Recent Results From KTeV

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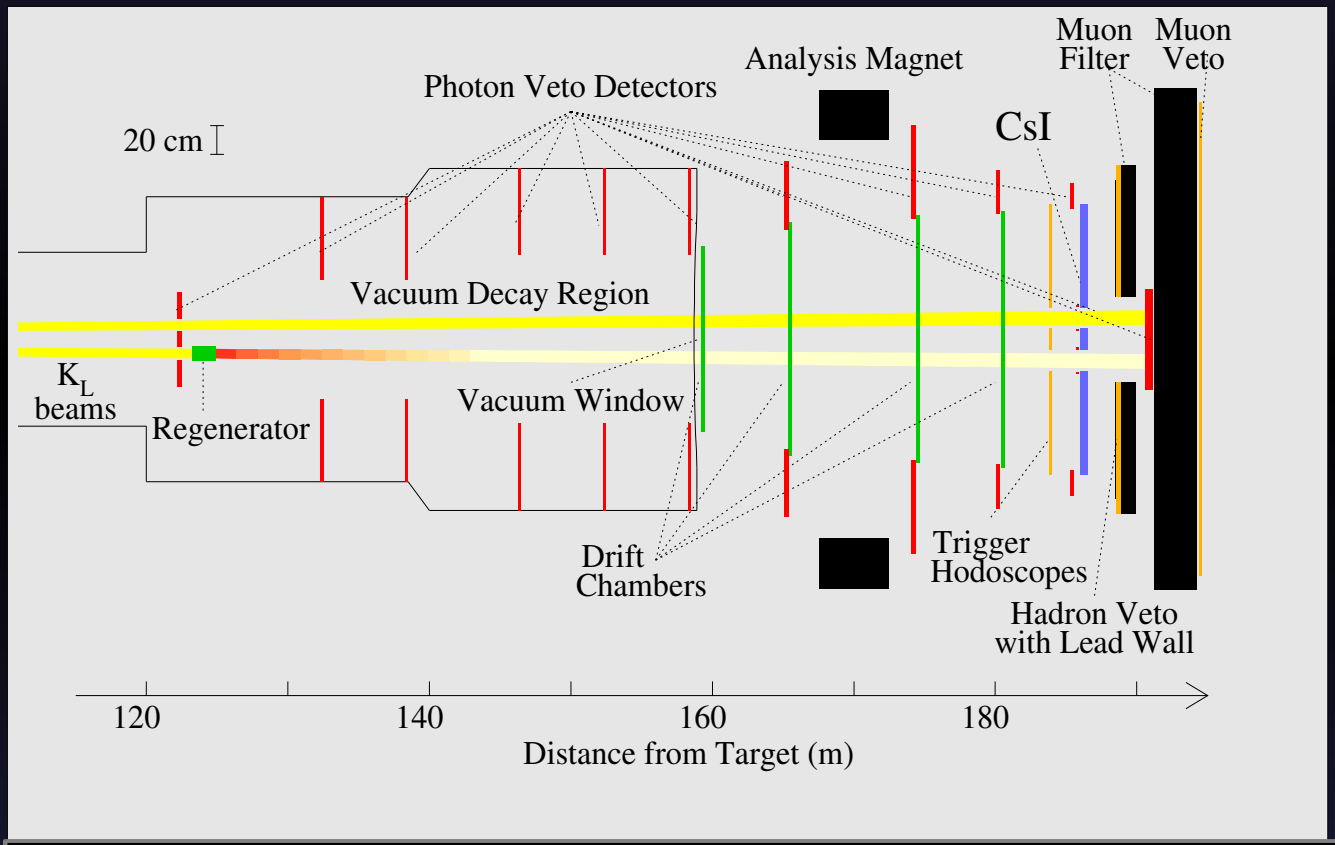
- $K_L \to \pi^+\pi^-\gamma$
- $K_L \to \pi^+\pi^-\gamma^*,\ \gamma^* \to e^+e^-$
- $K_L \to \pi^0\pi^0\gamma$
- $K_L \to \pi^+\pi^-\pi^0\gamma$
- $K_L \to \pi^+\pi^-\pi^0\gamma^*,\ \gamma^* \to e^+e^-$
- $K_L \to \pi^0\pi^0\pi^0\gamma$
- $K_L \to \pi^0\pi^0\pi^0\gamma^*,\ \gamma^* \to e^+e^-$

The KTeV Collaboration

- Universidade Estadual de Campinas
- Universidade de Sao Paulo
- U. Chicago
- U. Colorado
- Osaka University
- U. Wisconsin
- U. Arizona
- UC San Diego
- Elmhurst College
- Fermilab
- UCLA
- Rice
- U. Va.

The KTeV/E832 Detector

Pure K_L "vacuum" beam



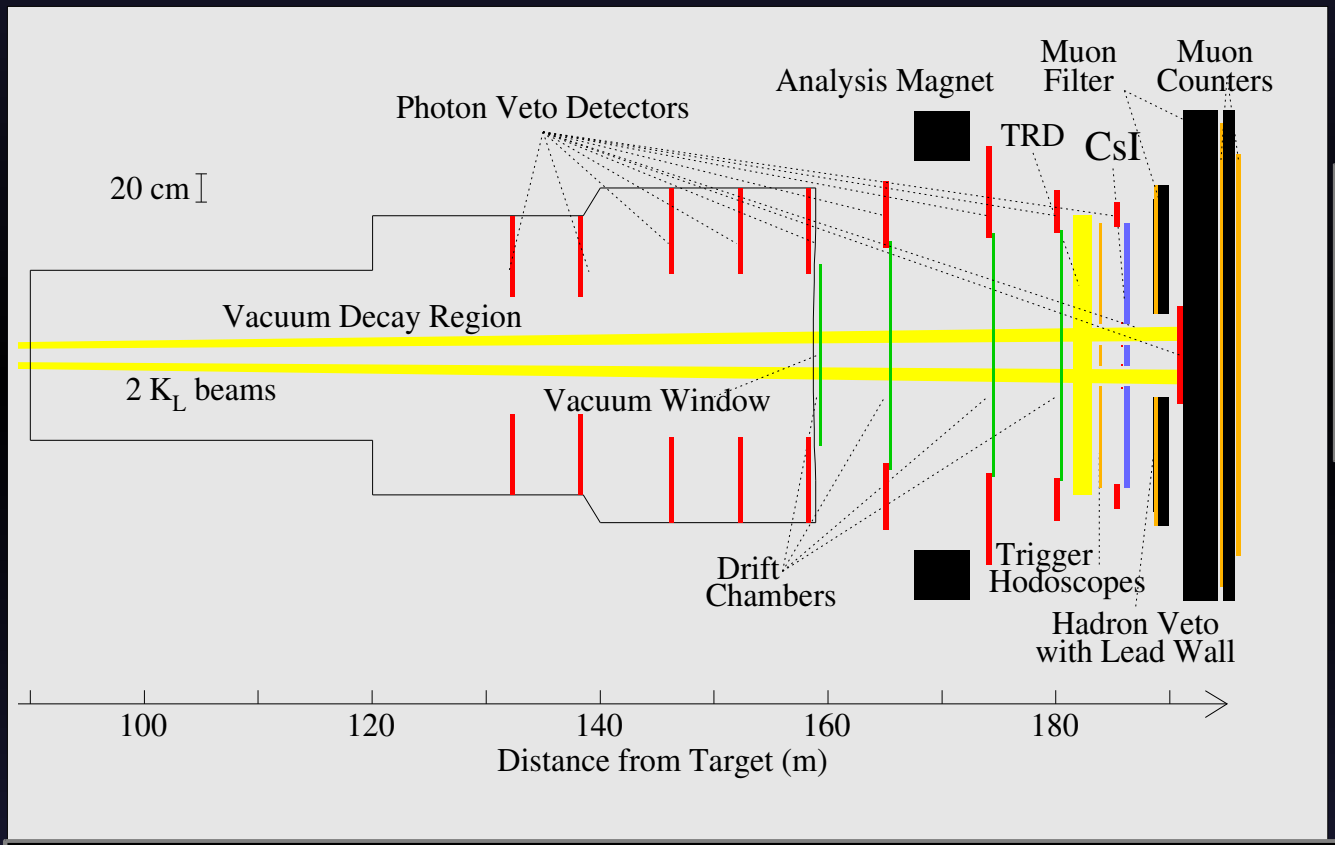
Two Beams

Coherent K_L and K_S "regenerator" beam

Used for measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ in $K \to \pi\pi$

The KTeV/E799 Detector

Two Beams: BOTH are pure K_L "vacuum" beam

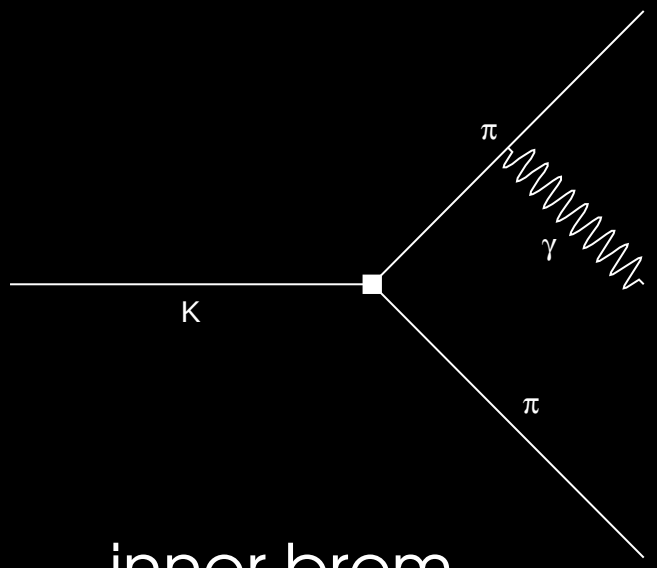


E799 adds a Transition Radiation Detector for π/e discrimination.

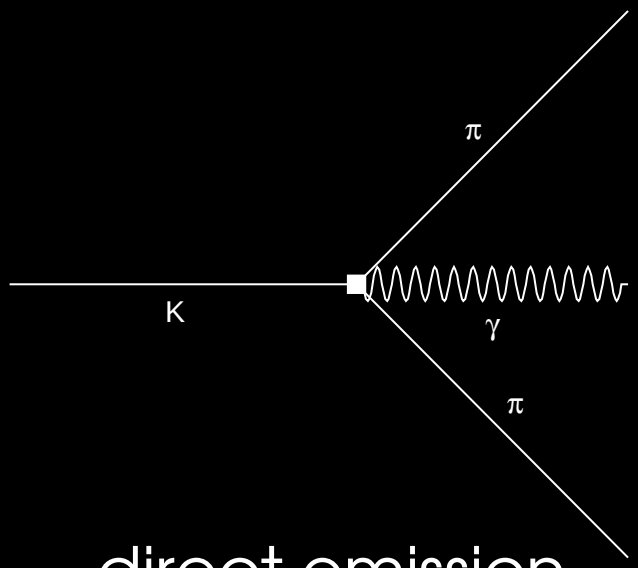
Higher Intensity beams used for rare kaon decay searches and studies

$K_L \to N\pi\gamma,\ N\pi\gamma^*$

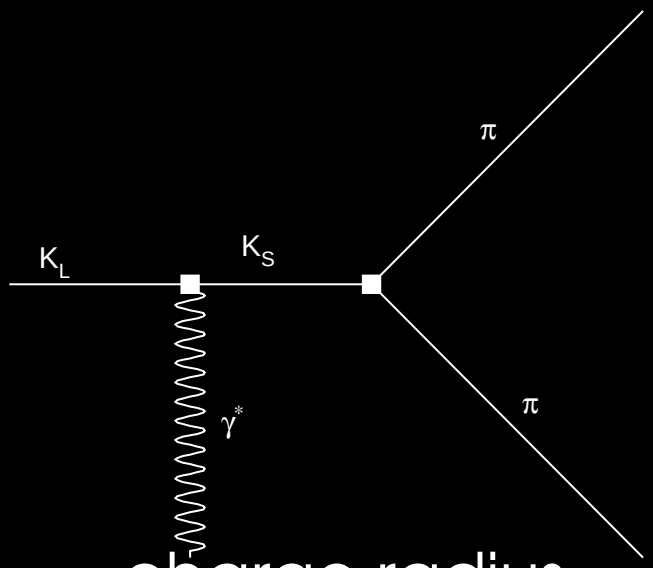
- These decays exhibit multiple sources of photon emission:
- inner bremsstrahlung: charged modes only



inner brem



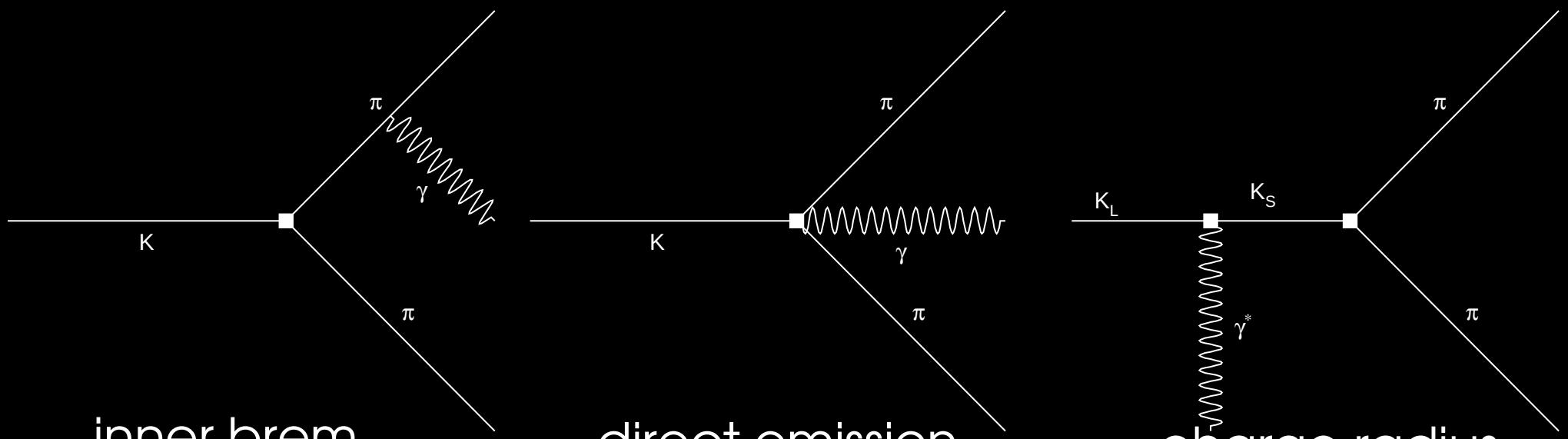
direct emission



charge radius

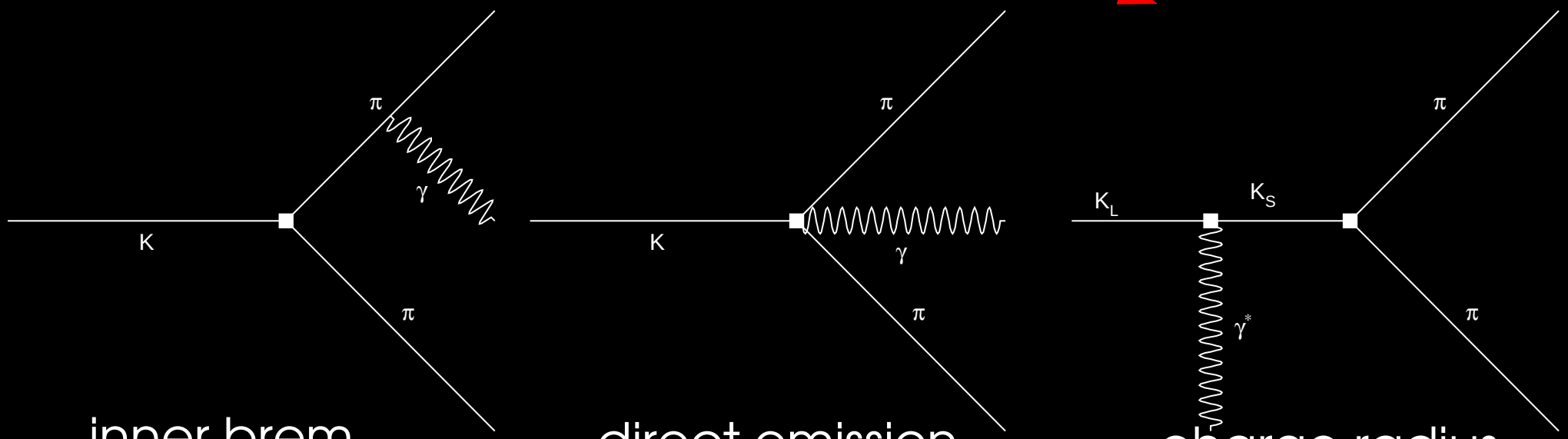
$K_L \rightarrow N\pi\gamma^{(*)}$

- These decays exhibit multiple sources of photon emission:
- direct emission: all modes
  - M1,E1,M2,E2 ... multipole terms possible



$K_L \rightarrow N\pi\gamma^{(*)}$

- These decays exhibit multiple sources of photon emission.
- charge radius: virtual photon modes only



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

- M1 DE is lowest order term, IB and E1 DE violate CP
- Must include energy dependence in M1 amplitude:

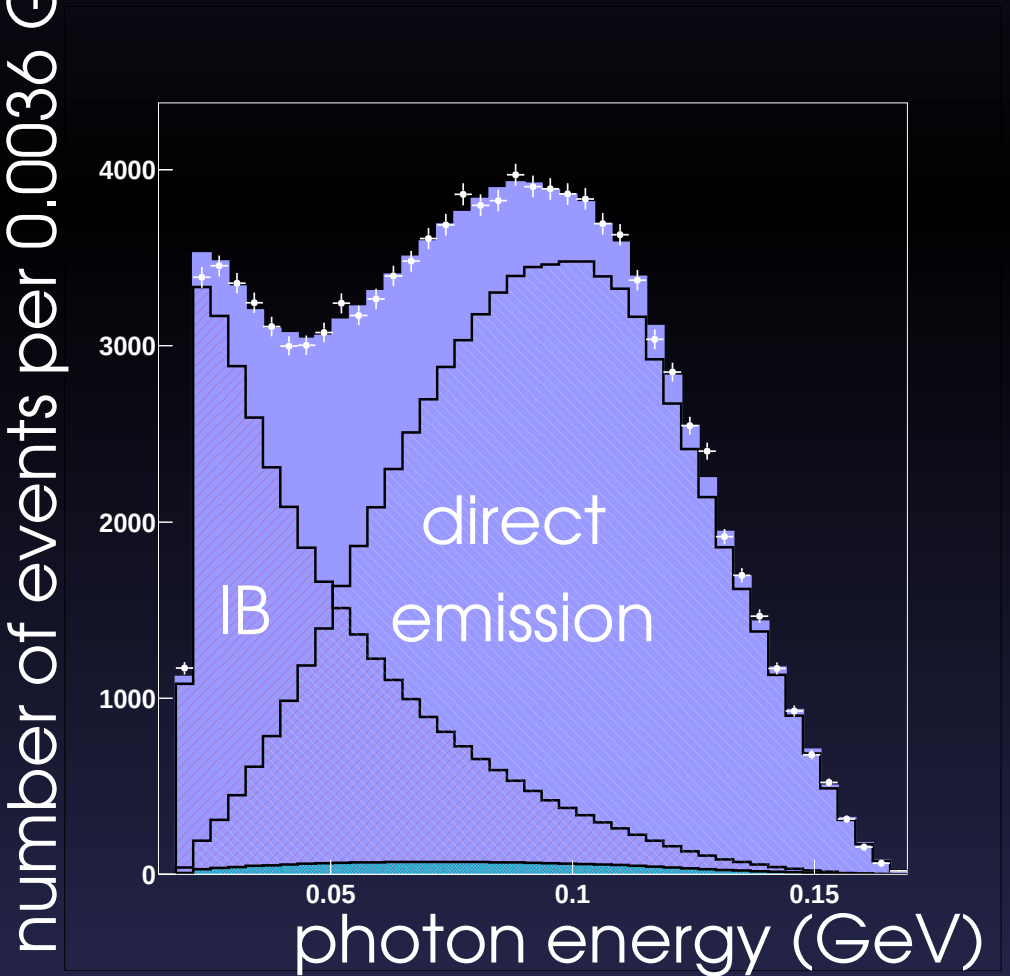
$$M(K_L) = i\, g_{M1} \left| \frac{a_1/a_2}{M_\rho^2 - M_K^2 + 2E_\gamma M_K} + 1 \right| e^{i\delta_1}$$

- Fit data using above amplitude, float variables in yellow.

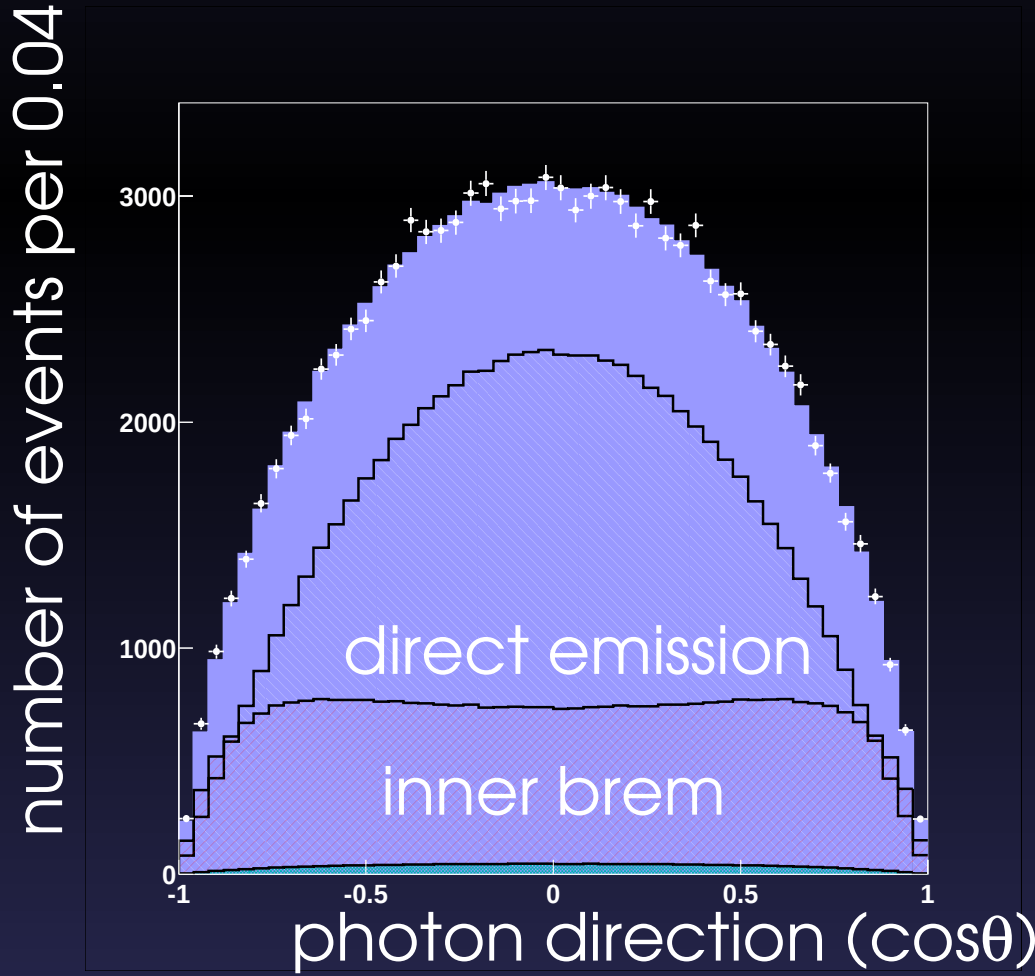
$K_L \to \pi^+\pi^-\gamma$

- A likelihood fit was made to the ~111.4K events after all cuts

$\chi^2_{DOF} = 85.8/85$

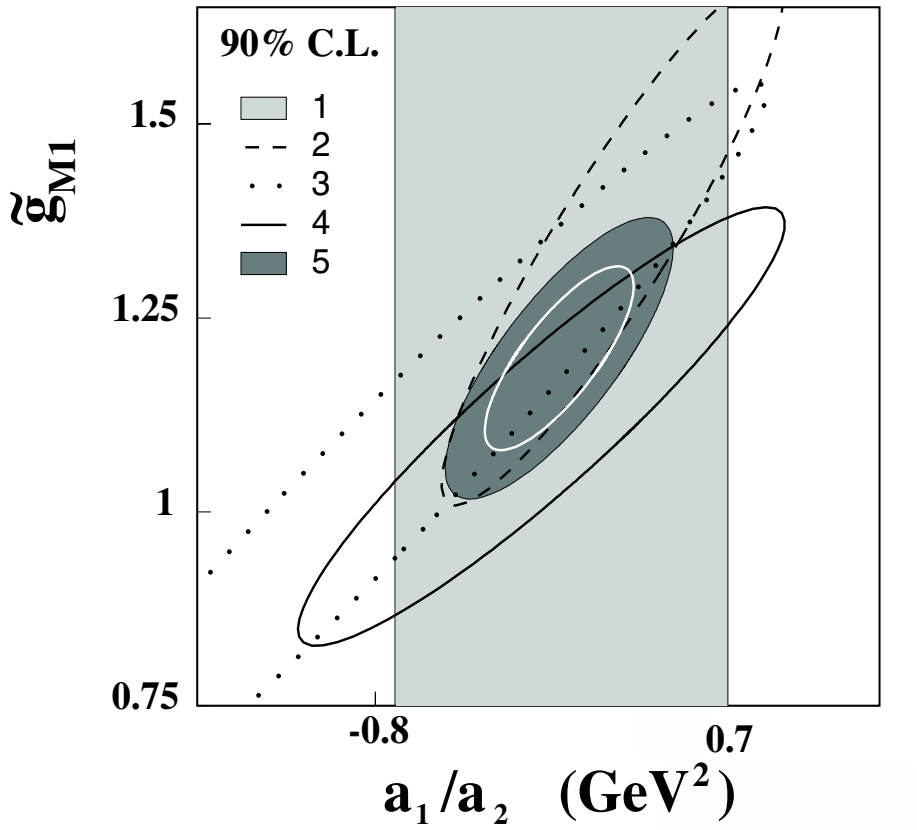


$\chi^2_{DOF} = 118.0/99$



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

- Parameters for CP conserving M1 direct emission



- Legend:
  - 1) 96 KTeV $K_L \rightarrow \pi^+\pi^-\gamma$
  - 2) 97 KTeV $K_L \rightarrow \pi^+\pi^-e^+e^-$
  - 3) NA48 $K_L \rightarrow \pi^+\pi^-e^+e^-$
  - 4) 97+99 KTeV $K_L \rightarrow \pi^+\pi^-e^+e^-$
  - 5) This result:
    - g_{M1} = 1.198
    - a_1/a_2 = -0.738

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

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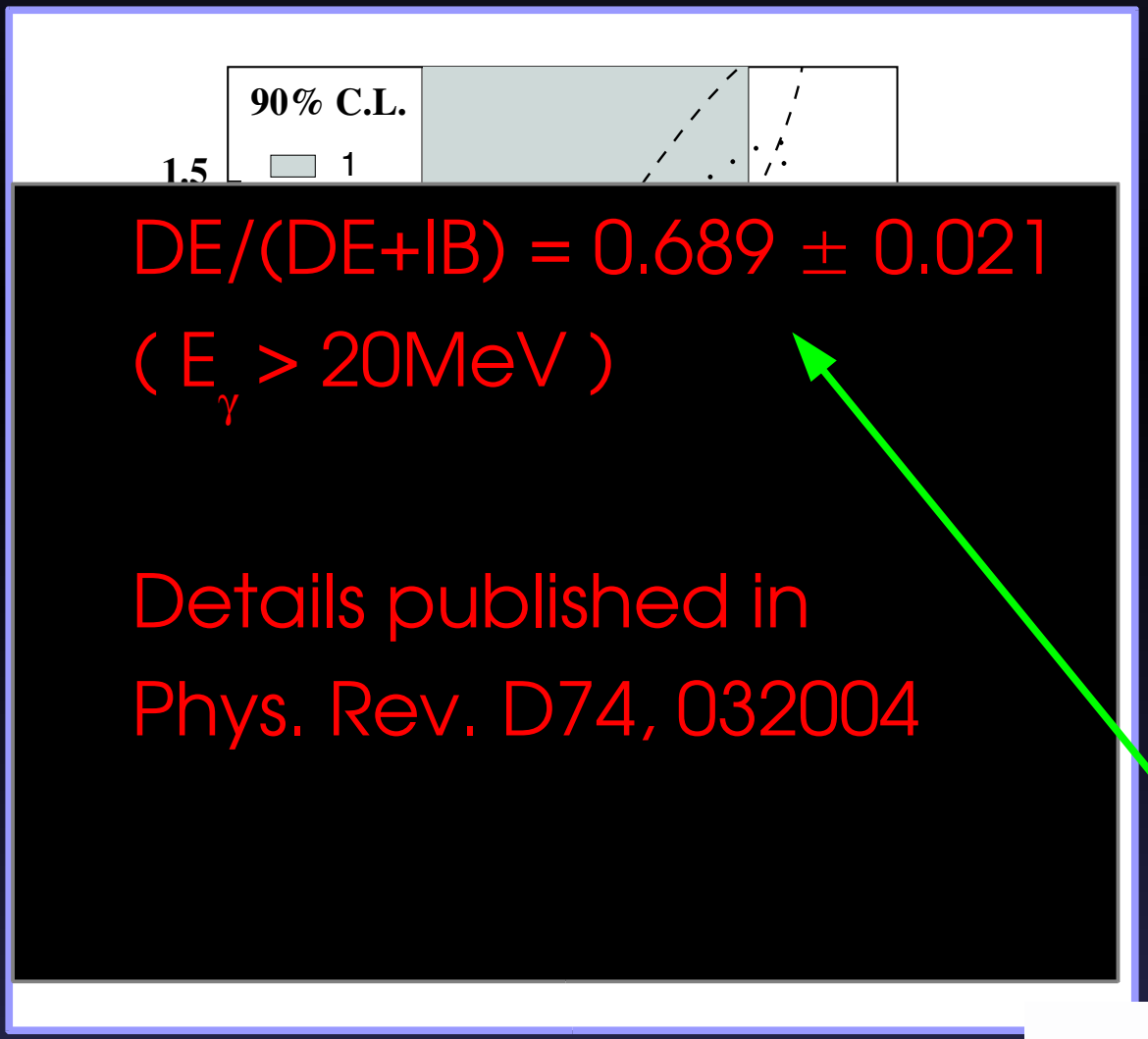

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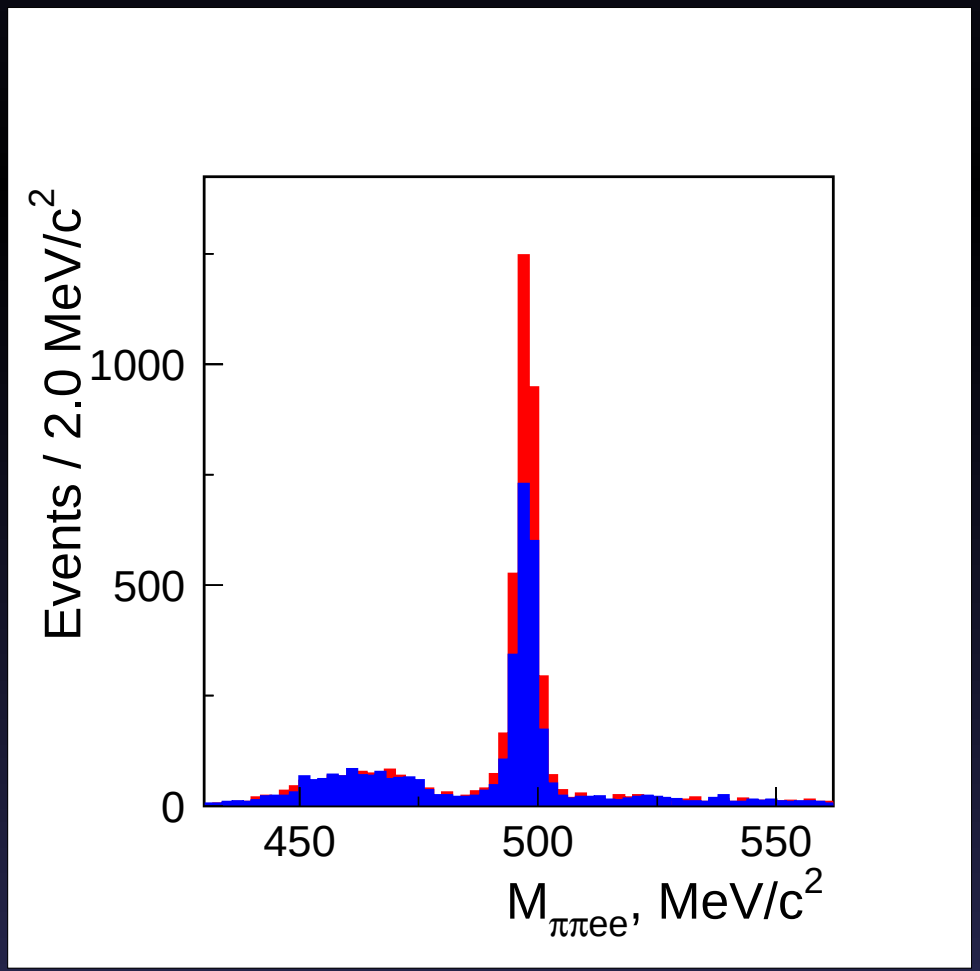
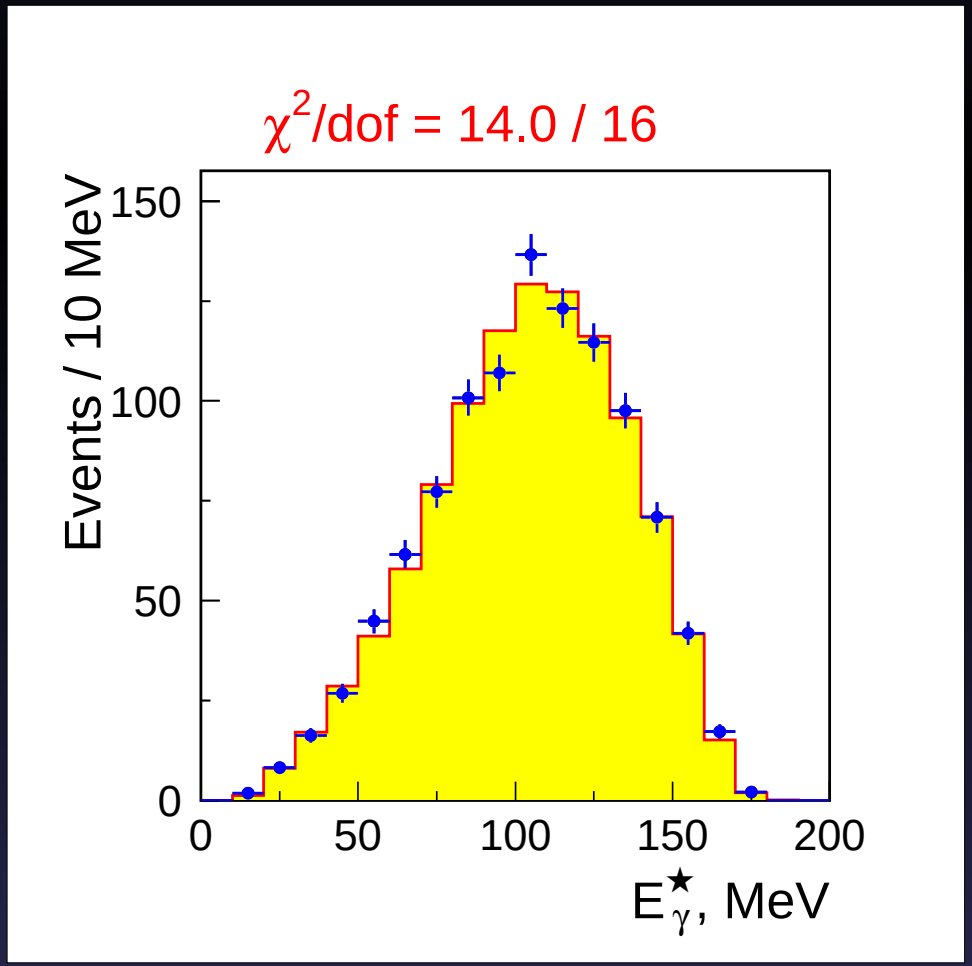
$K_L \rightarrow \pi^+\pi^-e^+e^-$

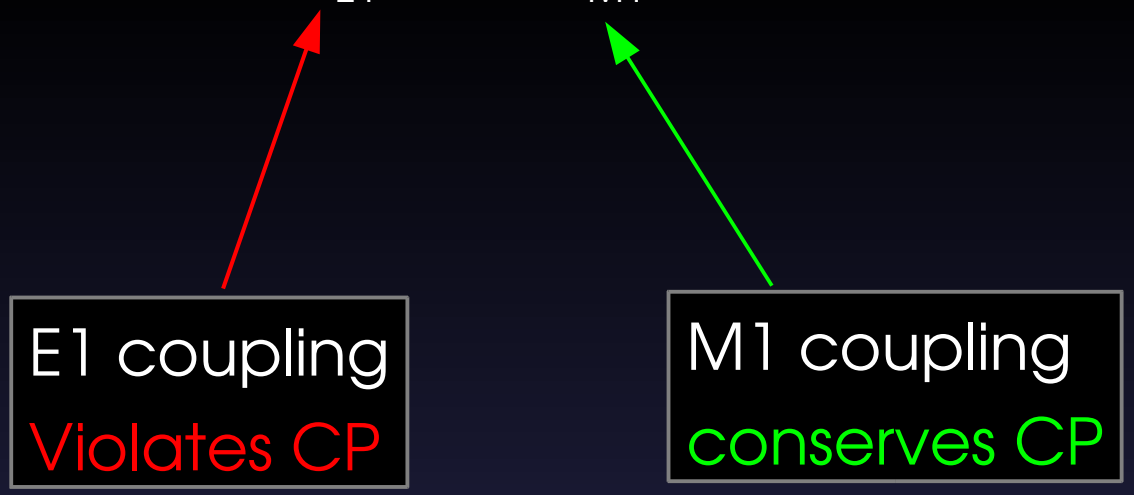
- Similar to $K_L \rightarrow \pi^+\pi^-\gamma$, but with a virtual photon emitted.
- Over 5000 events after all cuts……





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

- In $K_L \rightarrow \pi^+\pi^-e^+e^-$, unlike in $K_L \rightarrow \pi^+\pi^-\gamma$, M1 and E1 amplitudes interfere with each other, resulting in better sensitivity to the CP violating E1 direct emission process:
  - $|g_{E1}| / |g_{M1}| < 0.04$ (90% C.L.)



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

- There is another process that can contribute, namely the charge radius process, in which K_L -> K_S γ^*
  - g_{CR} = 0.163 ± 0.014(stat) ± 0.023(syst)

    charge radius coupling
  - leads to.....
  - $\langle r^2_{K0} \rangle$ = (-0.077 ± 0.007 ± 0.011) fm^2

    K0 charge radius

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charge radius coupling

  - leads to.....

Details published in PRL 96, 101801

  - $\langle r^2_{K0} \rangle$ = (-0.077 ± 0.007 ± 0.011) fm^2

K0 charge radius

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

- This decay probes higher order terms in the multipole expansion compared to $K_L \rightarrow \pi^+\pi^-\gamma^{(*)}$
  - With a real photon and no charged particles, this decay should be dominated by the E2 direct emission process
  - Bose statistics, combined with gauge invariance rule out the possibility of M1 or E1 terms

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

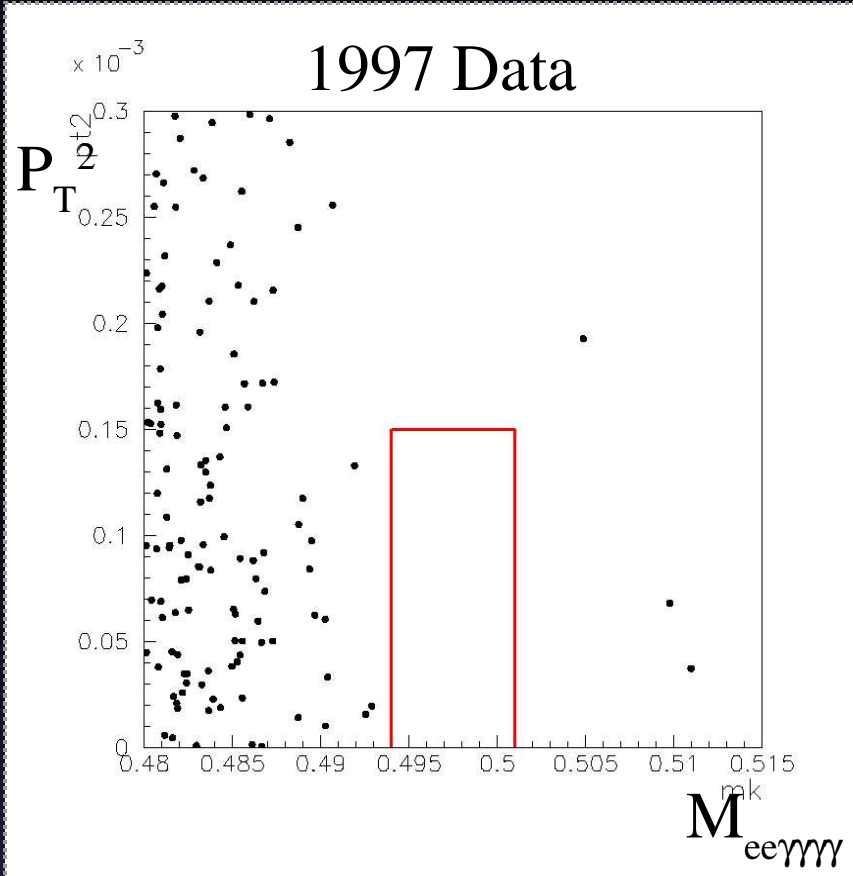
- This process vanishes at $O(p^4)$ in ChPT, so it is a probe of $O(p^6)$
  - Nuclear Phyiscs B396:53
- Current theoretical estimates of branching ratio:
  - $Br(K_L \rightarrow \pi^0\pi^0\gamma) < 1 \times 10^{-8}$ Physics Letters B307,182
  - $Br(K_L \rightarrow \pi^0\pi^0\gamma) < 7 \times 10^{-11}$ Nuclear Physics B413,321
    - $O(p^6)$ estimate

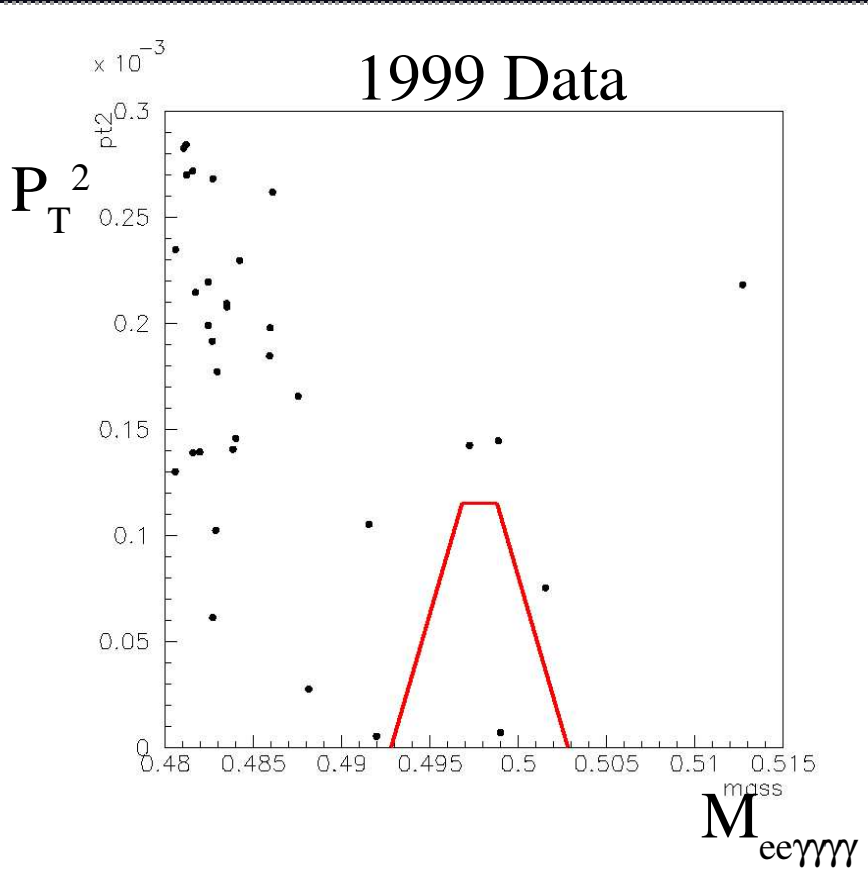
$K_L \rightarrow \pi^0\pi^0\gamma$

- Search for events with a Dalitz decay, i.e. $K_L \rightarrow \pi^0\pi^0{}_D\gamma$, $\pi^0{}_D \rightarrow e^+e^-\gamma$
- Normalization mode is $K_L \rightarrow \pi^0\pi^0\pi^0{}_D$, with one photon lost down the calorimeter's beam holes.

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

- For the entire KTeV E799 dataset, one event is seen in the signal region after all cuts.





Result for $K_L \rightarrow \pi^0\pi^0\gamma$

- Use unified confidence belt method to determine final result.
  - Phys Rev D57,3873
- Method indicates that we must quote an upper limit, which leads to:

  $Br(K_L \rightarrow \pi^0\pi^0\gamma) < 2.32 \times 10^{-7}$ (90% C.L.)

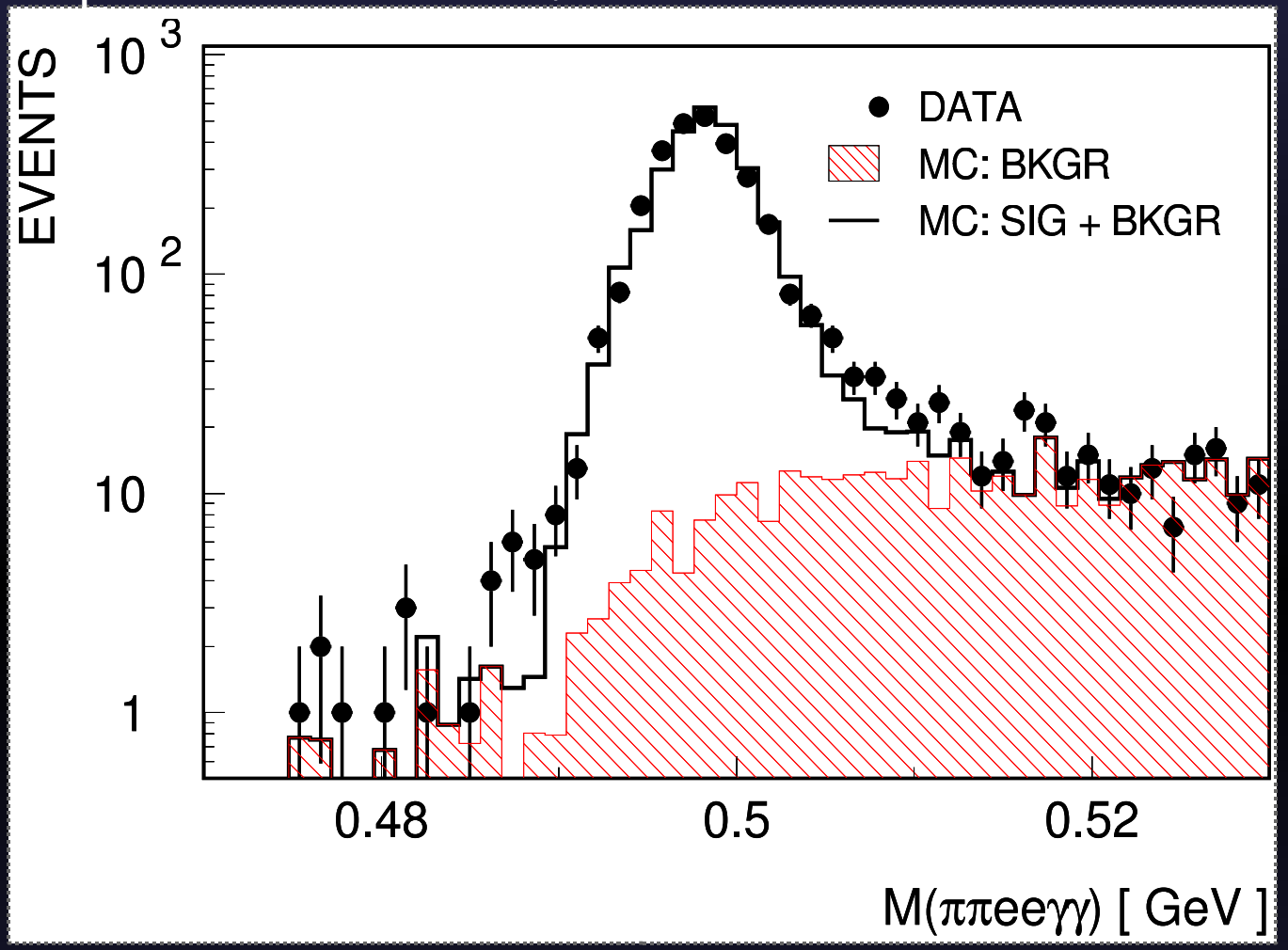
  PRELIMINARY :1997+1999 DATA

$K_L \rightarrow \pi\pi\pi\gamma^{(*)}$

- The analysis of $K_L \rightarrow \pi^+\pi^-e^+e^-$ displayed an example of the charge radius transition $K_L \rightarrow K_S\ \gamma^*$, where $K_S \rightarrow \pi^+\pi^-$ and $\gamma^* \rightarrow e^+e^-$
- Does the transition $K_L \rightarrow K_L\ \gamma^*$ exist?
- Look for common K_L decays accompanied by a e^+e^- pair.
  - $K_L \rightarrow \pi\pi\pi$ accounts for ~31% of the K_L's width.
  - Look for $K_L \rightarrow \pi^+\pi^-\pi^0\gamma^{(*)}$ and $K_L \rightarrow \pi^0\pi^0\pi^0\gamma^{(*)}$

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

- Result with 40% of KTeV E799 data
- 2847 candidate events
- Using $\pi^0 \rightarrow e^+e^-\gamma$



- Br($K_L \rightarrow \pi^+\pi^-\pi^0\gamma$, E_γ^{CM} >10MeV) =
  - Measured : Not ready yet
  - Theory : (1.65 ± 0.03) x 10^{-4} (Z. PHYS. C 76,301)

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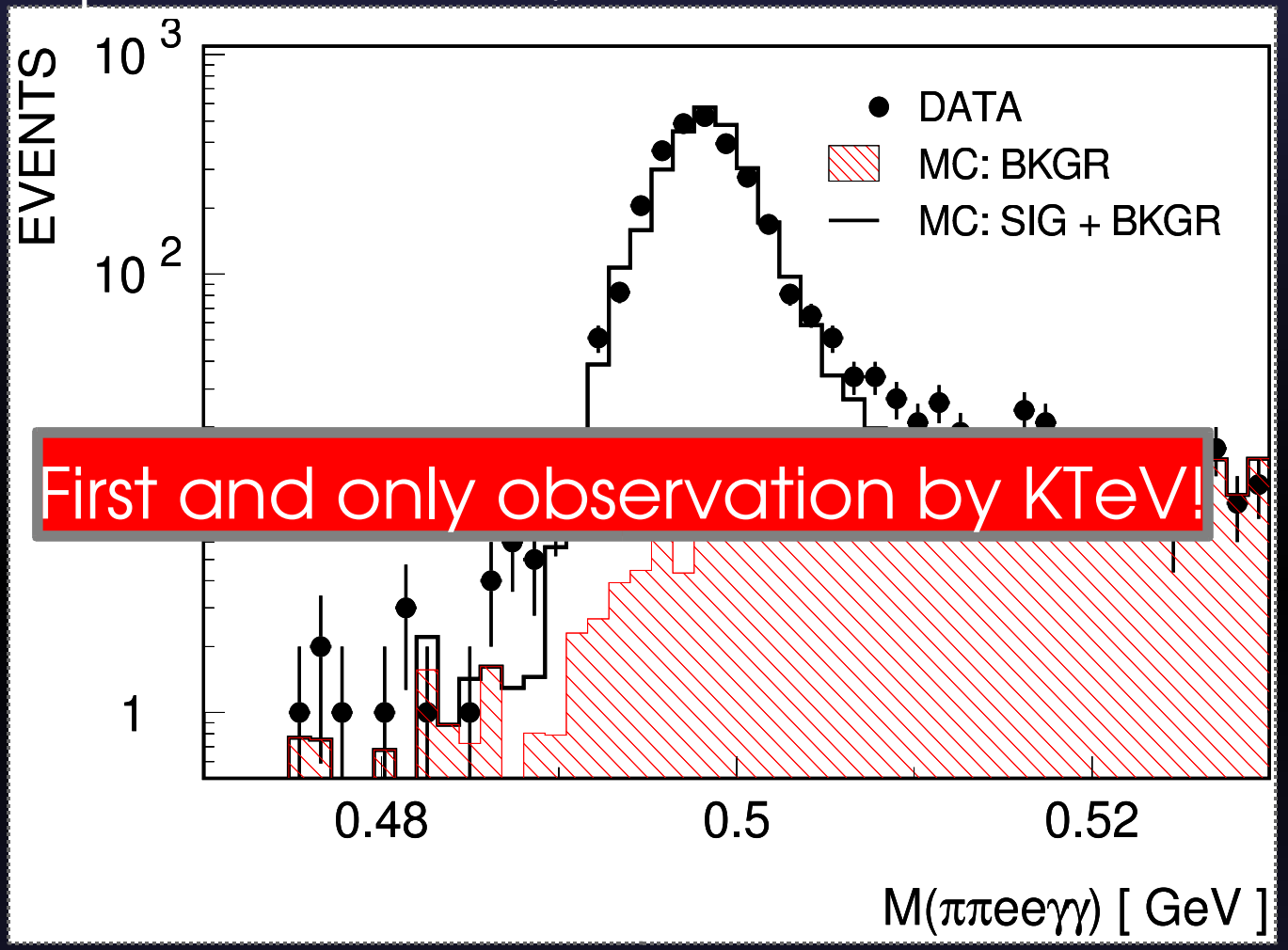

- $Br(K_L \rightarrow \pi^+\pi^-\pi^0\gamma, E_\gamma^{CM} > 10MeV)$ =
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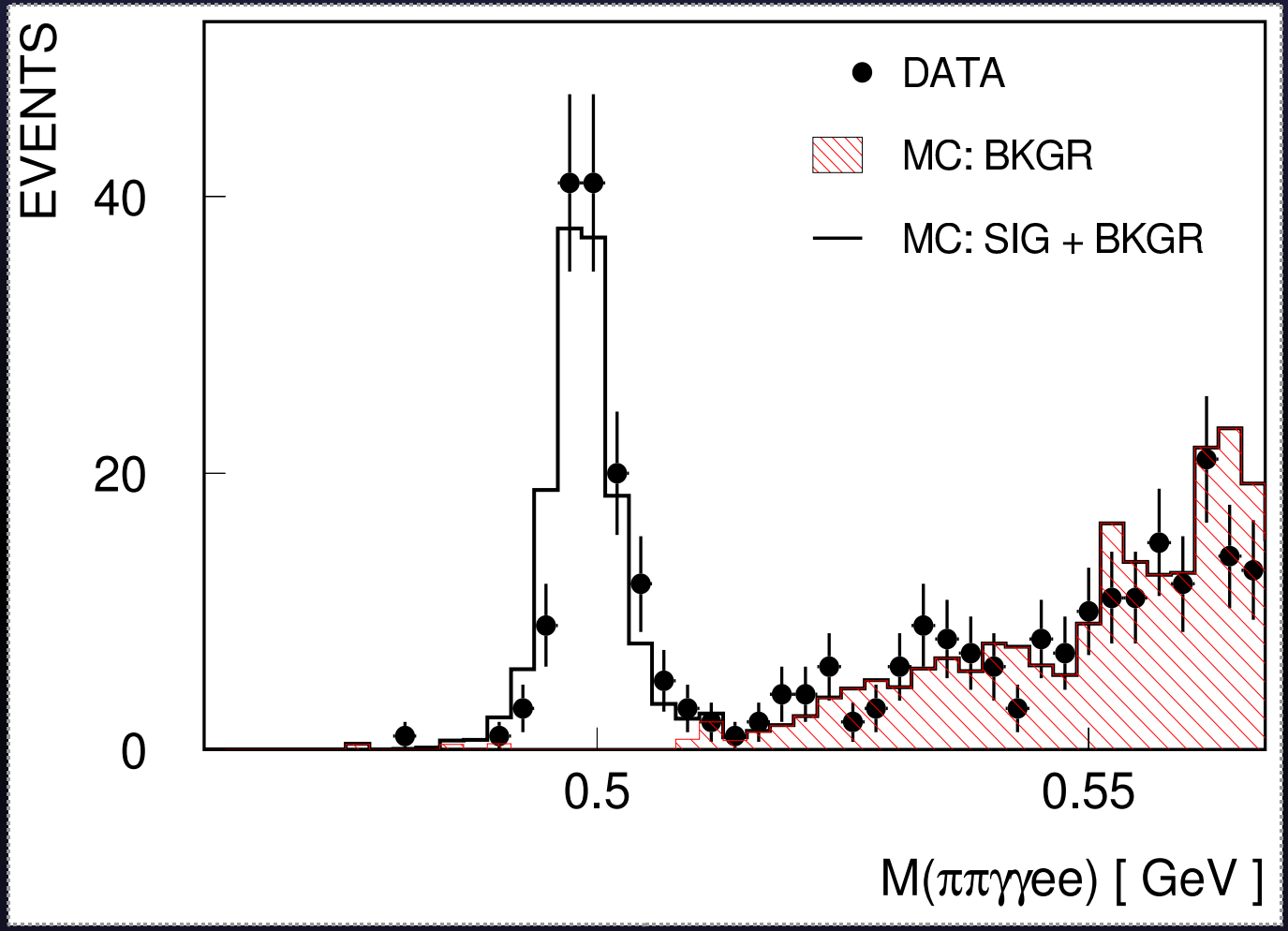
$K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-$

- Using 40% of KTeV E799 data
- 132 candidates
- ***PRELIMINARY!***

No Theory On This Mode!



- $Br(K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-, E^{CM}_{\gamma} > 20MeV) =$
  - Measured: $(1.60 \pm 0.18(stat) \pm ??) \times 10^{-7}$

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

- Using 40% of KTeV E799 data
- 132 candidates
- ***PRELIMINARY!***

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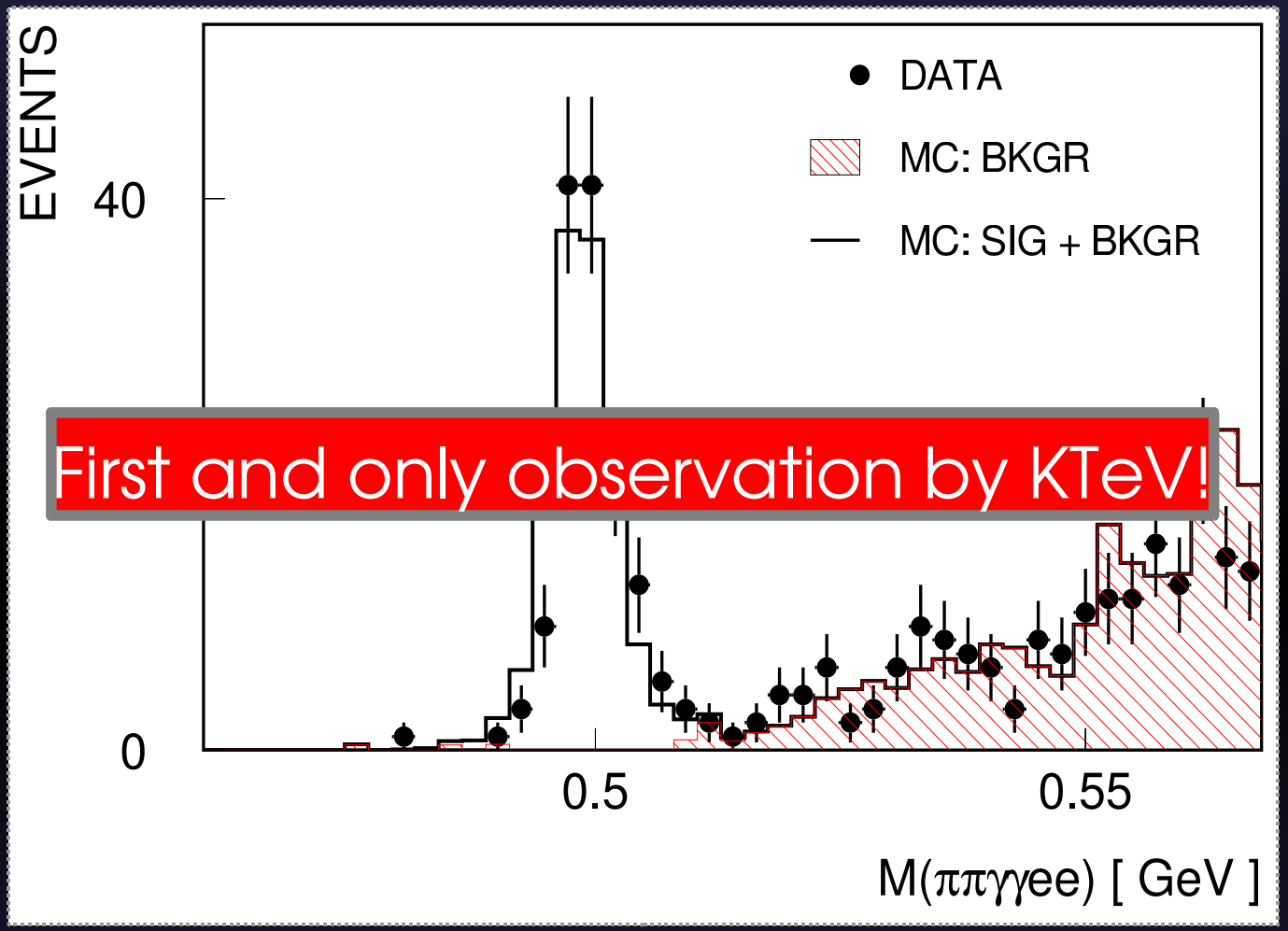
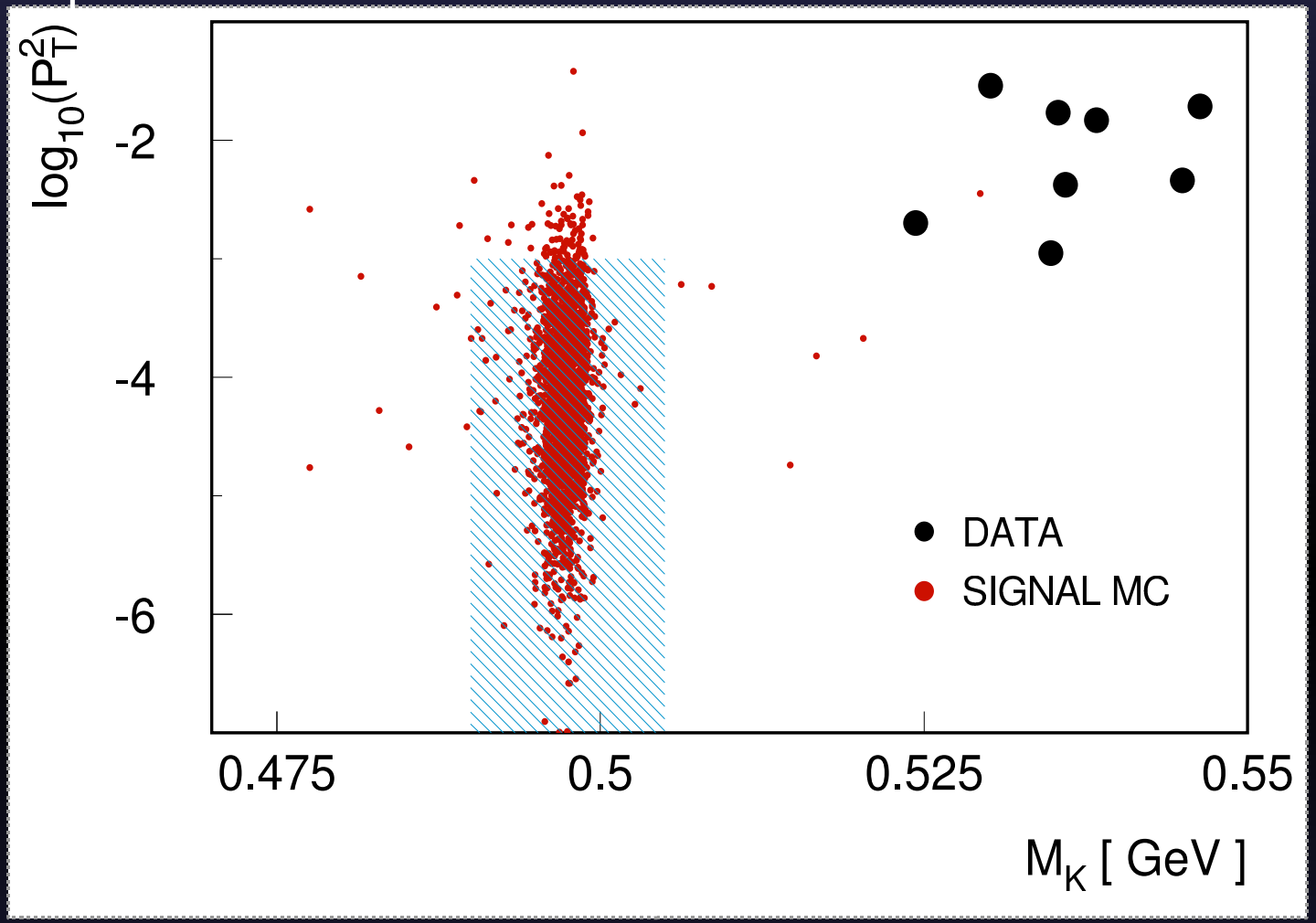


- $Br(K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-, E^{CM}_{\gamma} > 20MeV) =$
  - Measured: $(1.60 \pm 0.18(stat) \pm ??) \times 10^{-7}$

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

- Results with full KTeV E799 data

No Theory For This Mode!



- No events seen
- First experimental study, will have to use phase space in order to produce limit on branching ratio

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

- Analysis still in progress
- Will use $\pi^0 \rightarrow e^+e^-\gamma$
- Have the same situation as $K_L \rightarrow \pi^0\pi^0\pi^0e^+e^-$
  - Can only produce phase space limit
- Only direct emission process should contribute.

Bottom Line For $K_L \to \pi\pi\pi\gamma^{(*)}$

- Once the branching ratios have been measured, the form factors for the observed modes can be explored.
- $K_L \to \pi^0\pi^0\pi^0\gamma^{(*)}$ must be due to direct emission and charge radius transitions
- The lack of theoretical work on most of these modes limits us to quoting results based on phase space.

Ongoing Work by KTeV

- Final value for Re(ε'/ε)
- $K_{L,S} \rightarrow \pi^+\pi^-\gamma$ direct CP violation search
- $K_L \rightarrow \pi e \nu e^+e^-$ branching ratio
- $K_L \rightarrow \pi^0 ee\gamma$, $\pi^0\gamma\gamma$ branching ratio
- $K_L \rightarrow \pi^0\pi^0\pi^0$ form factor
- $K_L \rightarrow e^+e^-\gamma$ branching fraction and FF
- $\pi^0 \rightarrow e^+e^-\gamma$ branching fraction
- $K_L \rightarrow \pi^0\pi^0\mu e$, $\pi^0\mu e$ and $\pi^0 \rightarrow \mu e$ limits
- $K_L \rightarrow \pi^0\pi^0\mu\mu$ search

Conclusions

- New branching ratio limit for

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

- New FF measurements for

$$K_L \to \pi^+\pi^-\gamma \text{ , } K_L \to \pi^+\pi^-e^+e^-$$

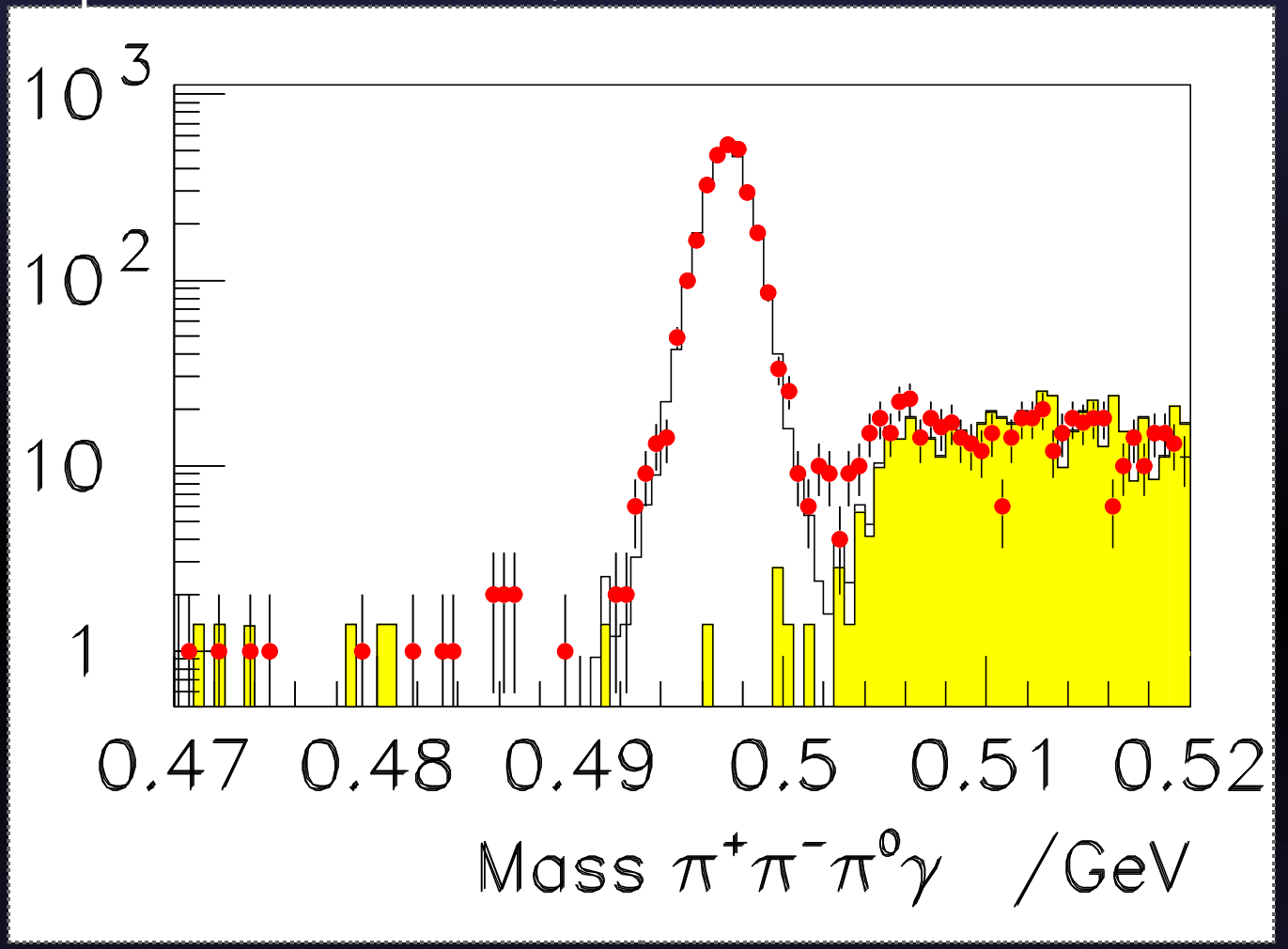
- First Observations/Limits :

$$K_L \to \pi^+\pi^-\pi^0\gamma \text{ , } K_L \to \pi^+\pi^-\pi^0 ee \text{, } K_L \to \pi^0\pi^0\pi^0 ee$$

Extra Slides

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

- Result from KTeV E832 data
- 2853 candidates
- ***PRELIMINARY !***



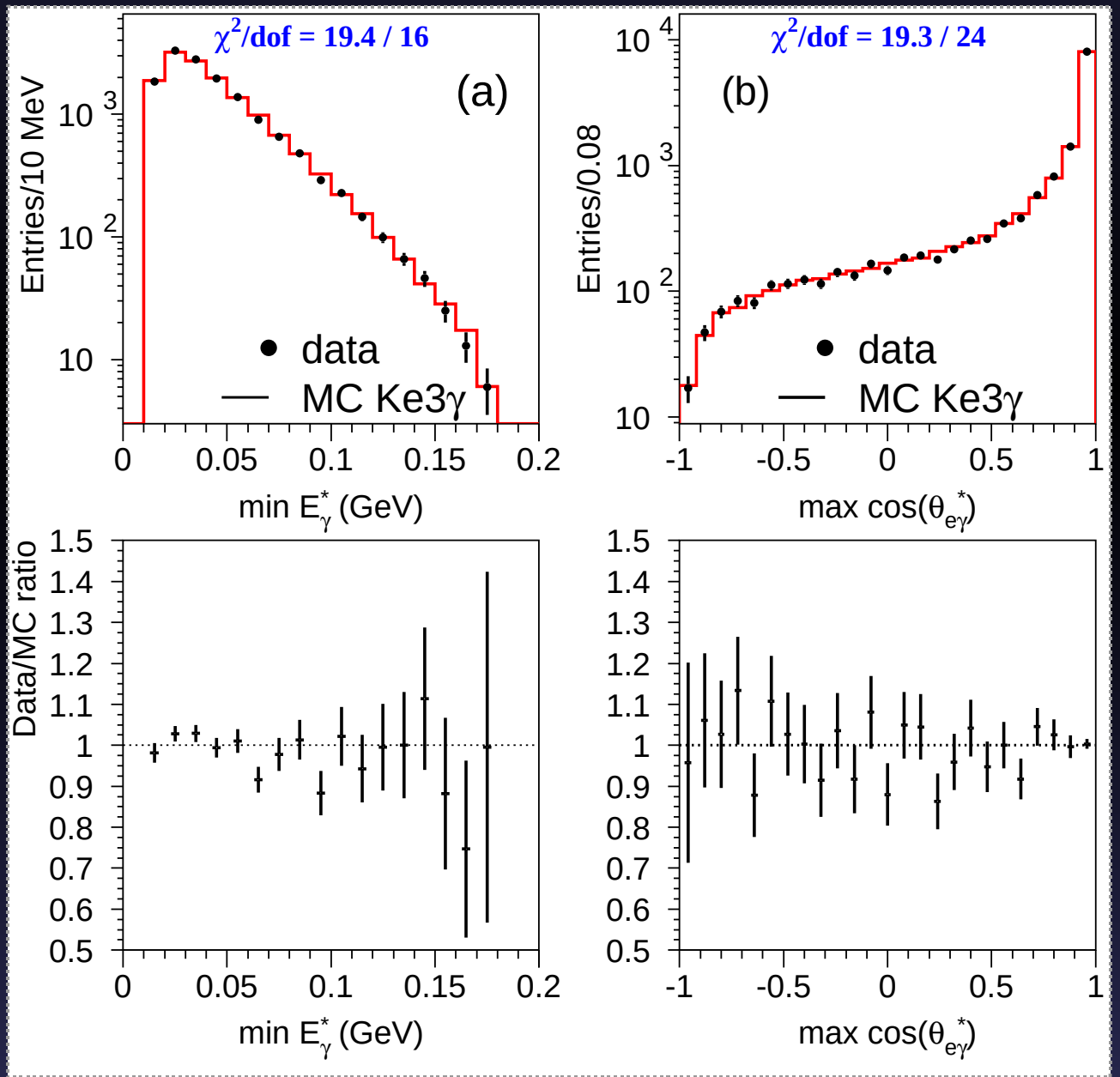
- $Br(K_L \rightarrow \pi^+\pi^-\pi^0\gamma, E_\gamma^{CM} > 10MeV) =$
  - Measured : $(1.66 \pm 0.03 \pm 0.03 \pm 0.03) \times 10^{-4}$
  - Theory : $(1.65 \pm 0.03) \times 10^{-4}$ (Z. PHYS. C 76,301)

Radiative Semileptonic Decays

- Radiative modes were studied in order to correct the semileptonic branching ratios used to determine V_{US}.
- Troy Andre's KLOR program was used to generate events with full first order corrections.
  - KLOR (hep-ph 0406006) can be found at http://kpasa.fnal.gov:8080/public/pubs/ktev/klor/klor.tar.gz

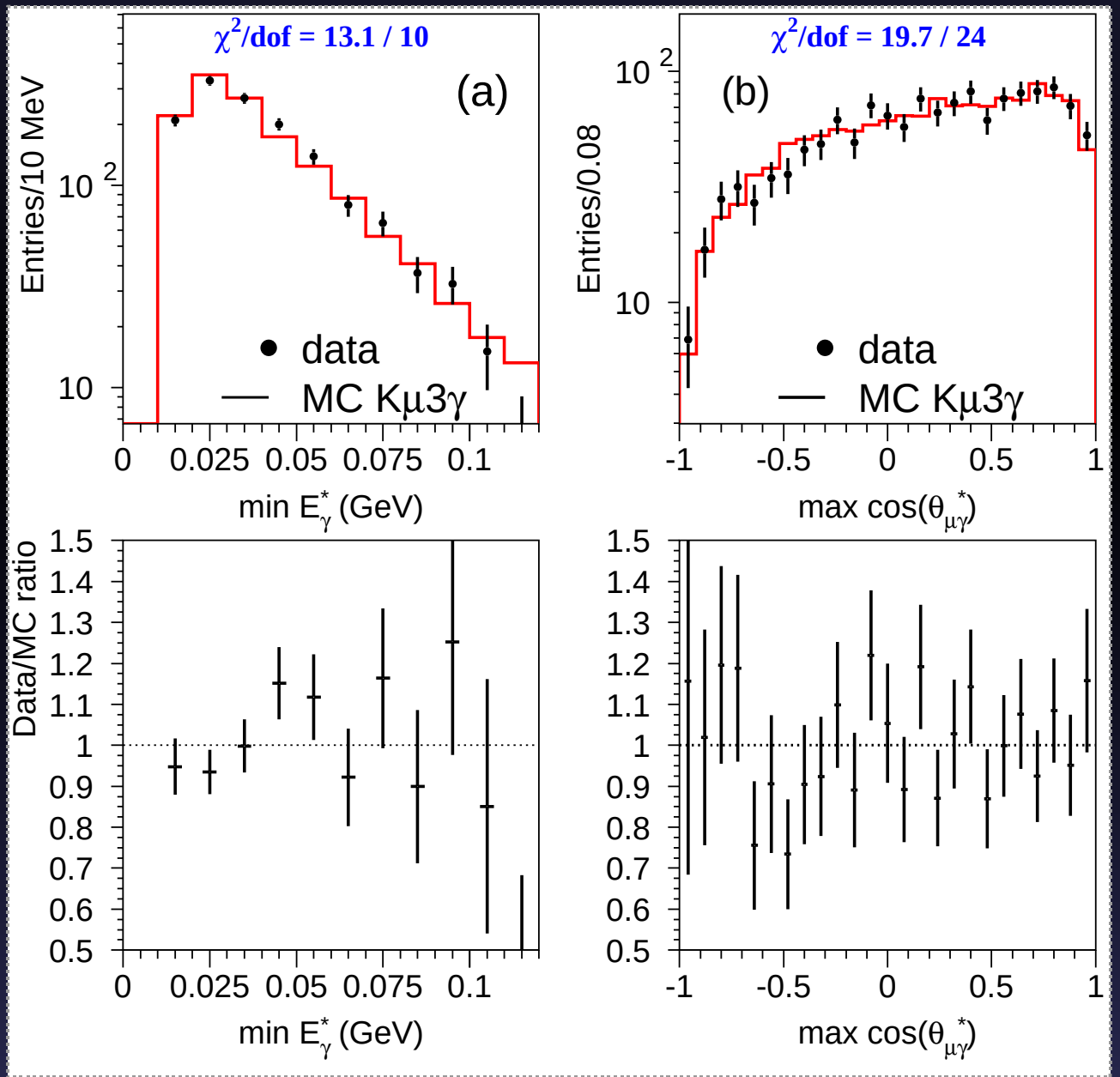
$K_L \to \pi e \nu \gamma$

$$\frac{\Gamma\left(K_L \to \pi e \nu \gamma ; E_\gamma > 10\,MeV\right)}{\Gamma\left(K_L \to \pi e \nu\right)} = (4.942 \pm 0.042 \pm 0.046)\%$$



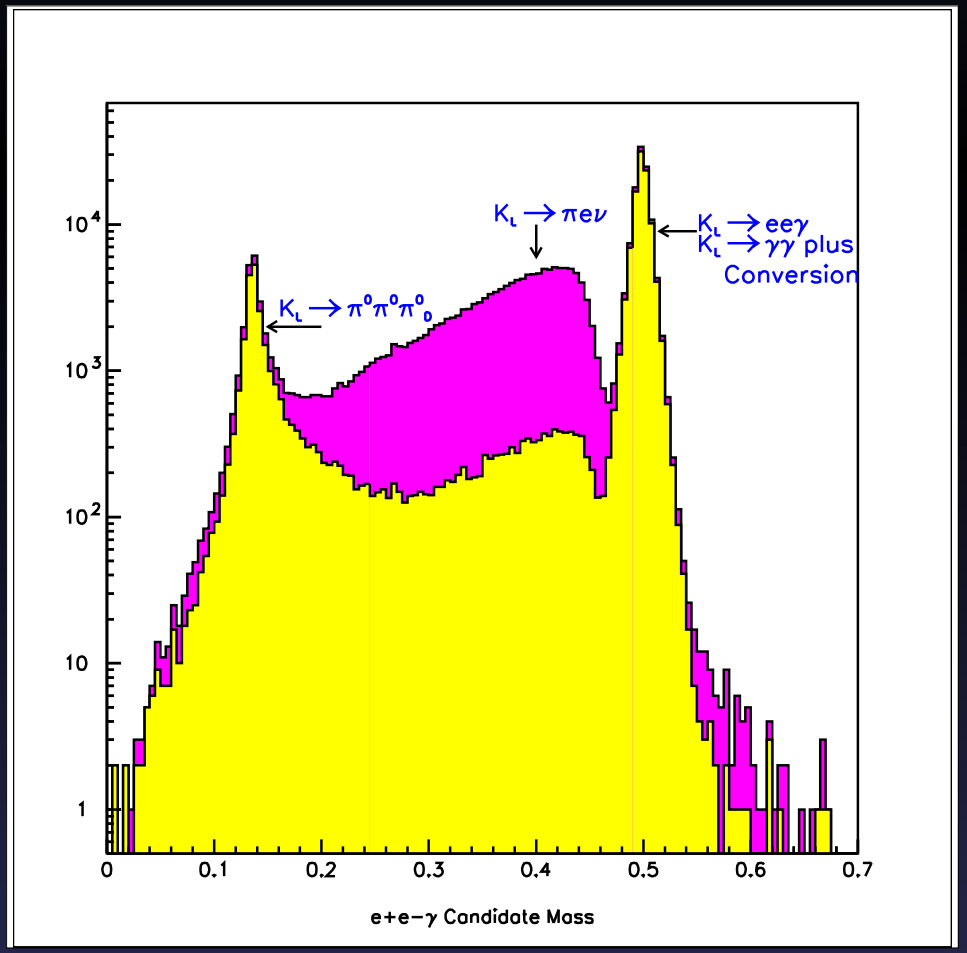
$K_L \to \pi\mu\nu\gamma$

$$\frac{\Gamma\left(K_L \to \pi\,\mu\,\nu\,\gamma\,; E_\gamma > 10\,MeV\right)}{\Gamma\left(K_L \to \pi\,\mu\,\nu\right)} = (0.530 \pm 0.014(stat) \pm 0.012(syst))\%$$



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

- This mode is the final state of $K_L \rightarrow \gamma^*\gamma$
- Allows the form factor for $K_L \rightarrow \gamma\gamma$ to be explored
- Allows test of ChPT to $O(p^6)$ via branching ratio measurements:
  - Phys.Lett. B398:387:
- Allows test of DIP model
  - Phys. Lett. B423:385
- Can also test BMS model
  - Phys. Lett. B131:229



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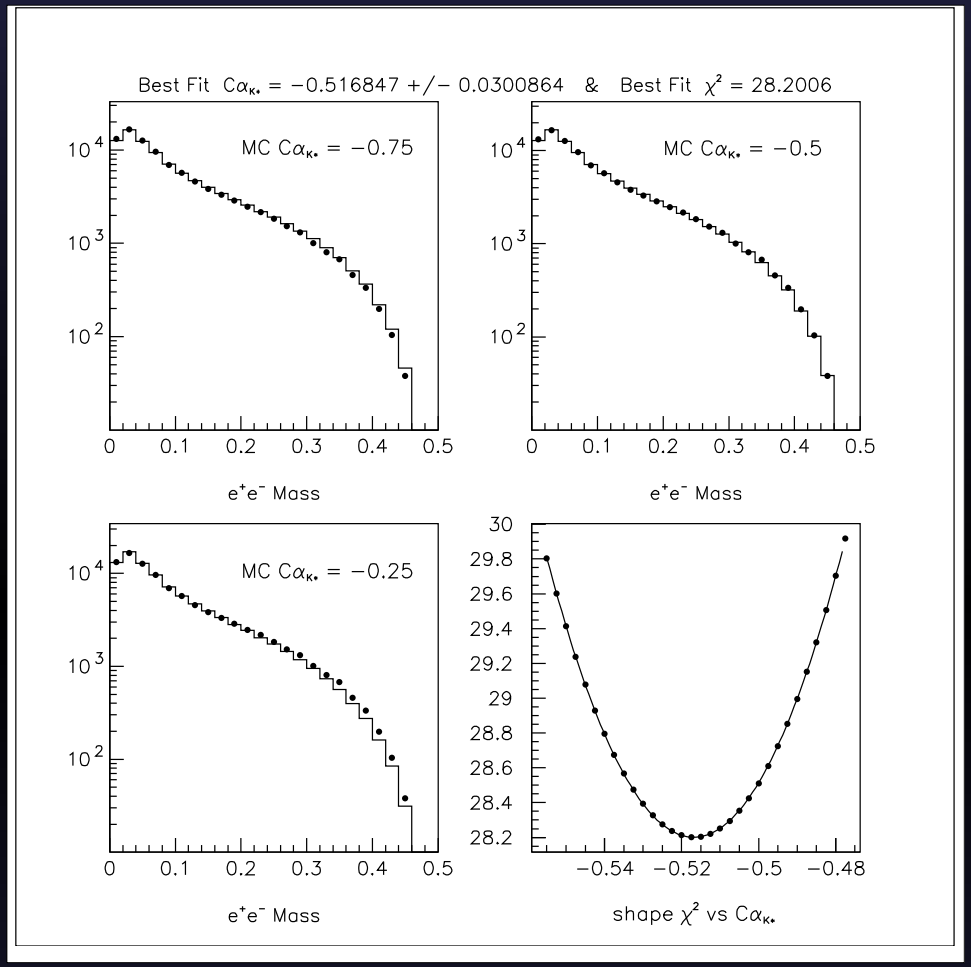
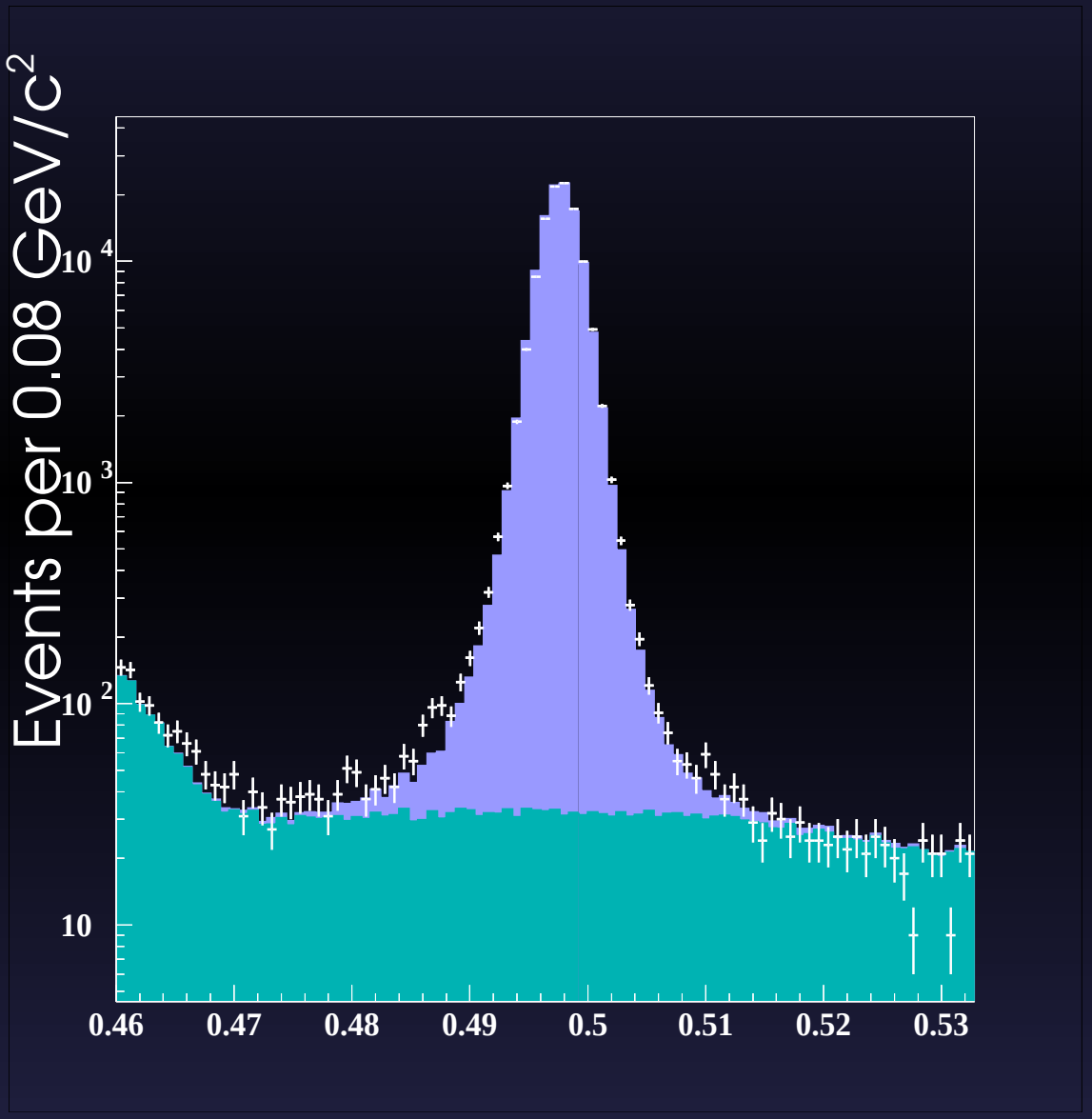


PRELIMINARY

- New Form Factor Results:
  - For BMS model: $C\alpha_{K^*} = -0.517 \pm 0.030(stat) \pm 0.022(syst)$
  - For DIP model: $\alpha_{DIP} = -1.729 \pm 0.043(stat) \pm 0.028(syst)$

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

- 111.4K events after all cuts.
- Background is 0.6%



Model of decay for $K_L \rightarrow \pi^+\pi^-\gamma$

- Three different decay amplitudes contribute to $K_L \rightarrow \pi^+\pi^-\gamma$

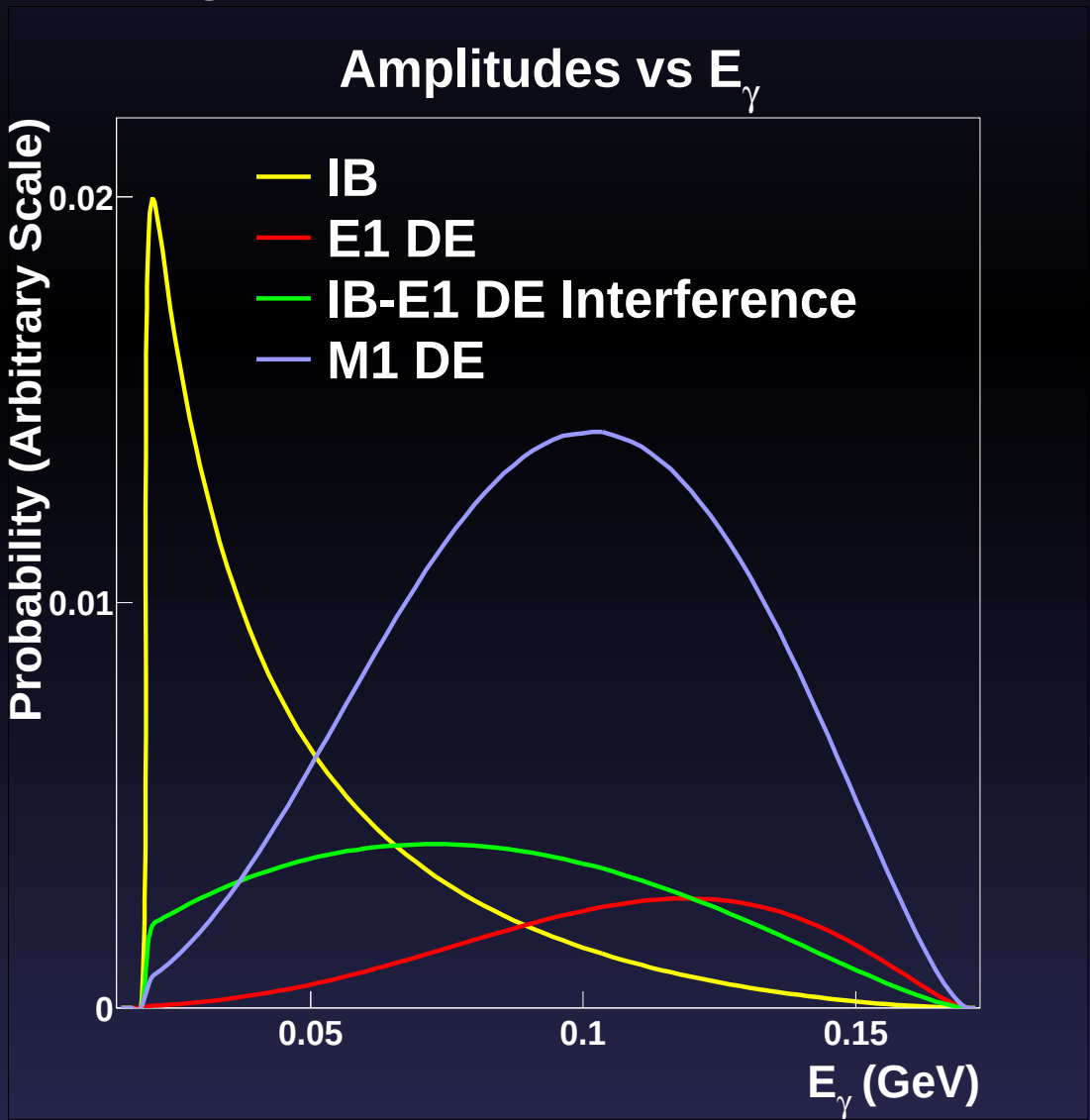
$$E_{IB}\left(K_L\right) = \left| 4\frac{M_K^{\,2}}{E_\gamma^2} \right| \frac{\eta_{+-}\, e^{i\delta_0}}{1-\beta^2\cos^2\left(\theta\right)}$$

$$M_{DE}\left(K_L\right) = i\,\widetilde{g}_{M1} \left| \frac{a_1/a_2}{M_\rho^2 - M_K^2 + 2E_\gamma M_K} + 1 \right| e^{i\delta_1}$$

$$E_{DE}\left(K_L\right) = g_{E1}\, e^{i\left(\delta_1+\phi_\epsilon\right)}$$

Energy Spectrum

- E_γ spectrum dominated by low energy IB photons and high energy M1 DE photons
- Normalization between components is arbitrary



More Results For $K_L \rightarrow \pi^+\pi^-\gamma$

- Determined upper limit for CP violating direct emission:
  - $g_{E1} < 0.21$ (90% Confidence)
  - Sensitivity : 0.078(stat) , 0.117(syst)

References

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