B Decays with Tau Leptons in the Final State

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Representing

Outline

- Motivation – why study τ final states?
- $B \rightarrow \tau\nu$
- $B \rightarrow D\tau\nu$ and $D^{(*)}\tau\nu$
- $B \rightarrow l\tau$
- $B \rightarrow K\tau\mu$
- Summary and Outlook

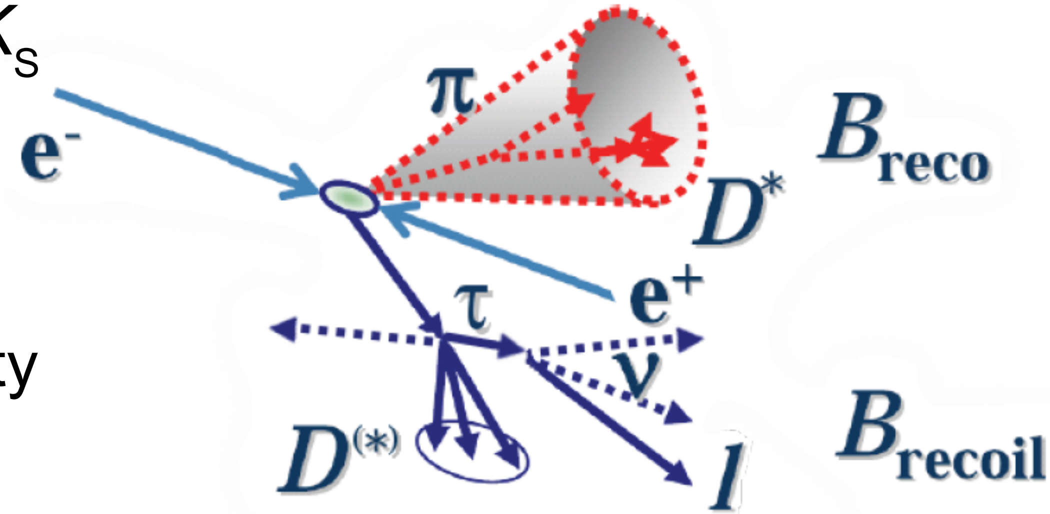
Motivation

- Learn about SM
  - f_B, form factors test QCD calculations
- Many models of physics beyond the SM predict enhanced 3rd generation couplings
  - Higgs bosons: $m_\tau \gg m_e$, m_μ
  - SUSY with LFV in slepton sector
  - GUTs

Experimental Techniques: B Tagging

τ decays, 1-3 ν in final state – challenging!

- Tag $B_{reco} \to D^{(*)} n_1\pi\, n_2\pi^0\, n_3K\, n_4K_S$
  - Study **recoiling** B meson
  - Low efficiency (~3×10^{-3})
  - Full reconstruction: high purity sample with kinematic constraints



- Tag $B_{SL} \to D^{(*)} l\nu$
  - Partial reconstruction: higher efficiency, lower purity
  - Complementary sample

- Motivation – why study τ final states?
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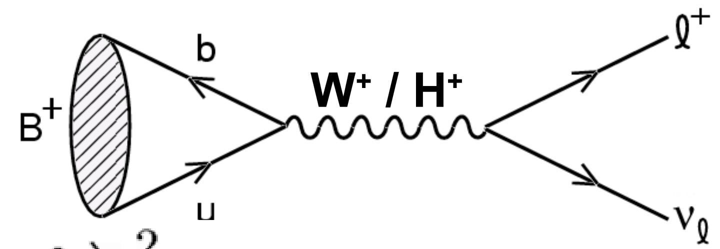
$B \to \tau\nu$



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

- Purely leptonic decay helicity suppressed in SM
  - $B \to \tau\nu$ is most accessible channel
  - Can use $B \to \tau\nu$ to measure f_B
  - Or, assuming f_B is known, can use $B \to \tau\nu$ to constrain charged Higgs:

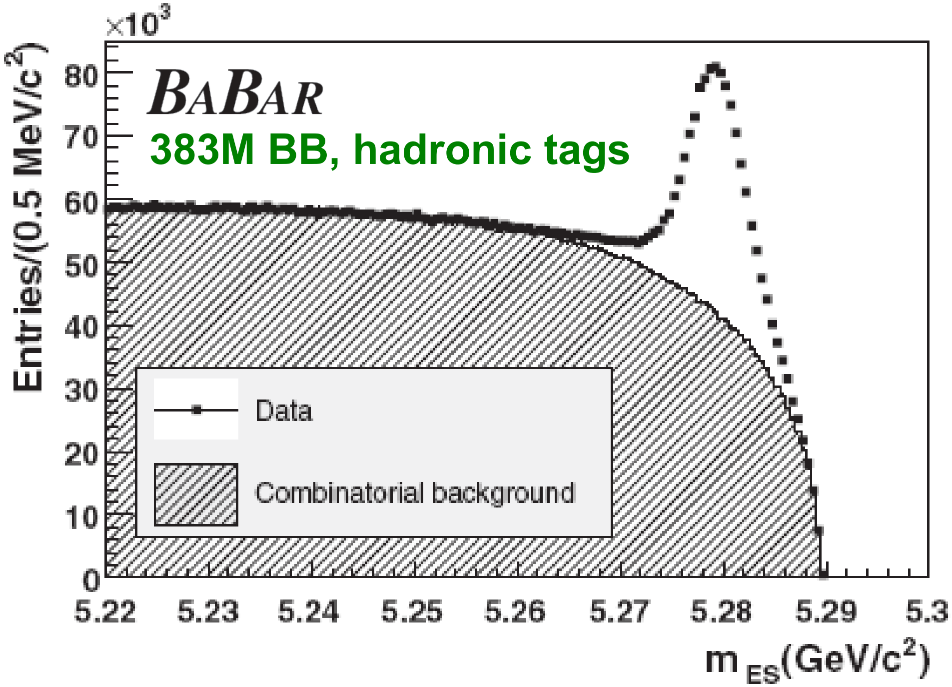
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \times \left(1 - \tan^2\beta \frac{m_{B\pm}^2}{m_{H\pm}^2}\right)^2$$

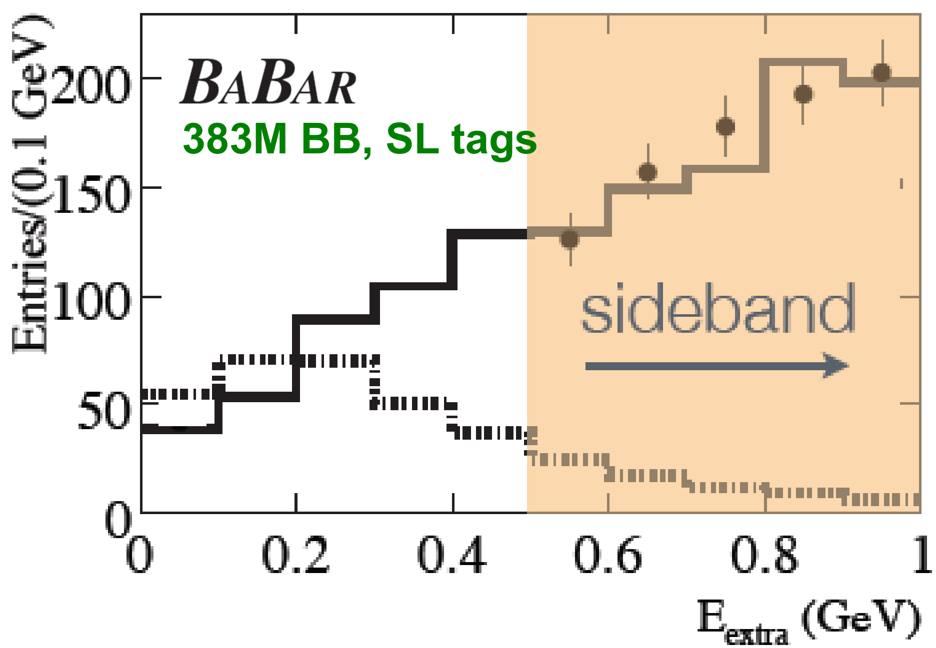
$B \to \tau\nu$: Event Selection

- Use both hadronic and semileptonic tags
- Reconstruct τ as $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, $\tau \to \rho\nu$
- Candidate selection optimized based on
  - Momentum of τ daughter
  - Event shape requirements for continuum rejection
  - Hermeticity requirements (common to all recoil analyses)
    - Expect zero remaining charged tracks, K_S in the event
    - Expect small E_{extra} , sum of energies of remaining neutrals, used as signal discriminant

$B\to\tau\nu$: Background Estimation

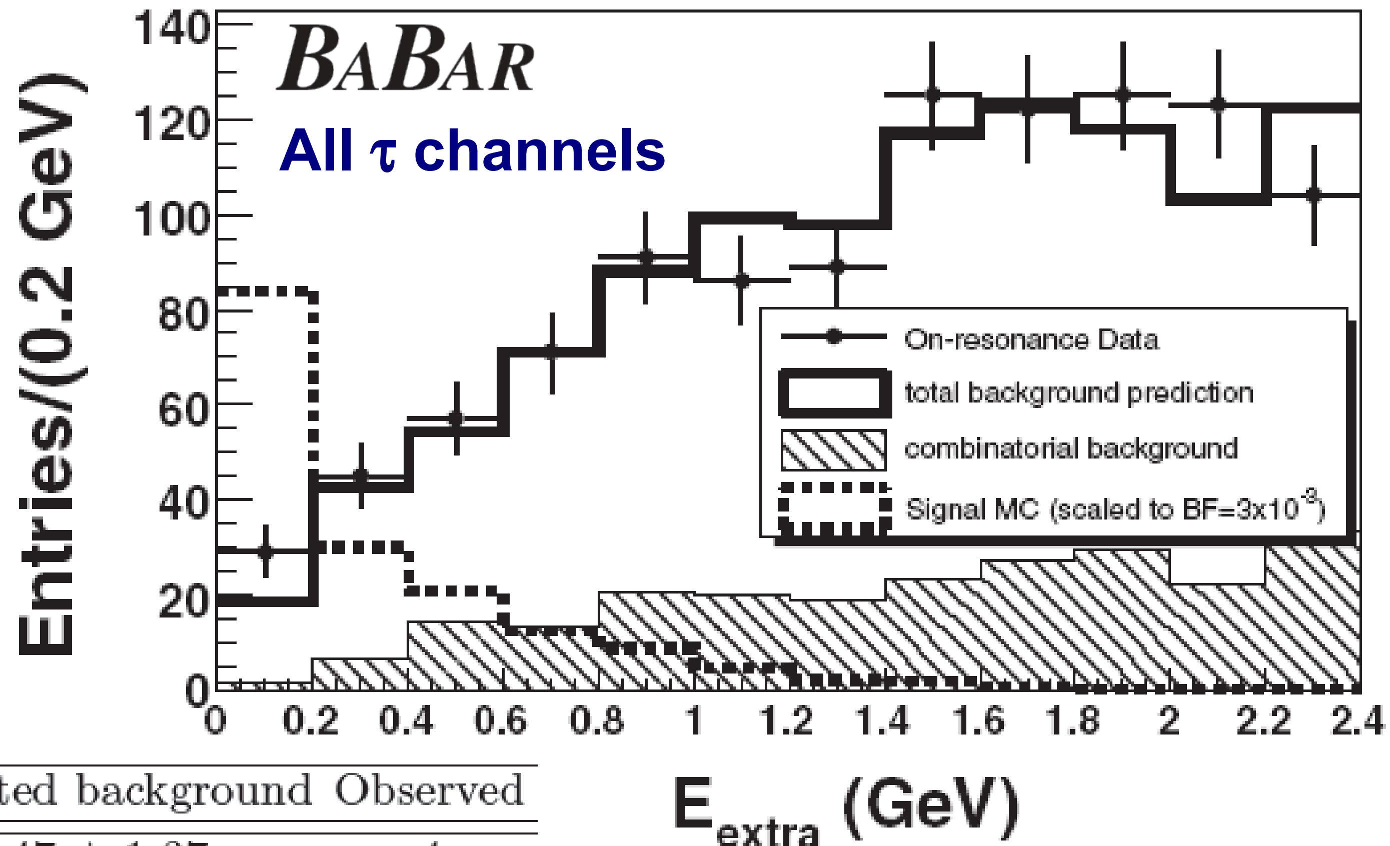
- Use sidebands in data to estimate background yield
  - E_{extra}, B_{tag} mass sidebands





$$N_{\rm exp,Sig} = N_{\rm data,SideB} \cdot \frac{N_{\rm MC,Sig}}{N_{\rm MC,SideB}}$$

$B \to \tau\nu$: Hadronic Tag Signal Yields



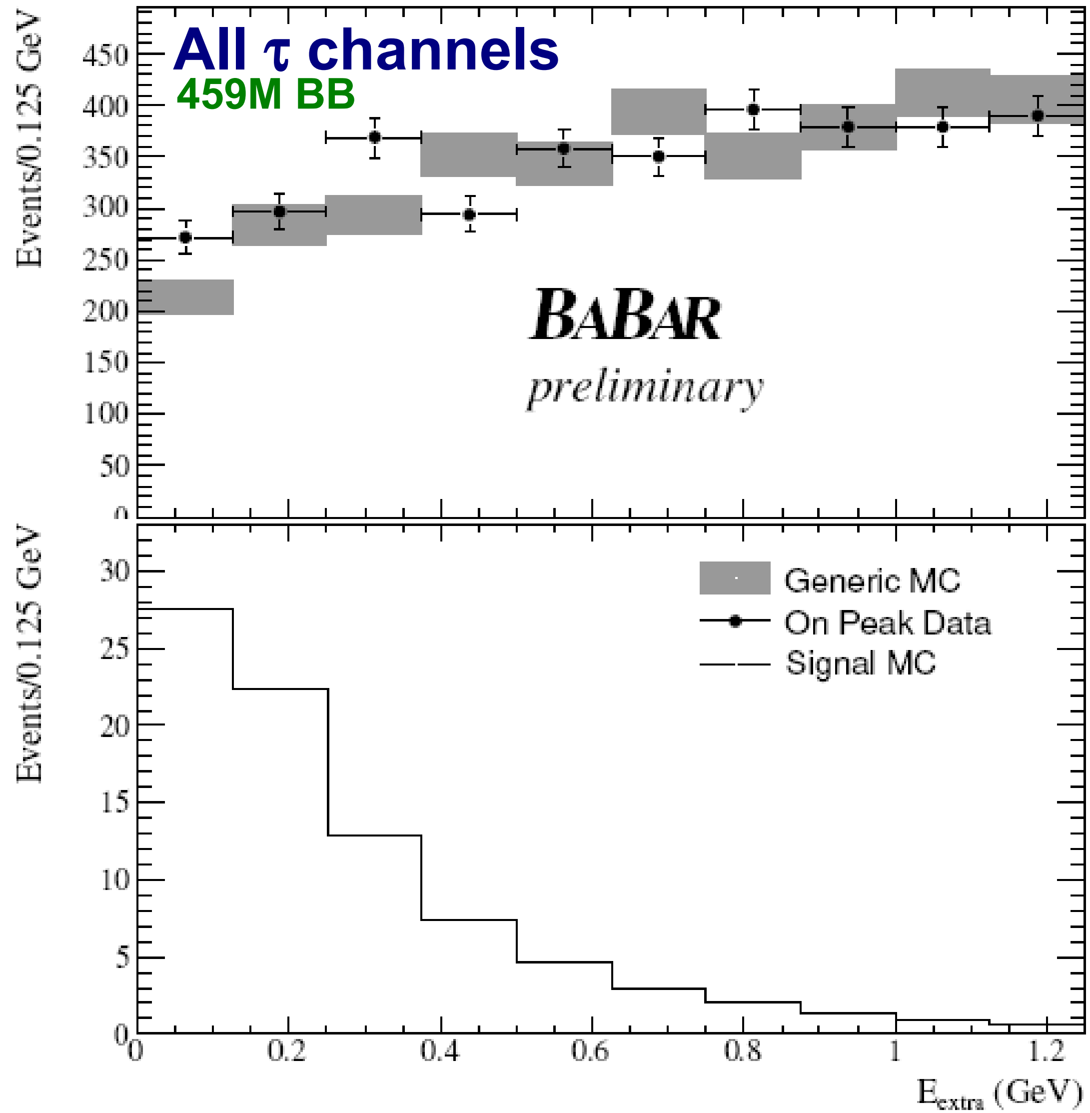
τ decay mode	Expected background	Observed
$\tau^+ \to e^+\nu\overline{\nu}$	1.47 ± 1.37	4
$\tau^+ \to \mu^+\nu\overline{\nu}$	1.78 ± 0.97	5
$\tau^+ \to \pi^+\overline{\nu}$	6.79 ± 2.11	10
$\tau^+ \to \pi^+\pi^0\overline{\nu}$	4.23 ± 1.39	5
All modes	14.27 ± 3.03	24

383M BB, PRD77, 011107 (2008)

$B \to \tau\nu$: SL Tag Signal Yields

New results (CKM 2008)

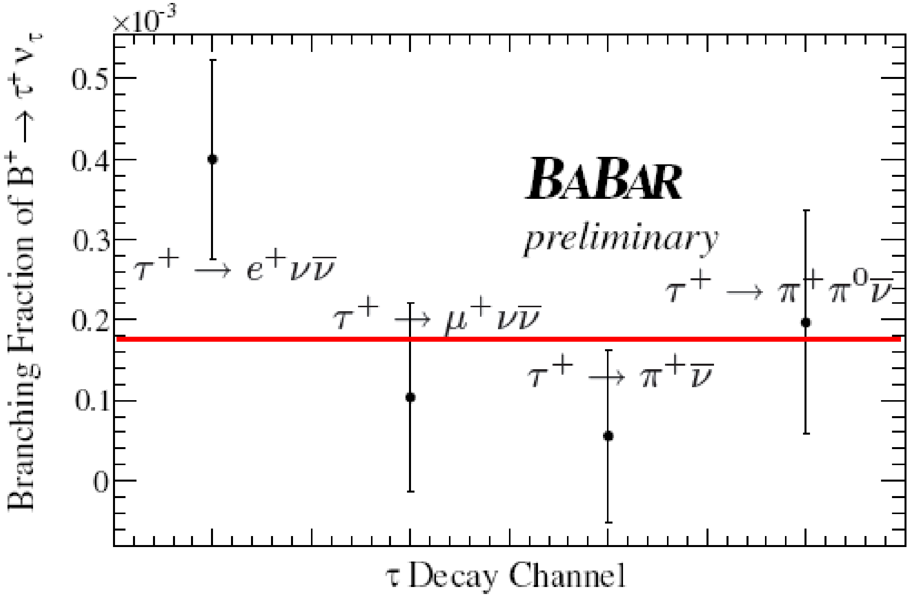
Mode	Expected Background (N_{BG})	Observed Events (N_{obs})
$\tau^+ \to e^+ \nu_e \overline{\nu}_\tau$	91 ± 13	148
$\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau$	137 ± 13	148
$\tau^+ \to \pi^+ \overline{\nu}_\tau$	233 ± 19	243
$\tau^+ \to \pi^+ \pi^0 \overline{\nu}_\tau$	59 ± 9	71
$B^+ \to \tau^+ \nu_\tau$	521 ± 31	610



$B \to \tau\nu$: SL Tag Branching Fractions

Mode	Branching Fraction
$\tau^+ \to e^+ \nu_e \overline{\nu}_\tau$	$(4.0 \pm 1.2) \times 10^{-4}$
$\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau$	$\left(1.0^{+1.2}_{-0.9}\right) \times 10^{-4}$
$\tau^+ \to \pi^+ \overline{\nu}_\tau$	$\left(0.6^{+1.1}_{-0.5}\right) \times 10^{-4}$
$\tau^+ \to \pi^+ \pi^0 \overline{\nu}_\tau$	$\left(2.0^{+1.4}_{-1.3}\right) \times 10^{-4}$
$B^+ \to \tau^+ \nu_\tau$	$(1.8 \pm 0.8 \pm 0.1) \times 10^{-4}$

P(χ^2) = 18%



$B \to \tau\nu$: Systematic Uncertainties

- Many systematics studied using double-tag samples
  - Both *B* mesons reconstructed in a tag mode
- E_{extra} modeling
- Detector efficiency

Hadronic tag analysis

Source of systematics	e^+	μ^+	π^+	$\pi^+\pi^0$	Total
MC statistics	3.1	0.6	1.5	2.6	4.3
Particle Identification	1.5	1.3	0.2	0.2	2.0
π^0	...	...	...	1.4	1.4
Tracking	3.7	0.4	0.1	1.6	5.8
E_{extra}	4.7	0.6	0.9	2.6	8.8
Signal *B*					11.6
Tag *B*					3
Total					12

$B \rightarrow \tau\nu$: Results

- SM using $|V_{ub}|=(4.43 \pm 0.54)\times 10^{-3}$, $f_B=189 \pm 27$ MeV

$$\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = (1.2 \pm 0.4) \times 10^{-4}$$

- BaBar results:

383M BB, PRD77, 011107 (2008)

  - Hadronic $\mathcal{B}(B^+ \rightarrow \tau^+\nu) = (1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4}$
  - SL $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = (1.8 \pm 0.8 \pm 0.1) \times 10^{-4}$
  - Average $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = (1.8 \pm 0.6) \times 10^{-4}$

459M BB, in preparation

Excludes zero at 3.2σ

- Belle results:

449M BB, PRL99, 251802 (2006)

  - Hadronic $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$
  - SL $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}$

ICHEP 2008

- Motivation – why study τ final states?
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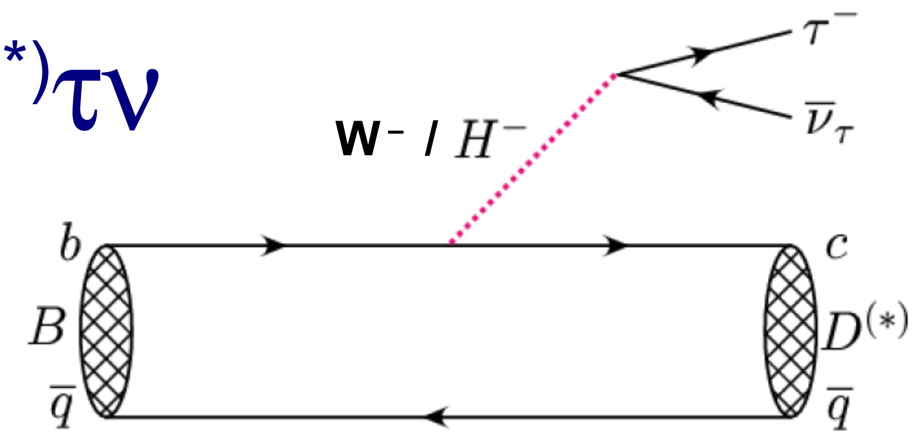
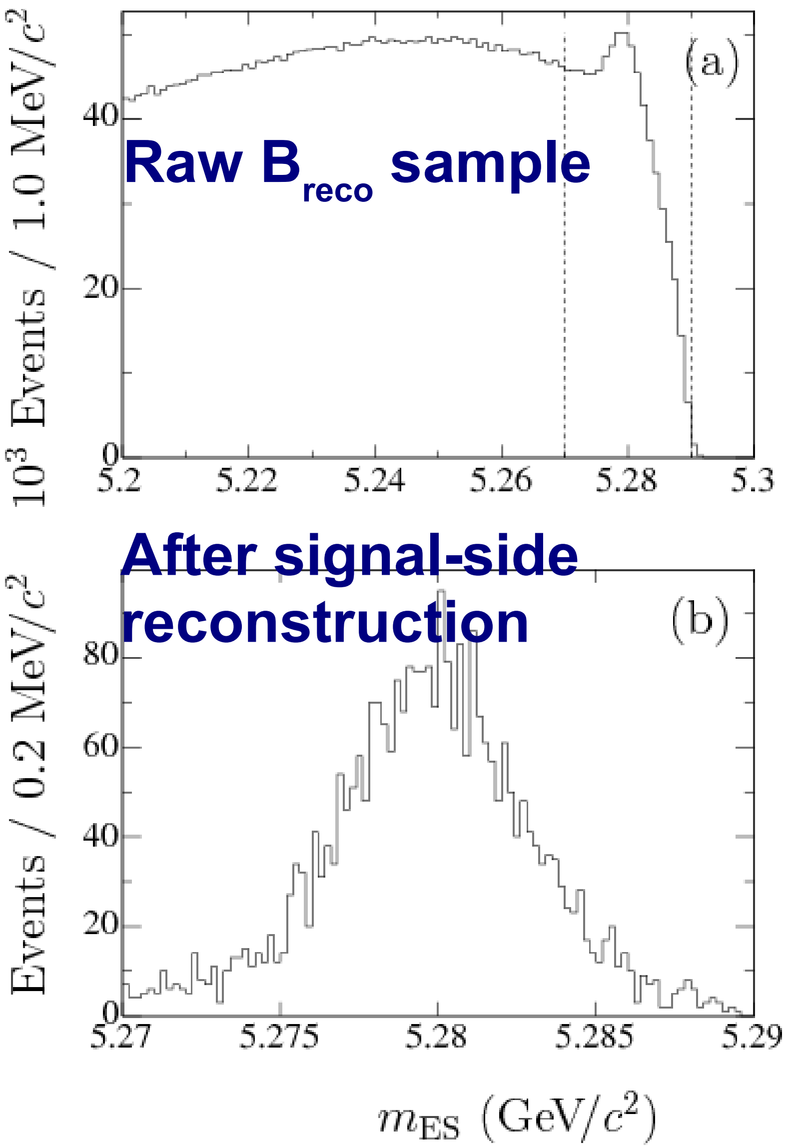
$B \to D^{(*)} \tau \nu$



- No helicity suppression
- Light lepton modes are very well studied
  - QCD effects under control, very clean probe of NP
- 3-body decay, study differential distributions as well as BF
  - q^2, D^* polarization, τ polarization (daughter momentum)

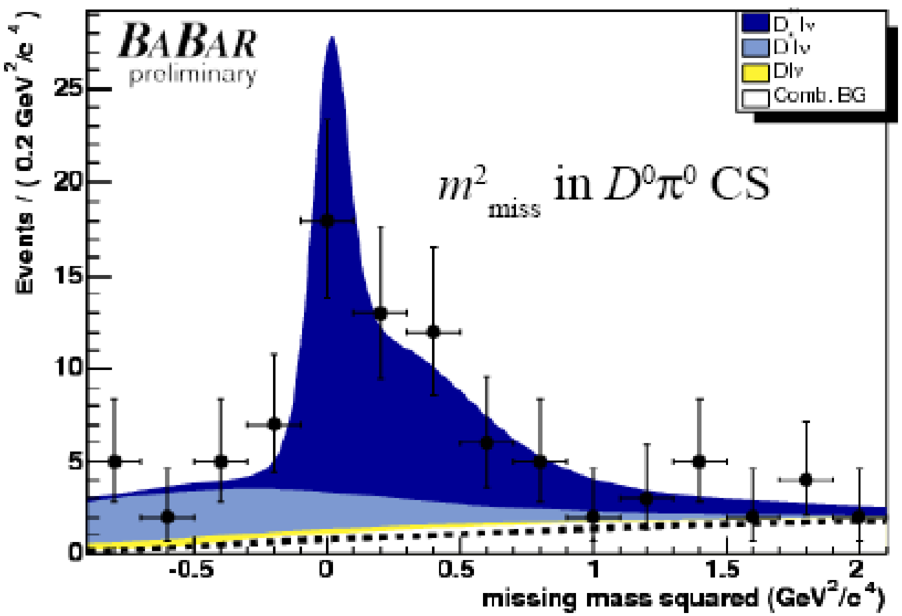
$B \to D^{(*)} \tau \nu$: Event Selection

- Hadronic B_{reco} tag
- Reconstruct τ as $\tau \to l \nu \nu$
- D^0, D^+, D^{*0}, D^{*+} in 12 hadronic final states
- Charge correlation between B_{reco}, $D^{(*)}$, l
- Reject combinatorial BG:
  - $q^2 > 4$ GeV^2
  - $p_{miss} > 200$ MeV
  - No extra tracks, $E_{extra} < 150$-300 MeV



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

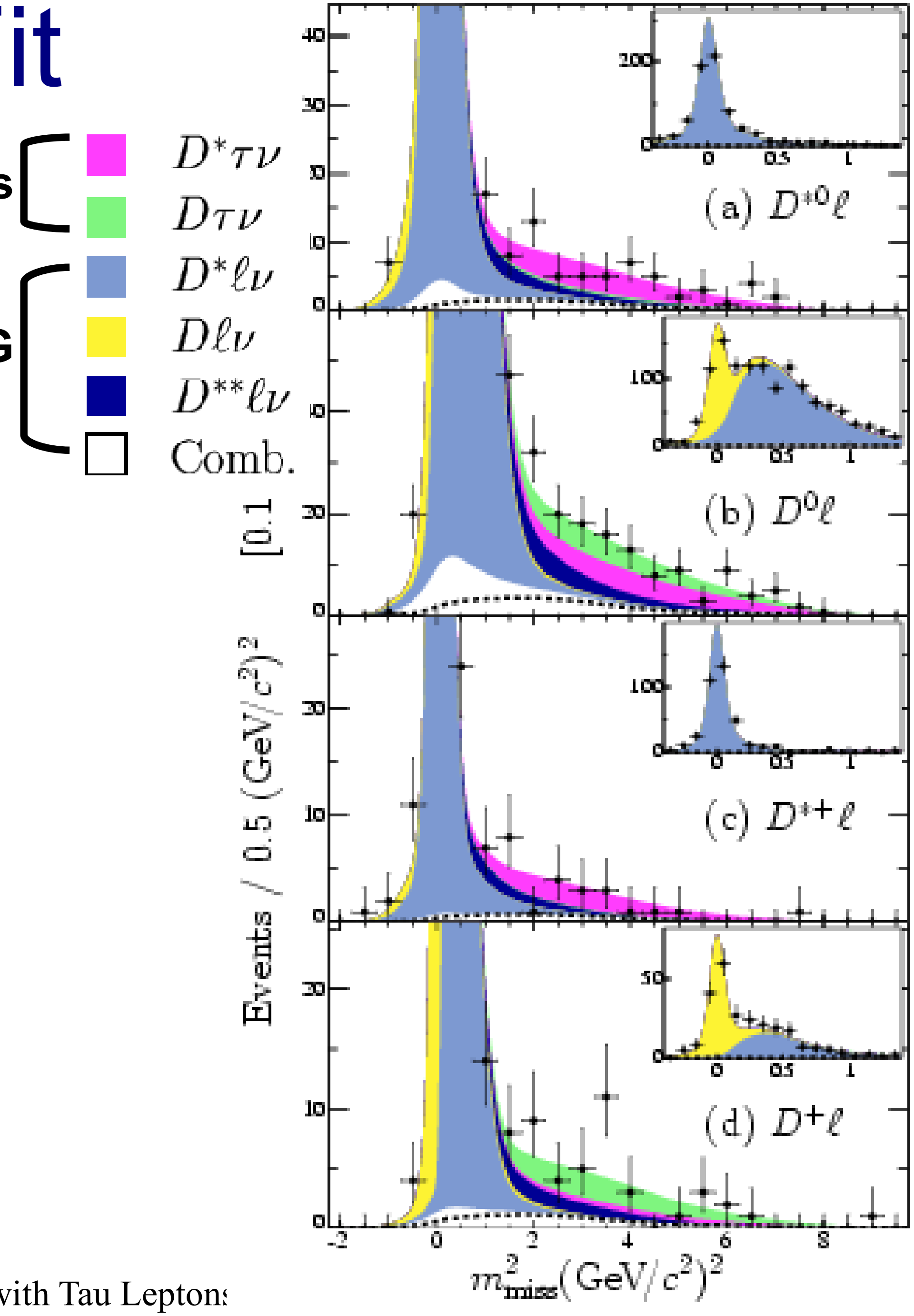
- Most background $B \to D l \nu$, $B \to D^* l \nu$
- Use m^2_{miss} to discriminate signal from BG
  - Light lepton BG has 1 $\nu \Rightarrow m^2_{miss} \approx 0$
  - Signal events have 3 $\nu \Rightarrow$ very large m^2_{miss}



- $B \to D^{**} l \nu$ BG constrained using control samples
  - Add a π^0 to signal reconstruction
  - Reduce sensitivity to details of D^{**} model (D_1, D_2^*, D_0^*, D_1', non-resonant)

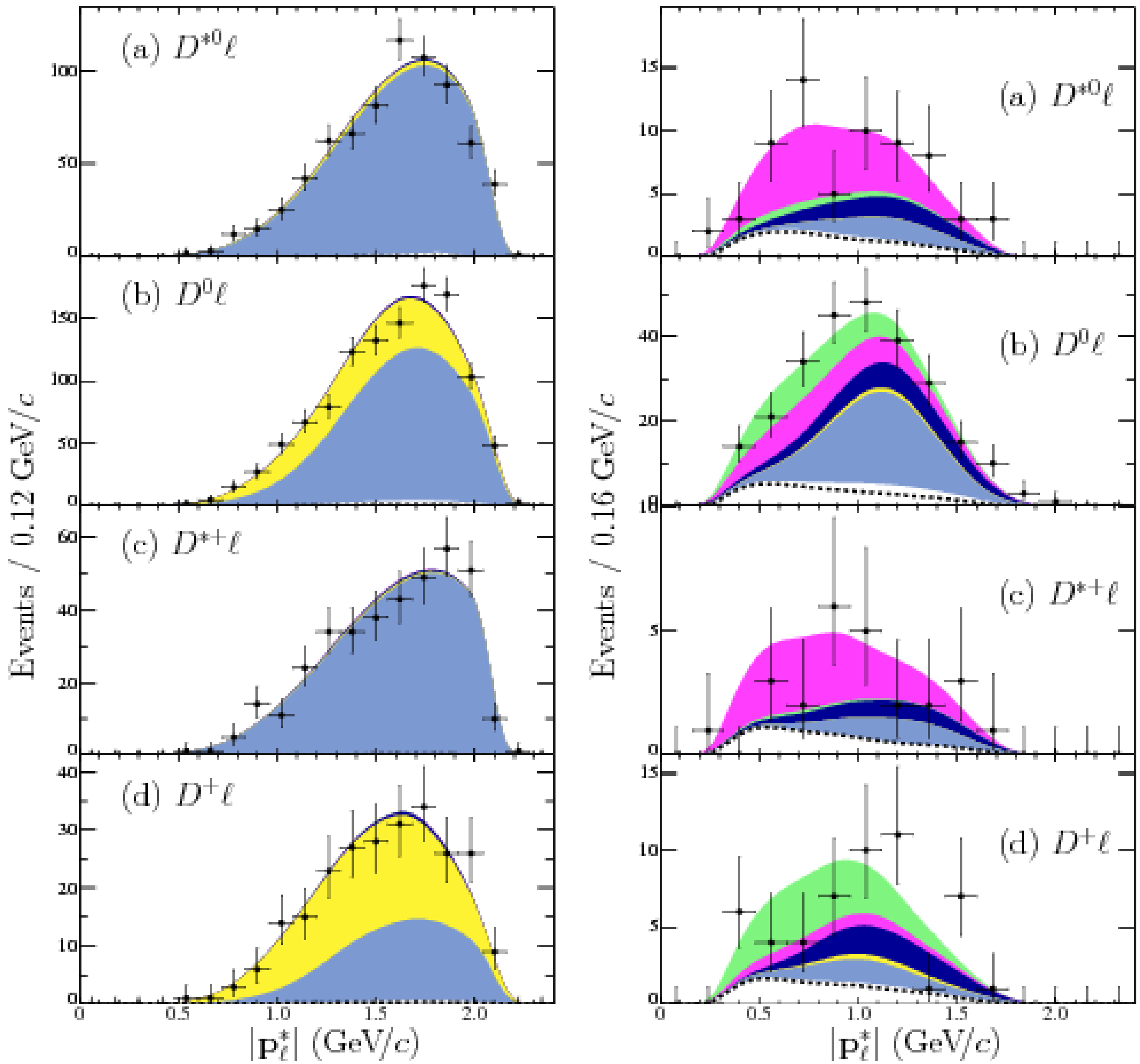
$B \to D^{(*)}\tau\nu$: Signal Fit

- Fit m^2_{miss}, p^*_l
- Simultaneous fit to four signal channels, 4 D^{**} control samples
- Constraints relate crossfeed yields among all channels
- Measure both signal and light lepton modes
  - Normalize result to light leptons



$B \rightarrow D^{(*)}\tau\nu$: p^*_l Projections

Normalization region (low m^2_{miss})



Signal region (high m^2_{miss})

$D^*\tau\nu$
$D\tau\nu$
$D^*\ell\nu$
$D\ell\nu$
$D^{**}\ell\nu$
Comb.

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

Standard Model — Chen and Geng, JHEP 10 053 (2006)

Decay Mode	$\mathcal{B}$ (%)
$\overline{B}^0 \to D^- \tau^- \overline{\nu}_\tau$	0.69 ± 0.04
$\overline{B}^0 \to D^{*-} \tau^- \overline{\nu}_\tau$	1.41 ± 0.07

BaBar — 232M BB, PRL 100 021801 (2008)

Mode	$\mathcal{B}$ [%]	
$B^- \to D^0 \tau^- \overline{\nu}_\tau$	$0.67 \pm 0.37 \pm 0.11 \pm 0.07$	
$B^- \to D^{*0} \tau^- \overline{\nu}_\tau$	$2.25 \pm 0.48 \pm 0.22 \pm 0.17$	
$\overline{B}^0 \to D^+ \tau^- \overline{\nu}_\tau$	$1.04 \pm 0.35 \pm 0.15 \pm 0.10$	
$\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$	$1.11 \pm 0.51 \pm 0.04 \pm 0.04$	
$B \to D \tau^- \overline{\nu}_\tau$	$0.86 \pm 0.24 \pm 0.11 \pm 0.06$	**3.6σ**
$B \to D^* \tau^- \overline{\nu}_\tau$	$1.62 \pm 0.31 \pm 0.10 \pm 0.05$	**6.2σ**

Belle — 535M BB, PRL 99 191807 (2007)

$$\mathcal{B}(\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$$

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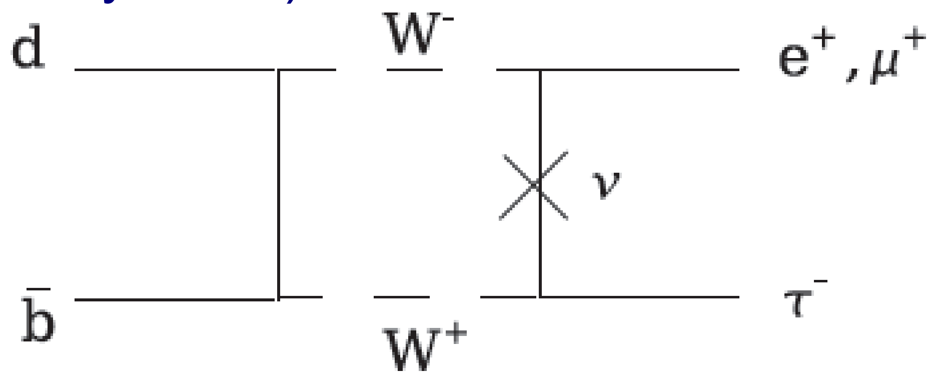
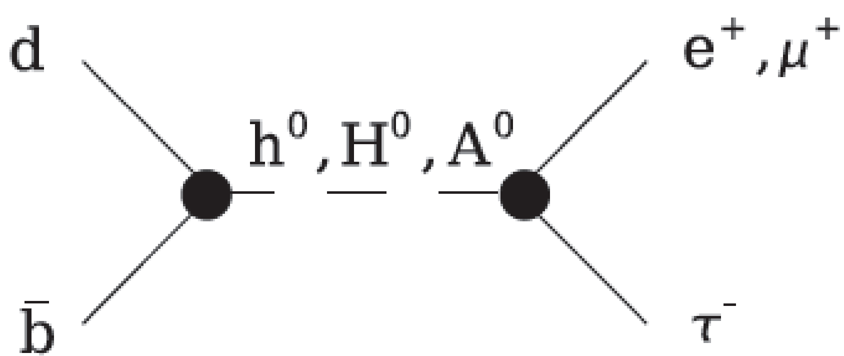
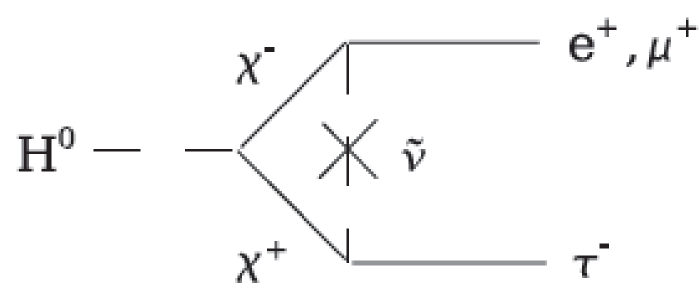
$B \to l\tau$

- Decays $B \to e\tau$, $B \to \mu\tau$ violate lepton flavor
  - Allowed (but very small) in SM via neutrino mixing:



  - Can be enhanced in SUSY by LFV in slepton sector

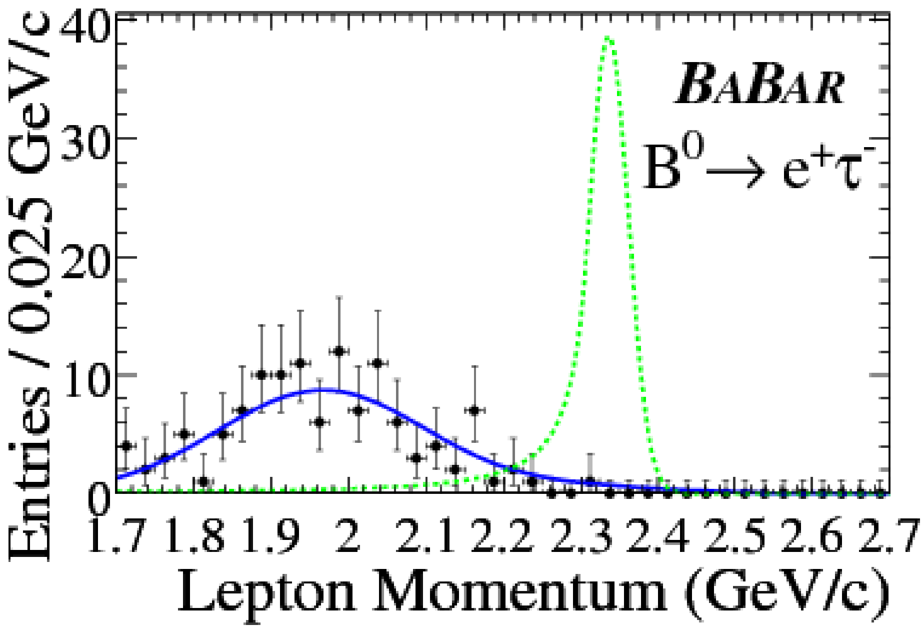


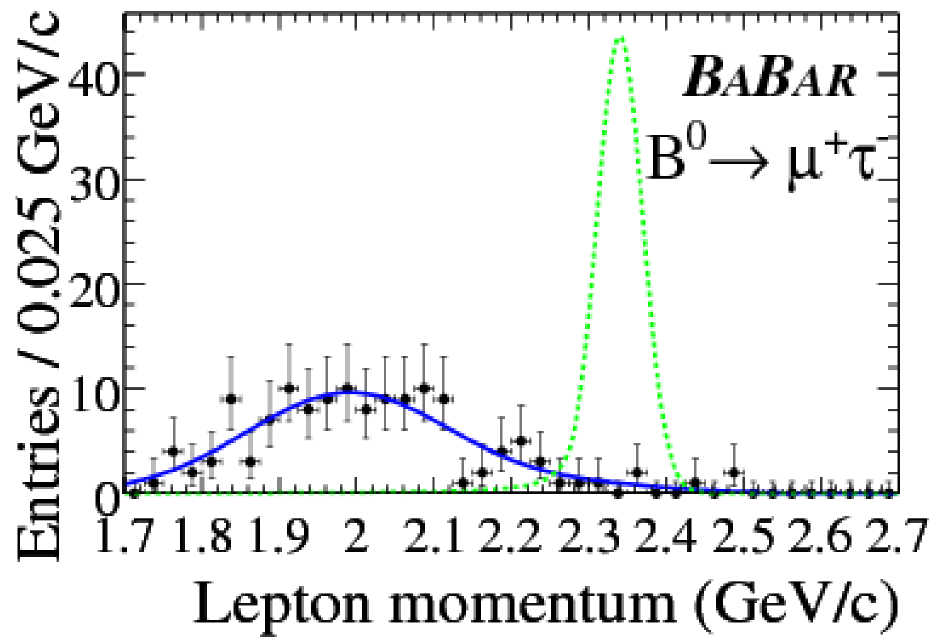


$B \to l\tau$: Results

- Look for $l\tau$ on recoil of hadronic tag
  - Two body decay: p(l) peaks at 2.3 GeV/c

378M BB PRD 77 091104 (2008)





$$\mathcal{B}^{90\%C.L.}(B \to e/\mu\ \tau) < 2.8/2.2 \times 10^{-5}$$

Λ_{bd} > 11.6 TeV
prev > 8.2 TeV

(CLEO: $\mathcal{B} < 11/3.8 \times 10^{-5}$) **10M BB, PRL 93 241802 (2004)**

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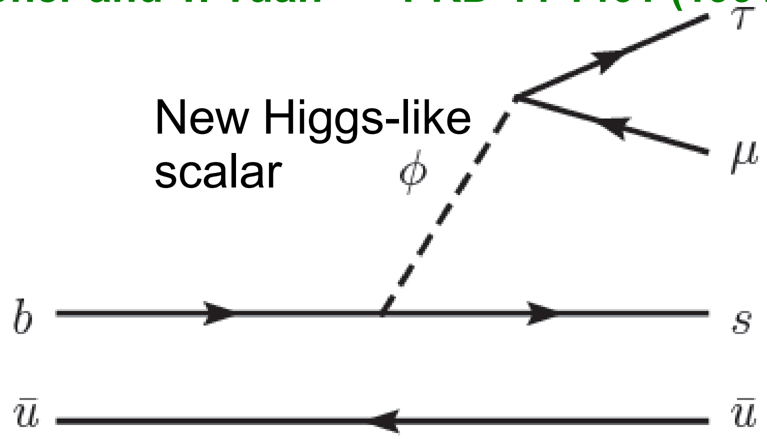
$B \to K\tau\mu$

- In GUT, natural FCNC Yukawa coupling between generations $i, j \sim \sqrt{(m_i m_j)}$
  - Effect largest in 3→2 transitions: $b \to s$, $\tau \to \mu$

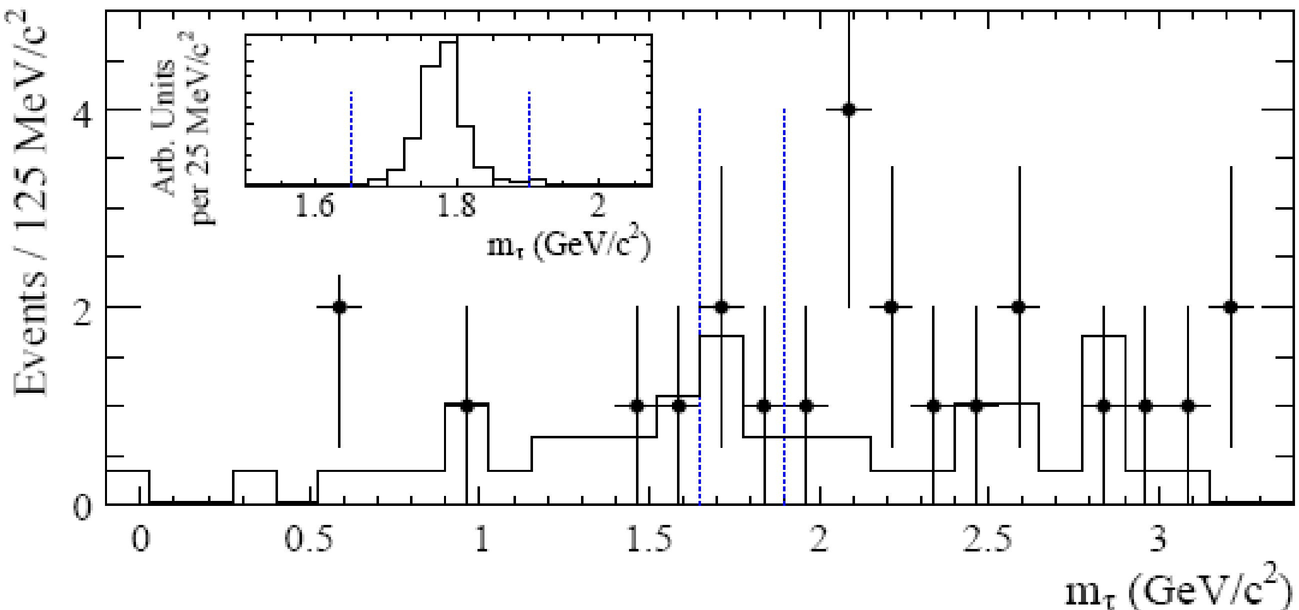
T.P. Cheng and M. Sher PRD 35 3484 (1987)
M. Sher and Y. Yuan PRD 44 1461 (1991)



- Limits on these models from $B \to Kll'$, $B_s \to \mu\mu$
  - $K\tau\mu$ would test different couplings, naturalness

$B \rightarrow K\tau\mu$: Results

- Reconstruct everything but τ: hadronic B_{tag} + $K\mu$
  - Constrained kinematics: measure τ mass
  - $B \rightarrow D^{(*)}\mu\nu$ ($D^0 \rightarrow K\pi$) control sample: check technique, normalize signal



Only measurement!

$$\mathcal{B}^{90\%C.L.}(B \rightarrow K\mu\tau) < 7.7 \times 10^{-5}$$

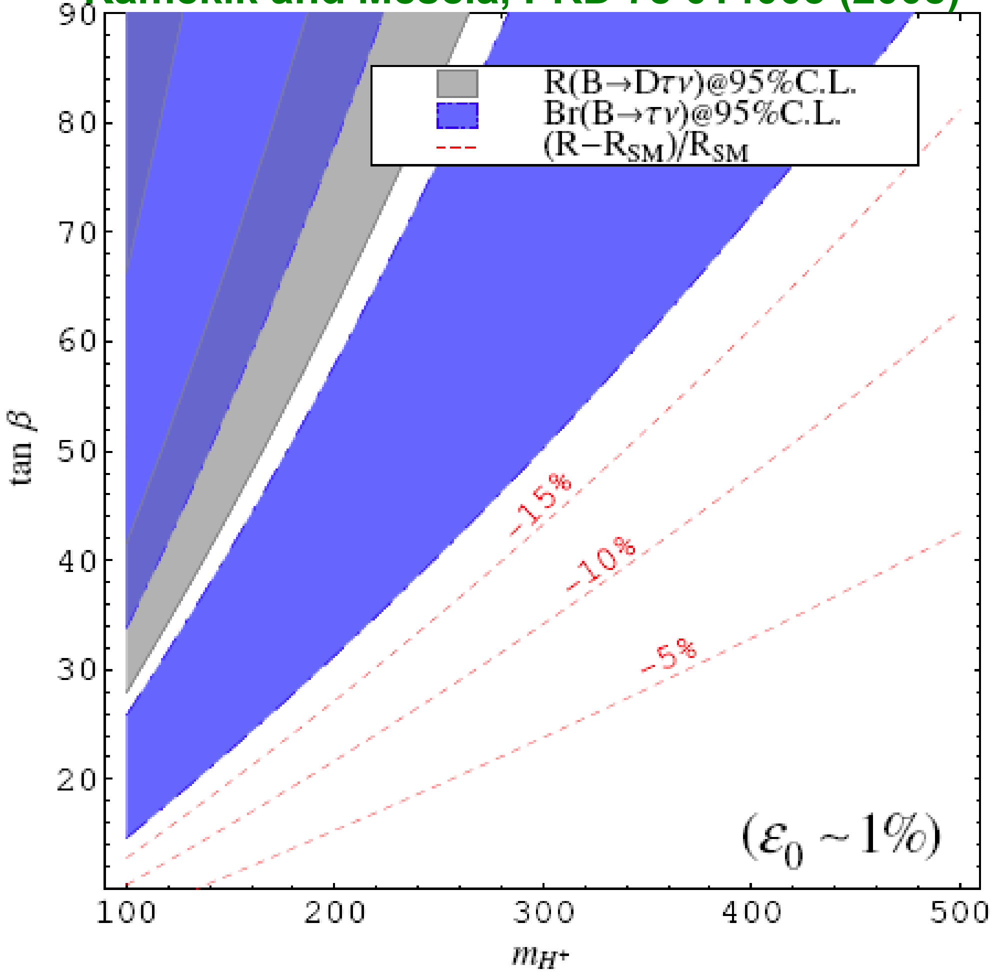
383M BB PRL 99 201801 (2007)

Λ_{bs} > 13 TeV

prev > 2.6 TeV

Summary and Outlook

Kamekik and Mescia, PRD 78 014003 (2008)

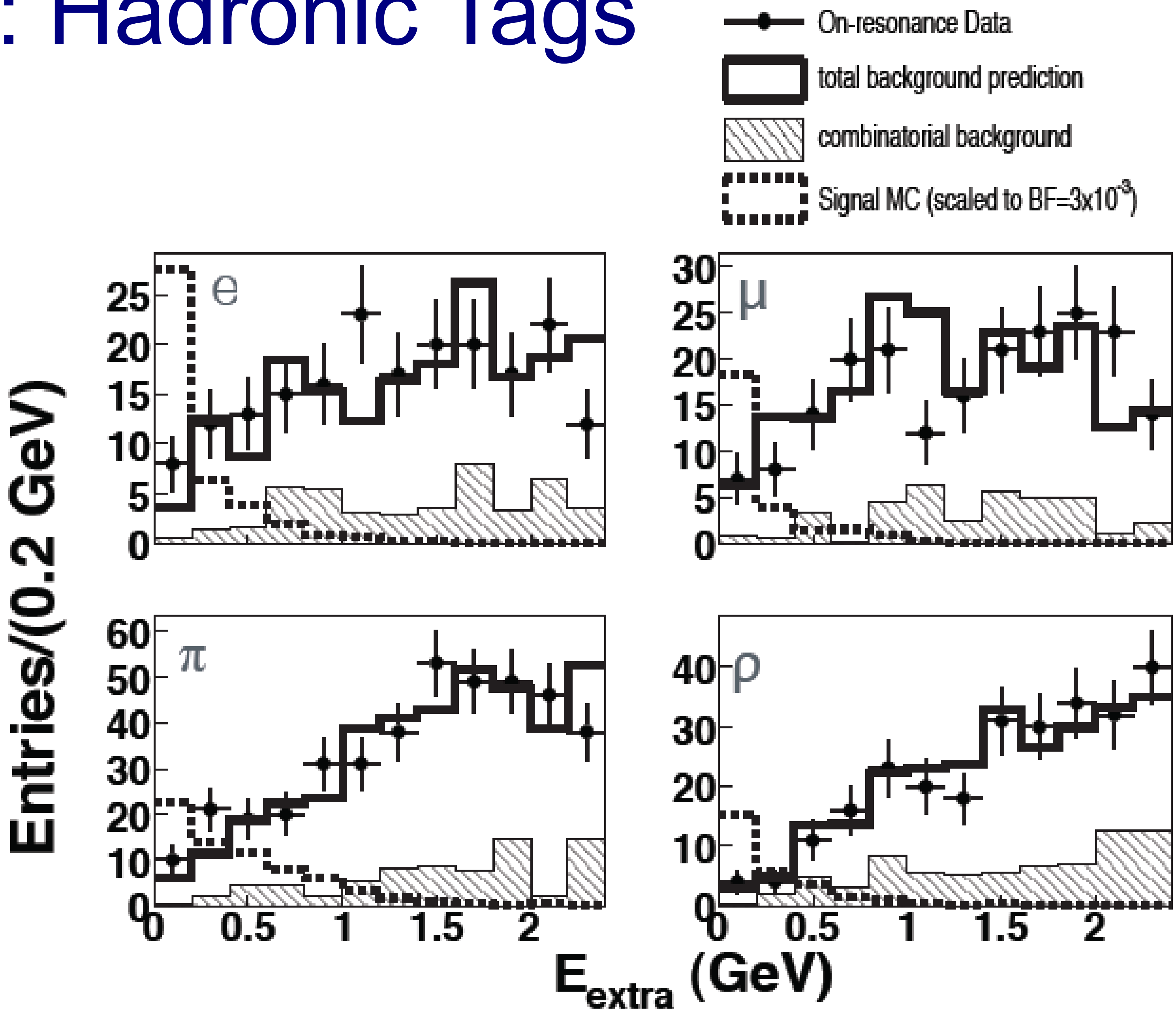


- $B \to \tau\nu$ and $B \to D\tau\nu$ already restrict Higgs parameter space in 2HDM, MFV MSSM
  - $D^{*}\tau\nu$ not yet included
  - Updates to final data sample expected to improve these limits

- New limits on LFV modes further restrict NP models

Backup

$B \to \tau\nu$: Hadronic Tags



$B \to \tau\nu$: SL Systematic Uncertainties

Source	Applicable Mode(s)	Fractional Uncertainty (%)
B Counting	All	1.1
Tag efficiency	All	2.4
E_{extra}	All	2.1
π^0 Reconstruction	$\tau^+ \to \pi^+\pi^0\overline{\nu}_\tau$	3.0
Tracking Efficiency	$\tau^+ \to e^+\nu_e\overline{\nu}_\tau$	0.36
	$\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$	0.36
	$\tau^+ \to \pi^+\overline{\nu}_\tau$	0.36
	$\tau^+ \to \pi^+\pi^0\overline{\nu}_\tau$	0.36
Particle Identification	$\tau^+ \to e^+\nu_e\overline{\nu}_\tau$	2.5
	$\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$	3.1
	$\tau^+ \to \pi^+\overline{\nu}_\tau$	0.8
	$\tau^+ \to \pi^+\pi^0\overline{\nu}_\tau$	1.5

$B \to D^{(*)}\tau\nu$: Systematic Uncertainties

Source	Fractional error (%)					
	$D^0\tau\nu$	$D^{*0}\tau\nu$	$D^+\tau\nu$	$D^{*+}\tau\nu$	$D\tau\nu$	$D^*\tau\nu$
MC stat. (PDF shape)	11.5	8.4	4.5	1.8	6.9	4.7
MC stat. (constraints)	4.2	1.9	6.1	1.3	3.6	1.4
Comb. BG modeling	7.5	4.1	11.5	2.6	9.1	2.9
D^{**} modeling	5.7	0.5	1.6	0.2	3.0	0.4
$B \to D^*$ form factors	1.9	0.7	0.8	0.2	1.4	0.4
$B \to D$ form factors	0.2	0.7	0.6	0.2	0.3	0.4
π^0 crossfeed constraints	0.5	1.1	0.5	0.9	0.5	1.0
D^{**} feed-down	0.4	0.1	0.1	0.3	0.2	0.2
$D^{**}\tau^-\overline{\nu}_\tau$ abundance	0.4	1.3	0.3	0.2	0.3	0.8
$m^2_{\rm miss}$ tail modeling	1.5	0.5	1.2	0.4	1.6	0.1
MC stat. (efficiency)	1.23	1.09	1.47	1.05	0.96	0.76
Bremsstrahlung/FSR	0.55	0.51	0.26	0.42	0.40	0.47
Tracking ε	0.01	0.02	0.002	0.03	0.01	0.02
e PID ε	0.53	0.54	0.60	0.57	0.61	0.56
μ PID ε	0.53	0.60	0.66	0.58	0.59	0.59
K PID ε	0.15	0.05	0.22	0.03	0.18	0.04
π PID ε	0.07	0.07	0.17	0.04	0.12	0.05
K^0_S ε	0.07	0.00	0.07	0.08	0.07	0.04
Neutral (π^0 and γ) ε	0.01	0.04	0.02	0.05	0.02	0.04
Daughter $\mathcal{B}$'s	0.07	0.27	0.04	0.08	0.08	0.30
$\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2
Total additive	15.6	9.7	14.0	3.6	12.5	5.8
Total multiplicative	1.60	1.49	1.77	1.42	1.38	1.26
Total	15.6	9.9	14.0	3.9	12.5	6.0
$\mathcal{B}(B \to D^{(*)}\ell^-\overline{\nu}_\ell)$	10.2	7.7	9.4	3.7	6.8	3.4

Additive systematics studied with ensembles of signal fits

Multiplicative systematics mostly cancel due to relative normalization