A search for $K_L \to \pi^0 \nu \bar{\nu}$ at KEK-PS E391a experiment

Oct. 30th 2006

APS-DPF/JPS Joint Meeting

T. Sumida (Kyoto Univ.)

The E391a collaboration

The E391a collaboration

- 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.

The E391a experiment

- 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
    - using full sample to check data
    - analyzing 1/3 data to study backgrounds
  - Run-III : Nov. 2005 - Dec. 2005

Report the current status of Run-II 1/3 data analysis

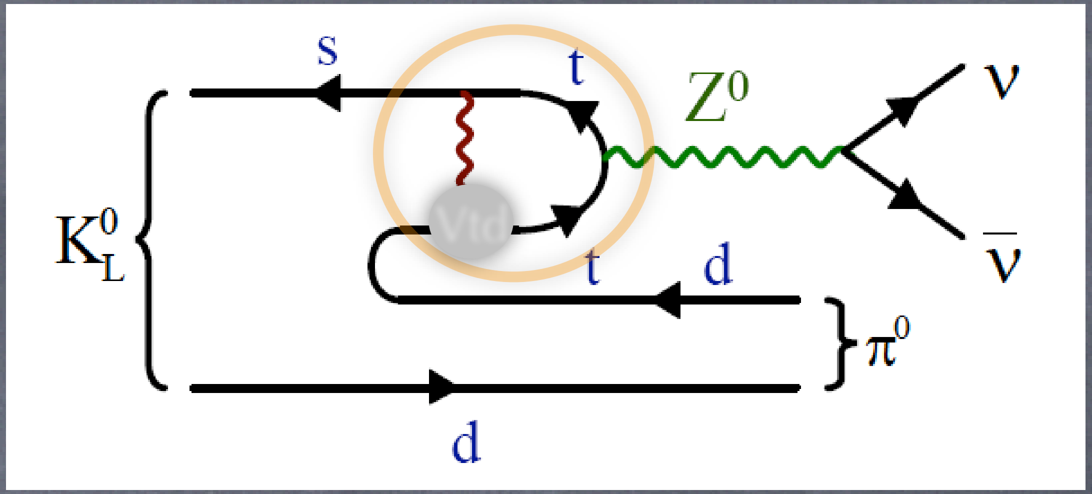
Physics motivations

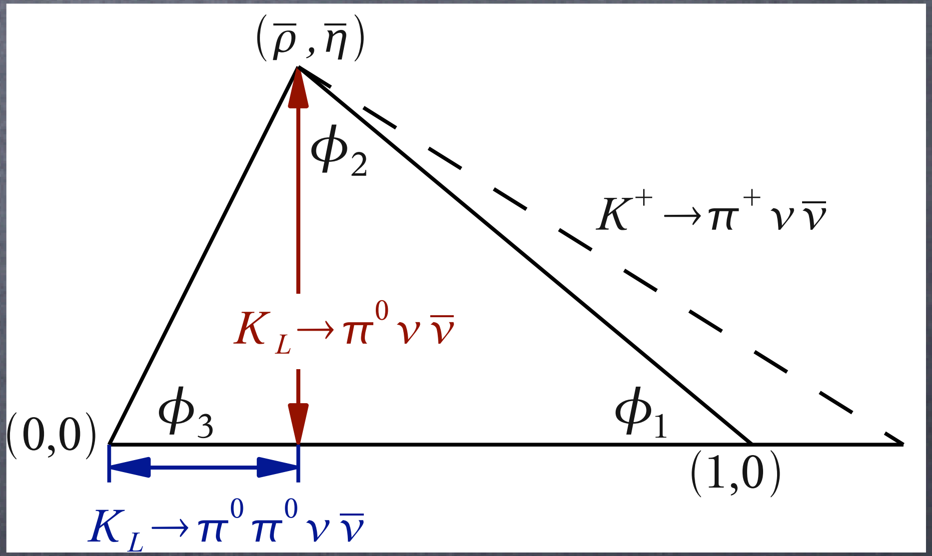
- $K_L \to \pi^0 \nu\nu$
  - Direct CP violation
  - FCNC process with $\Delta S = 1$
- Measurement of the branching ratio
  - $A(K_L \to \pi^0 \nu\nu) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td}$

    $= 2 \times V_{ts} \times Im(V_{td}) \propto \eta$

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

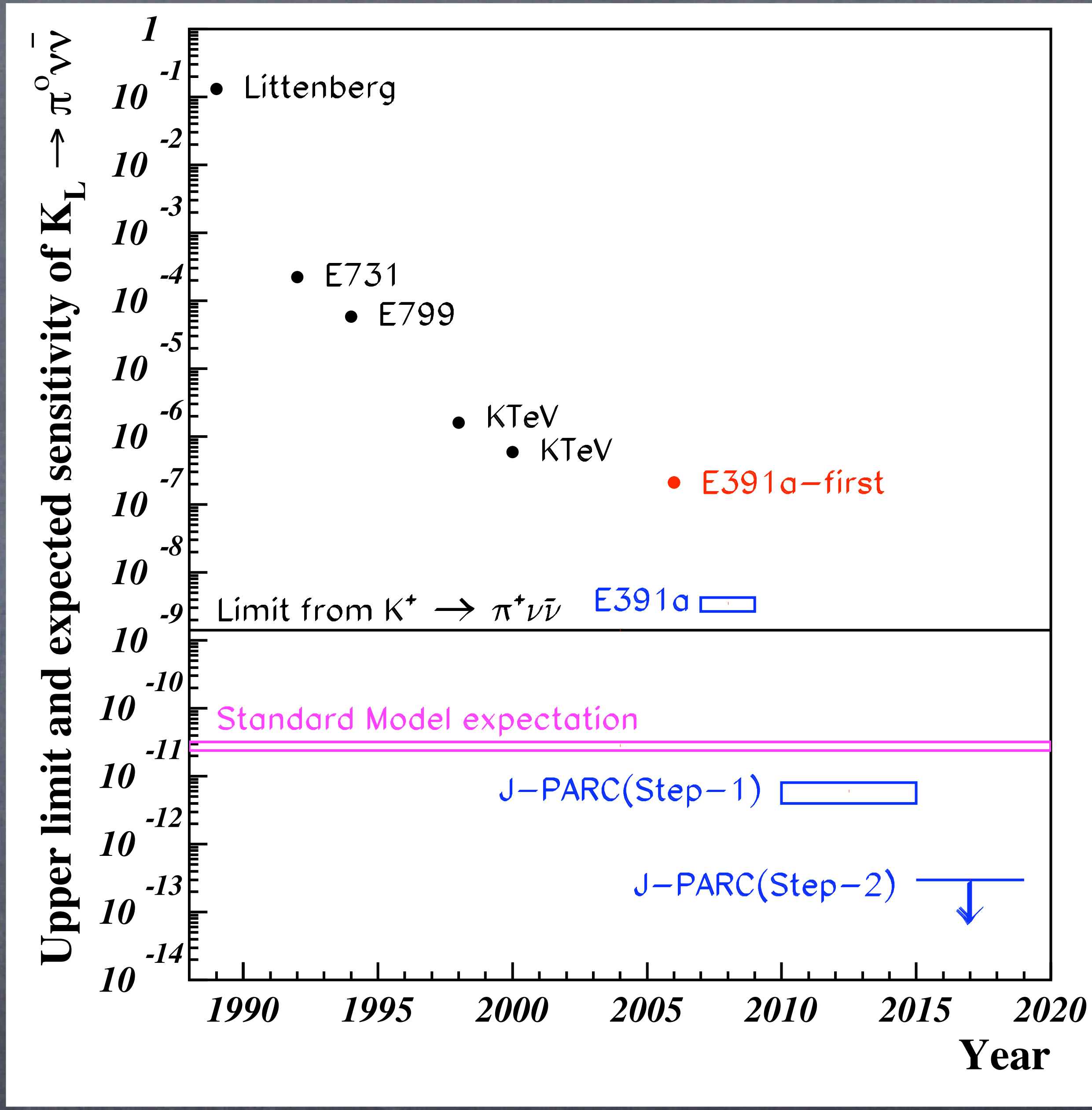
    : **Direct measurement of η**
  - small theoretical uncertainty
    - Br→η : **σ ~1-2%**
  - **$Br(K_L \to \pi^0 \nu\nu)_{SM} \sim (2.8 \pm 0.4) \times 10^{-11}$**
  - **Unitary triangle by Kaon**
    - consistency between K^0 and K^+
    - comparison with B
  - Loop in the diagram (EW penguin)
    - The probe for new physics





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

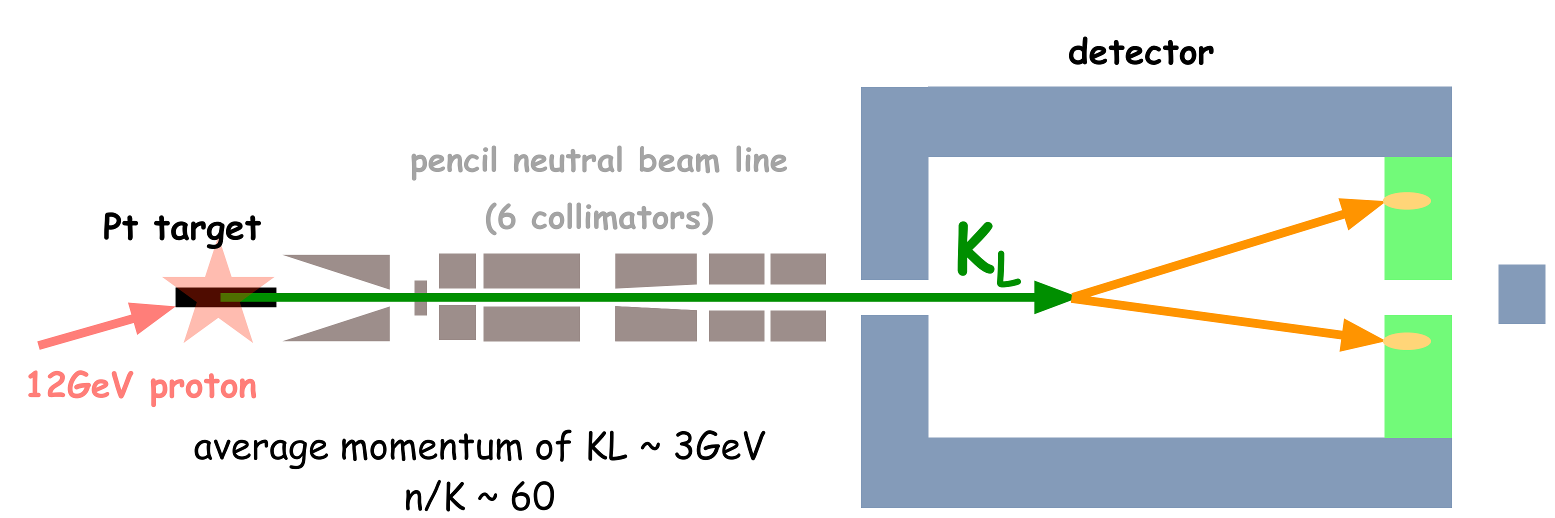
- extremely challenging
  - small branching fraction
    - many background sources
  - 3 body decay
    - weak kinematical constraint
  - all particles neutral
- Current upper limit
  - Br < 2.1×10^{-7} (90% C.L.)
    - E391a, PRD 74:051105, 2006
- Step by Step approach
  - E391a
    - The first dedicated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



Principle of the experiment

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

(1) measure the gamma hit position and energy



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↓

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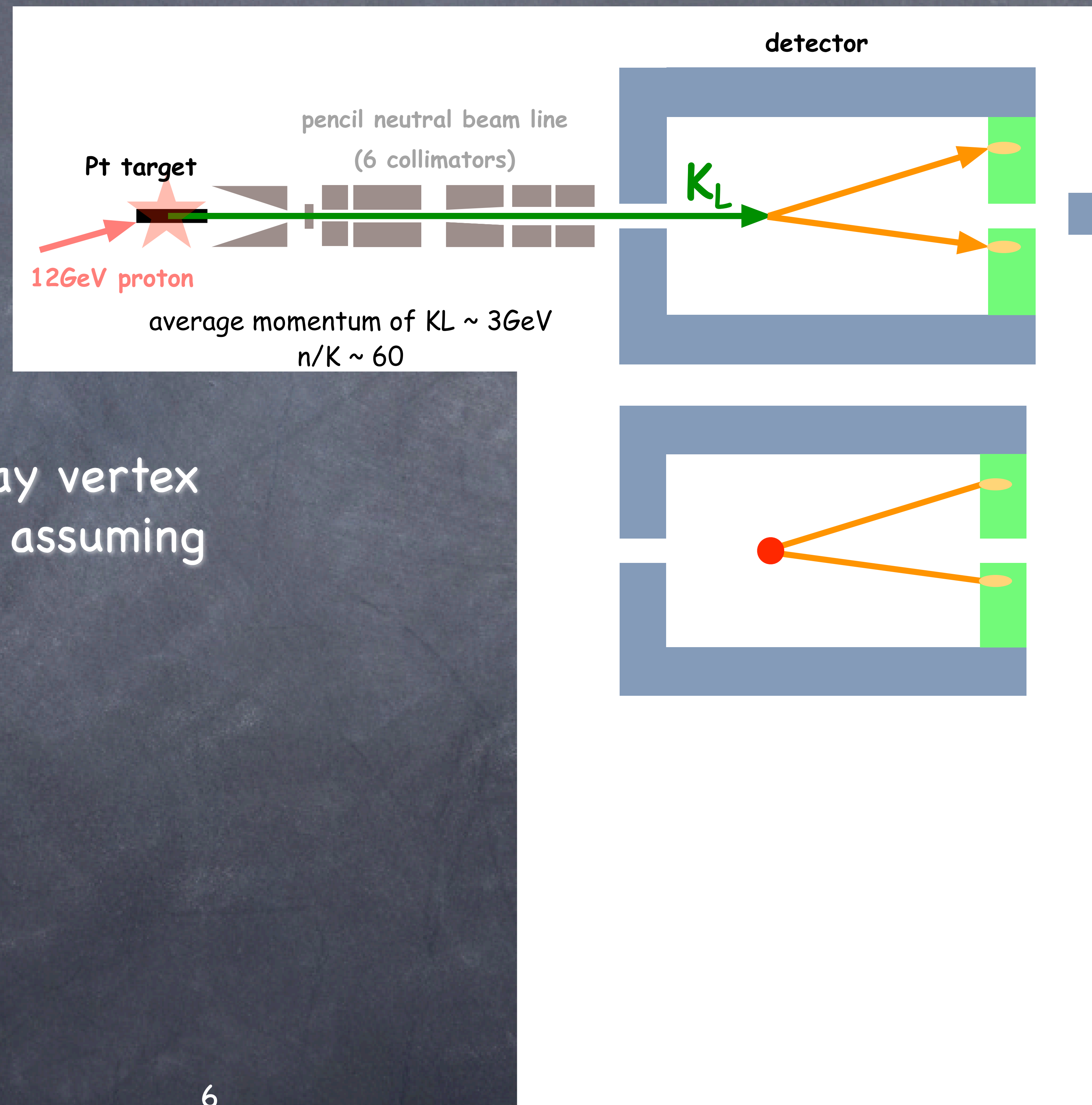

Principle of the experiment

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

(1) measure the gamma hit position and energy

↓

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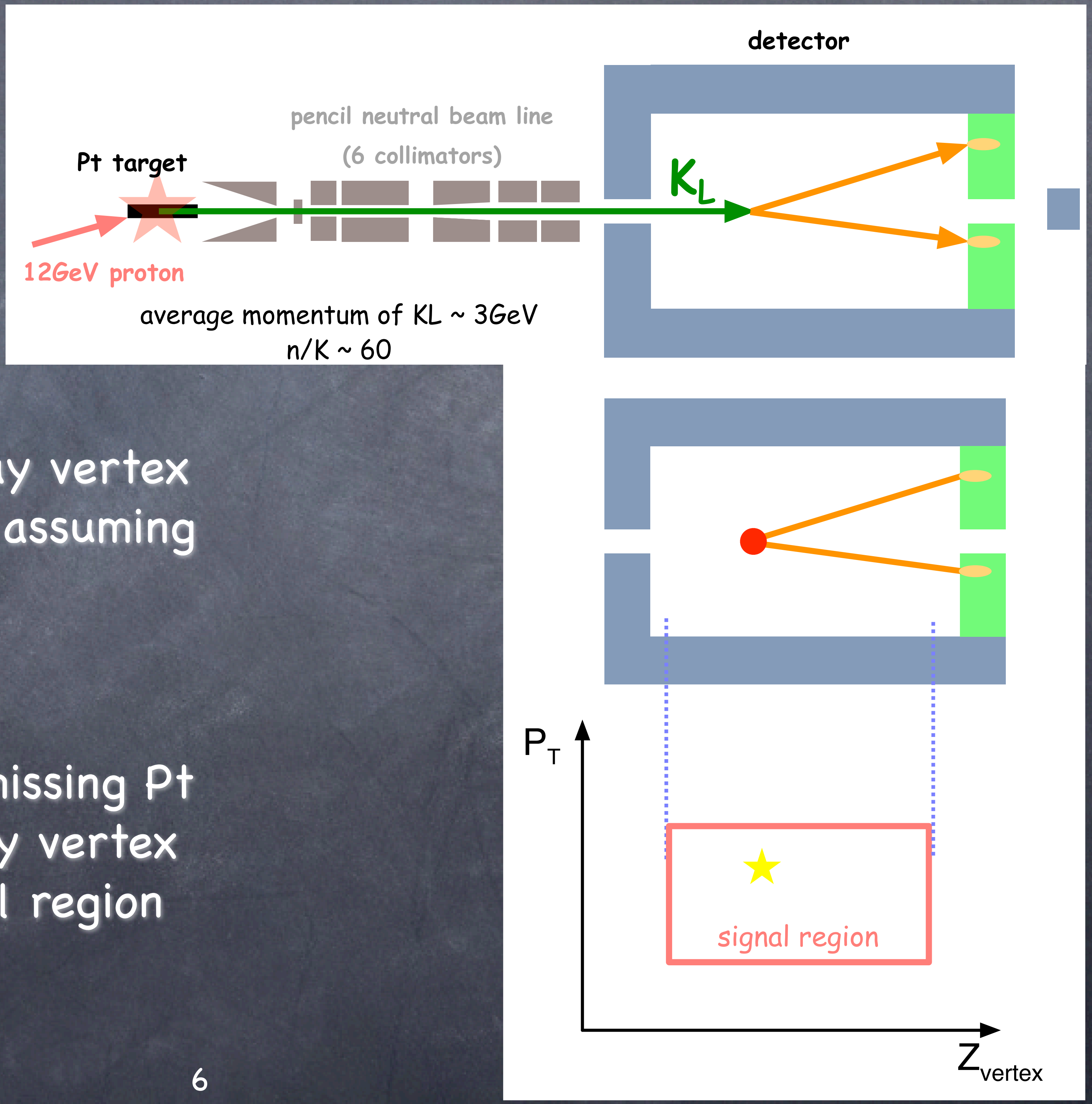
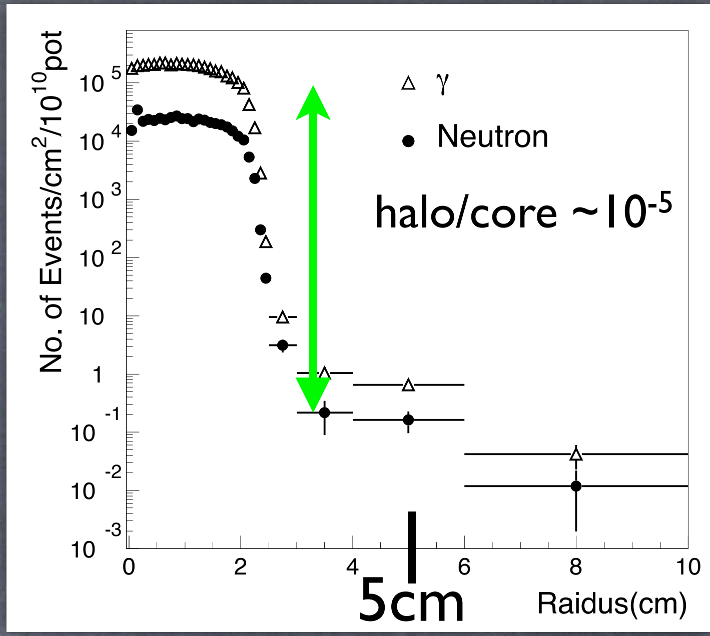
↓

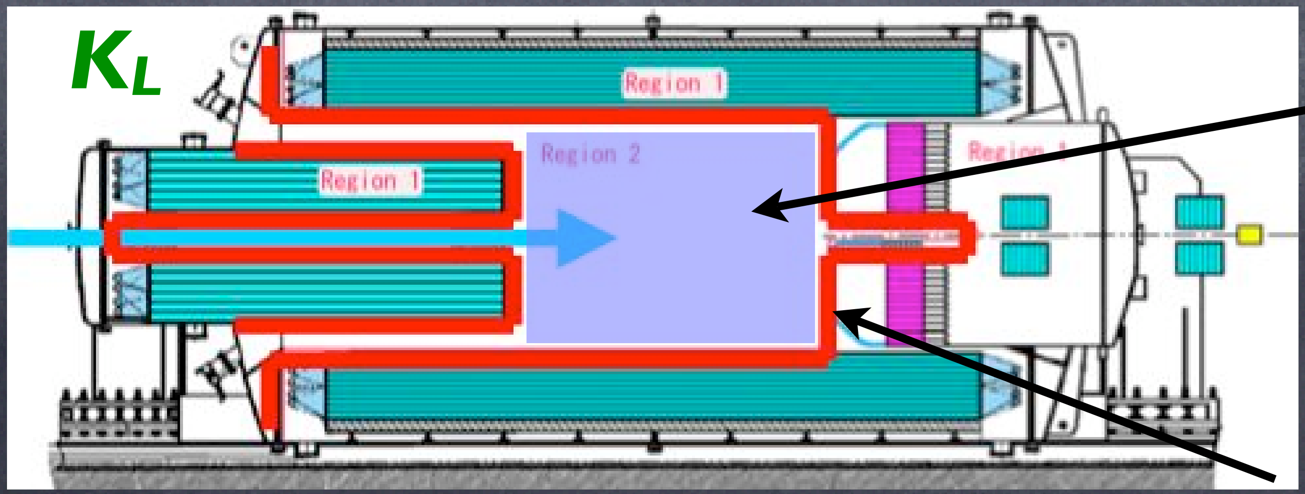
(3) require the missing Pt and the decay vertex in the fiducial region



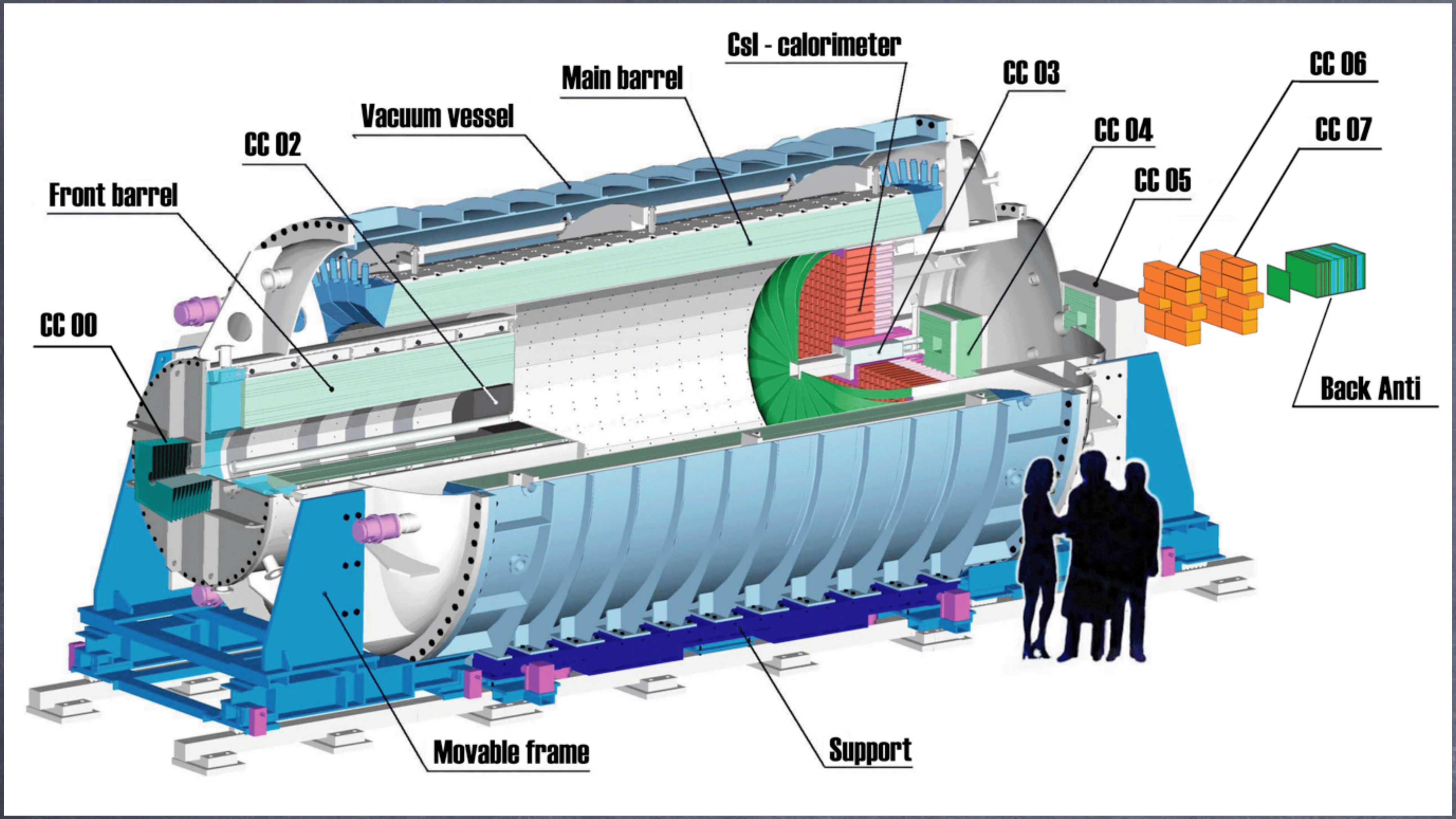
Features of E391a

- "Pencil" beamline
  - 8cm diameter at CsI (16m from the target)
- Hermetic veto system
  - reject the background from $KL \rightarrow 2\pi^0$
- 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





E391a Detector



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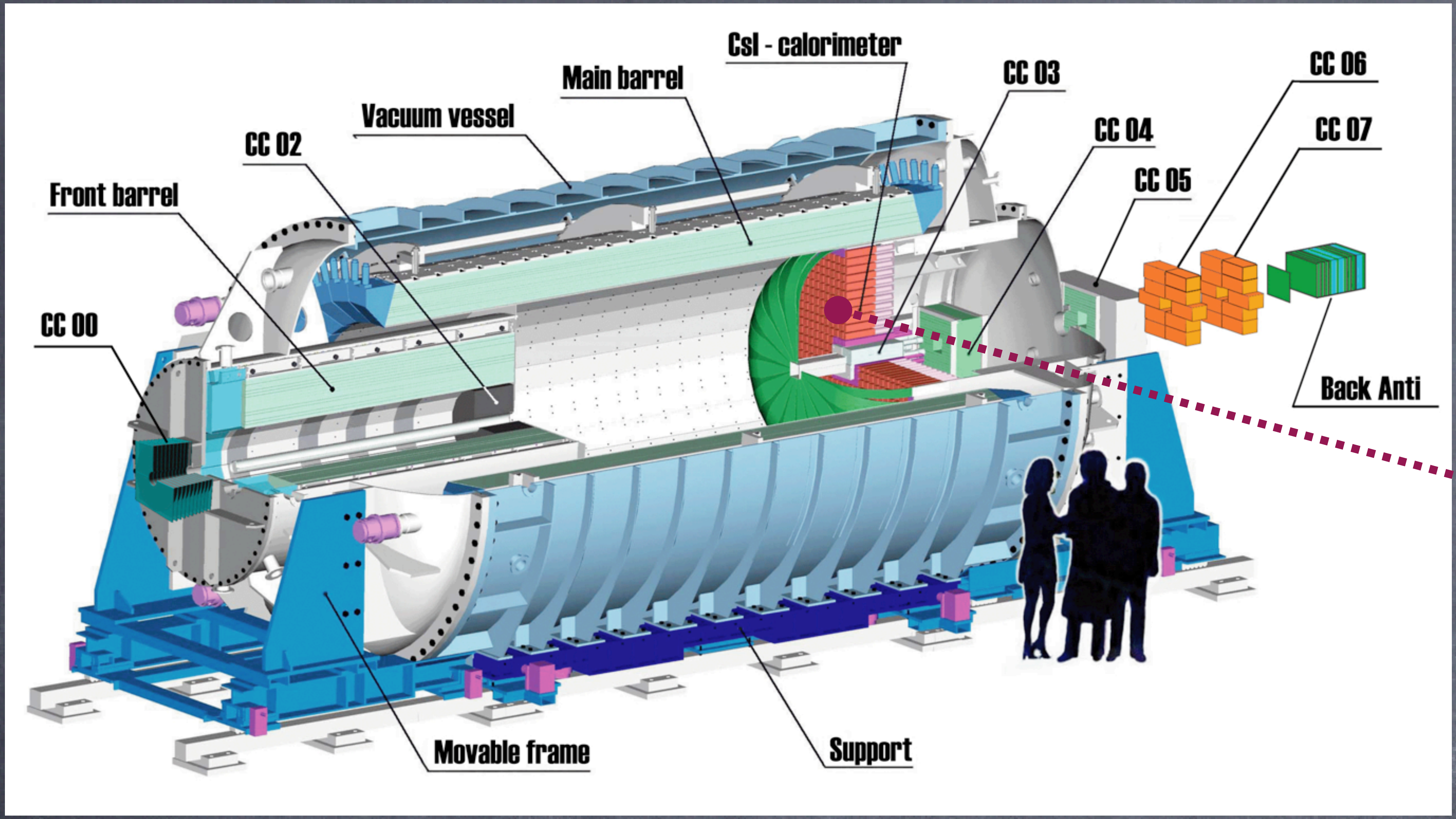

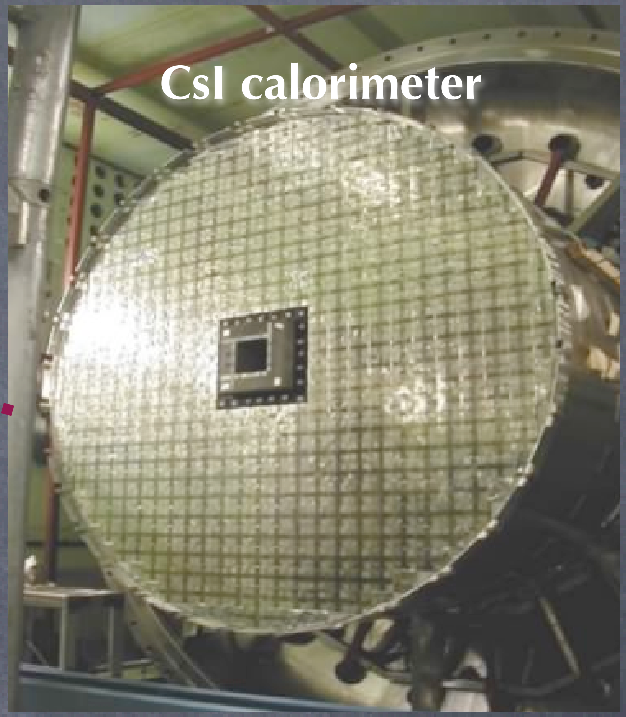

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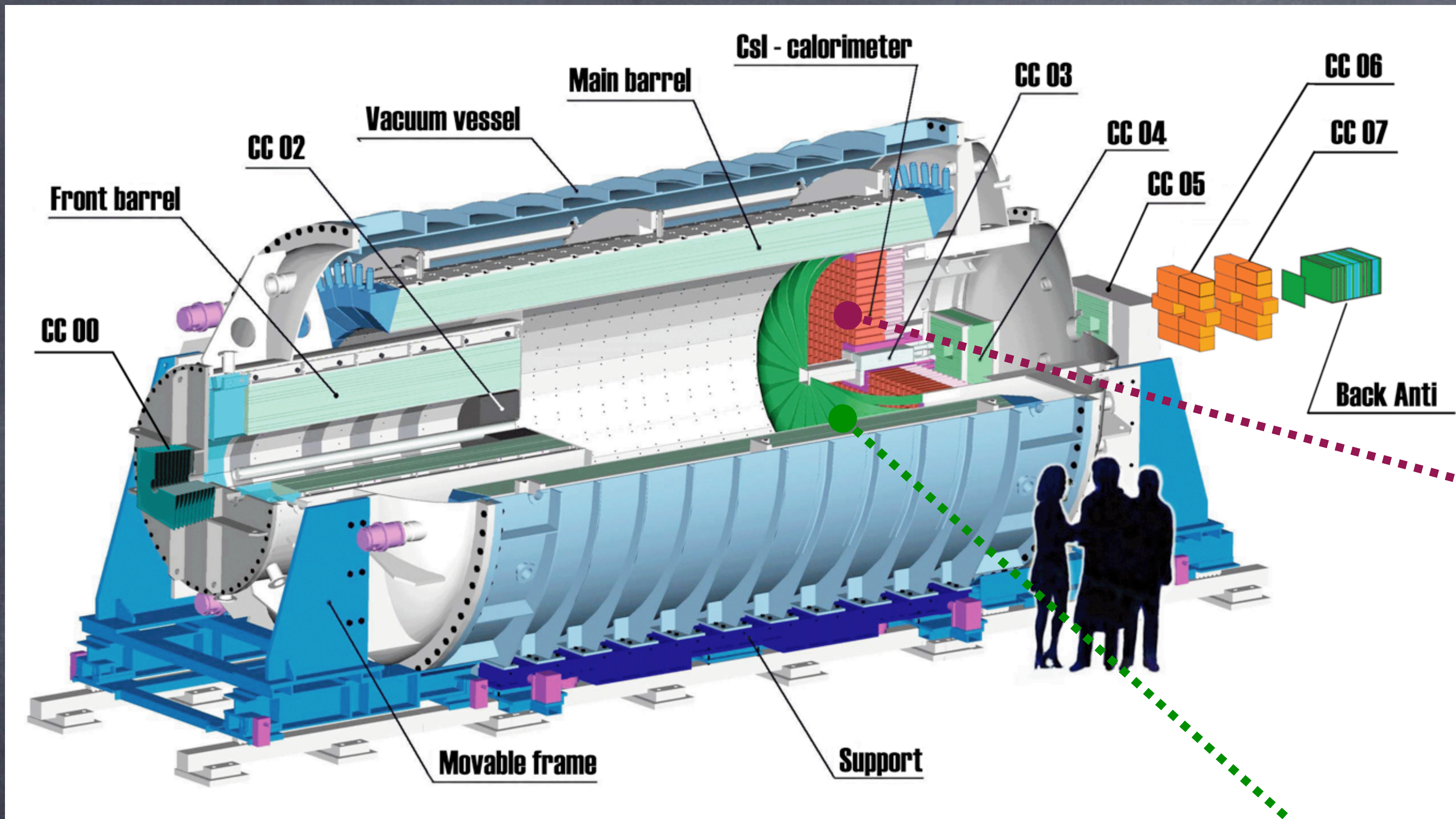

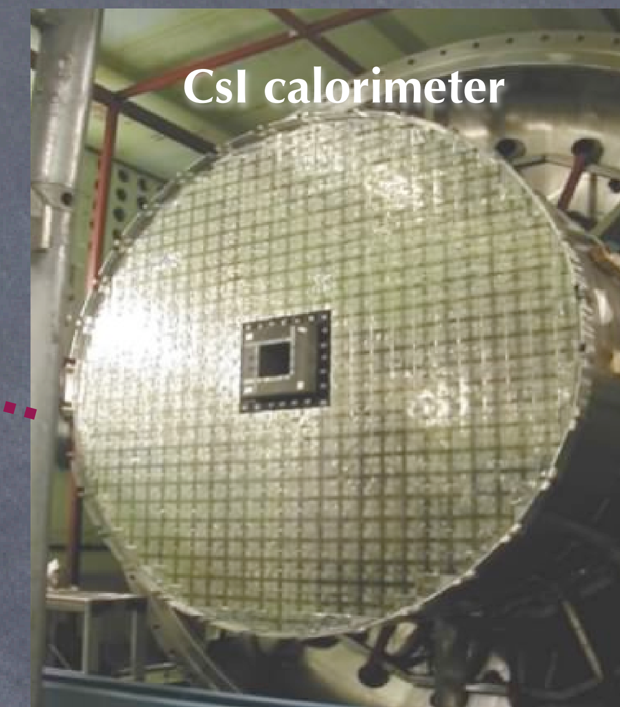

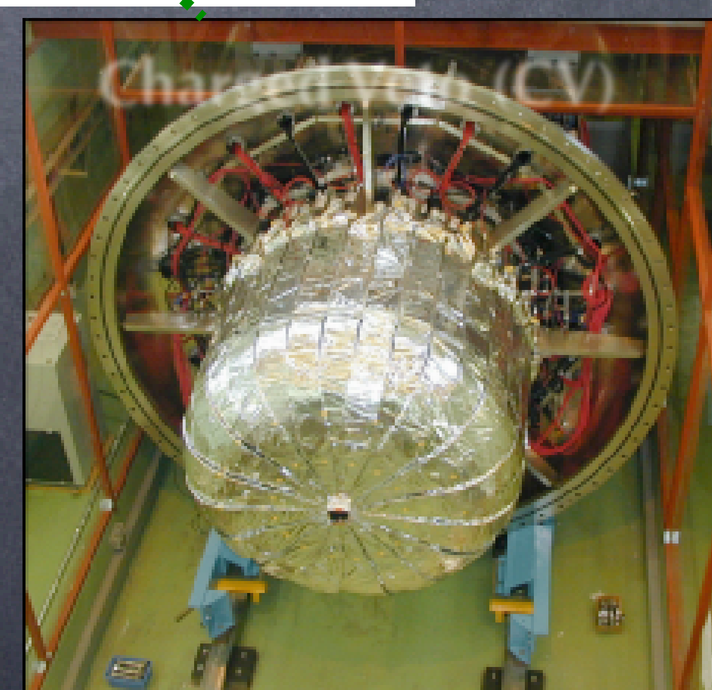

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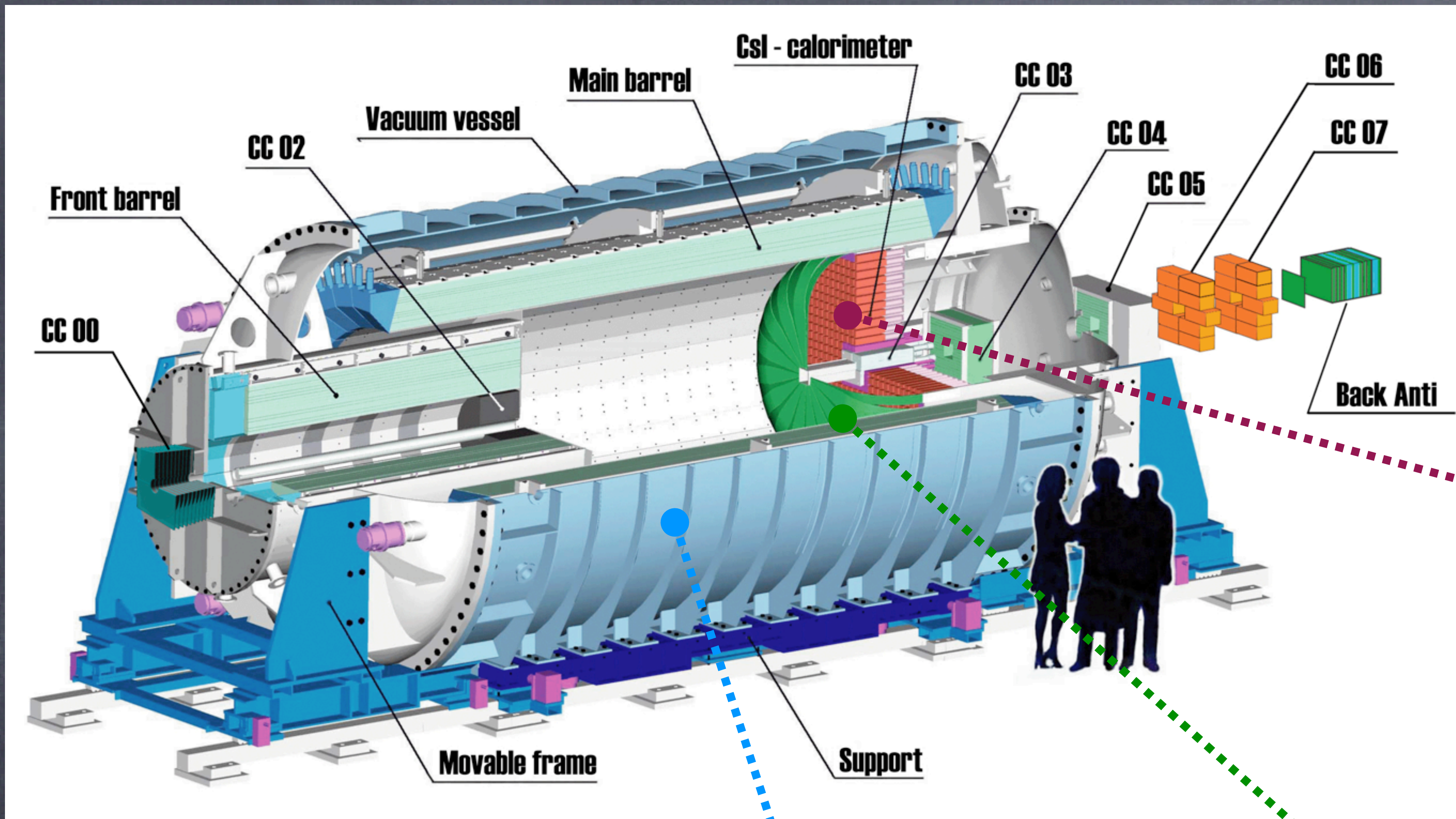

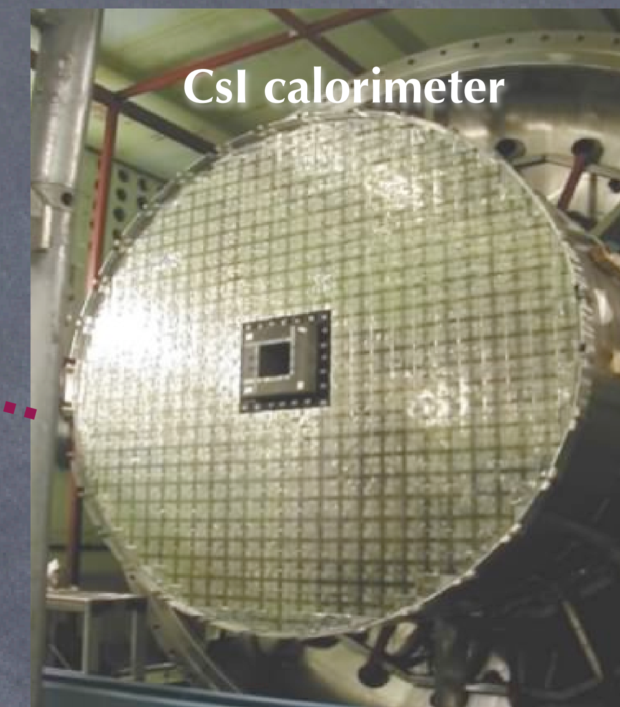

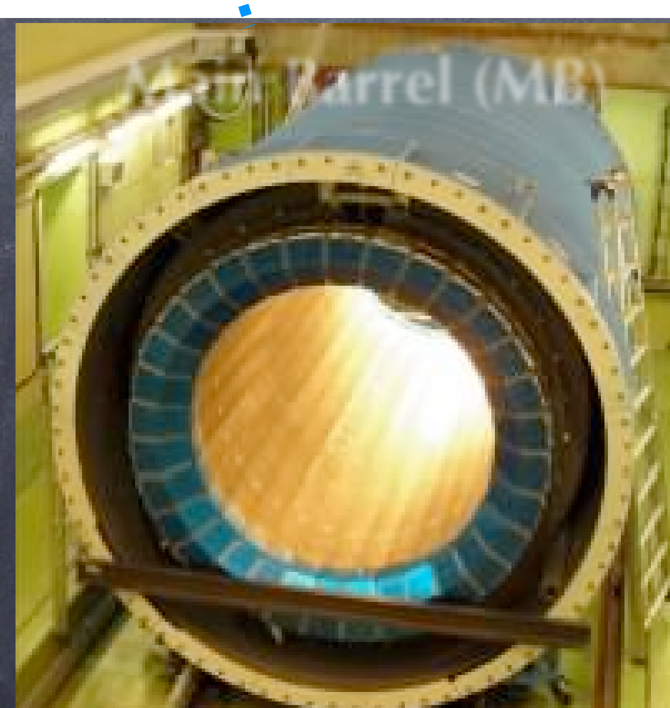

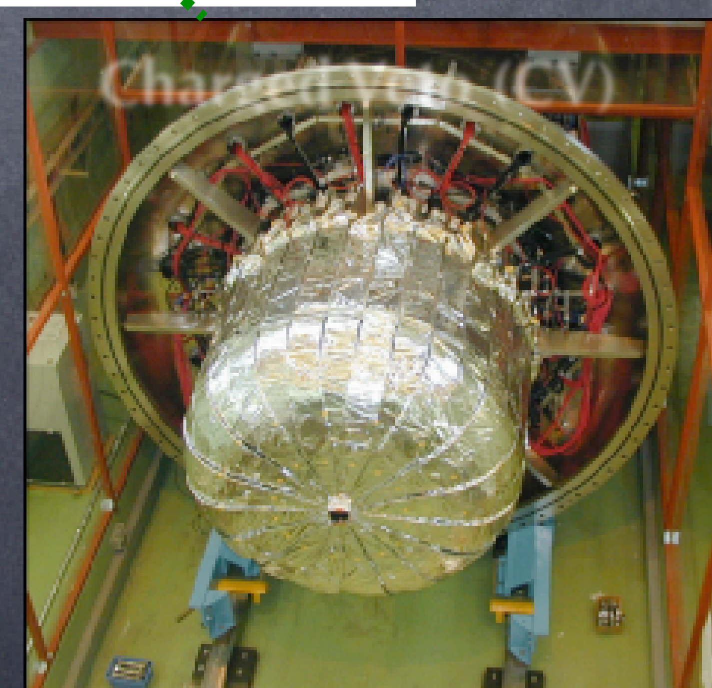

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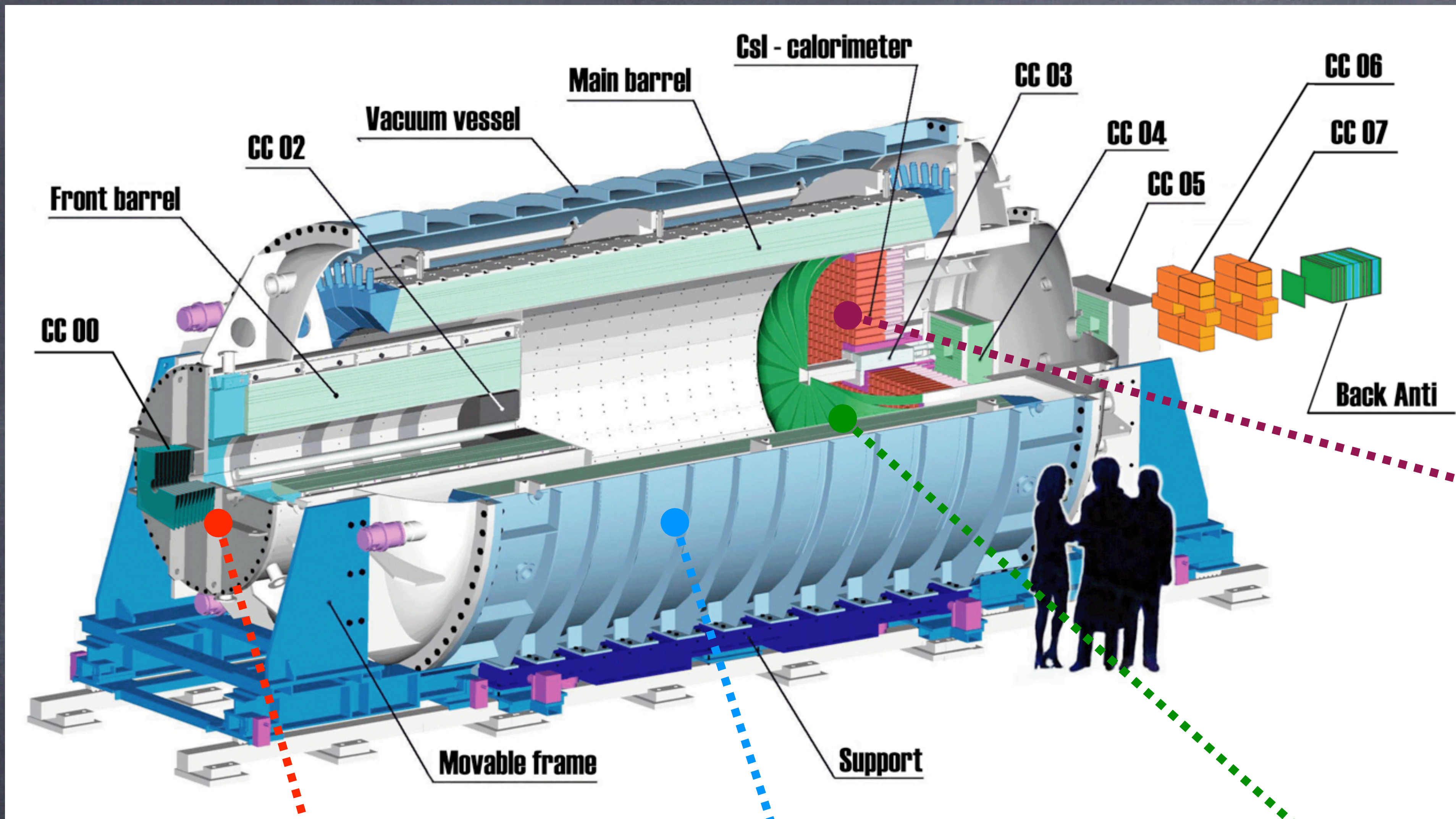

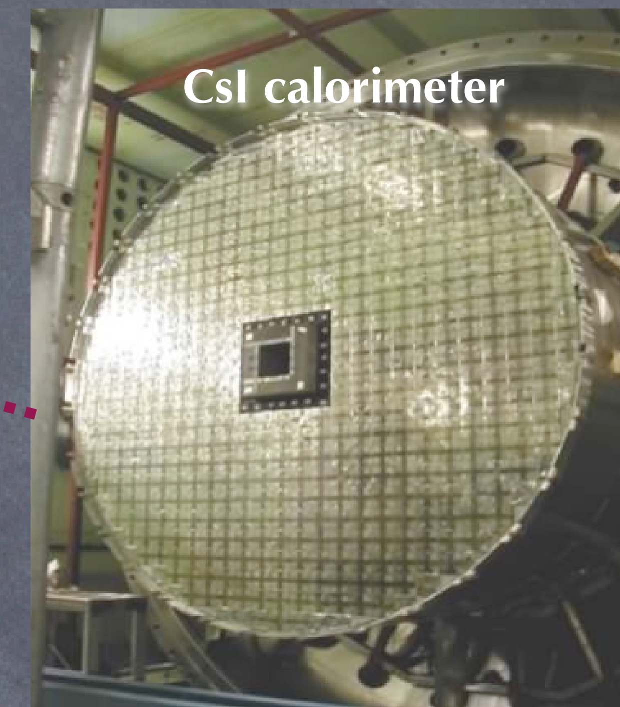

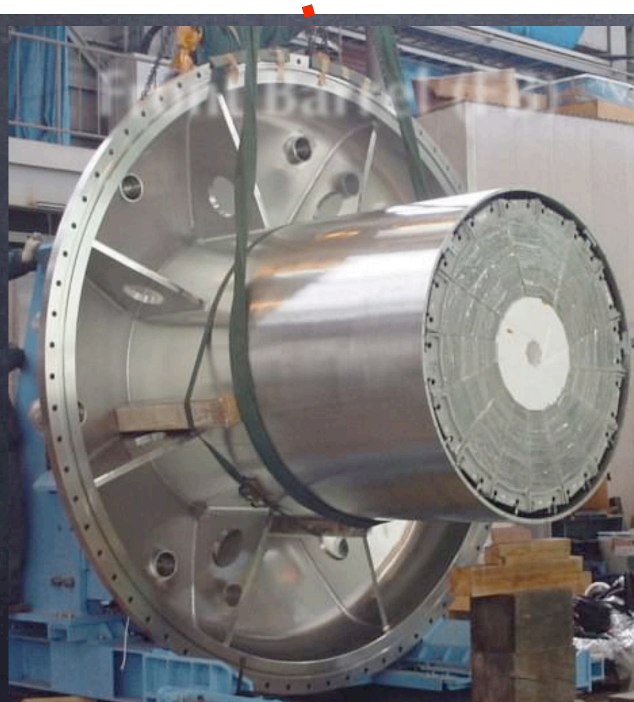

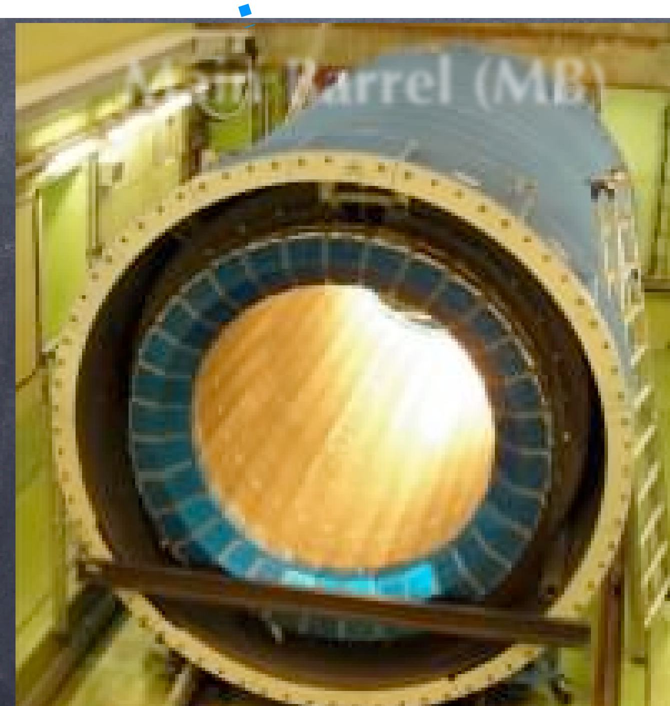

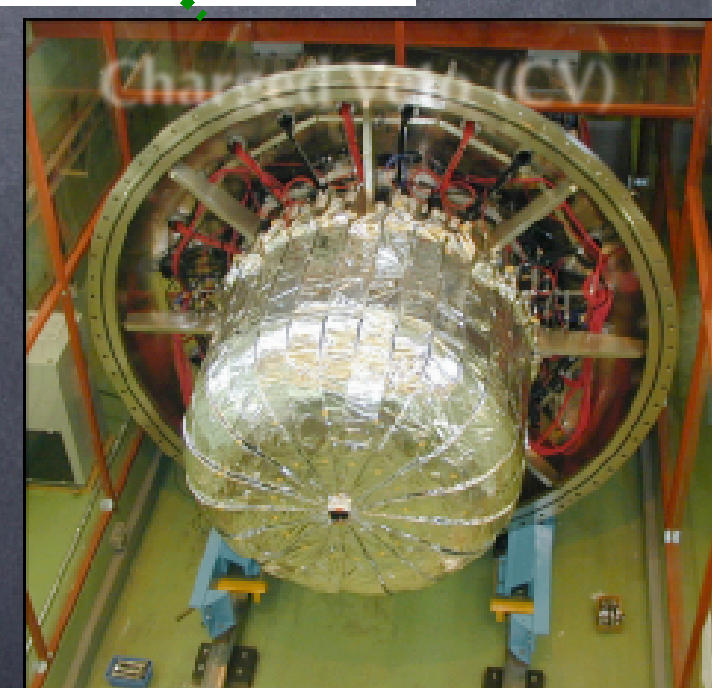

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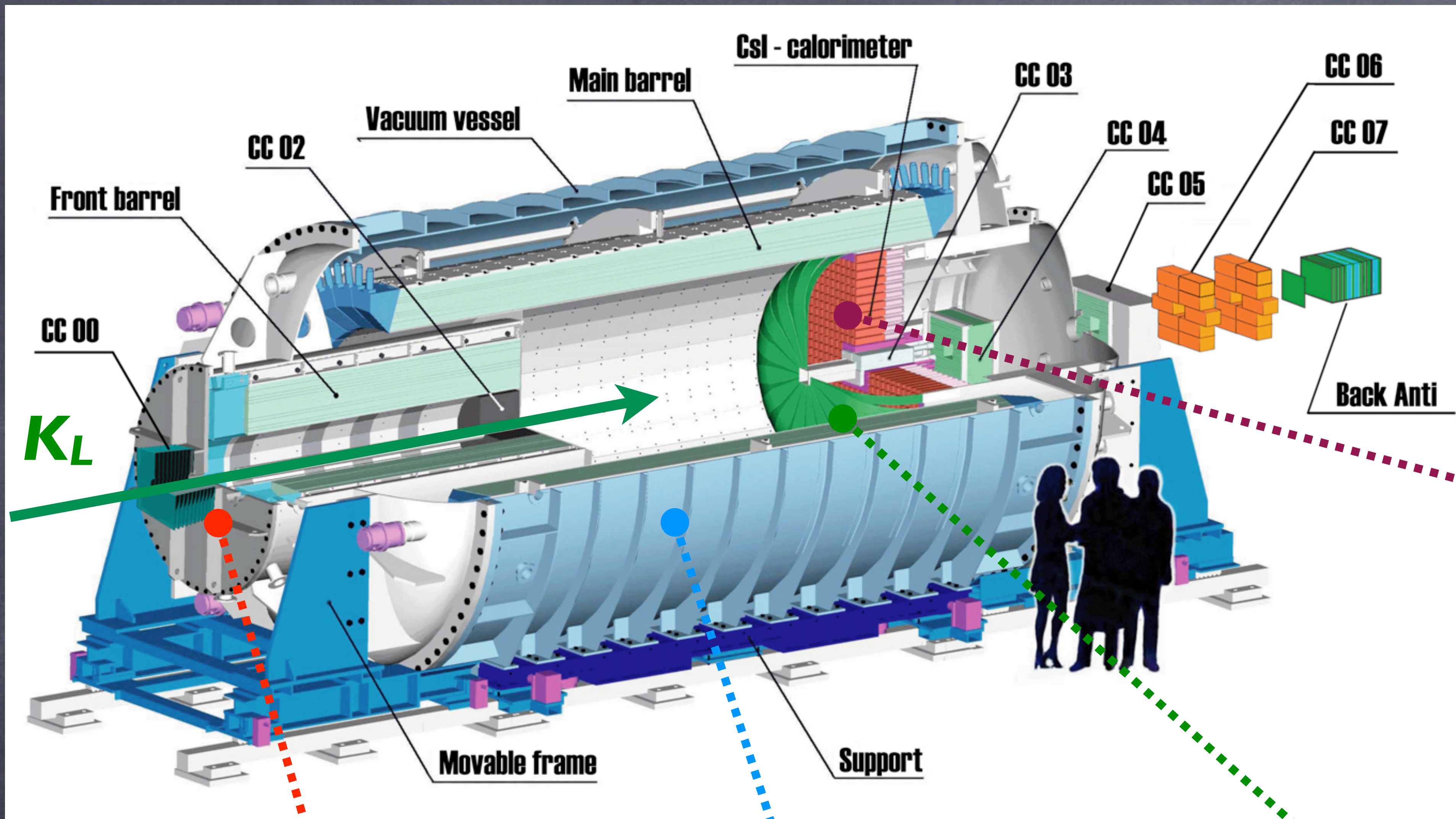

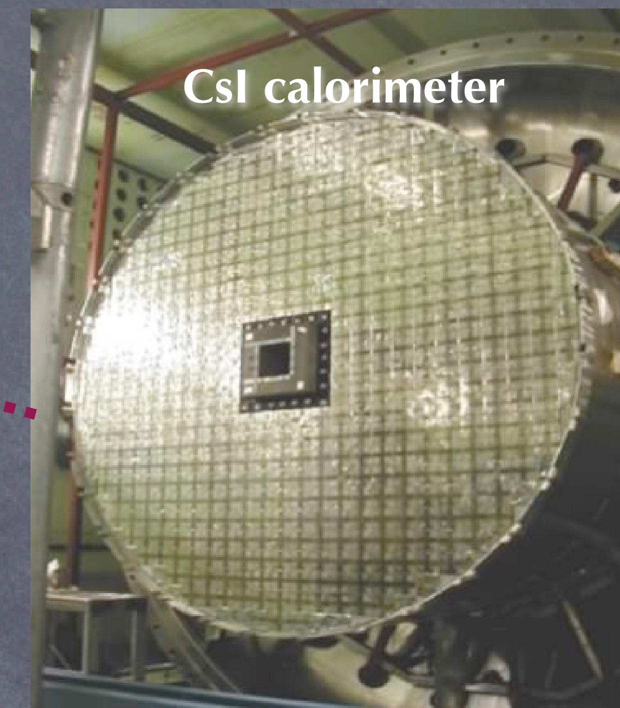

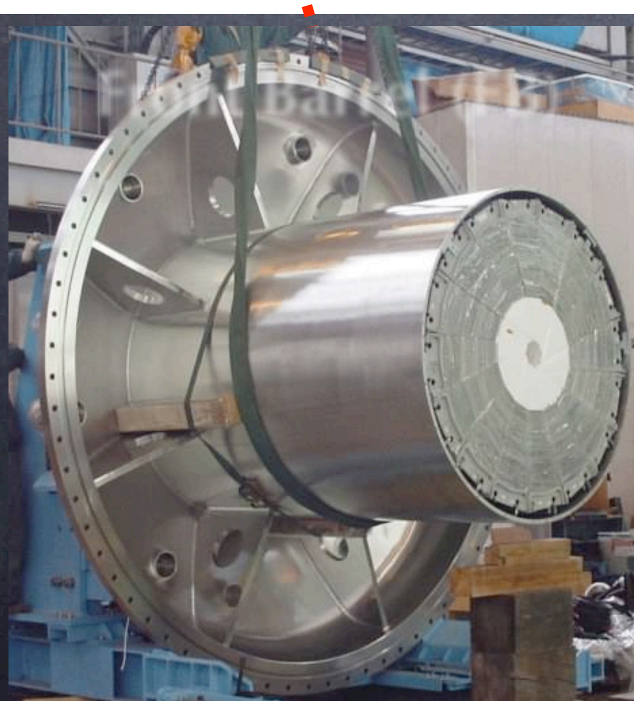

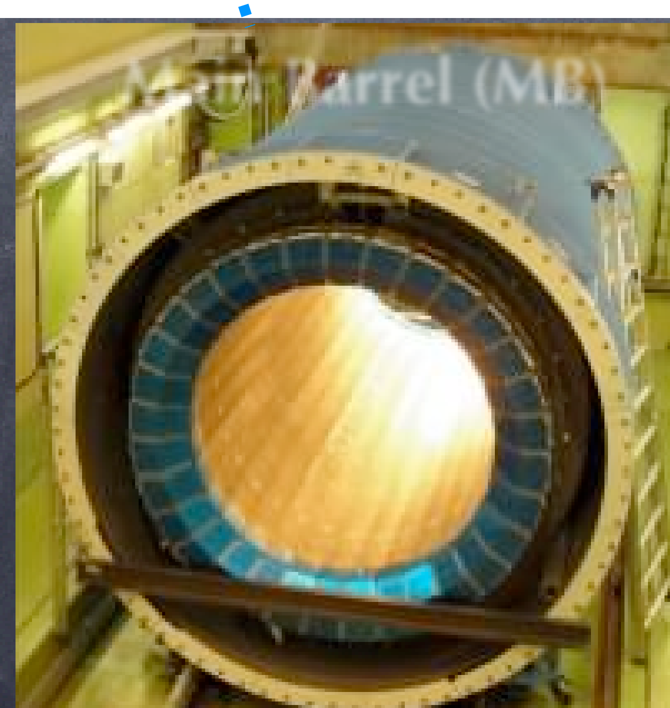

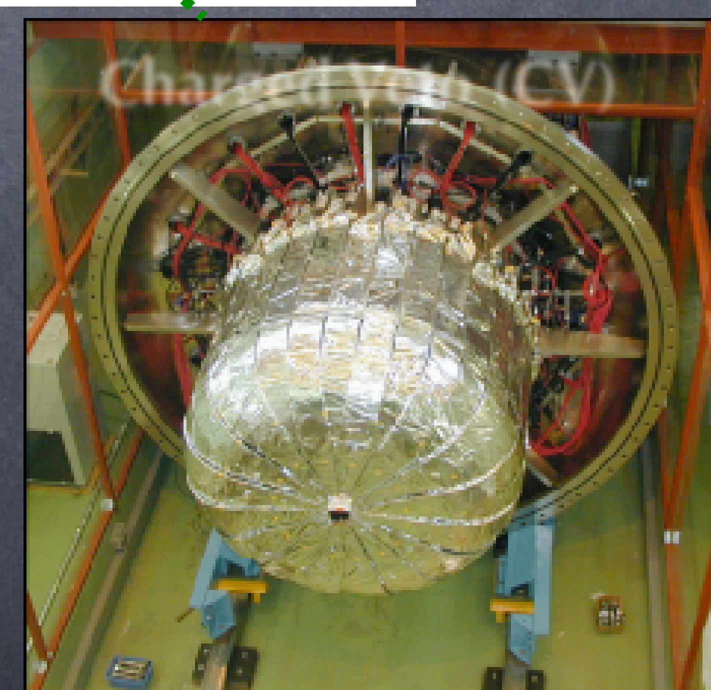

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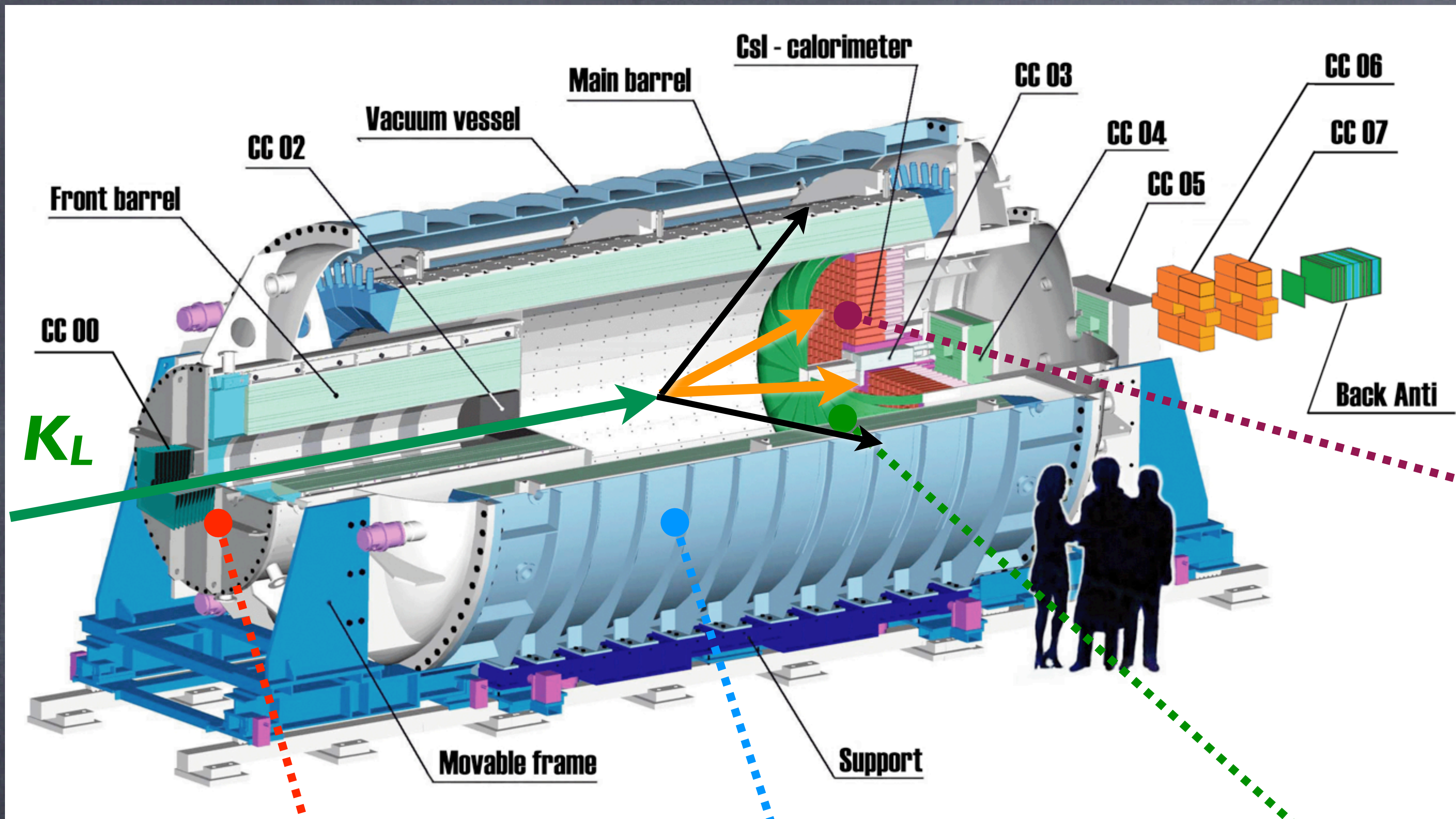
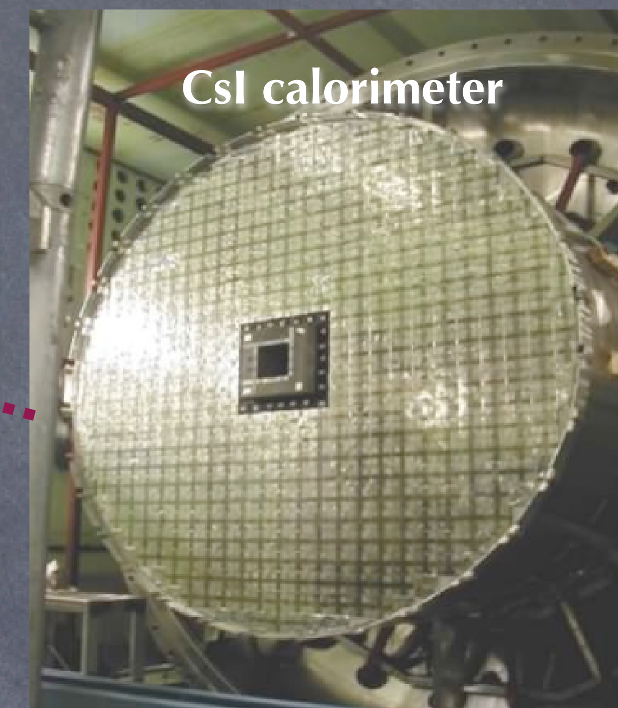
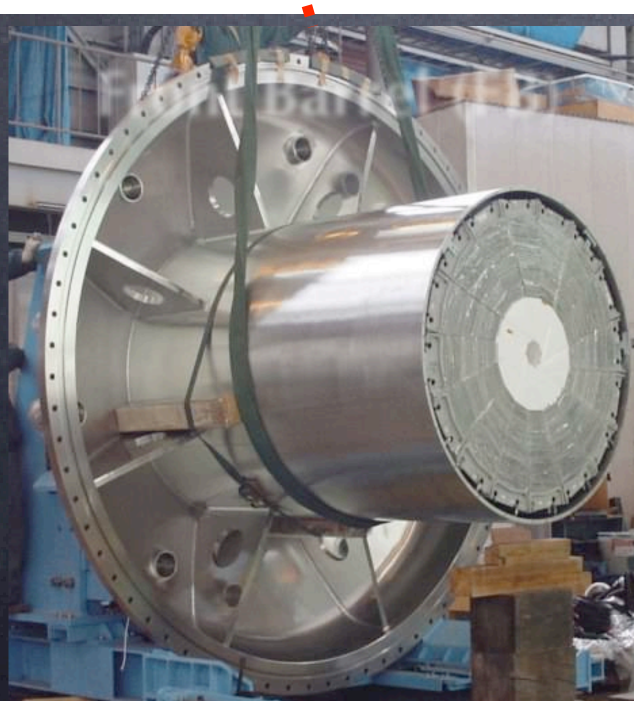
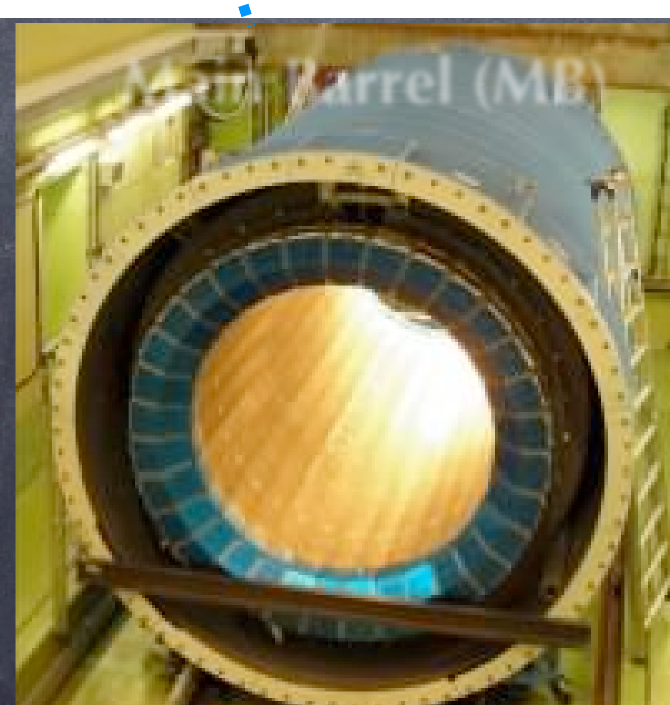
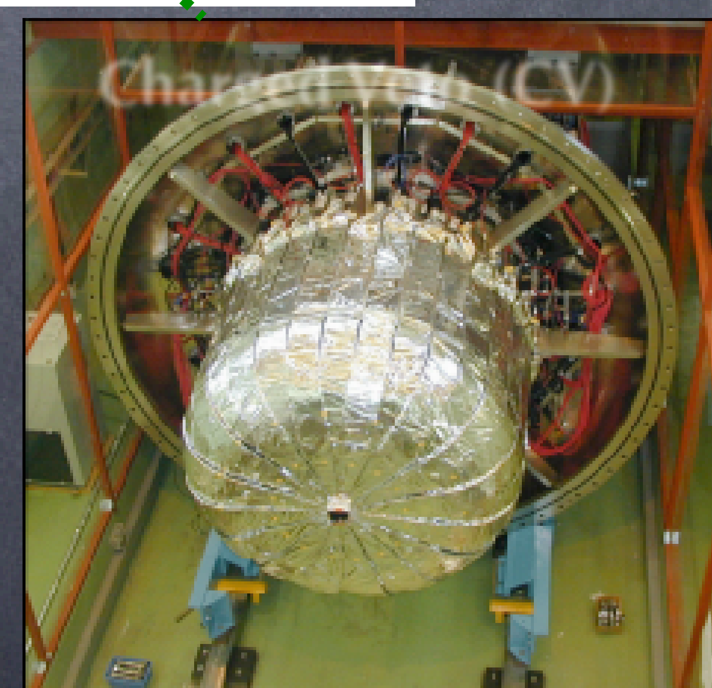


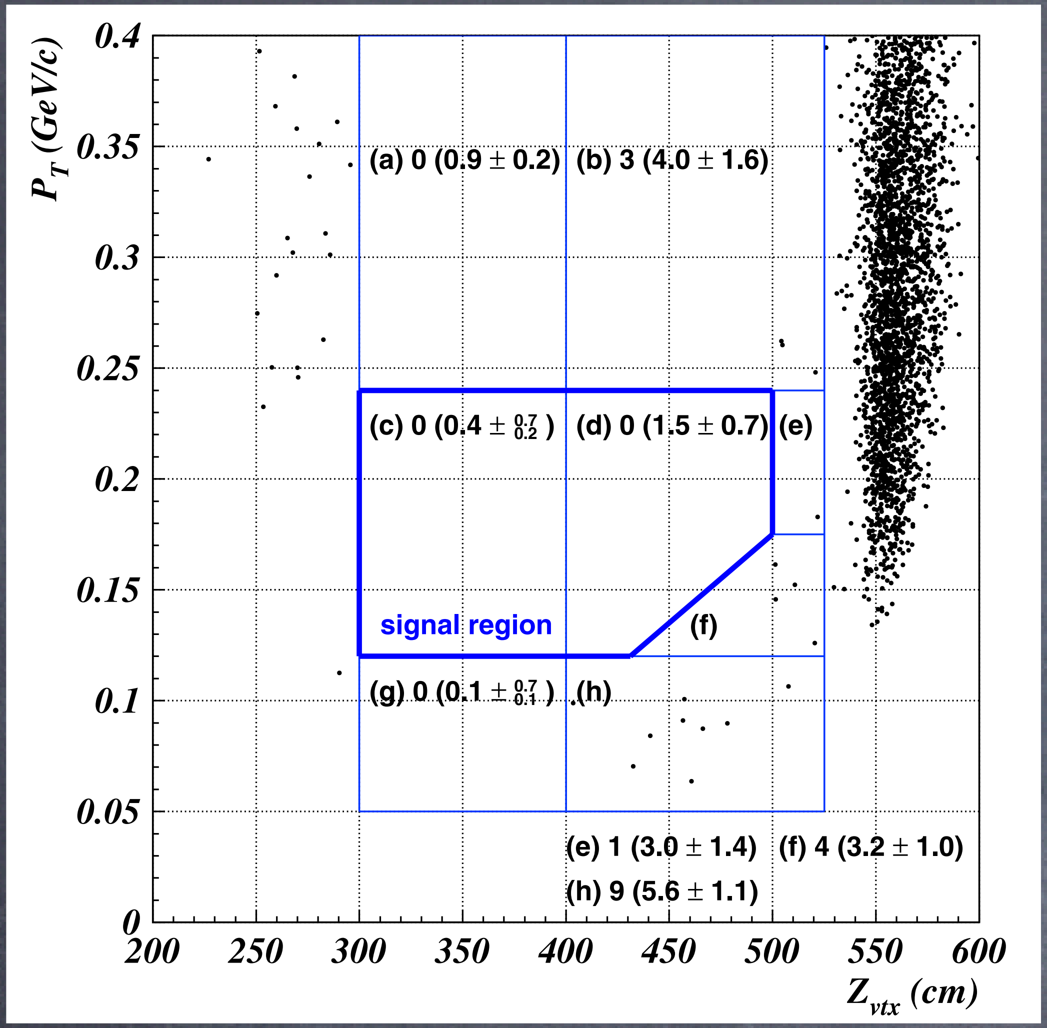




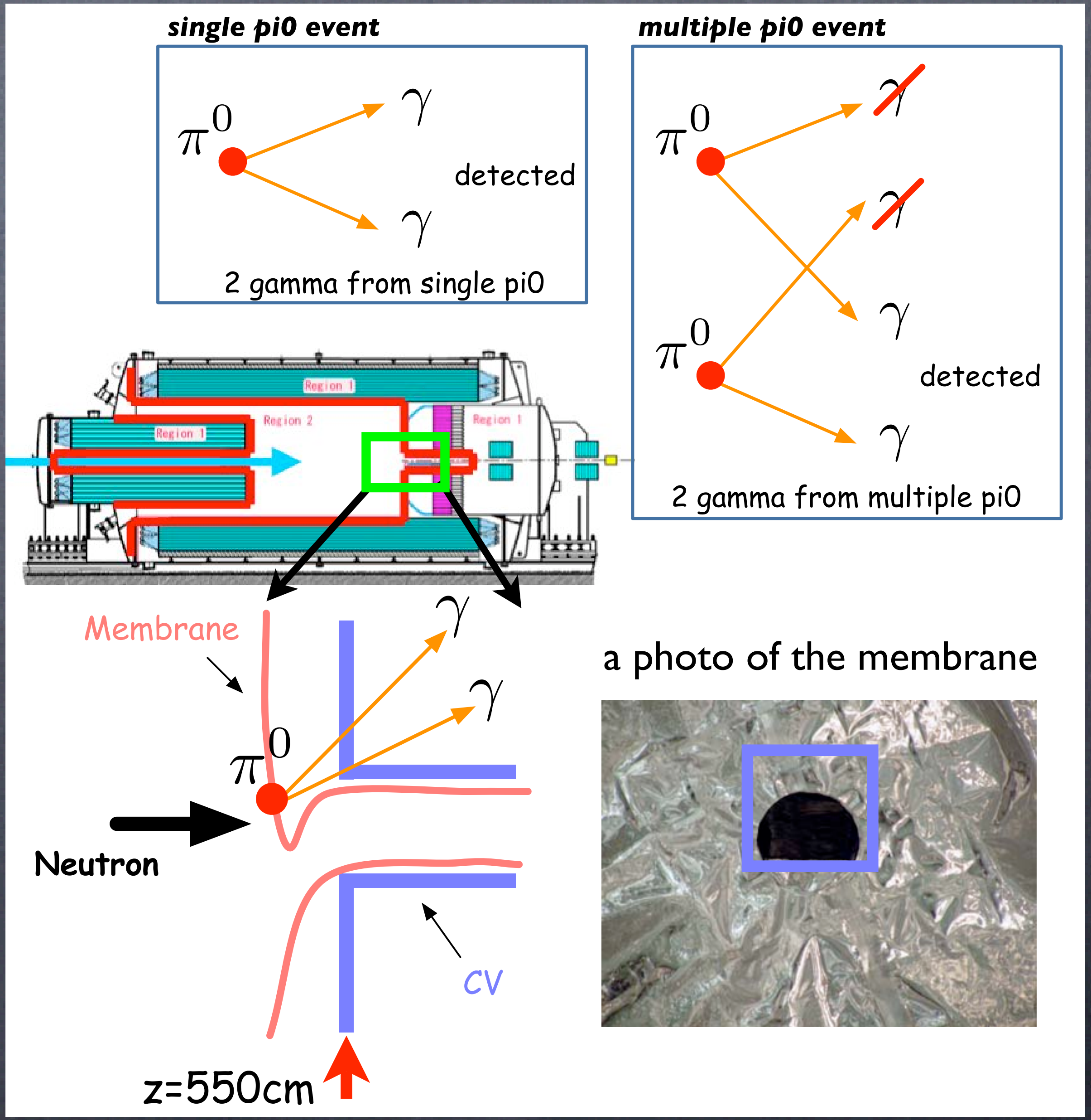




Result from Run-I 1week



- 10% of Run-I data
- Establish the basic analysis methods
- Set a new upper limit Br < 2.1×10^{-7}
  - published (PRD 74:051105, 2006)



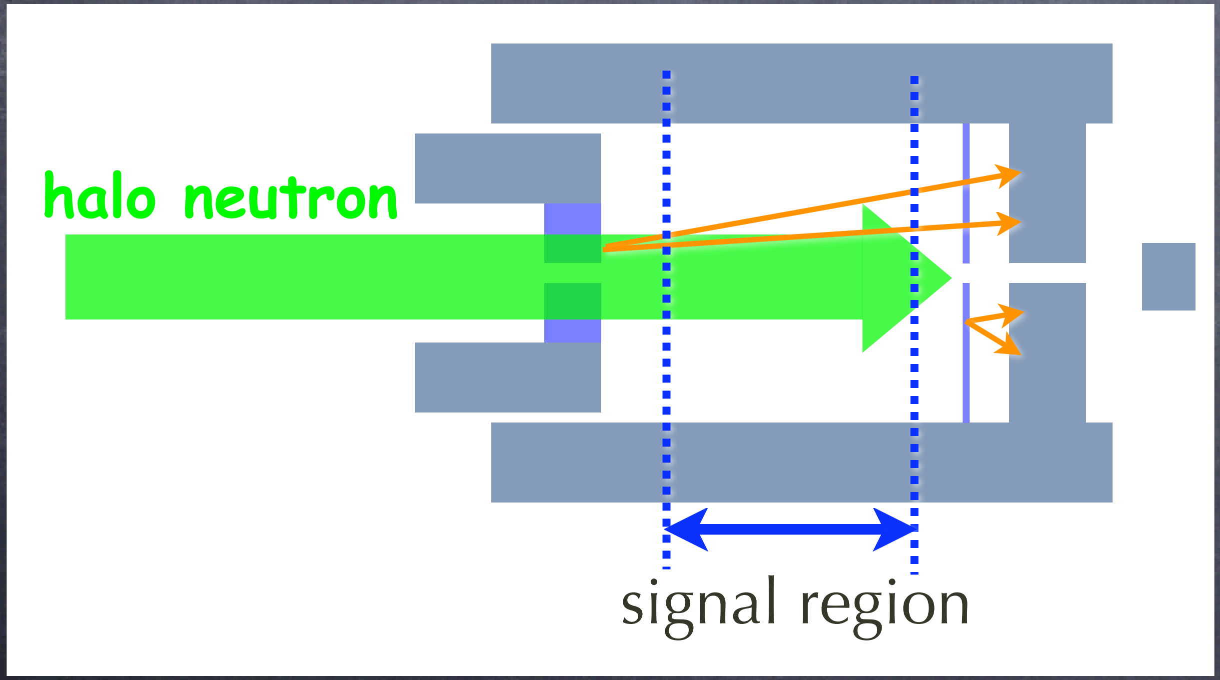
- Huge backgrounds
  - core neutrons hit the drooping membrane

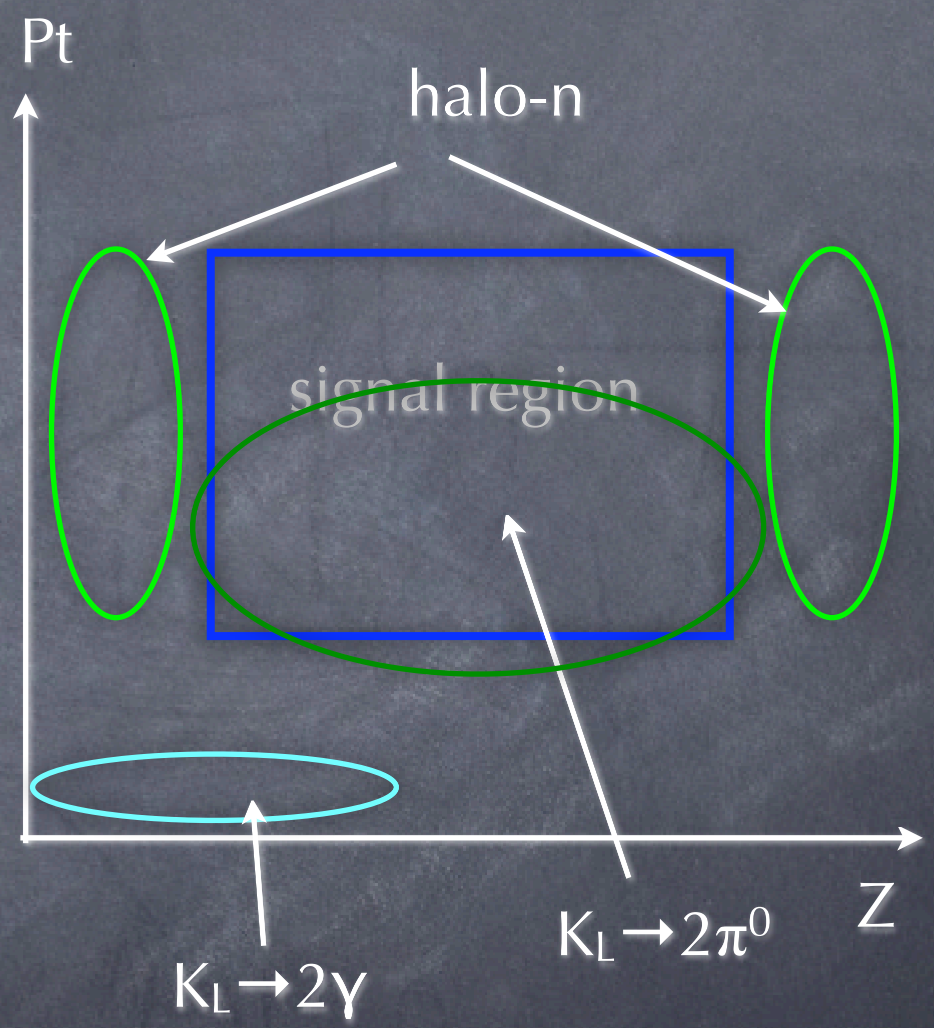
Analysis overview in Run-II

- Data sets
  - 4γ, 6γ sample : full data
    - estimation of the number of KL
  - 2γ sample : 1/3 data
    - background study after the "membrane" problem
- 2γ analysis
  - Cuts
    - photon vetoes
      - MainBarrel, FronBarrel
      - CsI, collar counters, BackAnti
    - charged particle vetoes
      - CV, BCV, BHCV
    - gamma quality cuts
    - kinematics of π^0s
  - blind method

Background sources

- Main Background in Run-II
  - $K_L \to 2\pi^0 \to 4\gamma$ (Br~10^{-3}) with 2γ missing
  - Halo neutrons around the beam
    - hitting CC02, CV

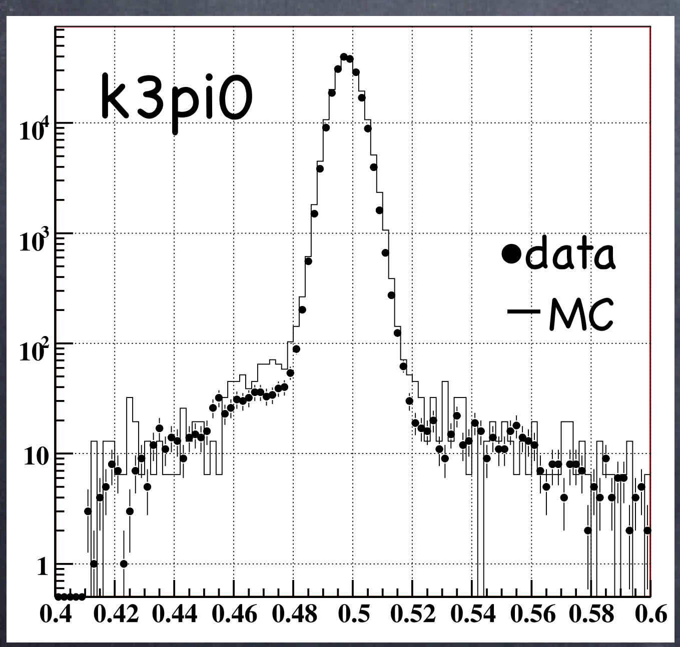




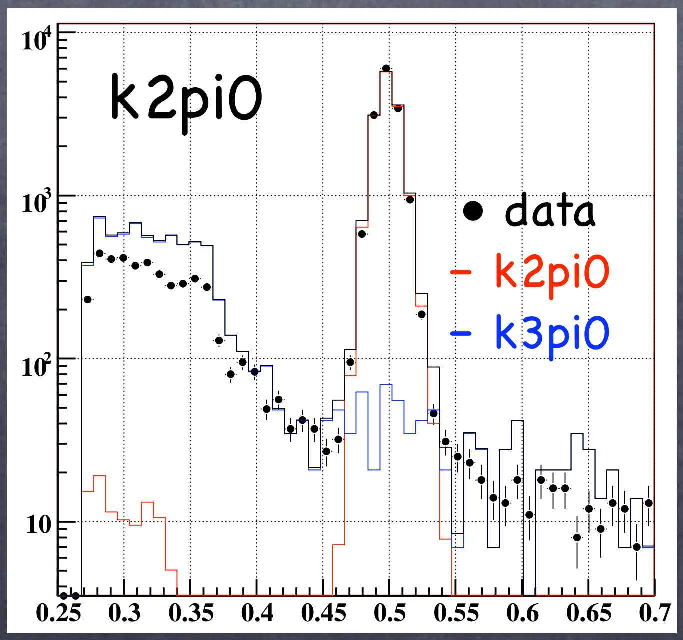
KL reconstruction

- Number of reconstructed KL with full data in Run-II
  - $KL \to 3\pi^0$, $KL \to 2\pi^0$: $0.47 < m < 0.53$ (GeV/c^2)
  - $KL \to 2\gamma$: $Pt^2 < 0.001$, acop. angle < 10 deg.

	# of rec. with data	acceptance	branching fraction	# of KL decay
$KL \to 3\pi^0$	164446	6.39×10^{-6}	$0.1956 \times (0.98797)^3$	4.59×10^{9}
$KL \to 2\pi^0$	11955	8.97×10^{-5}	$8.69\times10^{-4} \times (0.98797)^2$	5.28×10^{9}
$KL \to 2\gamma$	7503	2.25×10^{-4}	5.48×10^{-4}	5.17×10^{9}



inv. mass(GeV/c^2)



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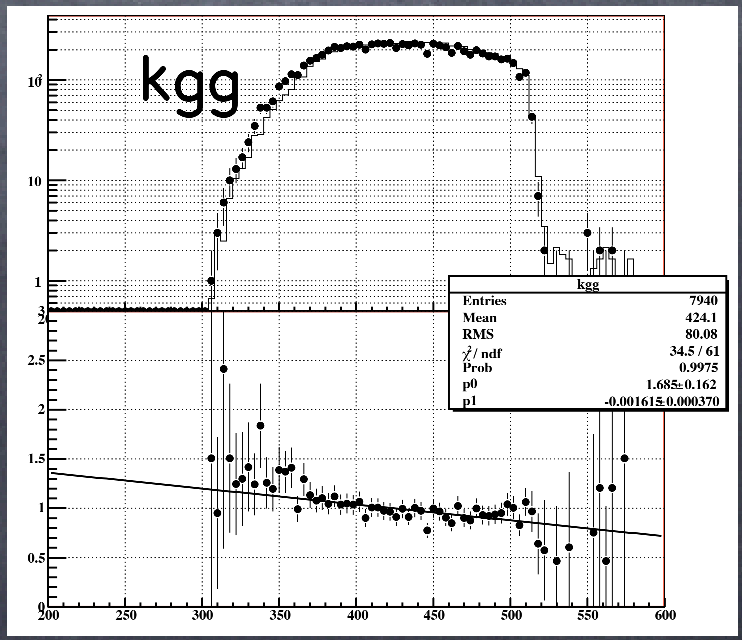
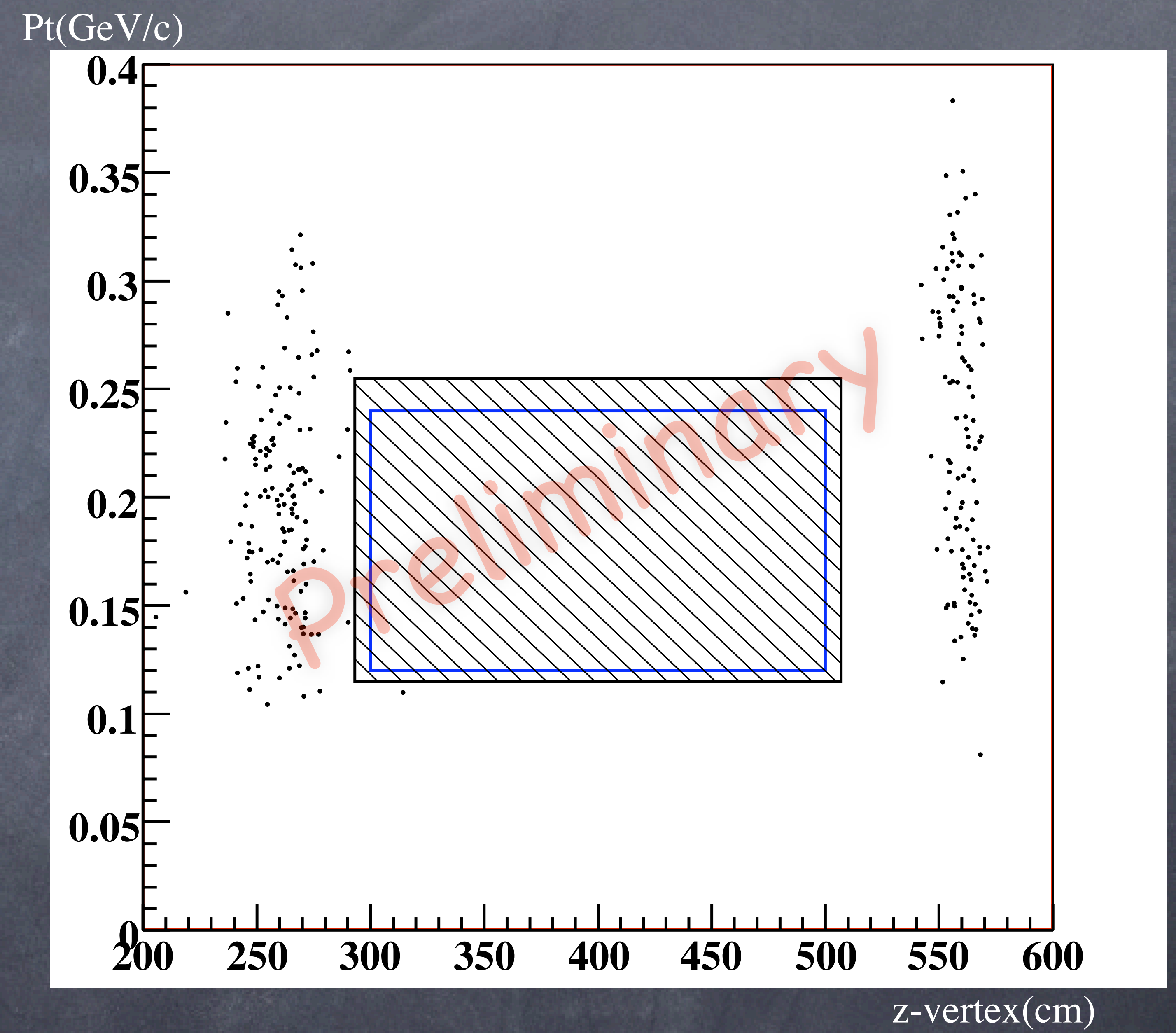


z-vertex(cm)

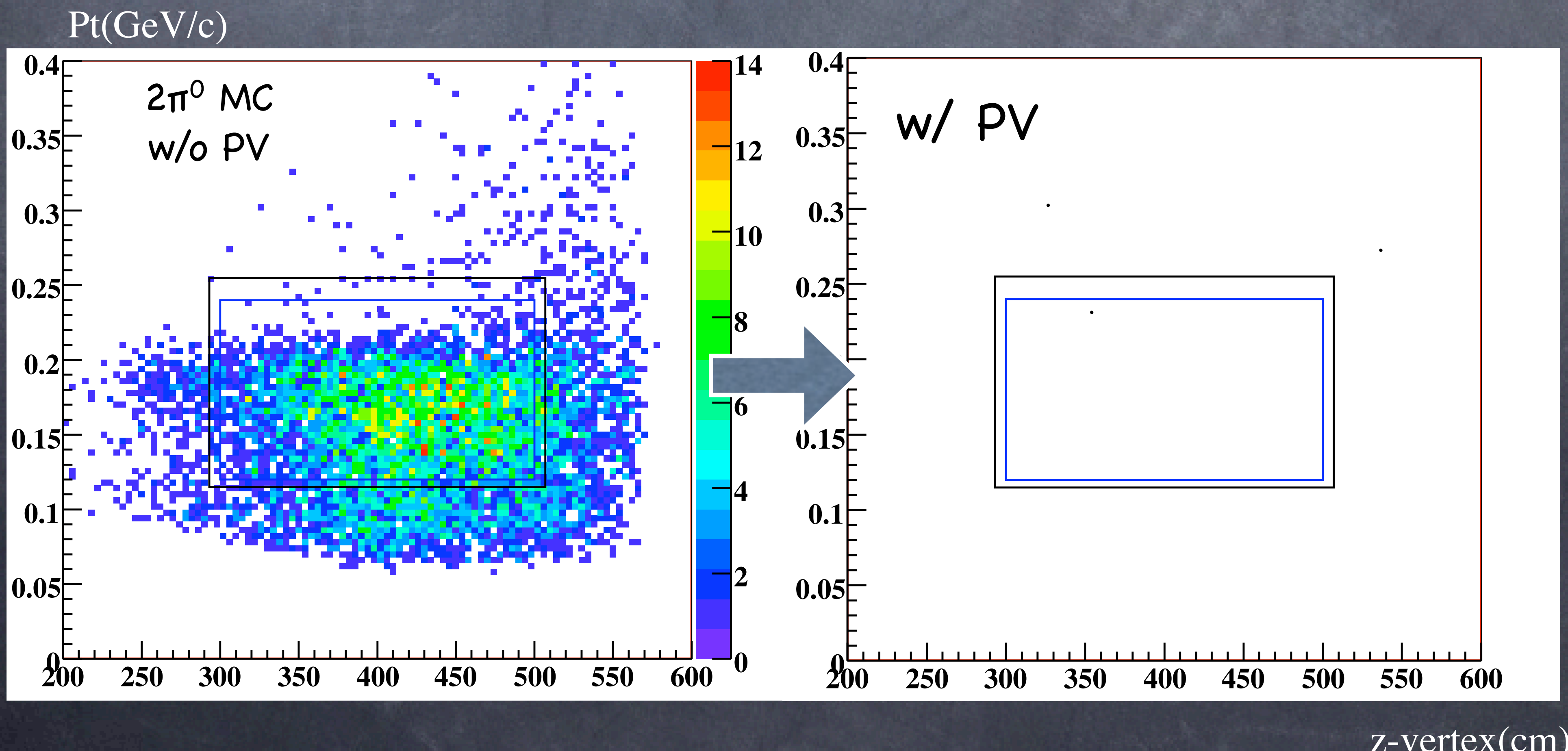
"Final" plot

- Set blind box
  - wider than signal box
- Tentative final plot
  - Halo neutron events
    - CC02
    - CV
- Clear at 300-500 cm



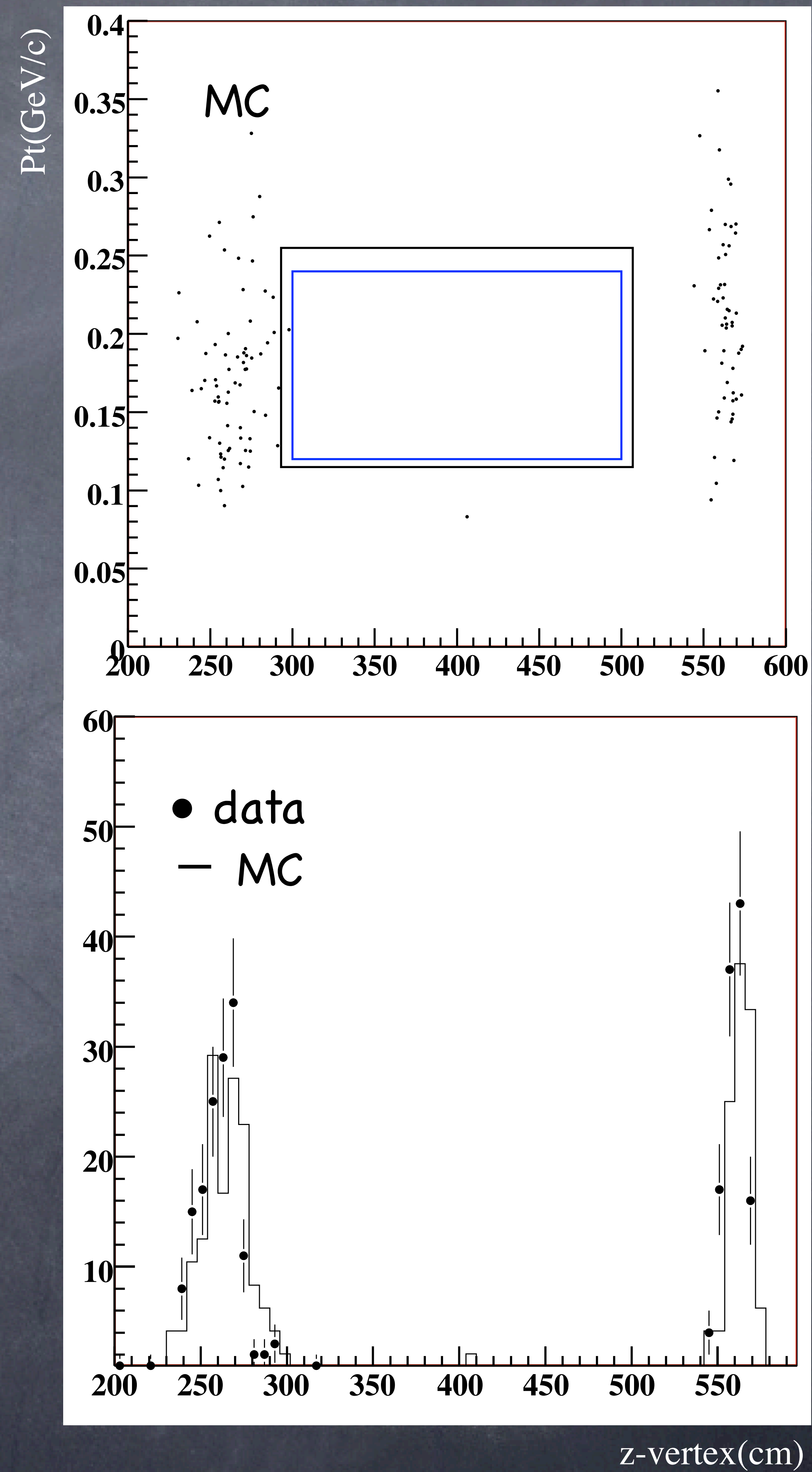
$K_L \rightarrow \pi^0\pi^0$ background

- the background calculation with MC
  - count the number of events in 2γ sample with $KL \rightarrow 2\pi^0$ MC
- result with x36 higher statistics than data
  - 1 event in the box
  - 0.03 events in 1/3 data (0.08 events in full data)



Halo neutron Background

- BG events well reproduced by MC
  - statistics : 1/1.76 of data
    - CC02 events
      - 148±18 (data: 149)
    - CV events
      - 112±15 (data: 119)
- Events around the signal box
  - optimizing the boundary at CC02

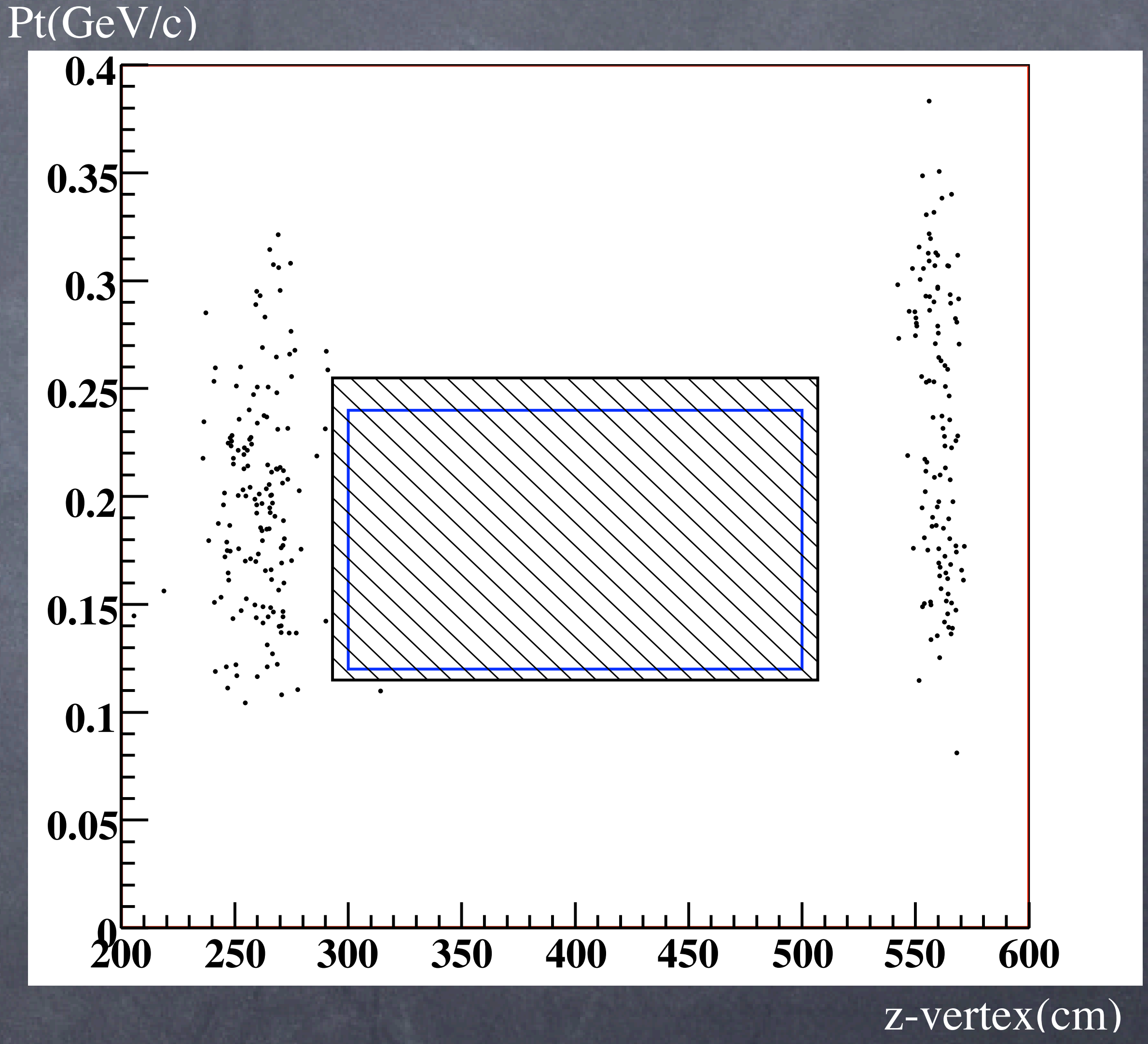


Single Event Sensitivity

- Acceptance by $K_L \to \pi^0 \nu\bar{\nu}$ signal MC
  - $A = 1.64 \times 10^{-2}$
- Number of KL
  - $N_{KL} = 5.28 \times 10^{9}$

Preliminary

- Expected Single Event Sensitivity w/ full data in Run-II
  - $SES = 1 / (1.64\times10^{-2} * 5.28 \times10^{9})$
    $= 1.15 \times 10^{-8}$



Summary

- It is very important to measure the branching fraction of $K_L \rightarrow \pi^0 \nu\nu$ for test of the Standard Model and New Physics
- We successfully carried E391a Run-II(Feb.-Apr. 2005) with several crucial upgrades from Run-I
- We analyzed 1/3 data in Run-II
  - KL parameters by $K_L \rightarrow 3\pi^0$, $K_L \rightarrow 2\pi^0$, $K_L \rightarrow \gamma\gamma$
  - Background well understood
    - $K_L \rightarrow 2\pi^0$, halo neutrons
- SES = 1.15×10^{-8} with full data

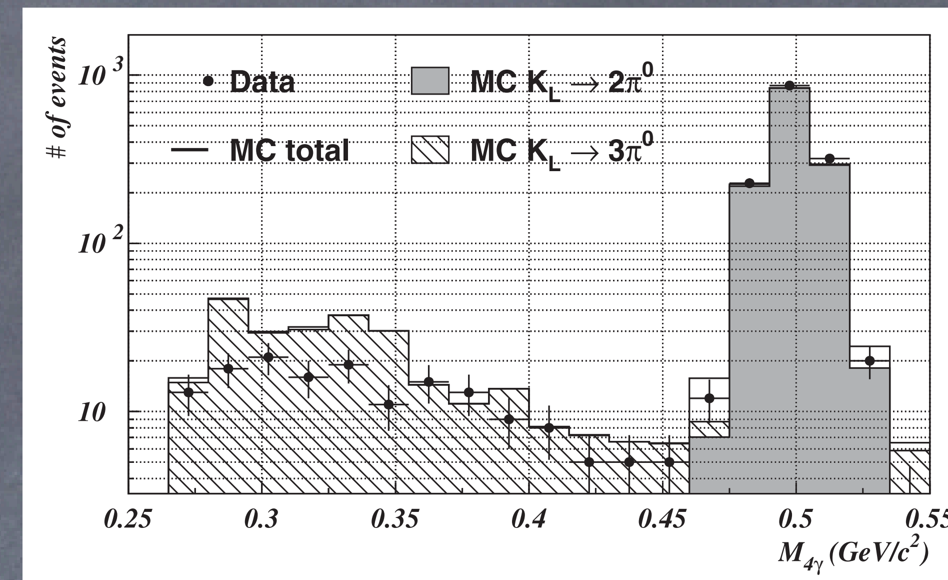
- Future Prospects
  - Further study for the halo neutron background
    - optimization for the boundary of the signal region
  - Check other background sources

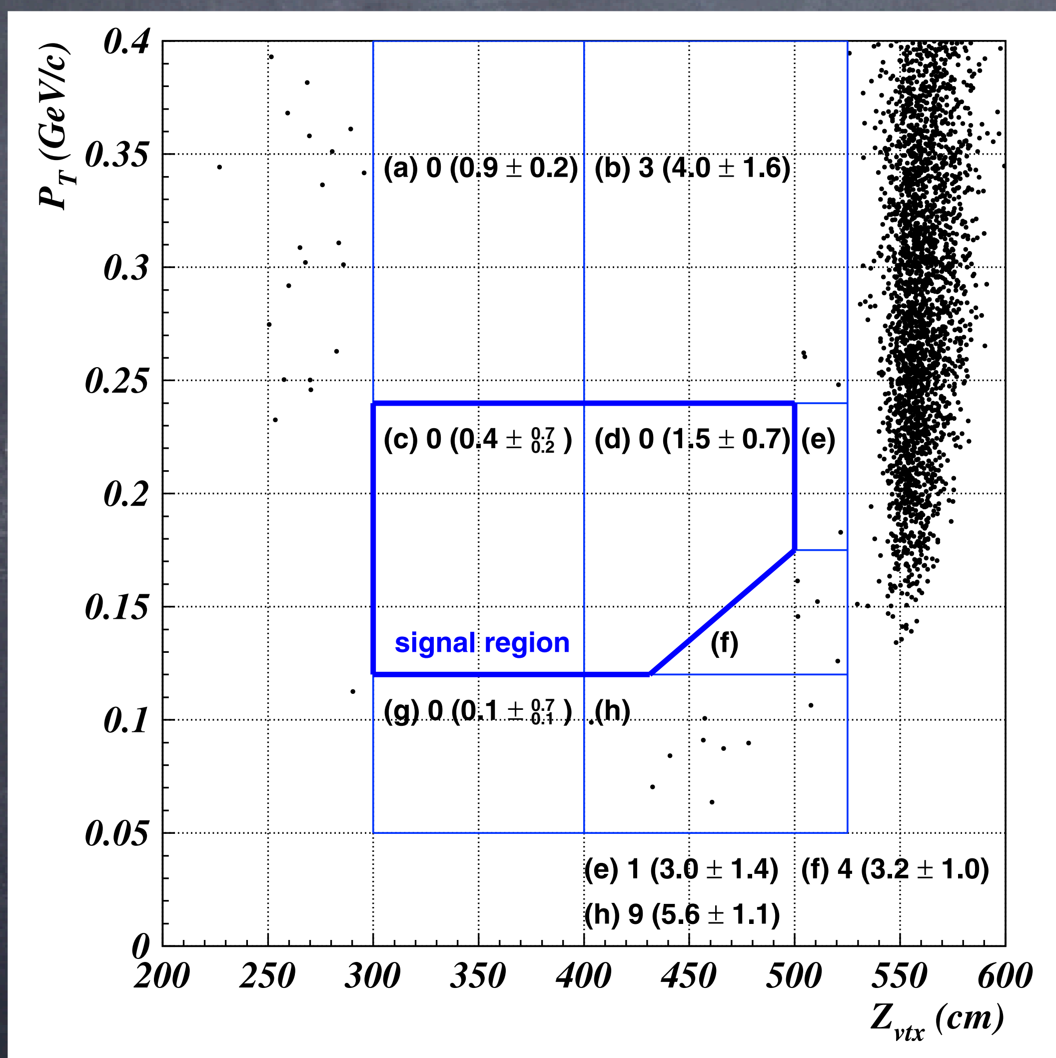
    ⇒ Open the box in a few months

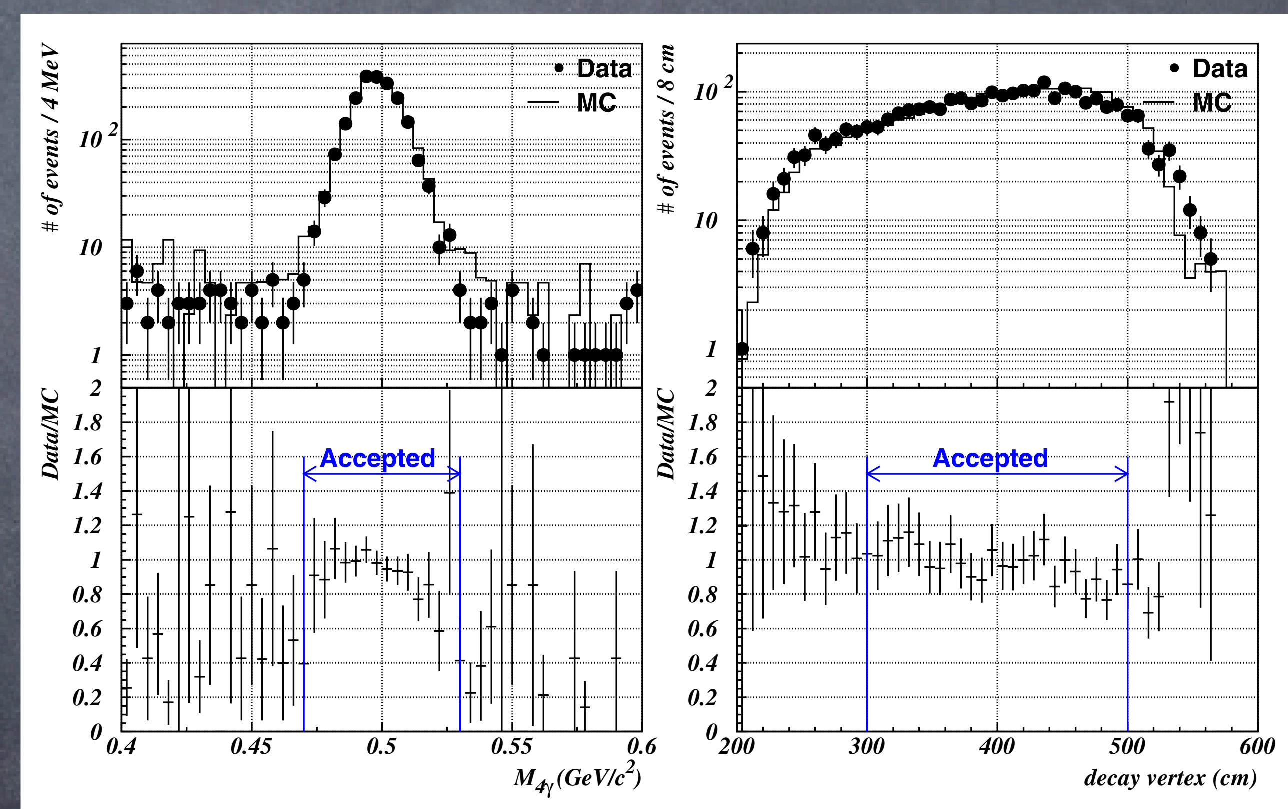
  - Analysis of Run-III data
  - Final sensitivity expected to be below 5×10^{-9}

Backup Slides

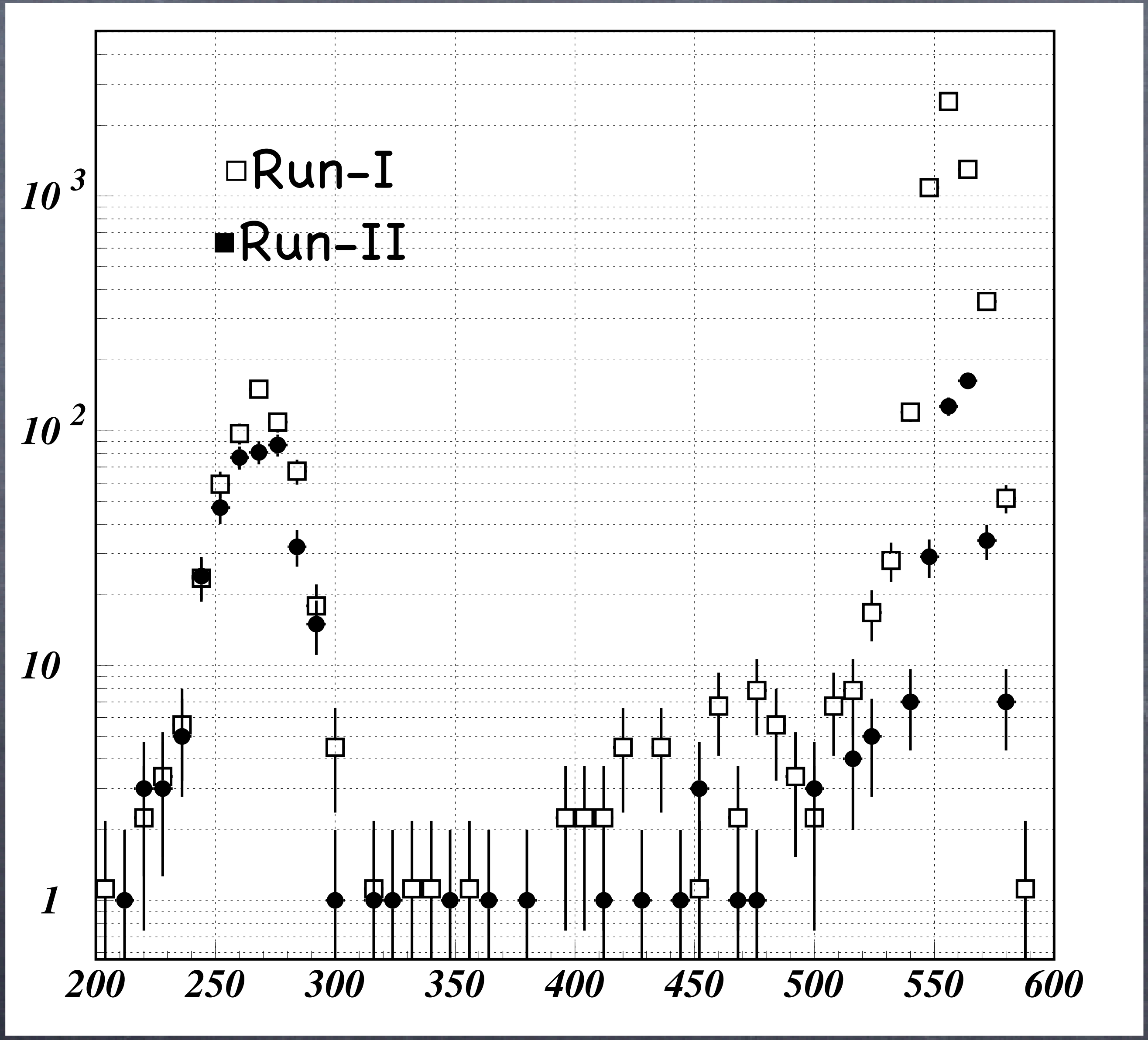
Plots in Run-I 1week



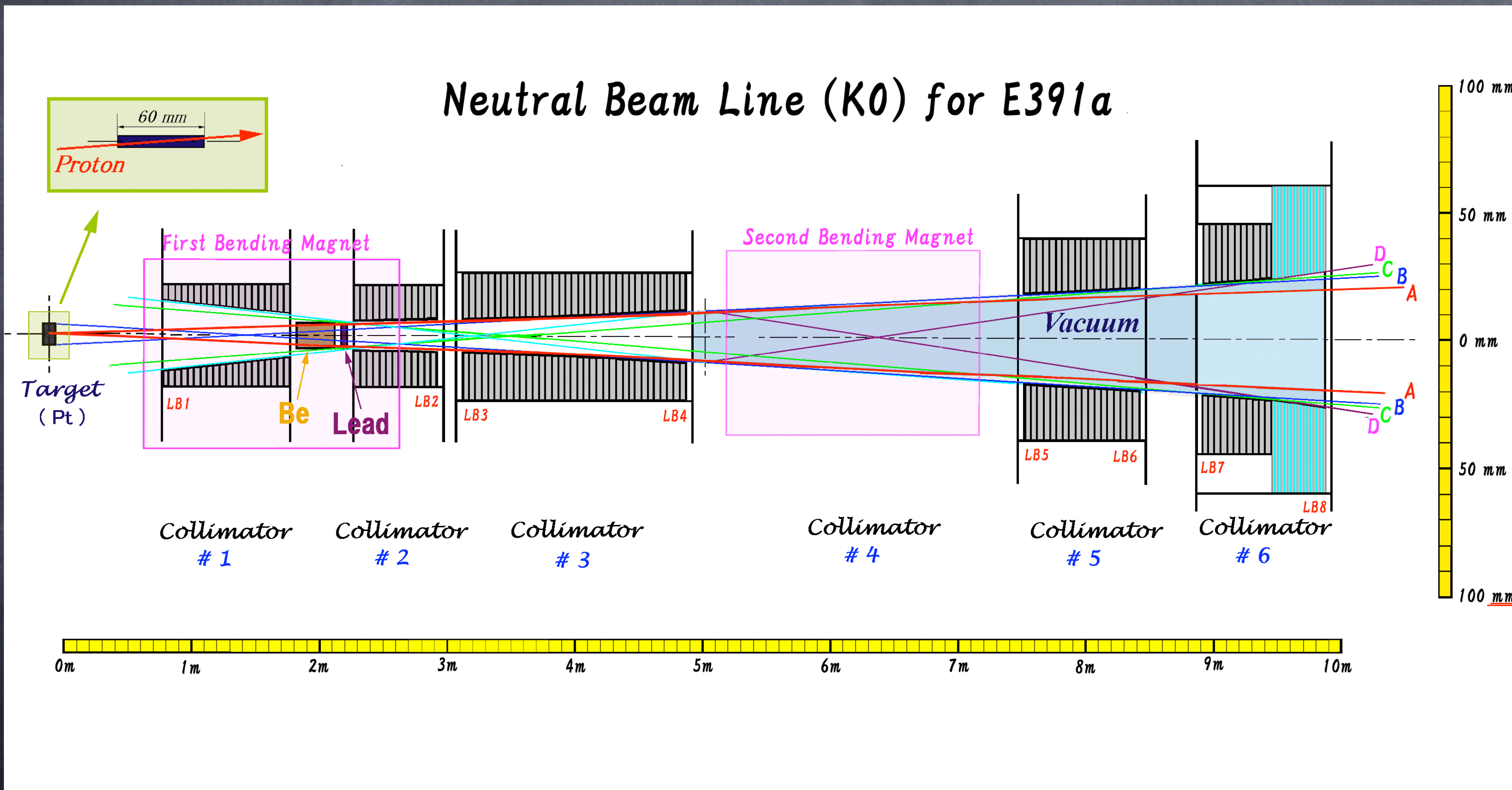




Direct comparison between Run-I nad RunII



E391a Beam-line



π^0 reconstruction with 2γ

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

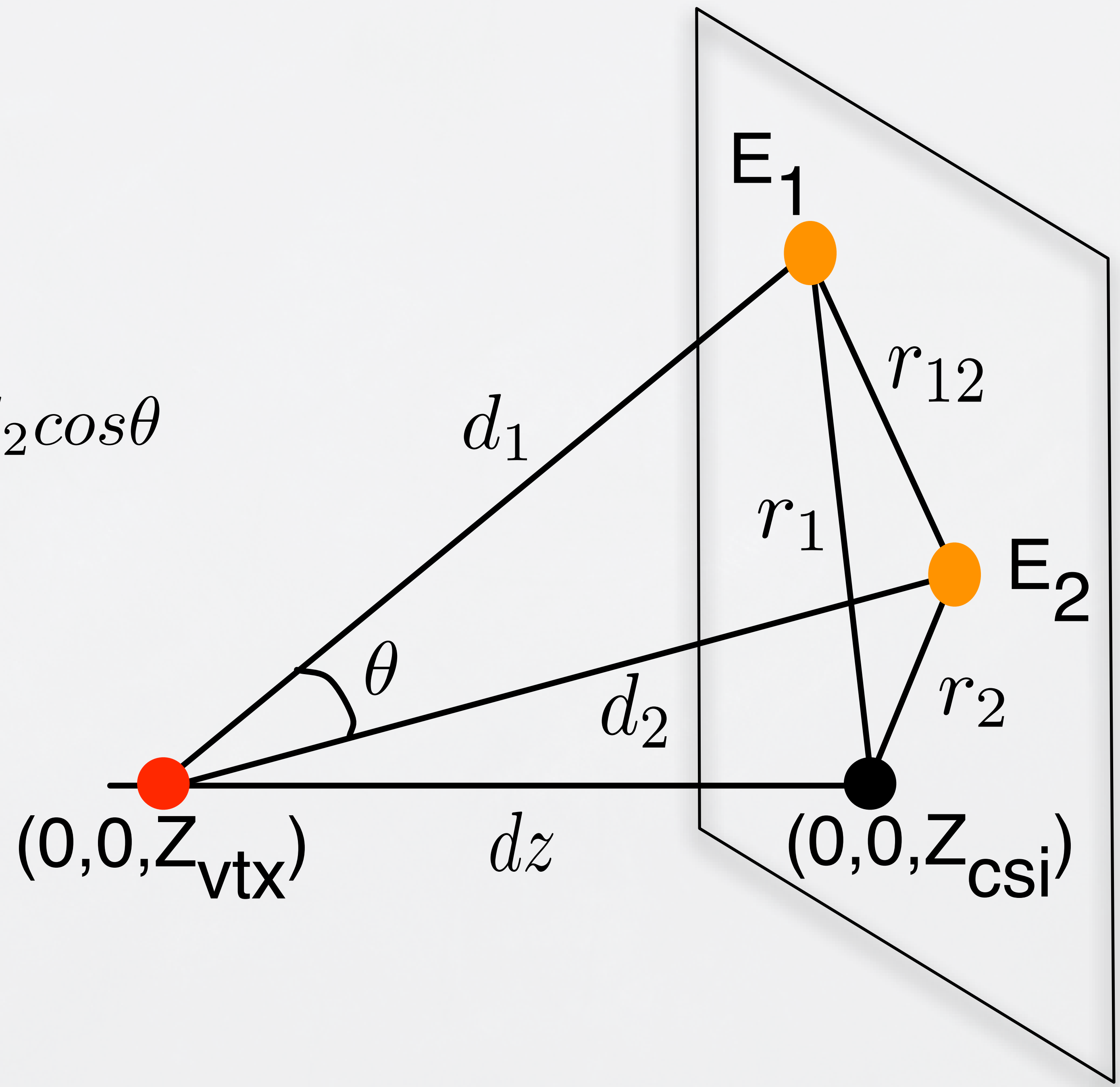
$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

$$r_{12}^2 = d_1^2 + d_2^2 - 2d_1d_2\cos\theta$$

$$d_1 = \sqrt{r_1^2 + (dz)^2}$$

$$d_2 = \sqrt{r_2^2 + (dz)^2}$$

$$dz \equiv Z_{csi} - Z_{vtx}$$



Gamma selection cuts

- Energy cuts
- Shape cuts

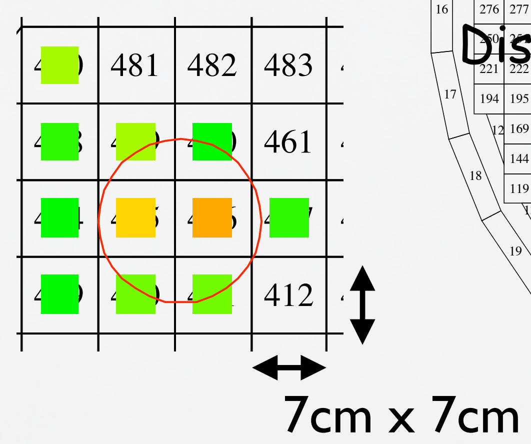
$$Balance = \frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}}$$

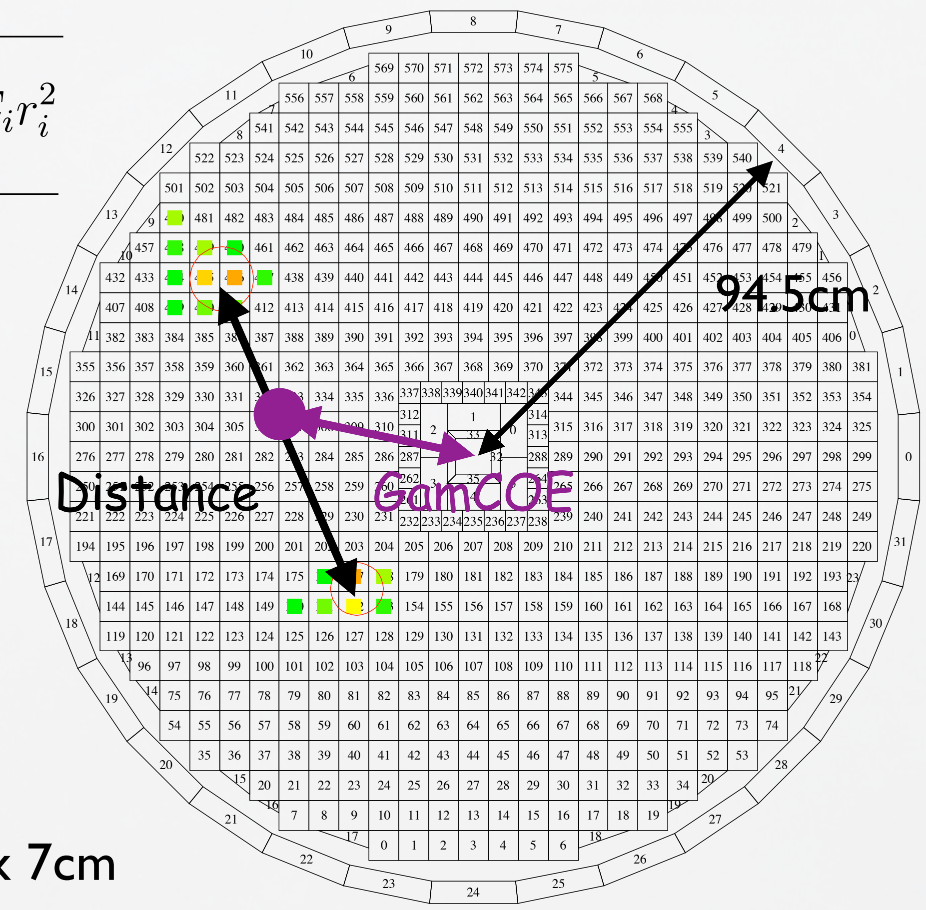
$$TDI = \frac{1}{N}\sqrt{\sum_{i=1(E_i>1MeV)}^{N} (T_i - T_m)^2}$$

$$Erat = \frac{E_1 + E_2 + E_3}{E_{tot}}$$

$$T_m = \frac{1}{n}\sqrt{\sum_{i=1(E_i>5MeV)}^{n} T_i}$$

$$RMS = \sqrt{\frac{\sum_{i=1(E_i>5MeV)}^{n} E_i r_i^2}{E_{tot}}}$$

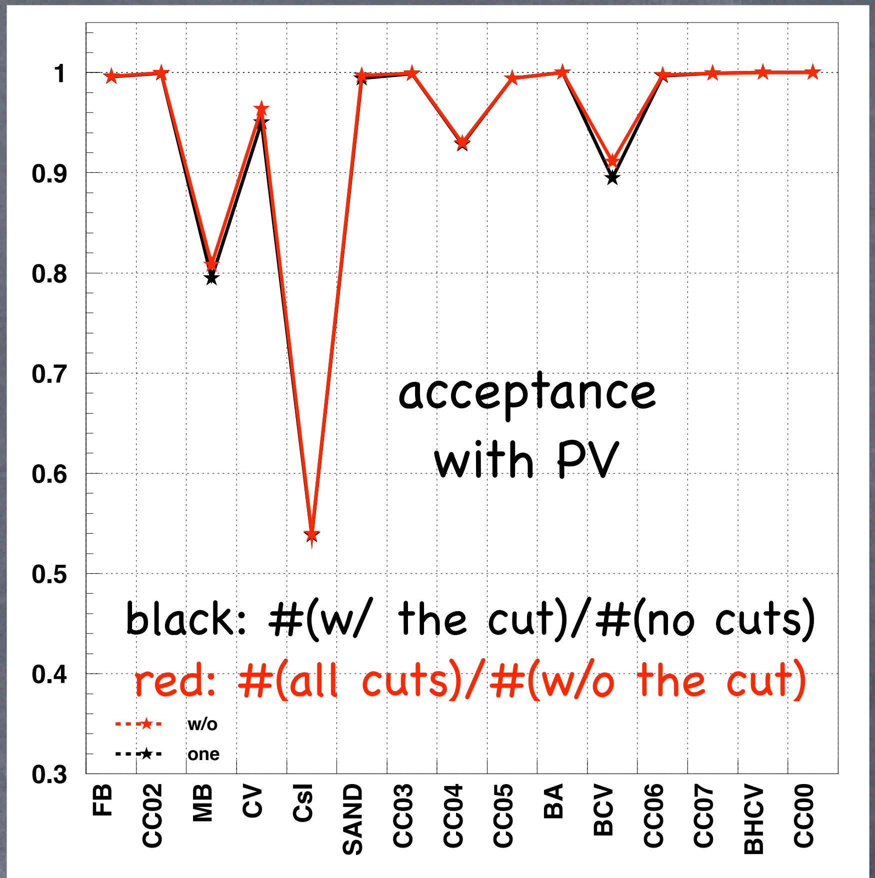


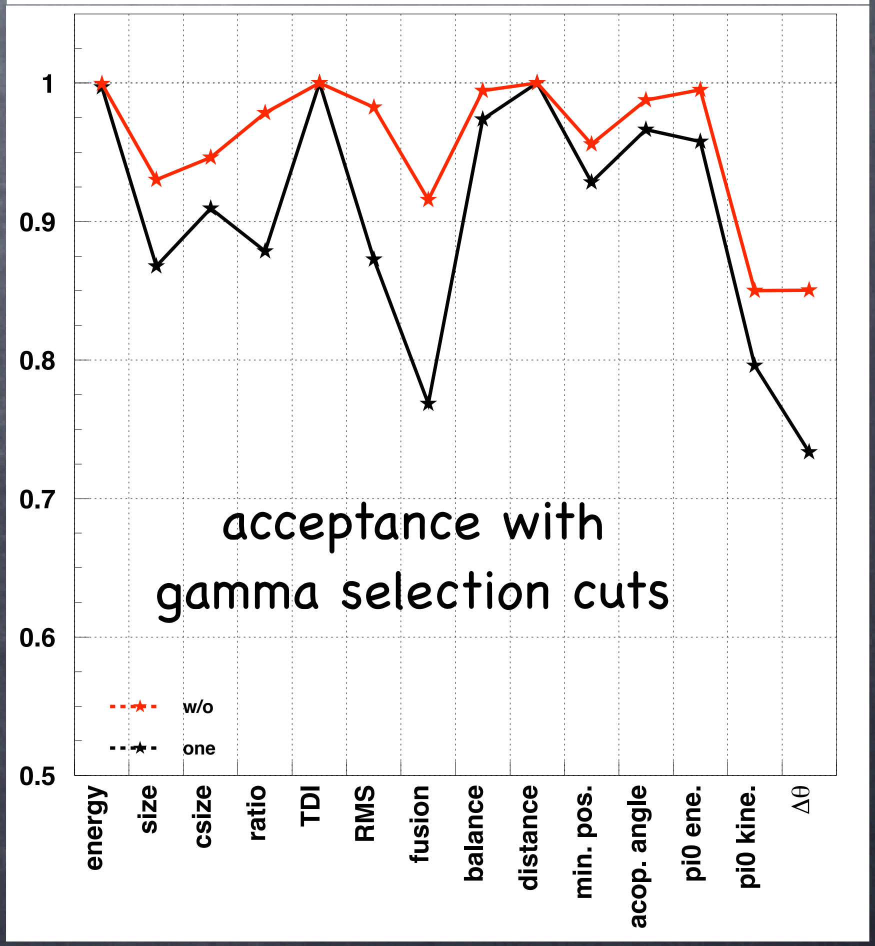


Acceptance

- Signal acceptance for KL→$\pi^0\nu\nu$
  - calculated with MC
  - decaying at the fiducial
  - acceptance: 1.93 %
- Accidental loss
  - estimated with data
    taken with a trigger by Target Monitor
  - total accidental loss: 15.5% (.845 acceptance)

- Total acceptance
  - A = 1.93 x 0.845
    = 1.64 %





photon veto Cuts

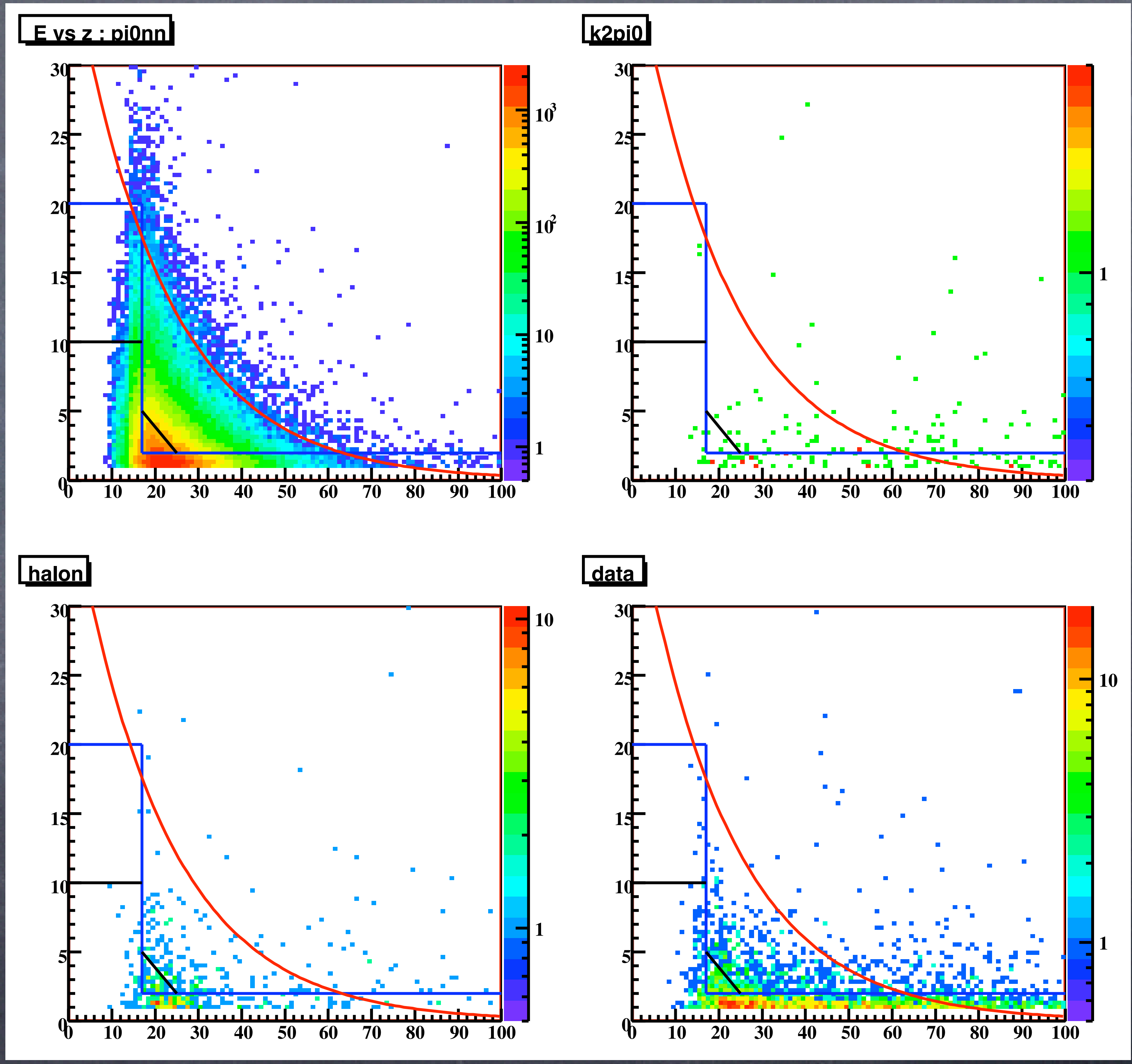
- FB: 1.0MeV
- CC02: 2.4MeV
- MB: inner 1.0, outer 0.5 MeV
- Outer CV 0.3MeV
- Inner CV 0.7MeV
- CsI single crystal
  - 2.0 MeV for d>17cm
  - 20MeV for d<17cm
- Sandwich 2.0MeV
- CC03 6.0MeV
- CC04 sci 0.7MeV
- CC04 cal 1.0MeV
- CC05 sci 0.7MeV
- CC05 cal 3.0MeV
- BA (sci 20MeV)
  - && (qtz 0.5MIPs)
- BCV 0.5MeV
- CC06 10MeV
- CC07 10MeV
- BHCV 0.1MeV
- CC00 2.0 MeV

gamma, pi0 Cuts

- gamma E1 > 250MeV, E2> 150MeV
- cluster size >= 3
- crystal size >=5
- Energy ratio > 0.88
- TDI < 3.0
- RMS < 5.2, RMS-sum < 9.5
- Energy balance < 0.75
- gamma distance > 15cm
- gamma position > 15cm
- fusion NN > 0.7
- Δtheta = > - 20

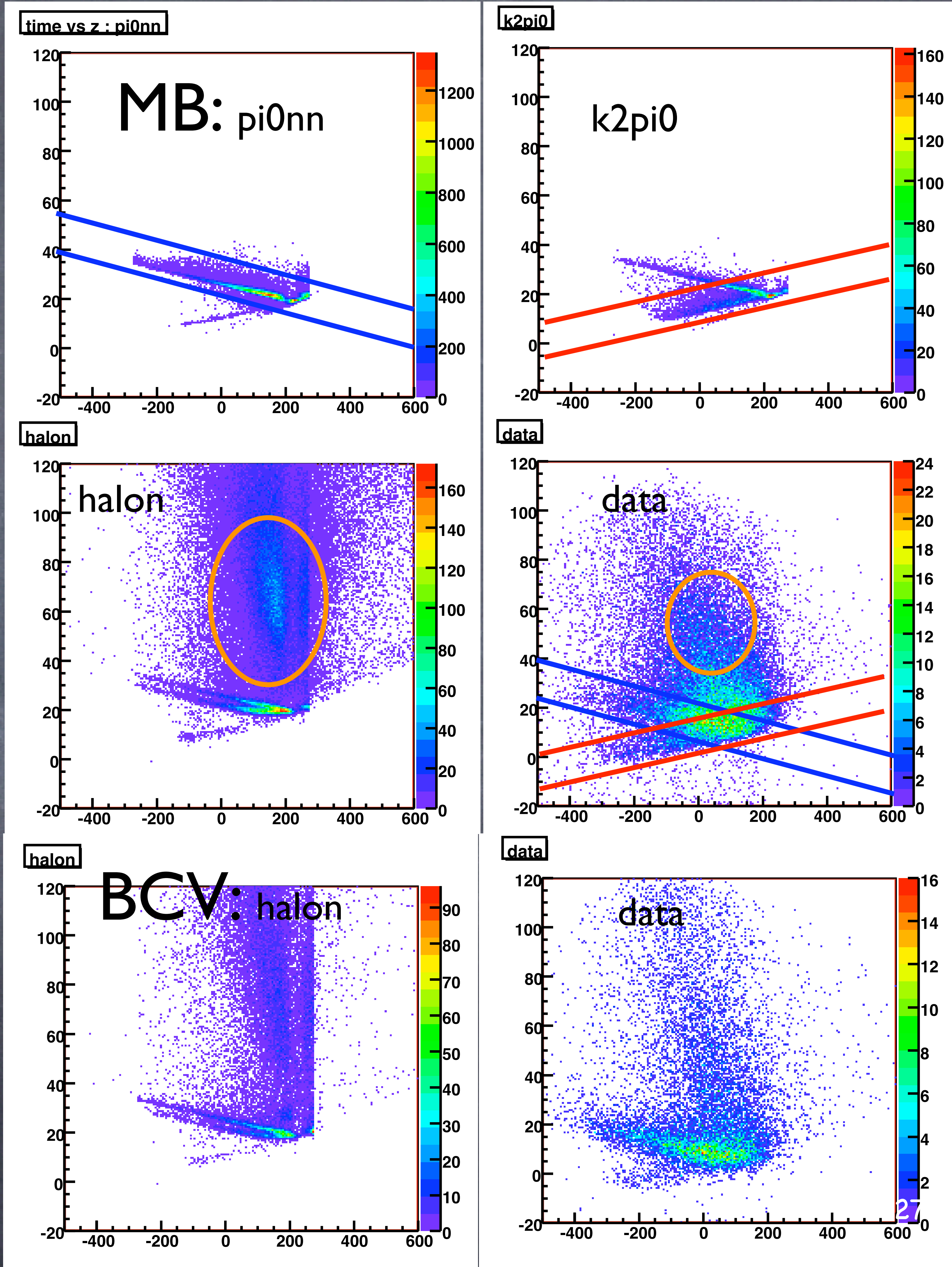
CsI veto

- "dense" region
  - $\pi^0 \nu\nu$
    - 17<d<30, E<5MeV
  - data
    - d>20, E<3MeV
- New ideas
  - Fancy function
    - ~10% loss (now 45%)
    - too loose
  - Avoid only the dense region
    - d>25cm: 2MeV
    - 17cm<d<25cm: 5→2MeV
    - d<17cm: 10MeV for



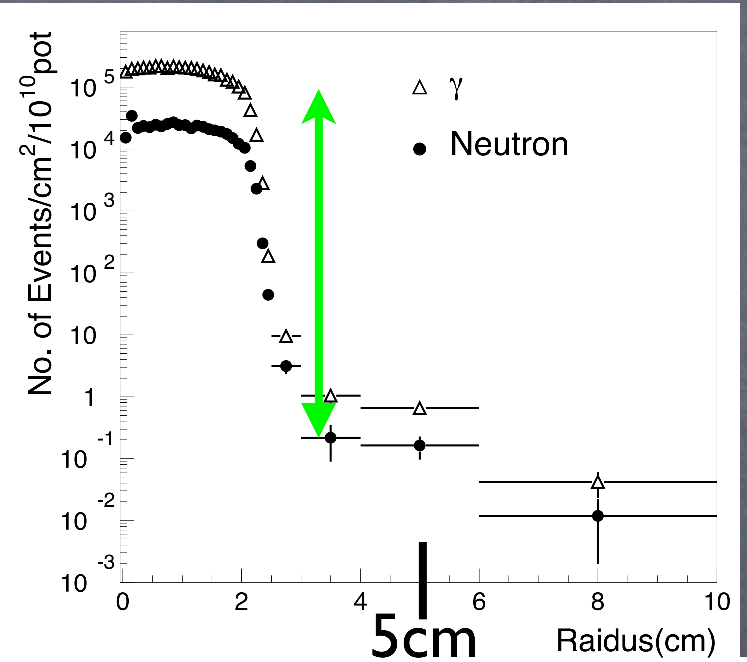
Timing information in the barrel counters

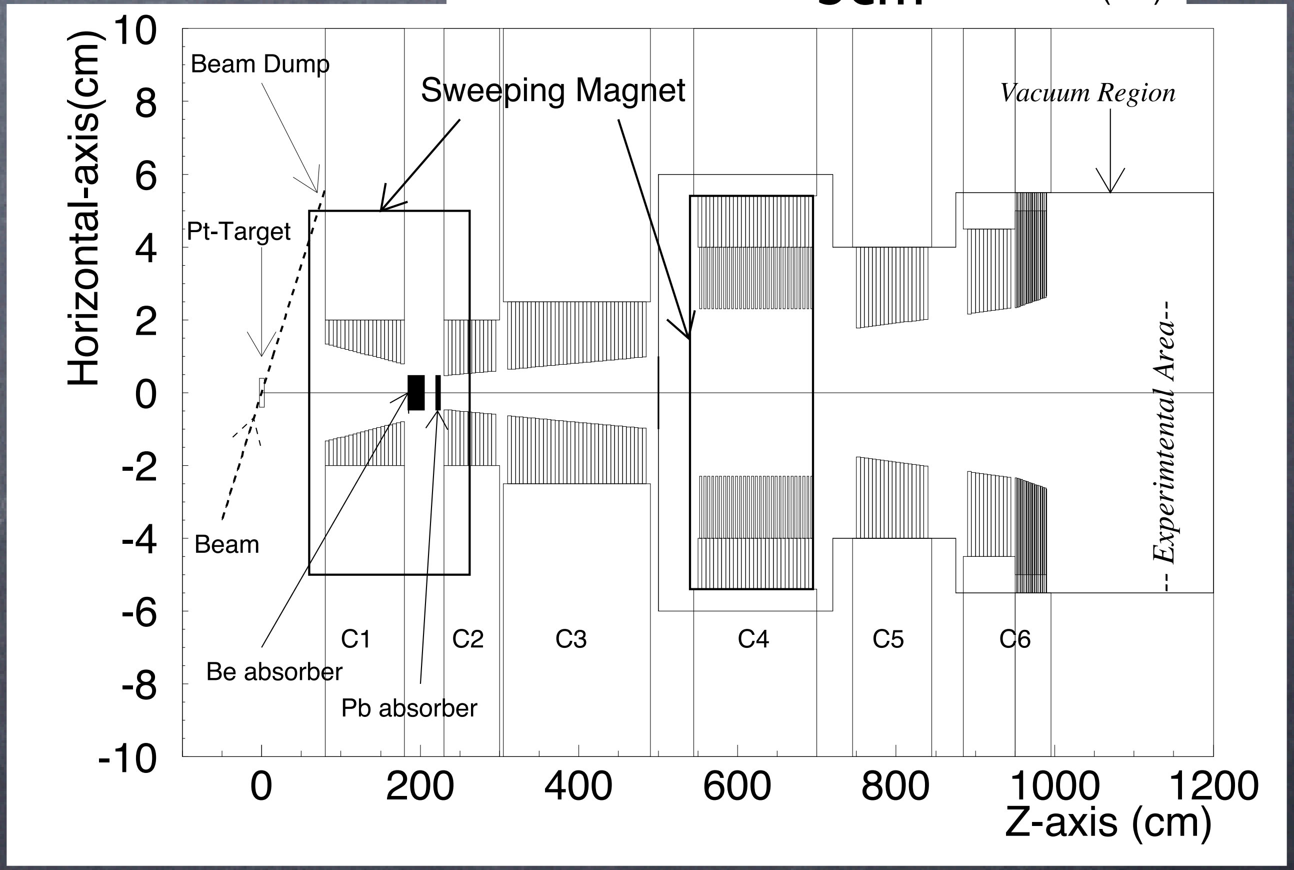
- Back-splash from CsI
- delayed events with halon



Halo neutron MC

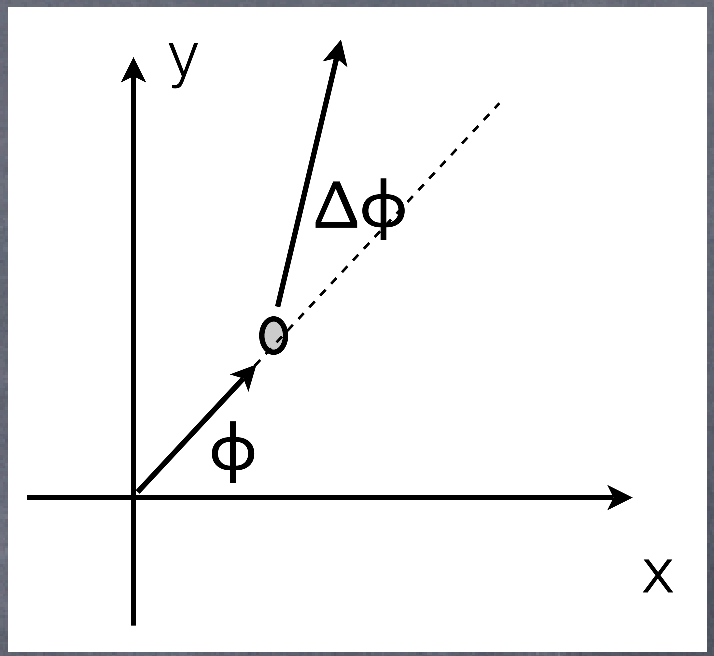
- Method
  - target simulation
    - 12GeV proton on target
  - beamline simulation
    - inject particles from target into collimator
    - collect neutrons which hit the detector
  - detector simulation
    - inject halo neutrons

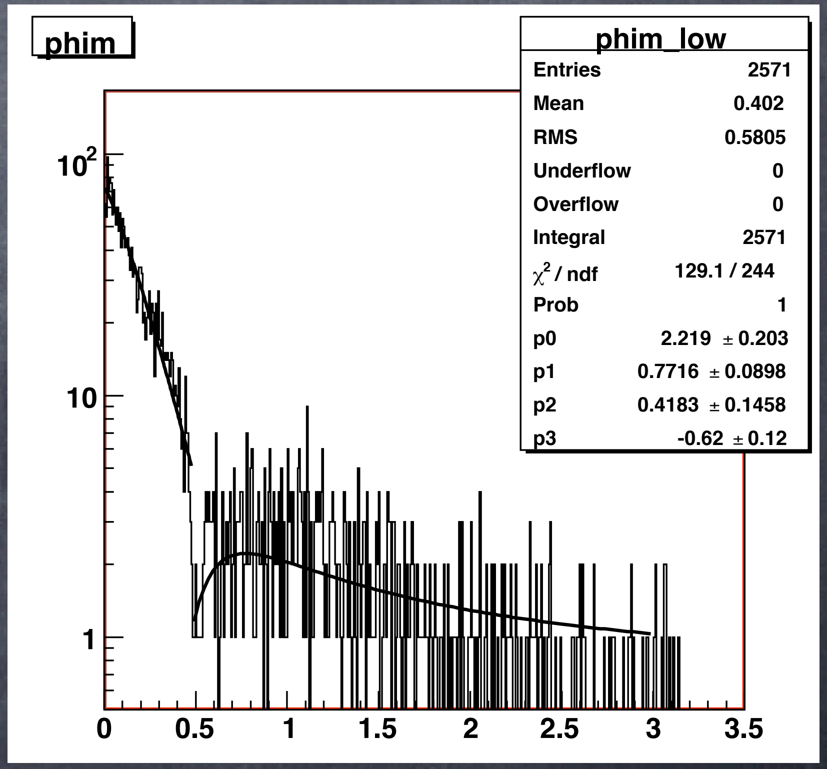




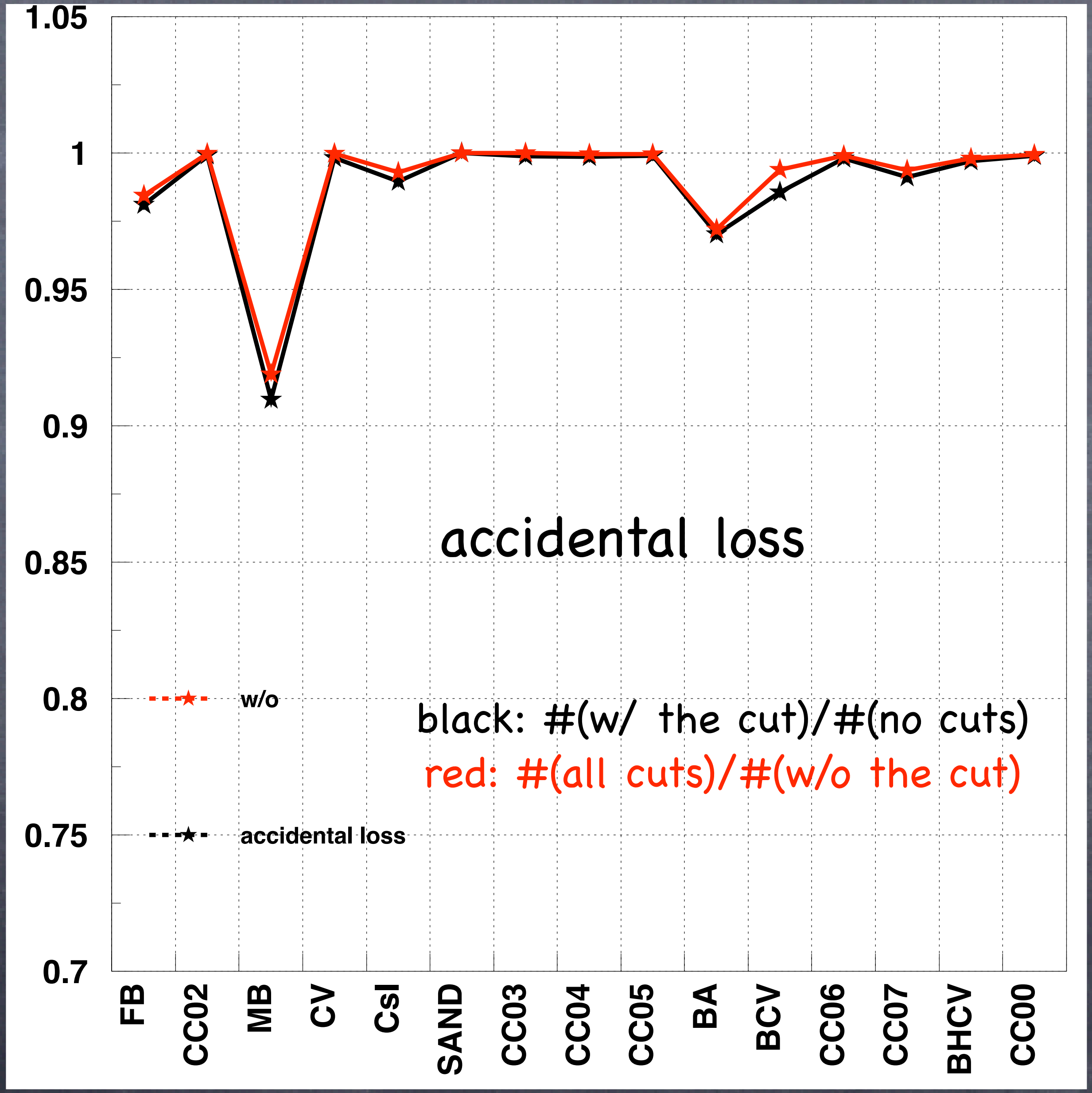
Halo neutron MC(2)

- Halo neutron generation
  - parameters
    - p, R, θ, ΦR, ΔΦ
- use halon seed from the beamline simulation
  - w/ different random seed
  - uniform Φ distribution
  - add small fluctuation
    - p: 2%, r: 1%, θ:1%, ΔΦ: 0.1%





Accidental loss



signal distribution