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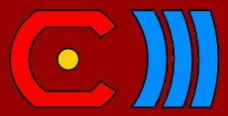



# $\pi^0$ decays with WASA-at-COSY

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on behalf of the WASA-at-COSY Collaboration
Uppsala University

October 10, 2011

STORI' 11, Frascati, 10-14 oct. 2011

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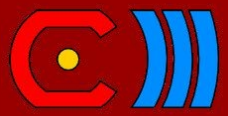
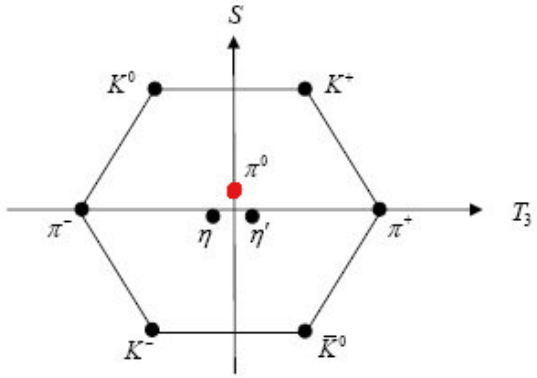




# Outline

1. $\pi^0$ decay
   - $\pi^0 \longrightarrow e^+e^-\gamma$
   - $\pi^0 \longrightarrow e^+e^-$
2. Results from WASA-at-COSY
   - $\pi^0$ with WASA-at-COSY
   - Experimental technique
3. Summary and outlook

# Properties of $\pi^0$




Mass: 134.98 $MeV/c^2$

quark content: $\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$

Life time: $8.4 * 10^{-17}$ s

$J^{PC} = 0^{-+}$

| decay | $BR$ |
|---|---|
| $2\gamma$ | $98.823 \pm 0.034\,(\%)$ |
| $e^+e^-\gamma$ | $1.174 \pm 0.035\,(\%)$ |
| $e^+e^-e^+e^-$ | $(3.34 \pm 0.16) \times 10^{-5}$ |
| $\nu\bar{\nu}\gamma$ | $< 6 \times 10^{-4}$ |
| $\nu\bar{\nu}$ | $< 2.7 \times 10^{-7}$ |
| $e^+e^-$ | $(7.48 \pm 0.29) \times 10^{-8}$ |

# Single Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$

## $\pi^0$ *Transition Formfactor:*

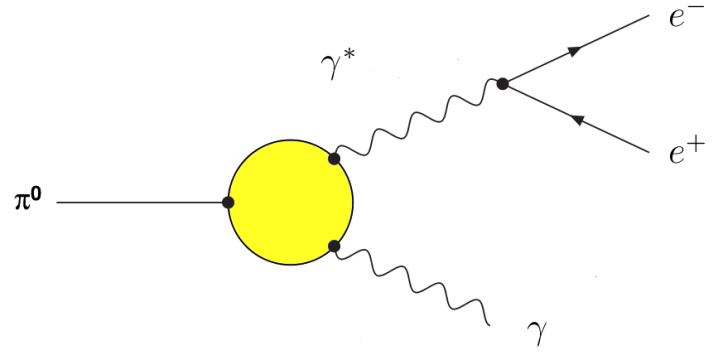
$$q^2 = (P_{e^+} + P_{e^-})^2 = M^2_{\gamma^*}$$

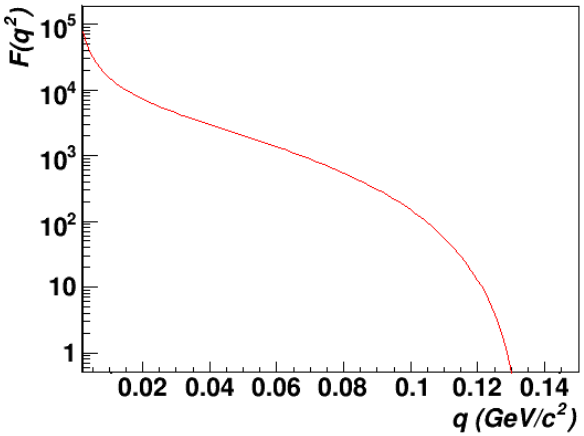
$$\frac{d\Gamma}{dq} = |F(q^2)|^2 \left(\frac{d\Gamma}{dq}\right)_{point}$$

$$F_{QED}(q) = 1 - bq^2 \quad (\text{low } q^2)$$

$$b = 6 < r^2_{rms} >= \frac{1}{\Lambda^2}$$

$$\Lambda \simeq M_\rho = 770\ MeV/c^2$$



# $\pi^0 \to e^+e^-$ decay

$\pi^0 \to e^+e^-$ in SM:

- One-loop at lowest order
- Suppressed w.r.t $\pi^0 \to 2\gamma$ by $\alpha^2$ and $2(m_e/m_\pi)^2$
- $\mathcal{B}^{\text{SM}}_{\text{theory}}(\pi^0 \to e^+e^-) = (6.23 \pm 0.09) \times 10^{-8}$ [1]

KTeV @ Fermilab 2007 (794 events in $K_L \to 3\pi^0$):

- $\mathcal{B}^{\text{KTeV}}_{\text{no-rad}}(\pi^0 \to e^+e^-) = (7.48 \pm 0.29_{stat} \pm 0.25_{syst}) \times 10^{-8}$ [2]

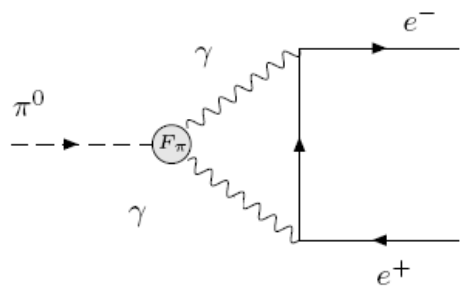



Fig: Feynman diagram of $\pi^0 \to e^+e^-$ in SM

[1] A. Dorokhov, M. A. Ivanov, Phys. Rev. D **75** (2007) 114007

[2] E. Abouzaid *et. al*, Phys. Rev. D **75** (2007) 012004

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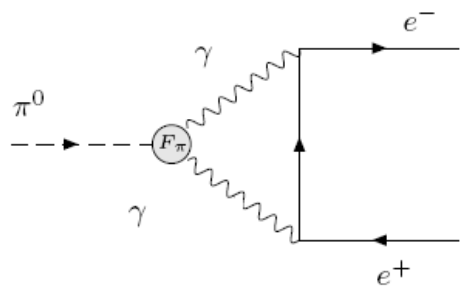



Fig: Feynman diagram of $\pi^0 \to e^+e^-$ in SM

- Theory is 3.3 standard deviations lower than the KTeV result.

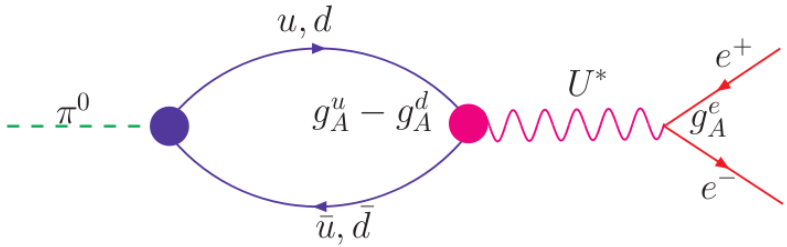
[3] A. Dorokhov, M. A. Ivanov, Phys. Rev. D **75** (2007) 114007

[4] E. Abouzaid *et. al*, Phys. Rev. D **75** (2007) 012004

# Search for New Physics

MeV (light) Dark Matter [5]

- Neutral scalar $\chi$, $m_\chi \sim 1 - 10\text{MeV}$
- $\chi\chi \to e^+e^- \Rightarrow$ Could explain the large amount of 511 keV photons from galactic center.[6]
- Mechanism for $\chi$ annihilation: light vector boson $U$, $m_U \sim 10 - 100\text{MeV}$
- If $U$ couples both to $l$ and $q$: can enhance $\mathcal{B}(\pi^0 \to e^+e^-)$




[5] C. Boehm and P.Fayet, Nucl. Phys. B **683** (2004) 219

[6] Y Kahn,M. Schmitt, T.M.P. Tait, Phys. Rev. D 78 (2008) 115002

# New Physics in $\pi^0 \to \gamma e^+e^-$?

New Boson that couples to $\gamma$: $\pi^0 \to \gamma U^* \to \gamma\gamma^* \to \gamma e^+e^-$ [7]
Current upper limit in $\pi^0 \to \gamma e^+e^-$ by SINDRUM collaboration [8] :

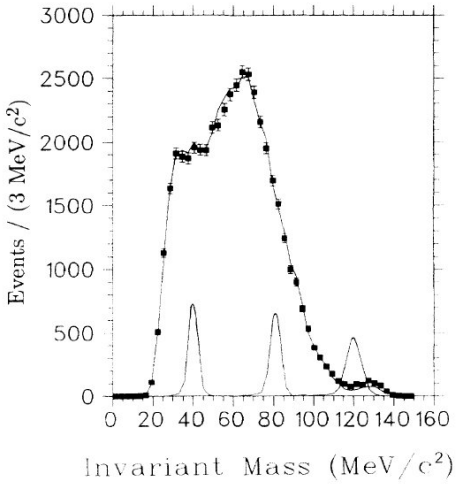



FIG. 2. Distribution of $e^+e^-$ invariant mass for class-A events which are predominantly $\pi^0 \to e^+e^-\gamma$.

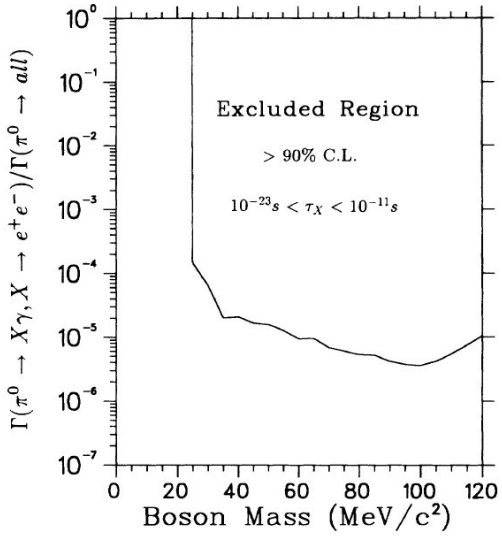



FIG. 4. The region of $M_X$ this experiment can exclude, at >90% confidence level, for branching ratio $\Gamma(\pi^0 \to X\gamma, X \to e^+e^-)/\Gamma(\pi^0 \to \text{all})$.

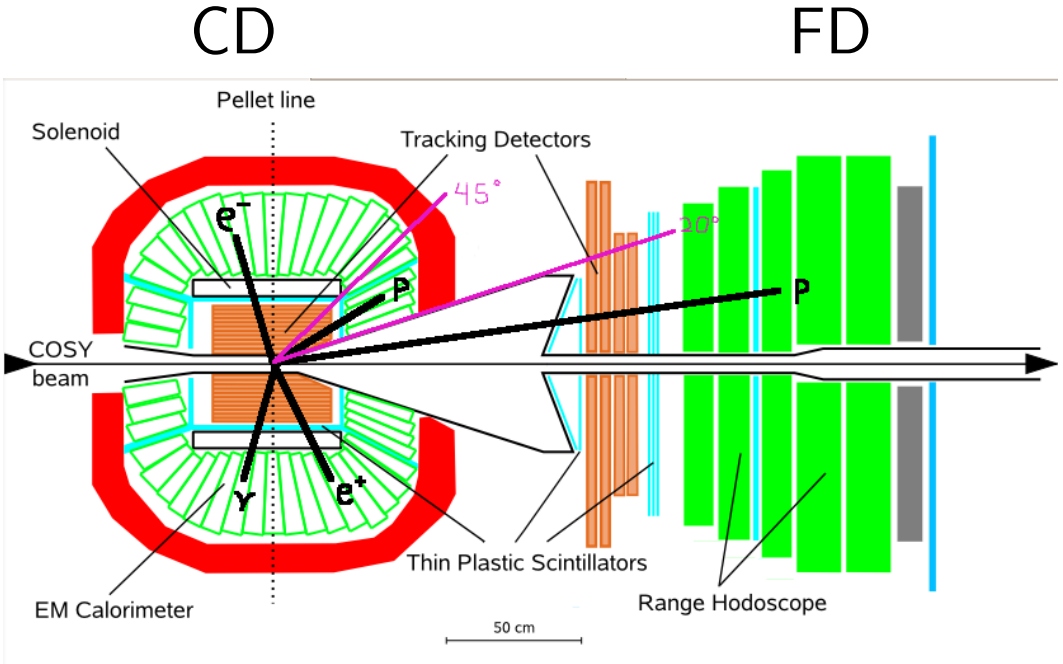
- 100.000 $\pi^0 \to \gamma e^+e^-$
- Upper limit only set above 30 MeV
- $e^+e^-$ mass resolution: 6%

[7] M. Reece and L.-T. Wang JHEP 07.051 (2009)

[8] R. Meijer Drees et al. (SINDRUM 1 Collaboration), Phys.Rev.Lett. 68(1992) 3845h

# WASA-at-COSY

WASA designed for $\pi^0$ leptonic decay




WASA-at-COSY setup with $pp \rightarrow pp\left(\pi^0 \rightarrow e^+e^-\gamma\right)$

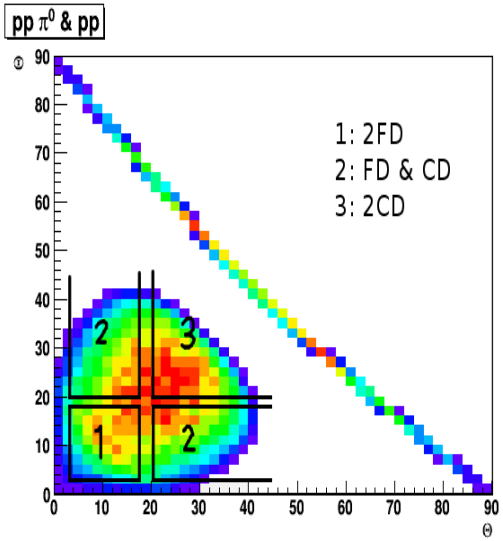
- Pellet target and Be-beampipe to minimize external conversion
- Lepton momentum resolution in central tracker: 2% $(90^o, 50\ MeV/c)$ - 12% $(25^o, 150\ MeV/c)$.

# $\pi^0$ production in pp collision

- $\pi^0$ are produced in pp collisions at 550 MeV at maximum cross-section (1.3 mb) below $\pi^-\pi^+$ threshold.

| | |
|---|---|
| $pp \rightarrow pp$ | 25 |
| $pp \rightarrow pp\pi^0$ | 1.3 |
| $pp \rightarrow d\pi^+$ | 2.8 |
| $pp \rightarrow pn\pi^+$ | 5.2 |

Cross sections (mb) at $T_p^{\text{lab}} = 550$ MeV.




$\theta$ - $\theta$ distribution for the two protons from elastic scattering and $\pi^0$ production.

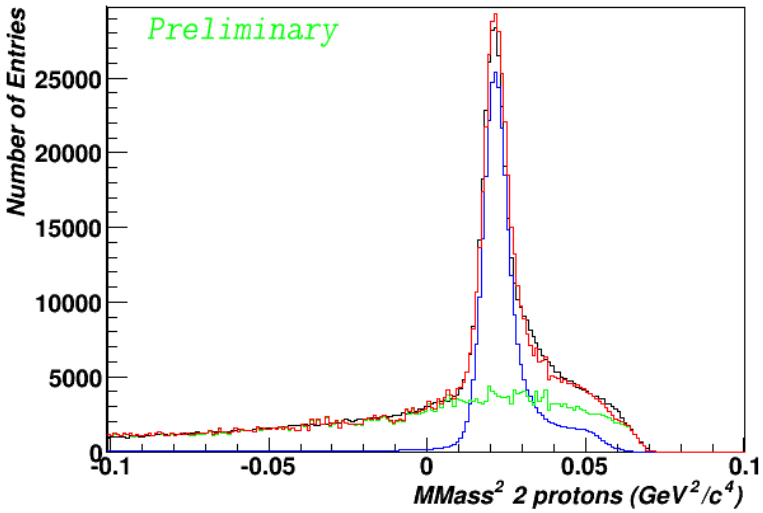
Main Trigger:

- $\pi^0$ production: 2 charged in FD ($\theta < 20°$)
- $\pi^0$ charged decay: 2 charged in CD ($\theta > 45°$)
- Only $\pi^0$ channel and accidental coincidences fulfil trigger

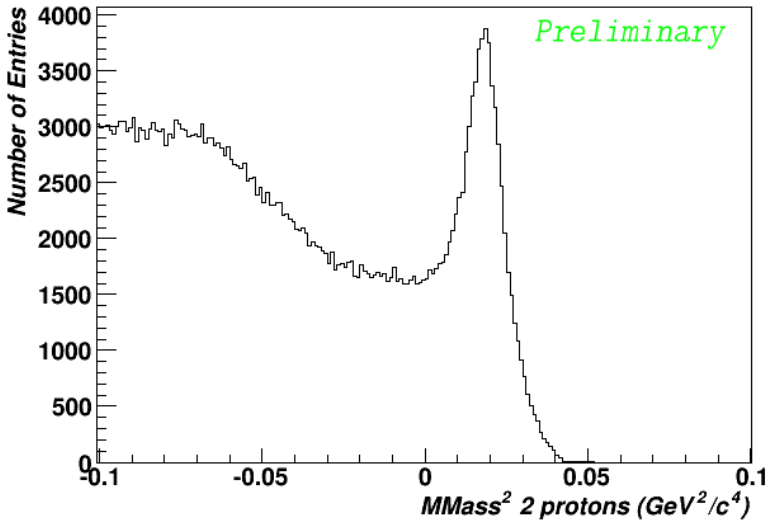
# Test Run Spring 2010

Missing mass 2 proton

2 FD protons




1 FD proton & 1 CD proton




— : Data

— : MC Coincidence from two elastic $pp \rightarrow pp$ events

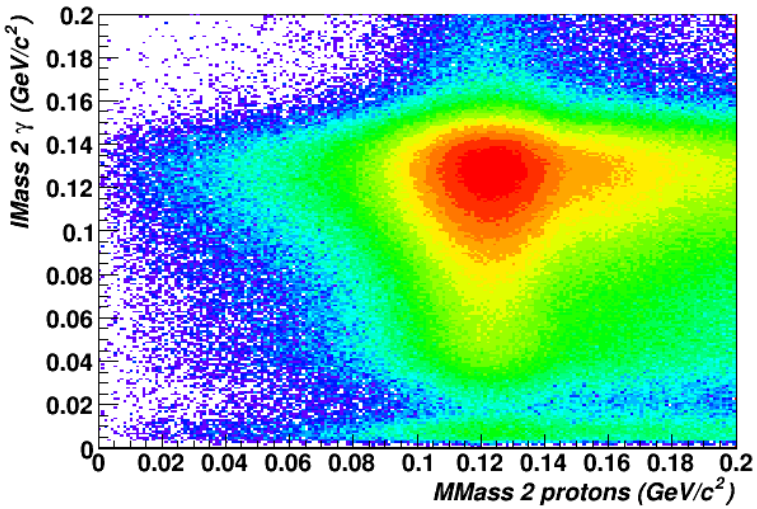
— : MC $pp \rightarrow pp\pi^0$

— : Total MC sample

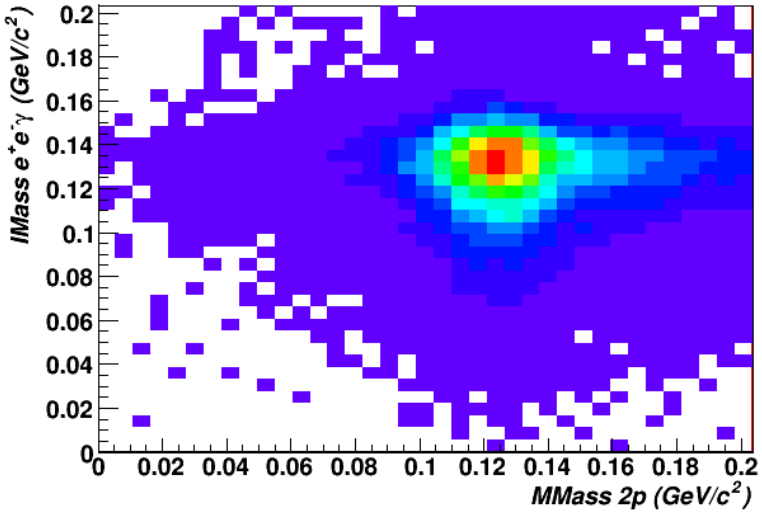
- $2 * 10^{10}$ $\pi^0$ produced
- $2 * 10^8$ $pp \rightarrow pp\pi^0$ tagged

# Invariant Mass of $2\gamma$ and $e^+e^-\gamma$

- $2 * 10^8$ $\pi^0 \longrightarrow 2\gamma$ on disk
- $1.5 * 10^7$ $\pi^0 \longrightarrow e^+e^-\gamma$ on disk




Missing Mass of 2 protons in FD vs Invariant Mass of $2\gamma$

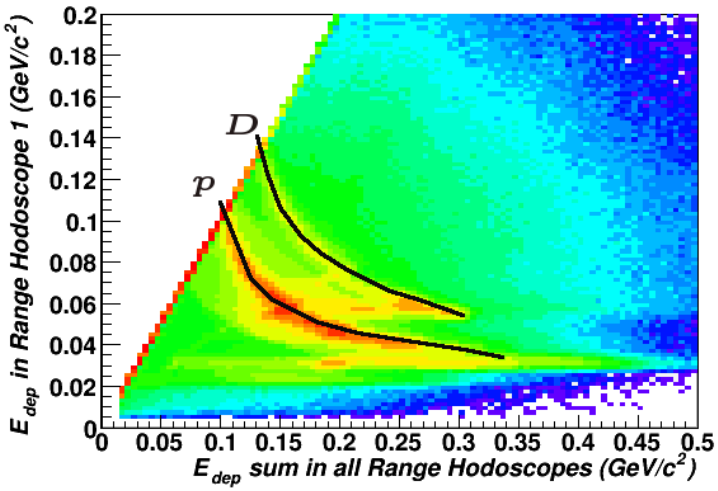



Missing Mass of 2 protons in FD vs Invariant Mass of $e^+e^-\gamma$

- $1.5 * 10^8$ $\pi^0 \longrightarrow 2\gamma$ reconstructed
- $1.2 * 10^6$ $\pi^0 \longrightarrow e^+e^-\gamma$ reconstructed

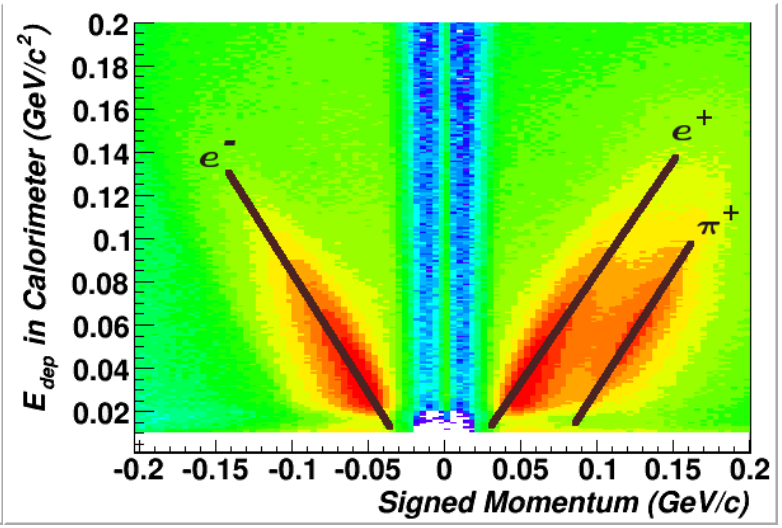
# PID

p-d separation in FD



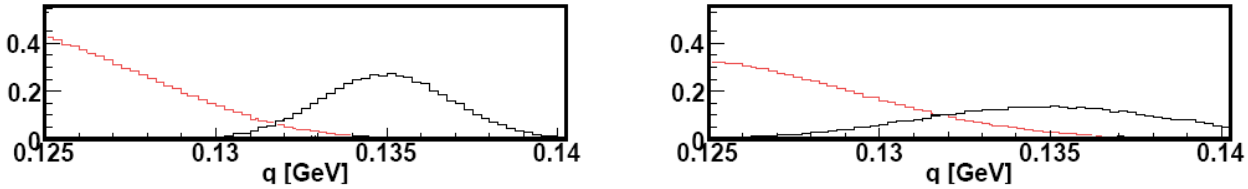

$\Delta E - E$ in FD

$e^+$ $\pi^+$ separation in CD



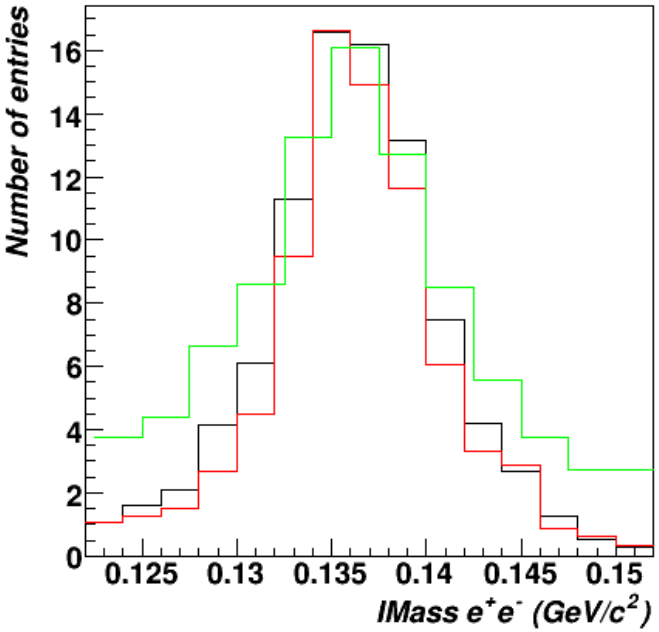

E vs $p * q$ in CD

# Momentum improvement




$\pi^0 \longrightarrow e^+e^-$ and $\pi^0 \longrightarrow e^+e^-\gamma$ simulation at 2 and 4 % $e^+e^-$ mass resolution

- Good inv mass resolution mandatory for $\pi^0 \longrightarrow e^+e^-$
- Vertex point used to track particles with desired momentum resolution




MC $\pi^0 \longrightarrow e^+e^-$:

— : no vertex cuts

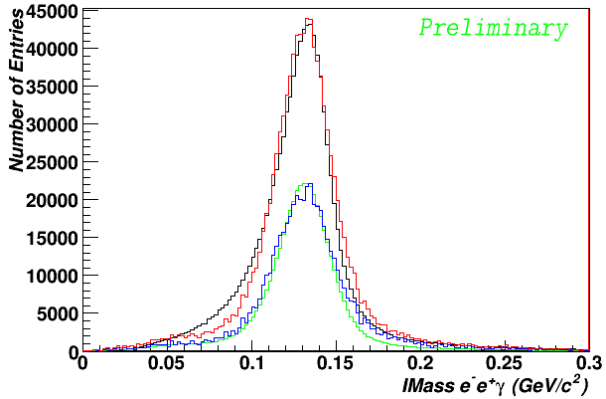
— : vertex cuts in X-Y plane

— : 3-D vertex cuts

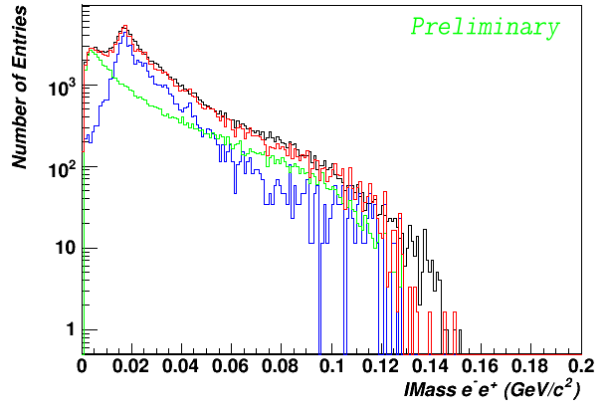
# $\pi^0 \rightarrow e^+e^-\gamma$

- 40.000 of high resolution data available
- No U-boson peak in current sample

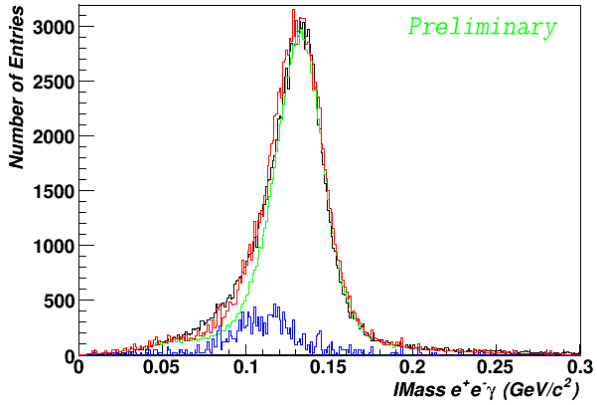
Invariant Mass $e^+e^-\gamma$

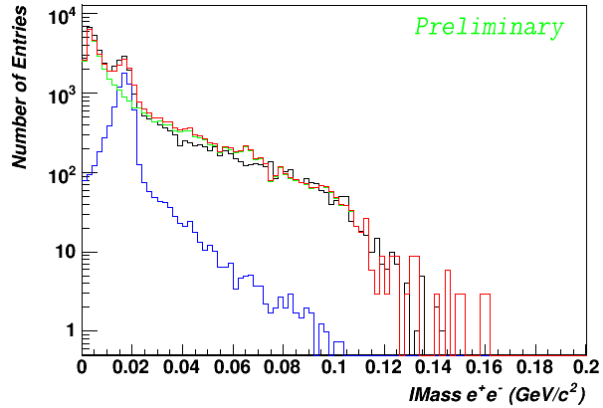



Invariant Mass $e^+e^-$ in $e^+e^-\gamma$ peak




Vertex cut removes external conversion:




— : Data

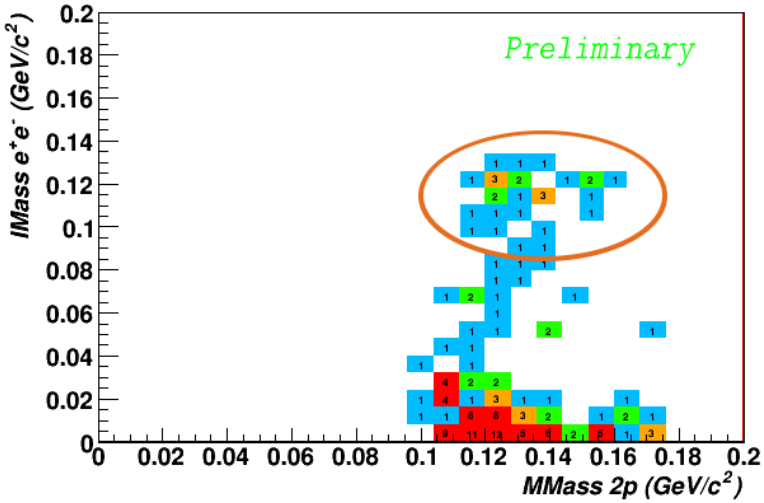
— : MC External conversion

— : MC $\pi^0 \rightarrow e^+e^-\gamma$

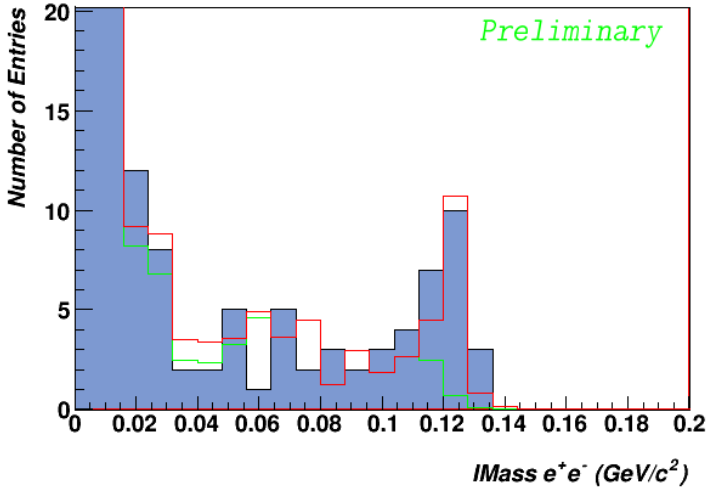
— : Total MC sample

# $\pi^0 \longrightarrow e^+e^-$

- 15 event candidates in current data sample




Missing Mass of 2 protons in FD vs Invariant Mass of $e^+e^-$




Invariant Mass of $e^+e^-$ pair in CD

Blue filled: Data

Green: MC $e^+e^-\gamma$ background

Red: MC $\pi^0 \longrightarrow e^+e^-$ plus $e^+e^-\gamma$ and external conversion

# Summary and outlook

- 1 week of test run: $2 * 10^{10}$ $\pi^0$ produced
- $\pi^0 \longrightarrow e^+e^-\gamma$
  - 40.000 $\pi^0 \longrightarrow e^+e^-\gamma$ in current sample
  - Extend upper limit on U-Boson search to lower masses
- $\pi^0 \longrightarrow e^+e^-$
  - 15 $\pi^0 \longrightarrow e^+e^-$ candidates
  - 50 $\pi^0 \longrightarrow e^+e^-$ feasible per week