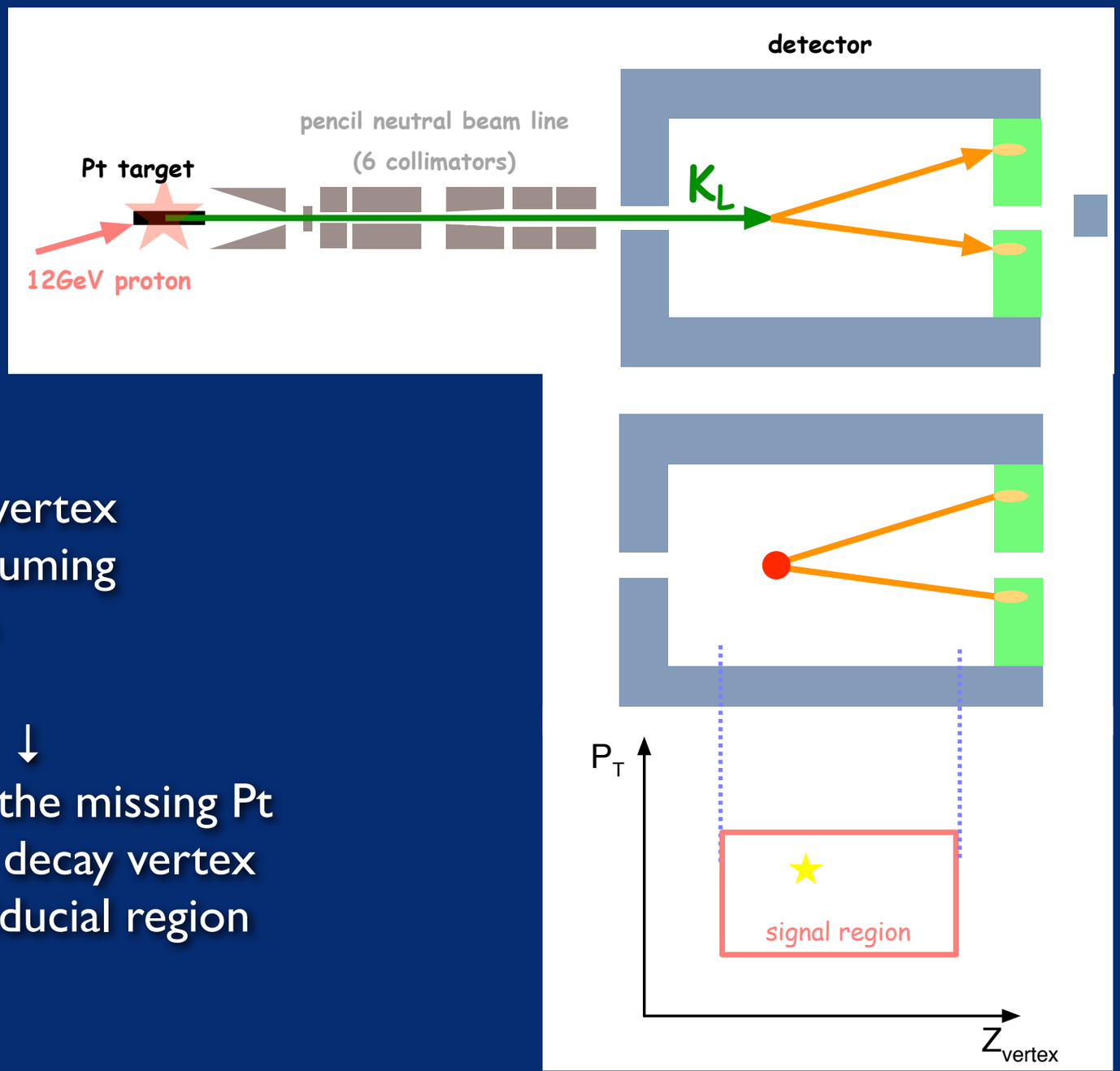
(1) measure the gamma hit position and energy with the CsI calorimeter

↓

(2) reconstruct decay vertex on the beamline assuming $M_{2\gamma} = M_{\pi 0}$

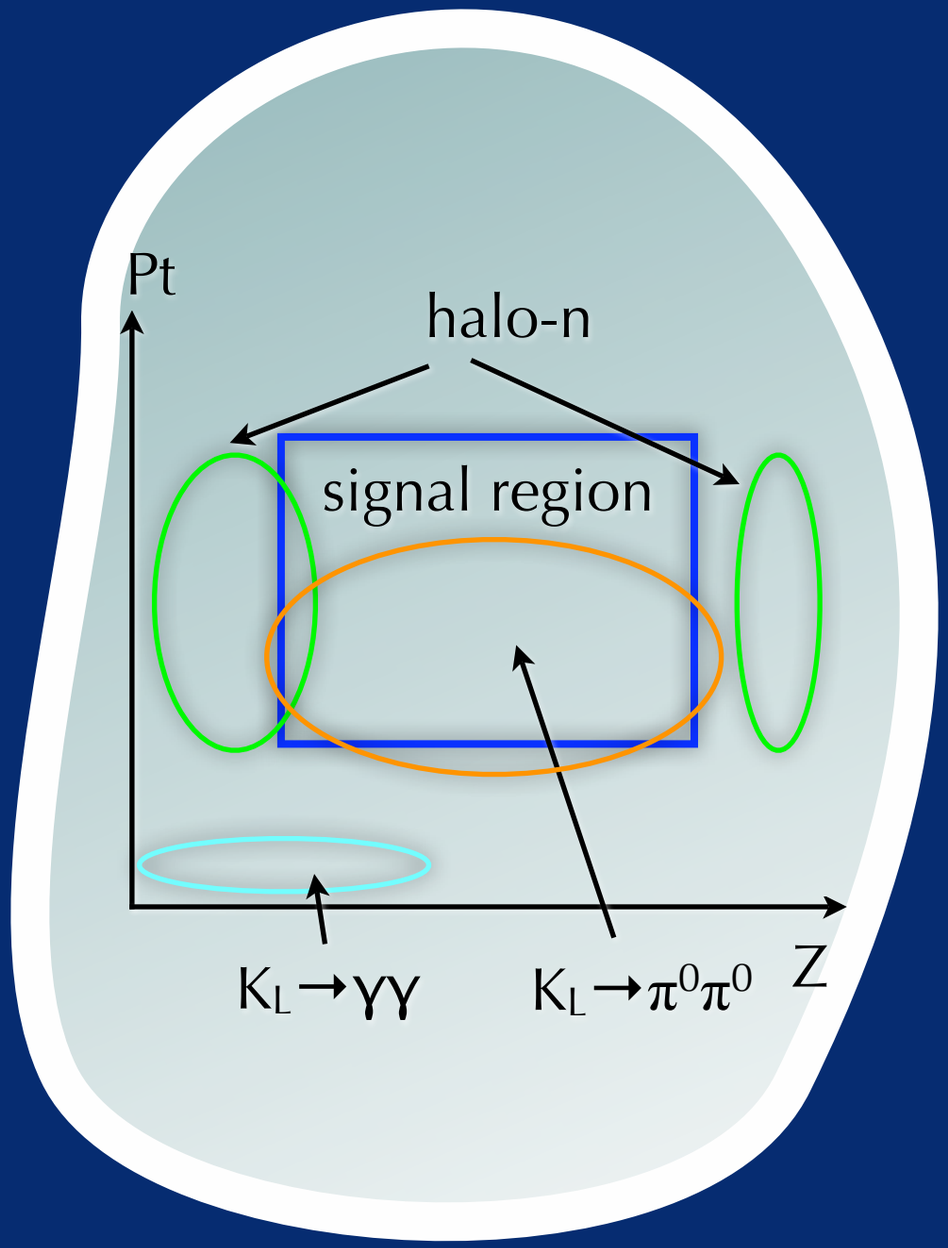
↓

(3) require the missing Pt and the decay vertex in the fiducial region



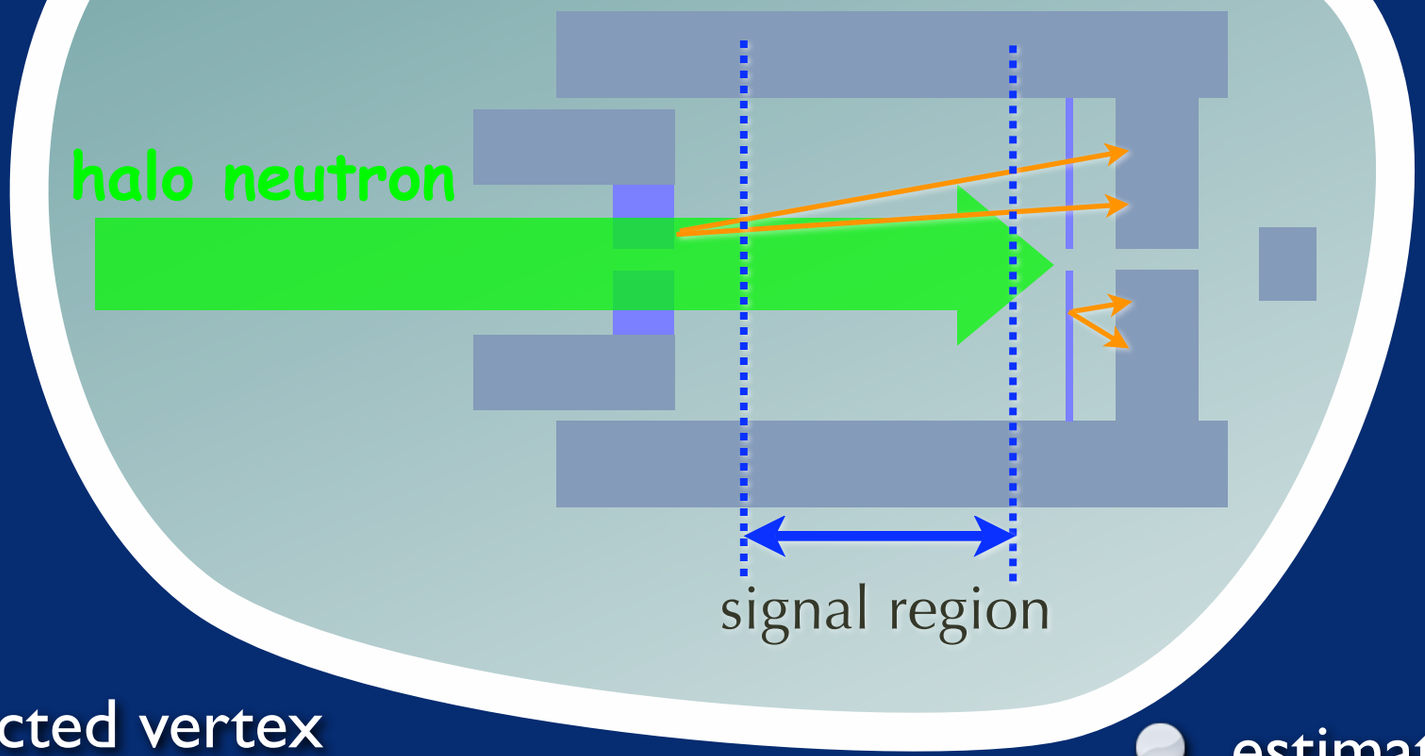
Backgrounds for $K_L \to \pi^0 \nu\bar{\nu}$

- KL decay
  - $K_L \to \gamma\gamma$
    - no extra particles
    - cut
      - Pt
      - acoplanarity angle
    - negligible
  - $K_L \to \pi^0\pi^0 \to 4\gamma$
    - 2 gamma missing
    - cut
      - veto counters
      - "fusion" of gammas
    - estimated to be 0.1±0.1 events
- π^0 production by halo neutrons
- others ??



Halo neutron background

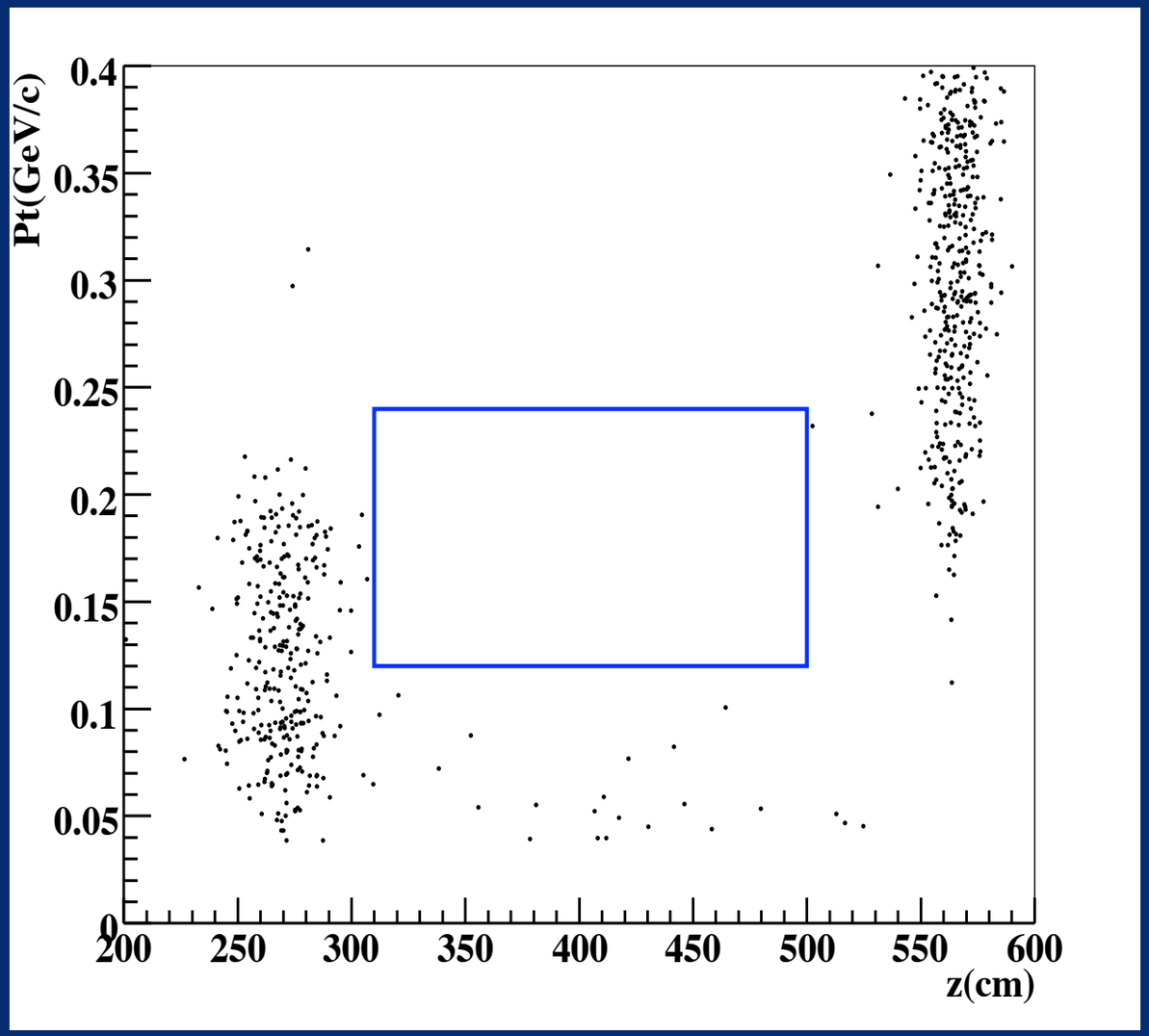
- π^0's from the interaction at some detectors



- cut
  - reconstructed vertex
  - vertices moved by shower leakage and additional energy deposition
- estimation
  - upstream (CC02)
    - special run
  - downstream (CV)
    - π0 generation in MC

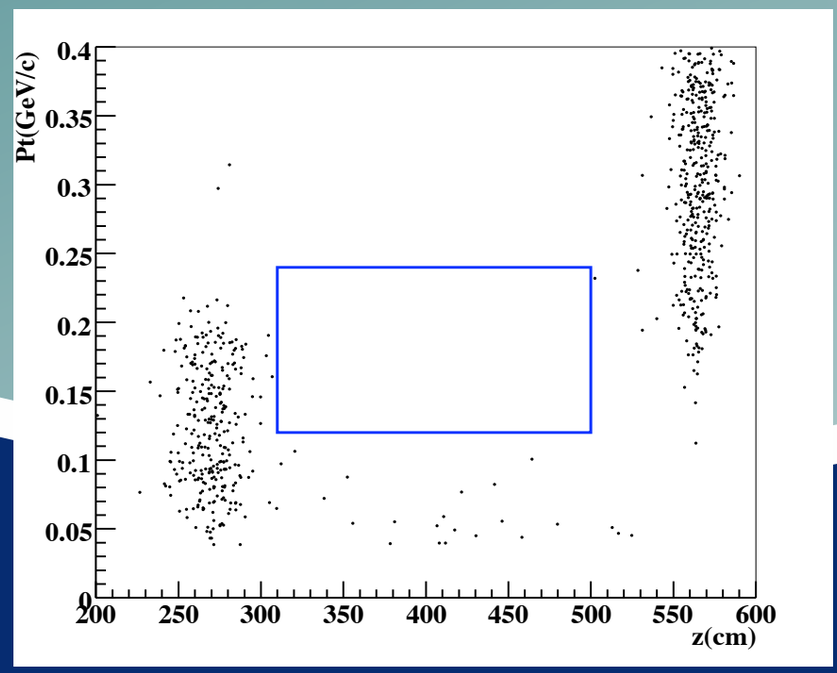
“Final” Plot

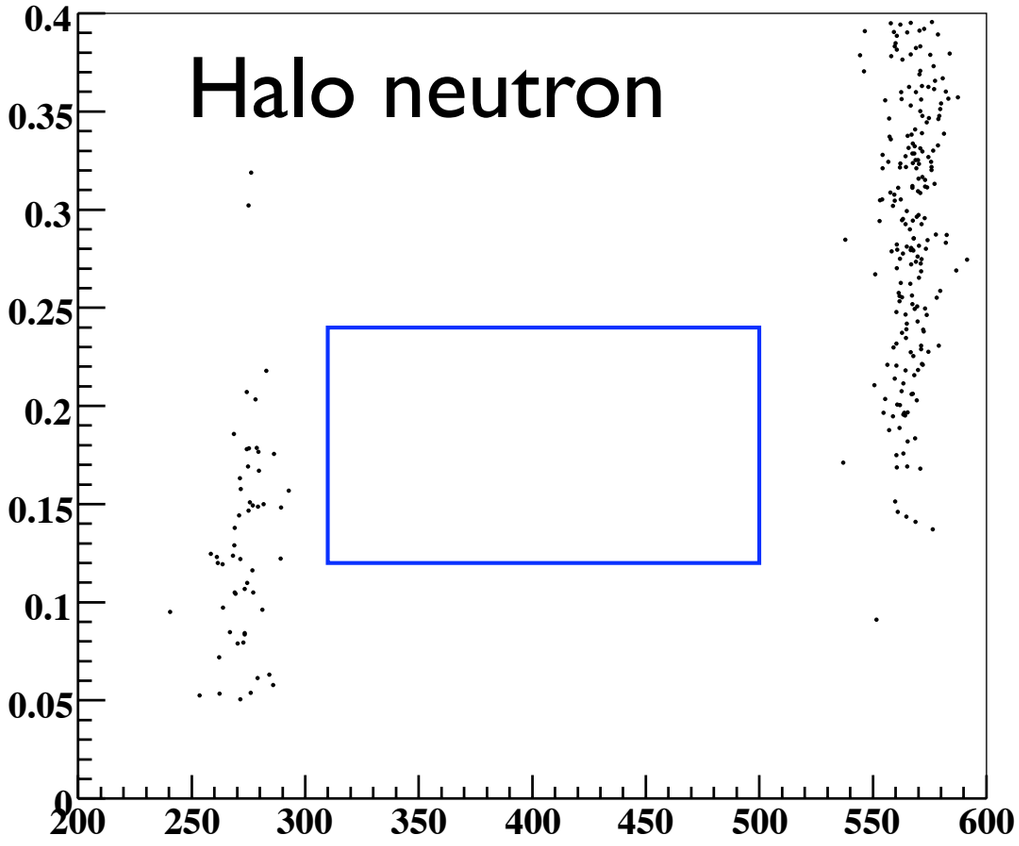
- cut
  - tight photon vetoes
  - gamma quality selection
- single π^0 event plot with the full data sample
  - “blind” signal region
    - z: 310-500 cm
    - Pt: 0.12-0.24 GeV/c
- remaining events
  - upstream
  - downstream
  - low Pt events

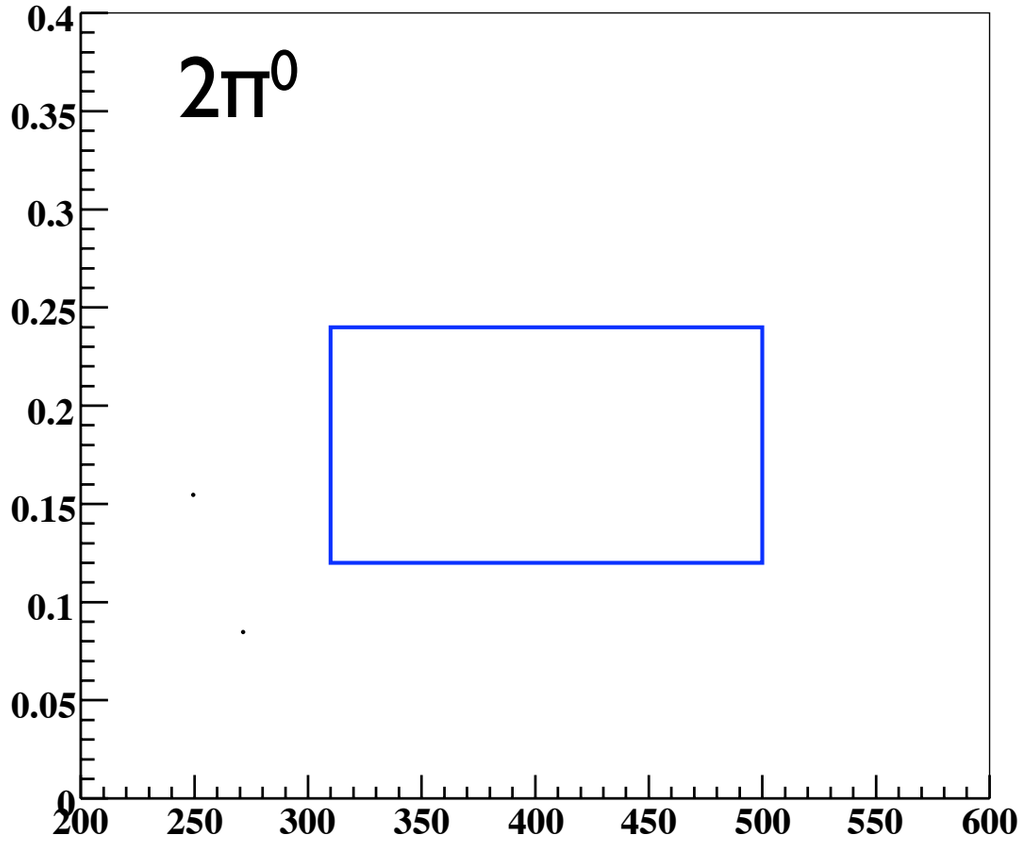


Low Pt events

- MC result for Halo neutrons, $K_L \rightarrow 2\pi^0$
  - no contribution
    ⇒ Low Pt events : another background

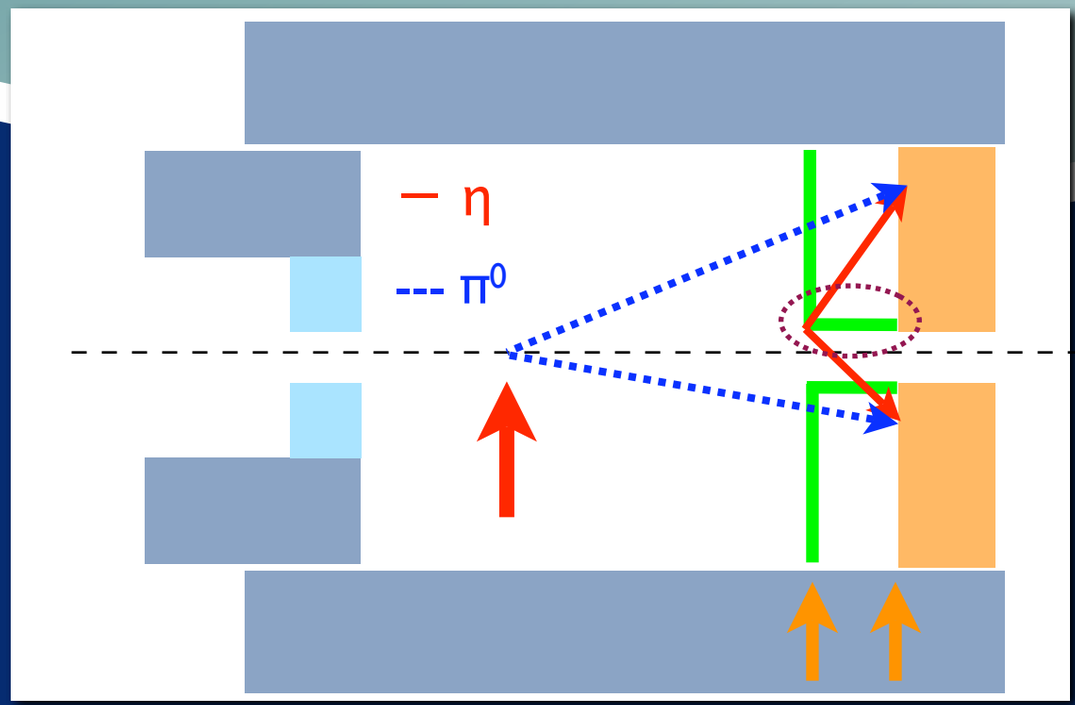


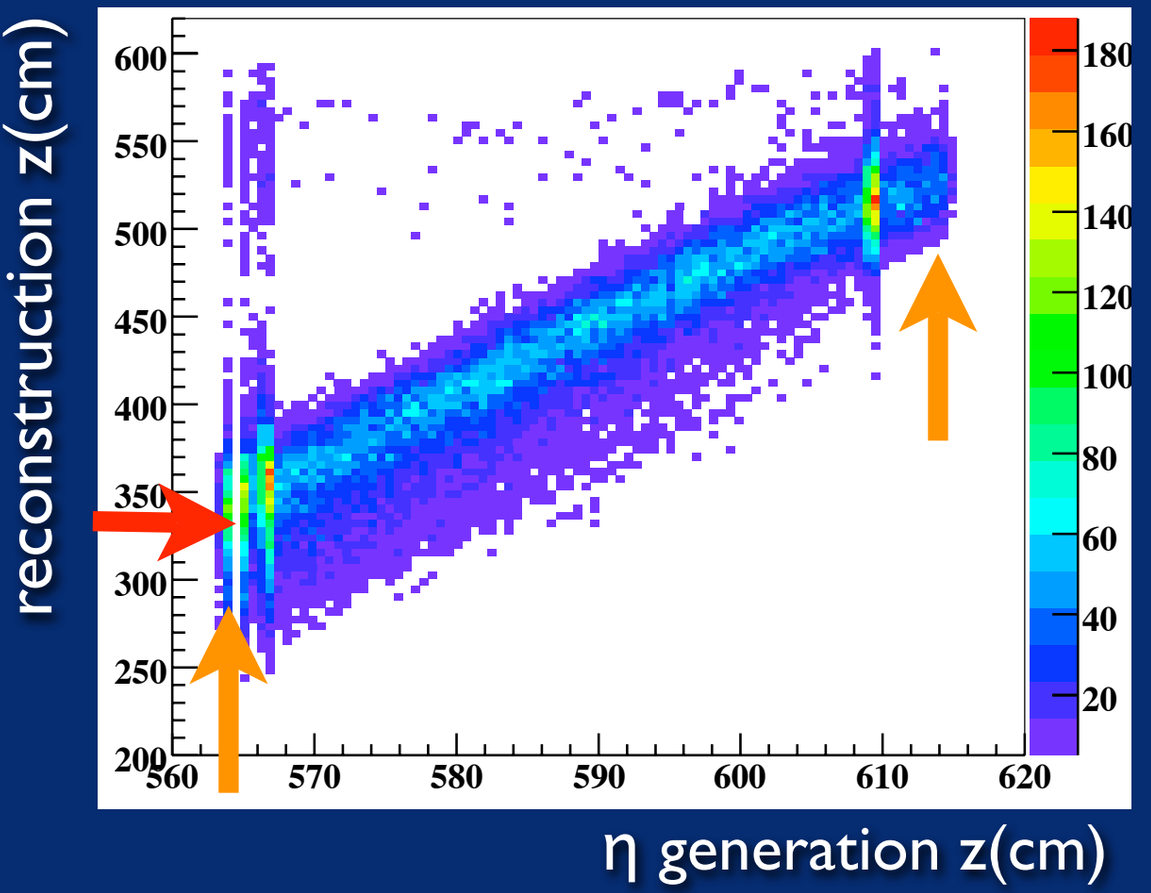




Eta production MC

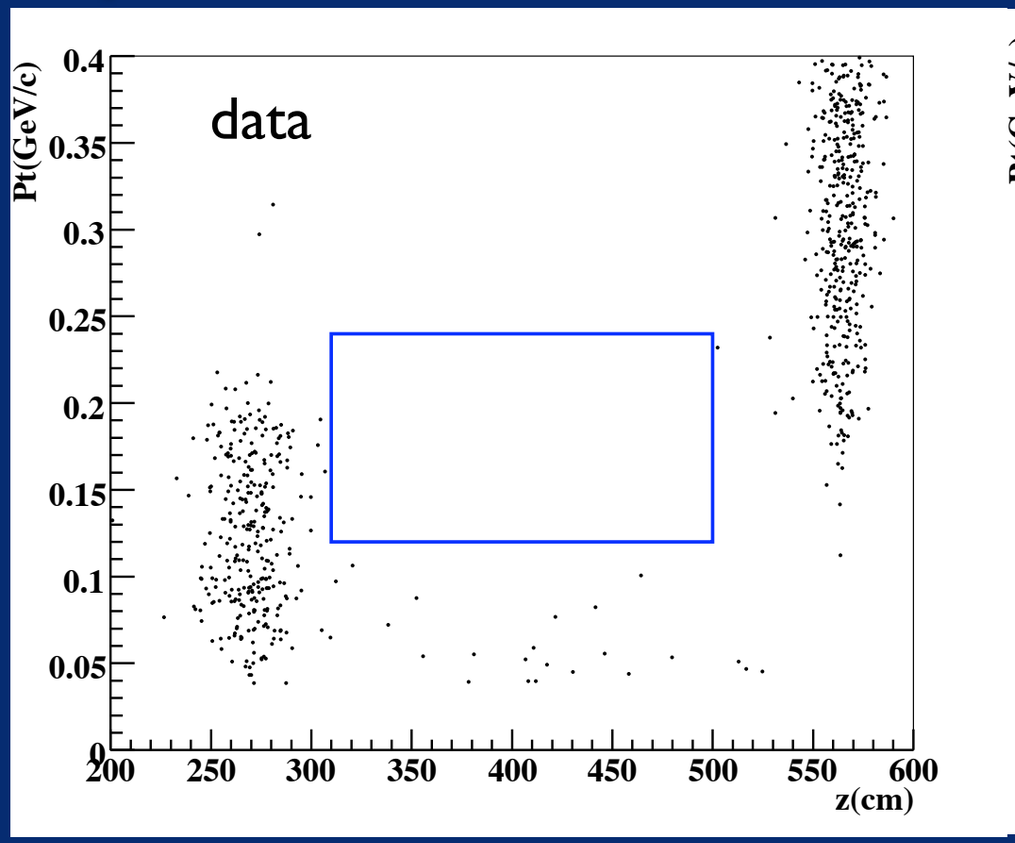
- η's produced at CV by halo neutrons
  - could be reconstructed into signal box assuming π^0 mass
    - ex.) η generated at z = 570cm
      → reconstructed at z = 370cm
- MC simulation
  - The latest hadronic package in geant4.8.3 (May 2007)
    - Binary Cascade model in QBBC

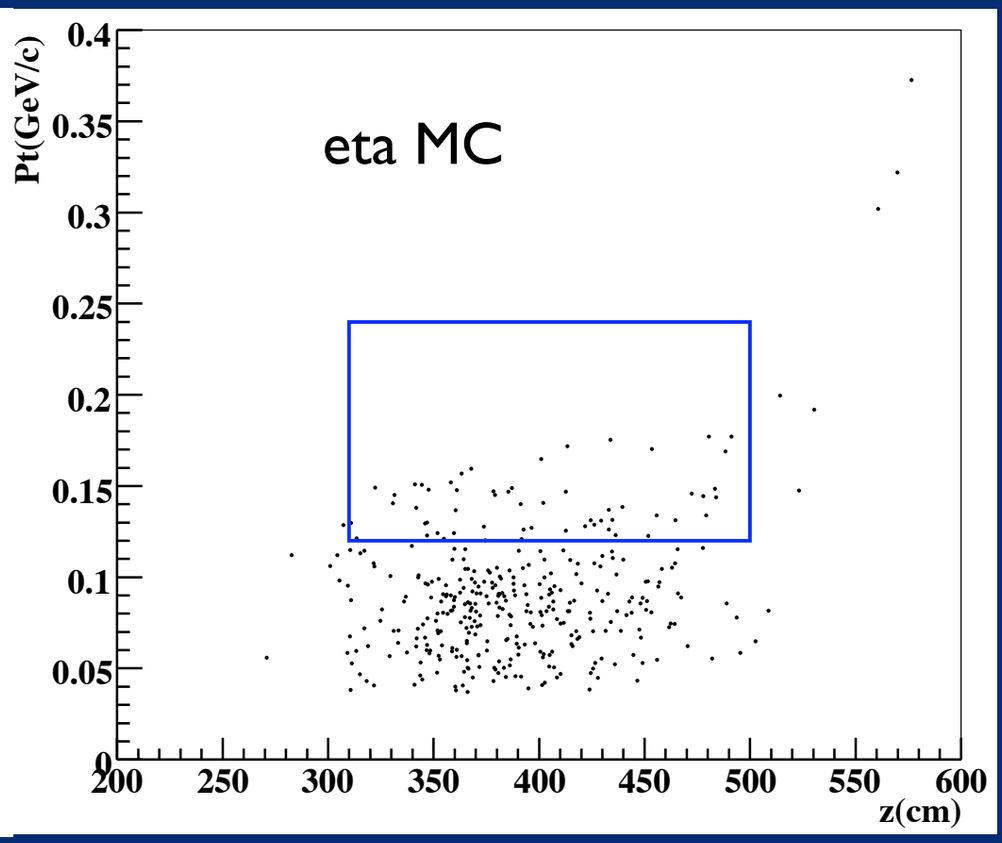




Result of η production MC

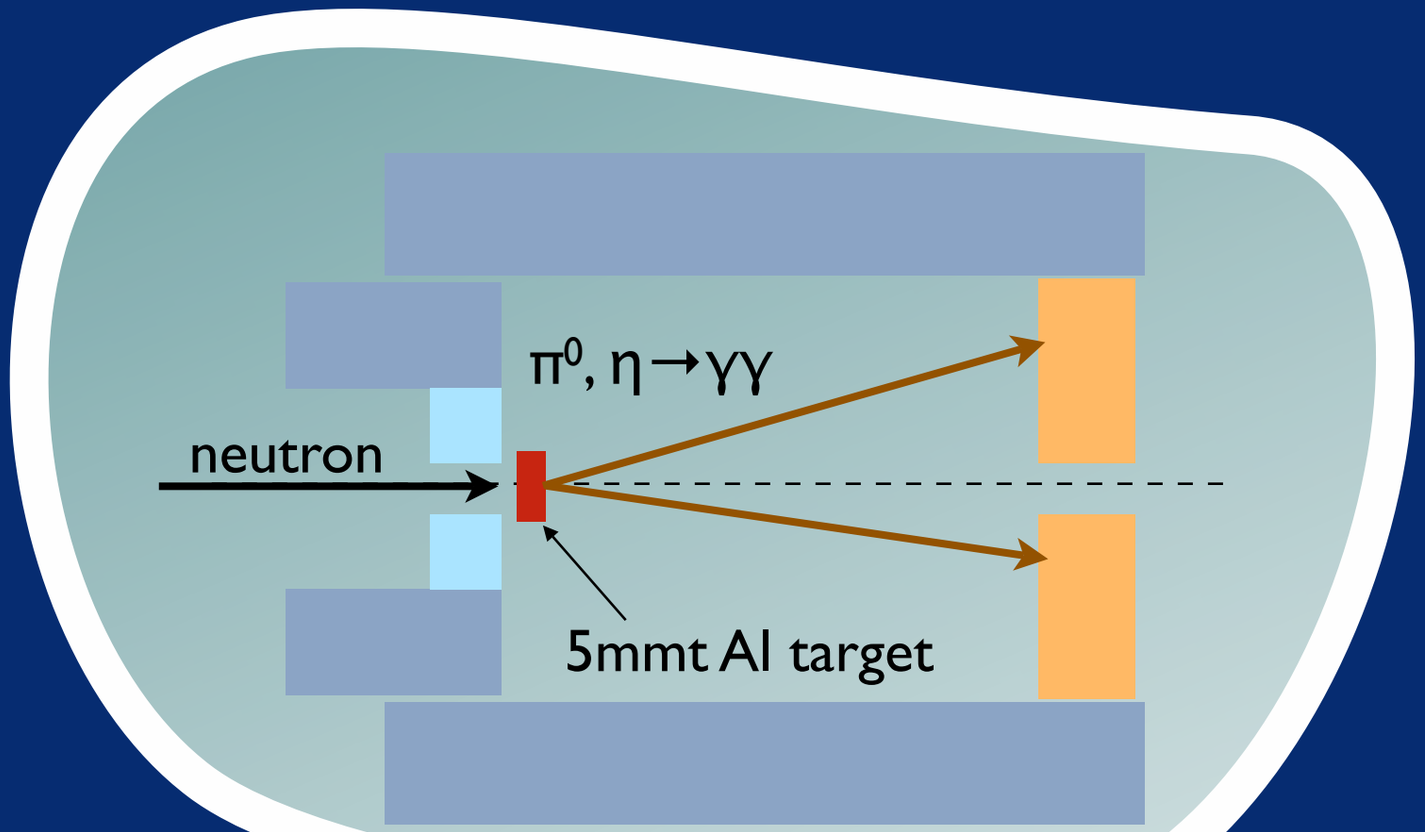
- number of low Pt (< 0.12 GeV/c)events at 320-500cm
  - data: 18 events
  - η MC: 768 events
    - cf.) POT normalization →data = MC x 1.3
  - others
    - downstream: 0.18 events
    - upstream: 0.06 events





η production in the target run

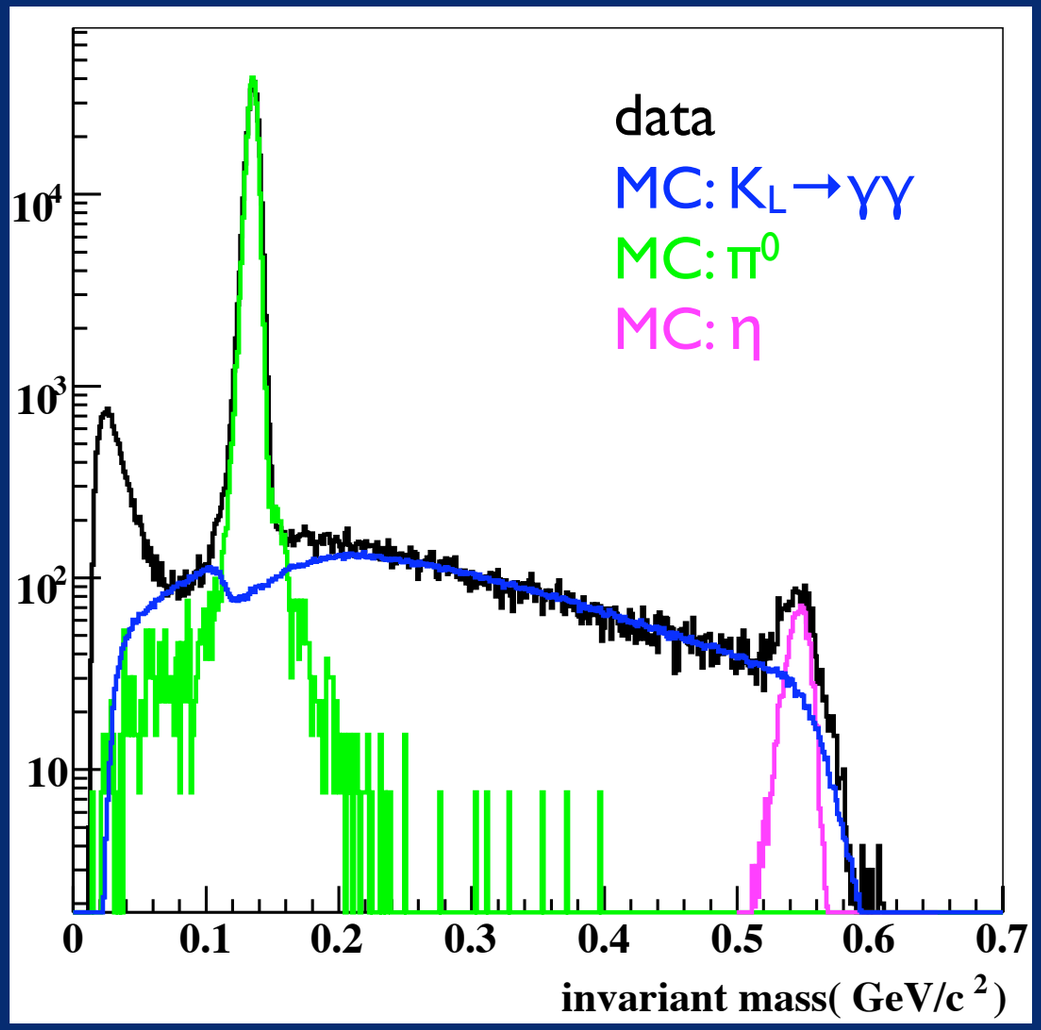
- check the Pt distribution of η

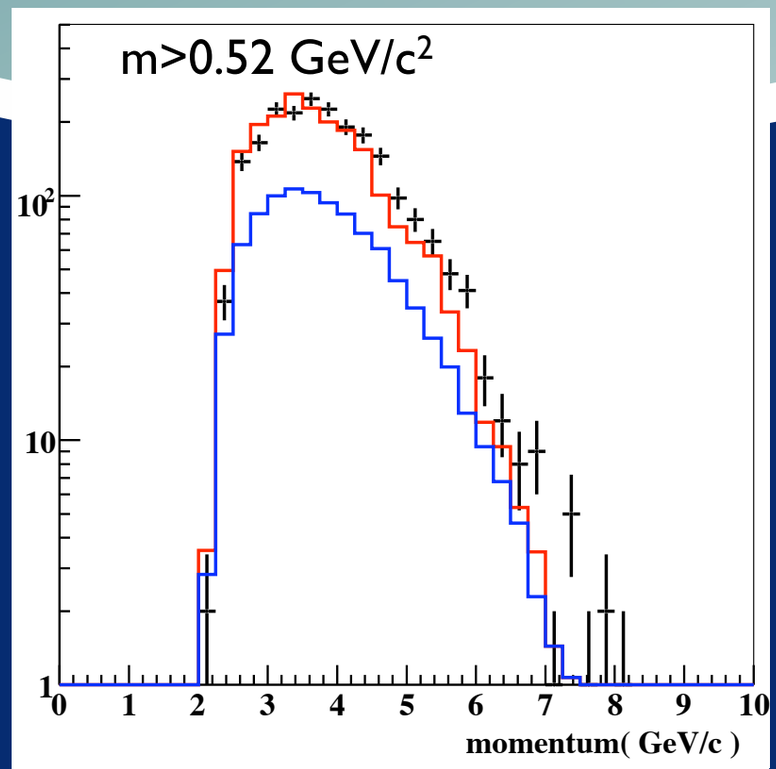


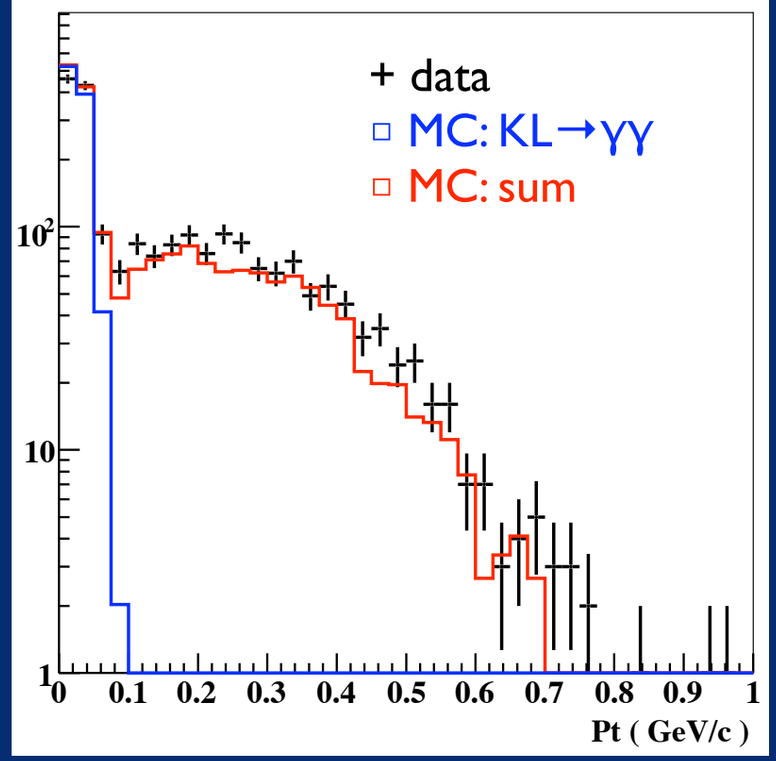
- Target run
  - reconstruct 2gamma invariant mass with fixed z
- MC
  - tune the number of particles simultaneously produced with η

Result of η production

- Pt not required
- number of η event
  - data = MC x 1.50
    w/ invariant mass > 0.52 GeV/c^2







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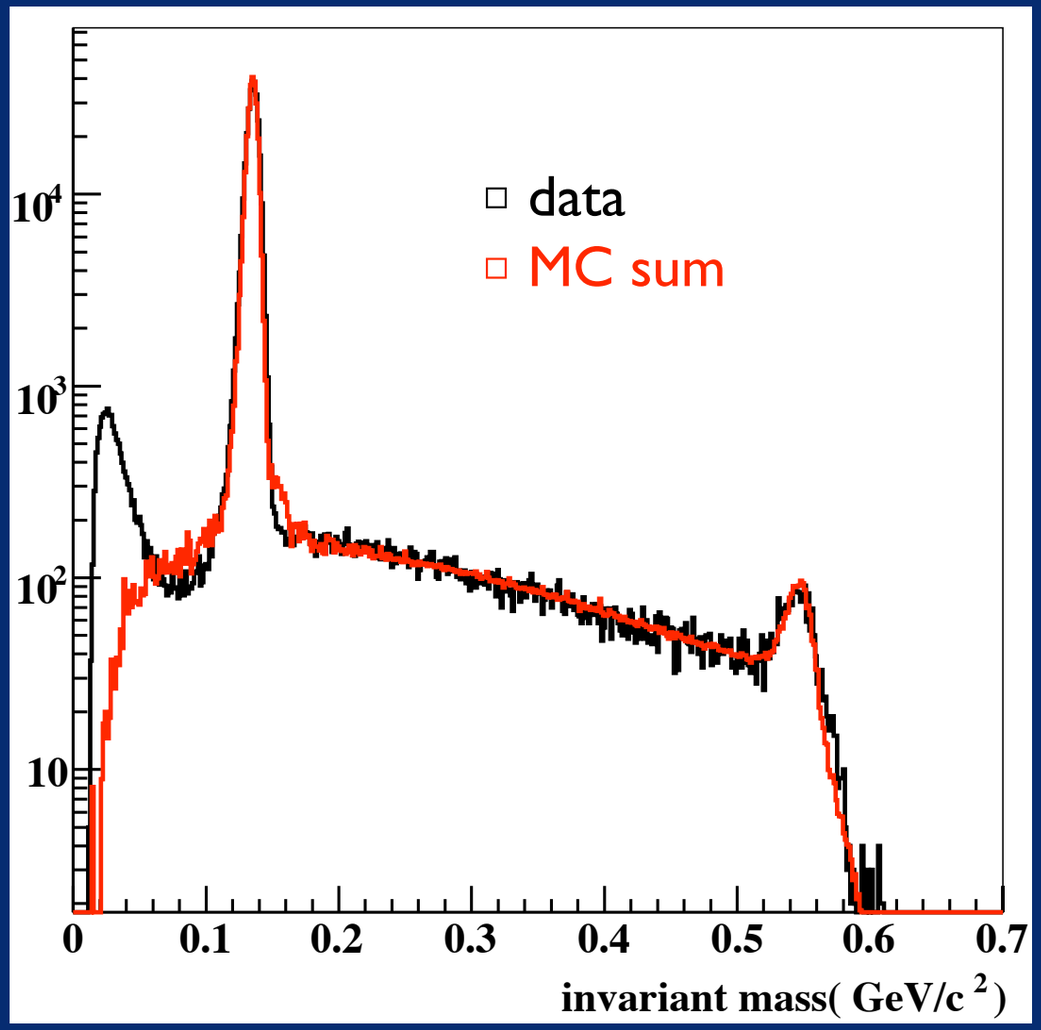
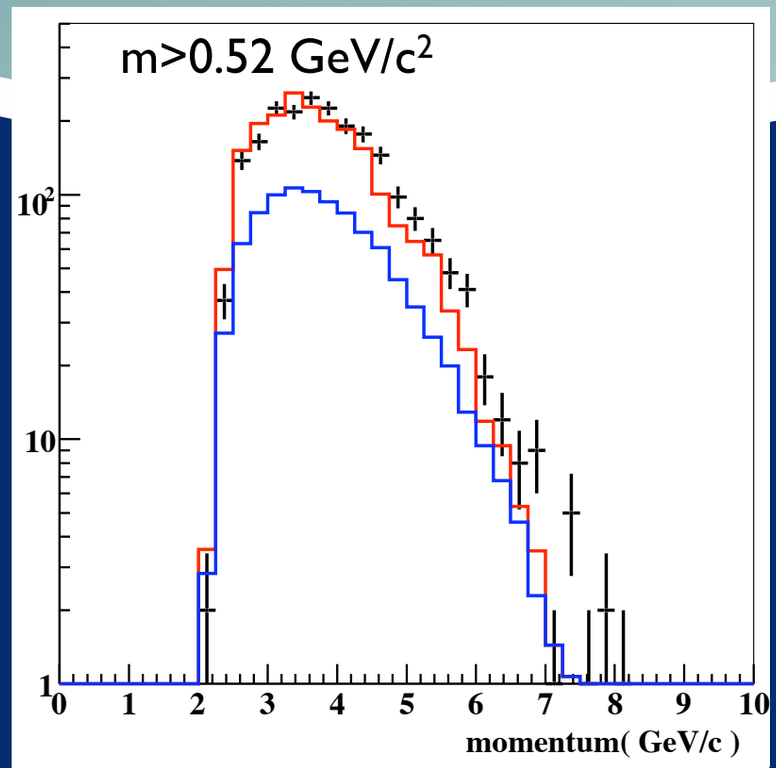
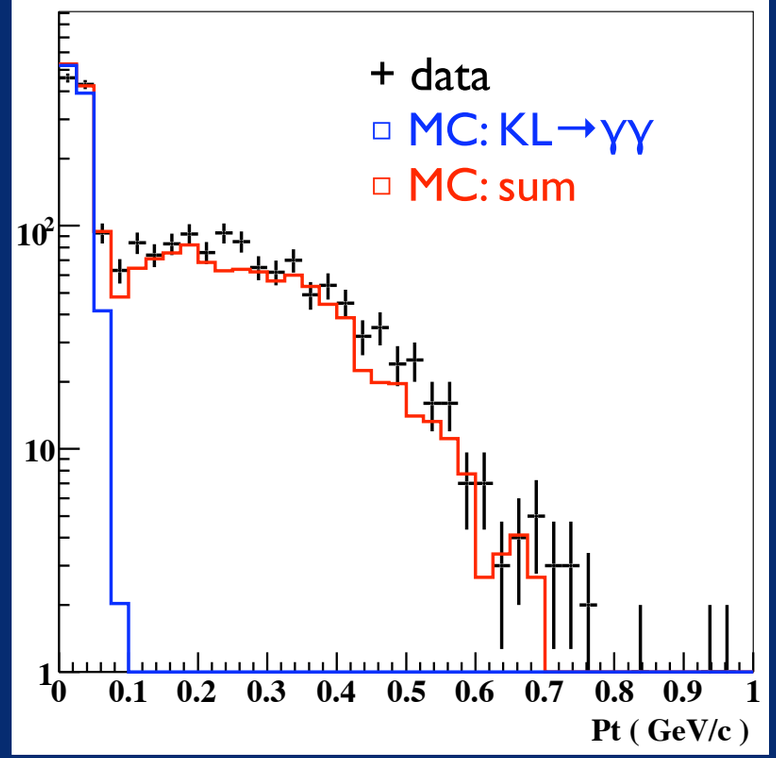
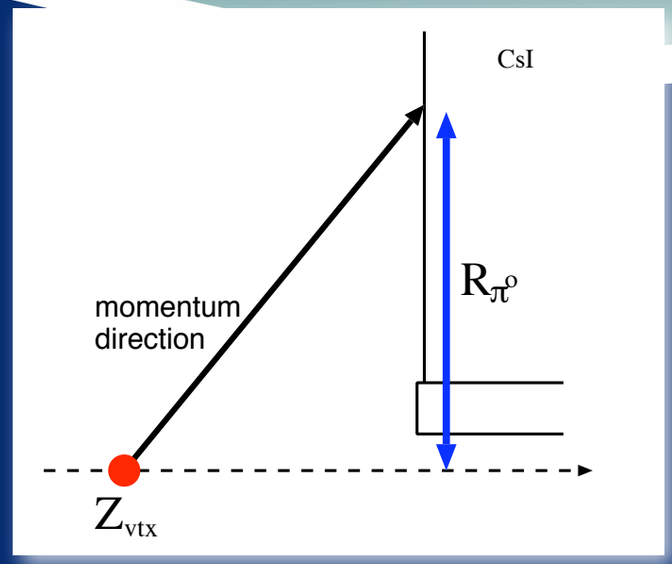


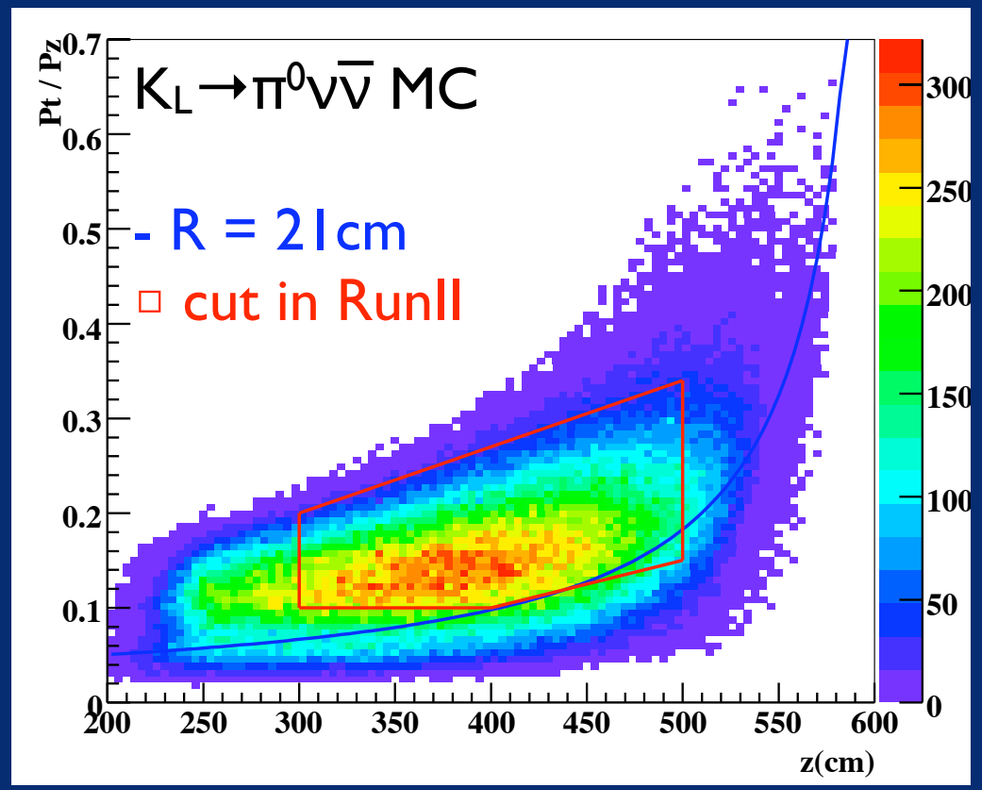


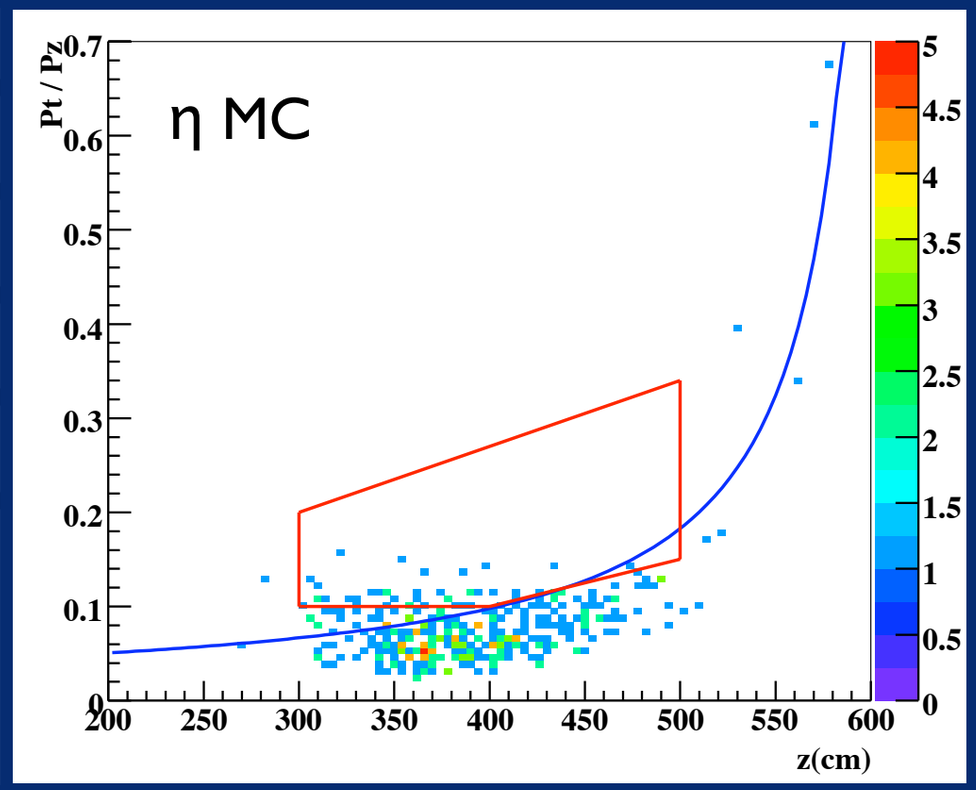


Cuts for η BG

- π0 projection R cut
  - Pt / Pz vs. z-vertex

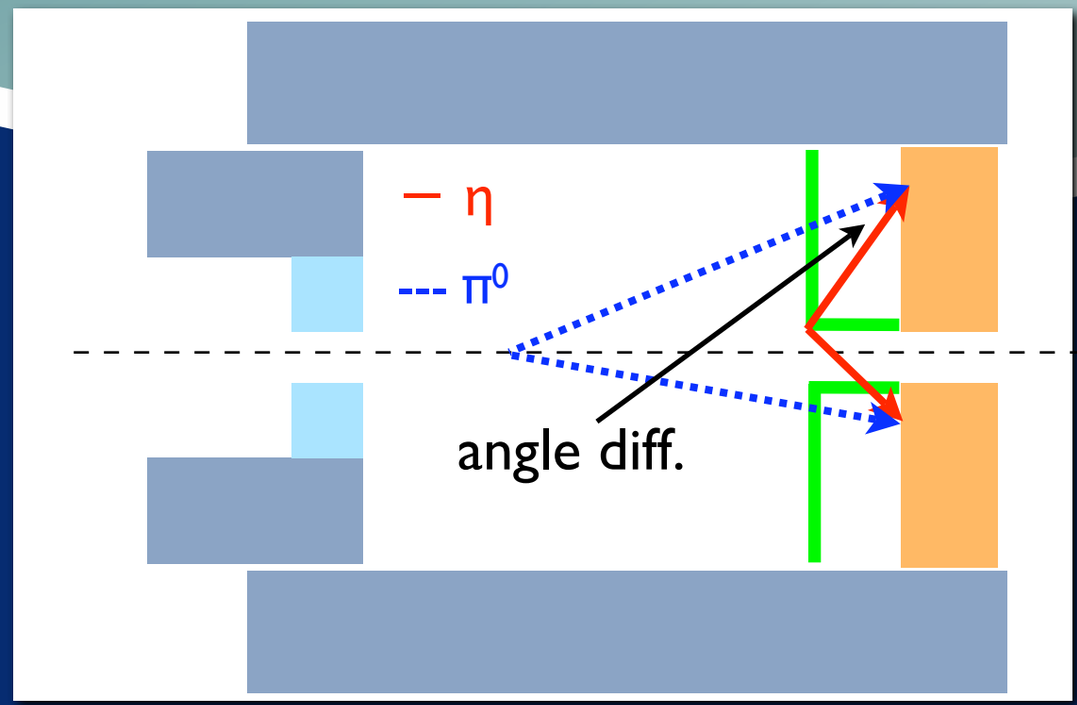




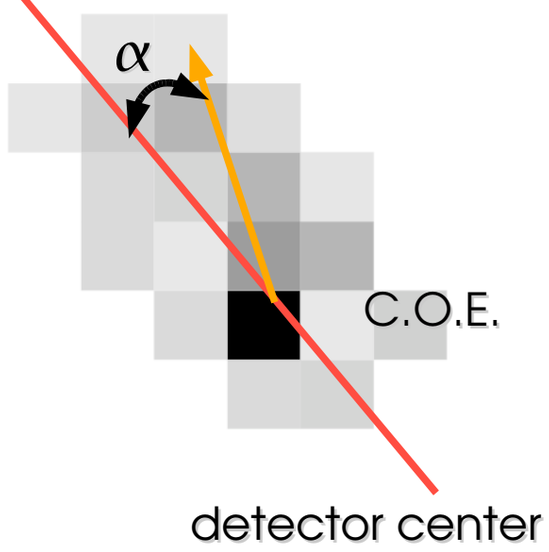


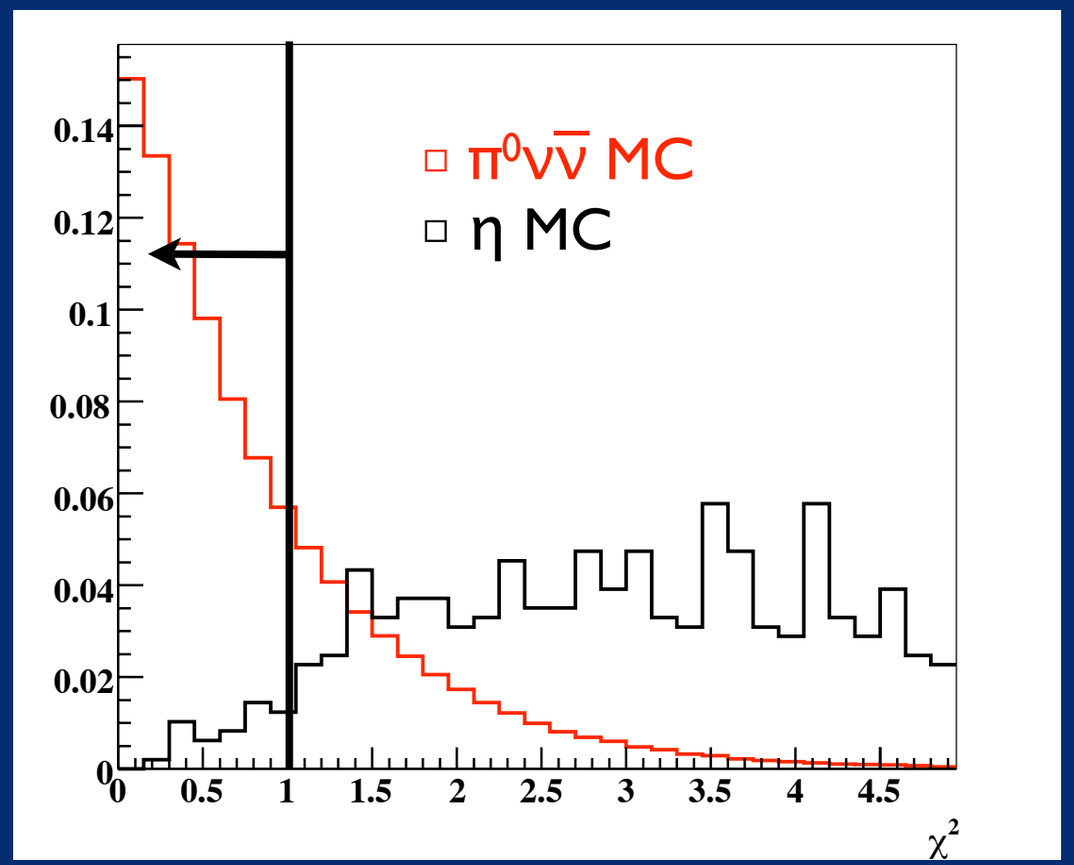
Cuts for η BG (cont'd)

- injection angle of gamma
  - reconstructed : θ_{rec}
  - measurement w/ energy shape: θ_{rl}
- $X^2 = (\theta_{rl}-\theta_{rec}) / \sigma_{rl}$



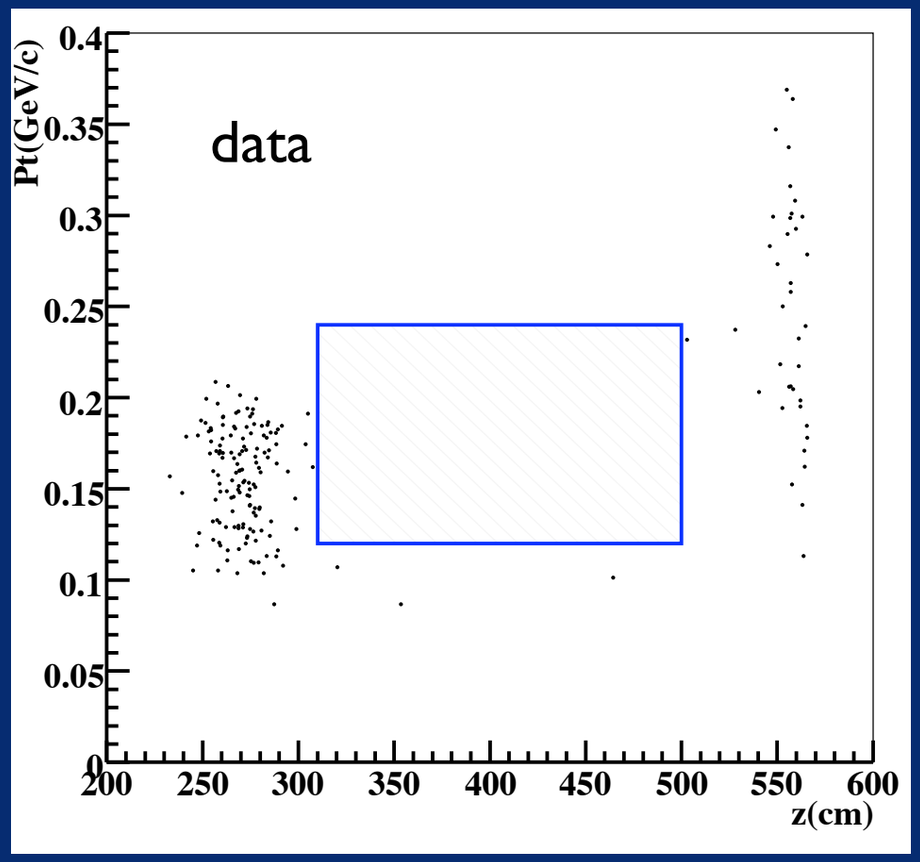
$$r_l = \sqrt{\frac{\sum E_i \times [d_i P_l(\cos\alpha)]^2}{E_{total}}} \quad , \quad P_l : \text{Legendre Poly.}$$

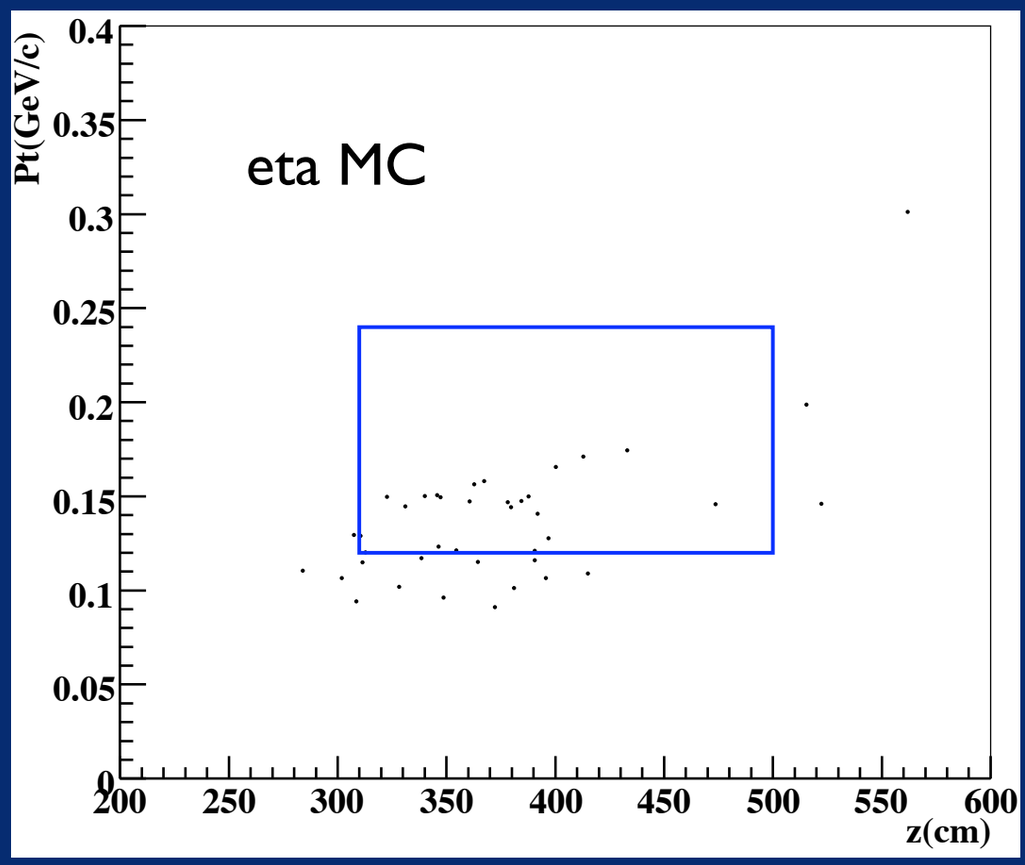




Result of η BG estimation

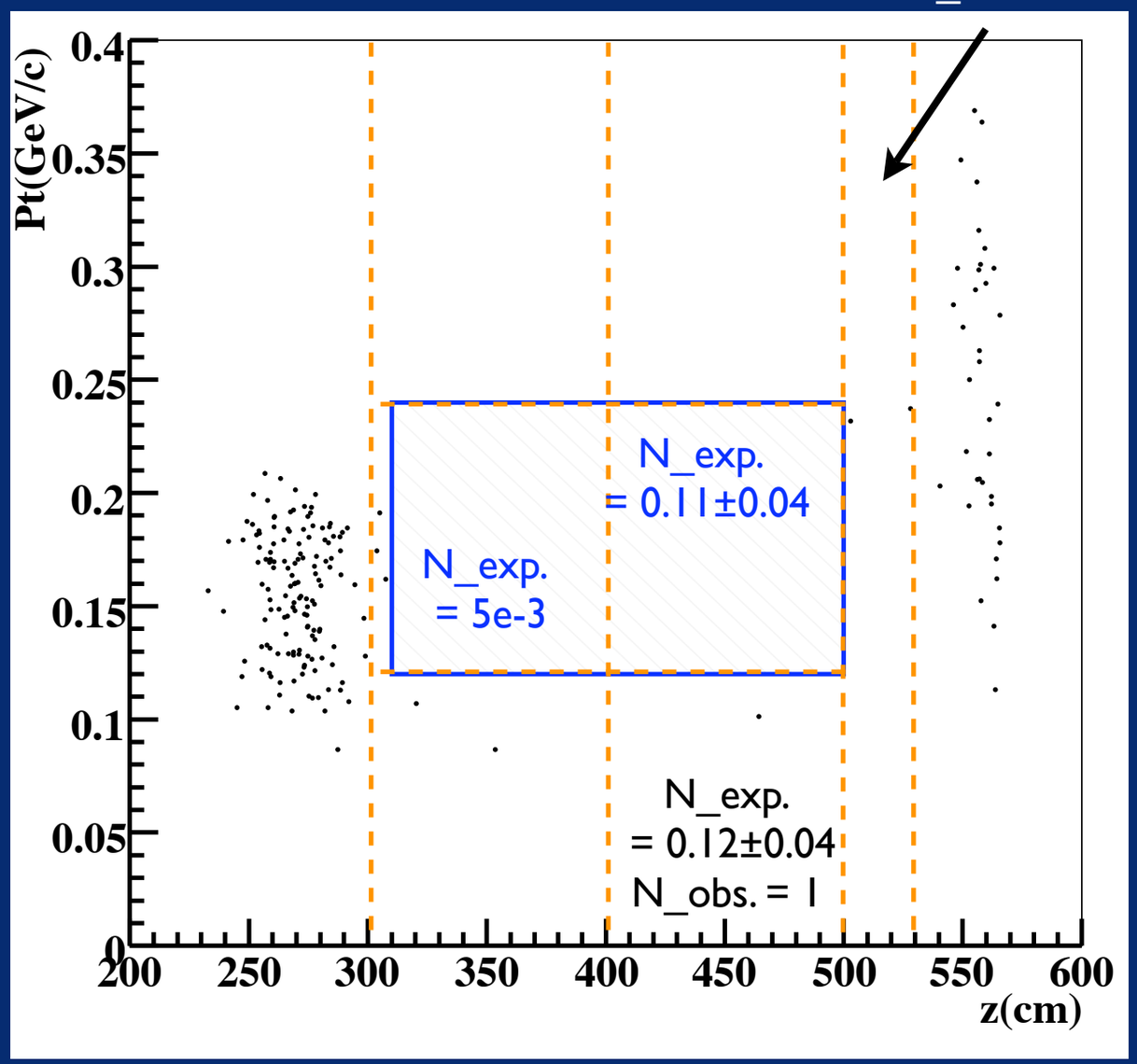
- new cuts applied
  - ~ 1/10 rejection
  - x 0.60 acceptance
- 24 events remaining w/ η MC
  - x normalization with low Pt events
    = 0.43 ± 0.11 events

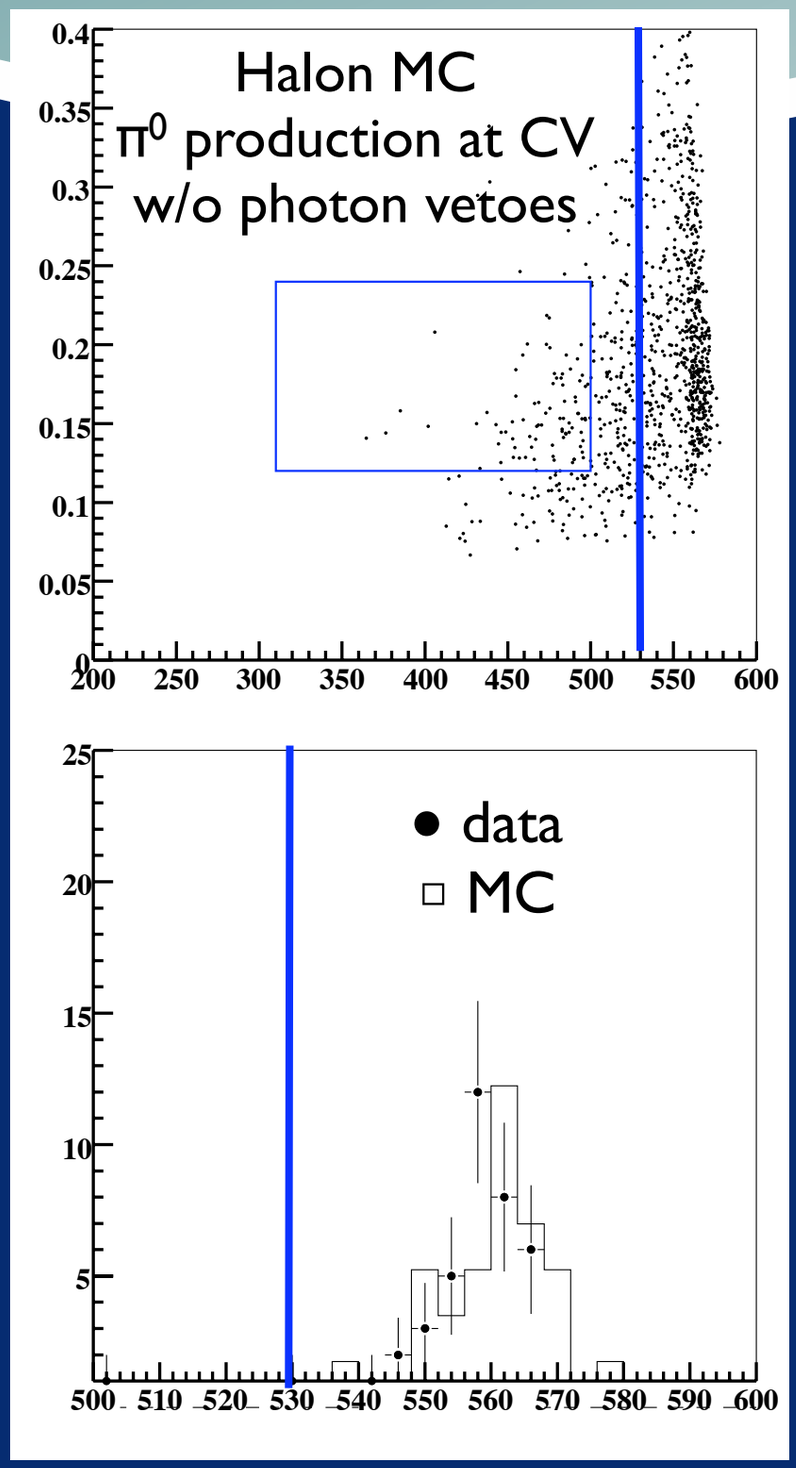




Downstream background

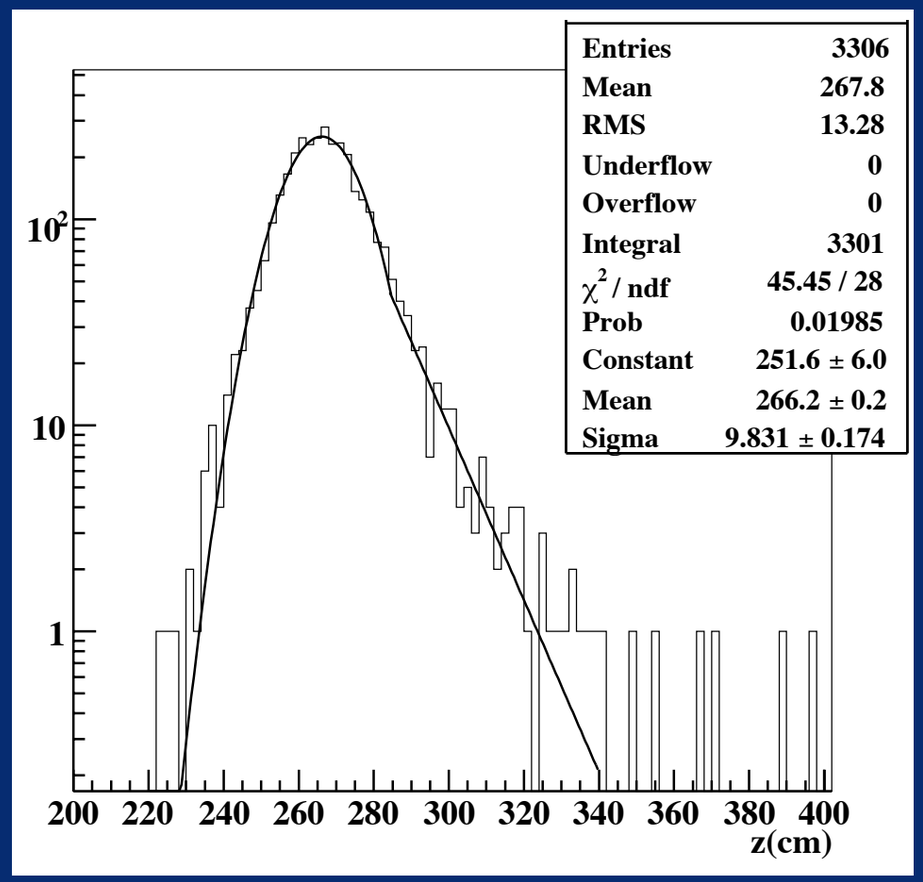
- Halo neutron MC
  - Statistics: 1/1.78 of data
- Bifurcation method
  - 0.11 event in the box

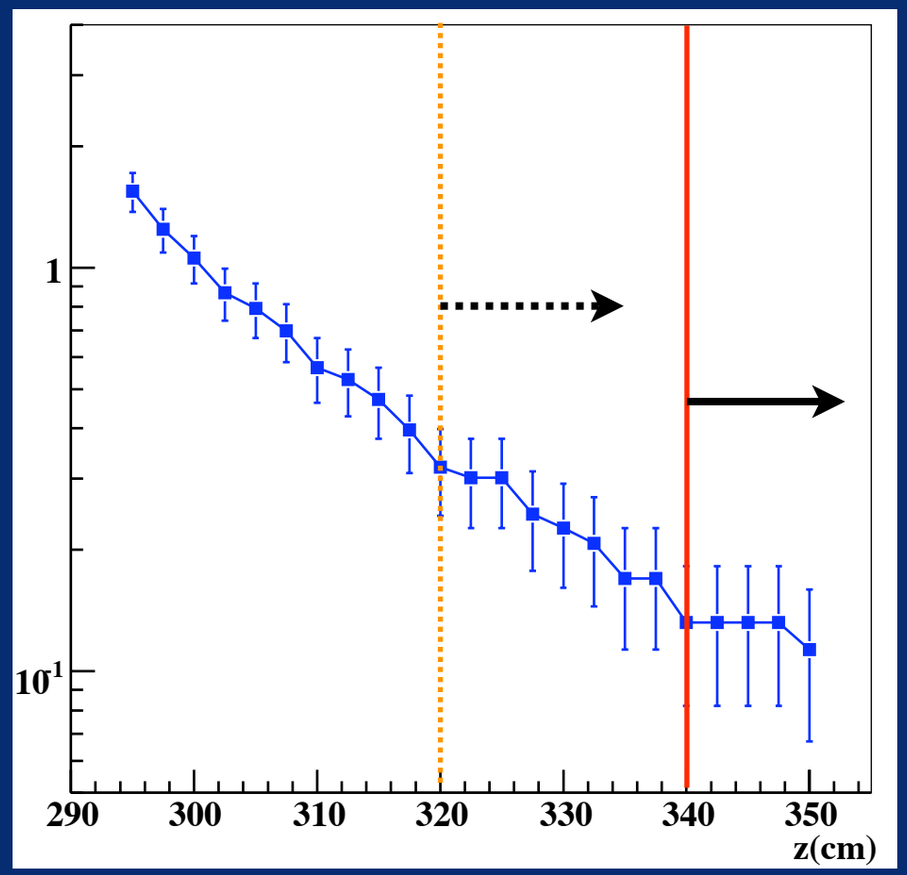




Upstream background

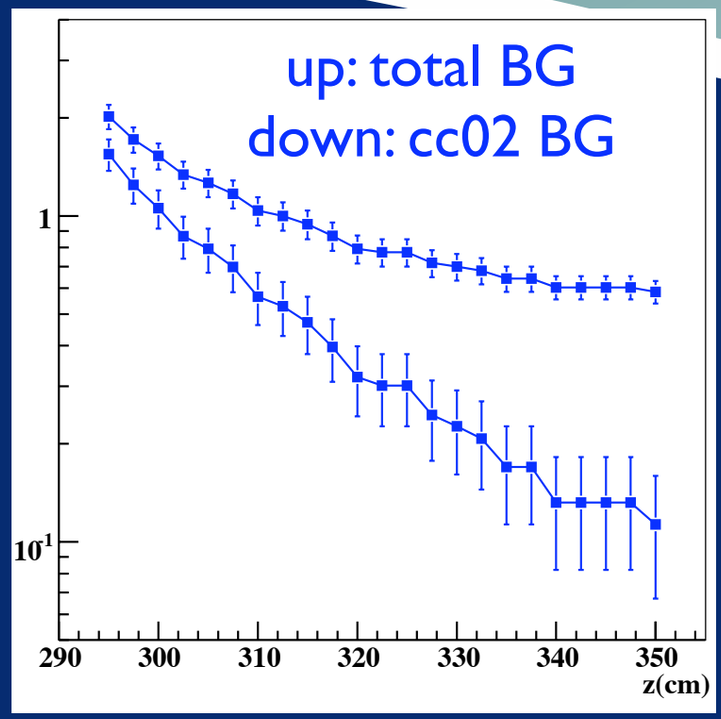
- using target run data
  - count the number of events in the box
- BG events
  - 320 - 500: 0.32±0.10
  - 340 - 500: 0.13±0.05

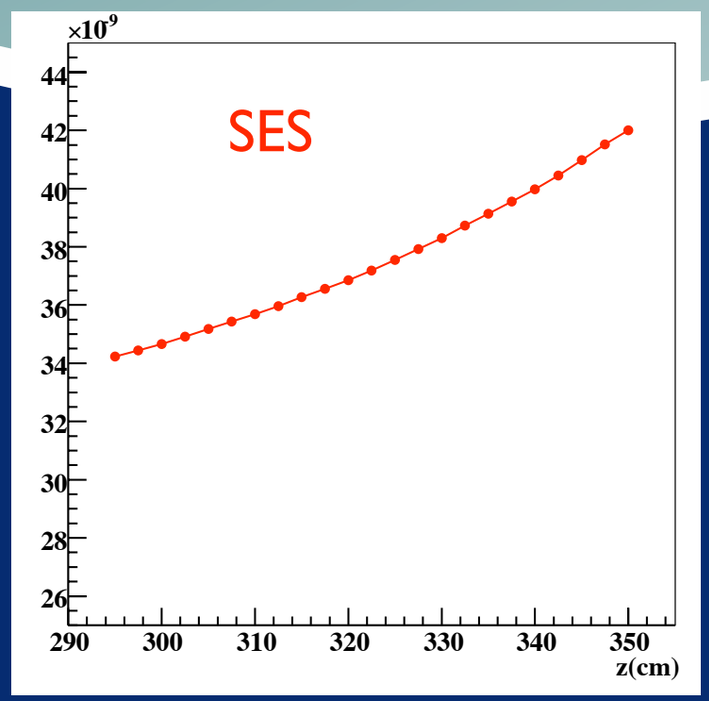


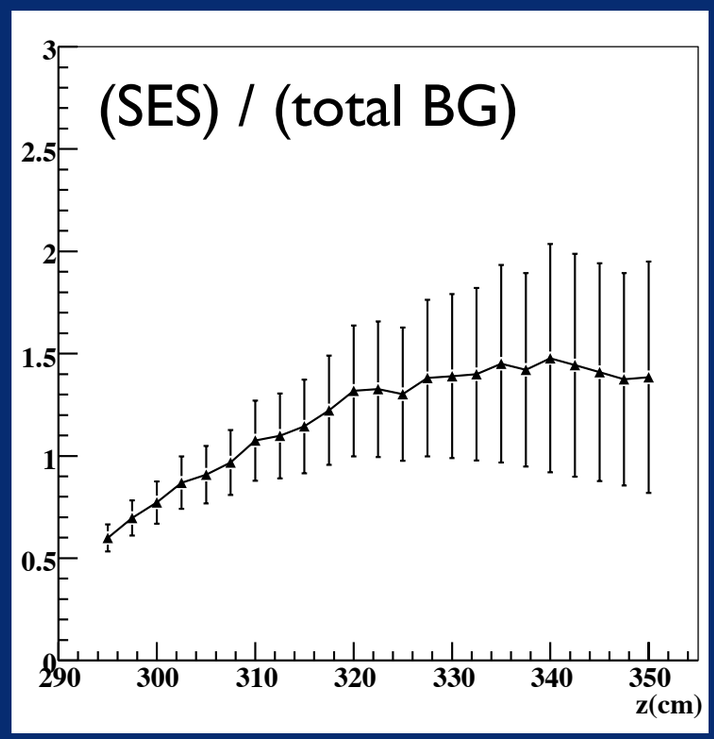


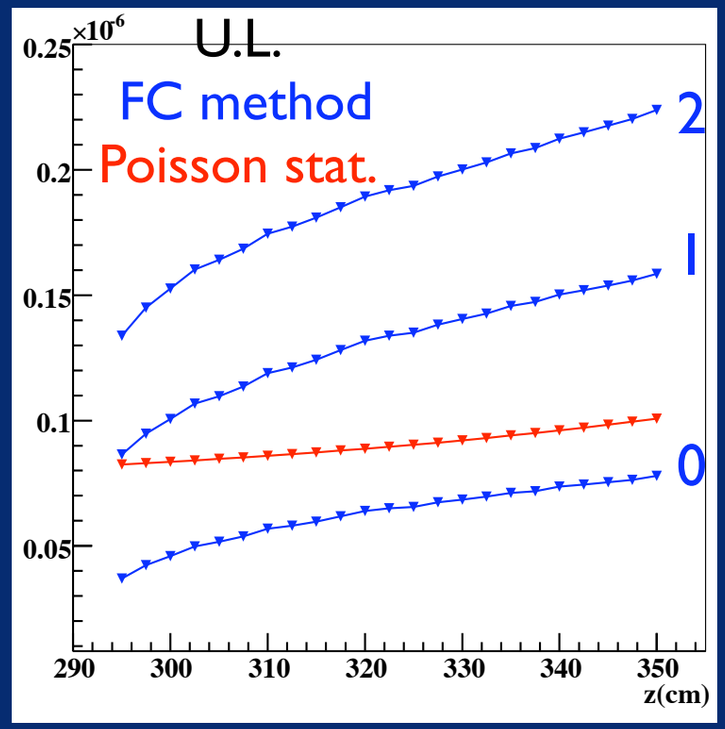
Total background

- values of BGs
  - CV: 0.11
  - $K_L \rightarrow 2\pi^0$: 0.1
  - Eta: 0.43
  - CC02
    - z=320cm: 0.32
    - z=340cm: 0.13
- Single Event Sensitivity (SES)
  - 3-4 x 10^{-8}
- S/N : x 15 improved from RunI
- Expected Upper Limit
  - Br < 0.9x10^{-8}









Summary

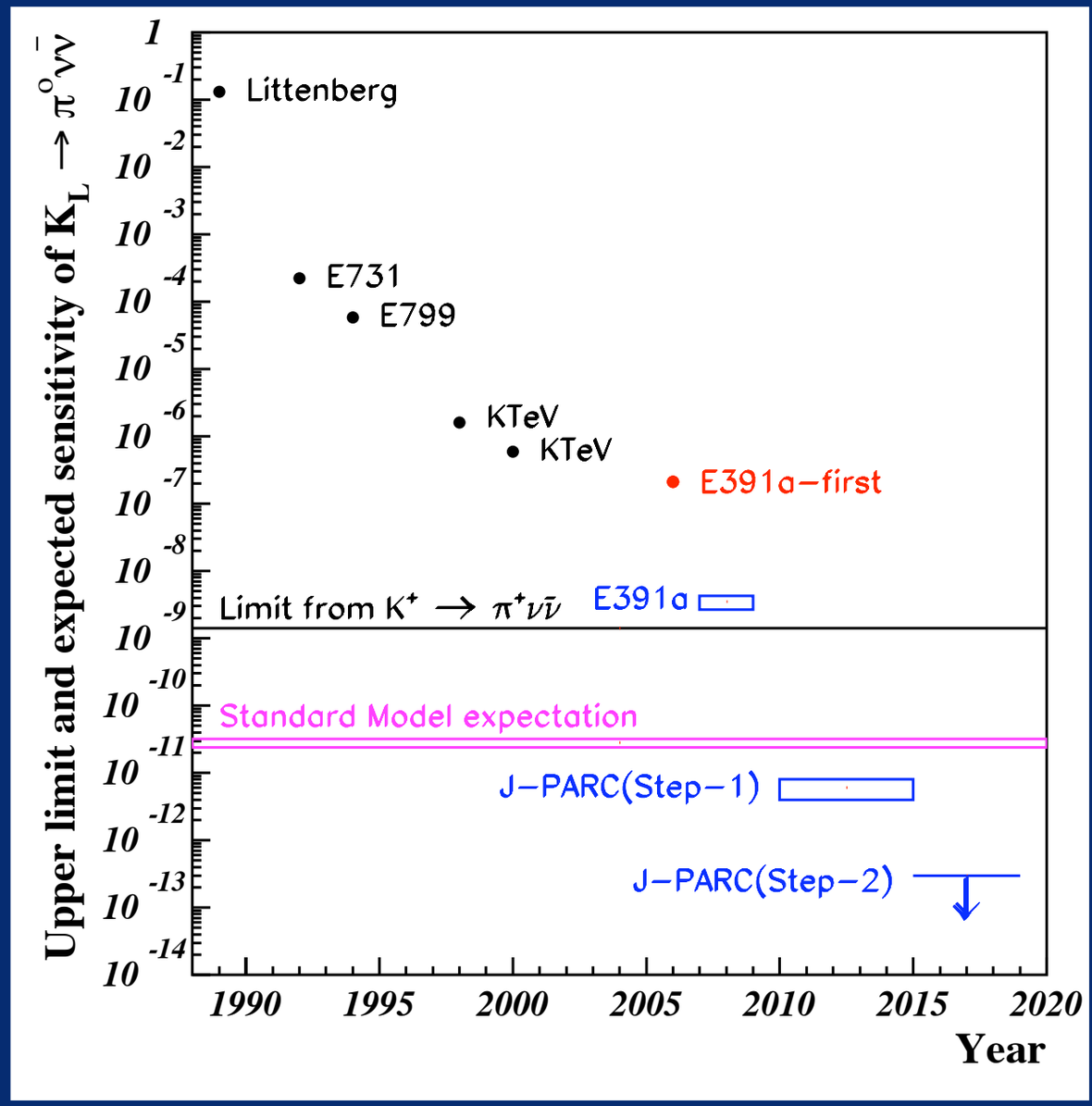
- Now we understand all the sources in the 2gamma (single π0) events in E391a
  - upstream, downstream
    → Halo neutrons
  - low Pt → eta
    - estimation done with a MC based on geant4
- total background level
  - ~0.6 events

- To do
  - cross check
  - further optimization holding background level
    ⇒ Open the box !!

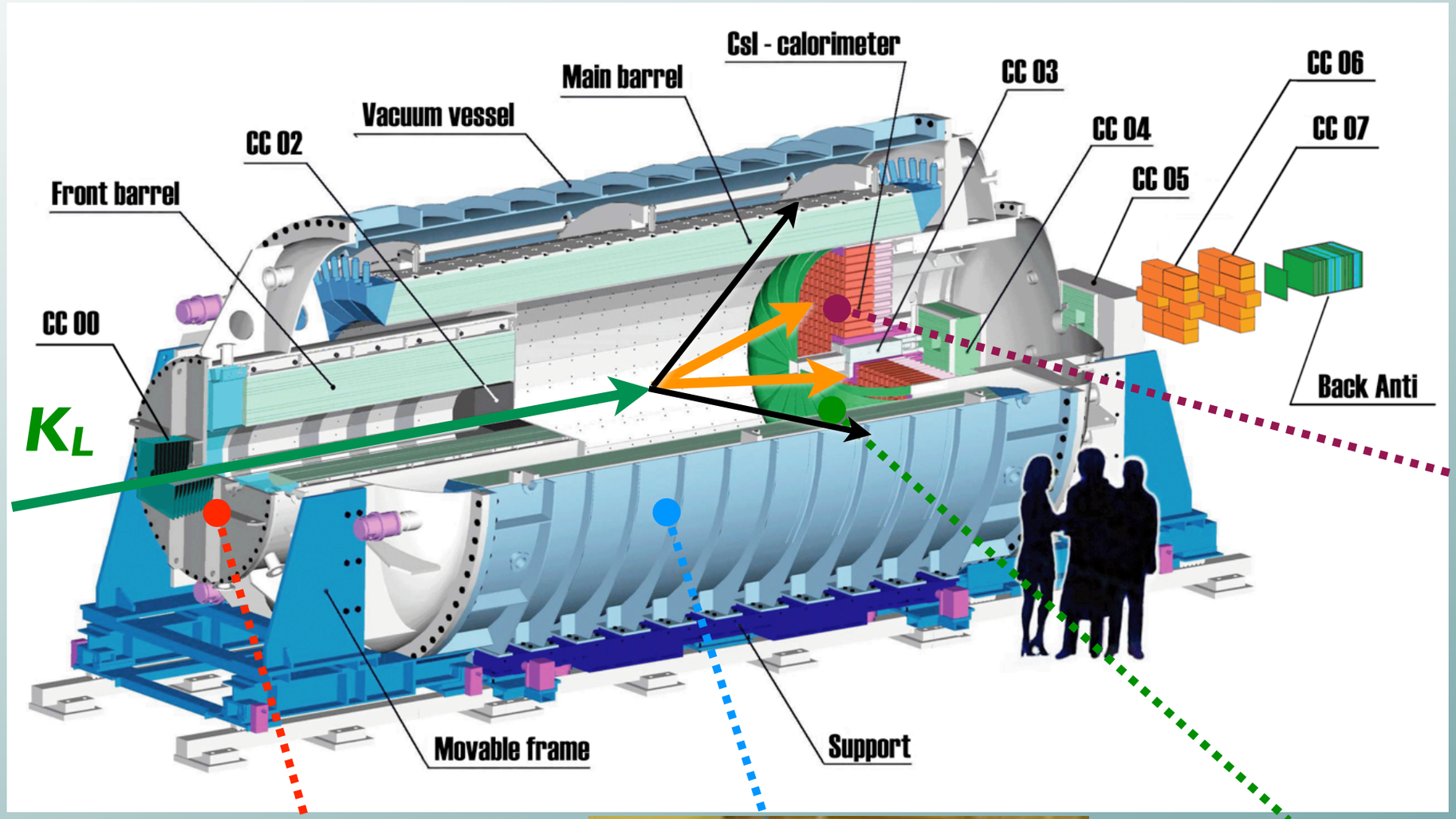
Backup slides

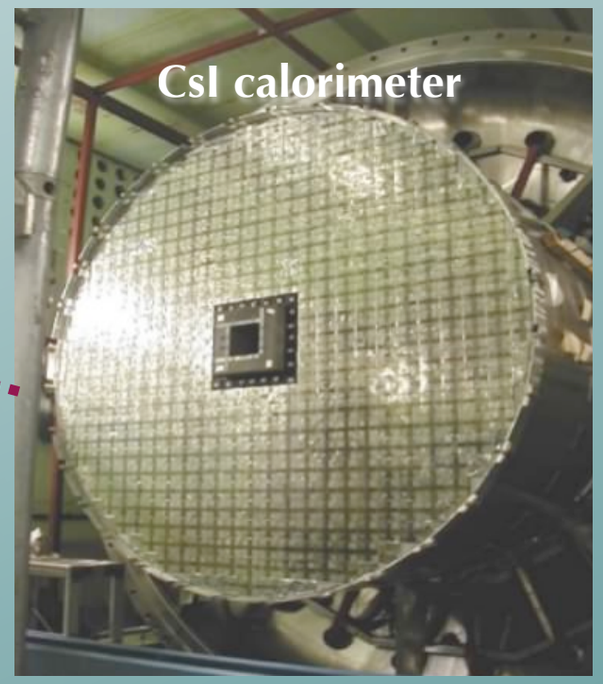
$K_L \to \pi^0 \nu\bar{\nu}$ experiments

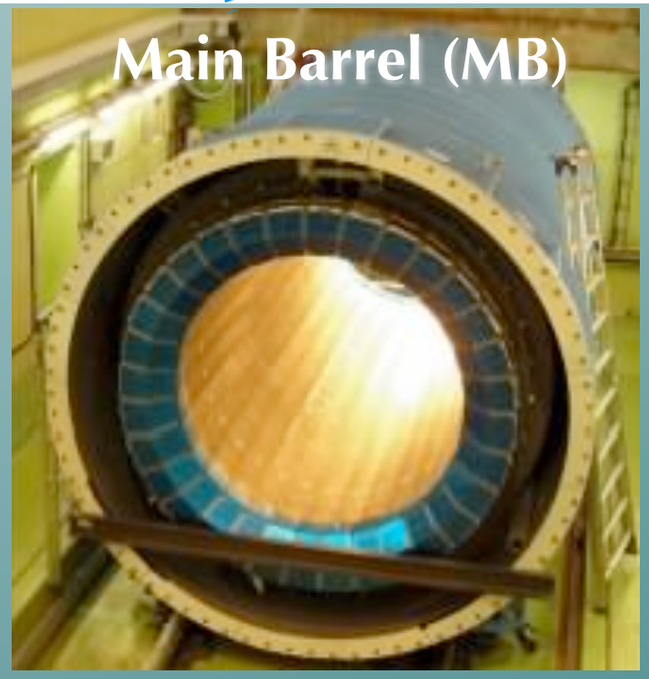
- extremely challenging
  - small branching fraction
  - many background sources
- 3 body decay
  - weak kinematical constraint
  - all particles neutral
- Current upper limit
  - Br < 2.1×10^{-7} (90% C.L.)
    - E391a, PRD 74:051105, 2006
- Step by Step approach
  - E391a
    - The first dedicated experiment to establish experimental method
    - measurement at $O(10^{-9})$
  - J-Parc E14
    - Step-1: 8×10^{-12}, event observation
    - Step-2: ~10^{-13}, precise measurement



The E391a Detector

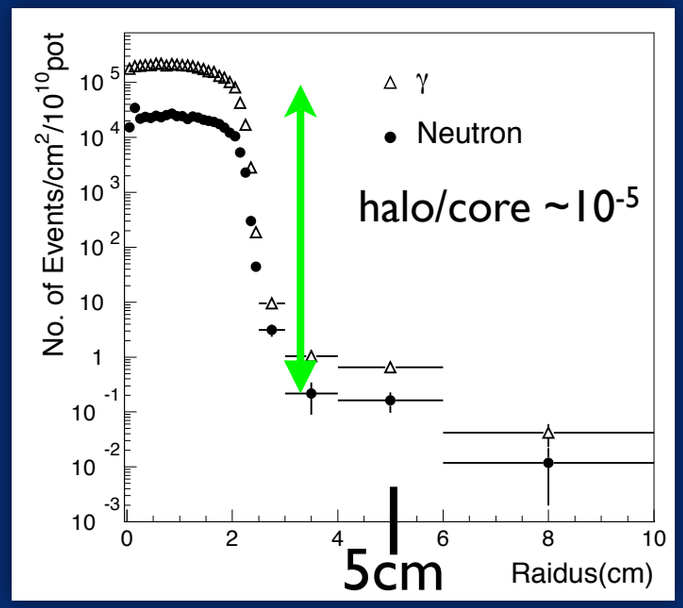


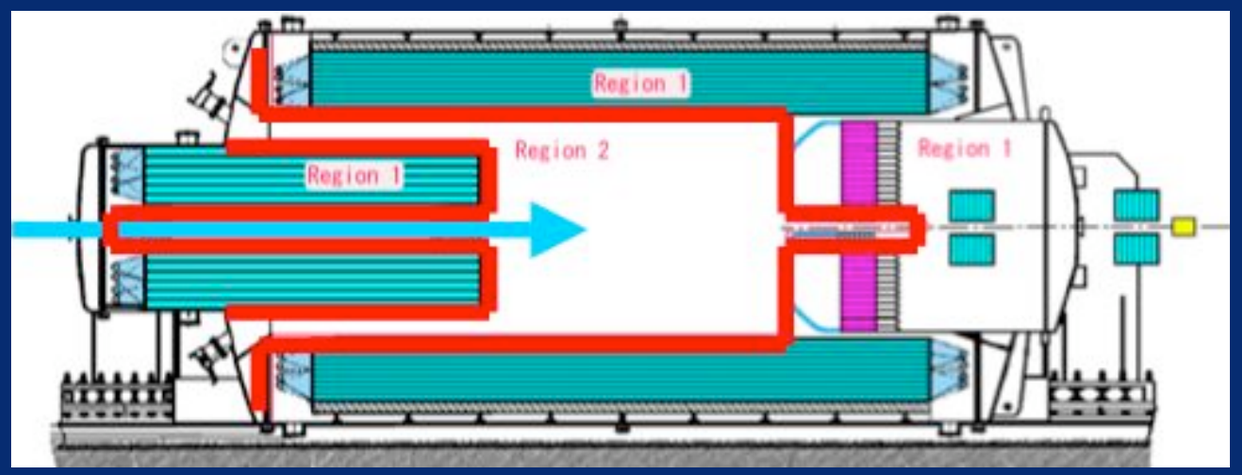




Features of E391a

- "Pencil" beamline
  - 8cm diameter at CsI (16m from the target)
- Hermetic veto system
  - reject the background from $K_L \rightarrow 2\pi^0$
- Vacuum
  - Evacuate decay region to reduce the background from the interaction between neutrons and the residual gas
    - Decay region: 10^{-5} Pa
    - Detector region: 0.1 Pa
      - separated with thin material





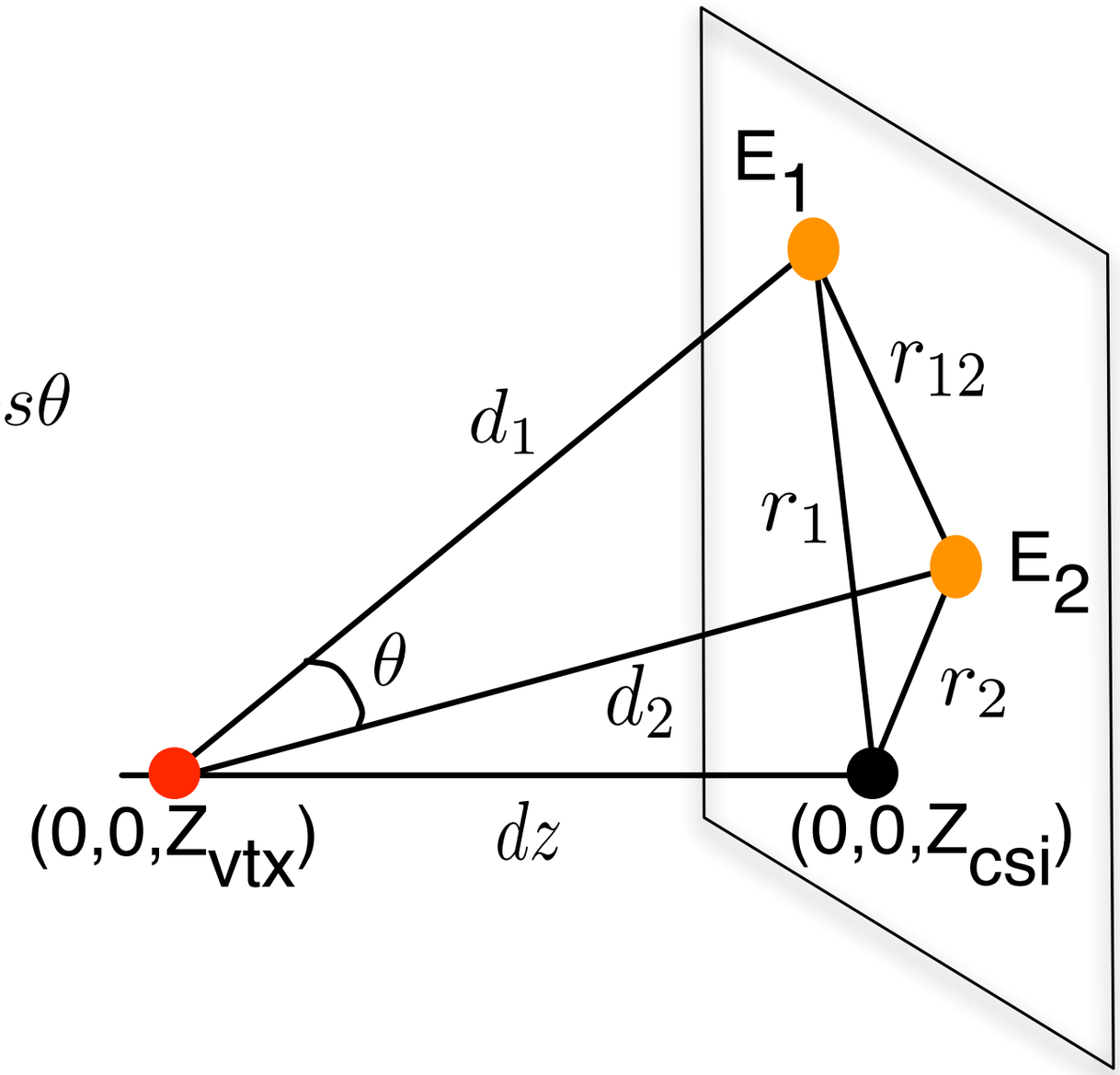
High vacuum
~10^{-5}Pa

Membrane
(0.2 mm, CH2, 1g/cm³)

π0 reconstruction with 2γ

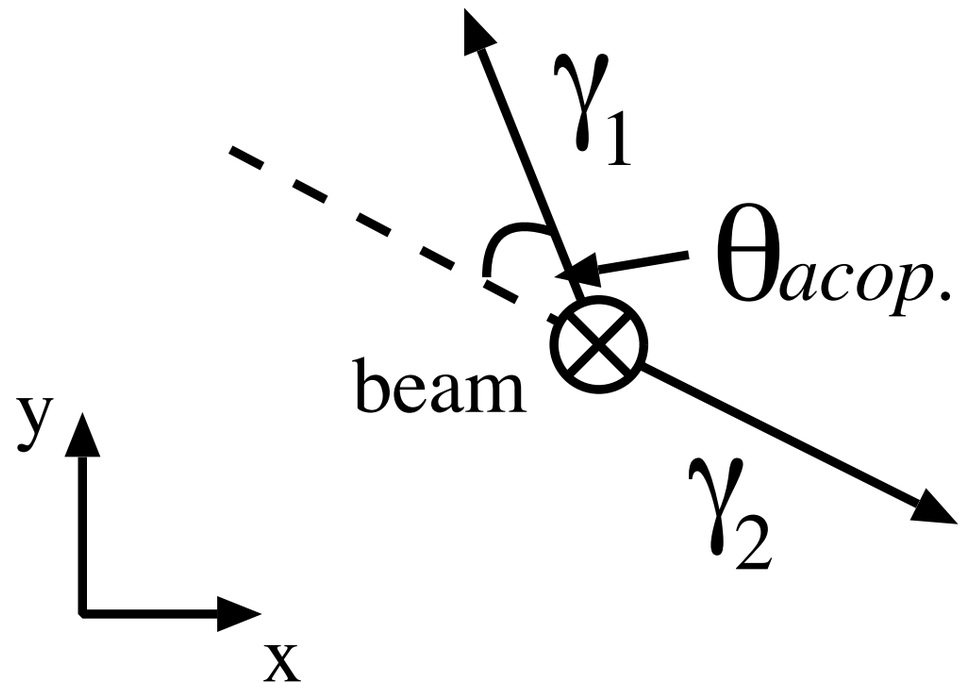
- assume 2γ invariant mass is $M_{\pi 0}$

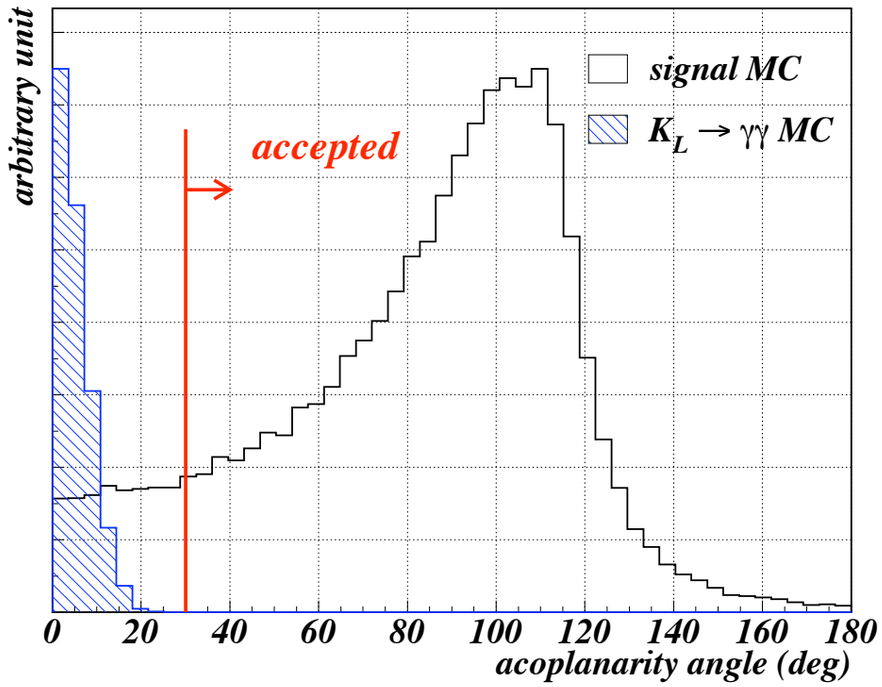
$$
\begin{aligned}
cos\theta &= 1 - \frac{M_{\pi^0}^2}{2E_1E_2} \\
r_{12}^2 &= d_1^2 + d_2^2 - 2d_1d_2cos\theta \\
d_1 &= \sqrt{r_1^2 + (dz)^2} \\
d_2 &= \sqrt{r_2^2 + (dz)^2} \\
dz &\equiv Z_{csi} - Z_{vtx}
\end{aligned}
$$



π0 cuts

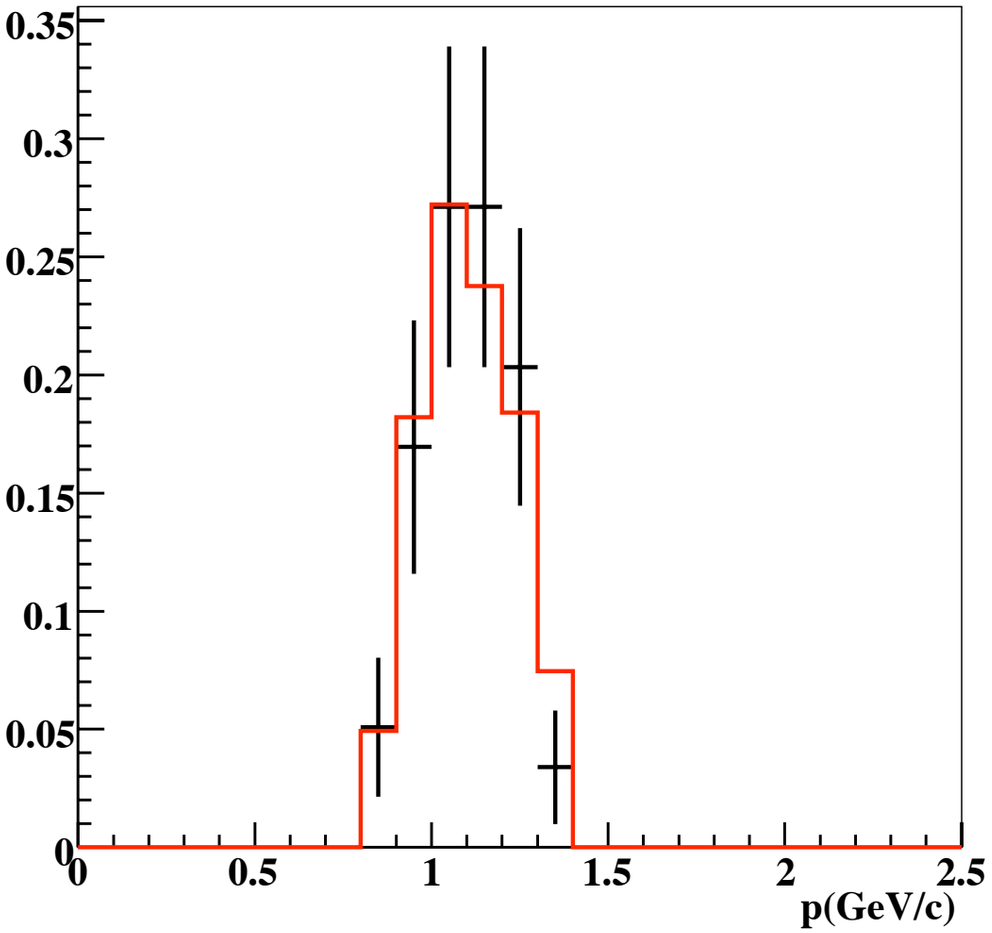
- acoplanarity angle

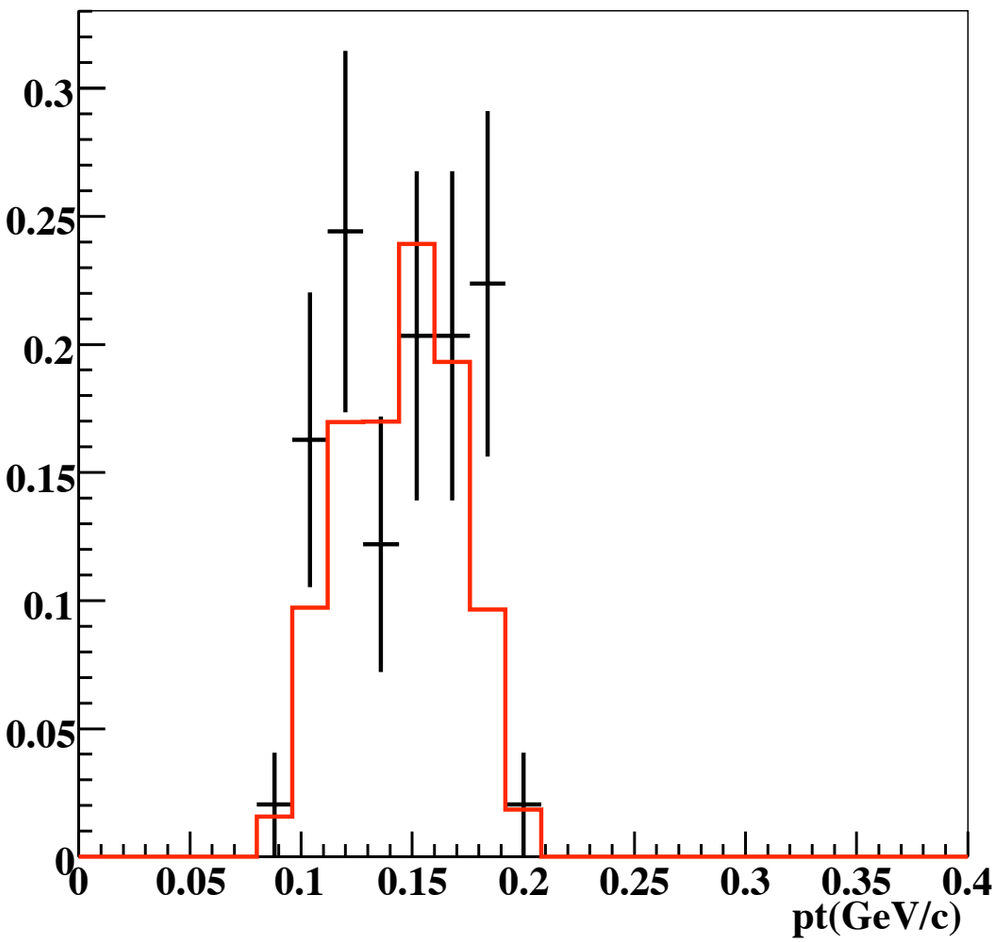




events in the target run

- momentum and pt of π^0
- limited by the geometrical acceptance
- distributions from the target run and physics run show good agreement
  ⇒ estimate shower leakage probability



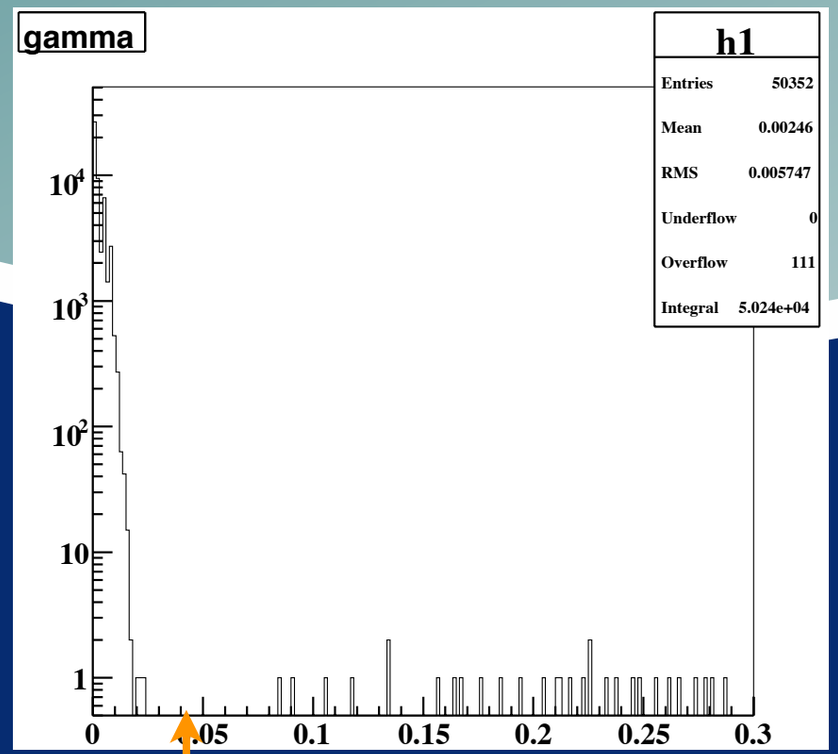


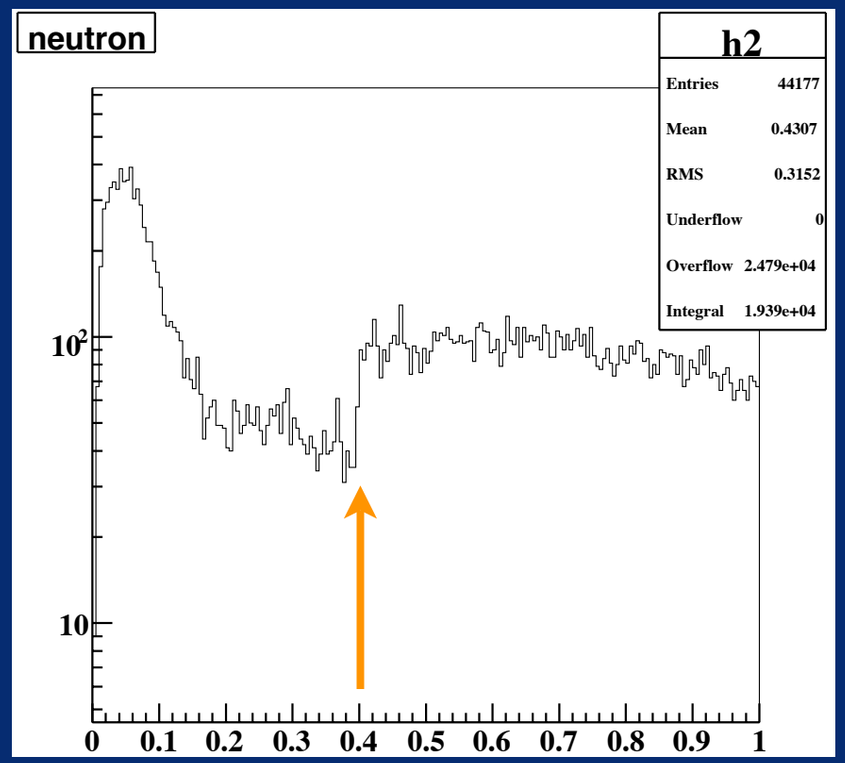
Normalization

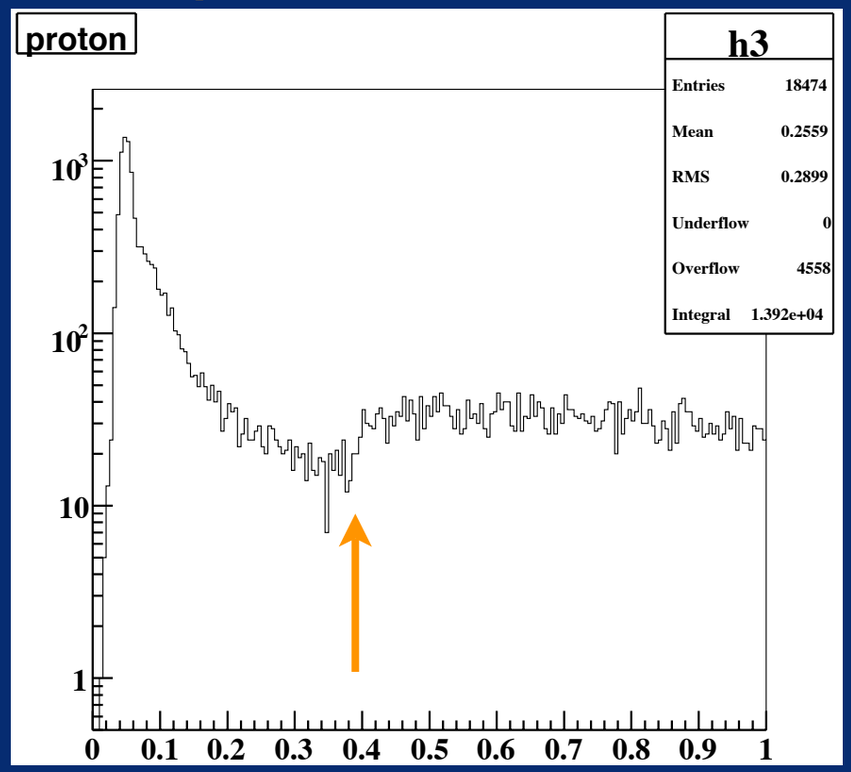
- 3 steps
  - beamline simulation (geant3)
    - 436.25 halon / 10^{10} POT : fixed → N_{halon}
  - gsim4test (geant4)
    - 5×10^{8} halon incident
    - number of collected eta events
      - 20555 events : easily change due to the condition to collect "clean" eta events
        - if the condition is loose → many events, low probability to remain in the final state
  - gsim (geant3)
    - 1×10^{8} eta events generated
- Comparison of Statistics
  - POT
    - POT in gsim4test: 5×10^{8} / N_{halon} = (POTg4)
    - probability of eta events occurrence: 20555 / (POTg4) = P_{eta} : most uncerntain
    - POT in gsim: 5×10^{8} / P_{eta} = (POTgsim)
    - compare (POTgsim) to POT of data : (POTdata)
      - (POTdata)/(POTgsim) = 1.41×10^{18} / 1.67×10^{20} = 0.504×10^{-2}: POTnorm
  - Low Pt events (most reliable)
    - just compare the number of events in z: 320-500, Pt<0.12 GeV/c without the (Pt/Pz v.s. z) cut

“cutoff” in geant4

- halon + CV (CC00, CC02)
  - sample: eta produced events
- some structure in the momenta distributions of produced particles
  - condition of particles generated in gsim
  - γs
    - p > 0.04 GeV/c
  - neutrons
    - p > 0.395 GeV/c
  - protons
    - p > 0.395 GeV/c







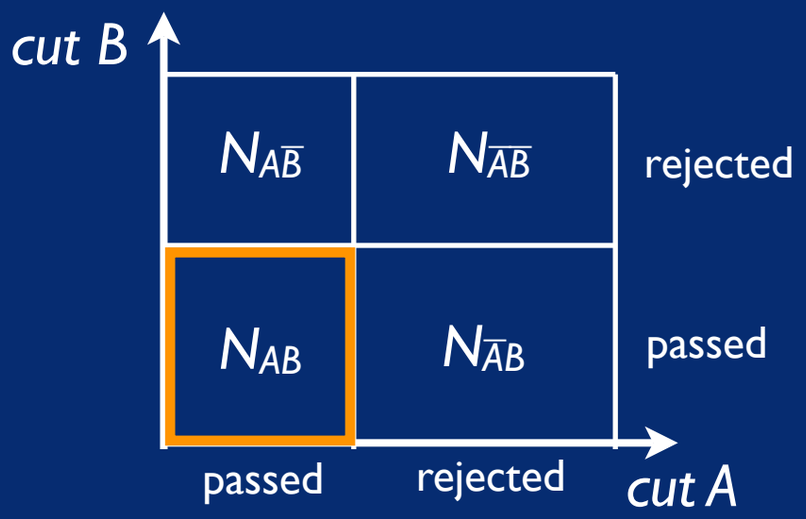
GeV/c

Downstream events

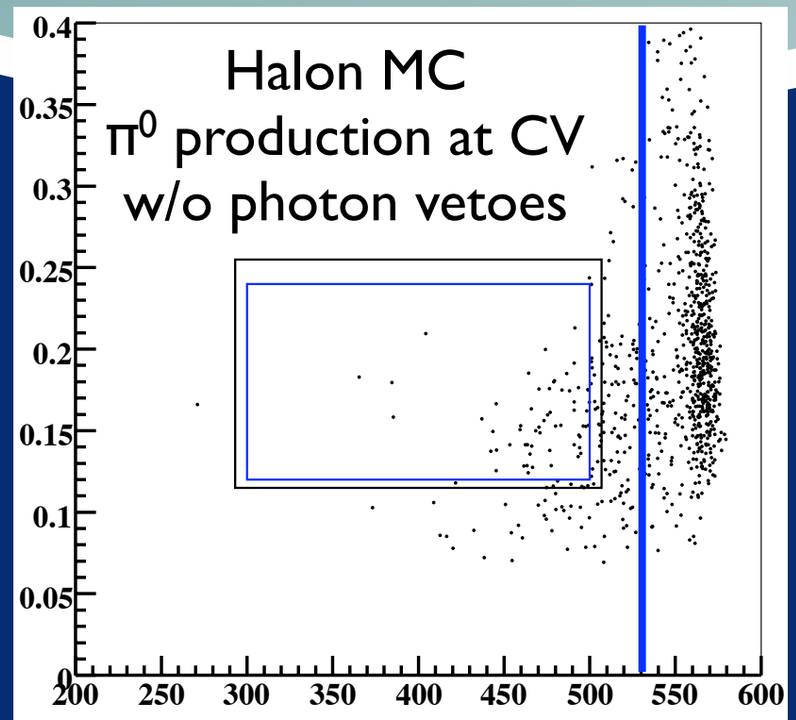
- looking at events with π0 productions at CV
  - data: 43 events, MC: 51.6±9.6 events
- BG sources
  - multi π^0 production
  - direct hits of neutrons
- bifurcation method
  - works at the downstream
  - BG estimation w/ MC to select only CV events

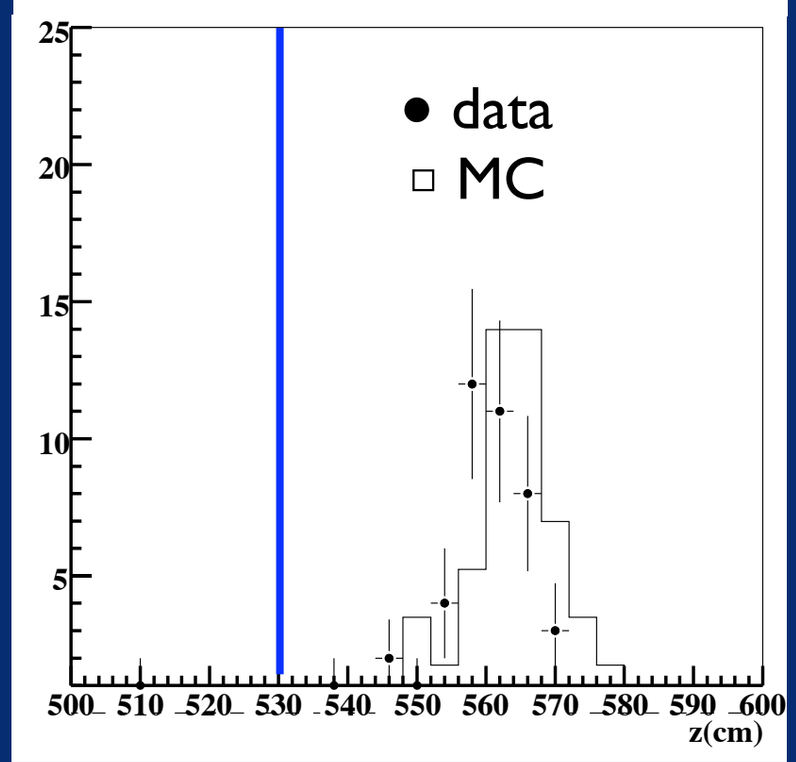
$N_{X\bar{Y}}$: number of events w/ cuts
" $\bar{}$ " : rejected

$$N_{A\bar{B}} / N_{A\bar{B}} = N_{\bar{A}B} / N_{\bar{A}\bar{B}}$$
$$\Rightarrow N_{AB} = (N_{\bar{A}B} \times N_{A\bar{B}}) / N_{\bar{A}\bar{B}}$$



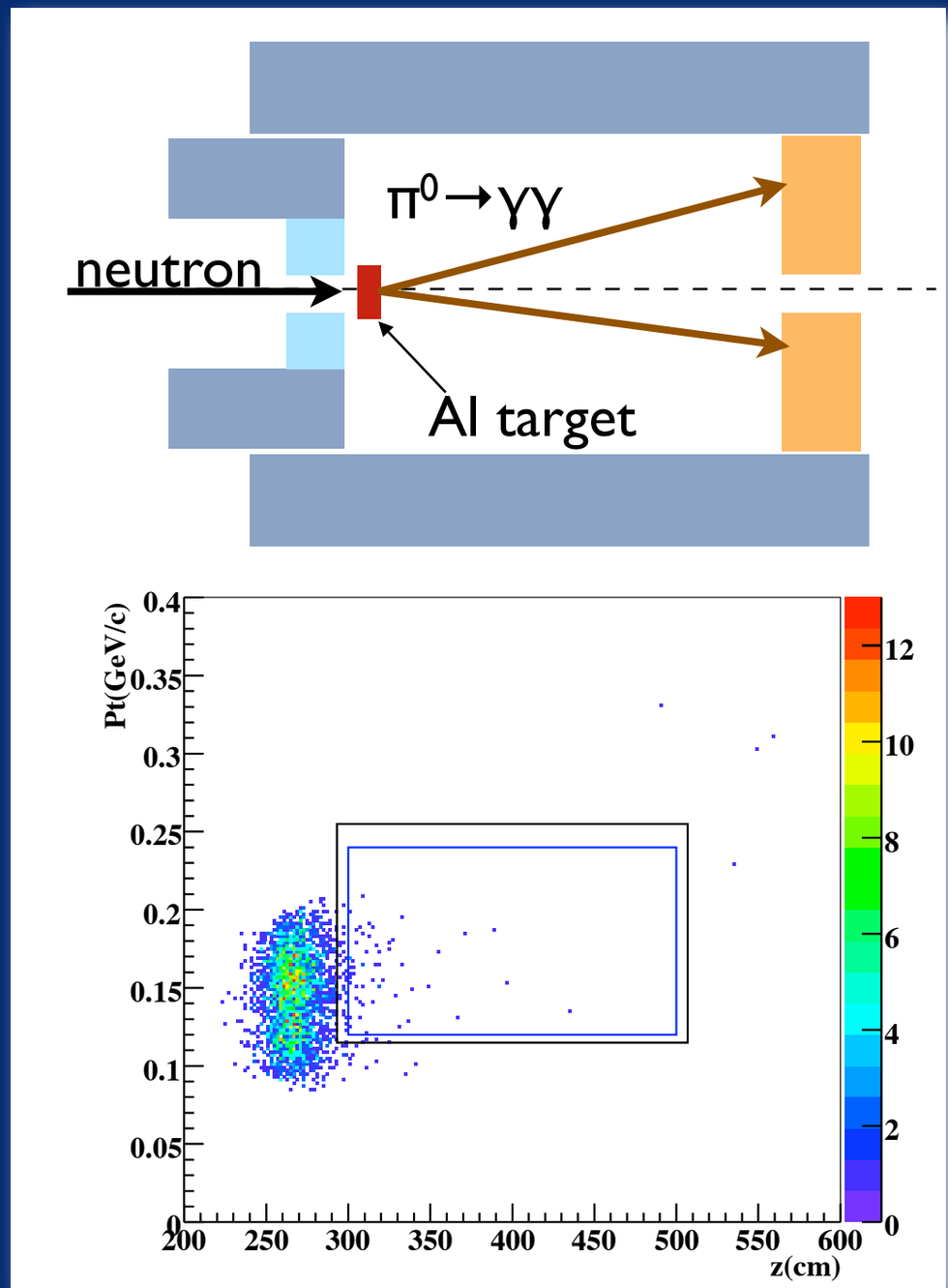
- cut sets
  - setup cuts
    - "pi0" cuts
  - set A
    - all veto detectors
  - set B
    - gamma selection





Upstream events

- estimation by π^0 production target run
  - 5mm-thick Al production target at the entrance of decay region
- "core" neutrons hit it and produce π^0's
  - used for correction of calibration w/ known vertex
- Half intensity of primary proton
- look at the behavior of the tail by leakage
- same cuts for $\pi^0\nu\bar{\nu}$ analysis
- ~ 3000 CC02 events (halon MC: ~20 events)



signal distribution