Evidence for an excess of $B \rightarrow D^{(*)}\tau\nu$ decays

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representing the BaBar Collaboration

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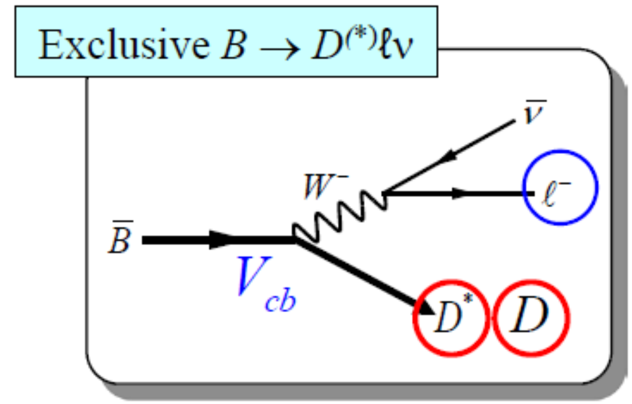
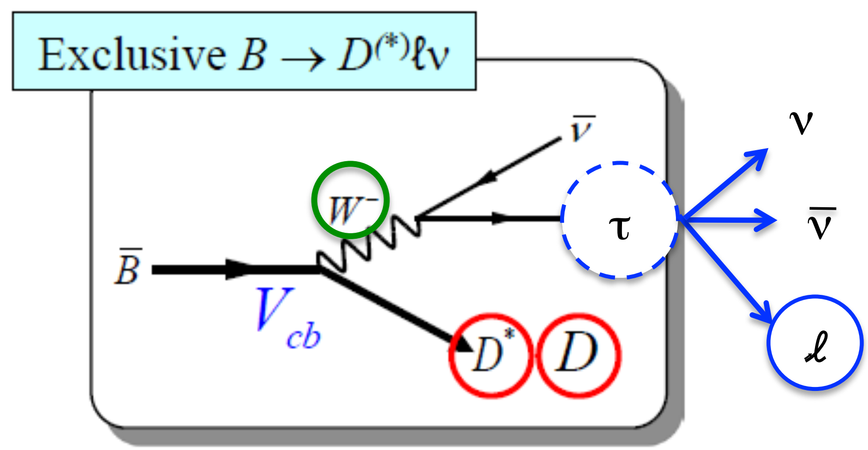
BABAR seen recently in Kruger Park

Goal: new physics in charged-current decays to 3rd generation

- Tree-level decays $B \rightarrow D^{(*)} l \nu$ are ~free from NP effects
  - Clean experimental signature ($D^{(*)}$ plus e or μ)
  - One missing neutrino
  - Large BF (~2% / ~5% for D / D^*)



- Compare with $B \rightarrow D^{(*)} \tau \nu$
  - SM rate well predicted
  - Charged Higgs contributes at tree level
  - Can give *O(1)* change in rate



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Contrast $B \rightarrow \tau\nu$ and $B \rightarrow D^{(*)}\tau\nu$

	$B \rightarrow \tau\nu$	$B \rightarrow D^{(*)}\tau\nu$
CKM angle	$\lvert V_{ub} \rvert$	$\lvert V_{cb} \rvert$
SM BF	~1*10^{-4} × BF($\tau \rightarrow$e, μ, π, ρ)	~2% × BF($\tau \rightarrow$e or μ)
σ_{theory} on BF prediction	~25%	~5%
decay distributions	none (2-body)	sensitive to vector vs. scalar currents

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$B \rightarrow D^{(*)}\tau\nu$ decay rate

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |p^*_{D(*)}| q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_S|^2\right]$$

- $D^{(*)}$ momentum in CM frame
- momentum transfer to $\tau\nu$
- Helicity amplitudes common to *e, μ, τ*. Only H_0 affects $D(\ell/\tau)\nu$
- Helicity amplitude only relevant for τ

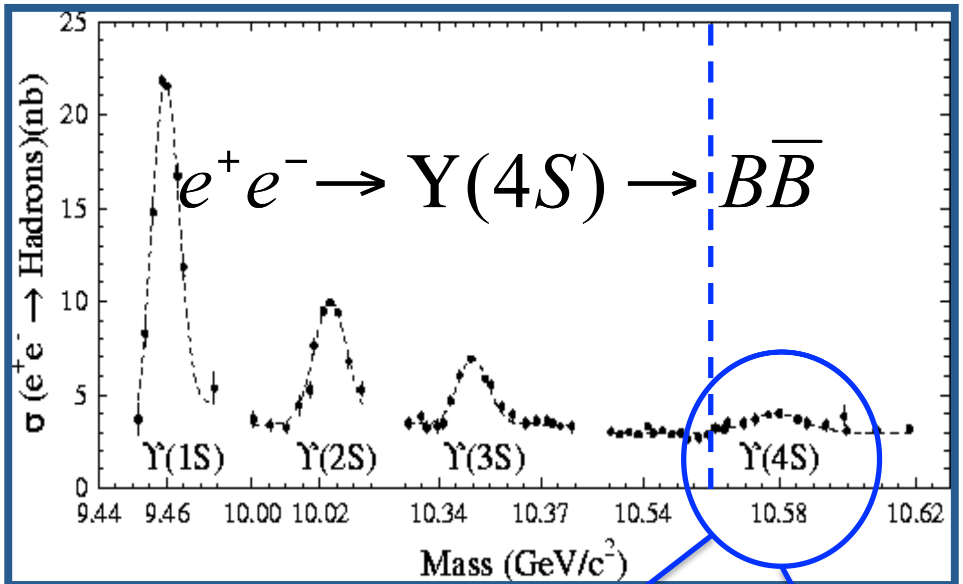
- Many common factors in decay rates to *e, μ, τ*
- Hadronic FFs parametrized using HQET; $H_{\pm,0}$ measured for *e, μ*
- Common experimental factors (efficiency, acceptance…)

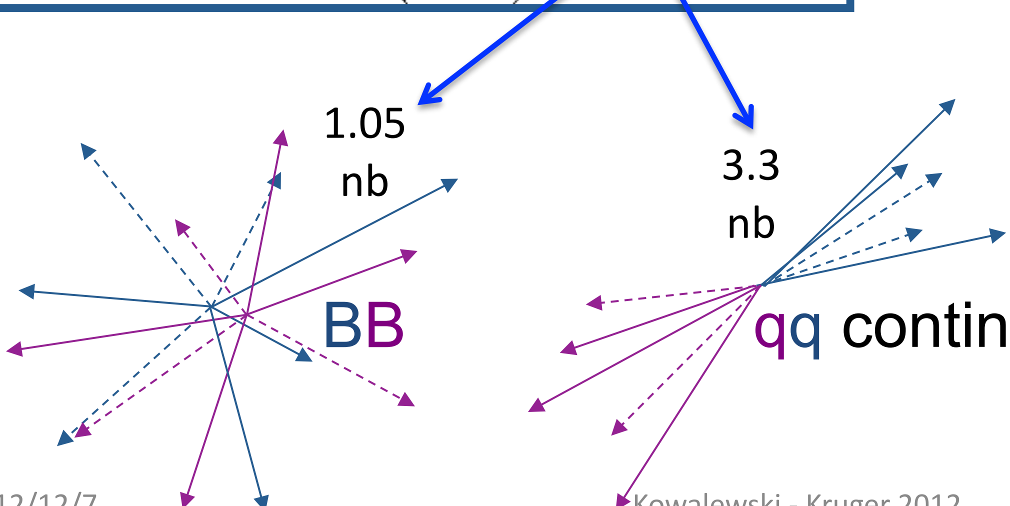
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)} = \frac{\text{signal}}{\text{normalization}}$$

$$\mathcal{R}_{SM}(D) = 0.297 \pm 0.017$$
$$\mathcal{R}_{SM}(D^*) = 0.252 \pm 0.003$$

Predictions

Experimental environment at Y(4S)



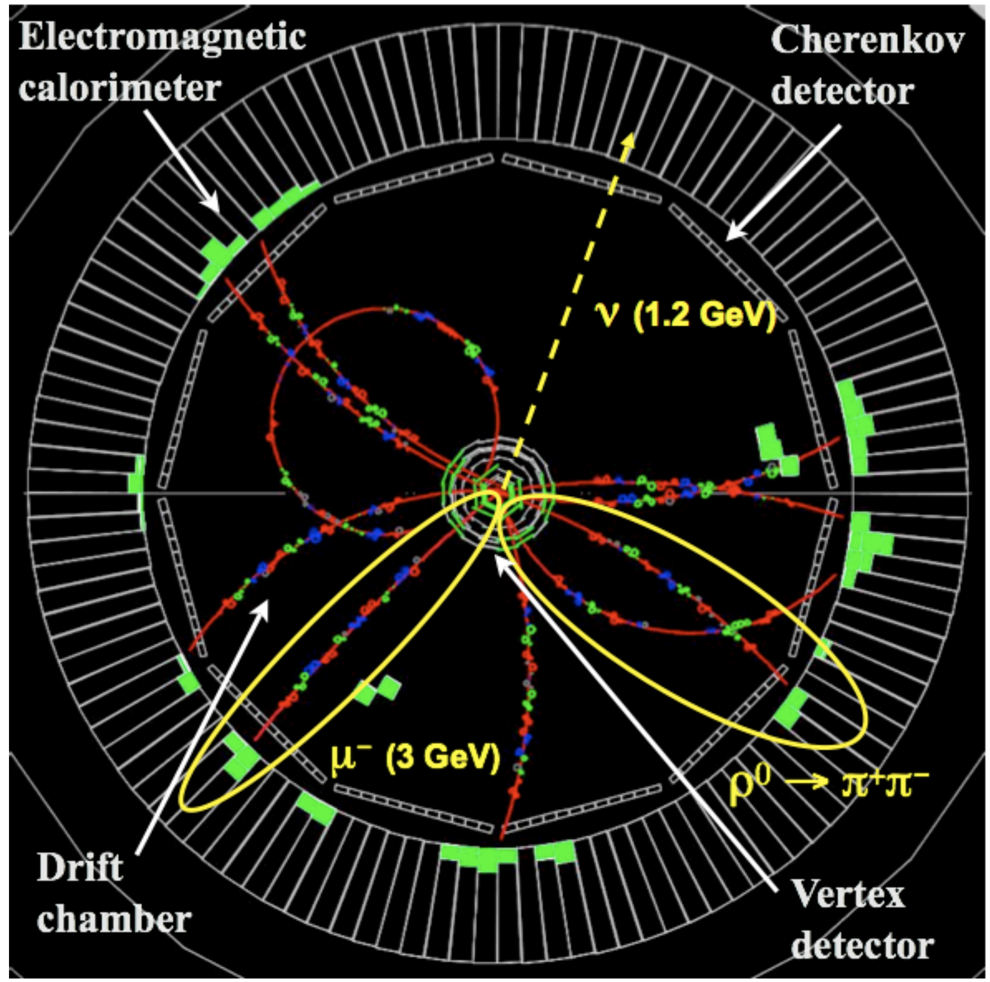


- BBbar form ~1/4 of hadronic cross-section
- Decay products of B and Bbar overlap completely
- E_B determined by beam energy in CM frame – single missing neutrino gives sharp peak in $M^2_{miss} = (\Sigma E_i)^2 - (\Sigma p_i)^2$

471M BBbar events
40 fb^{-1} continuum

Y(4S) decay

- BaBar has inner silicon tracker, drift chamber, DIRC, EMC, coil and muon detectors (not shown)
- Charged multiplicity ~11 on average, neutral multiplicity similar
- Can impose momentum balance in 3 dimensions



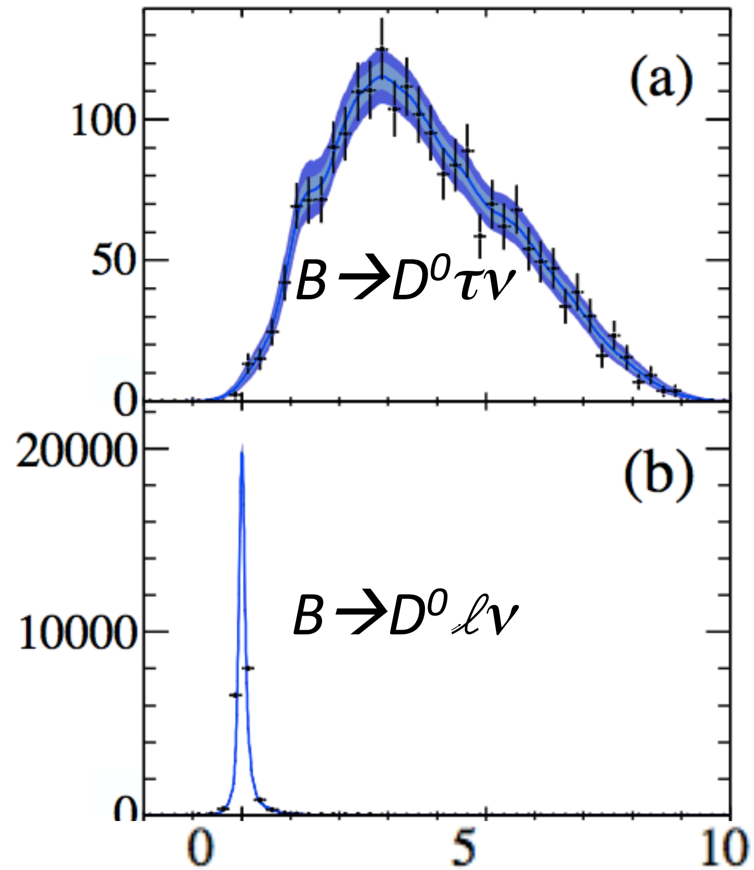
Strategy – tag one B, use M^2_{miss}

- Presence of 3 neutrinos in signal → fully reconstruct one B and demand second B leave $D^{(*)}$, e or μ and missing mass

$$M^2_{miss} = \left(p_{e+e-} - p_{Btag} - p_{D(*)} - p_{\ell}\right)^2$$

- Copious $B \to D^{(*)} \ell \nu$ normalization modes have single missing neutrino:
  → they peak sharply in M^2_{miss}

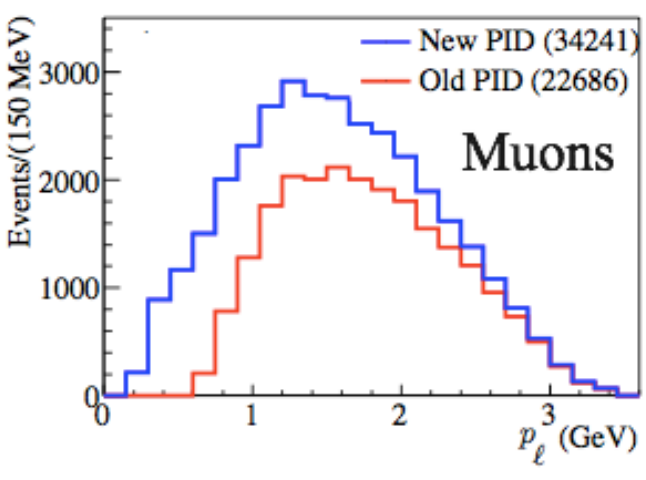
From simulation



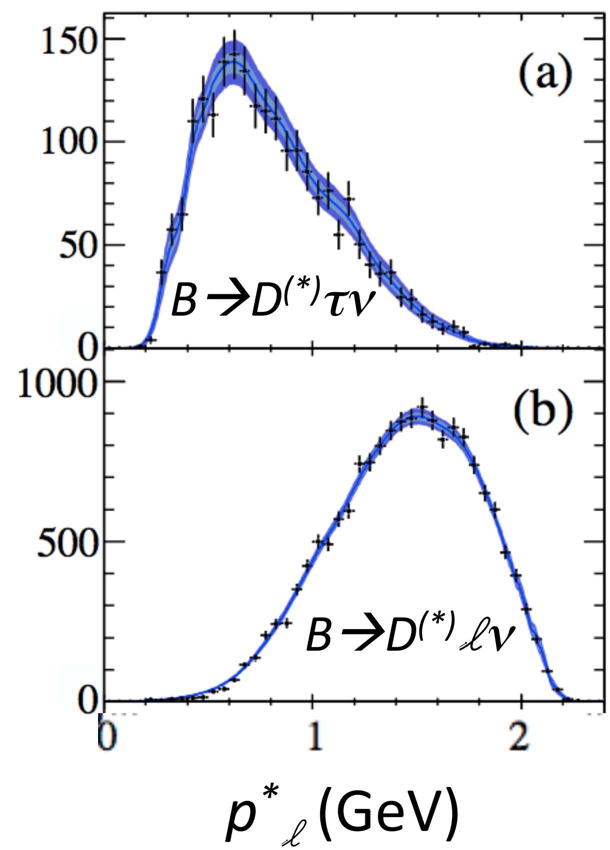
Strategy – exploit lepton momentum

- Lepton momentum spectra in CM differ for signal and normalization decays: *e* and μ from τ are substantially softer

- Lepton ID improved at low momentum (new algorithm, looser criteria)

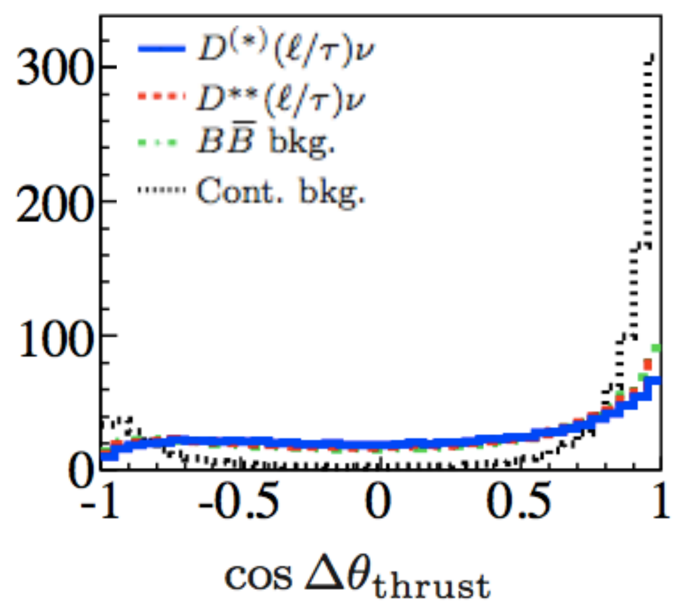


From simulation



Event selection summary

- Require one hadronic B decay, an *e* or μ and a *D* or D^*
- Add further requirements on event topology:
  - hadronic B and semileptonic B charge correlation (+/- or 0/0)
  - no unassigned charged tracks
  - little unassigned EM energy (E_{extra})
- Form a Boosted Decision Tree based on
  - angle between the thrust axes of the B tag and signal B candidates ($\Delta\theta_{thrust}$)
  - reconstructed masses of all *D* candidates
  - $\Delta m = m_{D^*} - m_D$ for all D^* candidates
  - $\Delta E = E_{beam} - E_B$ for tag B
  - charged multiplicity of tag B



Hadronic B tagging

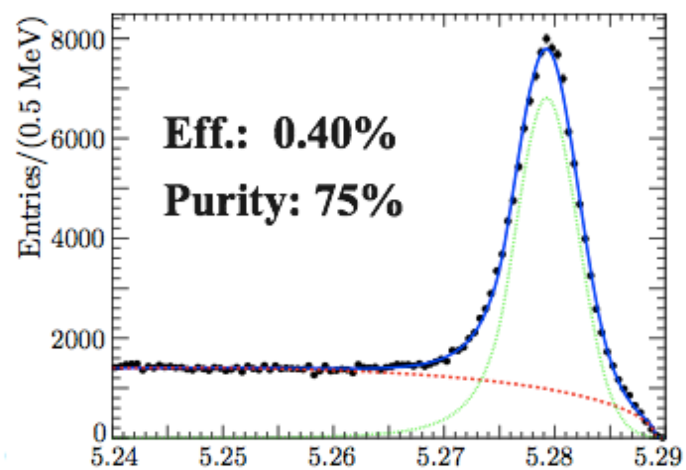
- Hadronic *B* decays have typical product BFs of ~10^{-3} or less, e.g. BF($B \to D\pi$)*BF($D \to K\pi$) = $2*10^{-4}$
  → Need to sum large number of modes

- Reconstruct seed meson ($D^{(*)}$, $D_s^{(*)}$ or J/ψ); add up to 5 particles (of which up to 2 neutrals) → ~3000 distinct modes

- Require $|E_B - E_{beam}| < 4\sigma_E$
- Multiple candidates per event – select tag + signal combination with smallest E_{extra}

- New tagging gives efficiency 2x higher than previous method

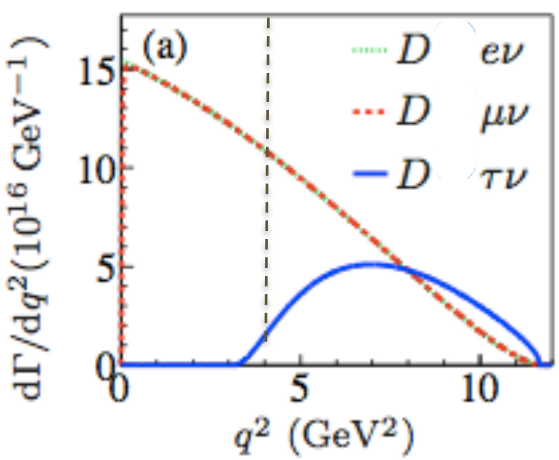
From simulation

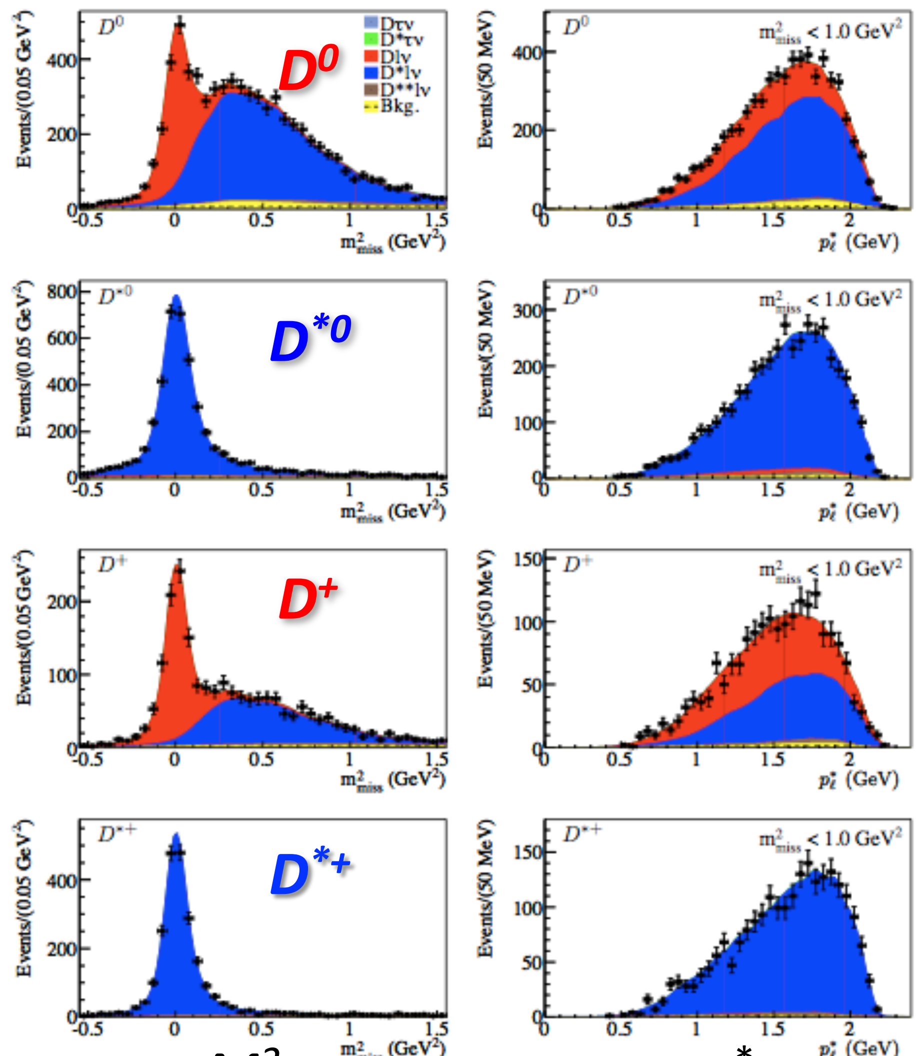


$$m_{ES} = \sqrt{E_{beam}^2 - p_{tag}^2}$$

Normalization decays $B \rightarrow D^{(*)} \ell \nu$

- Soft pion from $D^* \rightarrow D\pi$ often missed: ***feed-down***
- Decays with $q^2 < 4\ GeV^2$ provide control sample

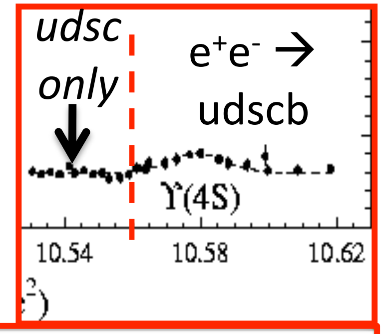


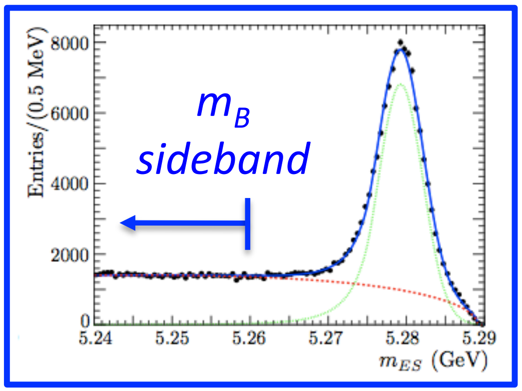


M^2_{miss} p^*_ℓ

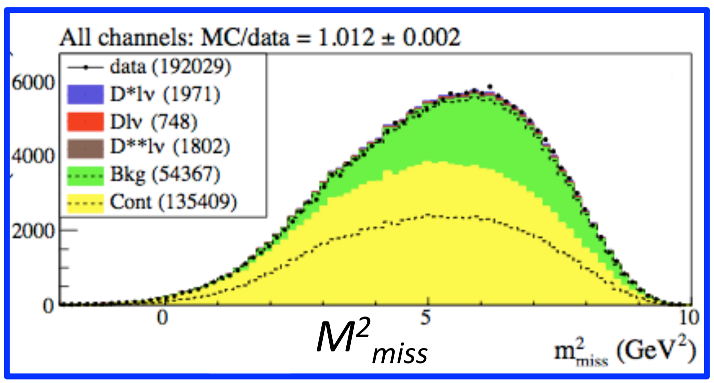
Fixed backgrounds, control samples

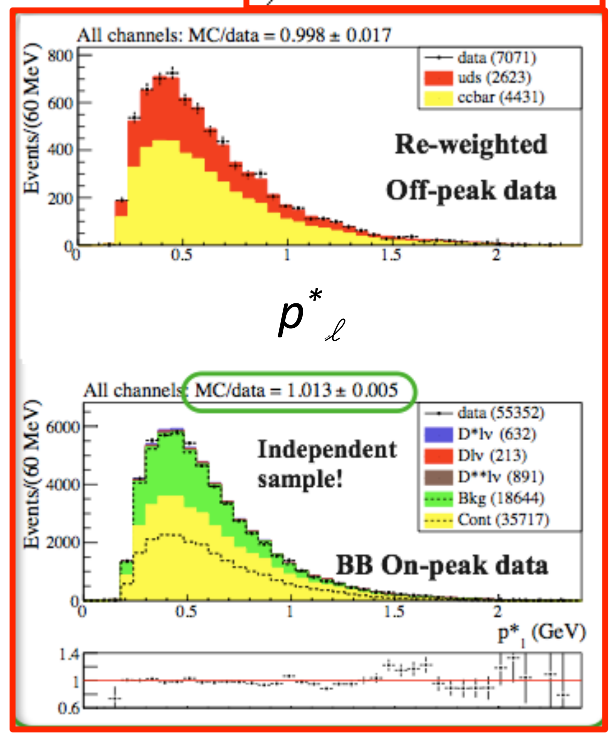
- Combinatorial *B* background: *m_{ES} [5.20, 5.26]GeV* and *E_{extra} >0.5 GeV*
- *qq* continuum: *off-peak data at E_{cm}=10.54 GeV*





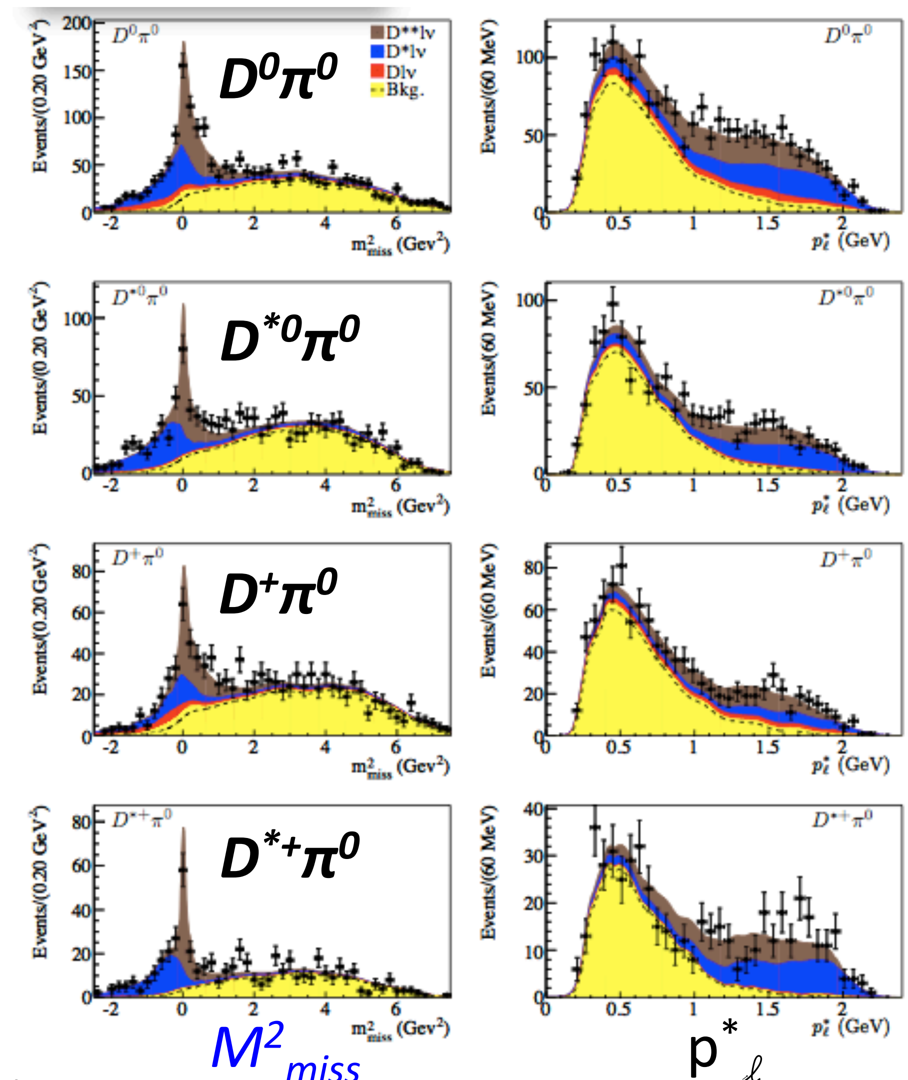
Two of the many control samples available…





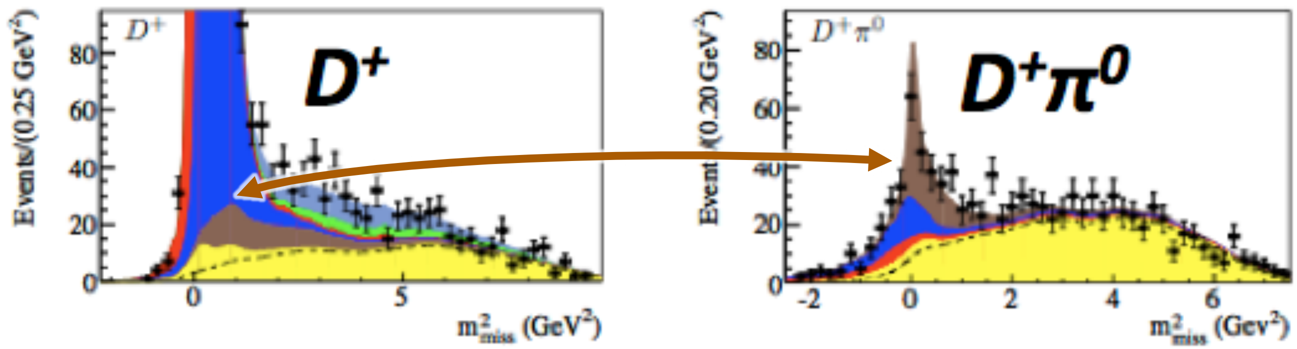
$B \rightarrow D^{**}(\ell/\tau)\nu \rightarrow D^{(*)}[n\pi](\ell/\tau)\nu$

- Higher mass charm states (D^{**}) with missing particles mimic signal:
  $B \rightarrow D^{**}(\ell/\tau)\nu$
  $\rightarrow D^{(*)}\ell\nu + M^2_{miss}$
- Explicitly reconstruct $B \rightarrow D^{(*)}\pi^0\ell\nu$ and use yield to constrain D^{**} background in fit
- Sensitive to both resonant and non-resonant D^{**}



Fit model

- Unbinned ML fit in 2-d space of M^2_{miss} , p^*_ℓ
- 8 input samples: $D^{(*)0}\ell$, $D^{(*)+}\ell$, $D^{(*)0}\pi^0\ell$, $D^{(*)+}\pi^0\ell$
- Constraints on relative yields of D^{**} in signal, $D^{(*)}\pi^0$ samples



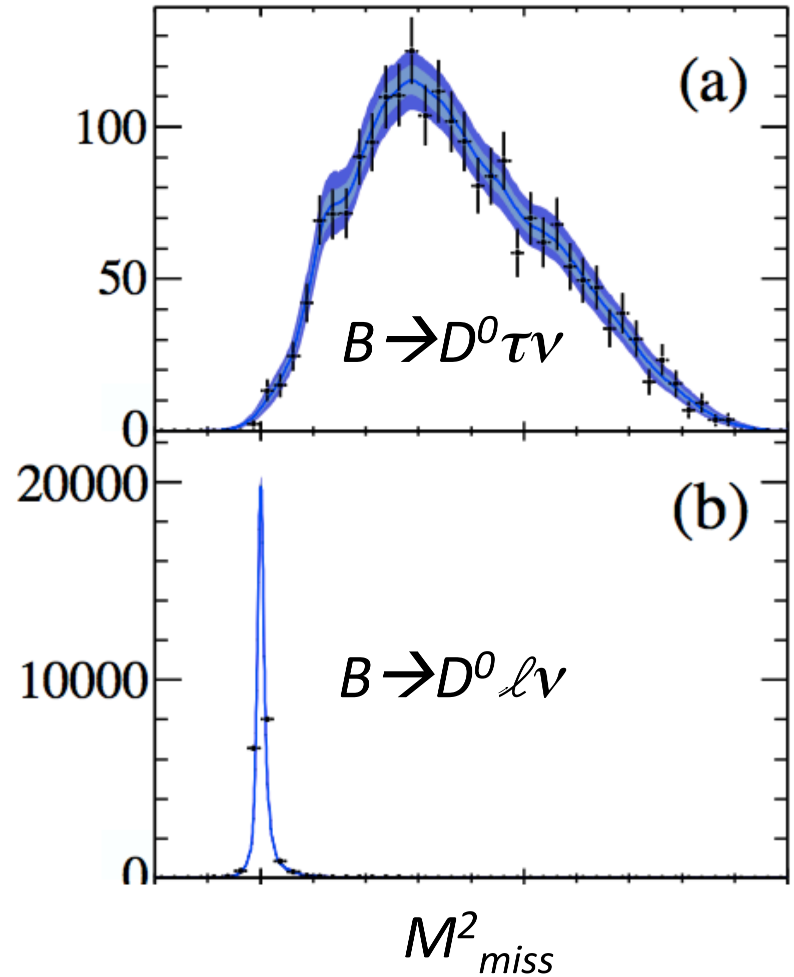
- Fixed yields: continuum, BB combinatorial, charge cross-feed
- Yields in $D^{(*)}\ell$ samples:
  - signal (4)
  - normalization (4 + 2 feed-down)
- Yields in $D^{(*)}\pi^0\ell$ samples

22 free parameters

Alternative fit imposing isospin constraint has 17 free parameters

PDF construction

- 56 individual 2-d PDFs needed (M^2_{miss} projection of 2 components shown at right)
- Based on MC ($9*\mathcal{L}_{data}$ for BBbar, $2*\mathcal{L}_{data}$ for continuum)
- PDFs based on non-parameteric kernel estimation, uncertainties on bootstrapping



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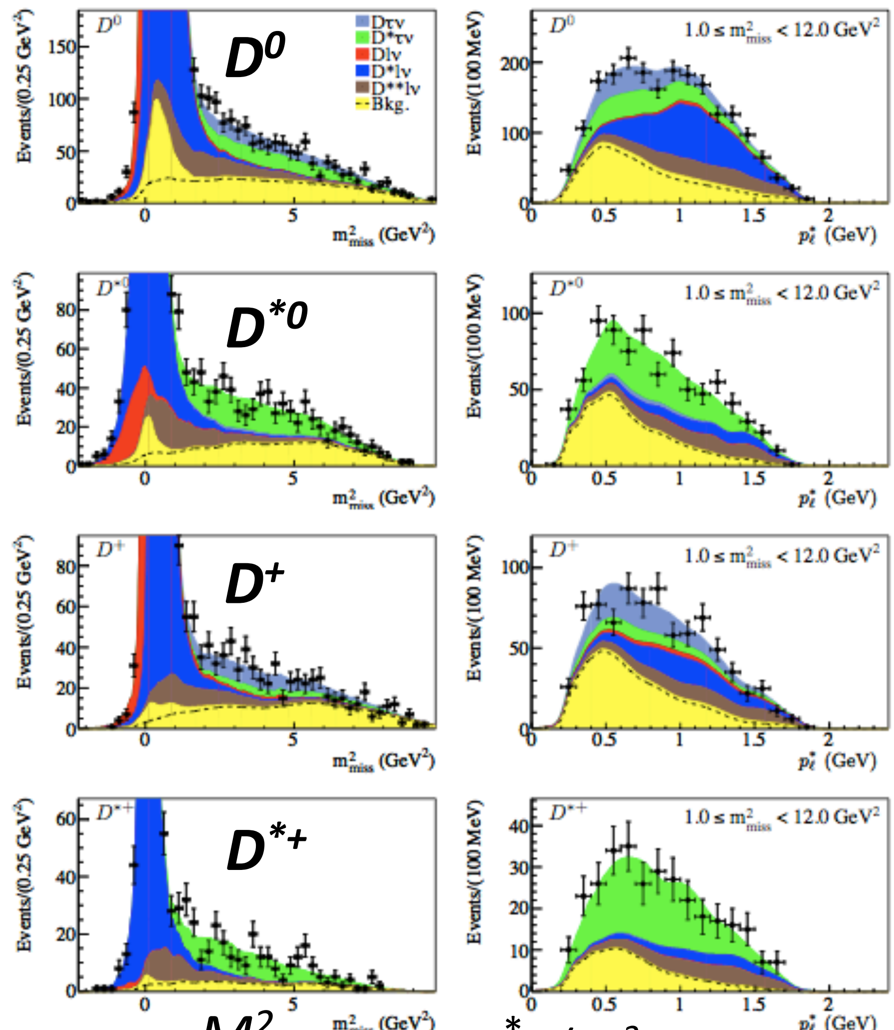
Fit projections

- Clear signals in all 4 channels; good fit quality
- $B \rightarrow D^{(*)}\pi^0 \ell\nu$ channels shown previously
- Full normalization modes shown previously



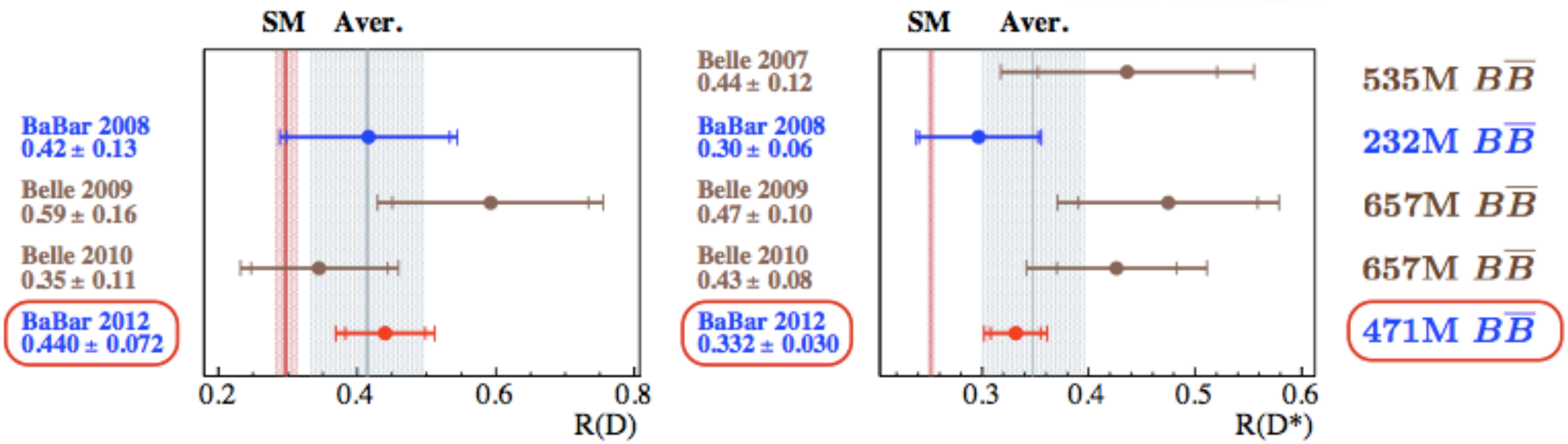
M^2_{miss} p^*_ℓ (M^2_{miss}>1.5 GeV^2)

Fit results

Phys. Rev. Lett. 109, 101802 (2012)

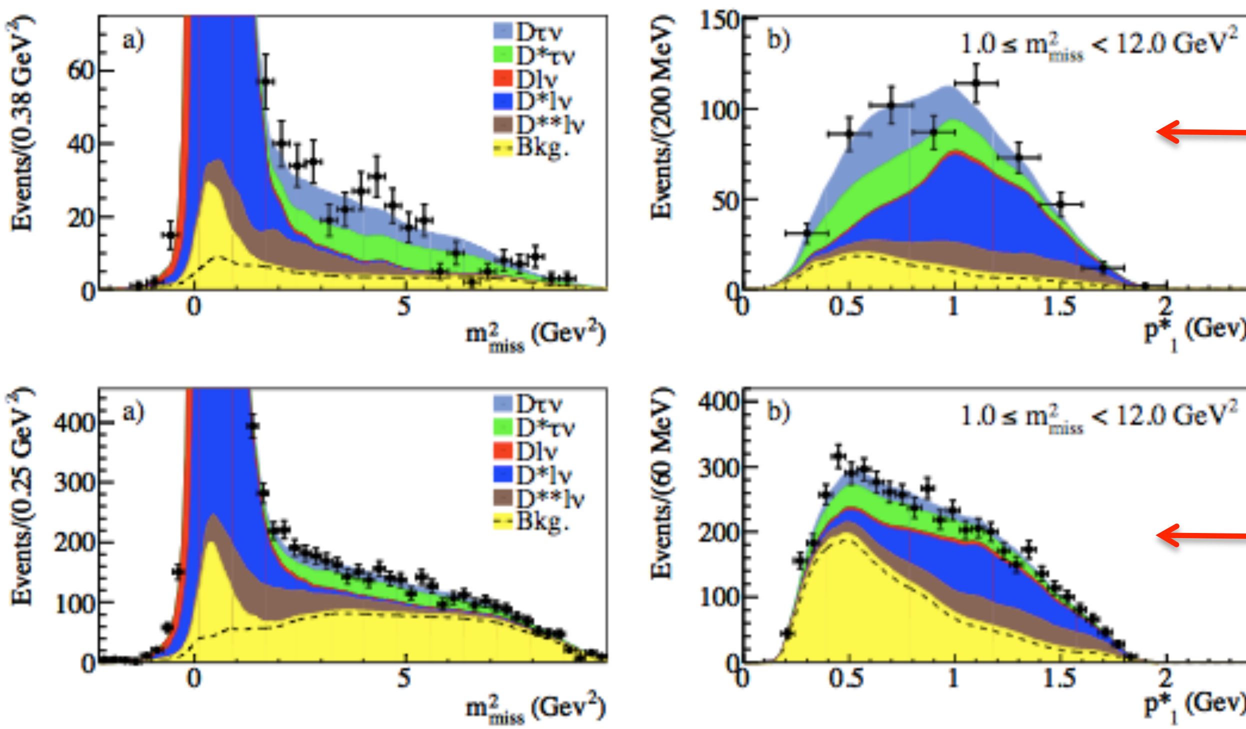
Decay	N_{sig}	N_{norm}	$\varepsilon_{\text{sig}}/\varepsilon_{\text{norm}}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	Σ_{stat}	Σ_{tot}
$B^- \to D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	0.367 ± 0.011	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.12 \pm 0.04$	5.5	4.7
$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	0.227 ± 0.004	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.11 \pm 0.06$	11.3	9.4
$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	0.384 ± 0.014	$0.469 \pm 0.084 \pm 0.053$	$1.01 \pm 0.18 \pm 0.11 \pm 0.04$	6.1	5.2
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	0.217 ± 0.005	$0.355 \pm 0.039 \pm 0.021$	$1.74 \pm 0.19 \pm 0.10 \pm 0.06$	11.6	10.4
$\overline{B} \to D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	0.372 ± 0.010	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.10 \pm 0.04$	8.4	6.8
$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	0.224 ± 0.004	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.10 \pm 0.06$	16.4	13.2

- First $D\tau\nu$ result above 5σ significance
- Compatible with previous results and their average



Stability tests

- Results consistent over run periods, between *e* and *μ*
- Consistent across wide range of S/B (altered BDT cuts)



	S/B	R(D⁰)
Tight	1.3	0.42±0.09
Nominal	0.8	0.43±0.08
Loose	0.3	0.35±0.10

Systematic uncertainties

- Largest uncertainties from modeling of D^{**} background (composition, decay modes, slow-π cross-feed)
- Uncertainties on bkg yields (continuum, BBbar) fixed in the fit
- Uncertainty on efficiency doesn't impact significance
- Main systematic uncertainties are Gaussian-distributed

Source	Uncertainty (%) $R(D)$	Uncertainty (%) $R(D^*)$	ρ
$D^{**}\ell\nu$ background	5.8	3.7	0.62
MC statistics	5.0	2.5	-0.48
Cont. and $B\overline{B}$ bkg.	4.9	2.7	-0.30
$\varepsilon_{\rm sig}/\varepsilon_{\rm norm}$	2.6	1.6	0.22
Systematic uncertainty	9.5	5.3	0.05
Statistical uncertainty	13.1	7.1	-0.45
Total uncertainty	**16.2**	**9.0**	**-0.27**

ρ = correlation between *R(D)* and *R(D*)*; negative due to $D^* \rightarrow D$ feed-down

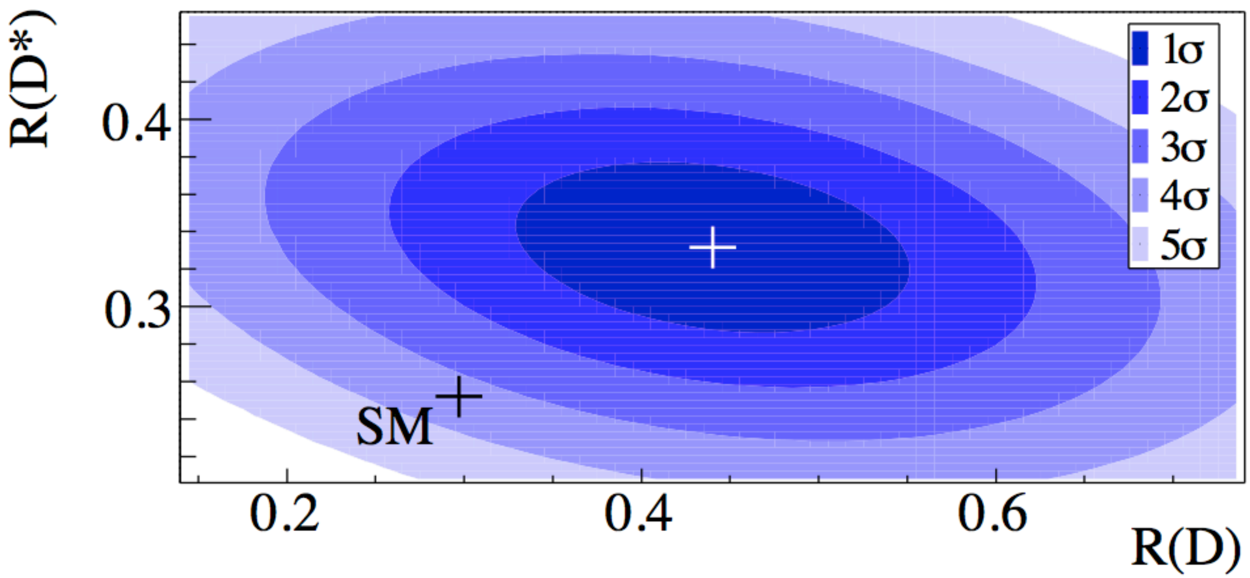
Comparison with SM predictions

$$R(D) = \begin{cases} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{cases} \Bigg\} \; \mathbf{2.0\sigma}$$

$$R(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{cases} \Bigg\} \; \mathbf{2.7\sigma}$$

Combined: $\mathbf{3.4\sigma}$

Using other calculations of SM values, smallest discrepancy is 3.2σ



Measurements of R(D), R(D^*) anti-correlated (due to $D^* \to D$ feed-down); $\rho = -0.27$

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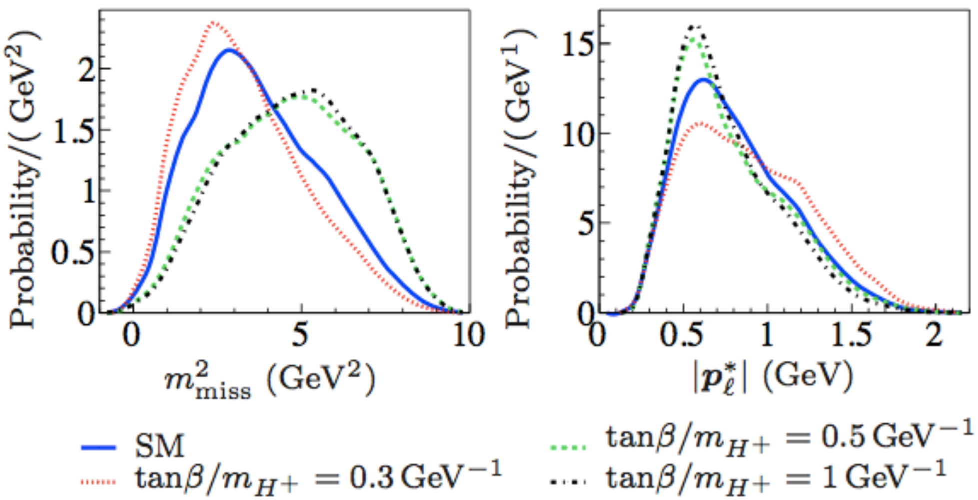
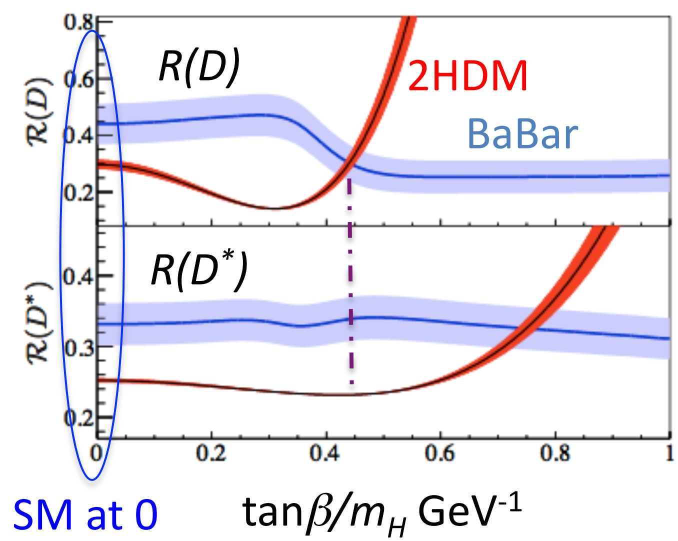
MSSM: 2HDM-Type II model



- Shape of q^2 and of fit variables sensitive to amount of H^+
- Fit yields and efficiencies sensitive to $\tan\beta/m_H$

- R(D) and R(D^*) do not both agree with predictions for any single value of $\tan\beta/m_H$
  → 2HDM-Type-II excluded over full parameter space# at 99.8% cl



relies on m_H<15 GeV being excluded by $b \rightarrow s\gamma$

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Recent theoretical work

- These results spawned many recent preprints; they can be accommodated in 2HDM-Type-III scenarios (independent LH and RH scalar couplings) and via mediators with non-zero spin

1. arXiv:1211.0348 B decays with τ-leptons in non-universal left-right models, Xiao-Gang He, German Valencia
2. arXiv:1210.8443 Sensitivity to charged scalars in $B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$ decays, Alejandro Celis, Martin Jung, Xin-Qiang Li, Antonio Pich
3. arXiv:1210.5076 B decay anomalies in an effective theory, Debajyoti Choudhury, Dilip Kumar Ghosh, Anirban Kundu
4. arXiv:1208.4134 Hints of R-parity violation in B decays into τν, N. G. Deshpande, A. Menon
5. arXiv:1207.5973 Exclusive weak B decays involving τ lepton in the relativistic quark model, R. N. Faustov, V. O. Galkin
6. arXiv:1206.4992 Refining new-physics searches in B -> D tau nu decay with lattice QCD, Jon A. Bailey, A. Bazavov, C. Bernard, C. M. Bouchard, C. DeTar, Daping Du, A. X. El-Khadra, J. Foley, E. D. Freeland, E. Gamiz, Steven Gottlieb, U. M. Heller, Jongjeong Kim, A. S. Kronfeld, J. Laiho, L. Levkova, P. B. Mackenzie, Y. Meurice, E. T. Neil, M. B. Oktay, Si-Wei Qiu, J. N. Simone, R. Sugar, D. Toussaint, R. S. Van de Water, Ran Zhou
7. arXiv:1206.4977 $B \to D\tau\nu$ vs. $B \to D\mu\nu$, Damir Becirevic, Nejc Kosnik, Andrey Tayduganov
8. arXiv:1206.3760 Diagnosing New Physics in $b \to c\, \tau\nu$ decays in the light of the recent BaBar result, Alakabha Datta, Murugeswaran Duraisamy, Diptimoy Ghosh
9. arXiv:1206.2634 Explaining B->Dτν, B->D*τν and B->τν in a 2HDM of type III, Andreas Crivellin, Christoph Greub, Ahmet Kokulu
10. arXiv:1206.1872 Implications of lepton flavor universality violations in B decays, Svjetlana Fajfer, Jernej F. Kamenik, Ivan Nisandzic, Jure Zupan

Summary

- Observation of enhanced semi-tauonic decays:

$$R(D) = 0.440 \pm 0.058 \pm 0.042$$
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

Phys. Rev. Lett. 109, 101802 (2012)

- $B \rightarrow D\tau\nu$ channel observed 6.8σ with significance
- Combined departure from SM: >3.2σ
- Incompatible with MSSM 2HDM of type II (excluded at 99.8%)
- PRD in preparation includes additional kinematic distributions
- Further results can be expected from Belle and BaBar on these decays

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Backup Slides

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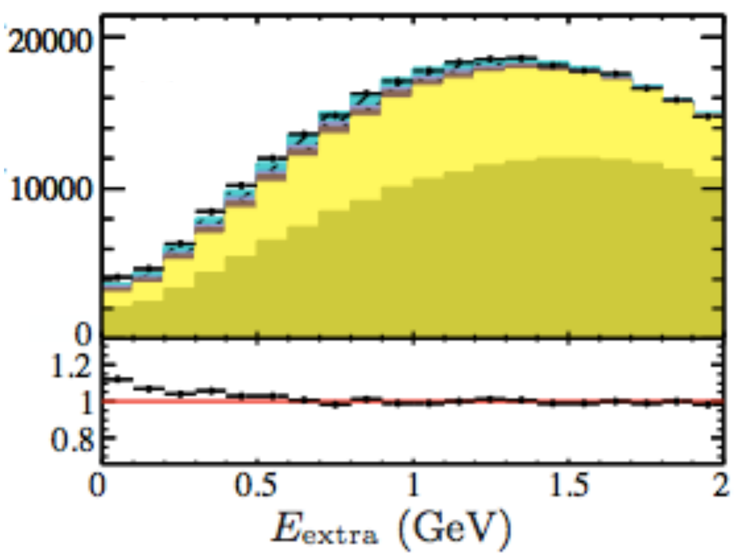
Adjustments to simulation

- Control samples used to adjust small data-MC differences and to validate modeling
  - B mass sideband $5.20 < m_{ES} < 5.26$ GeV
  - E_{extra} sidebands $0.5 < E_{extra} < 1.2$ GeV and 1.2 $GeV < E_{extra} < 2.4$ GeV
  - Pure normalization mode sideband $q^2 < 4$ GeV^2
  - Reverse cuts on BDT (veto signal)



Example: E_{extra} difference independent of m_{ES} so correct E_{extra} modeling in signal region using m_{ES} sideband