Absolute measurements of Pure leptonic D_s decays and f_{D_s} decay constant from BaBar

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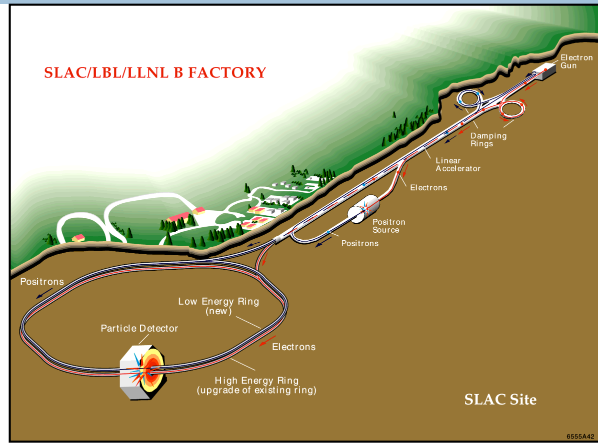
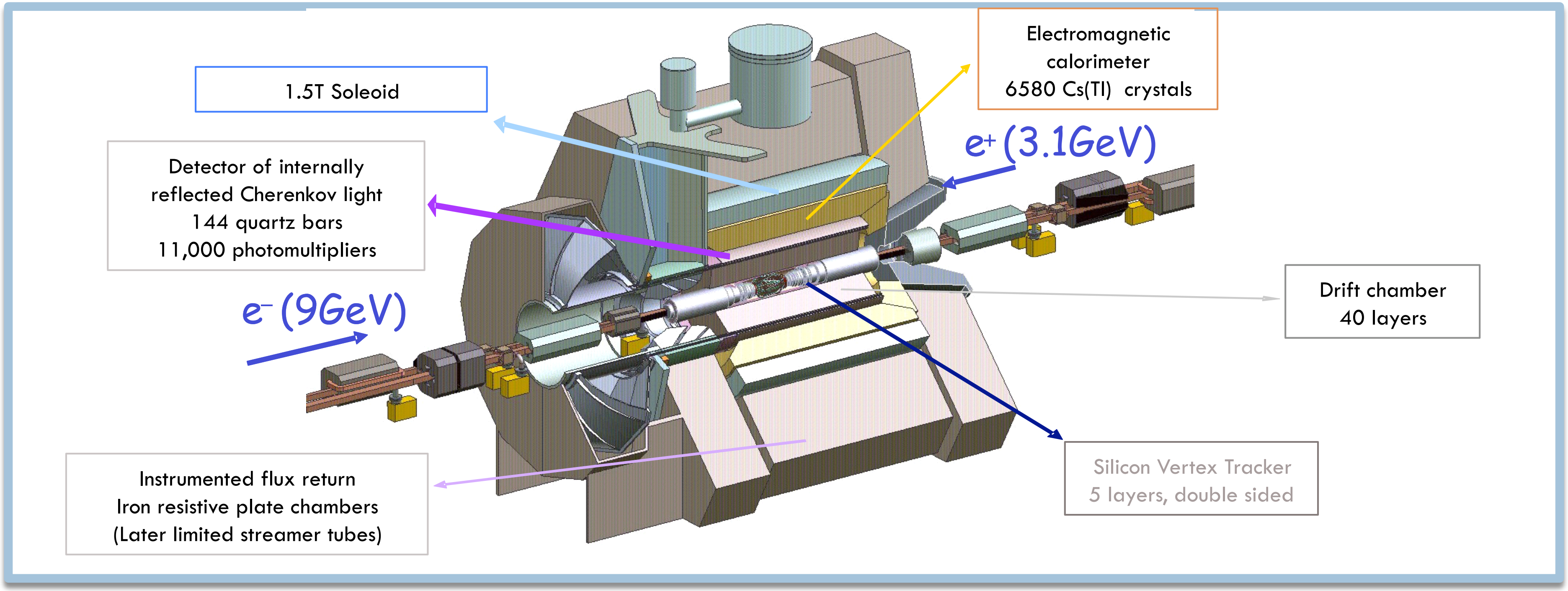
Overview

- The BaBar experiment
- Motivation
- Reconstruction
- Systematic uncertainties
- Results
- Summary and conclusion

The BaBar experiment

- The BaBar detector is at the SLAC National Accelerator Laboratory, home of the PEP-II asymmetric energy e^+e^- collider.
- The experiment was an excellent B, charm and τ factory, generating over 700 million cc pairs, from December 1999 to April 2008.

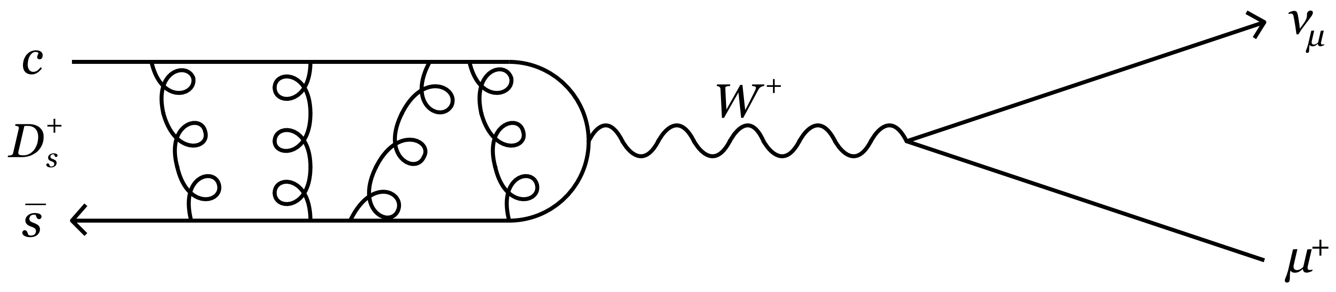




Motivation

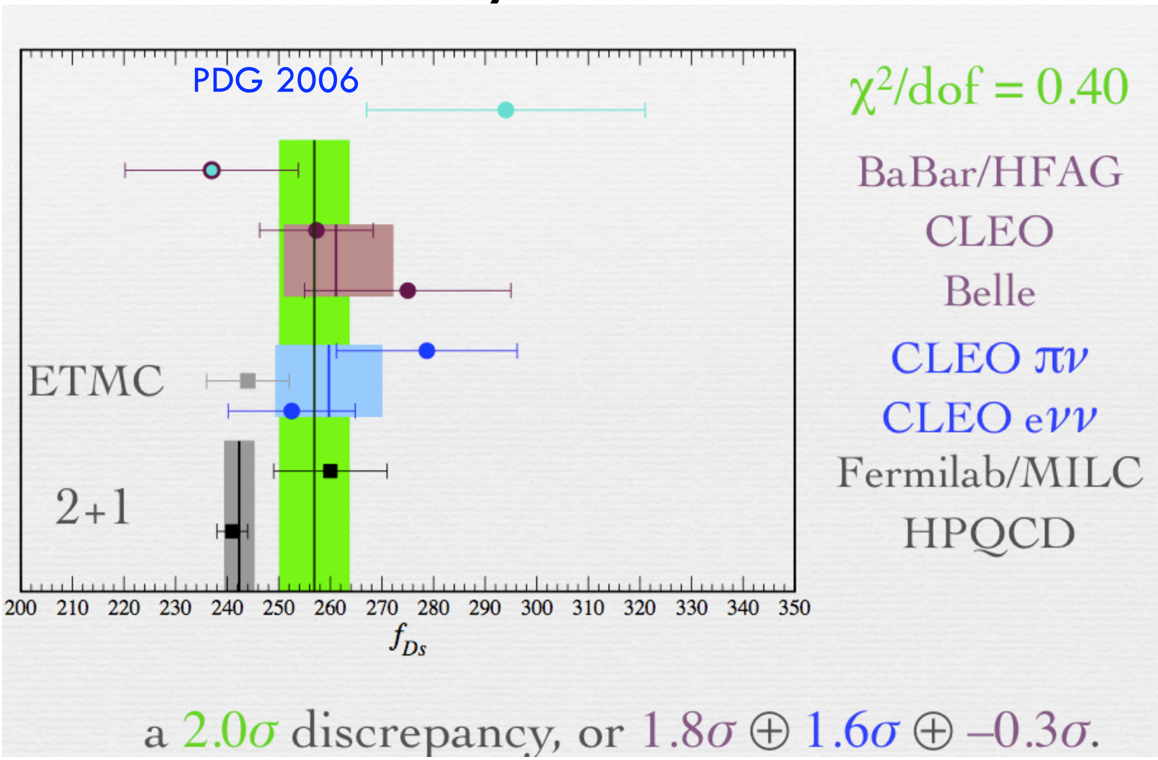
- In the standard model the leptonic decays of the D_s meson provide a clean way to measure the decay constant f_{Ds}:

$$B(D_s \to l\upsilon) = \frac{\Gamma(D_s \to l\upsilon)}{\Gamma(D_s \to all)} = \frac{G_F^2}{8\pi}|V_{cs}|^2 f_{D_s}^2 M_{D_s}^3 \left(\frac{m_l}{M_{D_s}}\right)^2 \left(1 - \frac{m_l^2}{M_{D_s}^2}\right)^2$$



Motivation

- In October 2009 unquenched lattice quantumchromodynamical (UL-QCD) calculations of the decay constant f_{Ds} disagree with experimental results by 2σ:

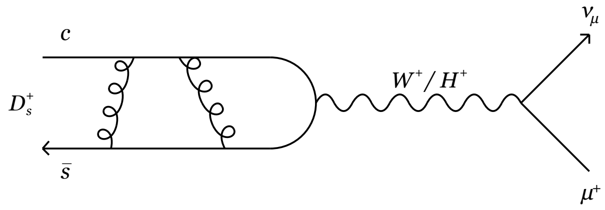


- Green band: world average of experimental results.
- Gray band: World average of UL-QCD calculations
- Pink band: $D_s \to \mu\ \nu$ measurements
- Blue band: $D_s \to \tau\ \nu$ measurements

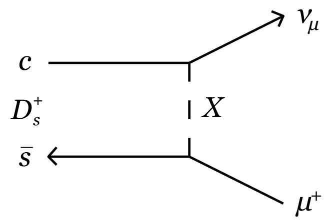
Status of f_{Ds} October 2009.
http://www.slac.stanford.edu/exp/seminar/talks/2009/20091027_Kronfeld.pdf

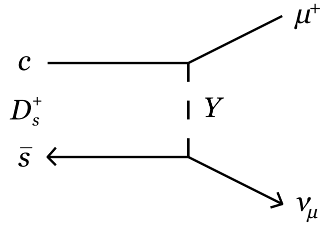
Motivation

- This discrepancy could be the result of new physics:
  - Charged Higgs boson



  - Leptoquarks





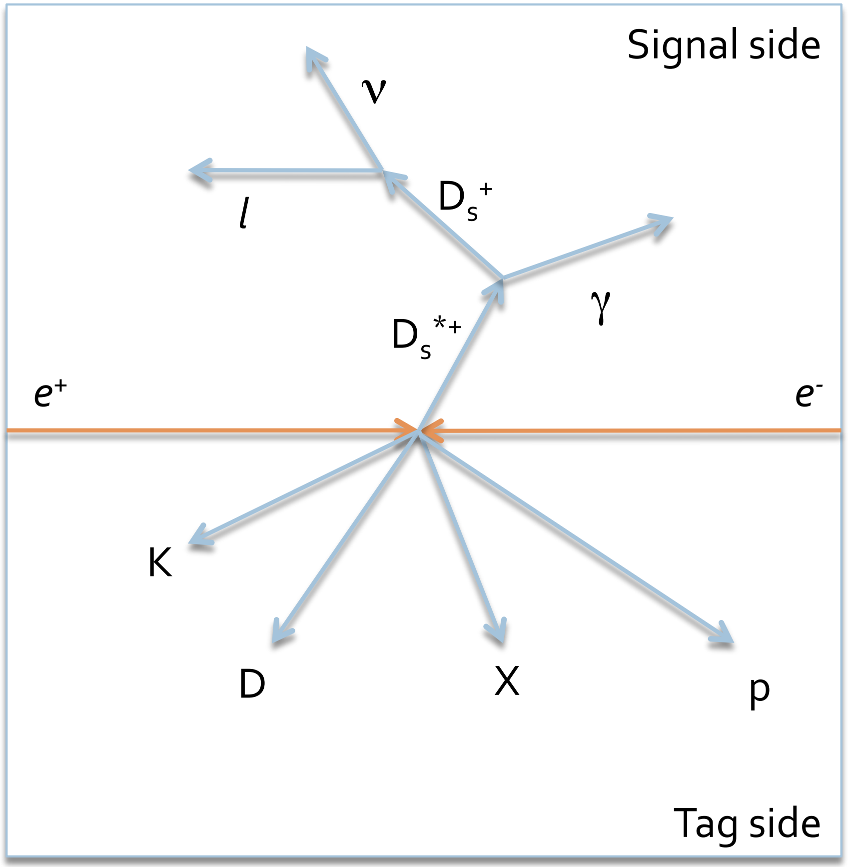
  - SUSY
  - More details in the backup slides.

Analysis strategy

- The event reconstruction allows an absolute measurement of branching fractions.
- The number of D_s mesons produced at BaBar is measured (the denominator.)
- The number of $D_s \rightarrow l\nu$ events is measured (the numerator.)
- The branching fraction is obtained by calculating the efficiency corrected ratio of these numbers.
- This analysis uses the entire dataset, including $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$ and off-peak data.

Event reconstruction

- The event topology is split into two halves:
  - Tag side
    - Charm tag (D)
    - Flavor balancing kaon (K)
    - Baryon balancing proton (p)
    - Fragmentation system (X)
  - Signal side
    - D_s meson (D_s)
    - Photon (γ)
    - Lepton (l)



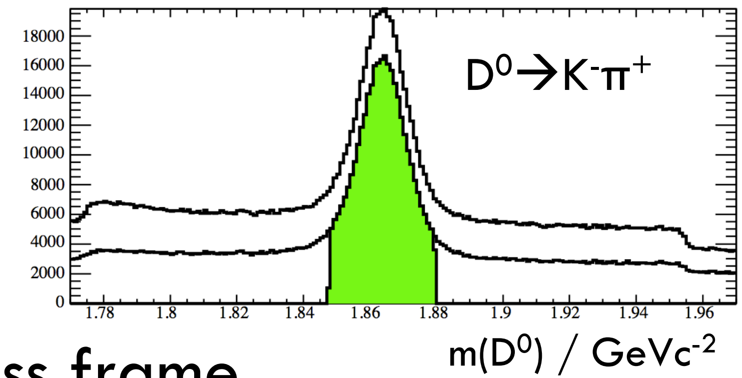
Charm tag reconstruction

- The charm tag is reconstructed in the following modes:

D^0		D^+		Λ_c^+	
Mode	Branching fraction	Mode	Branching fraction	Mode	Branching fraction
$D^0 \to K^-\pi^+$	3.9%	$D^+ \to K^-\pi^+\pi^+$	9.4%	$\Lambda_c^+ \to pK^-\pi^+$	5.0%
$D^0 \to K^-\pi^+\pi^0$	13.9%	$D^+ \to K^-\pi^+\pi^+\pi^0$	6.1%	$\Lambda_c^+ \to pK^-\pi^+\pi^0$	3.4%
$D^0 \to K^-\pi^+\pi^-\pi^+$	8.1%	$D^+ \to K^0_S\pi^+$	1.5%	$\Lambda_c^+ \to pK_S^0$	1.1%
$D^0 \to K^0_S\pi^+\pi^-$	2.9%	$D^+ \to K^0_S\pi^+\pi^0$	6.9%	$\Lambda_c^+ \to \Lambda\pi^+$	1.1%
$D^0 \to K^-\pi^+\pi^-\pi^+\pi^0$	4.2%	$D^+ \to K^0_S\pi^+\pi^-\pi^+$	3.1%	$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	3.6%
$D^0 \to K^0_S\pi^+\pi^-\pi^0$	5.4%			$\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$	2.6%
				$\Lambda_c^+ \to \Sigma\pi^+$	1.1%

Charm tag selection

- The charm tag modes selections were optimized with respect to significance using $8 fb^{-1}$ of data.
- Selection variables are:
  - tag mass.
  - particle identification.
  - momentum in the center of mass frame.
  - $P(\chi^2|n)$ of a kinematic fit of the tag.



- Significance ranges from 9 ($\Lambda_c^+ \rightarrow \Sigma\pi^+$) to 350 ($D^0 \rightarrow K^-\pi^+$)
- Tags are 74% D^0, 23% D^+, 4% Λ_c^+.

Fragmentation system

- The energy at BaBar is far above $c\bar{c}$ production threshold.
- Additional mesons are produced at the interaction point.
- We reconstruct the fragmentation system in the following states:

No pions	$\pi^\pm$	$\pi^\pm\pi^\pm$	$\pi^\pm\pi^\pm\pi^\pm$
π^0	$\pi^\pm\pi^0$	$\pi^\pm\pi^\pm\pi^0$	

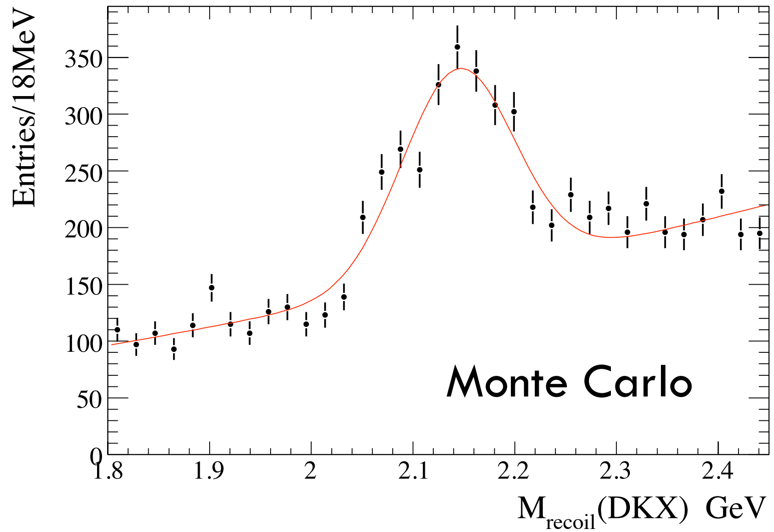
- $K\bar{K}$ contributions are negligible.

Fragmentation system

- The reconstruction of the fragmentation system is often incomplete due to:
  - Misreconstruction.
  - Missing particles in the event.
  - Particle identification efficiency effects.
- Define:
  - n_X^T as the true number of pions from fragmentation.
  - n_X^R as the reconstructed number of pions from fragmentation.
- Unfold the n_X^T distribution from n_X^R.

D_s^{*+} reconstruction

- A D_s^{*+} meson is reconstructed recoiling against the DKX system.
- A photon consistent with the decay $D_s^{*+} \to D_s^{+} \gamma$ is identified.
- A kinematic fit is performed to the whole event.



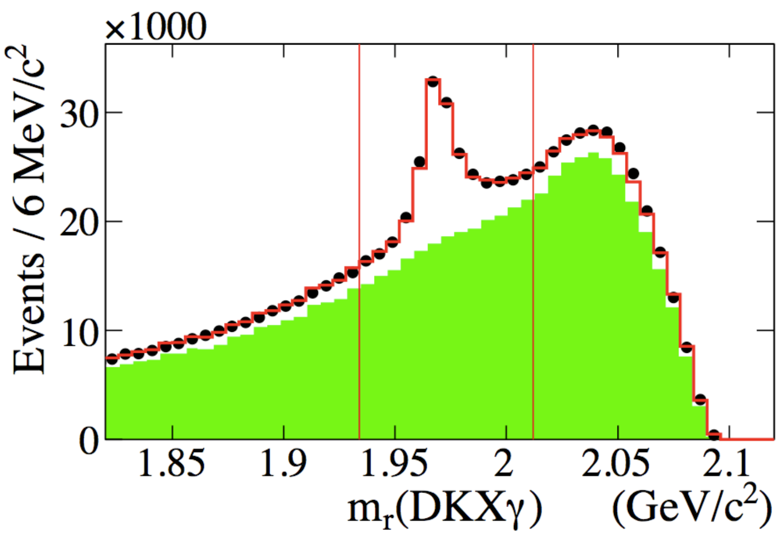
- The mass of the D_s^{*+} candidate is then constrained to the mass provided by the Particle Data Group.

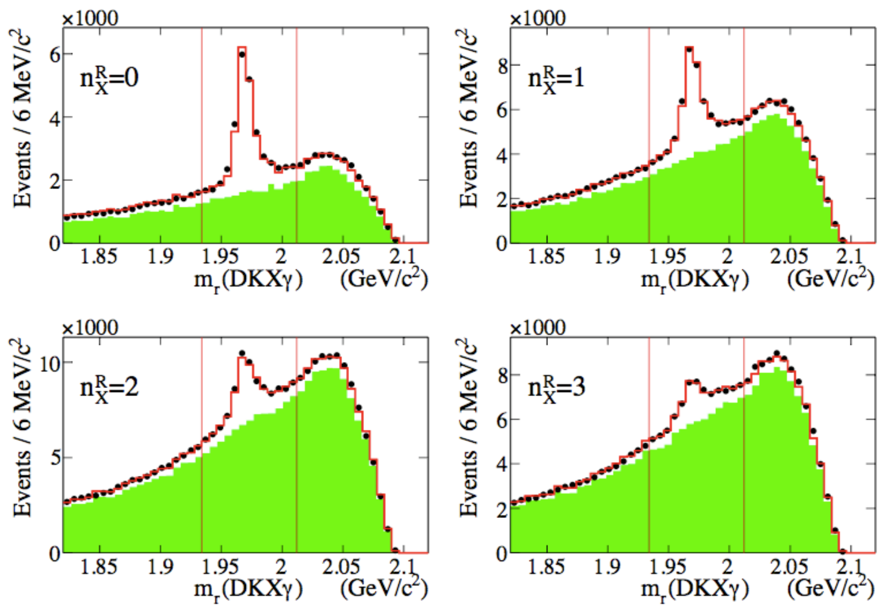
Right sign and wrong sign

- We define right sign and wrong sign reconstructions:
  - Right sign: any reconstruction where the DKX system flavor and charge are consistent with recoiling against a D_s^{*+}.
  - Wrong sign: any reconstruction where the DKX system flavor and charge are not consistent with recoiling against a D_s^{*+}.
  - Other: any other reconstruction (eg where the charge of the system recoiling against the DKX system would be zero.)

D_s yield extraction

- The yield of Ds mesons is determined using a 2-D fit to:
  - Mass recoiling against the DKX γ system
  - n_X^R, the reconstructed number of pions in the fragmentation system.
- We obtain $n(D_s) = 67{,}200 \pm 1500$.



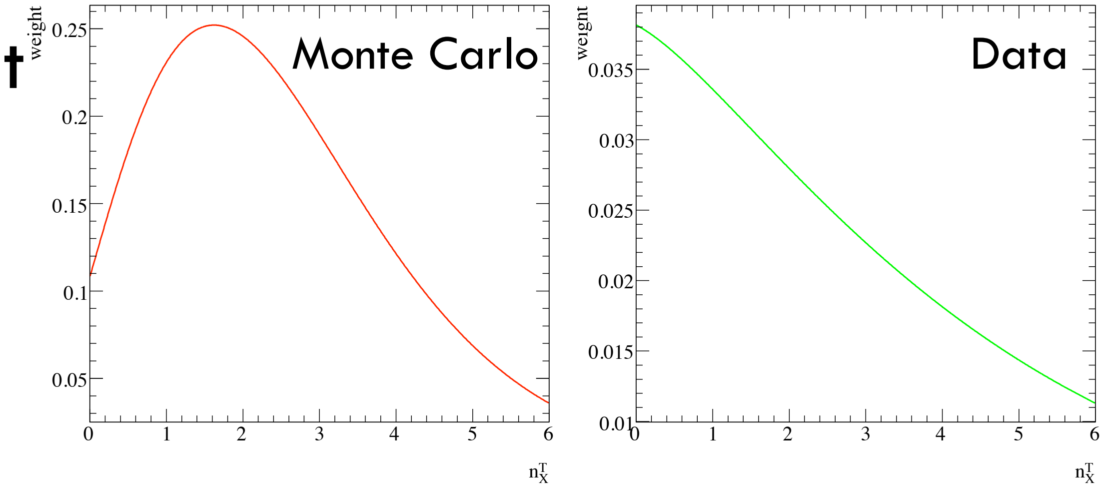


n_X^T unfolding

- While the 2-D fit is being performed the n_X^T distribution is unfolded.
- A weights model for each value of $n_X^T=j$ is constructed:

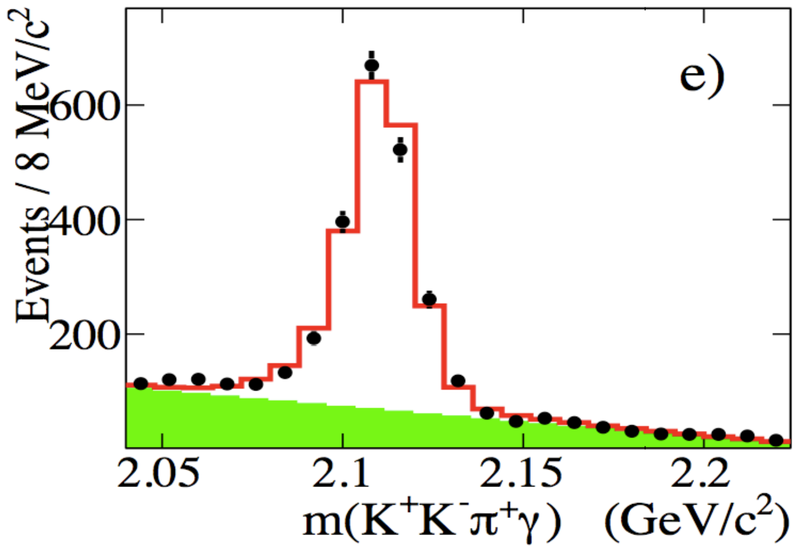
$$w_j^{RS} = \frac{(j-\alpha)^\beta e^{-\gamma j}}{\sum_{k=0}^{6}(k-\alpha)^\beta e^{-\gamma k}}$$

- The parameters are floated in the 2-D fit
- Efficiencies are calculated after n_X^T unfolding.



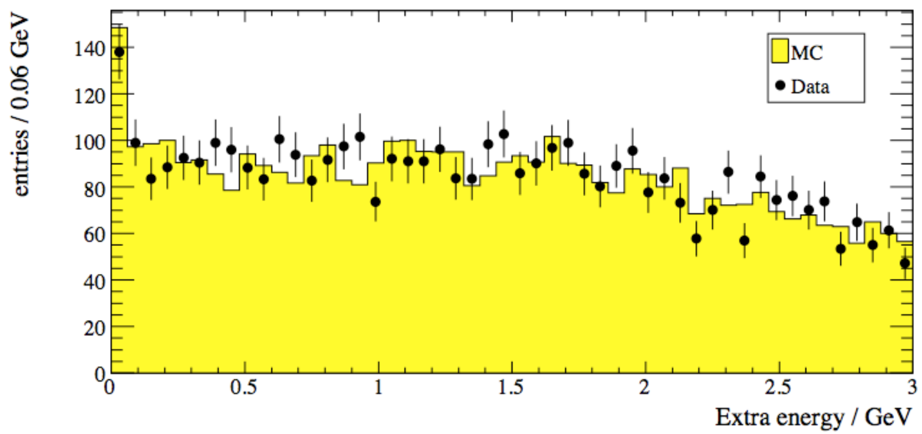
$D_s \rightarrow KK\pi$ crosscheck

- To validate the D_s reconstruction technique a $D_s \rightarrow KK\pi$ crosscheck is used.
- Due to resonances, an efficiency weighted Dalitz plot is used.
- We obtain $B(D_s \rightarrow KK\pi) = (5.78 \pm 0.20 \pm 0.30) \times 10^{-2}$
- Consistent with the Particle Data Group.



Extra energy

- An important variable in the analysis is the extra energy, E_{Extra}.
- E_{Extra} is the energy in the calorimeter where:
  - Each cluster of calorimeter crystals does not overlap with the the candidates in the reconstruction.
  - Each cluster has a minimum energy of 30MeV.
- If the only remaining particles in the event are neutrinoes, we expect E_{Extra} to be very small.



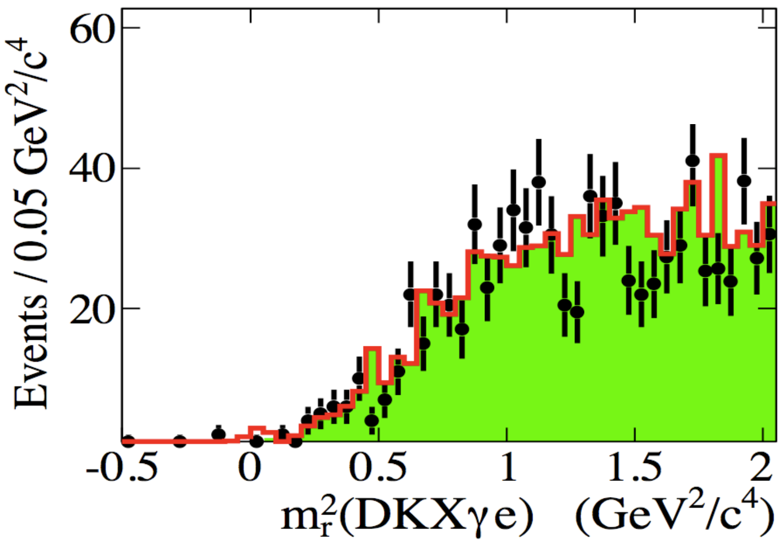
$D_s \rightarrow e\nu$ reconstruction

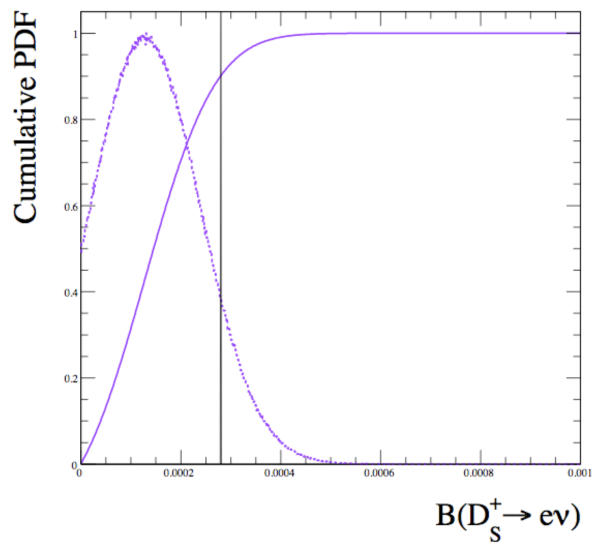
- An electron candidate is identified, using standard particle identification techniques.
- The mass of the D_s candidate is constrained to the mass provided by the Particle Data Group.
- We require $E_{Extra}<1GeV$.
- A kinematic fit to the whole event is performed.
- A binned maximum likelihood fit to the mass squared recoiling against the DKX γ e system, m_m^2, is performed.

$D_s \to e\nu$ limit extraction

- We obtain a yield of 6.1 ± 2.2 ± 5.2 events.
- A Bayesian limit is obtained, assuming a uniform prior distribution for $B(D_s \to e\nu)$.
- Using Monte Carlo integration we obtain:

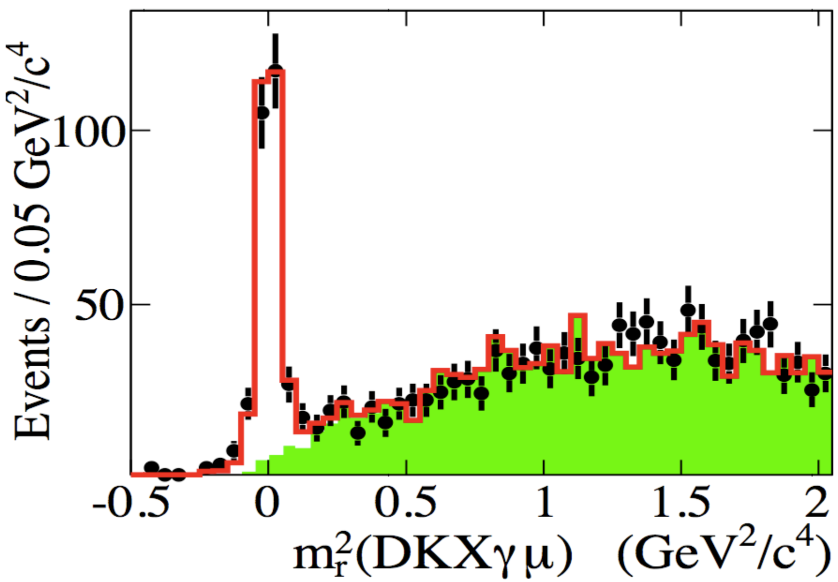
$$B(D_s \to e\nu) < 2.8 \times 10^{-4}$$





$D_s \to \mu\ \nu$ reconstruction

- The same fit and selection criteria are used to measure the branching fraction $B(D_s \to \mu\ \nu)$.
  - This time we identify a muon candidate.



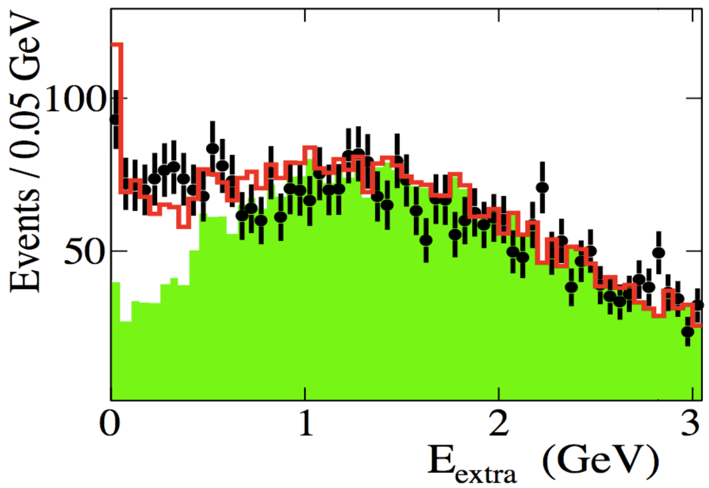
We obtain events 274 ± 17, which yields $B(D_s \to \mu\ \nu) = (6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$

$D_s \to \tau\ \nu$ reconstruction

- We measure the final states
  - $\tau \to e \nu\ \nu$
  - $\tau \to \mu\ \nu\ \nu$
- Particle identification procedure remains the same as for $D_s \to e \nu$ and $D_s \to \mu\ \nu$ as appropriate.
- For $D_s \to \tau\ \nu$; $\tau \to \mu\ \nu\ \nu$ we require $m_m^2 > 0.3$ GeV^2c^{-4} to remove backgrounds from $D_s \to \mu\ \nu$ events.
- For $D_s \to \tau\ \nu$ decays we perform a binned maximum likelihood fit to E_{Extra}.

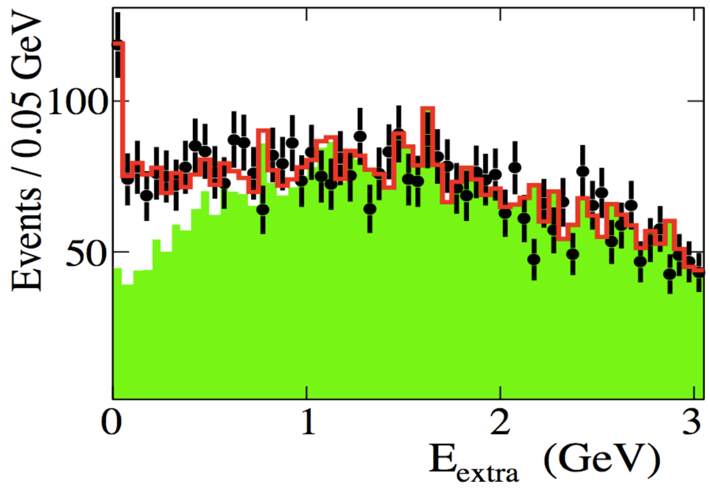
$D_s \rightarrow \tau\ \nu$ reconstruction

- We obtain the following yields of events:



Left: $\tau \rightarrow e\,\nu\ \nu$

Right: $\tau \rightarrow \mu\ \nu\ \nu$



Mode	Yield	Branching fraction
$D_s \rightarrow \tau\ \nu$; $\tau \rightarrow e\,\nu\ \nu$	408 ± 42	$(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$
$D_s \rightarrow \tau\ \nu$; $\tau \rightarrow \mu\ \nu\ \nu$	340 ± 32	$(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$
Combined		$(5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$

Systematic uncertainties

- Due to the nature of the reconstruction, most of the systematic uncertainties cancel out exactly.
- The remaining dominant systematic uncertainties arise from:

Decay mode	Dominant uncertainty	Contribution to uncertainty
$D_s \rightarrow e\nu$	n_X^T weights model	2.8%
$D_s \rightarrow \mu\nu$	Signal and background models	3.4%
$D_s \rightarrow \tau\nu$; $\tau \rightarrow e\nu\nu$	Background model	9.6%
$D_s \rightarrow \tau\nu$; $\tau \rightarrow \mu\nu\nu$	Background model	11.7%

Results

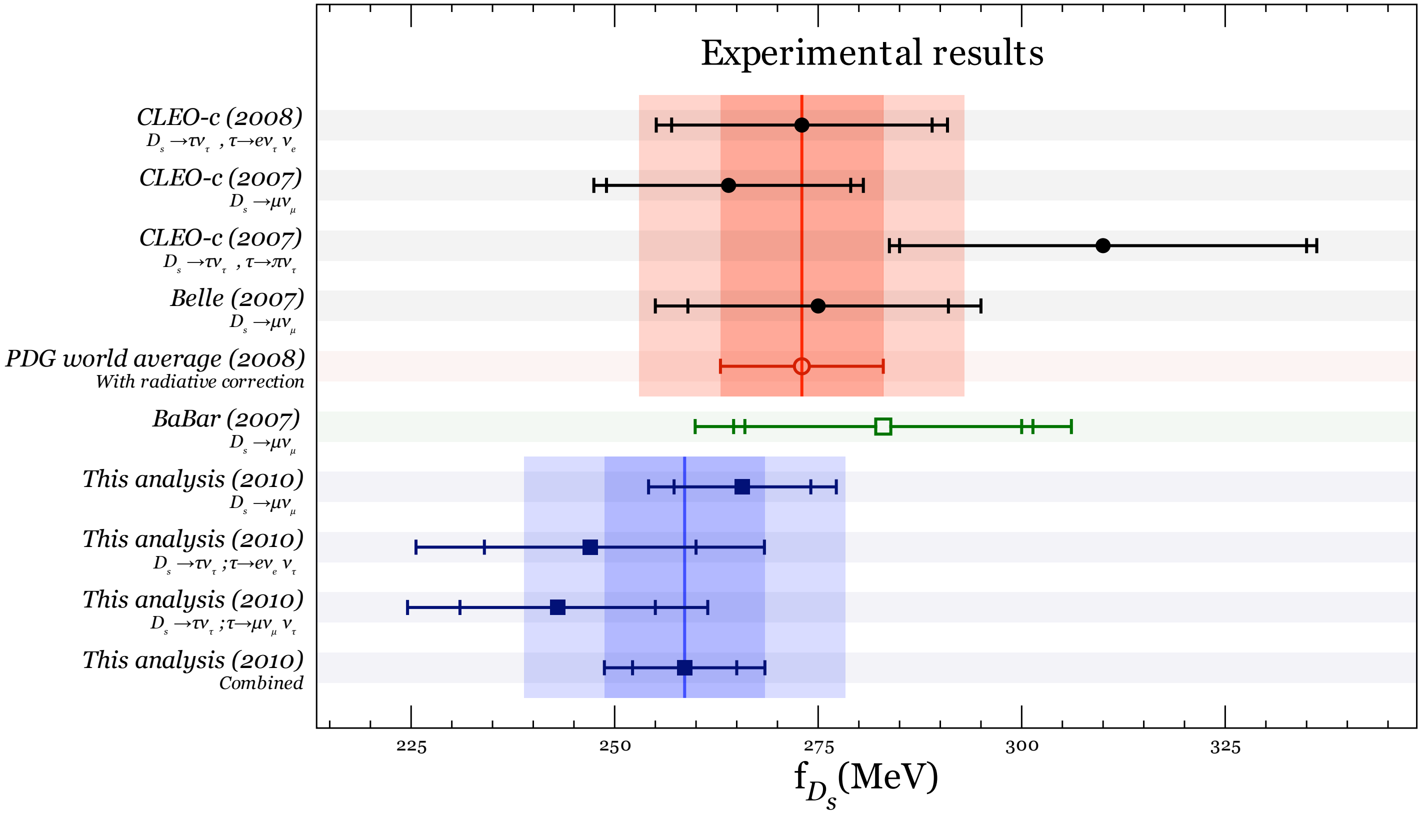
- Values for f_{Ds} are obtained using the formula:

$$f_{D_s^+} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi B(D_s^+ \to \ell\nu)}{M_{D_s^+} \tau_{D_s^+}}}$$

Decay mode	$B(D_s \to l\nu)$	f_{Ds}
$D_s \to \mu\nu$	$(6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$	$(265.7 \pm 8.4 \pm 7.9)$ MeV
$D_s \to \tau\nu$; $\tau \to e\nu\nu$	$(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$	$(247 \pm 13 \pm 17)$ MeV
$D_s \to \tau\nu$; $\tau \to \mu\nu\nu$	$(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$	$(243 \pm 12 \pm 14)$ MeV
Combined		$(258.6 \pm 6.4 \pm 7.5)$ MeV

Results

- These results are very competitive:



- HPQCD (2010) give $f_{D_s} = (248.0 \pm 2.5)$ MeV

Conclusion and summary

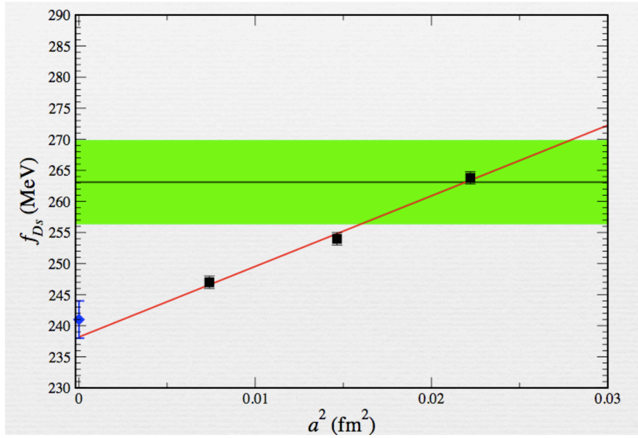
- BaBar used its entire dataset to provide precise absolute measurements of the branching fractions:
  - $B(D_s \to e\nu) < 2.8 \times 10^{-4}$
  - $B(D_s \to \mu\nu) = (6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$
  - $B(D_s \to \tau\nu) = (5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$
  - $B(Ds \to KKp) = (5.78 \pm 0.20 \pm 0.30) \times 10^{-2}$
- The resulting value for f_{Ds} is competitive with the world average.
- These results give $f_{Ds} = (258.6 \pm 6.4 \pm 7.5)$ MeV
  - 1.0σ from most recent UL-QCD expectation (HPQCD).
- Publication accepted by PRD-RC (DVR1031).

Backup

- New physics potential
- Excited charm tag reconstruction
- Flavor and baryon balancing
- $D_s \rightarrow K_S K$ crosscheck

New physics potential

- Is UQ-LQCD f_{Ds} calculation wrong?
  - The same method gives high accuracy calculation for f_D.
  - The disagreement increases as the lattice spacing decreases.
  - We'd expect to see a similar disagreement for f_D.
    - Another analyst is currently measuring f_D using $B(D \rightarrow \mu \nu)$



- What about leptoquarks?
  - Limits on proton lifetime constrain possible models.
  - Measurements of $\tau \rightarrow \eta \nu$ and $D \rightarrow \mu \mu$ constrain couplings to the kinds of quarks. (eg leptoquarks would have to prefer the s quark to the d quark)
- And a Higgs?
  - A Higgs boson would tend to couple to the $c\bar{s}$ more than $c\bar{d}$. This could be the first sign of a Higgs boson!

Excited charm tags

- In order to "clean up" the event, we attempt to reconstruct excited charm tags in the decay modes:

$D^{*+} \rightarrow D^0 \pi^+$	$D^{*0} \rightarrow D^0 \pi^0$
$D^{*+} \rightarrow D^+ \pi^+$	$D^{*0} \rightarrow D^0 \gamma$

- Reconstructions are **not** rejected if they fail to meet these criteria.
- Reconstructing these tags reducing combinatorial backgrounds in later reconstruction.

Flavor and baryon balancing

- We require flavor to be balanced in the event:
  - The charm tag balances the charm of the D_s meson.
  - An additional kaon is required to balance the strangeness of the D_s meson.
    - Both $K^{\pm}$ and K_S^0 are considered
  - If a Λ_c^+ is present, a proton is required to balance the baryon number of the Λ_c^+.

$D_s \to K_S K$ crosscheck

- Another crosscheck ($D_s \to K_S K$) is used to perform studies in the data:
  - This is not blind.
  - It's used mainly to check shapes of probability density functions.
  - It showed that the kinematic fit χ^2 distribution was not well modeled in MC.
  - Used to inform smearing and shifting of signal probability density function.