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VISPA – Victoria Subatomic Physics and Accelerator Research Centre

B → $D^{(*)}\pi^+\pi^- l^- \nu$ and prospects for measuring related decay modes

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on behalf of the BaBar Collaboration

NSERC CRSNG

BaBar

INSTITUTE OF PARTICLE PHYSICS

Thank you to the Kobayashi-Maskawa Institute for the kind invitation

- Weak interactions have a rich history at Nagoya – in science and perhaps in literature too?

- If you've read this novel (whose main characters grow up in Nagoya) you'll agree that Tsukuru Tazaki is a singlet that doesn't interact strongly…

Outline of talk

- Importance of higher-mass $B \rightarrow X_c l\nu$ (l = e or μ) decays as potential sources of background for $B \rightarrow D^{(*)}\tau\nu$ measurements

- Current status of $B \rightarrow X_c l\nu$ decays

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

- Prospects for measuring additional modes at Belle II and LHCb

A source of background for $B \rightarrow D^{(*)}\tau\nu$

- Unmeasured $B \rightarrow X_c l\nu$ decays are of concern because they
  - have higher multiplicity (more opportunities for particles to escape detection and fake additional neutrinos)
  - have higher mass (bigger overlap with kinematics of $B \rightarrow X_c \tau\nu$ decays)
- Measurements of $B \rightarrow D^{(*)}\tau\nu$ use $B \rightarrow D^{(*)}\pi^0 l\nu$ control samples to assess uncertainties coming from these unknown decays
  - method assumes ratio of $B \rightarrow D^{(*)}\tau\nu$ background to $B \rightarrow D^{(*)}\pi^0 l\nu$ yield is the same in data and MC
  - departures must be modeled based on assumptions about the decays that contribute background

The presence of intermediate resonances in multi-body hadronic final states (e.g. $D^{(*)}\pi\pi$) makes isospin relations between modes with and without π^0 model dependent.
This is reflected in the estimate given later in this talk:

$$\frac{BF\left(B \rightarrow D^{(*)}\pi^+\pi^-\ell\nu\right)}{BF\left(B \rightarrow D^{(*)}\pi\ \pi\ \ell\nu\right)} = 0.50 \pm 0.17$$

$B \rightarrow X_c l\nu$ decays – current status

- Inclusive BF from global fit to moments (HFAG 2016); ***quoted as B^0 BF*** it is
  $BF(B^0 \rightarrow X_c l\nu) = 10.25 \pm 0.15\%$
- Recent measurements of $D^* l\nu$ are lower than previous; HFAG 2016 input
  $BF(B^0 \rightarrow D^{*+} l\nu) = 4.88 \pm 0.10\%$
  $BF(B^0 \rightarrow D^+ l\nu) = 2.13 \pm 0.07\%$
- $D^{(*)}\pi^+ l\nu$ measured for B^+ and B^0 (HFAG); estimate π^0 modes from isospin
  $BF(B^0 \rightarrow D^*\pi l\nu) = 0.47 \pm 0.05\% + ½\times(\tau_0/\tau_+) \times (0.60 \pm 0.06\%) = 0.75 \pm 0.06\%$
  $BF(B^0 \rightarrow D\pi l\nu) = 0.42 \pm 0.06\% + ½\times(\tau_0/\tau_+) \times (0.41 \pm 0.05\%) = 0.61 \pm 0.06\%$
- $D_s K l\nu + D_s^* K l\nu$ measured (PDG):
  $BF(B^0 \rightarrow D_s^{(*)} K l\nu) = (0.06 \pm 0.01\%) \times (\tau_0/\tau_+)$

  B^+ decays
- So far: $\Sigma = 8.43 \pm 0.15\%$
- $D^{(*)}\pi^+\pi^- l\nu$ measured for B^+ and B^0; $\pi^+\pi^0$, $\pi^0\pi^0$ *unknown*; take $\pi^+\pi^-/\pi\pi \cong 0.50 \pm 0.17$
  $BF(B^0 \rightarrow D^*\pi^+\pi^- l\nu) = 0.09 \pm 0.03\%$; $BF(B^0 \rightarrow D\pi^+\pi^- l\nu) = 0.14 \pm 0.03\%$
  $BF(B^0 \rightarrow D^{(*)}(\pi\pi)_{all} l\nu) = 0.47 +0.26 -0.15\%$
- All measurements (as B^0): $\Sigma_{all} = 8.90 \pm 0.30\%$ so gap is $1.36 \pm 0.34\%$

$B \rightarrow X_c l\nu$ decays – current status

- Inclusive BF from global fit to moments (
  $BF(B^0 \rightarrow X_c l\nu) = 10.25 \pm 0.15\%$
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  $BF(B^0 \rightarrow D^{*+} l\nu) = 4.88 \pm 0.10\%$
  $BF(B^0 \rightarrow D^+ l\nu) \;\; = 2.13 \pm 0.07\%$
- $D^{(*)}\pi^+ l\nu$ m … FAG);
  $BF(B^0 \rightarrow D^*$ … $\times(\tau_0/\tau_+$
  $BF(B^0 \rightarrow D\pi l\nu)$ $= 0.42 \pm 0.06\% + ½\times(\tau_0/\tau_+$
- $D_s K l\nu + D_s^* K l\nu$ measured (PDG):
  $BF(B^0 \rightarrow D_s^{(*)} K l\nu)$ $= (0.06 \pm 0.01\%) \times(\tau_0/\tau_+$
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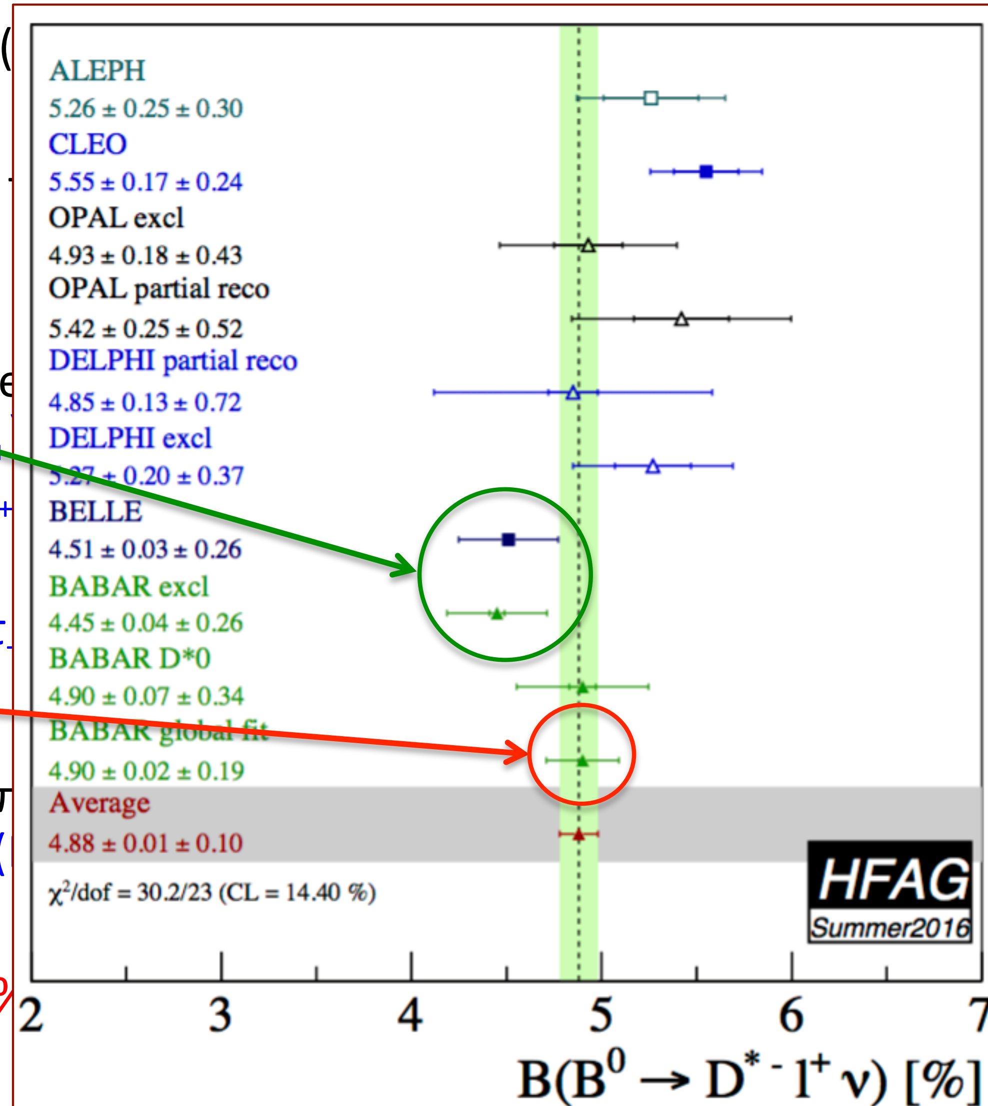
- All measurements: $\Sigma_{all} = 8.90 \pm 0.30\%$

Directly measured
$B^0 \rightarrow D^{*+} l\nu$

Mostly sensitive to $B^+ \rightarrow D^{*0} l\nu$
(but quoted as B^0)



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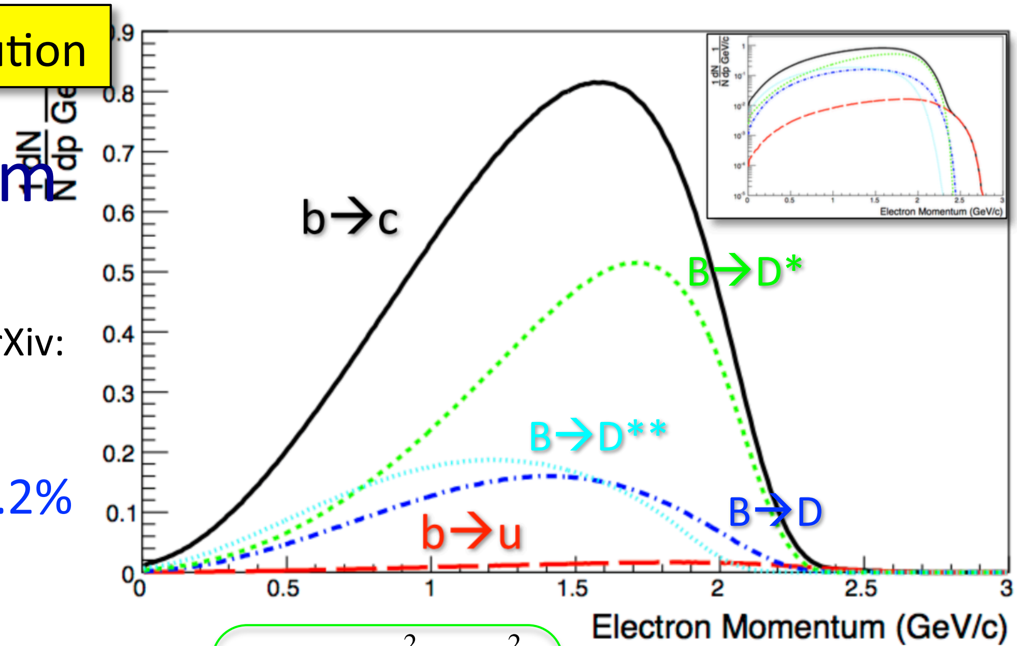
second word of caution

Filling up the electron spectrum

BABAR

- Fit to inclusive electron spectrum (BaBar arXiv: 1611:05624, accepted by PRD) needs more D^*
- These fits suggest $BF(B^0 \rightarrow D^{*+} l\nu) \sim 5.6 \pm 0.2\%$
- If this were the case, the gap would be 0.61 ± 0.35
- Due to kinematics, it's hard to mimic $D^{*+} l\nu$ with higher-mass X_c – so what's going on?

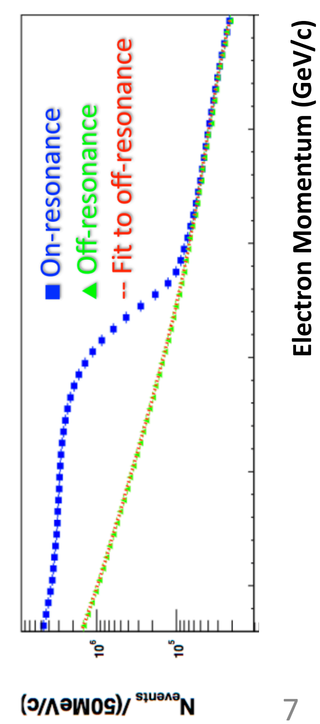


$$E_e^{max} = \frac{m_B^2 - m_X^2}{2m_B}$$
$$dE_e^{max} \approx -0.4\, dm_X$$

BABAR	DN	BLNP	GGOU	DGE
$De\nu$	2.311 ± 0.095	2.286 ± 0.095	2.306 ± 0.095	2.308 ± 0.096
$D^*e\nu$	5.838 ± 0.059	5.630 ± 0.061	5.802 ± 0.059	5.836 ± 0.059
$D^{(*)}\pi e\nu$	< 0.099	< 0.034	< 0.087	< 0.078
$D^{**}e\nu$	2.348 ± 0.096	2.621 ± 0.102	2.398 ± 0.099	2.351 ± 0.096
$D'^{(*)}e\nu$	0.054 ± 0.015	0.028 ± 0.015	0.049 ± 0.015	0.053 ± 0.014
$X_u e\nu$	0.154	0	0.171 ± 0.007	0.158 ± 0.006
$D \rightarrow e$	0.981	7	0.979 ± 0.007	0.981 ± 0.007
$r_L/r_L^{(0)}$	1.0002	007	1.0002 ± 0.0007	1.0002 ± 0.0007
$Xe\nu$	10.70 ± 0.05	10.81 ± 0.05	10.73 ± 0.05	10.71 ± 0.05
$\chi^2/ndof$	93		94.0/85	92.7/85

Average $B^+/B^0 \rightarrow X_c l\nu$ contributions in fit

Average $B^+/B^0 \rightarrow X_c l\nu$ BF



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

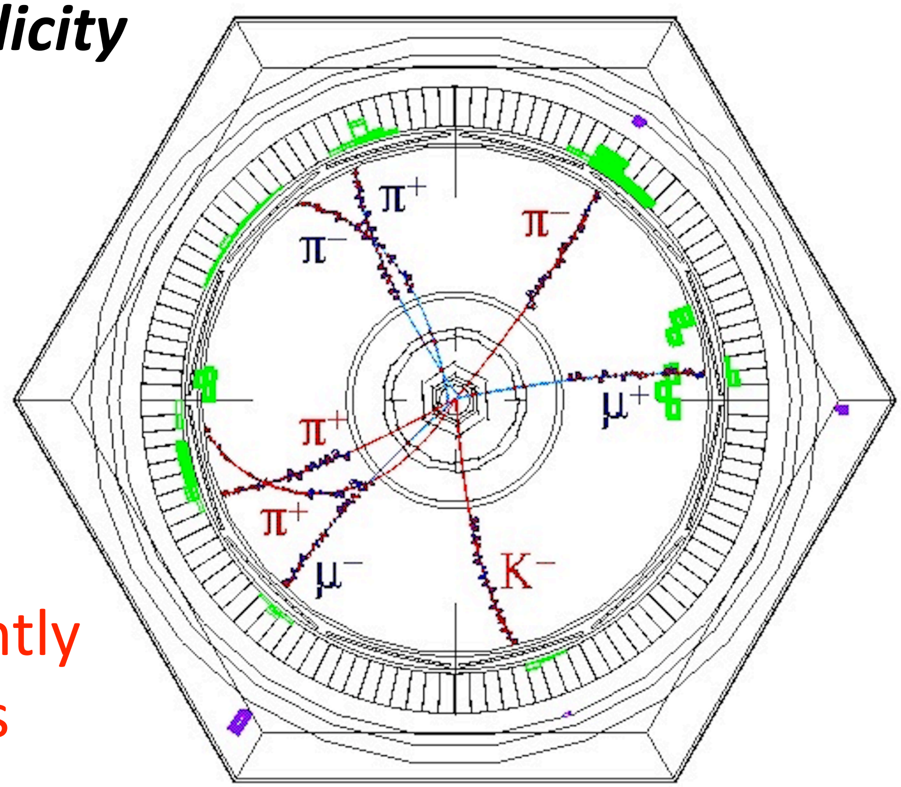
- Search for signal B decays $B \to D^{(*)}\pi^+\pi^- l^- \nu$; $l^- = e^-$ or μ^-
- Reconstruct both signal B and tag B in each event
- Tag B reconstruction based on charm meson seed plus additional hadrons; 2968 different decay channels
- $\varepsilon \times BF$ for tag B is not precisely known, so normalize using ratio

$$R^{(*)}_{\pi^+\pi^-} \equiv \frac{BF\left(B \to D^{(*)}\pi^+\pi^-\ell^-\nu\right)}{BF\left(B \to D^{(*)}\ell^-\nu\right)}$$

- Calculate missing 4-momentum $p_{miss} = p(e^+e^-) - p(B_{tag}) - p(B_{sig})$
- Use $U = E_{miss} - |\mathbf{p}_{miss}|$ to discriminate signal from backgrounds
- Keep signal decays blinded

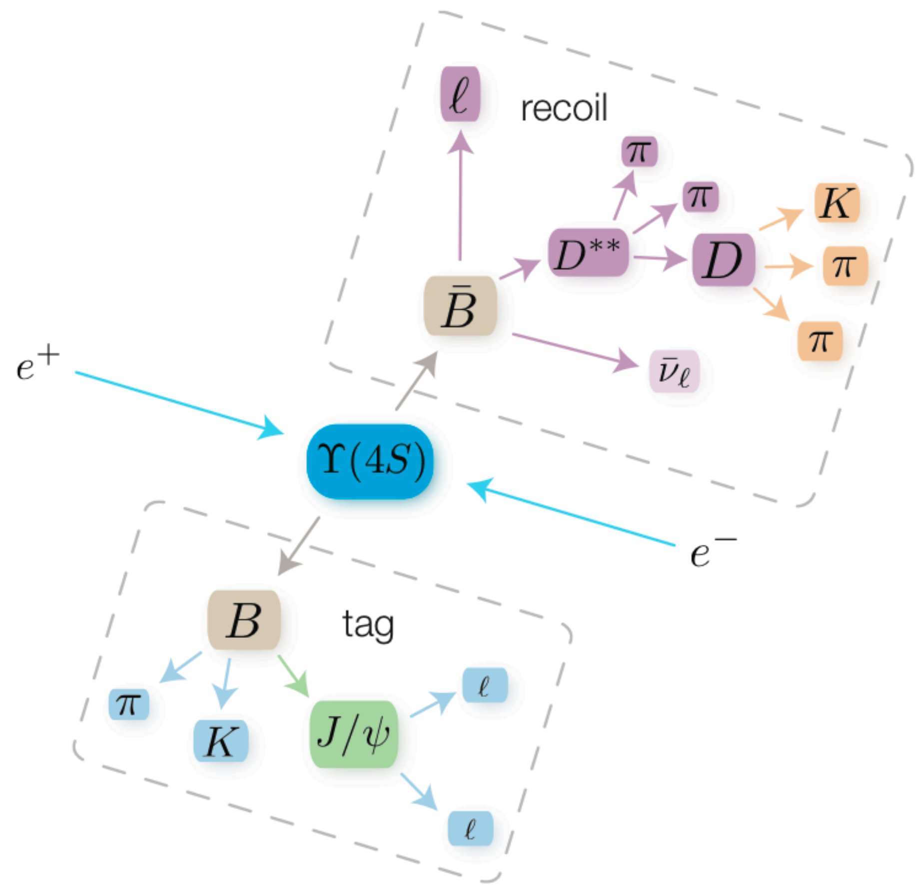
B-tagged analyses

- B mesons produced nearly at rest; decay products overlap
- Hadronic B tagging allows assignment of particles to signal B and determines the B momentum vector
- Works beautifully for ***low-multiplicity*** signal modes like $B \rightarrow \pi l^- \nu$
- ***High-multiplicity*** signals (like $B \rightarrow D^{(*)}\pi^+\pi^- l^- \nu$ with subsequent $D^{(*)}$ decay) are much more challenging due to assignment ambiguities; leads to cross-feed components that behave differently from signal or other backgrounds



Selection criteria

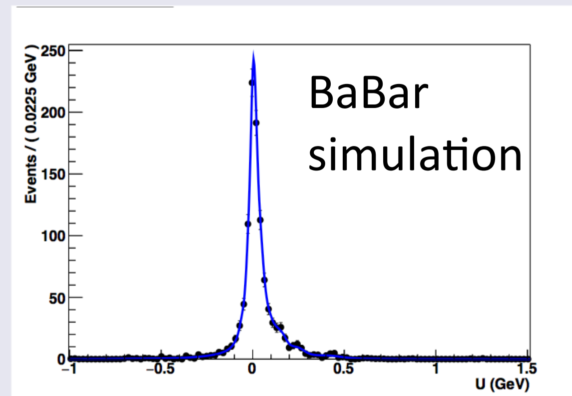
- Require identified e or μ with $p_{cms} > 0.6$ GeV
- Reconstruct D or D^* (charged or neutral), π^+ and π^-
- High multiplicity → multiple $B_{tag}B_{sig}$ combinations: select B_{tag} candidate with energy closest to $\sqrt{s}/2$
- Veto $D^{*+}\pi^- l^- \nu$ reconstructed as $D^0\pi^+\pi^- l^- \nu$
- Construct Fisher discriminant in each signal channel to reduce non-semileptonic backgrounds



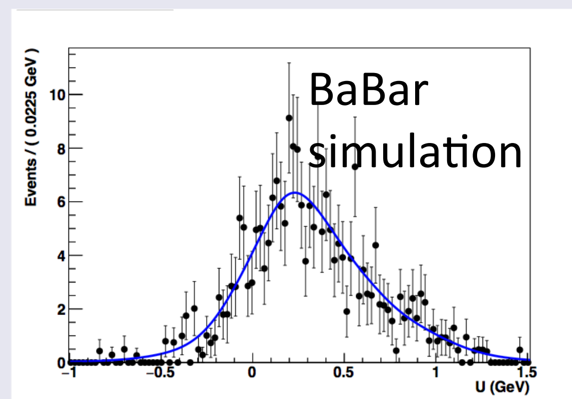
Fit procedure, PDFs

- Unbinned max-likelihood fit to $U = E_{miss} - |\mathbf{p}_{miss}|$ distribution; only free parameters are yields
- PDFs from MC histograms using parametric kernel estimation
- Fit components for $B \rightarrow D^{(*)}\pi^+\pi^- l^- \nu$:
  1. true $B \rightarrow D \pi^+\pi^- l^- \nu$;
  2. true $B \rightarrow D^* \pi^+\pi^- l^- \nu$;
  3. true $B \rightarrow D^{(*)}\pi l^- \nu$;
  4. true $B \rightarrow D^{(*)} l^- \nu$;
  5. other BBbar
  6. continuum qqbar

example signal PDF: true $B \to D^0\pi\pi\ell\nu$ reconstructed as $B \to D^0\pi\pi\ell\nu$



example signal PDF: true $e^+e^- \to q\bar{q}$ reconstructed as $B \to D^0\pi\pi\ell\nu$



Normalization mode yields

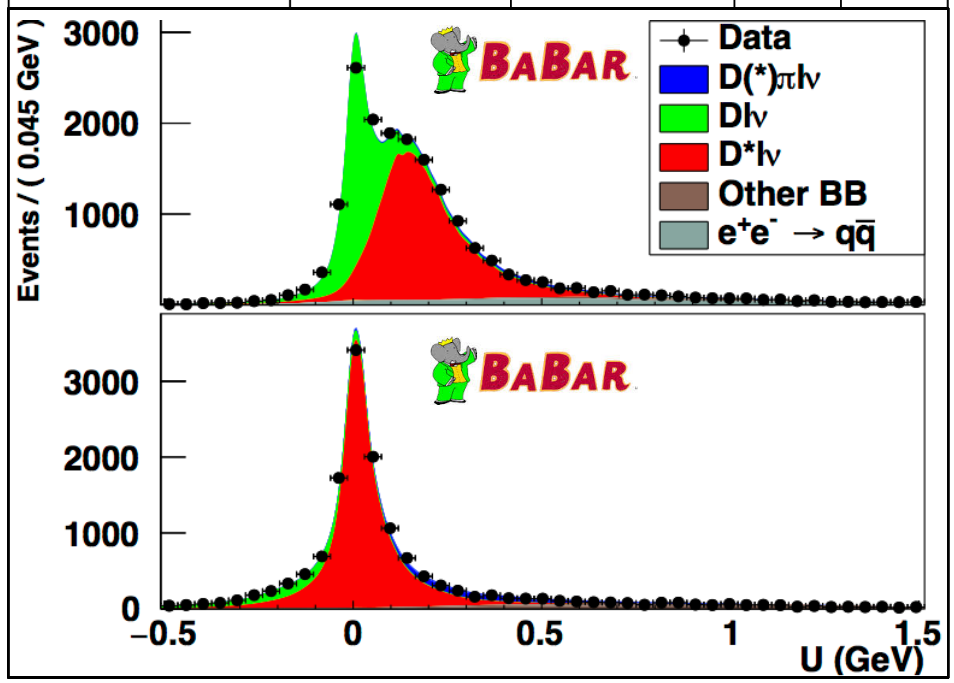
- Large yields in all $B \rightarrow D^{(*)} l^- \nu$ channels

- Large feed-down from D^* to D; separate using $U = E_{miss} - |\mathbf{p}_{miss}|$

- Backgrounds from other sources are small

BaBar PRL 116, 041801 (2016)

Channel	Yield	$\epsilon \times 10^4$	$\mathcal{S}$	$\mathcal{S}_{tot}$
$D^0\ell^-\overline{\nu}_\ell$	5567 ± 102	2.73 ± 0.01	> 40	> 40
$D^+\ell^-\overline{\nu}_\ell$	3236 ± 74	1.69 ± 0.01	> 40	> 40
$D^{*0}\ell^-\overline{\nu}_\ell$	9987 ± 126	2.03 ± 0.01	> 40	> 40
$D^{*+}\ell^-\overline{\nu}_\ell$	5404 ± 83	1.14 ± 0.01	> 40	> 40



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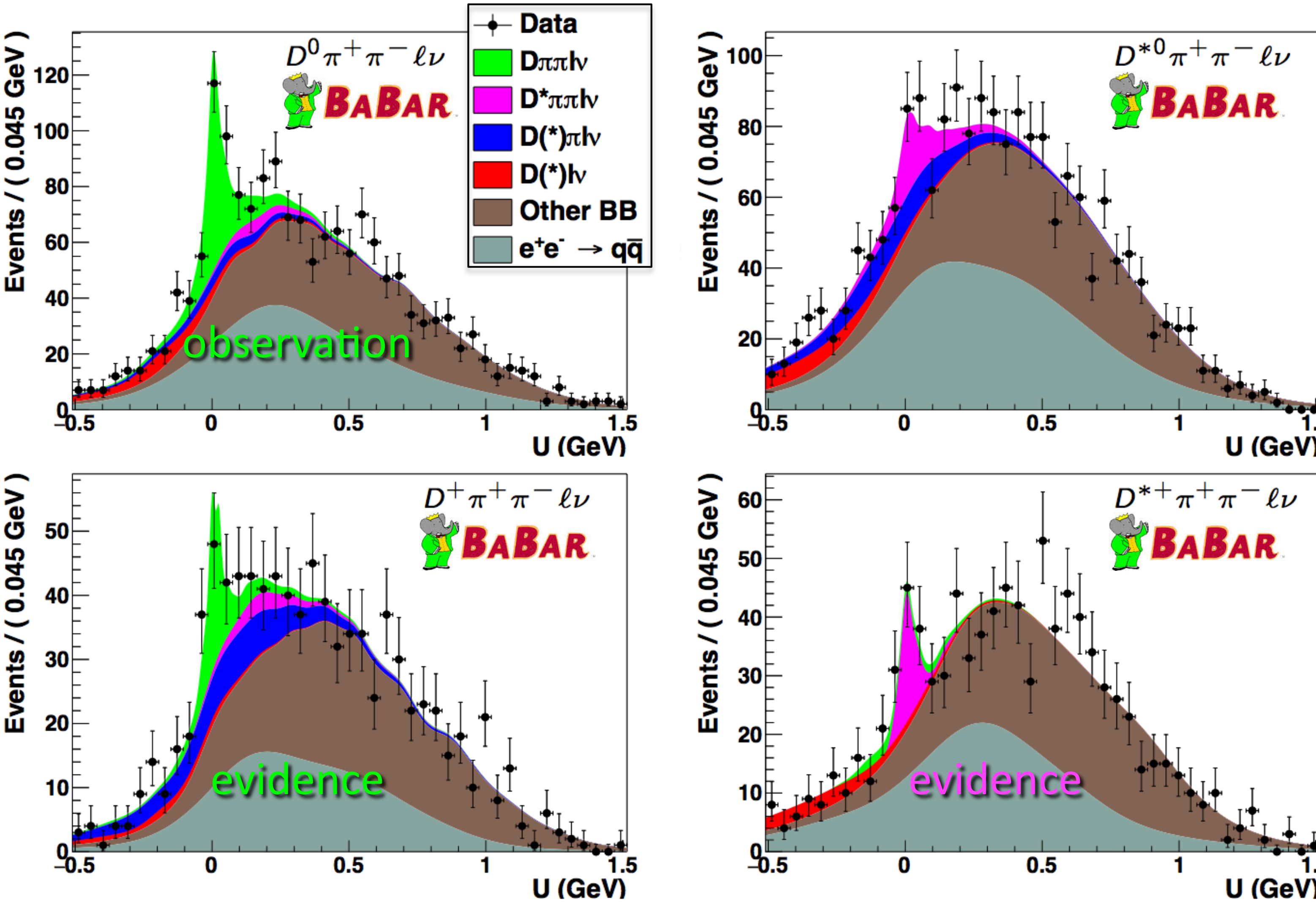
$B \to D^{(*)}\pi^+\pi^- l^- \nu$ yields

BaBar PRL 116, 041801 (2016)

Channel	Yield	$\epsilon \times 10^4$	$\mathcal{S}$	$\mathcal{S}_{tot}$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	171 ± 30	1.18 ± 0.03	5.4	5.0
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	56 ± 17	0.51 ± 0.02	3.5	3.0
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	74 ± 36	1.11 ± 0.02	1.8	1.6
$D^{*+}\pi^+\pi^-\ell^-\overline{\nu}$	65 ± 18	0.49 ± 0.02	3.3	3.0



$\mathcal{S}$ = statistical significance

$\mathcal{S}_{tot}$ = significance with systematics

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

BaBar PRL 116, 041801 (2016)

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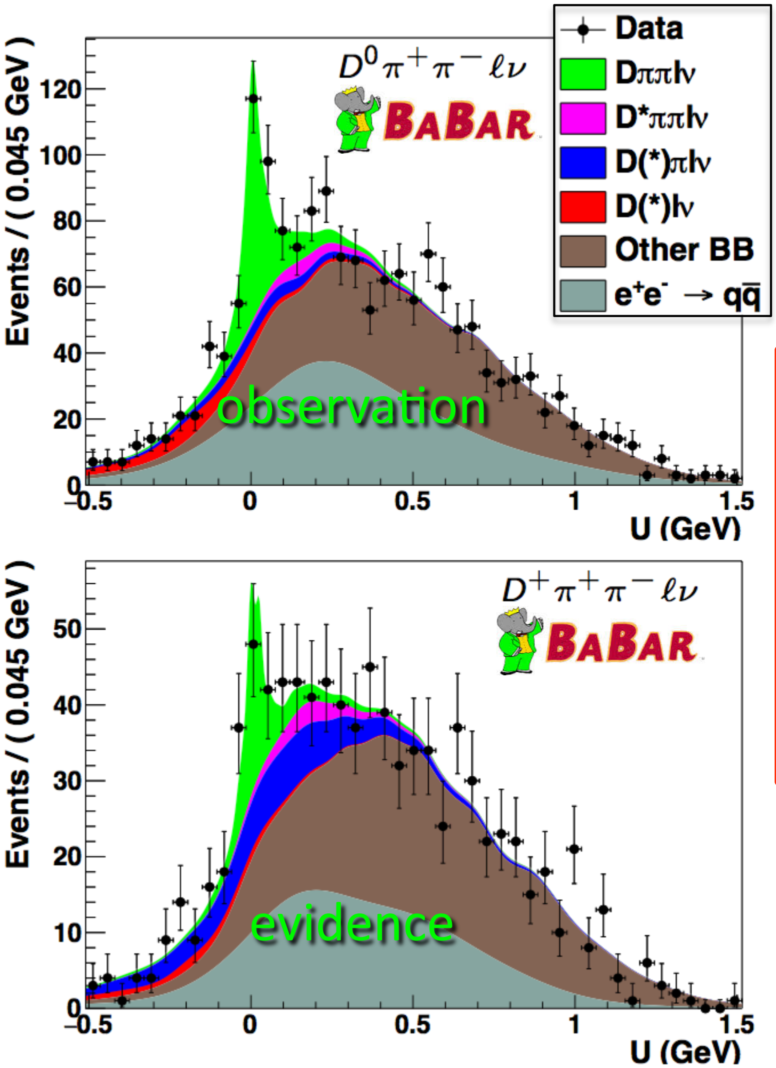

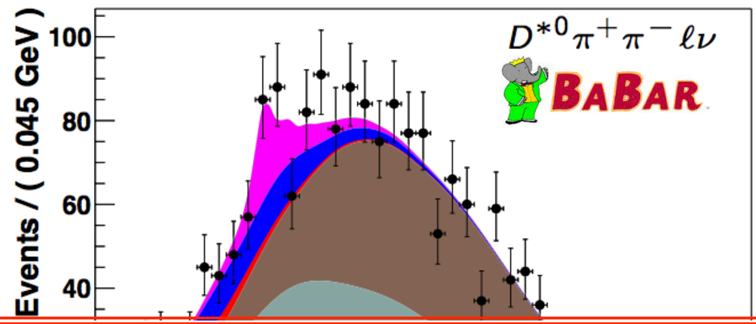

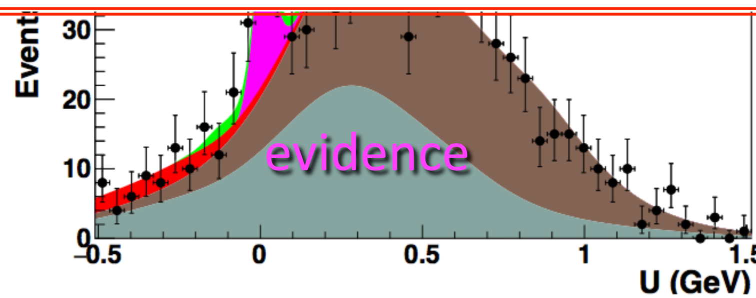

$\mathcal{S}$ = statistical significance

$\mathcal{S}_{tot}$ = significance with systematics

The only known source of B → $D\pi^+\pi^- l^- \nu$ decays is B → $D_1(2420)\, l^- \nu$ with $D_1(2420) \to D\pi^+\pi^-$.

If these decays are vetoed the yields become

84.3 ± 27.7 for $B^- \to D^0\pi^+\pi^- l^- \nu$

37.3 ± 15.9 for $B^0 \to D^+\pi^+\pi^- l^- \nu$

Results for $R^{(*)}_{\pi^+\pi^-}$

BABAR

- Ratios measured for both B^+ and B^0
- BF determined using PDG values for normalization modes
- Semileptonic widths for B^+, B^0 are equal: Isospin average shown

Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	B^+ BF $\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\overline{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\overline{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\overline{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

BaBar PRL 116, 041801 (2016)

- Many systematic uncertainties cancel in ratio; leading sources:
  - PDF shapes: 7—21%
  - signal decay modeling: 8—19%
  - modeling of Fisher discriminant: 4—5%

$$R^{(*)}_{\pi^+\pi^-} \equiv \frac{BF\left(B \to D^{(*)}\pi^+\pi^-\ell^-\nu\right)}{BF\left(B \to D^{(*)}\ell^-\nu\right)}$$

Extrapolation to all $B \rightarrow D^{(*)}\pi\pi\, l^- \nu$ decays

- Mechanism for $B \rightarrow D^{(*)}\pi^+\pi^-\, l^- \nu$ unknown; consider decays $B \rightarrow X_c\, l^- \nu$ via
  1. 3-body phase space $X_c \rightarrow D^{(*)}\pi\pi$
  2. $X_c \rightarrow D^{(*)}f_0(500)$, $f_0(500) \rightarrow \pi\pi$
  3. $X_c \rightarrow D^{(*)}\rho$, $\rho \rightarrow \pi\pi$
  4. $X_c \rightarrow Y_c\pi$, $Y_c \rightarrow D^{(*)}\pi$

Any combination of $\pi^{\pm}, \pi^0$

- Use isospin factors to estimate *BF*$(B \rightarrow D^{(*)}\pi\pi\, l^- \nu)$ from the measured *BF*$(B \rightarrow D^{(*)}\pi^+\pi^-\, l^- \nu)$
- The $\pi^+\pi^-/\pi\pi$ ratio in this choice of models is covered by the factor $\pi^+\pi^-/\pi\pi = 0.50 \pm 0.17$ (33% relative uncertainty)
- This provides motivation for measuring modes with π^0

Comments on other decay modes

- We talk about "states" but we measure topologies
- Given the limited success we've had measuring broad P-wave D states (and decay BFs) I'm not optimistic about measuring the resonance content of the X_c spectrum with precision
- Experimentally we should be able to measure the BF and $m(X_c)$ distribution for
  - $B \rightarrow D^{(*)}\pi l\nu$, $B \rightarrow D^{(*)}\eta l\nu$…
  - $B \rightarrow D^{(*)}\pi^+\pi^- l\nu$, $B \rightarrow D^{(*)}\pi^+\pi^0 l\nu$, $B \rightarrow D^{(*)}(\pi^+\pi^-\pi^+) l\nu$…
  - $B \rightarrow D_s^{(*)}K l\nu$, $B \rightarrow D_s^{(*)}K\pi l\nu$, …
- Only the decays in color have been measured

Comments on other decay modes (2)

- With higher statistics, B-tagged measurements of $D^{(*)}$+0π and $D^{(*)}$+1π modes will be clean, uncertainties will shrink. Maybe we'll even figure out what the correct $B \to D^{*} l^{+} \nu$ BF is….
- Even with Belle II and LHCb upgrades, $D^{(*)}$+2π modes are challenging, especially those with one or more π^0s. Early studies of $D^{(*)}\pi^+\pi^0$ suggest that signal/noise is at least 3 times worse (lower efficiency, lower resolution, more background)
- Belle II will be able to do $D^{(*)}\eta$ ($\eta \to \gamma\gamma$) and maybe ($\eta \to 3\pi$)
- Can LHCb help with $D^{(*)}\pi^+\pi^-$ and $D^{(*)}\pi^-\pi^+\pi^-$ modes?

Conclusions

- $B \rightarrow X_c l\nu$ decays are background for $B \rightarrow D^{(*)}\tau\nu$ measurements
- Composition of $B \rightarrow X_c l\nu$ decays not known precisely; even the largest B decay BF ($D^{(*)}l\nu$) may not be well understood
- First measurement of B decays to $D^{(*)}\pi^+\pi^- l^- \nu$ BaBar
  - Observation of the decay $B^- \rightarrow D^0\pi^+\pi^- l^- \nu$
  - Evidence for $B^0 \rightarrow D^+\pi^+\pi^- l^- \nu$ and $B^0 \rightarrow D^{*+}\pi^+\pi^- l^- \nu$
- $D^{(*)}\pi\pi l^- \nu$ accounts for ~5% of all $B \rightarrow X_c l^- \nu$
- Future measurements are needed to fill in the picture
  - modes $B \rightarrow D^{(*)}\pi^-\pi^0 l^- \nu$ and $B \rightarrow D^{(*)}\pi^0\pi^0 l^- \nu$
  - $B \rightarrow D^{(*)}\eta l\nu$; $B \rightarrow D^{(*)}\pi^-\pi^+\pi^- l\nu$, …

Backup

$D^{(*)}\pi^{+}\pi^{-}l^{-}\nu$ systematic uncertainties (%)

BaBar PRL 116, 041801 (2016)

	D^0	D^+	D^{*0}	D^{*+}
PDF	6.5	10.7	21.1	10.9
PID	0.7	1.5	1.1	1.3
MisID	0.6	1.1	1.0	0.8
Trk eff	0.5	0.2	1.6	4.6
Photon eff	0.4	1.0	0	1.0
D, D* BFs	0.6	0.6	0.7	0.7
Fisher	3.7	5.2	3.8	4.7
Slow π0 eff	0	0.2	1.8	1.3
Signal FF	3.0	3.2	4.4	4.4
Peaking bkg	0.9	13.8	6.3	4.4
Xc decay	6.6	10.5	13.3	13.3
neut frac	0.6	0.4	1.6	1.2
Signal B decay	4.2	0	13.8	1.9
Total	**11.4**	**21.4**	**30.0**	**19.7**

Correlation coefficients for BaBar fit to inclusive electron spectrum

BaBar arXiv:1611:05624, accepted by PRD

	$De\nu$	$D^*e\nu$	$D^{(*)}\pi e\nu$	$D^{**}e\nu$	$D'^{(*)}e\nu$	$X_ue\nu$	$D\to e$	a_0	a_1	a_2	a_3	a_4	a_5	$r_L/r_L^{(0)}$
$De\nu$	1	-0.827	0.032	-0.398	-0.449	-0.305	-0.060	0.018	-0.048	0.058	-0.036	0.023	-0.032	0.001
$D^*e\nu$		1	-0.024	-0.158	0.784	-0.128	0.309	0.050	0.029	-0.146	0.126	0.038	0.125	0.008
$D^{(*)}\pi e\nu$			1	-0.031	0.004	0.027	0.012	-0.066	0.033	0.033	-0.048	-0.044	-0.052	-0.028
$D^{**}e\nu$				1	-0.601	0.598	-0.361	-0.062	0.030	0.055	-0.063	-0.055	-0.066	-0.012
$D'^{(*)}e\nu$					1	-0.236	0.206	0.069	-0.051	-0.034	0.053	0.070	0.063	0.001
$X_ue\nu$						1	-0.252	-0.461	0.310	0.252	-0.369	-0.425	-0.363	-0.107
$D\to e$							1	-0.108	0.204	-0.189	0.104	-0.102	0.037	-0.116
a_0								1	-0.827	-0.196	0.670	0.980	0.671	0.139
a_1									1	-0.315	-0.190	-0.870	-0.209	-0.103
a_2										1	-0.801	-0.122	-0.818	0.012
a_3											1	0.610	0.947	0.035
a_4												1	0.627	0.027
a_5													1	-0.006
$r_L/r_L^{(0)}$														1