BABAR Results on Leptonic and Radiative *B* and Charm Decays

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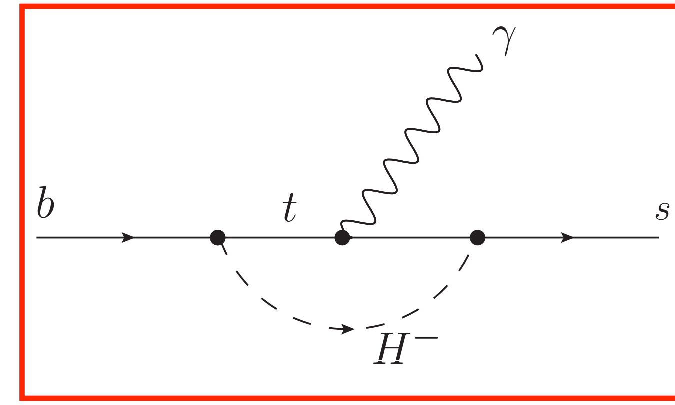
Outline

- Radiative and Leptonic Decays
- The *BABAR* Detector and Dataset
- $A_{CP}(B \rightarrow X_{s+d}\,\gamma)$
- $B \rightarrow K\nu\bar{\nu}$
- $B^{+} \rightarrow \tau^{+}\nu_{\tau}$
- $D_s^{-} \rightarrow \ell^{-}\,\bar{\nu}_{\ell}$
- Summary

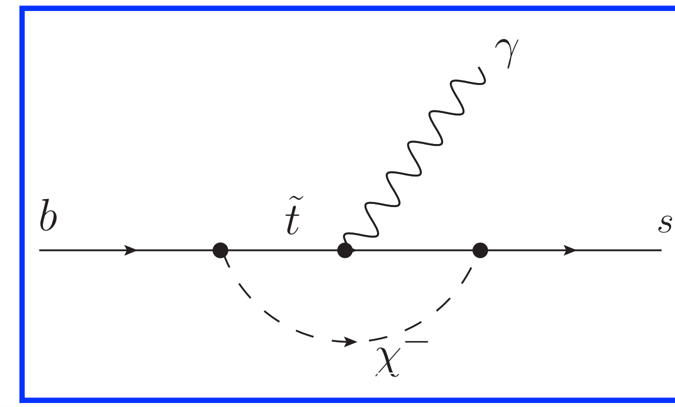
Radiative and Leptonic Decays

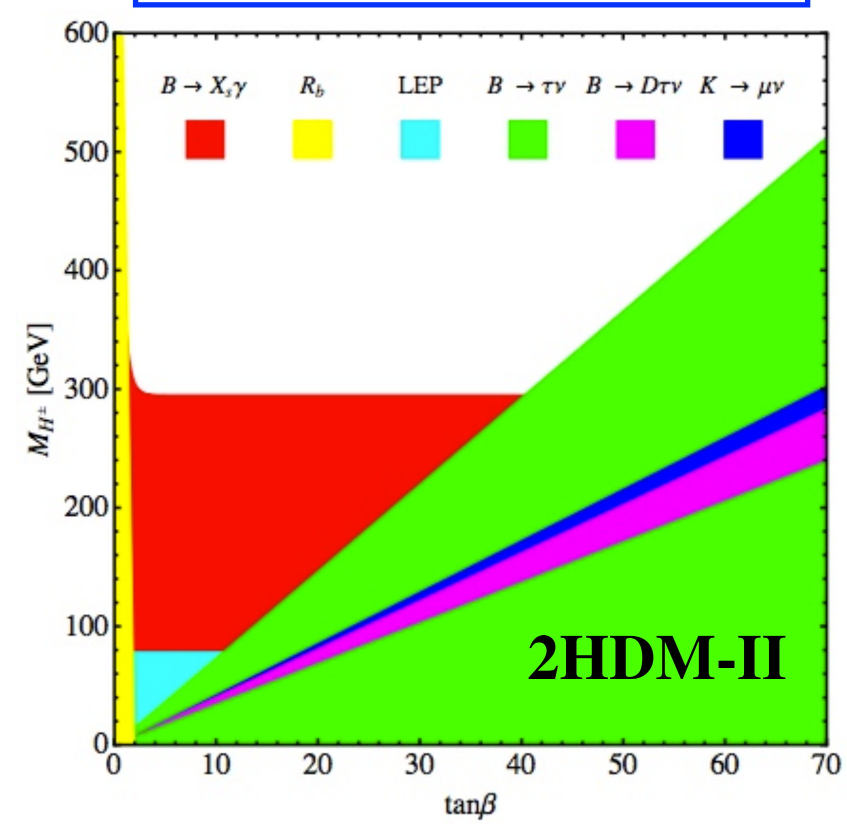
- Radiative Decays
  - Lowest order SM contributions often involve loops ($B \to X_s \gamma$, $B \to X_d \gamma$)
  - Sensitive to new, heavy virtual particles in loops
  - BFs typically ~ 10^{-4} or less
- Leptonic Decays
  - Clean probe of theoretical quantities
  - BFs ~ 10^{-4} (10^{-2} for charm) or less due to helicity suppression and CKM factors
- Offer precision tests of Standard Model predictions
  - Any large deviation from SM prediction could be an indication of New Physics
  - Low energy indirect NP searches are complimentary to direct searches at high energy machines like LHC and Tevatron

Charged Higgs



MSSM

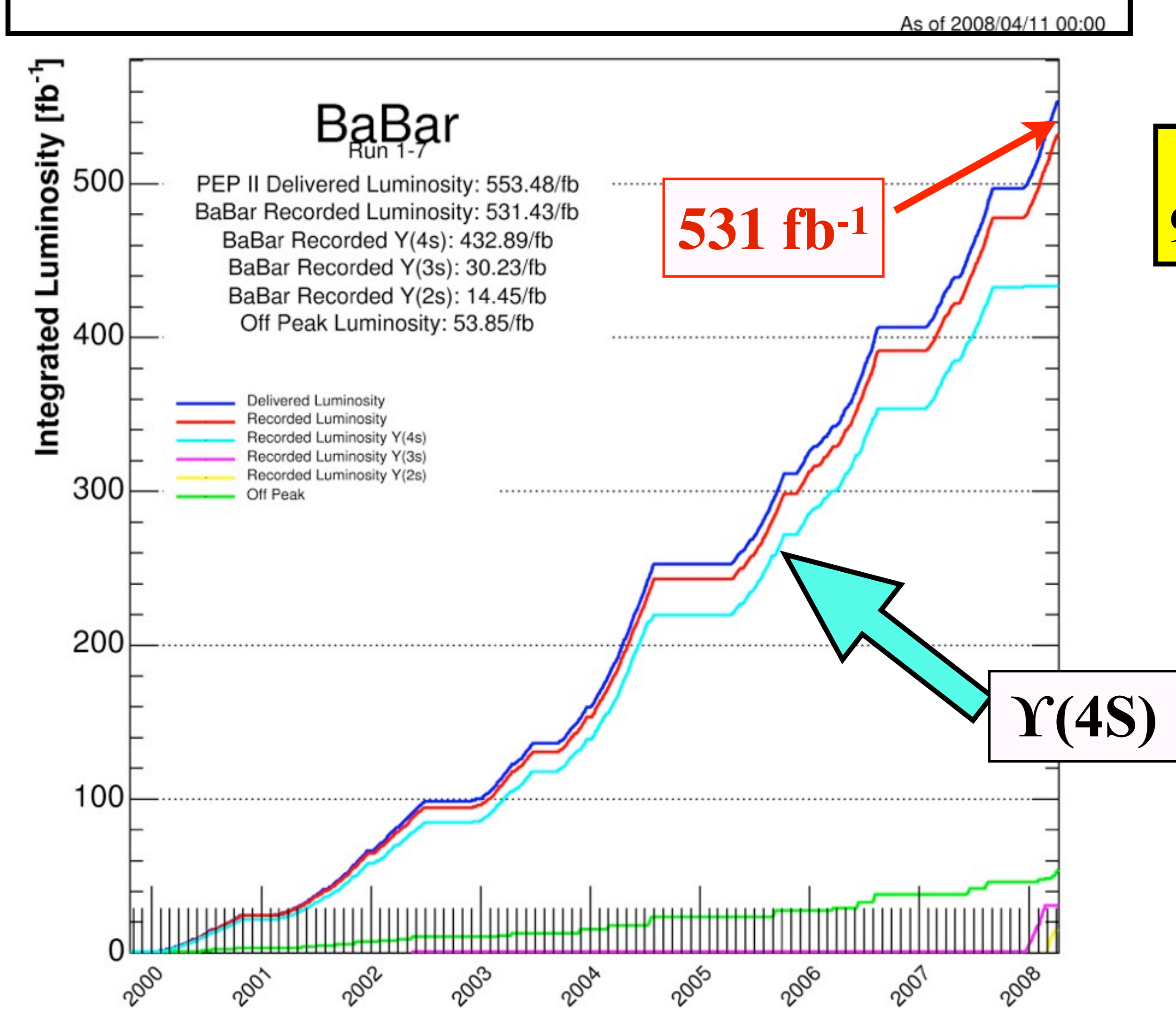


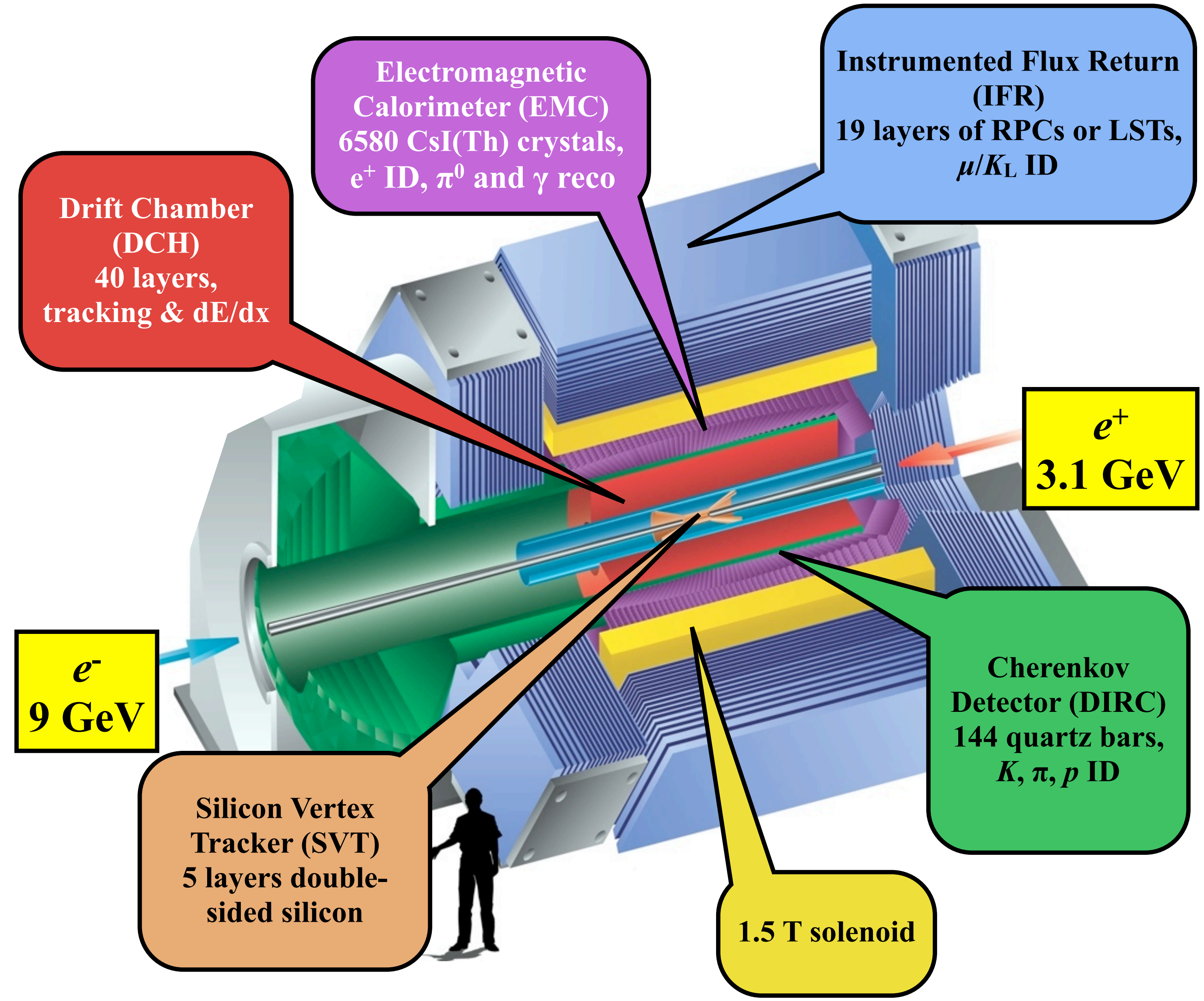


(Haisch, arXiv:0805.2141)

The *BABAR* Detector & Dataset

- **Asymmetric energy**
  - **E_{cms} = 10.58 GeV**
  - **$e^+e^- \to \Upsilon(4S) \to B\bar{B}$**
- **Wide range of flavor physics results in *B*, charm, and τ sectors**





Total dataset: ~ 430 fb^{-1} at Υ(4S)

Type	N (x10^6)
$B\bar{B}$	470
$c\bar{c}$	690
$\tau^+\tau^-$	500

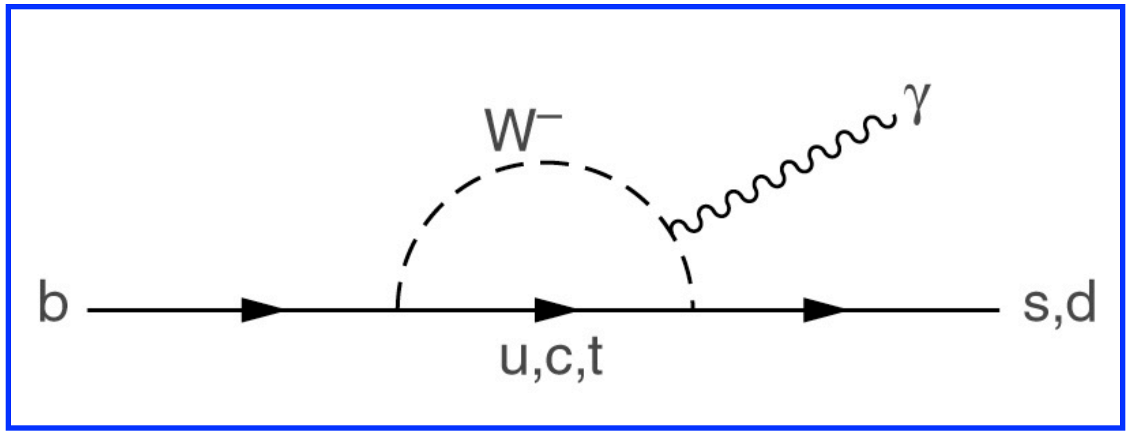
$$A_{CP}(B \to X_{s+d}\,\gamma)$$

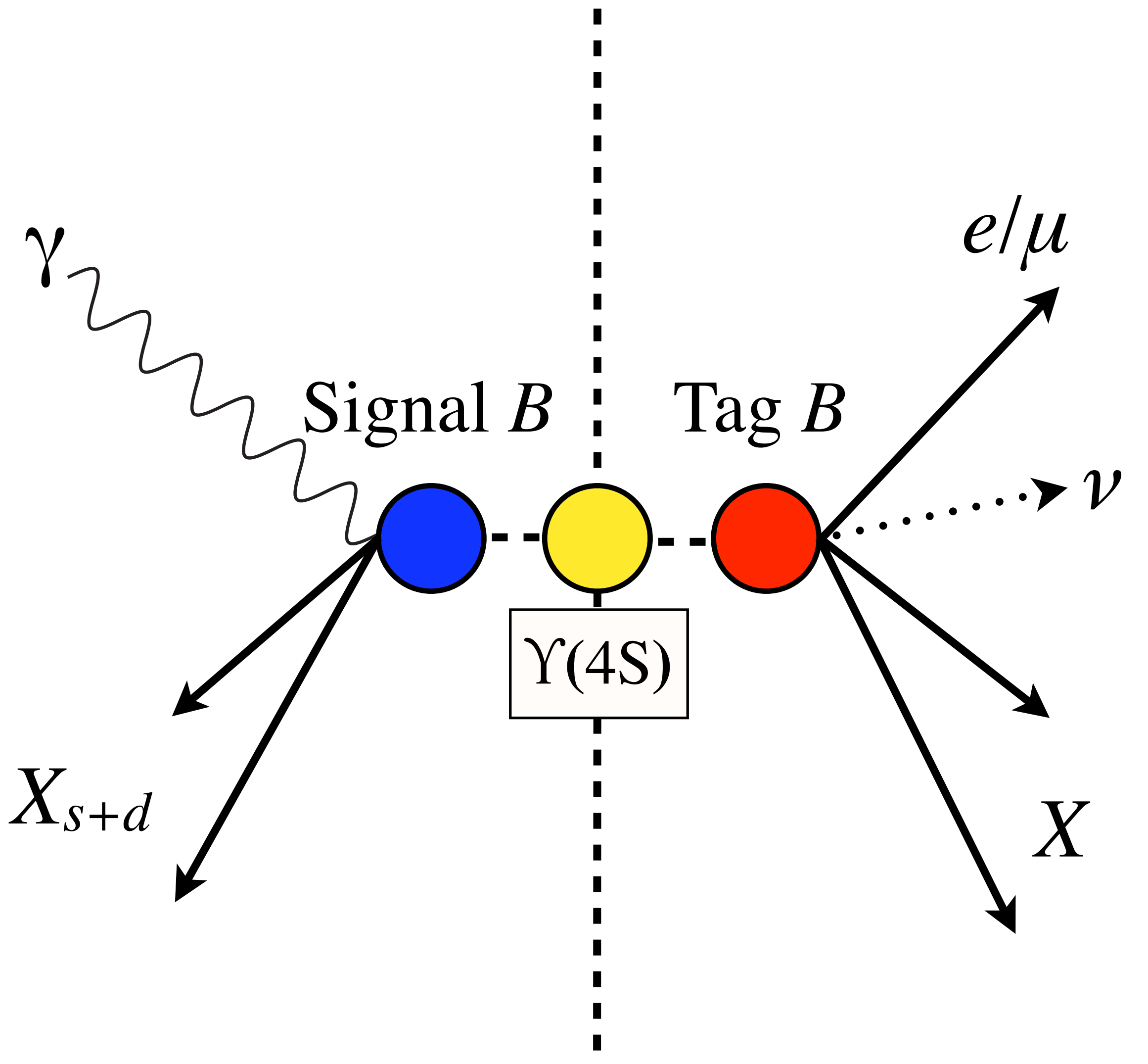
$A_{CP}(B\to X_{s+d}\gamma)$: Background and Predictions

- LO contribution electroweak penguin
  - Measurable inclusive rate equal within a few % of partonic rate
- New Physics may enter at same order as SM
  - Sizable deviations from SM predictions (BF & A_{CP})
- SM $\mathcal{B}(B\to X_s\gamma)$ at NNLO ($E_\gamma > 1.6$ GeV)
  - $\mathcal{B}(B\to X_s\gamma) = (3.15\pm0.23)\times10^{-4}$ [1]
- Direct *CP* asymmetry [2]

$$A_{CP} = \frac{\Gamma(b\to s\gamma + b\to d\gamma) - \Gamma(\bar{b}\to\bar{s}\gamma + \bar{b}\to\bar{d}\gamma)}{\Gamma(b\to s\gamma + b\to d\gamma) + \Gamma(\bar{b}\to\bar{s}\gamma + \bar{b}\to\bar{d}\gamma)}$$

  - $A_{CP}(B\to X_{s+d}\gamma) \approx 10^{-6}$
- Photon spectrum moments
  - Can be used to extract HQE parameters m_b and μ_π^2





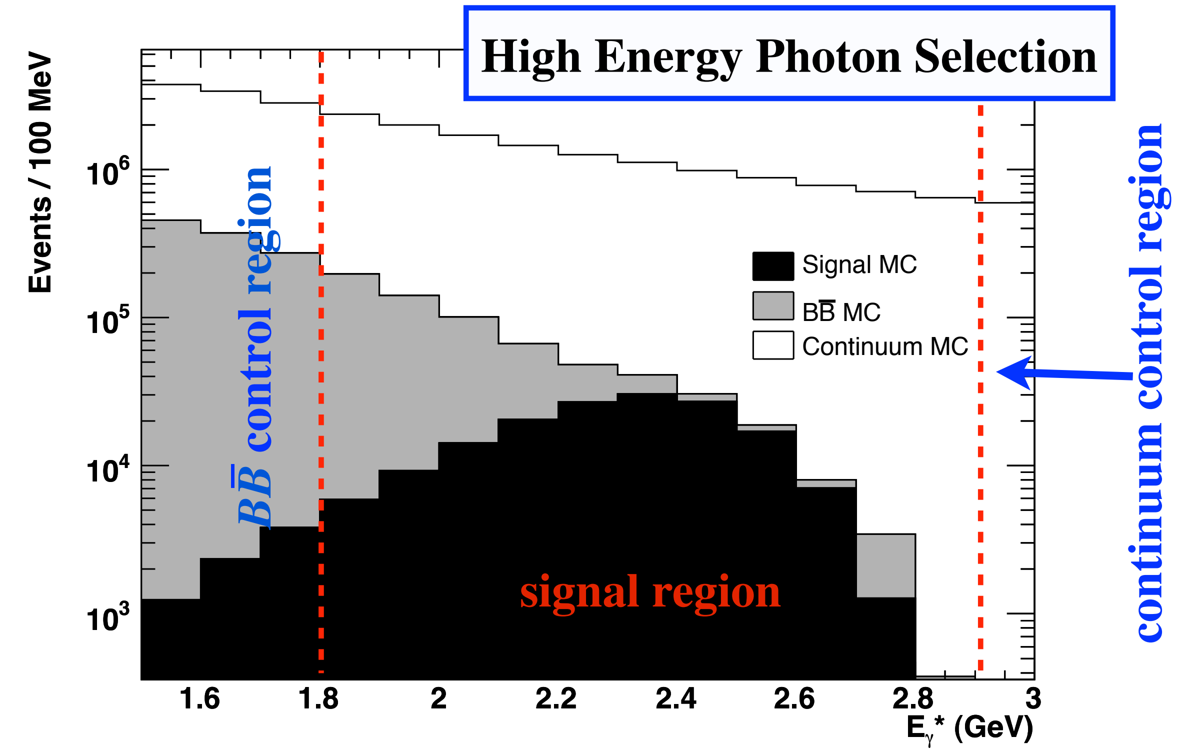
[1] Misiak *et al.*, PRL 98:022002 (2007)
[2] Hurth *et al.*, Nucl. Phys. B 704:56 (2005)

$A_{CP}(B \to X_{s+d}\,\gamma)$: Analysis Strategy

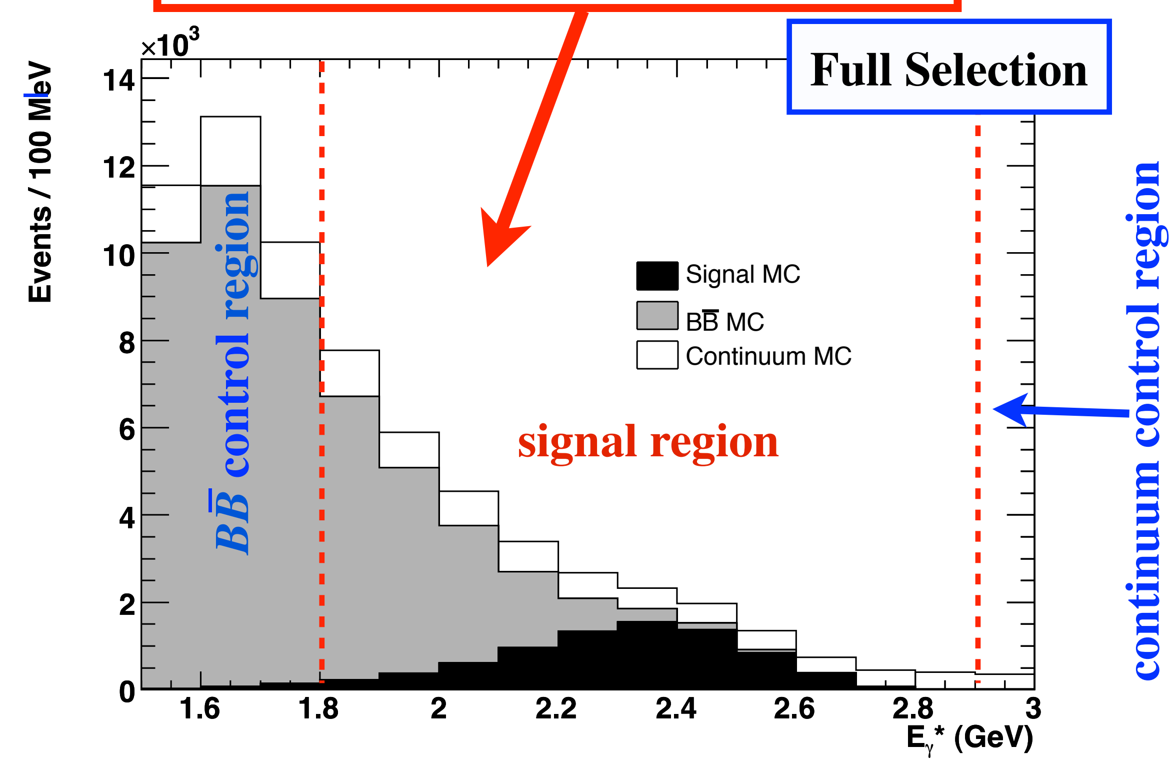
- Measurement uses 347 fb^{-1}
- High energy photon: $1.5 < E^{*}_{\gamma} < 3.5$ GeV
- Veto π^0/η decays

*** indicates $\Upsilon(4S)$ frame**

- Continuum background
  - Leptonic tag
    - e/μ candidate with $p^{*}_{\ell} > 1.05$ GeV/c
    - $\cos\theta^{*}_{\gamma,\ell} > -0.7$
    - $E^{*}_{\mathrm{miss}} > 0.7$ GeV
  - Neural network exploiting jet-like topology
  - Remaining background subtracted using scaled off-resonance data
- $B\overline{B}$ background
  - Subtracted using data corrected MC



After selection, signal eff. of ≈ 2.5% while only 0.0005% of continuum and 0.013% of $B\overline{B}$ background remain



$A_{CP}(B \to X_{s+d}\,\gamma)$: Results

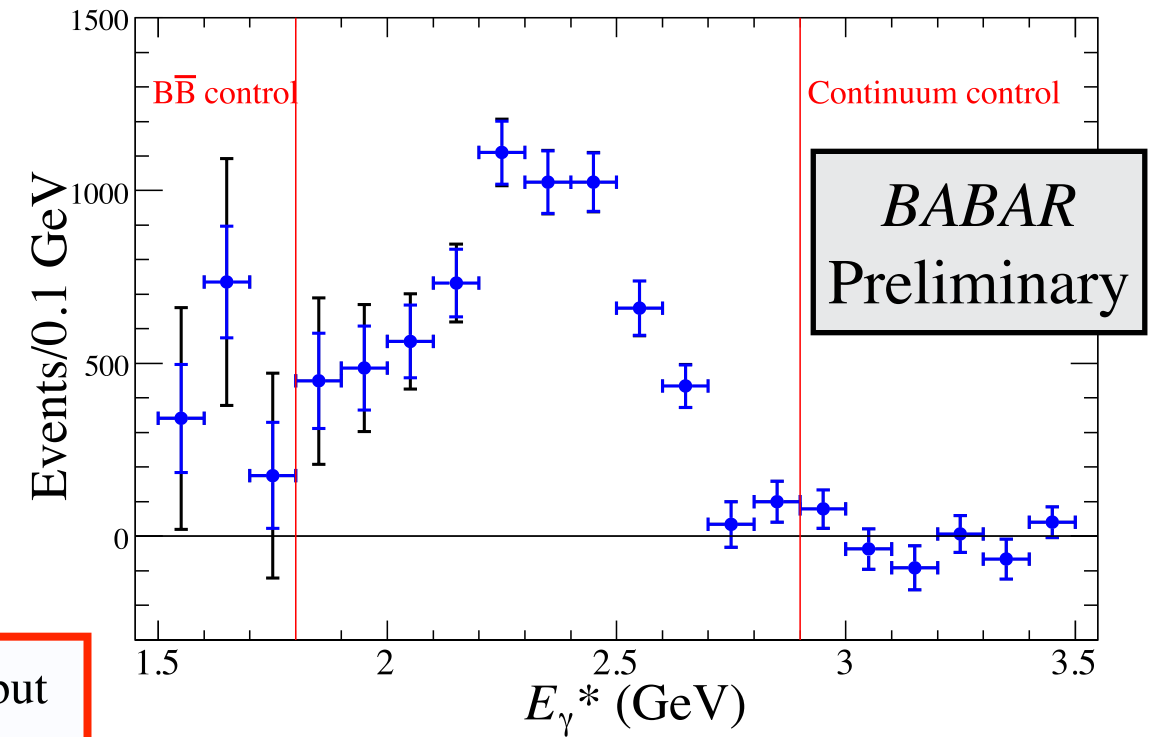
- Continuum region ($2.9 < E^{*}_{\gamma} < 3.5$ GeV)
  - -100 ± 138 (stat.) events
- $B\bar{B}$ region ($1.53 < E^{*}_{\gamma} < 1.8$ GeV)
  - 1252 ± 272 (stat.) ± 841 (syst.) events
- *CP* asymmetry
  - Lepton charge gives *B* flavor
  - Correct for mis-tag rate, *w*
  - Insensitive to photon energy cut
    - Optimized for $2.1 < E^{*}_{\gamma} < 2.8$ GeV
- Common systematics cancel in ratio

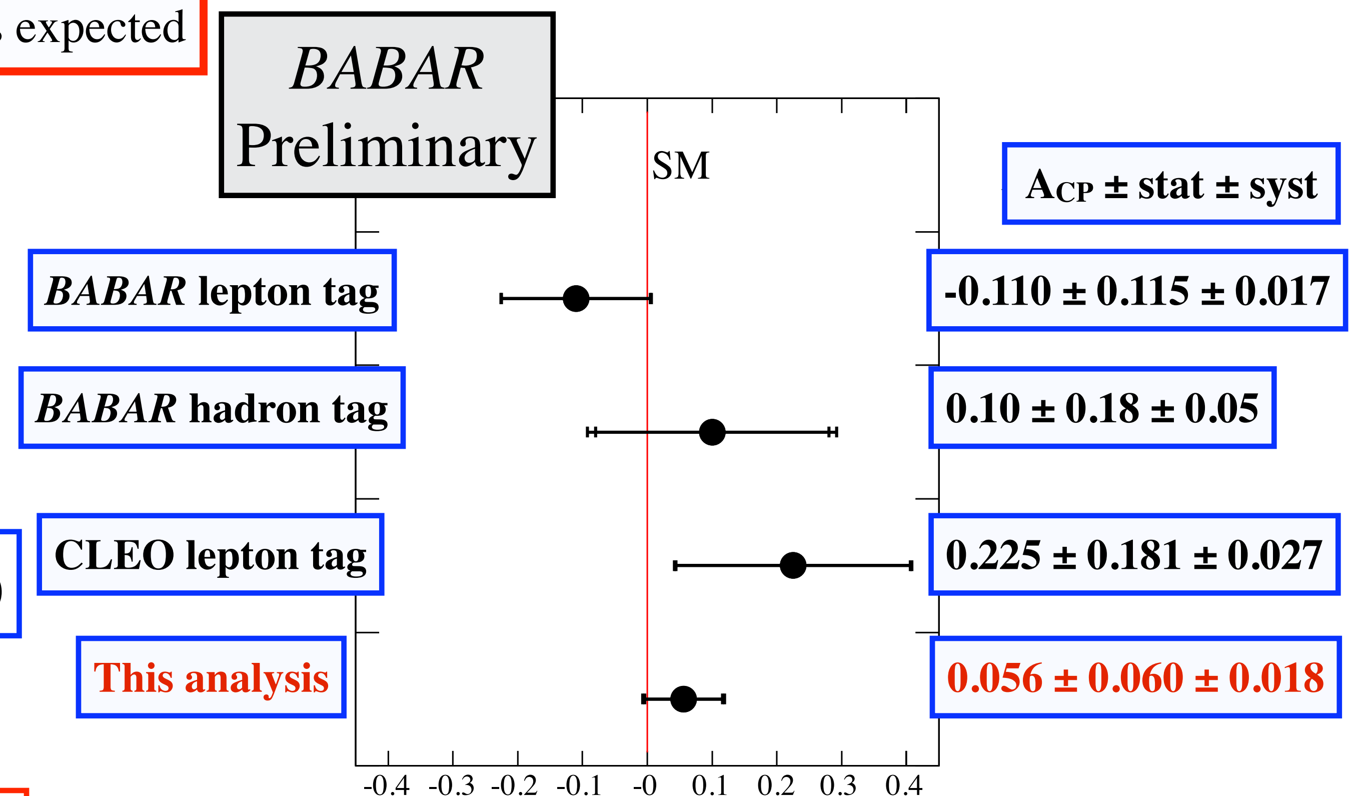
Differs from null by 1.4σ but assumes no signal, when 100-400 signal events expected

$$A_{CP} = \frac{A_{CP}^{\rm meas}}{1-2w} + \Delta A_{CP}$$

-0.004 ± 0.013 (A_{CP} bkg)

0.131 ± 0.0064 (B^0 oscillations)





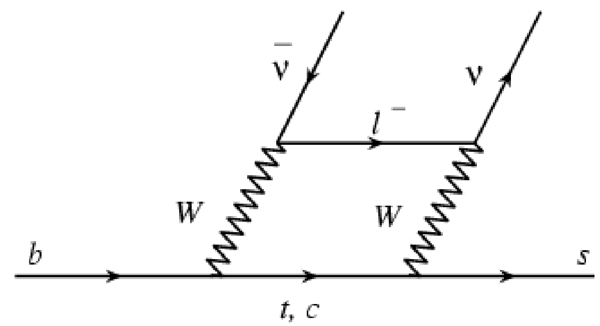
Search for $B \to K\nu\bar{\nu}$

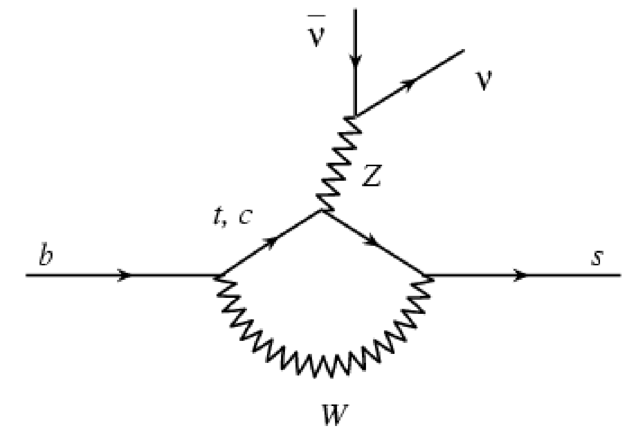
Phys. Rev. D 82, 112002 (2010)

$B \to K\nu\bar{\nu}$: Analysis Strategy

Full *BABAR* dataset
~418 fb^{-1}

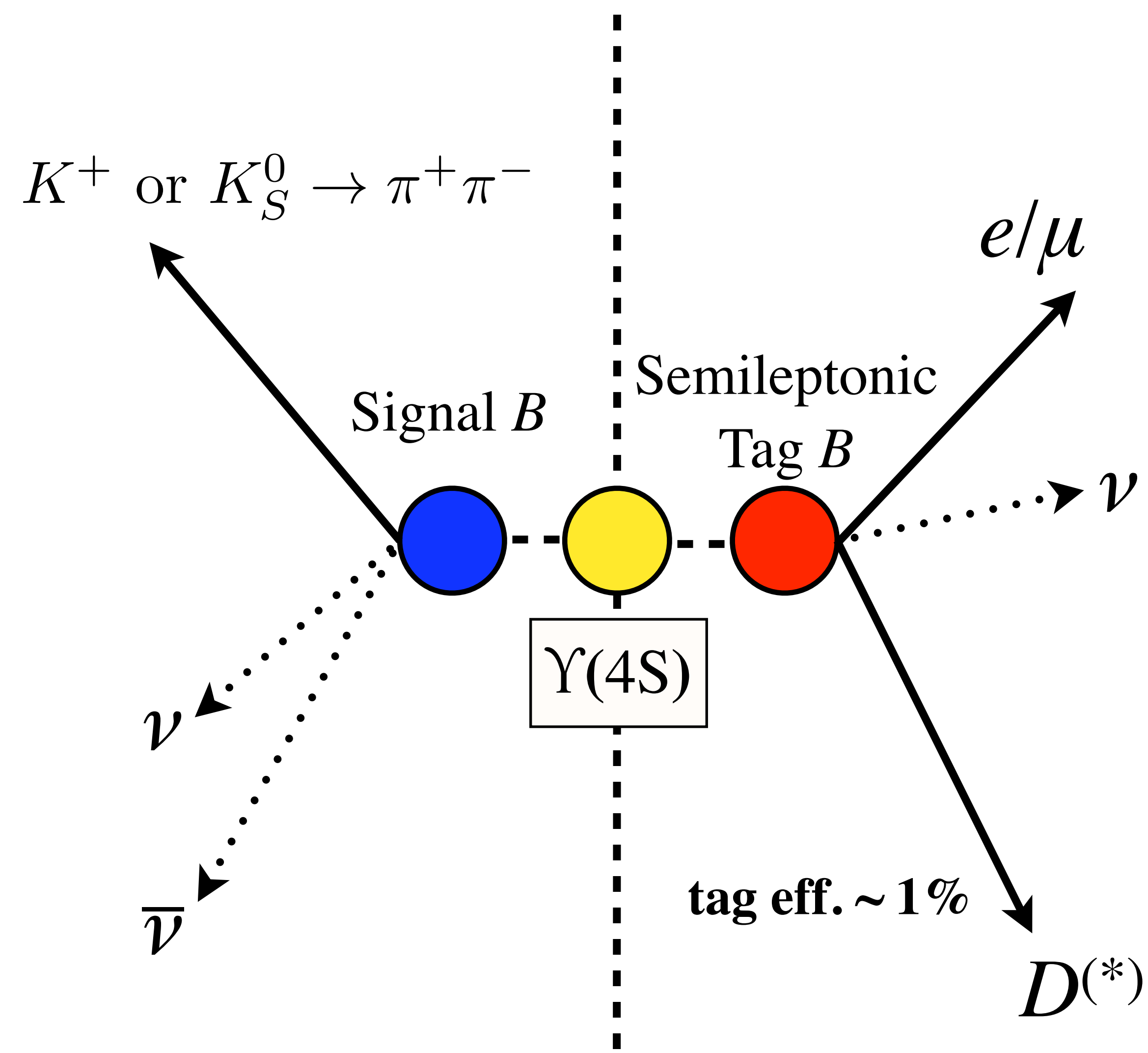
- FCNC in SM ⇒ must proceed through loops
  - $\mathcal{B}(B^+ \to K^+\bar{\nu}\nu) \approx 3.8 \times 10^{-6}$
  - Sensitive to new heavy particles appearing in loops ⇒ may increase $\mathcal{B}(B^+ \to K^+\bar{\nu}\nu)$ 10x SM value
- Presence of two neutrinos ⇒ few kinematic handles available for reconstruction of signal *B*
  - Reconstruct "other *B*" in event in $B \to D^{(*)}\ell\nu$ mode (larger efficiency than hadronic tag)
  - Look for signal decay among remaining particles in event





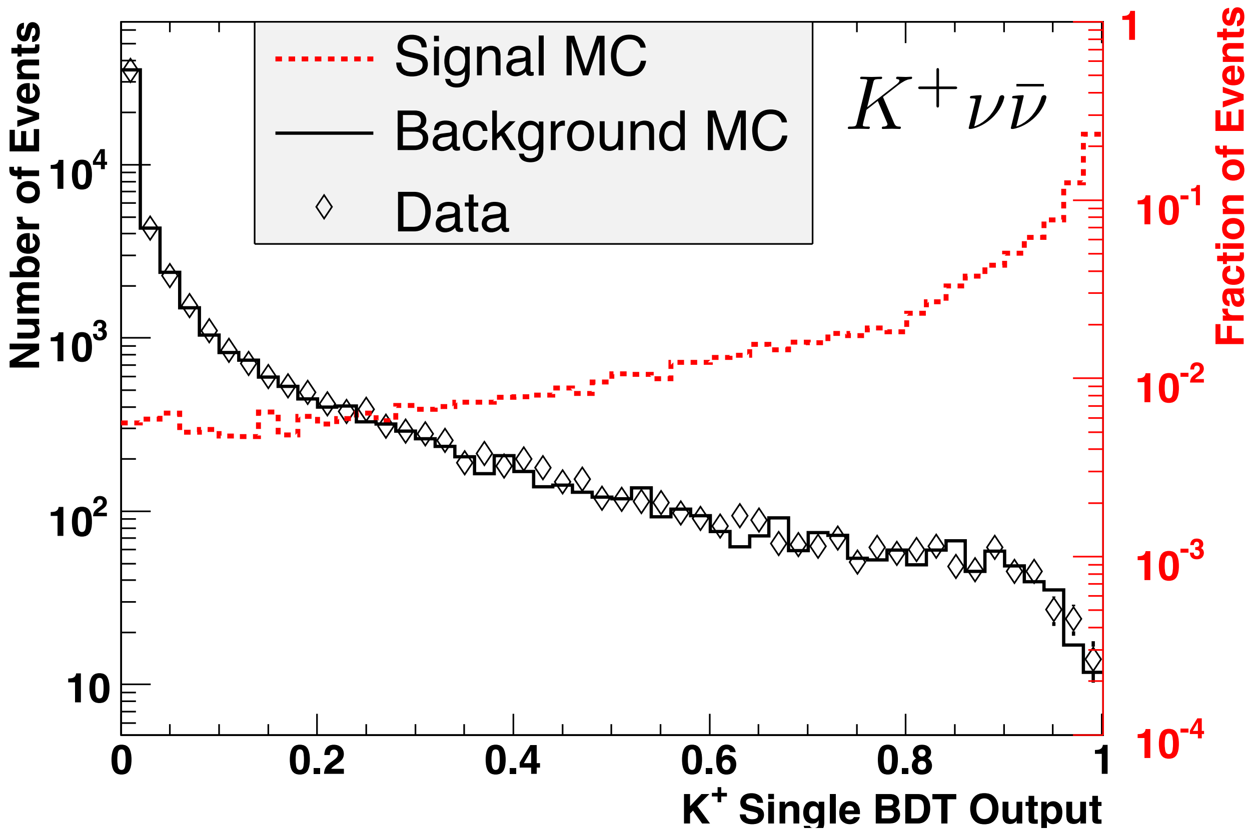
Charm meson modes reconstructed in semileptonic tagging

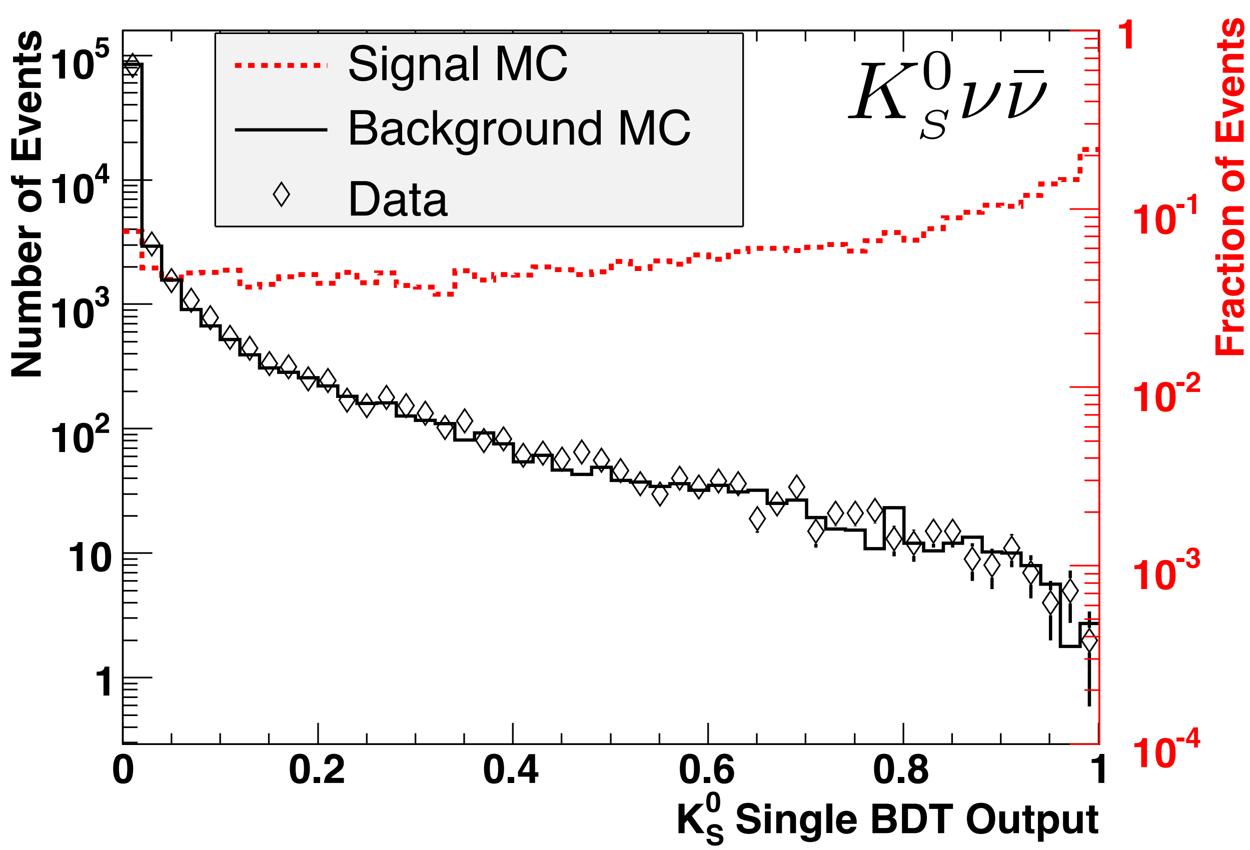
$$
\begin{array}{lcl}
D & \rightarrow & K^-\pi^+,\ K^-\pi^+\pi^+,\ K^-\pi^+\pi^+\pi^-, \\
 & & K^-\pi^+\pi^0,\ K^0_S\pi^+,\ K^0_S\pi^+\pi^- \\
D^{*0} & \rightarrow & D^0\pi^0 \\
D^{*+} & \rightarrow & D^0\pi^+,\ D^+\pi^0
\end{array}
$$



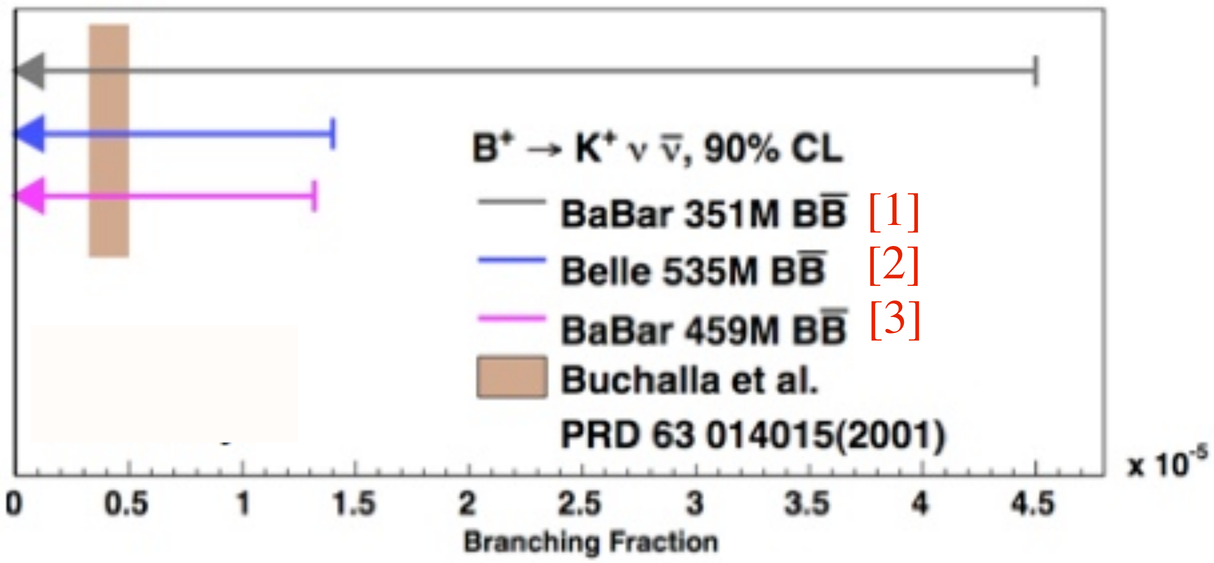
$B\rightarrow K\nu\bar{\nu}$: Analysis Strategy

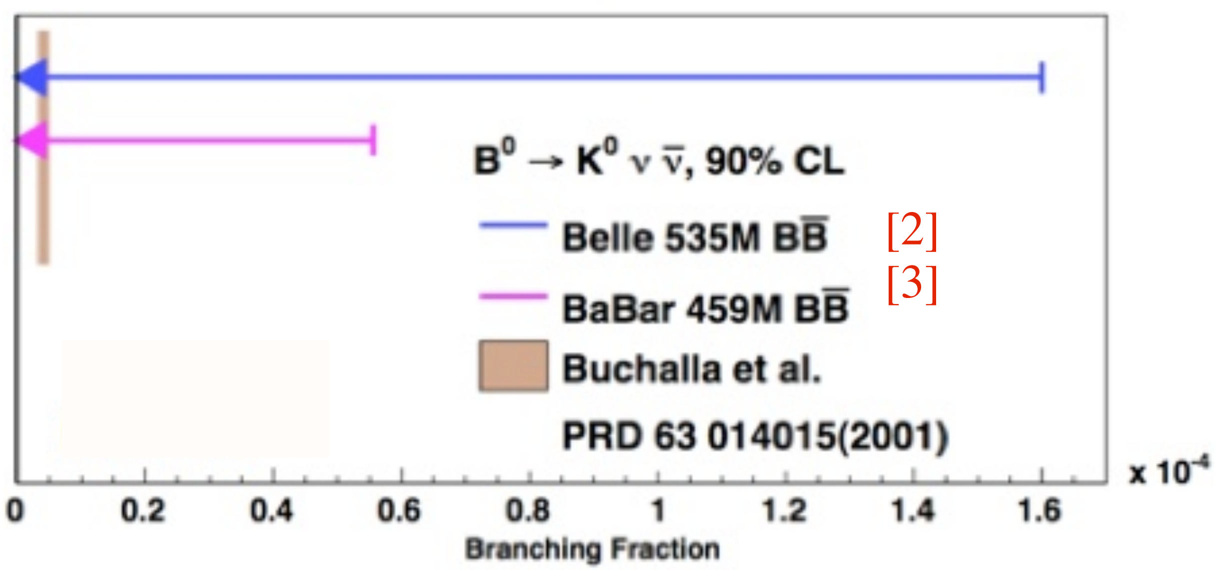
- Suppress large remaining background using ensemble of Bagged Decision Trees (BDT)
  - Trained on simulated signal and background events
  - Ensembles use 26 (K^+) or 38 (K^0_s) variables relating to:
    - missing four-momentum
    - overall event properties
    - signal kinematics
    - Tag *B* reconstruction quality
- Selection chosen to optimize signal significance: $s/(s+b)^{1/2}$





$B \to K\nu\bar{\nu}$: Results





No significant signal observed. Best upper limits to date.

[1] Aubert *et al.*, PRL 94, 101801 (2005)
[2] Villa *et al.*, PRL 99, 221802 (2007)
[3] Phys. Rev. D 82, 112002 (2010)

Expected events

Mode	ϵ (in %)	$N_{\rm sgnl}$	$N_{\rm bkgd}$
K^+	0.16	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$
K^0_S	0.06	0.5 ± 0.1	$3.9 \pm 1.3 \pm 0.4$
low-q^2 K^+	0.24	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$
high-q^2 K^+	0.28	2.1 ± 0.3	$187 \pm 10 \pm 46$

Observed events

Mode	$N_{\rm obs}$	$N_{\rm excess}$	Prob.
K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$	38%
K^0	$6.1^{+4.0}_{-2.2}$	$2.2^{+4.1}_{-2.8}$	23%
low-q^2 K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$	38%
high-q^2 K^+	164^{+13}_{-13}	-23^{+49}_{-48}	33%

Upper limits

Mode	BF $\times 10^{-5}$	90% CL $\times 10^{-5}$	95% CL $\times 10^{-5}$
K^+	$0.2^{+0.8}_{-0.7}$	1.3	1.6
K^0	$1.7^{+3.1}_{-2.1}$	5.6	6.7
Comb. K^+, K^0	$0.5^{+0.7}_{-0.7}$	1.4	1.7
Low-q^2 K^+	$0.2^{+0.6}_{-0.5}$	0.9	1.1
High-q^2 K^+	$-1.8^{+3.8}_{-3.8}$	3.1	4.6

$B^+ \rightarrow \tau^+ \nu_\tau$

$B^+ \to \tau^+ \nu_\tau$: Background & Predictions

Helicity suppression term
$e:\mu:\tau \sim 10^{-7}:5\times10^{-3}:1$

Sensitive to $f_B\,|V_{ub}|$

Standard Model

$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+}$$

Inputs

$|V_{ub}| = (3.89 \pm 0.44)\times10^{-3}$ [1]

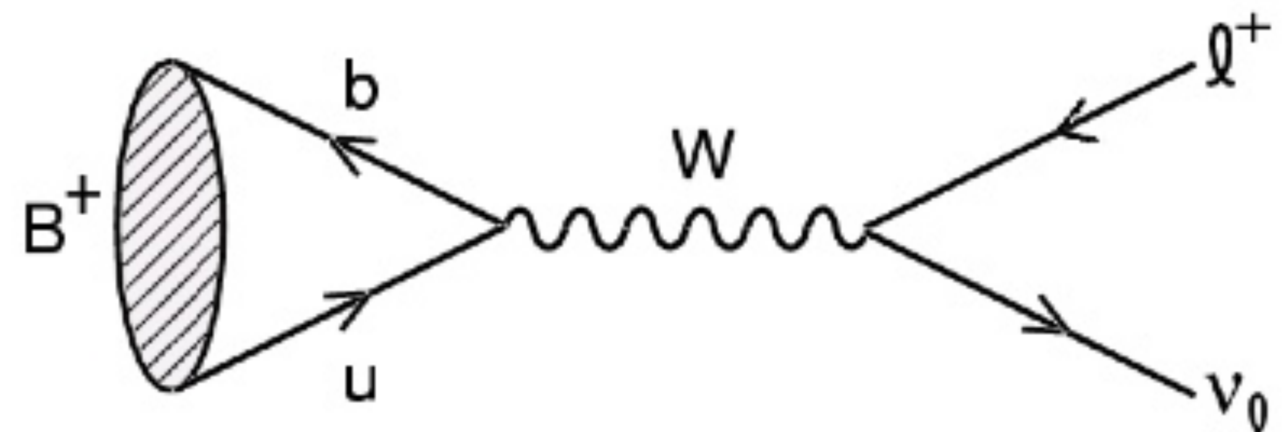
$f_B = (190 \pm 13)$ MeV [2]

$\tau_{B+} = 1.638$ ps

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.0 \pm 0.3)\times10^{-4}$$

Errors on $|V_{ub}|$ and f_B dominant uncertainty on theoretical prediction.

- Test SM and search for New Physics
  - Sensitive to product $f_B\,|V_{ub}|$
  - Two-Higgs doublet model can be mediated by charged Higgs [3]



New Physics

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\rm 2HDM} = \mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\rm SM} \left(1 - \tan^2\beta \frac{m_B^2}{m_H^2}\right)^2$$

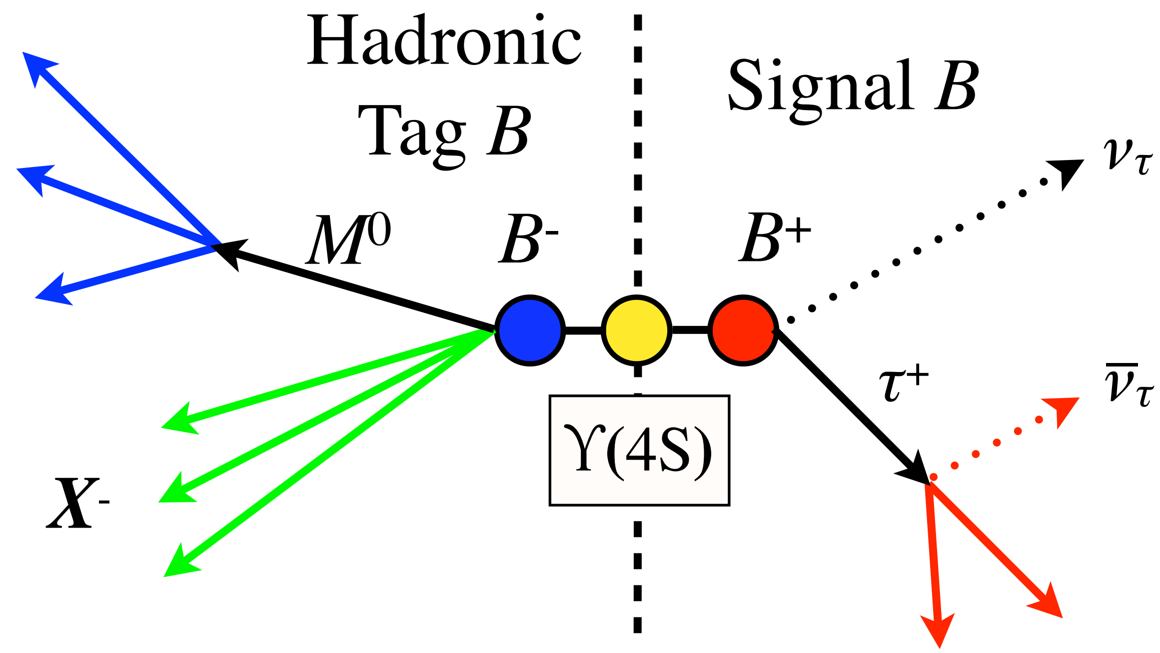
[1] K. Nakamura *et al*. (Particle Data Group), Journal of Physics G37, 075021

[2] HPQCD Collaboration, arXiv:0902.1815v2

[3] W. S. Hou, Phys. Rev. D 48 (1993) 2342

$B^+ \rightarrow \tau^+ \nu_\tau$: Analysis strategy

- Few kinematic handles to reconstruct signal B
- Fully reconstruct "other B" (tag B)
  - Remove many tracks and clusters from further consideration
  - Only consider decay modes with >10% purity
  - Reconstruct signal from remaining clusters and tracks
- Look for a single charged track in rest of event
  - Reconstruct four τ decay modes: $e^+\nu\nu$, $\mu^+\nu\nu$, $\pi^+\nu$, $\rho^+\nu$ (~70% total BF)
- Reject background using likelihood ratio
  - $D^{(*)0}$/ J/ψ momentum in CM
  - Magnitude of tag B thrust
  - Cosine of angle between tag B thrust and thrust of rest of the event



$$B^- \rightarrow M^0 X^-$$

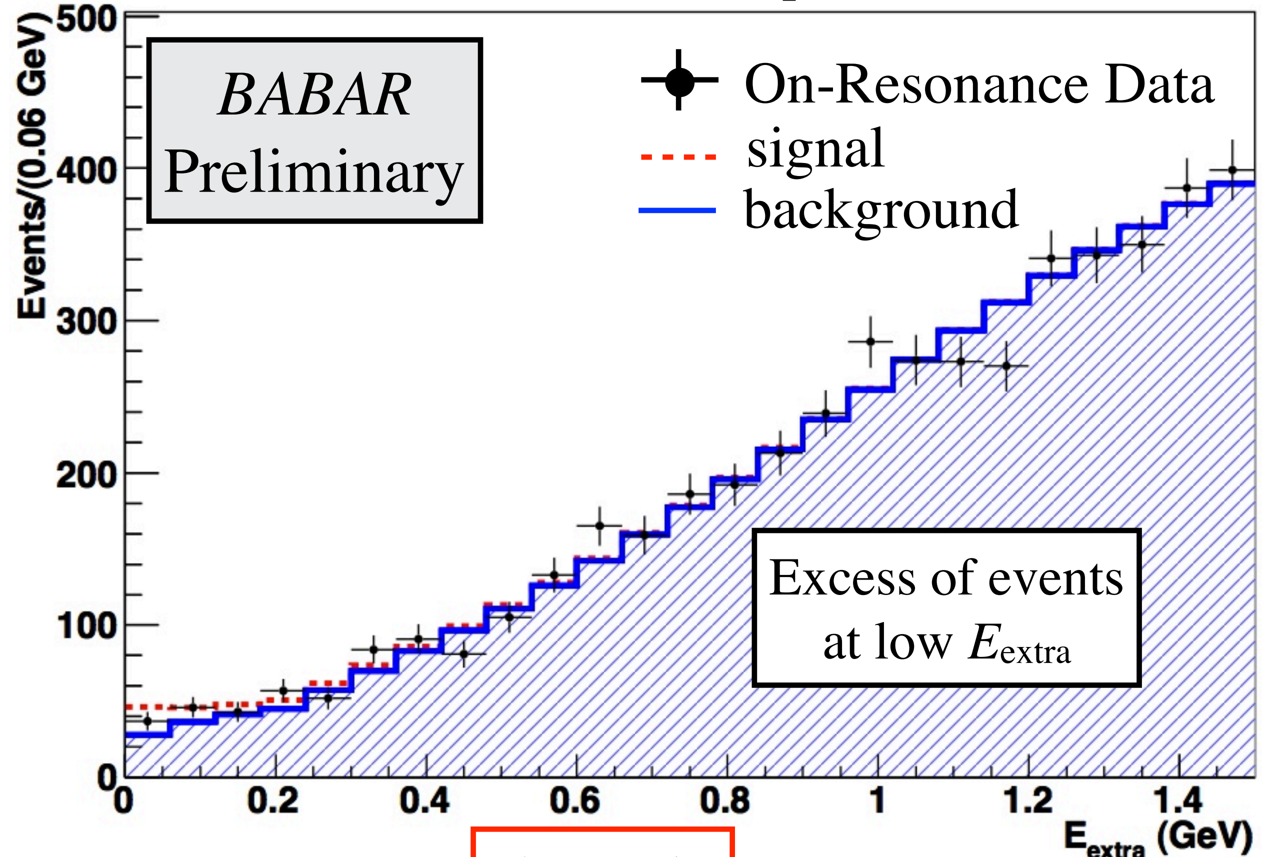
$$M^0 = \begin{array}{lll} D^0 & \rightarrow & K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^-\pi^+, \\ & & K^0_S\pi^0,\ K^0_S\pi^+\pi^-,\ K^0_S\pi^+\pi^-\pi^0, \\ & & K^+K^-,\ \pi^+\pi^- \\ D^{*0} & \rightarrow & D^0\pi^0,\ D^0\gamma \\ J/\psi & \rightarrow & e^+e^-,\ \mu^+\mu^- \end{array}$$

$$\begin{array}{lll} X^- & = & n\pi^\pm + mK + p\pi^0 + qK^0 \\ & & n+m \leq 5, \quad m,\ p,\ q \leq 2 \end{array}$$

$B^+ \to \tau^+ \nu_\tau$: Results

- Most powerful discriminating variable: **E_{extra} (sum of neutral cluster energy not associated w/ tag B or π^0 from ρ^+ decay)**
- Optimize for smallest statistical + systematic uncertainty
- Unbinned extended maximum likelihood fit to E_{extra}
  - Simultaneously fit 4 τ decay modes
  - Signal PDF from MC
  - Combinatorial PDF from m_{ES} side band
  - Peaking PDF from B^+B^- MC

Full *BABAR* dataset
(~468 million $B\bar{B}$ pairs)



Fit Results

Decay Mode	$\epsilon \times 10^{-4}$	Branching Fraction ($\times 10^{-4}$)	Significance σ
$\tau^+ \to e^+ \nu \bar{\nu}$	2.73	$0.39^{+0.89}_{-0.79}$	0.5
$\tau^+ \to \mu^+ \nu \bar{\nu}$	2.92	$1.23^{+0.89}_{-0.80}$	1.6
$\tau^+ \to \pi^+ \nu$	1.55	$4.0^{+1.5}_{-1.3}$	3.3
$\tau^+ \to \rho^+ \nu$	0.85	$4.3^{+2.2}_{-1.9}$	2.6
combined	8.05	$1.80^{+0.57}_{-0.54}$	3.6

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$$

Systematics

Source of systematics	BF uncertainty (%)
B counting	0.5
Tag B efficiency	5.0
Background PDF	12
Signal PDF	1.7
MC statistics	0.8
Electron identification	2.6
Muon identification	4.7
Kaon identification	0.4
Tracking	1.4
Total	14

$B^+ \to \tau^+ \nu_\tau$ using semileptonic tag

Combine with statistically independent measurement from *BABAR* [1]

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.79 \pm 0.49) \times 10^{-4}$$

[1] B. Aubert *et al.*, (*BABAR* Collaboration), Phys. Rev. D 81, 051101(R) (2010)

$$D_s^- \to \ell^- \bar{\nu}$$

Phys. Rev. D RC 82, 091103 (2010)

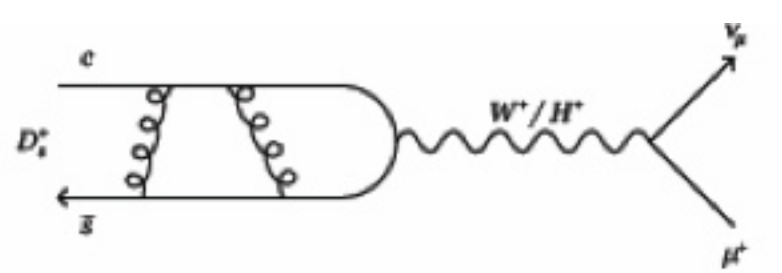
$D_s^- \to \ell^- \bar{\nu}$: Background

- Clean probe of f_{Ds}
  - Compare with SM prediction from LQCD
- Previously, tension between measured value of f_{Ds} and LQCD prediction of ~3σ [1]
  - Possible sign of New Physics

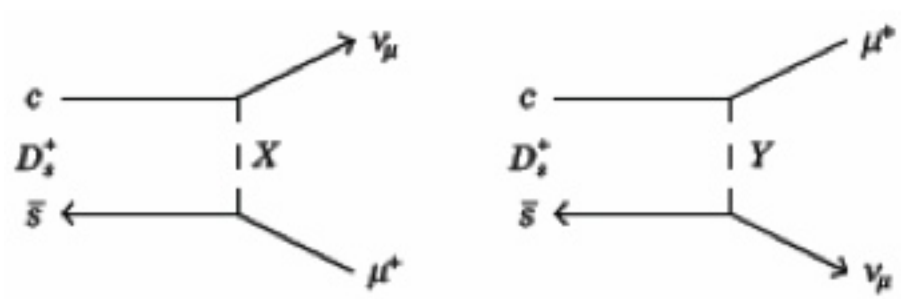
Leptonic branching fraction

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

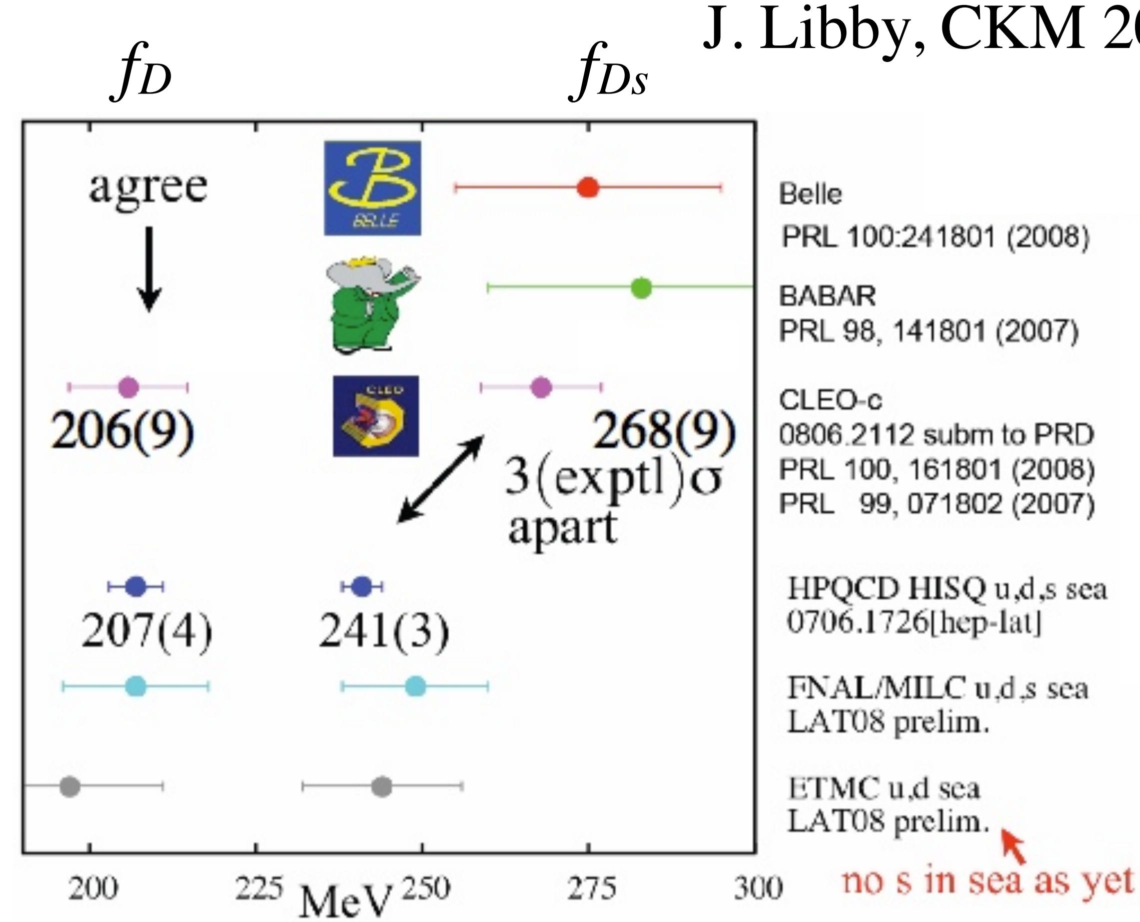
Charged Higgs



Leptoquarks



J. Libby, CKM 2008



[1] C. Davis *et al.*, PRD 82, 114504 (2010)

$D_s^- \to \ell^- \bar{\nu}$: Analysis Strategy

Reconstruct

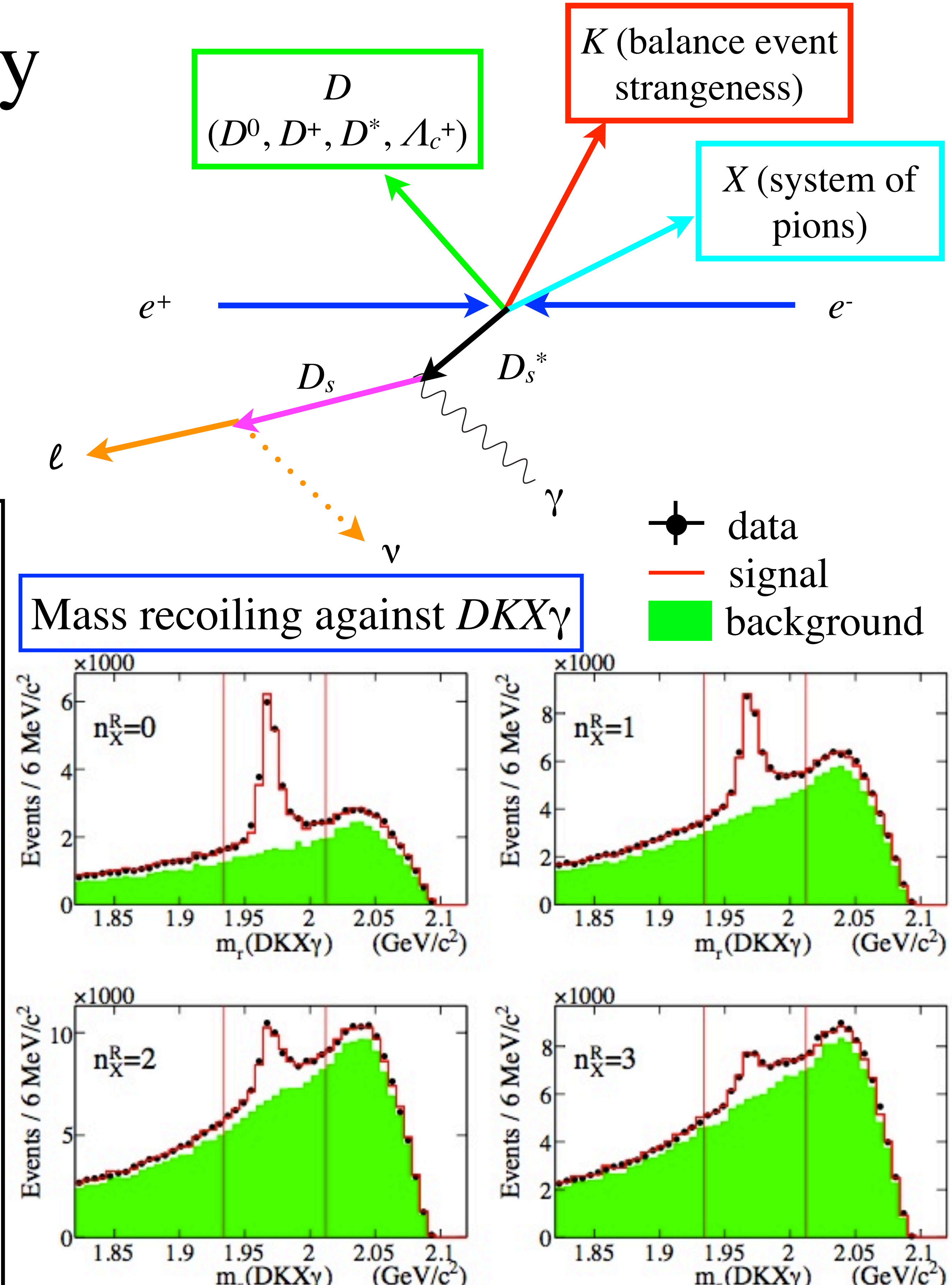
$e^+e^- \to c\bar{c} \to DKXD_s^{*-},\ \ D_s^{*-} \to D_s^- \gamma$

D is $D^0, D^+, D^*, \Lambda_c^+$
K is K^+ or K^0_S
X is system of up to three pions

- Inclusive sample of D_s by reconstructing mass recoiling against $DKX\gamma$ system

$$m^2_{D_s} = [p_{e^+} + p_{e^-} - (p_D + p_K + p_X + p_\gamma)]^2$$

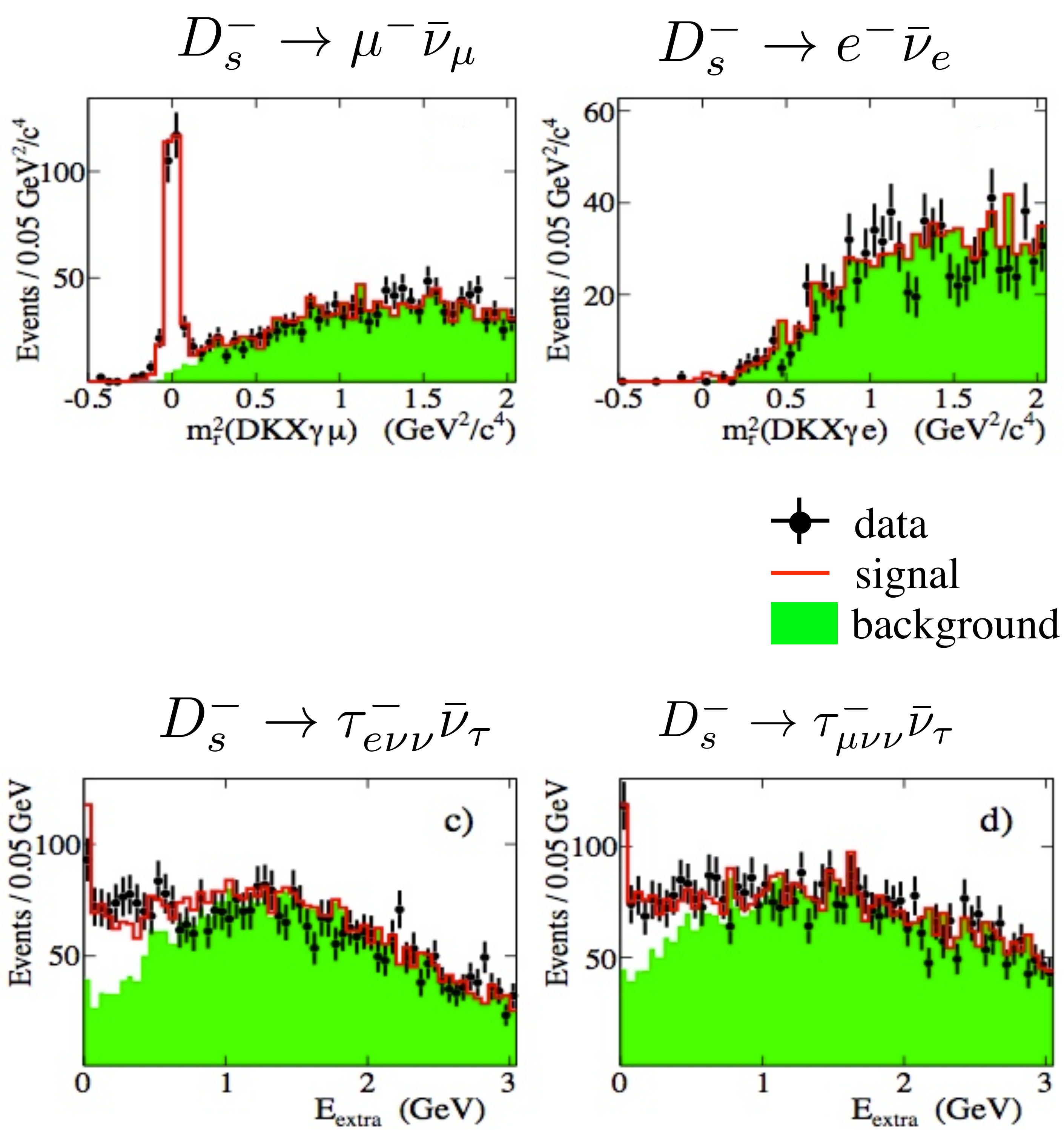
- Yield determined from 2d fit to mass recoiling against $DKX\gamma$ system and number of pions reconstructed in X system n^R_X
  - Inclusive D_s yield: $N_{Ds} = (67.2 \pm 1.5)\text{x}10^3$
- Reconstruct D_s decays in four decay modes
  - $\boldsymbol{D_s^- \to e^-/\mu^- \nu}$
  - $\boldsymbol{D_s^- \to \tau^- \nu_\tau, \tau^- \to e^-/\mu^- \nu\nu_\tau}$



$D_s^- \to \ell^- \bar{\nu}$: Analysis Strategy

- ***$D_s^- \to e^-/\mu^- \nu$***
  - Only one charged track remaining in event (ID as lepton)
  - Kinematic fit for neutrino mass
    - Mass recoiling against *DKX*γ constrained to PDG mass of D_s^+
  - Binned maximum likelihood fit to mass recoiling against *DKX*γ*e*/*μ* system squared to extract yield

- ***$D_s^- \to \tau^- \nu_\tau$, $\tau^- \to e^-/\mu^- \nu\nu_\tau$***
  - Only one charged track remaining in event (ID as lepton)
  - Multiple neutrinos in event
  - Binned maximum likelihood fit to E_{extra} (sum of EMC energy not associated with *DKX*γ or D_s^-)
    - Peaks near zero for signal



$D_s^- \to \ell^- \bar{\nu}$: Results

Phys. Rev. D RC 82, 091103 (2010)

Mode	Yield	$\mathcal{B}\,(10^{-3})$	f_{D_s} (MeV)
$D_s^- \to e^-\bar{\nu}_e$	$6.1 \pm 2.2 \pm 5.2$	< 0.23 (90% C.L.)	-
$D_s^- \to \mu^-\bar{\nu}_\mu$	275 ± 17	$6.02 \pm 0.38 \pm 0.34$	$265.7 \pm 8.4 \pm 7.7$
$D_s^- \to \tau^-_{e\nu\nu}\bar{\nu}_\tau$	408 ± 42	$50.7 \pm 5.2 \pm 6.8$	$247 \pm 13 \pm 17$
$D_s^- \to \tau^-_{\mu\nu\nu}\bar{\nu}_\tau$	340 ± 32	$49.1 \pm 4.7 \pm 5.4$	$243 \pm 12 \pm 14$

***BABAR* average**
f_{Ds} = (258.6 ± 6.4 ± 7.5) MeV

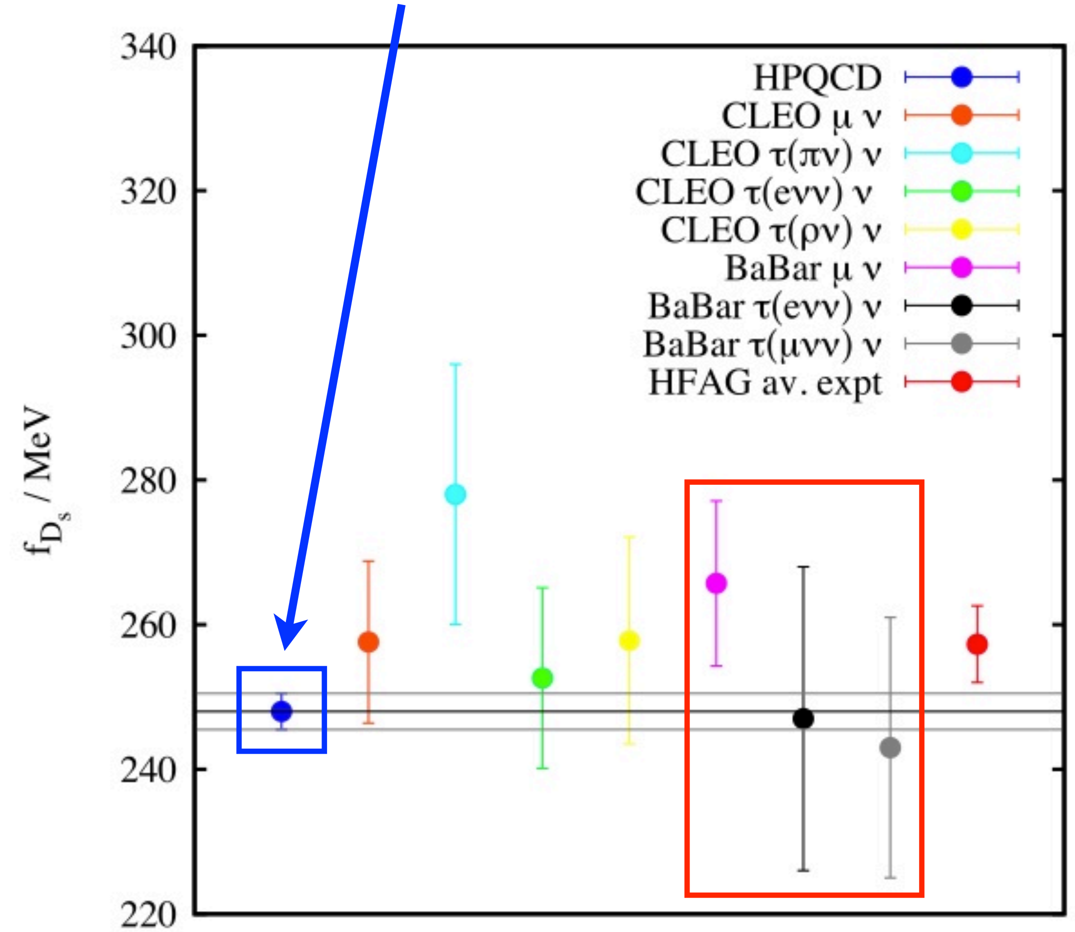
- f_{Ds} error-weighted average
  - New HFAG average 1.6σ from HPQCD value

Full *BABAR* dataset
521 fb^{-1}

- Analysis cross-checked with $D_s^- \to K^-K^+\pi^-$
  - Consistent with previous CLEO-c result

	BF ± stat. ± syst.
BABAR	(5.78 ± 0.20 ± 0.30)%
CLEO-c	(5.50 ± 0.20 ± 0.30)% [1]

LQCD
f_{Ds} = (248 ± 2.5) MeV



C. Davis *et al.*, PRD 82, 114504 (2010)

[1] J.P. Alexander *et al.*, PRD 79, 052001 (2009)

Summary

- Radiative and leptonic *B* and charm decays provide precision tests of Standard Model predictions

- Excellent environment to search for physics beyond SM and to constrain parameter space of New Physics models

- All results presented are consistent with SM expectations

- We look forward to interesting flavor results coming from LHCb and, in the more distant future, Belle-2 and SuperB.