Methods of the increasing the efficiency of registration the rare decay $K_L^0 \to \pi^0 \nu\bar{\nu}$ in the E391 experiment

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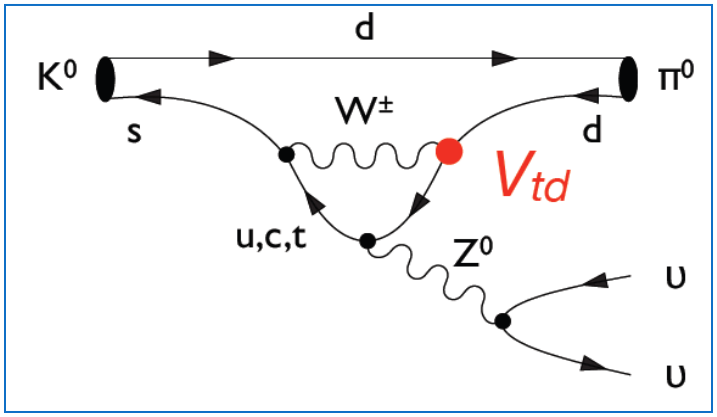
$K_L^0 \to \pi^0 \nu\bar{\nu}$ Decay



- "Direct" CP violating process
  - indirect contribution ≈ 10^{-3} (negligibly small)
- Measures η in CKM matrix

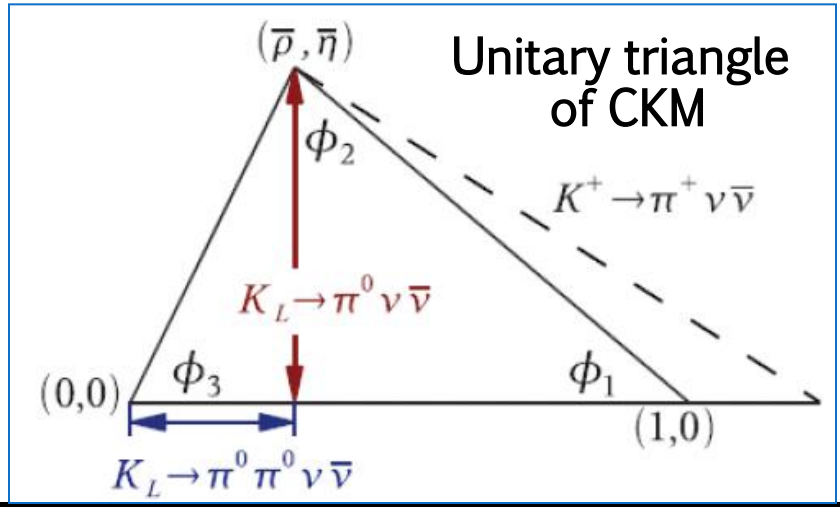
$$Br(K_L^0 \to \pi^0 \nu\bar{\nu}) \propto \eta^2$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Small theoretical uncertainty (≈2%)
  - Precise check of SM
- Rare decay in SM prediction

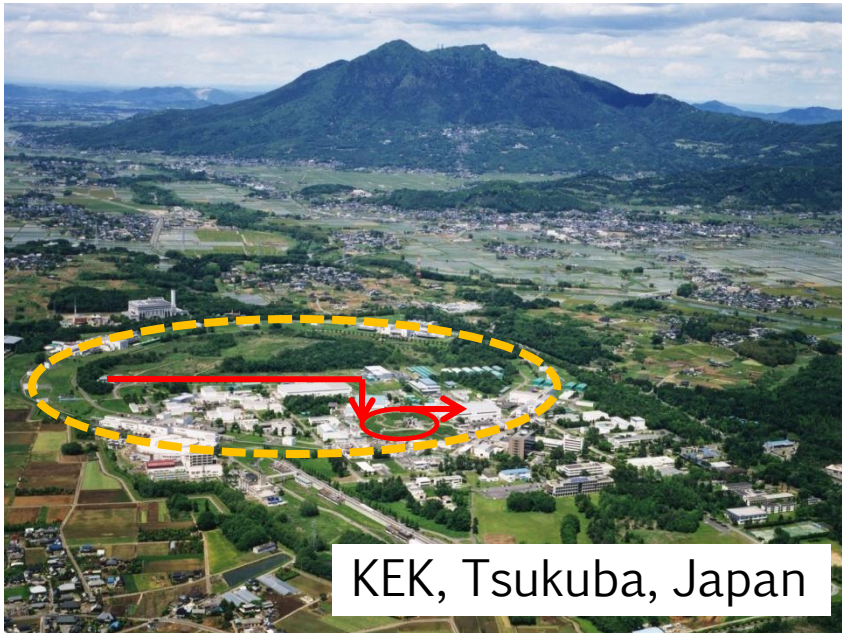
$$Br(K_L^0 \to \pi^0 \nu\bar{\nu}) = 3.0 \times 10^{-11}$$

- Probe to New Physics

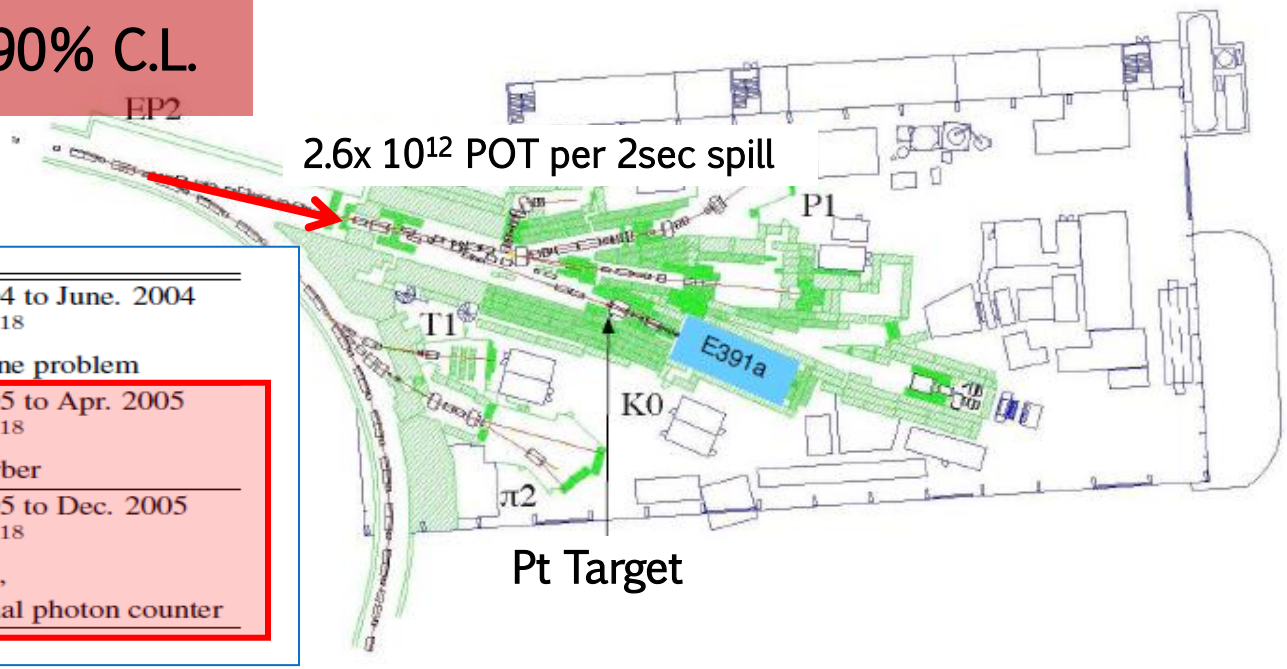


The E391 Experiment

- Measures $Br(K_L^0 \to \pi^0 \nu\bar{\nu})$ @KEK 12GeV Proton Synchrotron
  - First dedicated experiment for this mode
  - Pilot experiment for KOTO (J-PARC E14)
  - Physics runs in 2004-2005
  - New Upper Limit:



Br < 2.6x10^{-8} @ 90% C.L.

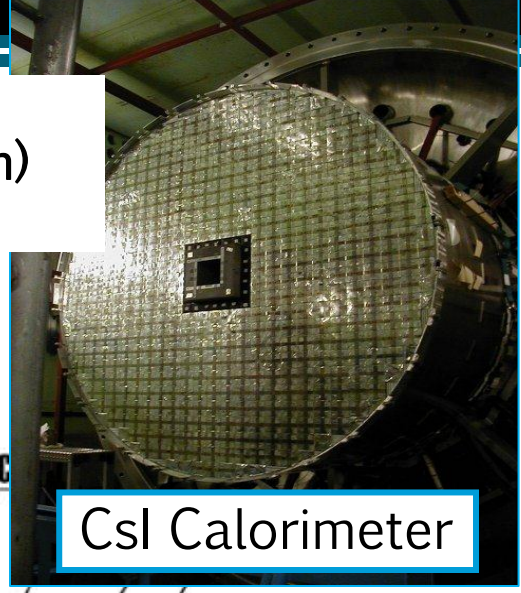


Run-I	Period	Feb. 2004 to June. 2004
	Total protons	2.1×10^{18}
	Remarks	Membrane problem
Run-II	Period	Feb. 2005 to Apr. 2005
	Total protons	1.4×10^{18}
	Remarks	Be absorber
Run-III	Period	Oct. 2005 to Dec. 2005
	Total protons	1.2×10^{18}
	Remarks	New BA, Additional photon counter

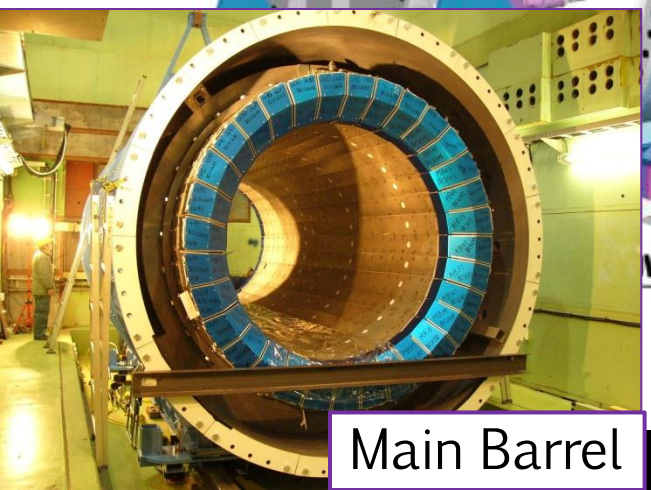
E391 Setup

Pure CsI crystal
7x7x30cm (5x5x50cm)
576 channels

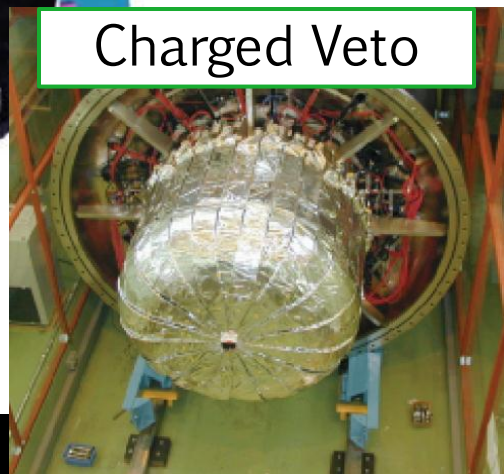
Front Barrel



CsI Calorimeter



Main Barrel



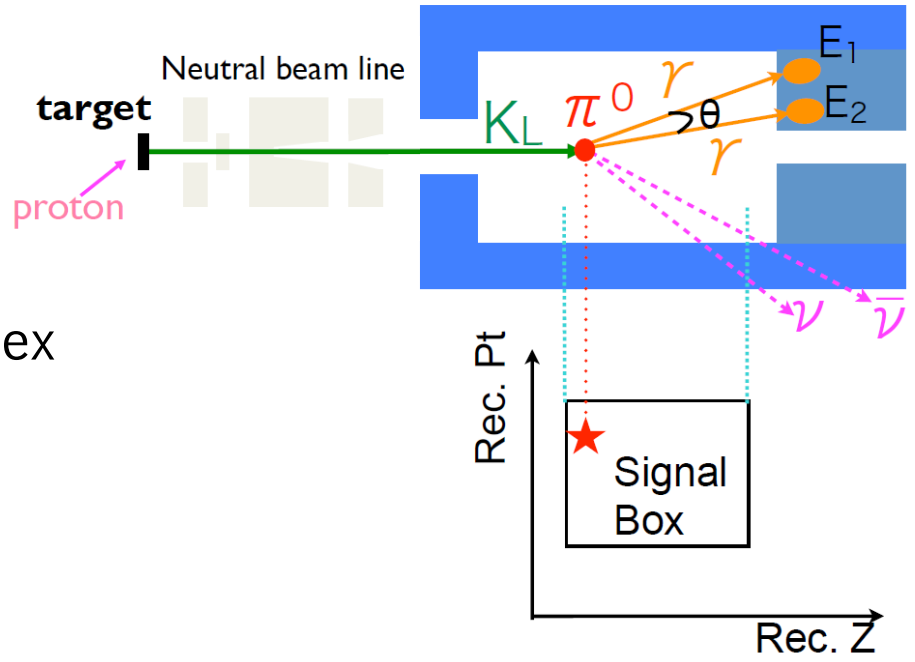
Charged Veto

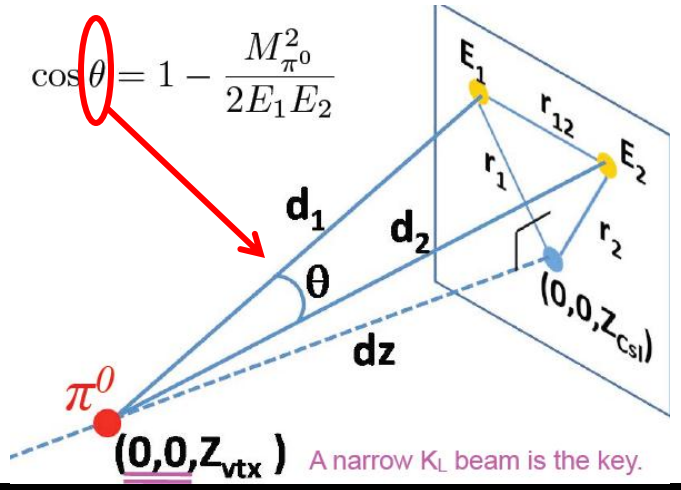
Experimental Principle

- "2γ + nothing"
  - 2γ – CsI calorimeter (E, x, y)
  - "nothing" – hermetic veto system
- Reconstruct the pi0 decay Z-vertex
  - on the beam line (Xvtx=Yvtx=0)
  - with M(pi0) assumption
    - "pencil" beam to improve Pt resolution

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

- Select signal events using reconstructed decay vertex and reconstructed transverse momentum
  - Required **Pt** and **Z** vertex in the signal box





Experimental Principle

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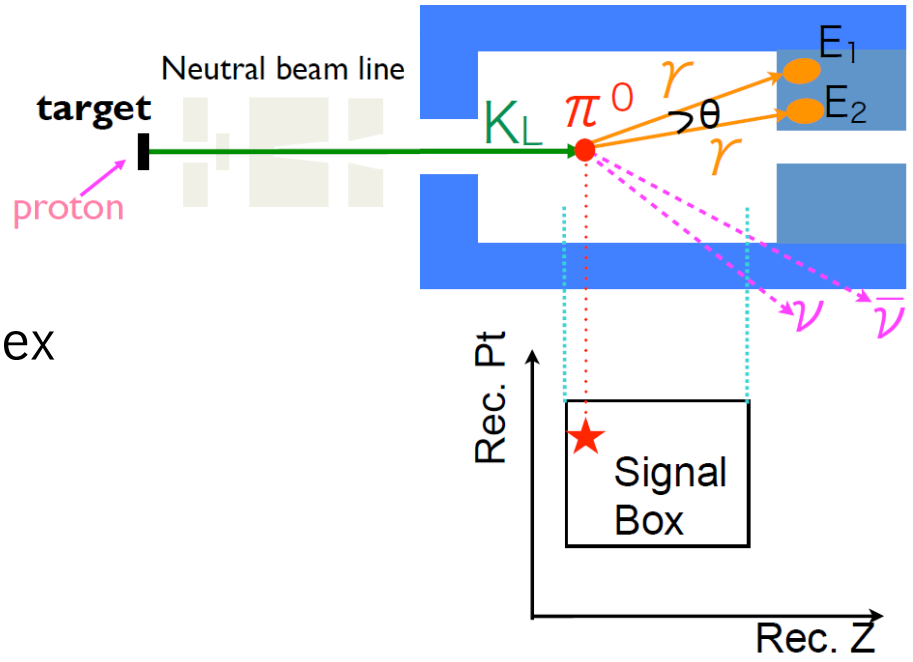
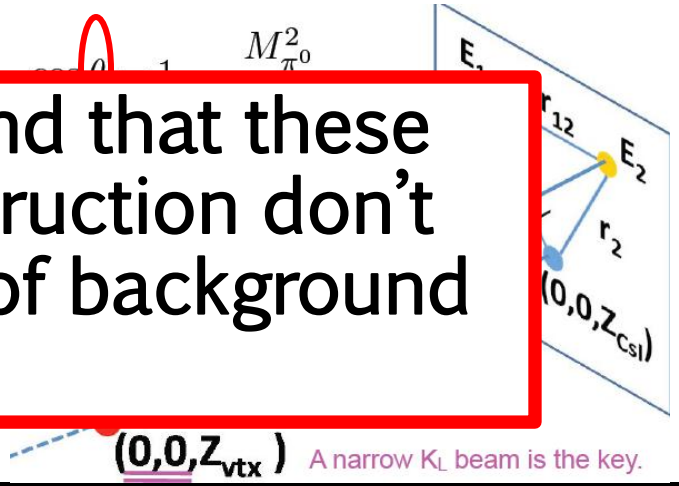


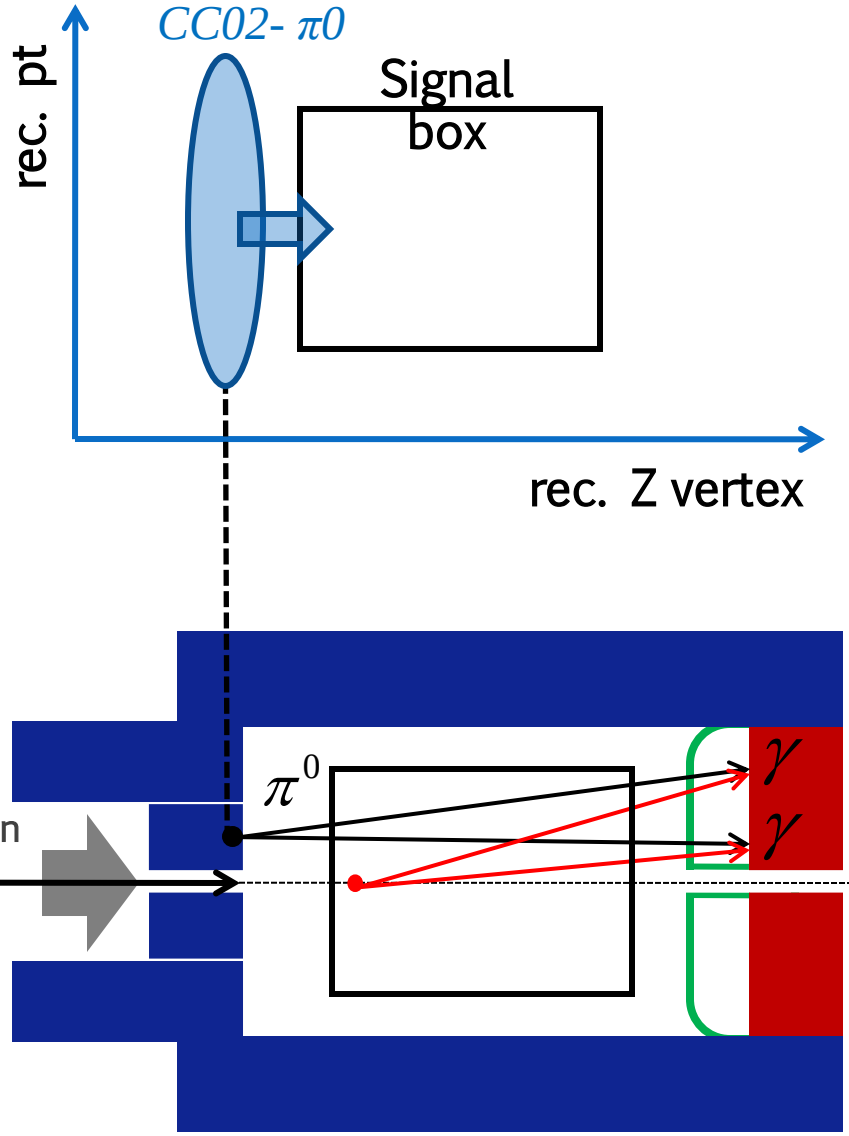
$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

- During of analysis, it was found that these approaches for event reconstruction don't provide effective suppression of background events

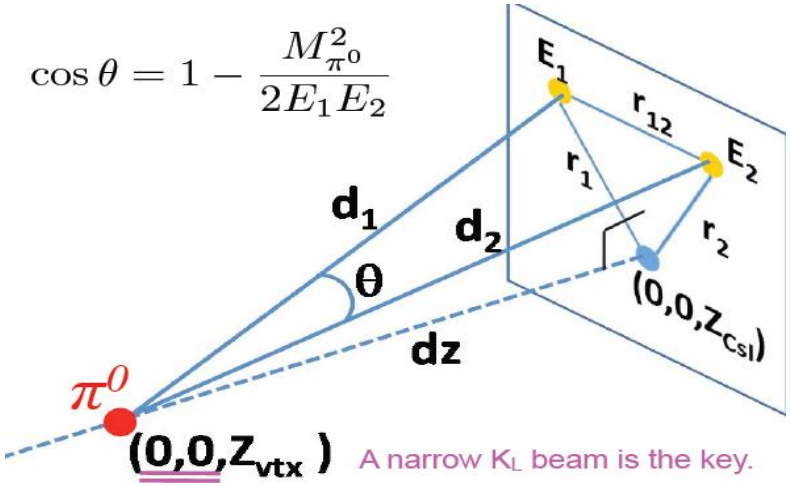


Background Sources from miss-reconstruction

- CC02 pi0 BG
  - energy γ was miss-measured

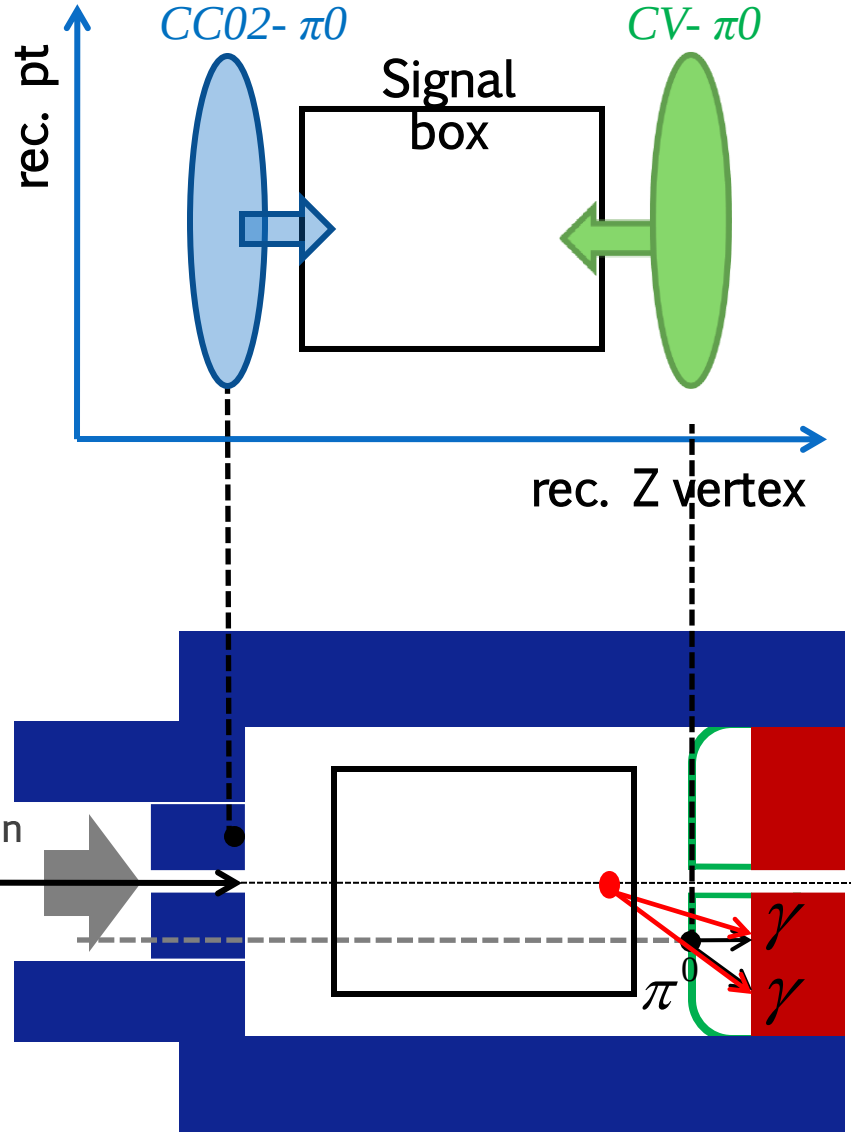


$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

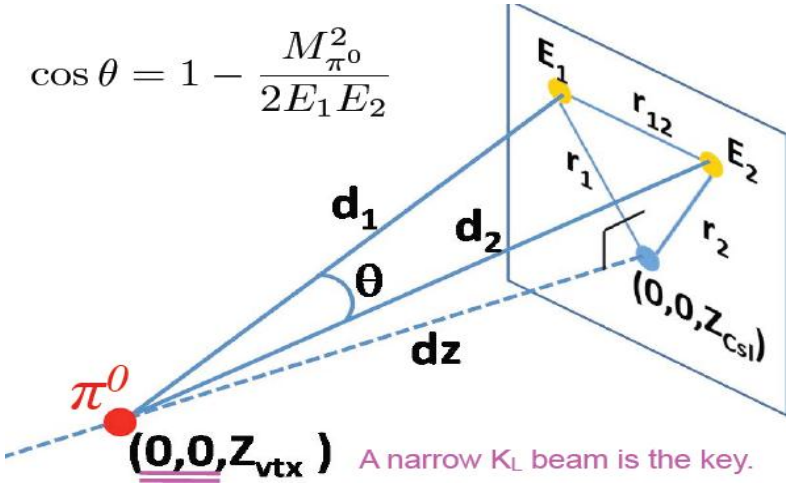


Background Sources from miss-reconstruction

- CC02 pi0 BG
  - energy γ was miss-measured
- CV pi0 BG
  - fusion γ cluster

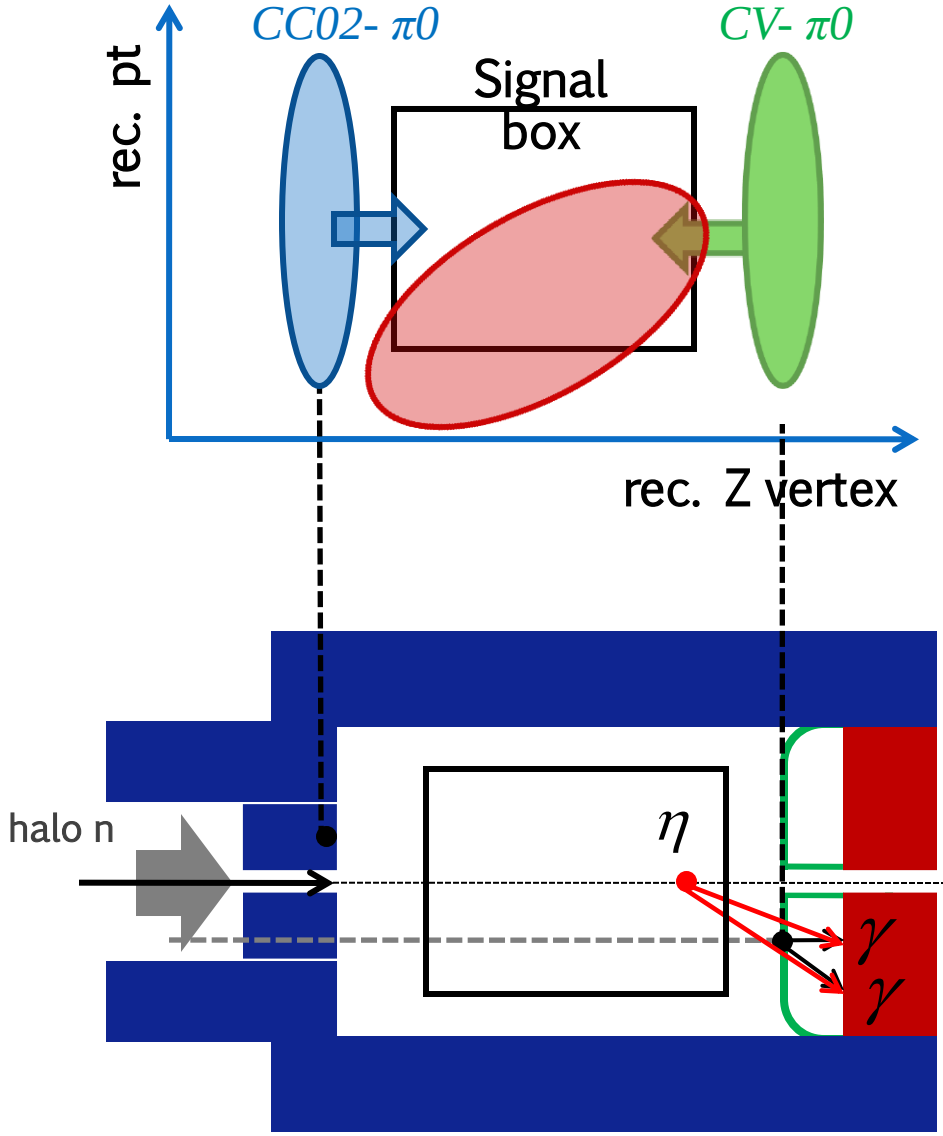


$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

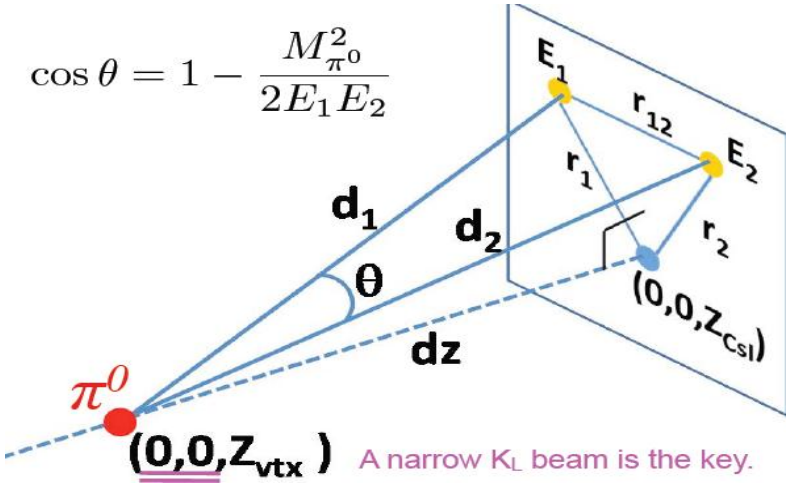


Background Sources from miss-reconstruction

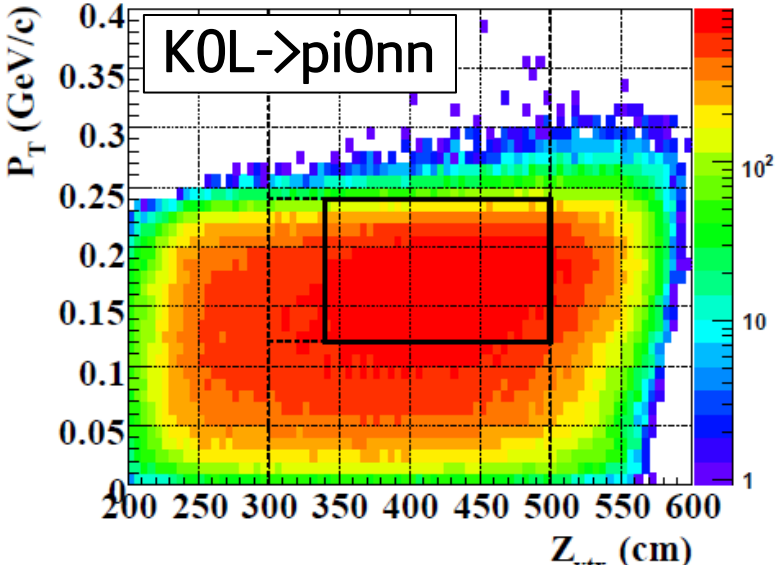
- CC02 pi0 BG
  - energy γ was miss-measured
- CV pi0 BG
  - fusion γ cluster
- CV eta BG
  - difference in M(pi0) and M(η)

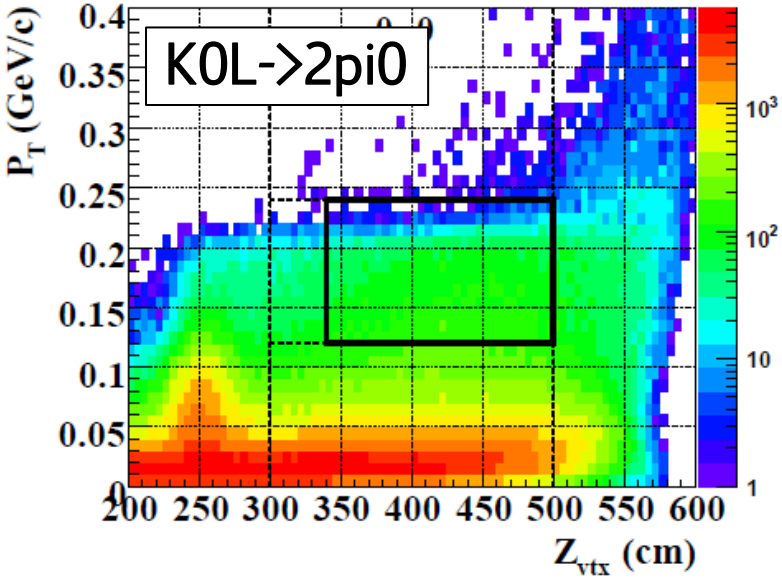


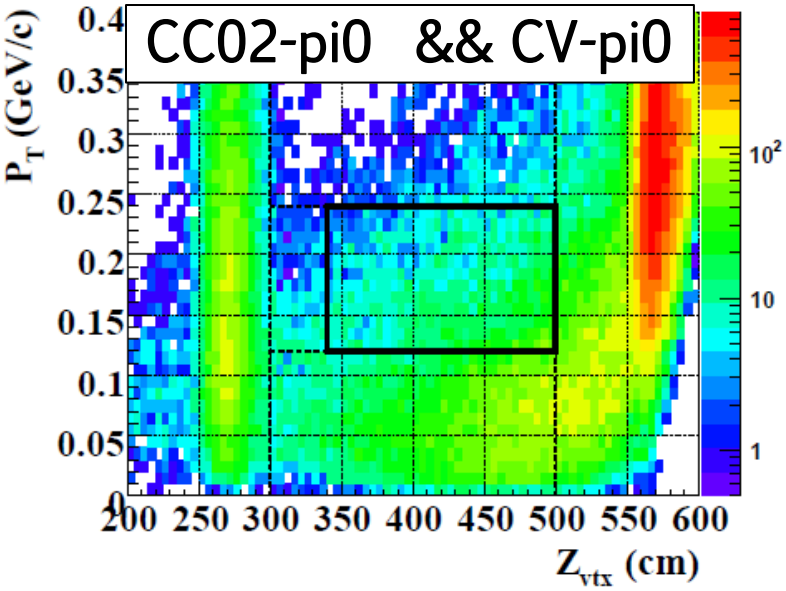
$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

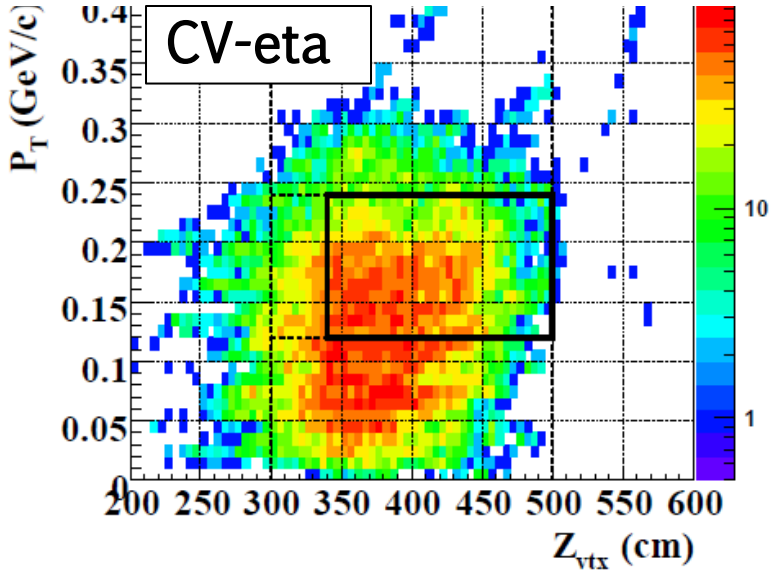


Main Background Sources (MC simulation)





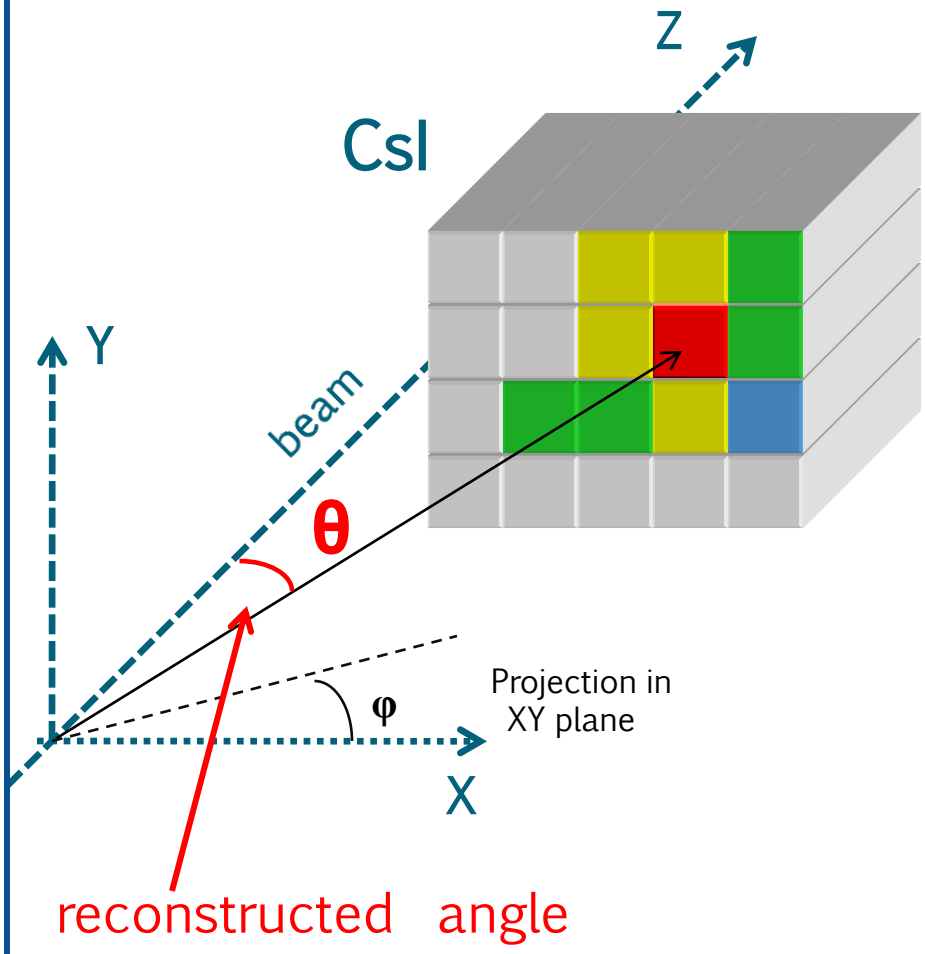




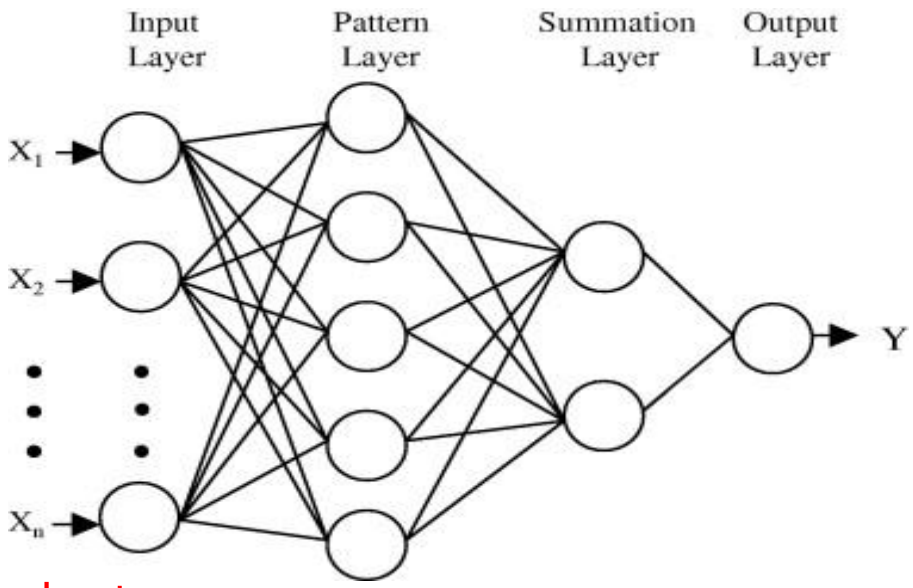
Motivation 1

- For more deep BG suppression and signal selection it will be very helpful to obtain angle information of each photon
  - We can reconstruct Zvtx without pi0 mass assumption

Method for the Photon Angle Reconstruction



Generalized Regression Neural Network with Radial Basis Function



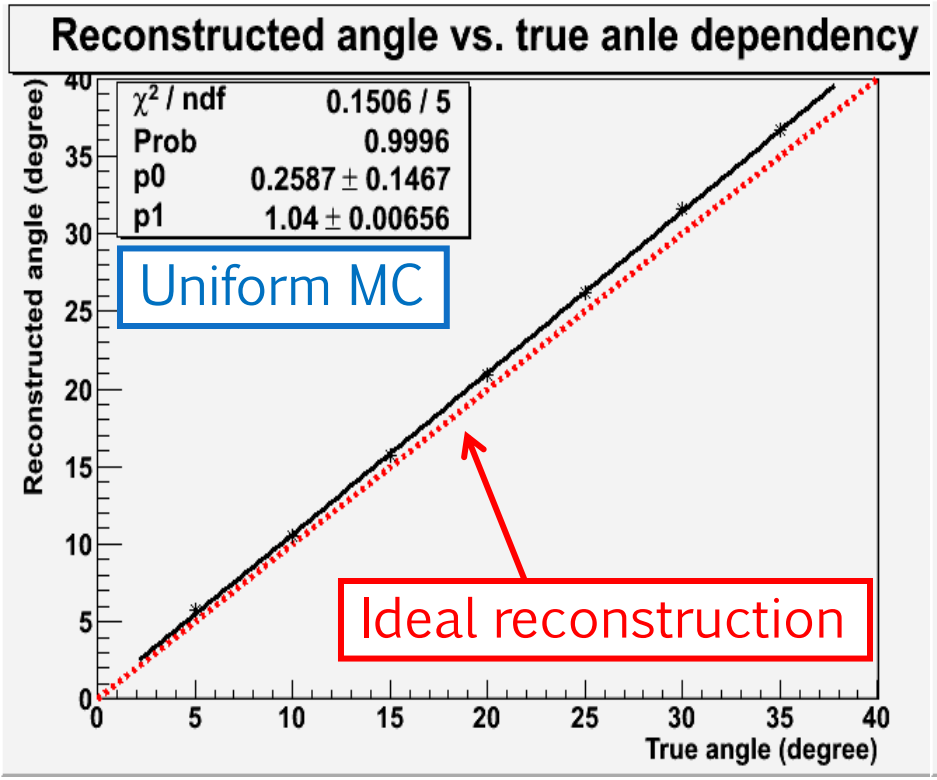
Inputs:
- E gamma
- E of each crystal in cluster

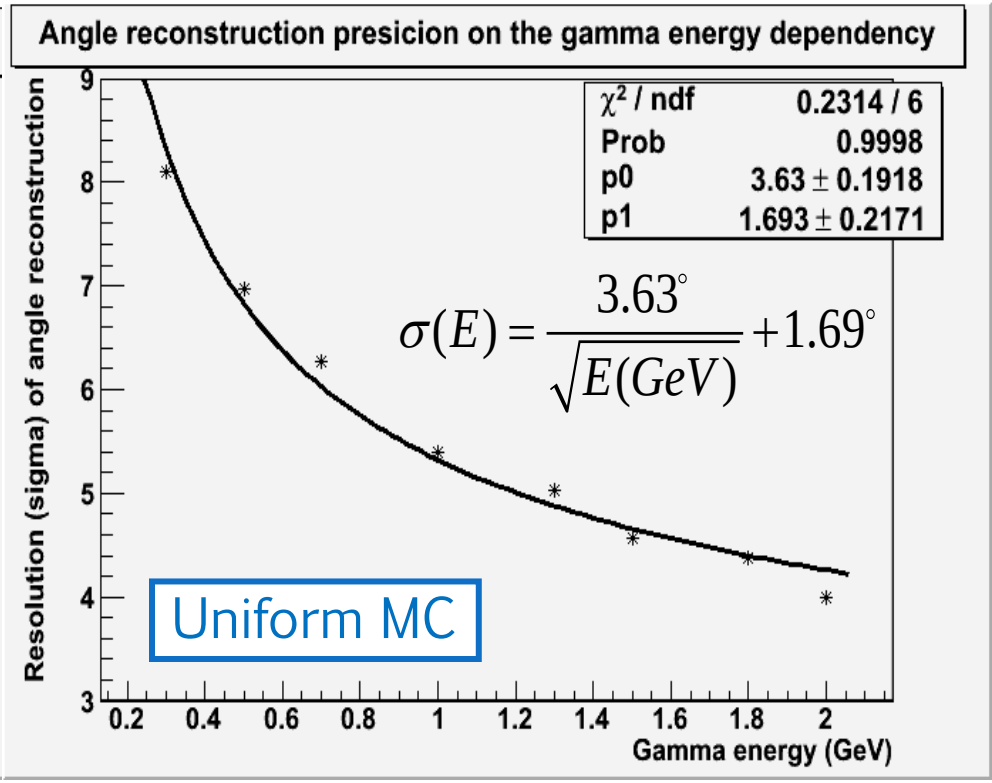
Outputs:
Angle θ

Training samples:
- 7x7 matrix of 7.0x7.0cm crystals
- x, y = [-3.5; 3.5] cm step=0.35cm
- E = [200; 2500] MeV step=50MeV
- Phi = [0;45] deg. step=3 deg.
- Theta = [0; 50] deg. step=0.5 deg

Photon Angle Reconstruction: Performance of NN

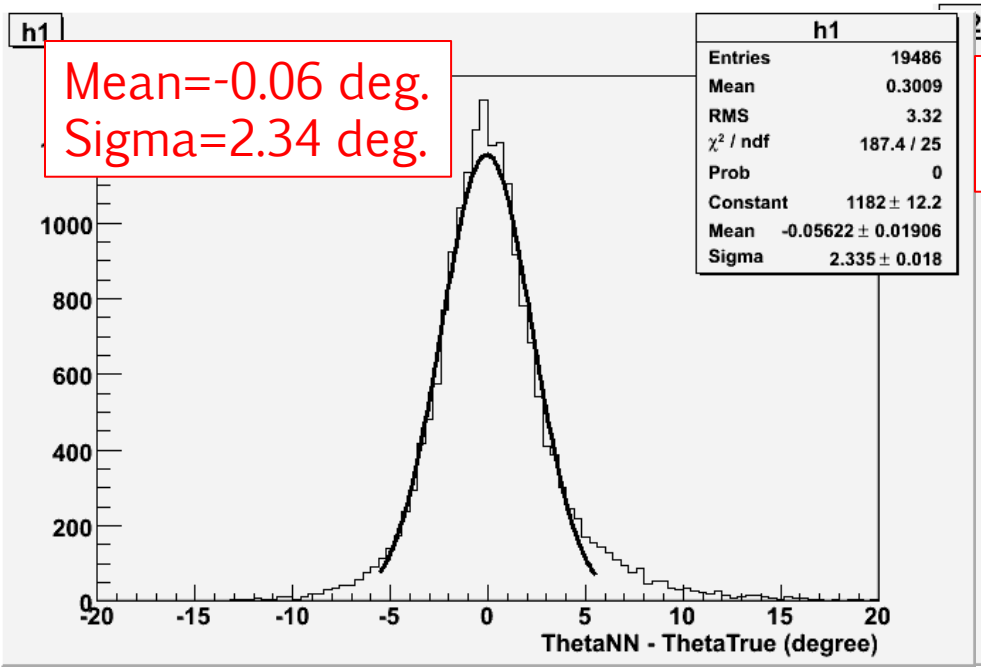
Linearity of reconstructed angle vs. true angle(left) and direction reconstruction precision vs. gamma energy (right). This distributions were obtained from special uniform MC

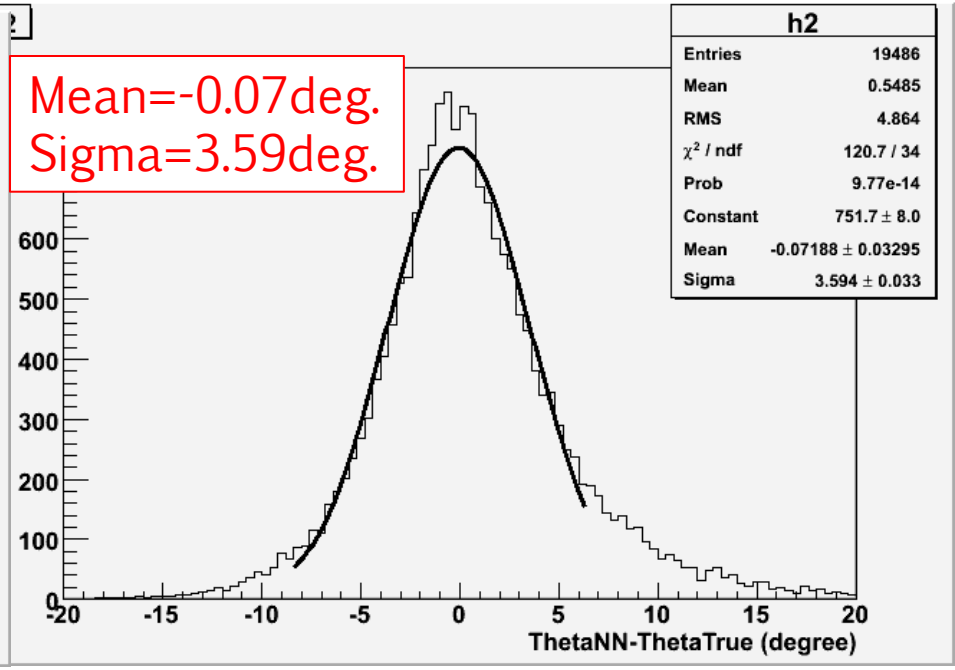




Photon Angle Reconstruction: Performance of NN

Differences between angle obtained from NN and angle obtained from kinematic(left for higher energy gamma, right for lower energy gamma). This distributions were obtained from MC K0L->piOnunubar

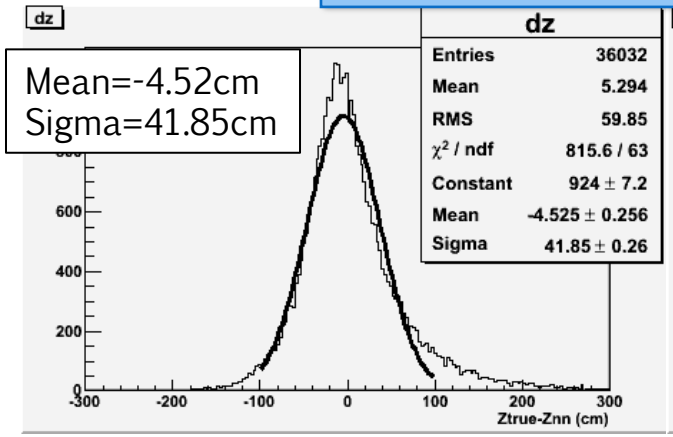




K0L->pi0nunubar MC sample

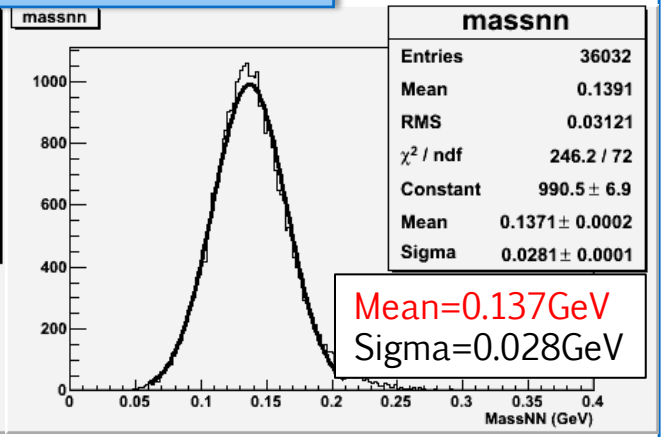
Photon Angle Reconstruction: Mass & Zvtx reconstruction

K->piOnunubar sample (MC)



Mean=-4.52cm
Sigma=41.85cm

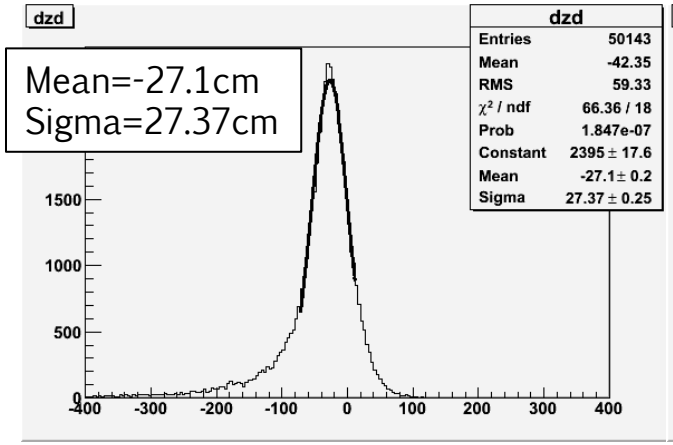
Znn-Zkine (cm)



Mean=0.137GeV
Sigma=0.028GeV

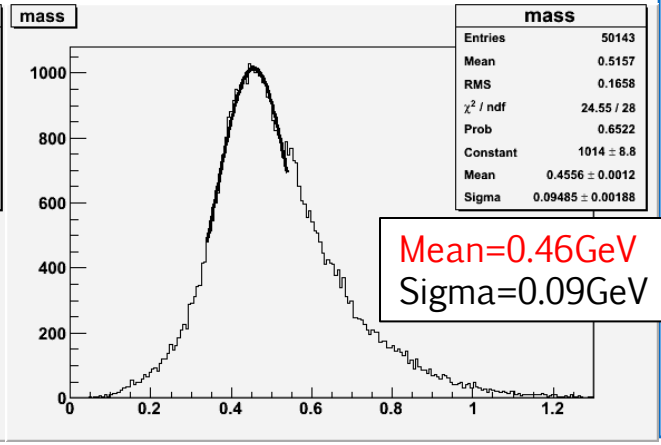
MassNN (GeV)

K->gg sample (MC)



Mean=-27.1cm
Sigma=27.37cm

Znn-Zkine (cm)



Mean=0.46GeV
Sigma=0.09GeV

MassNN (GeV)

On reconstruction we use **kinematic fitting** (with assumption of single vertex of reconstructed gamma)

Main condition:

$$z_{g1} - z_{g2} = \frac{\sqrt{x_1^2 + y_1^2}}{tg(\theta_1)} - \frac{\sqrt{x_2^2 + y_2^2}}{tg(\theta_2)} \equiv 0$$

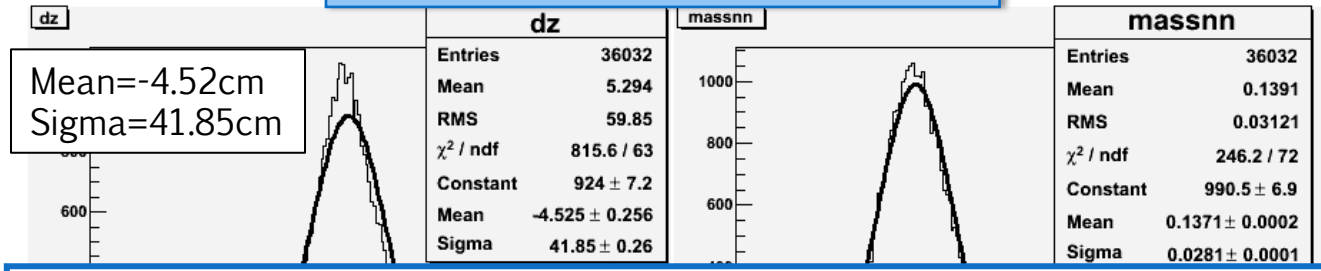
The constraint is imposed using the Lagrange multiplier method:

$$\chi^2 = \frac{(\theta_1 - \theta_1^0)^2}{\sigma_{\theta_1}^2} + \frac{(\theta_2 - \theta_2^0)^2}{\sigma_{\theta_2}^2} + +2\lambda\left(\frac{\sqrt{x_1^2 + y_1^2}}{tg(\theta_1)} - \frac{\sqrt{x_2^2 + y_2^2}}{tg(\theta_2)}\right)$$

Where θ_1^0, θ_2^0 are the initial measurements of θ_1, θ_2

Photon Angle Reconstruction: Mass & Zvtx reconstruction

K->piOnunubar sample (MC)

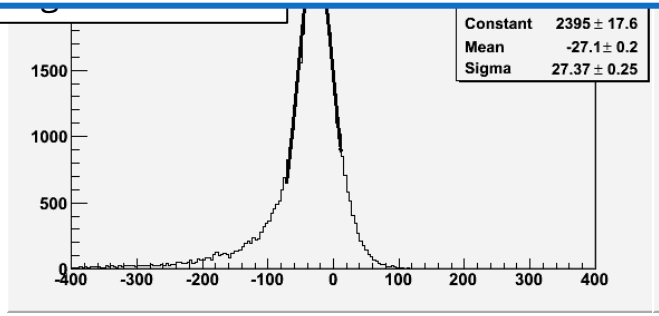


Mean=-4.52cm
Sigma=41.85cm

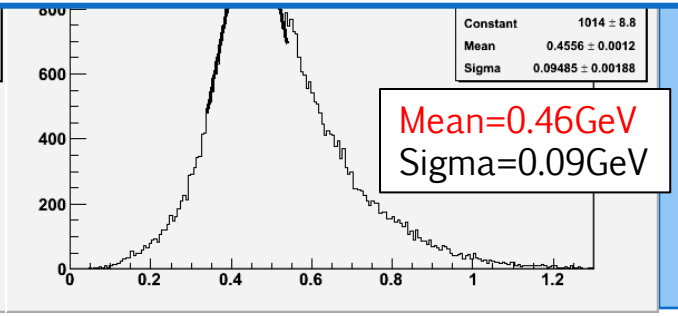
On reconstruction we use **kinematic fitting** (with assumption of single vertex of reconstructed gamma)

Main condition:

- Using angle information we reconstruct mass of X->2gamma (first time in experiment!)
- New variables for events selection: M(pi0), θ_{rec}-θ_{true}
- Involving new variables into analysis allowed to **increase sensitivity on 35%** (Run2 statistics)



Znn-Zkine (cm)

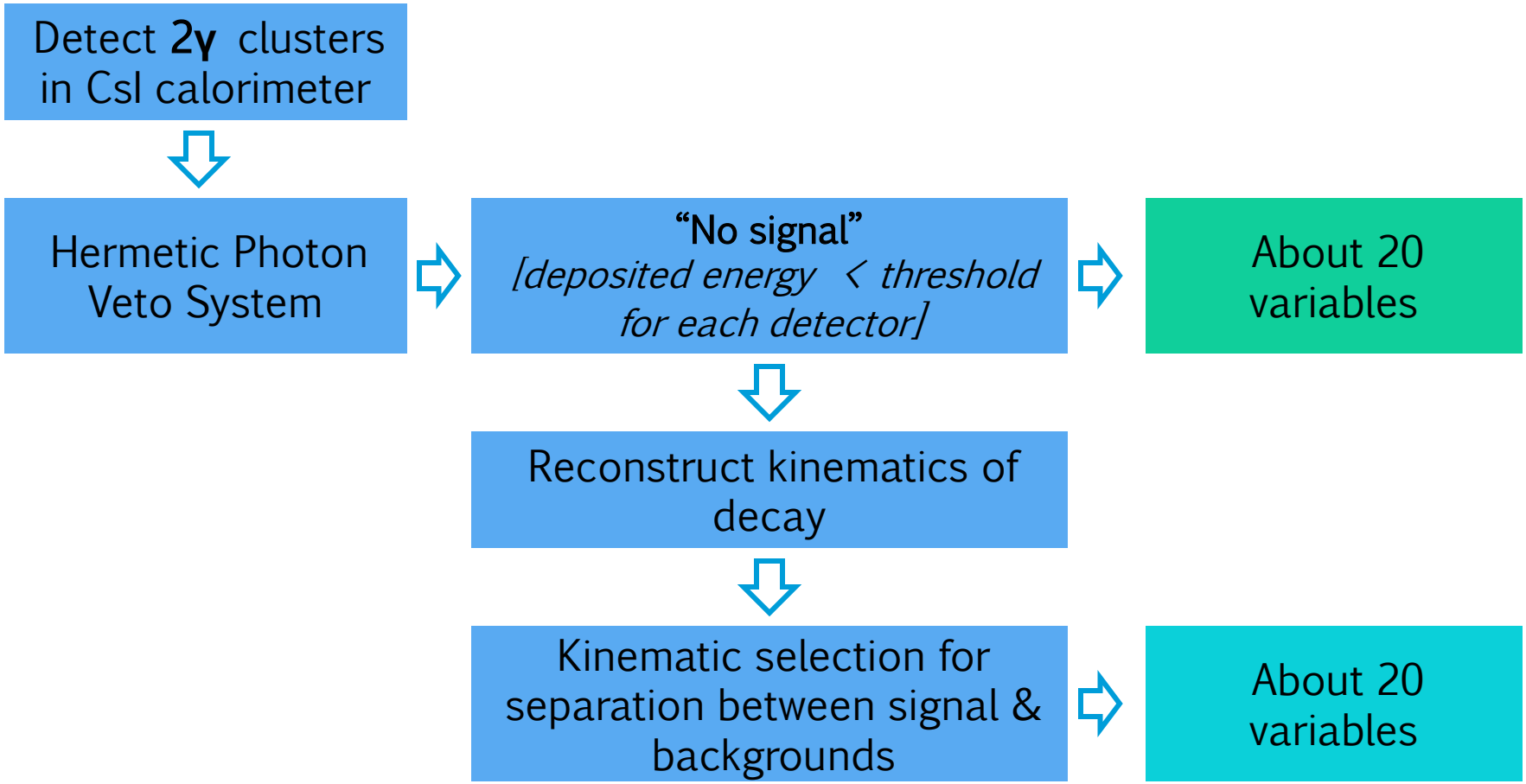


MassNN (GeV)

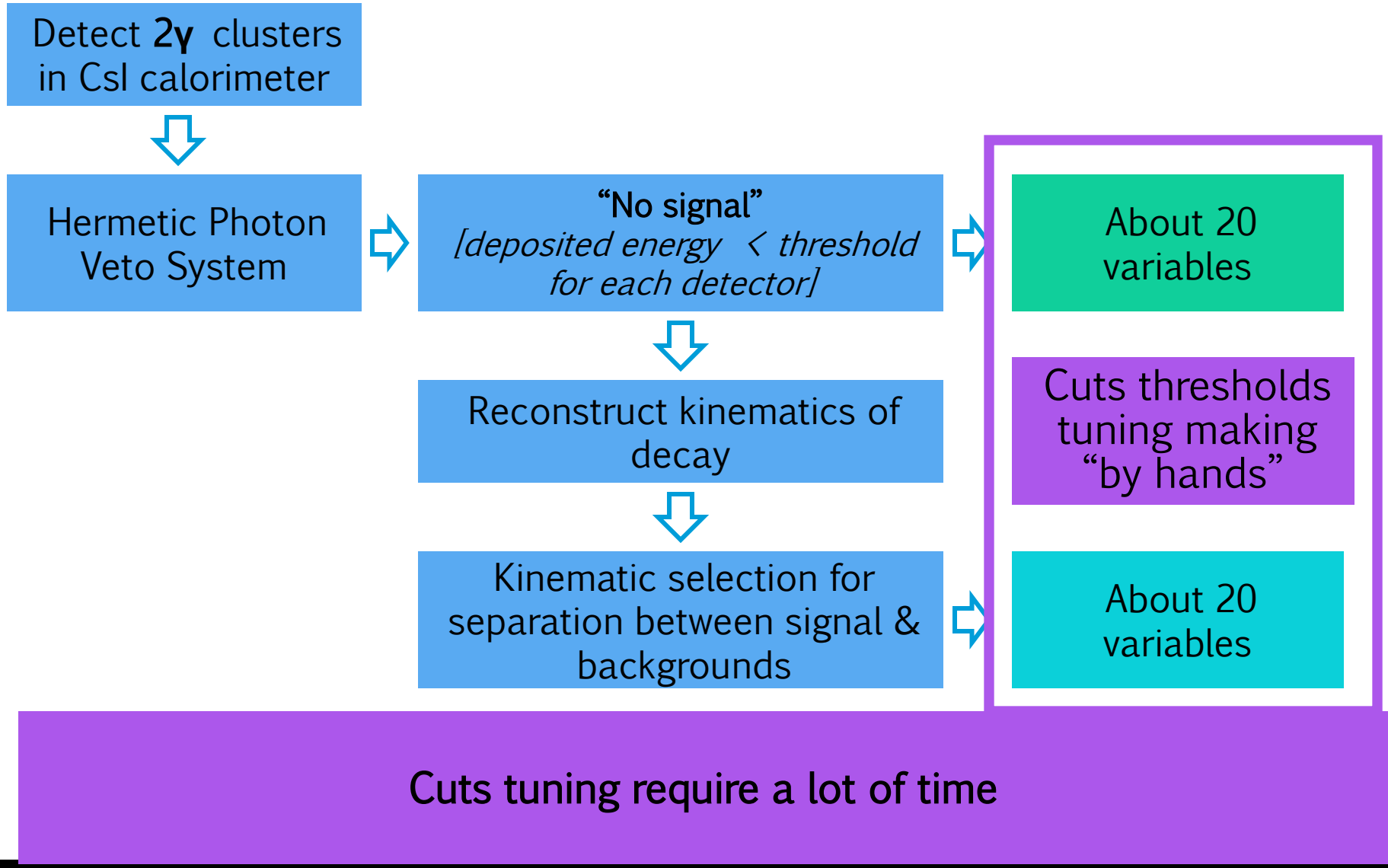
$$+2\lambda\left(\frac{\sqrt{x_1^2+y_1^2}}{tg(\theta_1)}-\frac{\sqrt{x_2^2+y_2^2}}{tg(\theta_2)}\right)$$

Where θ_1^0, θ_2^0 are the initial measurements of θ_1, θ_2

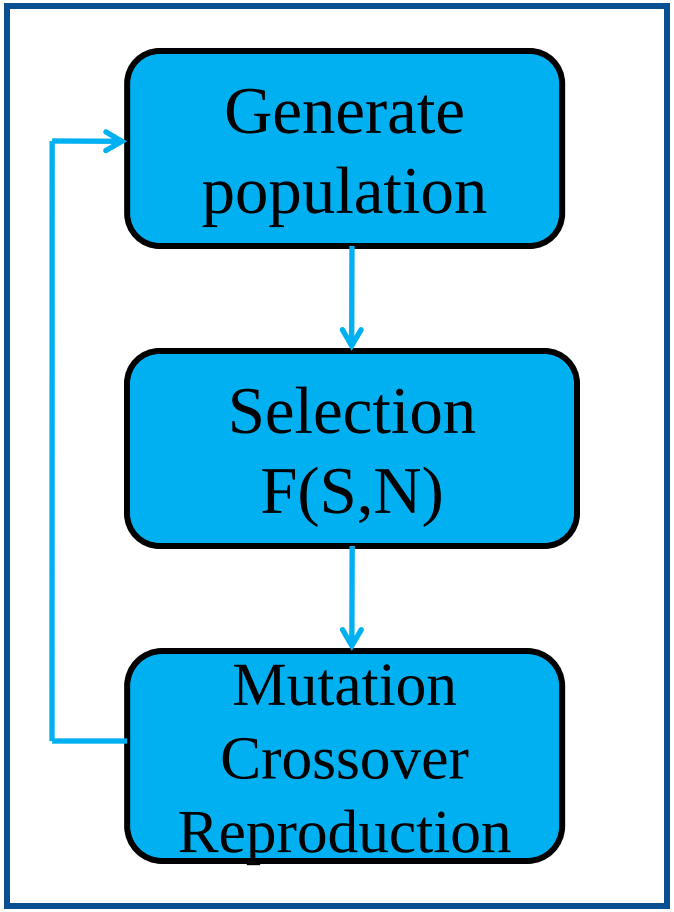
Motivation 2: Brief Scheme of Event Selection in E391



Motivation 2: Brief Scheme of Event Selection in E391



Automatic cuts optimization with Genetic Algorithms



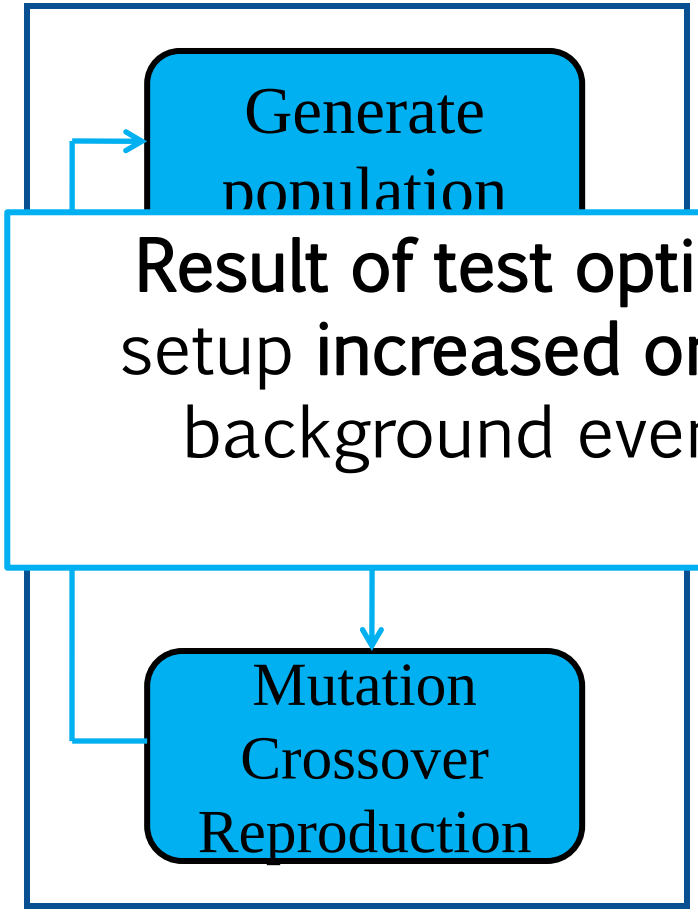
- **Main goal**: Fully automatic cuts optimization with complete BG estimation and acceptance calculation

- **Different ways for optimization**: by introducing different kinds of fitness functions we could change direction of searching – significantly increasing acceptance (S-signal) or suppressing background (N-noise) or keeping S/N ratio.

- **Optimization principle:**
  1) Generate initial population of cuts
  2) For each "individual" (set of cuts) :
     - evaluate acceptance
     - evaluate background
     - calculate **fitness function F(S,N)**
  3) Select better individuals in population
  4) Generate new population -> go to step 2

Free source code: http://garage.cse.msu.edu/software/lil-gp/

Automatic cuts optimization with Genetic Algorithms



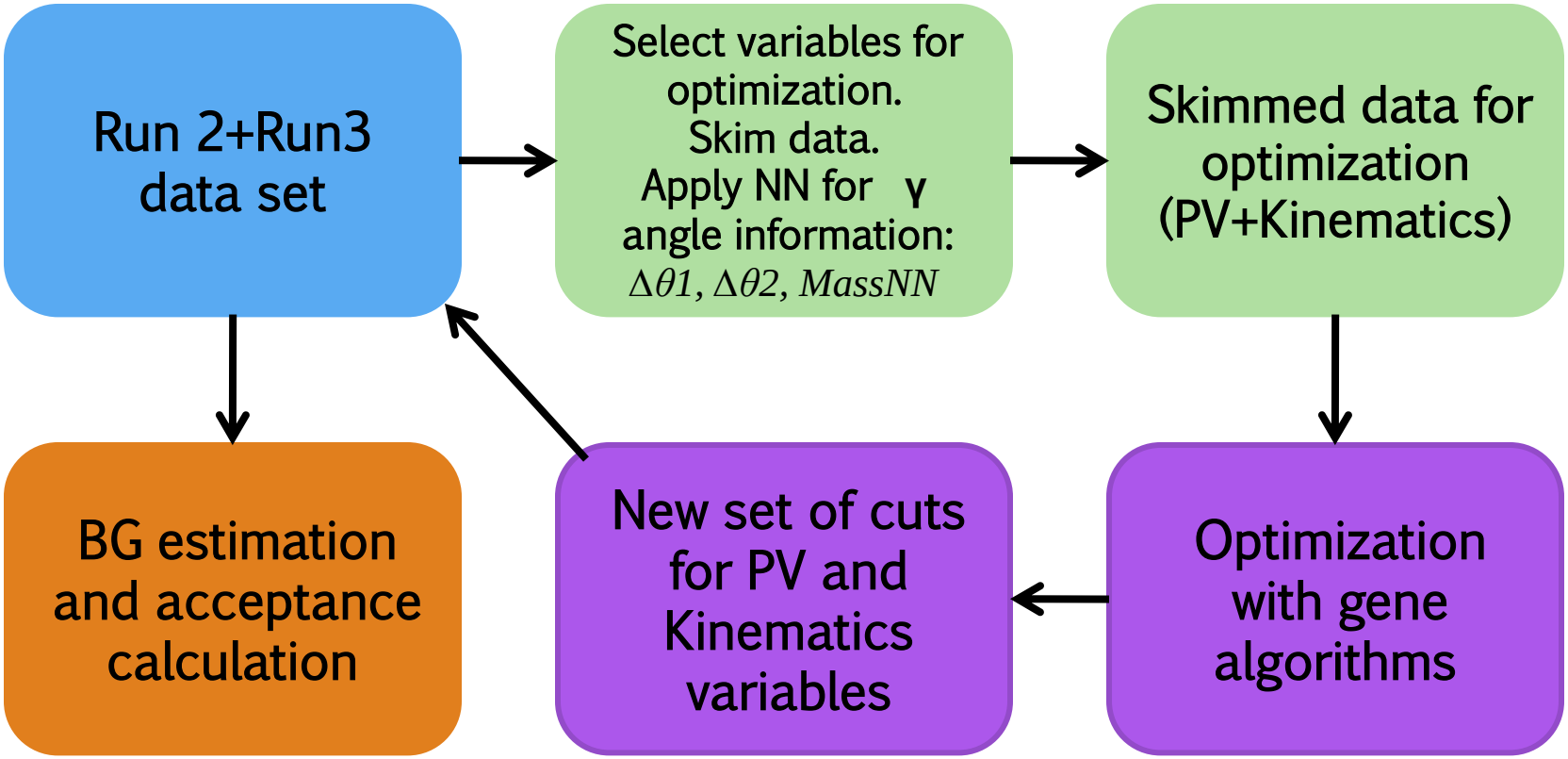
- **Main goal**: Fully automatic cuts optimization with complete BG estimation and acceptance calculation
- **Different ways for optimization**: by introducing

Result of test optimization: sensitivity the E391a setup **increased on 42 %,** and the contribution of background events **decreased by 29 %** (Run2 result)

2) For each "individual" (set of cuts) :
   - evaluate acceptance
   - evaluate background
   - calculate **fitness function F(S,N)**
3) Select better individuals in population
4) Generate new population -> go to step 2

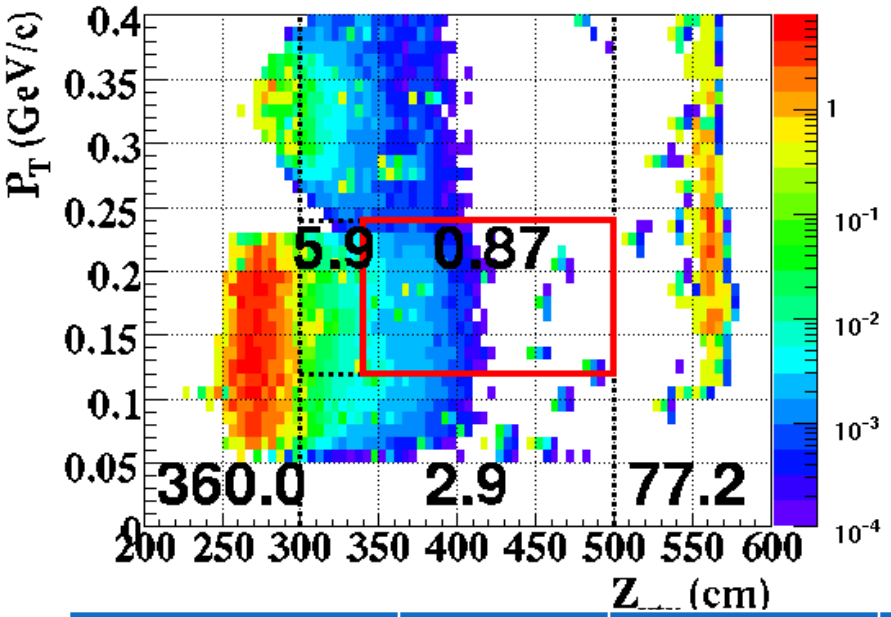
Free source code: http://garage.cse.msu.edu/software/lil-gp/

Motivation 3: E391 Data Reanalysis with 2 methods

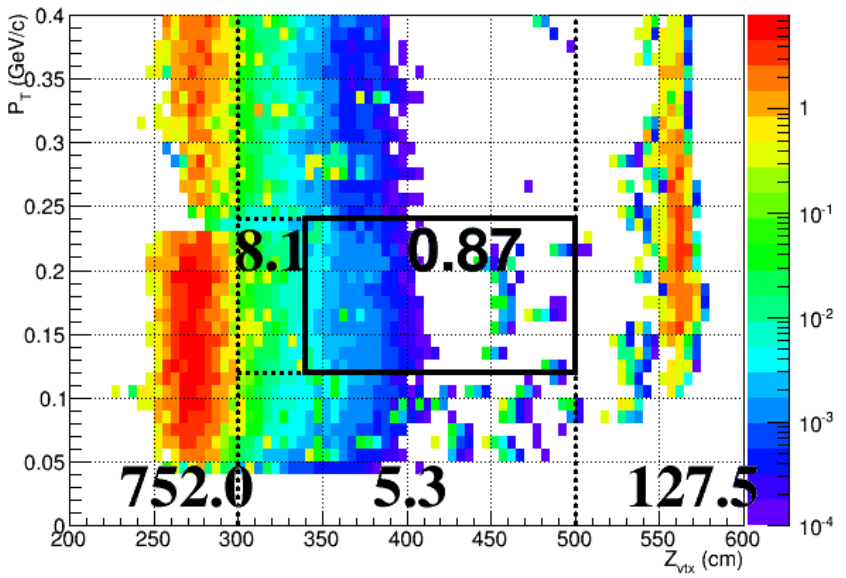


Results: Summary BG (Run2+Run3)

E391 analysis



E391 reanalysis

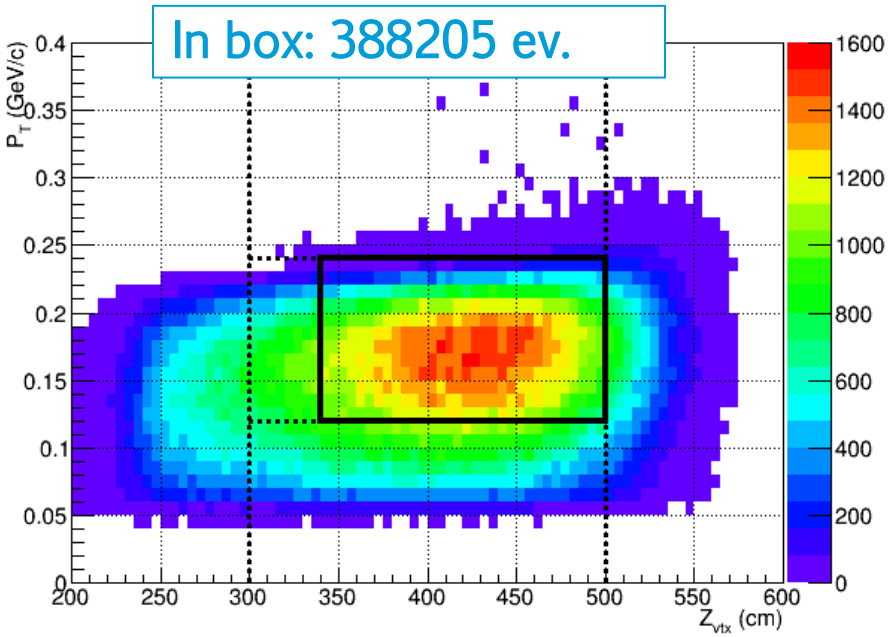


	K->2pi0	CC02-pi0	CV-pi0	CV-eta	Signal Box
E391 analysis	0.02	0.66	negligible	0.19	0.87
New analysis	0.03	0.29	0.34	0.25	0.87

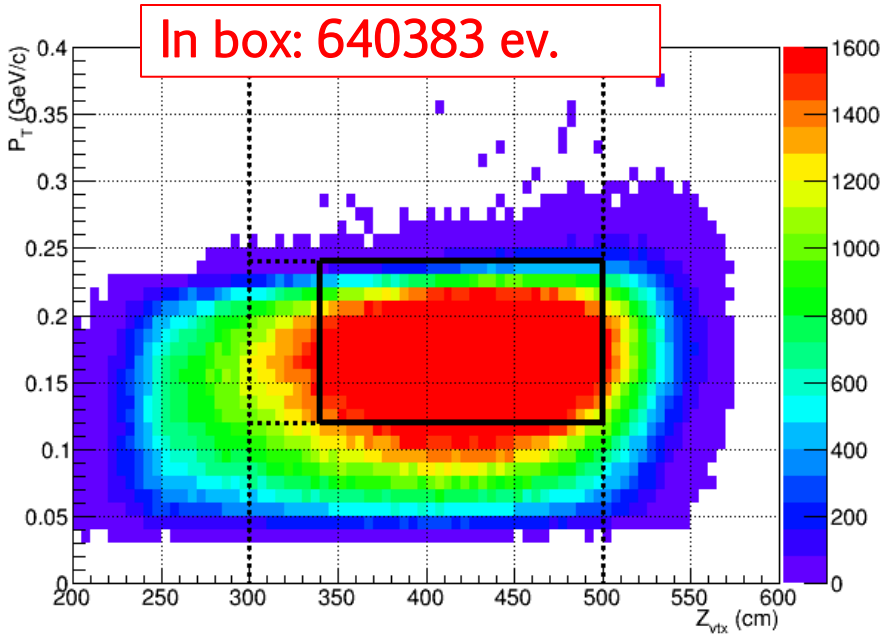
Total BG: the same level
(In comparison with E391 final result)

Results: Acceptance (Run2+Run3)

E391 analysis



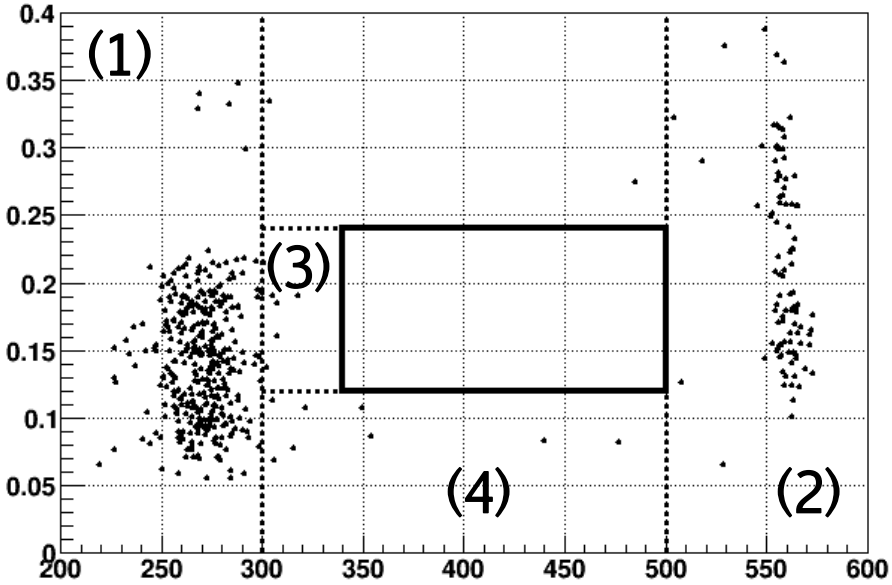
E391 reanalysis



Total BG: the same level
Acceptance : increased on 65%
(In comparison with E391 final result)

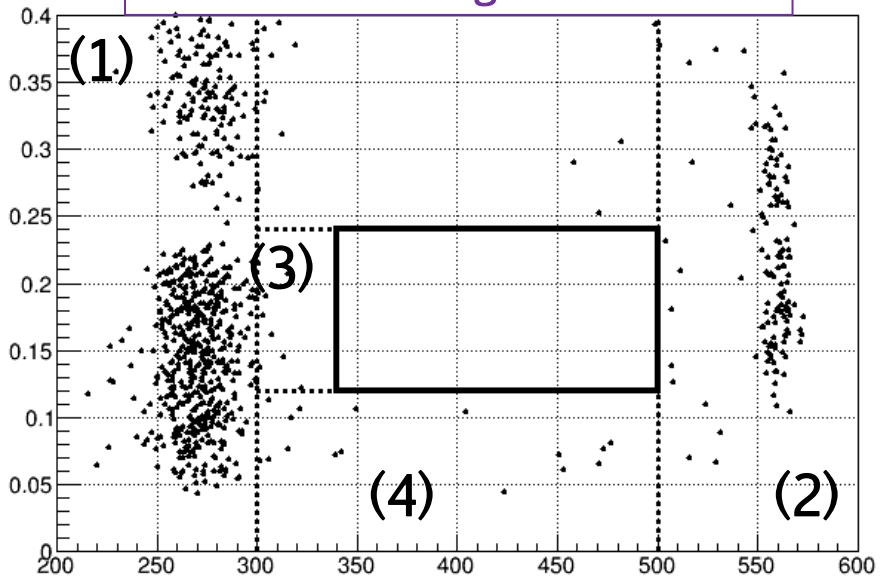
Results: Final Plot (Run2+Run3 data)

E391 analysis



E391 reanalysis

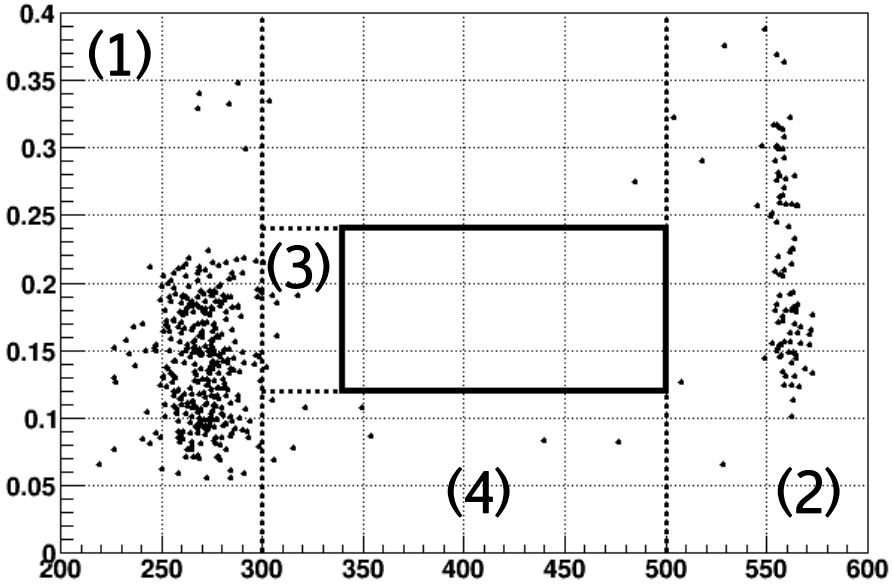
No events in signal box!!



	Region-1	Region-2	Region-3	Region-4	Signal box
Data	752 (360)	151 (101)	9 (8)	16 (8)	0 (0)
MC BG	752 (360)	127.5 (77.2)	8.1 (5.9)	5.3 (2.9)	0.87 (0.87)

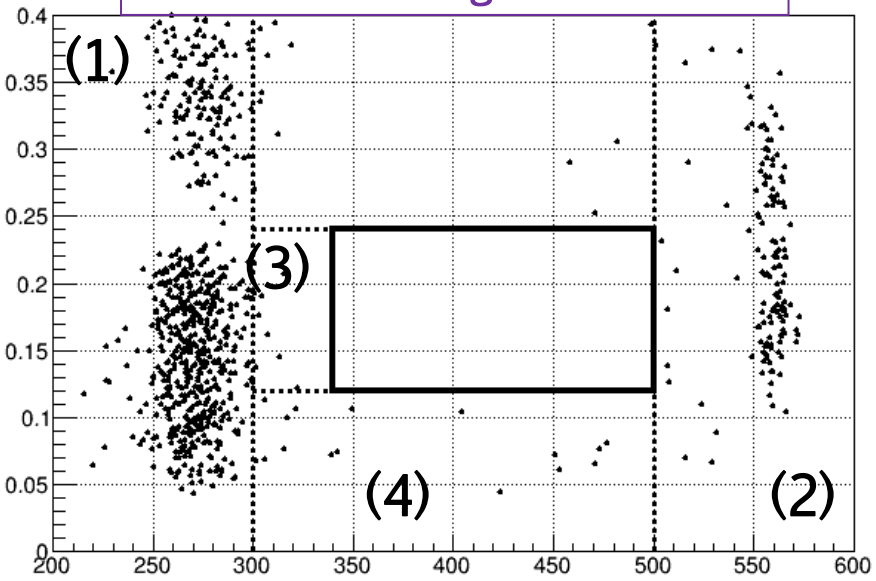
Results: Final Plot (Run2+Run3 data)

E391 analysis



E391 reanalysis

No events in signal box!!



	Signal box
Data	0 (0)
MC BG	0.87 (0.87)

Total BG: the same level

Acceptance : increased on 65%

Data : No events in signal box!!

(In comparison with E391 final result)

Thank you for attention!