Charm Meson Decay Constants

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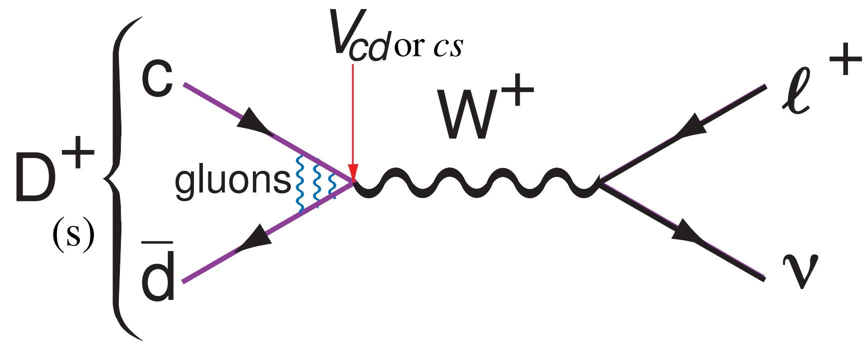
Leptonic Decays: $D \to \ell^+\nu$

c and $\bar{q}$ can annihilate, probability is proportional to wave function overlap

Standard Model decay diagram:



In general for all pseudoscalars:

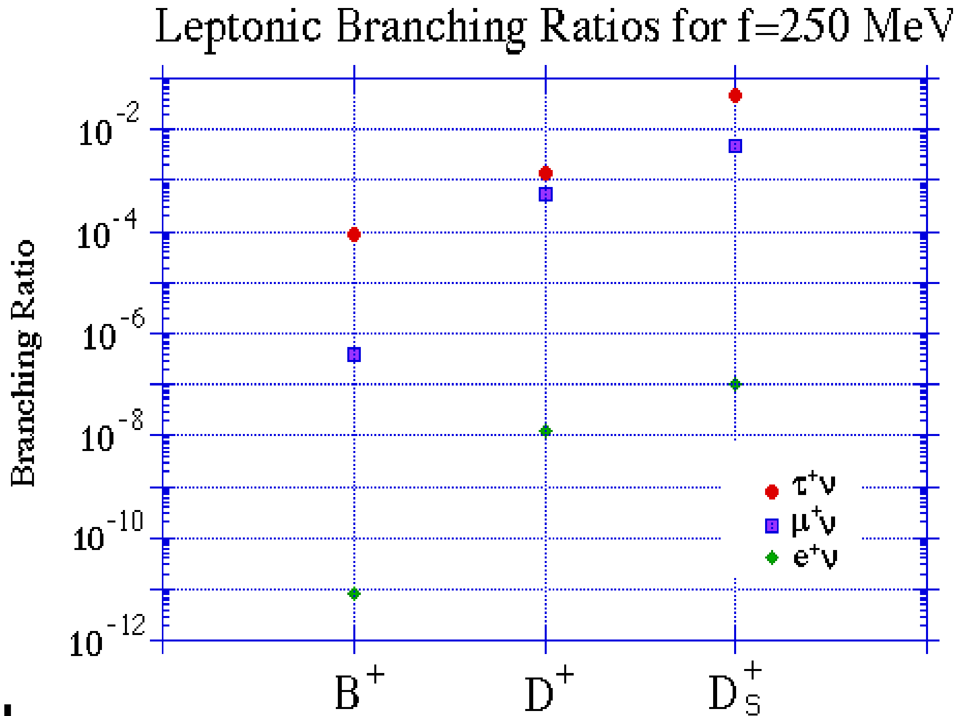
$$\Gamma(P^+ \to \ell^+\nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if V_{Qq} is known, here take $V_{cd} = V_{us} = 0.2256$,

$V_{cs} = V_{ud} - V_{cb}/4 = 0.9734$

Experimental Considerations

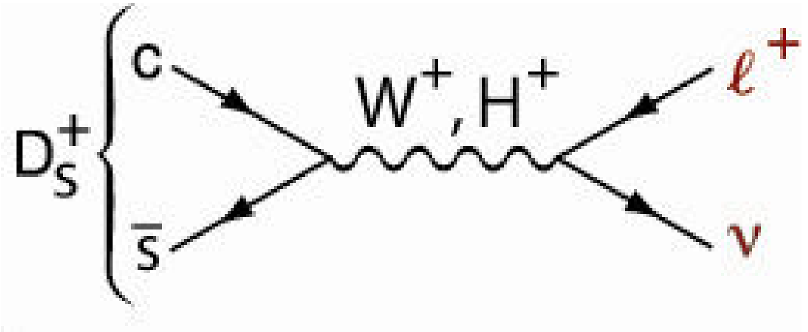
- In principle have access to 6 decays
  $D^+ \rightarrow e^+\nu,\ \mu^+\nu,\ \tau^+\nu$
  $D_S^+ \rightarrow e^+\nu,\ \mu^+\nu,\ \tau^+\nu$
- Helicity suppression causes $e^+\nu$ mode to be highly suppressed



- $D \rightarrow \tau^+\nu$ has at 2 neutrinos missing, so is more difficult to detect
- Only B^+ available, not B^o or B_S & $\mathcal{B}$ is low

Reasons to Measure

- Lattice calculations needed for all sorts of heavy flavor parameters, e.g. $\xi = f_B/f_{Bs}$, $B \to \pi \ell \nu$ form-factors…f_D & f_{Ds}/f_D provide an experimental check
- Possibilities to see effects of New Physics
  - Interference with H^+.
  - Rate ratio



$$\frac{\Gamma(P^+ \to \tau^+ \nu)}{\Gamma(P^+ \to \mu^+ \nu)} = m_\tau^2 \left(1 - \frac{m_\tau^2}{M_P^2}\right)^2 \Big/ m_\mu^2 \left(1 - \frac{m_\mu^2}{M_P^2}\right)^2$$

is sensitive to neutrino couplings, e.g. a sterile neutrino coupling differently to ν_μ & ν_τ, or any model which doesn't couple as m_ℓ^2, e.g. Leptoquarks

CLEO's Technique for $D^+ \to \mu^+\nu$

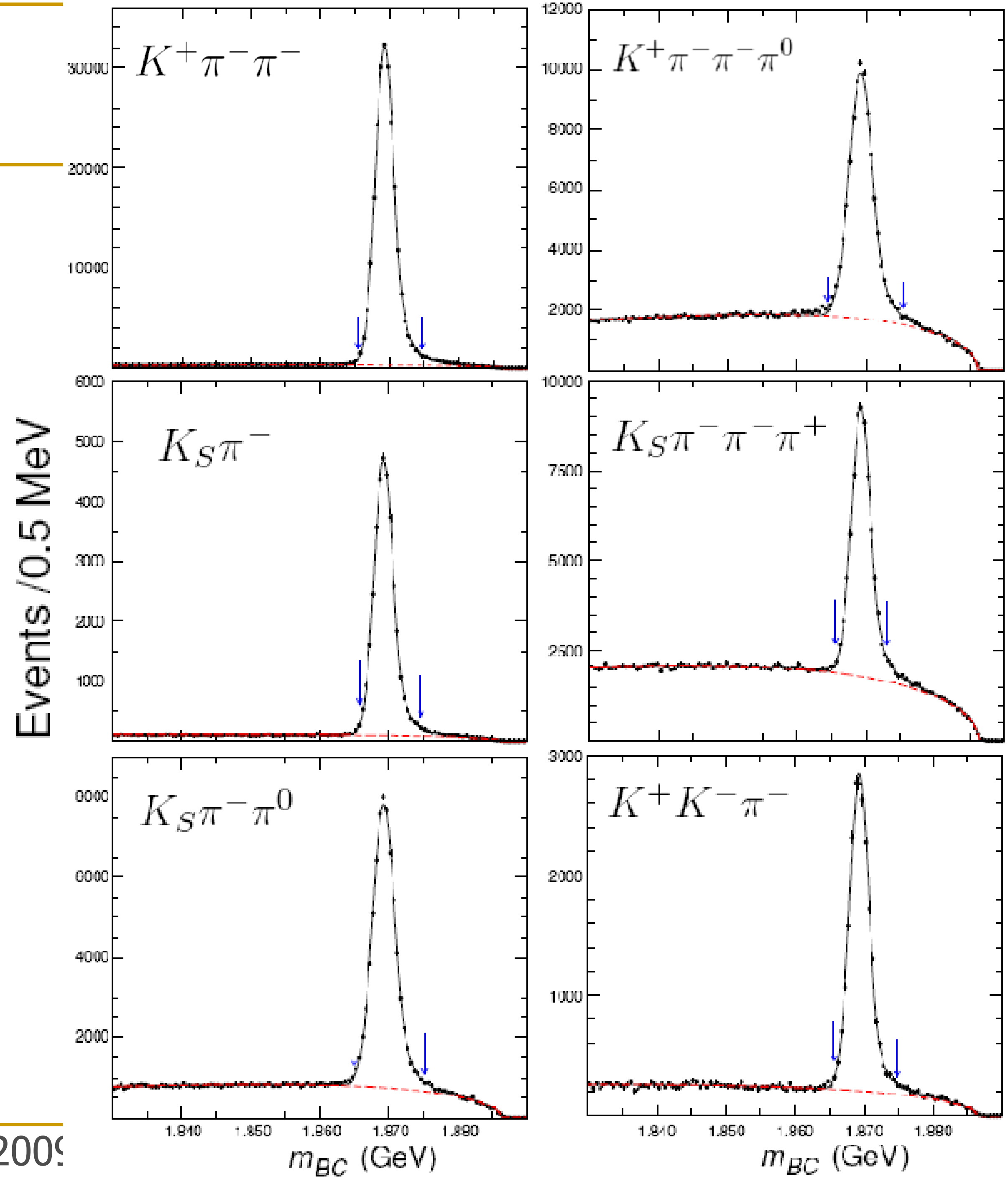
- Exploit $e^+e^- \to D^-D^+$
- Fully reconstruct a D^-, and count total # of tags
- Seek events with only one additional oppositely charged track within $|\cos\theta| < 0.9$ & no additional photons > 250 MeV (to veto $D^+ \to \pi^+\pi^o$)
- Charged track must deposit only minimum ionization in calorimeter [< 300 MeV: case (i)]
- Compute MM^2. If close to zero then almost certainly we have a $\mu^+\nu$ decay.

$$\mathbf{MM}^2 = (E_{D^+} - E_{\ell^+})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+})^2$$

We know $E_{D^+} = E_{beam}$, $\mathbf{p}_{D^+} = - \mathbf{p}_{D^-}$

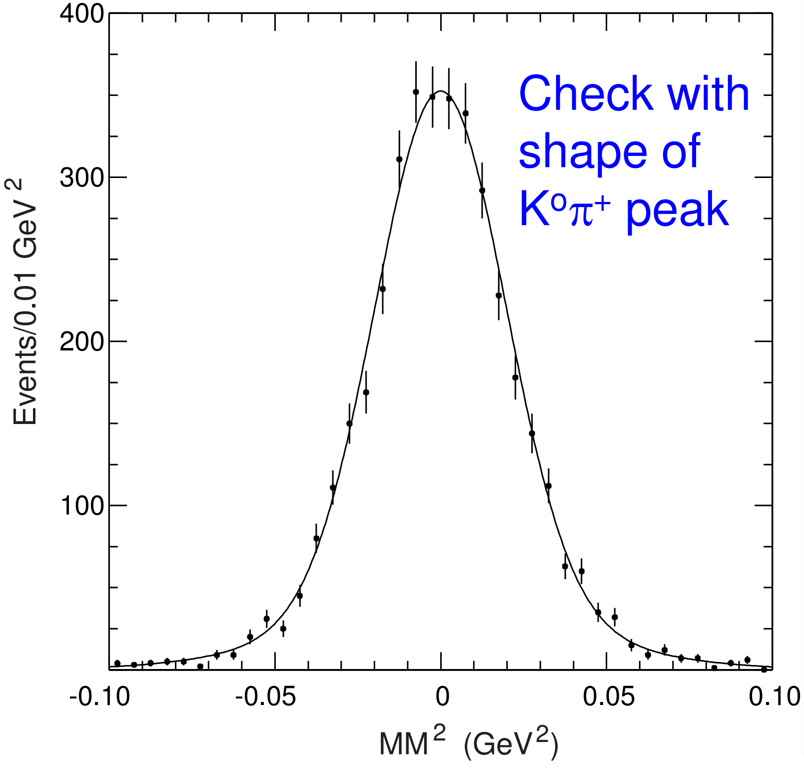
Tags

- Total of 460,000
- Background 89,400

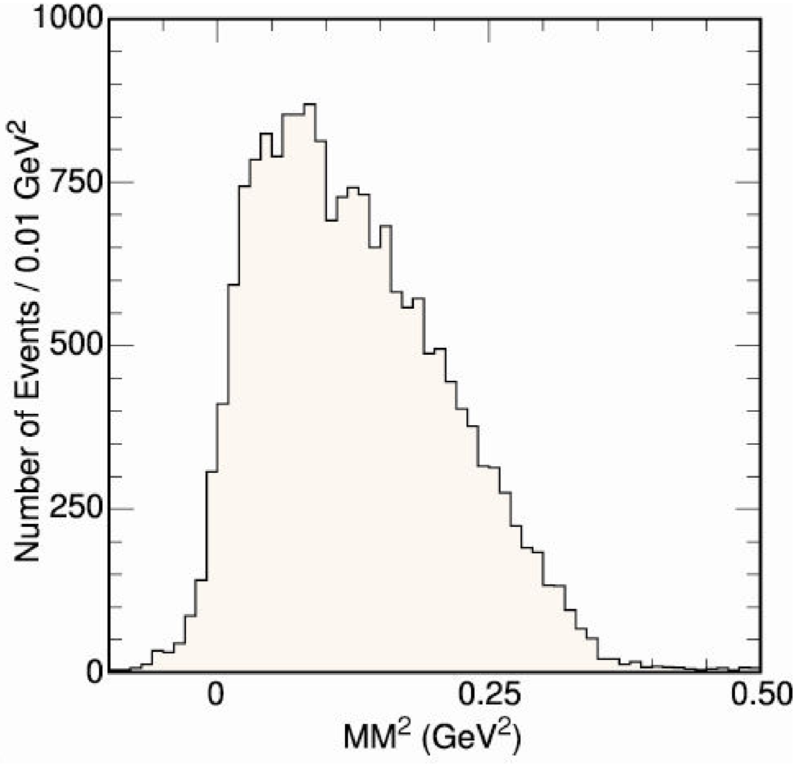


MM^2 Signal Shapes

$$MM^2 = (E_{Beam} - E_{\ell^+})^2 - (-\vec{p}_{D^-} - \vec{p}_{\ell^+})^2$$



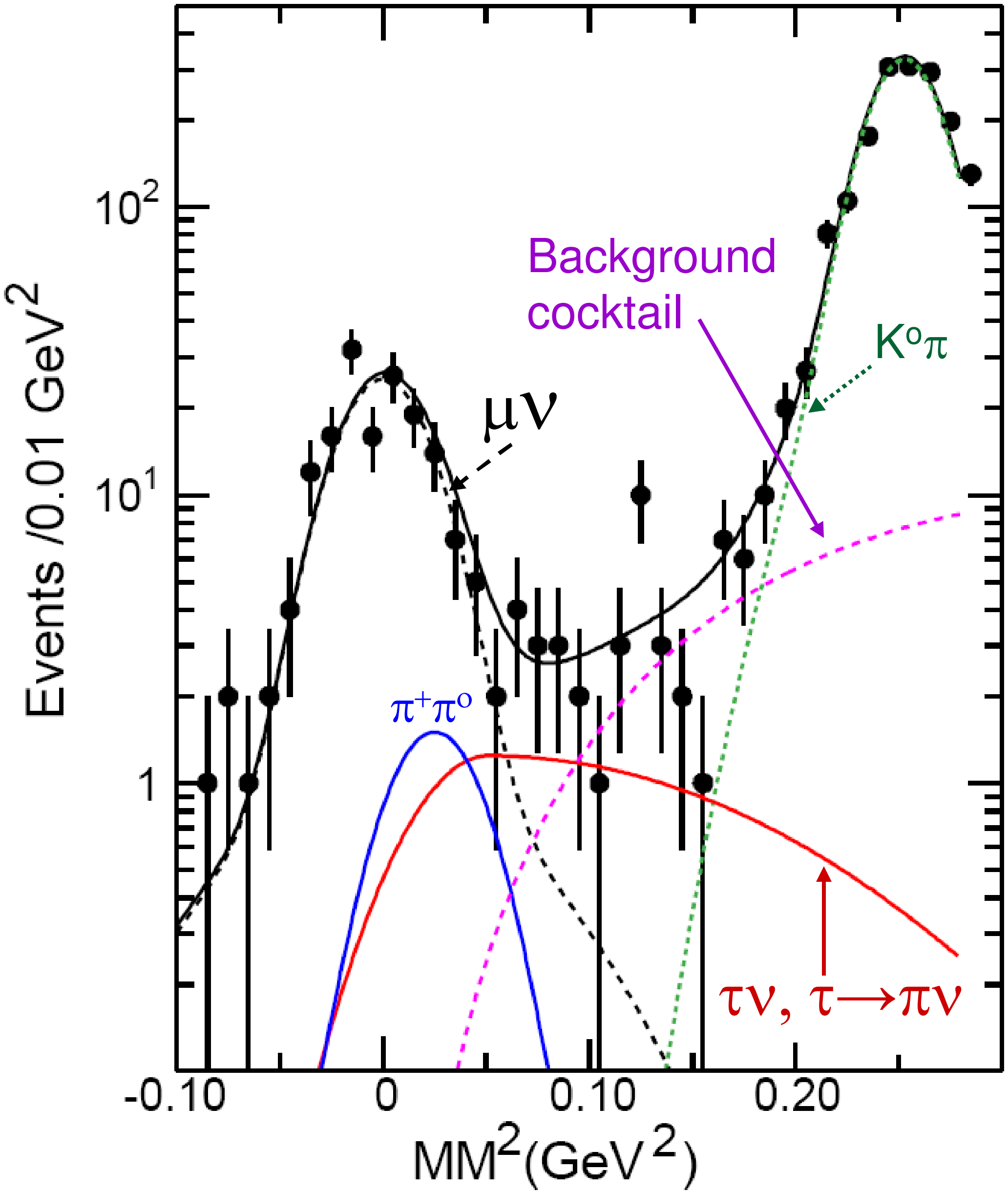
Monte Carlo Signal μν



Monte Carlo Signal τν, τ→πν

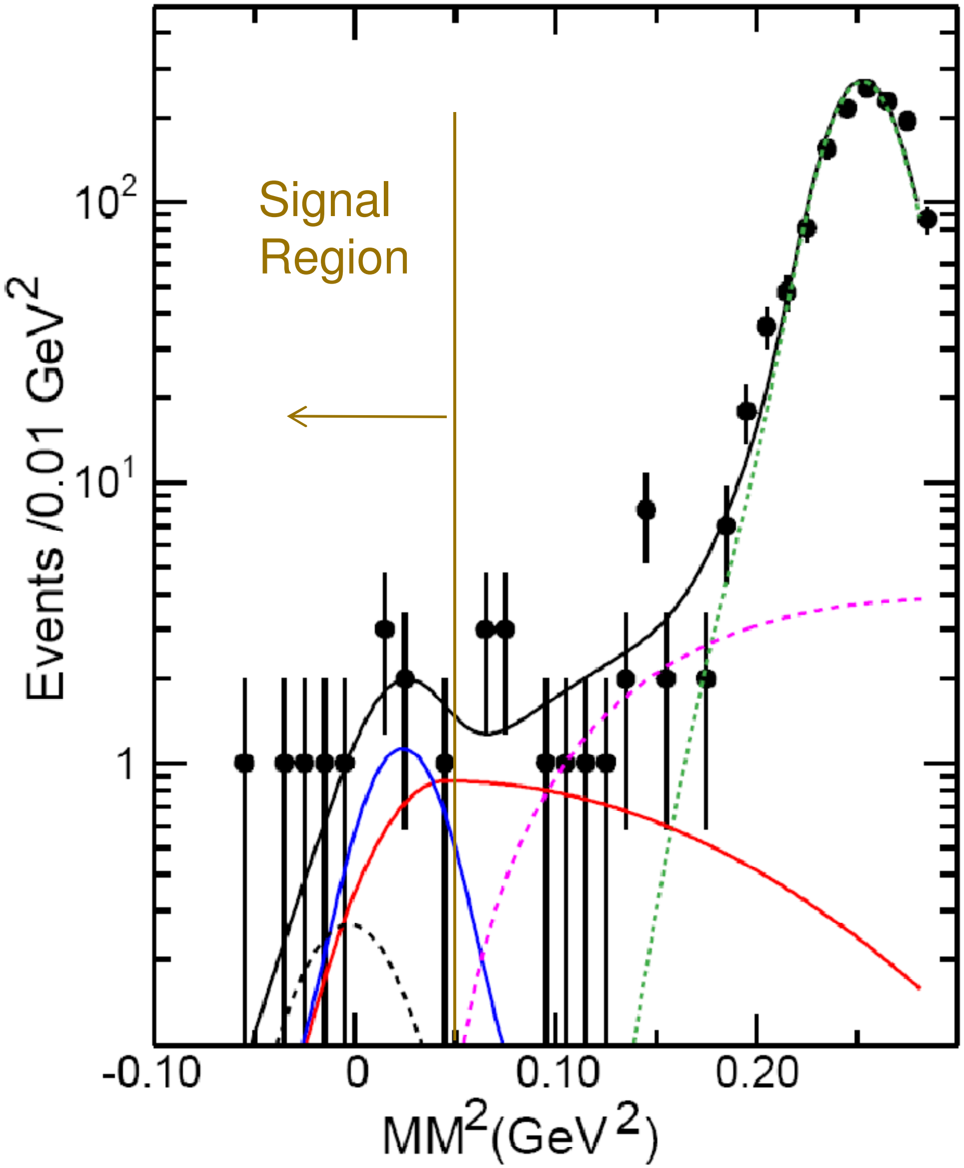
Fit MM^2 to sum of signal & bkgrd

- Case(i) E< 300 MeV where $\tau^+\nu/\mu^+\nu$ is **fixed** to SM ratio
  - 149.7±12.0 $\mu\nu$
  - 28.5 $\tau\nu$
- Case(i) E< 300 MeV where $\tau^+\nu/\mu^+\nu$ is allowed to **float**
  - 153.9±13.5 $\mu\nu$
  - 13.5±15.3 $\tau\nu$



Background Check

- Use case(ii) E>300 MeV in EM calorimeter
- Fix $\tau\nu$ from case(i) $\mu\nu$.
- Consider signal region $|MM^2|<0.05$ GeV^2. Expect 1.7 $\mu\nu$ + 5.4 $\pi^+\pi^o$ + 4.0 $\tau\nu$ = 11.1
- Find 11 events
- Extra bkgrnd=-0.1±3.3 events



Systematic Errors

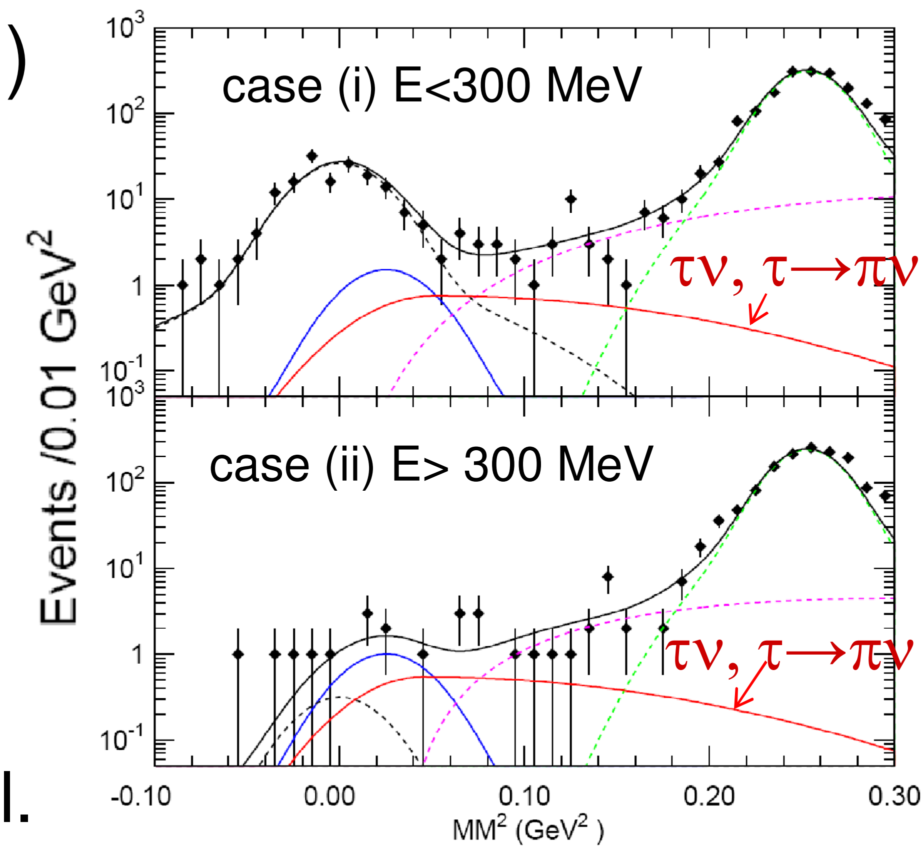
Source of Error	%
Finding the μ^+ track	0.7
Minimum ionization of μ^+ in EM cal	1.0
Particle identification of μ^+	1.0
MM^2 width	0.2
Extra showers in event > 250 MeV	0.4
Background	0.7
Number of single tag D^+	0.6
Total	**2.2**

Branching Fractions & f_{D+}

- Fix $\tau\nu/\mu\nu$ at SM ratio of 2.65
  - $\mathcal{B}(D^+\to\mu^+\nu)= (3.82\pm0.32\pm0.09)\times10^{-4}$
  - $f_{D+}=(205.8\pm8.5\pm2.5)$ MeV
  - This is best number in context of SM
- Float $\tau\nu/\mu\upsilon$
  - $\mathcal{B}(D^+\to\mu^+\nu)= (3.93\pm0.35\pm0.10)\times10^{-4}$
  - $f_{D+}=(207.6\pm9.3\pm2.5)$ MeV
  - This is best number for use with Non-SM models
- *These are final numbers with 818 pb^{-1}*
- *This is the only measurement*

Upper limits on τν & eν

- Here we fit both case(i) & case(ii) constraining the relative τν yield to the pion acceptance, 55/45.
- Find
  - $\mathcal{B}(D^+ \rightarrow \tau^+\nu) < 1.2\times10^{-3}$, @ 90% c.l.
  - $\mathcal{B}(D^+ \rightarrow \tau^+\nu)/2.65\mathcal{B}(D^+ \rightarrow \mu^+\nu) < 1.2$ @ 90% c. l.
- Also $\mathcal{B}(D^+ \rightarrow e^+\nu) < 8.8\times10^{-6}$, @ 90% c.l.



Measurements of f_{Ds}

Start with $D_S^+ \rightarrow \mu^+ \nu$

Use $e^+e^- \to D_S D_S^*$ at 4170 MeV

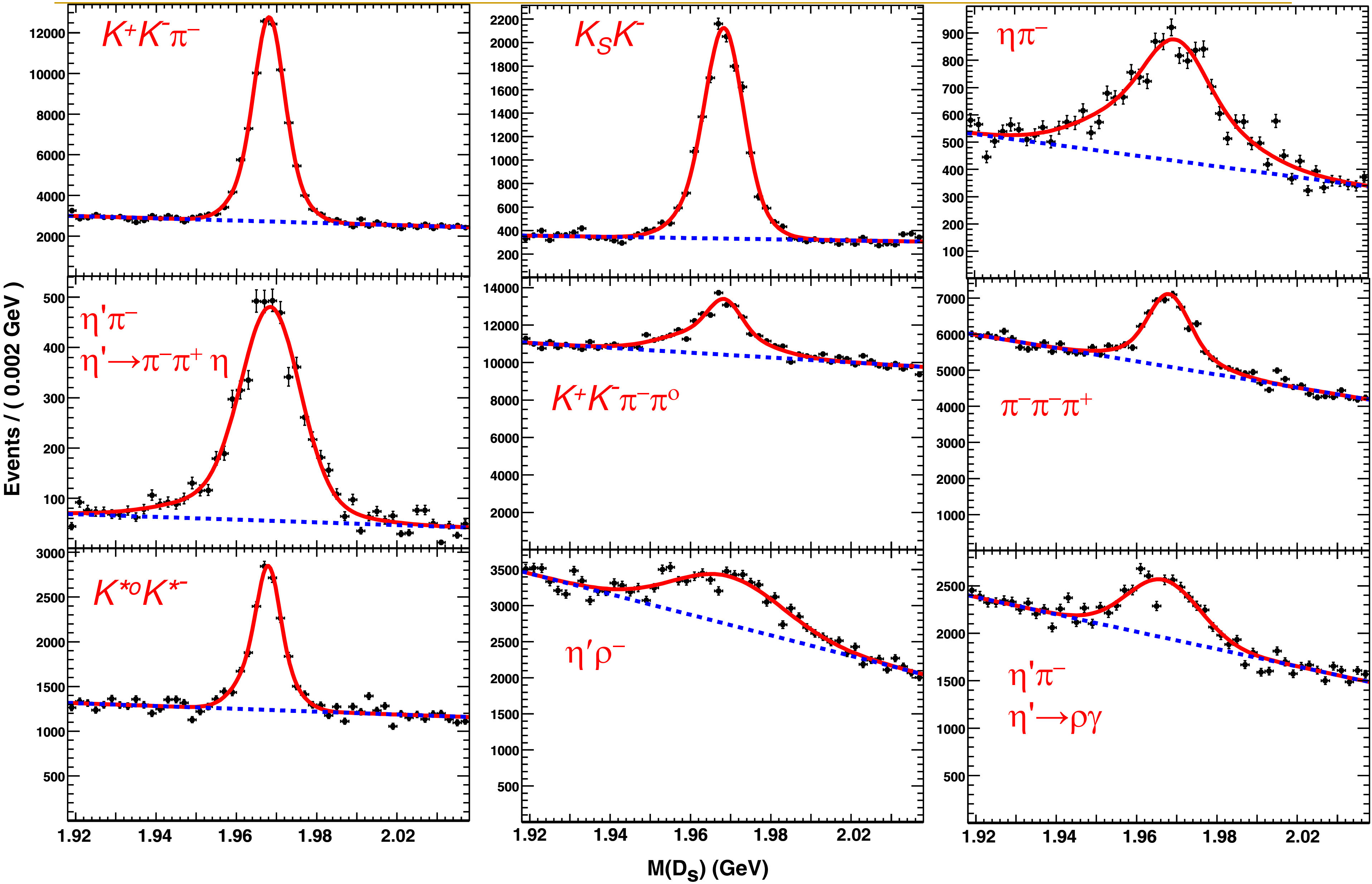
- Reconstruct D_S^-
- Find the γ from the D_S^* & compute MM^2 from D_S^- & γ

$$MM^{*2} = (E_{CM} - E_{D^-} - E_\gamma)^2 - (-\vec{p}_{D^-} - \vec{p}_\gamma)^2$$

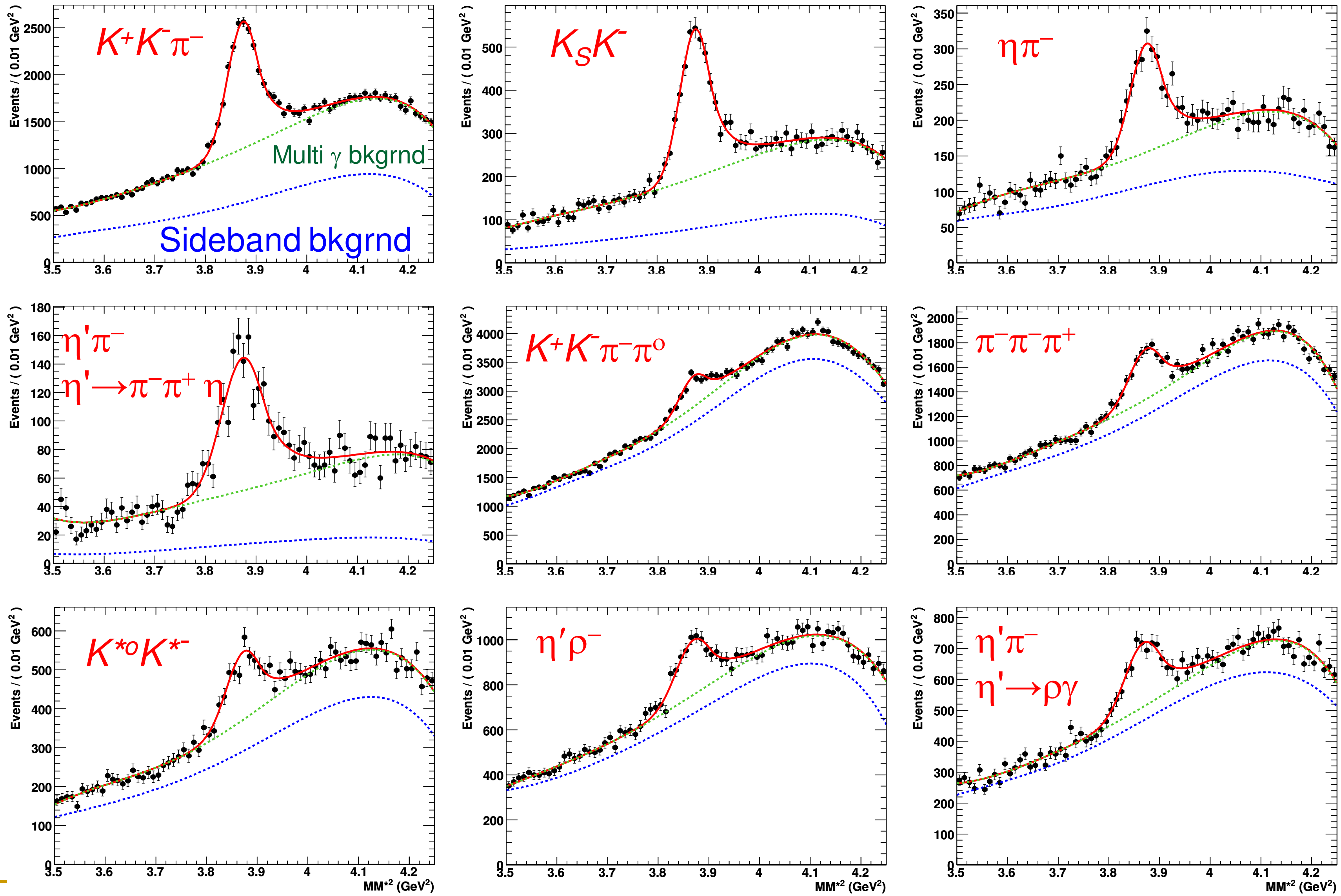
- Select combinations consistent with a missing D_S^+ & count the number
- Find MM^2 from candidate muon for (i) < 300 MeV in Ecal, (ii) E>300 MeV or (iii) e^- cand.

$$MM^2 = (E_{CM} - E_{D^-} - E_\gamma - E_\mu)^2 - (-\vec{p}_{D^-} - \vec{p}_\gamma - \vec{p}_\mu)^2$$

D_S^- Tags: Invariant Mass

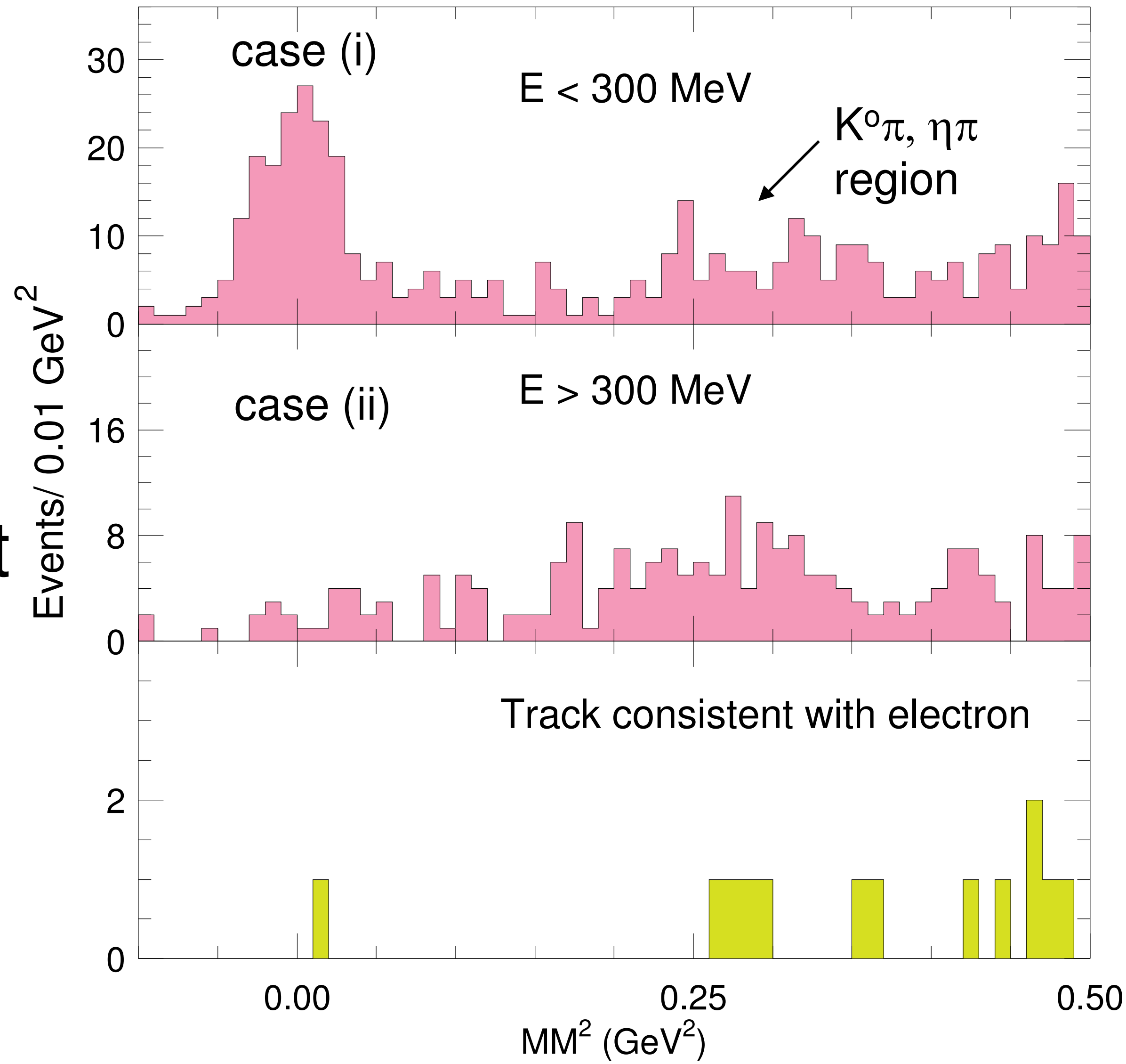


MM*^{2} Distributions From $D_S^- + \gamma$

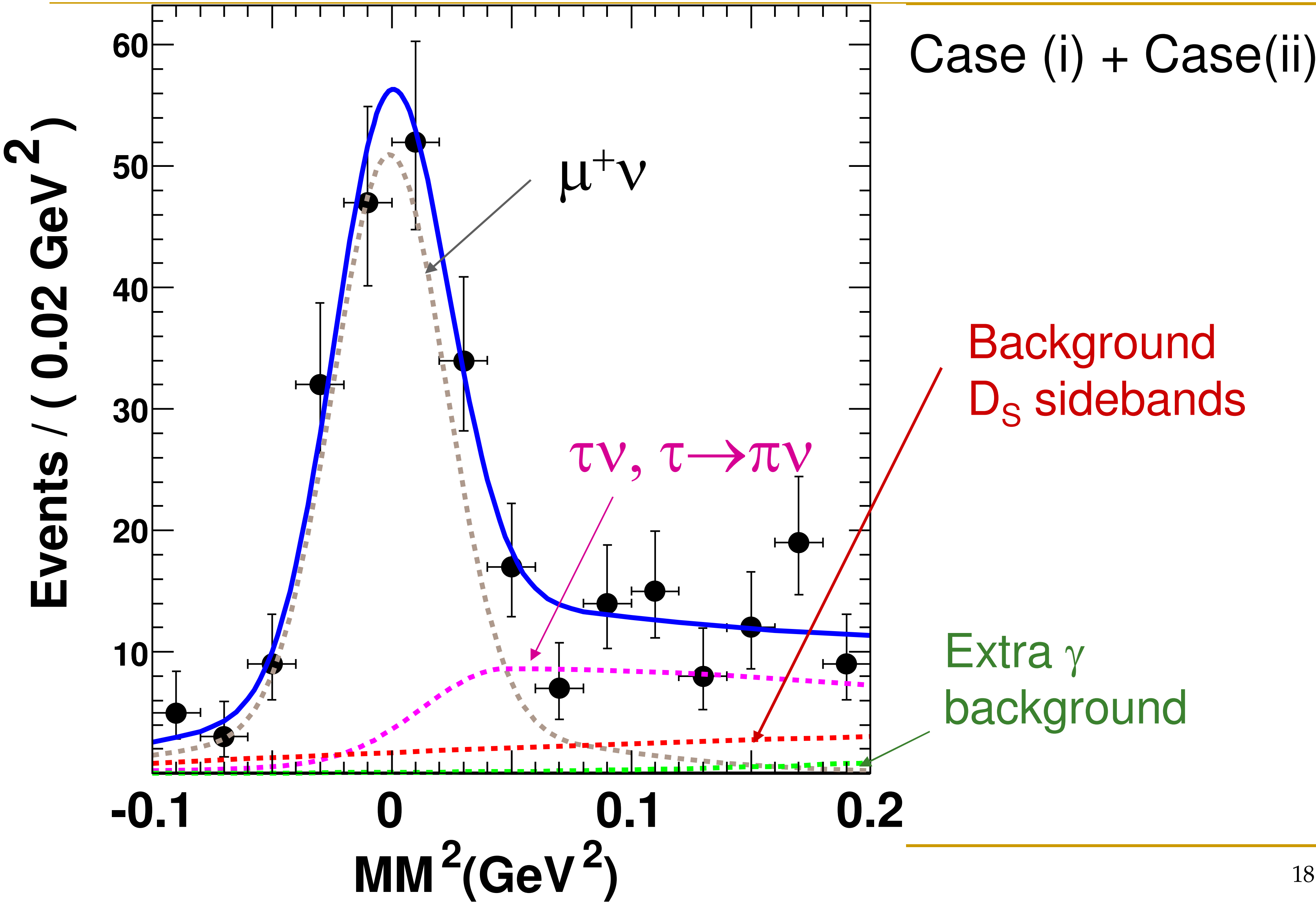


MM^2 data for D_s

- Total of 30848±695 tags
- 99% of $\mu^+\nu$ in E < 300 MeV
- 55%/45% split of $\tau^+\nu$, $\tau^+\rightarrow\pi^+\nu$ in two cases
- Small e^- background



Fit to signal & background



Systematic Errors

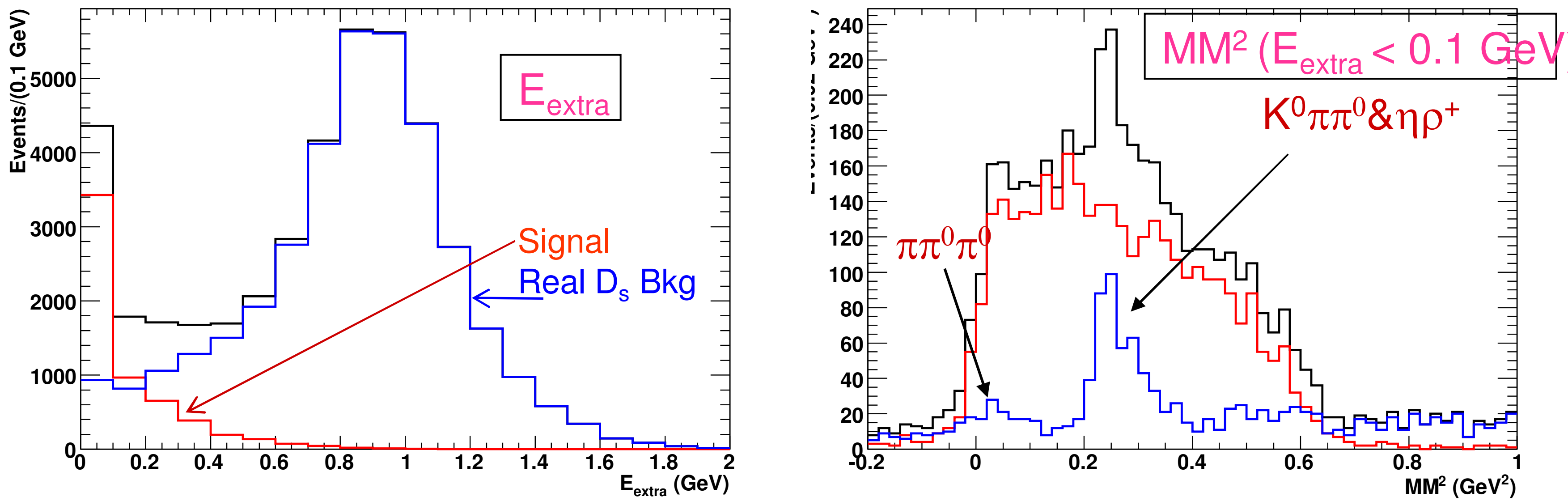
Source of Error	%
Finding the μ^+ track	0.7
Particle identification of μ^+	1.0
MM^2 width	0.2
Extra showers in event > 300 MeV	0.4
Background	1.0
Number of single tag D_S^-	2.0
Tag Bias	1.0
Radiative Correction	1.0
Total	**3.0**

$D_S^+ \to \tau^+\nu$, $\tau^+ \to \rho^+\nu$

- Because of the two neutrinos, the signal does not peak in MM^2, but the most important backgrounds do
- Consider the extra energy, E_{extra}, deposited in the Calorimeter unmatched to the D_S^- tag or the $\pi^+\pi^o$ from the ρ^+ decay. In principle, for real τ^+ decays $E_{extra}=0$. In fact some small fraction of real decays will have $E_{extra} > 0$ due to interactions in the detector, & some fraction of the background will have $E_{extra} \sim 0$ due to missed energy or false matching.

Analysis Strategy

- Signal and MC predicted backgrounds



- Measure the $\mathcal{B}$ of the 3 indicated peaking modes. Use same set of D_S^- tags. Find:

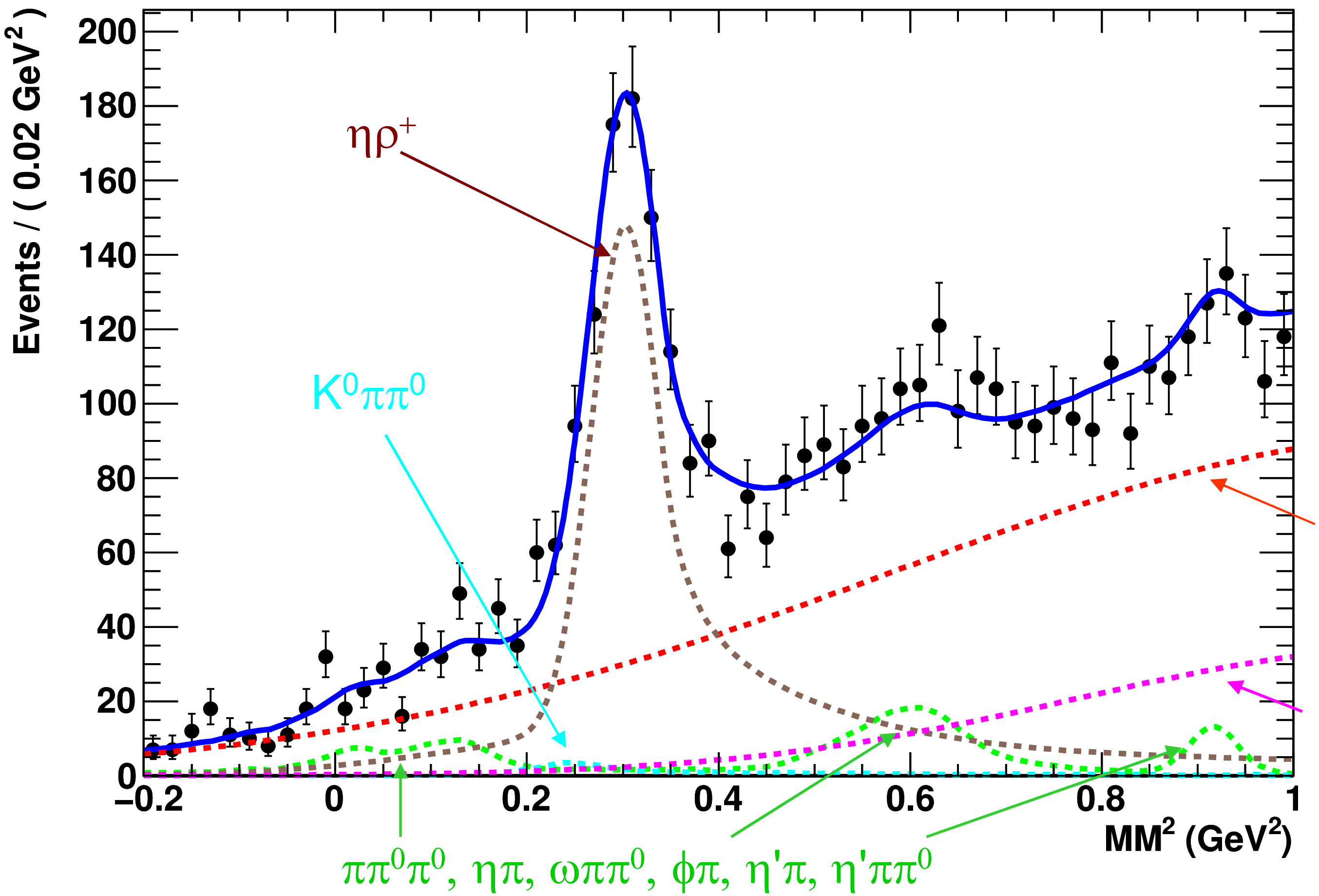
$$\begin{aligned}
\mathcal{B}(D_s^+ \to K^0\pi^+\pi^0) &= (1.00 \pm 0.18 \pm 0.04)\%, \\
\mathcal{B}(D_s^+ \to \pi^+\pi^0\pi^0) &= (0.65 \pm 0.13 \pm 0.03)\%, \\
\mathcal{B}(D_s^+ \to \eta\rho^+) &= (8.9 \pm 0.6 \pm 0.5)\%.
\end{aligned}$$

Analysis Strategy II

- We will fit the simultaneous the invariant tag mass & the MM^2 distributions, separately in three E_{extra} intervals, <0.1 GeV where signal dominates, (0.1, 0.2) GeV where S & B are equivalent, and >0.8 GeV for checking of understanding background, where signal is absent.
- In the fits, we put Gaussian constraints on the bkgrnd yields using known branching fractions and their errors. For the remaining sum of small modes we use the MC estimated rate with a rather large error. Thus the uncertainties in the background will be taken care of in the statistical error.

Fit to $E_{extra} > 0.8$ GeV

- No signal, fit consistent with bkgrnd expectations

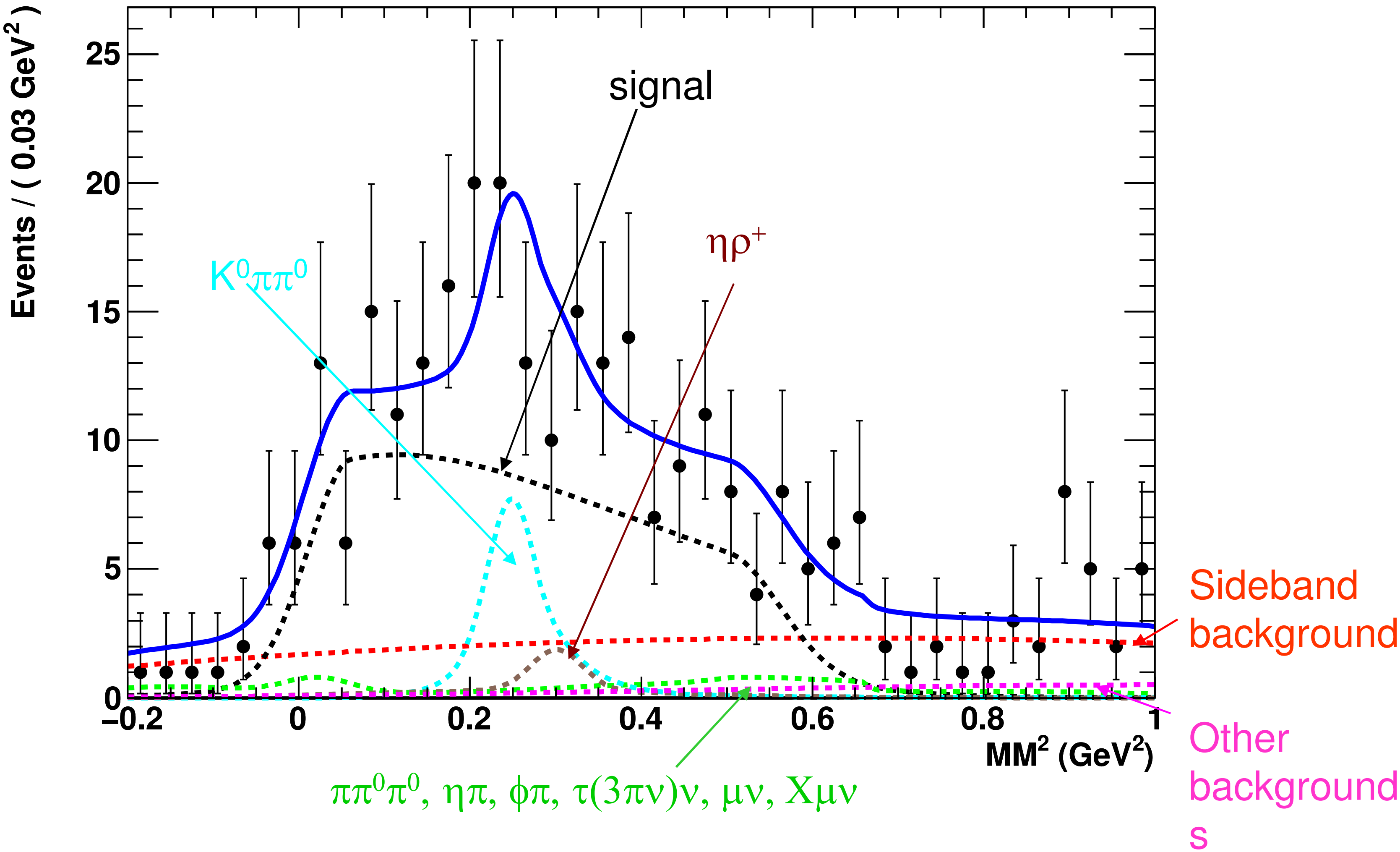


Points are data blue curve is overall fit

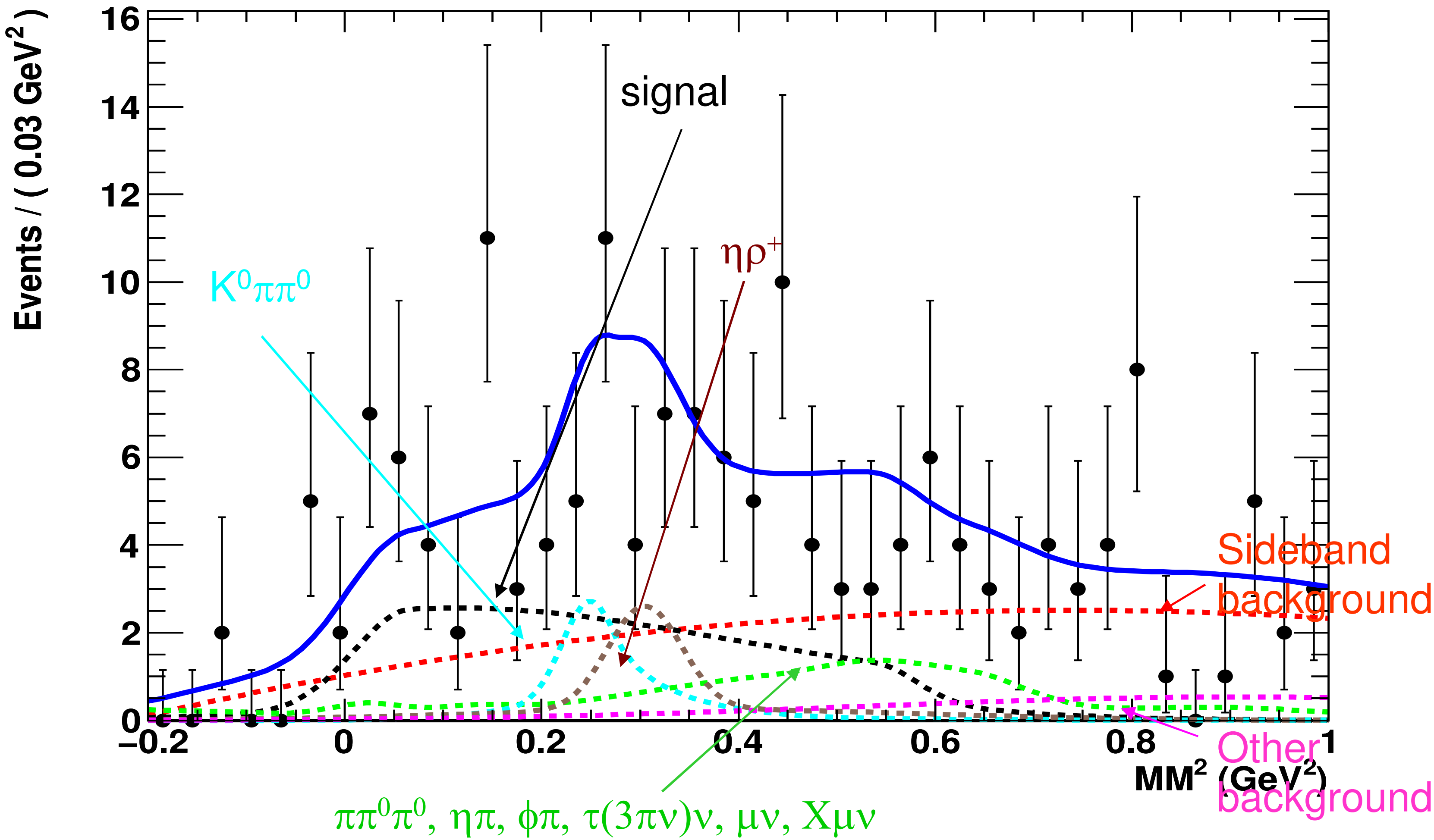
Sideband background

Other background with shape fixed to MC

Signal Region I: E_{extra}<0.1 GeV



Signal Region II: $0.2<E_{extra}<0.1$ GeV



Branching Fraction

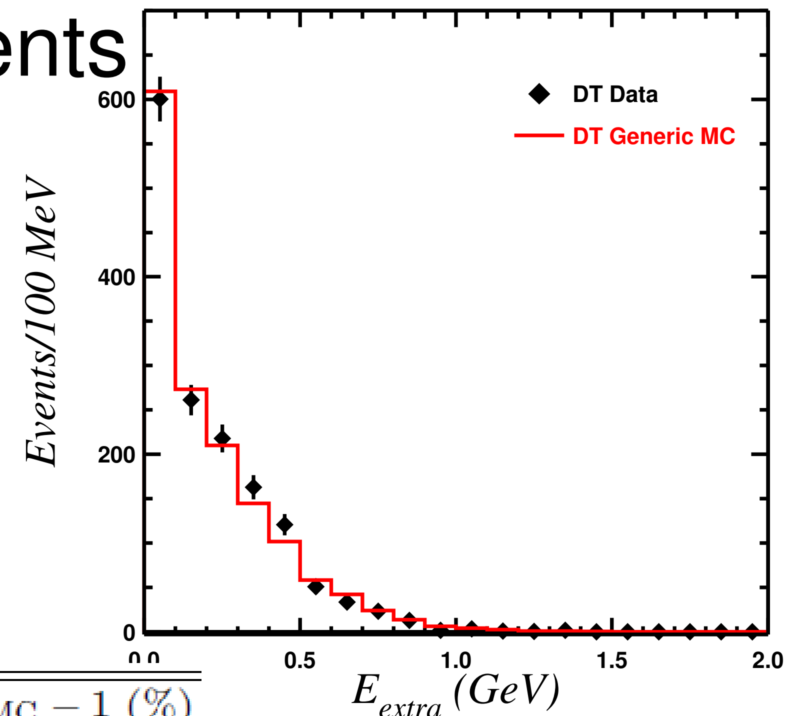
$E_{extra} \in$	Signal yields	Efficiency	$\mathcal{B}(D_s^+ \to \tau^+ \nu)$
[0,100] MeV	155.2 ± 16.5	25.3%	**$(5.48 \pm 0.59)\%$**
[100,200] MeV	43.7 ± 11.3	6.9%	**$(5.65 \pm 1.47)\%$**
[0,200] MeV	198.8 ± 20.0*	32.2%	**$(5.52 \pm 0.57 \pm 0.21)\%$**

- Sum of the above two

- $f_{D_s} = 257.8 \pm 13.3 \pm 5.2$ MeV

Systematic Errors

- Measure efficiency of E_{extra} cut. Use fully reconstructed $D_s D_s^*$ events
- Value at 300 MeV is chosen, because it has the same efficiency as $\rho^+\nu$ for E_{extra} 200 MeV



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$E_{\rm extra}$ (MeV)	$\epsilon_{\rm Data}(\%)$	$\epsilon_{\rm MC}(\%)$	$\epsilon_{\rm Data}/\epsilon_{\rm MC} - 1$ (%)
<100	40.24 ± 1.27	40.81 ± 0.31	-1.4 ± 3.2
<200	57.75 ± 1.28	59.12 ± 0.31	-2.3 ± 2.2
<300	72.35 ± 1.16	73.21 ± 0.28	-1.2 ± 1.6
<400	83.27 ± 0.97	82.91 ± 0.24	0.4 ± 1.2

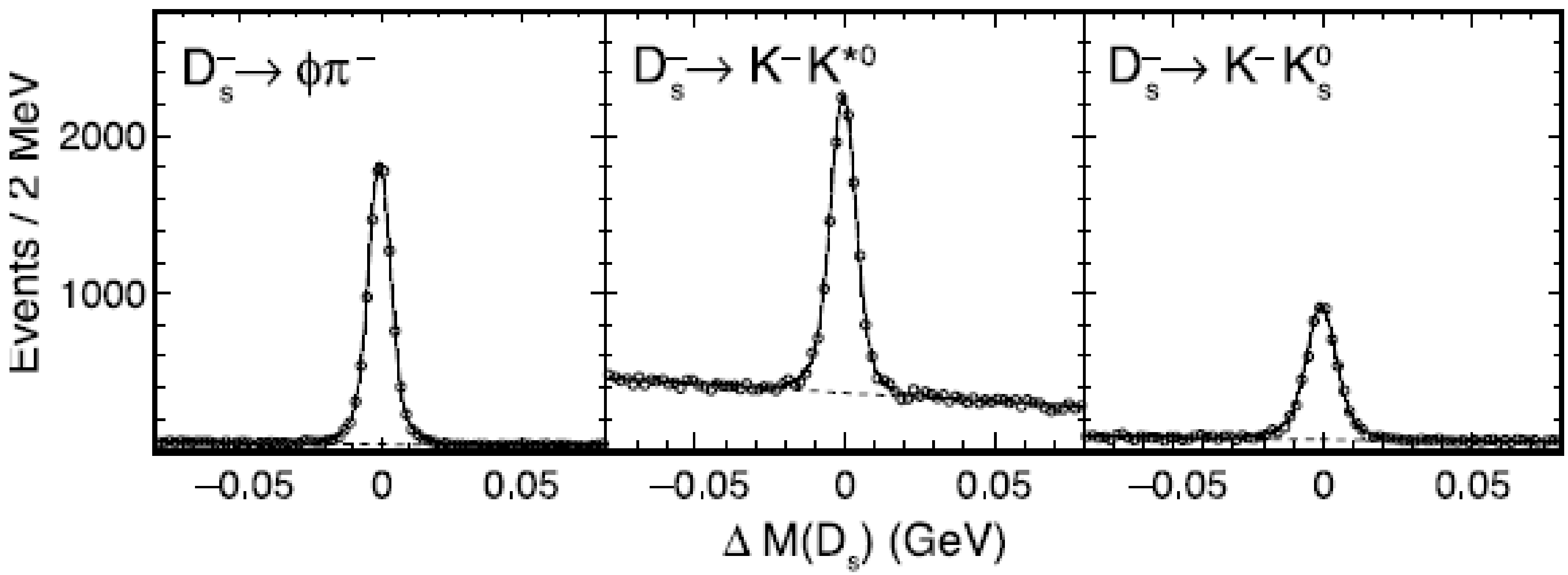
← set $\sqrt{1.2^2+1.6^2}$ = 2.0% error

Summary of Systematic Errors

Source of Error	%
Finding the π^+ track	0.3
Particle identification of π^+	1.0
π^0 efficiency	1.3
$E_{extra} < 200$ MeV signal efficiency	2.0
$E_{extra} < 200$ MeV& π^0 efficiencies on background	1.1
Background modeling	1.1
Number of single tag D_s^-	2.0
Tag Bias	1.0
Total	**3.8**

CLEO: $D_S^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

- $\mathcal{B}(D_S^+ \to \tau^+\nu) \bullet \mathcal{B}(\tau^+ \to e^+\nu\nu)$~1.3% is "large" compared with expected $\mathcal{B}(D_S^+ \to Xe^+\nu)$~8%
- We will be searching for events opposite a tag with one electron and not much other energy
- Opt to use only a subset of the cleanest tags

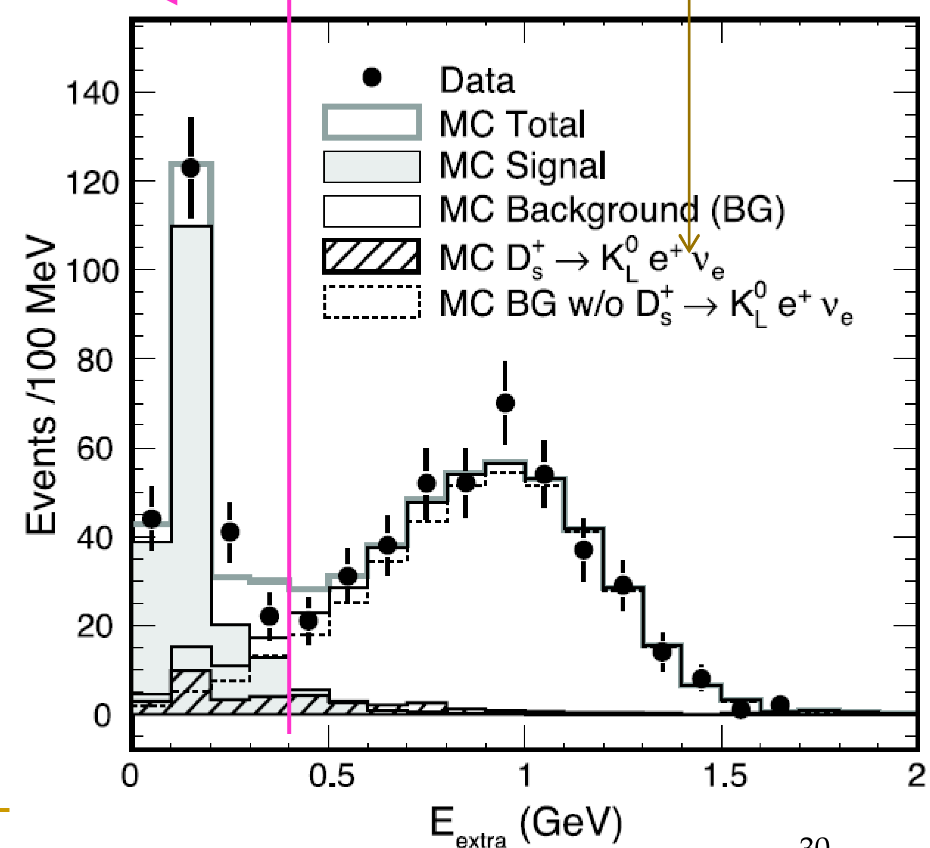


Measuring $D_S^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

- Technique is to find events with an e^+ opposite D_S^- tags & no other tracks, with Σ calorimeter energy
  < 400 MeV
- No need to find γ from D_S^*
- $\mathcal{B}(D_S^+ \to \tau^+\nu)$ $=(5.30\pm0.47\pm0.22)\%$
- $f_{D_S}=252.5\pm11.1\pm5.2$ MeV

Largest source of systematic error

400 MeV



Results

- $\mathcal{B}(D_s^+ \to \tau^+ \upsilon)$ from CLEO

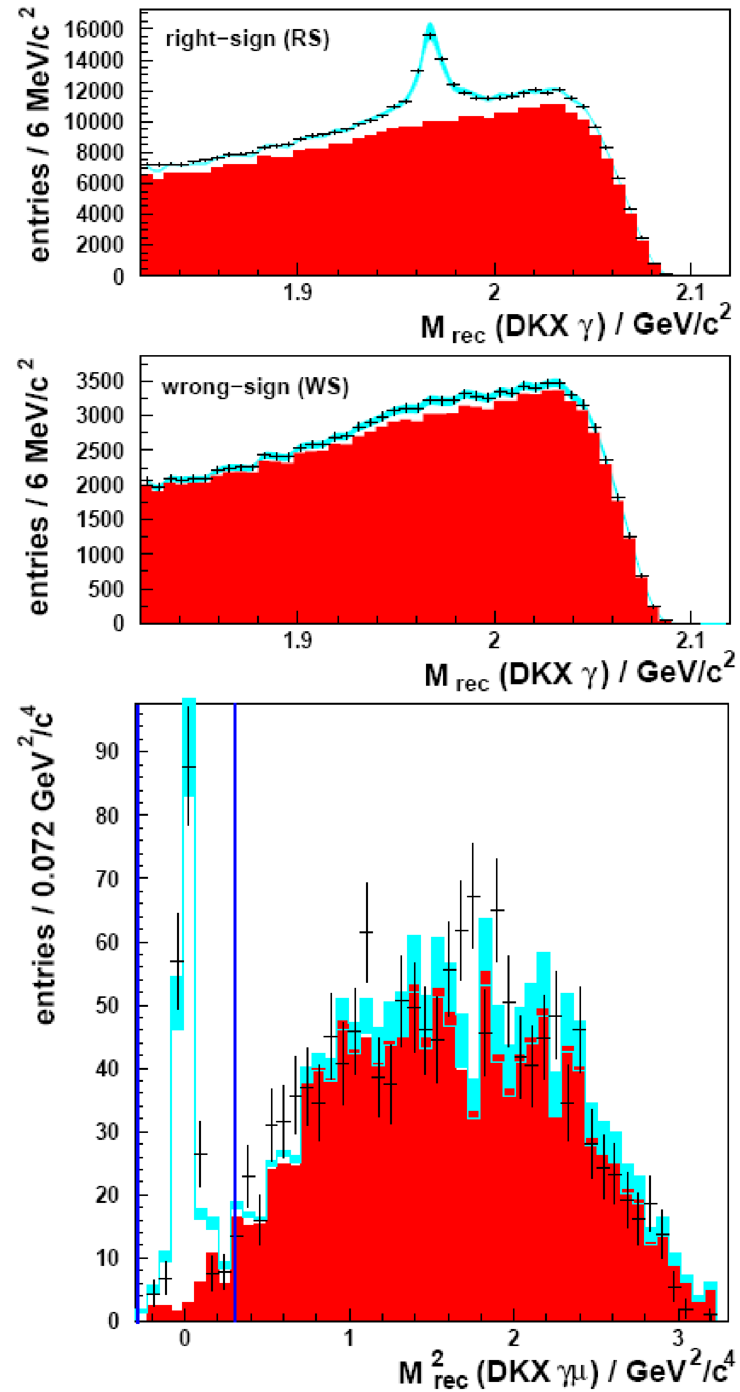
Mode	Branching Fraction (%)	f_{D_s} (MeV)
$\tau^+ \to \rho^+ \nu$	$5.52 \pm 0.57 \pm 0.21$	$257.8 \pm 13.3 \pm 4.9$
$\tau^+ \to e^+ \nu\nu$	$5.30 \pm 0.47 \pm 0.22$	$252.6 \pm 11.1 \pm 5.2$
$\tau^+ \to \pi^+ \nu$	$6.42 \pm 0.81 \pm 0.18$	$278.0 \pm 17.5 \pm 4.4$
Average	$5.54 \pm 0.32 \pm 0.15$	**$259.2 \pm 7.8 \pm 3.4$**

- For New Physics searches important to separate $\tau^+\upsilon$ and $\mu^+\upsilon$ [See A.G. Akeroyd and F. Mahmoudi, JHEP 0904, 121(2009)]
- Recall for $\mu^+\upsilon$ $f_{D_s} = (257.6 \pm 10.3 \pm 4.3)$ MeV
- Ratio $f_{D_s}(\tau^+\upsilon)/f_{D_s}(\mu^+\upsilon) = (1.01 \pm 0.05)$ consistent with unity

Belle: $D_S^+ \to \mu^+\nu$

- Look for $e^+e^- \to DKX\gamma(D_S)$, where $X=n\pi$ & the D_S is not observed but inferred from calculating the MM
- Then add a candidate μ^+ and compute MM^2
- $\mathcal{B}(D_S^+ \to \mu^+\nu) =$ $(0.644\pm0.076\pm0.057)\%$
- $f_{D_S}=275\pm16\pm12$ MeV

arXiv:0709.1340v2 [hep-ex]



Results II

- Average of All CLEO measurements: f_{Ds} =(259.0 $\pm$ 6.2 $\pm$ 3.0) MeV
- Plus Belle (275 $\pm$ 16 $\pm$ 12) MeV gives

  f_{Ds} =(260.7 $\pm$ 6.5) MeV
- Follana et. al (241 $\pm$ 3) MeV, difference 2.4σ
- A. Bazavov et al. [Fermilab Lattice and MILC Collaborations], PoS LATTICE 2009 (2009) 249 now claim f_{Ds} =(260 $\pm$ 10) MeV
- Is discrepancy due to faulty calculation, or new physics?

Other Non-absolute Measurements

Exp.	mode	$\mathcal{B}$	$\mathcal{B}(D_S \to \phi\pi)$ (%)	f_{Ds} (MeV)
CLEO [11]	$\mu^+\nu$	$(6.2 \pm 0.8 \pm 1.3 \pm 1.6) \cdot 10^{-3}$	3.6±0.9	$273 \pm 19 \pm 27 \pm 33$
BEATRICE [12]	$\mu^+\nu$	$(8.3 \pm 2.3 \pm 0.6 \pm 2.1) \cdot 10^{-3}$	3.6±0.9	$312 \pm 43 \pm 12 \pm 39$
ALEPH [13]	$\mu^+\nu$	$(6.8 \pm 1.1 \pm 1.8) \cdot 10^{-3}$	3.6±0.9	$282 \pm 19 \pm 40$
ALEPH [13]	$\tau^+\nu$	$(5.8 \pm 0.8 \pm 1.8) \cdot 10^{-2}$		
L3 [14]	$\tau^+\nu$	$(7.4 \pm 2.8 \pm 1.6 \pm 1.8) \cdot 10^{-2}$		$299 \pm 57 \pm 32 \pm 37$
OPAL [15]	$\tau^+\nu$	$(7.0 \pm 2.1 \pm 2.0) \cdot 10^{-2}$		$283 \pm 44 \pm 41$
BaBar [16]	$\mu^+\nu$	$(6.74 \pm 0.83 \pm 0.26 \pm 0.66) \cdot 10^{-3}$	4.71±0.46	$283 \pm 17 \pm 7 \pm 14$

HFAG reinterpretation: 237 ± 13 ± 5

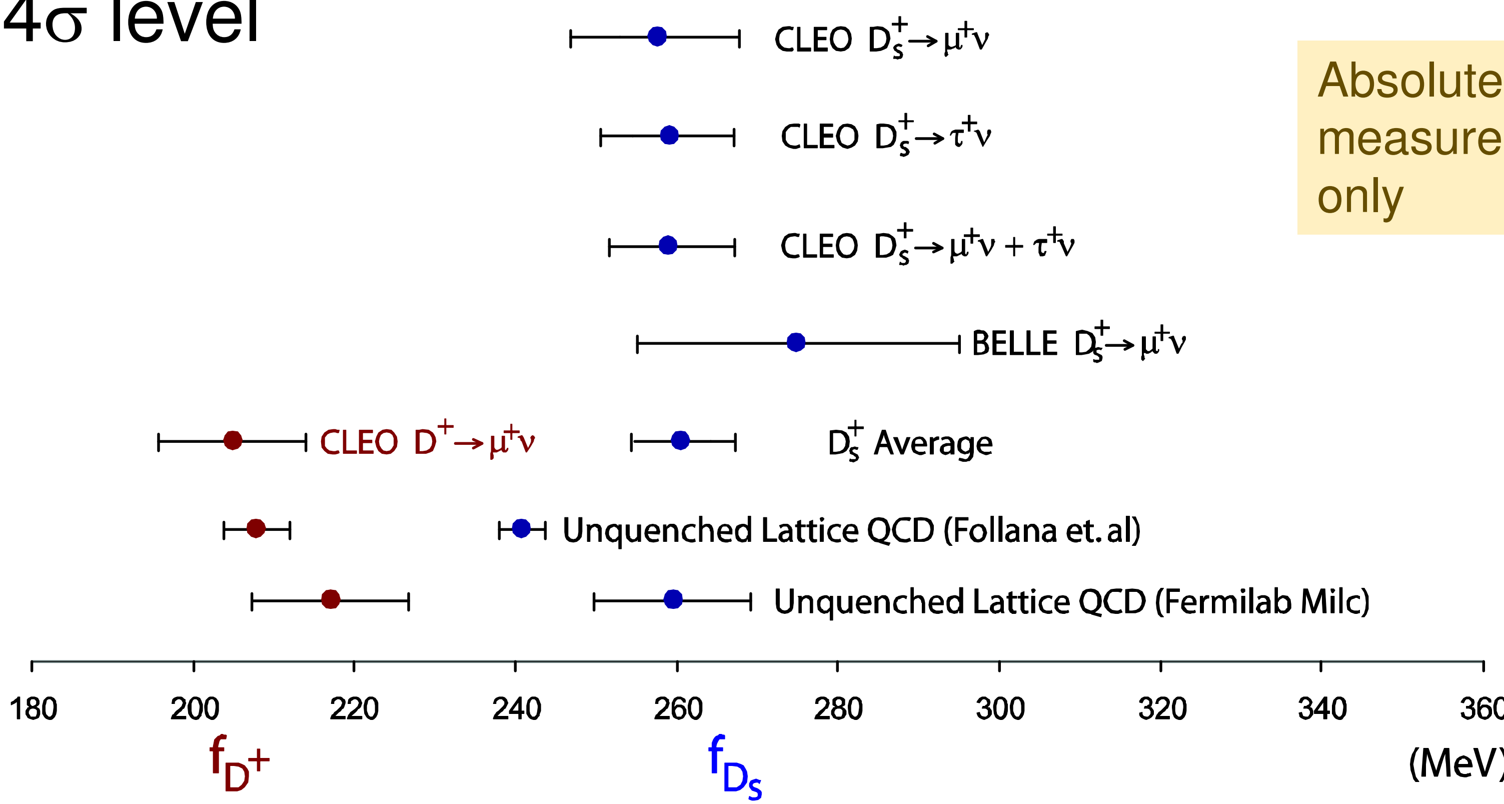
See Rosner & Stone, arXiv:0802.1043 for references

Beyond the SM Theories

- Leptoquark models & special Two-Higgs doublet model (Dobrescu & Kronfeld) [arXiv:0803.0512-hep-ph]
- R-parity violating Supersymmetry (Akeroyd & Recksiegel [hep-ph/0210376])
- A. Kundu & S. Nandi, "R-parity violating supersymmetry, B_S mixing, & $D_S^+ \to \ell^+\nu$" [arXiv:0803.1898])
- Bhattacharyya, Chatterjee & Nandi [arXiv:0911.3811v1-hep-ph]
  - Dosner et al show that the above models should effect $\tau\nu$ and $\mu\nu$ differently [arXiv:0906.5585-hep/ph]
- Gninenko & Gorbunov argue that the neutrino in the D_s decay mixes with a sterile neutrino, which enhances the rate, but should act the same in D^+ & D_S, & could be different for $\mu^+\nu$ & $\tau^+\nu$ [arXiv:0907.4666-hep-ph]

Conclusions

- We are in close agreement with the Follana et al calculation for f_{D^+}. This gives credence to their methods, but here is a disagreement with f_{D_s} at the 2.4σ level



Absolute B measurements only

Conclusions II

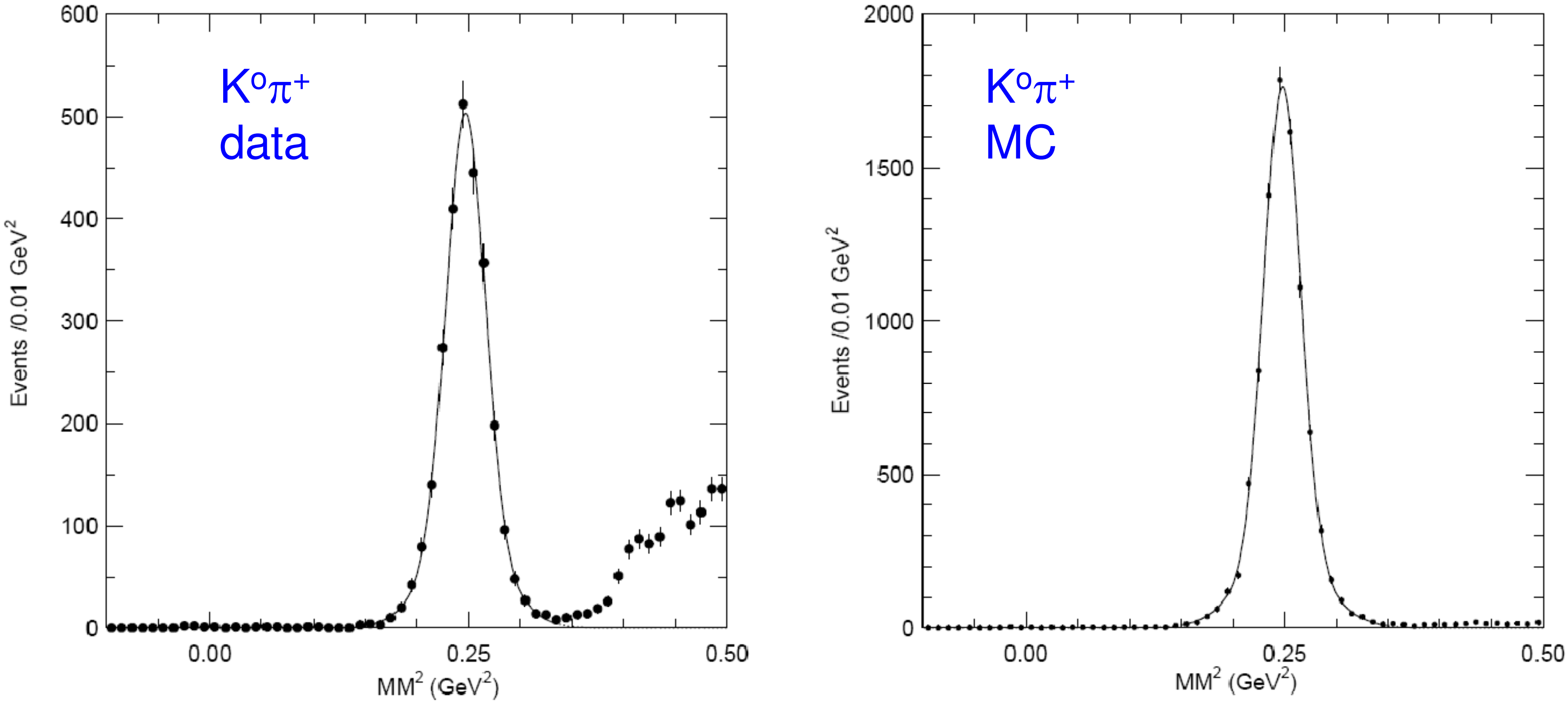
- Although the calculations are somewhat different for f_{Bs}/f_B, if theoretical predictions of f_{Ds}/f_{D+} do not agree with the data, why should we believe f_{Bs}/f_B from theory? What does this do to the CKM fits? (This statement assumes that NP is not present!)
- Perhaps new lattice calculations using somewhat different methods will help resolve this situation, along with new data from BES III

The End

Efficiencies

- Tracking, particle id, E<300 MeV (determined from μ-pairs) = 85.3%
- Not having an unmatched shower > 250 MeV 95.9%, determined from double tag, tag samples
- Easier to find a $\mu\nu$ event in a tag then a generic decay (tag bias) (1.53%)

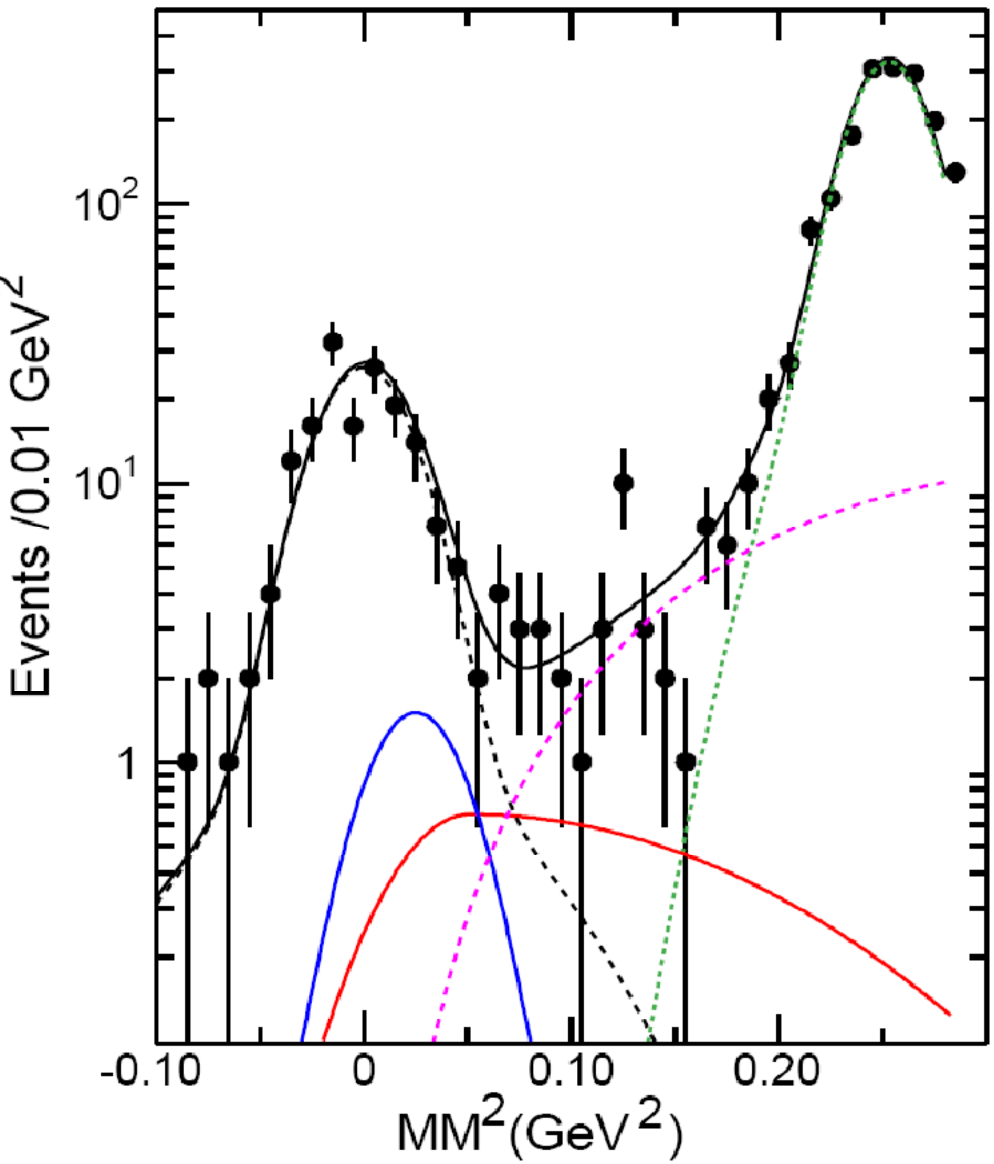
μν Signal Shape Checked



- Data σ=0.0247±0.0012 GeV^2
- MC σ=0.0235±0.0007 GeV^2
- Both average of double Gaussians

Case(i) With $\tau^+\nu/\mu^+\nu$ Floating

- Fixed
  - 149.7±12.0 μυ
  - 28.5 τν
- Floating
  - 153.9±13.5 μυ
  - 13.5±15.3 τν



New Physics Possibilities III

- Leptonic decay rate is modified by $H^{\pm}$
- Can calculate in SUSY as function of m_q/m_c,
- In 2HDM predicted decay width is x by

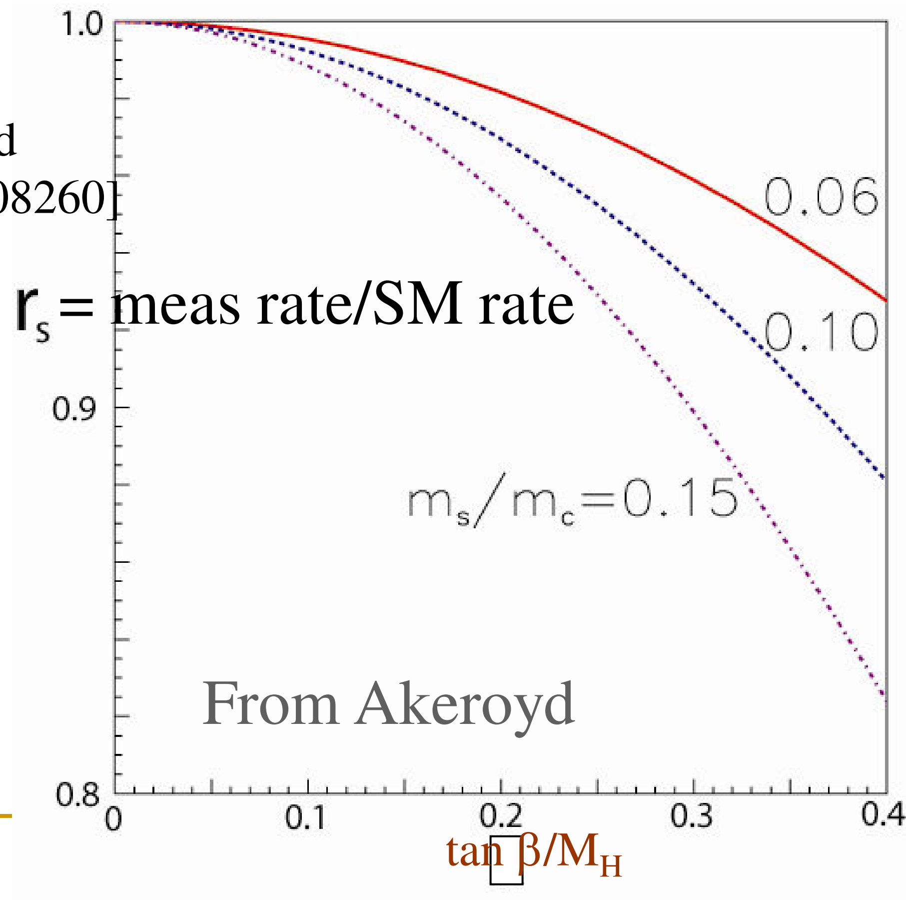
$$r_q = \left[1 - M_D^2 \left(\frac{\tan\beta}{M_{H^\pm}}\right)^2 \left(\frac{m_q}{m_c + m_q}\right)\right]^2$$

See Akeryod [hep-ph/0308260]

- Corrected

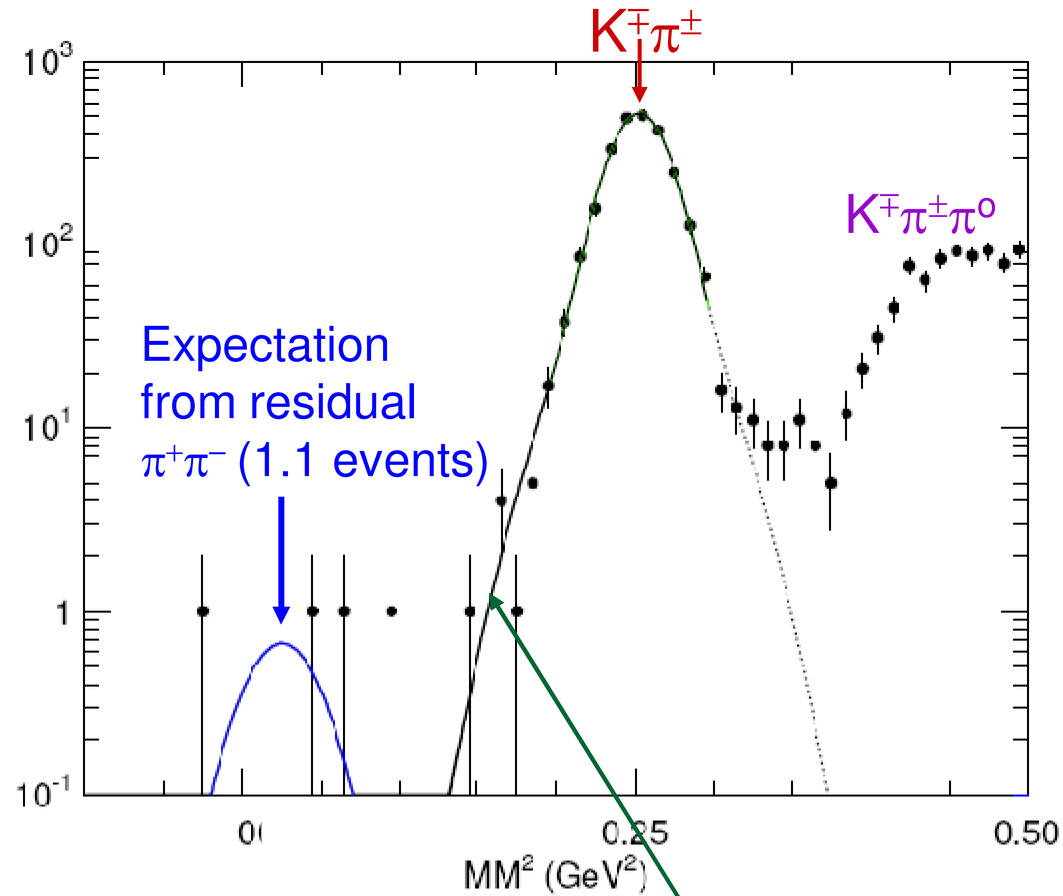
$$r_q = \left[1 + \left(\frac{M_D^2}{m_c + m_q}\right)\left(\frac{1}{M_{H^\pm}}\right)^2 \left(m_c - m_q \tan^2\beta\right)\right]^2$$

- Since m_d is ~0, effect can be seen only in D_S



Model of $K^o\pi^+$ Tail

- Use double tag $D^o \bar{D}^o$ events, where both $D^o \rightarrow K^{\mp}\pi^{\pm}$
- Make loose cuts on 2nd D^o so as not to bias distribution: require only 4 charged tracks in the event

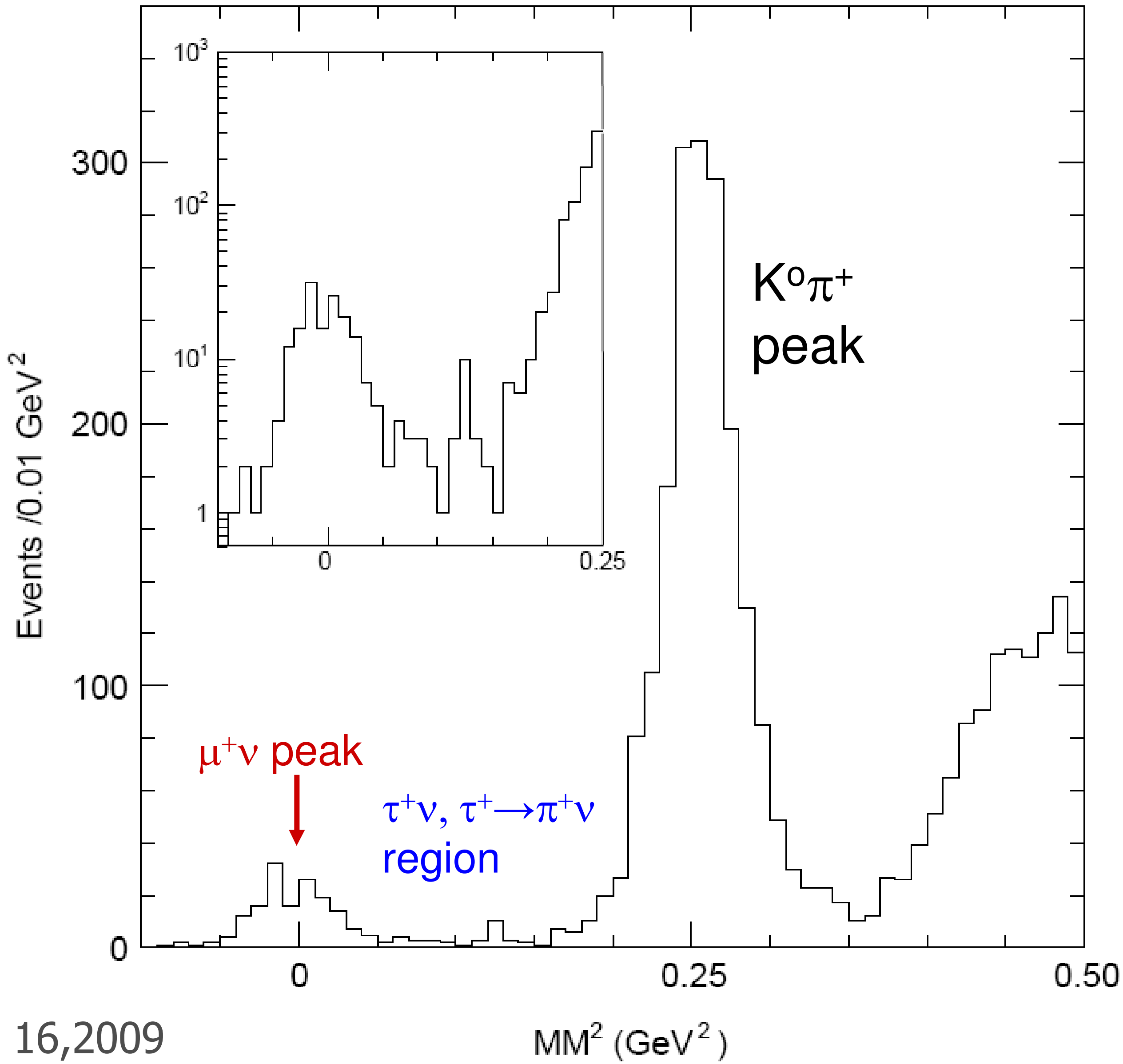


Computed ignoring charged kaon

Gives an excellent description of shape of low mass tail
"Extra" 1.3 event background in signal region

The MM² Distribution

- For E< 300 MeV in CsI



Residual Backgrounds for μυ

- Monte Carlo of Continuum, D°, radiative return and other D^+ modes, in $\mu\nu$ signal region

Mode	# of events
Continuum	0.8±0.4
$\overline{K}^0\pi^+$	1.3±0.9
D^0 modes	0.3±0.3
Sum	2.4±1.0

- This we subtract off the fitted yields

CP Violation

- D^+ tags 228,945±551
- D^- tags 231,107±552
- $\mu^-\nu$ events 64.8±8.1
- $\mu^+\nu$ events 76.0±8.6

$$A_{CP} \equiv \frac{\Gamma(D^+ \to \mu^+\nu) - \Gamma(D^- \to \mu^-\nu)}{\Gamma(D^+ \to \mu^+\nu) + \Gamma(D^- \to \mu^-\nu)} = 0.08 \pm 0.08$$

- $-0.05 < A_{CP} < 0.21$ @ 90% c. l.