Semileptonic Decays at CLEO:

Search for Two Gluon Couplings in $\mathbf{D \to \eta'}$

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The η' Problem

- **1997 CLEO Measurements of: $B \rightarrow X\eta'$**
  - **Naïve 97 Expectation:** $\frac{Br(B^+ \rightarrow \eta' K^+)}{Br(B^+ \rightarrow \eta_c K^+)} = 3 \times 10^{-4}$
  - **Measured Value:** $\frac{Br(B^+ \rightarrow \eta' K^+)}{Br(B^+ \rightarrow \eta_c K^+)} = 8.7 \times 10^{-2}$
  - $B^0 \rightarrow \eta' K^0$
    - Measured: $(68 \pm 4) \times 10^{-6}$
    - Factorization Prediction: $(20\text{-}40) \times 10^{-6}$
  - **Are we forgetting a diagram?**

The QCD Anomaly

- What is η'? What is η?
  - The physical η' and η mesons are combinations of the quark quantum states η^8 (octet) and η^0 (singlet)
  - η mostly octet
  - η' mostly singlet
- Anomalous Contribution to Axial vector Current
  - Involved in calculating particle decays

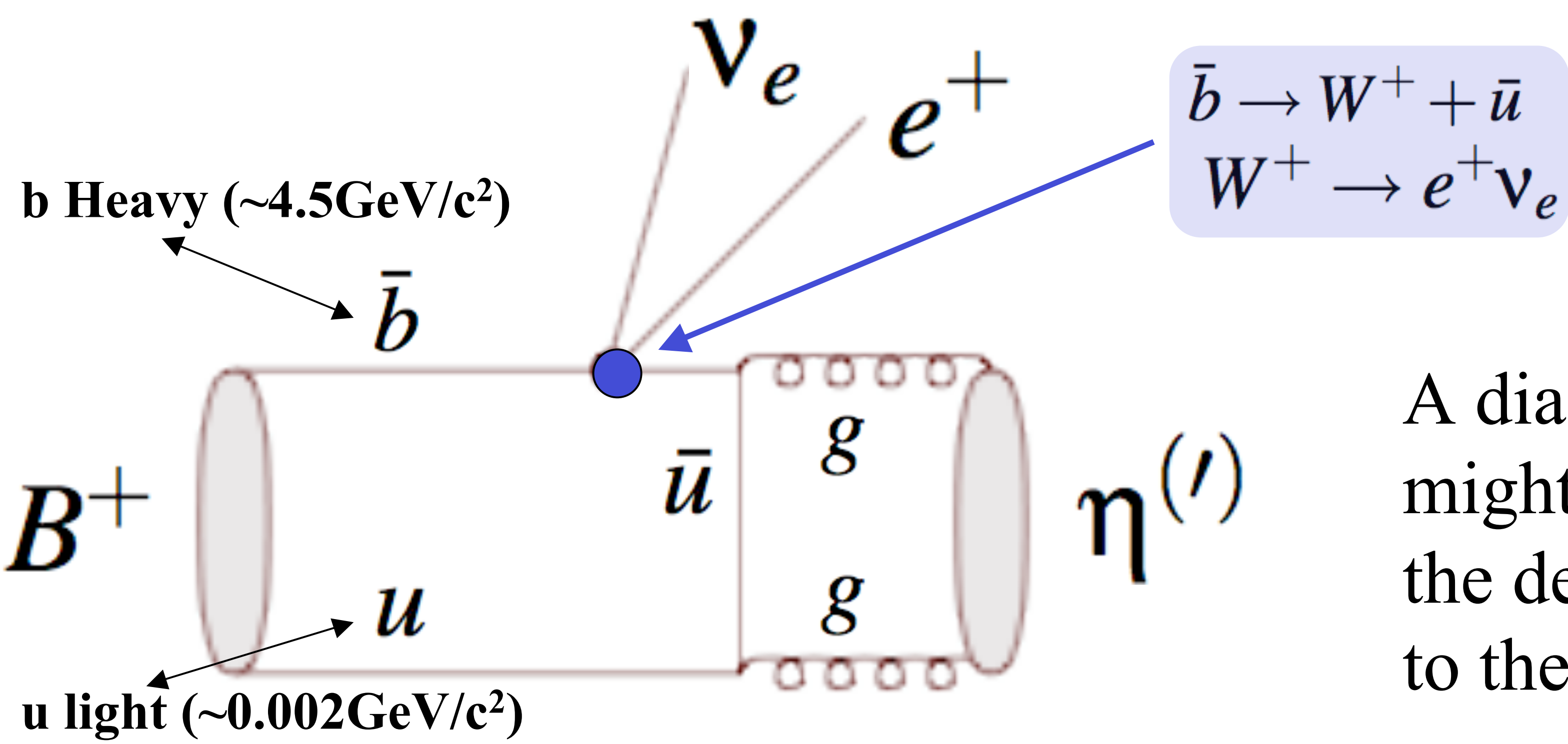
Couplings to 2 gluons

$$\partial_\mu j^{\mu a 5} = -\frac{g^2}{16\pi^2}\tilde{G}^{\mu\nu c} G^d_{\mu\nu}\, tr[\tau^a]\, tr[t^c t^d]$$

Symmetry Factor
0 for η^8, 1 for η^0

Semileptonic Decays

- Purely hadronic decays difficult to calculate.
- Semileptonic decays isolate B to η and B to η′.



A diagram that might increase the decay rates to the η′

Results of B Semileptonic

- What did I find in the B System?
  - Pre-thesis project.
  - Measurement:
    - Data: $Br(B \to \eta l \nu)$: $(0.44 \pm 0.23_{stat} \pm 0.11_{syst})\text{x}10^{-4}$
    - Data: $Br(B \to \eta' l \nu)$: $(2.66 \pm 0.80_{stat} \pm 0.57_{syst})\text{x}10^{-4}$
  - Theory For No gluon couplings:
    - Theory: $Br(B \to \eta l \nu)$: $(0.4)\text{x}10^{-4}$
    - Theory: $Br(B \to \eta' l \nu)$: $(0.2)\text{x}10^{-4}$

η Consistent **η' 10x Prediction!**

Can we see it in D?

- D meson Similar to B meson:
  - A heavy quark (b,c) paired with light quark (u,d)
  - Expect less enhancement, but idea the same.
- Is it possible to be in D too?
  - Previous Upper Limit (1/3 full data set):
    - Data (90% limit): Br($D \rightarrow \eta' l \nu$): < (0.32)x$10^{-3}$
  - Theory For No gluon couplings:
    - Theory: Br($B \rightarrow \eta' l \nu$): (0.16)x$10^{-3}$

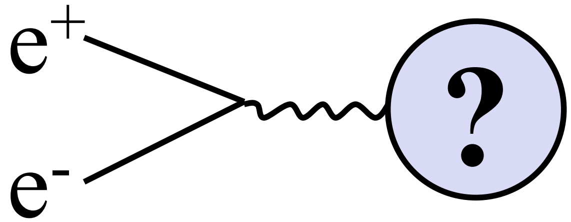
Still Room

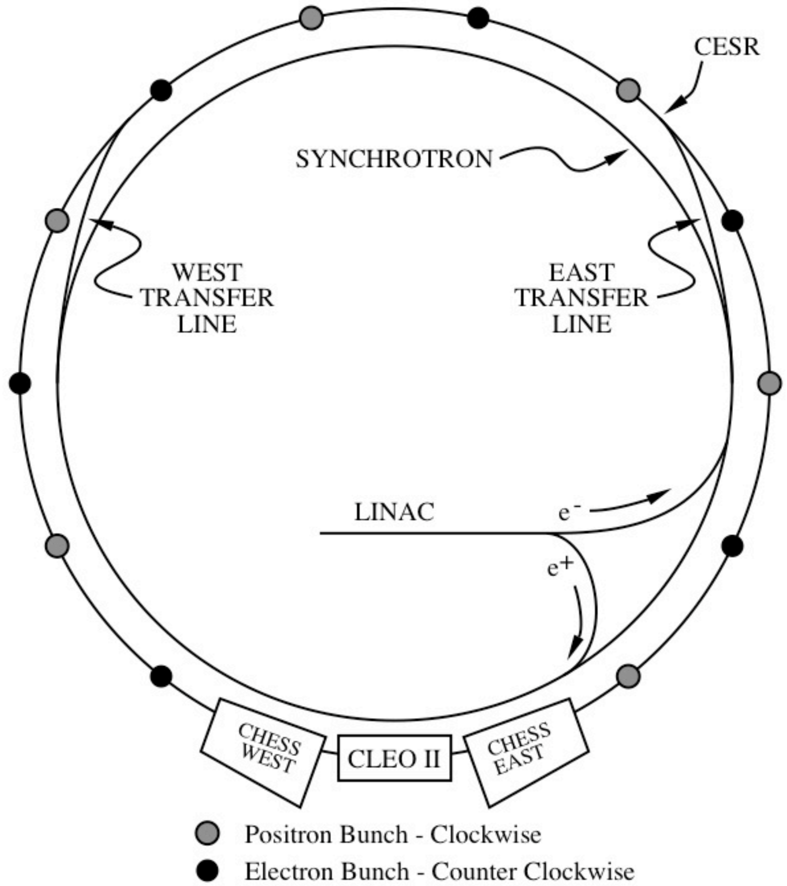
- Thesis: Look for Evidence in the D decays

CESR/CLEO Ect.

- How do we make these measurements?

CESR





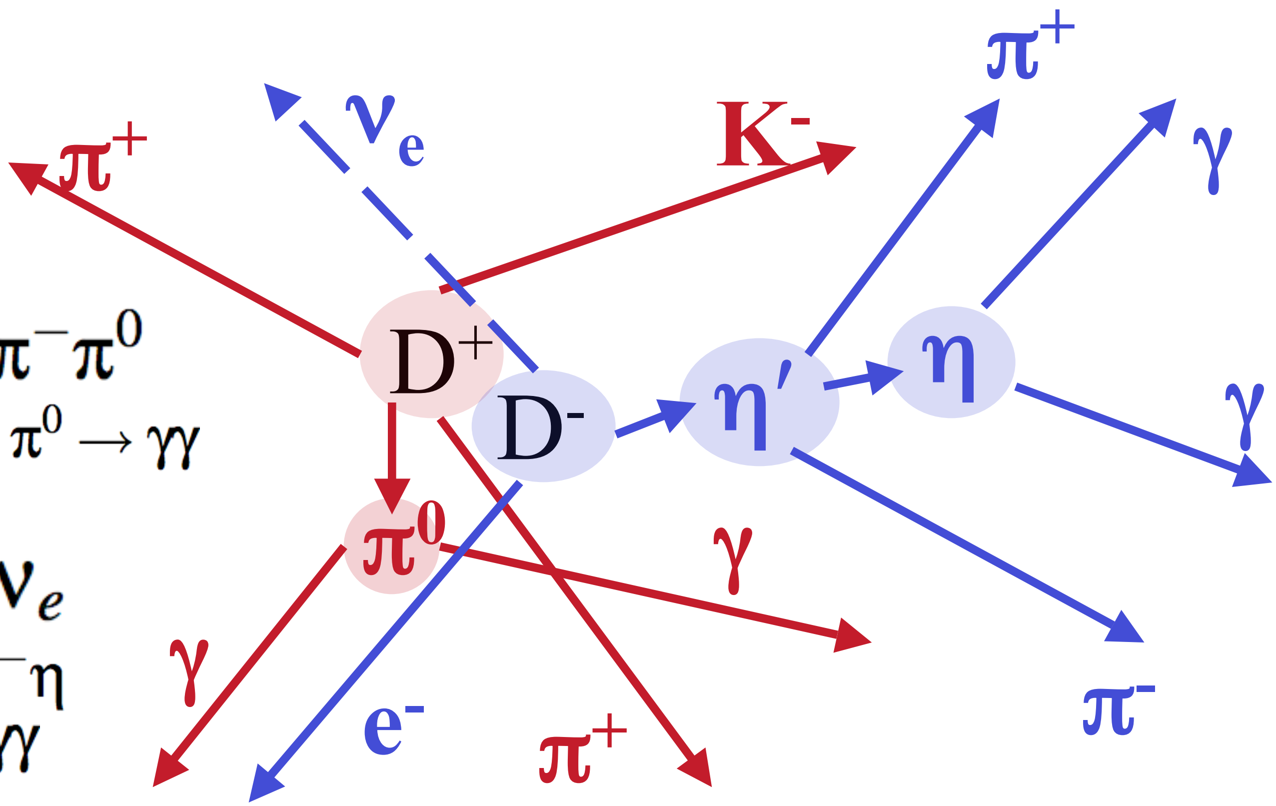
- CESR: Cornell Electron Storage Ring
- Accelerates bunches of electrons and positrons to equal Energy.
- Stores them in a stable orbit.
- Produces controlled collisions.
- Creates pairs of heavy mesons (B^+B^-, D^+D^-) nearly at rest.

What do the D's Look Like?

- Consider two D's at rest by one another.
  - Signal D (the decay we're looking for)
  - "Other Side" D (random hadronic decay)
  - The daughters of the two will be mixed up

$$D^+ \to K^- \pi^+ \pi^- \pi^0$$
$$\pi^0 \to \gamma\gamma$$

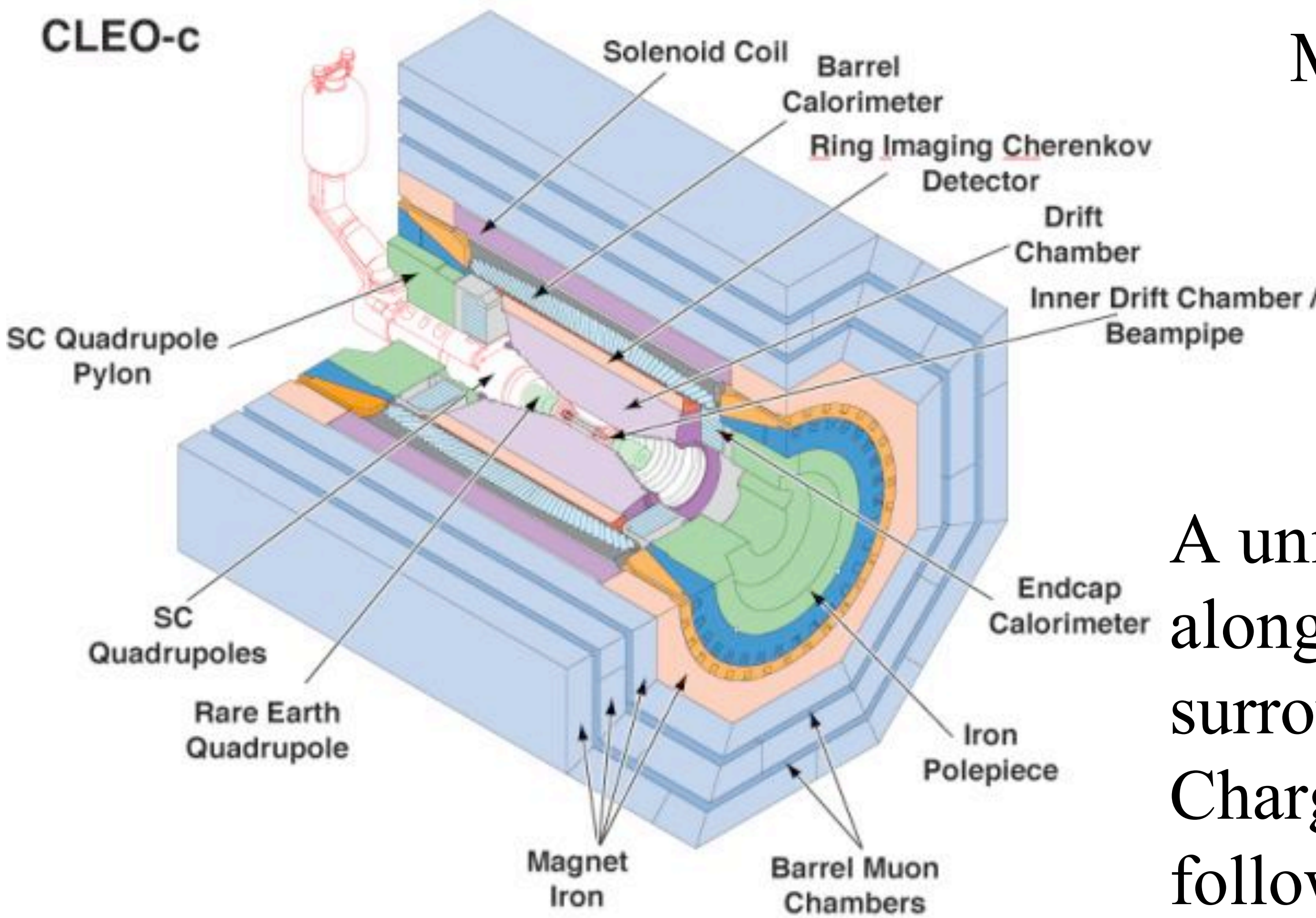
$$D^- \to \eta' e^- \nu_e$$
$$\eta' \to \pi^+ \pi^- \eta$$
$$\eta \to \gamma\gamma$$



CLEO

- General purpose detector
- High Hermiticity

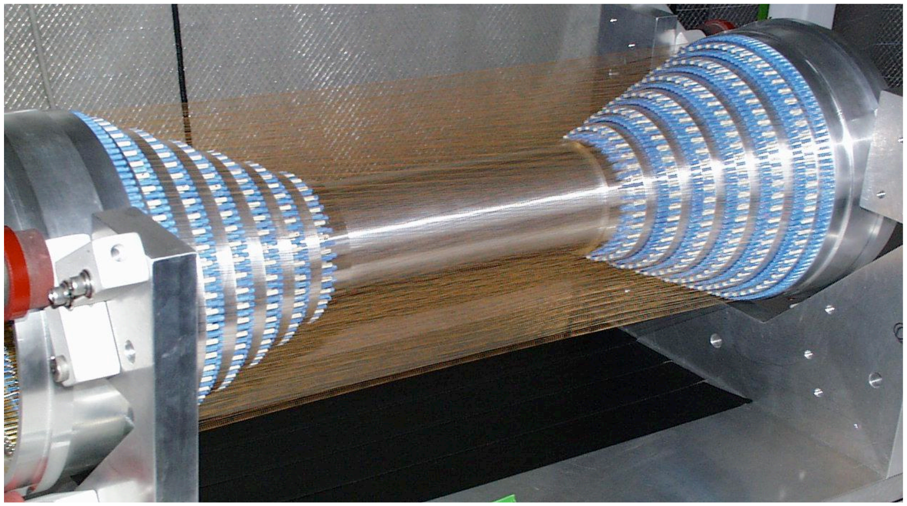
After 28 years,
Last event taken:
March 4, 2008

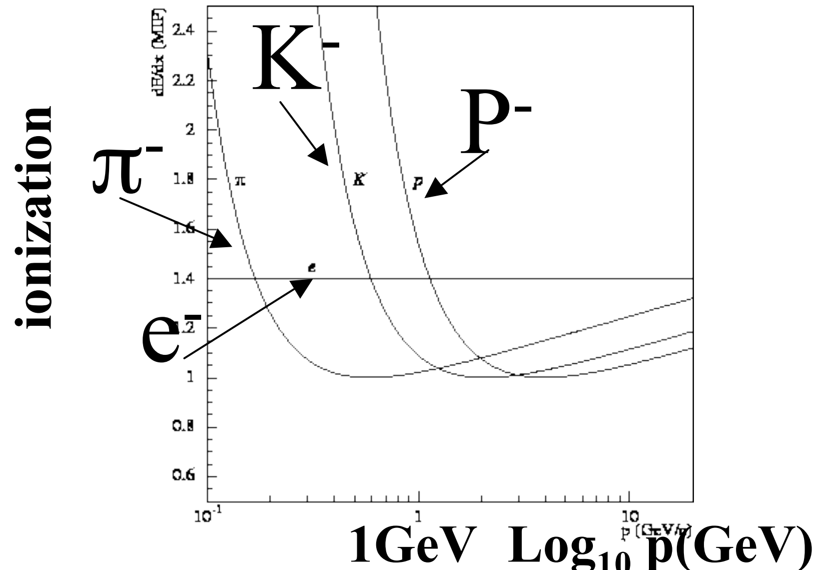


A uniform B field along beam axis surrounds detector. Charged Particles follow a Helix path

Drift Chambers

- CLEO-C has 2 drift chambers. (Hi-res Inner, Lo-Res outer)



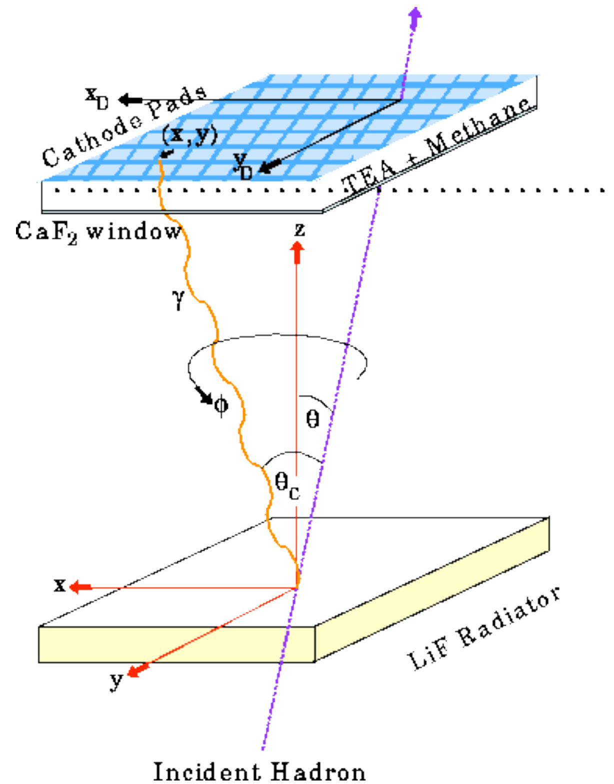


- The drift chambers "track" the paths taken by charged particles.
  - The curvature of the "track" trajectory gives us the momentum
  - The magnitude of the ionization hints at the mass.

RICH

- Ring Image Cherenkov Detector
  - Particles moving faster than light in a medium produce Cherenkov radiation.
  - The angle between particle and photon related to particle speed.
  - Helps to identify “tracks”

$$\cos(\theta_c) = \frac{1}{n(v/c)}$$

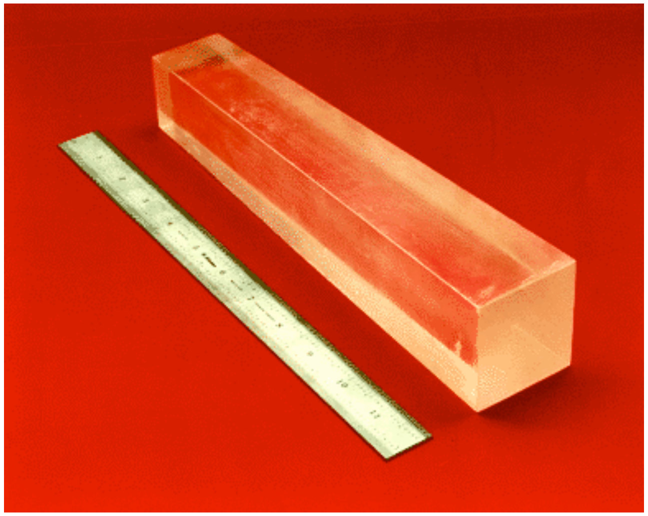


Crystal Calorimeter

- Neutral Particles and Photons deposit energy in the calorimeter and create "showers"
  - Covers 98% detector volume
  - 7800 thallium-doped Cesium Iodide (CsI) crystals.
  - Energy Resolution:

$$\sigma_E/E = 0.35/E_{GeV}^{3/4} + 1.9 - 0.1E_{GeV}$$

- Tracks will also deposit energy
  - May create a "fake" photon



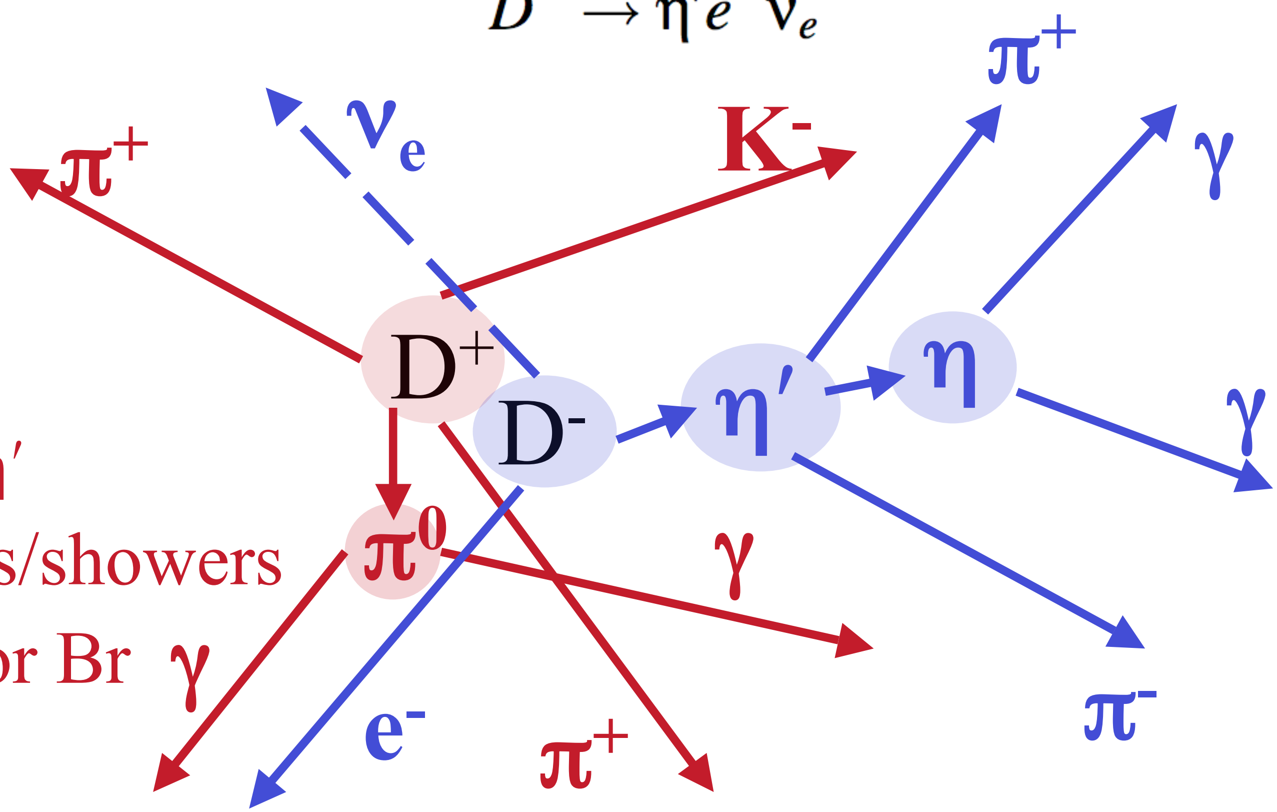
My Goal

- Measure the $D \rightarrow \eta' e \nu$ branching fraction to 3σ or better uncertainty.
  - Two Different Methods in use for semileptonic D decays:
    - D-Tagging method
      - Used for previous upper limit.
      - PRO: Low Systematic Uncertainties, Low backgrounds
      - CON: Low detection efficiency (not taking full advantage of data)
    - Neutrino Reconstruction method.
      - Used to study semileptonic B decays.
      - PRO: High detection efficiency (taking full advantage of data)
      - CON: More backgrounds, More sources of Systematic uncertainty.
  - Start with Neutrino Reconstruction, make improvements inspired by D-Tag's.

D-Tagging

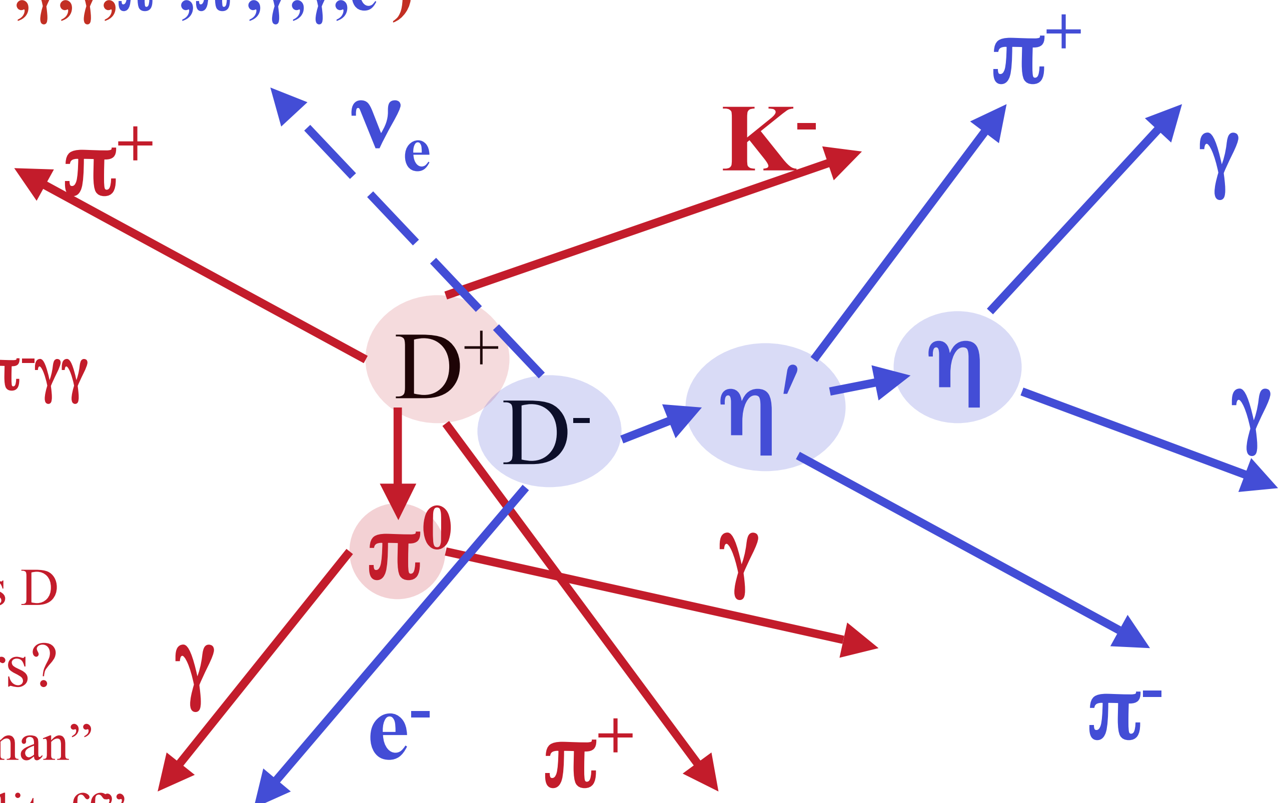
- Search for specific D hadronic decay candidates:
  - Well known, high-res decay (mostly tracks):
    - $K_s\pi$, $K\pi\pi$, $K\pi\pi\pi^0$, $K_s\pi\pi^0$, $K_s\pi\pi\pi$, $KK\pi$
- Pick Best : (Example)
  - $K^-\pi^+\pi^+$
  - $K^-\pi^+\pi^+$
  - $K^-\pi^+\pi^+\pi^0$
- Look for $e^-\pi^+\pi^-\gamma\gamma$
  - $M_{\gamma\gamma}$ consistent η
  - $M_{\pi\pi\gamma\gamma}$ consistent η'
- Ignore extra tracks/showers
- Divide by #tags for Br

$$D^+ \to K^-\pi^+\pi^-\pi^0$$
$$D^- \to \eta' e^-\nu_e$$



Neutrino Reconstruction

- Measure the Missing Energy and Momentum:
  - Look for any event consistent with there being 1 neutrino.
  - As long as "Other side" hadronic, it doesn't matter
- $\mathbf{E_{miss}=E_{cm}-E(K^-,\pi^+,\pi^+,\gamma,\gamma,\pi^+,\pi^-,\gamma,\gamma,e^-)}$
- $\mathbf{P_{miss}=P_{cm}-P(K^-,\pi^+,\pi^+,\gamma,\gamma,\pi^+,\pi^-,\gamma,\gamma,e^-)}$
- **Quality cuts:**
  - **Net charge** = 0
  - Number Leptons=1
  - Missing Mass$^2 \approx 0$
- Look for (e^- or e^+)$\pi^+\pi^-\gamma\gamma$
  - $M_{\gamma\gamma}$ consistent η
  - $M_{\pi\pi\gamma\gamma}$ consistent η'
  - With Neutrino makes D
- Extra Tracks/Showers?
  - Exclude tracks "Trkman"
  - Exclude showers "splitoff"



Tag/Neutrino B vs. D

- Tagging:
  - For B Decays ~5% of events used.
  - For D Decays ~22% of events used.
- Neutrino Reconstruction:
  - For B Decays ~80% of events used.
  - For D Decays ~50% of events used.

Previous CLEO $D \to \eta' e \nu$

- D-Tag analysis was previously done on 1/3 data set
  - Only used 2 η' decay modes:
    - $\eta' \to \pi^+ \pi^- \eta$; $\eta \to \gamma\gamma$
    - $\eta' \to \pi^+ \pi^- \eta$; $\eta \to \pi^+ \pi^- \pi^0$
  - 1/3 Full Data set (all that was available at the time)
  - No signal found.
  - Even with full data set a 3σ measurement of branching fraction probably not possible using the tag method.

No Decay Mode Left Behind

η' Decay Modes	
$\eta' \to \gamma\gamma$	2.12%
$\eta' \to \rho\gamma$	29.5%
Mρ(1) 0.30-0.54GeV	1.4%
Mρ(2) 0.54-0.66GeV	4.3%
Mρ(3) 0.66-0.78GeV	15.5%
Mρ(4) 0.78-0.90GeV	8.1%
✔ $\eta' \to \pi\pi\eta$	44.3%
✔ $\eta' \to \gamma\gamma$	17.5%
✔ $\eta' \to \pi\pi\pi^0$	10.0%
$\eta' \to \pi^0\pi^0\pi^0$	14.4%
$\eta' \to \pi^0\pi^0\eta$	20.9%
$\eta' \to \gamma\gamma$	8.2%
$\eta' \to \pi\pi\pi^0$	4.7%
$\eta' \to \pi^0\pi^0\pi^0$	6.8%

η Decay Modes	
✔ $\eta \to \gamma\gamma$	39.4%
✔ $\eta \to \pi\pi\pi^0$	22.6%
$\eta \to \pi^0\pi^0\pi^0$	32.5%

✔ = included in Jan 2007 Tagged analysis

At this point all listed modes are reconstructed in untagged analysis until proven worthless.

Expected Neutrino Reconstruction Results

- MC Studies:
  - Assume Previous upper limit for answer.
  - Tune Cuts to optimize Figure of Merit (FOM) in "signal bin"
    - "signal bin" = $|M_{BC}-M_D| < 0.015$ GeV

$$FOM = \frac{S^2}{S+B} \qquad M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_e + \vec{p}_{miss} + \vec{p}_{\eta'}|^2}$$

- We only had N_σ=2.8

The number of standard deviations the signal is above backgrounds.

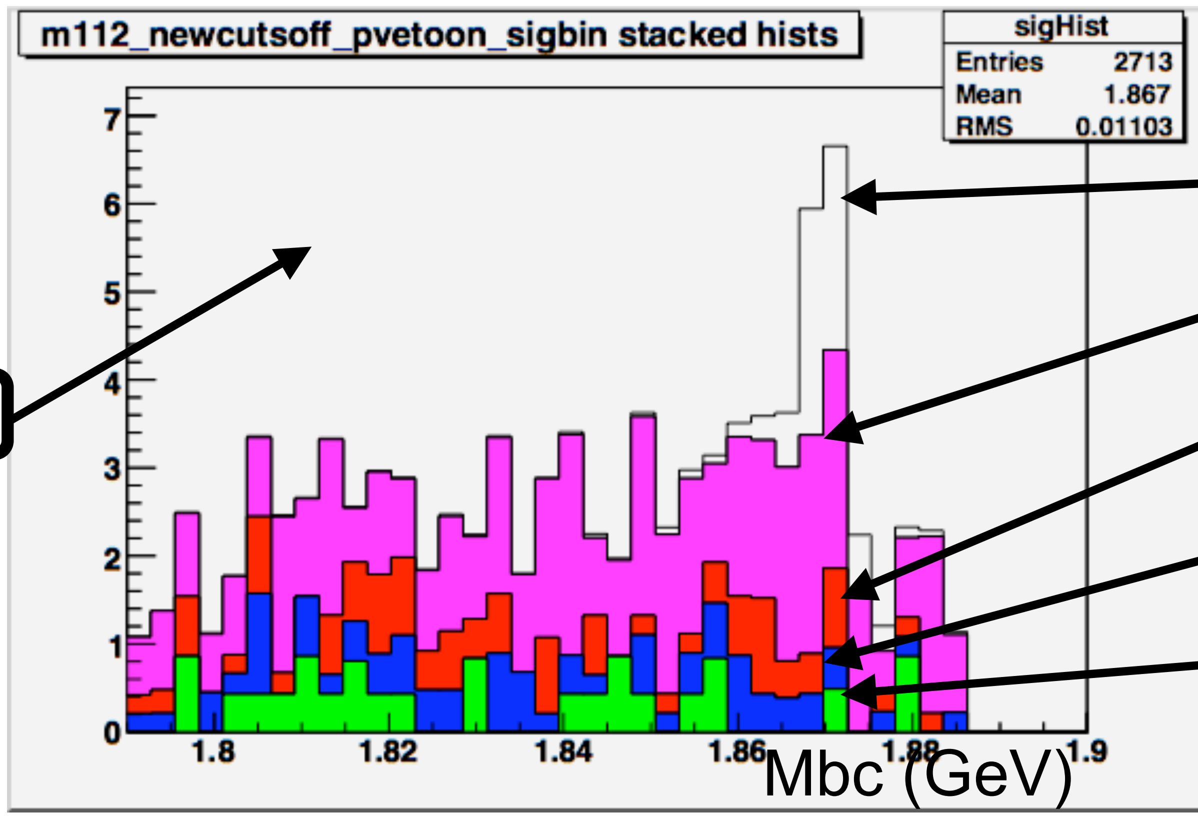
$$N_\sigma = \sqrt{\sum_i \frac{S_i^2}{S_i + B_i}}$$

Quest for 3σ

Strategy: Focus on difficult but high BR $\eta' \rightarrow \rho^\circ \gamma$, use lessons learned from this on everything else.

Binned in ρ° mass:
300-540MeV
540-660MeV
660-780MeV
780-900MeV

Note,due to lack of phase space in decay, peak of rho is not 770

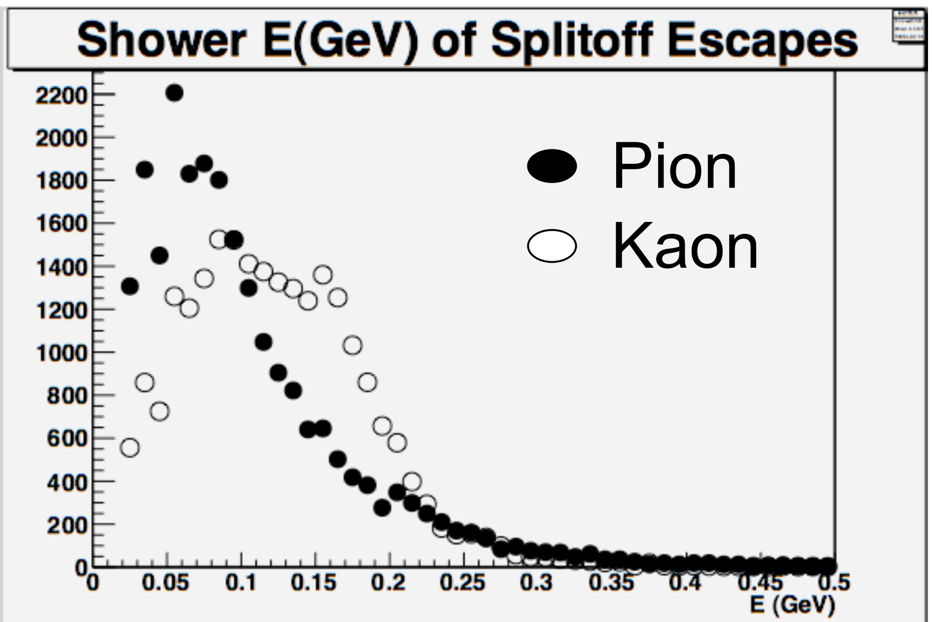


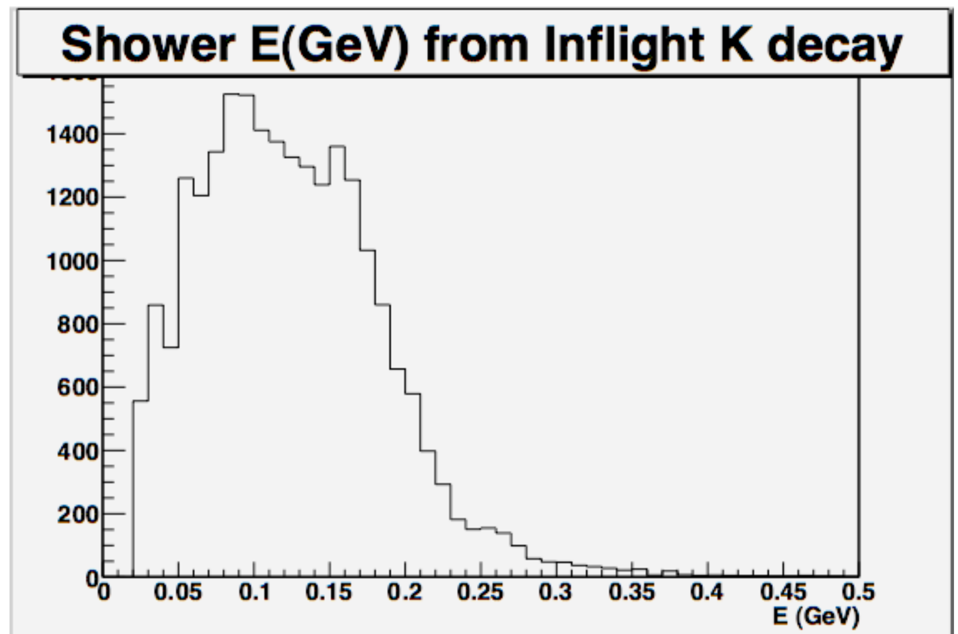
K*eν background:

Can't distinguish: [Kππ][K*(kπ)eν] from [?][η'(ρ°γ)eν]

Poor Neutrino Resolution from Extra Photons:

- "Splitoff Escapes" (15% from K, 5% from Pi)
- Inflight K -> X pi0 (more than 5%, not inc collisions)
- ***Almost*** impossible to cut out





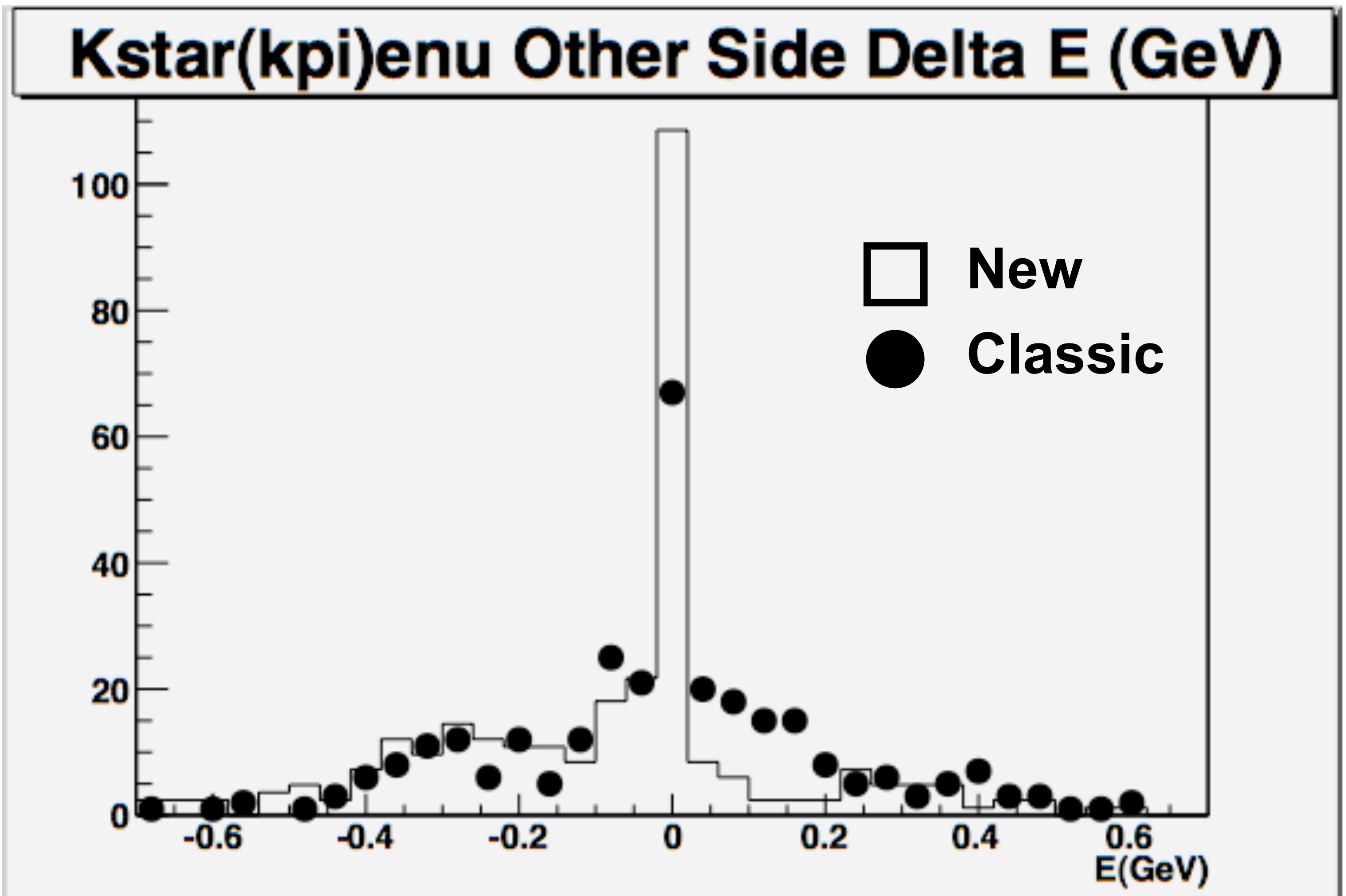
Golden Algorithm

- Main Goal: Remove extra showers
- Use Modified "Golden π^0" Idea (Chulsu & Nadia)
  - Was contender to replace the "Splitoff" algorithm.
  - "Splitoff" worked better, so this was abandoned.
- Create List of π^0 candidates
  - Use all showers far from tracks.
- Pick π^0 candidates with the smallest |pull|
  - Pull = $(M_{recon}-M_{true})/\sigma_M$
  - Use each shower only once
- π^0 with |pull| > 3.0 not included.

New Neutrino Algorithm

- **Generic "Other Side" D Reconstruction.**
  - **Exclude Signal D tracks, showers**
  - **Use Each Shower, track, K_s only once:**
    - "Splitoff" App. Show.,
    - Trkmn Tracks,
    - $K_S \to \pi\pi$ candidates
  - **Assign Showers to $X \to \gamma\gamma$ Candidates**
    - Best |pull| π^0 (-5.0 to 3.0)
    - Best pull π^0 or η (-25.0 to 15.0)
  - **Assign best $K_S \to \pi\pi$**
  - **Remaining tracks assigned π^+ or K^+ (RICH, Ionization)**
  - **Deal With Extra Showers:**
    - If $K^\pm$, veto extra showers <0.25GeV
    - If no $K^\pm$, veto extra showers < 0.10 GeV
  - **Sum Error matrices to calculate uncertainty in M_D**

Improvement over Classic Neutrino Reconstruction



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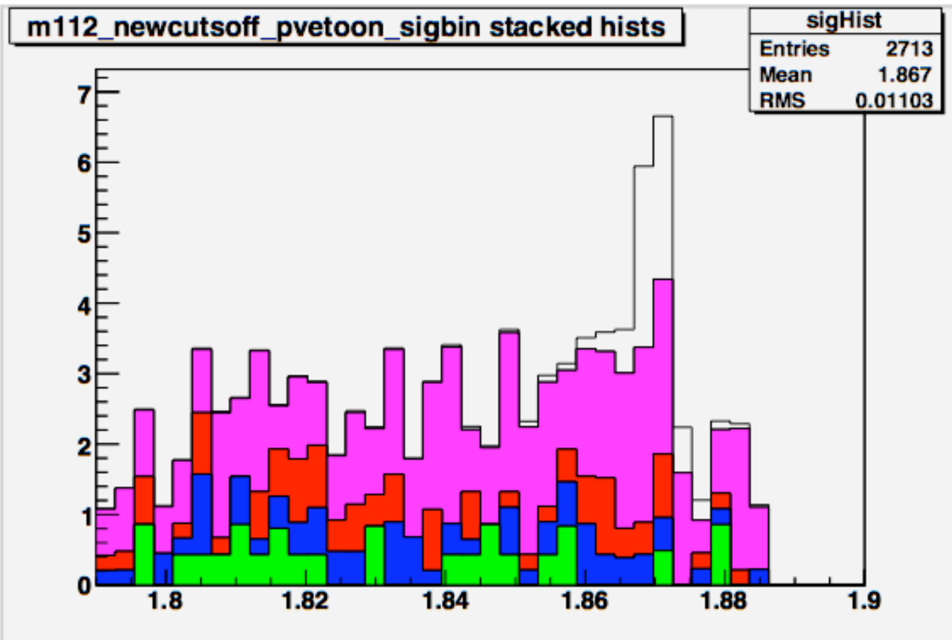
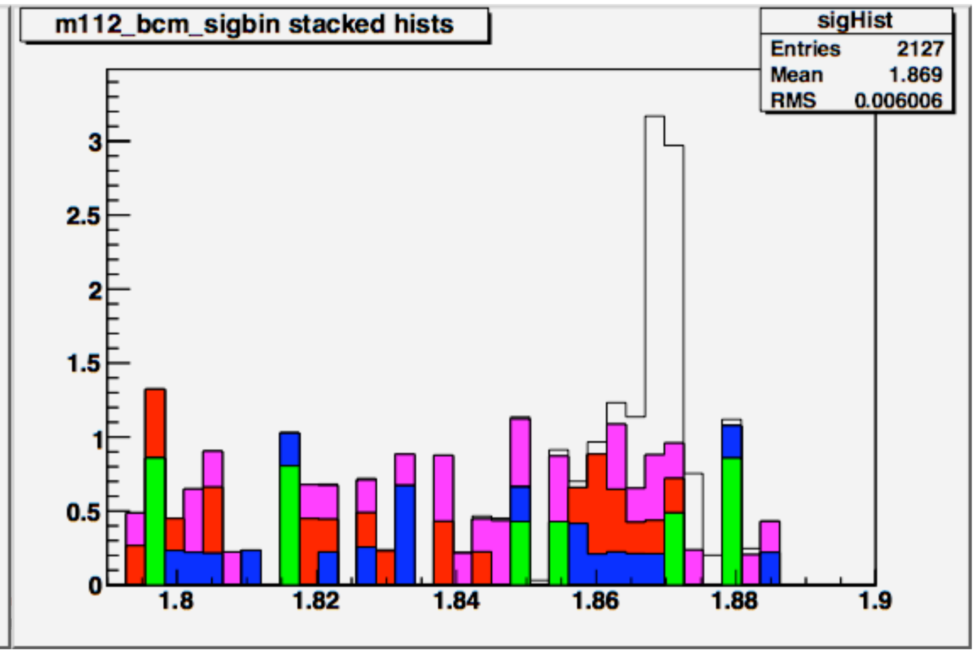
K*enu Veto:

- Calculate: $D_{pull}=(M_D-1.869\text{GeV})/\sigma_D$
- Find Best D_{pull} out of $(\eta',\eta,\rho,\rho^0,\pi,\pi^0,k,k_s,k^*)e\nu$
  - (|vee|<0.15 && |dele|<0.15)
- Require: $D^2_{pull}(\eta' e\nu;\ \eta'\rightarrow\rho^\circ\gamma) - D^2_{pull}(\text{best}) < 9$
- Also remove "wrong sign K" Events
  - Other Side Kaons should have same charge as signal lepton
- More Restrictive other side track cuts (if not part of $K_S\rightarrow\pi\pi$)

Before



After



New Binning (High/Low Quality)

- Perform New Neutrino Reconstruction analysis.
- Bin results into H (high quality) L (low quality)
  - H bin:
    - |Dpull| < 3.0,
    - No un-vetoed Extra Showers
    - $\mathbf{M_{BC}}$ 1.8629GeV to 1.8789GeV
    - All $\pi^\circ$and η pull: -5.0 to 3.0
  - L bin: everything else

Why Bin?

- Imagine you have 14 Signal Events Over 14 Background.

$$N_\sigma^2 = \frac{S^2}{S+B} = \frac{14^2}{14+14} = 7$$

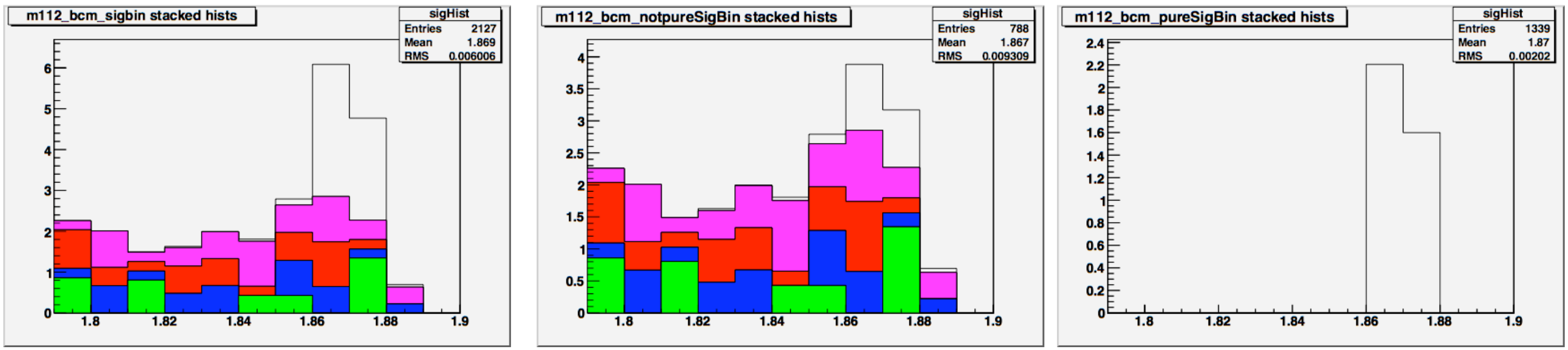
- If you had a cut that removed all of your background, and half of your signal?

$$N_\sigma^2 = \frac{S_1^2}{S_1+B_1} + \frac{S_2^2}{S_2+B_2} = \frac{7^2}{7} + \frac{7^2}{7+14} = 9.33$$

New Binning (High/Low Quality)

$\eta'(\rho^{\circ}\gamma)e\nu$
$M(\rho^{\circ})$ 660-780MeV

All **L Bin** **H Bin**



M_{BC} (GeV)

With all the improvements N_{σ} goes from 2.8 to 3.8

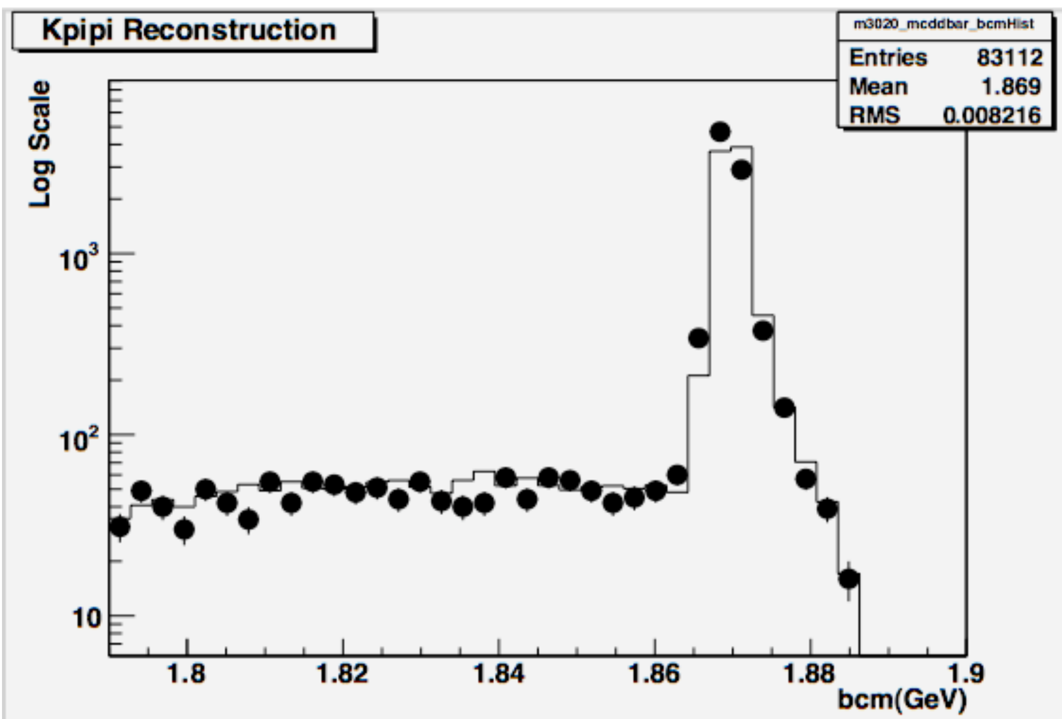
Good News/ Bad News

- Bad News First.
  - The Cost of this improvement is higher sensitivity to D hadronic branching fractions.
- Good News:
  - The new algorithm can be used to measure those branching fractions.

Not just for Neutrinos

- Neutrino reconstruction works with or without the neutrino. (Num Electron =0, low missing Energy)
- Replace Xeν with Kππ, use same algorithm on other side.

Log Scale



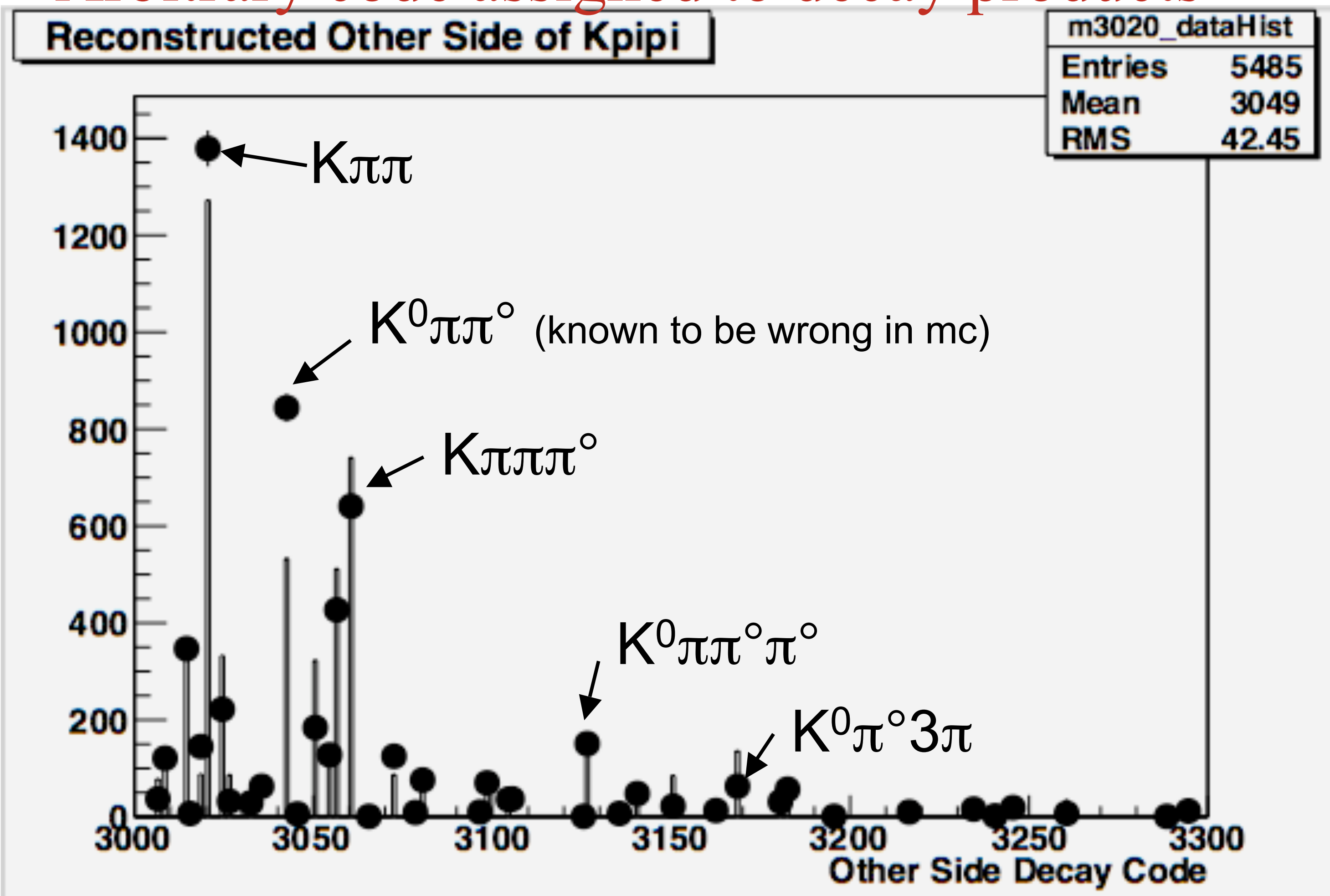
● Data

□ Ddbar+Cont

Beam Constrained Mass (GeV)

Other Side D Decays

- Use High Quality Bin like a generic tag.
- Arbitrary code assigned to decay products



Solving for Branching fractions

- Normalize MC to data using known kππ fraction
- Get generator level event information
- Create cross feed matrix. Invert, and solve for mode weights.

May also have systematics wrapped into it

$$\begin{pmatrix} R_1G_1 & R_1G_2 & \cdots & R_1G_N \\ R_2G_1 & R_2G_2 & \cdots & R_2G_N \\ \cdots & \cdots & \cdots & \cdots \\ R_NG_1 & R_NG_2 & \cdots & R_NG_N \end{pmatrix} \begin{pmatrix} W_1 \\ W_2 \\ \cdots \\ W_N \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ \cdots \\ D_N \end{pmatrix} - \begin{pmatrix} C_1 \\ C_2 \\ \cdots \\ C_N \end{pmatrix}$$

R_iG_k = N true **k** recon as **i**

W_k = (true Br)$_k$/(MC Br)$_k$

D_k = N data in mode k

C_k = Cont in mode k **Very small**

D+ Hadronic Branching Fractions

Decay Mode	RCG Branching Fraction	PDG Branching Fraction	N sigma Diff
pi pi0	9.21E-04 +/- 1.00E-04	1.28E-03 +/- 8.00E-05	-2.80
3pi	3.67E-03 +/- 2.06E-04	3.31E-03 +/- 2.10E-04	1.22
pi Ks	1.48E-02 +/- 4.55E-04	1.47E-02 +/- 6.00E-04	0.08
pi 2pi0	6.42E-03 +/- 8.48E-04	4.80E-03 +/- 4.00E-04	1.73
3pi 1pi0	1.24E-02 +/- 5.37E-04	1.18E-02 +/- 9.00E-04	0.53
pi eta(gg)	1.18E-03 +/- 1.16E-04	1.36E-03 +/- 1.20E-04	-1.08
5pi	1.75E-03 +/- 1.98E-04	1.68E-03 +/- 1.70E-04	0.27
K Ks	3.13E-03 +/- 2.17E-04	2.95E-03 +/- 1.90E-04	0.64
ks pi pi0	6.80E-02 +/- 1.40E-03	7.00E-02 +/- 5.00E-03	-0.39
K K pi	8.64E-03 +/- 3.76E-04	1.00E-02 +/- 4.00E-04	-2.48
Ks 3pi	2.86E-02 +/- 8.34E-04	3.10E-02 +/- 2.20E-03	-1.01
K 2pi pi0	5.29E-02 +/- 1.26E-03	6.00E-02 +/- 2.80E-03	-2.30
pi 2Ks	3.50E-03 +/- 4.53E-04	5.30E-03 +/- 2.30E-03	-0.77
K 4pi	6.31E-03 +/- 4.45E-04	5.80E-03 +/- 6.00E-04	0.68
3pi eta(gg)	1.40E-03 +/- 1.58E-04	9.30E-04 +/- 1.90E-04	1.90
2Ks K	2.47E-03 +/- 3.33E-04	4.60E-03 +/- 2.10E-03	-1.00

The above uses Br($k\pi\pi$)=0.0915

28 are 3σ or better

Uncertainties are Statistical only

D^0 Hadronic Branching Fractions

Decay Mode	RCG Branching Fraction	PDG Branching Fraction	N sigma Diff	% Difference
pi pi	1.65E-03 +/- 9.68E-05	1.36E-03 +/- 3.20E-05	2.81	18.98%
pi0 pi0	7.57E-04 +/- 9.87E-05	7.90E-04 +/- 8.00E-05	-0.26	-4.33%
K pi	3.82E-02 +/- 4.70E-04	3.80E-02 +/- 7.00E-04	0.18	0.39%
2pi pi0	1.47E-02 +/- 3.93E-04	1.31E-02 +/- 6.00E-04	2.23	11.51%
4pi	8.52E-03 +/- 2.80E-04	7.31E-03 +/- 2.70E-04	3.11	15.29%
Ks pi0	1.16E-02 +/- 3.96E-04	1.14E-02 +/- 1.20E-03	0.18	2.02%
2K	4.42E-03 +/- 1.67E-04	3.84E-03 +/- 1.00E-04	2.96	13.96%
Ks 2pi	3.10E-02 +/- 6.36E-04	2.90E-02 +/- 1.90E-03	1.01	6.77%
ks pi pi0	6.80E-02 +/- 1.40E-03	7.00E-02 +/- 5.00E-03	-0.39	-2.90%
2pi 2pi0	1.11E-02 +/- 7.00E-04	9.80E-03 +/- 9.00E-04	1.14	12.42%
K 3pi	8.48E-02 +/- 9.97E-04	7.72E-02 +/- 2.80E-03	2.56	9.39%
4pi pi0	3.85E-03 +/- 3.31E-04	4.10E-03 +/- 5.00E-04	-0.41	-6.22%
Ks 2pi0	1.10E-02 +/- 6.15E-04	1.05E-02 +/- 2.00E-03	0.23	4.42%

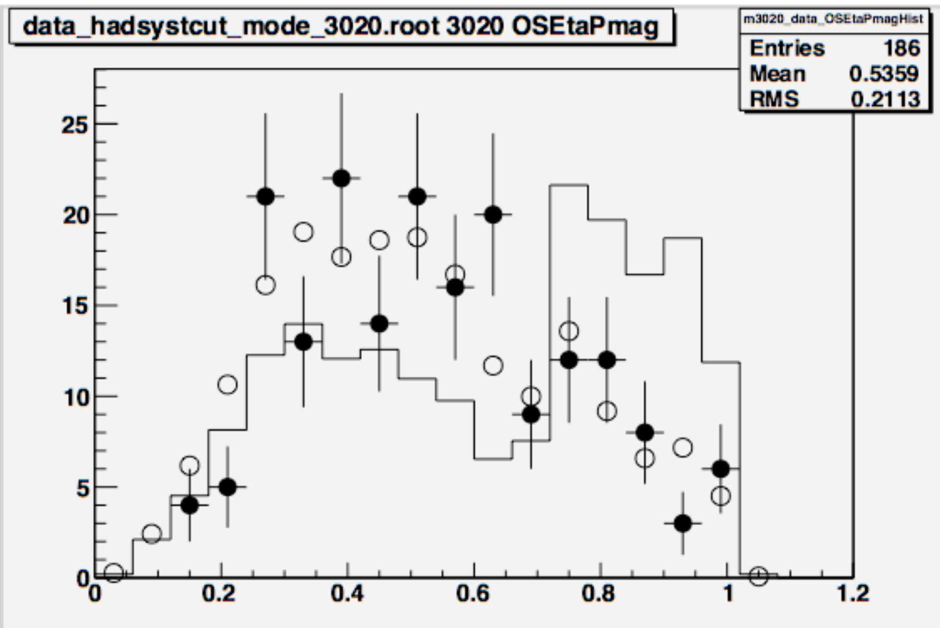
32 at 3σ or better

The above uses $Br(K\pi\pi^0)=0.1457$

Uncertainties are Statistical only

Effects of Reweighting

- After re-weighting my branching fractions, efficiency of $D \rightarrow \eta' e\nu$ goes down by ~3% of itself.
- Multiplicities of particles and momentum distributions on other side improve.



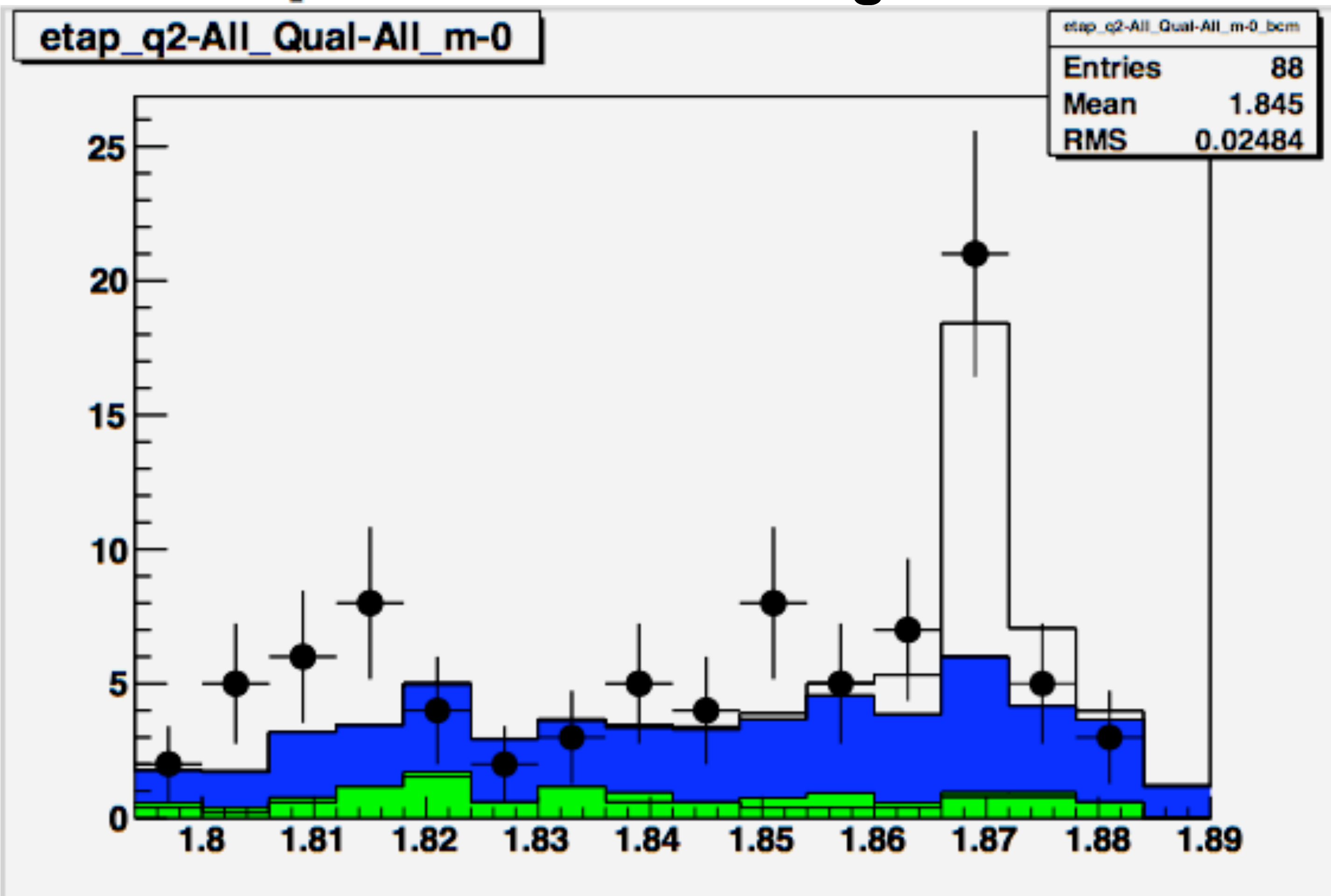
Background η momentum spectrum (GeV)

- ● **Data**
- ○ **Reweighted MC**
- □ **MC**

Preliminary Results

$D^+ \to \eta' e^+ \nu$

All bins expecting signal added together

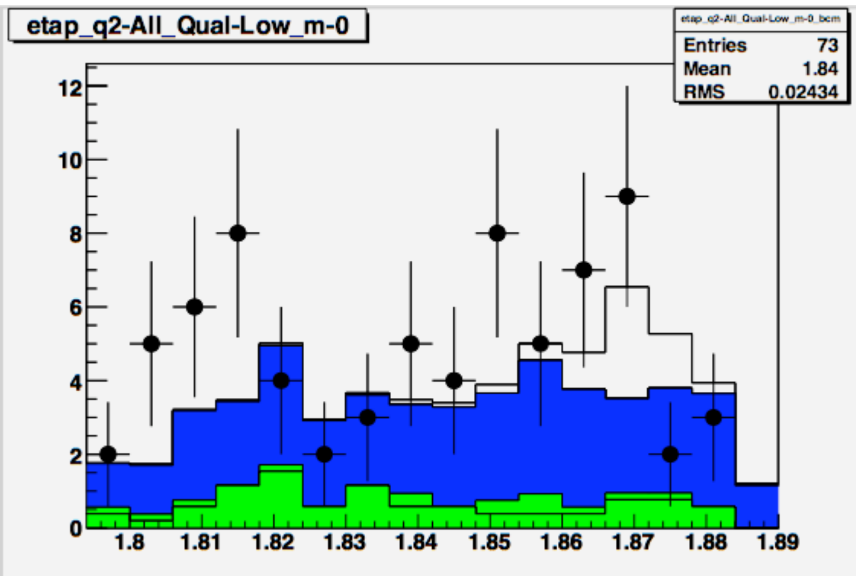


Beam Constrained Mass (GeV)

High/Low Bins

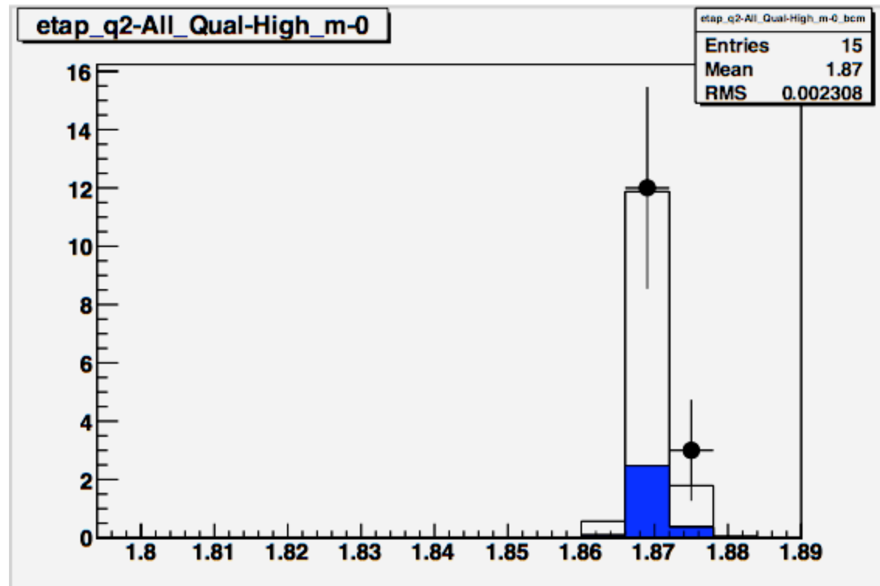
$$D^+ \to \eta' e^+ \nu$$

Low Quality



B.C.M. (GeV)

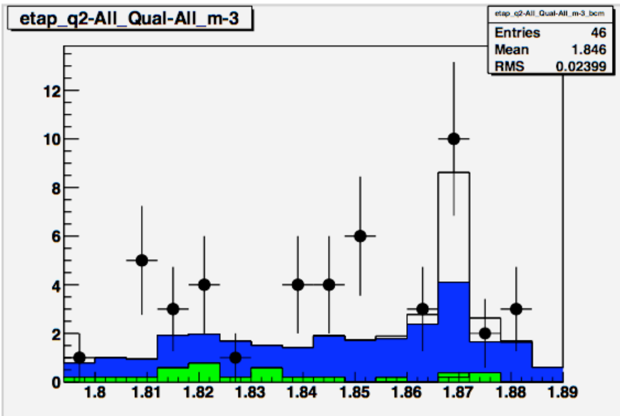
High Quality



B.C.M. (GeV)

Decay Modes

$$\eta' \to \rho^0 \gamma$$

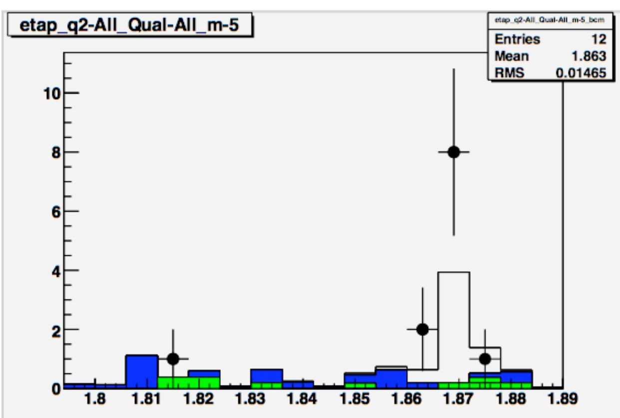


$$D^+ \to \eta' e^+ \nu$$

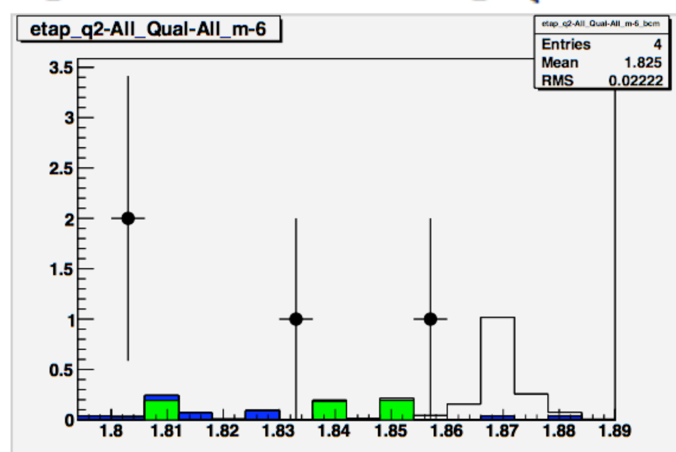
Both Quality Bins

Beam Constrained Mass (GeV^2) for each decay mode

$$\eta' \to \pi\pi\eta(\gamma\gamma)$$



$$\eta' \to \pi\pi\eta(\pi\pi\pi^0)$$



VERY Preliminary

Efficiency Corrected Yields:

- $\eta' e\nu$: 915 +/- 266
  - $\Delta(-2\mathrm{Log}(L)) = 22.5$ (4.7σ)
- Remaining Details:
  - Finishing up Systematic Studies

Summary

- Developed improved method for reconstructing Semileptonic Decays at CLEO
- Measured $D \rightarrow \eta' e \nu$ branching fraction to 3σ
- Measured ~60 D hadronic decays to 3σ or better.
- Used to improve Collaboration Monte Carlo
- Another Grad Student (D. Hertz) applied my code to improving measurement $D \rightarrow \mu \nu$