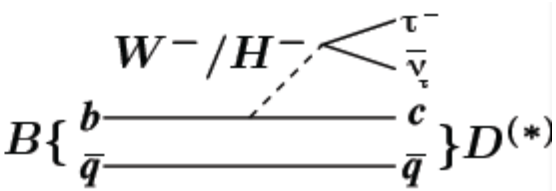
BABAR Measurements of $B^+ \to \tau^+\nu_\tau$ and $B \to D^{(*)}\tau^+\nu_\tau$

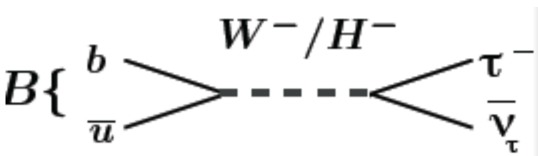
Vera Lüth
SLAC - Stanford University

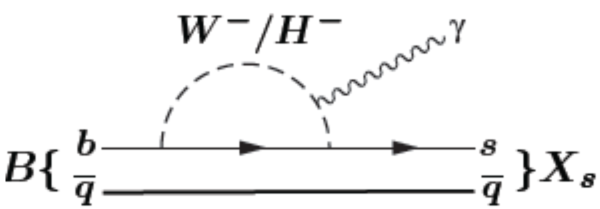
Workshop on B decays Involving τ Leptons
Nagoya, March 27-28, 2017

Search for non-SM Couplings in B Decays

The original idea was to look for evidence for a Charged Higgs boson! *







Decay	Theory	BF	Comments
$B \rightarrow D^{(*)}\tau\nu$	Tree level $\pm 7\%$	1-2 %	Excellent Normalization $B \rightarrow D^{(*)} \ell \nu$
$B \rightarrow \tau\nu$	Tree level $\pm 20\%$	0.01% helicity suppressed	Single charged particle plus 2-3 neutrinos
$B \rightarrow X_s \gamma$ $\rightarrow X \ell^+ \ell^-$	Loop $\pm 7\%$	0.03%	Inclusive measurement, backgrounds!

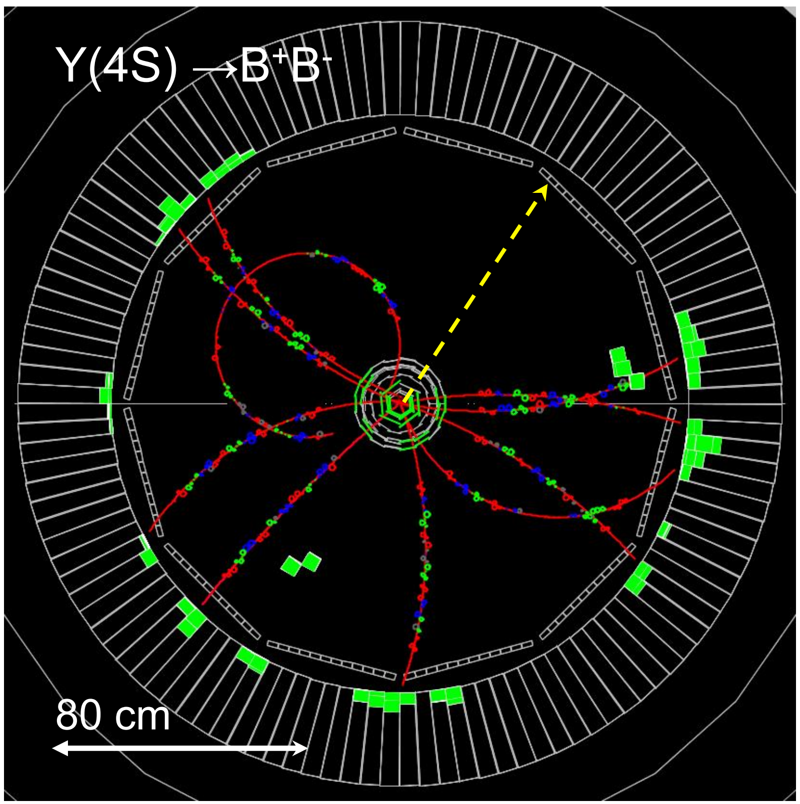
*) This work was started in 2002 by J. Richman and his student M. Mazur (UCSB)

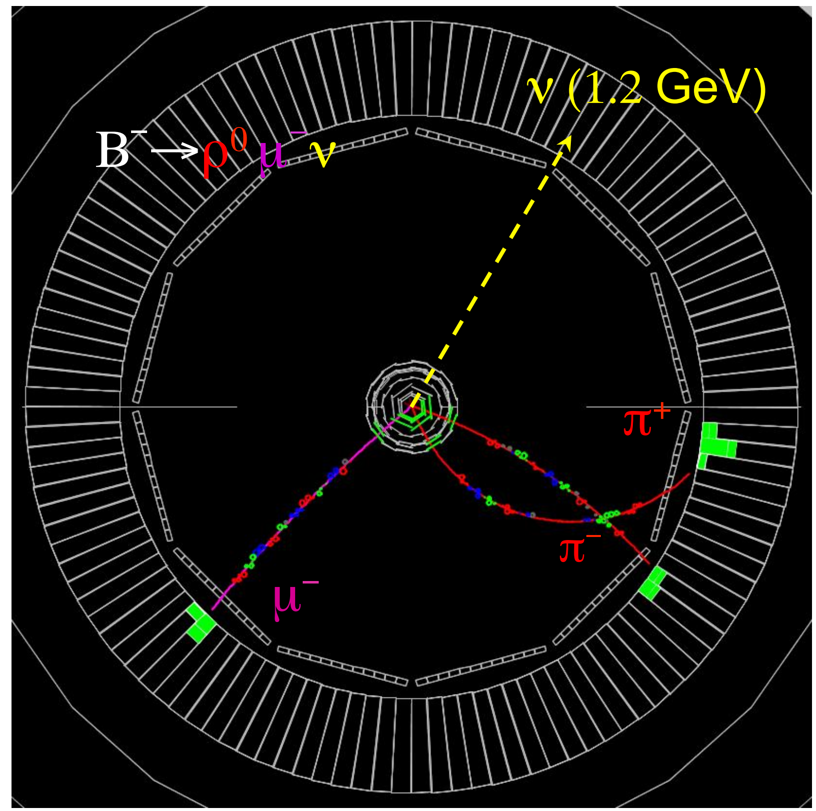
$B^+ \to \tau^+\nu_\tau$ and $B \to D^{(*)}\tau^+\nu_\tau$ Measurements

- Major experimental challenges
  - Small BF $\sim 10^{-4}$ $(\tau^+\nu_\tau)$ and $\sim 10^{-2}$ $(D^{(*)}\tau^+\nu_\tau)$
  - 2-3 neutrinos in final state,
  - Large BG from continuum and other $B\bar{B}$ events
- Solutions
  - Full reconstruction of $\Upsilon(4S) \to B\bar{B}$ events, except for ν
  - Conservation of total charge and flavor quantum numbers
  - Tagging of one B decays determines kinematics of second B meson
    - hadronic ~ 0.2 – 0.5%
    - s.l. decay ~ 1-3 %
    - Inclusive ~ 3-5%
  - Signal signatures:
    - for $B^+ \to \tau^+\nu_\tau$: 1 charged track from $\tau^+ \to e^+\nu\nu$, $\mu^+\nu\nu$, $\pi^+\nu$, $\rho^+\nu$
    - for $B \to D^{(*)}\tau^+\nu_\tau$: 1 $e^\pm$ or $\mu^\pm$ plus a D or D* decay

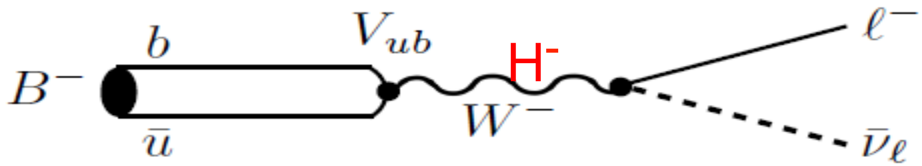
Reconstruction of $\Upsilon(4S) \rightarrow B\bar{B}$ Decays

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+_{tag}\, B^-_{signal}\, (\rightarrow \rho^0\, \mu^-\, \nu_\mu)$





$B^+ \to \tau^+\nu$ Decays



In the SM this decay proceeds via weak quark annihilation,

$$\Gamma^{SM}(B^- \to \ell^-\overline{\nu}_\ell) = \frac{G_F^2\, m_B\, m_\ell^2}{8\pi} |V_{ub}|^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \times f_B^2$$

The B decay constant f_B encapsulates all hadronic effects

Lattice QCD: $f_B = 0.191 \pm 0.009$ GeV

Eur. Phys. J. C74:2890 (2014)

HFAG-2014: $|V_{ub}| = (3.53 \pm 0.29)\ 10^{-3}$

The latest CKM Fitter results in a SM prediction of the branching fraction

$$\mathscr{B}^{SM}(B^- \to \tau^-\overline{\nu}_\tau) = (0.75 \pm^{0.10}_{0.05}) \times 10^{-4}$$

In the type II 2HDM, the charged Higgs modifies the BF

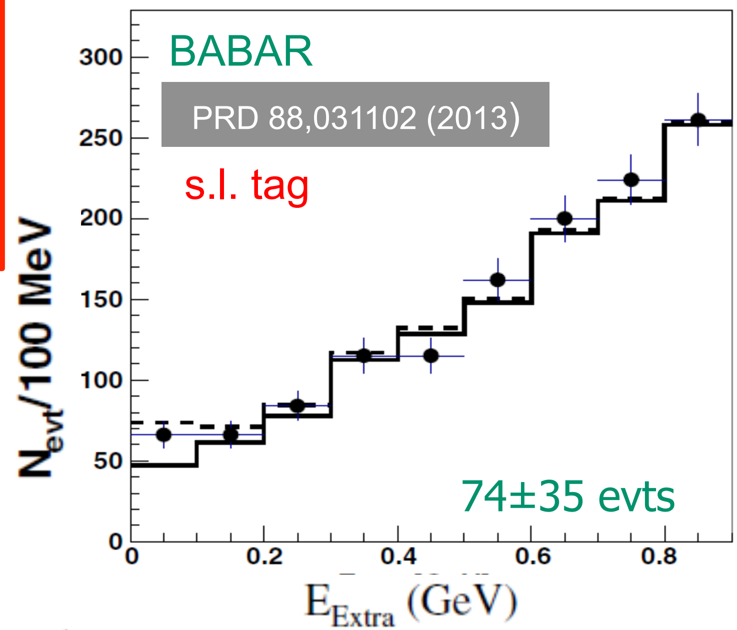
$$\mathcal{B}(B^+ \to \ell^+\nu)_{2HDM} = \mathcal{B}(B^+ \to \ell^+\nu)_{SM} \times (1 - M_B^2 \tan^2\beta / M_H^2)^2$$

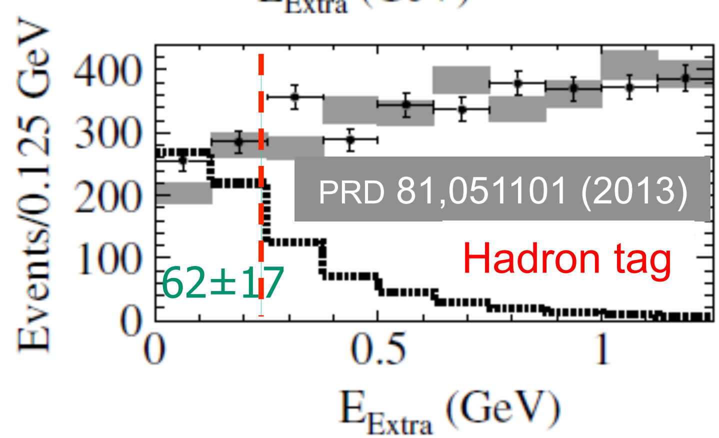
$B^+ \to \tau^+\nu$ Decays- BABAR Measurements

- Very challenging: 2-3 ν
- 4 $\tau^{\pm}$ decays: total BF 70%
  $\tau^{\pm} \to e^{\pm}\nu\nu$, $\mu^{\pm}\nu\nu$,
  $\tau^{\pm} \to \pi^{\pm}\nu$, $\rho^{\pm}\nu$
- Very large BG, very small # of signal events!

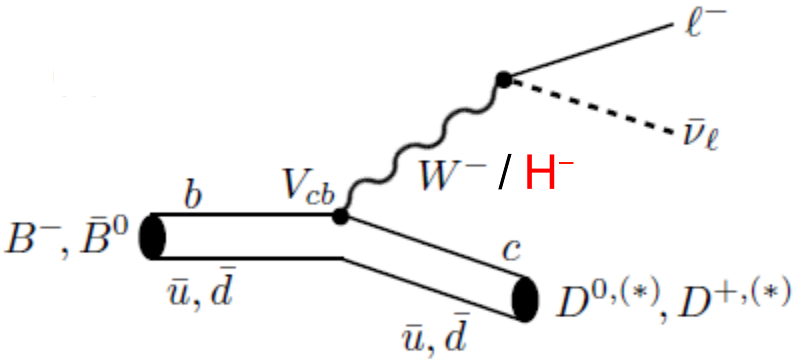
$E_{extra} = \Sigma E_{cal}$
suppresses background particles!
Very sensitive to inefficiencies and noise

τ Decay	had. Tag	s.l. tag (S/BG)
eνν	4±9	40±16 (0.5)
μνν	13±20	13±16 (0.1)
πν	17±6	9±19 (0.04)
ρν	24±10	12±11 (0.2)
All	62±17	74±35 (0.15)
BF (10^{-4})	1.8±0.5±0.3	1.7±0.8±0.2





$B \to D^{(*)} \tau \nu$ Decays



Z. Phys, C46, 93 (1990)

- S.L. decays involving a $\tau^{\pm}$ have an additional helicity amplitude (for $D^*\tau\nu$)

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

For $D\tau\nu$, only H_{00} and H_s contribute!

- A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect Hs

$$H_s^{2HDM} = H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- for $D\tau\nu$
+ for $D^*\tau\nu$

PRD 78, 015006 (2008)
PhD 85, 094025 (2012)

This could enhance or decrease the BF, depending on $\tan\beta/m_H$

Ratio of B → $D^{(*)}\tau\nu$ vs B → $D^{(*)} l \nu$ Decays

- To test the SM Prediction, BABAR measures the ratios

$$R(D) = \frac{\Gamma(\bar{B} \to D\tau\nu)}{\Gamma(\bar{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau\nu)}{\Gamma(\bar{B} \to D^*\ell\nu)}$$

Purely leptonic
τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- $B\bar{B}$ events are fully reconstructed:
  - hadronic B tag (tag efficiency improved)
  - $e^{\pm}$ or $\mu^{\pm}$: (extend to lower momenta, p_l^*>0.2 or 0.3 GeV)
  - no additional charged particles, E_{extra}<0.5GeV (no cut)
  - kinematic selections: q^2>4 GeV^2

  Background suppression by BDT (combinatorial BG and $D^{**}l\nu$)

- Full BABAR data sample, MC correction based on data control samples

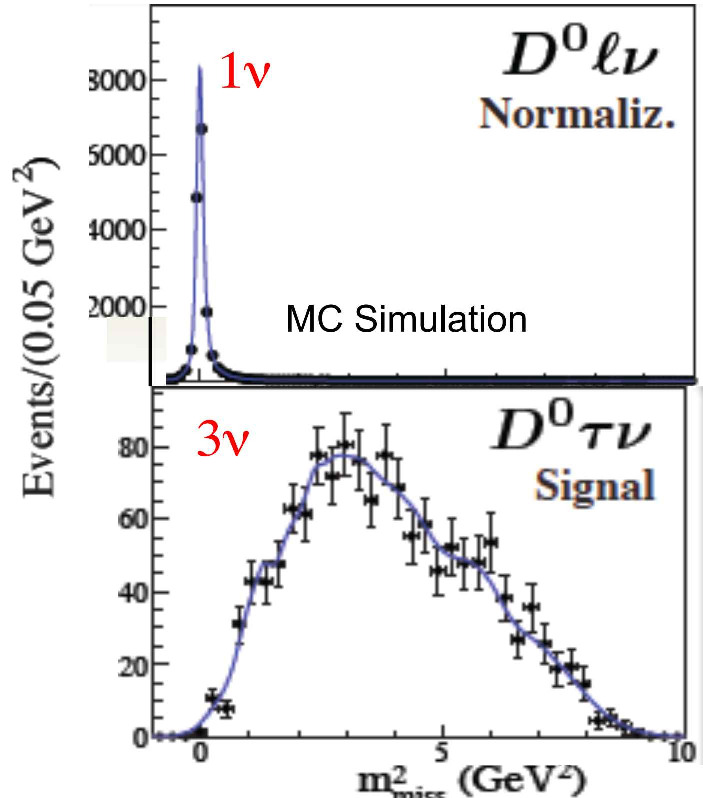
B→ $D^{(*)}\tau\nu$: Extraction of Yields from M.L. Fit

- Unbinned 2-D M.L. fit

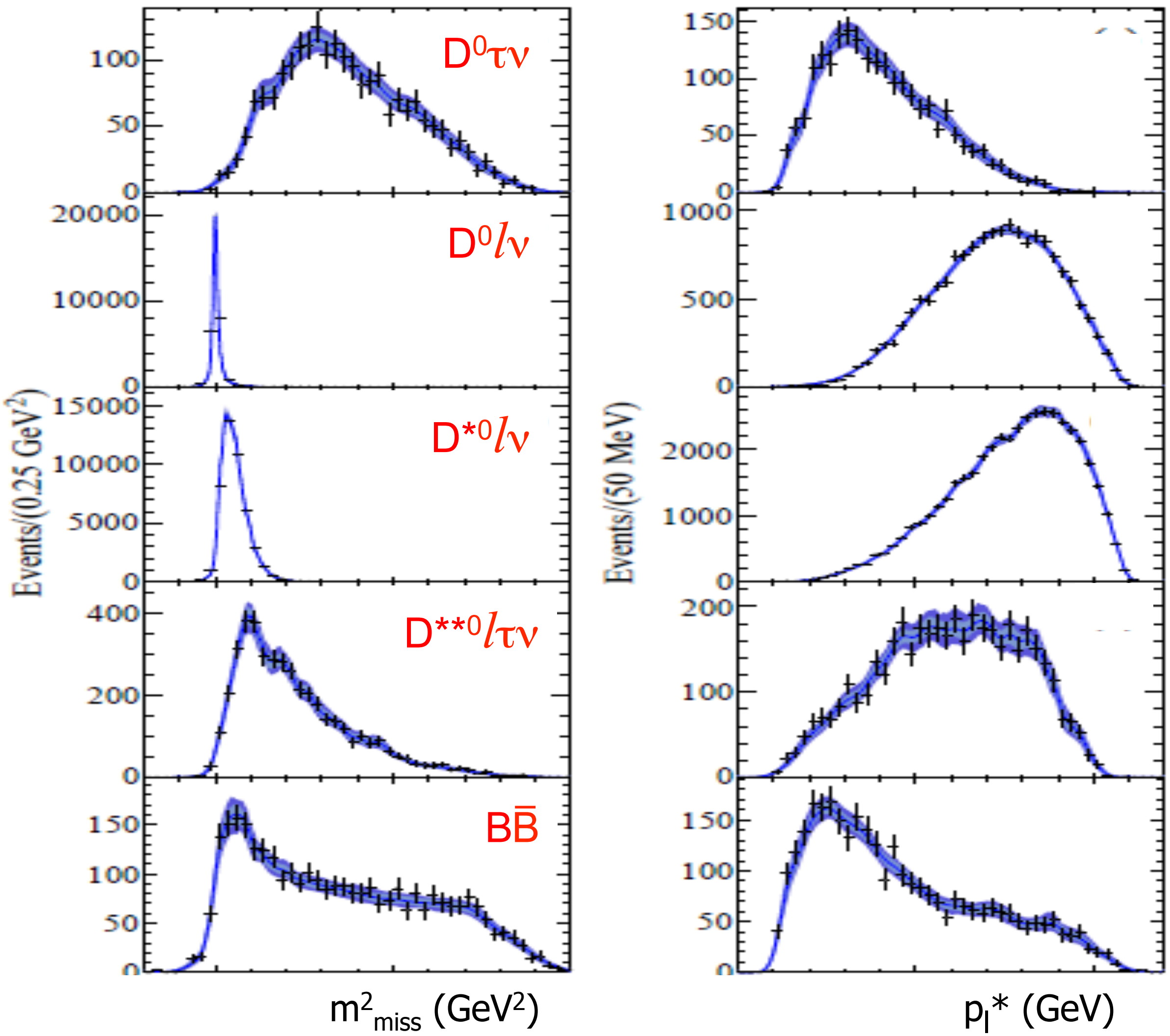
$$m^2_{miss} = (P_{ee} - P_{Btag} - P_{D^{(*)}} - P_\ell)^2 \qquad p^*_\ell$$

Missing mass squared — $e^\pm, \mu^\pm$ momentum in B rest frame

  - 4 signal samples: $D^0 l$, $D^{*0} l$, $D^+ l$, $D^{*+} l$, ($e^\pm$ or $\mu^\pm$)
  - 4 $D^{(*)}\pi^0 l\nu$ control samples
- PDFs from MC (approximated using Keys fct.)
- Fitted Yields (22 free parameters)
  - 4 $D^{(*)}\tau\nu$ Signal
  - 4 $D^{(*)} l\nu$ Normalization
  - 4 $D^{**} l\nu$ Background
- Fixed Backgrounds
  - B^0–B^+ cross feed
  - $B\bar{B}$ combinatorial BG
  - Non- $B\bar{B}$ continuum: $e^+e^- \to f\bar{f}$ (γ)



2-D PDFs Based on Keys Functions



2-D m^2_{miss} vs p^*_l, difficult to describe analytically

- correlations
- irregular functions

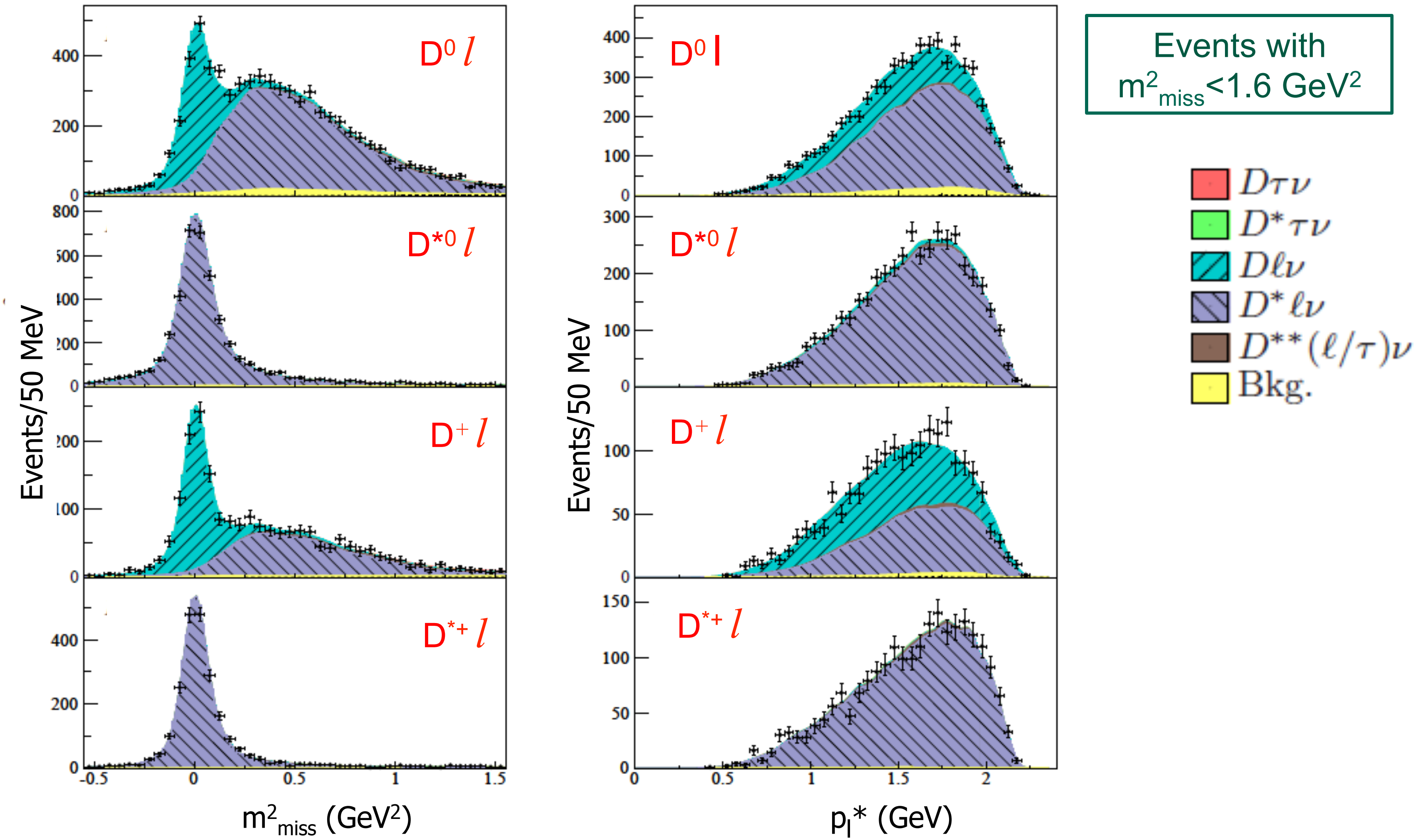
Solution

- non-parametric Kernal Estimators (KEYS)
- optimize bias vs variance (smoothing)

56 2-D PDFs

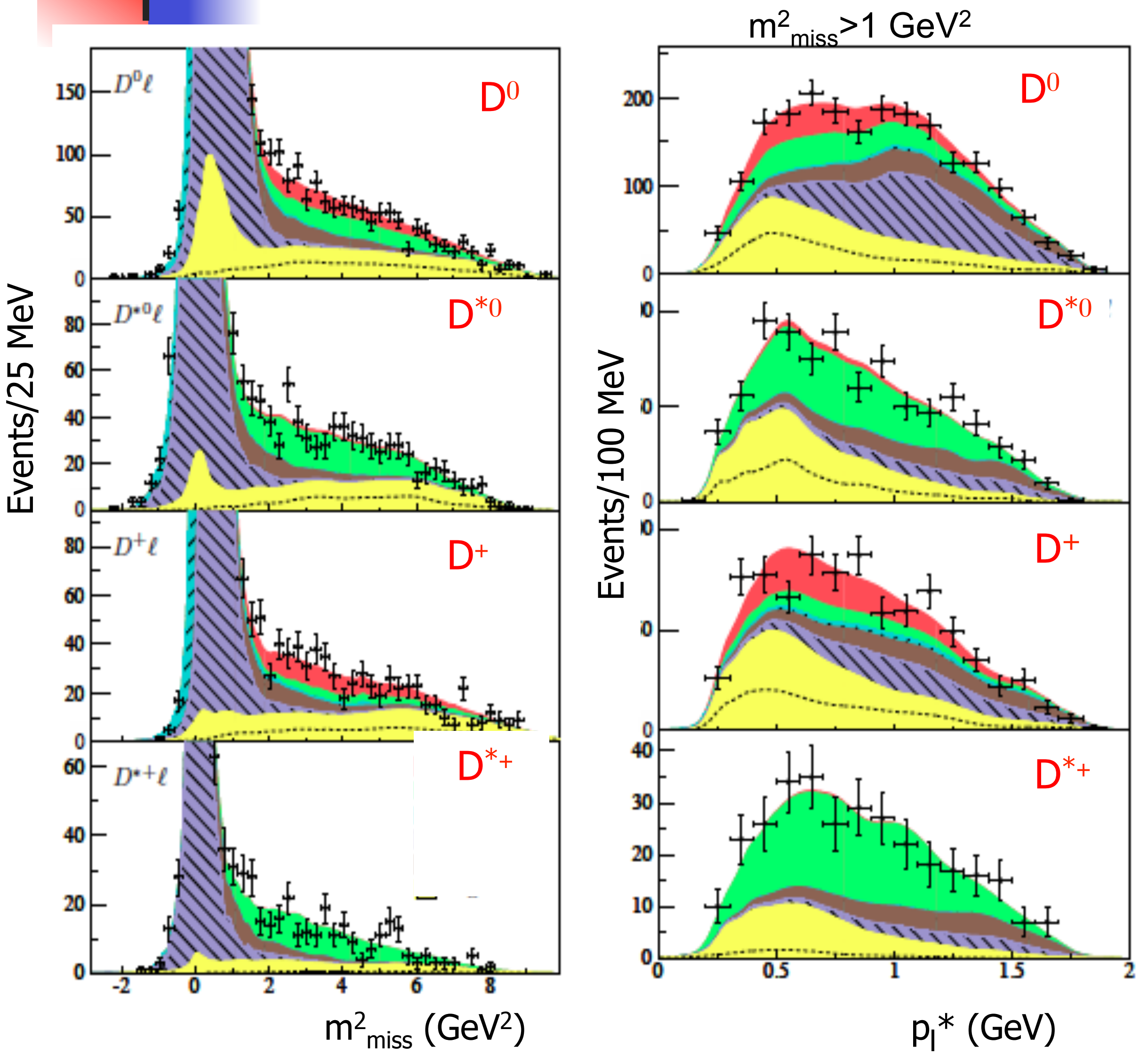
- D, D*τ signals (8)
- D, D*l Normalization (8)
- D**l /τ (8)
- Normalization feed down
- Signal feed down
- $B^0 - B^+$ crossfeeds
- BG $B\bar{B}$
- BG non-$B\bar{B}$

Cross Checks: Fit Normalization $B \rightarrow D^{(*)} l \nu$



Results of Fit: B→ Dτν and B→ D*τν

BABAR
PRD 88:072012 (2013)



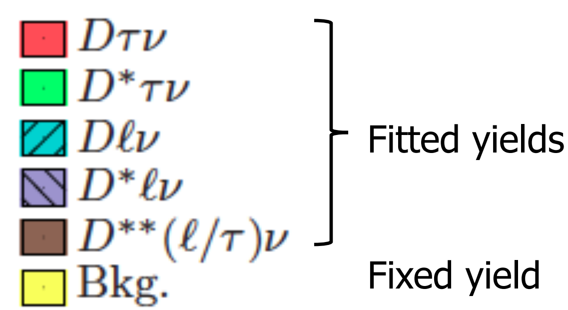
Fit results, combined using Isospin relations:

B →D τ ν

N_{signal}	489 ± 63
R(D)	0.440 ± 0.058
syst. error	± 0.042

B →D* τ ν

N_{signal}	888 ± 63
R(D*)	0.332 ± 0.024
syst. error	± 0.018



Systematic Uncertainties

ρ Correlation between R(D) and R(D*)

Principal Uncertainties:

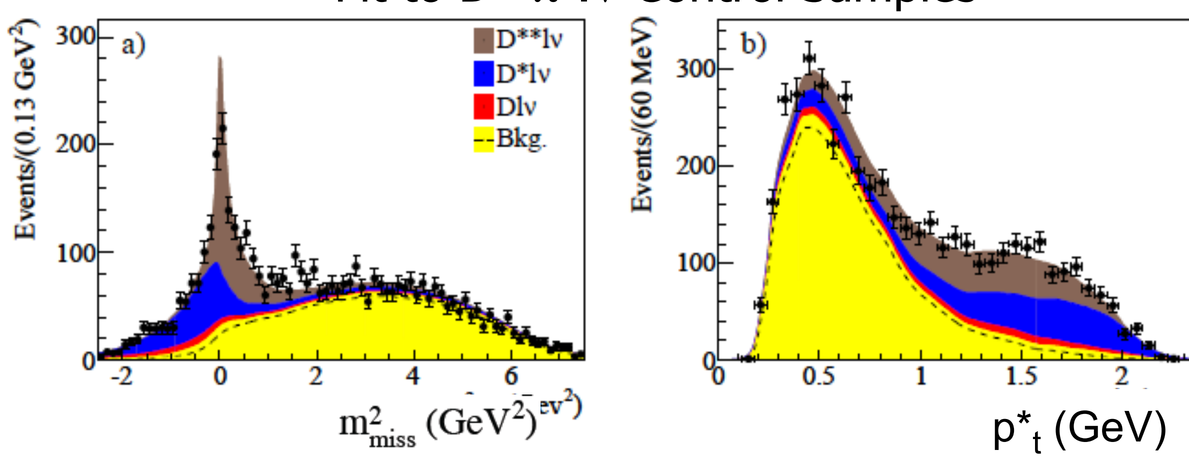
- $D^{**} l\,\nu$: conservative 15%
  constraints and fit to $D\pi$ sample,
- Limited MC signal samples
  2-dim PDFs with ~2000 events
- Continuum and $B\bar{B}$ background
  Corrections and MC statistics

Largest errors 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
$\varepsilon_{sig}/\varepsilon_{norm}$	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

Fit to $D^{(*)}\pi^0 l\nu$ Control Samples

Fit to $D^{(*)}\pi^0 l\nu$ control sample for sum of 4 channels
$D^0\pi^0 l\nu$, $D^{*0}\pi^0 l\nu$,
$D^+\pi^0 l\nu$, $D^{*+}\pi^0 l\nu$

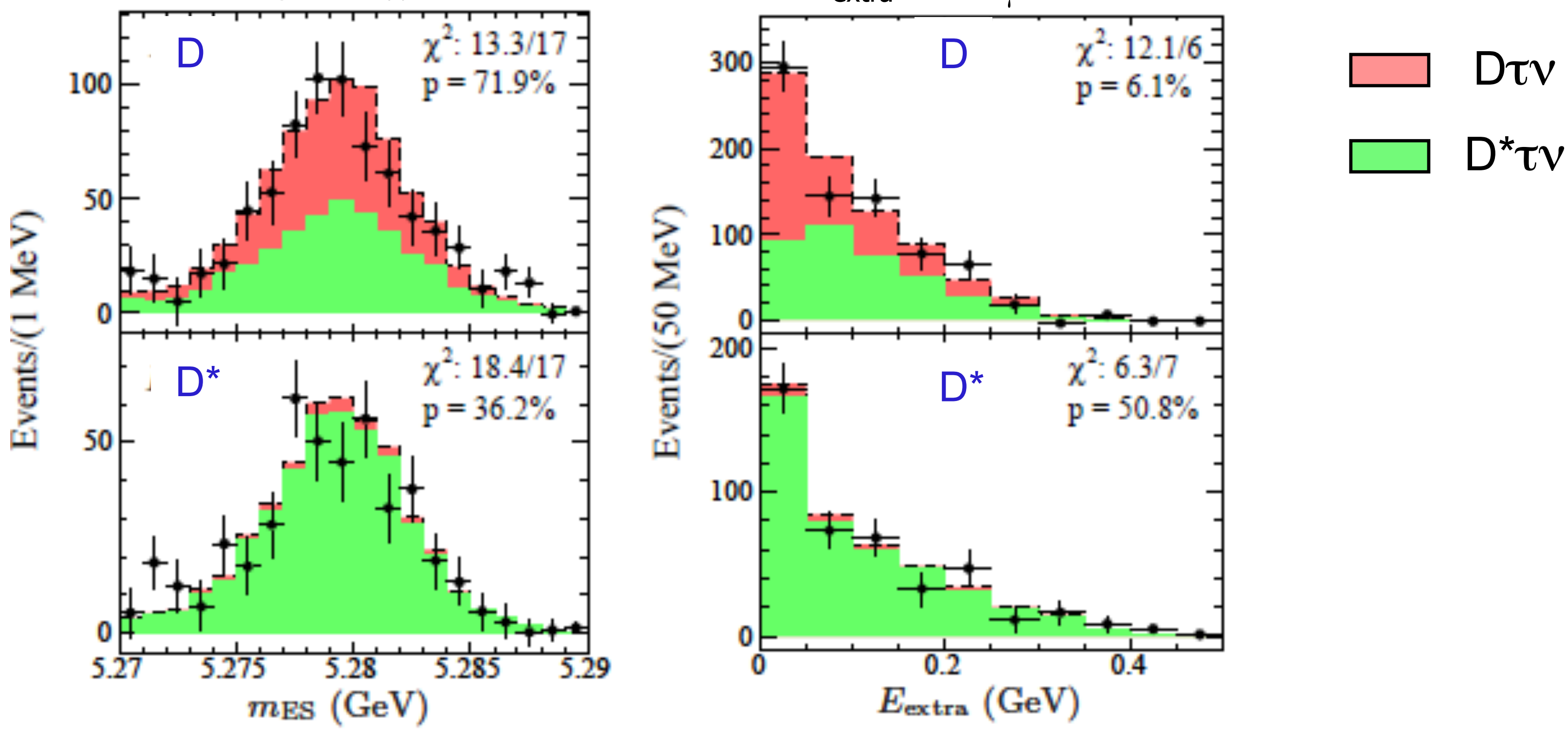


Cross Check on MC for Signal and Backgrounds

- Detailed comparisons of data control samples with MC
  - Prior to fit (off- and on-resonance data) rescale distributions: p^*_l, m_{ES}, E_{extra}
  - Post fit (unfitted distributions in signal region)

Background subtracted distributions $B \to D^{(*)}\tau\nu$ (post-fit)

$m_{ES} = \sqrt{E^2_{beam} - p^2_B}$ $\quad$ $E_{extra} = \Sigma E_\gamma(\text{other})$



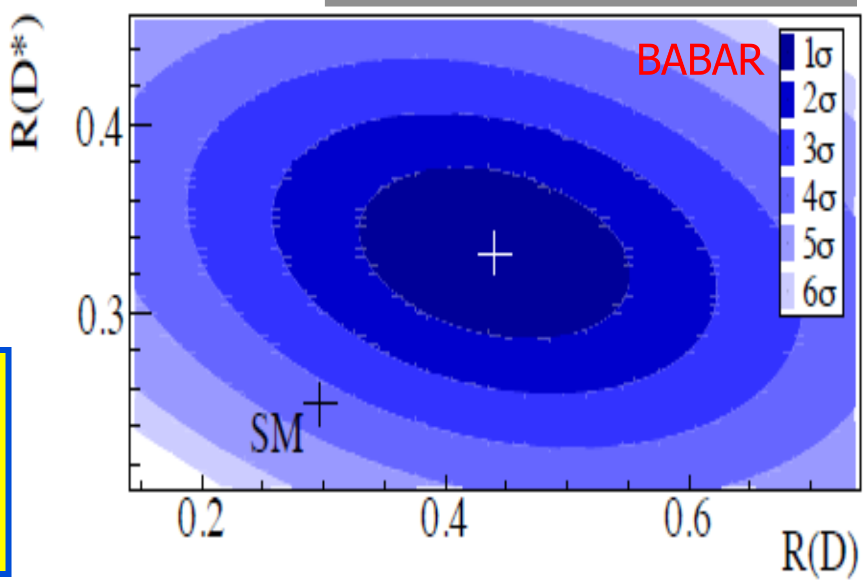
S.M. Predictions of R(D) and R(D*)

SM Predictions:
PRD 92, 034506 (2015)
PRD 92, 054510 (2015)
PRD 85, 094025 (2012)

Comparison with S.M. calculation:

	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.300 ± 0.008	0.252 ± 0.003
Difference	2.0 σ	2.7 σ

BABAR, PRD 072012 (2013)



The combination of the two measurements (-0.27 correlation) yields χ^2/NDF=14.6/2.

The data are inconsistent with the SM prediction at a level of 3.4 σ !!

Can we Explain the Excess Events?

- A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect H_S

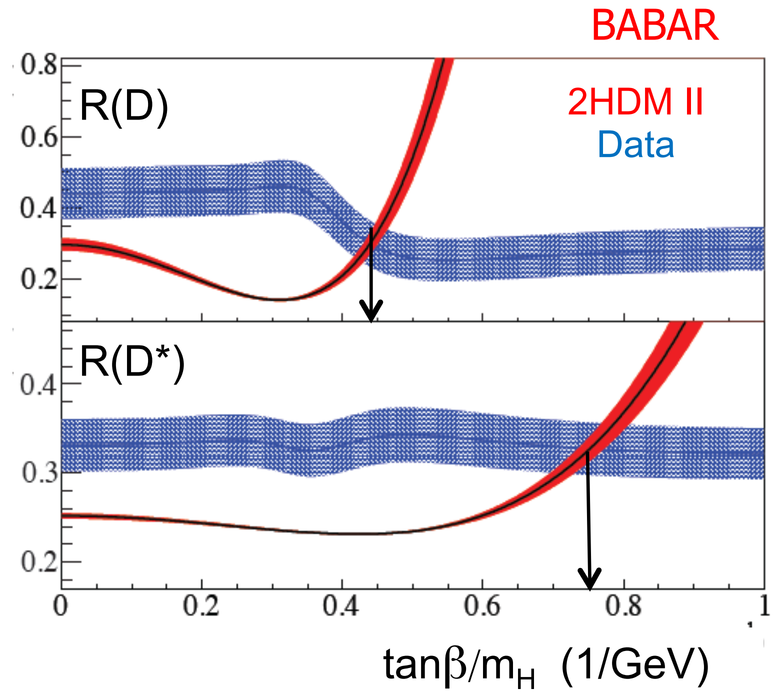
$$H_s^{2HDM} = H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m^2_{H\pm}} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- for $D\tau\nu$
+for $D^*\tau\nu$

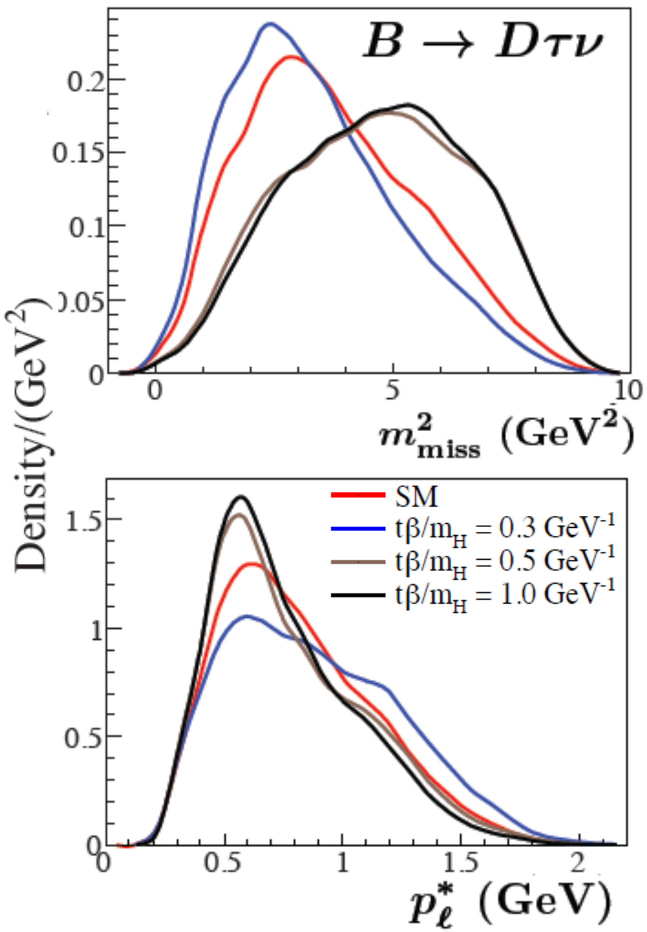
PRD 78, 015006 (2008)
PhD 85, 094025 (2012)

This could enhance or decrease the ratios R(D*) depending on $\tan\beta/m_H$

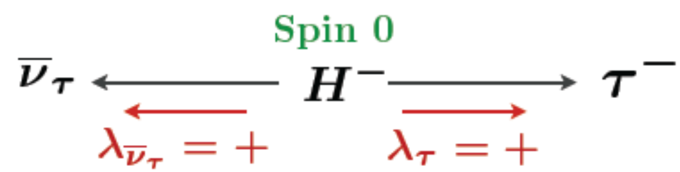
- We estimate the effect of 2HDM, accounting for differences in signal yield and efficiency.
- The data match 2HDM Type II contribution at
  $\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)
  $\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)
- The combination of R(D) and R(D*) excludes the Type II 2HDM in the $\tan\beta$ - m_H parameter space with P >99.8%, for m_H>15 GeV !



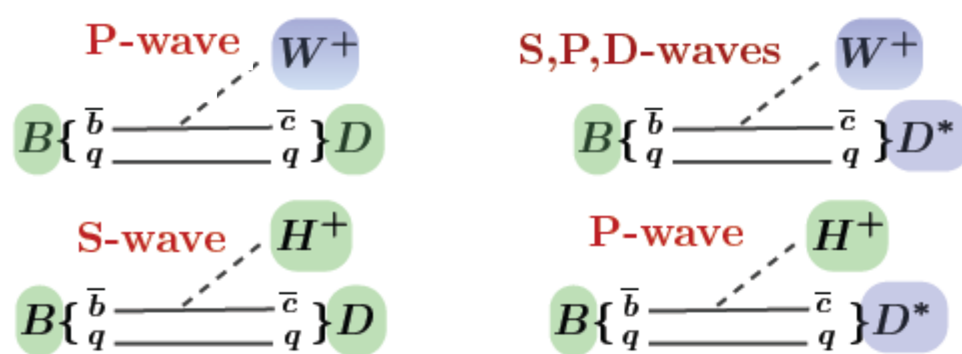
Dependence of MC Signal Yield on 2HDM II



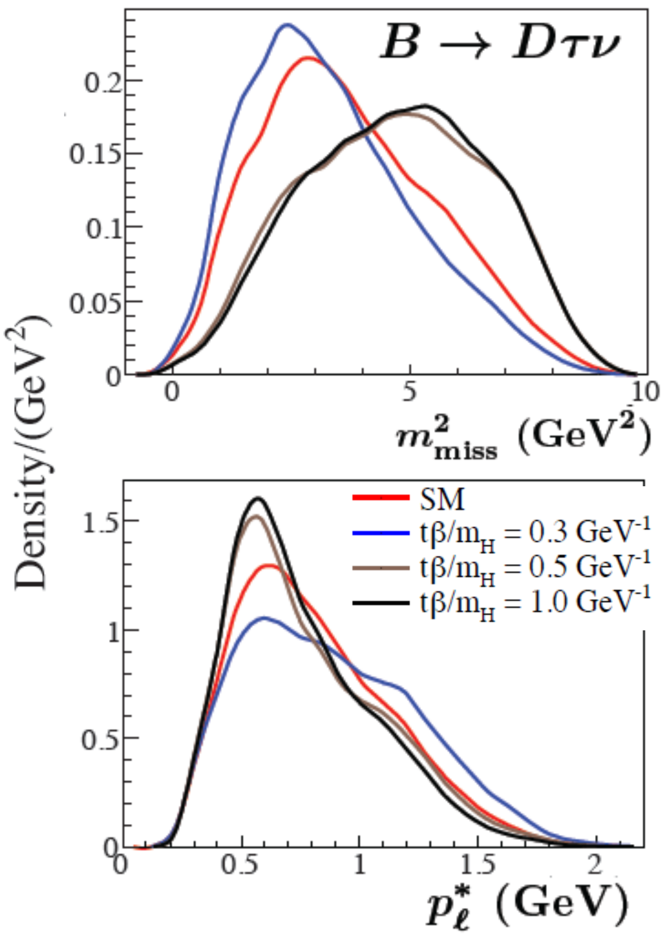
- τ Polarization in B→Dτν Decays
  - SM LH: 70%. RH: 30%
  - 2HDM LH: 0% RH: 100%

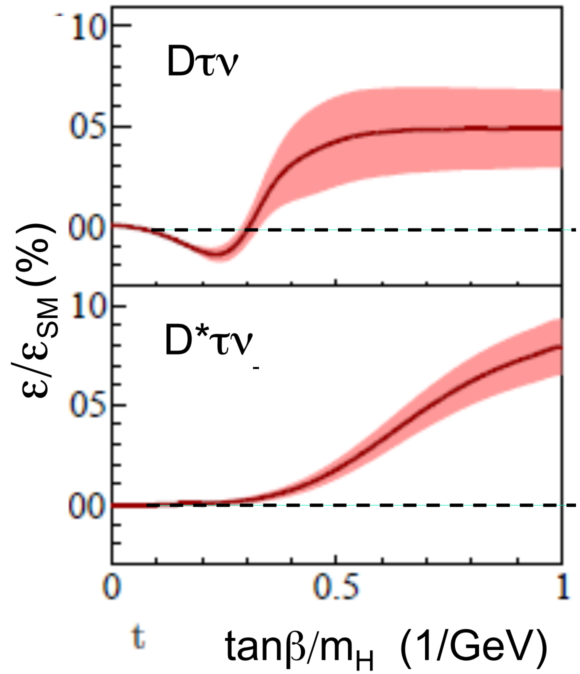


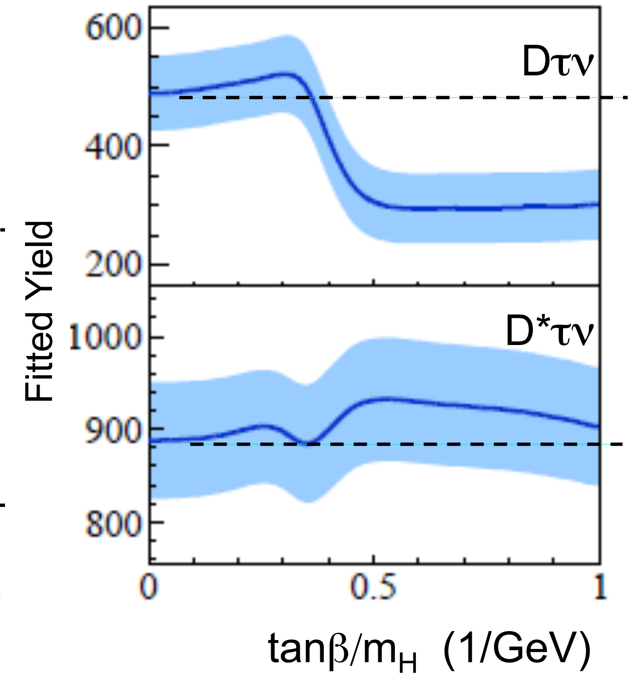
- Impact on fitted distributions large for B→Dτν
  - missing mass sq: $m^2_{miss} \sim q^2$
  - p^*_l, momentum of secondary lepton from $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ decays in B rest frame



Dependence of MC Signal Yield on 2HDM II







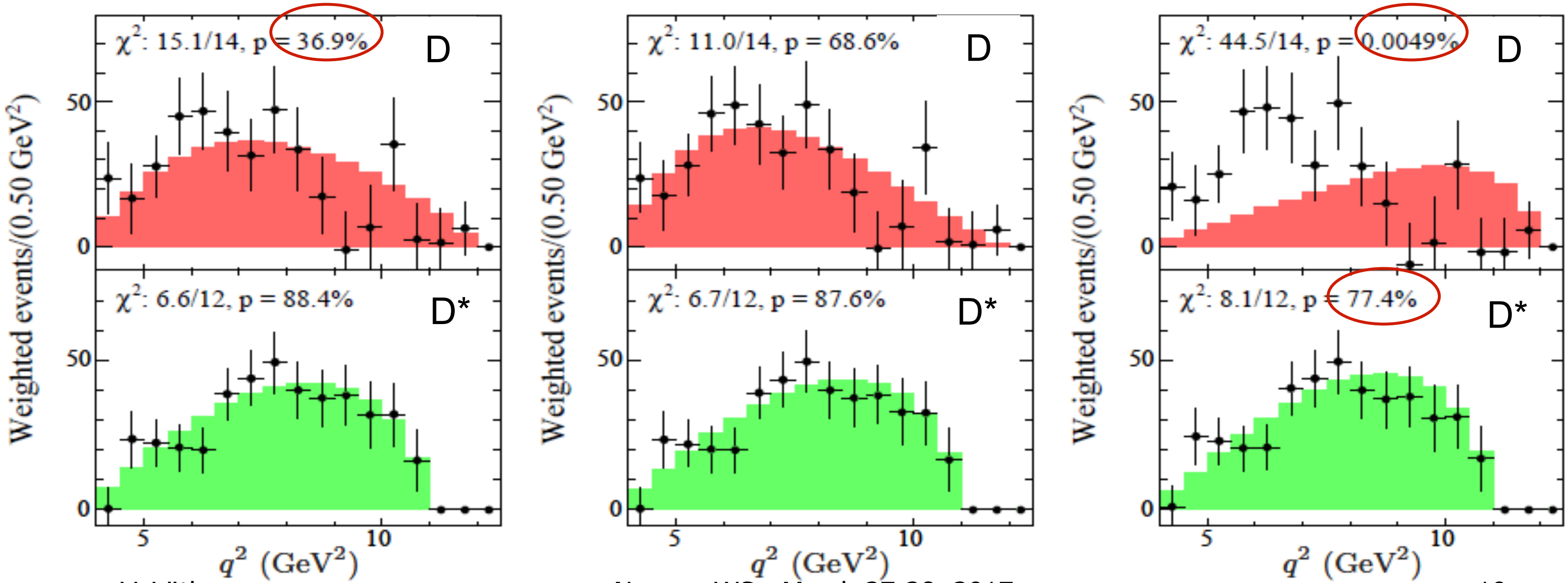
- Change in $\tan\beta/m_H$ impacts m^2_{miss} :
  - detection efficiency + (5-10)% for $D\tau\nu$ and $D^*\tau\nu$
  - fitted signal yield - 40% for $D\tau\nu$

Impact of 2HDM II on q^2 Distribution

$$m^2_{\text{miss}} = (\overbrace{p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)}}}^{q} - p_\ell)^2$$

- q^2 is closely related to m^2_{miss}:
  - $D^*\tau\nu$: small impact on q^2 as expected
  - $D\tau\nu$: for $\tan\beta/m_H \geq 0.45\ \text{GeV}^{-1}$ the 2HDM type II is excluded at 2.9 σ, other 2HDM with small scalar terms cannot be excluded!

$\tan\beta/m_H = 0\ \text{GeV}^{-1}$ | $\tan\beta/m_H = 0.3\ \text{GeV}^{-1}$ | $\tan\beta/m_H = 0.45\ \text{GeV}^{-1}$



Consistency with 2HDM Type II and III

- The 2HDM charged Higgs contributes to the scalar helicity amplitude Hs:

$$H_s^{2\mathrm{HDM}} \approx H_s^{\mathrm{SM}} \times \left(1 + (S_R \pm S_L)\frac{q^2}{m_\tau(m_b \mp m_c)}\right).$$

S_L and S_R complex parameters
upper sign: D, lower sign D*

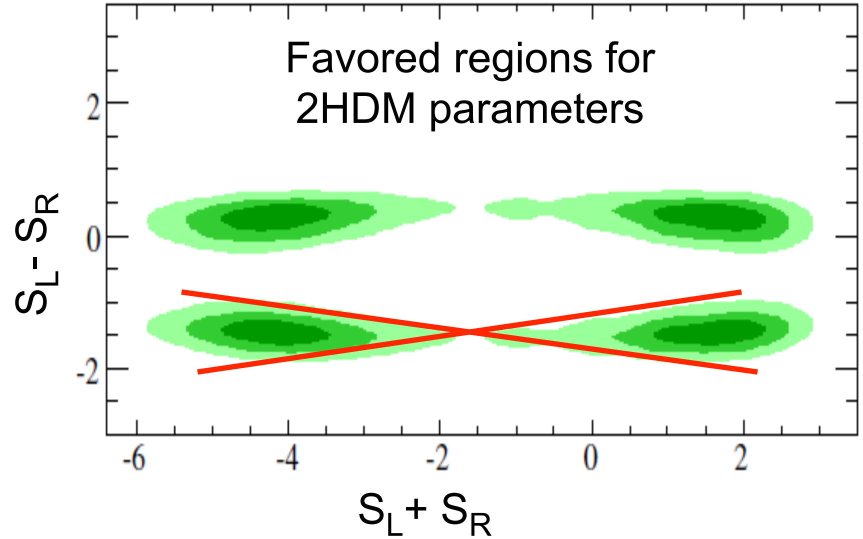
- For the type II 2HDM, $S_L = 0 \qquad S_R = -m_b m_\tau \tan^2\beta / m_{H^\pm}^2$

- For the type III 2HDM, real values of S_L and S_R in four regions :

- $S_L - S_R < 0$ is excluded by the observed large impact on the q^2 dependence for $D\tau\nu$

- The solutions with $S_L - S_R \sim +0.4$ only weakly impact the q^2 dependence for $D\tau\nu$, thus cannot be excluded.

- SM and other processes proceeding via P wave (spin1) appear to be favored.



Summary

- The isolation and reconstruction of the decay $B^+ \rightarrow \tau^+ \nu_\tau$ remains a challenge, currently limited by statistics, background uncertainties and efficiency corrections.

  Cleaner tagging techniques require much larger data sets.

  Relative measurements will further reduce uncertainties in efficiencies.

  New analyses and much larger data set from Belle II should solve this!

- The excess (3.4 σ) of events in $B \rightarrow D\tau\nu$ and $B \rightarrow D^*\tau\nu$ decays observed by BABAR remains puzzling.

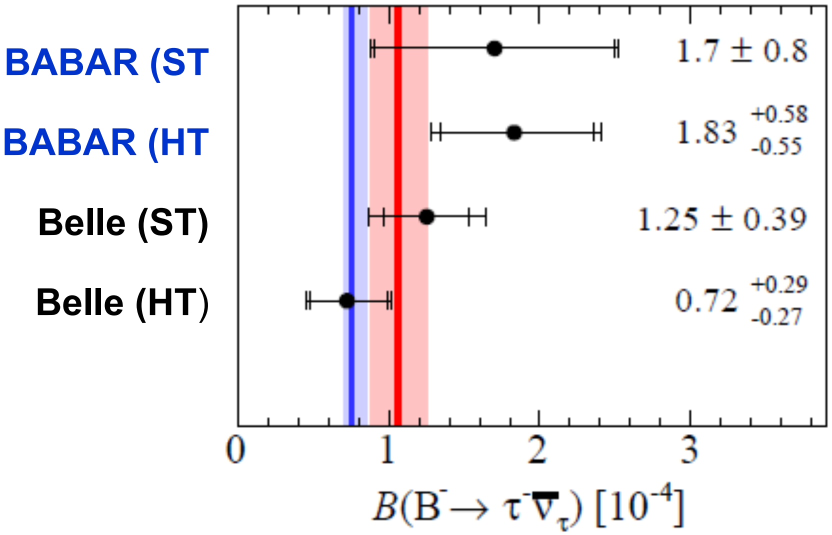
  It cannot be explained by a 2DHM Higgs of Type II, though extensions of 2HDM appear to work, as do NP contributions with spin 1 coupling.

  Confirmation by LHCb and Belle are encouraging, but stronger evidence needed – more data on R_D and differential distributions, τ helicity!

- More tests of theoretical interpretation are expected soon.

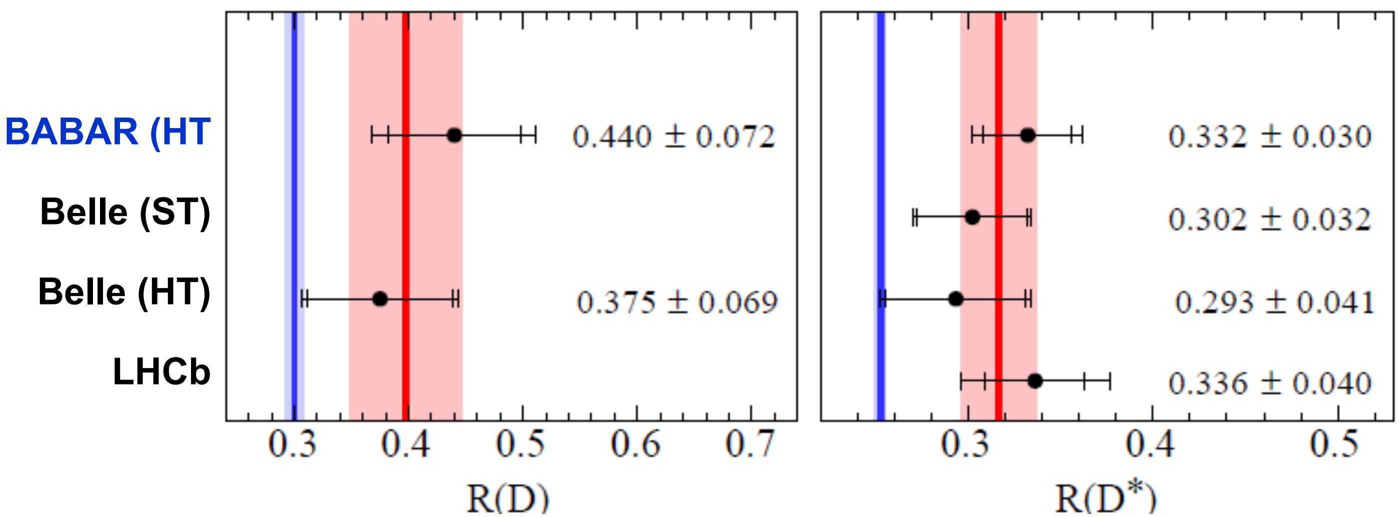
ご清聴あり\がとうございました

Current HFAG Averages



$$\mathscr{B}(B^- \to \tau^- \overline{\nu}_\tau) = (1.06 \pm 0.19) \times 10^{-4}.$$

$$\mathscr{R}(D) = 0.397 \pm 0.040_{\rm stat} \pm 0.028_{\rm syst},$$
$$\mathscr{R}(D^*) = 0.316 \pm 0.016_{\rm stat} \pm 0.010_{\rm syst}.$$



BABAR: Systematic Uncertainties $B^+ \to \tau^+ \nu_\tau$

Source	Relative Uncertainty (%)
Histogram PDF shapes	8.5
Continuum description	14.1
Signal reconstruction efficiency	0.6
Background branching fractions	3.1
Efficiency correction	12.6
τ decay branching fractions	0.2
Best candidate selection	0.4
Tracking efficiency	0.4
π^0 reconstruction efficiency	1.1
Efficiency of *PID* cut	0.5
Charged track veto	1.9
Number of $B\bar{B}$ pairs	1.4
Total	22.0

BABAR: Syst. Uncertainties $B^+ \to D(*)\tau^+\nu_\tau$

Source of uncertainty	Fractional uncertainty (%) $\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Additive uncertainties						
PDFs						
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0
$\bar{B} \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	0.3	0.2	0.2	0.1	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5	0.7	0.5	0.7	0.5
$\mathcal{B}(\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6
Cross-feed constraints						
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4
Isospin constraints	...	...	...	...	1.2	0.3
Fixed backgrounds						
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3
Multiplicative uncertainties						
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2
$\bar{B} \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	1.6	0.4	1.6	0.3	1.6	0.4
Lepton PID	0.9	0.9	0.9	0.8	0.9	0.9
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2
Total syst. uncertainty	12.2	6.7	11.4	6.0	9.6	5.6
Total stat. uncertainty	19.2	9.8	18.0	11.0	13.1	7.1
Total uncertainty	22.8	11.9	21.3	12.5	16.2	9.0

Cross Check on MC for Signal and Backgrounds

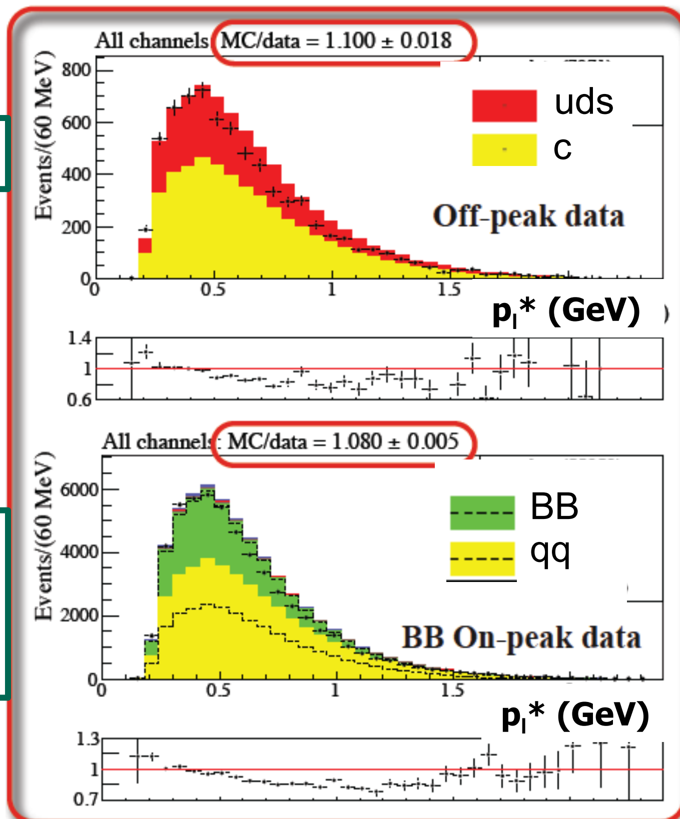
Detailed comparisons of data control samples with MC

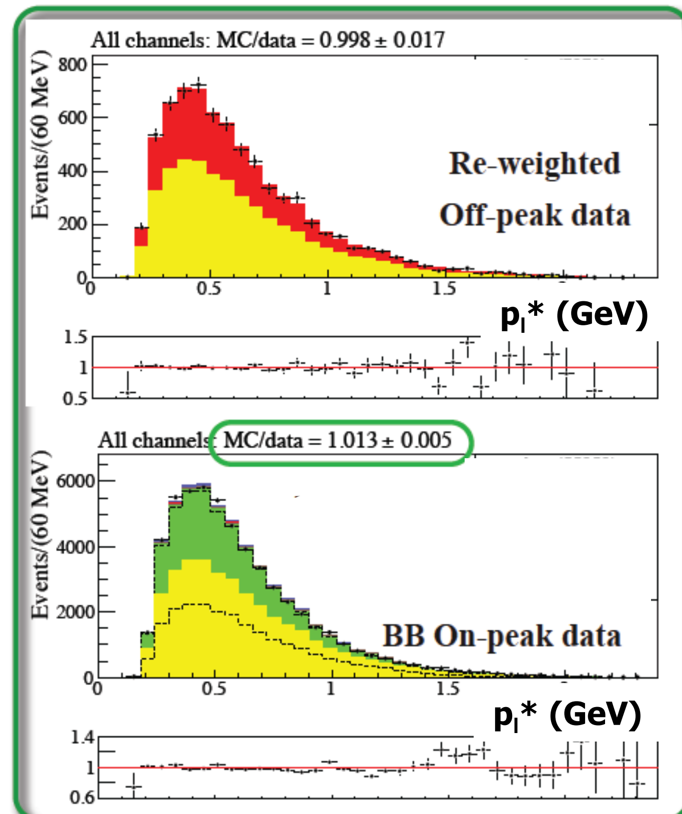
- Prior to fit (off and on resonance data) rescale distributions: p^*_l, m_{ES}, E_{extra}

Correct off-resonance p^*_l spectrum + use same correction for on-resonance

Off resonance data

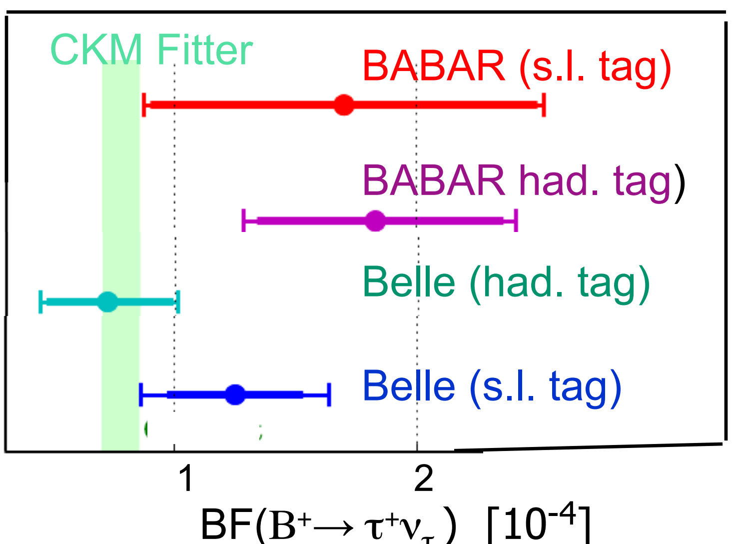
On resonance data
$1.2 < E_{extra} < 2.4$GeV
$E_{extra} = \Sigma E_\gamma$ (other)





Status $B^+ \to \tau^+\nu_\tau$ Measurements

Experiment	Tag	# Signal Events $e\nu\nu$	$\mu\nu\nu$	$\pi\nu$	$\rho\nu$	all	BF (10^{-4})
BABAR(2013)	Hadronic	4±9	13±20	17±6	24±10	62±17	1.83±0.53±0.24
Belle (2013)	Hadronic	16±11	26±15	8±10	14±19	62±23	0.72±0.27±0.11
BABAR (2010)	Semi. Lept.	40±16	13±16	9±19	12±11	74±35	1.7±0.8±0.2
Belle (2014)	Semi. Lept.	47±25	13±21	57±21	119±33	222±50	1.25±0.28±0.27



Most recent Belle result with s.l. tag much improved statistically, 2D fit improves systematics!

Estimated WA: (not be taken too seriously)

$BF(B^+ \to \tau^+\nu_\tau) = (1.06 \pm 0.19)\ 10^{-4}$

To be compared with CKM fitter:

$BF(B^+ \to \tau^+\nu_\tau) = (0.753 \pm 0.102)\ 10^{-4}$