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

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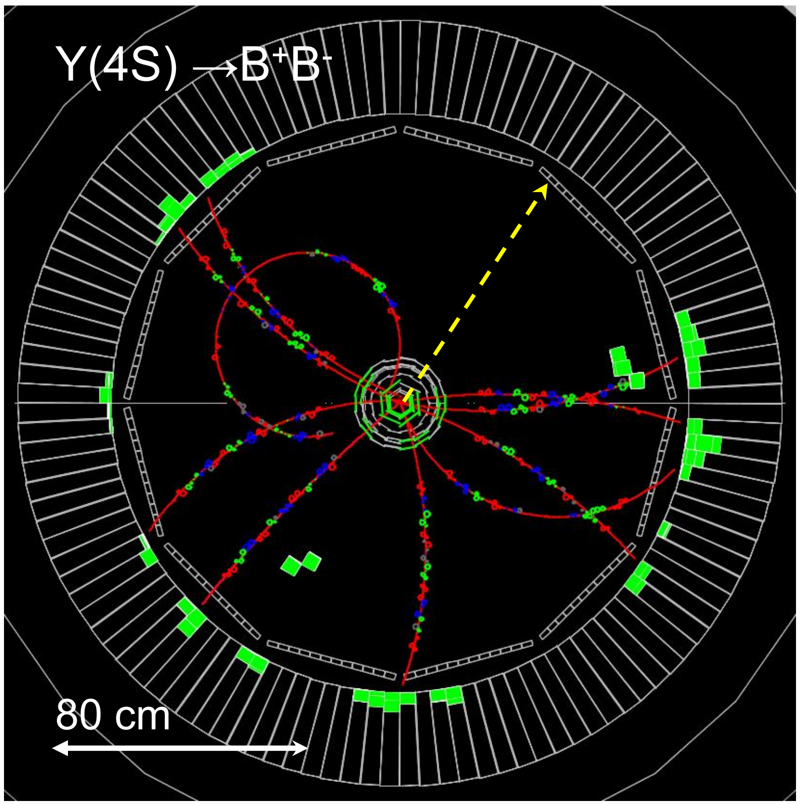
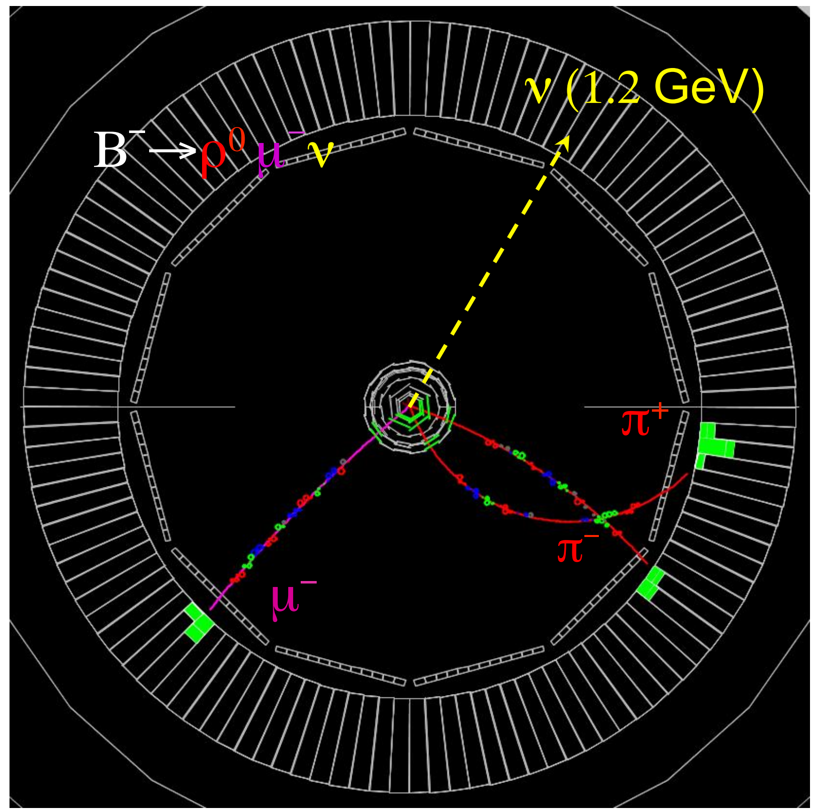
$B^+ \to \tau^+\nu_\tau$ and $B \to D^{(*)}\tau^+\nu_\tau$ Measurements

- 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 non-$B\bar{B}$ and other $B\bar{B}$ events
- Solutions
  - Full reconstruction of $\Upsilon(4S) \to B\bar{B}$ events,
  - Conservation of total charge and flavor quantum numbers
  - Tagging of one B decays determines kinematics of second B meson
    - hadronic ~ 0.3 – 0.8%
    - s.l. decay ~ 1-3 %
    - Inclusive ~ 3-5%
  - Signal:
    - for $B^+ \to \tau^+\nu_\tau$: 1 charged track from $\tau \to e^+\nu\nu, \mu^+\nu\nu, \pi^+\nu, \rho^+\nu$
    - for $B \to D^{(*)}\tau^+\nu_\tau$: in addition D and D* decays

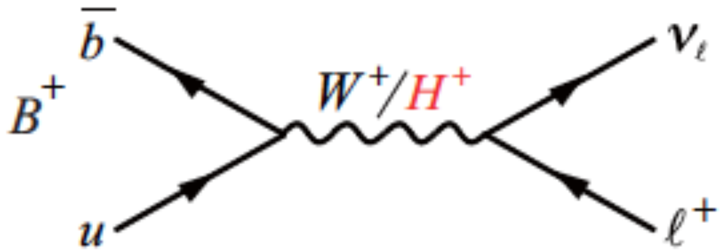
Reconstruction of $\Upsilon(4S) \rightarrow B\bar{B}$ Decays

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+_{tag}\ B^-_{signal}$





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



In the SM, this decay proceeds via quark annihilation and the BF is given by

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

All hadronic effects are encapsulated by the B decay constant, which can be calculated in Lattice QCD: $f_B = 0.191 \pm 0.009$ GeV.

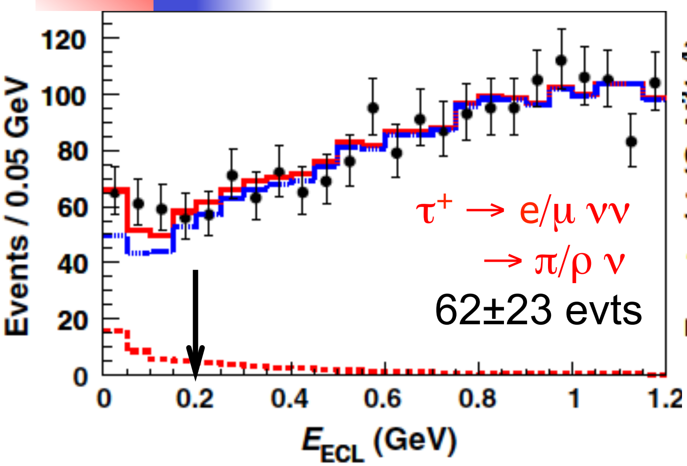
The latest CKM Fitter results in a SM prediction of

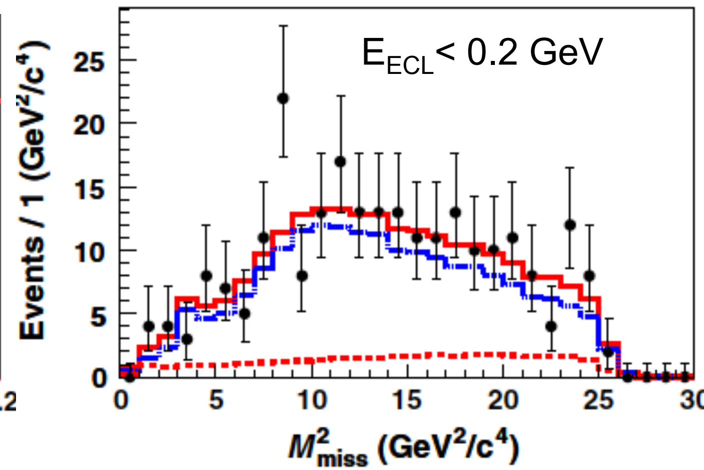
$$BF(B^+ \to \tau^+\nu_\tau) = (0.753 \pm 0.102)\, 10^{-4}$$

In the context of the Type II 2HDM, the charged Higgs modifies the BF

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

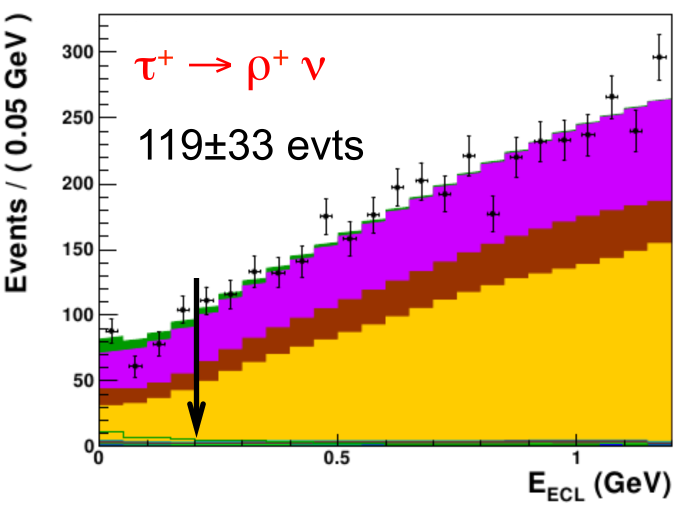
Recent Results: Full Belle Data Set $B^+ \to \tau^+ \nu_\tau$

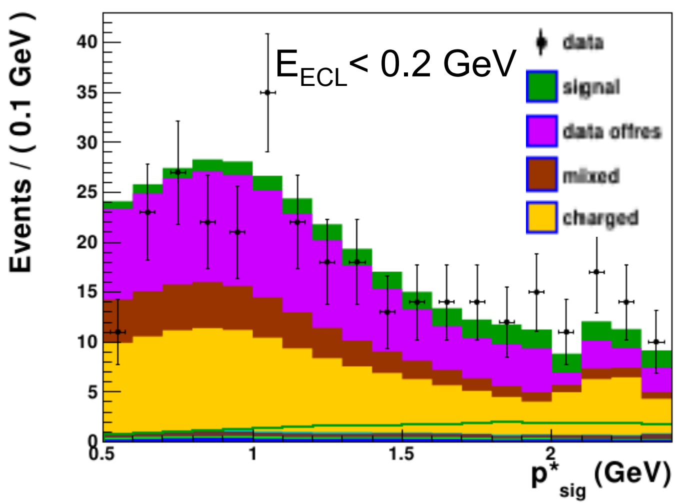




PRL 110, 131801 (2013)

- Highly efficient hadronic B tag
  $\varepsilon_{tag} \times \varepsilon_{sig} = 0.11\%$
- Combined fit to 4 modes, PDFs from 1-dim. hist. of E_{ECL} and M^2_{miss} for signal and sum of BGs



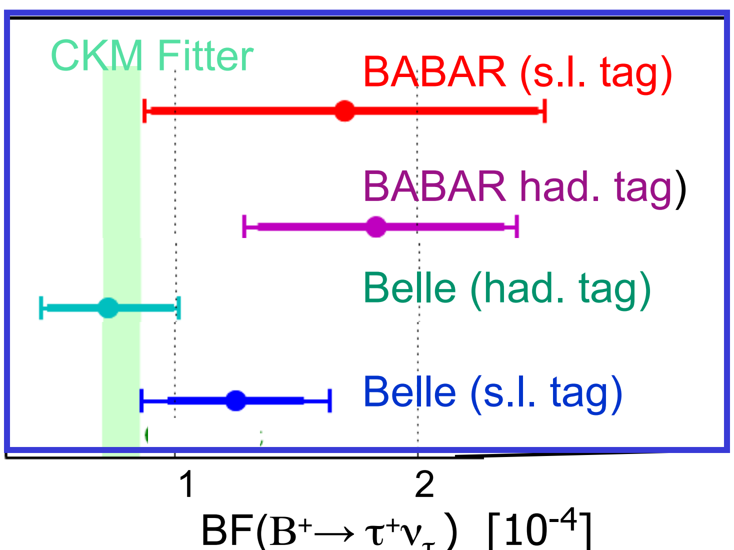


arXiv: 1409.5269 (2014)

- S.L. Tag: $B^+ \to D^{(*)0} e/\mu^+ \nu$
  $\varepsilon_{tag} \times \varepsilon_{sig} = 0.23\%$
- ML fit to 4 τ decay modes, PDFs from E_{ECL} vs P_{sig} . for signal and BGs,
  1-D for $\tau \to e\nu\nu$, $\mu\nu\nu$
  2-D for $\tau \to \pi\nu$, $\rho\nu$
- Systematics dominated by non-$B\bar{B}$ and efficiencies!

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!

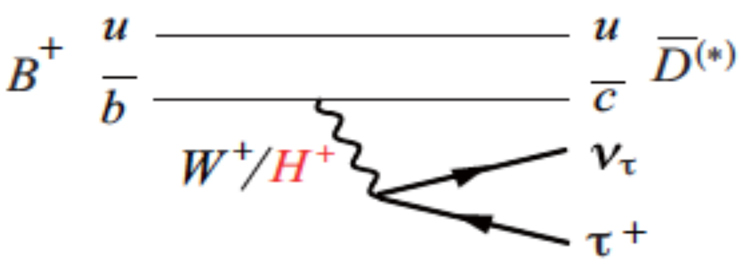
Estimated WA:

$BF(B^+ \to \tau^+\nu_\tau) = (1.10 \pm 0.22)\ 10^{-4}$

To be compared with CKM fitter:

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

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



Z. Phys, C46, 93 (1990)

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

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

For $D\tau\nu$, H_+ and H_- do not contribute!

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

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

- 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 $\tan\beta/m_H$

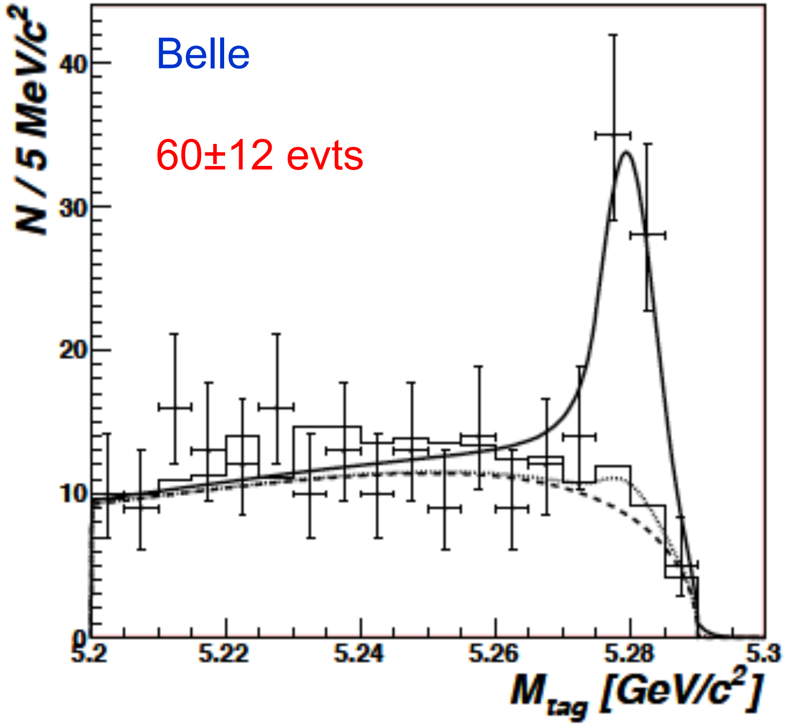
Belle: First Observation of $B^0 \to D^{*-} \tau^+ \nu_\tau$

- Belle reported the 1st observation of $B^0 \to D^{*-} \tau^+ \nu_\tau$ using the following sequence
  - Identify B^0 signal candidates
  - Check consistency of remaining tracks with a hadronic $\bar{B}^0$ decay (inclusive)
  - Check tag on control sample with $B^0 \to D^{*-} \pi^+$
  - Reduce BG by
    - Restriction on M_{tag} and ΔE_{tag} distribution
    - Signal kinematic variables: E_{vis}, E_{miss}, X_{mis}
- Extract signal yield from ML fit to M_{tag} distribution

  Signal PDF: Crystal Ball fct

  BG PDF: Argus fct. + peaking BG
- Comparable stat. and syst. uncertainties, dominated by fit fct. uncertainties.

PRL 99, 191807 (2007)



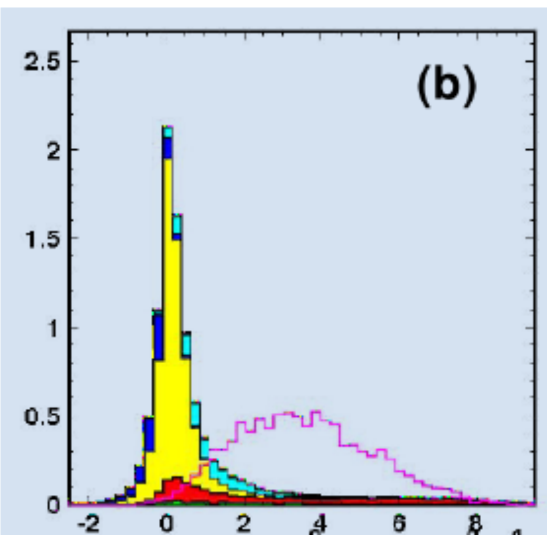
$$BF(B^0 \to D^{*-} \tau^+ \nu_\tau) = (2.02 \pm 0.40 \pm 0.37)\ \%$$

Belle: $B^+ \rightarrow \bar{D}^{(*)0} \tau^+ \nu_\tau$ Kinematic Discrimination

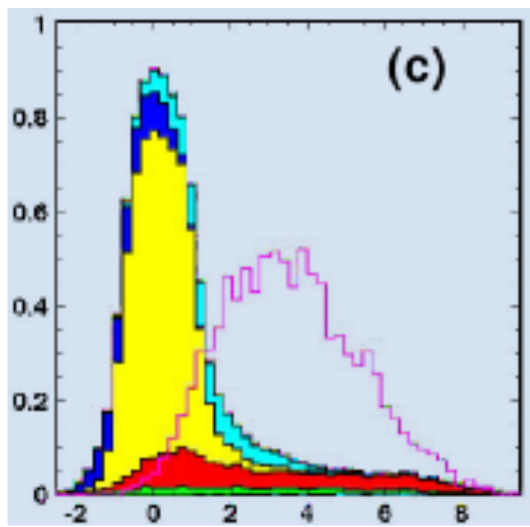
- 2nd Belle analysis extends inclusive hadron tag method
- BG reduction from a number of kinematic variables

M_{tag}, ΔE_{tag}, E_{D*}, X_{miss}, E_{vis}, q^2, R_2

PRD 82, 072005 (2010)

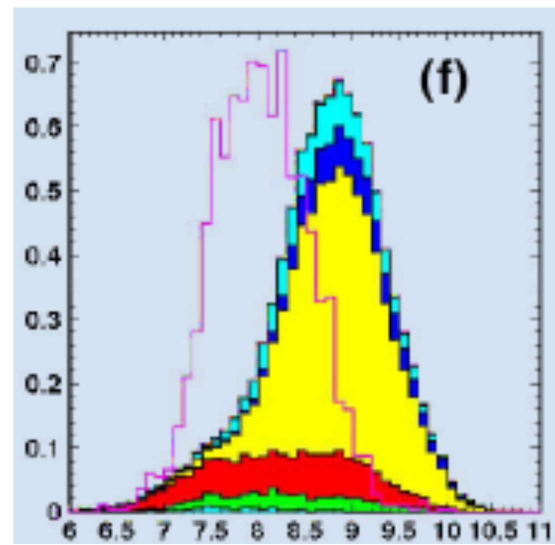


$M^2_{miss} = E^2_{miss} - (P_{sig} - P_{D(*)} - P_x)^2$



$X_{miss} = (E_{miss} - |p_{D*} + P_x)/p_{beam}$

$> 2.0 \rightarrow 2.75$ GeV

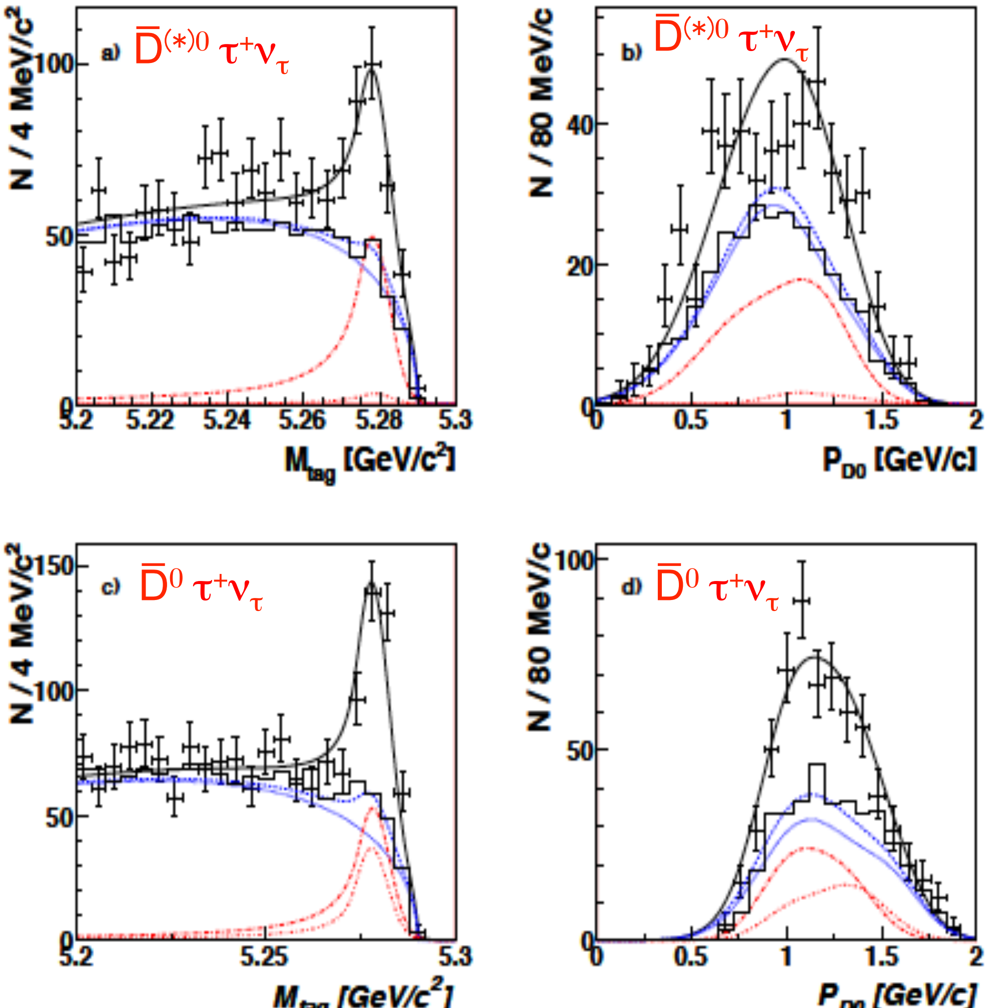


$E_{vis} = \Sigma E_\iota$

$> 8.3 \rightarrow 8.5$ GeV

Belle: $B^+ \to \bar{D}^{(*)0} \tau^+ \nu_\tau$ Signal Extraction

PRD 82, 072005 (2010)



Signal and combinatorial BG extracted from unbinned ML fit to two B_{tag} distributions, parameterized as sum of two functions:

Mass M_{tag}: Signal: "Crystal Ball" function
BG: "Argus" Function

Momentum $P_{D(*)}$
Signal: Sum of 2 Gaussians
BGs: Sum of 2 Gaussians

Decay	# Signal Evts	BF(%)
D^{*0} τν	446±58 (226)	2.12±0.28±0.29
D^0 τν	146±42 (15)	0.77±0.22±0.12

Number in parentheses indicate D (D*) signal extracted from D* (D) distributions!

Systematic uncertainties of 15% dominated by reconstruction of signal and tag B decays

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

- To test the SM Prediction, BABAR measures the ratios

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

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

BABAR, PRL 101802 (2012)

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

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

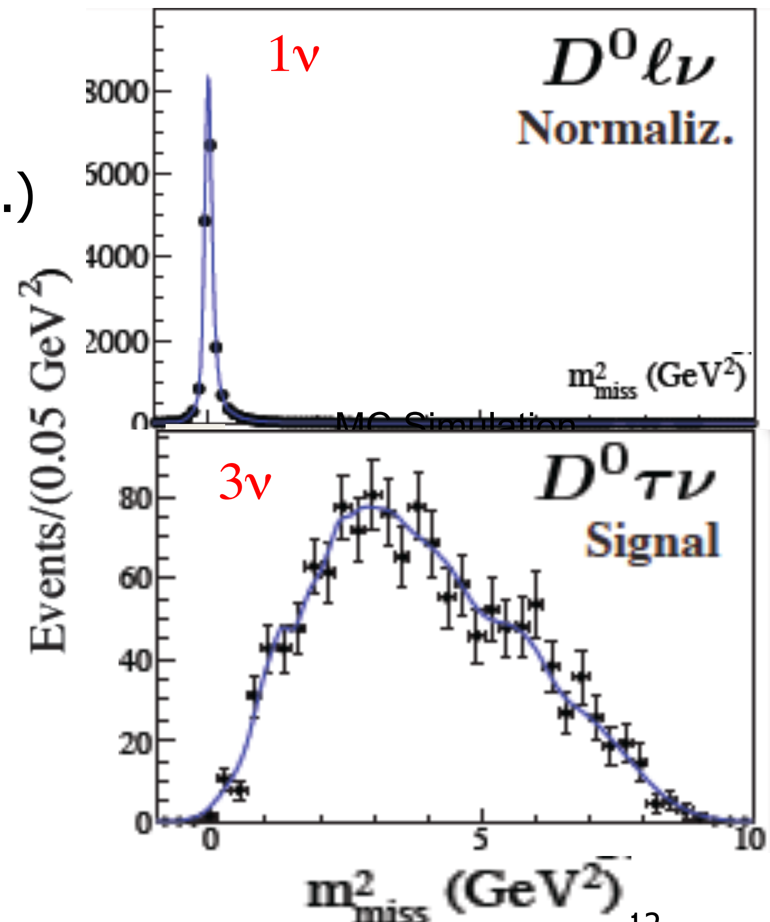
- Full BABAR data sample, MC corrections based on data control samples

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

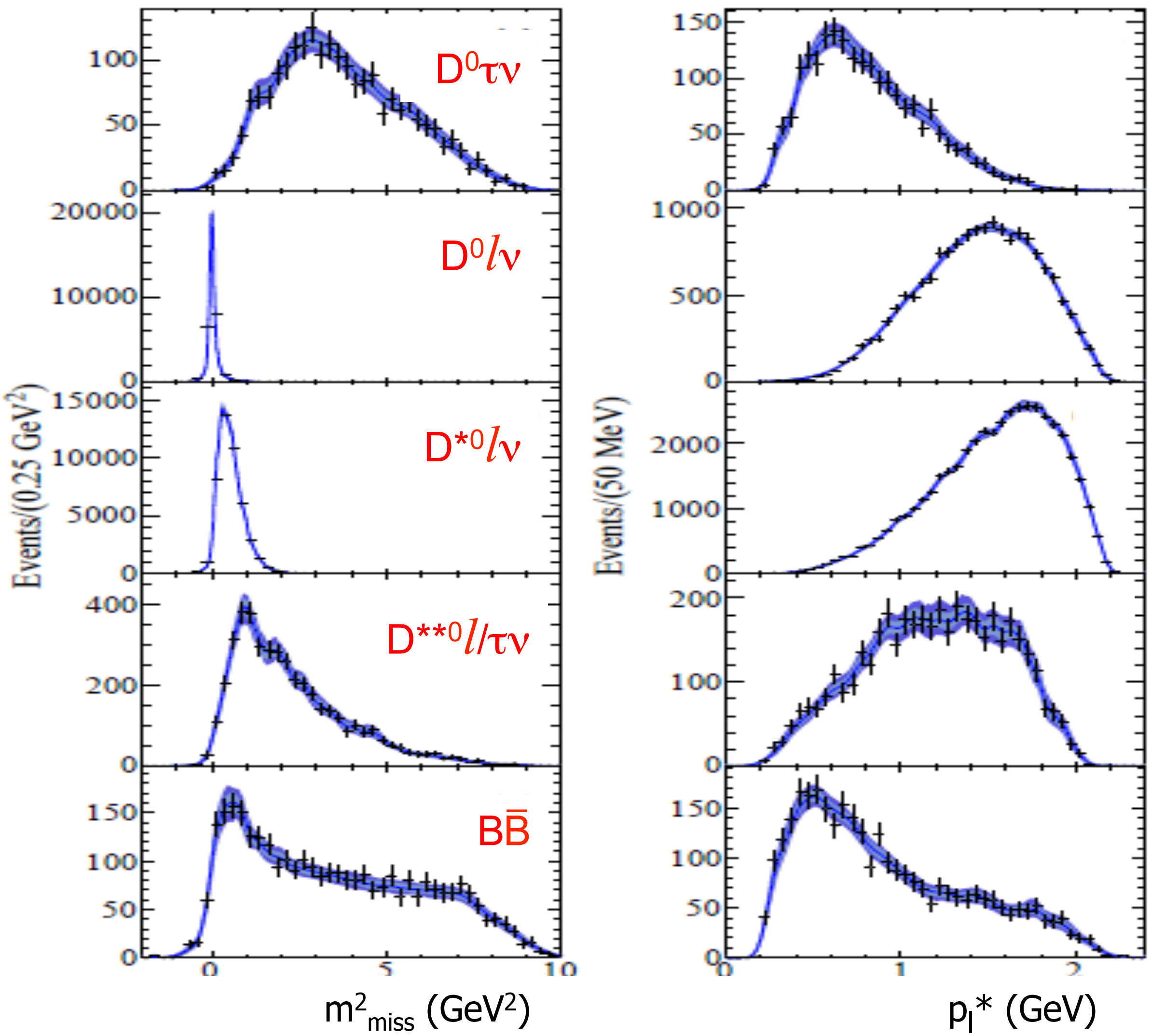
$$m^2_{miss} = (P_{ee} - P_{Btag} - P_{D(*)} - P_\ell)^2$$
Missing mass sq

p^*_ℓ Lepton momentum in B rest frame

- Unbinned M.L. fit
  - 2-D distributions:
  - 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
  - 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
  - Continuum $e^+e^- \to f\bar{f}$ (γ)



2-D PDFs Based on Keys Functions (56 total)

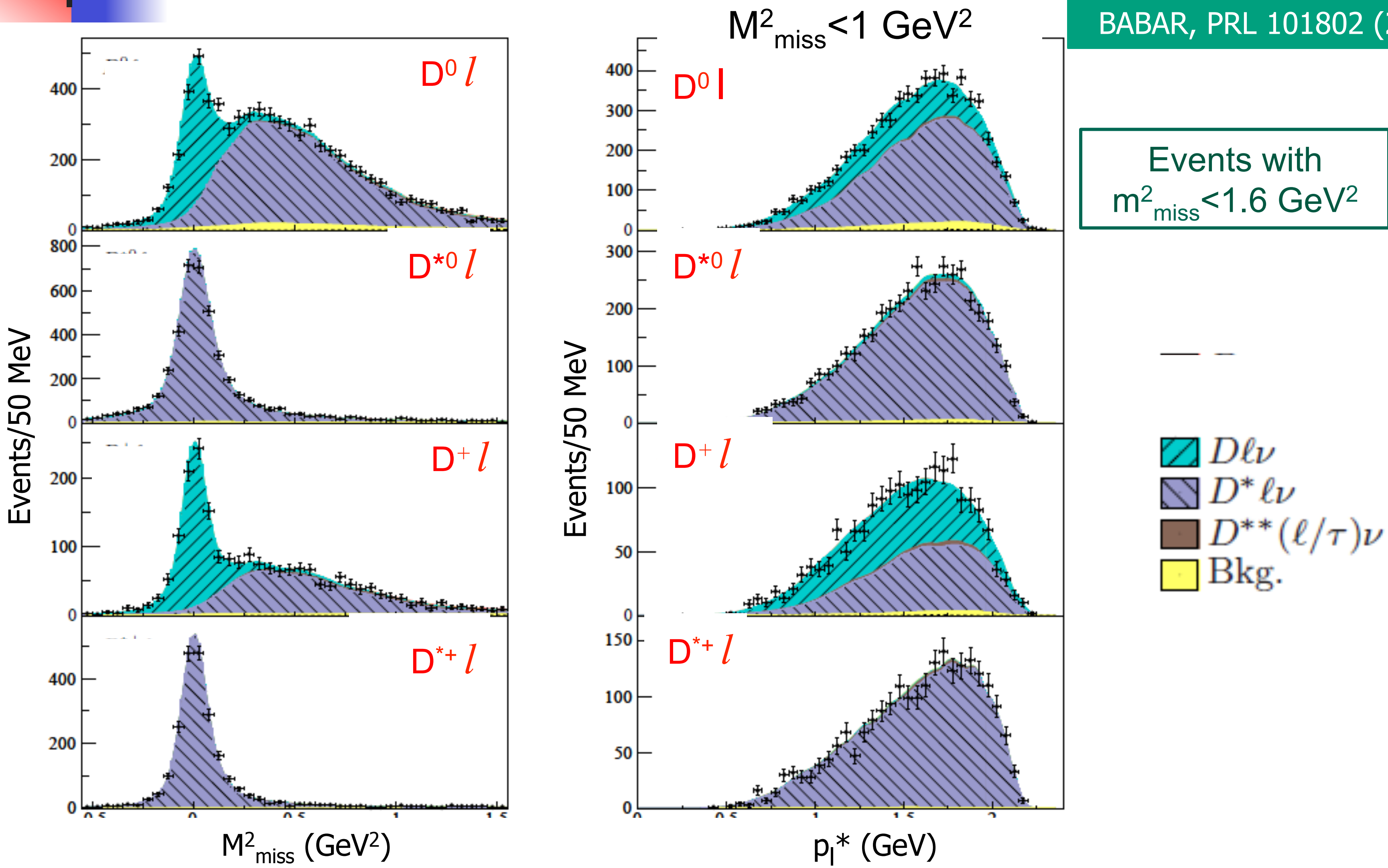


- 2-D m^2_{miss} vs p^*_l, difficult to describe analytically
  - correlations
  - irregular functions
- Solution
  - non-parametric Kernal Estimators (KEYS)
  - optimize bias vs variance (smoothing)

Blue bands mark 2σ variations due to the stat. uncertainties of MC samples

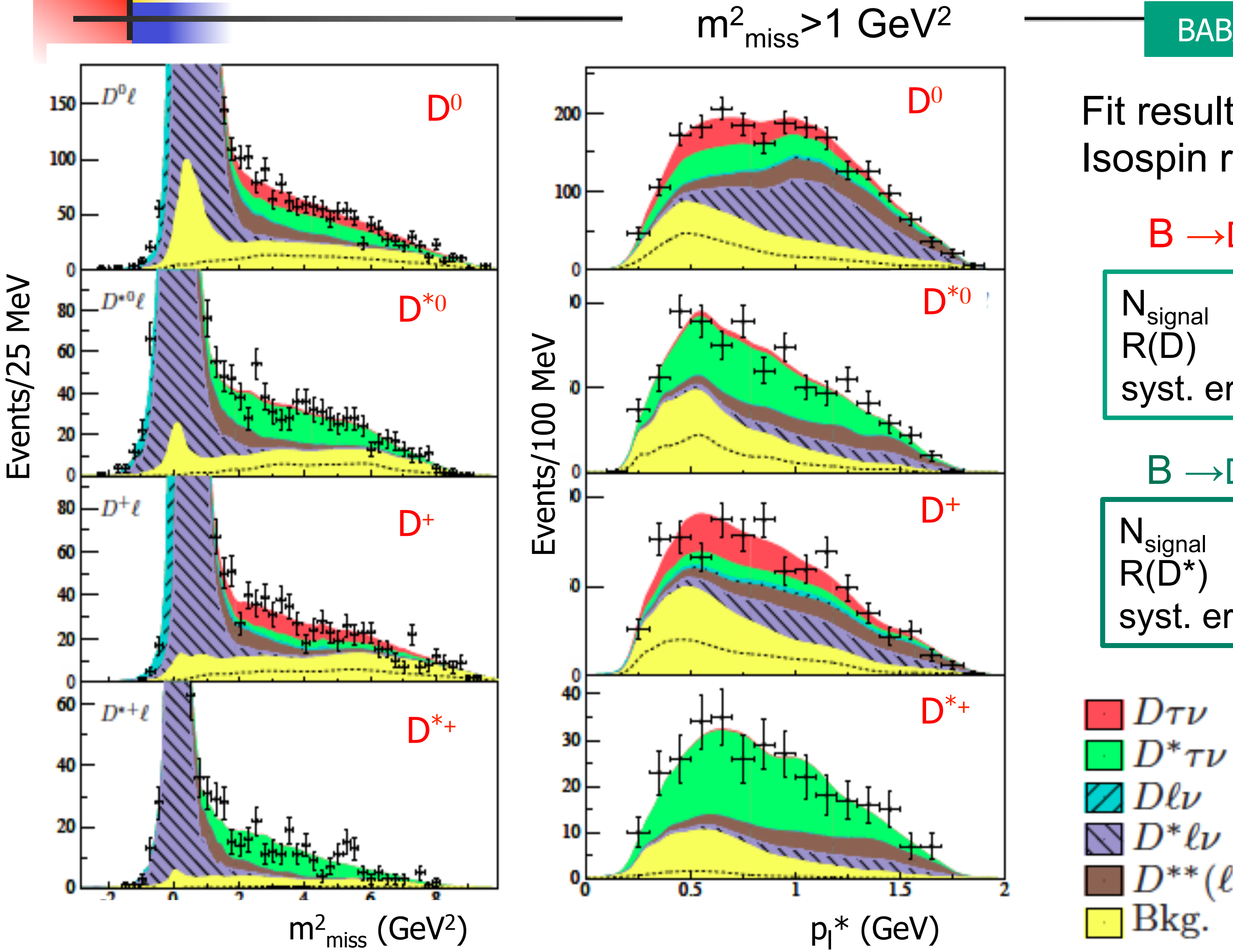
Fit Results: Normalization $B \to D^{(*)} l \nu$

BABAR, PRL 101802 (2012)



Results of Fit: B→ Dτν and B→ D*τν

BABAR, PRL 101802 (2012)



Fit results, combined using Isospin relations:

B →D τ ν

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

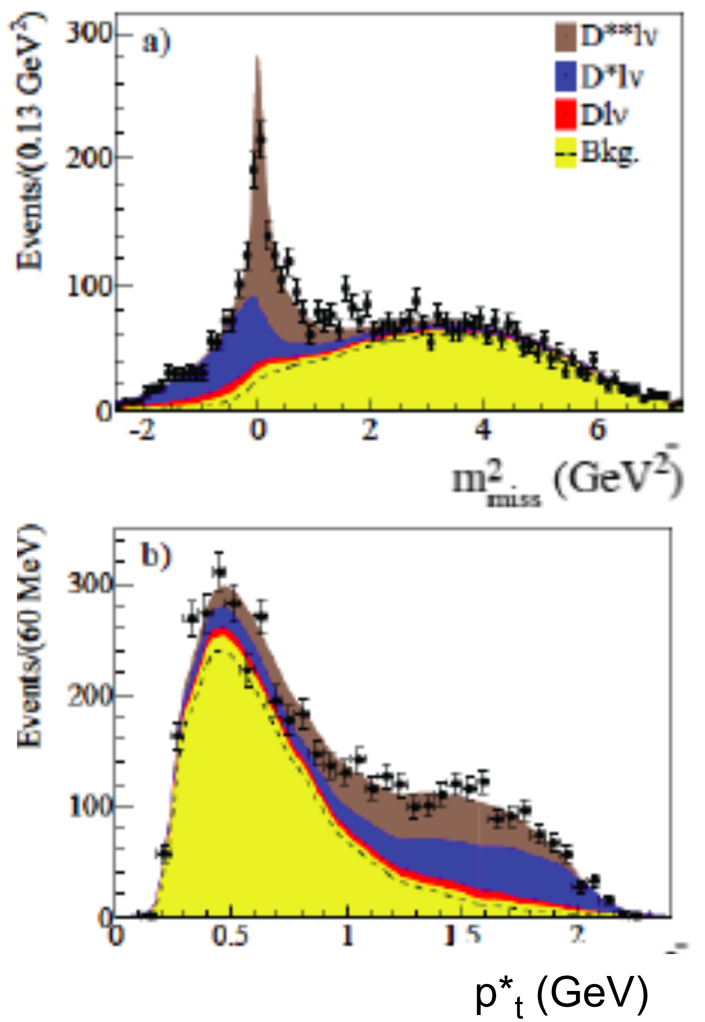
B →D* τ ν

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

Systematic Uncertainties

Source	Uncertainty (%) $\mathcal{R}(D)$	$\mathcal{R}(D^*)$	ρ
$D^{**}\ell\nu$ background	5.8	3.7	0.62
MC statistics	5.0	2.5	-0.48
$q\bar{q}$ and $B\bar{B}$ bkg.	4.9	2.7	-0.30
$\epsilon_{sig}/\epsilon_{norm}$	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 the sum of the 4 channels:

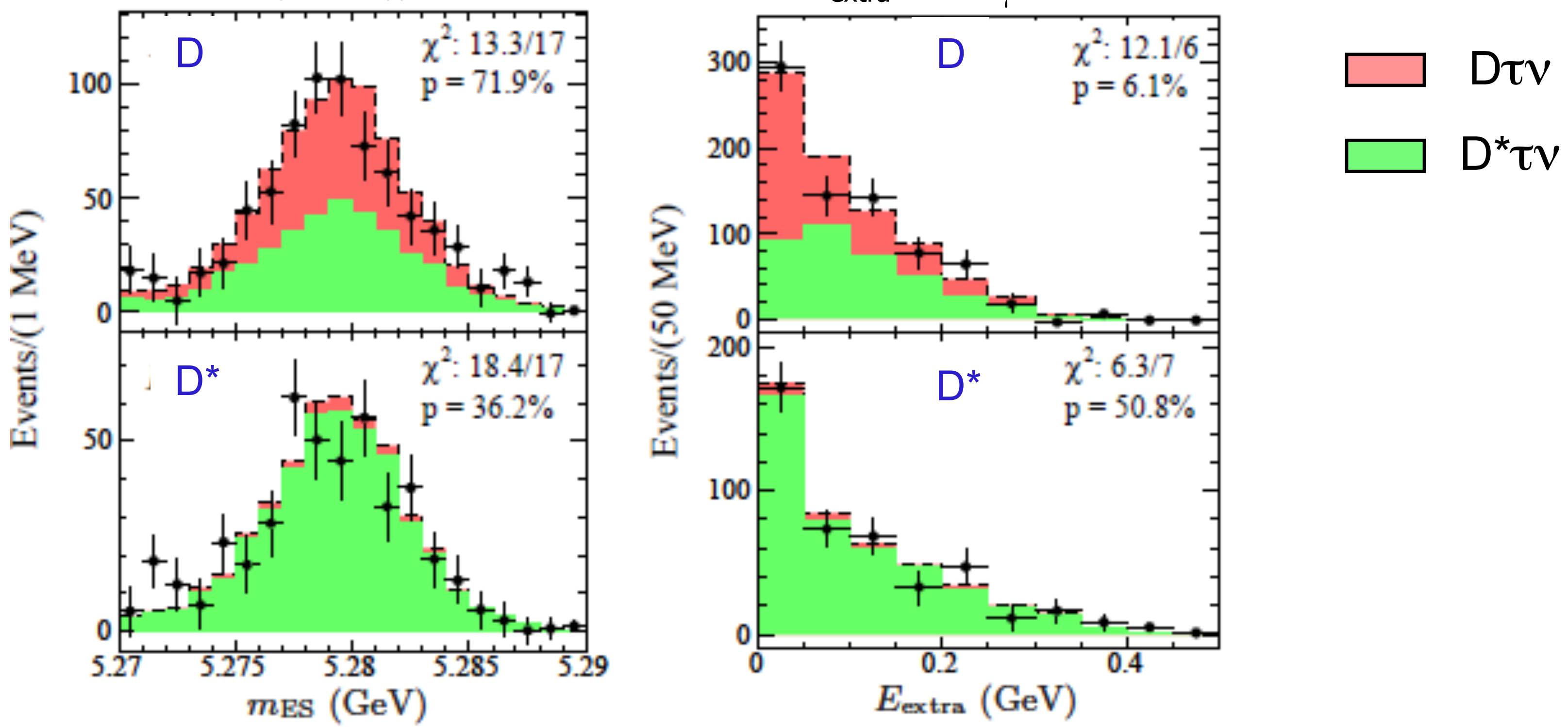
$D^0\pi^0 l\,\nu$, $D^{*0}\pi^0 l\,\nu$,
$D^+\pi^0 l\,\nu$, $D^{*+}\pi^+ l\,\nu$

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)

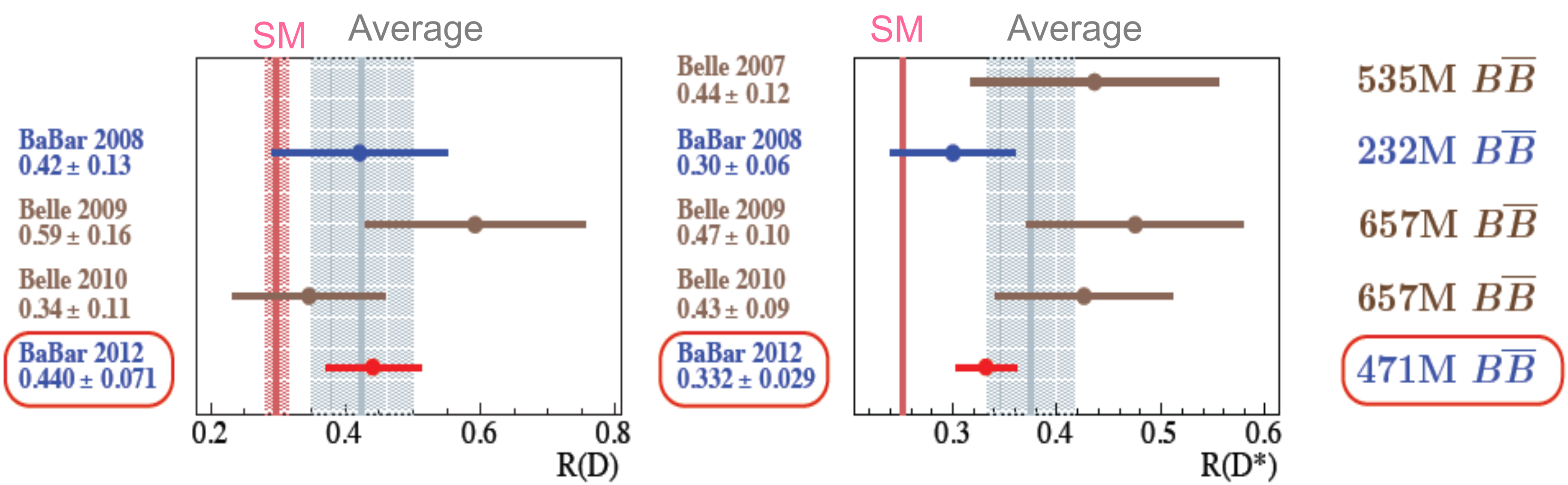
Background subtracted distributions $B \to D^{(*)}\tau\nu$ (post-fit)

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



Comparison to Previous Measurements

NB: Average does not include this measurement



The new measurements are fully compatible with earlier results!

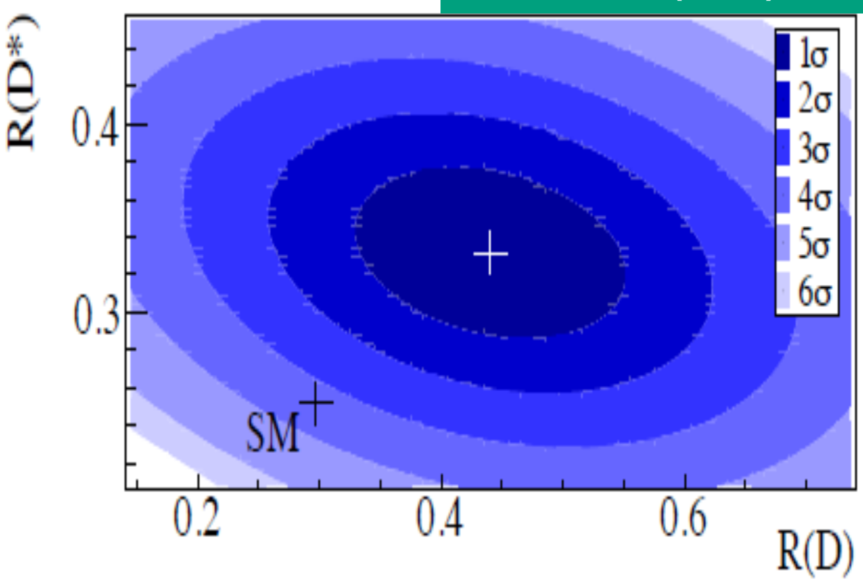
S.M. Predictions of R(D) and R(D*)

SM:
Z. Phys, C46, 93 (1990)
PRD 82, 0340276 (2010)
PRD 85, 094025 (2012)
and recent updates

Comparison with S.M. calculation:

	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.297 ± 0.017	0.252 ± 0.003
Difference	2.0 σ	2.7 σ

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



The combination of the two measurements (-0.27 correlation) yields χ^2/NDF=14.6/2, i.e. Prob. = 6.9 x10^{-4} !!

The data are inconsistent with the SM prediction at 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

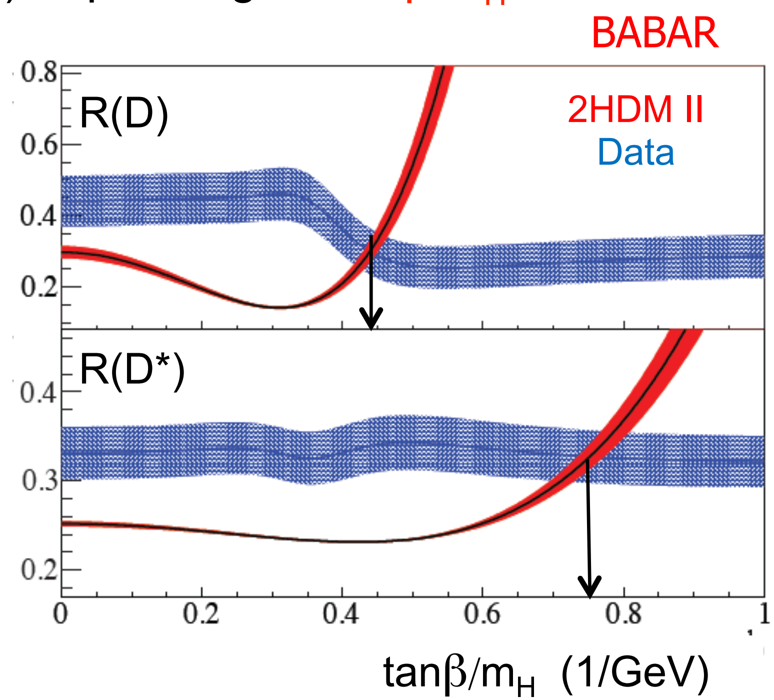
$$H_s^{2HDM} = H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_{H\pm}^2}\frac{q^2}{1 \mp m_c/m_b}\right)$$

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

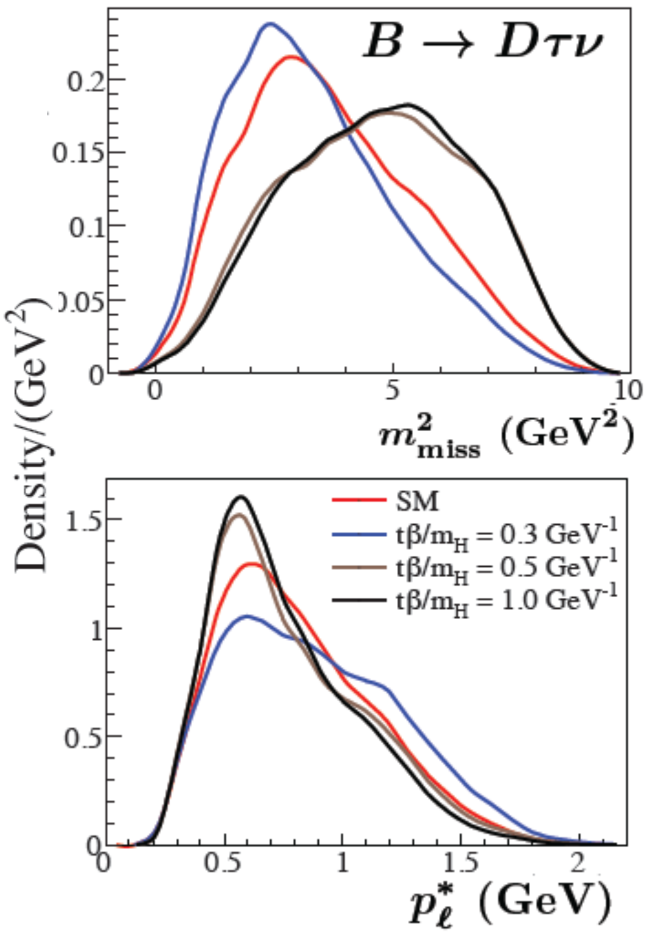
PRD 78, 015006 (2008)
PRD 85, 094025 (2012)

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

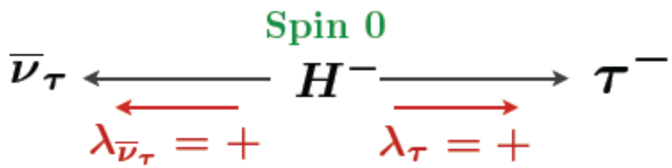
- We estimate the effect of 2HDM, accounting for difference in signal yield and efficiency.
- The data match 2HDM Type II contribution at
  $\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)
  $\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)
- The combination of R(D) and R(D*) excludes the Type II 2HDM in the full $\tan\beta$-m_H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



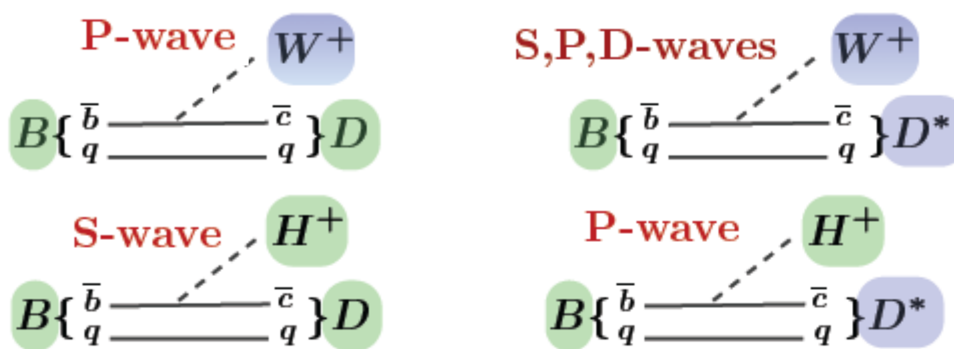
Dependence of MC Signal Yield on 2HDM II



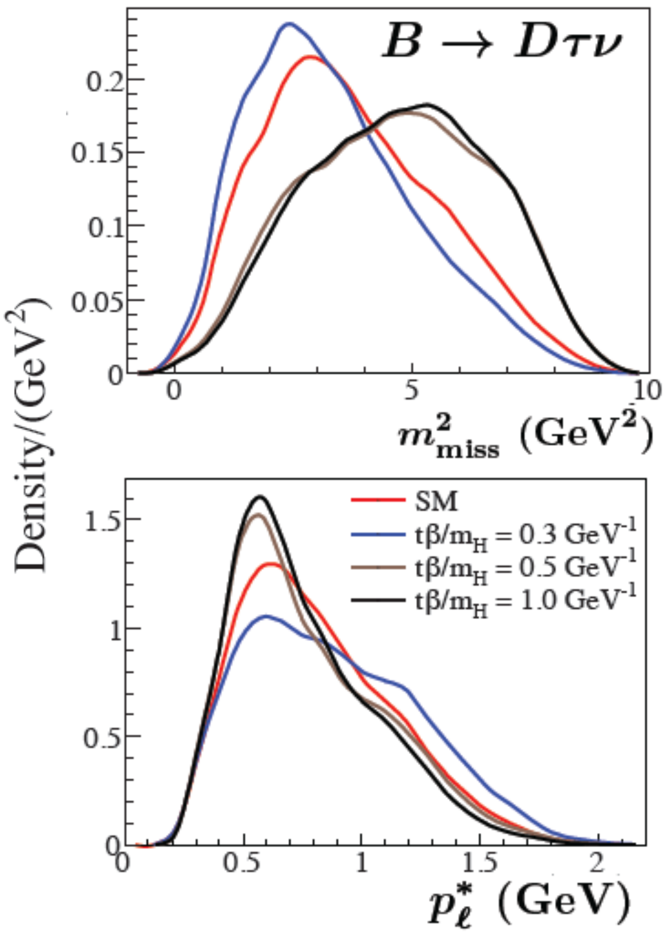
- τ Polarization in B→Dτν Decays
  - SM LH: 70%. RH: 30%
  - 2HDM LH: 0% RH: 100%

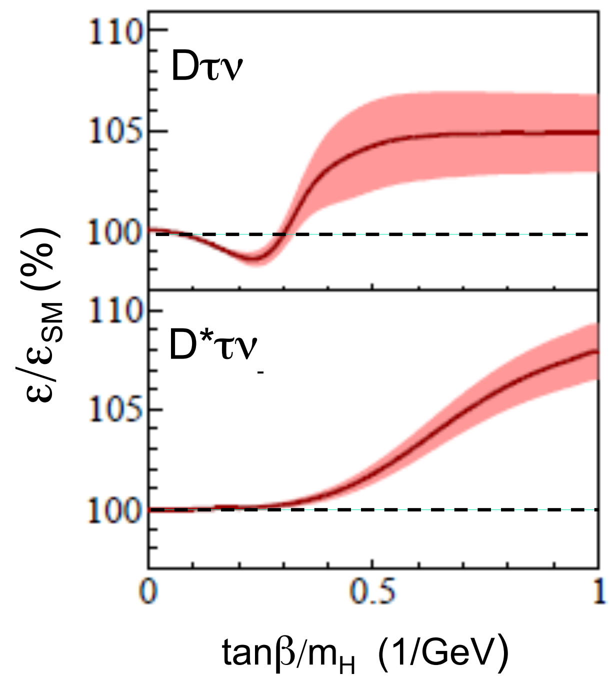


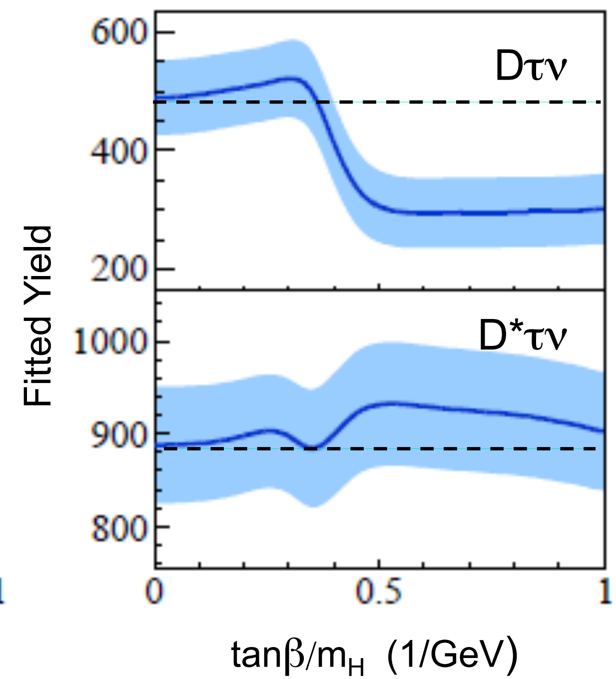
- Impact on fitted distributions large for B→Dτν
  - missing mass sq: $m^2_{miss} \sim q^2$
  - p^*_l, momentum of secondary lepton from $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ decays in B rest frame



Dependence of MC Signal Yield on 2HDM II





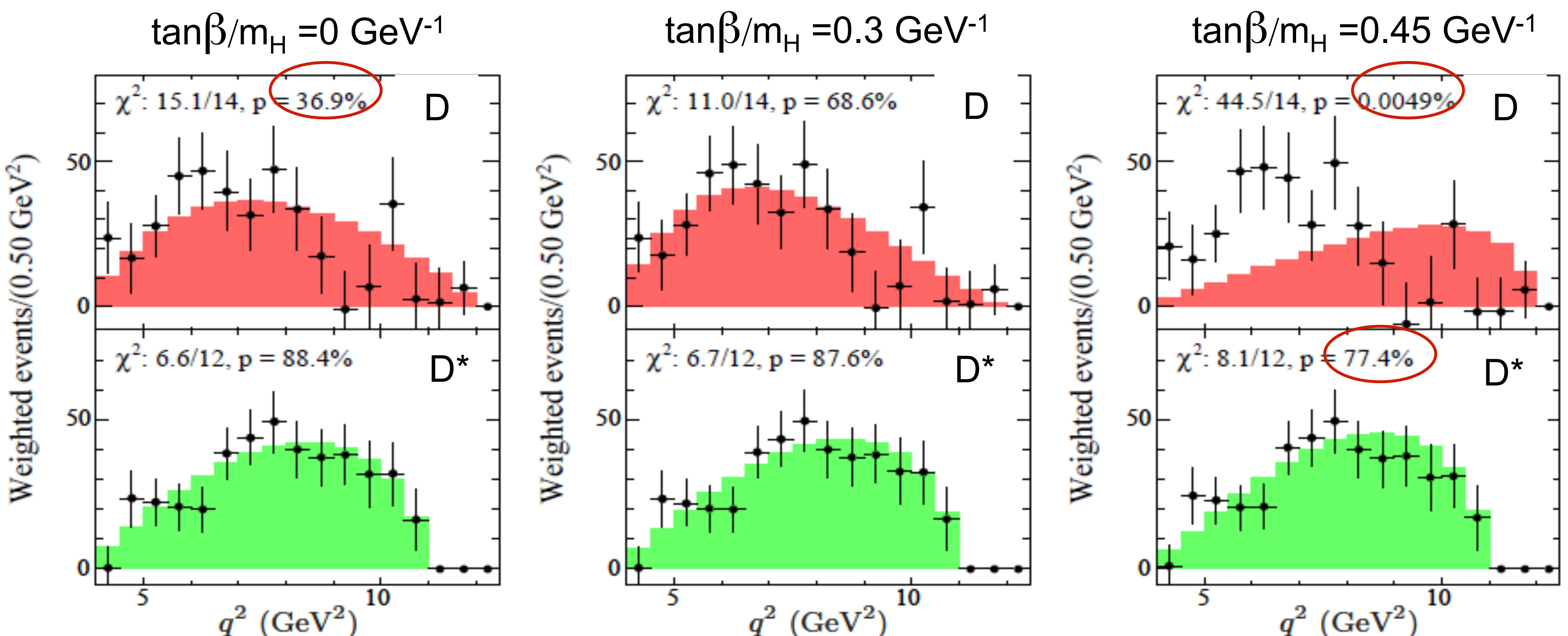


- Change in tanβ/m$_H$ impacts m^2_{miss} :
  - detection efficiency 5-10% for Dτν and D*τν
  - fitted signal yield 40% for Dτν

Impact of 2HDM II on q^2 Distribution

BABAR, Phys. Rev. D88, 072012 (2013)

- q^2 is closely related to m^2_{miss}: $m^2_{\rm miss} = (\underbrace{p_{e+e-} - p_{B_{\rm tag}} - p_{D^{(*)}}}_{q} - p_\ell)^2$
  - $D^*\tau\nu$: small impact on q^2 as expected
  - $D\tau\nu$: for $\tan\beta/m_H \geq 0.45$ GeV^{-1} the 2HDM type II is excluded at 2.9 σ, other 2HDM with small scalar terms cannot be excluded ,
  - Also, NP with spin 1 can explain the excess in R(D(*)) and do not impact q^2



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 may further reduce uncertainties in efficiencies.

  New analyses and much larger data set by Belle II should address this!

  May be LHC_b will surprise us ??

- The excess (3.4 σ) of events in $B \rightarrow D \tau \nu$ and $B \rightarrow D^* \tau \nu$ decays observed by BABAR in 2012 remains puzzling.

  This 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.

  Results from Belle and LHC_b are expected very soon.

Merci de votre attention

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

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

Cross Check on MC for Signal and Backgrounds

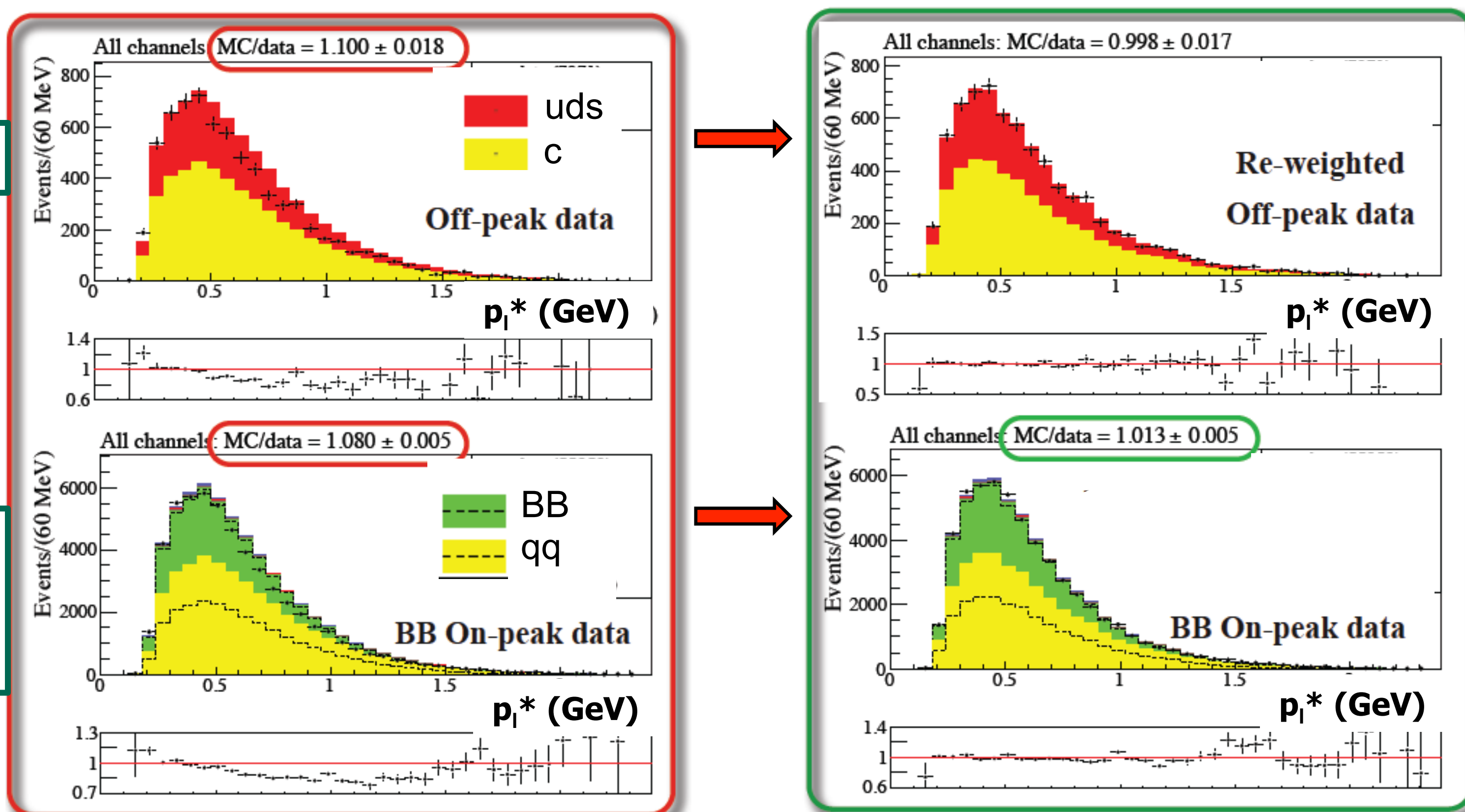
Detailed comparisons of data control samples with MC

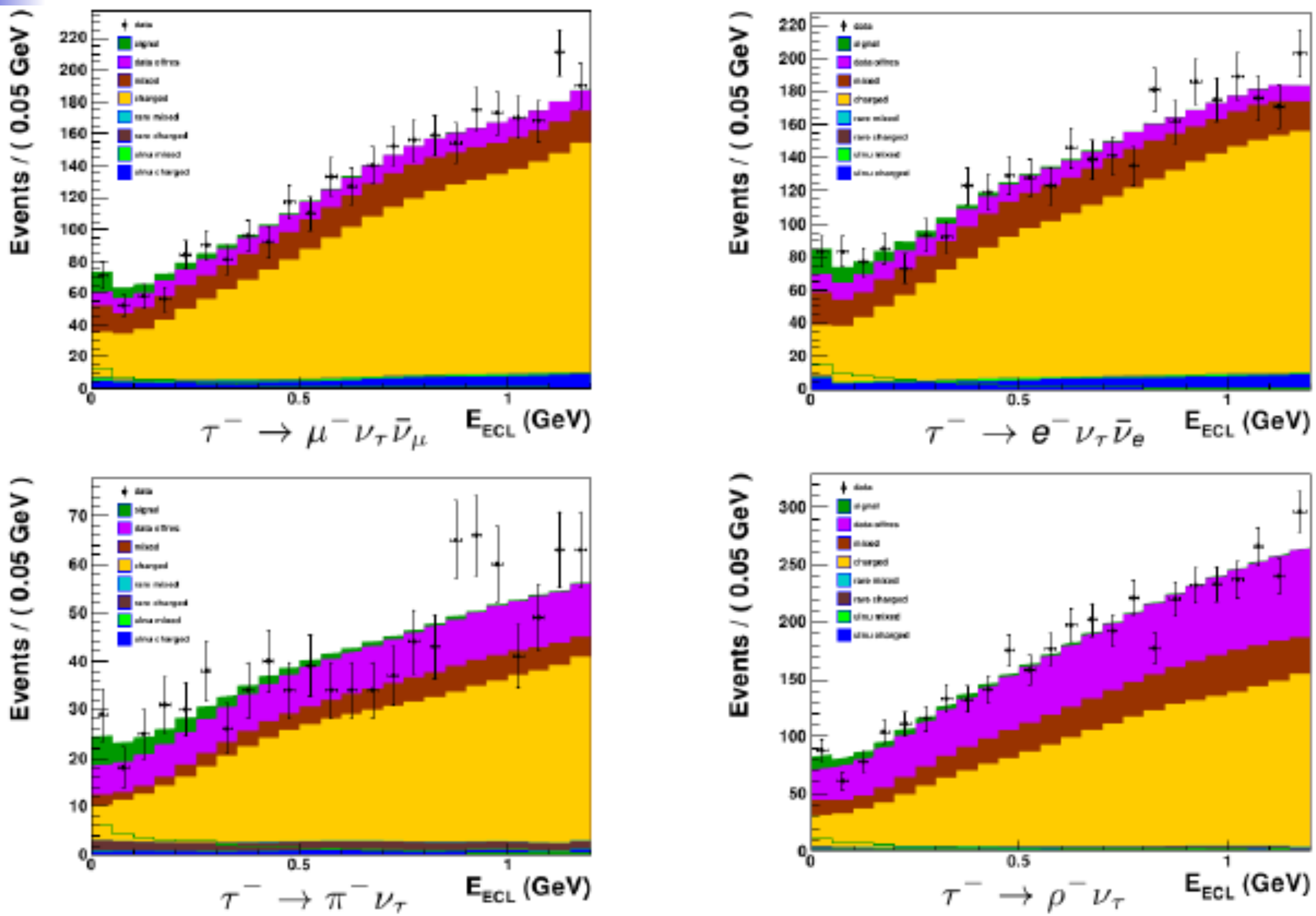
- Prior to fit (off and on resonance data) rescale distributions: p^*_l, m_{ES}, E_{extra}

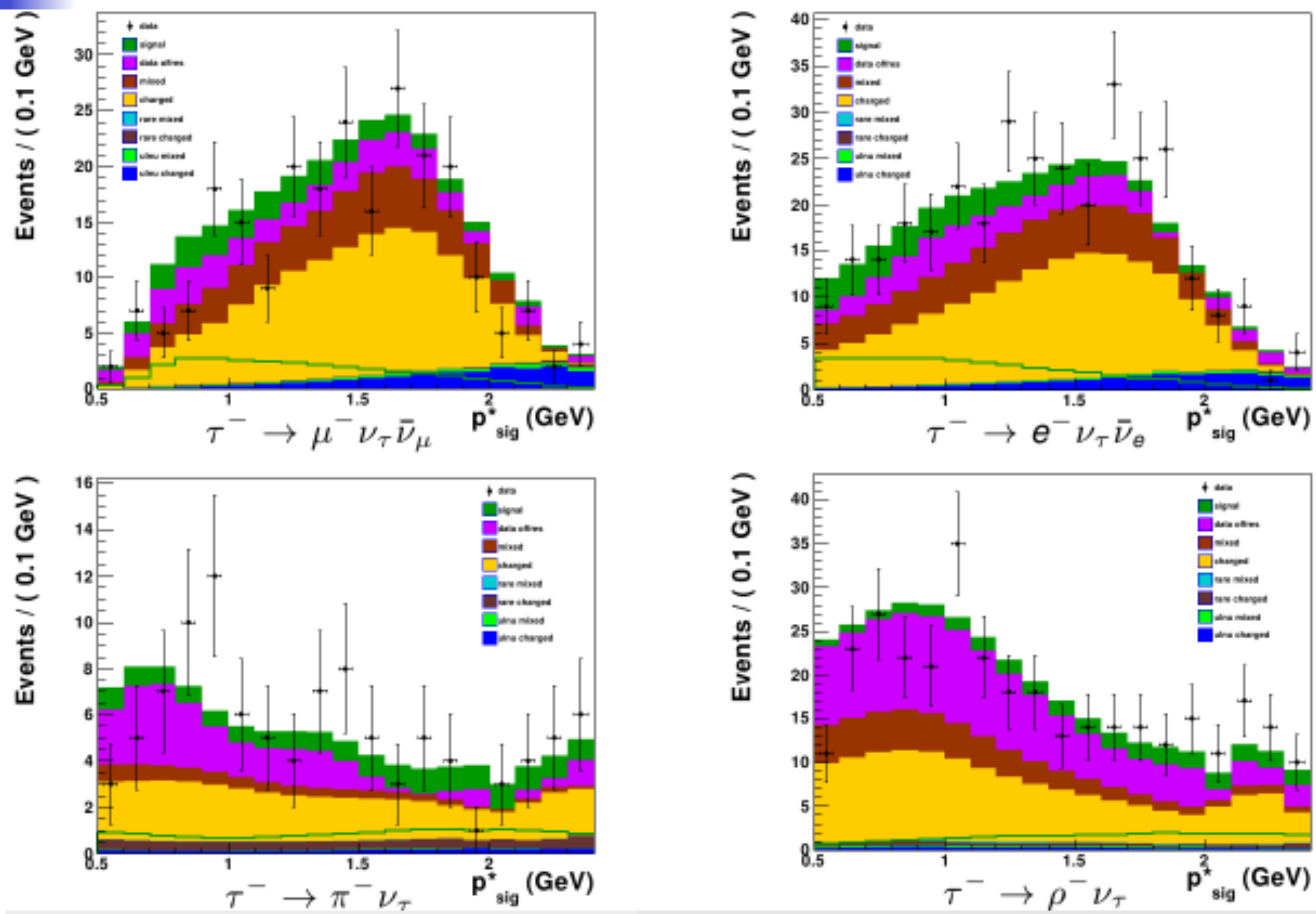
Correct off-resonance p^*_l spectrum + use same correction for on-resonance

Off resonance data

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




Events / (0.05 GeV)
E_{ECL} (GeV)
$\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
$\tau^- \to e^- \nu_\tau \bar{\nu}_e$
$\tau^- \to \pi^- \nu_\tau$
$\tau^- \to \rho^- \nu_\tau$


Events / (0.1 GeV)
data
signal
mixed
charged
rare mixed
rare charged
p*sig (GeV)
$\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
$\tau^- \to e^- \nu_\tau \bar{\nu}_e$
$\tau^- \to \pi^- \nu_\tau$
$\tau^- \to \rho^- \nu_\tau$