New Results from KTeV

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for the KTeV collaboration

BEACH 2008

New Symmetry Related Results from KTeV

- Today I'll present:
  - Analyses related to the CP conserving contributions to $K_L \to \pi^0 l^+ l^-$
  - New limits on Lepton Flavor Violation
  - Determination of the parity of the π^0

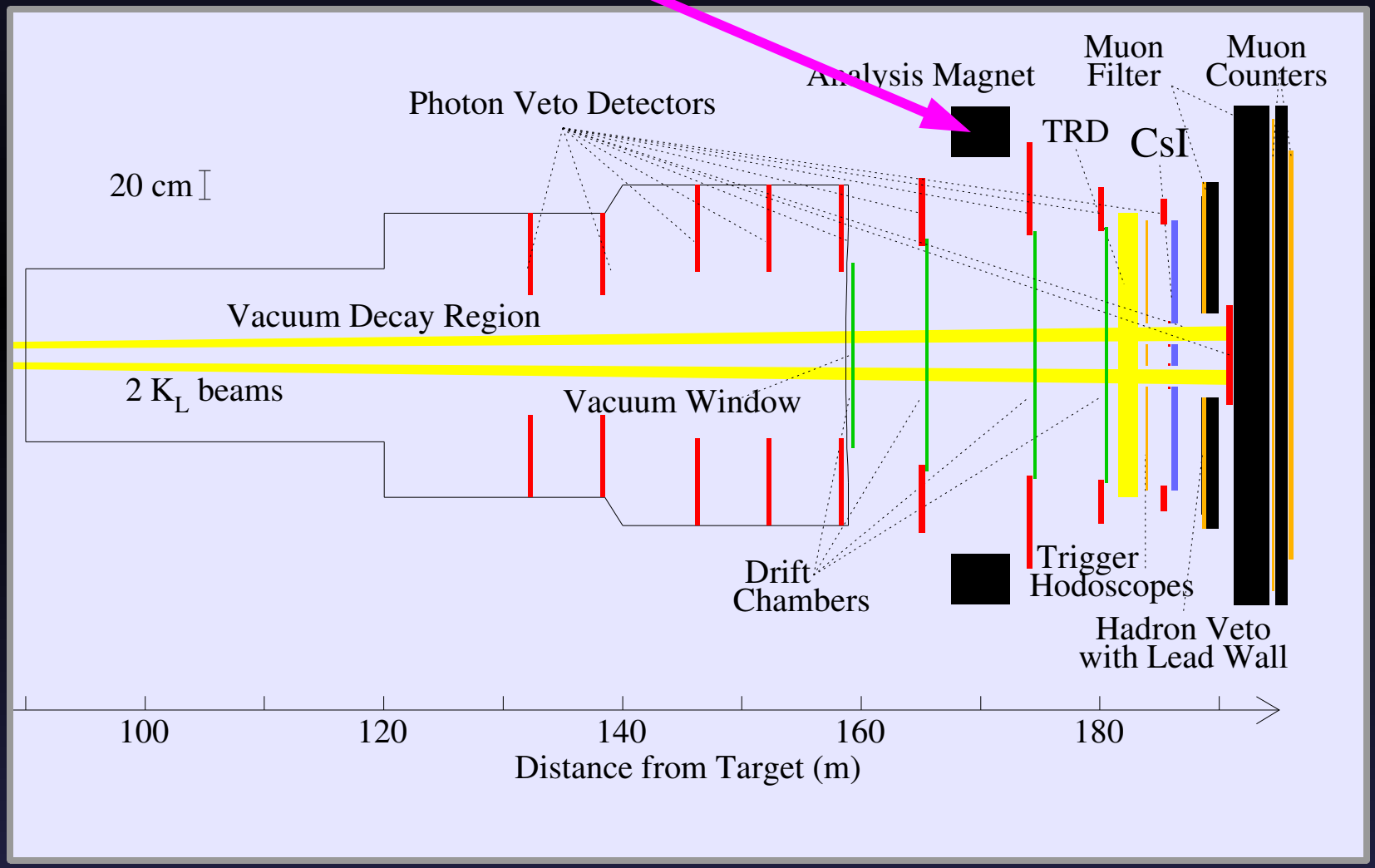
Kaons at the TeVatron

- E832: dedicated configuration for measurement of Re(e'/e)
- 1 coherent K_L-K_S beam
- 1 pure K_L beam

- E799: dedicated configuration for rare decay searches
- Twin pure K_L beams
- Transition radiation detectors to improve particle ID
  - For $K_L \rightarrow \pi^0 e^+ e^-$
- Higher beam intensity

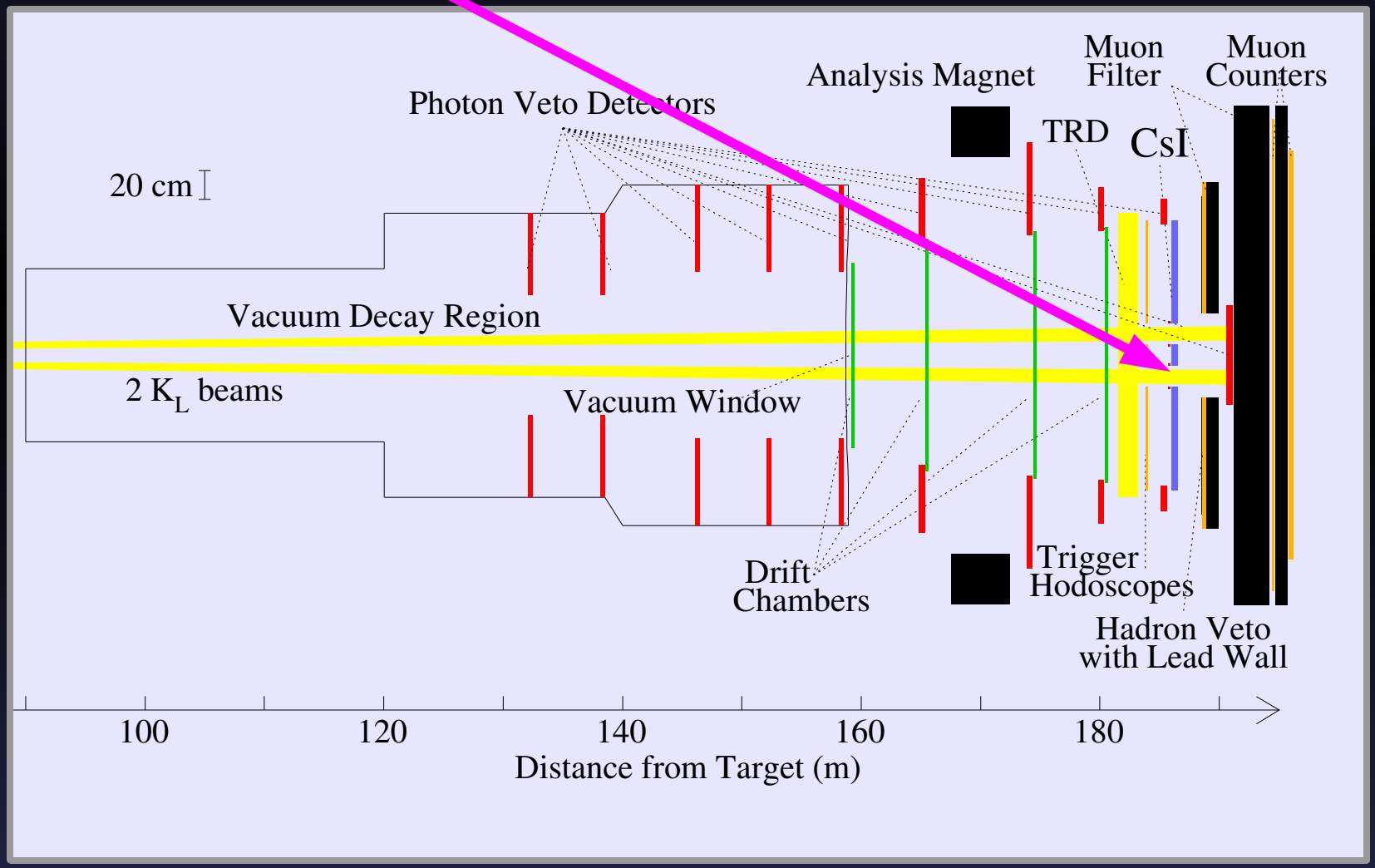
Kaons at the TeVatron

- Momentum resolution: $\frac{\sigma_p}{p(GeV/c)} \approx \left(1.7 + \frac{p}{14}\right) \times 10^{-3}$



Kaons at the TeVatron

- CsI energy resolution: $\frac{\sigma_E}{E(GeV/c)} \approx \left(0.004 + \frac{.02}{\sqrt{E}}\right)$



$K_L \to \pi^0 \gamma\gamma$ + $K_L \to \pi^0 ee\gamma$

- Excellent tests of χPT
  - No free parameters in branching ratio to $O(p^4)$
  - $O(p^6)$ terms include Vector Meson exchange terms (strength of which is described by A_V)
    - $O(p^6)$ terms increase branching ratios by factor of 2-3

$K_L \to \pi^0 \gamma\gamma$ + $K_L \to \pi^0 ee\gamma$

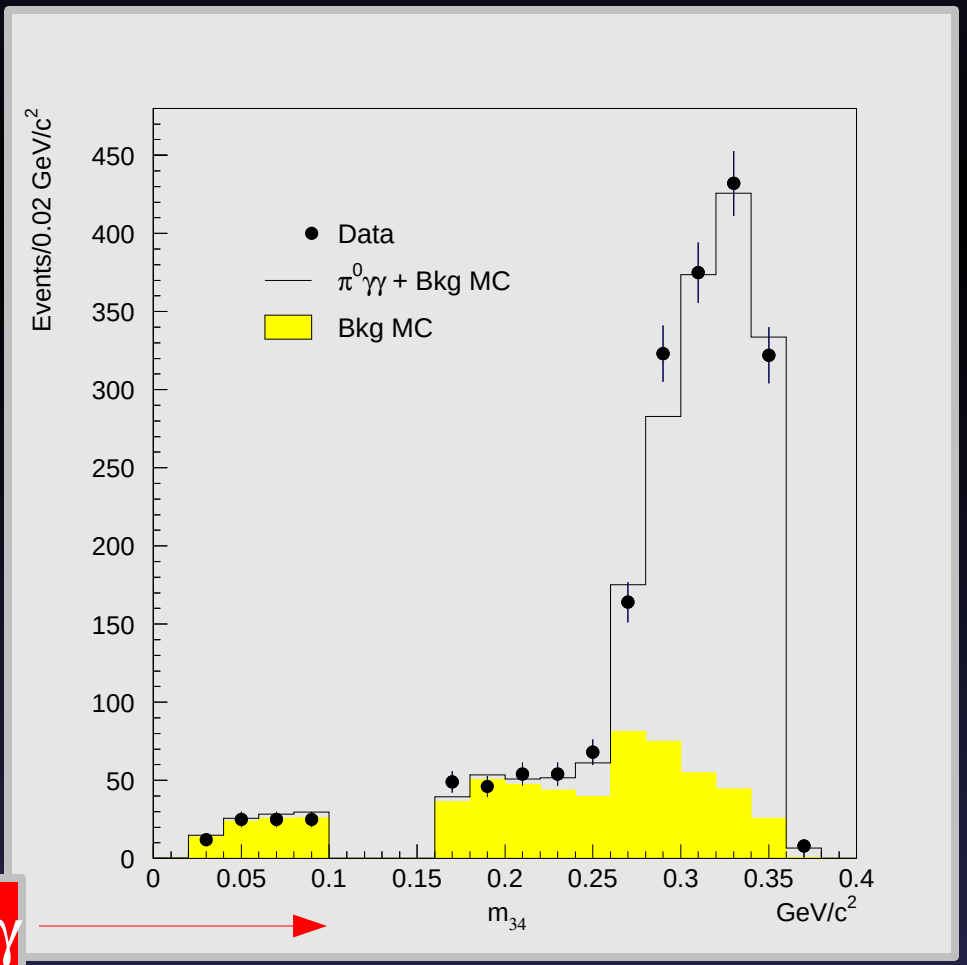
- A_V determines CP conserving part of $K_L \to \pi^0 l^+ l^-$
  - CP conserving part is from $K_L \to \pi^0 \gamma^* \gamma^*$
- Indirect CP violating part of $K_L \to \pi^0 l^+ l^-$ determined by $Br(K_S \to \pi^0 l^+ l^-)$

$K_L \to \pi^0 \gamma\gamma$

- Selection requirements:
  - Require 4 photon clusters in CsI, each with an energy > 2.0 GeV
  - Require energy center to be in vacuum beam hole in CsI calorimeter
    - Rejects events from mixed K_L-K_S regenerator beam
  - Two photons must reconstruct to within 3MeV of the π^0 mass, while the other two must <u>not</u>.

$K_L \to \pi^0\gamma\gamma$

- After all cuts, left with 1982 events
- Background is ~ 30% of signal...
- Normalize with $K_L \to \pi^0\pi^0$
  - Same final state



Invariant mass of $\gamma\gamma$ part of $\pi^0\gamma\gamma$

$K_L \to \pi^0\gamma\gamma$

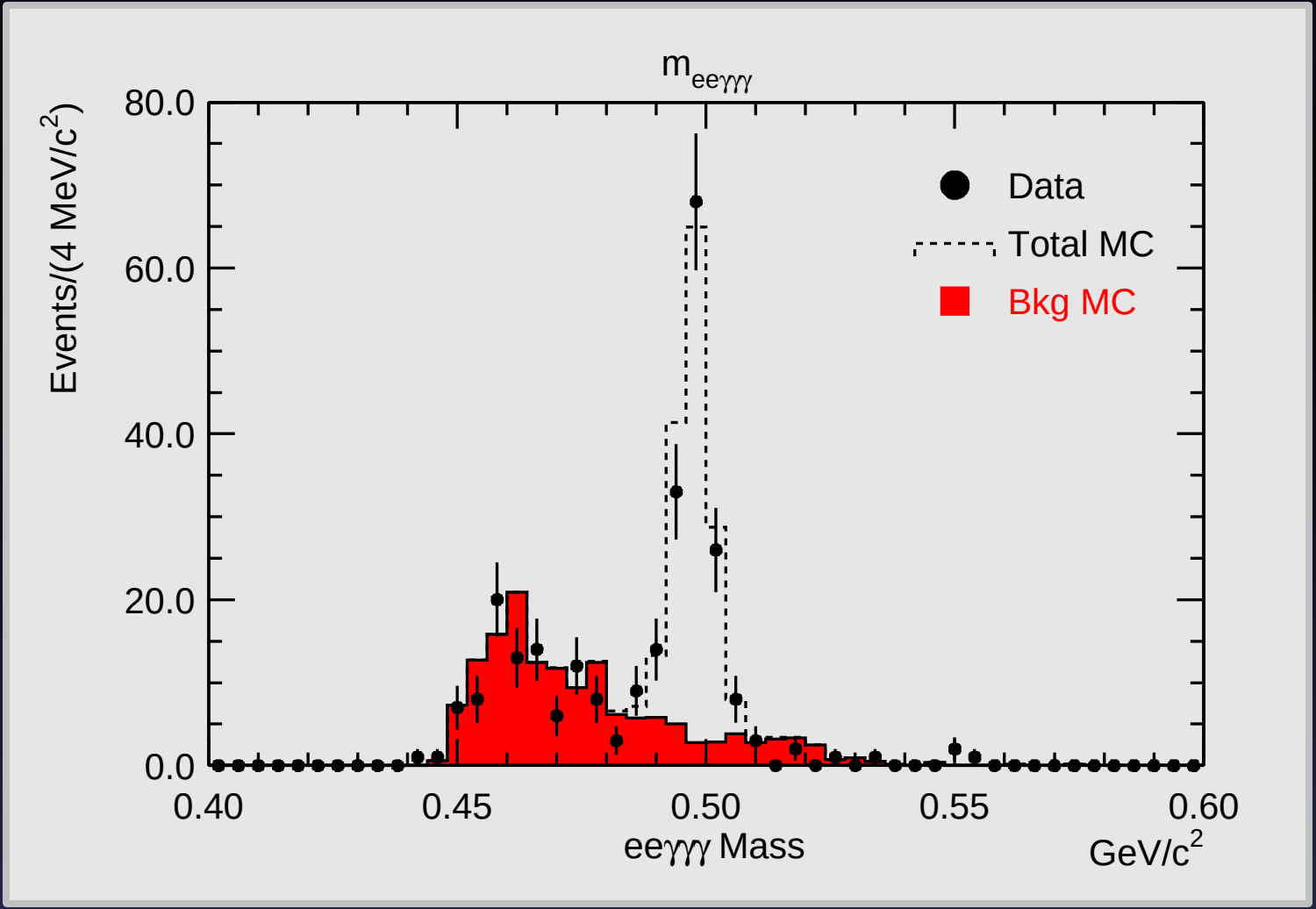
- Result:
  - $Br(K_L \to \pi^0\gamma\gamma) = (1.29 \pm 0.03_{stat} \pm 0.05_{syst}) \times 10^{-6}$
  - Compare to NA48: $(1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \times 10^{-6}$
- This uses the full KTeV dataset, and with better modeling of the $K_L \to \pi^0\pi^0\pi^0$ background, supersedes our older result

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

- Selection requirements...
  - Look for two tracks and 3 neutral CsI clusters
  - Two neutral clusters must combine to an invariant mass near the π^0 mass
  - Neutral decay vertex used to compute:
    - $M_{ee\gamma}$
    - $M_{ee\gamma\gamma}$
    - Mass resolution is better than charged vertex since ee pair are very close to each other in the DCs
  - None of the 3 possible $ee\gamma$ solutions can reconstruct into a π^0.

$K_L \to \pi^0 e^+ e^- \gamma$

- After all cuts, observe 139 events with an expected background of 14.4 +/- 2.5 events



$K_L \to \pi^0 e^+ e^- \gamma$

- Normalize using $K_L \to \pi^0 \pi^0{}_D$
  - Same final state as signal
- Final result:
  - $Br(K_L \to \pi^0 e^+ e^- \gamma) = (1.62 \pm 0.14_{stat} \pm 0.09_{syst}) \times 10^{-8}$
  - Obsolete value of $Br(K_L \to \pi^0 \pi^0)$ threw off old KTeV result.
  - χPT to $O(p^6)$ predicts 1.51×10^{-8}
- This mode won't contribute much background to $K_L \to \pi^0 ee$
  - Distribution of $M_{\pi 0 ee}$ peaks well away from M_K

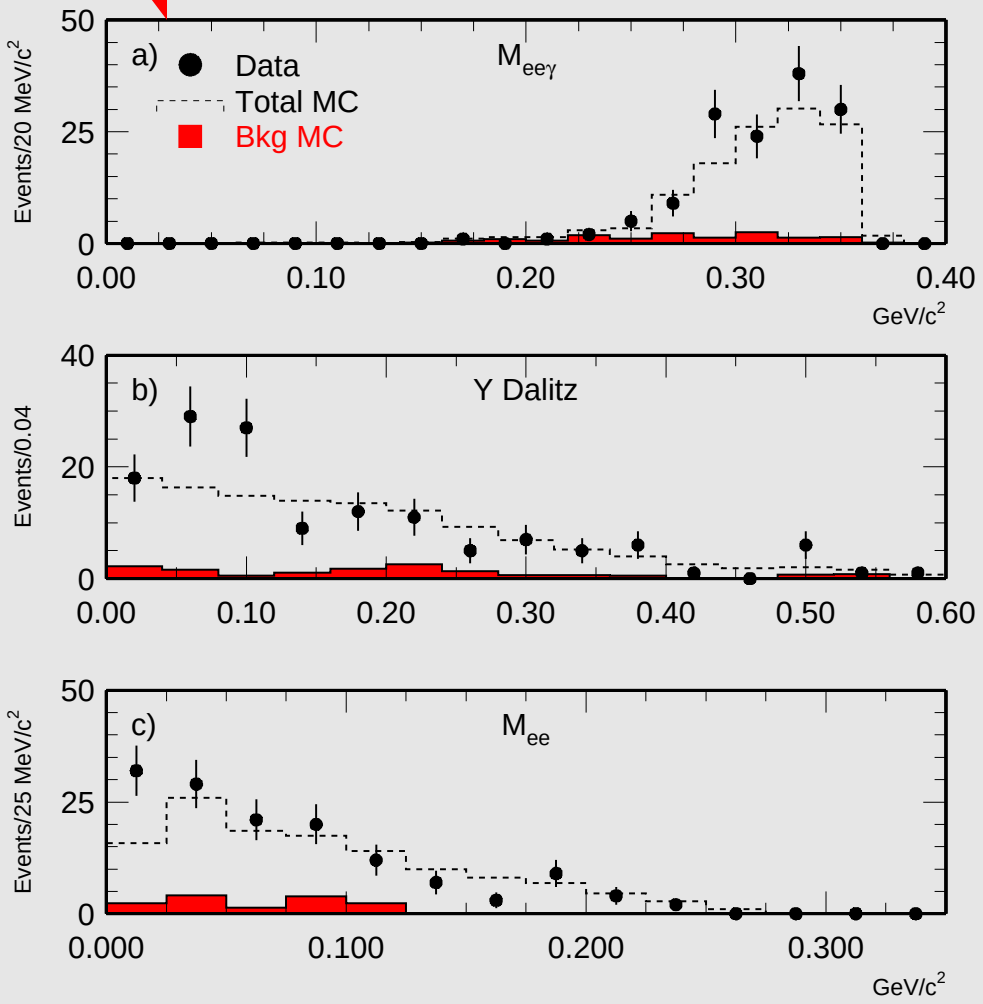
Extracting A_V

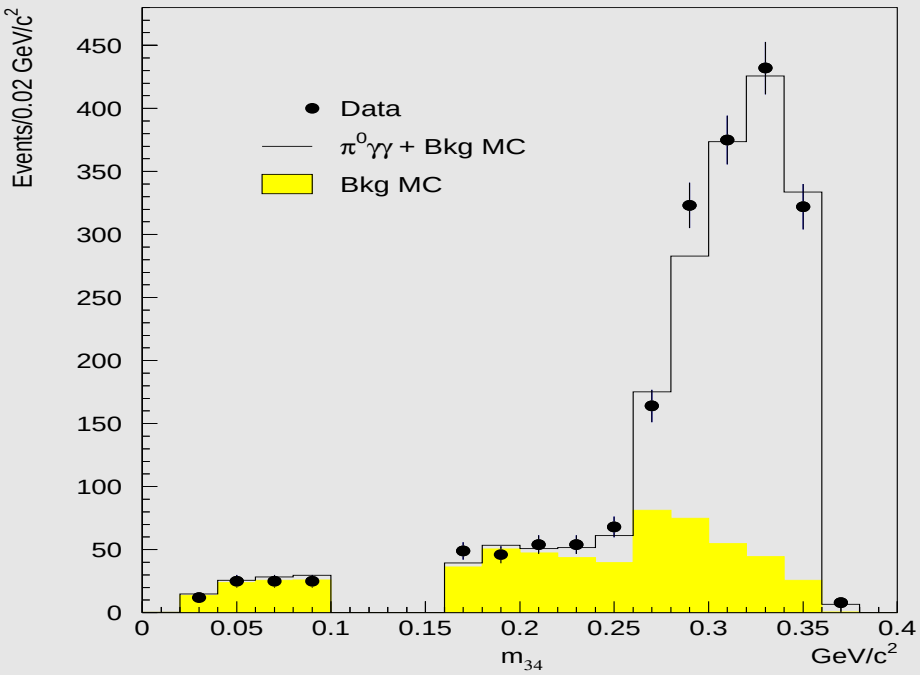
- $K_L \rightarrow \pi^0\gamma\gamma$
- Maximum likelihood fit to the two Dalitz parameters:
  - $Z_{Dalitz}=m_{34}^2/M_K^2$
  - $Y_{Dalitz}=(E_{\gamma 3}-E_{\gamma 4})/M_K$

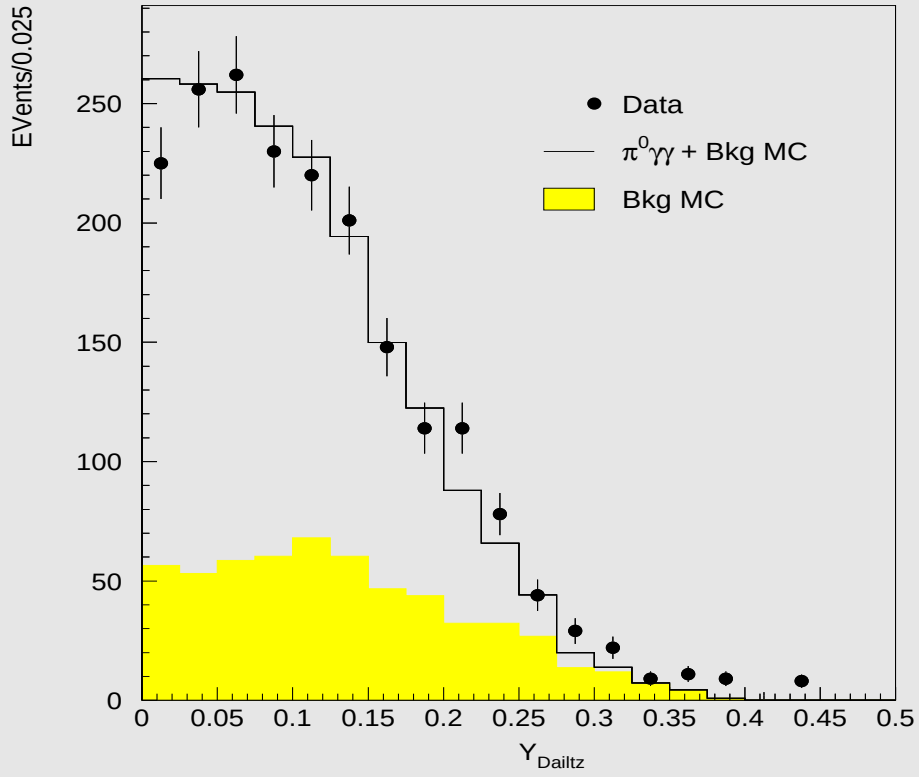
- $K_L \rightarrow \pi^0 ee\gamma$
- Maximum likelihood fit to the three Dalitz parameters:
  - $Z_{Dalitz} = M_{ee\gamma}^2/M_K^2$
  - $Y_{Dalitz} = (E_{\gamma}-E_{ee})/M_K$
  - $Q_{Dalitz} = M_{ee}^2/M_K^2$

Data + Best Fit

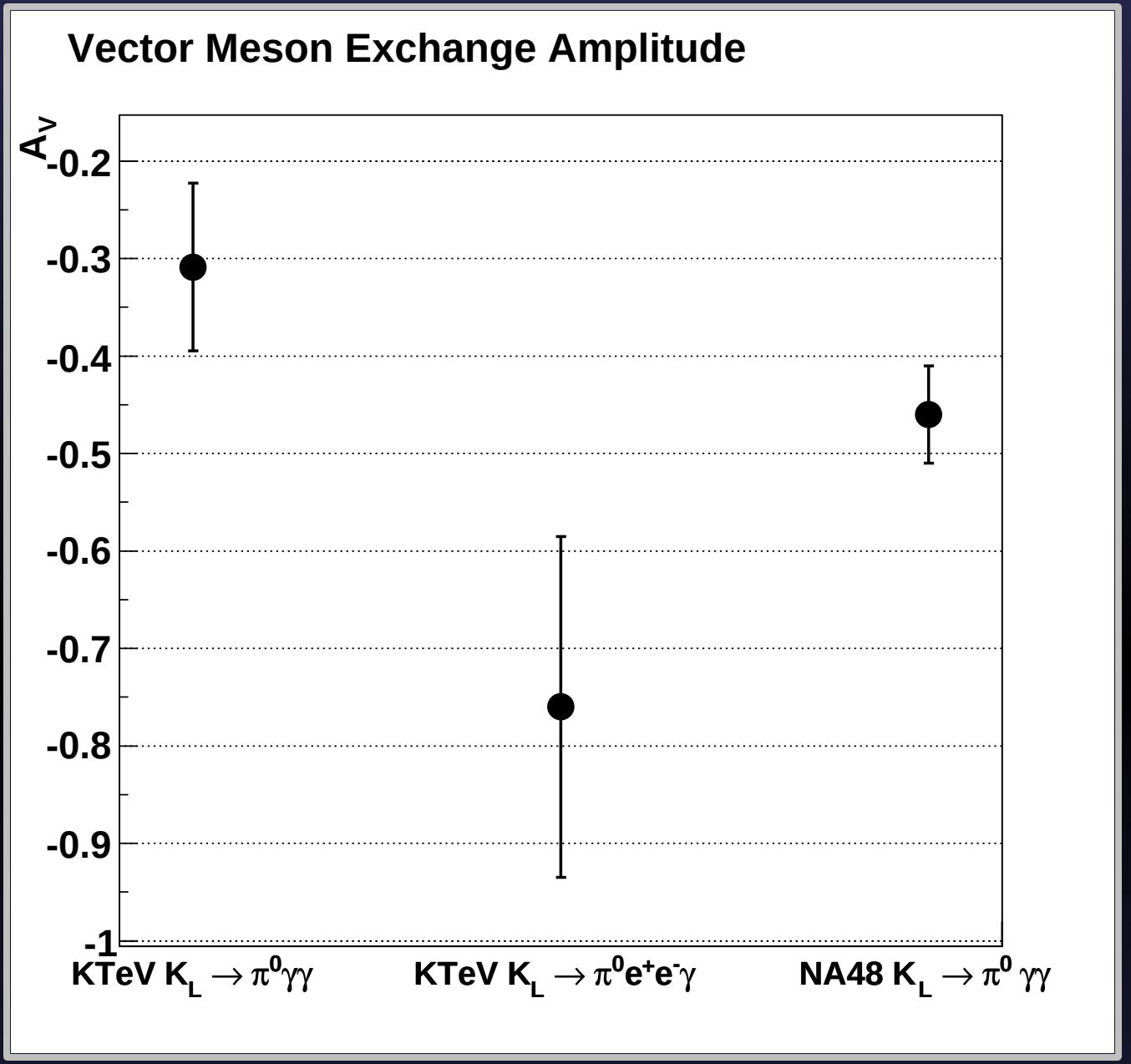
$K_L \rightarrow \pi^0 ee\gamma$ $K_L \rightarrow \pi^0\gamma\gamma$







Results for A_V



- Values imply that $K_L \to \pi^0 l^+ l^-$ is indeed dominated by CPV terms

Signature of Lepton Flavor Violation

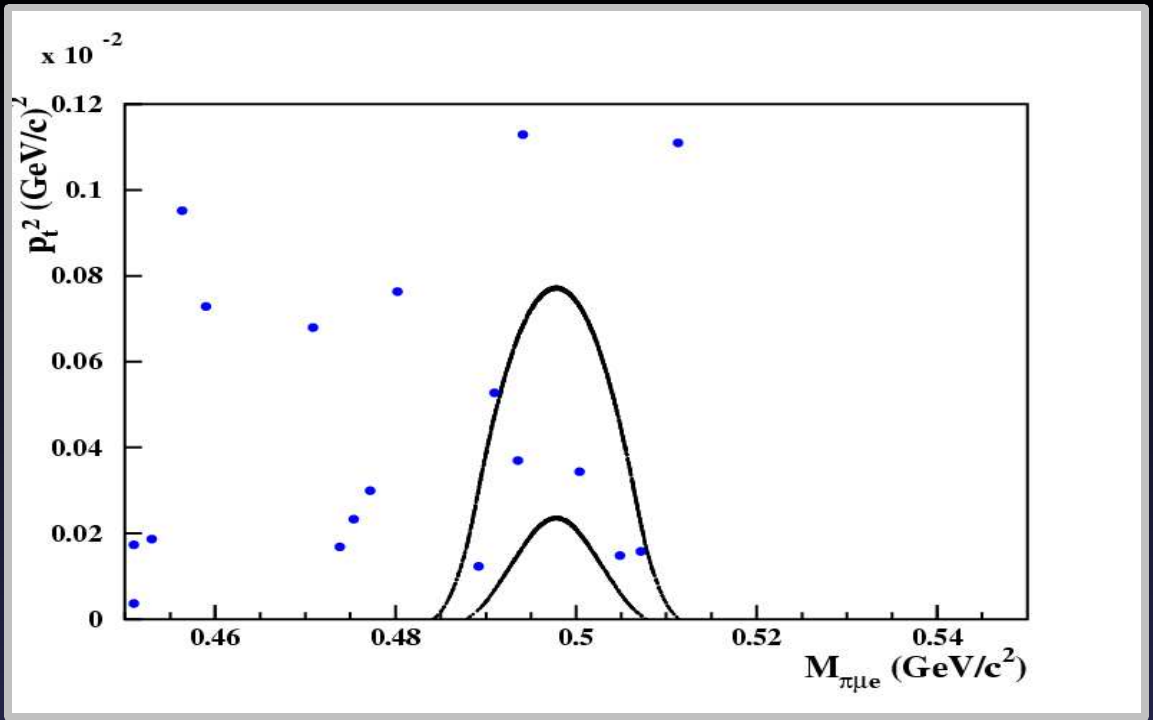
- Look for two charged tracks in detector:
  - One muon
    - Track must match hits in the muon hodoscopes
  - One electron
    - Track momentum = cluster energy in CsI
    - TRD info is consistent with an electron
- Allows searches for:
  - $K_L \rightarrow \pi^0 \mu e$
  - $K_L \rightarrow \pi^0 \pi^0 \mu e$
  - $\pi^0 \rightarrow \mu e$

LFV: $K_L \rightarrow \pi^0 \mu e$

- Highest background out of our trio of LFV decays
  - Ke3/Ke4 + π decay or π punch through to muon hodoscopes = fake signal
    - Make tight cut on accidental acitvity in detector
    - Apply cut on calculated $|p_\nu|$ assuming Ke4 decay
      - Real Ke4 events produce positive values
      - Other events produce negative (non-physical) values

LFV: $K_L \rightarrow \pi^0 \mu e$

- Sum of background estimates:
  - 4.21 +/- 0.53 in control region
    - contains 99% of signal
  - 0.66 +/- 0.23 in signal region
    - contains 95% of signal



- Observe after all cuts:
  - 5 events in control region
  - 0 events in signal region

LFV: $K_L \to \pi^0 \mu e$

- Sum of background estimates:
  - 4.21 +/- 0.53 in control region
    - contains 99% of signal
  - 0.66 +/- 0.23 in signal region
    - contains 95% of signal
- Observe after all cuts:
  - 5 events in control region
  - 0 events in signal region

- Resulting limit:
  - $Br(K_L \to \pi^0 \mu e) < 7.56 \times 10^{-11}$ (90% C.L.)
  - Factor of 83 lower than previous limit

LFV: $K_L \to \pi^0\pi^0\mu e$

- Extend $K_L \to \pi^0\mu e$ search
- Attempt to reconstruct 2nd π^0
  - Slashes backgrounds
  - Offset by relaxing cuts to improve sensitivity
    - Remove tight cuts on accidental activity
    - Remove cuts on TRD information for electron track
- Largest background from $K_L \to \pi^0\pi^0\pi^0_D$
  - Need a bad electron cluster in CsI combined with an accidental muon in the muon hodoscope
  - Apply VERY loose TRD cut on muon track

LFV: $K_L \to \pi^0\pi^0\mu e$

- Expect 0.44 +/- 0.23 events in signal region
- Observe no events in signal region
- Br($K_L \to \pi^0\pi^0\mu e$) < 1.7 X 10^{-10} (90% CL)
  - First reported limit on this decay mode
- Note that $K_L \to \pi^0\pi^0\pi^0$, with $\pi^0 \to \mu e$ produces the same final state....

LFV: $\pi^0 \rightarrow \mu e$

- Analysis can be extended by placing an extra constraint:
  - $M_{\mu e}$ reconstructs near $M_{\pi 0}$
- Resulting limit:
  - $Br(\pi^0 \rightarrow \mu e) < 3.59 \text{ X } 10^{-10}$ (90% CL)
- Limit 10x(2x) lower than previous best limit on $\pi^0 \rightarrow \mu^- e^+ (\mu^+ e^-)$
- Equally sensitive to both charge modes

LFV limits

- Important note:
  - Zero background for all LFV modes
  - Note that the expectations for backgrounds were:
    - ~0.66 events ($K_L \to \pi^0 \mu e$)
    - ~0.44 events ($K_L \to \pi^0 \pi^0 \mu e$)
    - ~0.03 events ($\pi^0 \to > \mu e$)
- It would be straightforward to improve these limits with a KTeV - like experiment and additional beam intensity

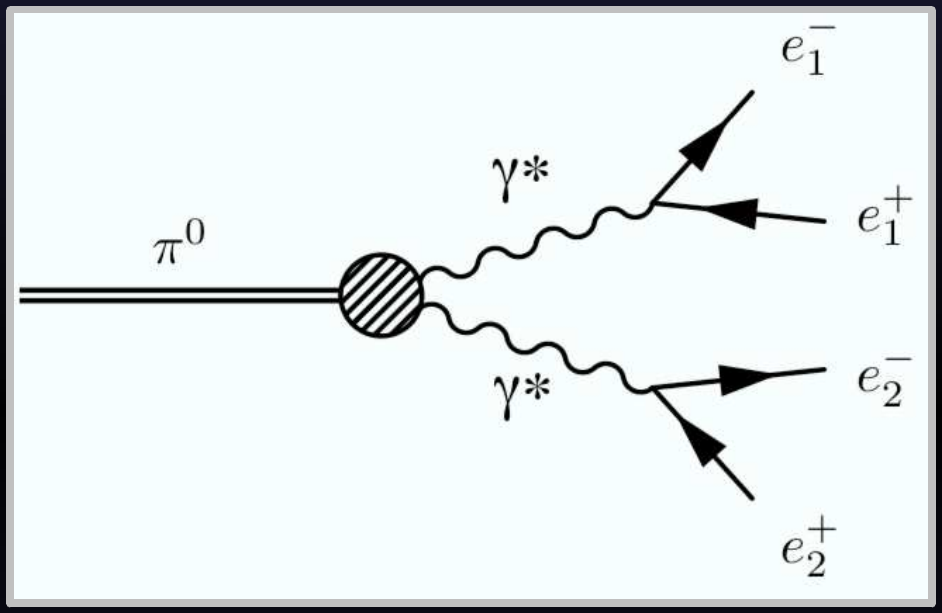
$\pi^0 \rightarrow e^+e^-e^+e^-$

- Previous evidence of parity of π^0 not as strong as one would think
  - Evidence is either indirect.....
  - Or direct, but significant to 3.6 σ, and 46 years old
  - Plane of e+e- pair in $\gamma^* \rightarrow$e+e- reveals polarization of photon
  - Use both Dalitz planes to probe parity of π^0.

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

- Looking for $K_L \rightarrow \pi^0\pi^0\pi^0{}_{DD}$

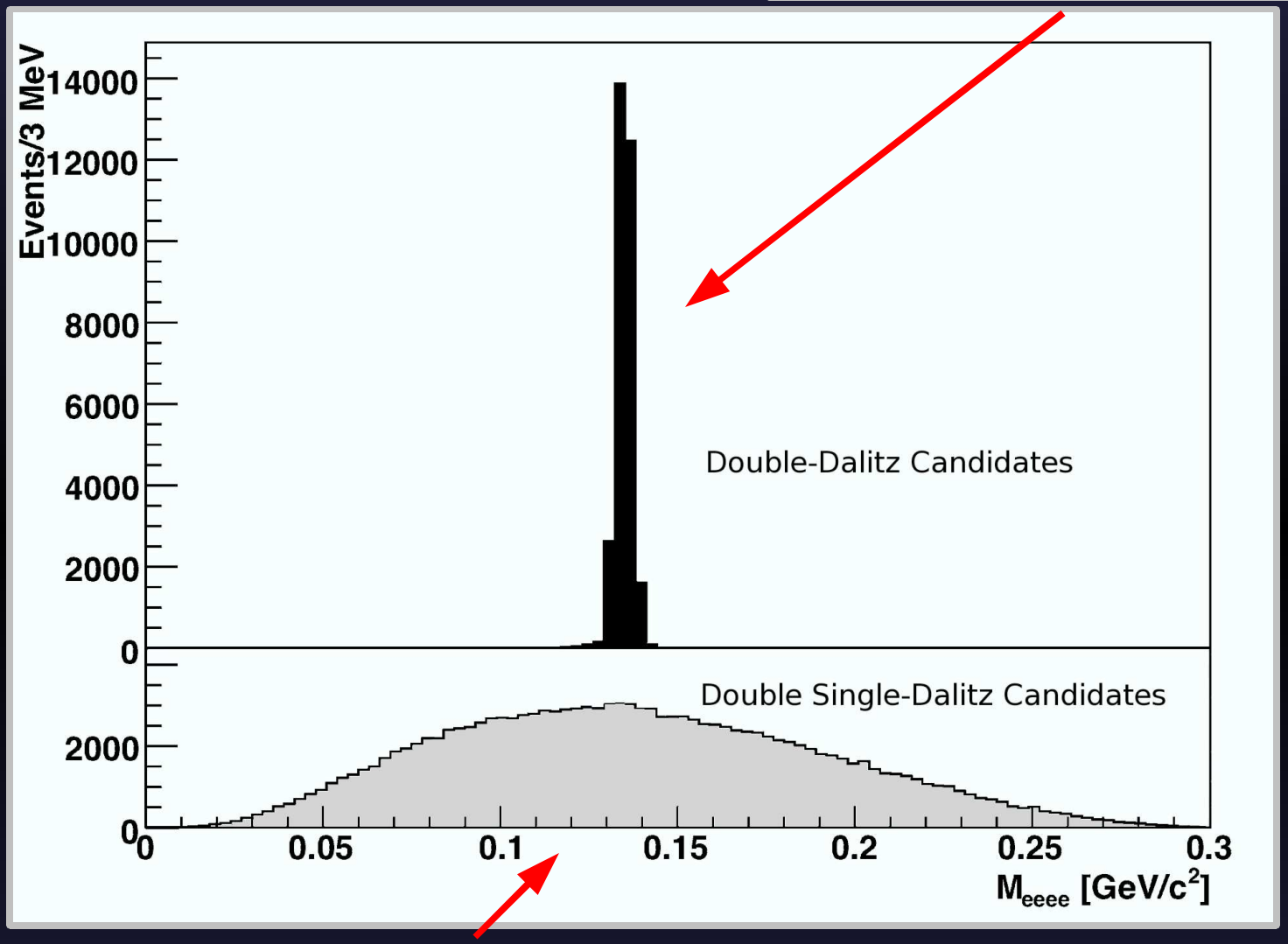
  $\pi^0{}_{DD} = \pi^0 \rightarrow \gamma^*\gamma^* \rightarrow e^+e^-e^+e^-$



- Require:
  - 4 photons for 2 π^0s
    - Require $M_{\gamma\gamma} = M_{\pi 0}$
  - 4 tracks for last π^0
    - Require $M_{eeee} = M_{\pi 0}$
  - $M_{\gamma\gamma\gamma eeee} = M_K$
  - Summed momentum of all particles points back to target

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

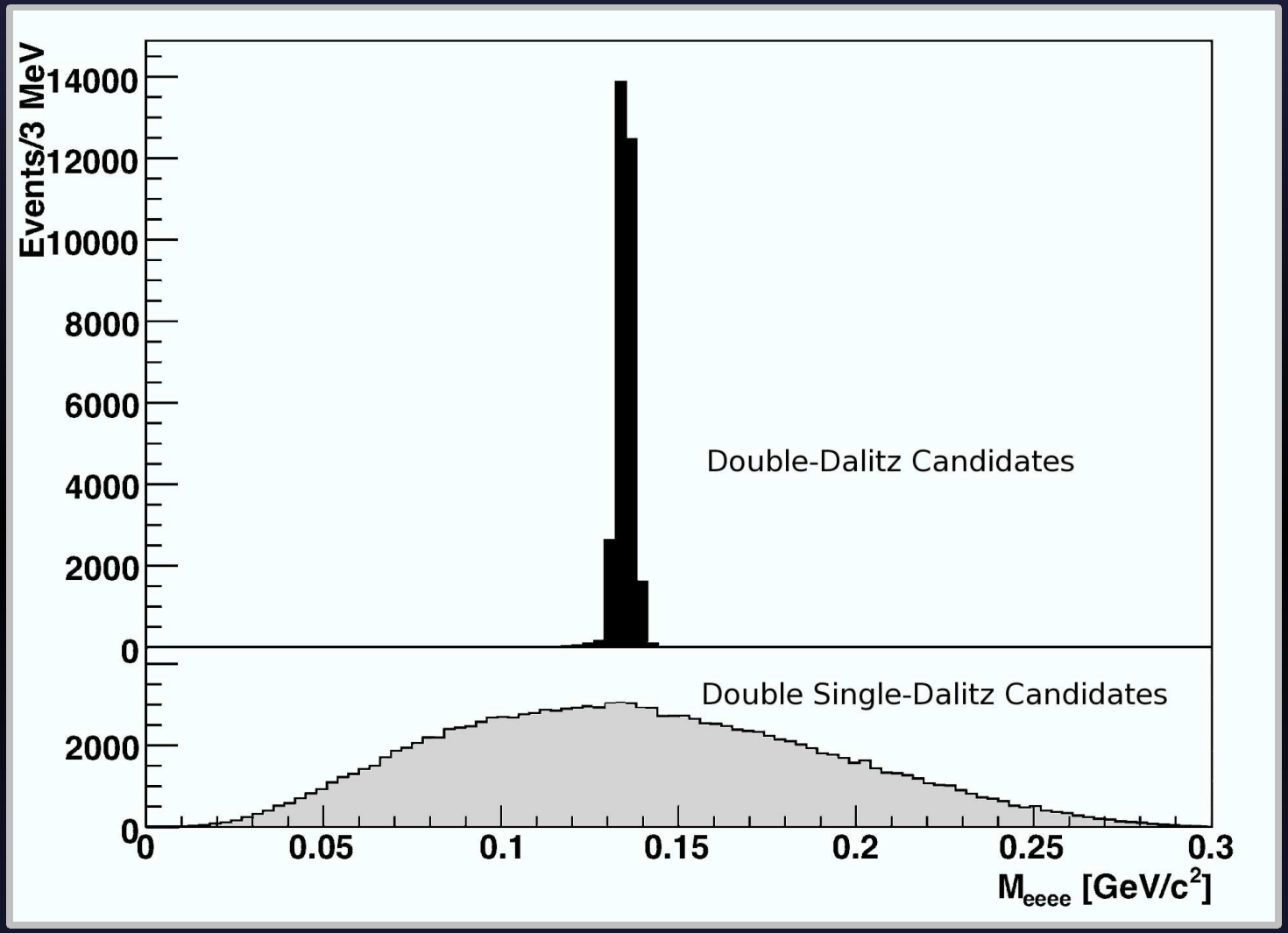
30511 signal events
0.6% residual background



141251 normalization events
0.5% residual background

Normalize with $K_L \to \pi^0_D\pi^0_D\pi^0$, $\pi^0 \to \gamma\gamma$

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

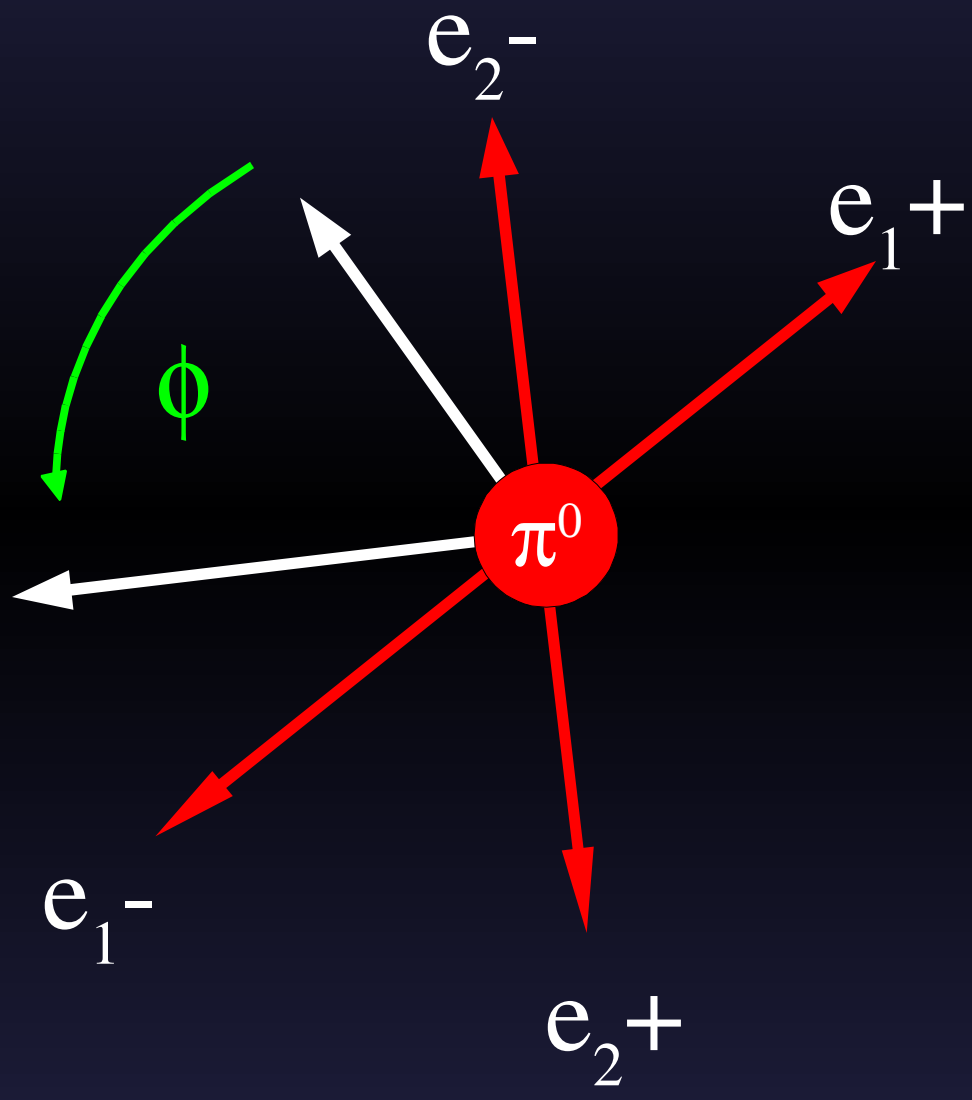


Resulting Branching Ratio:

$Br(\pi^0 \rightarrow e^+e^-e^+e^-) = (3.26 \pm 0.18) \times 10^{-5}$

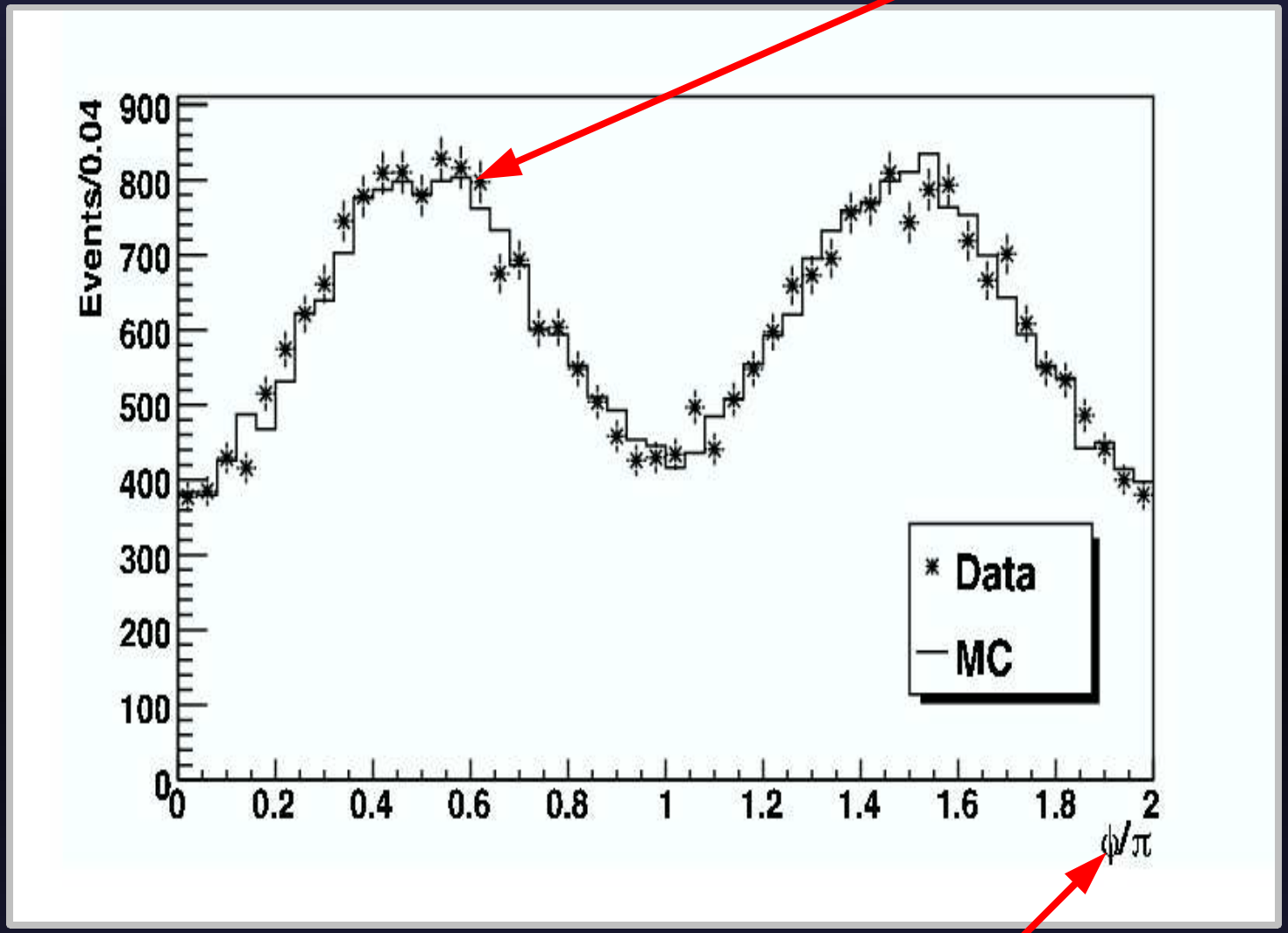
$\pi^0 \rightarrow e^+e^-e^+e^-$

- Measure angle between plane defined by each e^+ e^- pair
- Angle is with respect to the pair with the lowest M_{ee}



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

Dalitz pairs prefer to be orthogonal! Parity =-1



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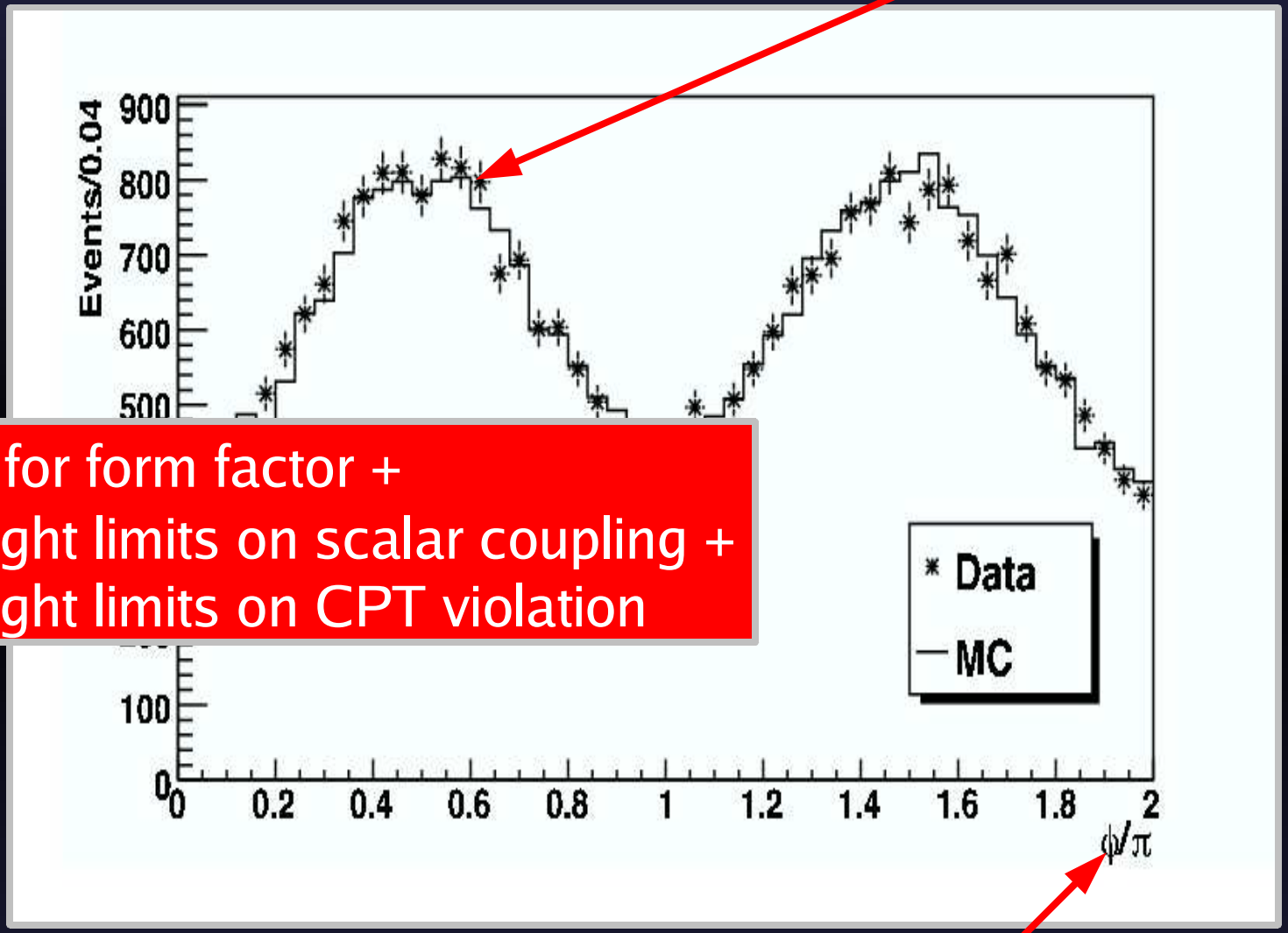

Also fit for form factor +
place tight limits on scalar coupling +
place tight limits on CPT violation

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Conclusions

- KTeV has produced new results on $K_L \to \pi^0 ee\gamma$ and $K_L \to \pi^0\gamma\gamma$
  - $K_L \to \pi^0 ee$ is predominantly CP violating
- KTeV has produced new limits on Lepton Flavor Violation
- KTeV has produced overwhelming proof that the π^0 is a pseudoscalar
- KTeV is still active.....

KTeV's Status

- Just produced final (and most precise) measurement of Re(e'/e) + study of dipion rescattering – see Rick's talk after the break
- Forthcoming results:
  - Search for Direct CPV in $K_{L,S} \to \pi^+\pi^-\gamma$
  - Search for $K_L \to \pi^0\pi^0\mu^+\mu^-$
  - Search for $K_L \to \pi^0\mu^+\mu^-$ (with full dataset)

Extra Slides

LFV normalization modes

- $K_L \to \pi 0 \mu e$: $K_L \to \pi^+ \pi^- \pi^0$
- $K_L \to \pi^0 \pi^0 \mu e$: $K_L \to \pi^0 \pi^0 \pi^0{}_D$
- $\pi^0 \to \mu e$: $K_L \to \pi^0 \pi^0 \pi^0{}_D$
- Include 2% systematic due to muon trigger

References

$K_L \to \pi^0\gamma\gamma$ + $K_L \to \pi^0 ee\gamma$

- Excellent tests of χPT
  - No free parameters in branching ratio to $O(p^4)$
  - $O(p^6)$ terms include Vector Meson exchange terms (strength of which is described by A_V)
    - O(p6) terms increase branching ratios by factor of 2-3

Phys Rev D56 1605 (1997)

Nuclear Phys B492: 417 (1997)

Phys Rev D66:074006 (2002)

Also see references in arXiv:0805.0031 and arXiv:0706.4074

$K_L \to \pi^0\gamma\gamma$

See full paper @ arXiv:0805.0031

- Result:
  - $Br(K_L \to \pi^0\gamma\gamma) = (1.29 \pm 0.03_{stat} \pm 0.05_{syst}) \times 10^{-6}$
  - Compare to NA48: $(1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \times 10\text{-}6$
- This uses the full KTeV dataset, and with better modeling of the $K_L \to \pi^0\pi^0\pi^0$ background, supersedes our older result

Phys Letters B536 229 (2002)

$K_L \to \pi^0 e^+ e^- \gamma$

- Normalize using $K_L \to \pi^0\pi^0{}_D$
  - Same final state as signal
- Final result:
  - $Br(K_L \to \pi^0 e^+ e^- \gamma) = (1.62 \pm 0.14_{stat} \pm 0.09_{syst}) \times 10^{-8}$
  - Obsolete value of Br(K… eV result.
  - χPT to 0(p6) predicts 1.51×10^{-8}
- This mode won't contribute much background to $K_L \to \pi^0 ee$
  - Distribution of $M_{\pi 0ee}$ peaks well away from M_K

See full paper @ arXiv:0706.4074

Phys Rev D56 1605 (1997), but using different value of A_V (see above reference)

Extracting A_V

- $K_L \rightarrow \pi^0\gamma\gamma$
- Maximum likelihood fit to the two Dalitz parameters:
  - $Z_{Dalitz}=m_{34}^2/M_K^2$
  - $Y_{Dalitz}=(E_{\gamma 3}-E_{\gamma 4})/M_K$

Model described in
Nuclear Physics B492 417 (1997)

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  - $Z_{Dalitz} = M_{ee\gamma}^2/M_K^2$
  - $Y_{Dalitz} = (E_\gamma-E_{ee})/M_K$
  - $Q_{Dalitz} =M_{ee}^2/M_K^2$

Results for A_V

- $K_L \rightarrow \pi^0\gamma\gamma$
- $A_V = -0.31 \pm 0.05_{stat} \pm 0.07_{syst}$
- Compare to:
  - NA48 value: $-0.46 \pm 0.03_{stat} \pm 0.04_{syst}$

- $K_L \rightarrow \pi^0 ee\gamma$
- $A_V = -0.76 \pm 0.16_{stat} \pm 0.07_{syst}$

LFV: All modes

- Full details of regarding all modes can be found in:
  - arXiv: 0711. 3472

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

- Previous evidence of parity of π^0 not as strong as one would think
  - Evidence is either indirect.....
  - Or direct, but significant to 3.6 σ, and 46 years old Phys Rev 126,1844 (1962)
  - Plane of e+e- pair in $\gamma^* \to e+e-$ reveals polarization of photon
  - Use both Dalitz planes to probe parity of π^0.

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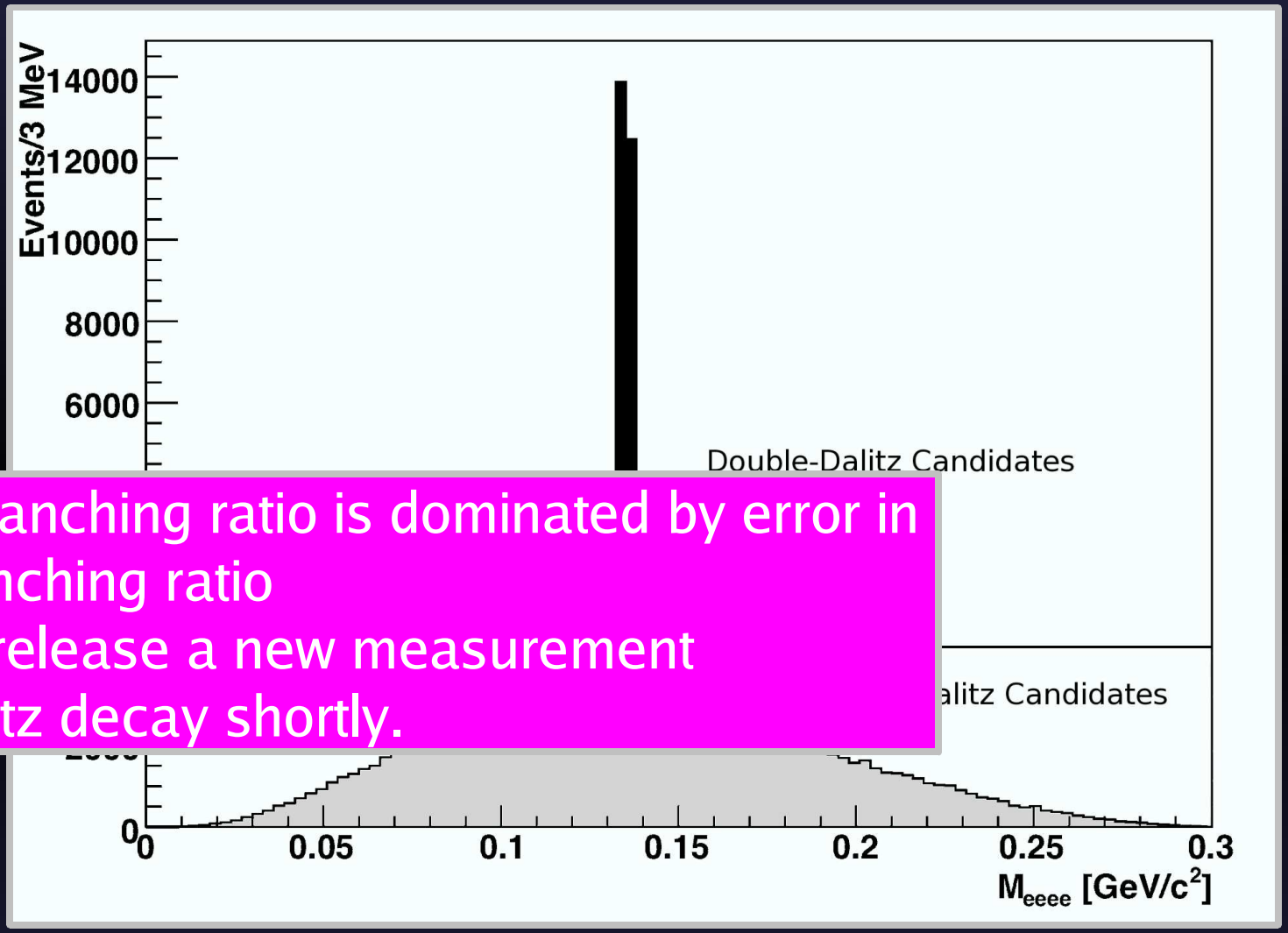
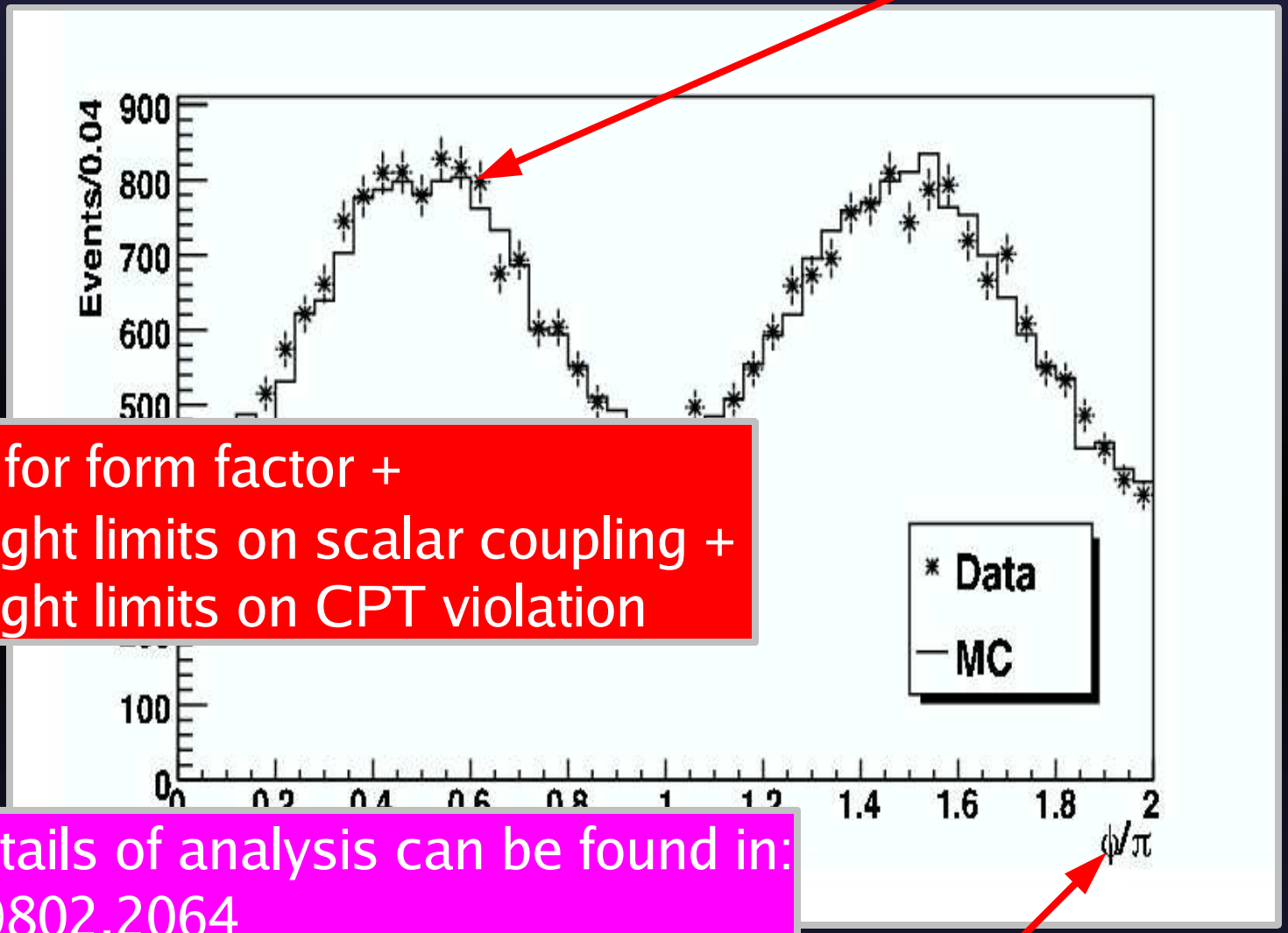


Error in branching ratio is dominated by error in Dalitz branching ratio
KTev will release a new measurement of the Dalitz decay shortly.

Resulting Branching Ratio:
$Br(\pi^0 \to e^+e^-e^+e^-) = (3.26 \pm 0.18) \times 10^{-5}$

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

Dalitz pairs prefer to be orthogonal! Parity =-1



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place tight limits on CPT violation

Full details of analysis can be found in:
arXiv:0802.2064

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