Measurements of f_{D^+} and f_{D_s}

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With thanks to S. Stone, L. Zhang and D. Asner

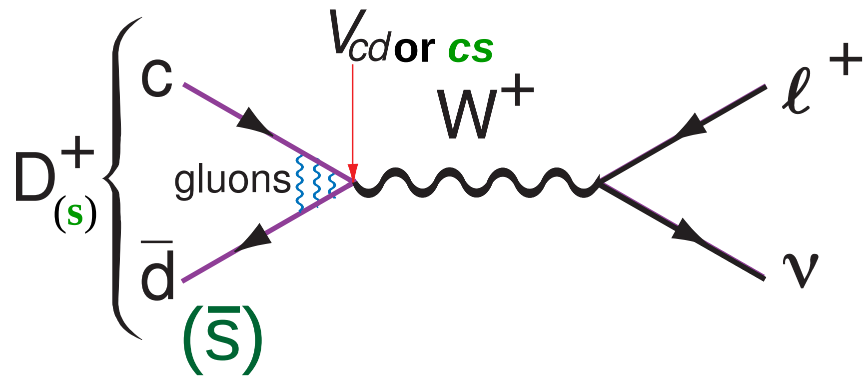
Outline

- Introduction and motivation
- f_{D^+} determination at CLEO-c
- f_{D_s} determinations at:
  - CLEO-c with $D_s \to \mu\nu$ and $D_s \to \tau(\pi\nu)\nu$
  - CLEO-c with $D_s \to \tau(e\nu\nu)\nu$
  - Belle with $D_s \to \mu\nu$
  - BABAR with $D_s \to \mu\nu$
- Conclusions and outlook

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:

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

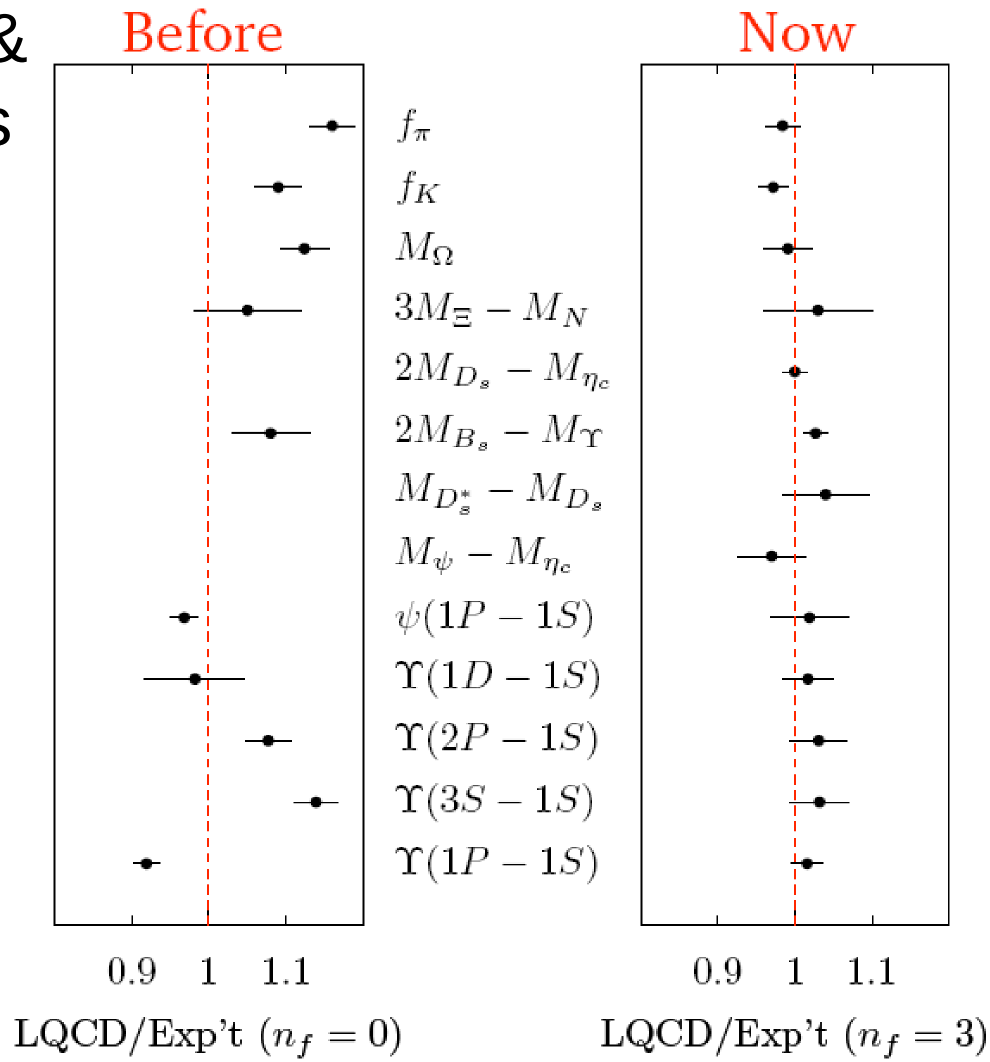
Calculate, or measure f_D if V_{Qq} is known, here take $V_{cd} = V_{us} = 0.2256$, $V_{cs} = V_{ud} = 0.9742$

Relationship to CKM

- Only a few measurements are independent of strong interaction calculations
  - CP violation where we interfere one decay diagram with a mixing diagram ($B^o \to J/\psi\ K^o$)
- Many important quantities measured in CKM are combinations of strong and weak parameters
  - Interpreting B and B_S mixing in terms of CKM parameters requires knowledge of f_{B_s}/f_B
  - Extracting V_{ub} requires knowledge of absolute value of form-factors for $B \to \pi(\rho)\ell\nu$ at least at one value of q^2

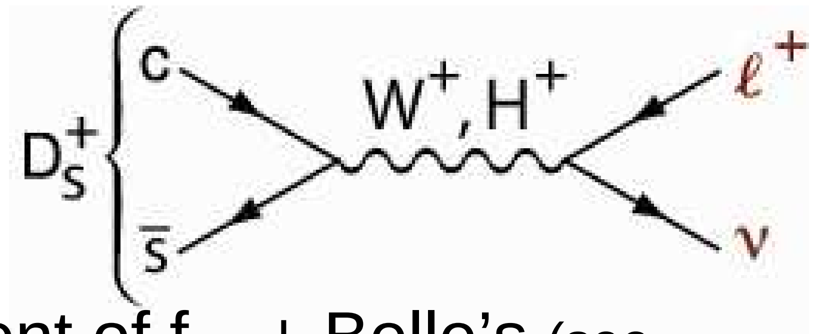
New Unquenched Lattice Calc

- Follana et al HPQCD & UKQCD collaborations (PRL **100,** 062002 (2008))
  New predictions of
  f_{D^+}= 207±4 MeV
  f_{Ds} = 241±3 MeV
- Older unquenched from FNAL+MILC +HPQCD are:
  f_{D^+}= 201±3±17 MeV
  f_{Ds} = 249±3±16 MeV
  (Aubin et al., PRL 95, 122002 (2005))



Beyond the SM sensitivity

- Besides the obvious interest in comparing with lattice & other calculations of f_D there are NP possibilities

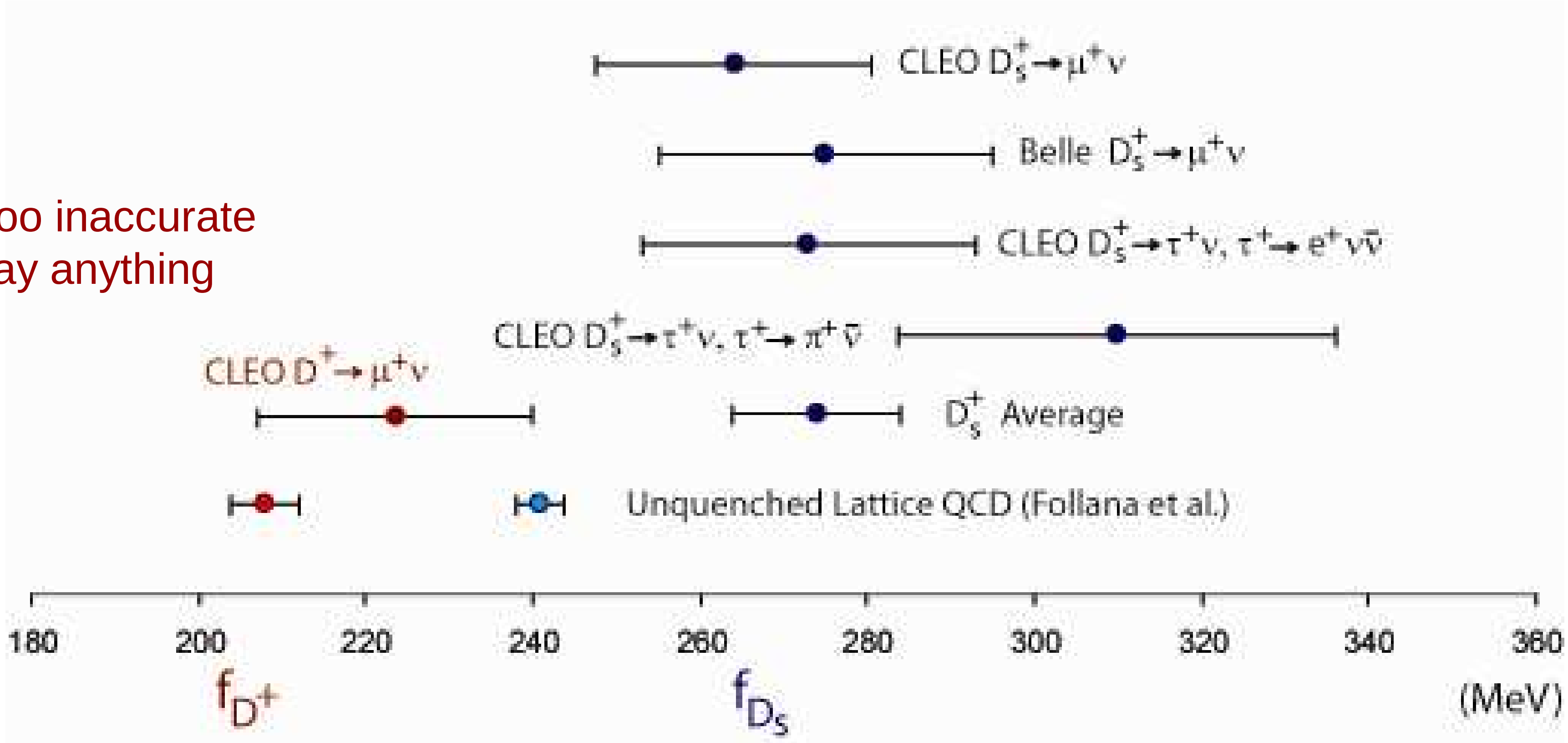


- CLEO's previous measurement of f_{Ds} + Belle's (see Rosner & Stone arXiv:0802.1043) give f_{Ds}=274±10 MeV as compared with 241±3 MeV 2+1 unquenched lattice QCD calculation of Follana et.al (PRL **100,** 062002 (2008))
- Dobrescu & Kronfeld (arXiv:0803.0512) argue that this can well be the effect of NP, either charged Higgs (their own model) or leptoquarks
- CLEOs previous measurement of f_{D^+} was too inaccurate to challenge Follana et al., theory 207±4 versus 223±17 MeV (CLEO)

Situation Prior To FPCP 2008

- Experiment f_{Ds}: CLEO measures both $\mu^+\nu$ & $\tau^+\nu$, & Belle measures $\mu^+\nu$. Average is 3.3 σ away, could be a fluctuation

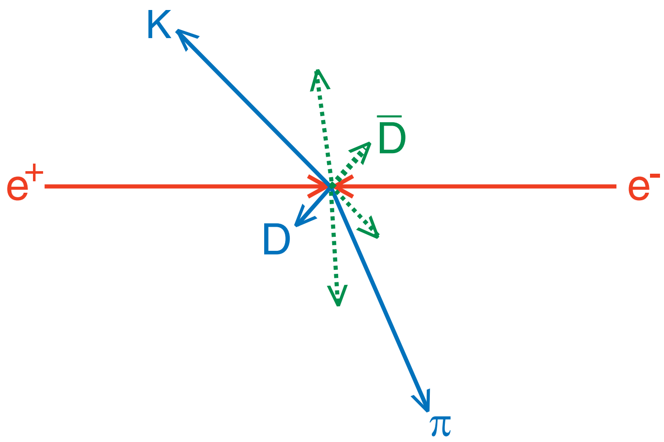
D+ too inaccurate
to say anything



- **Updates to both CLEO measurements**

Favoured methods at CLEO-c

- Two-body production $e^+e^- \to D\overline{D}$
- Double tags at 3770 MeV:
  - fully reconstruct one D^0 or D^+, then one can either
    - fully reconstruct the other D for absolute branching ratios and quantum correlations or
    - look for events with one missing particle in leptonic decays, semileptonic decays or hadronic K_L decays



- Similarly, double tags at 4170 MeV:
  - here look for a D_S or a D_S*
- Some measurements also done using single tags

Basic Technique for $D^+ \to \mu^+\nu$

1. Fully reconstruct a $D^\pm$, and count total # of tags
2. Seek events with only one additional oppositely charged track within $|\cos\theta|<0.9$ & no additional photons > 250 MeV (to veto $D^+ \to \pi^+\pi^o$)
3. Charged track must deposit only minimum energy (from ionization) in calorimeter, E < 300 MeV
   - True for 98.8% of muons
   - Rejects 45% of π's
4. Compute missing-mass squared (MM^2). If close to zero then almost certainly we have a $\mu^+\nu$ decay.

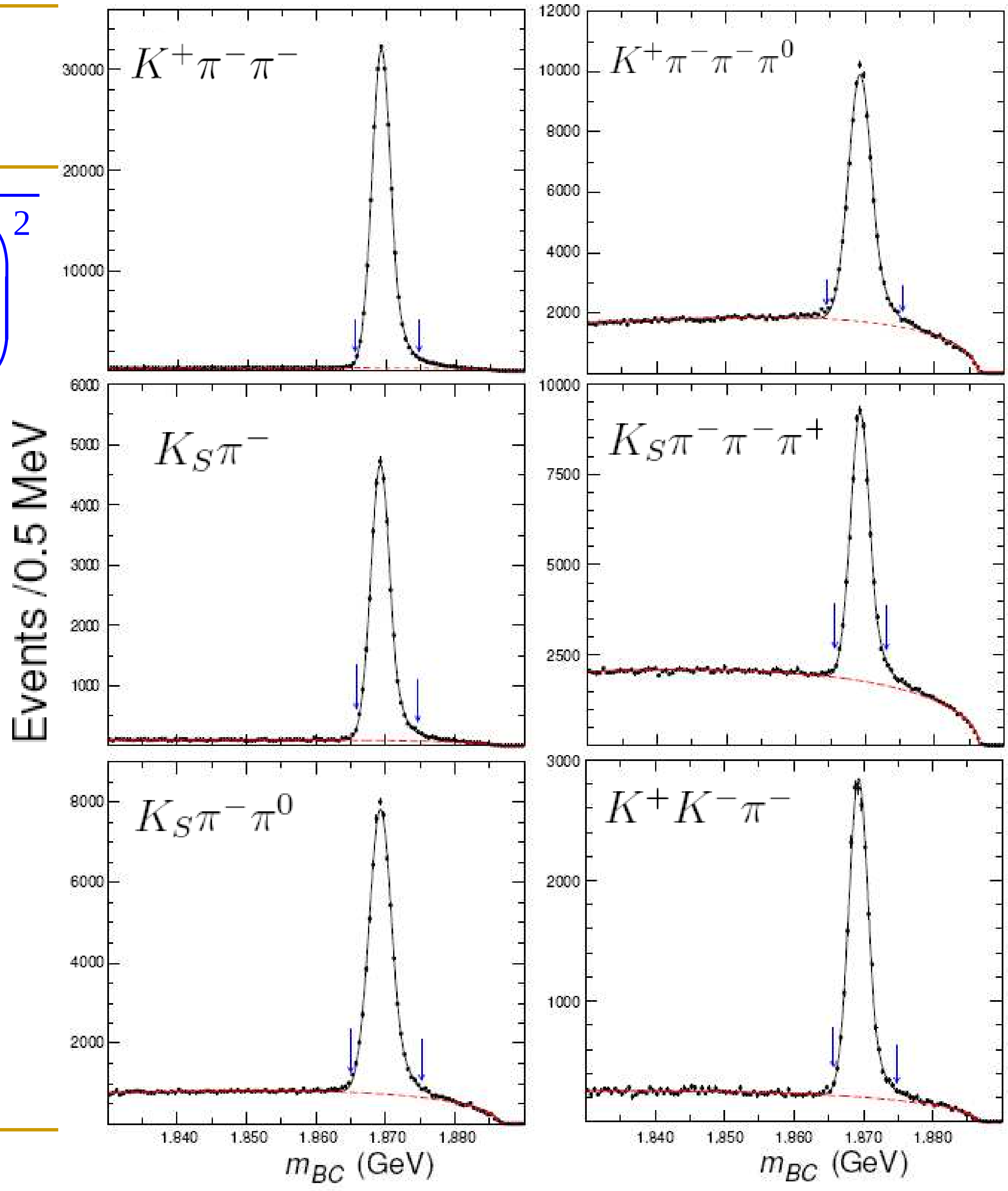
$$MM^2 = (E_{D^+} - E_{\ell^+})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+})^2$$

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

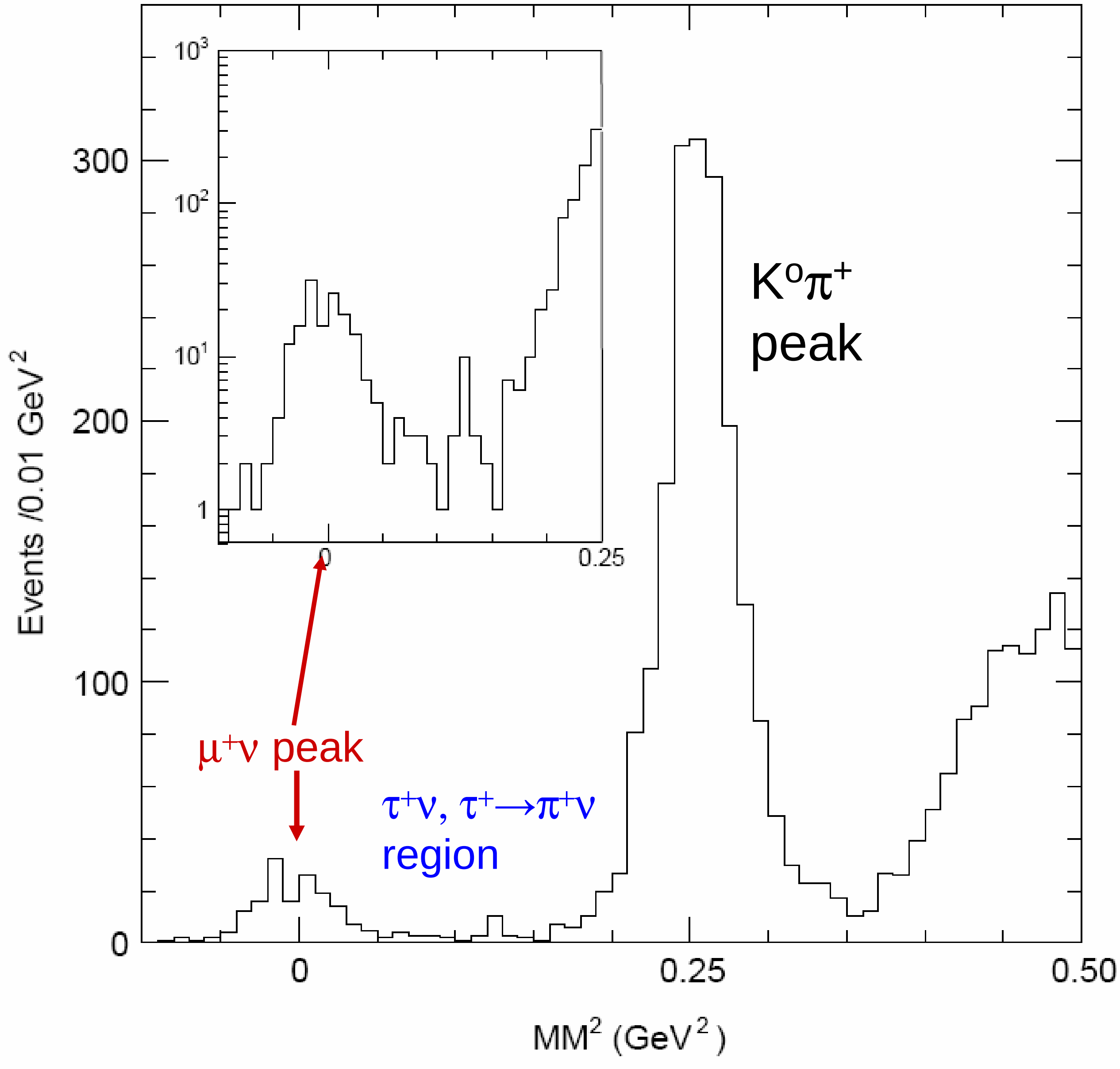
Tags

$$m_{BC} = \sqrt{E_{beam}^2 - \left(\sum_i \vec{p}_i\right)^2}$$

- Particle ID from RICH & dE/dx
- Total of 460,000 tags
- Background 89,400

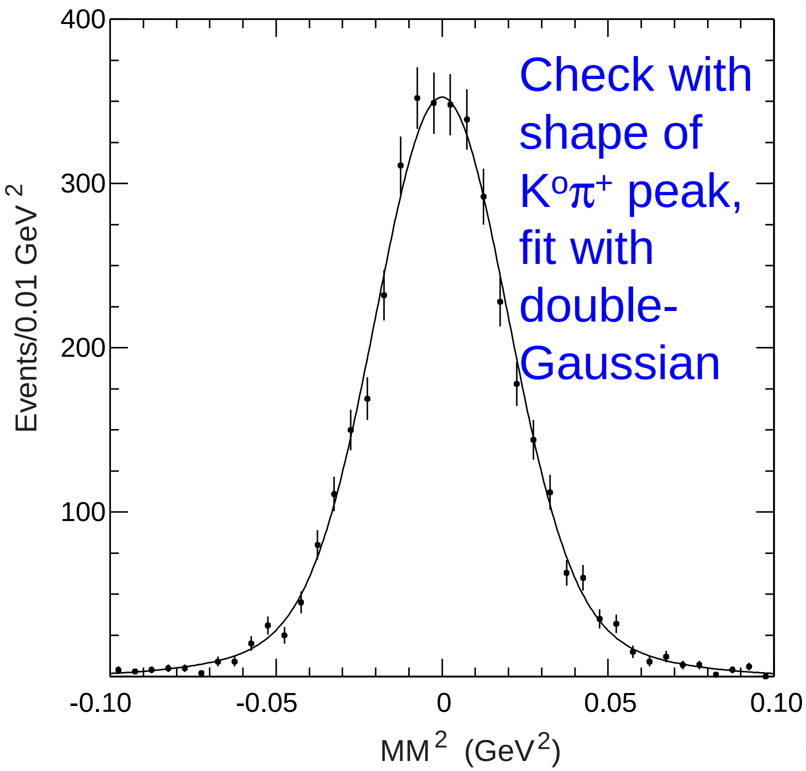


The MM^2 Distribution

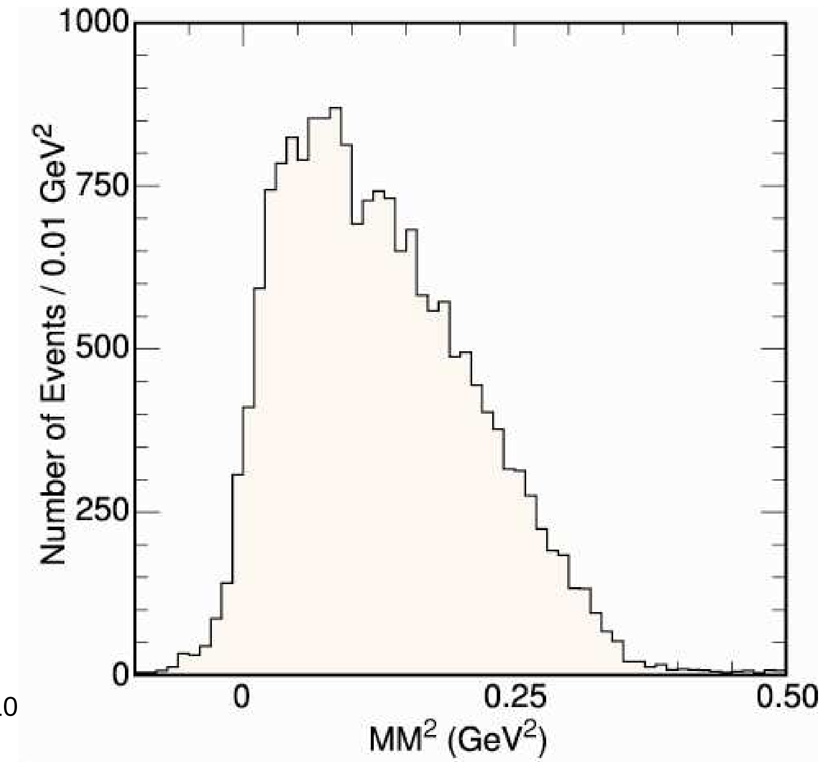


MM² Signal Shapes

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



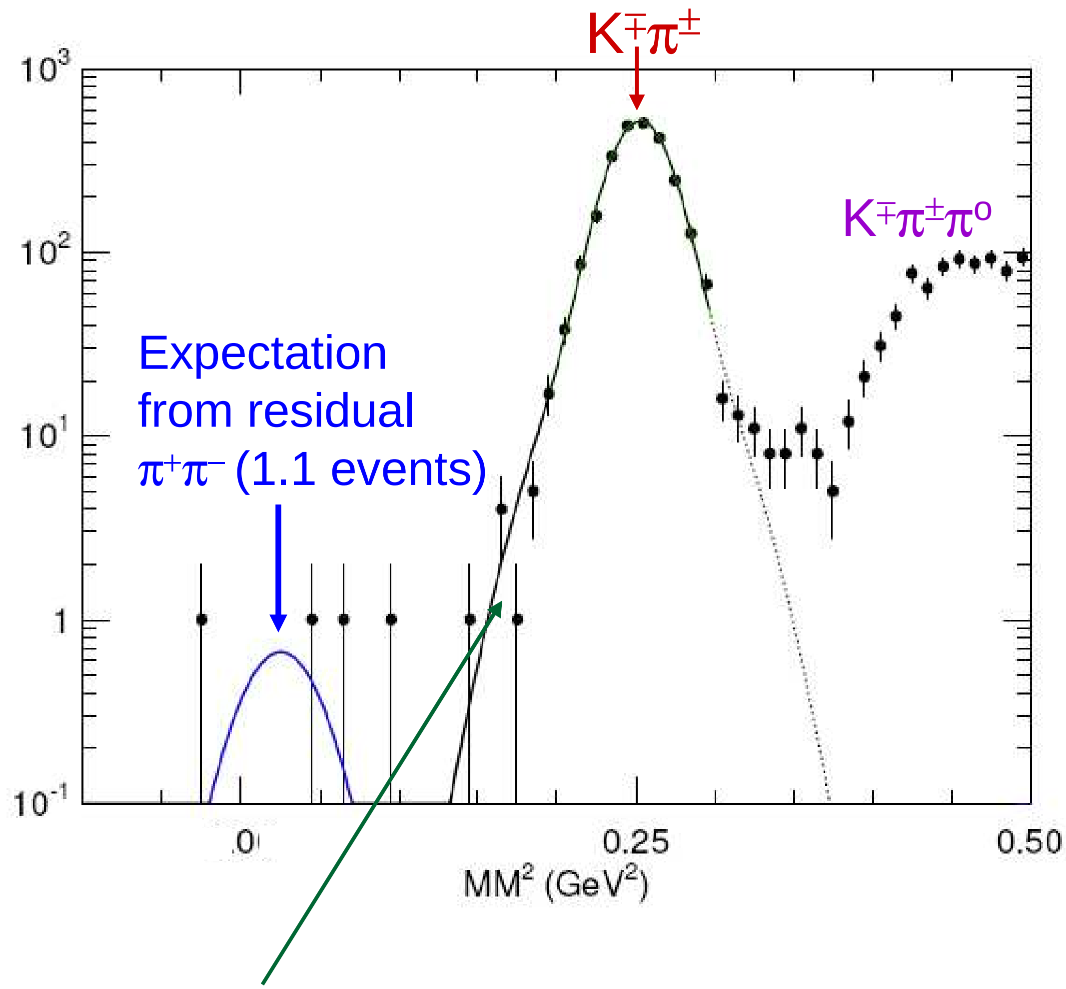
Monte Carlo Signal μν



Monte Carlo Signal τν, τ→πν

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

- Use double tag D^0 $\bar{D}^0$ events, where both $D^0 \rightarrow K^{\mp}\pi^{\pm}$
- Make loose cuts on 2nd D^0 so as not to bias distribution:
  - require only 4 charged tracks in the event
- Compute MM^2 ignoring $K^{\pm}$



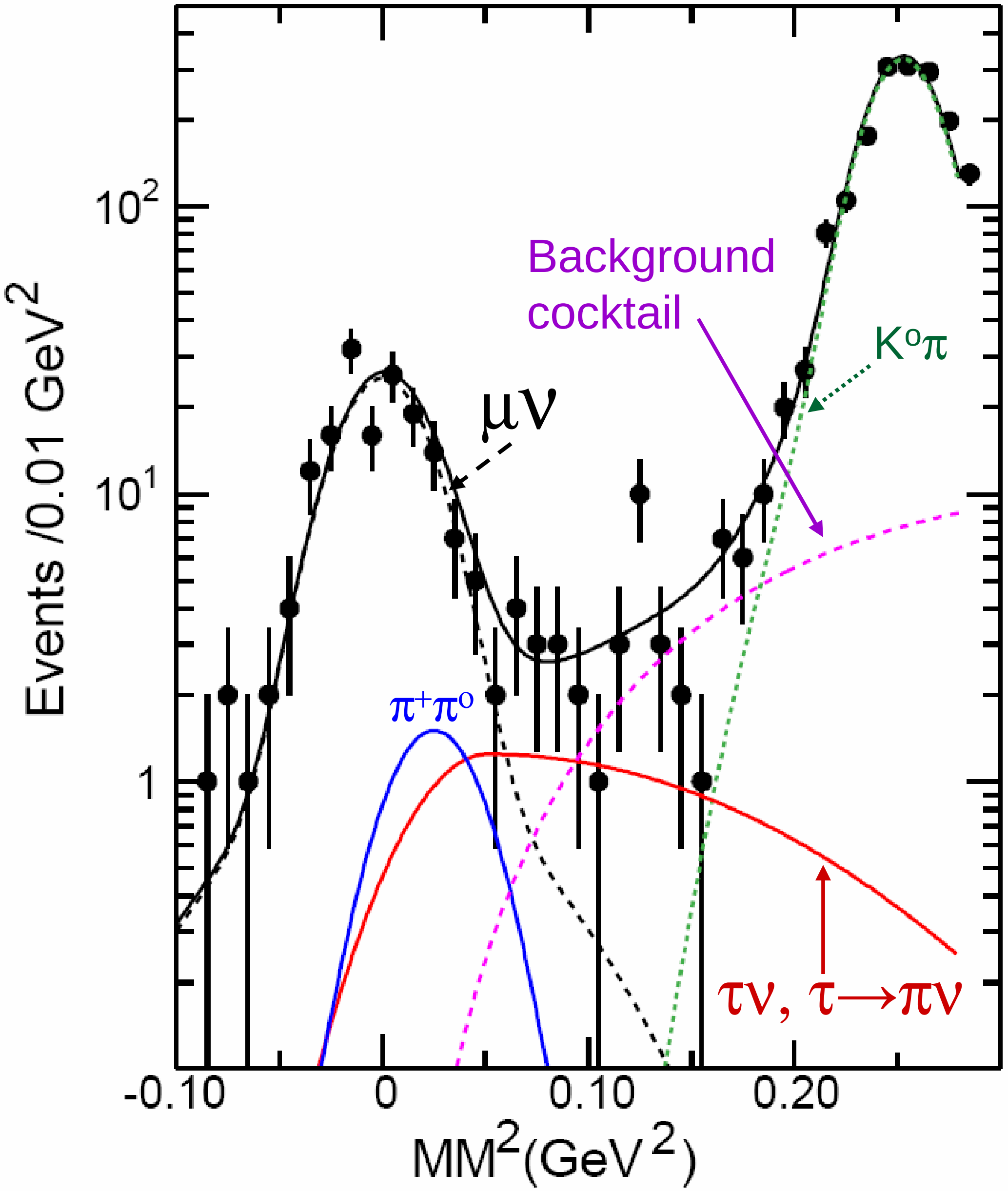
Gives an excellent description of shape of low mass tail
"Extra" 1.3 event background in signal region

Additional floating backgrounds

- Background cocktail composed of three-body modes
  - τ^+ decays: $\rho^+\nu$ and $\mu^+\nu\nu$
  - Semileptonic decays: $\pi^0\mu^+\nu$ (check with e^+)
  - Hadronic decays: $\rho^+\pi^0$
- We only use the shape in MM^2, not the absolute number

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 $\tau\nu$



Residual Backgrounds for μυ

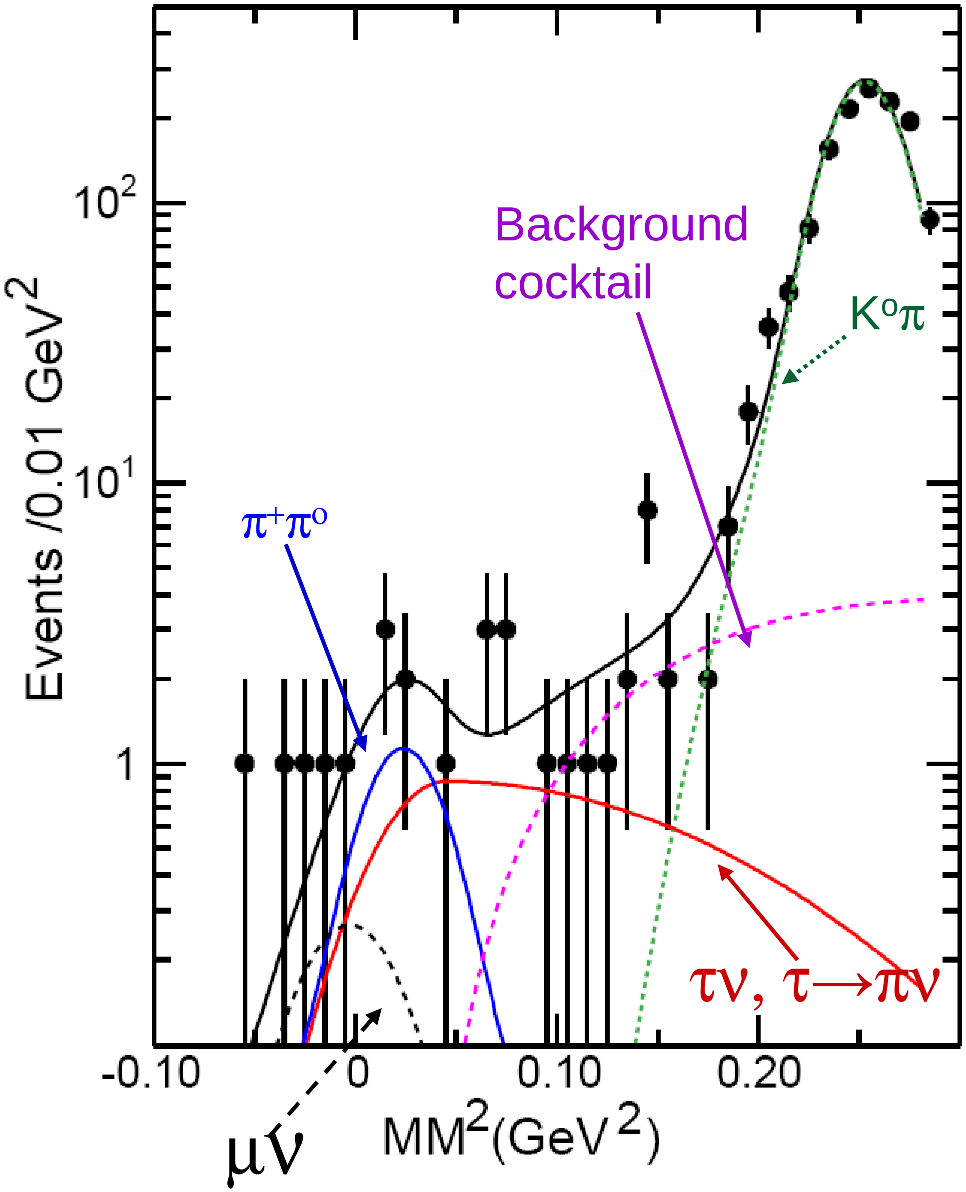
- Monte Carlo of continuum, D°, radiative return and other D^+ modes, in μν signal region

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

Background Check

- Use case (ii) E>300 MeV
- Fix τν & μν from case (i) μν.
- Consider signal region $|MM^2|<0.05$ GeV^2.
  - Expect 1.7 μν + 5.4 $\pi^+\pi^o$ + 4.0 τν = 11.1
  - Find 11 events
- Additional background
  - −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^+}

PRD 78, 052003 (2008)

- Fix $\tau\nu/\mu\nu$ at SM ratio of 2.65
  - $BF(D^+\to\mu^+\nu) = (3.82\pm0.32\pm0.09)\times10^{-4}$
  - $f_{D^+} = (205.8\pm8.5\pm2.5)$ MeV
  - This is best number in context of SM
- Float $\tau\nu/\mu\upsilon$
  - $BF(D^+\to\mu^+\nu) = (3.93\pm0.35\pm0.10)\times10^{-4}$
  - $f_{D^+} = (207.6\pm9.3\pm2.5)$ MeV
  - This is best number for use with BSM models
- These numbers have been radiatively corrected by 1% in the branching ratio for $D^+\to \gamma D^{*+}\to \gamma\mu^+\nu$
- Also, limits on $BF(D^+\to e^+\nu)$, $BF(D^+\to\tau^+\nu)$ and $A_{CP}(D^+\to\mu^+\nu)$
  - All agree with SM expectation

CLEO-c's improved measurement of f_{Ds}

- CLEO has two methods of measuring f_{Ds}
  - Measure $\mu^+\nu$ & $\tau^+\nu$, $\tau^+ \to \pi^+\nu$ using similar MM^2 technique used for D^+. Update result using new analysis & 30% more data (~400 pb^{-1})
    - Updated 2008
  - Measure $\tau^+ \to e^+\nu\nu$ by using missing energy. This result has not been updated (~300 pb^{-1})
    - PRL 100, 161801 (2008)

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

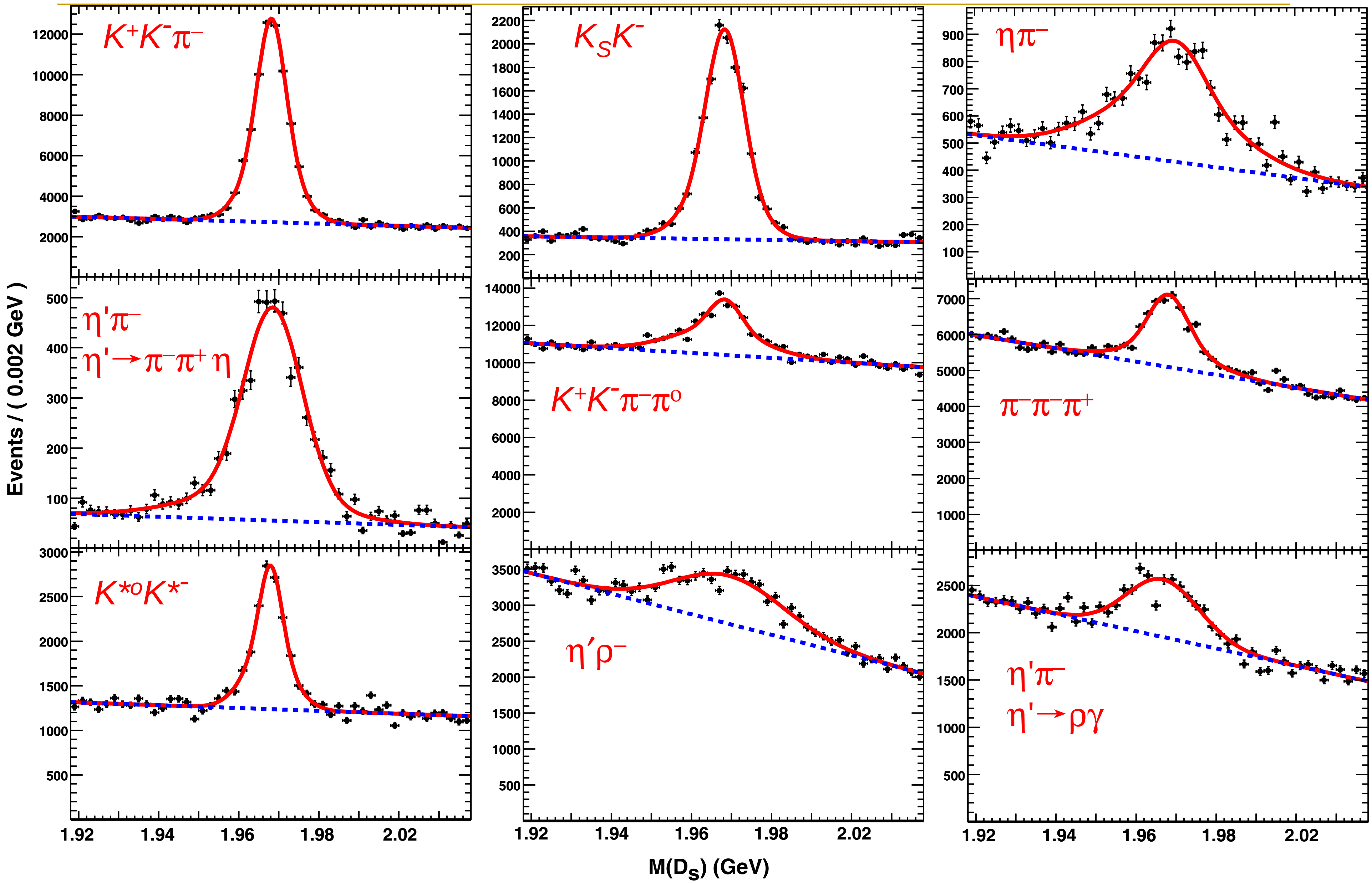
- Presence of D_S^* causes analysis changes:
  - Reconstruct D_S^-
  - Find the γ from the D_S^* & compute MM^{*2} from D_S^- & γ

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

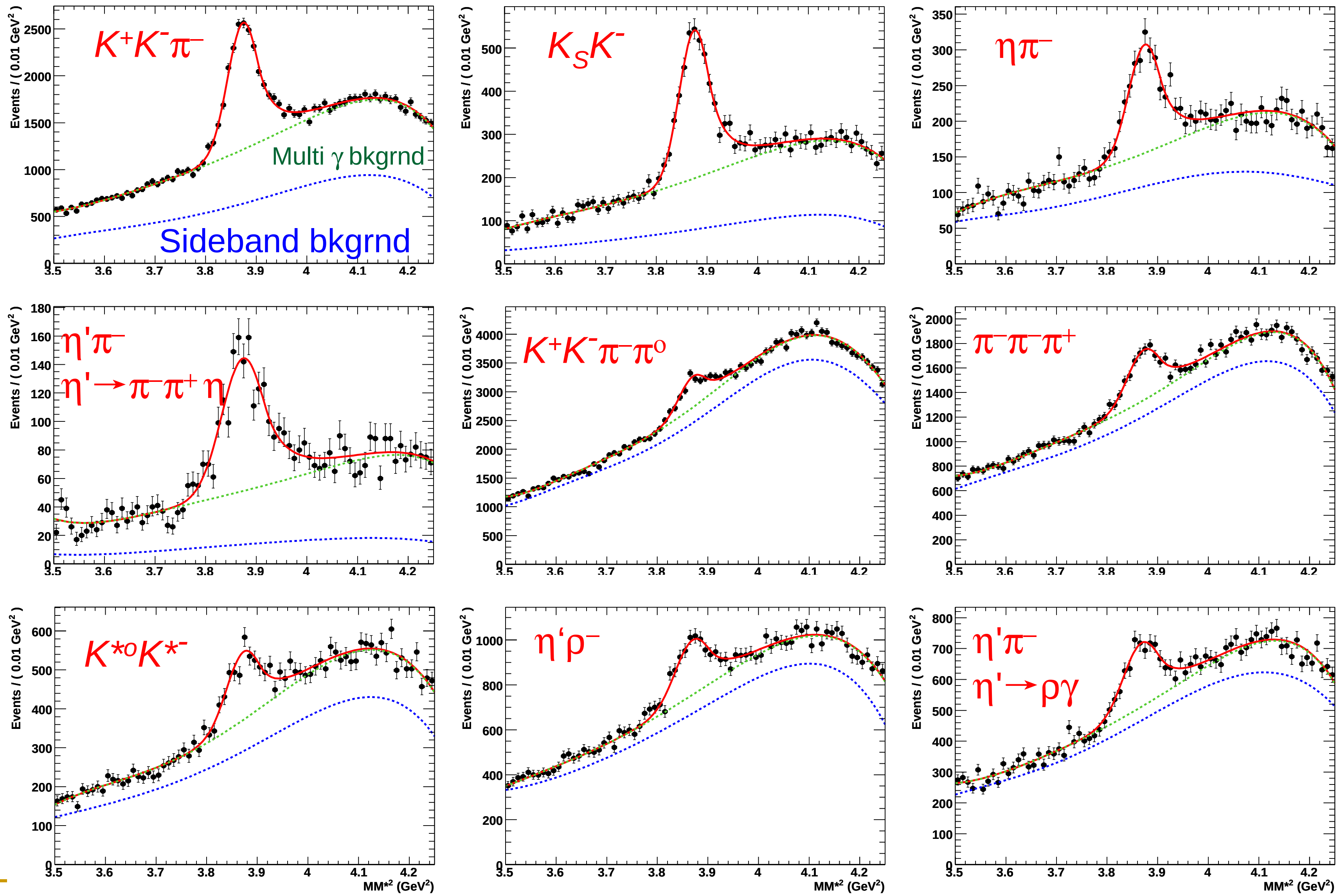
  - Select combinations consistent with a missing D_S^+ & count the number
  - Find MM^2 from candidate muon for (i) E< 300 MeV in Ecal, (ii) E>300 MeV or (iii) e^- cand.

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

D_S^- Tags: Invariant Mass

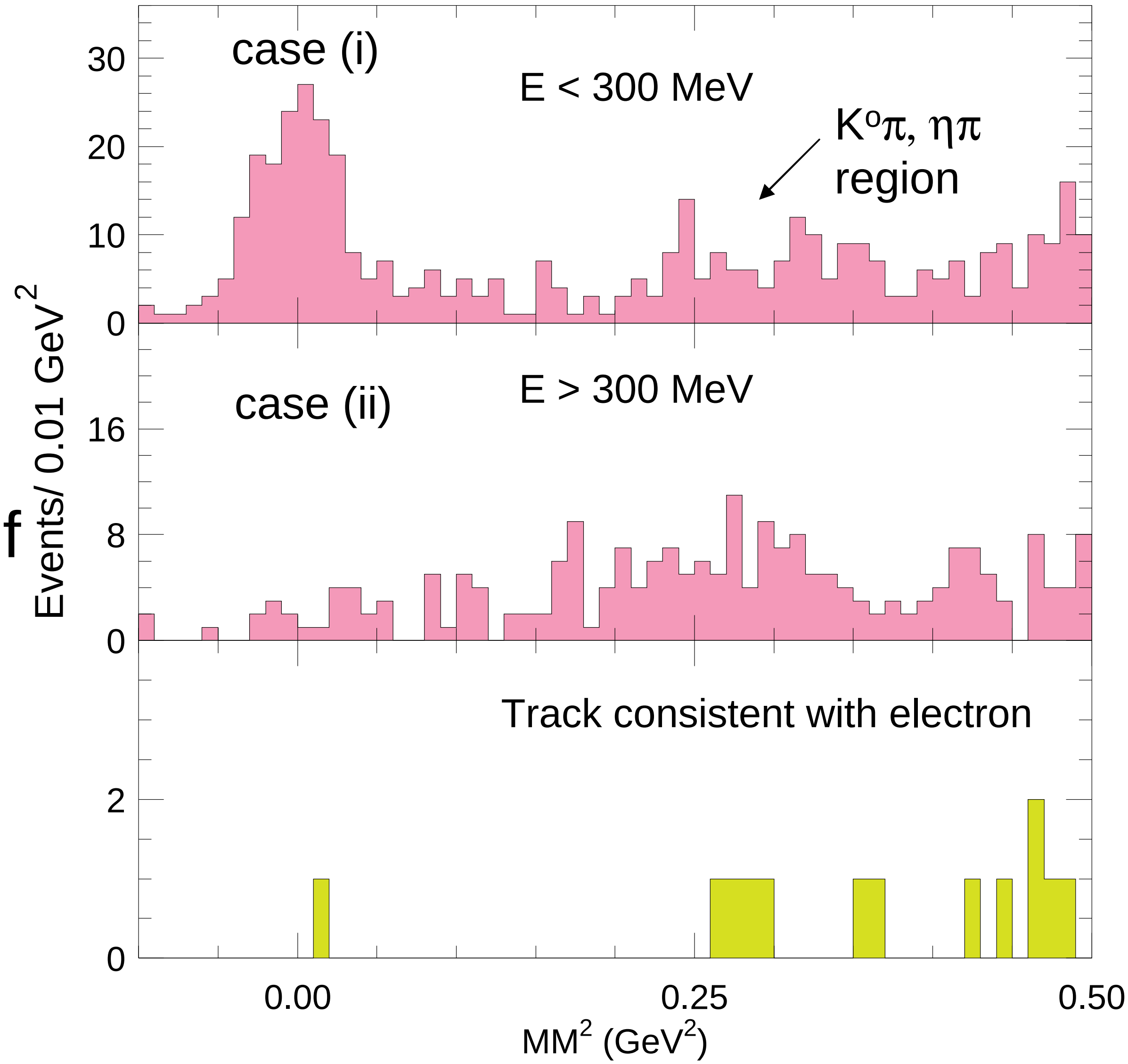


MM*^{2} Distributions From $D_S^- + \gamma$

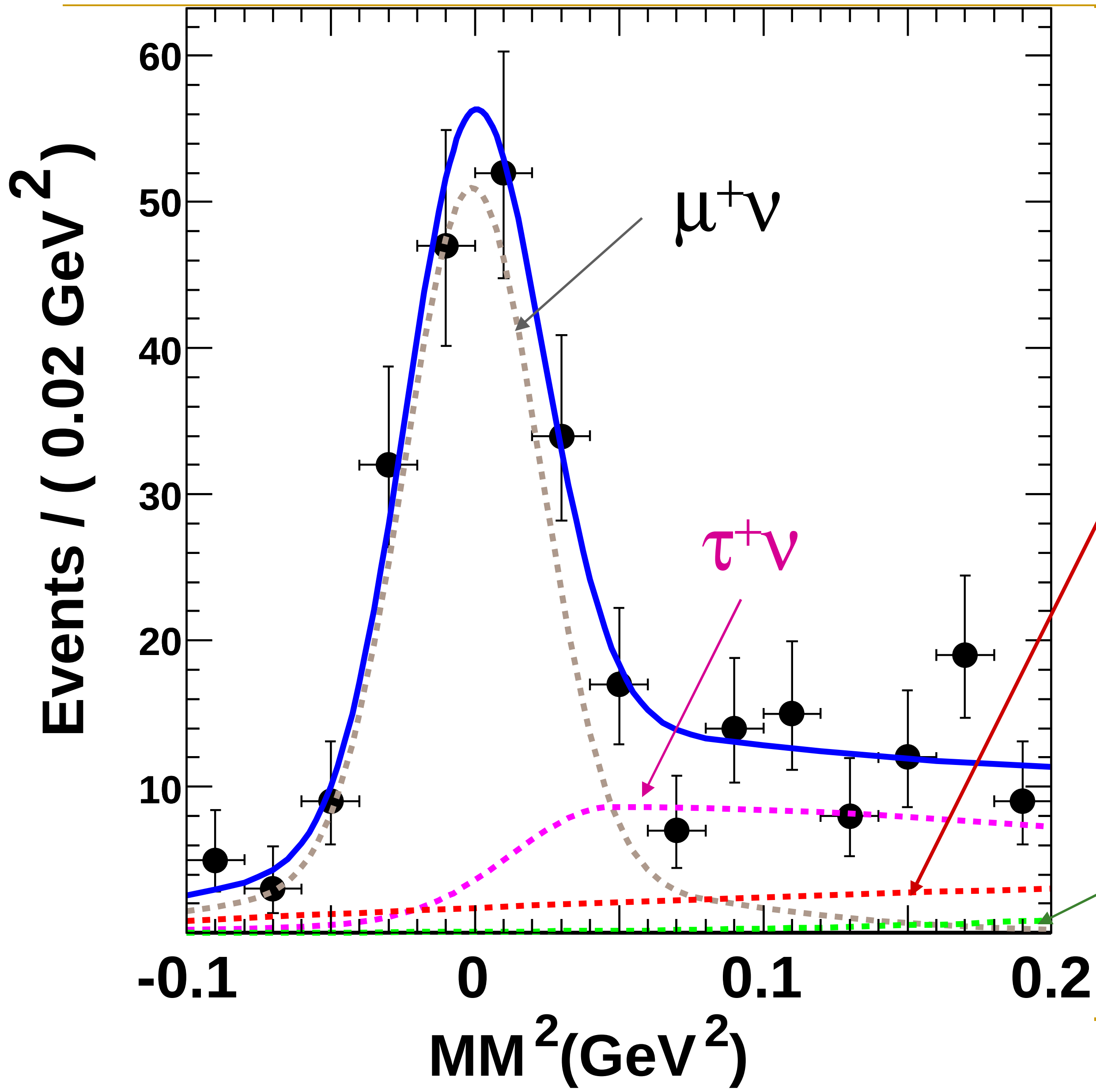


MM^2 data for D_S

- Total of 30848±695 tags
- 98.2% of $\mu^+\nu$ in E < 300 MeV
- 55%/45% split of $\tau^+\nu$, $\tau^+\to\pi^+\nu$ in two cases
- Small e^- background



Fit to signal & background



Case (i) + Case(ii)

Background D_S sidebands

Extra background from real D_S^+, mainly 3-body

Systematic Errors

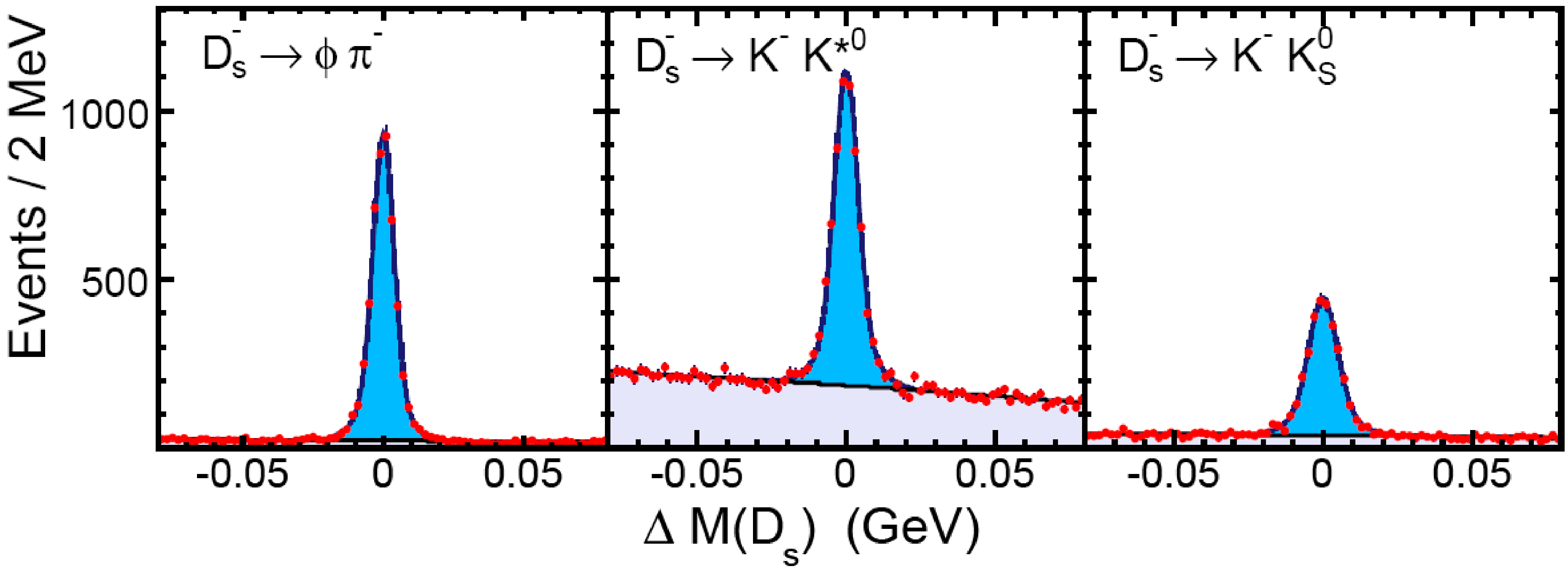
Source of Error	%
Finding the μ^+ track	0.7
Particle identification of μ^+	1.0
MM^2 width	0.2
Extra showers in event > 300 MeV	0.4
Background	0.5
Number of single tag D_S^-	3.0
Total	**3.3**

Branching Ratio & f_{D_s} *(preliminary)*

Mode	BF (%)	f_{D_s} (MeV)
(1) $\mu\nu+\tau\nu$ (fix SM ratio)	$BF^{eff}(D_s \to \mu\nu)$ = $(0.613\pm0.044\pm0.020)$	$268.2\pm9.6\pm4.4$
(2) $\mu\nu$ only	$BF(D_s \to \mu\nu)$ = $(0.600\pm0.054\pm0.020)$	$265.4\pm11.9\pm4.4$
(3) $\tau\nu$, $\tau\to\pi\nu$	$BF(D_s \to \tau\nu)$ = $(6.1\pm0.9\pm0.2)$	$271\pm20\pm4$

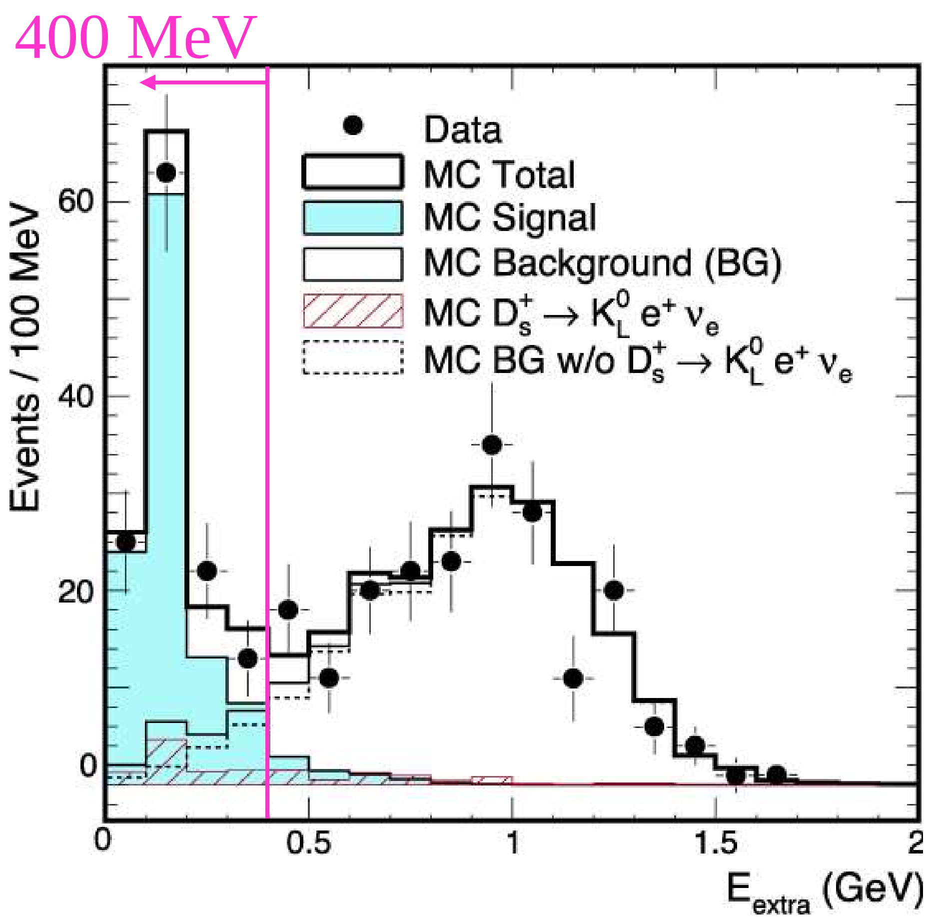
CLEO: $D_S^+ \to \tau^+ \nu$, $\tau^+ \to e^+ \nu \nu$

- $BF(D_S^+ \to \tau^+ \nu) \times BF(\tau^+ \to e^+ \nu \nu) \sim 1.3\%$ is significant compared with expected $BF(D_S^+ \to X e^+ \nu) \sim 8\%$
- Search for events opposite a tag with one electron and very little additional 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^*
- $BF(D_S^+ \to \tau^+\nu) = (6.17 \pm 0.71 \pm 0.36)\%$
- $f_{Ds} = 273 \pm 16 \pm 8$ MeV



PRL 100, 161801 (2008)

Branching Ratio & f_{D_s} *(preliminary)*

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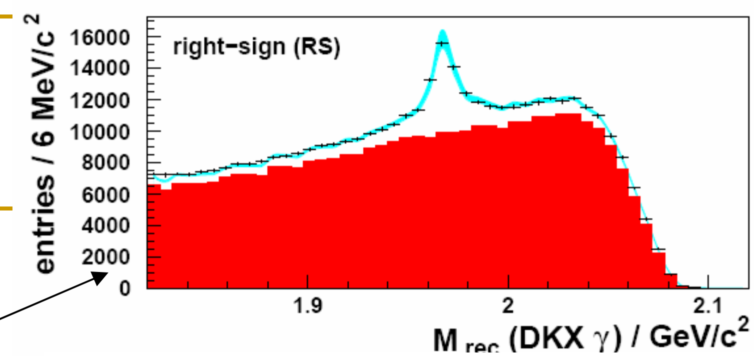
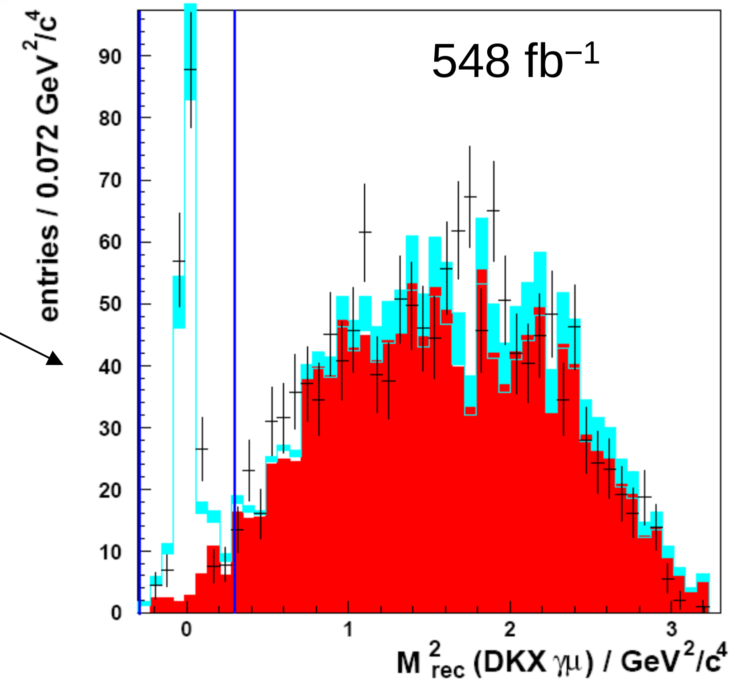
(1) $\mu\nu+\tau\nu$ (fix SM ratio)	$BF^{eff}(D_s \to \mu\nu)$ = $(0.613\pm0.044\pm0.020)$	$268.2\pm9.6\pm4.4$
(2) $\mu\nu$ only	$BF(D_s \to \mu\nu)$ = $(0.600\pm0.054\pm0.020)$	$265.4\pm11.9\pm4.4$
(3) $\tau\nu$, $\tau\to\pi\nu$	$BF(D_s \to \tau\nu)$ = $(6.1\pm0.9\pm0.2)$	$271\pm20\pm4$
(4) $\tau\nu$, $\tau\to e\nu\nu$	$BF(D_s \to \tau\nu)$ = $(6.17\pm0.71\pm0.36)$	$273\pm16\pm8$
CLEO Average of (1) & (4)	Rad. corr.	$269.4\pm8.2\pm3.9$ $267.9\pm8.2\pm3.9$

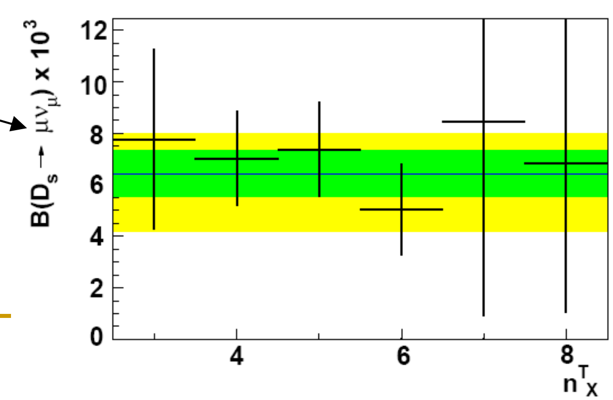
Belle: $D_S^+ \to \mu^+ \nu$

- 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
- $BF(D_S^+ \to \mu^+\nu) = (0.644 \pm 0.076 \pm 0.057)\%$
- **$f_{Ds} = 275 \pm 16 \pm 12$ MeV**
- Results stable as a function of final state multiplicity

PRL 100, 241801 (2008)







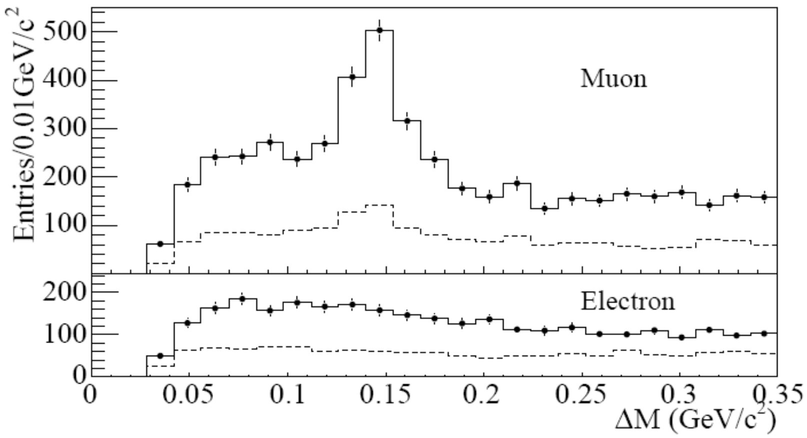
BABAR: $D_S^+ \to \mu^+ \nu$

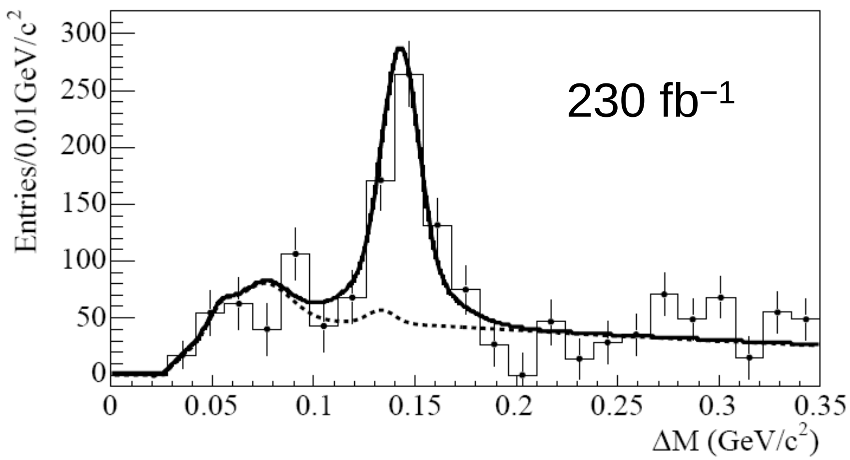
PRL 98, 141801 (2007)

- Look for events with a tag D^0, $D^\pm$, D^* or D_s with both a μ and a γ consitant to be from D_s^* decay in the rest of the event
- Approximate neutrino 4-mom to (E_{miss}, $\mathbf{p}_{miss}$)
- Compute

$$\Delta M = M(\mu\nu\gamma) - M(\mu\nu)$$

- Subtract background using sidebands and electron sample
  - Remaining background from mis-IDed muons in ccbar and mis-reconstructed signal
- Fit ΔM distribution to extract signal





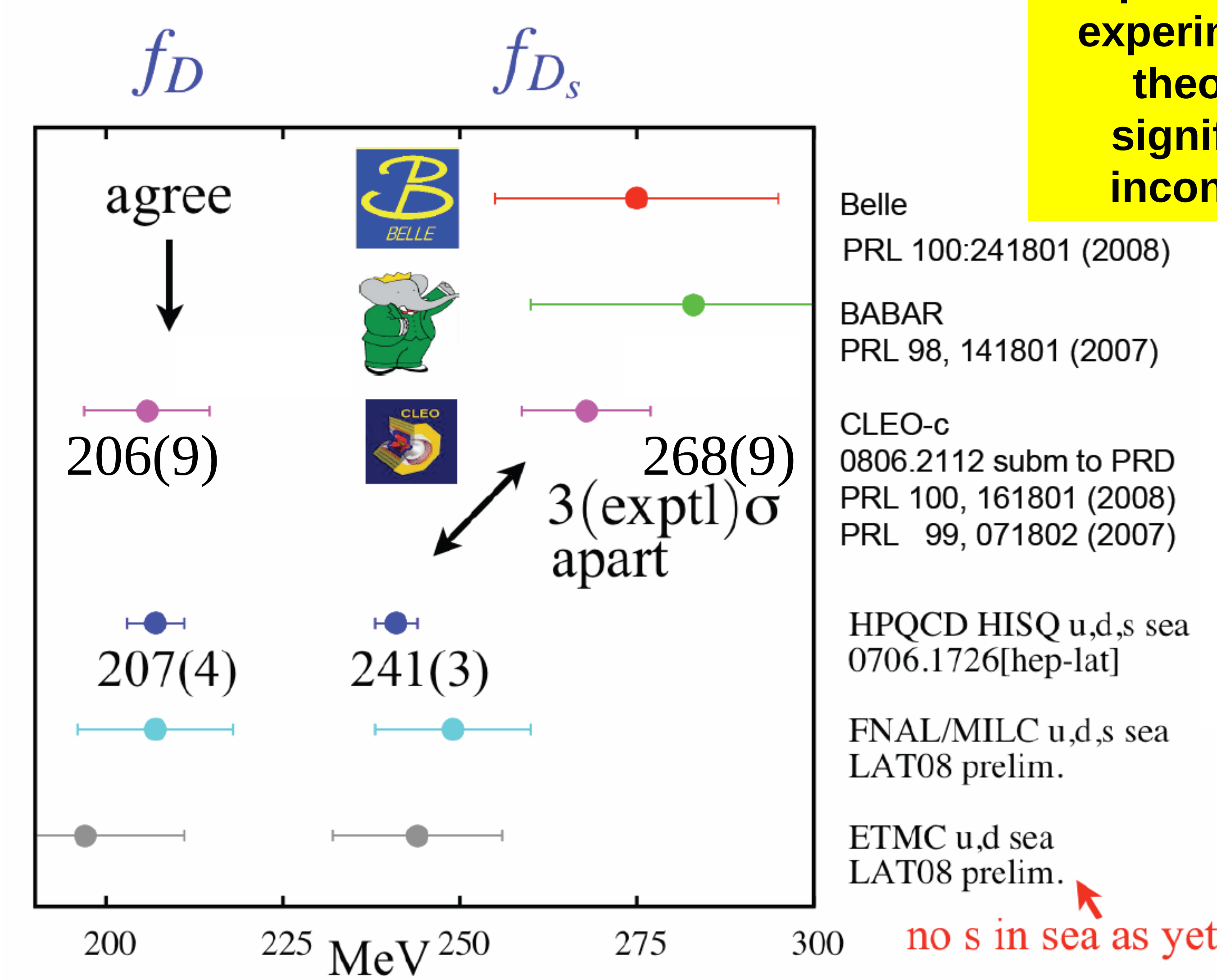
f_{D_s}=(283±17(stat)±7(syst)±14($D_s \to \phi\pi$)) MeV

f_{D_s} & f_{D_s}/f_{D^+}

- Weighted Average of absolute measurements from CLEO + Belle:
  - f_{Ds}=270.4±7.3±3.7 MeV,
  - the systematic uncertainty is uncorrelated between the measurements
- Using f_D+ = (205.8±8.5±2.5) MeV
  - f_{Ds}/f_D+ = 1.31±0.06±0.02
  - larger than LQCD predictions
- $\Gamma(D_S^+\to\tau^+\nu)/\Gamma(D_S^+\to\mu^+\nu)$=10.3±1.1
  - SM=9.72
  - Consistent with lepton universality

Conclusions

More data required to see if experiment and theory are significantly inconsistent



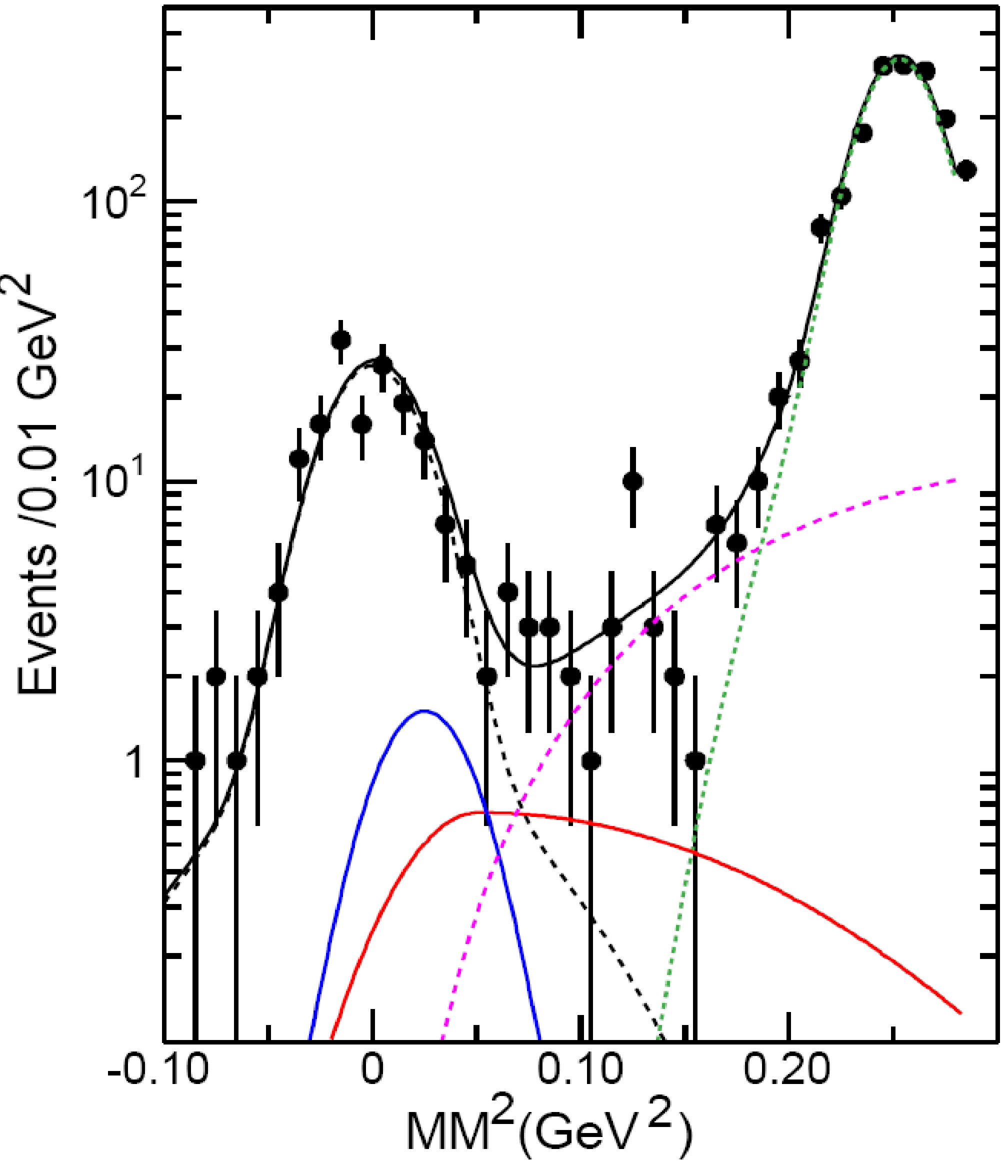
Future datasets

- CLEO will further update f_{Ds} using at total of ~600 pb^{-1}
  - 50% increase in data for $\mu\nu$
  - 100% increase in data for $\tau\nu$, $\tau\rightarrow e\nu\nu$
  - Improved D_s tag systematic to 3%→2%
- f_{D^+} will not see any major improvements until BES
  - Also for f_{Ds} can run at 4030 MeV for D_sD_s production only
    - Reduce tag yield systematic < 1%
- B-factories plans:
  - BABAR: absolute measurement with full set
  - Belle: update with final 0.9-1.0 ab^{-1} data set

Backup

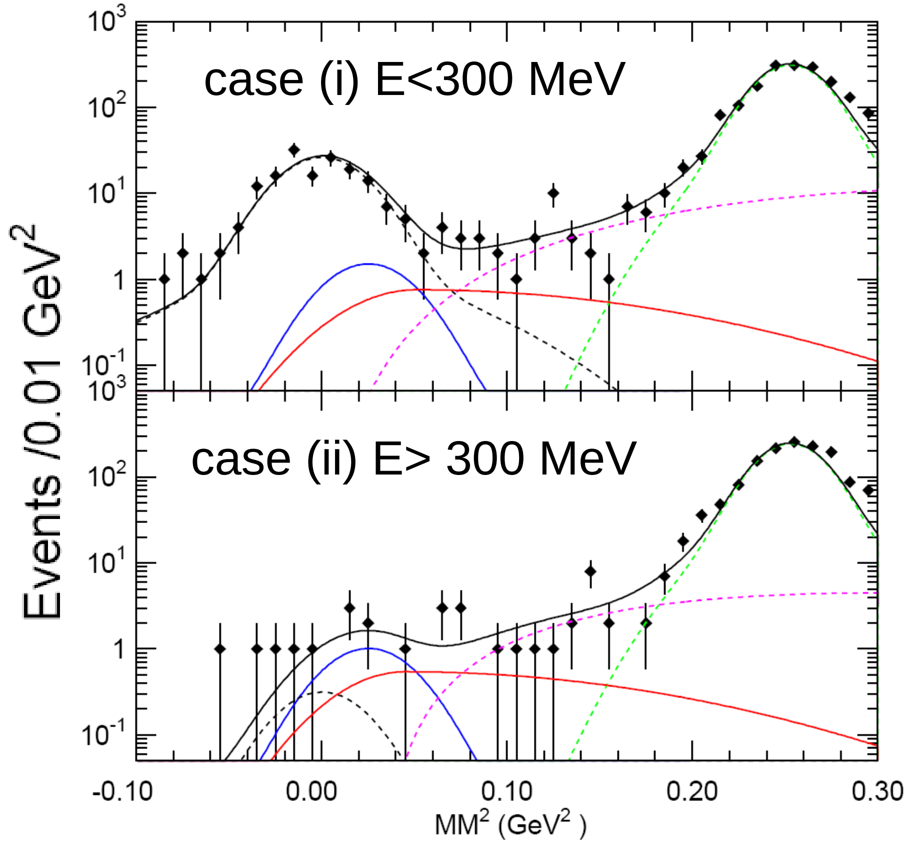
Case(i) With $\tau^+\nu/\mu^+\nu$ Floating

- Fixed
  - 149.7±12.0 $\mu\upsilon$
  - 28.5 $\tau\nu$
- Floating
  - 153.9±13.5 $\mu\upsilon$
  - 13.5±15.3 $\tau\nu$



Upper limits on $\tau^+\nu$ & $e^+\nu$

- Fit both case(i) & case(ii) constraining the relative $\tau\nu$ yield to the pion acceptance ratio 55:45.



- Find
  - BF($D^+\to\tau^+\nu$) < 1.2×10^{-3}, @ 90% c.l.
  - BF($D^+\to\tau^+\nu$)/2.65BF($D^+\to\mu^+\nu$) < 1.2 @ 90% c. l.
- Also BF($D^+\to e^+\nu$)< 8.8×10^{-6}, @ 90% c.l.

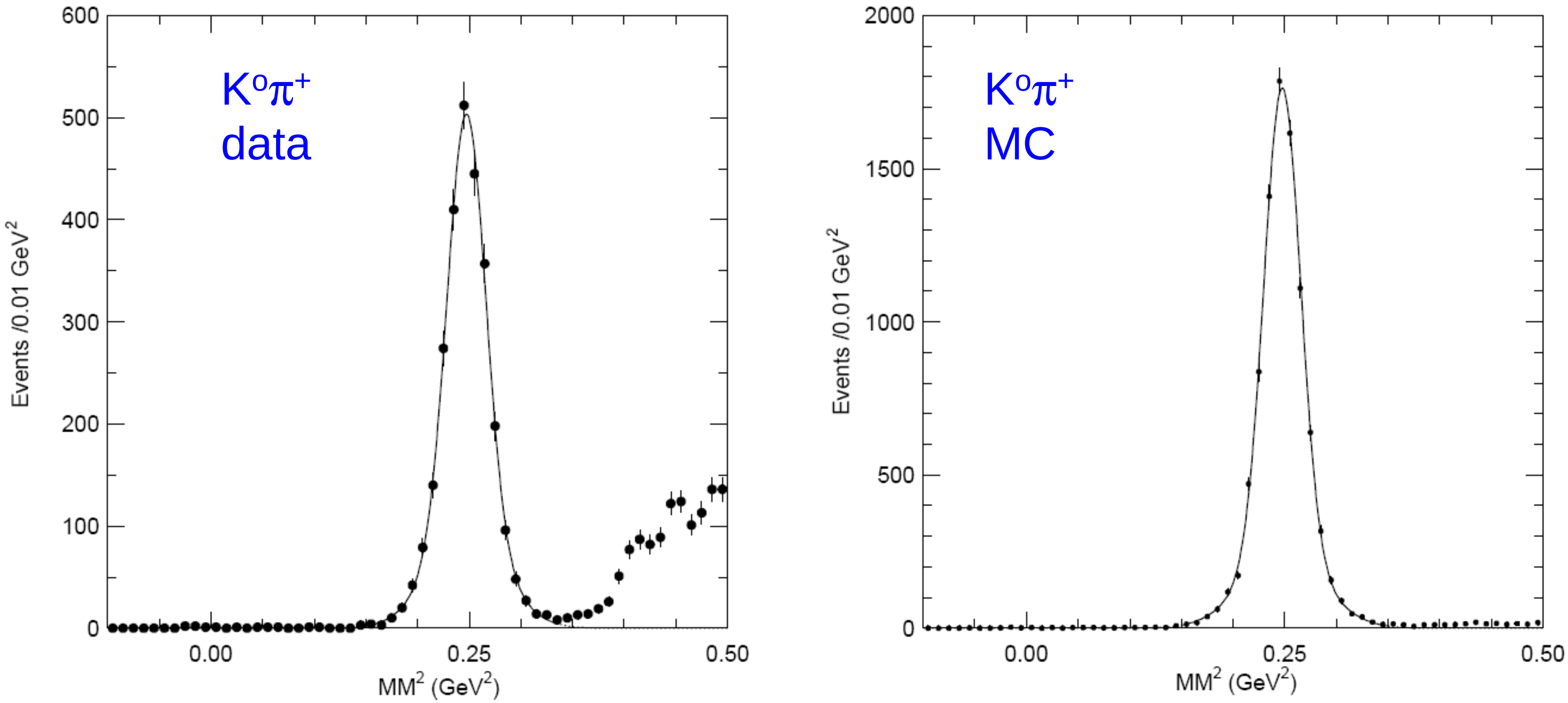
CP Violation

- 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.
  - Consistent with SM expectation of no direct CP violation

$\mu\nu$ Signal Shape Checked



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

Other Non-absolute Measurements

Exp.	mode	BF	BF($D_S \to \phi\pi$) (%)	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	$283 \pm 17 \pm 7 \pm 14$

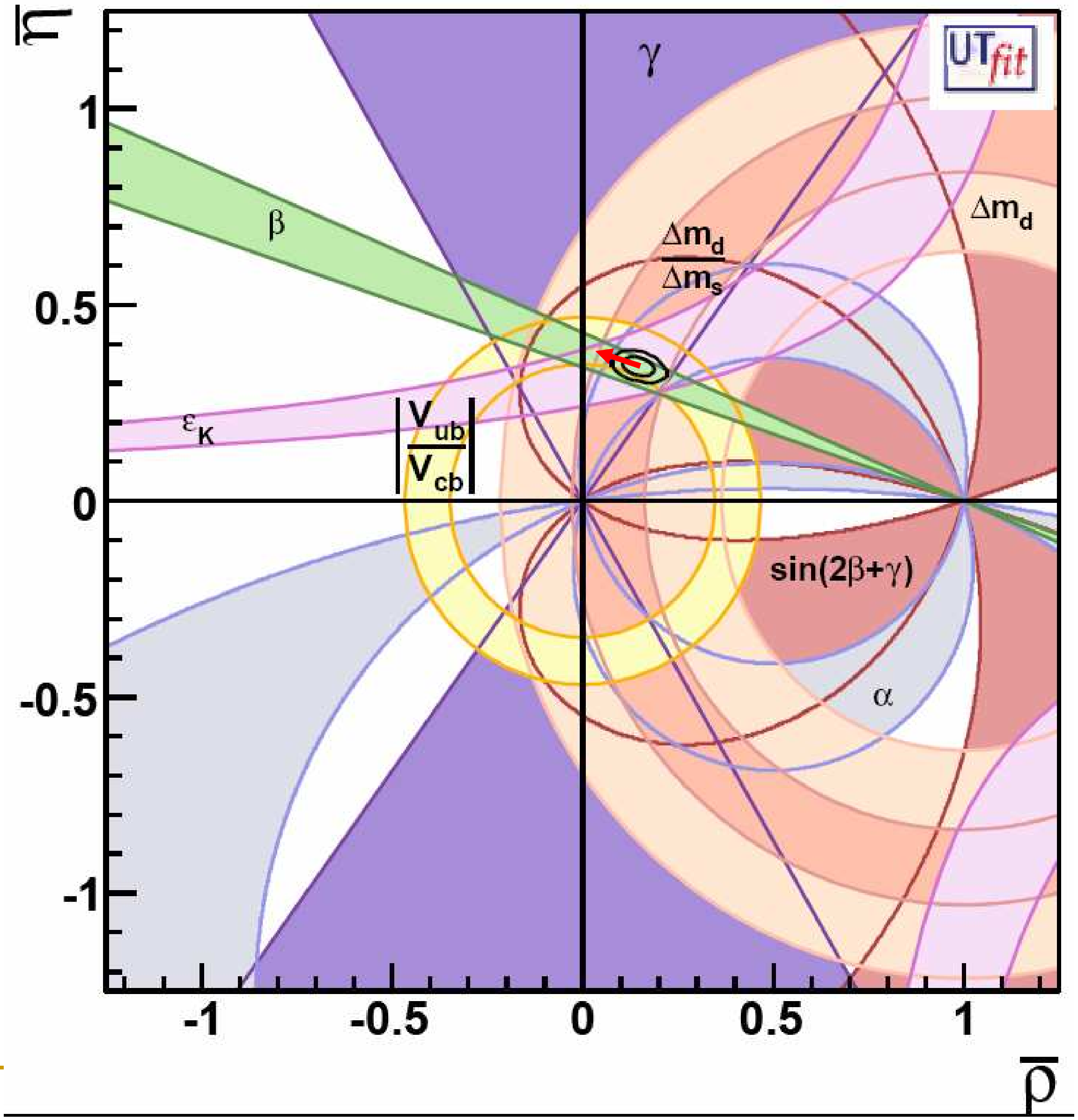
See arXiv:0802.1043 for references

Possibilities

- Pick your favorite of the three:
  - Experiment will eventually converge on SM predicted value
  - If LQCD 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?
  - If there is New Physics affecting leptonic D_S decays, how does it affect B_S mixing and other B_S decays? (See A. Kundu & S. Nandi, "R-parity violating supersymmetry, B_S mixing, & $D_S^+ \to \ell^+\nu$" [arXiv:0803.1898])

If there is a Shift ..

- If increases the radius of the $\Delta m_d/\Delta m_s$ constraint increases
- Red arrow indicates a shift of ~10% in f_{Bs}/f_B



New Physics Possibilities

- Ratio of leptonic decays

could be modified e.g. in Standard Model

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

- If $H^\pm$ couple proportional to $M^2 \Rightarrow$ no effect

See Hewett [hep-ph/9505246] & Hou, PRD 48, 2342 (1993).

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