Recent results on semileptonic B meson decays from Belle and Babar

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Topics

(I) exclusive $B \to Dl\nu$ $|V_{cb}|$ [Belle]

(II) exclusive $B \to D^{(*)}\pi^+\pi^- l\nu$ [Babar]

(III) semi-inclusive $B_s \to D_s^{(*)}Xl\nu$ [Belle]

(IV) $D^0 \to \pi^- e^+\nu$ form factor and $|V_{ub}|$ [Babar]

All results are based on new analyses
All are preliminary

Belle and Babar

Belle (KEK) 1999-2010:

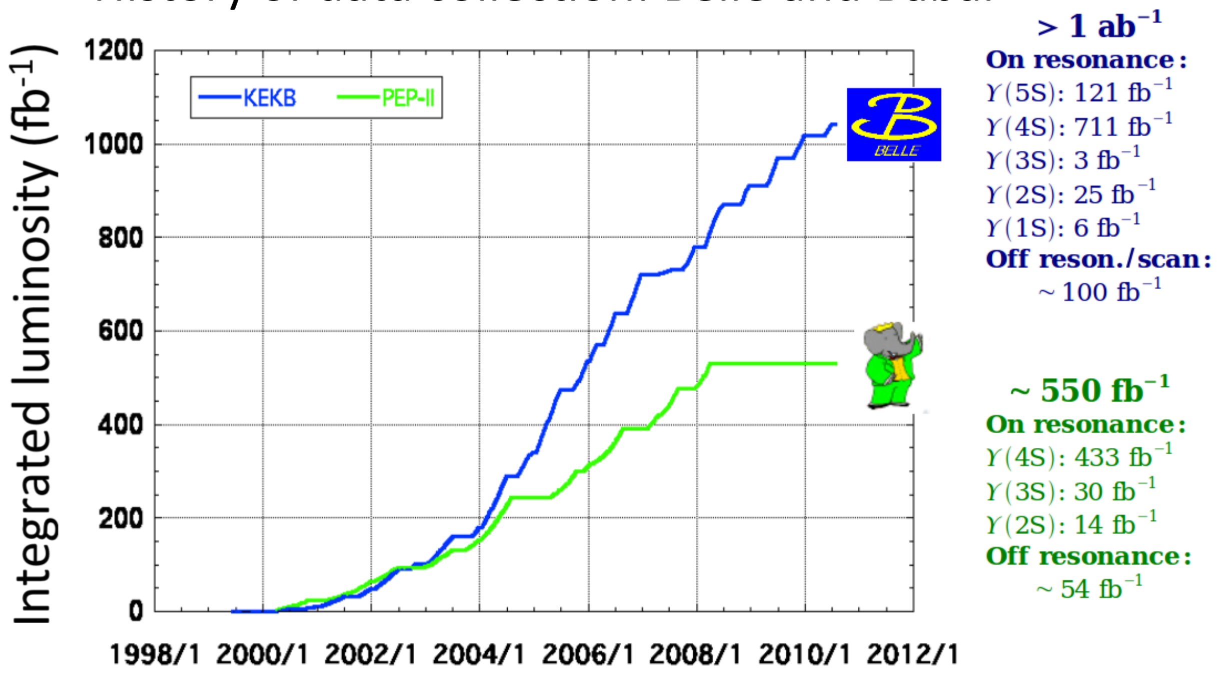
772×10^6 BB pairs at $\Upsilon(4S)$

7.1×10^6 B_sB_s pairs at $\Upsilon(5S)$

Babar (SLAC) 1999-2008:

471×10^6 BB pairs at $\Upsilon(4S)$

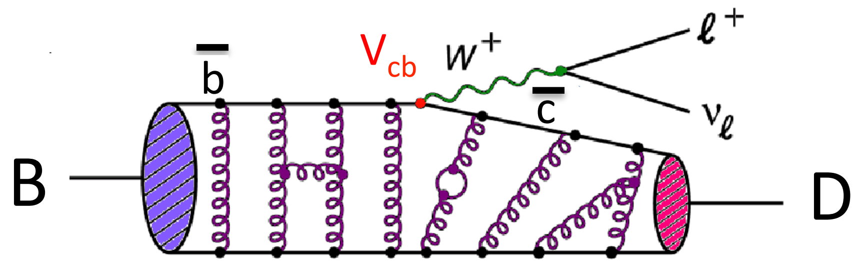
History of data collection: Belle and Babar



(I) $B \to D l \nu$ from Belle

Updates previous result [PLB526 (2002) 258, 10.2 fb^{-1}]
using the full Belle $\Upsilon(4S)$ data sample [711 fb^{-1}]

$B \to D l \nu$ and $|V_{cb}|$



Differential decay rate for exclusive $B \to D l \nu$ described by

$$\frac{d\Gamma(B \to D\ell\upsilon)}{dw} = \frac{G_F^2}{48\pi^3} m_D^3 (m_B + m_D)^2 (w-1)^{3/2} \, |\eta_{EW}|^2 |V_{cb}|^2 \, \mathcal{G}(w)^2$$

$$w = v_B \cdot v_D = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$ = product of 4-velocities; $q^2 = (p_\ell + p_\upsilon)^2$

- w = 1 corresponds to zero recoil (D meson produced at rest, q^2 is maximal)
- η_{EW} = electroweak correction = 1.0066 [A. Sirlin, Nucl. Phys. B196 (1982) 83]
- $\mathcal{G}(w)$ = form factor (only one form factor required for $m_l \ll m_B$)

$B \to D l \nu$ and $|V_{cb}|$

- $\mathcal{G}$(w=1) predicted by theory (lattice QCD)
- Extrapolate the measured differential decay rates to w=1 using a parameterization of the form factor $\mathcal{G}$(w)
- Standard parameterization of $\mathcal{G}$(w): [Caprini et al., Nucl. Phys. B520 (1998) 153]

$$\mathcal{G}(w) = \mathcal{G}(1)[1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3]$$

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

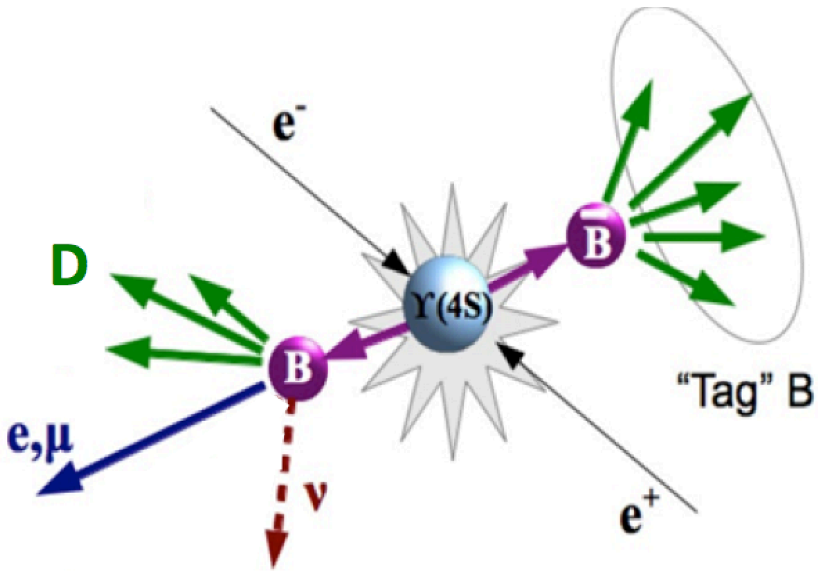
ρ = the shape parameter

→ simultaneously determine ρ^2 and the overall normalization $\eta_{EW}\mathcal{G}(1)|V_{cb}|$

$B \rightarrow Dl\nu$ and $|V_{cb}|$

- 770 x 10^6 $\Upsilon(4S) \rightarrow BB$ events
- Full reconstruction of the hadronic decay of one B (=B_{tag})

- More than 1110 distinct exclusive channels
- Allows reconstruction of the 4-momenta of both B mesons and thus of the neutrino



$B \to Dl\nu$ and $|V_{cb}|$

- The other B (=B_{sig}) is reconstructed in 1 of 4 final states:
  - $\bar{B}^0 \to D^+ l^- \bar{\nu}$
  - $B^- \to \bar{D}^0 l^- \bar{\nu}$

$l = e, \mu$

D meson reconstruction:

$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K_S\pi^+\pi^-$, $K_S\pi^+\pi^-\pi^0$, K^-K^+, $K_S\pi^0$, $\pi^+\pi^-$

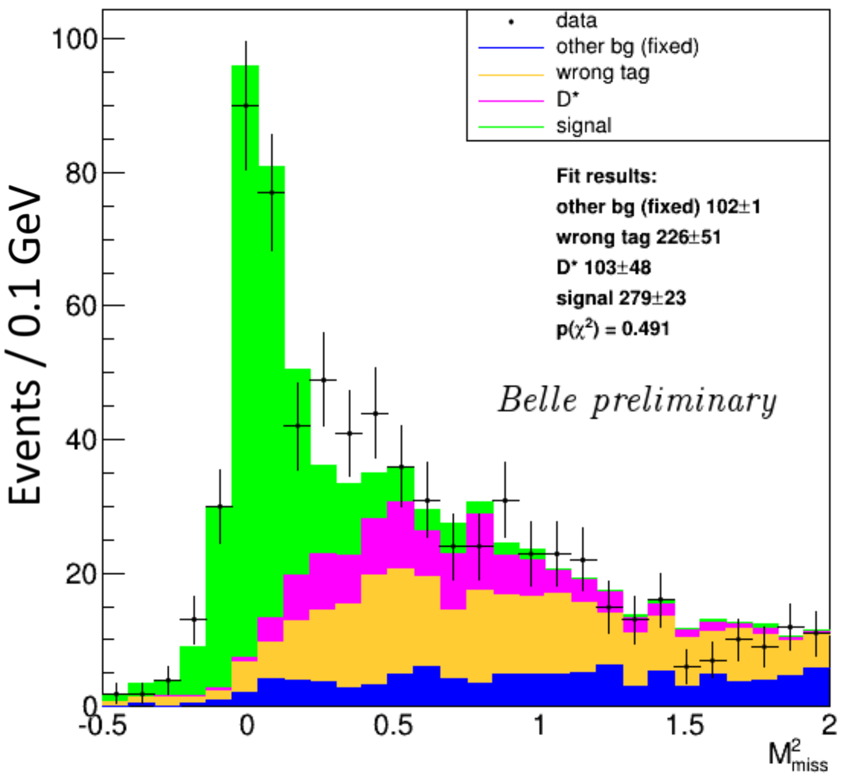
$D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S\pi^+$, $K_S\pi^+\pi^0$, $K^-K^+\pi^+$, K_SK^+, $K_S\pi^+\pi^-\pi^+$

$B \to Dl\nu$ and $|V_{cb}|$

BELLE

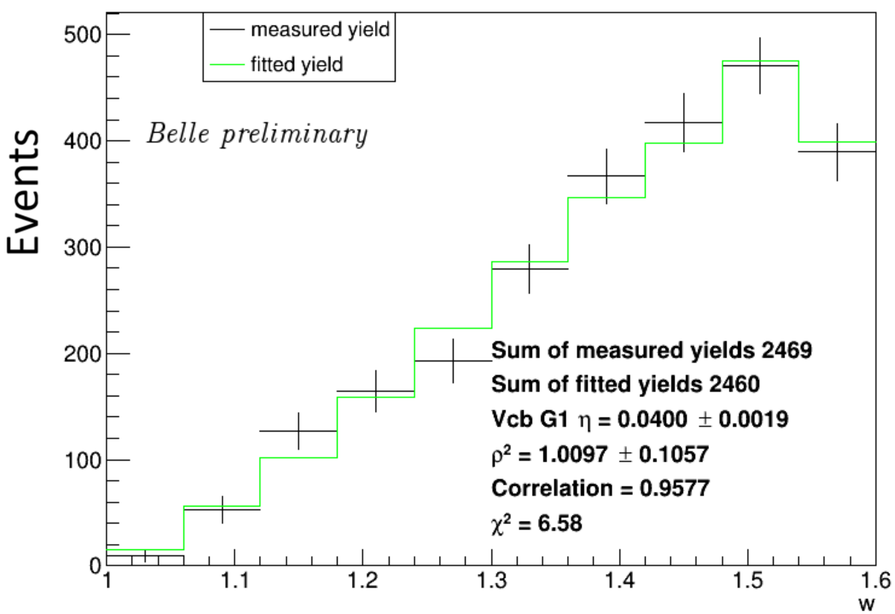
Calculate the missing mass: $M^2_{miss} = [p_{\Upsilon(4S)} - p_{B_{tag}} - p_D - p_l]^2$

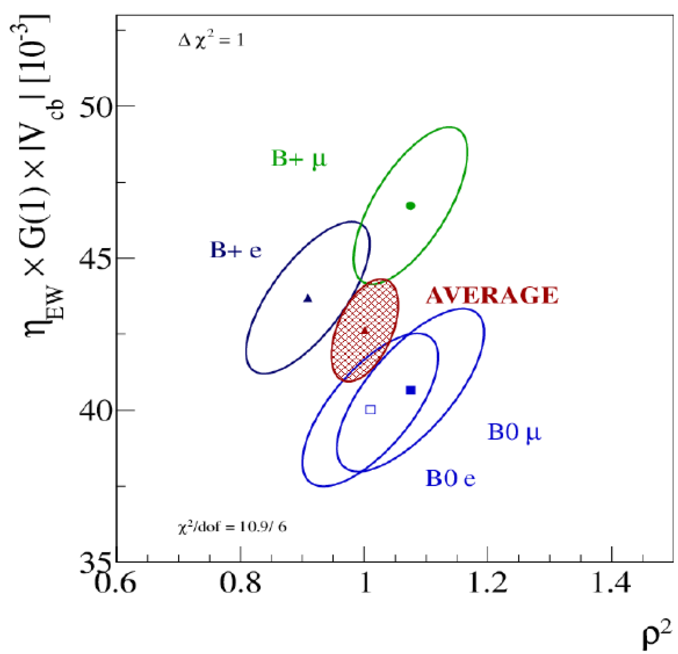
- M_{miss}^2 peaks at zero for events with one missing neutrino
- Events with unreconstructed particles (e.g. $D^* \to \pi D$) yield larger M_{miss}^2
- Use maximum likelihood fit to determine signal and background yields
- MC used to describe signal and background shapes



$B \to D l \nu$ and $|V_{cb}|$

- Determine signal yields in 10 bins of w
- Subtract background and correct for detection efficiency
- Fit form factor $\mathcal{G}(w)$ to determine ρ^2 and normalization $\eta_{EW}\mathcal{G}(1)|V_{cb}|$





$B \to D l \nu$ and $|V_{cb}|$

Preliminary combined results (4 channels):

$$\eta_{EW}\mathcal{G}(1)|V_{cb}| = 42.63 \pm 0.96\ (\text{stat}) \pm 1.39\ (\text{syst}) \times 10^{-3}$$

$$\rho^2 = 1.001 \pm 0.051\ (\text{stat}) \pm 0.018\ (\text{syst})$$

- Improves precision of previous Belle result by a factor of 4
- Most precise single measurement (preliminary)
- Compares well in precision to current world average from Heavy Flavor Averaging Group:

$$\eta_{EW}\mathcal{G}(1)|V_{cb}| = 42.64 \pm 0.72\ (\text{stat}) \pm 1.35\ (\text{syst}) \times 10^{-3}$$

$$\rho^2 = 1.186 \pm 0.036\ (\text{stat}) \pm 0.041\ (\text{syst})$$

(II) $B \rightarrow D^{(*)}\pi^+\pi^- l\nu$ from Babar

$B \to D^{(*)}\pi^+\pi^- l\nu$

Measurements of exclusive B meson $b \to cl\nu$ decays exist for:

- $B \to D^{(*)} l\nu$ [Belle, Babar, CLEO, ARGUS]
- $B \to D^{(*)}\pi l\nu$ [Belle PRD 77 (2008) 091503; Babar PRL 100 (2008) 151802]

The sum of measured exclusive rates does not saturate the well-determined inclusive rate: $BF(B \to X_c l\nu) = 10.92 \pm 0.17\%$

$$\mathrm{BF}(B \to X_c l\upsilon) - \Sigma[\mathrm{BF}(B \to D^{(*)} l\upsilon) + \mathrm{BF}(B \to D^{(*)}\pi l\upsilon)]$$
$$= 1.45 \pm 0.29\%$$

[Bernlochner, Ligeti, Turczk, PRD 85 (2012) 094033]

$B \rightarrow D^{(*)}\pi^+\pi^- l\nu$

It is of interest to identify & measure the "missing" channels

- non-resonant ?
- higher mass D^{**} state ?
- consistency with heavy-quark effective theory (HQET)

Better understanding of higher multiplicity $B \rightarrow X_c l\nu$ decays can potentially reduce systematic uncertainties for

- V_{cb} and V_{ub} (for both, ~3σ discrepancy between results from inclusive and exclusive decays)
- $B \rightarrow D^{(*)}\tau l\nu$ (Babar observes a 3.4 σ discrepancy with the standard model [PRL 109 (2012) 101802 ; PRD 88 (2013) 072012])

$B \to D^{(*)}\pi^+\pi^- l\nu$

- 471×10^6 $\Upsilon(4S) \to BB$ events
- Full reconstruction of the hadronic decay of one B (=B_{tag})

- The other B (=B_{sig}) is reconstructed in 1 of 12 final states:

  $D^{(*)}l\nu$; $D^{(*)}\pi^{\pm}l\nu$; $D^{(*)}\pi^+\pi^- l\nu$; $l = e, \mu$
- No additional charged tracks

- $D^{(*)}$ meson reconstruction:

  $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+, K_S\pi^+\pi^-, K^-K^+, K_S\pi^0, \pi^+\pi^-$

  $D^+ \to K^-\pi^+\pi^+, K^-\pi^+\pi^+\pi^0, K_S\pi^+, K_S\pi^+\pi^0, K^-K^+\pi^+, K_SK^+, K_S\pi^+\pi^-\pi^+$

  $D^{*+} \to D^0\pi^+, D^+\pi^0$

  $D^{*0} \to D^0\pi^0, D^0\gamma$

$B \to D^{(*)}\pi^+\pi^- l\nu$

- Determine missing 4-momentum p_{miss} in event

$$p_{miss} = p_{\Upsilon(4S)} - p_{Btag} - p_{D^{(*)}(\pi)(\pi\pi)l} = (E_{miss}, \vec{p}_{miss})$$

- Define $U \equiv E_{miss} - |\vec{p}_{miss}|$

→ U peaks at zero for signal events: $E_{miss} = |\vec{p}_{miss}|$ for neutrinos

→ U ≠ 0 for events with additional unreconstructed particles

Maximum-likelihood fit of the U distribution

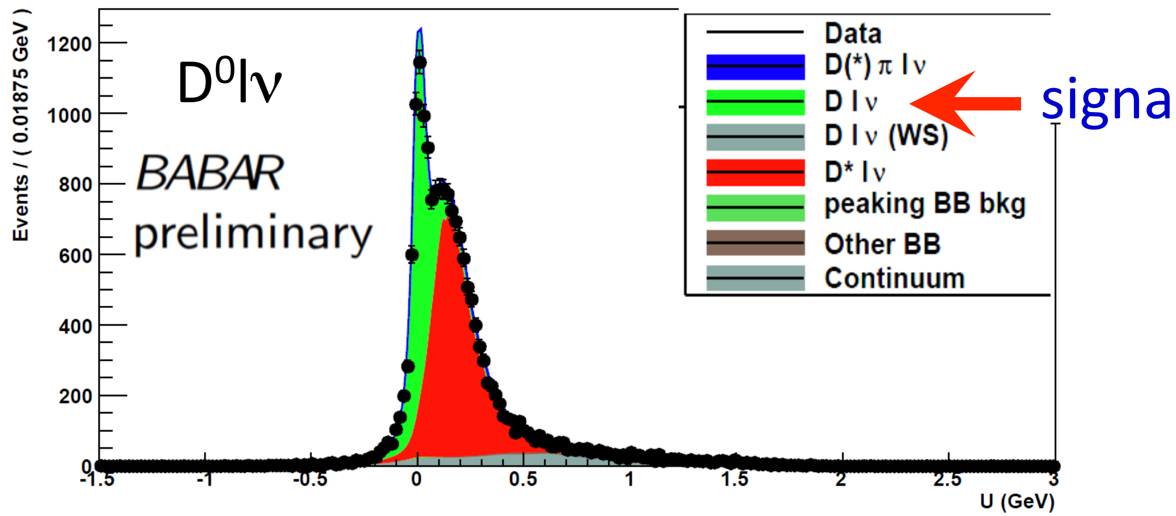
→ MC-derived shapes for signal and background components

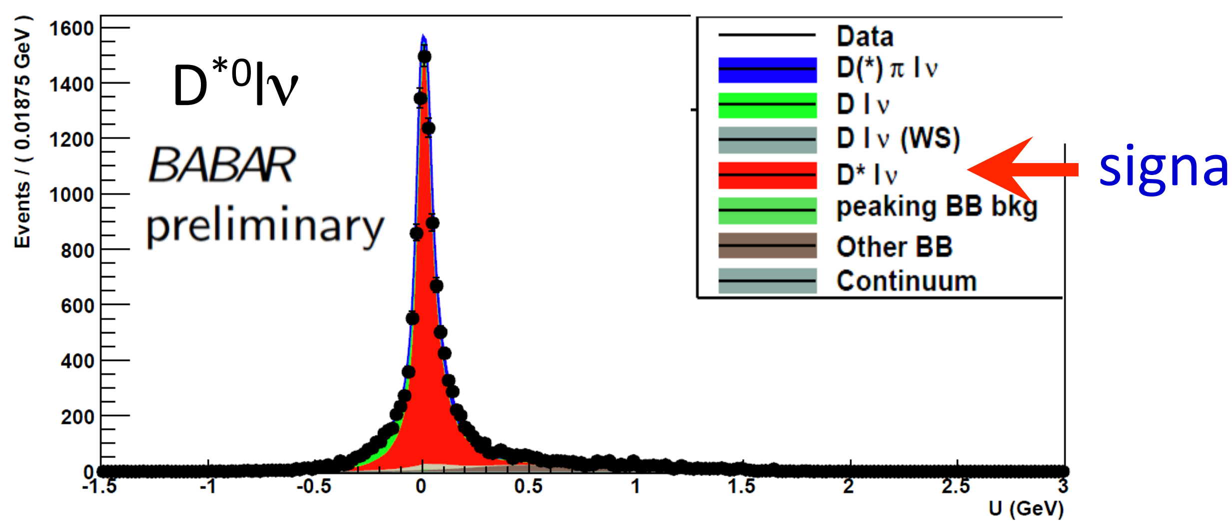
→ Signal and background event yields floated

→ Fit procedure validated with toy MC ensembles

$B \rightarrow D^{(*)}\pi^+\pi^- l\nu$

Normalization mode: $D^{(*)0}l\nu$

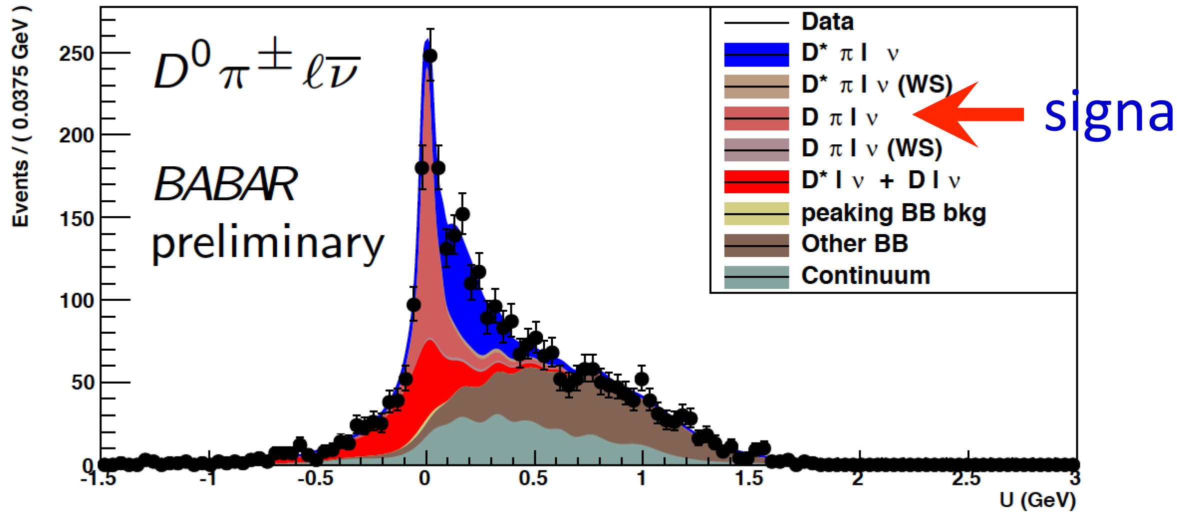


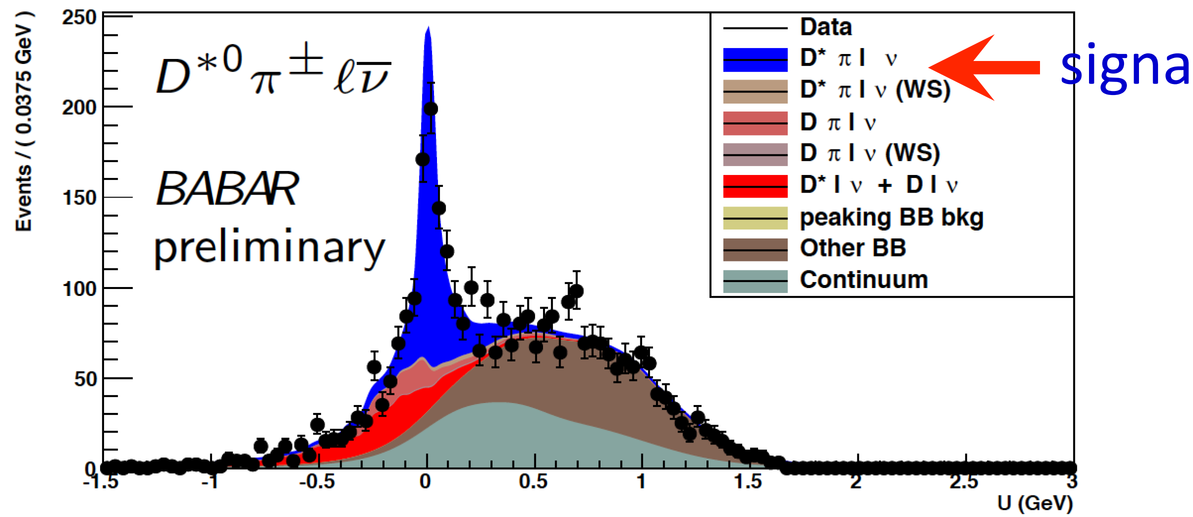


WS = wrong sign (charge of B_{sig} incorrectly determined)

$B \rightarrow D^{(*)}\pi^{+}\pi^{-}l\nu$

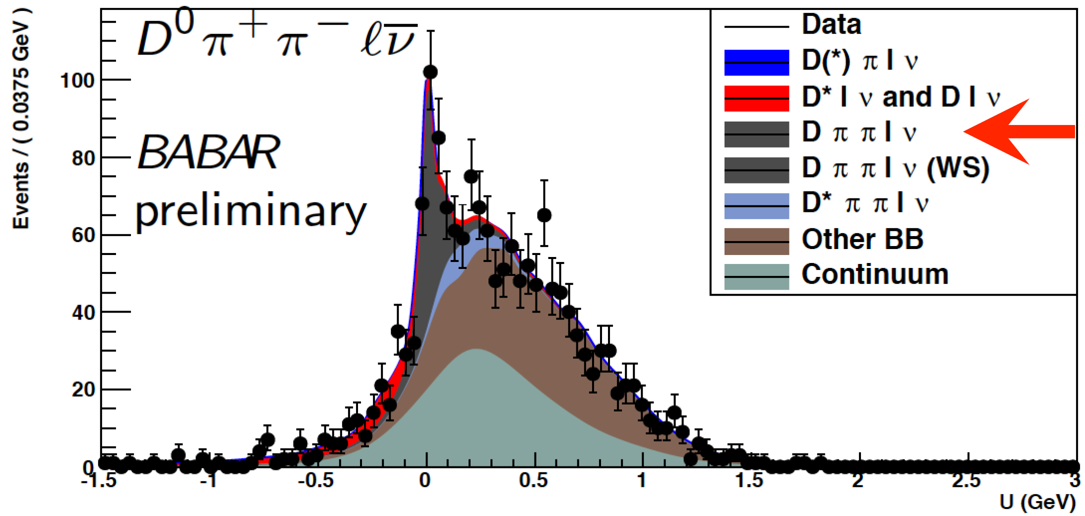
One-pion mode: $D^{(*)0}\pi^{\pm}l\nu$



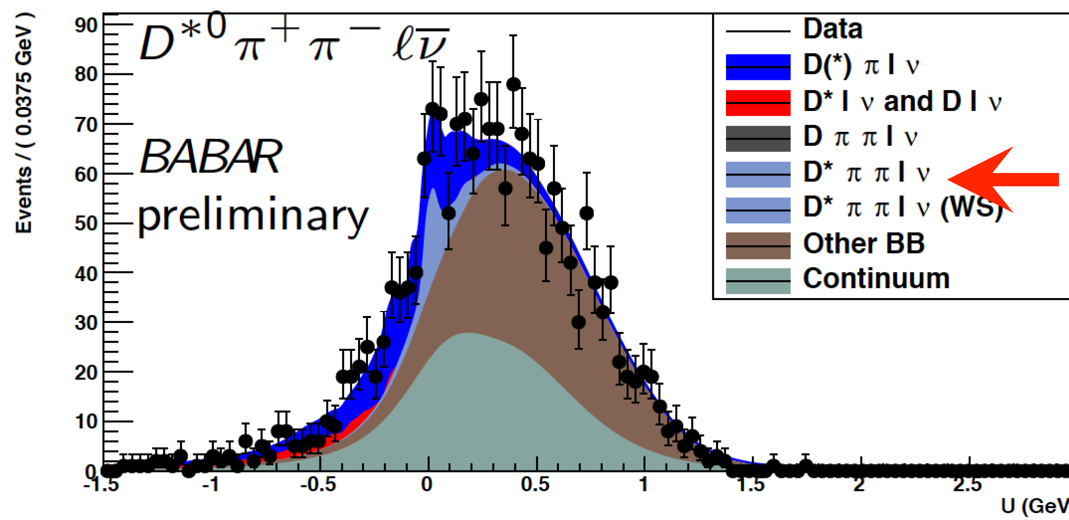


$B \to D^{(*)}\pi^+\pi^- l\nu$

Two-pion mode: $D^{(*)0}\pi^+\pi^- l\nu$



signal



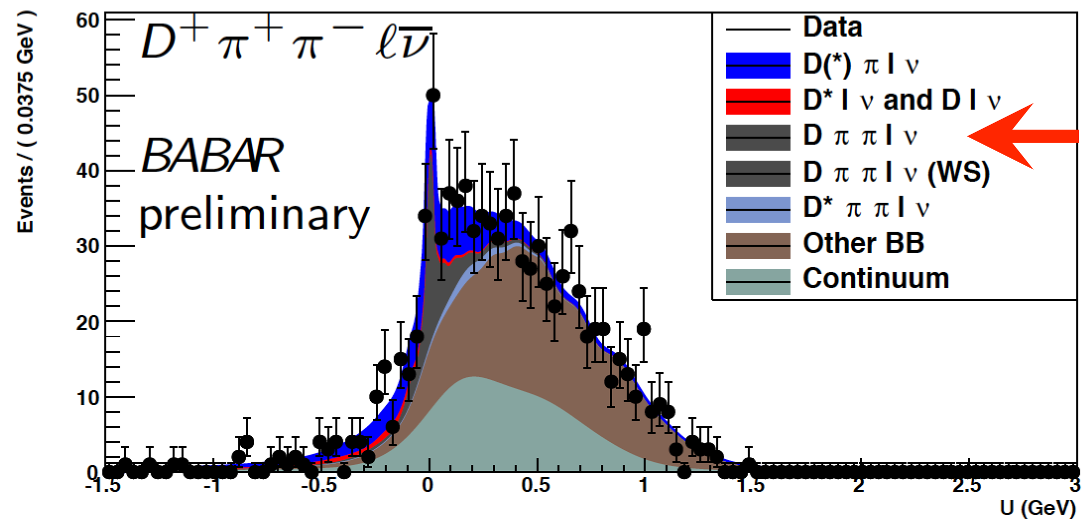
signal

clear $D^0\pi\pi l\nu$ signal: 4.4 σ

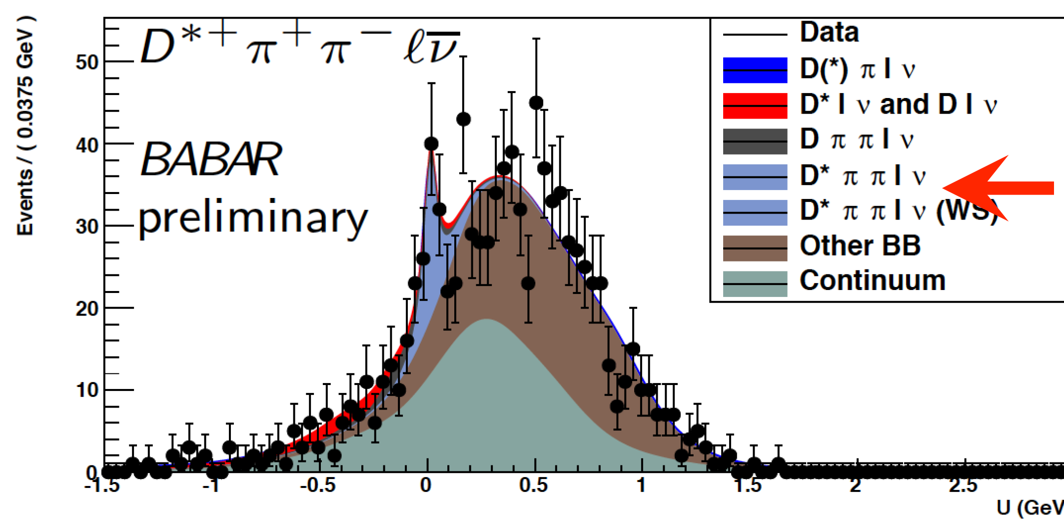
$D^{*0}\pi\pi l\nu$: 1.9 σ

$B \to D^{(*)}\pi^+\pi^- l\nu$

Two-pion mode: $D^{(*)+}\pi^+\pi^- l\nu$



signal



signal

$D^+\pi\pi l\nu$: 2.6 σ

$D^{*+}\pi\pi l\nu$: 2.9 σ

$B \to D^{(*)}\pi^+\pi^- l\nu$

Babar Preliminary

Signal	Normalization	$R^{(*)}_{n\pi}$	$B \to D^{(*)}n\pi l\nu$ branching ratio
$D\pi^\pm$	D	$0.1873 \pm 0.0107 \pm 0.0086$	$0.4476 \pm 0.0256 \pm 0.0206 \pm 0.0225$
$D^*\pi^\pm$	D^*	$0.1234 \pm 0.0056 \pm 0.0061$	$0.6108 \pm 0.0277 \pm 0.0302 \pm 0.0136$
$D\pi^+\pi^-$	D	$0.0733 \pm 0.0139 \pm 0.0081$	$0.1752 \pm 0.0332 \pm 0.0194 \pm 0.0088$
$D^*\pi^+\pi^-$	D^*	$0.0214 \pm 0.0062 \pm 0.0030$	$0.1059 \pm 0.0307 \pm 0.0149 \pm 0.0024$

Results for charged and neutral B's are combined

stat — syst — BF of normalization mode

- $D^{(*)}\pi^{\pm}l\nu$ results consistent with current world averages and about 20% more precise

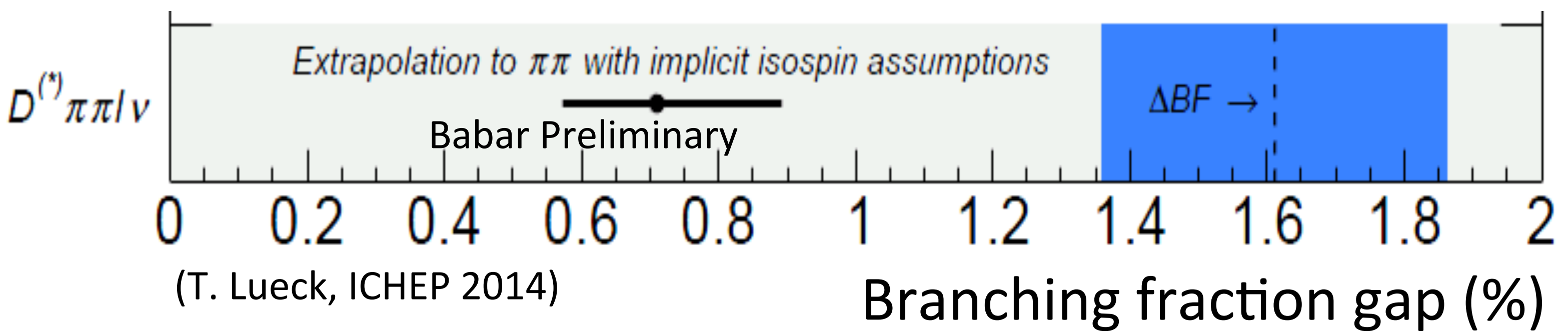
- $D\pi^+\pi^- l\nu$ combined results: 5.1σ → first observation
- $D^*\pi^+\pi l\nu$ combined results: 3.5σ → first evidence

$B \rightarrow D^{(*)}\pi^+\pi^- l\nu$

Impact on the inclusive – exclusive branching fraction gap:

$$\mathrm{BF}(B \rightarrow X_c l\upsilon) - \Sigma[\mathrm{BF}(B \rightarrow D^{(*)} l\upsilon) + \mathrm{BF}(B \rightarrow D^{(*)}\pi l\upsilon)]$$
$$= 1.45 \pm 0.29\%$$

[Bernlochner, Ligeti, Turczk, PRD 85 (2012) 094033]



(T. Lueck, ICHEP 2014)

The gap is reduced by about 60% but not fully explained !

(III) $B_s \rightarrow D_s^{(*)}Xl\nu$ from Belle

$B_s \to D_s^{(*)}Xl\nu$

- Exploit world's largest $\Upsilon(5S)$ sample: 7.1 million B_sB_s events
- Belle uniquely positioned for precision measurements of B_s branching fractions

- Measure $B_s \to D_s$ and $B_s \to D_s^*$ inclusive semileptonic transitions: "semi-inclusive"
- $D_s Xl\nu$: "X" includes feeddown from D_s^* & D_s^{**}
- $D_s^*Xl\nu$: "X" includes feeddown from D_s^{**}

Current PDG entries

- BF[$B_s \to D_sXl\nu$] = 7.9 ± 2.4% [Aleph, Delphi, OPAL]
- BF[$B_s \to D_s^*Xl\nu$]: no results

$B_s \to D_s^{(*)} X l \nu$

- D_s^- reconstructed in the $\phi\pi^-$ decay mode with $\phi \to K^+K^-$
- D_s^{*-} reconstructed in the $D_s^-\gamma$ decay mode
- Require event to contain charged lepton l (= e, μ) of opposite sign to the $D_s^{-(*)}$

Examine events using the X_{mis} variable

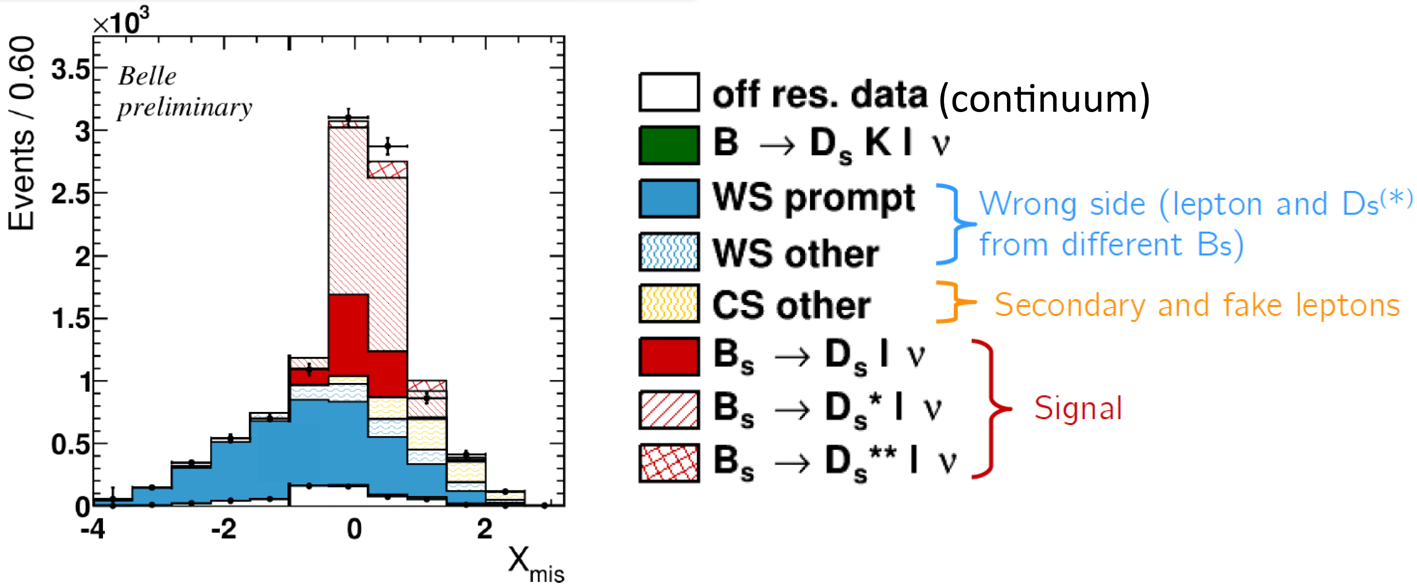
$$X_{mis} \equiv \frac{E^*_{beam} - E^*_{vis} - p^*_{vis}}{p^*_{beam}}$$

E^*_{vis} & p^*_{vis} *exclude* B_{tag} *daughters*

X_{mis} peaks at zero for signal events

$B_s \to D_s^{(*)} X l \nu$

X_{mis} distribution for $D_s X e \nu$ candidates:



Two principal background categories:

1) "Wrong side": $D_s^{(*)}$ and lepton arise from different B_s → small X_{mis}

2) "Fakes": 2ndry leptons & hadrons misidentified as leptons → large X_{mis}

$B_s \to D_s^{(*)}X l \nu$

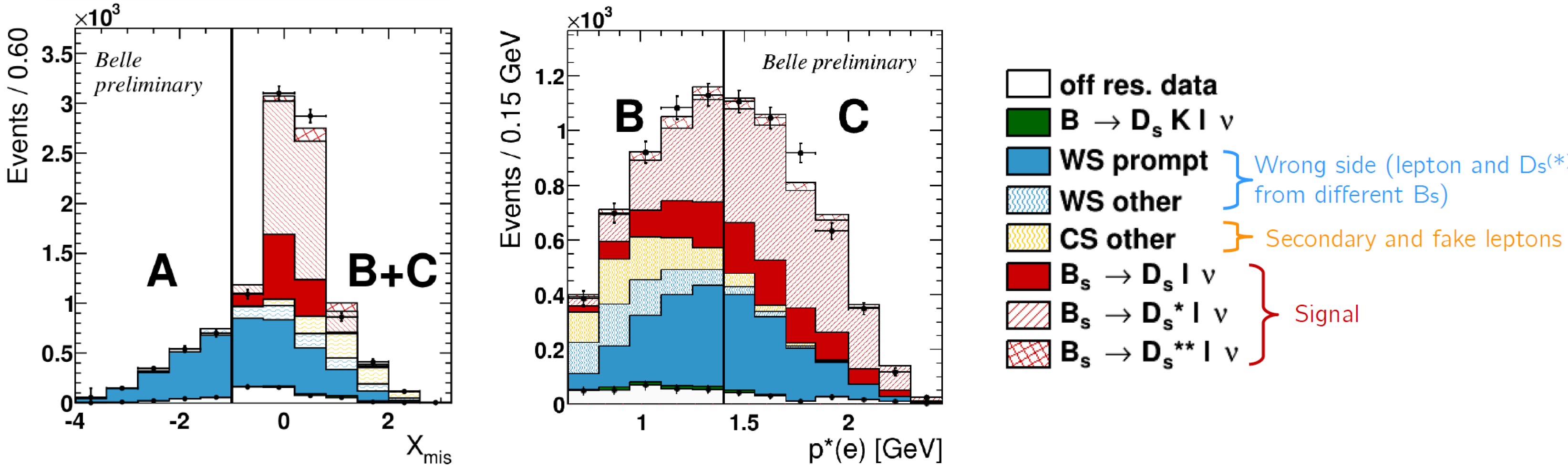
Divide data into three regions: A, B, and C

A: $X_{mis} < -1$: dominated by wrong-side background

B: $X_{mis} > -1$ and $p_l^* < 1.4$ GeV: enhances fake lepton component

C: $X_{mis} > -1$ and $p_l^* > 1.4$ GeV: enhanced signal-to-background ratio

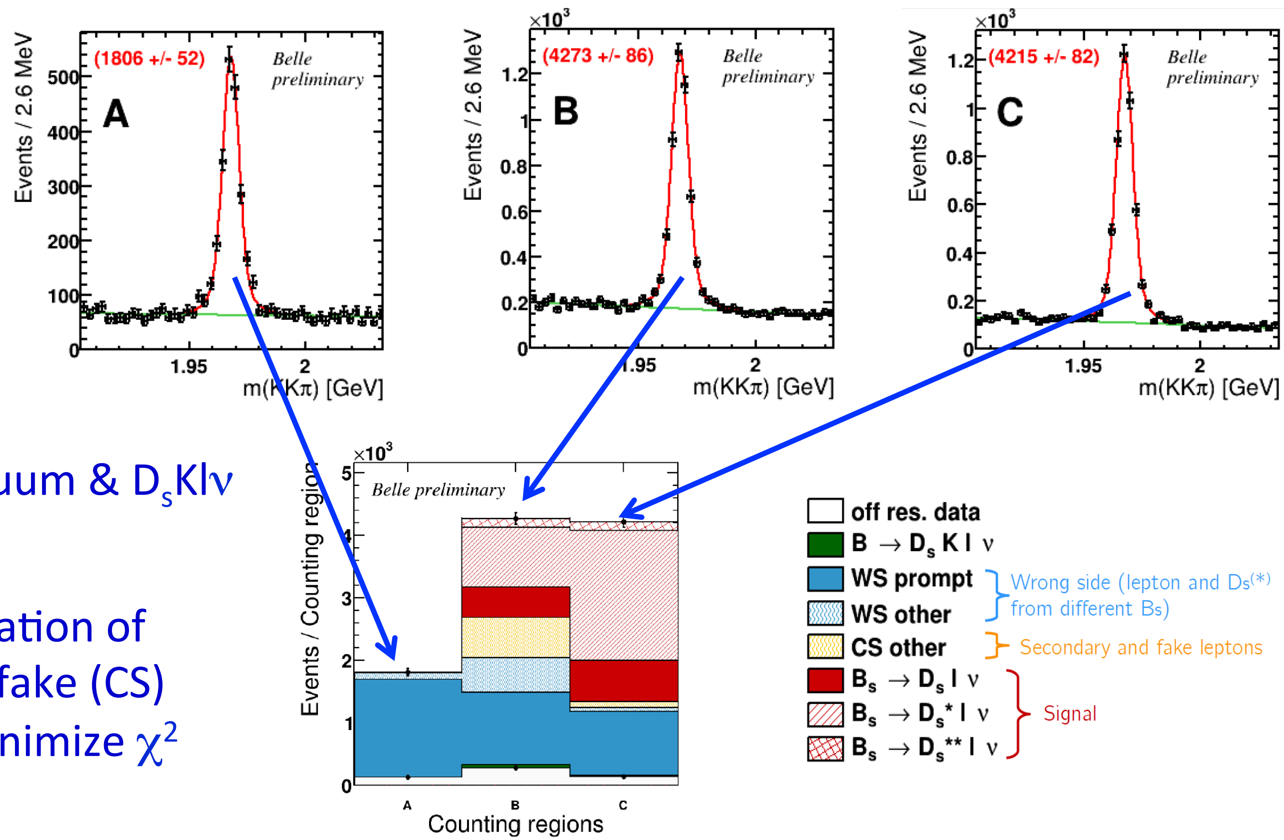
$D_s X e \nu$ candidates:



$B_s \to D_s^{(*)} X l \nu$

Fit number of D_s candidates in each region using the $m_{KK\pi}$ distribution:

$D_s X e \nu$:

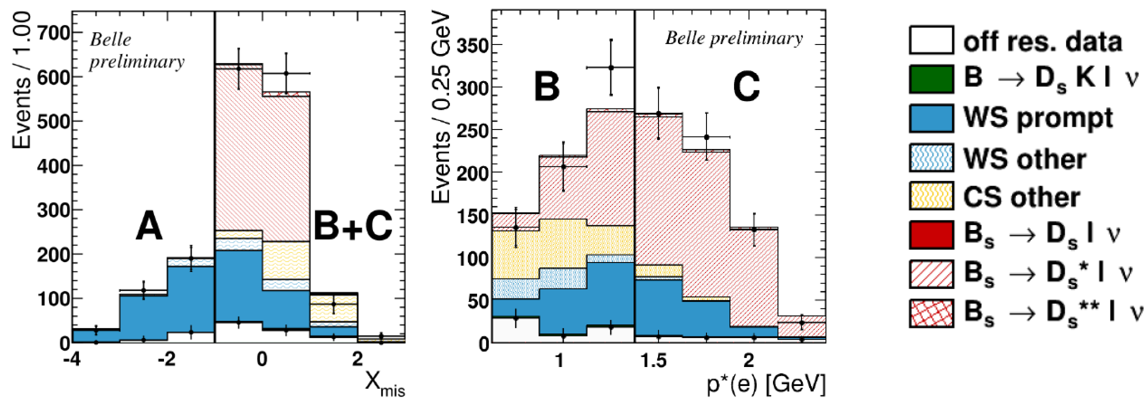


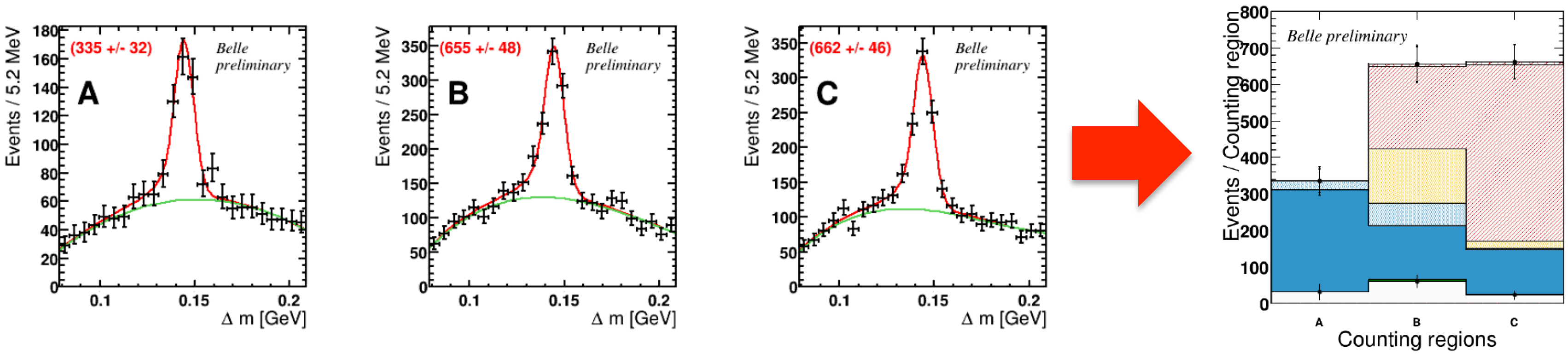
- Subtract continuum & $D_s K l \nu$ backgrounds
- Adjust normalization of signal, WS, and fake (CS) templates to minimize χ^2

$B_s \to D_s^{(*)} X l \nu$

For $D_s^* X l \nu$ channels, fit the $\delta m = m_{kk\pi\gamma} - m_{kk\pi}$ distribution:

$D_s^* X e \nu$:





$B_s \rightarrow D_s^{(*)}Xl\nu$

Results (e and μ channels combined):

Preliminary

Channel	Branching fraction (%)
$B_s \rightarrow D_sXl\nu$	8.2 ± 0.2 (stat) ± 0.8 (syst) ± 1.5 (N_{BsBs})
$B_s \rightarrow D_s^*Xl\nu$	5.4 ± 0.4 (stat) ± 0.5 (syst) ± 1.0 (N_{BsBs})

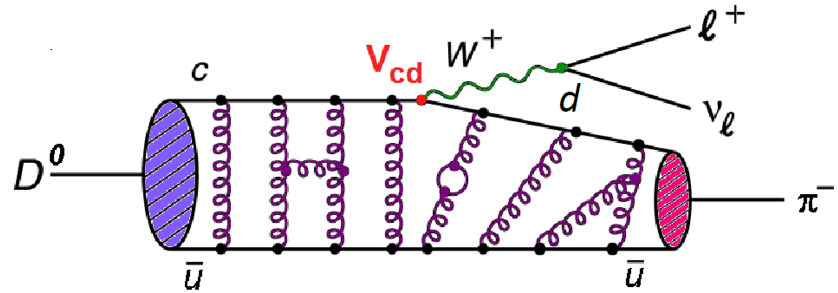
- First evidence for the $B_s \rightarrow D_s^*Xl\nu$ branching fraction (~4.5σ)
- $B_s \rightarrow D_sXl\nu$ branching fraction agrees with PDG value [= 7.9 ± 2.4%]; uncertainty reduced by 30% (expect to improve further with reductions to σ_{NBsBs})

- Results consistent with theory predictions for exclusive rates:
  $B_s \rightarrow D_s^*l\nu$: 2-8% ; $B_s \rightarrow D_sl\nu + D_s^*l\nu$: 3-12%

(IV) The $D^0 \rightarrow \pi^- e^+ \nu$ form factor and $|V_{ub}|$ from Babar

$D^0 \rightarrow \pi^- e^+ \nu$ form factor and $|V_{ub}|$

$D^0 \rightarrow \pi^- e^+ \nu$ decays:



Since $m_e << m_D$, only one form factor contributes: $f_{+,D\rightarrow\pi}$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cd}|^2 p_\pi^3 \left[f_{+,D\rightarrow\pi}(q^2) \right]^2$$

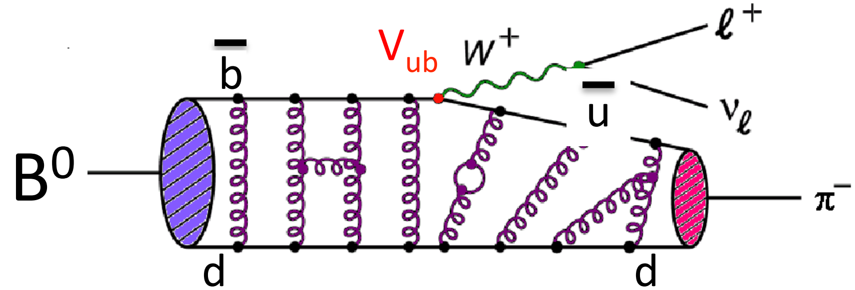
$p_\pi = \pi$ momentum in D rest frame

$q^2 = (p_e + p_\nu)^2$

- The form factor $f_{+,D\rightarrow\pi}$ can be related to the form factor $f_{+,B\rightarrow\pi}$ for $B^0 \rightarrow \pi^- e^+ \nu$ transitions [Isgur and Wise [PRD 42 (1990) 2388]]
- Provides an alternative theoretical approach to determine $|V_{ub}|$

$D^0 \rightarrow \pi^- e^+ \nu$ form factor and $|V_{ub}|$

$B^0 \rightarrow \pi^- e^+ \nu$ decays:



$$\frac{d\Gamma^B/dw_B}{d\Gamma^D/dw_D} = \frac{m_B}{m_D}\left(\frac{|V_{ub}|}{|V_{cd}|}\right)^2 \left|\frac{f^{\pi}_{+,B}(w_B)}{f^{\pi}_{+,D}(w_D)}\right|^2$$

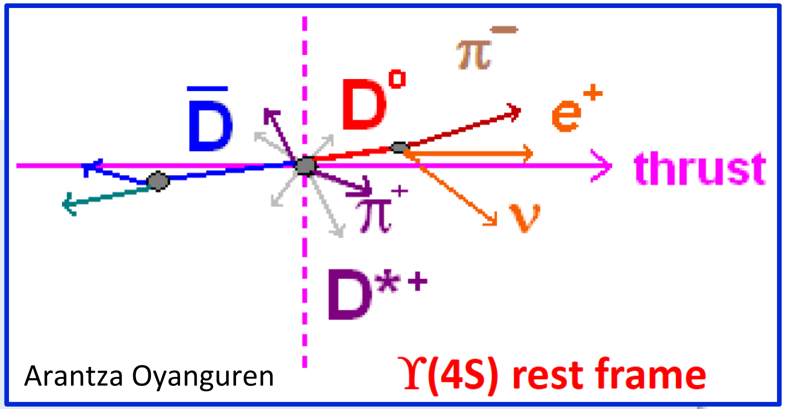
$$w_{B,D} = \frac{M_{B,D}{}^2 + m_\pi^2 - q^2}{2M_{B,D}m_\pi}$$ = product of 4-velocities = $v_{B,D} \cdot v_\pi$

$$\left|\frac{f^{\pi}_{+,B}(w_B)}{f^{\pi}_{+,D}(w_D)}\right| = \sqrt{\frac{m_B}{m_D}}\left[1 + \mathcal{O}\left(\frac{1}{m_{B,D}}\right)\right]$$ ≈ 1.8 ± 0.2 (lattice calculations)

[J. Koponen 1311.6931, E. Dalgic et al., PRD73(2007)074502; J.A. Bailey et al., PRD79(2009)054507]

Use $d\Gamma_B/dw_B$ results from Babar $B^0 \rightarrow \pi^- e^+ \nu$ study in PRD86(2012)092004

$D^0 \rightarrow \pi^- e^+ \nu$ form factor and $|V_{ub}|$

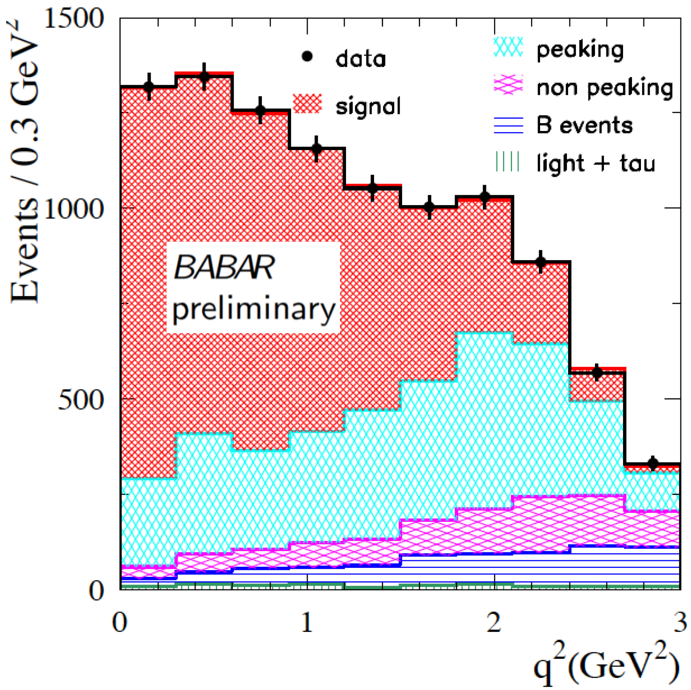


- Select $D^0 \rightarrow \pi^- e^+ \nu$ candidates from $D^{*+} \rightarrow D^0 \pi^+$ decays
  - Divide event into hemispheres using the thrust axis
  - Require an identified π^- and e^+ within a hemisphere
  - Define D^0 momentum from $-\Sigma p$ over all particles except π^-, e^+
  - Define ν momentum from the missing momentum
  - Impose mass-constrained kinematic fit of $D^{*+} \rightarrow D^0(\rightarrow \pi^- e^+ \nu)\pi^+$ decay chain, require $\chi^2_{fit} > 0.01$

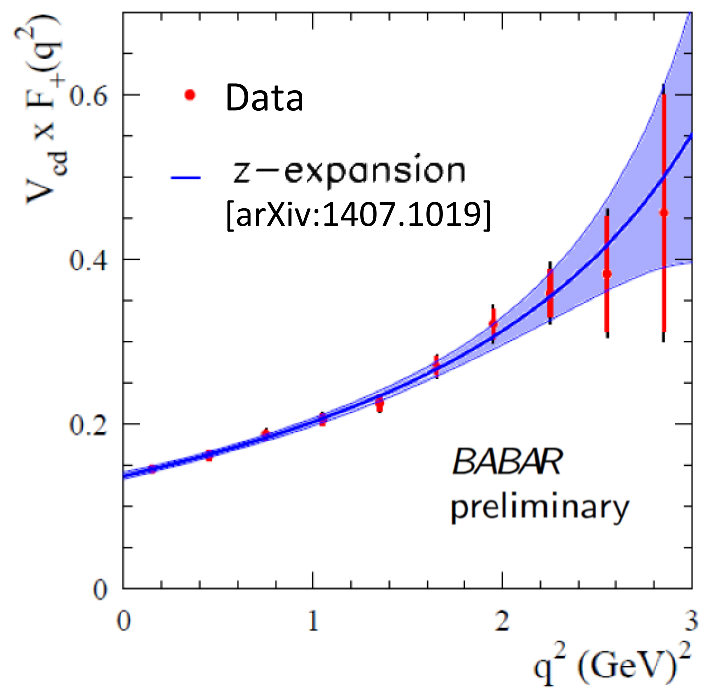
- Background from uds continuum and BB events reduced with Fisher discriminants, cut on $\delta m = m_{D0\pi+} - m_{D0}$
- "Peaking" background (true D^{*+}): use sideband data control samples.

$D^0 \to \pi^- e^+ \nu$ form factor and $|V_{ub}|$

Extracted $D^0 \to \pi^- e^+ \nu$ signal yield:

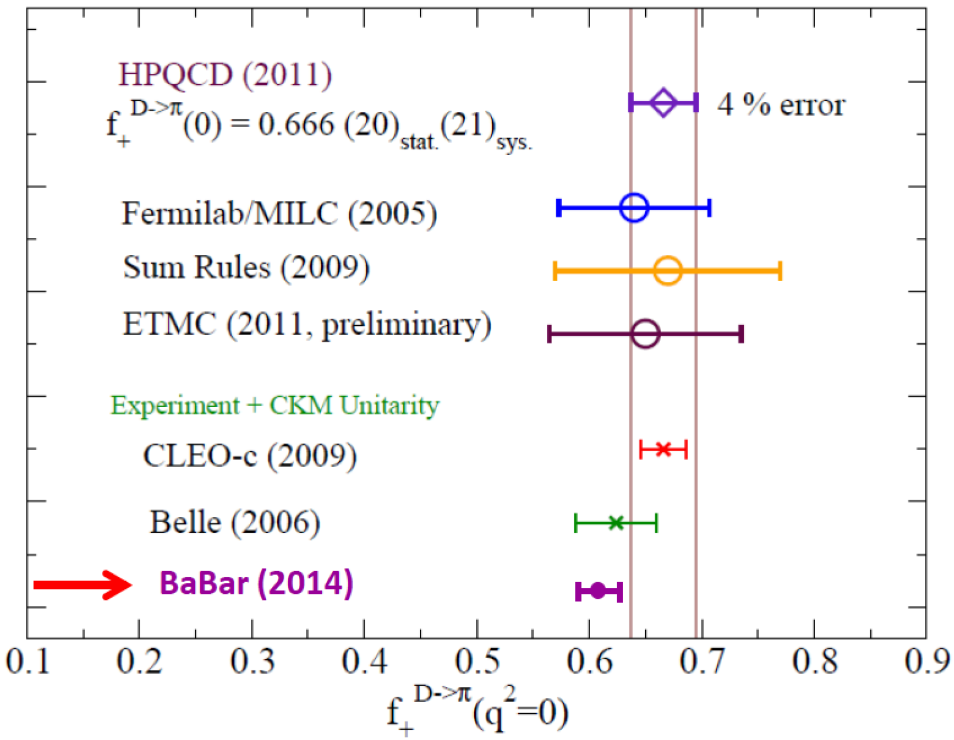


The $D^0 \to \pi^- e^+ \nu$ form factor:



Use power series ("z expansion") parameterization of the form factor to extrapolate measured results to q^2=0

$D^0 \rightarrow \pi^- e^+ \nu$ form factor and $|V_{ub}|$



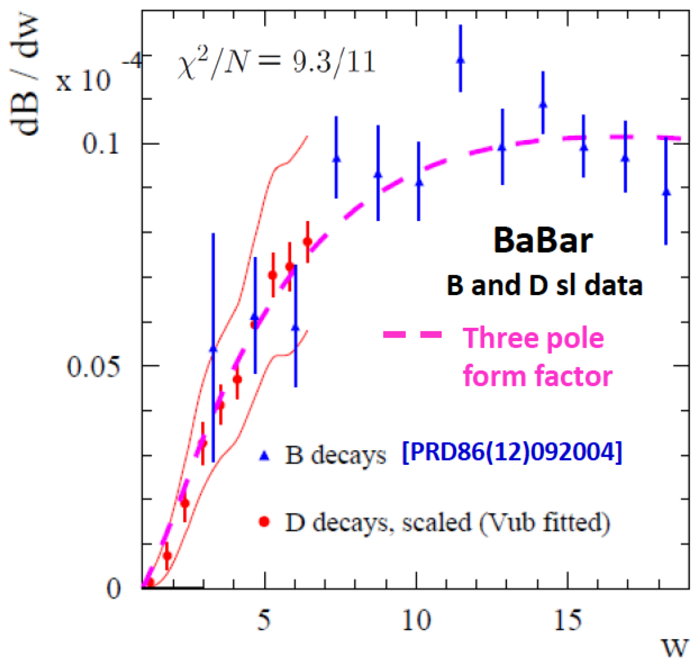
$f_{+,D\rightarrow\pi}(0) = 0.610\pm0017(\text{stat.})\pm0010(\text{syst})\pm0.005(|V_{cd}|)$

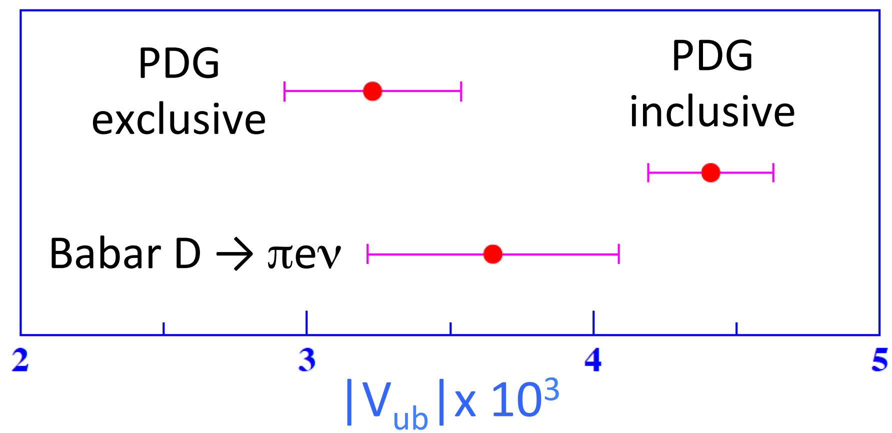
(using $|V_{cd}| = 0.2252\pm0.009$)

First result on this topic from Babar

$D^0 \to \pi^- e^+ \nu$ form factor and $|V_{ub}|$

- Combine $d\Gamma_{D\to\pi e\nu}/dw_B$ with the $d\Gamma_{B\to\pi e\nu}/dw_B$ measurements [PRD86(2012)092004]
- Use lattice results for $f_{+,B\to\pi} / f_{+,D\to\pi}$





→ $|V_{ub}| = 3.65 \pm 0.18(\text{exp}) \pm 0.40(R_{B/D}) \times 10^{-3}$

Alternative ("3 poles") parameterization of the form factor:

→ $|V_{ub}| = 2.6 \pm 0.2 \pm 0.4 \times 10^{-3}$

[D. Becirevic et al., arXiv:1407.1019]

Summary

- Updated results (Belle) on $|V_{cb}|$ from exclusive $B \to Dl\nu$
  → the most precise single measurement (preliminary)
- First observation (Babar) of exclusive $B \to D^{(*)}\pi^+\pi^- l\nu$
  → explains ~60% of the inclusive-exclusive BF gap in $b \to cl\nu$ decays
- First evidence (Belle) for the $B_s \to D_s^* Xl\nu$ branching fraction
- New approach (Babar) to determine $|V_{ub}|$, based on measurement of the $D^0 \to \pi^- e^+ \nu$ form factor

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