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

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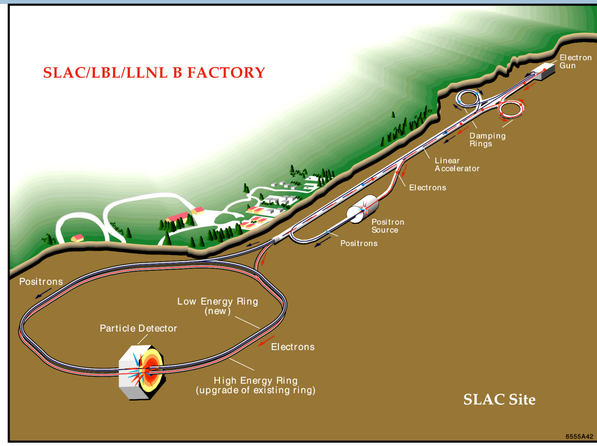
# Overview

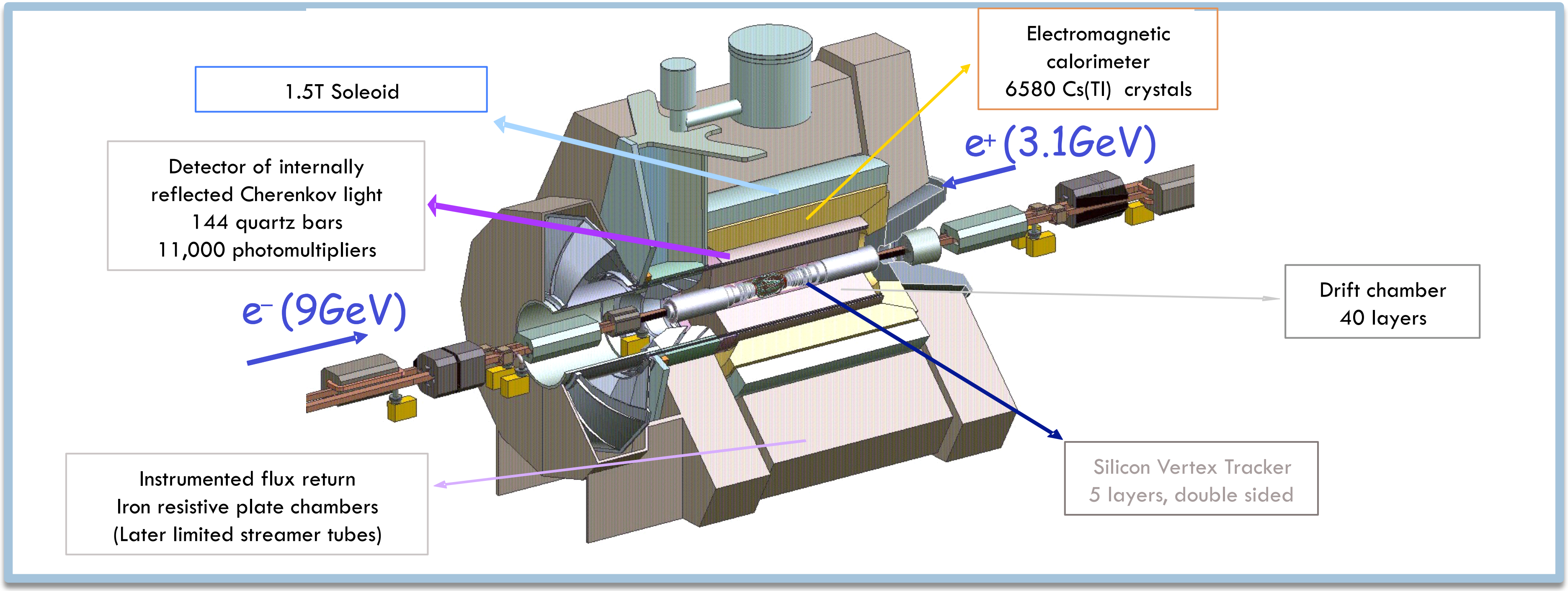


- The BaBar experiment
- Motivation
- Reconstruction
- Systematic uncertainties
- Results
- Summary and conclusion

# 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 $\tau$ factory, generating over 700 million cc pairs, from December 1999 to April 2008.



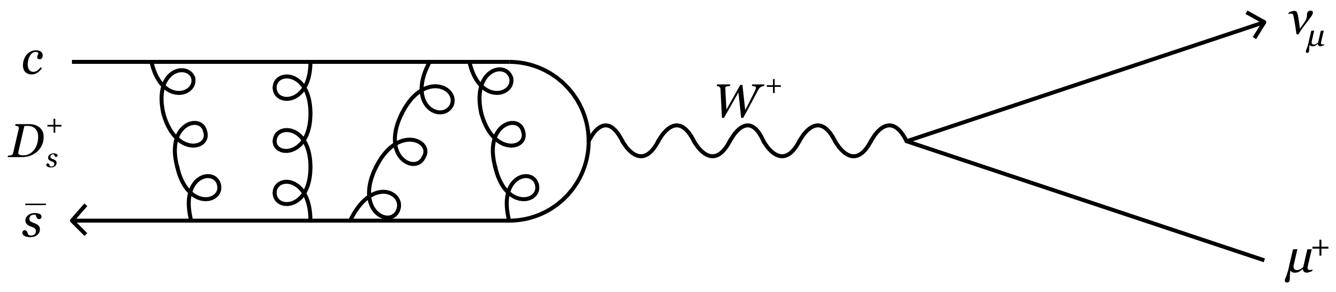



# Motivation



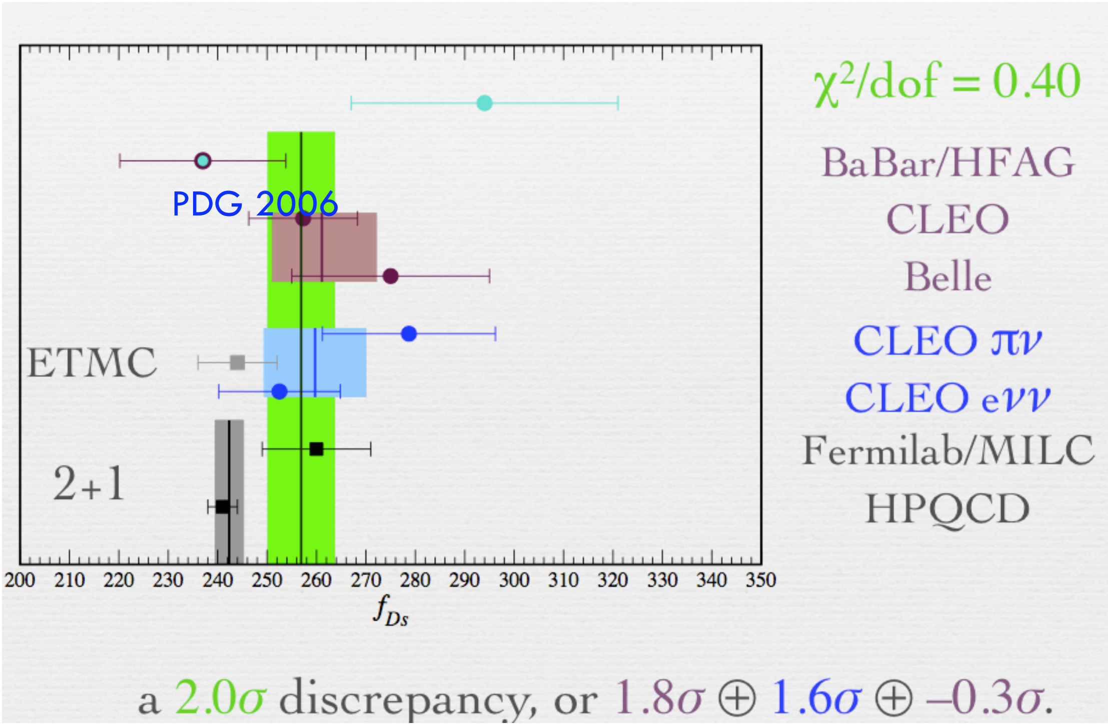
- In the standard model the leptonic decays of the $D_s$ meson provide a clean way to measure the decay constant $f_{Ds}$:

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



# Motivation

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




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

http://www.slac.stanford.edu/exp/seminar/talks/2009/20091027_Kronfeld.pdf

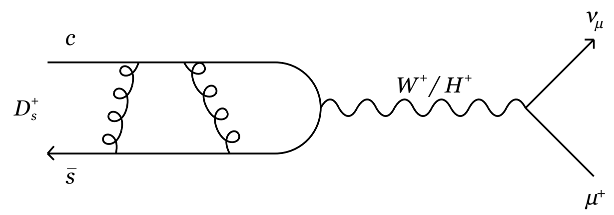
Previously $3.8\sigma$ disagreement.

Phys.Rev.Lett.100:241802,2008.

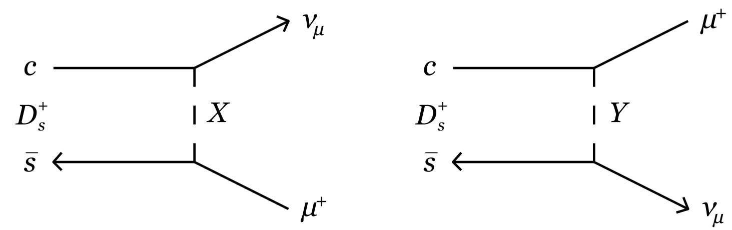
# Motivation



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




  - Leptoquarks




  - SUSY
  - More details in the backup slides.

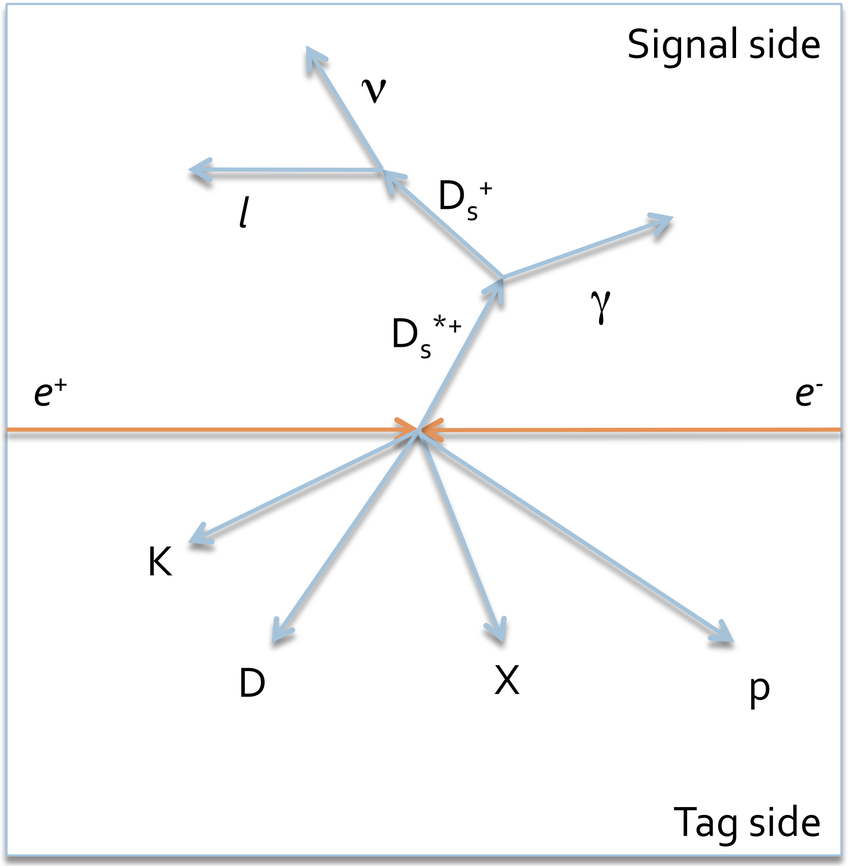
# Analysis strategy



- 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 ( $\gamma$ )
    - Lepton ($l$)



# Charm tag reconstruction



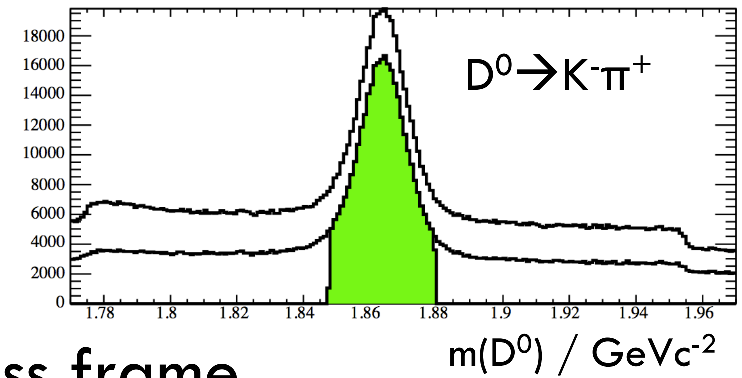
- The charm tag is reconstructed in the following modes:

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

# Charm tag selection



- The charm tag modes selections were optimized with respect to significance using 8fb$^{-1}$ 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 ($\Lambda_c^+ \to \Sigma \pi^+$) to 350 ($D^0 \to K^- \pi^+$)
- Tags are 74% $D^0$, 23% $D^+$, 4% $\Lambda_c^+$.

# 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 | $\pi^{\pm}$ | $\pi^{\pm}\pi^{\pm}$ | $\pi^{\pm}\pi^{\pm}\pi^{\pm}$ |
| $\pi^0$ | $\pi^{\pm}\pi^0$ | $\pi^{\pm}\pi^{\pm}\pi^0$ | |

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

# Fragmentation system

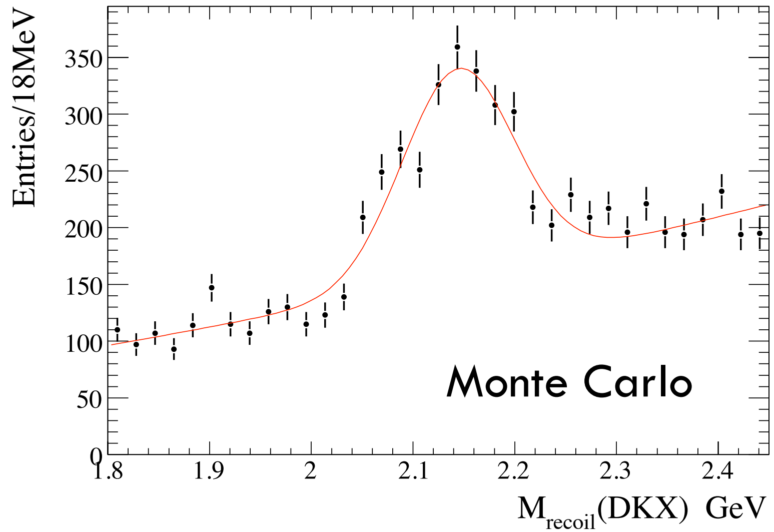


- The reconstruction of the fragmentation system is often incomplete due to:
  - Misreconstruction.
  - Missing particles in the event.
  - Particle identification efficiency effects.
- Define:
  - $n_X^T$ as the true number of pions from fragmentation.
  - $n_X^R$ as the reconstructed number of pions 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 $D_s^{*+} \rightarrow D_s^{+} \gamma$ 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

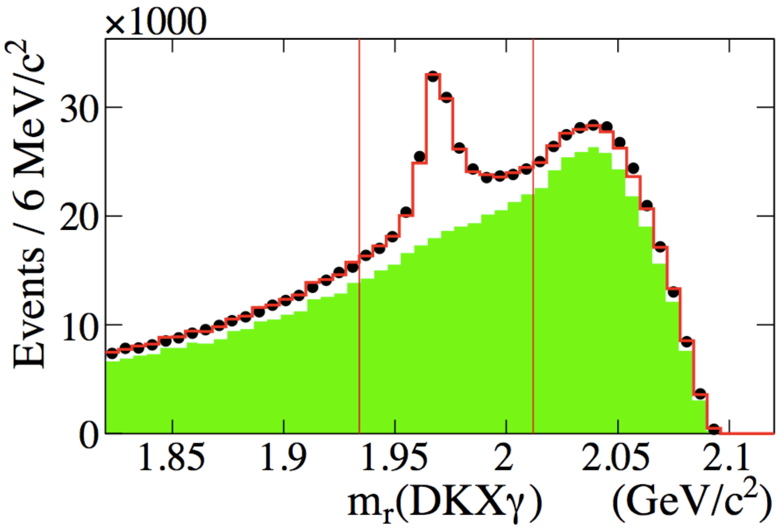


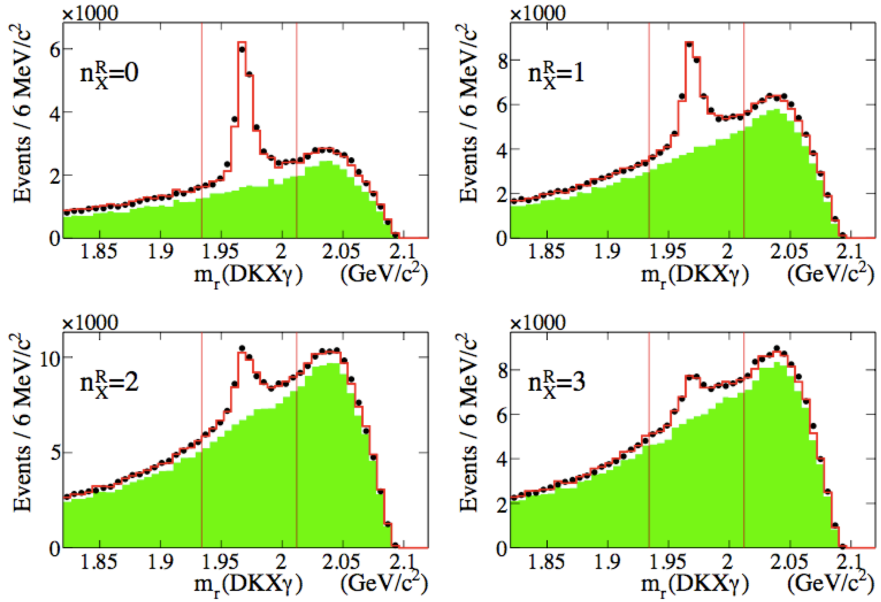
- We define right sign and wrong sign reconstructions:
  - Right sign: any reconstruction where the DKX system flavor and charge are consistent with recoiling against a $D_s^{*+}$.
  - Wrong sign: any reconstruction where the DKX system flavor and charge are not consistent with recoiling against a $D_s^{*+}$.
  - 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 $\gamma$ system
  - $n_X^R$, the reconstructed number of pions in the fragmentation system.
- We obtain $n(D_s) = 67{,}200 \pm 1500$.



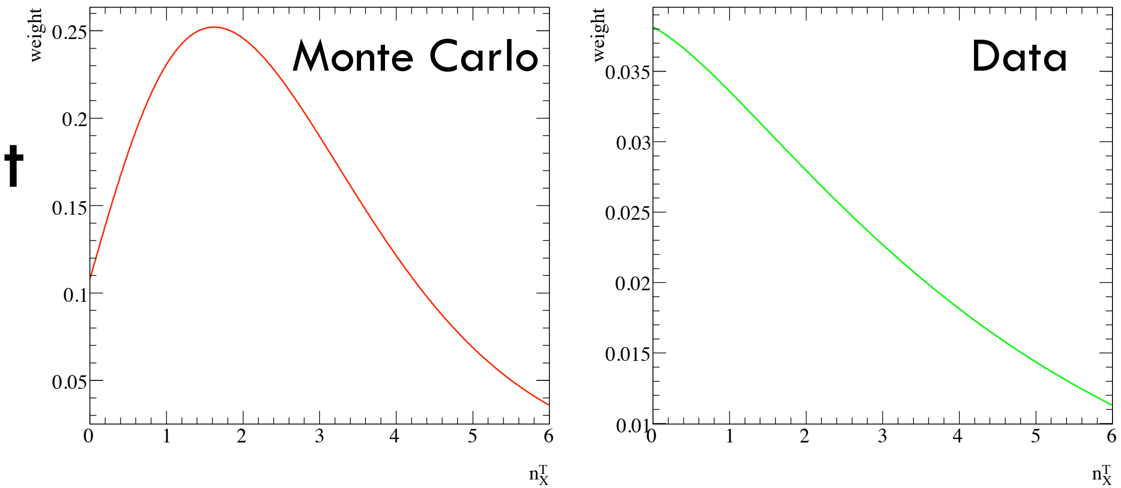
# $n_X^T$ unfolding



- 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:

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

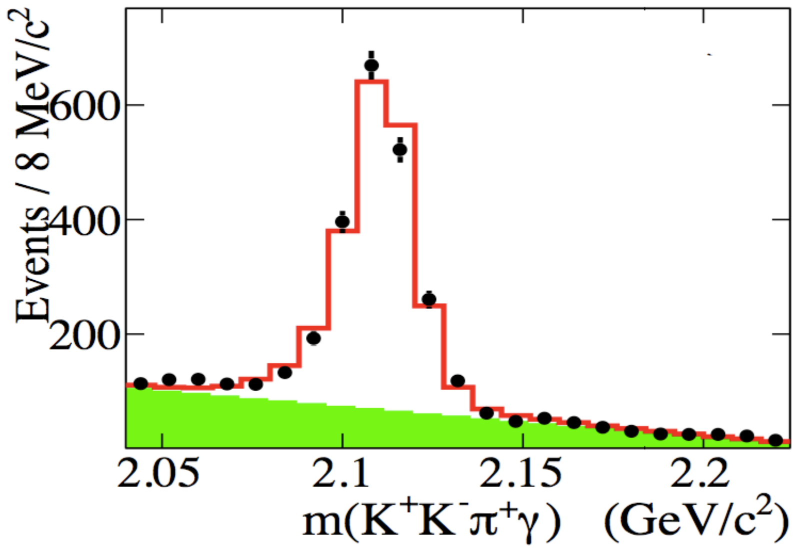
- This weights model accounts for data-Monte Carlo differences
- The parameters are floated in the 2-D fit
- Efficiencies are calculated after $n_X^T$ unfolding.



# $D_s \rightarrow KK\pi$ crosscheck



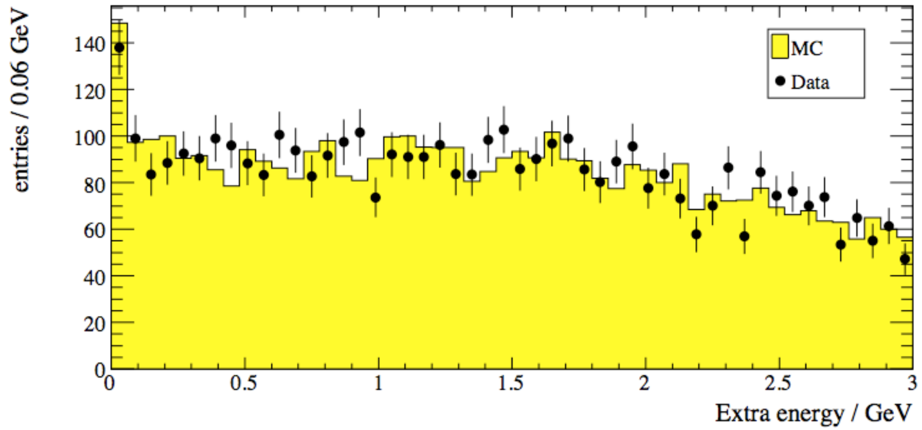
- To validate the $D_s$ reconstruction technique a $D_s \rightarrow KK\pi$ crosscheck is used.
- Due to resonances, an efficiency weighted Dalitz plot is used.
- We obtain $B(D_s \rightarrow KK\pi) = (5.78 \pm 0.20 \pm 0.30) \times 10^{-2}$
- Consistent with the Particle Data Group.
  - $(5.50 \pm 0.27) \times 10^{-2}$



# 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.



# $D_s \to e\nu$ reconstruction



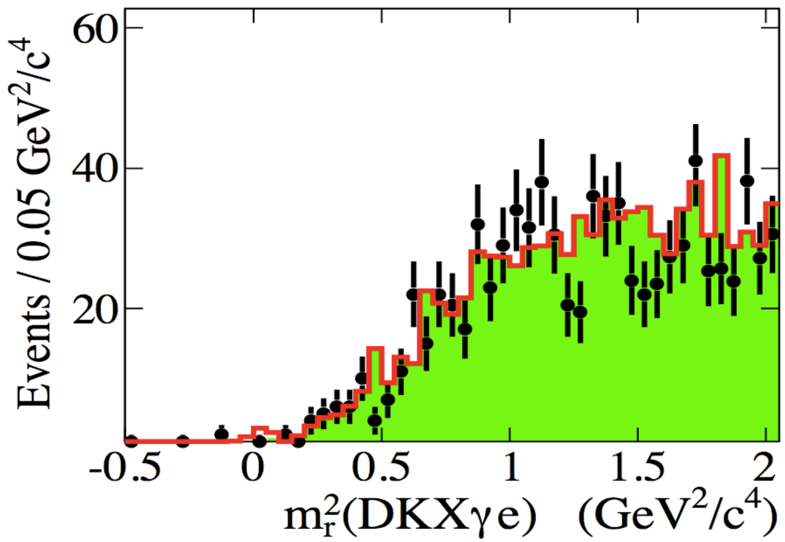
- An electron candidate is identified, using standard particle identification techniques.
- The mass of the $D_s$ candidate is constrained to the mass provided by the Particle Data Group.
- We require $E_{Extra} < 1$GeV.
- A kinematic fit to the whole event is performed.
- A binned maximum likelihood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

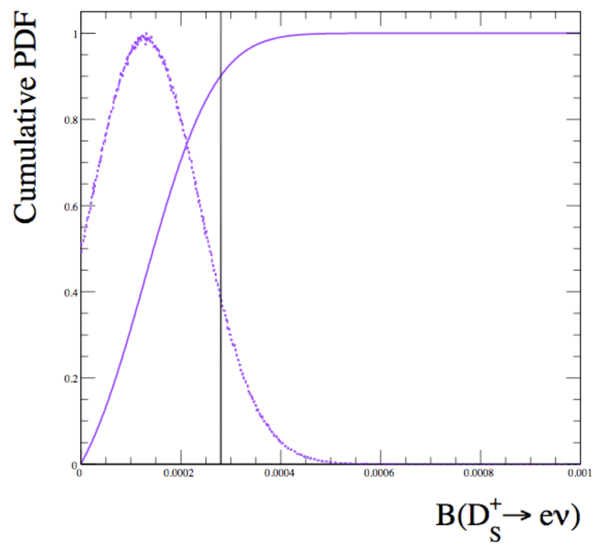
# $D_s \to e\nu$ limit extraction



- 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:

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

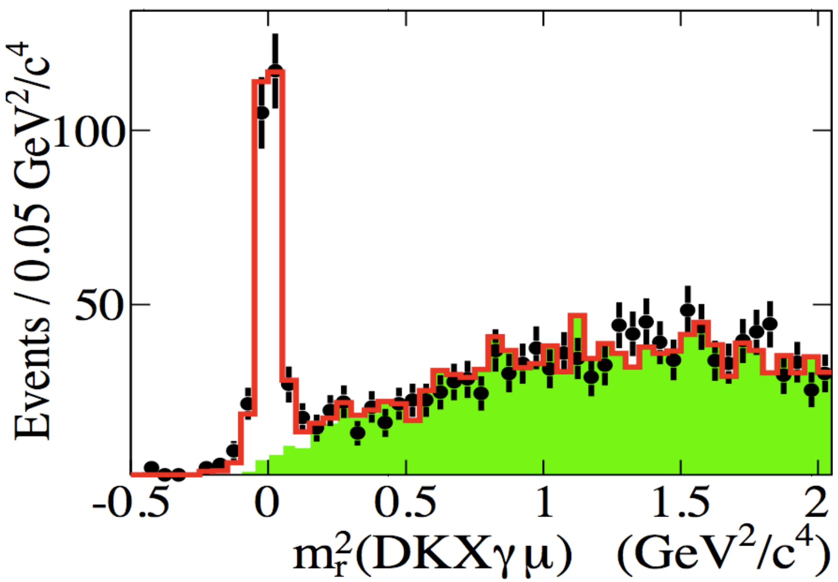


# $D_s \to \mu\ \nu$ reconstruction



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

# $D_s \rightarrow \tau\nu$ reconstruction

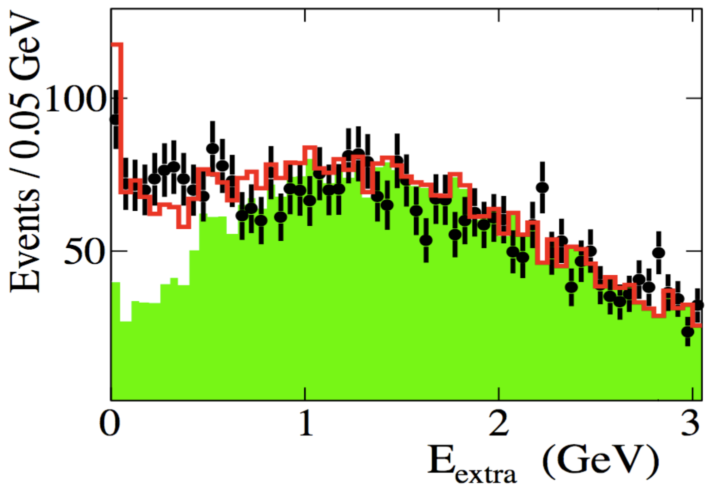


- We measure the final states
  - $\tau \rightarrow e\nu\nu$
  - $\tau \rightarrow \mu\nu\nu$
- Particle identification procedure remains the same as for $D_s \rightarrow e\nu$ and $D_s \rightarrow \mu\nu$ as appropriate.
- For $D_s \rightarrow \tau\nu$ ; $\tau \rightarrow \mu\nu\nu$ we require $m_m^2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

# $D_s \rightarrow \tau\ \nu$ reconstruction

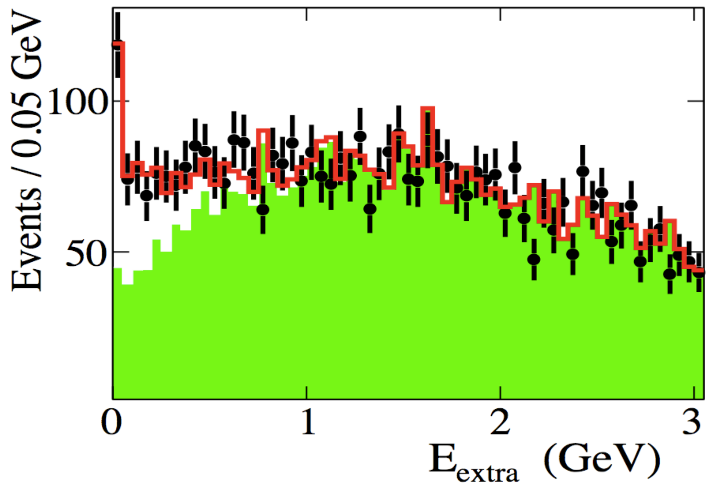


- We obtain the following yields of events:




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

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




| Mode | Yield | Branching fraction |
|---|---|---|
| $D_s \rightarrow \tau\ \nu$ ; $\tau \rightarrow e\ \nu\ \nu$ | $408 \pm 42$ | $(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$ |
| $D_s \rightarrow \tau\ \nu$ ; $\tau \rightarrow \mu\ \nu\ \nu$ | $340 \pm 32$ | $(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$ |
| 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 |
|---|---|---|
| $D_s \to e \nu$ | $n_X^T$ weights model | 2.8% |
| $D_s \to \mu \nu$ | Signal and background models | 3.4% |
| $D_s \to \tau \nu$ ; $\tau \to e \nu \nu$ | Background model | 9.6% |
| $D_s \to \tau \nu$ ; $\tau \to \mu \nu \nu$ | Background model | 11.7% |

# Results



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

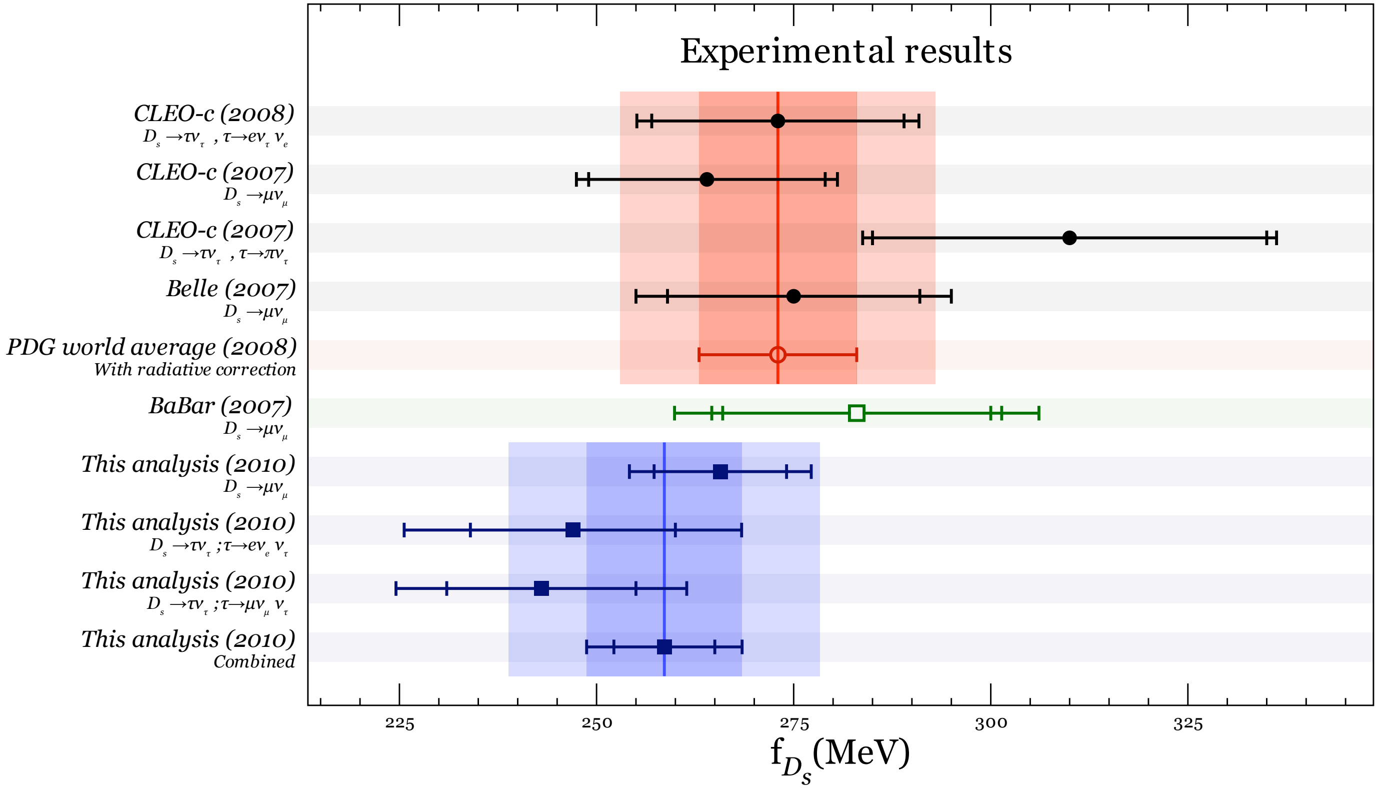
$$f_{D_s^+} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi B(D_s^+ \to \ell\nu)}{M_{D_s^+} \tau_{D_s^+}}}$$

| Decay mode | B(Ds→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 $f_{Ds}$ = (248.0 ± 2.5) MeV (arXiv:1008.4018)

# Conclusion and summary



- BaBar used its entire dataset to provide precise absolute measurements of the branching fractions:
  - $B(D_s \rightarrow e\nu) < 2.8 \times 10^{-4}$
  - $B(D_s \rightarrow \mu\nu) = (6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$
  - $B(D_s \rightarrow \tau\nu) = (5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$
    - $B(D_s \rightarrow \tau\nu; \tau \rightarrow e\nu\nu)/B(\tau \rightarrow e\nu\nu) = (4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$
    - $B(D_s \rightarrow \tau\nu; \tau \rightarrow \mu\nu\nu)/B(\tau \rightarrow \mu\nu\nu) = (5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$
  - $B(Ds \rightarrow KK\pi) = (5.78 \pm 0.20 \pm 0.30) \times 10^{-2}$
- 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
  - $1.0\sigma$ from most recent UL-QCD expectation (HPQCD).
- Publication accepted by PRD-RC (arXiv:1008.4080).

# Backup

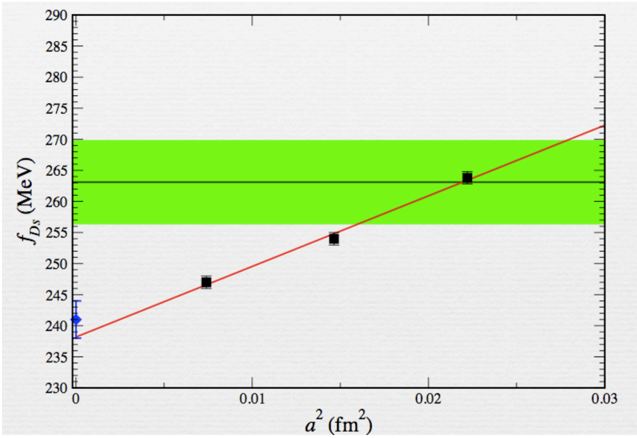


- New physics potential
- Excited charm tag reconstruction
- Flavor and baryon balancing
- $D_s \rightarrow K_S K$ crosscheck

# 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 $B(D \to \mu \nu)$




- What about leptoquarks?
  - Limits on proton lifetime constrain possible models.
  - Measurements of $\tau \to \eta \nu$ and $D \to \mu \mu$ 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 $\Lambda_c^+$ is present, a proton is required to balance the baryon number of the $\Lambda_c^+$.

# $D_s \rightarrow K_S K$ crosscheck



- Another crosscheck ($D_s \rightarrow K_S K$) 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 $\chi^2$ distribution was not well modeled in MC.
  - Used to inform smearing and shifting of signal probability density function.