KEK PS E391a実験における $K_L \to \pi^0 \nu\bar{\nu}$探索の最終結果

16th ICEPP Symposium

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  - $K_L \to \pi^0 \nu \bar{\nu}$を測定する意義
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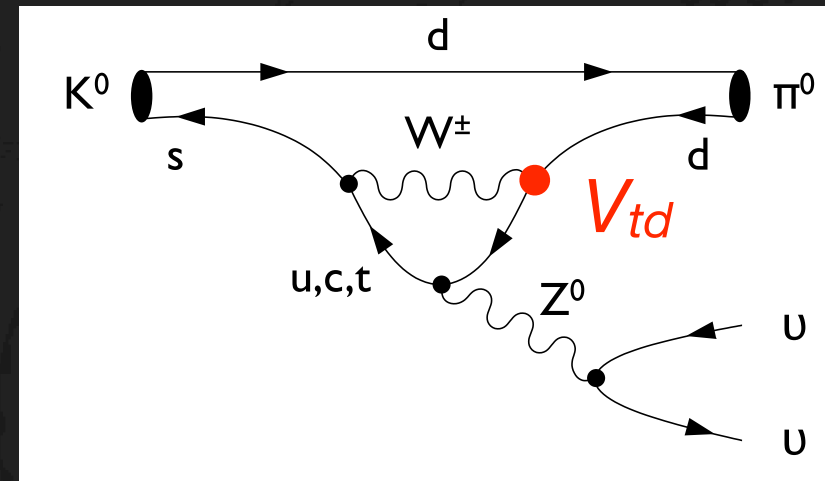
  - "halo neutron background"
  - イベント選択の最適化
- Results
  - sensitivity & results

Introduction

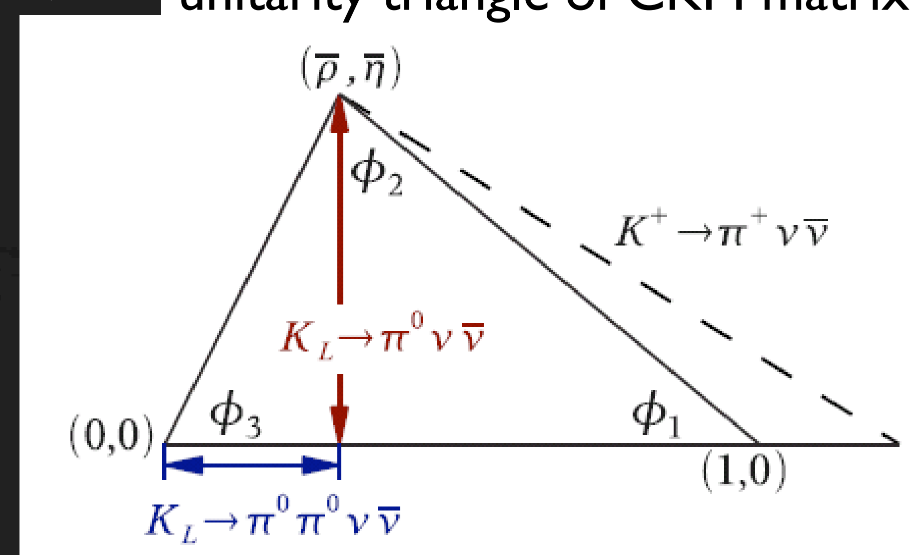
Physics motivation

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

- $K_L \to \pi^0 \nu \nu$崩壊の特徴
  - “直接的” CP violation
  - CKM行列の複素位相ηを観測
    $Br(K_L \to \pi^0 \nu \bar{\nu}) \propto \eta^2$
  - 理論的不定性が小さい : 1-2%
    ($K^+ \to \pi^0 e^+ \nu$ + isospin対称性)
  - rare decay
    : 分岐比 2.5×10^{-11} @SM



unitarity triangle of CKM matrix



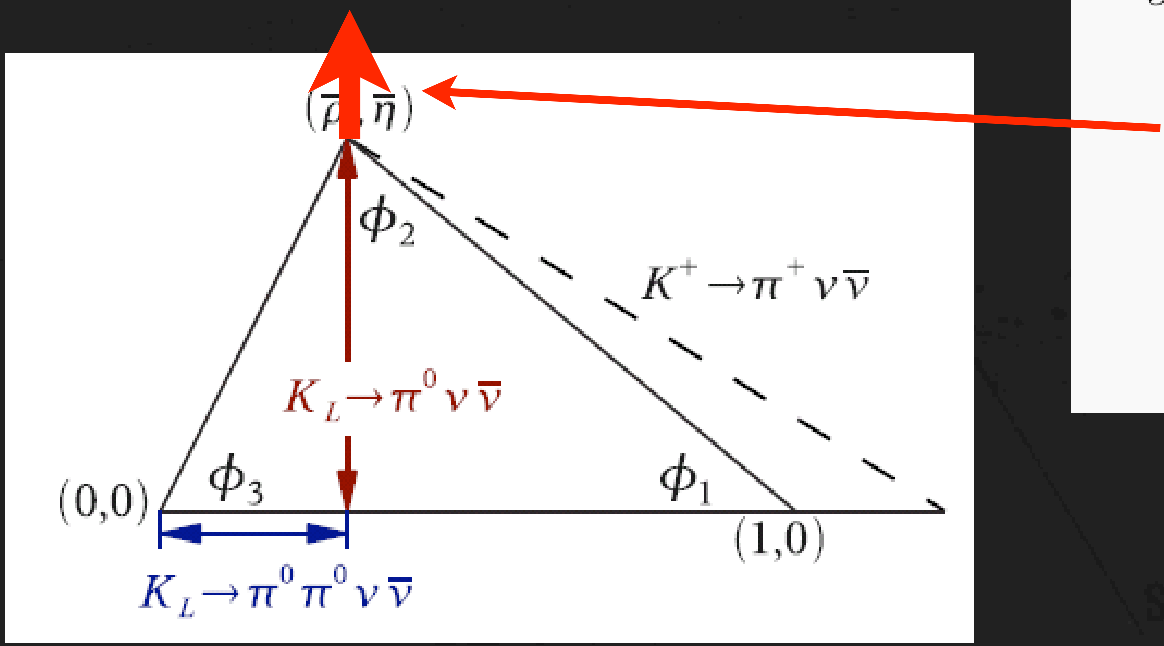
$K_L \to \pi^0 \nu \bar{\nu}$ Decay with NP

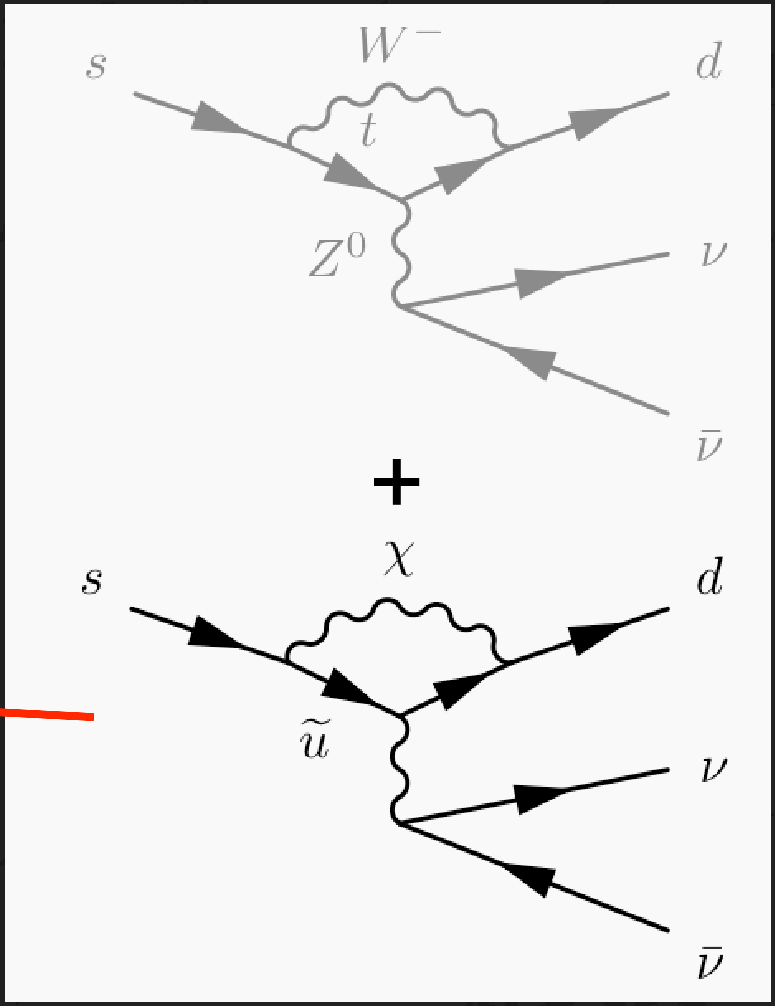
- もし新物理があれば…?

  新粒子がloop diagramを回る

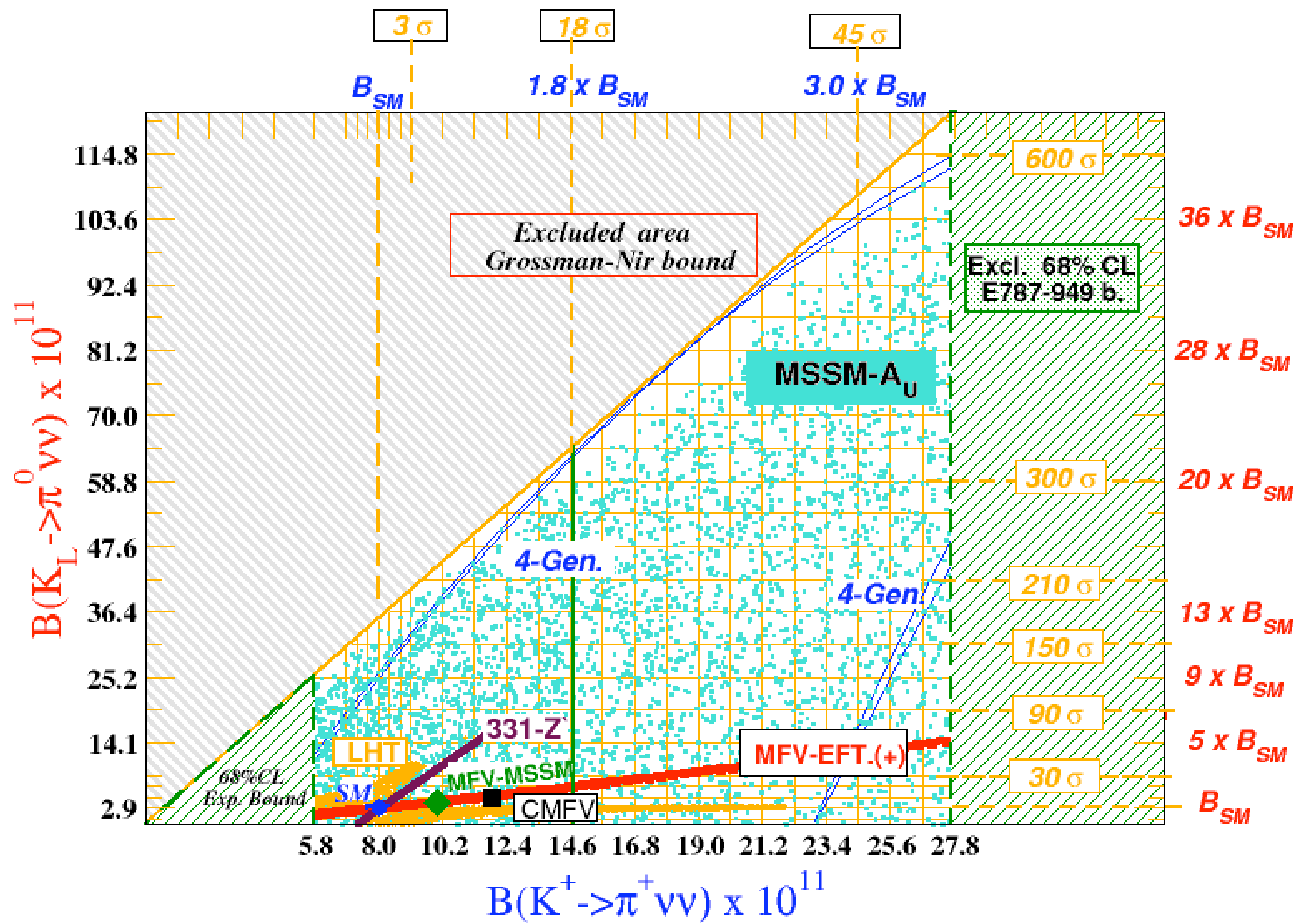
  →崩壊振幅を変化させる

  & 理論的不定性 : still 1-2%





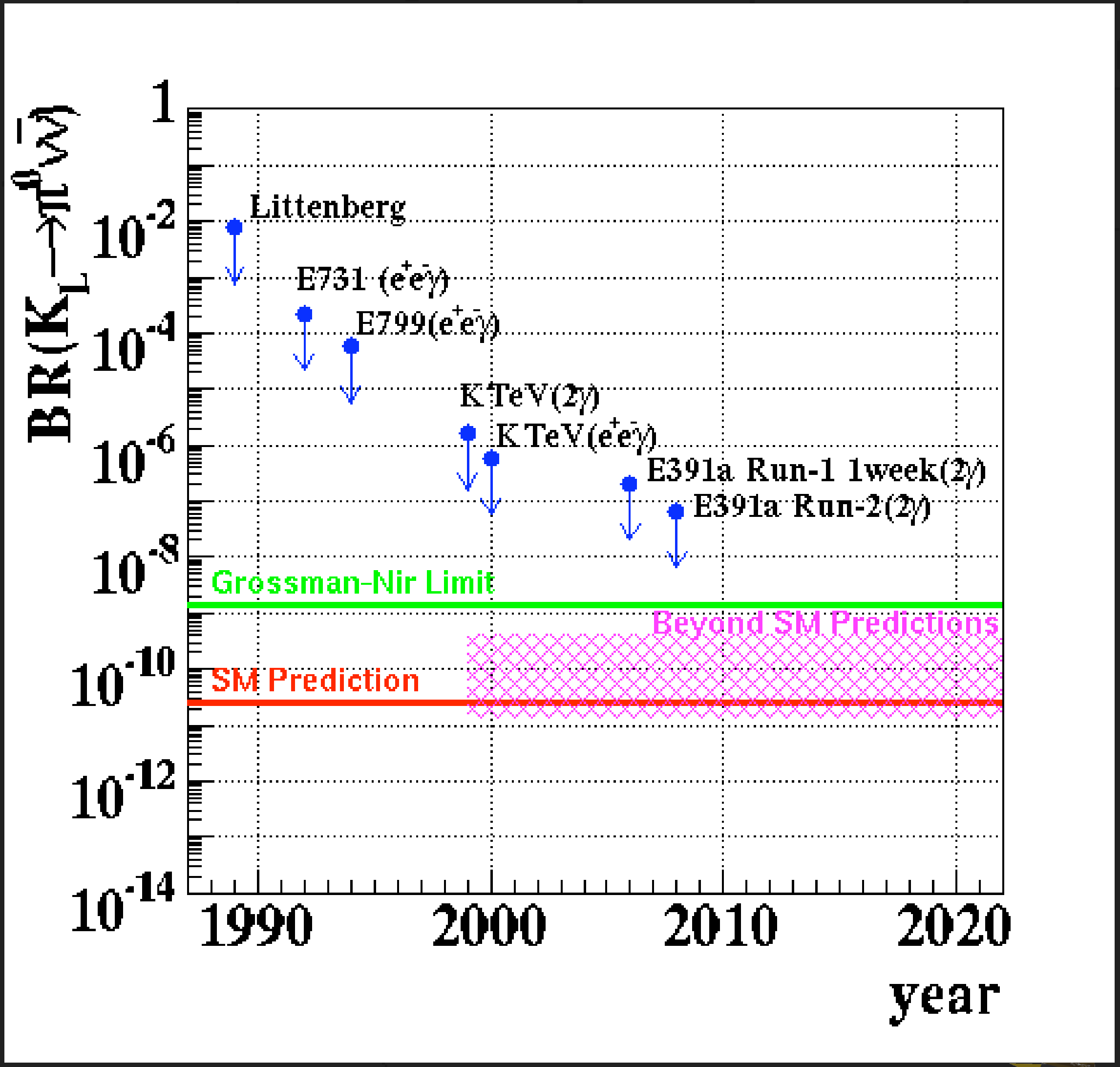
$K_L \to \pi^0 \nu \bar{\nu}$ Decay with NP



http://www.lnf.infn.it/wg/vus/content/Krare.html

History of $K_L \to \pi^0 \nu \bar{\nu}$ Search

- 上限値更新の歴史
- KTeV
  - $\pi^0 \to e^+e^-\gamma$
  - $Br < 5.9\times10^{-7}$
- KEK E391a (Run2)
  - $\pi^0 \to \gamma\gamma$
  - $Br < 6.7\times10^{-8}$

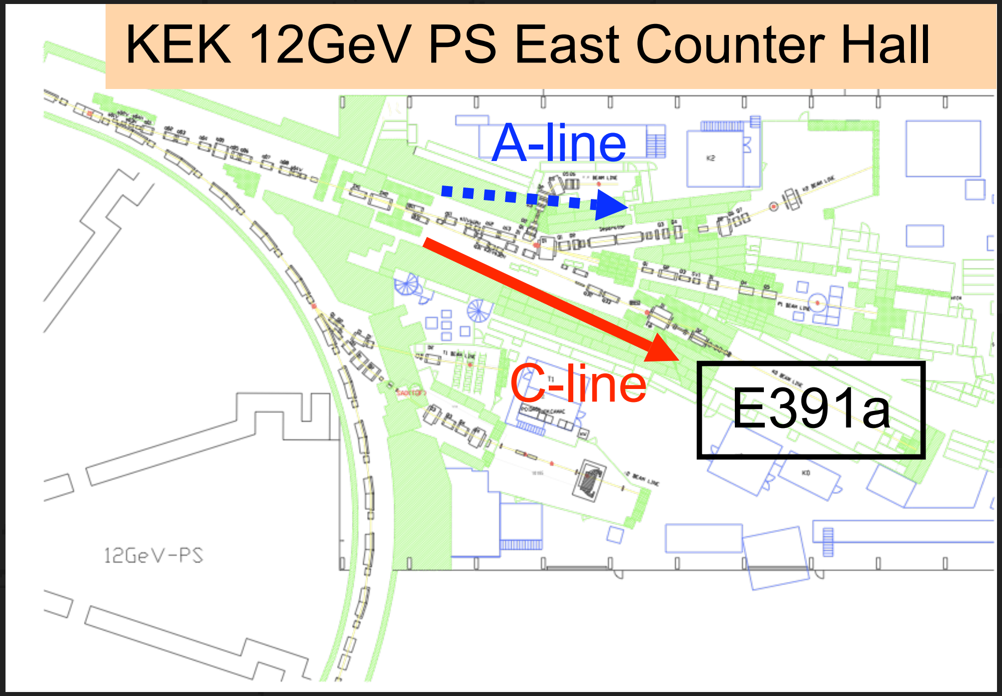


E391a Experiment

E391a Experiment

- $K_L \to \pi^0 \nu \overline{\nu}$ 探索実験 @ KEK 12GeV PS
  - 世界初のこのモードに特化した実験
  - 次期実験 K^{O}TO (J-PARC E14) のためのパイロット

- Three Physics Runs
  - Run1 (2004 Feb-Jul)
    "membrane" problem
  - Run2 (2005 Feb-Apr)
  - Run3 (2005 Nov-Dec)



最終解析には
Run2 + Run3 のsampleを使用

Experimental Principles

- シグナルモードの同定

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

  └→2γ →cannot detect

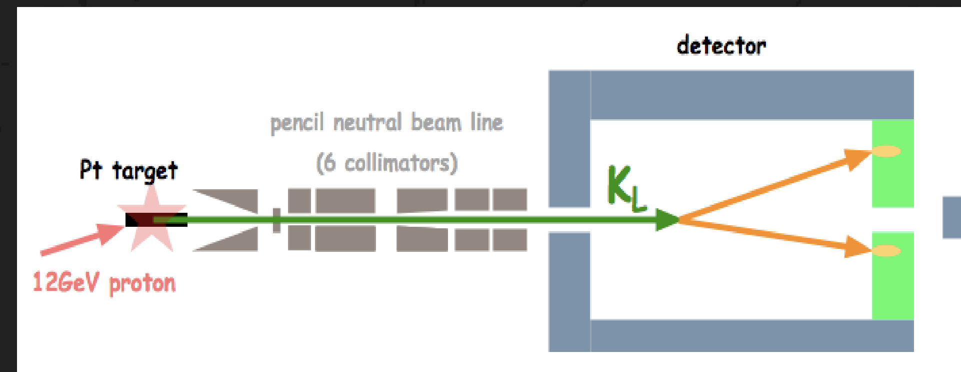
- "2γ + nothing"
  - 2γ → CsI calorimeter (energy, position)
  - nothing → hermetic veto detector
- 崩壊点を$M(\pi^0)$を仮定する事で再構成

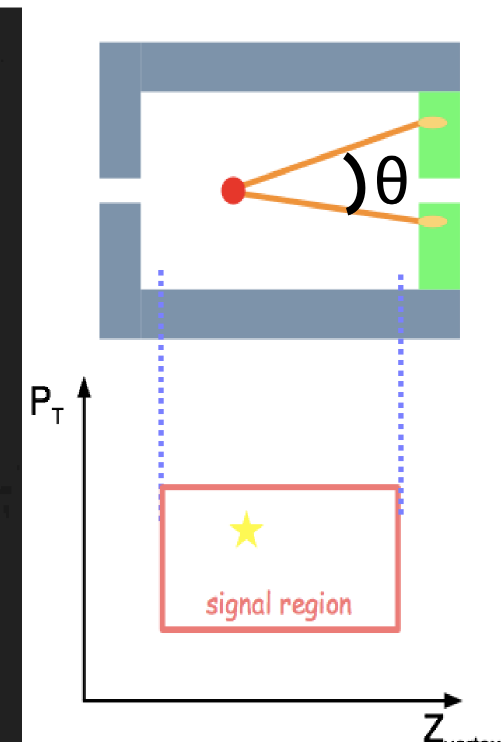
  $$M(\pi^0)^2 = 2E_1E_2(1-\cos\theta)$$

  "pencil" beam で p_T 分解能を確保

  - p_Tと崩壊点の情報から

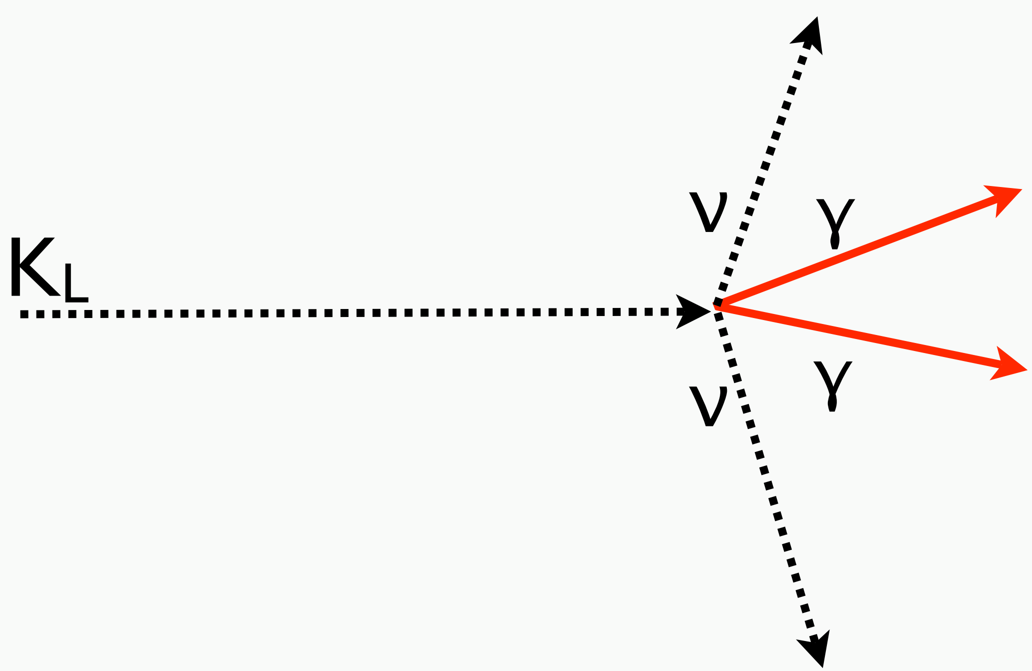
    signal regionを定義





E391a Detector

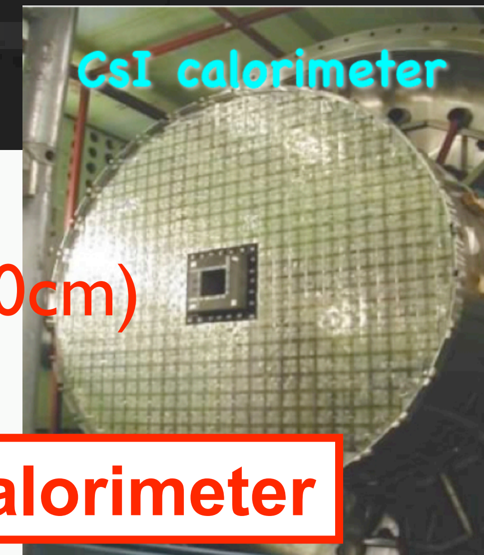
Signal Mode



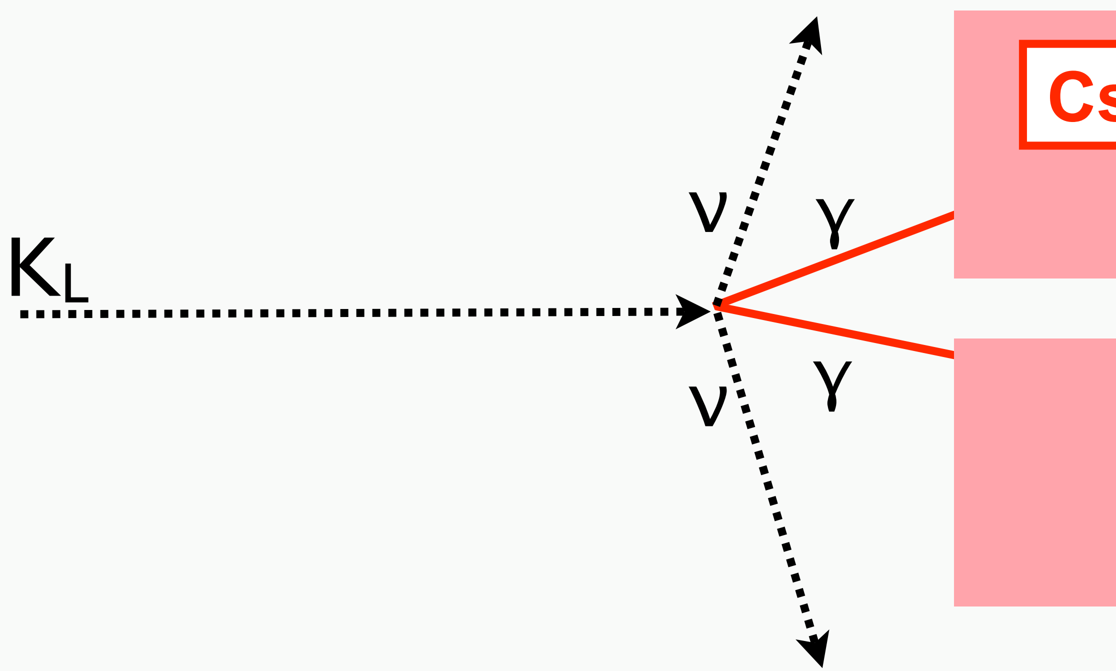
E391a Detector

Signal Mode

pure CsI crystal
7x7x30cm (5x5x50cm)
576 channels



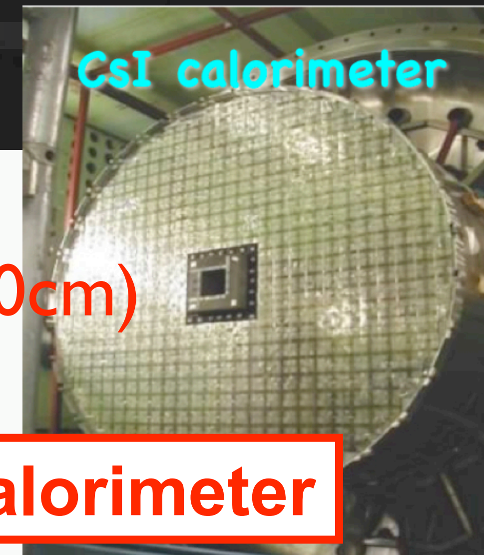
CsI Calorimeter

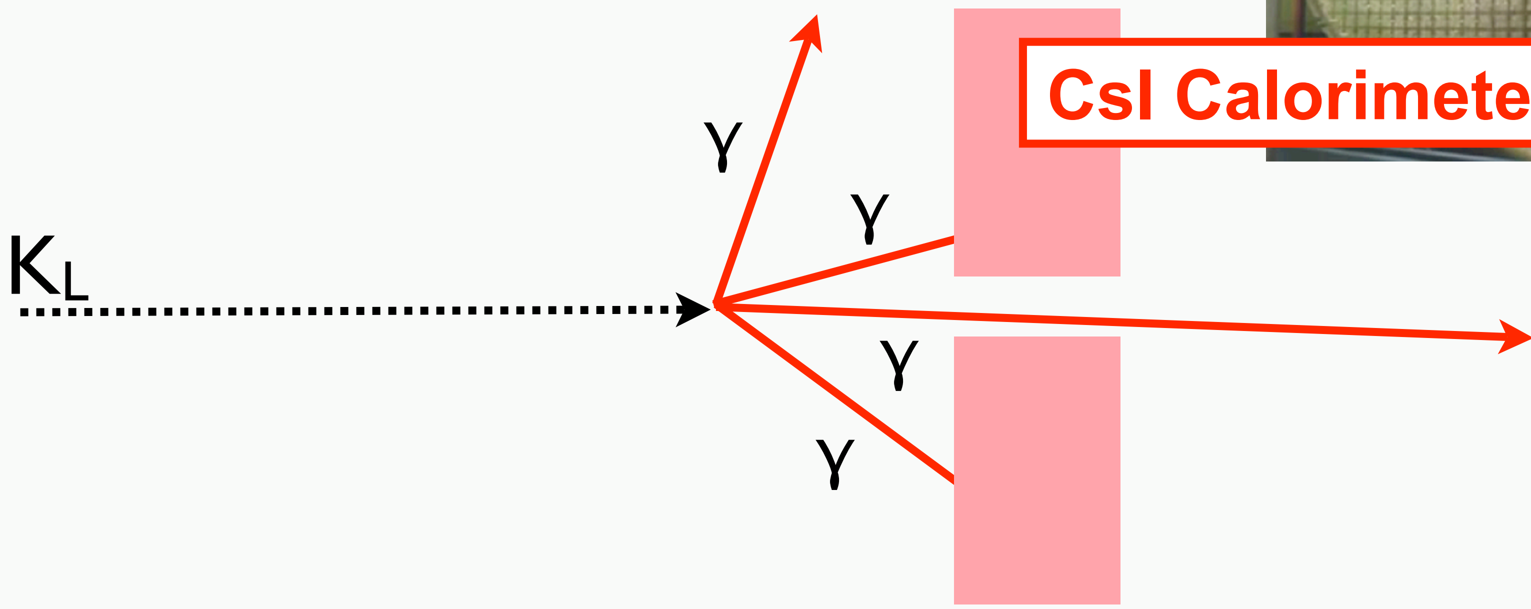


E391a Detector

Background : $K_L \rightarrow \pi^0\pi^0$

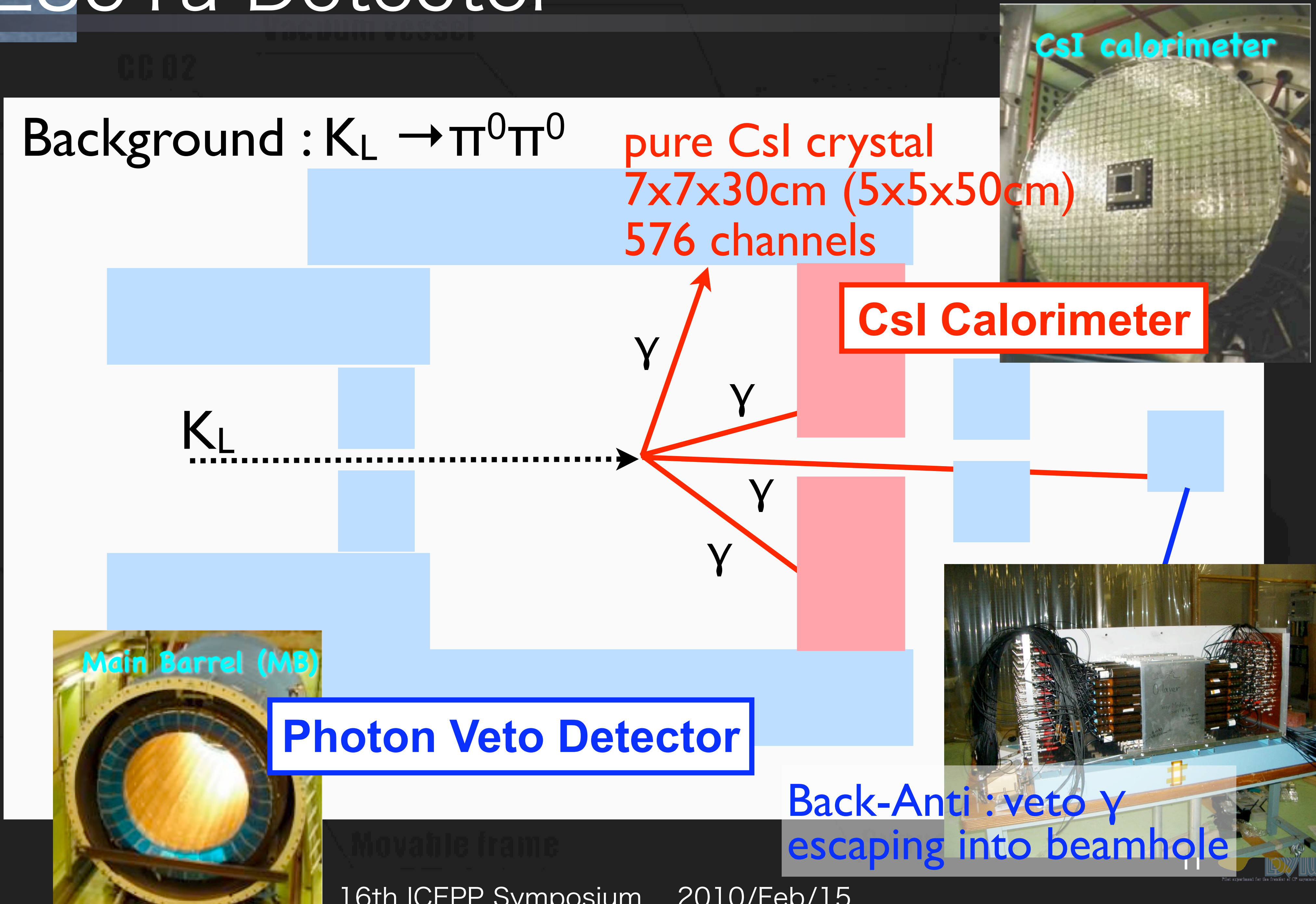
pure CsI crystal
7x7x30cm (5x5x50cm)
576 channels



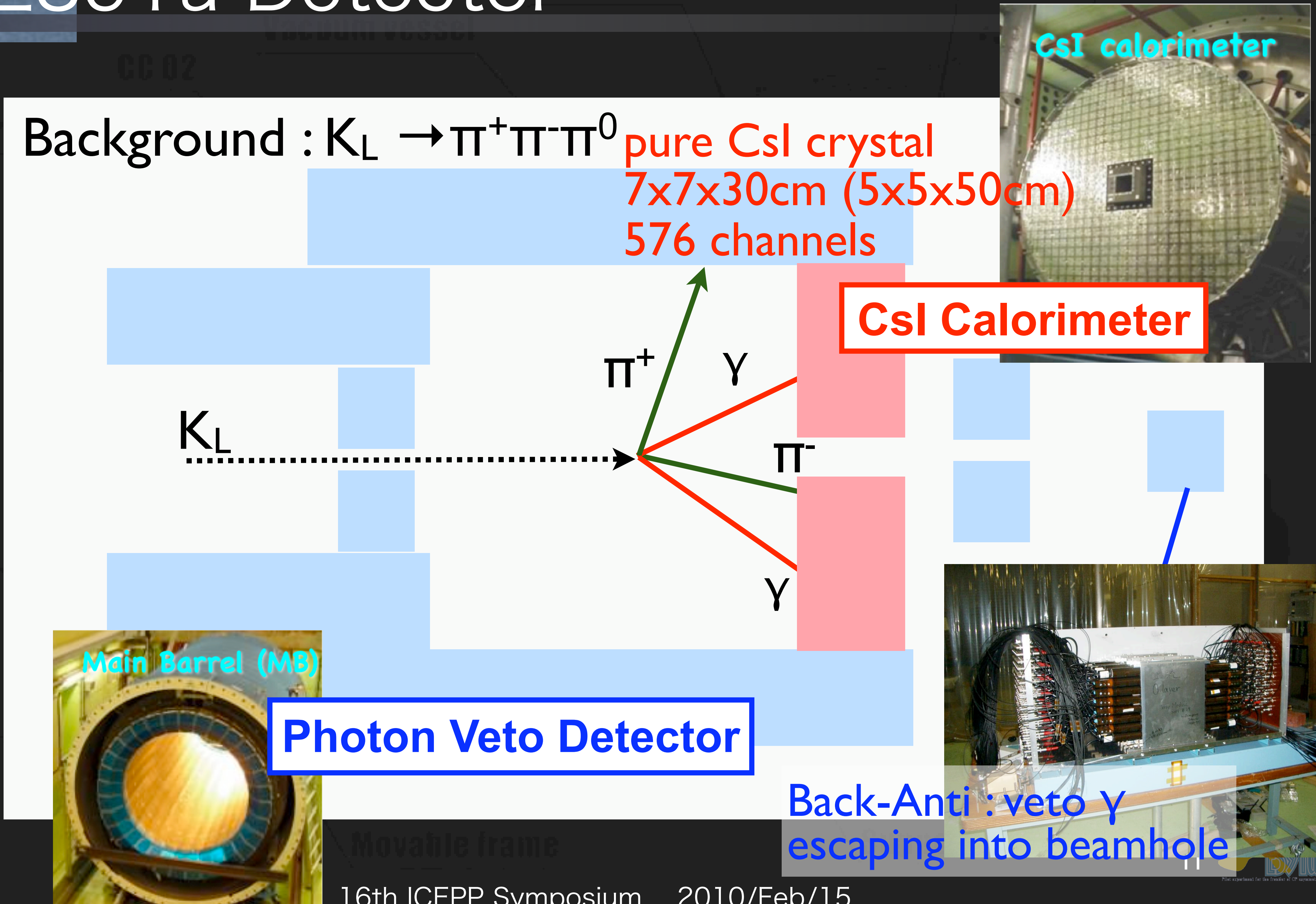


E391a Detector

Background : $K_L \rightarrow \pi^0\pi^0$



E391a Detector



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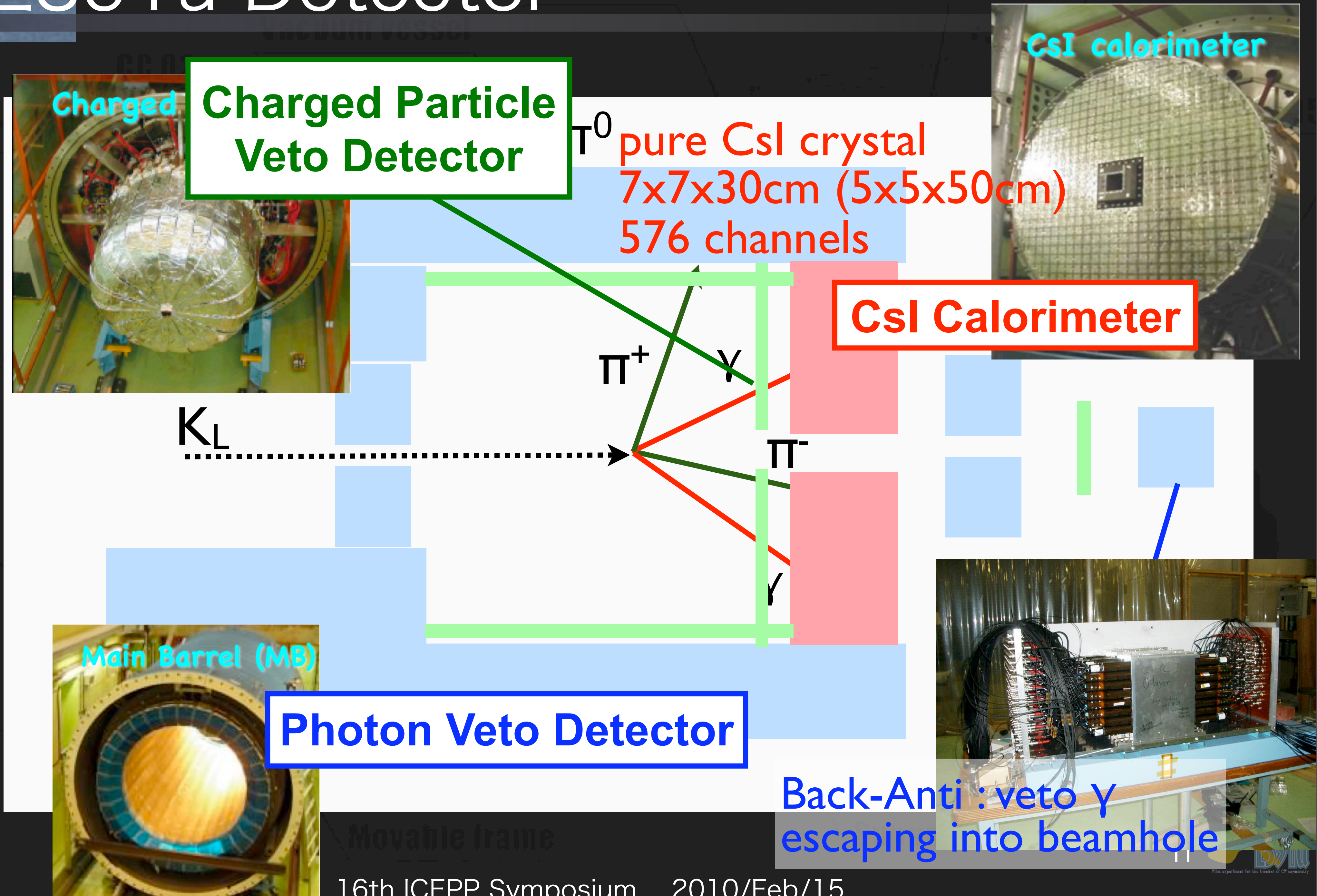
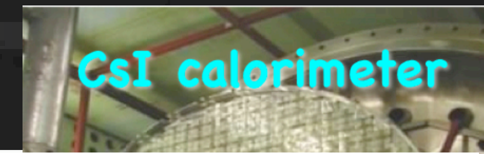
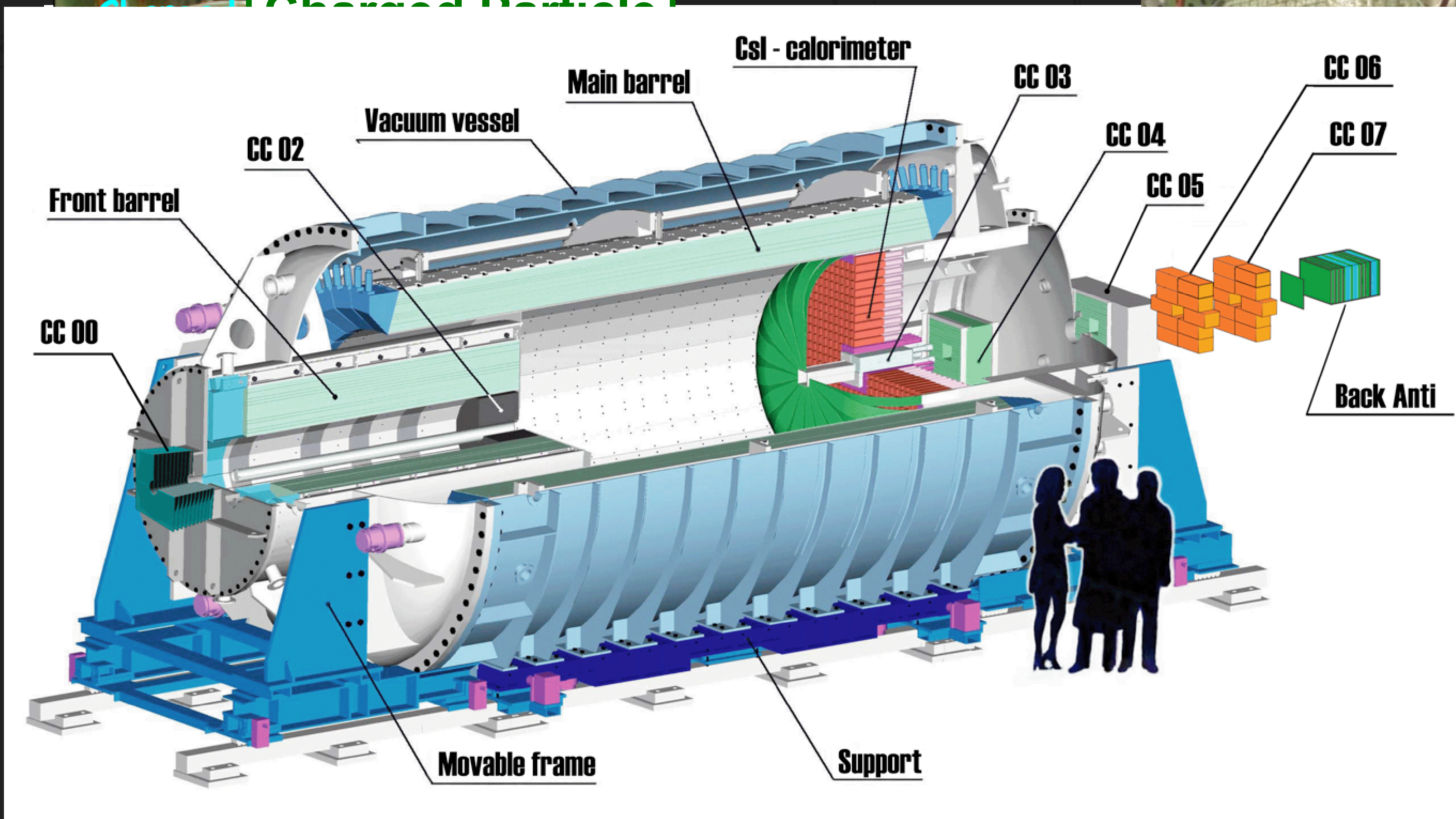


E391a Detector





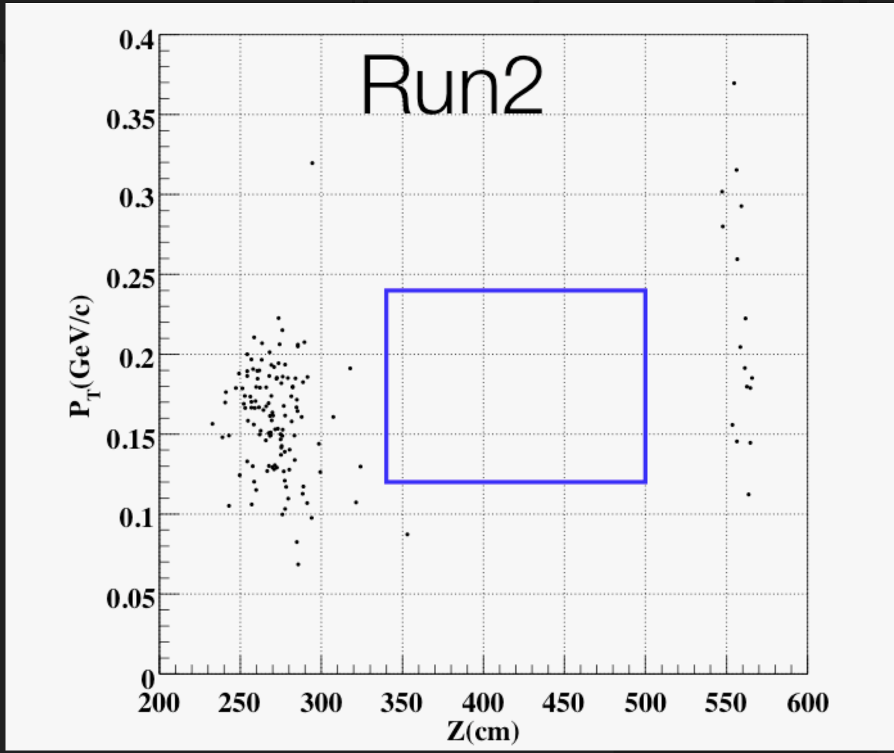
Strategy to Run2+3 Data Analysis

Review of Run2 Analysis

- 一つ前の解析：Run2 Result
  - blind analysis
  - No event observed in the signal box
  - Upper limit 6.7 x 10^{-8} (90% C.L.)

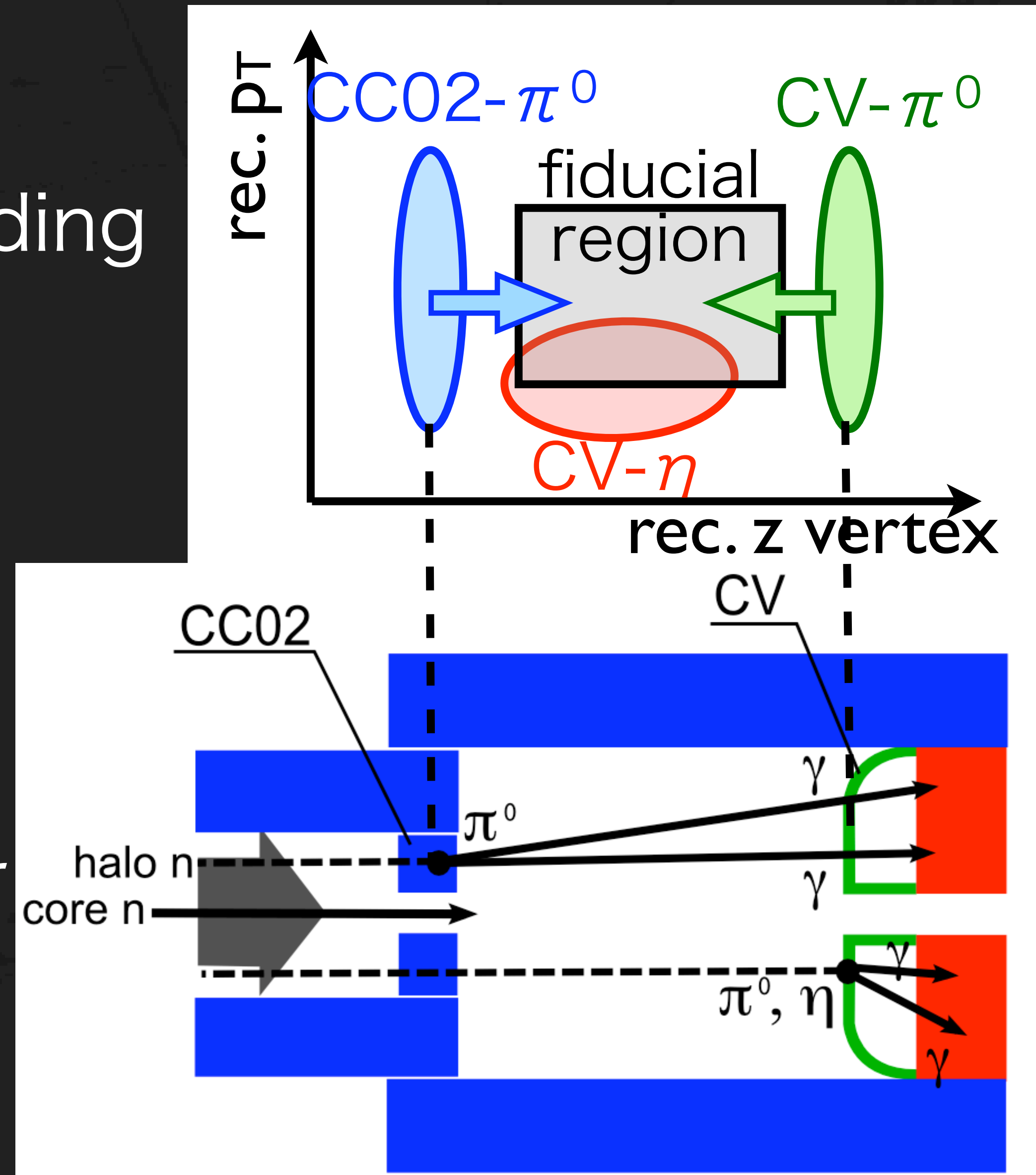
    (Phys. Rev. Lett. 100 201802, 2008)
- Run2解析から得られた事
  - 最大のバックグラウンド源

    → halo neutron BG
    - Collar Counter (CC02)-π^0 BG
    - CV-π^0 BG
    - CV-η BG



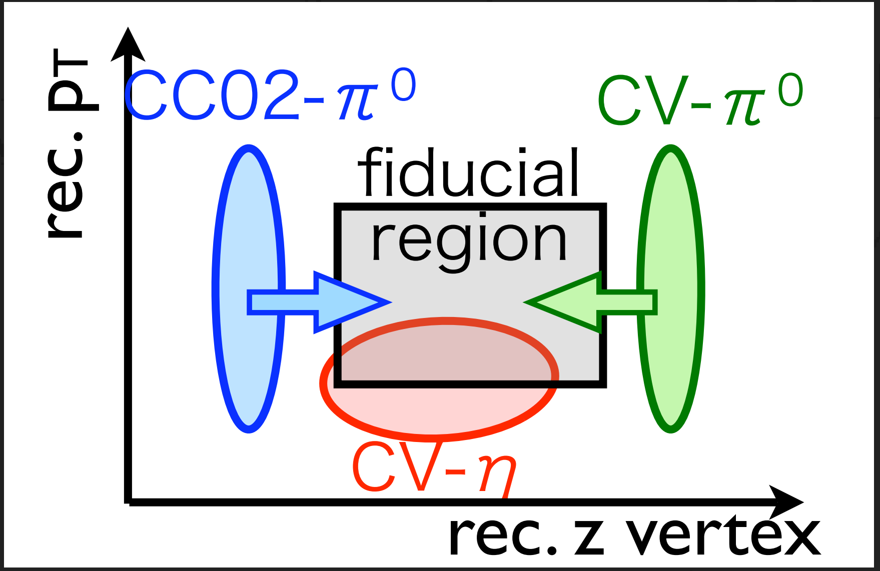
Halo Neutron Background

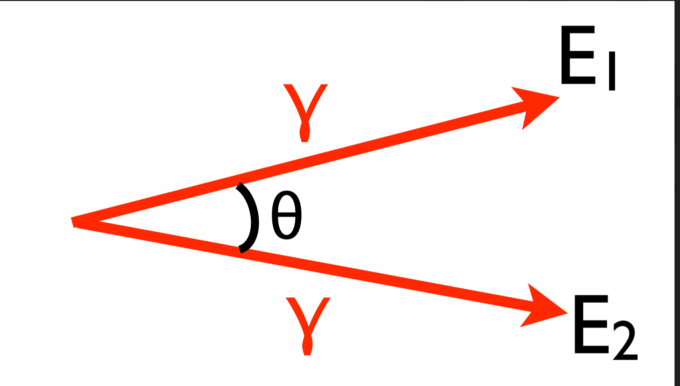
- Halo neutron
  - neutron flux surrounding beam core
- Halo neutron BG
  - halo-n hits detector around beam core
  - → creates $\pi^0, \eta \rightarrow 2\gamma$



Mechanism of Neutron Background

- Collar Counter (CC02) π^0 BG
  E_γを実際より低く見積もる
  (shower leakage
  & photo-nuclear effect)
  →θを大きく見積もる
- CV-π^0 BG
  E_γを実際より大きく見積もる
  (due to fusion cluster)
  → θを小さく見積もる
- CV-η BG
  M(π^0) と M(η) の違い
  → θを小さく見積もる





$$M(\pi^0)^2 = 2E_1E_2(1-\cos\theta)$$

Motivation for the Current Analysis

- halo neutron BG
  - CC02 π^0 BG (→ extrapolation of the Al-target data)
  - CV π^0 BG (→ bifurcation)
  - CV η BG (→ geant4 + geant3 MC)

以前のRun2解析では別々の方法で見積もり

→ バックグラウンドの統一的な扱いが困難
シグナル/バックグラウンドの効率的な最適化が難しい

新しい解析では
halo neutron BGの見積もりを統一的な方法で行う
→ シンプルで効果的なS/Nの最適化
→ バックグラウンドの統一的な理解

Study on Halo Neutron BG

Halo Neutron BG Study

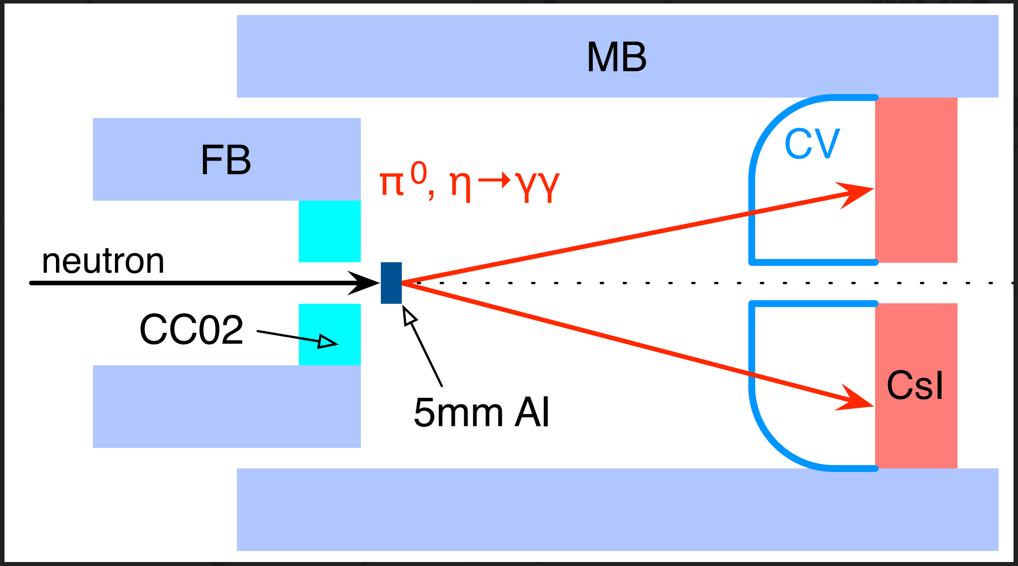
- Halo neutron BG studyの手順

1. FLUKAのhadronic interaction modelの信頼性を確認
   → 確認用に取られた測定データ(Al-plate run)を使用
2. イベント選択の最適化
3. バックグラウンドの見積もり

Al Target Run

- 確認すべき事
  - π^0, η の生成率

→ データとFLUKA simulation を比較する事で確認



- Al target run
  - 5mm厚のAl targetをビームライン中へ挿入

  → 2γの質量を再構成可能 (with fixed z-vertex)
  - Amount of statisitics

  - 5.57 x 10^{16} POT

π^0, η Production Rate

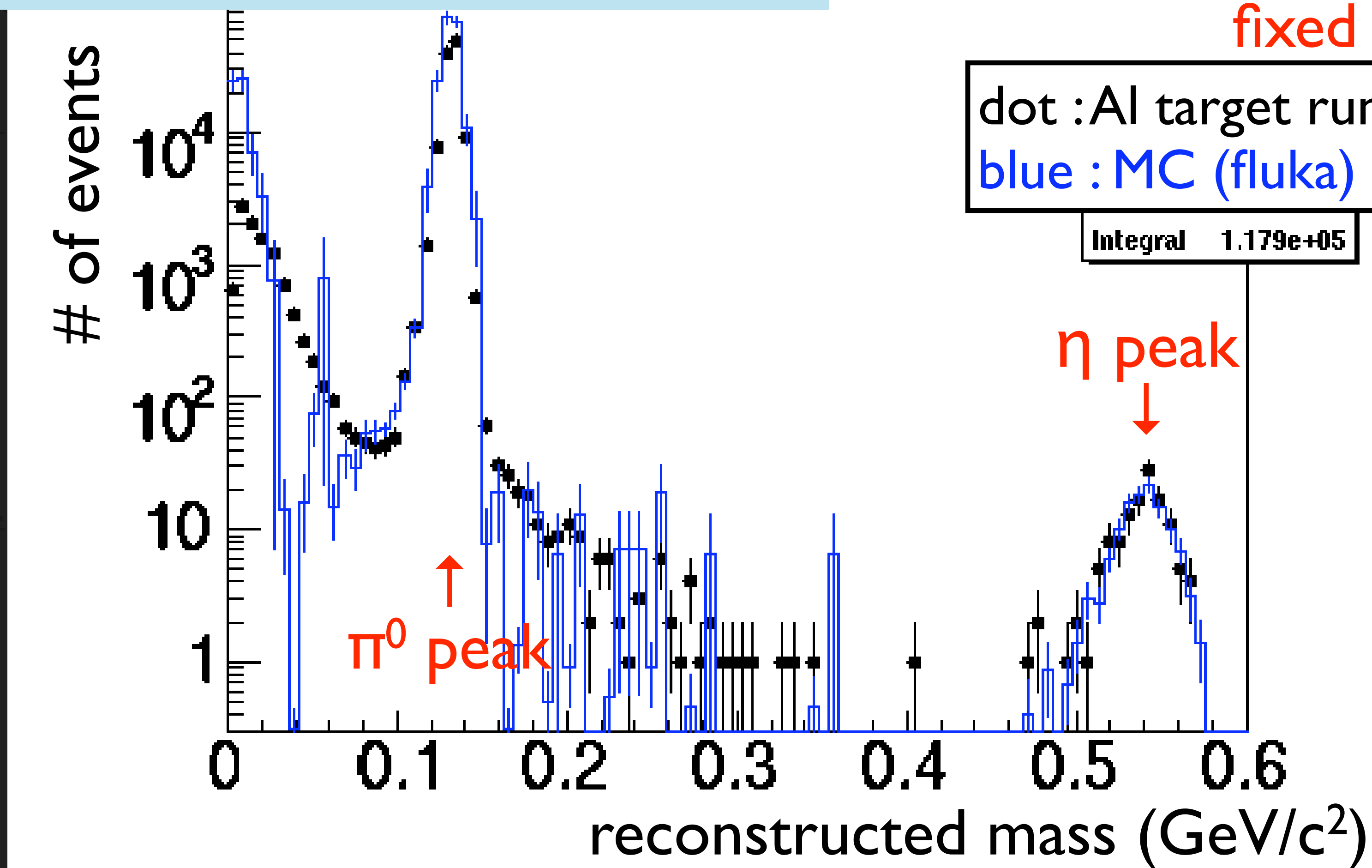
- Ratio π^0 / η → OK

Reconstructed mass of 2γ

measured by CsI

$$M(2\gamma)^2 = 2E_1E_2(1-\cos\theta)$$

calculated from fixed vtx-position



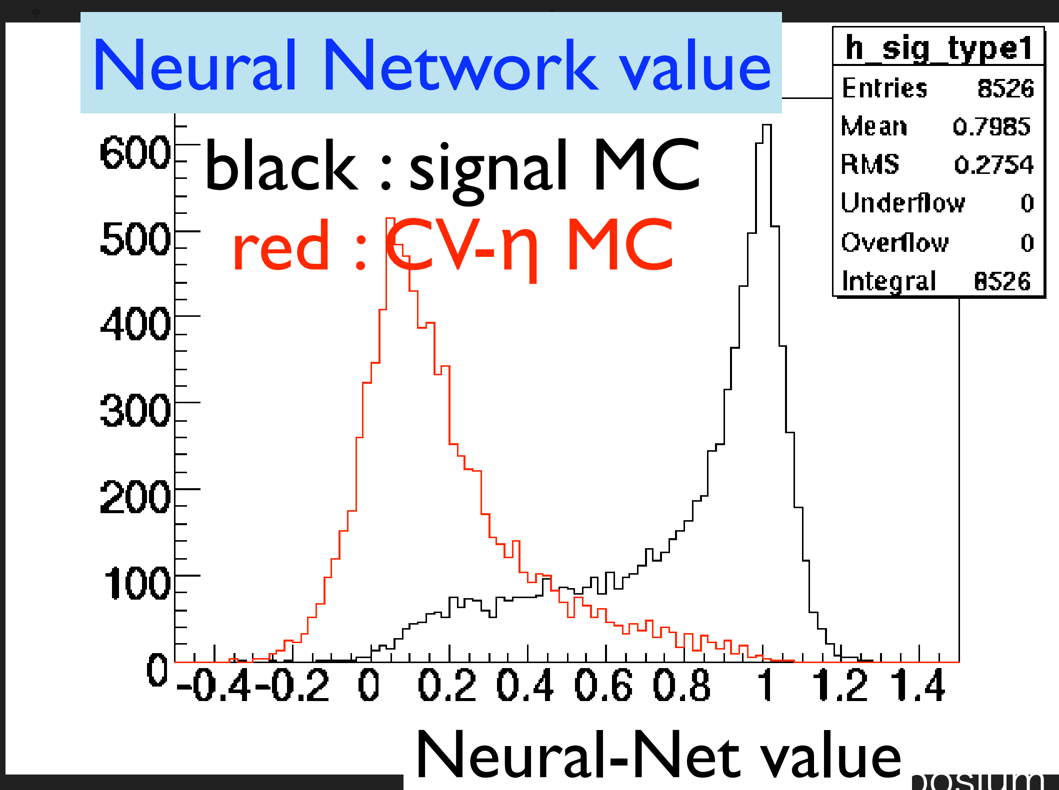
Cut Optimization

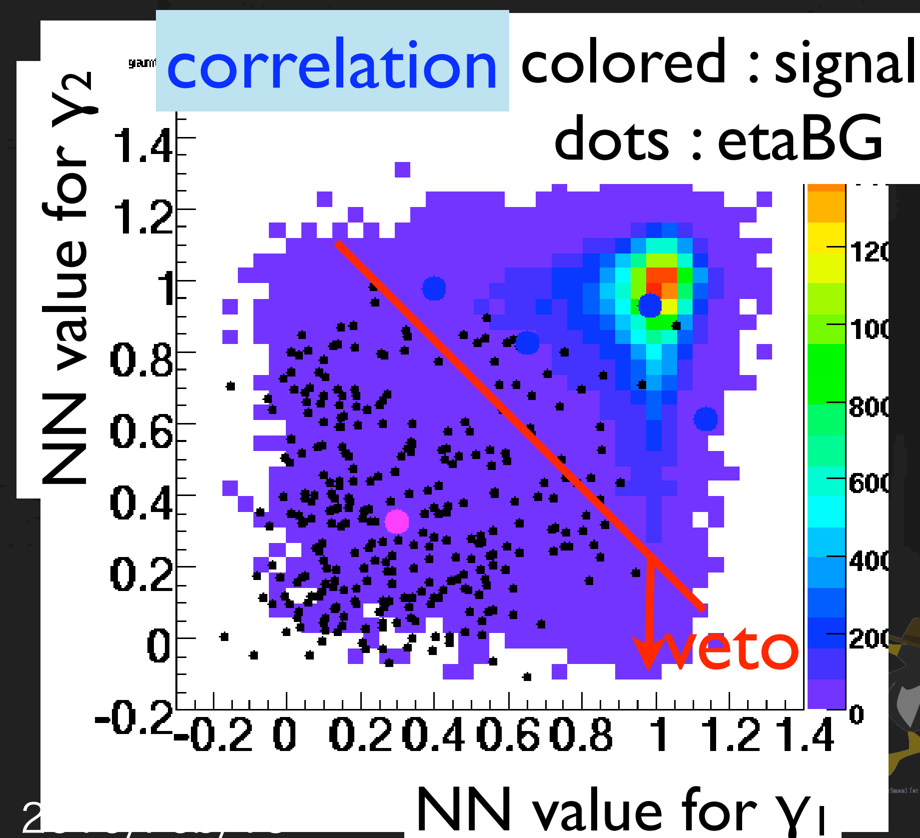
- Cut condition最適化の方針
  - S/NをRun2の結果と同等に保ちながらacceptanceを最大化する
  - 最適化の間は実データのシグナル領域を隠す
    → human-biasingを防ぐため

- 具体的には？
  - 新しいカット“cluster-shape NN”の導入
  - いくつかのカットを置き換え
  - パラメータの自動最適化

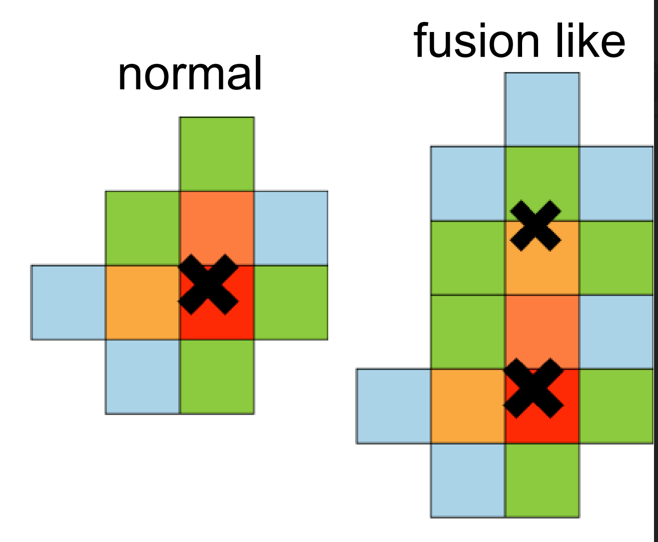
Cluster Shape NN Cut (for CV-η BG)

- CsIのヒットパターンを用いたNeural Network
  - CV-η BG は広がりを持ったクラスタを生成
  - (γが浅い角度でCsIに当る & γのエネルギーが高い)
- NNへの入力: energy, r, phi-position (each crystal)

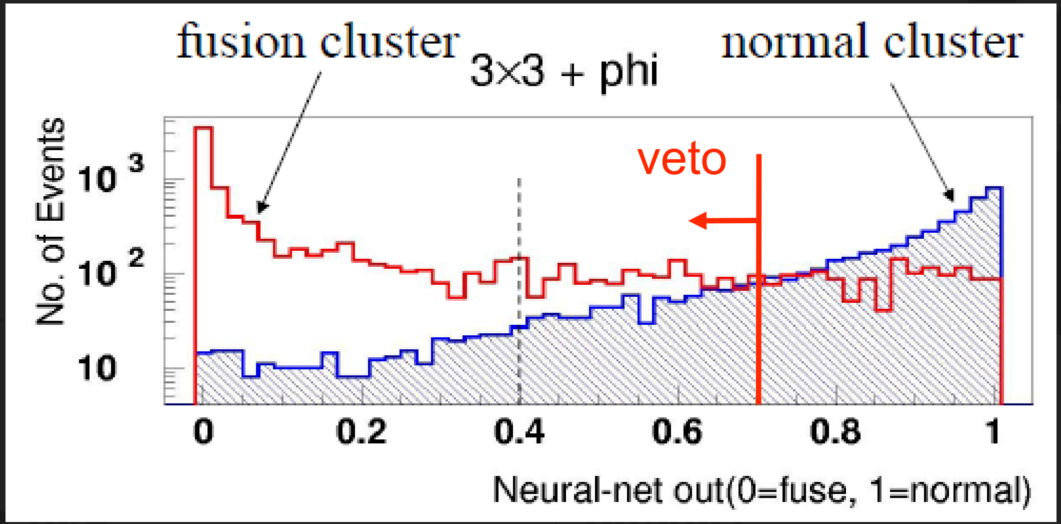




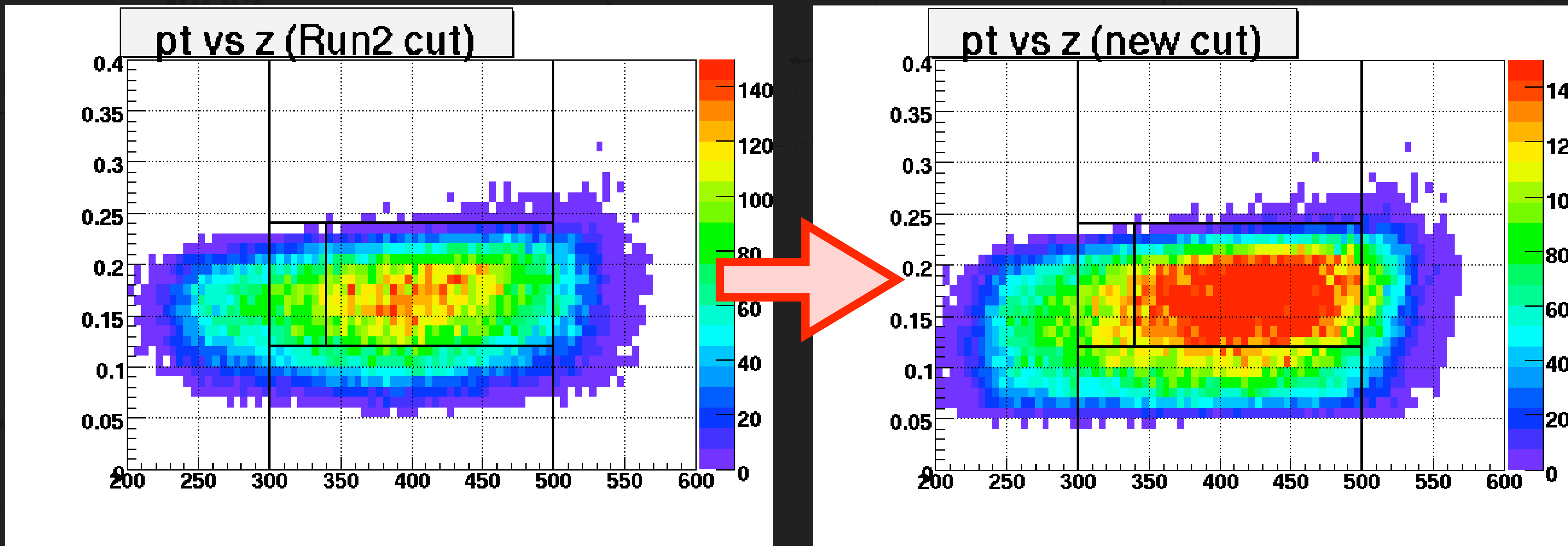
γ-fusion NN Cut (for CV-π^0 BG)



- CV-π^0 BG
  CsIでの“fusion” clusterが原因
- Run2からカットの変更で最適化
  cluster size cut → fusion NN cut
  ~40% accept. loss → ~20% accept. loss
  rejection power is similar (~70% reduction)



Result of Optimization



condition	Signal	S/N (arb.)
Run2(prev.)	30328	5054
New	45945(+51%)	5105

S/N : 以前のRun2解析と同等

acceptance : 以前のRun2解析から50%増加

Background Estimation

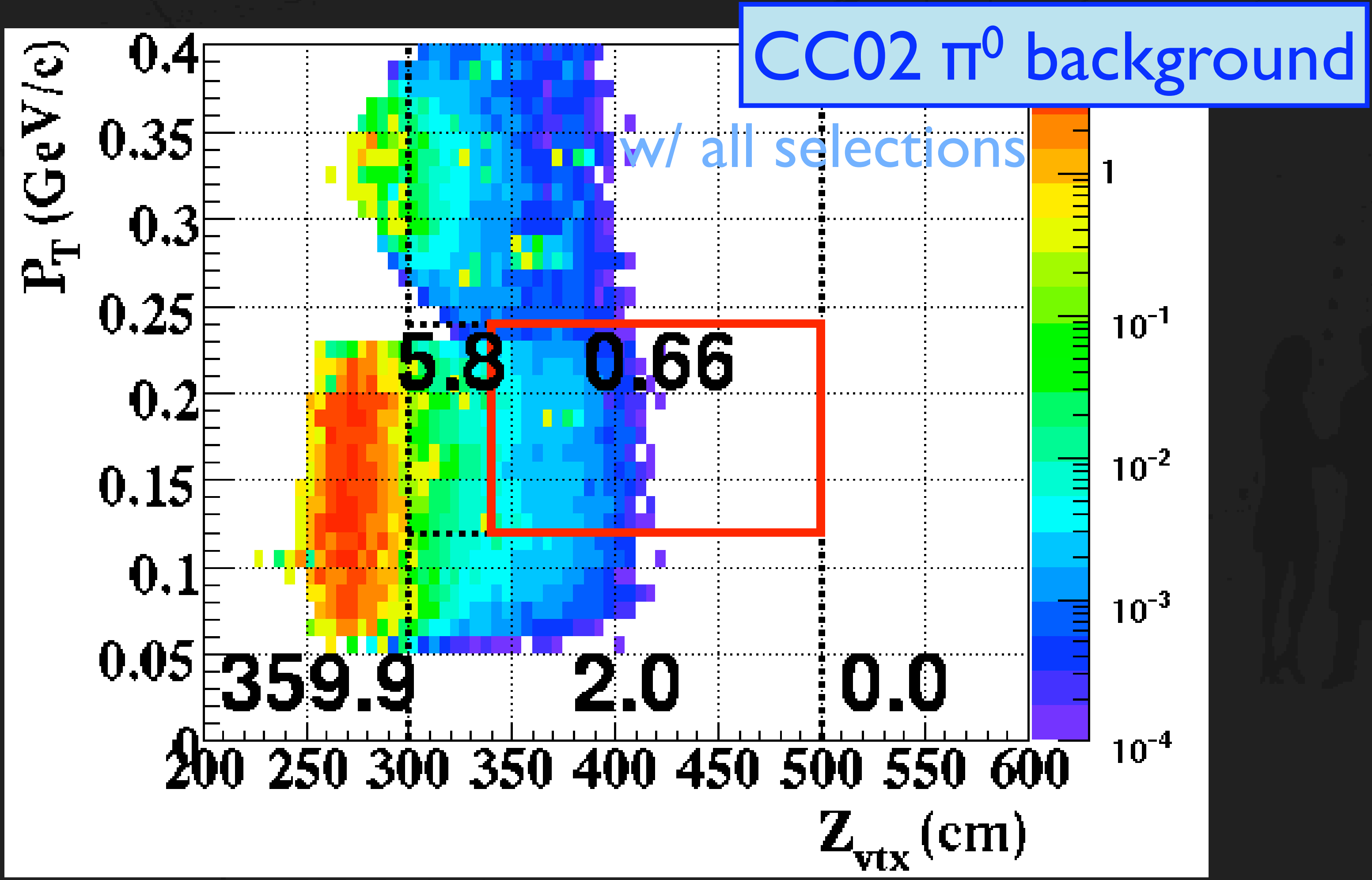
Halo neutron background
K_L background

Background Estimation

- Halo neutron background
  - CC02-π^0 : from upstream
  - CV-π^0 : from downstream
  - CV-η
- K_L originated background
  - neutral mode : $K_L \to 2\pi^0$, $K_L \to \gamma\gamma$
  - charged mode : $K_L \to \pi^+\pi^-\pi^0$

CC02-π^0 Background (upstream)

- CC02-π^0 BG (BG from upstream)
    - 0.66 ± 0.39 events

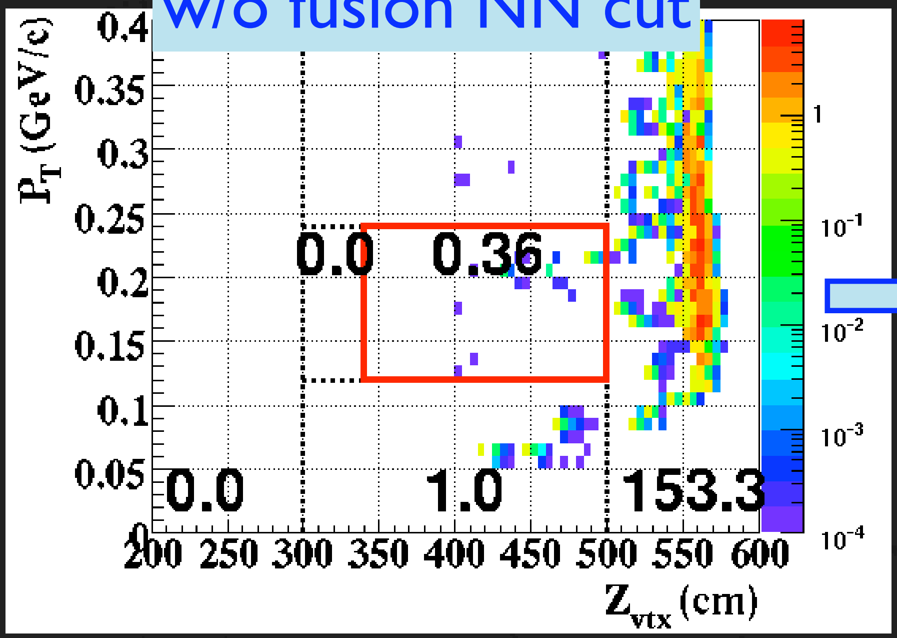


CV-π^0 Background (downstream)

- CV-π^0 BG (BG from downstream)
  - no events remained → < 0.36 events

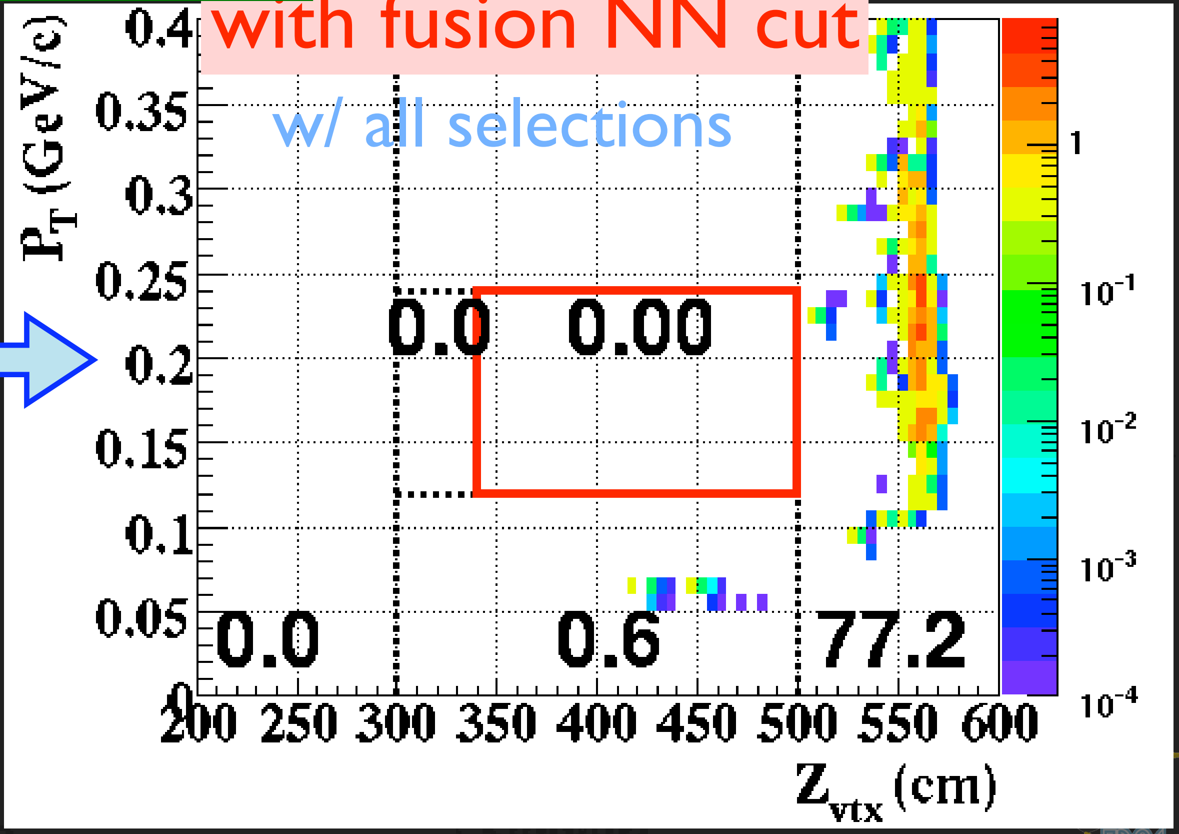
CV π^0 background

w/o fusion NN cut



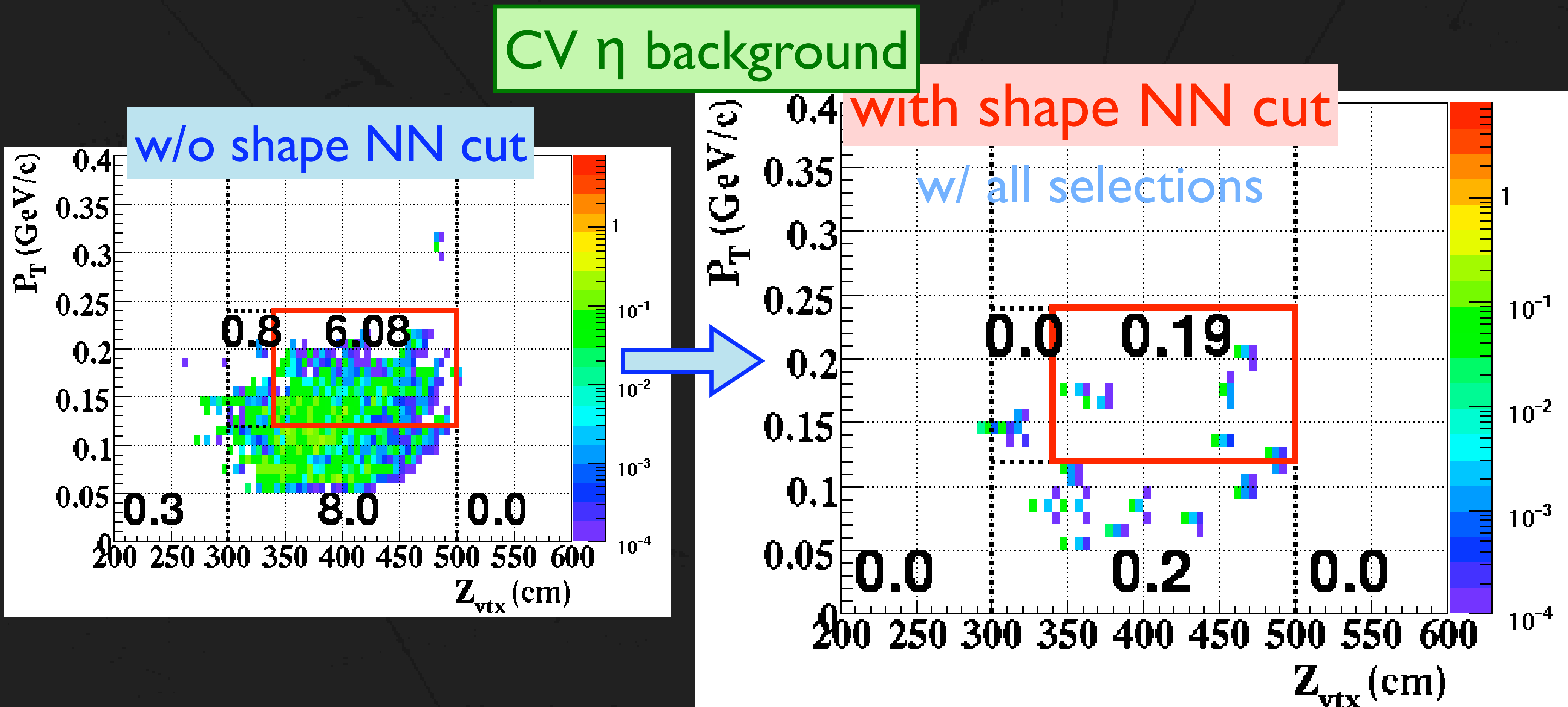
with fusion NN cut

w/ all selections



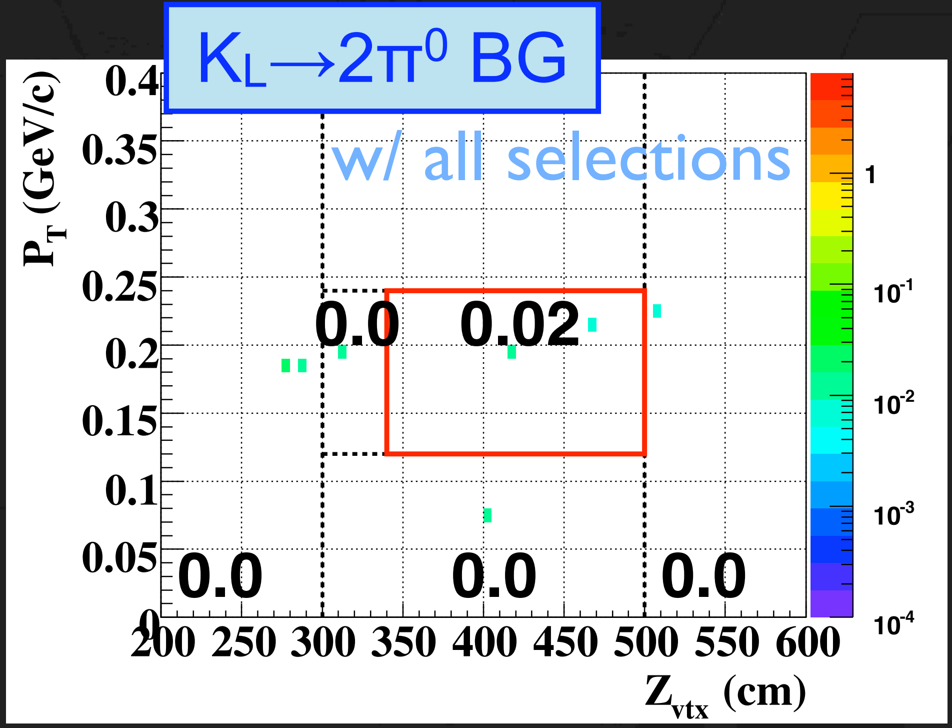
CV-η Background

- CV-η BG
  0.19 ± 0.13 events



K_L Decay Backgrounds

- K_L decay backgrounds
  - GEANT3 simulation
- $K_L \to 2\pi^0$
  vetoで余分な2つのγを検出
  統計量 : Run2+3の約65倍
  全カット適用後 : 2events
  : 0.024 ± 0.018



- 他のK_L decay BG's :
  $K_L \to \gamma\gamma$: P_T, kinematic selction → $O(10^{-5})$
  Charged modes : reduced by CV → $O(10^{-4})$

Summary of Background Estimation

- Summing up all background sources
  → estimated # of background : 0.87 ± 0.41

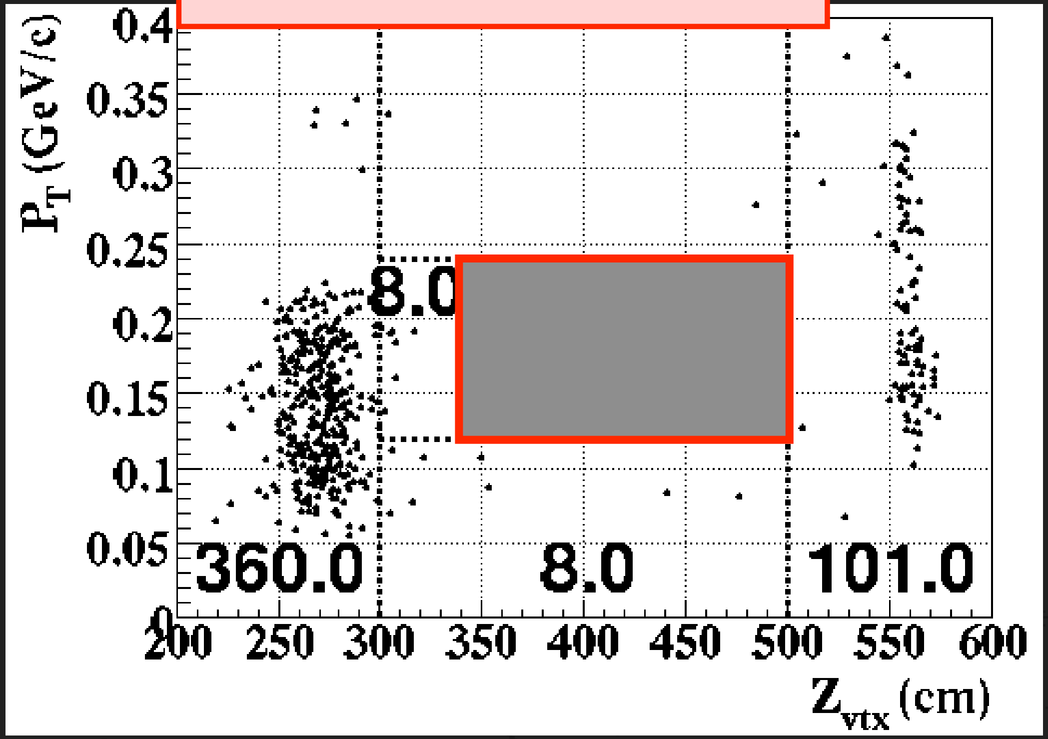
source		estimated BG
K_L	$K_L \to 2\pi^0$	0.024 ± 0.018
	others	small (~O(10^{-4}))
halo-n	CC02-π^0	0.66 ± 0.39
	CV-π^0	0.0 (<0.36)
	CV-η	0.19 ± 0.13
total		0.87 ± 0.41

for Run2 + Run3 data

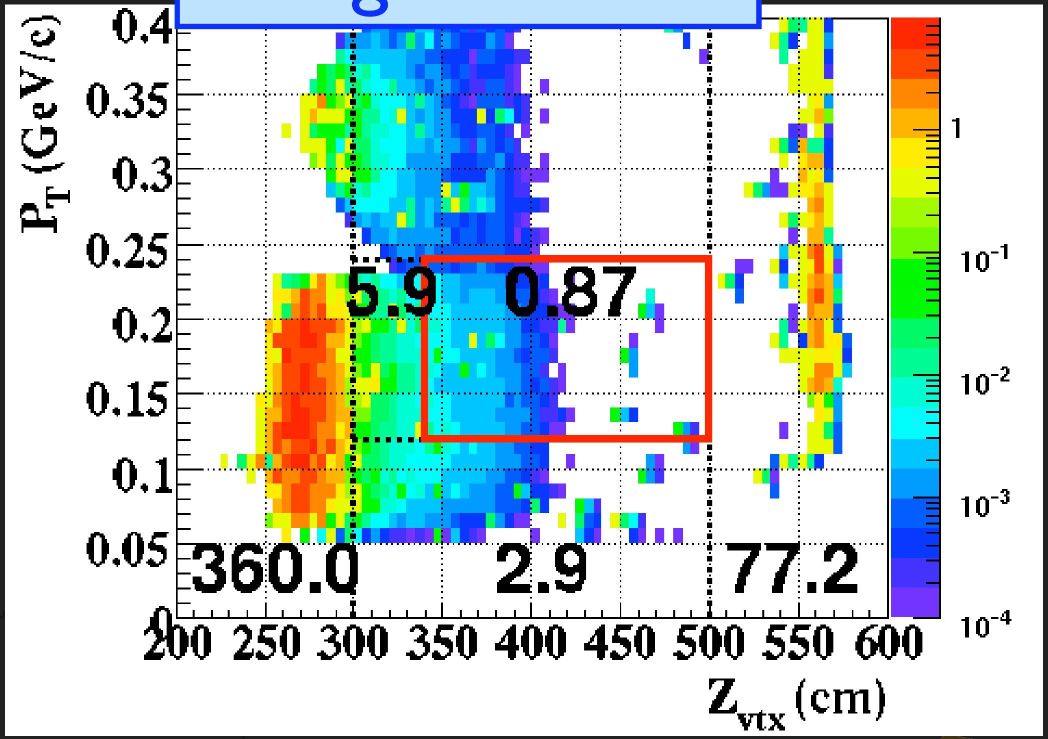
Summary of BG Estimation

- シミュレーションによる見積もりとデータを比較
  → データをよく再現している

Run2 + Run3 data



Background MC



Sensitivity & Results

of K_L decays
Sensitivity
Results

of K_L Decays

- E391a full dataで得られたK_L 崩壊数
  - $K_L \to 3\pi^0$, $2\pi^0$, $\gamma\gamma$の3 modesで見積もり

Run2 + Run3 data

mode	# of events in data	acceptance	flux
$K_L \to 3\pi^0$	118334	$(7.21 \pm 0.06) \times 10^{-5}$	$(8.41 \pm 0.03_{stat.} \pm 0.53_{syst.}) \times 10^9$ (-3.3%)
$K_L \to 2\pi^0$	2573.9	$(3.42 \pm 0.03) \times 10^{-4}$	$(8.70 \pm 0.17_{stat.} \pm 0.59_{syst.}) \times 10^9$ (---)
$K_L \to \gamma\gamma$	35367	$(7.18 \pm 0.03) \times 10^{-3}$	$(9.02 \pm 0.05_{stat.} \pm 0.51_{syst.}) \times 10^9$ (+3.7%)

cf.) Run2 only : flux = 5.13×10^9

→ Run2+Run3 = 統計量は以前の解析の1.7倍

Signal Acceptance

- Signal acceptance

$$A = \frac{\text{(イベント選択後に残るイベント数)}}{\text{(崩壊領域で崩壊した}K_L\text{数)}}$$

$$= \frac{\text{(\# accept MC)}}{\text{(\# generated}\rightarrow\text{decayed in MC)}} \times \text{(accidental loss)}$$

x (loss by time cuts)

accidental effect
17.4% loss (Run2)
20.6% loss (Run3)

= (1.06 ± 0.08)% for Run2
(1.01 ± 0.06)% for Run3

(cf. previous analysis with Run2 : 0.670%)

Sensitivity

- K_L flux
  - $(8.70 \pm 0.61) \times 10^9$ K_L decays for Run2 + Run3

- Single event sensitivity (S.E.S.)

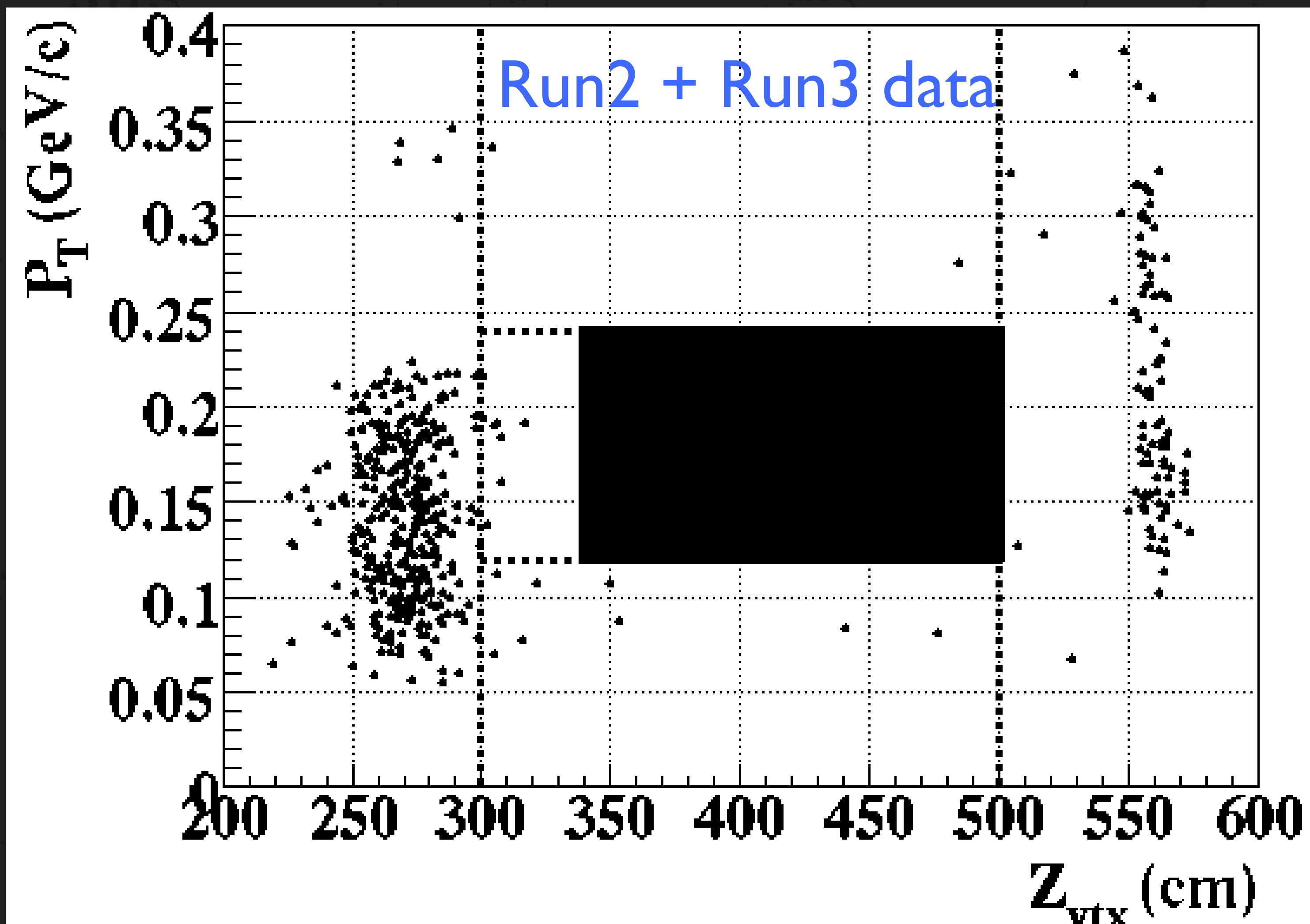
  “1eventの観測が期待できる分岐比”

  S.E.S. = 1/ (Acceptance x # of K_L)

  = $(1.11 \pm 0.10) \times 10^{-8}$ for Run2 + Run3

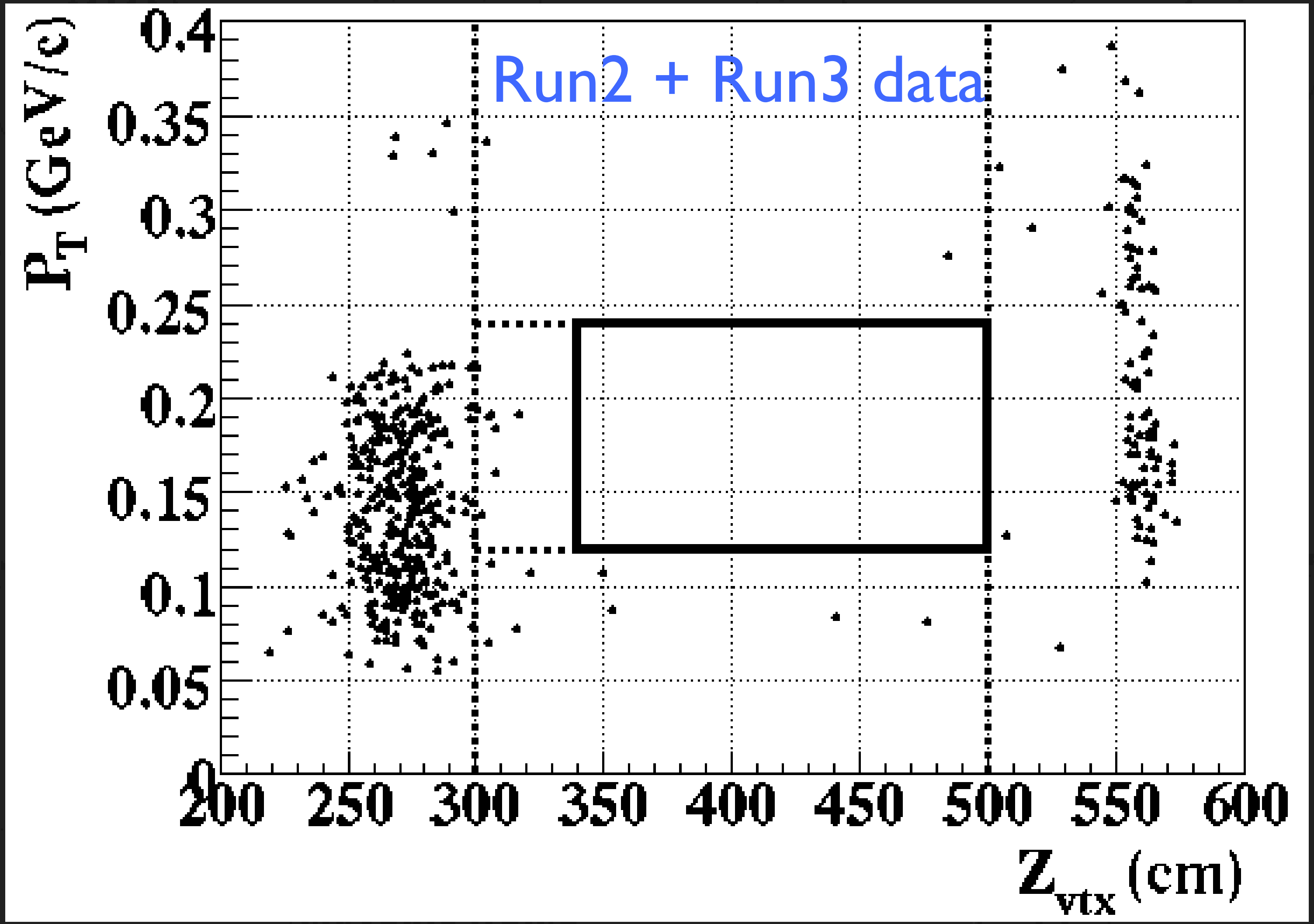
Now, Ready to Open the BOX

- Opening the box for Run2 + Run3 data



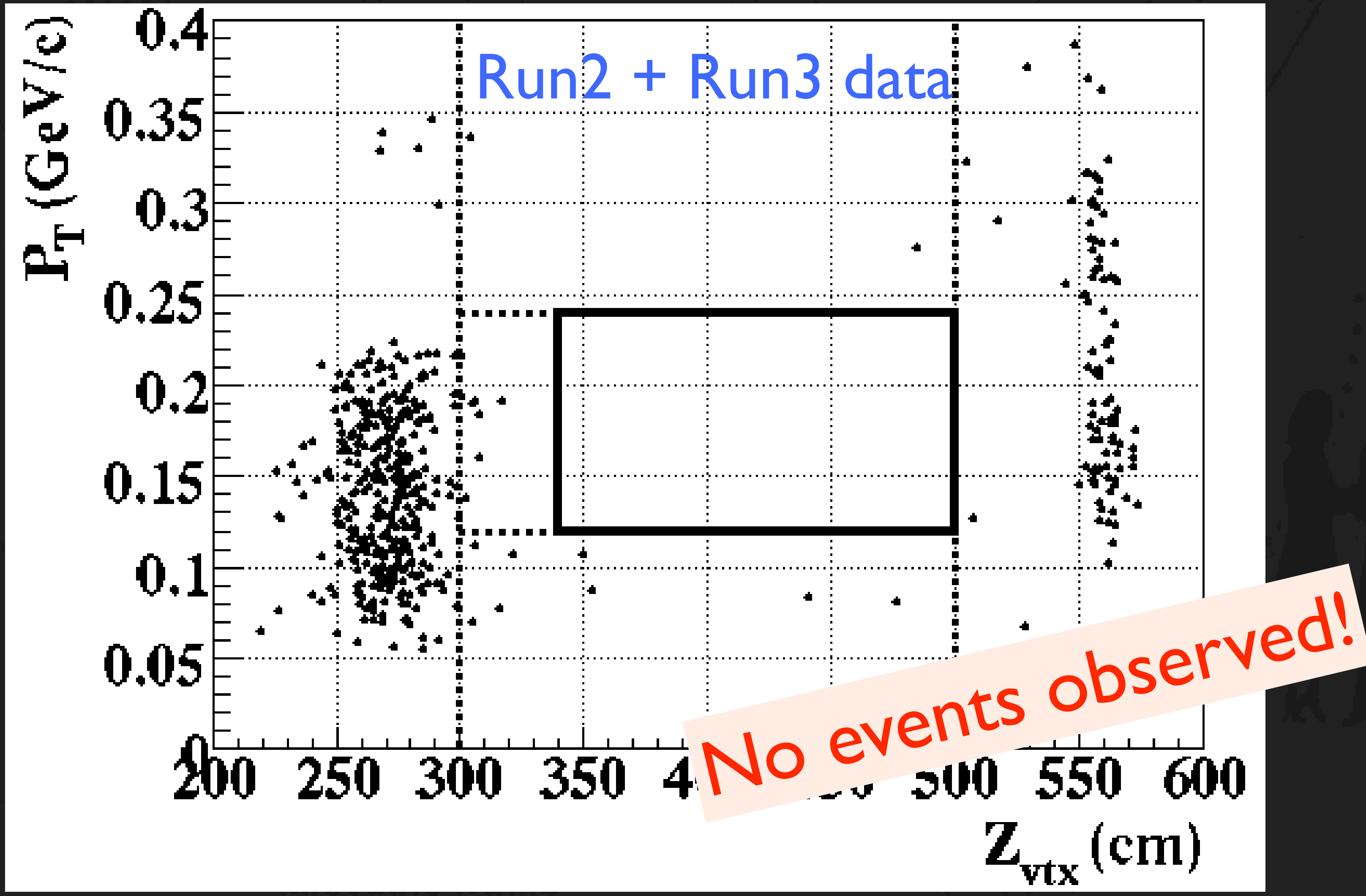
Now, Ready to Open the BOX

- Opening the box for Run2 + Run3 data



Now, Ready to Open the BOX

- Opening the box for Run2 + Run3 data



Results

- Acceptance = 1.06% (Run2) and 1.01% (Run3)

  (cf. Run2 previous : 0.670%)

- S.E.S. = 1/(Acc. x #KL)

  Run2 + Run3 : 1.11×10^{-8}

  (cf. Run2 previous : 2.91×10^{-8})

- 分岐比上限

  no events observed → x 2.3 with Poisson stat.

  E391a final : $BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (@90% C.L.)

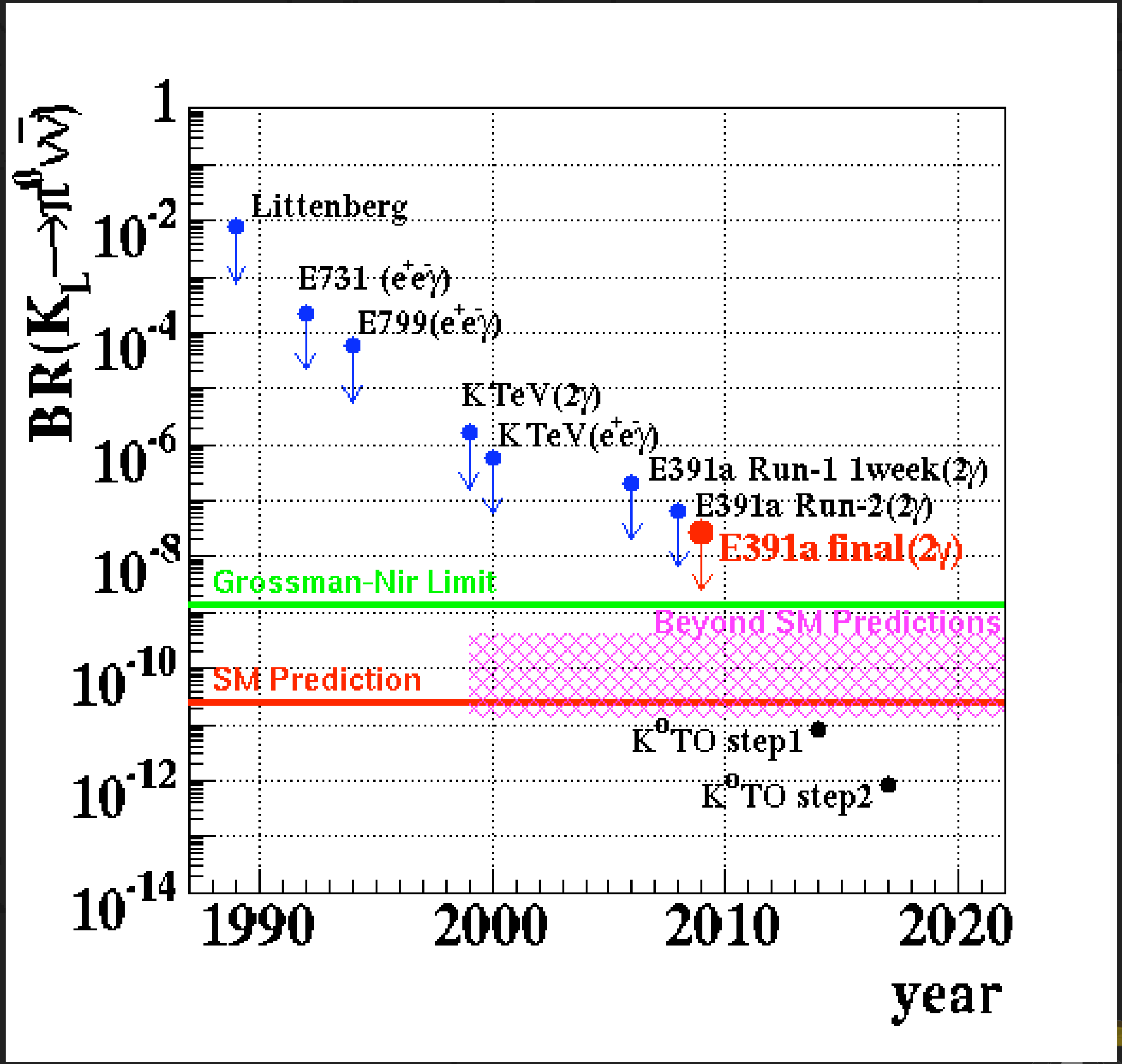
  (cf. Run2 previous : 6.7×10^{-8} @ 90% C.L.)

  → Improvement from the previous : x 2.6 (=1.7 x 1.5)

  統計 acceptance

Milestone

- 一歩前進!
- Next step : KOTO E391aでの知見を活かして…
  →next talk



Summary (1)

- $K_L \to \pi^0 \nu \bar{\nu}$崩壊
  - 新物理を探索する良い実験場：CPV, theoretically clean
- E391a experiment @ KEK 12GeV PS
  - first dedicated experiment for $K_L \to \pi^0 \nu \bar{\nu}$
- Features of Full Analysis
  - halo-n BG studyに重点
    simpleな手法で見積もり
    効果的にイベント選択を最適化 (+50% in acceptance)
  - データの統計量
    Run2+Run3で 以前の解析(Run2)の約1.7倍

Summary (2)

- Acceptance : 1.06% (Run2) & 1.01% (Run3)
- Sensitivity

  S.E.S. : 1.11 x 10^{-8} (Run2 + Run3)
- Opening the box for Run2 + Run3 data

  → No events observed!
- Upper Limit (E391a final)

  arXiv : 0911.4789

  $BR(K_L \to \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (@ 90% C.L.)

  (以前の解析から2.6倍の更新)
- E391a実験の手法の有効性を証明

  →その知見を活かしてJ-PARC K^OTO実験へ

Step-by-Step Approach

Pilot experiment for the frontier of CP asymmetry

Thank You!