Update on $K_{L,S} \to \pi^+\pi^-\gamma$

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KTeV meeting
May 10th 2008

Outline For Today's Talk

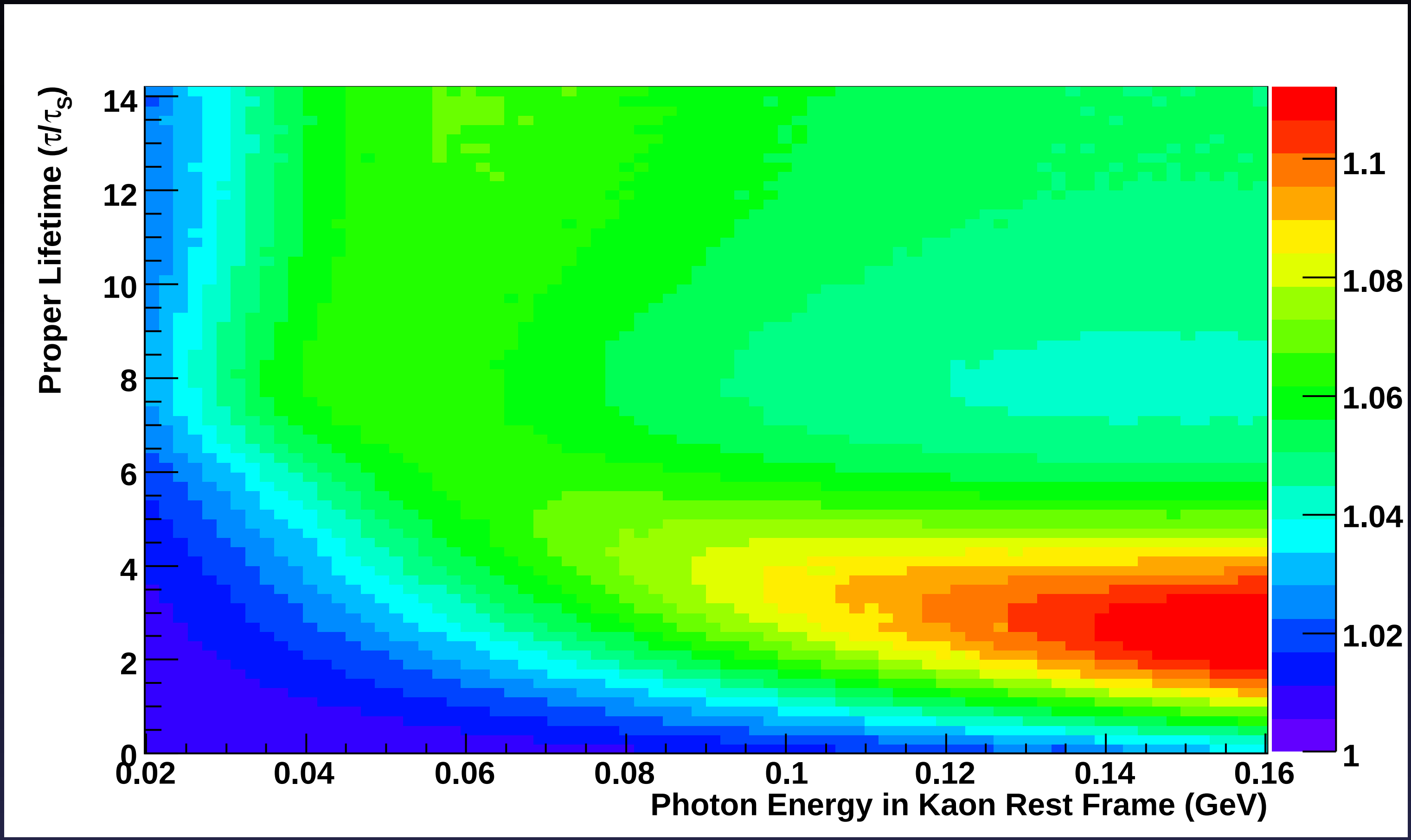
- Continued search for the “smoking gun” plot
- Next steps

The search for the “smoking gun” plot

- The likelihood fit yields a 6 σ (stat only) result for ehat
- It would be nice to show the effect of ehat on a plot
- Compare data to:
  - MC with best fit parameter values
  - MC with ehat = 0
- Use the fitter to reweight a large sample, which will eliminate statistical shifts between the two cases (zero and non-zero ehat)

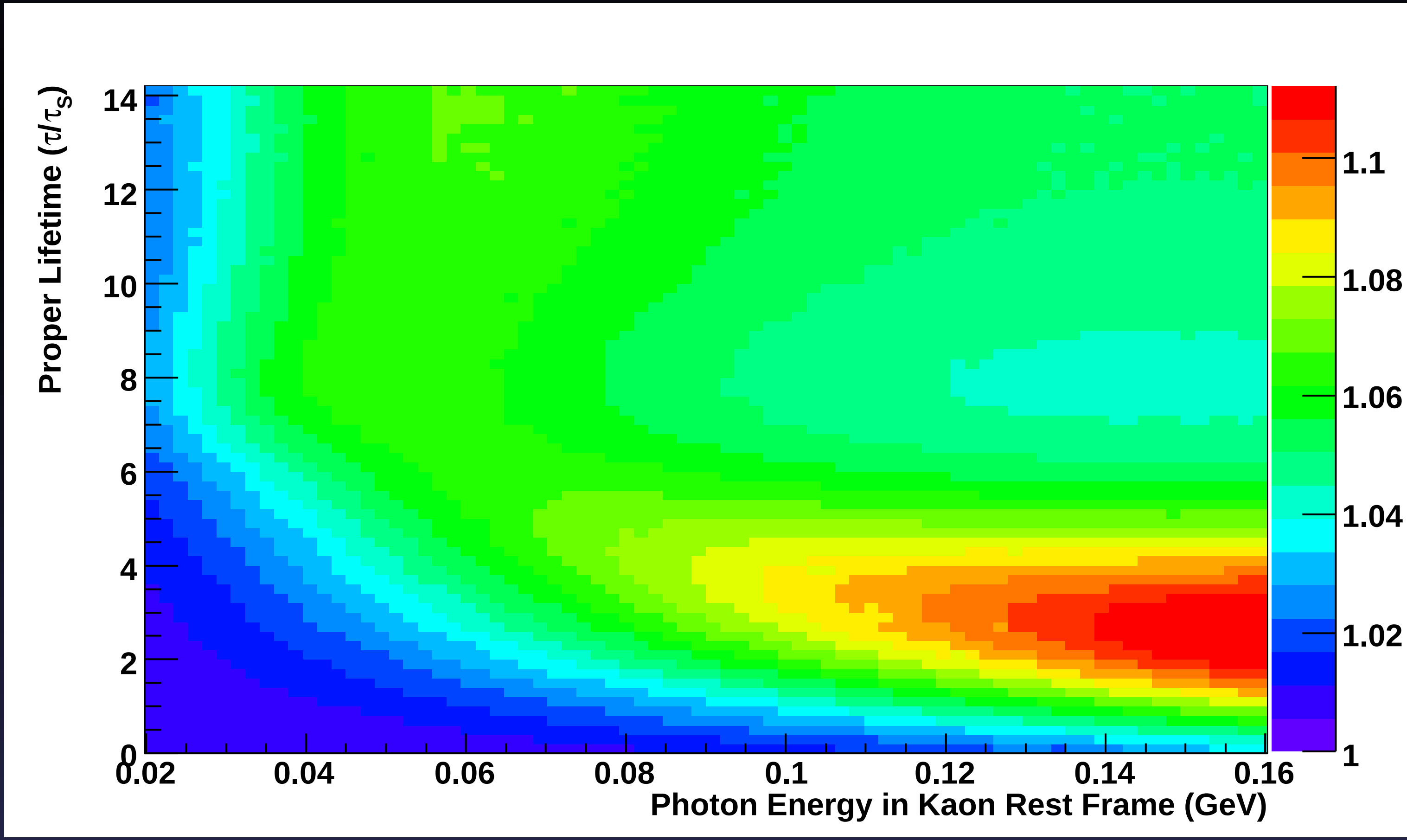
Comparing MC to MC

- As shown in the previous meeting, here's a 2D plot of the ratio (MC with bestfit parameters)/(MC with ehat =0)



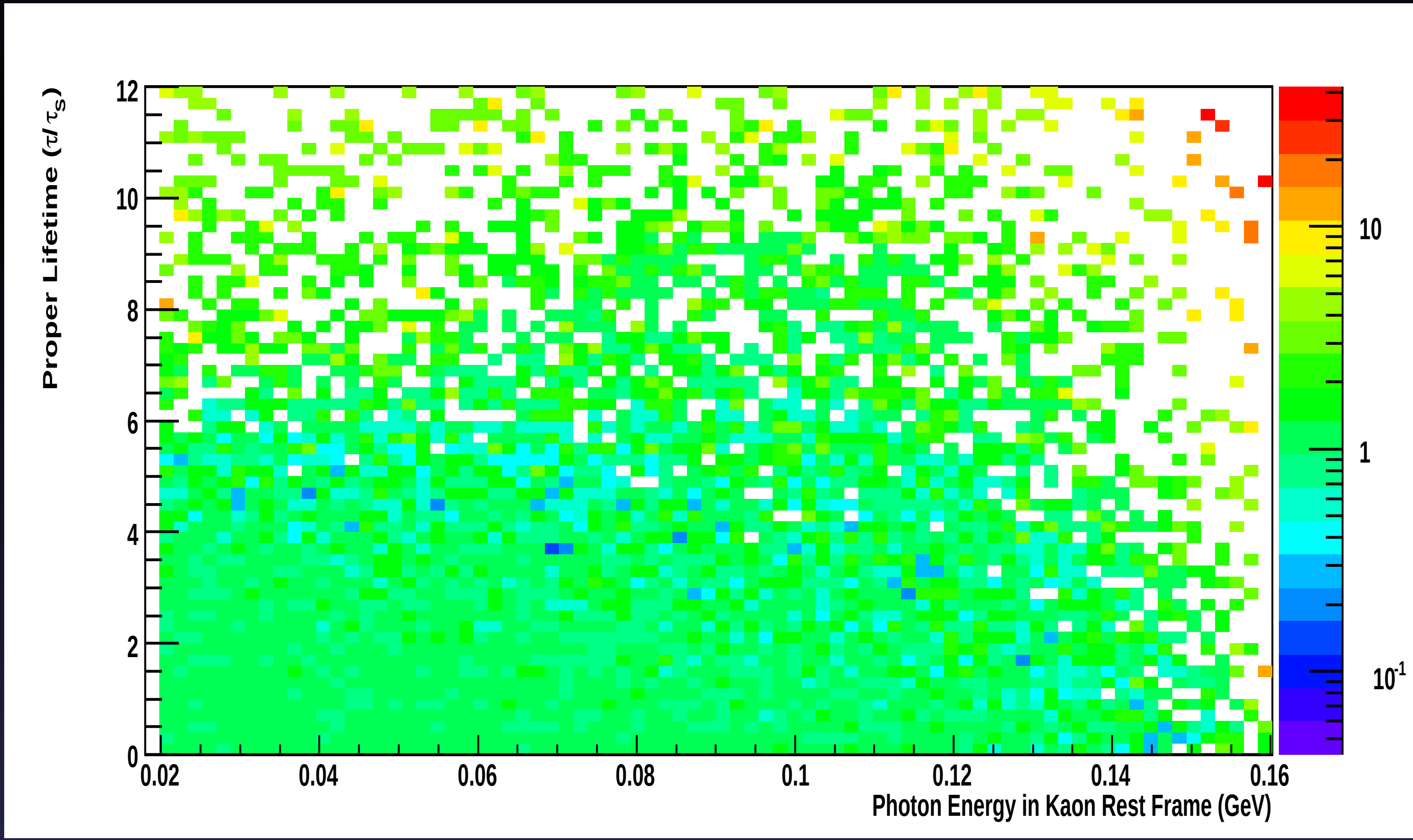
Comparing MC to MC

- This plot was produced in the likelihood fitter by reweighting the same, large flat MC sample.



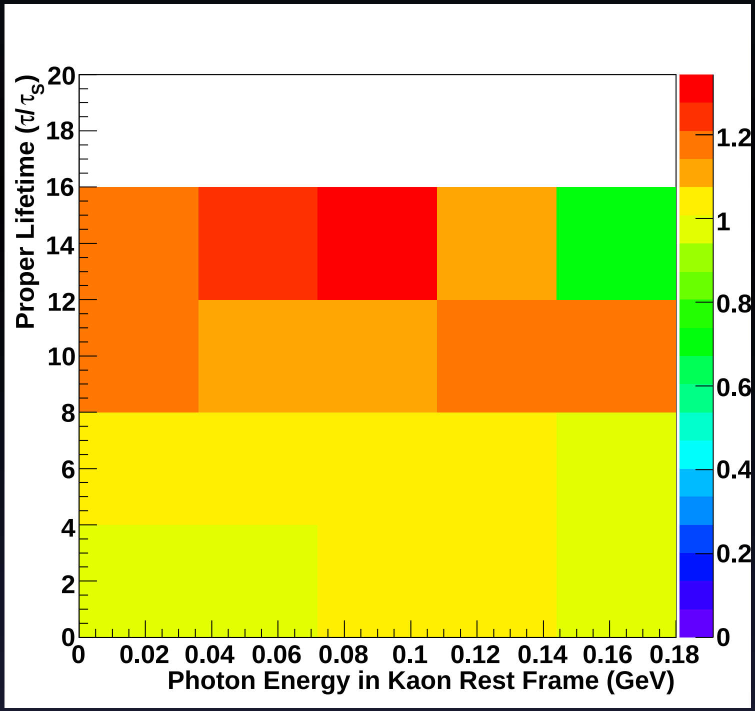
Comparing data to MC

- We'd like to compare data to MC in the same way, but the statistics aren't sufficient without serious rebinning:

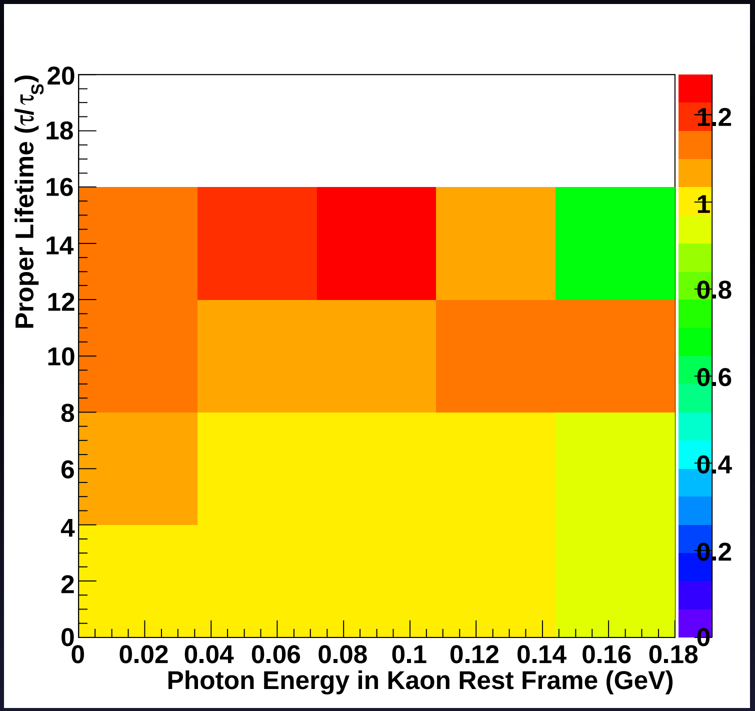


Data/MC

- Ratio of data/MC (with ehat =0)

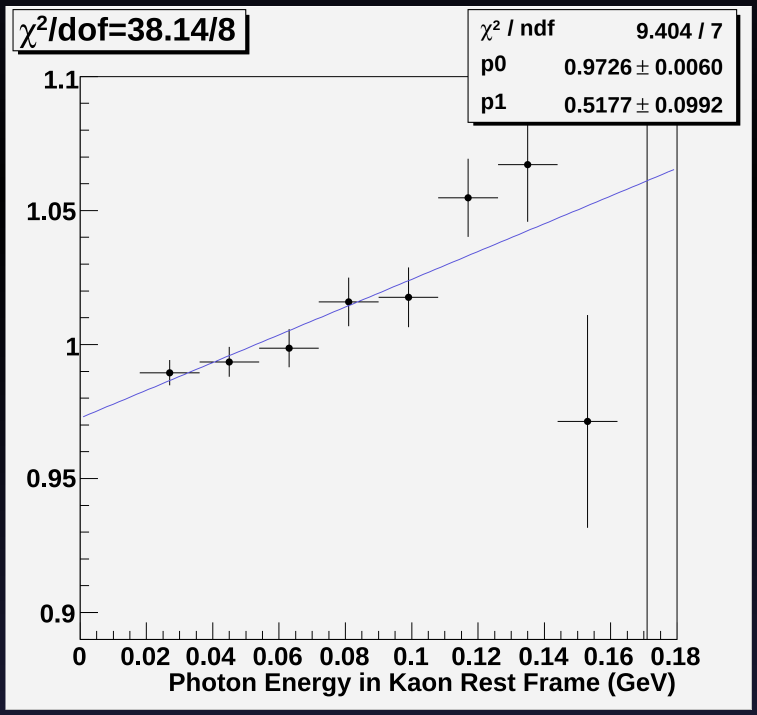


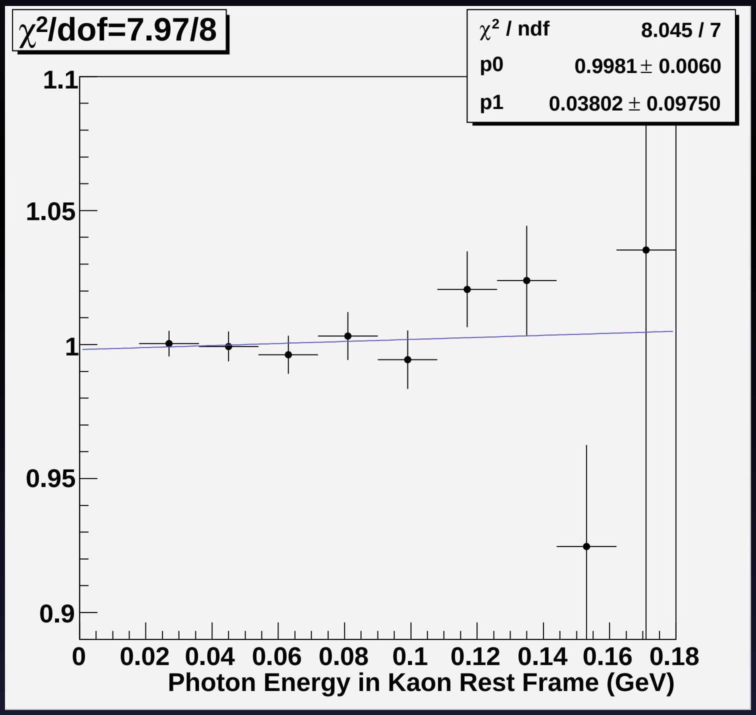
- Ratio of data/MC (with best fit parameters)



Data/MC – E_γ spectrum

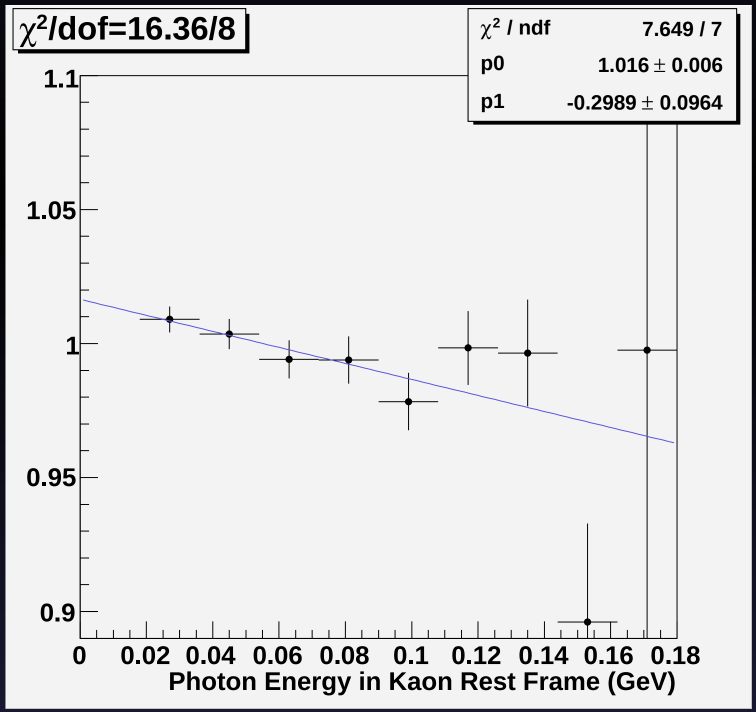
- Ratio of data/MC (with ehat =0)
- Ratio of data/MC (with best fit parameters)



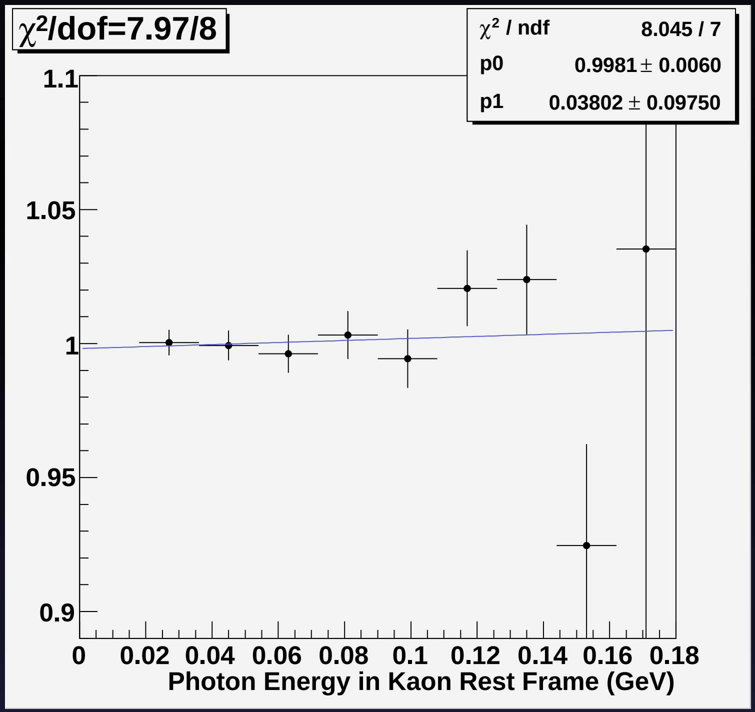


Data/MC

- Ratio of data/MC (with g_{E1} =0)

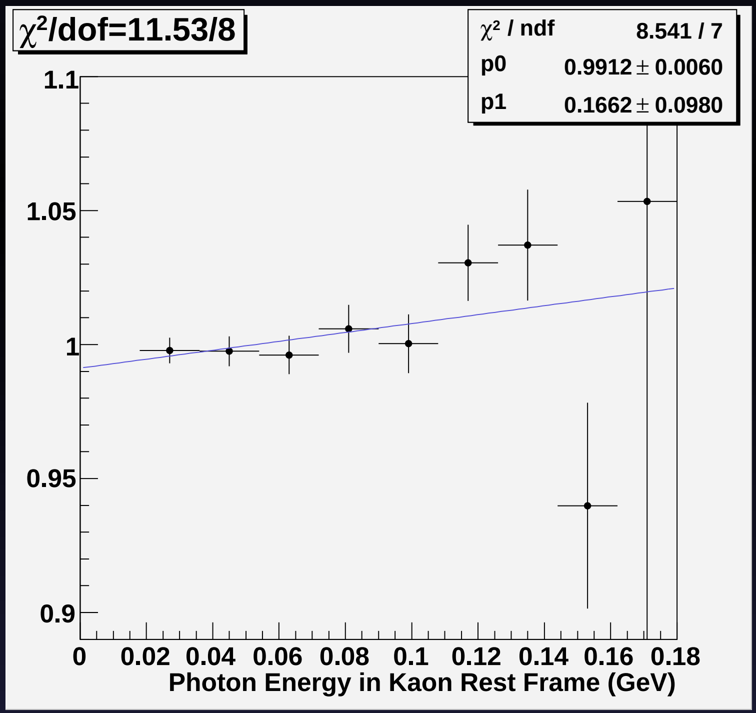


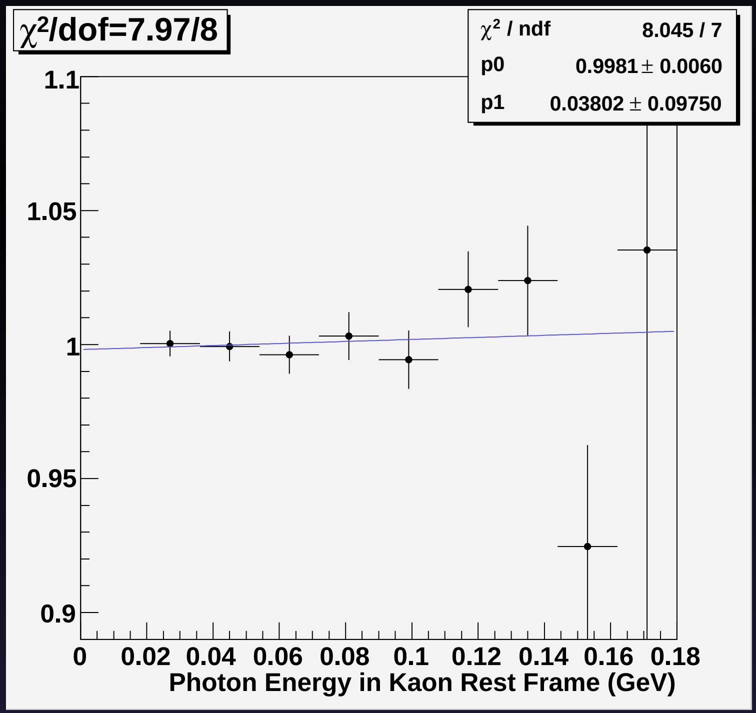
- Ratio of data/MC (with best fit parameters)



Data/MC

- Ratio of data/MC
(with g_{E1} = ehat = 0)
- Ratio of data/MC
(with best fit parameters)

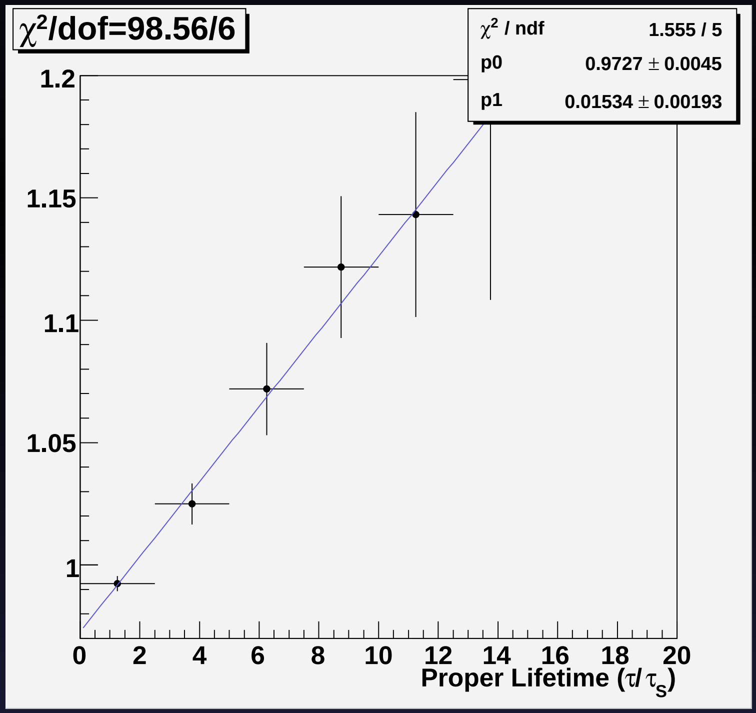




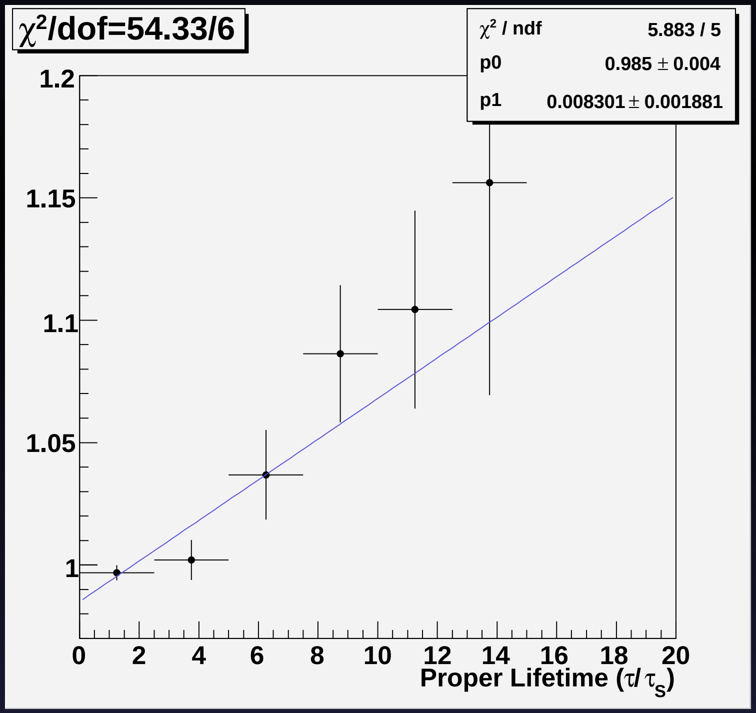
Due to the cancellation, we need to also find another sensitive plot

Data/MC-- Proper lifetime

- Ratio of data/MC (with ehat = 0)



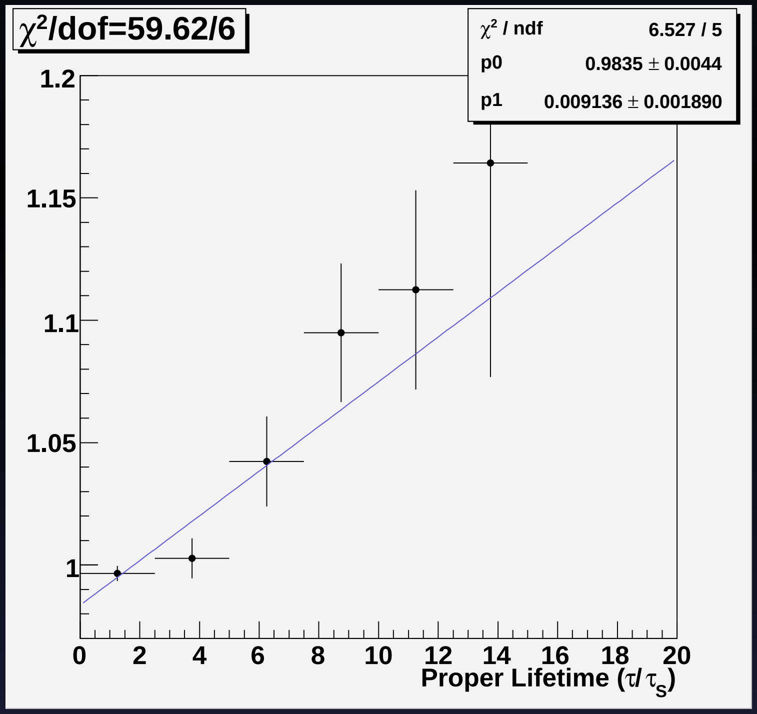
- Ratio of data/MC (with best fit parameters)

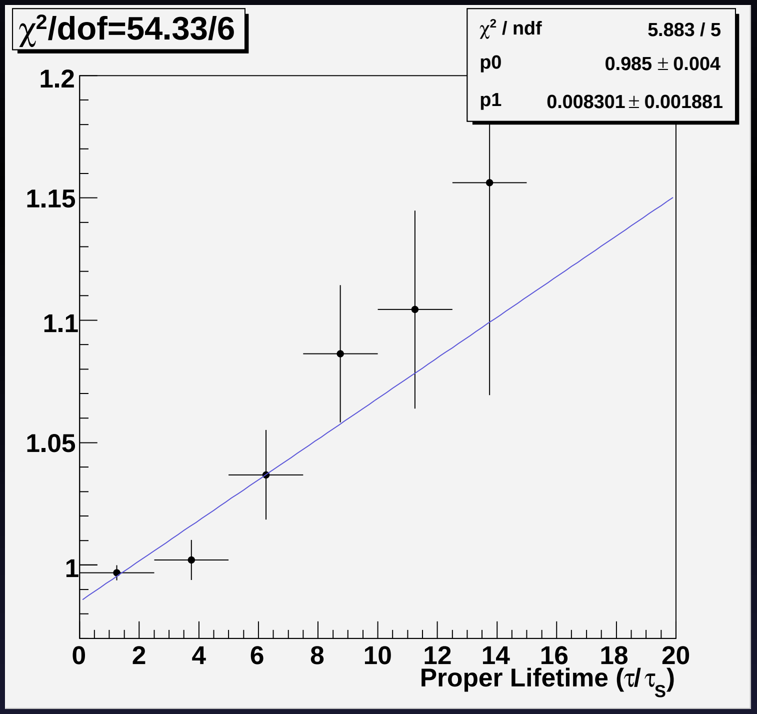


Best fit parameters also produce a slope --- due to momentum slope ?

Data/MC-- proper lifetime

- Ratio of data/MC (with $g_{E1} = 0$)
- Ratio of data/MC (with best fit parameters)





Negligible change --- only ehat has a large effect here

In summary

- The E_γ spectrum DOES appear sensitive to both ehat and g_{E1}.
  - They can in theory cancel each other out in such a way that there is no slope introduced
  - Not in χ^2 though --- best fit results in lowest χ^2
- The τ distribution is sensitive to ehat, but not g_{E1}.

Anything else?

- We have found at least two candidate "smoking gun plots" which must be used in conjunction with each other
  - Remember, we'd like to show that ehat, and not just E1 DE in general, is non-zero
  - Remember, ehat = Direct CP
- There are other ideas......

Another approach

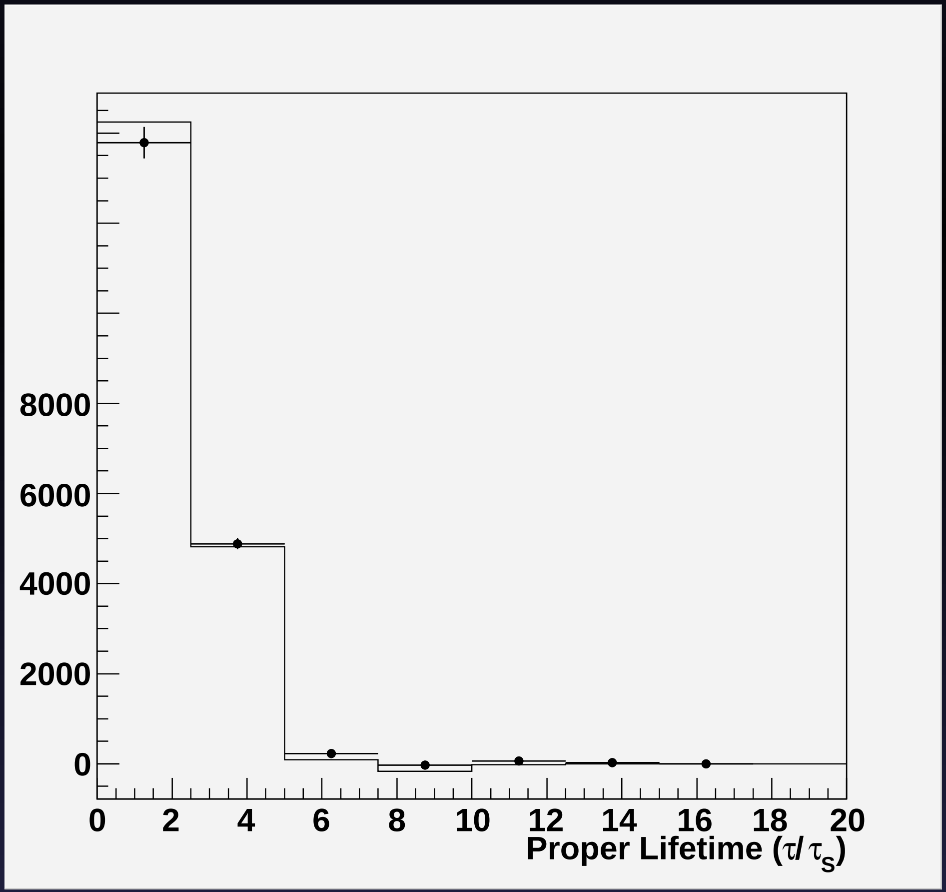
- Brad suggested doing a kind of background subtraction
  - E1 DE hidden by larger IB contributions
- Use parts of the triple differential decay rate, and subtract from data
  - Residual would then reflect the neglected parts of the rate

General Algorithm

- Compute nominal decay rate (full model) and plot
- Compute modified decay rate (with some terms neglected) and plot
- Compute normalization factor between nominal decay rate and data plots
- Apply the SAME normalization factor to the modified decay rate plot
- Subtract modified rate plot from data
- Subtract modified rate plot from nominal rate
- Check if the two resulting plots agree

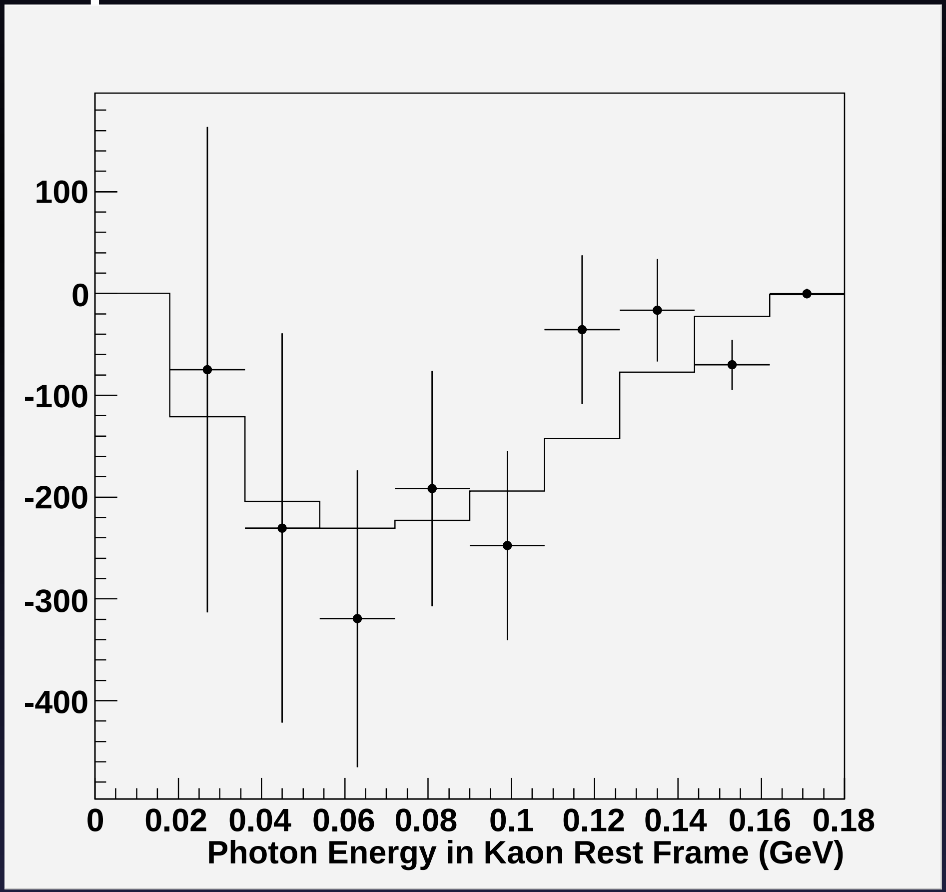
Example: KL-KS interference

- Compute the decay rate without the interference term
- Subtract from data and plot:
- We have interference !
- Points are model subtracted data
- Line is model prediction



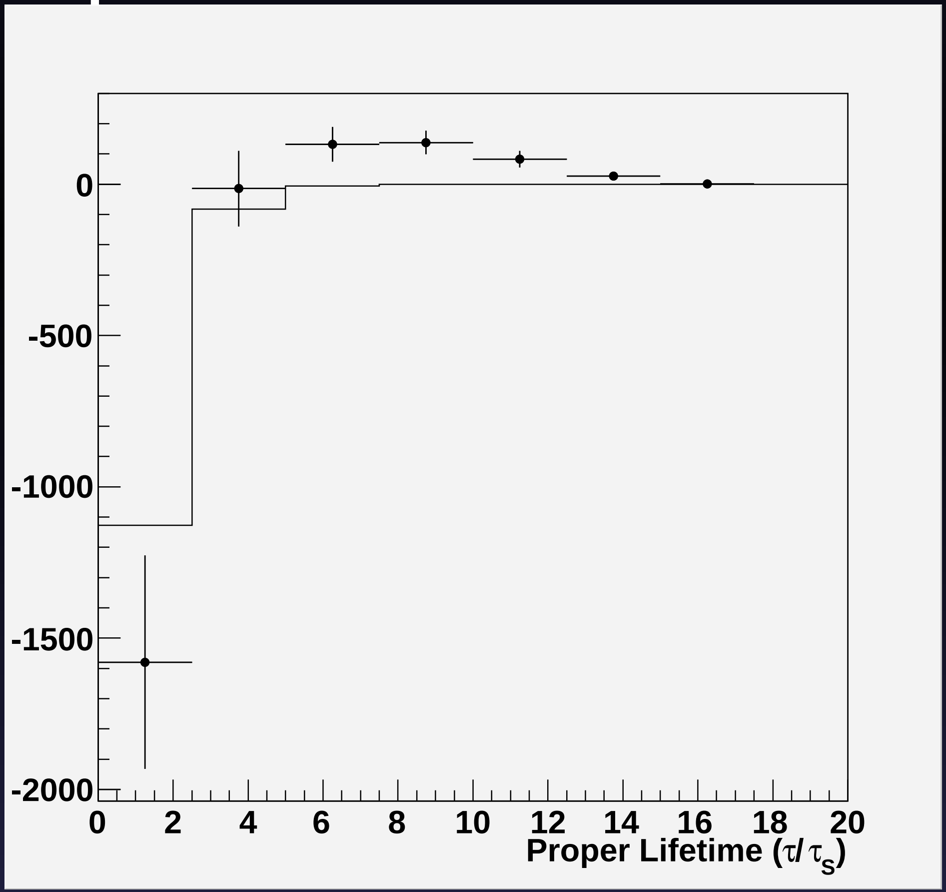
Next Example: E1 DE from K_S

- Compute the decay rate without the K_S E1 DE term (i.e. gE1)
- Subtract from data and plot:
- Interference is present?
- Points are model subtracted data
- Line is model prediction
- Implies gE1 is non-zero



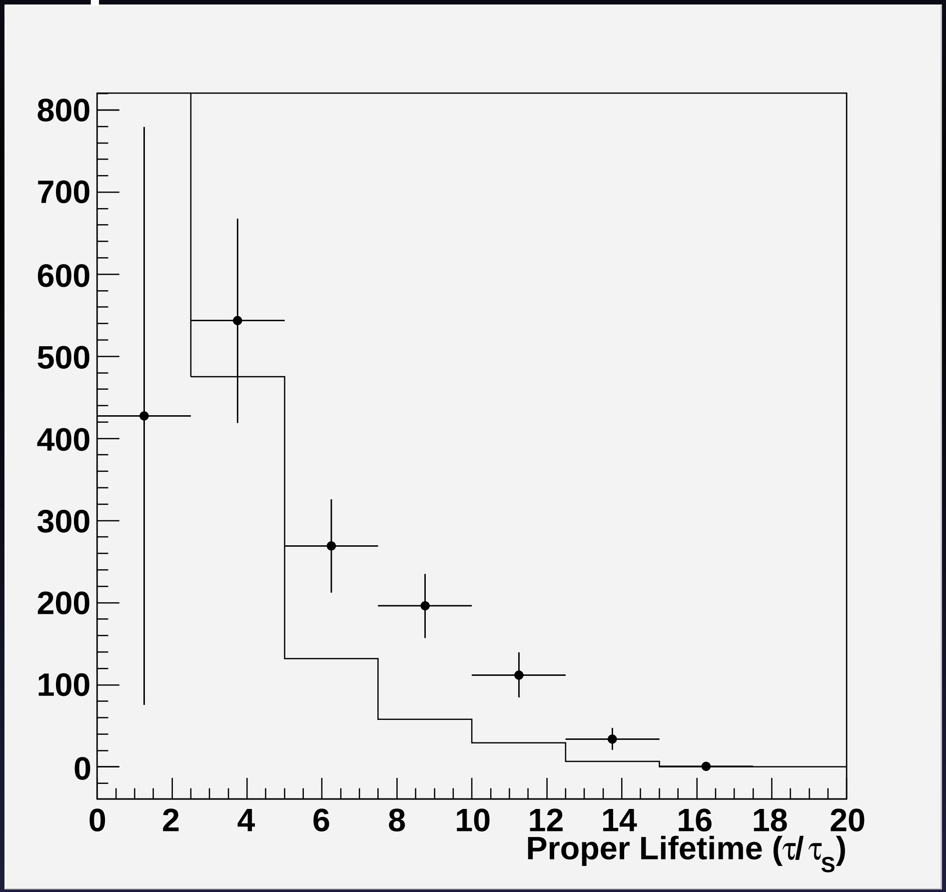
E1 DE from K_S -proper lifetime

- Compute the decay rate without the K_S E1 DE term (i.e. ge1)
- Subtract from data and plot:
- This is new ---with other methods, there isn't a big effect
- Points are model subtracted data
- Line is model prediction



E1 DE from K_L and interference

- Compute the decay rate without the K_L or interference E1 DE term (i.e. gE1 and ehat)
- Subtract from data and plot:
- Some evidence of agreement
- Points are model subtracted data
- Line is model prediction



E1 DE from K_L and interference

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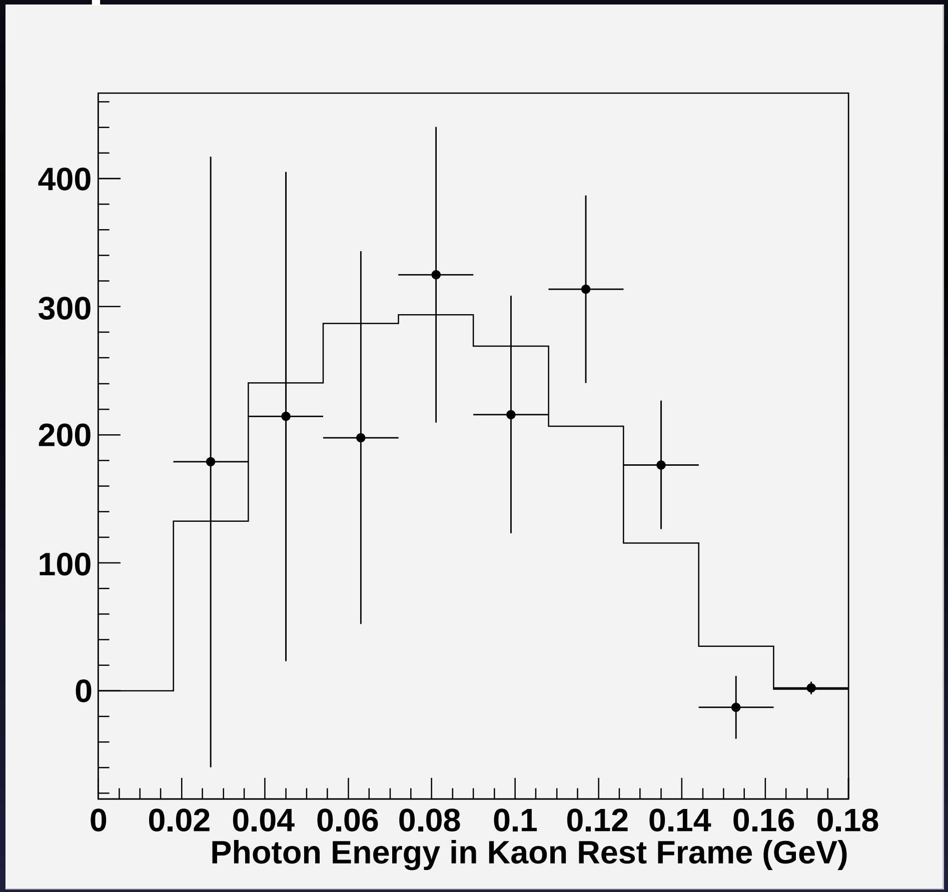


Outstanding issue

- It looks like the “subtraction” method may be helpful.
- I need to figure out how to isolate ehat type effects.
- g_{E1} has already been isolated
- Need to think about being more quantitative with this technique

To Do

- Ignore everything else now, and focus on the momentum slope issue.

To Do

- Once momentum issue is dealt with, measure momentum and z slopes out of fitter and redo the “flattening” systematics
  - Also attempt to determine correlation between z slope and momentum slope, and properly propagate error
- Produce “smoking gun plots”
  - data/MC ratios for E_γ and τ seem to work
  - So may Brad's subtraction idea

To Do

- Check resolution systematic and ensure that observed shift was not due to statistical fluctuation
- Check for double counting from the p_T^2 cut variation systematic and background systematic .
- Check E_γ (Lab Frame) cut variation – too many events added or removed?
- Recheck other cut variations as well

To Do

- Rethink the correlations between cut variations...
- Draw total error ellipse and extract total correlations between fit parameters ala Appendix D from Epsilon Prime PRD
- Carefully recalculate the systematic error on $\eta_{+-\gamma}$ --> compute each individual shift using shifts in ehat, etc.

Extra Slides

Decay Rate for $K_{L,S}\to\pi^+\pi^-\gamma$

- The decay rate is:

$$\frac{dN}{d\tau\, dE_\gamma\, d\cos(\theta)} = N_K \left[\left|\rho^2\right| \left[\frac{d\Gamma_{K_S\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)}\right] e^{-\frac{\tau}{\tau_s}} + \left[\frac{d\Gamma_{K_L\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos\theta}\right] e^{-\frac{\tau}{\tau_L}} \right.$$

$$\left. + 2Re\left[\rho \frac{d\gamma^*_{LS}}{dE_\gamma\, d\cos(\theta)} e^{i\Delta m_K \tau}\right] e^{-\left(\frac{1}{\tau_L}+\frac{1}{\tau_S}\right)\frac{\tau}{2}} \right]$$

where:

$$\frac{d\gamma_{LS}}{dE_\gamma\, d\cos(\theta)} \propto \left[E_{IB}(K_L)+E_{DE}(K_L)\right] * \left[E^*_{IB}(K_S)+E^*_{DE}(K_S)\right] + M(K_L)M^*(K_S)$$

$$\frac{d\Gamma_{K_L\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \propto \left|E_{IB}(K_L)+E_{DE}(K_L)\right|^2 + \left|M(K_L)\right|^2$$

$$\frac{d\Gamma_{K_S\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \propto \left|E_{IB}(K_S)+E_{DE}(K_S)\right|^2$$

Direct Vs Indirect CP Violation in E1

- The E1-DE K_L amplitude is a mixture of direct CP and indirect CP violating terms
- g_{E1} part of amplitude is present in K_L and K_S
- E-hat part is present in K_L only

$$|K_L\rangle \propto |K_2\rangle + \epsilon |K_1\rangle$$

Indirect CP Violation (via mixing)

g_{E1}

$\pi^+\pi^-\gamma$ via E1

Direct CP Violation (In Decay)

$\hat{\epsilon}$

$\pi^+\pi^-\gamma$ via E1

Decay Amplitudes

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

CP conserving

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

CP violating

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

CP violating

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

CP conserving

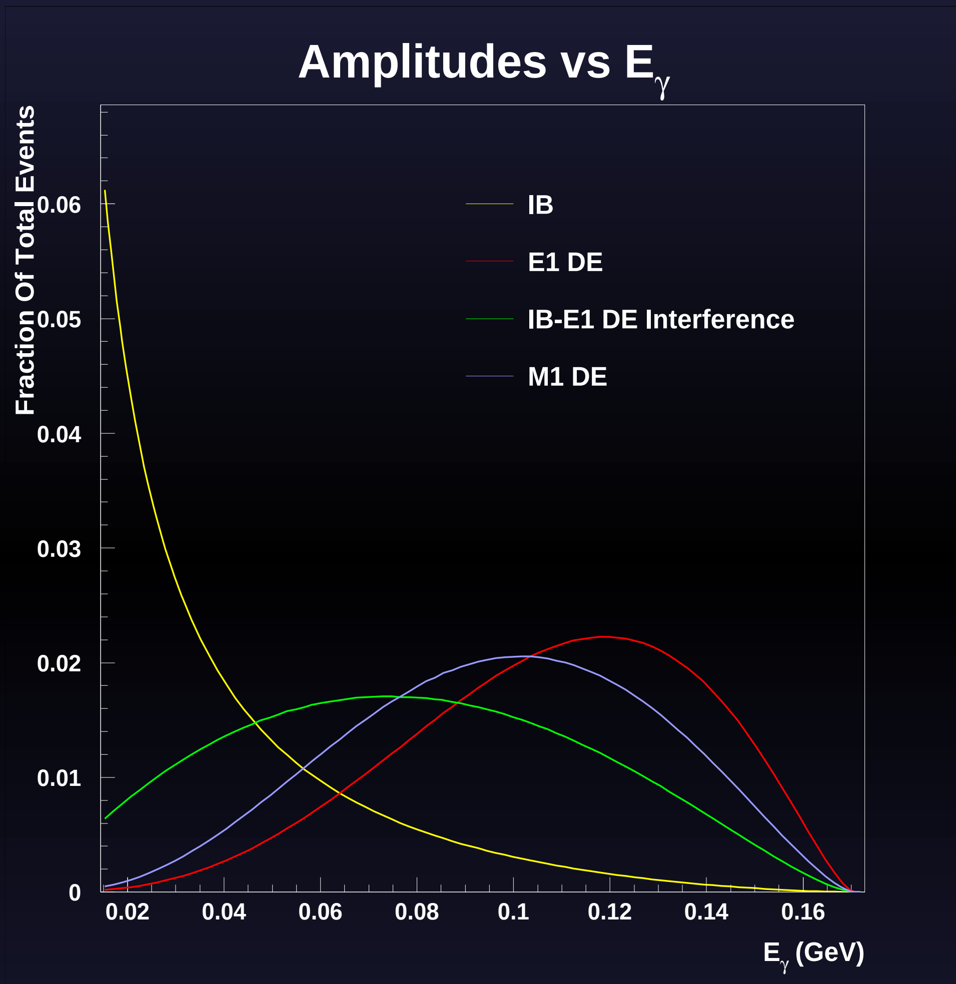
$$E_{DE}(K_S)=\frac{g_{E1}}{\epsilon}e^{i(\delta_1+\phi_\epsilon)}$$

CP conserving

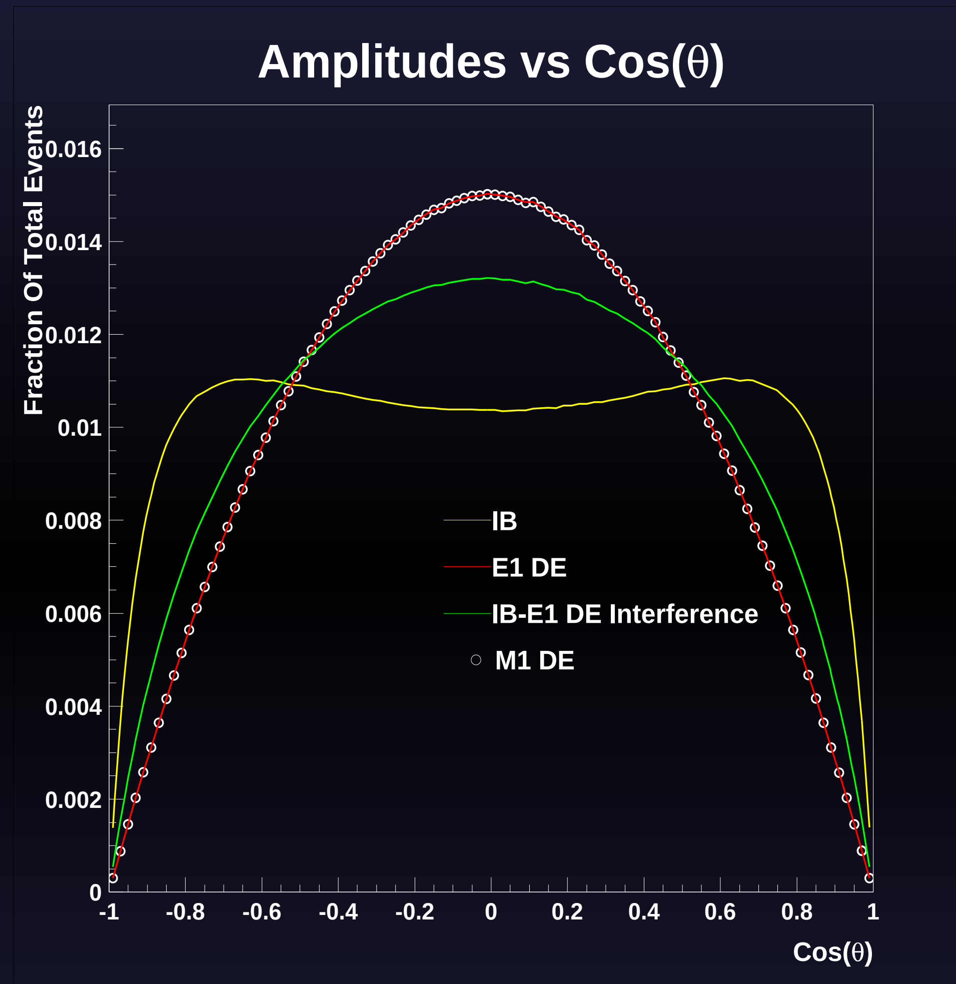
$$E_{DE}(K_L)=\underbrace{g_{E1}e^{i(\delta_1+\phi_\epsilon)}}_{\text{indirect CPV}}+\underbrace{i\,16\,\hat{\epsilon}\, e^{i\delta_1}}_{\text{direct CPV}}$$

CP violating

Amplitudes



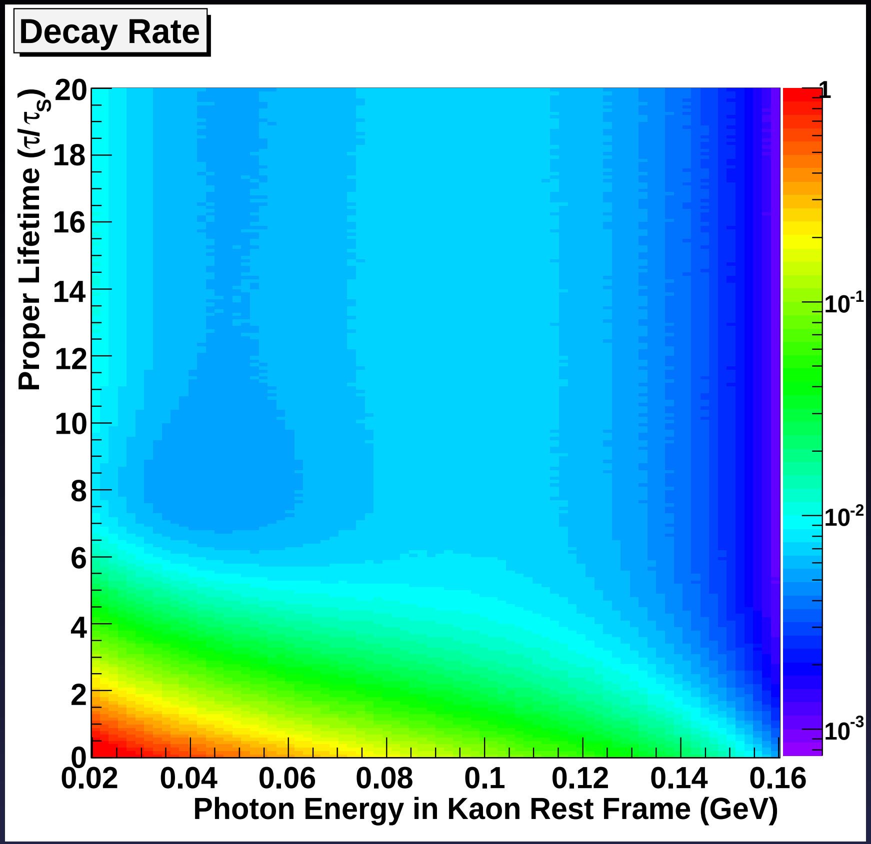
Dependence On E_γ

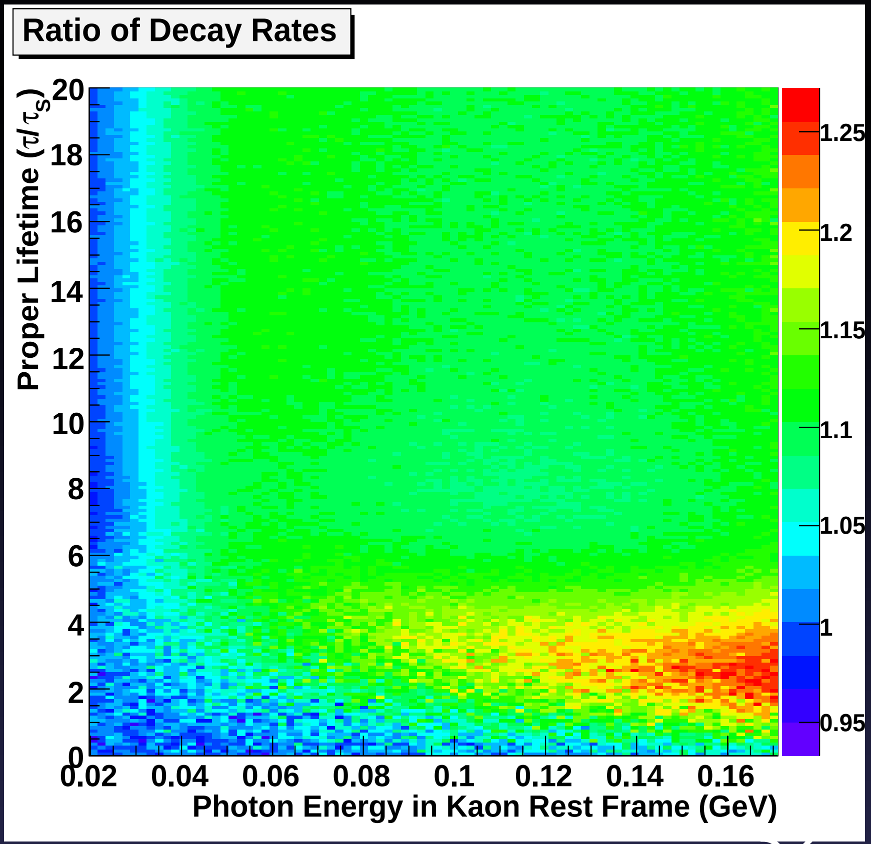


Dependence On Cosθ

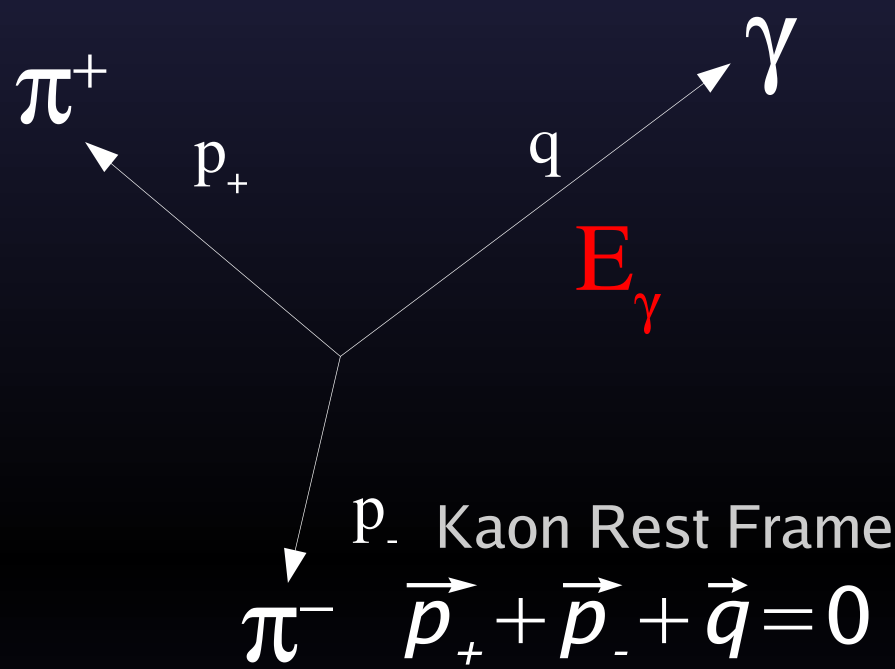
Projections of Decay Rate

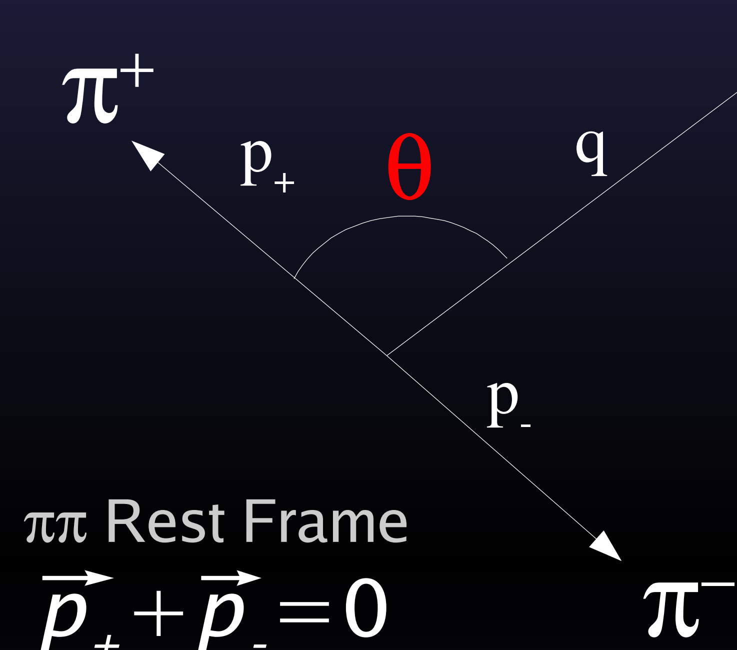
- The decay rate will give the density of events in phase space (τ, E_γ, $\cos\theta$)
- Plot of photon energy versus proper lifetime is interesting:

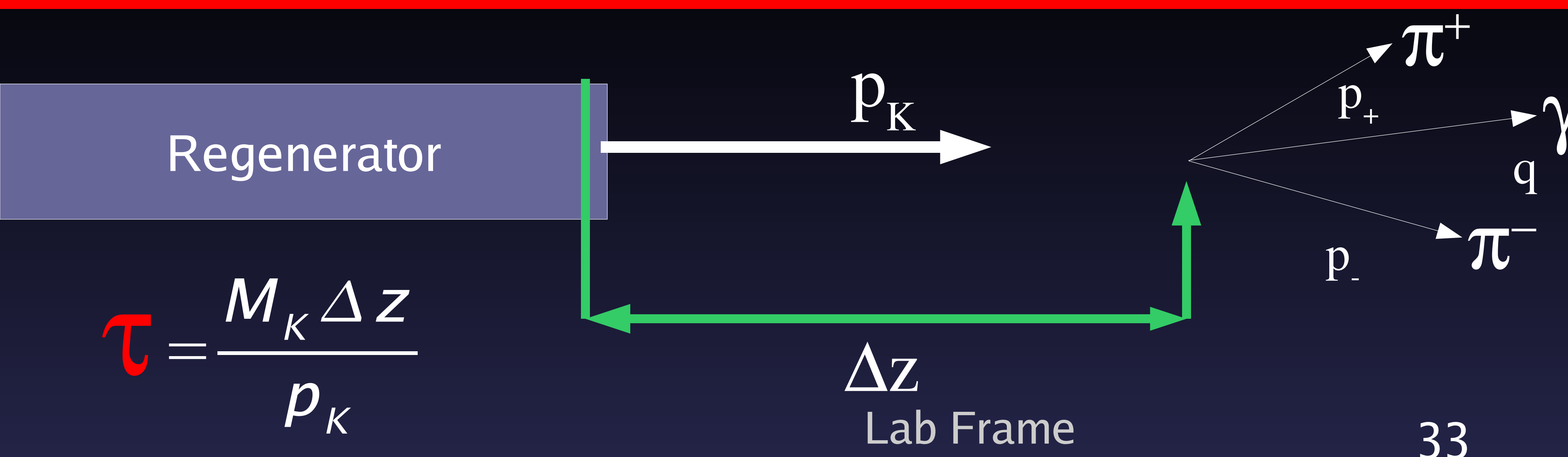




Kinematic Variables for $K \rightarrow \pi^+\pi^-\gamma$







$$\tau = \frac{M_K \Delta z}{p_K}$$

Analysis Cuts

Cut Variable	Keep Event If...
Kaon Mass	$0.48967\ GeV/c^2 < M_{\pi^+\pi^-\gamma} < 0.50567\ GeV/c^2$
P_T^2w.r.t Regenerator	$P_T^2 < 2.5 \times 10^{-4}\ GeV^2/c^2$
Kaon Momentum	40.0 GeV/c $< P_{\pi^+\pi^-\gamma} < 160.0$ GeV/c
Photon Energy in Lab Frame	$E_\gamma^* > 1.5$GeV
Photon Energy in Kaon Rest Frame, From Calorimeter	20.0MeV $< E_\gamma^* < 175.0$ MeV
Photon Energy in Kaon Rest Frame, From Kinematics	20.0MeV $< E_\gamma^* < 175.0$ MeV
$\pi\pi$ Invariant Mass, Implied From Above Cut	$0.2711\ GeV/c^2 < M_{\pi\pi} < 0.4772\ GeV/c^2$
Shape χ^2 For Photon Cluster	$\chi^2 < 48$
Outer Fiducial Cut For Photon Cluster	ISEEDRING < 18.1 cm
Inner Fiducial Cut For Photon Cluster	ISMLRING2 > 4.5 cm
Photon/Track Separation at CsI	d > 30 cm
Number of CsI clusters	NCLUS ≥ 3
pp0kin w.r.t. Target	$-0.10\ GeV^2/c^2 < P_{\pi^0}^2 < -0.0055\ GeV^2/c^2$
L3 pp0kin	passes
Z vertex	125.5 m $<$ VTXZ < 158.0 m
E/p	E/p < 0.85
Track Momentum	TRKP > 8.0 GeV
Vertex χ^2	VTXCHI < 50.0
Magnet Offset χ^2	TRKOCHI < 50.0
Track x separation at CsI	$\Delta x > 3.0$ cm
Track y separation at CsI	$\Delta y > 3.0$ cm
Total track separation at CsI	$\Delta r > 20.0$ cm
Number of Tracks	NTRK $= 2$
$\Lambda \rightarrow p\pi$ invariant mass	$M_{p\pi} < 1.112GeV/c^2$ or $M_{p\pi} > 1.119GeV/c^2$
Early energy in photon cluster	ADCSI_EARLY < 150 counts
In-time energy in photon cluster	ADCSI_INTIM > 115 counts
Photon/Upstream Track Projection at CsI	d > 2.0cm distance
Reconstruction Routines	Return no errors
Veto Cuts	All pass
Level 1 Trigger Verification	Event passes
Fiducial Cuts	All pass
Number of Photon Candidates That Pass ALL Cuts	$N_{COMBINATIONS} = 1$ ONLY