Leptonic B-decays at the B factories

Lattice QCD Meets Experiment Workshop

FNAL

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for the BaBar collaboration

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Outline

B leptonic decays

- A great variety of decays and rare searches.
- Leptonic decays

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- Leptonic decays
  - $B \to \tau\bar{\nu}$
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- Radiative leptonic decays
  - $B \to \gamma\ell\bar{\nu}$

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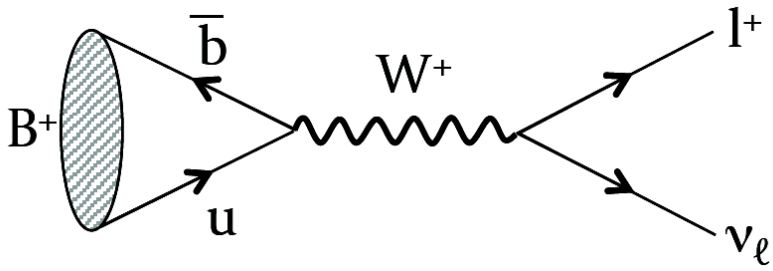
- Radiative leptonic decays
  - $B \to \gamma\ell\bar{\nu}$
- Lepton flavour violating decays
  - $B \to \ell\ell'$
  - $B \to K\ell\ell'$
- Not a comprehensive list...but some of the most recent/relevant results.
- Motivation?

Pure leptonic decays

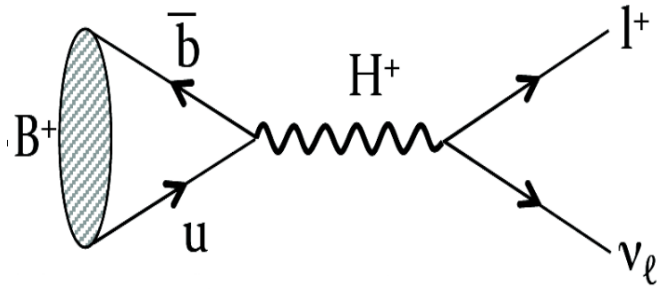
- In the Standard Model
  - Tree level mediated by only W boson.
  - Helicity suppressed
    - $B \to \tau\bar{\nu} \approx 10^{-4}$
    - $B \to \mu\bar{\nu} \approx 10^{-7}$
    - $B \to e\bar{\nu} \approx 10^{-12}$
  - Sensitive to f_B, *given* V_{ub}
  - V_{ub} and f_B dominate SM uncertainty.



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

Pure leptonic decays beyond SM

- Decay mediated by a Higgs
- Charged Higgs contribution is *not* helicity suppressed.
- Model dependent prediction.



$$\mathcal{B}(B \to \ell\nu)_{2HDM} = \mathcal{B}(B \to \ell\nu) \times (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$

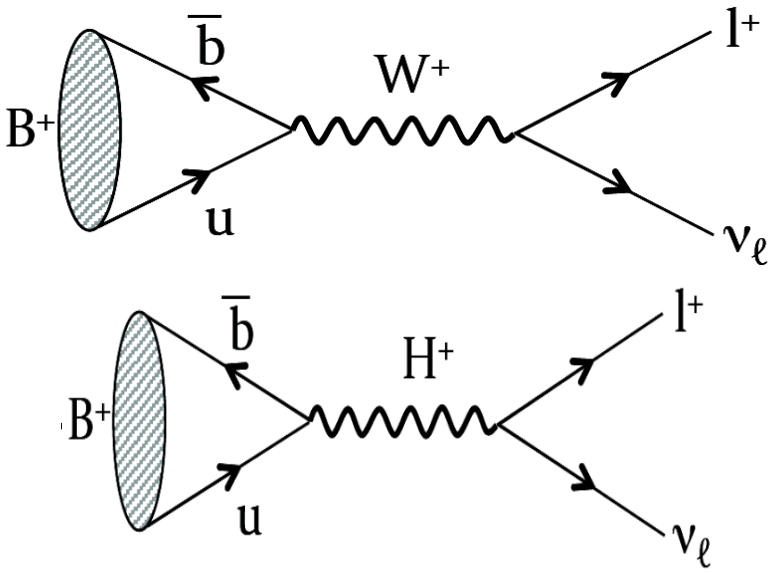
$$\mathcal{B}(B \to \ell\nu)_{SUSY} = \mathcal{B}(B \to \ell\nu) \times (1 - \frac{\tan^2}{1 + \eta_0 \tan\beta} \frac{m_B^2}{m_H^2})^2$$

W.S. Hou, Phys.Rev.D., 48 (1993) 2342

Akeroyd,Recksiegel J.Phys.G29:2311-2317, 2003

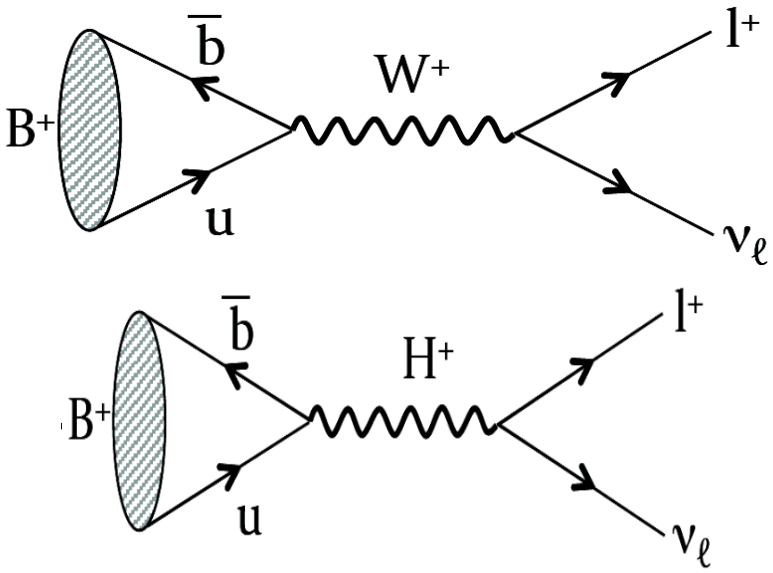
Pure leptonic decays beyond SM

- Complex interplay amongst the "unknowns".



Pure leptonic decays beyond SM

- Complex interplay amongst the "unknowns".
  - f_B
    - **QCD**
  - V_{ub}
    - **CKM matrix**
  - New physics
    - **2HDM,SUSY,MSSM,etc.**
  - $\mathcal{B}(B \to \ell\bar{\nu})$
    - **Experimental measurement**



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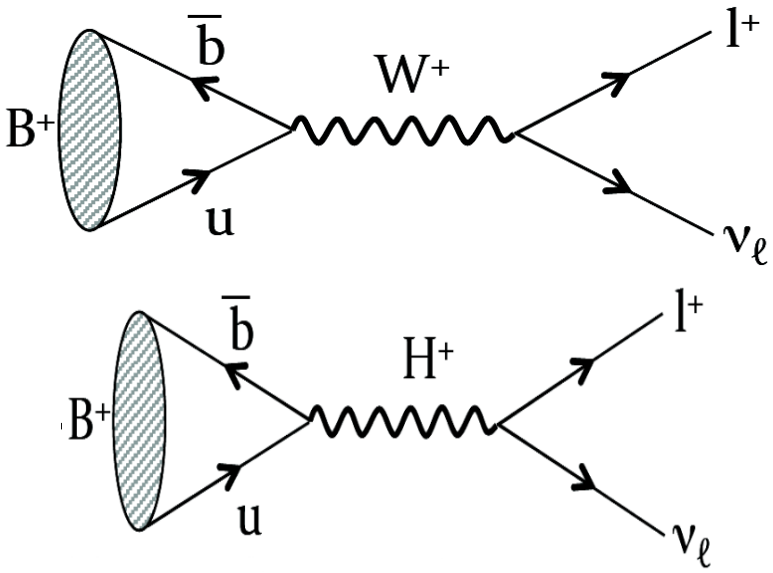

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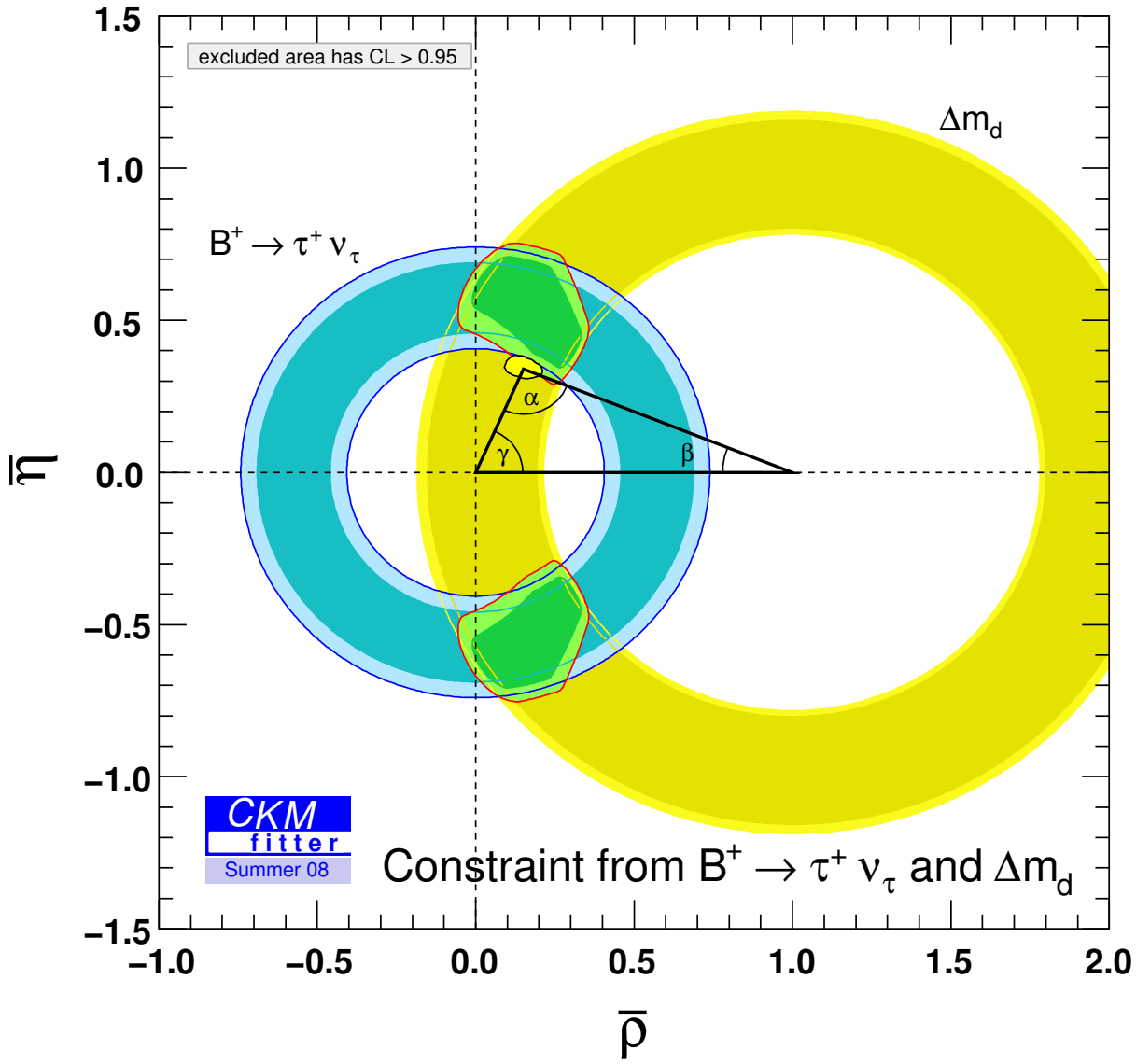
- Tensions...
  - V_{ub} and $\sin(2\beta)$
  - f_B and $\mathcal{B}(B \to \tau\nu)$
    - "Freedom" to choose what values to use.

Fit at the SM and beyond



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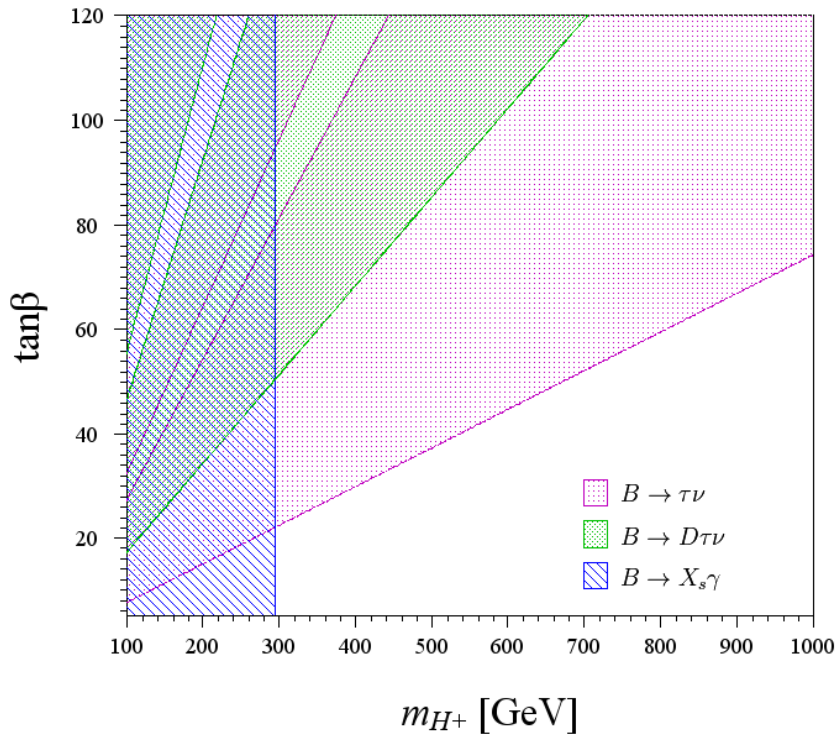
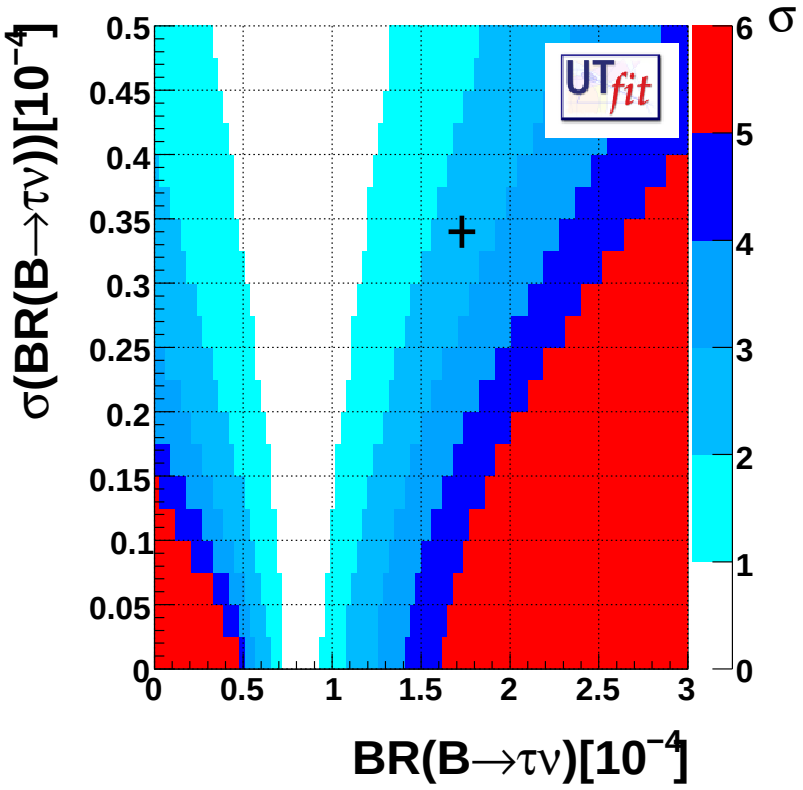


UTFit Collaboration arXiv:0908.3470



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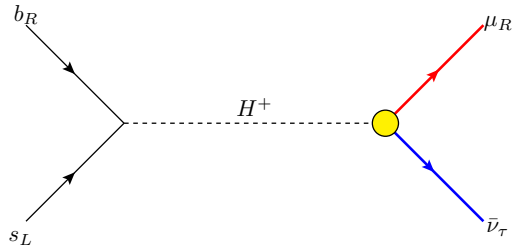
Lepton flavour universality test

- Potentially large violations of LF universality can appear in helicity-suppressed charged-current modes within the MSSM.
- Large tan β



$$\Gamma(B \to \mu\bar{\nu})^{exp} = \Gamma(B \to \mu\bar{\nu_\mu}) + \Gamma(B \to \mu\bar{\nu_e}) + \Gamma(B \to \mu\bar{\nu}_\tau)$$

G.Isidori, P.Paradisi, Phys.Lett.B 639,499

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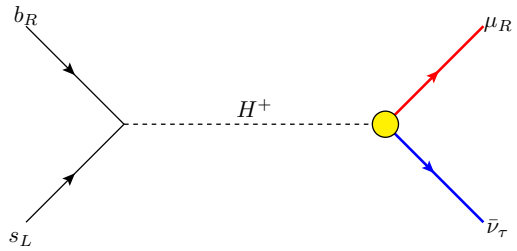

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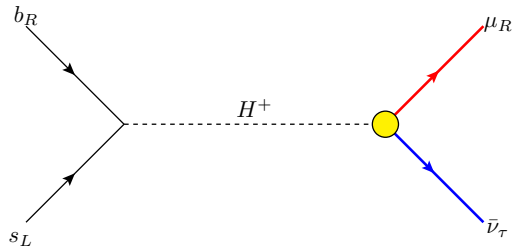

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- Experimental probe
- Out of reach of current B-factories.
  - $R^{\tau\mu} = \frac{\Gamma B \to \mu\bar{\nu}}{\Gamma B \to \tau\bar{\nu}}$ $\qquad$ $R^{\tau e} = \frac{\Gamma B \to e\bar{\nu}}{\Gamma B \to \tau\bar{\nu}}$
- Prediction in non-minimal LFV
  - $R^{\tau\mu} \sim 10\% R^{\tau\mu,SM}$
    $R^{\tau e} \sim 10^3 R^{\tau e,SM}$

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The B-factories

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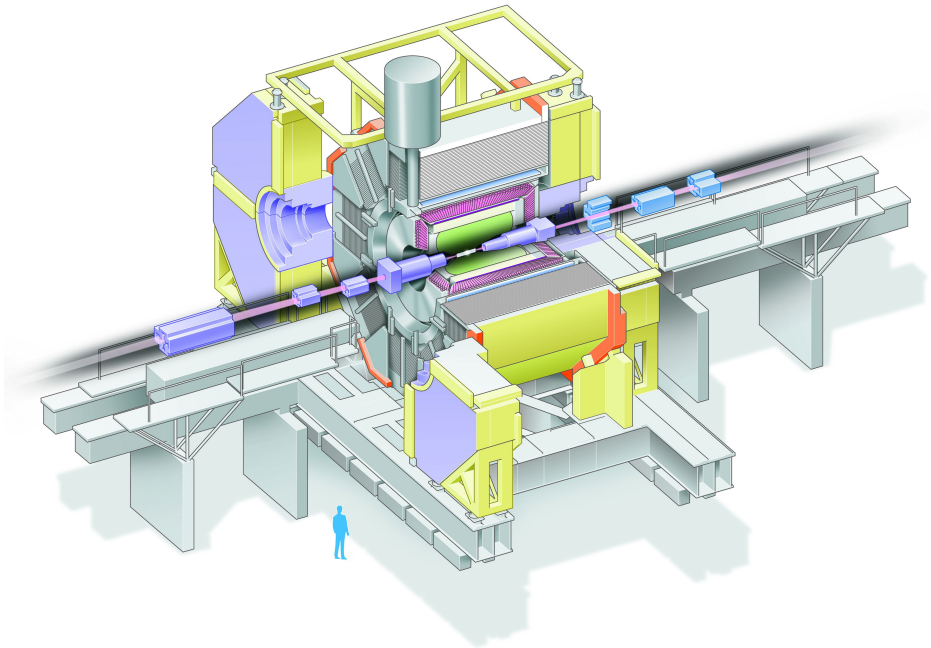
  - Belle (KEK)



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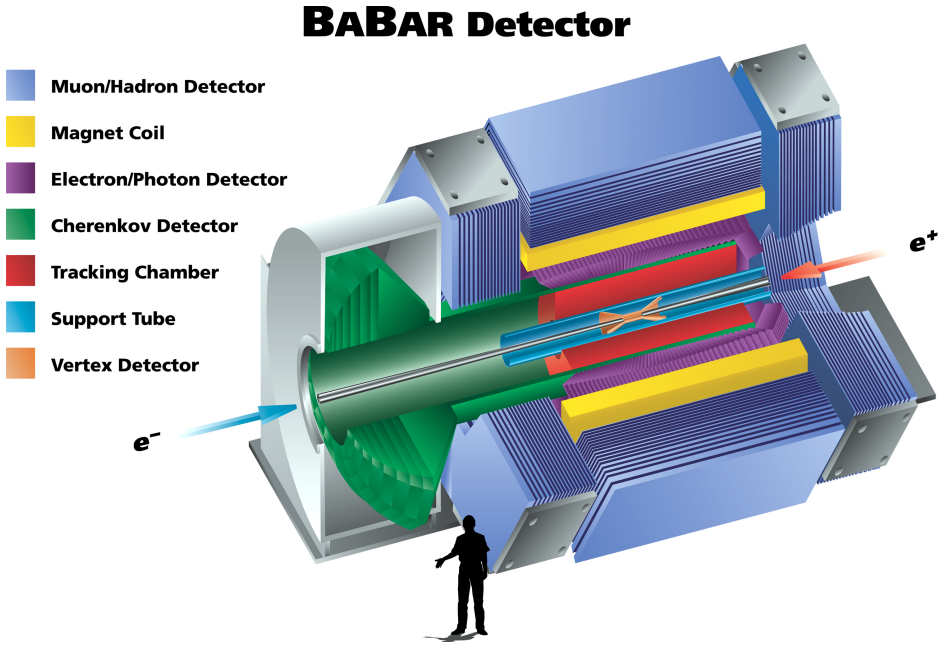

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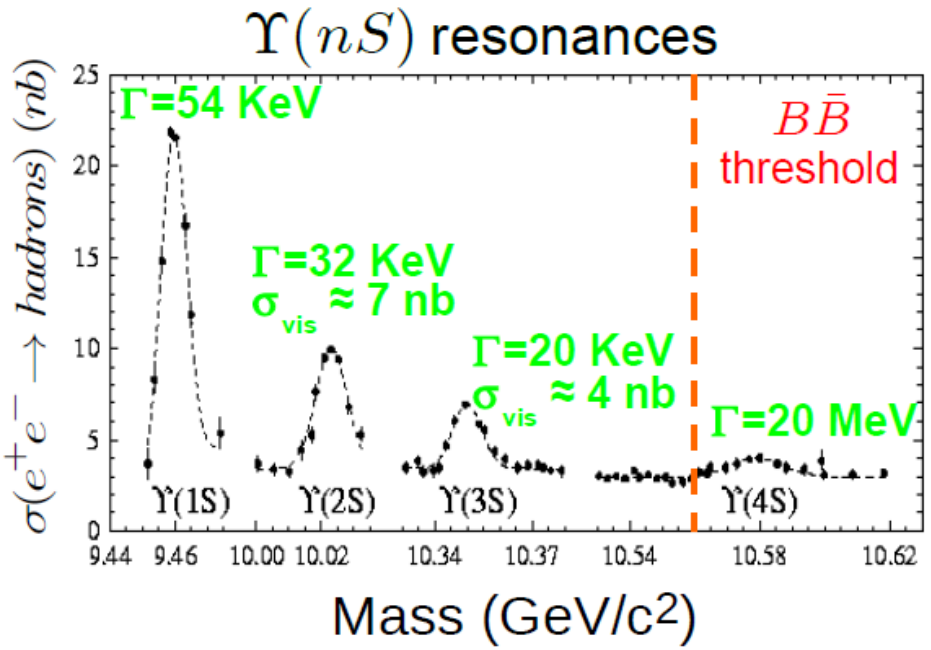
- Wealth of rich physics under the resonance $(c\bar{c}, \tau^+\tau^-, ...)$



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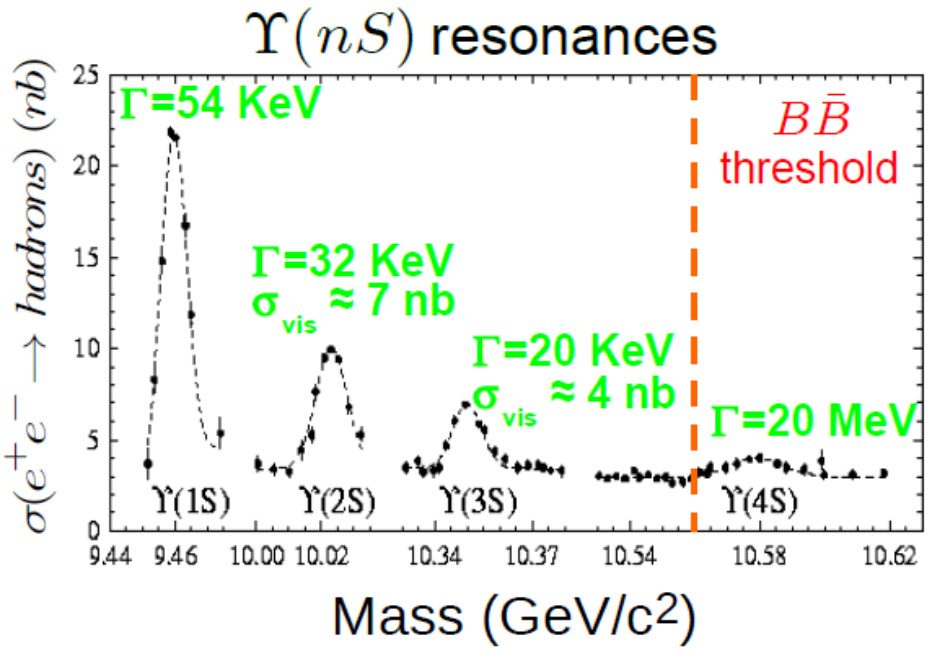

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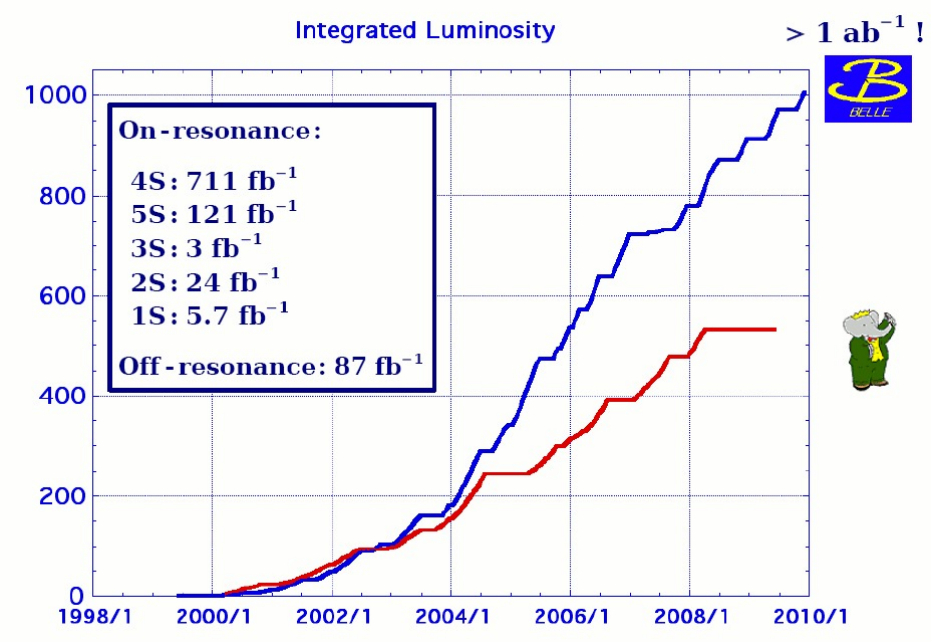
- Wealth of *backgrounds* under the resonance.
- High luminosity
- On the order of **1.5 billion $B\bar{B}$ pairs in the world's dataset!**



B-factory physics

- Colliding e^+e^- beams
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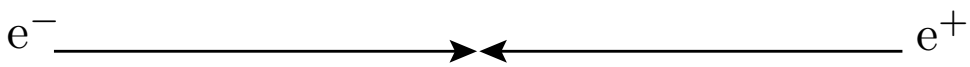

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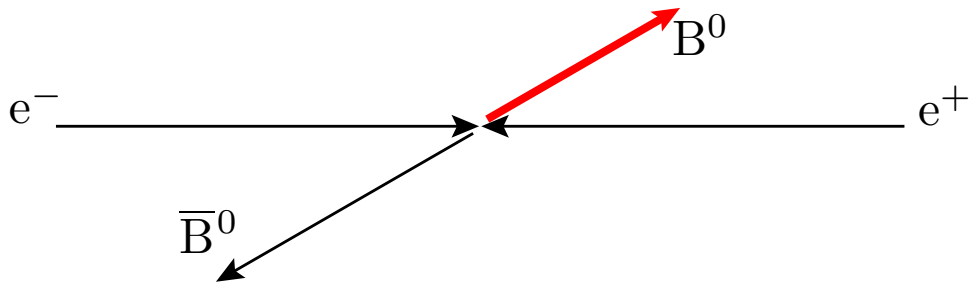

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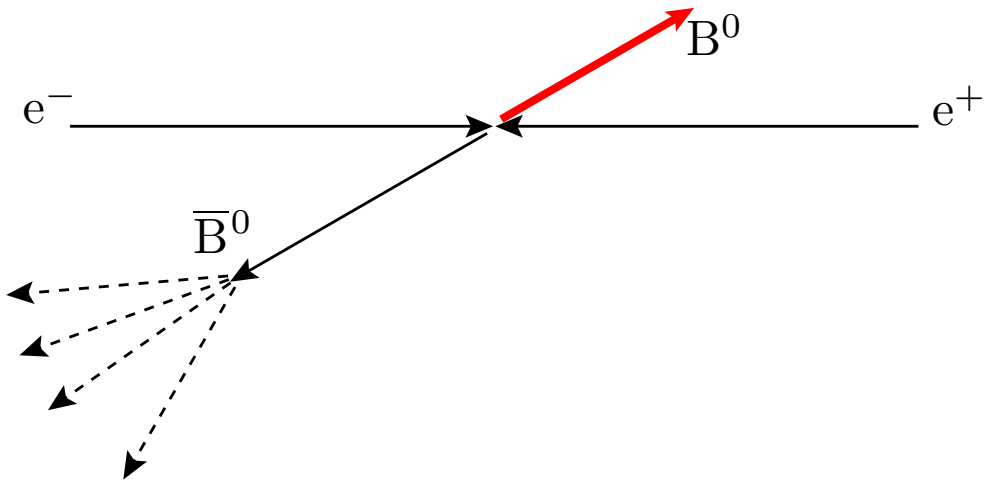
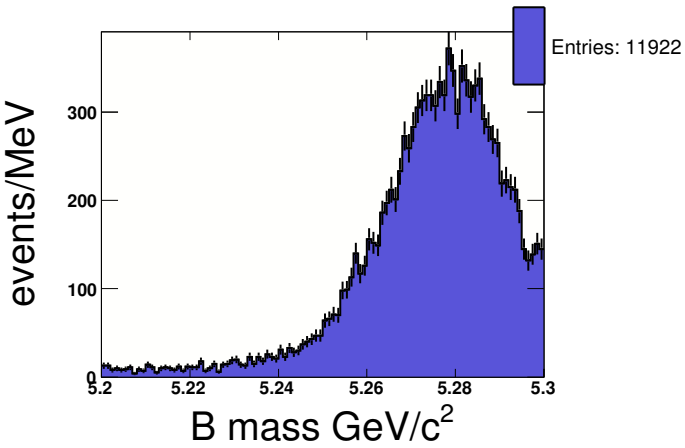
  - The other B decays in any number of ways.



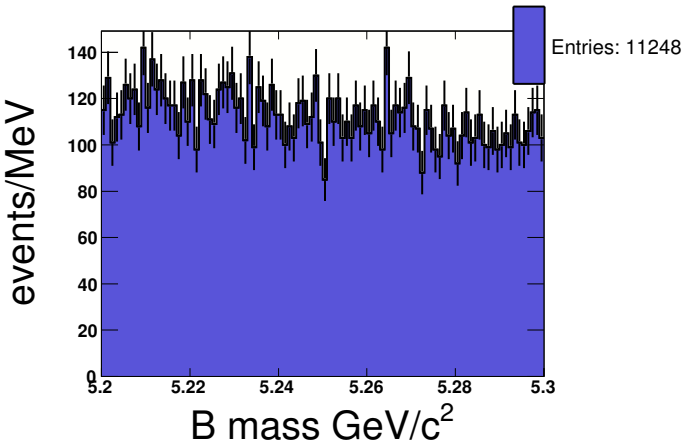
Beam constraints

- B mass
- Beam energy resolution is better than B energy (combined track $\vec{p}$) resolution.

Signal process (Monte Carlo)



All background processes (Monte Carlo)



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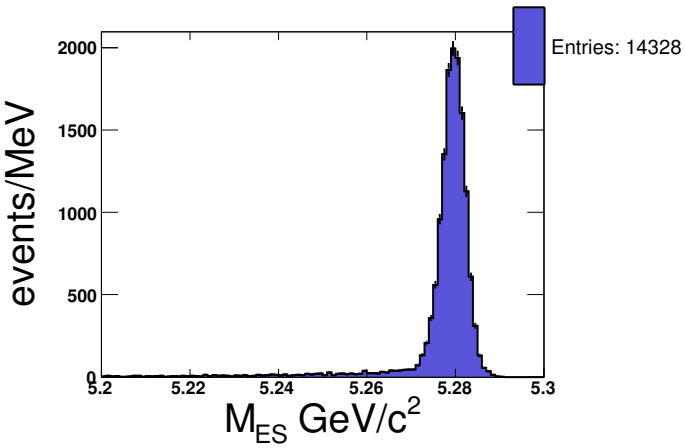

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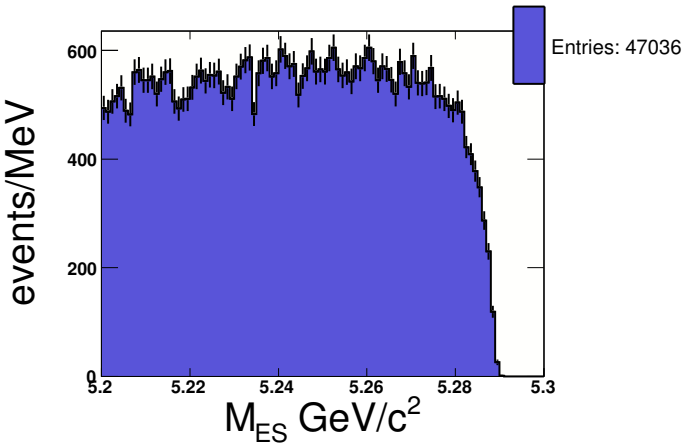

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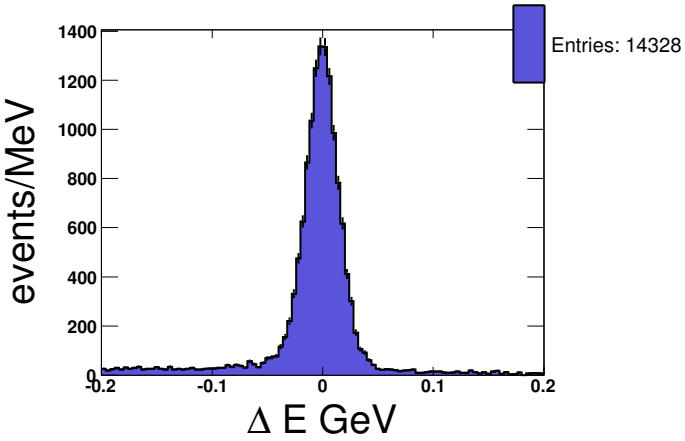

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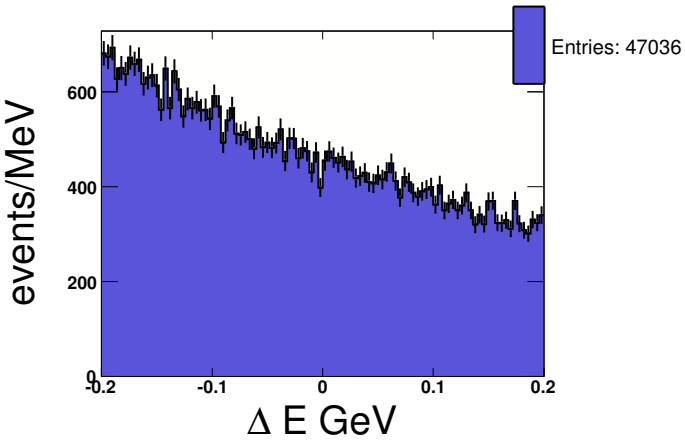

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- **Discriminating power in 2D plane.**

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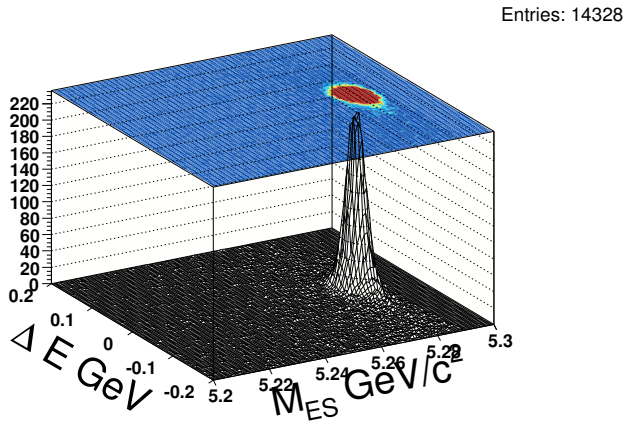

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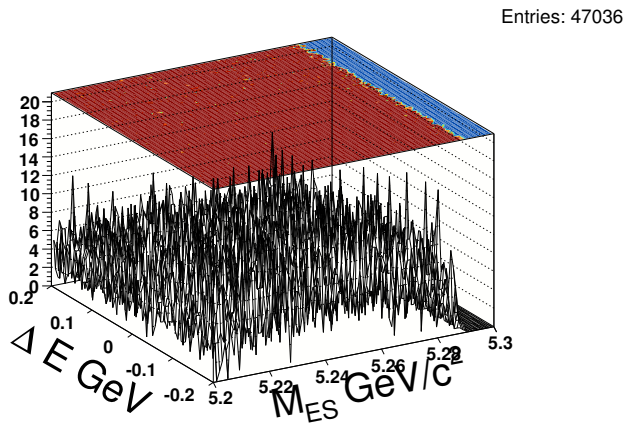
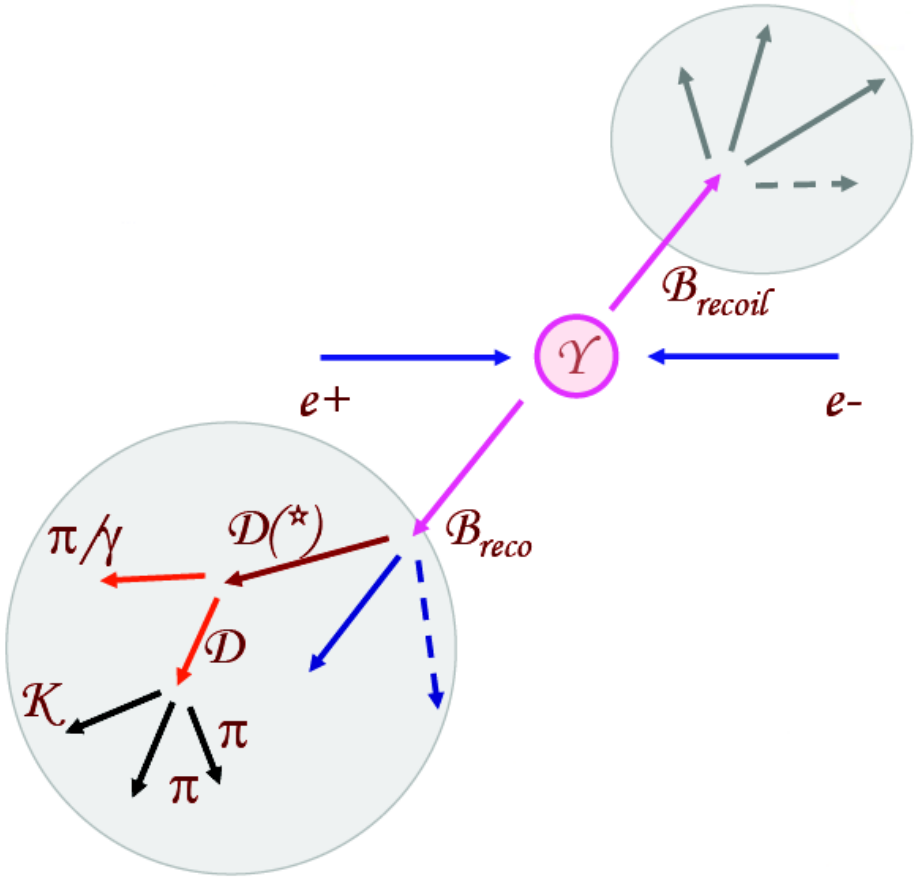


Tagging methods

- Completely reconstruct one B.
  - B_{reco} or B_{tag}
- Search the other B for decays of interest.
  - B_{recoil} or B_{sig}



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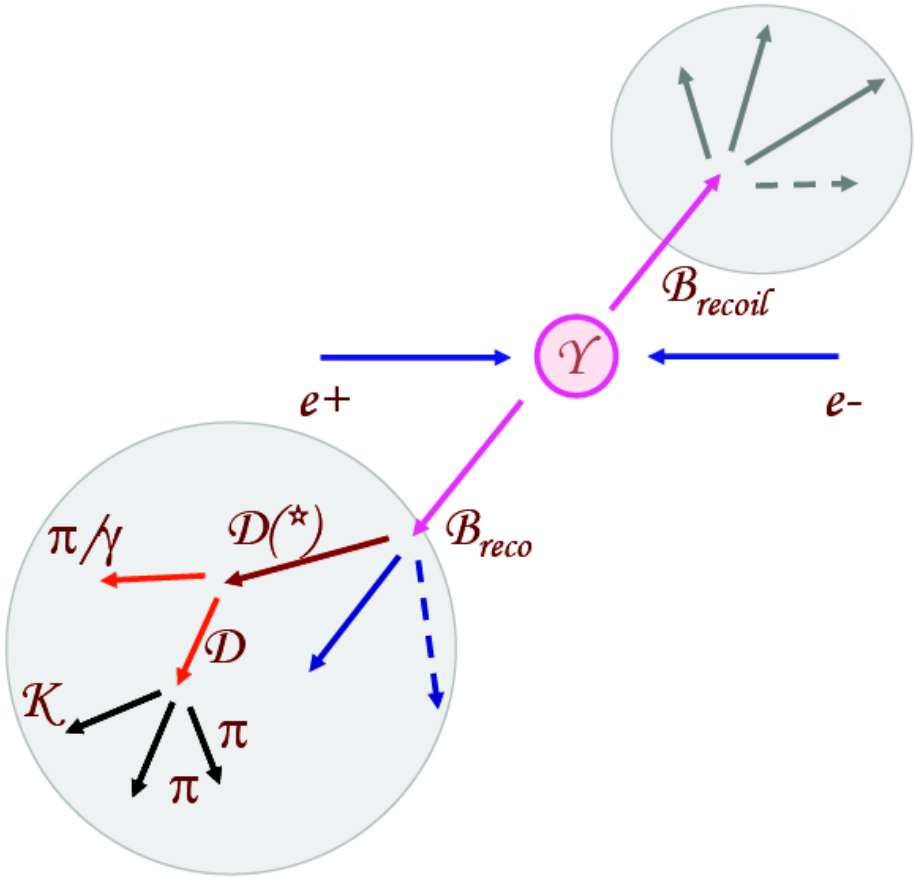

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- *Hadronic tag*
  - More pure.
  - Less efficient. ($\sim 0.2\%$)
  - ~ 1000 different decay modes!
  - $B \to D^{(*)} + \pi$
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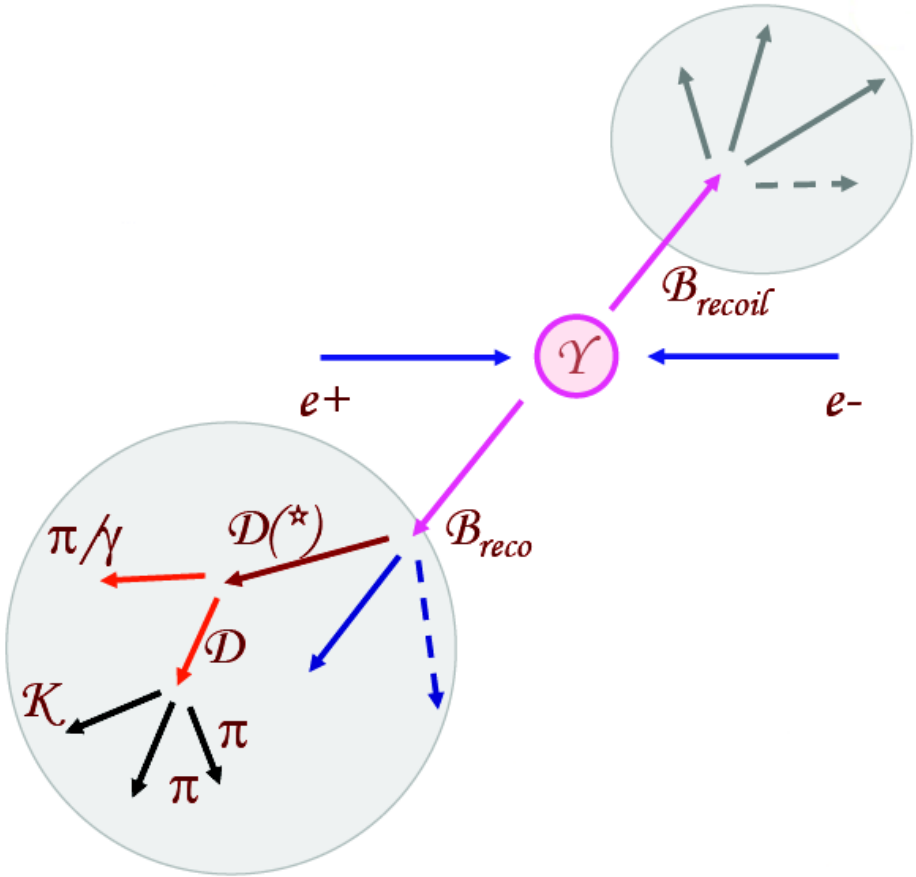
  - $B \to D^{(*)} + \pi K$
  - $\vdots$



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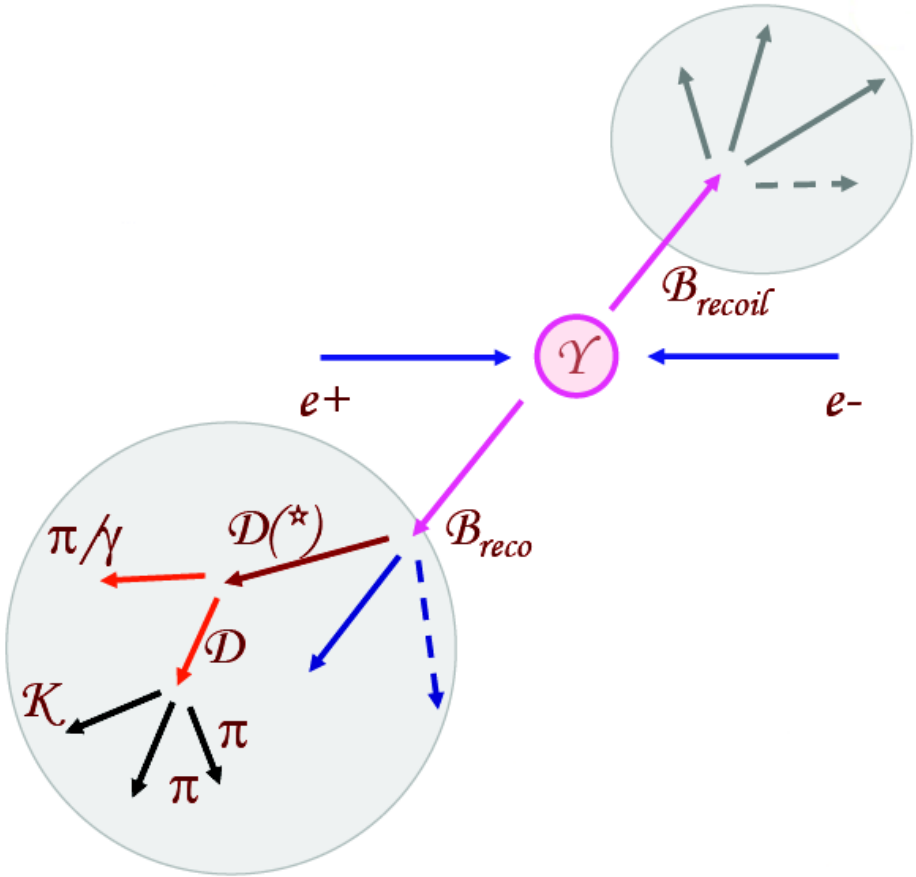
  - $\vdots$
- *Semileptonic tag*
  - Less pure.
  - More efficient. ($\sim 1.5\%$)
  - ν leads to "missing" energy
  - Handful of different decay modes.
  - $B \to D^{(*)} \ell \bar{\nu}$



$B \to \ell\nu$ WITH SEMILEPTONIC TAG

- Topology, kinematics and particle ID are used to suppress background.

Phys.Rev.D80:051101,2010 (arXiv:0809.4027) 459×10^6 $B\bar{B}$ *pairs*

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- $E_{\rm extra}$ strongest discriminating variable.
  - Extra neutral energy in the reaction.
  - ν' will **not** deposit extra energy.
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  - Peaks at 0 for reaction of interest.
- *Look at multiple decay modes of the* τ!
  - $\tau \to e\bar{\nu}\nu$
  - $\tau \to \mu\bar{\nu}\nu$
  - $\tau \to \pi\nu$
  - $\tau \to \rho\nu$

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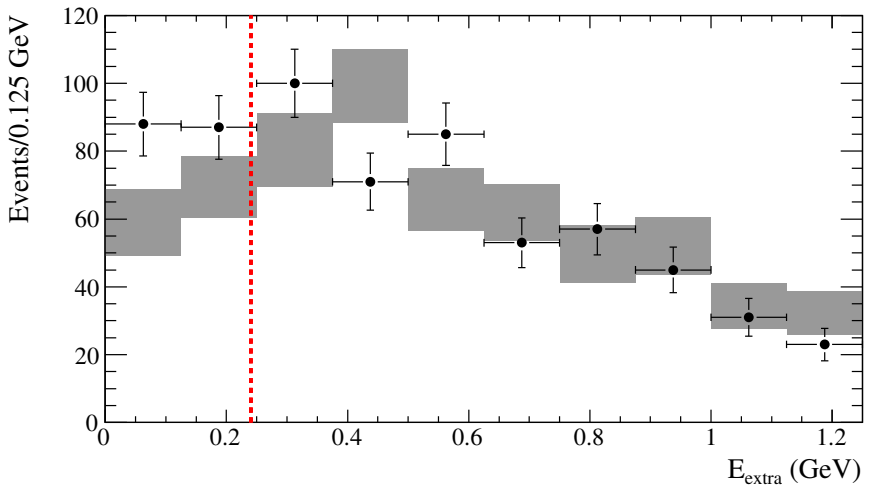

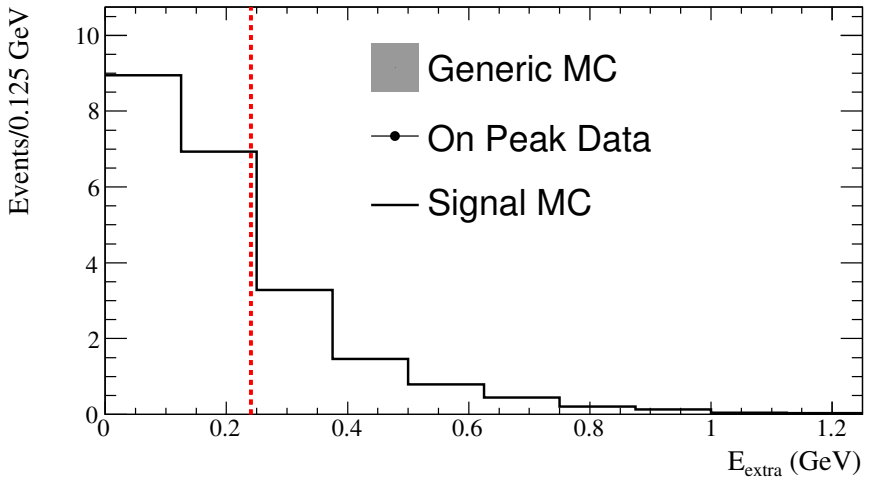

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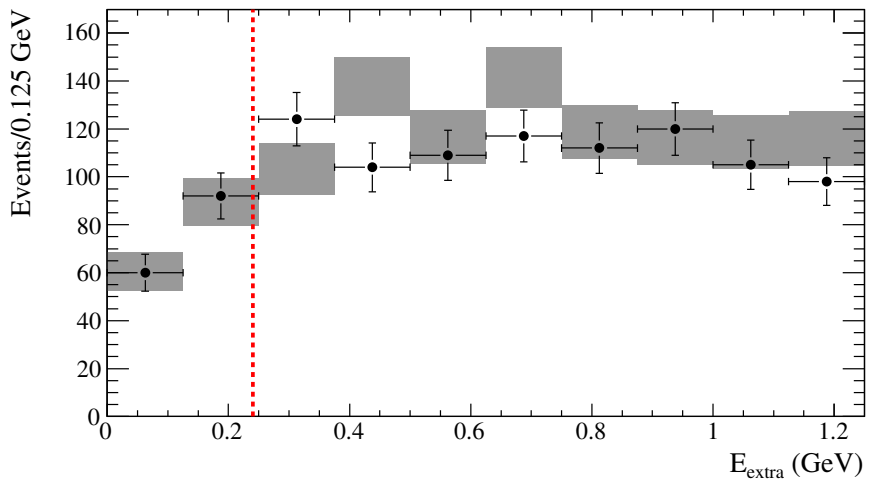
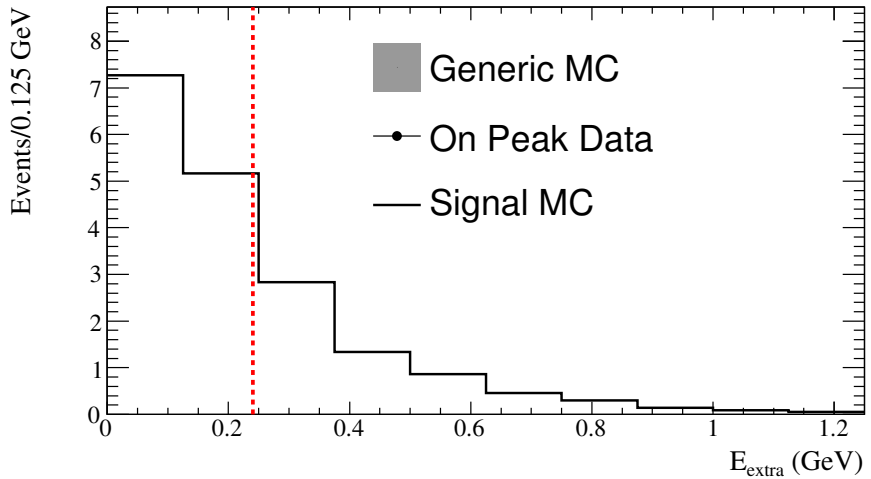
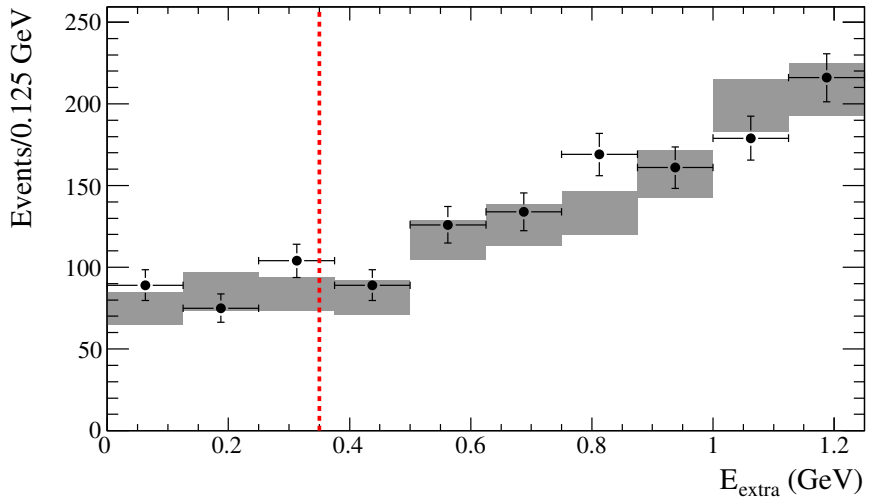
  - $\tau \to e\bar{\nu}\nu$
  - $\tau \to \mu\bar{\nu}\nu$

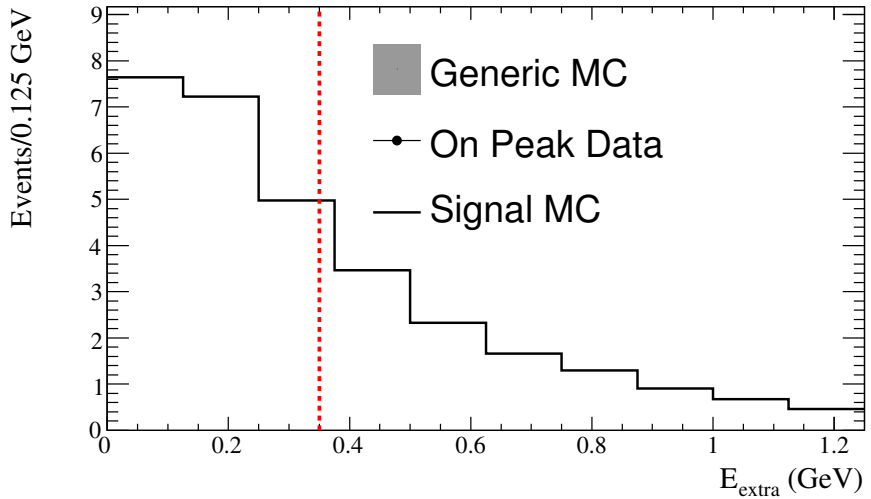




$B \to \ell\nu$ RESULTS

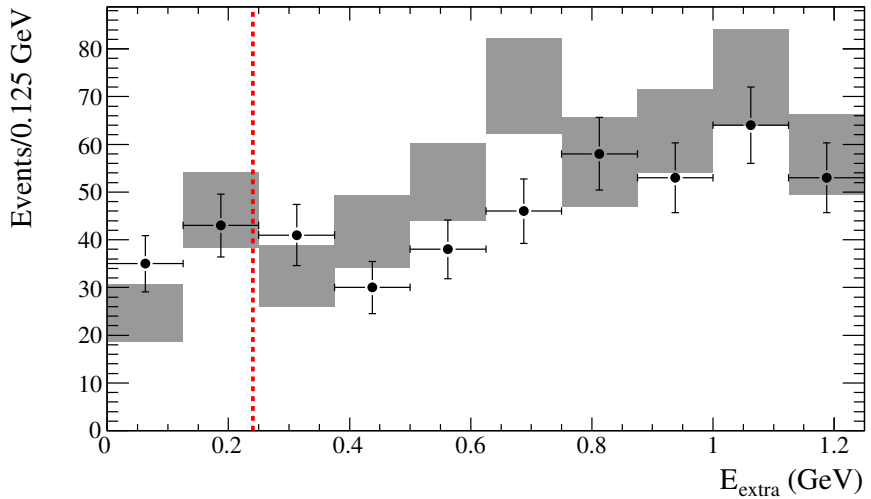
- $B \to \tau\bar{\nu}$
  - $\tau \to e\bar{\nu}\nu$
  - $\tau \to \mu\bar{\nu}\nu$
  - $\tau \to \pi\nu$

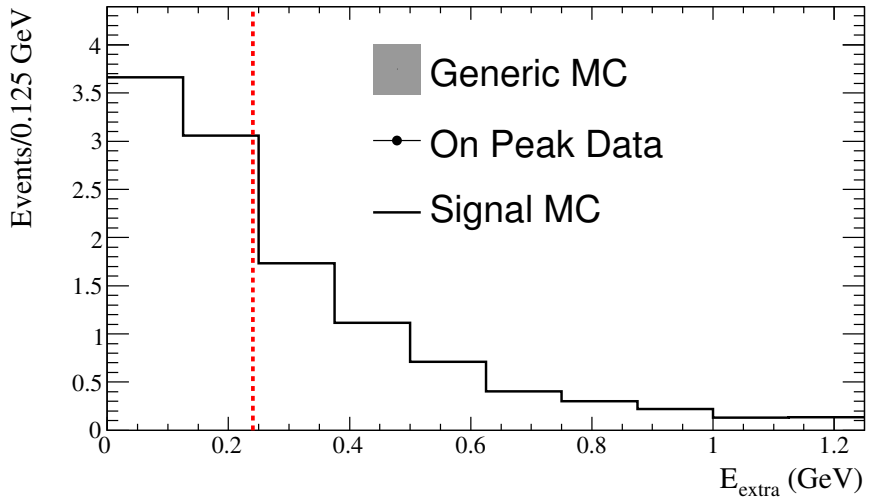




$B \to \ell\nu$ RESULTS

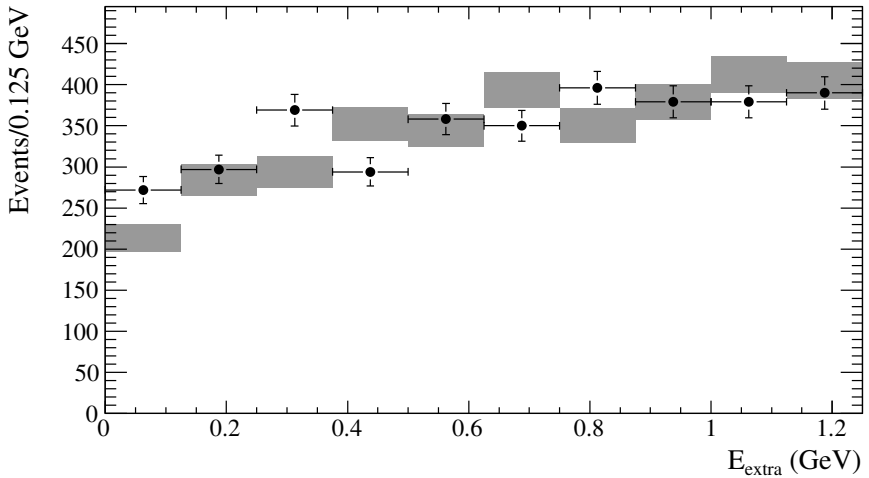
- $B \to \tau\bar{\nu}$
  - $\tau \to e\bar{\nu}\nu$
  - $\tau \to \mu\bar{\nu}\nu$
  - $\tau \to \pi\nu$
  - $\tau \to \rho\nu$

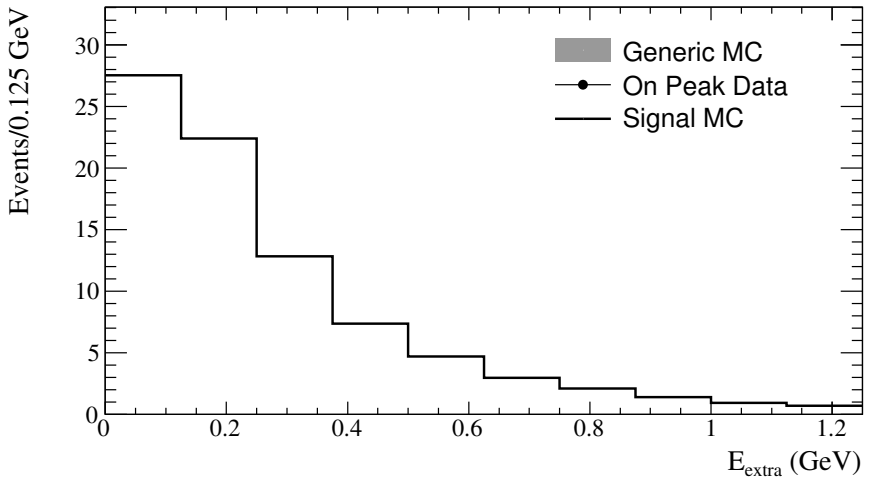




$B \to \ell\nu$ RESULTS

- $B \to \tau\bar{\nu}$
  - $\tau \to e\bar{\nu}\nu$
  - $\tau \to \mu\bar{\nu}\nu$
  - $\tau \to \pi\nu$
  - $\tau \to \rho\nu$
- $B \to \tau\bar{\nu}$ (Total)
  - SL:
    $\mathcal{B}(B \to \tau\bar{\nu}) = 1.8 \pm 0.8 \pm 0.1 \times 10^{-4}$
  - Had:
    $\mathcal{B}(B \to \tau\bar{\nu}) = 1.8 \pm 0.4 \pm 0.2 \times 10^{-4}$

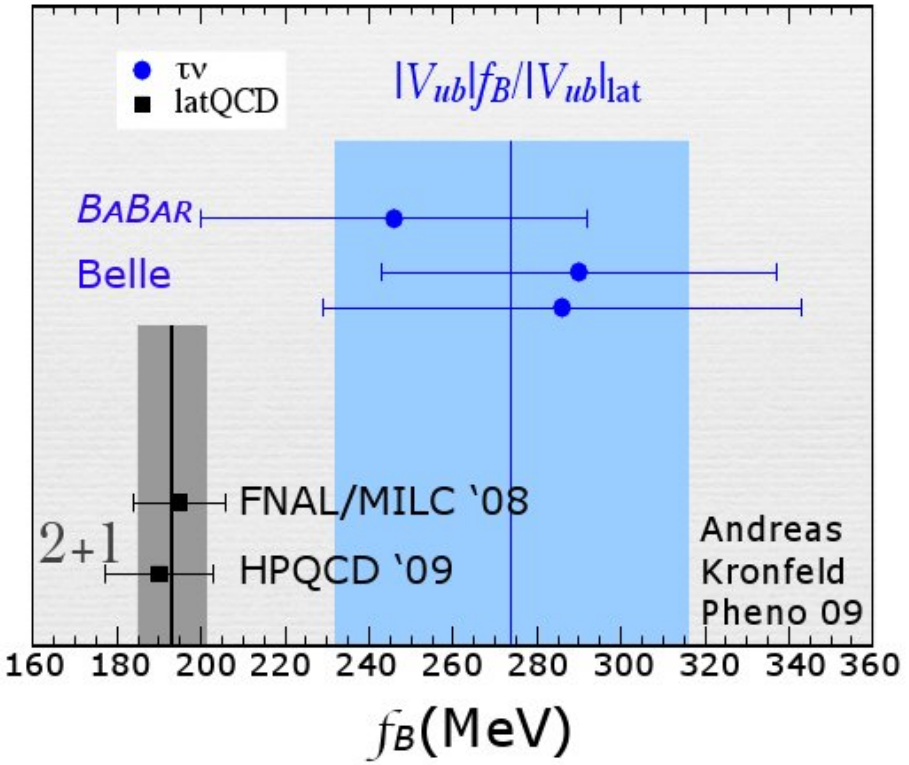




$B \to \ell\nu$ RESULTS

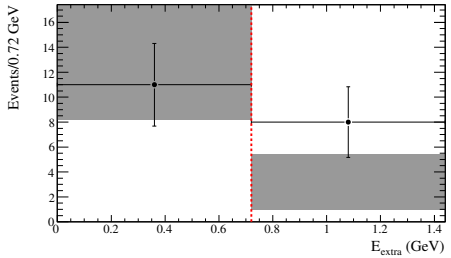
- $B \to \tau\bar{\nu}$
  - $\tau \to e\bar{\nu}\nu$
  - $\tau \to \mu\bar{\nu}\nu$
  - $\tau \to \pi\nu$
  - $\tau \to \rho\nu$
- $B \to \tau\bar{\nu}$ (Total)
  - SL:
    $\mathcal{B}(B \to \tau\bar{\nu}) = 1.8 \pm 0.8 \pm 0.1 \times 10^{-4}$
  - Had:
    $\mathcal{B}(B \to \tau\bar{\nu}) = 1.8 \pm 0.4 \pm 0.2 \times 10^{-4}$
  - 
  - *PRL 97,251802 (2006)*
  - *arXiv:0809.3834*
  - SL:
    $\mathcal{B}(B \to \tau\bar{\nu}) = 1.65 \pm 0.4 \pm 0.4 \times 10^{-4}$
  - Had:
    $\mathcal{B}(B \to \tau\bar{\nu}) = 1.79 \pm 0.5 \pm 0.5 \times 10^{-4}$

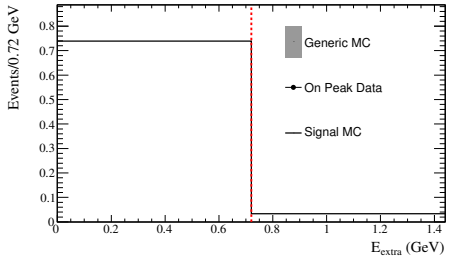
(using the BaBar published SL result)

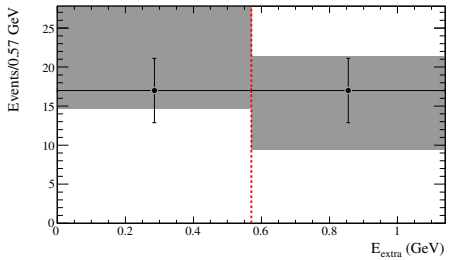


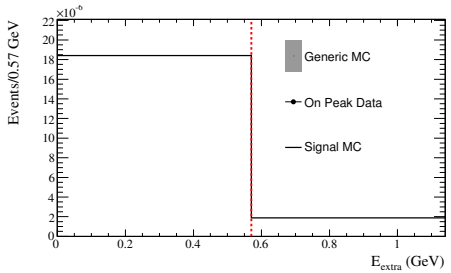
$B \to \ell\nu$ RESULTS

- $B \to \mu\bar{\nu}$
  - 11 observed
  - 15±10 expected bkg.
  - $\mathcal{B}(B \to \mu\bar{\nu})UL90\% = 11 \times 10^{-6}$
- $B \to e\bar{\nu}$
  - 17 observed
  - 24±11 expected bkg.
  - $\mathcal{B}(B \to e\bar{\nu})UL90\% = 7.7 \times 10^{-6}$



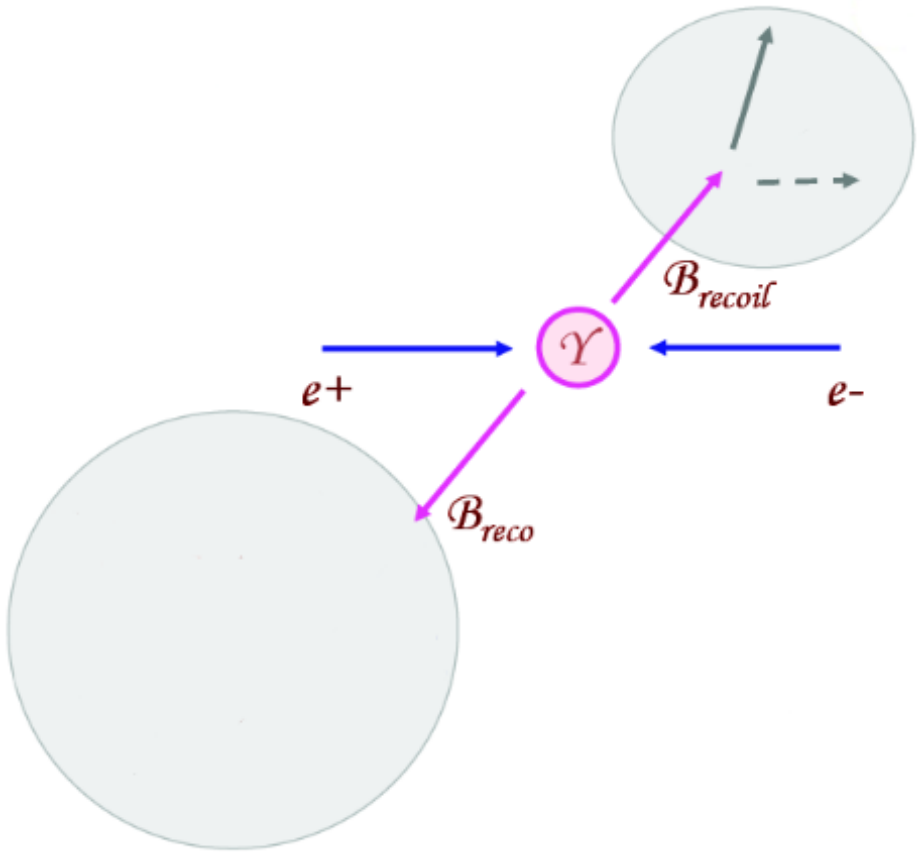






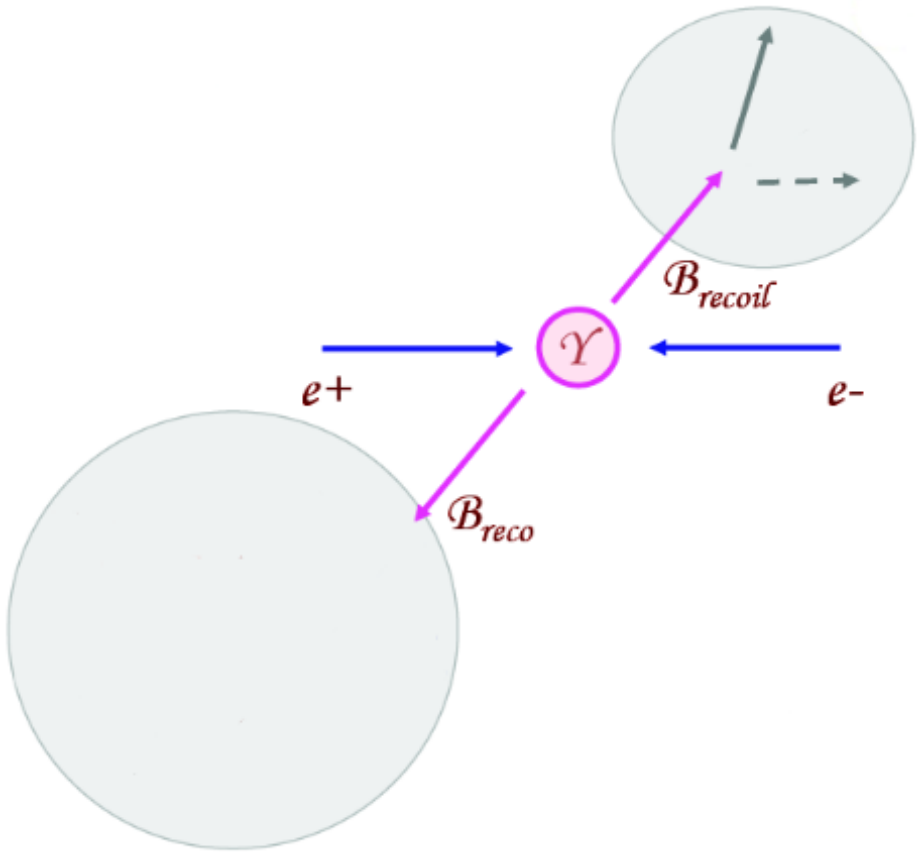
$B \to e/\mu\bar{\nu}$ INCLUSIVE

- Very rare (BR$\sim 10^{-7}, 10^{-12}$ respectively)
- Other experimental methods?
- *Inclusive measurement.*
- Very strong signal-side signature...



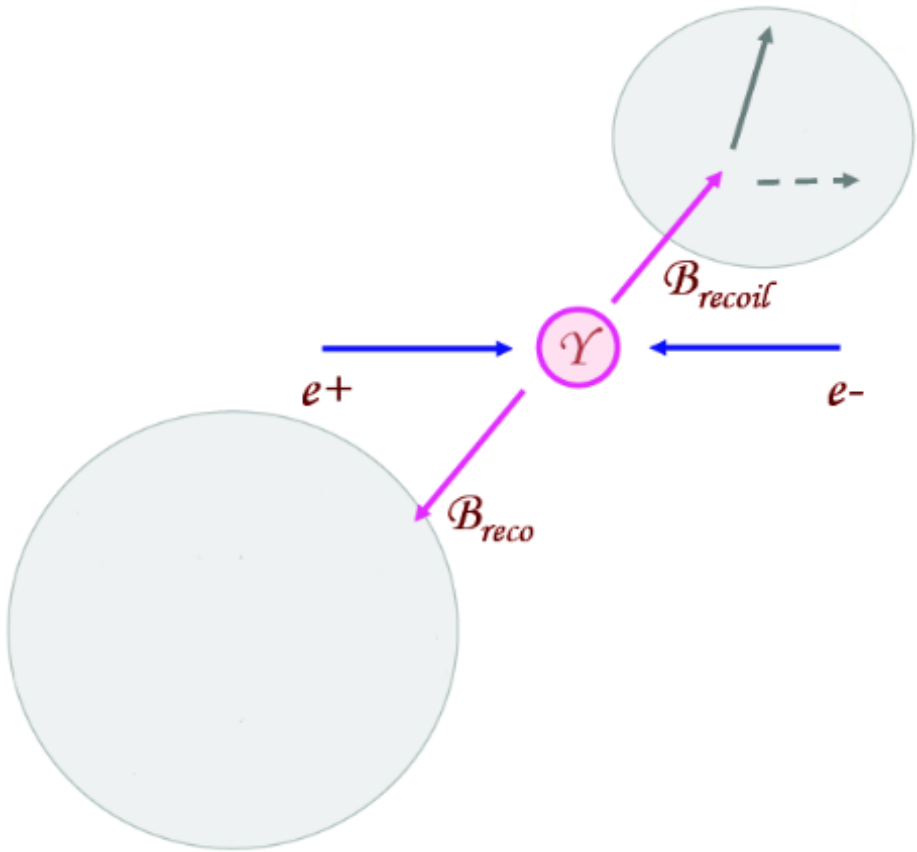
$B \to e/\mu\bar{\nu}$ INCLUSIVE

- Very rare (BR$\sim 10^{-7}, 10^{-12}$ respectively)
- Other experimental methods?
- *Inclusive measurement.*
- Very strong signal-side signature...
- A single, monochromatic lepton in the B rest frame.
  - Momentum smeared distribution in the CM frame.
  - Apply tight particle ID criteria and reject events with more leptons.



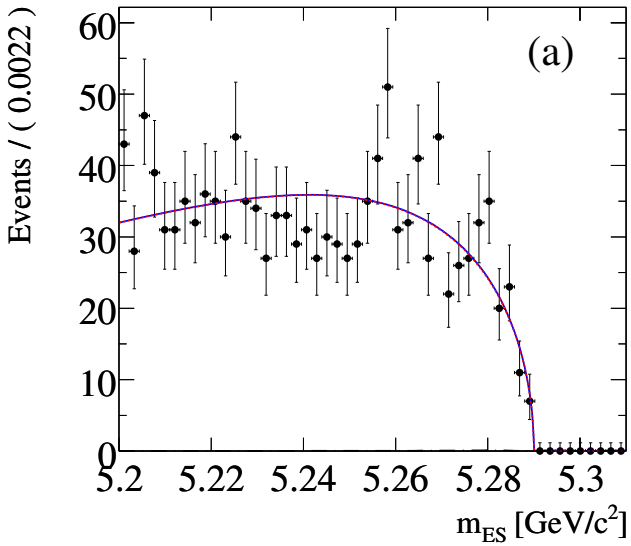
$B \to e/\mu\bar{\nu}$ INCLUSIVE

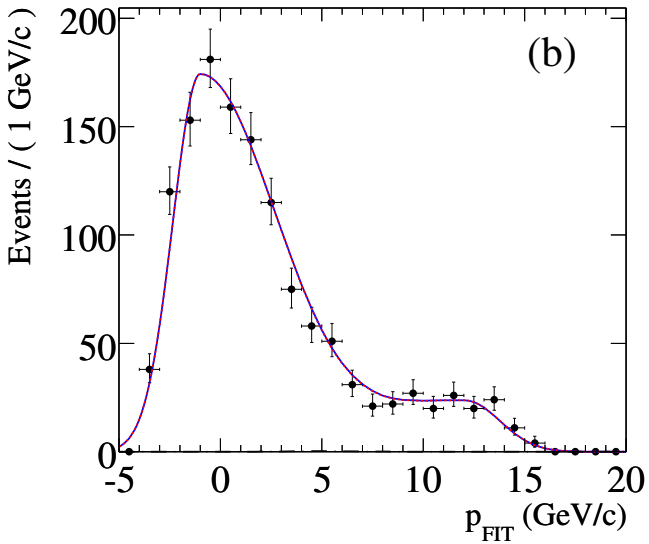
- Very rare (BR$\sim 10^{-7}, 10^{-12}$ respectively)
- Other experimental methods?
- *Inclusive measurement.*
- Very strong signal-side signature...
- A single, monochromatic lepton in the B rest frame.
  - Momentum smeared distribution in the CM frame.
  - Apply tight particle ID criteria and reject events with more leptons.
- Inclusive approach for the rest of the event.
  - Highly efficient...but high background too.
  - Build an inclusive 4-momentum with everything else in the event.
  - Discriminate with m_{ES} and ΔE
  - Background suppression with kinematic and topological variables combined with a Fisher discriminant.



$B \to e/\mu\bar{\nu}$ INCLUSIVE RESULTS

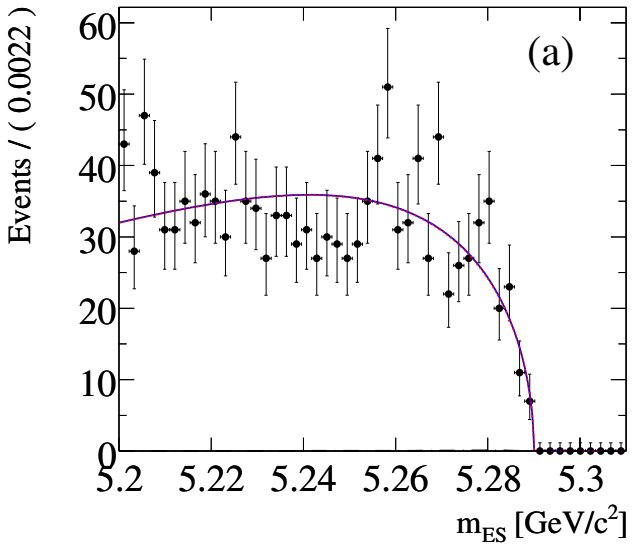
- Simultaneous fit to:
  - m_{ES} of the inclusive B.
  - p^*_ℓ: transformed lepton momentum (CM and B rest frame)

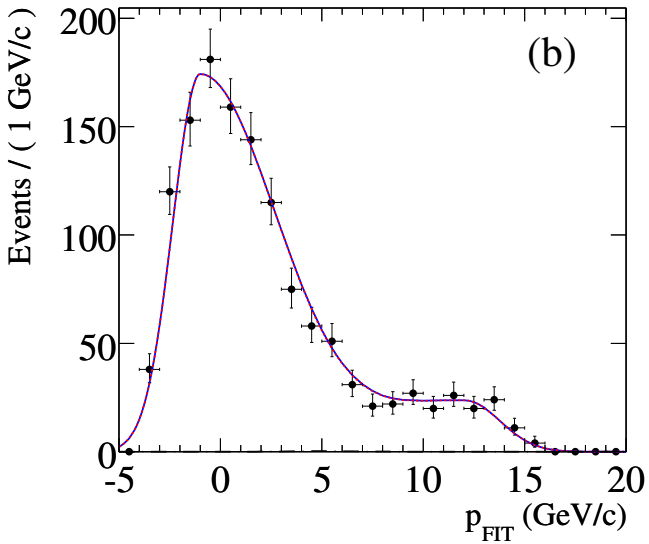




$B \to e/\mu\bar{\nu}$ INCLUSIVE RESULTS

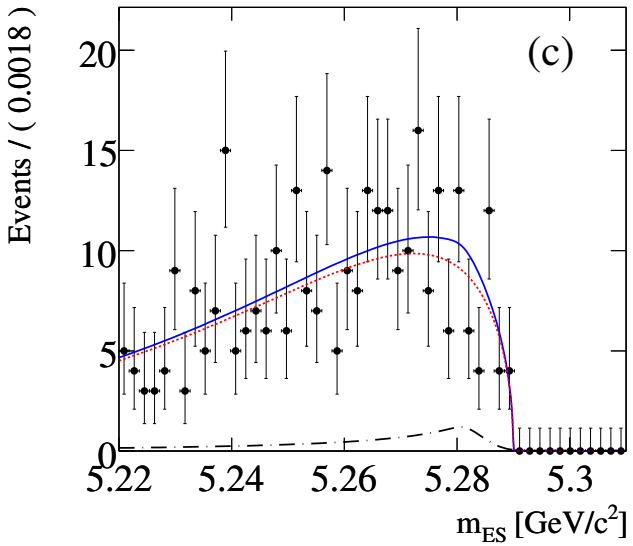
- Simultaneous fit to:
  - m_{ES} of the inclusive B.
  - p^*_ℓ: transformed lepton momentum (CM and B rest frame)
- $B \to e\bar{\nu}$
  - $\mathcal{B}$ at 90% CL $< 1.9 \times 10^{-6}$

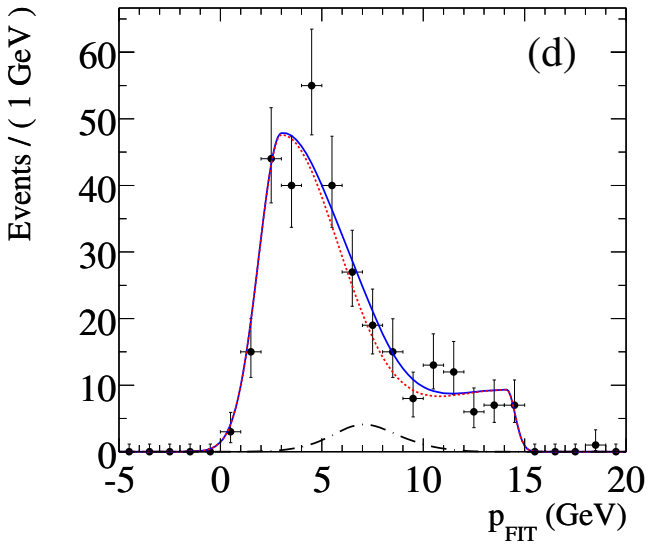




$B \to e/\mu\bar{\nu}$ INCLUSIVE RESULTS

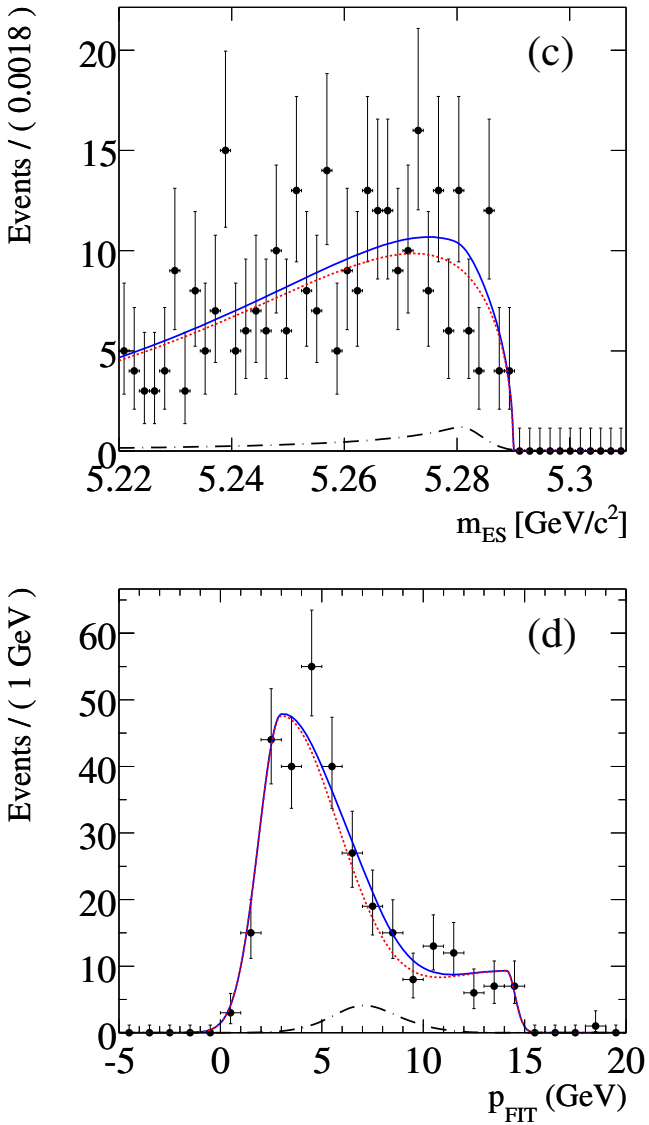
- Simultaneous fit to:
  - m_{ES} of the inclusive B.
  - p^*_ℓ: transformed lepton momentum (CM and B rest frame)
- $B \to e\bar{\nu}$
  - $\mathcal{B}$ at 90% CL $< 1.9 \times 10^{-6}$
- $B \to \mu\bar{\nu}$
  - $\mathcal{B}$ at 90% CL $< 1.0 \times 10^{-6}$





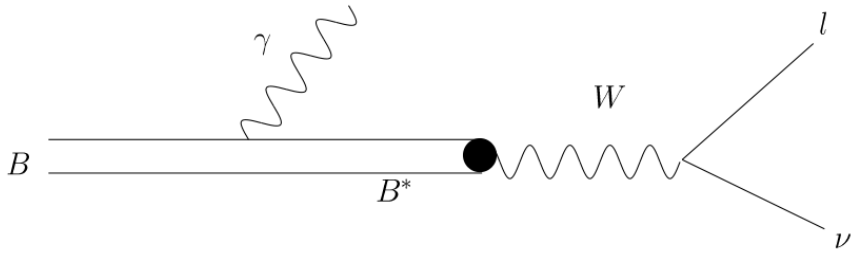
$B \to e/\mu\bar{\nu}$ INCLUSIVE RESULTS

- Simultaneous fit to:
  - m_{ES} of the inclusive B.
  - p^*_ℓ: transformed lepton momentum (CM and B rest frame)
- $B \to e\bar{\nu}$
  - $\mathcal{B}$ at 90% CL $< 1.9 \times 10^{-6}$
  - $\mathcal{B}$ at 90% CL $< 0.98 \times 10^{-6}$
- $B \to \mu\bar{\nu}$
  - $\mathcal{B}$ at 90% CL $< 1.0 \times 10^{-6}$
  - $\mathcal{B}$ at 90% CL $< 1.7 \times 10^{-6}$



$B \to \ell\nu\gamma$ WITH HADRONIC TAGS

- No helicity suppression.
- Dependence on α_{EM} and form factors.
- Model dependent
  - HQET LO: $f_A = f_V$
  - Others: $f_A = 0$
- Experimentally, making no requirements on lepton or photon momenta reduces the model dependence.

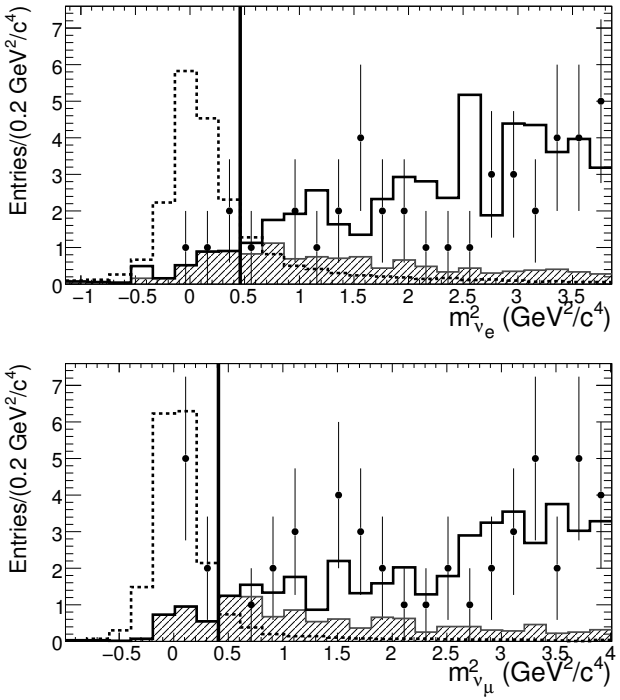


$$\mathcal{B}(B^+ \to \ell^+\nu\gamma) = \frac{\alpha G_F^2 m_B}{288\pi}|V_{ub}|^2 f_B^2 m_B^5 \tau_B \left(\frac{Q_u}{\lambda_B} - \frac{Q_u}{\lambda_b}\right)^2$$

PRD 80,111105 (2009) arXiv:0907.1681 $465 \times 10^6 B\bar{B}$ *pairs*

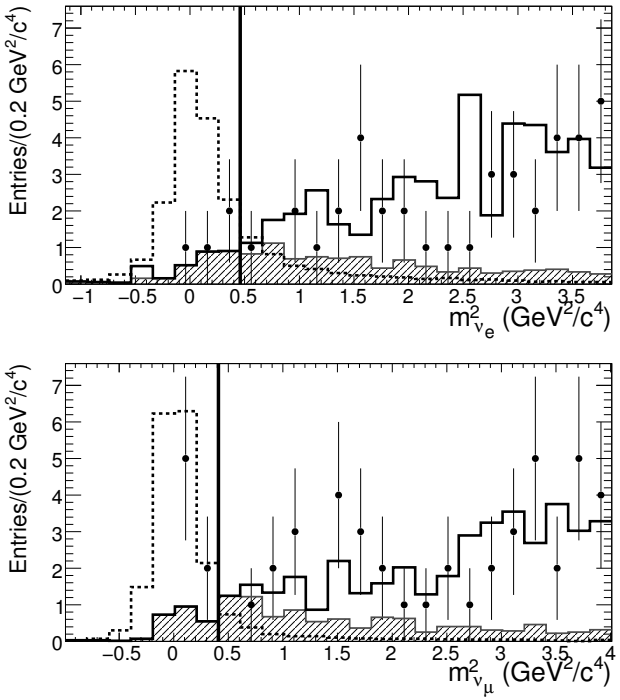
$B \to \ell\nu\gamma$ WITH HADRONIC TAGS RESULTS

- Model independent estimation of $\mathcal{B}$.
  - Cut and count analysis with UL determined with frequentist approach.



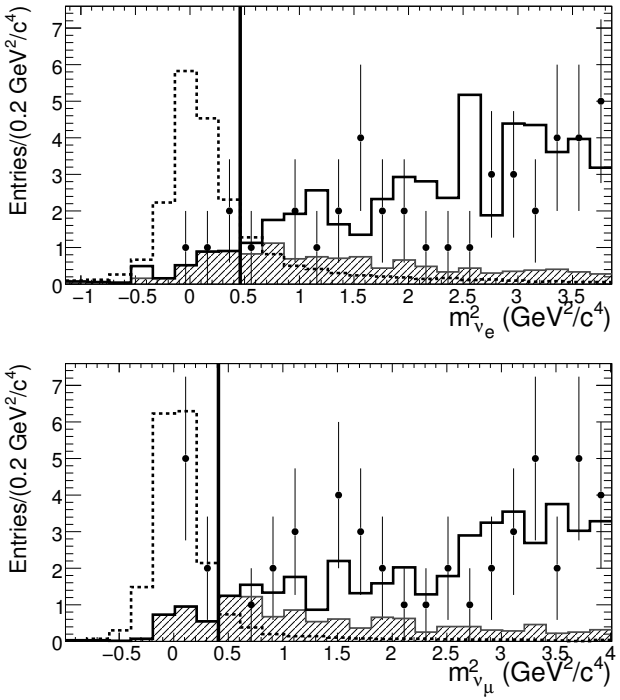
$B \to \ell\nu\gamma$ WITH HADRONIC TAGS RESULTS

- Model independent estimation of $\mathcal{B}$.
  - Cut and count analysis with UL determined with frequentist approach.
- $B \to e\bar{\nu}\gamma$
  - FC CL band: $< 17 \times 10^{-6}$



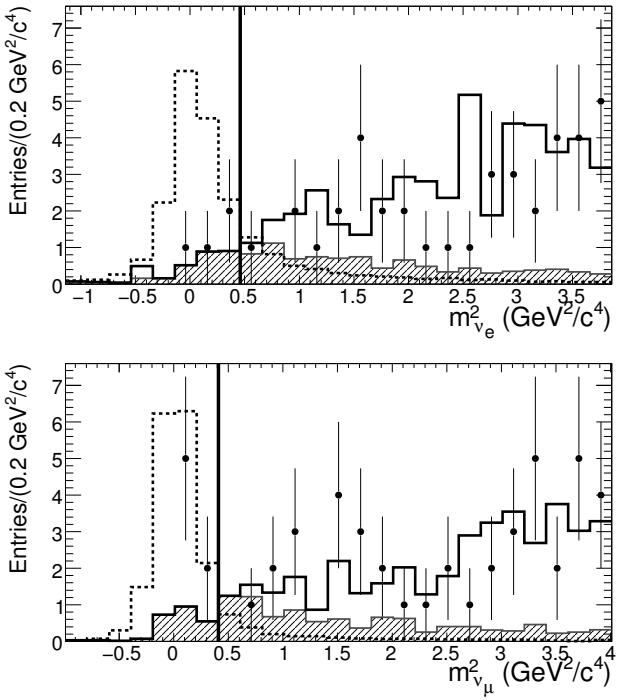
$B \to \ell\nu\gamma$ WITH HADRONIC TAGS RESULTS

- Model independent estimation of $\mathcal{B}$.
  - Cut and count analysis with UL determined with frequentist approach.
- $B \to e\bar{\nu}\gamma$
  - FC CL band: $< 17 \times 10^{-6}$
- $B \to \mu\bar{\nu}\gamma$
  - FC CL band: $< 26 \times 10^{-6}$
- $B \to \ell\bar{\nu}\gamma$
  - FC CL band: $< 15 \times 10^{-6}$
  - $\mathcal{B} = 6.47^{+7.6+2.8}_{-4.7-0.8} \times 10^{-6}$ at 2.1σ



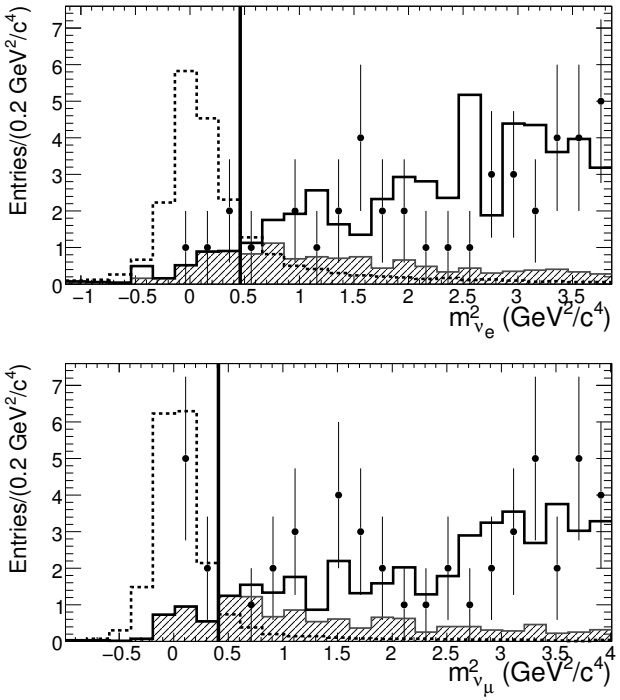
$B \to \ell\nu\gamma$ WITH HADRONIC TAGS RESULTS

- Model dependent estimation of $\mathcal{B}$.
  - Cut on $\ell - \gamma$ angle and $\nu - \gamma$ angle in hypothesis of $f_A = f_V$ or $f_A = 0$



$B \to \ell\nu\gamma$ WITH HADRONIC TAGS RESULTS

- Model dependent estimation of $\mathcal{B}$.
  - Cut on $\ell - \gamma$ angle and $\nu - \gamma$ angle in hypothesis of $f_A = f_V$ or $f_A = 0$
- $f_A = f_V$
  - $e\bar{\nu}\gamma < 8.4 \times 10^{-6}$
  - $\mu\bar{\nu}\gamma < 6.7 \times 10^{-6}$
  - $\ell\bar{\nu}\gamma < 3.0 \times 10^{-6}$



$B \to \ell\nu\gamma$ WITH HADRONIC TAGS RESULTS

- Model dependent estimation of $\mathcal{B}$.
  - Cut on $\ell - \gamma$ angle and $\nu - \gamma$ angle in hypothesis of $f_A = f_V$ or $f_A = 0$
- $f_A = f_V$
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  - $\ell\bar{\nu}\gamma < 3.0 \times 10^{-6}$
- $f_A = f_V$
  - $e\bar{\nu}\gamma < 8.4 \times 10^{-6}$
  - $\mu\bar{\nu}\gamma < 6.7 \times 10^{-6}$
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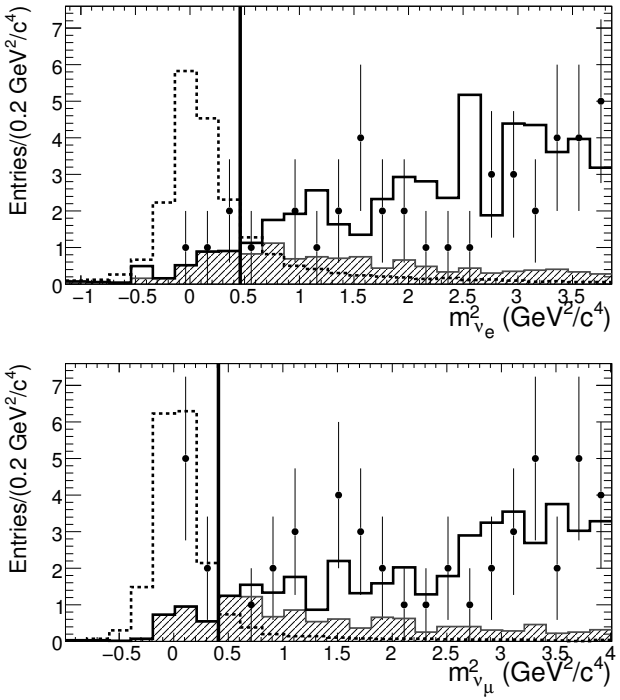


Lepton flavour violating modes

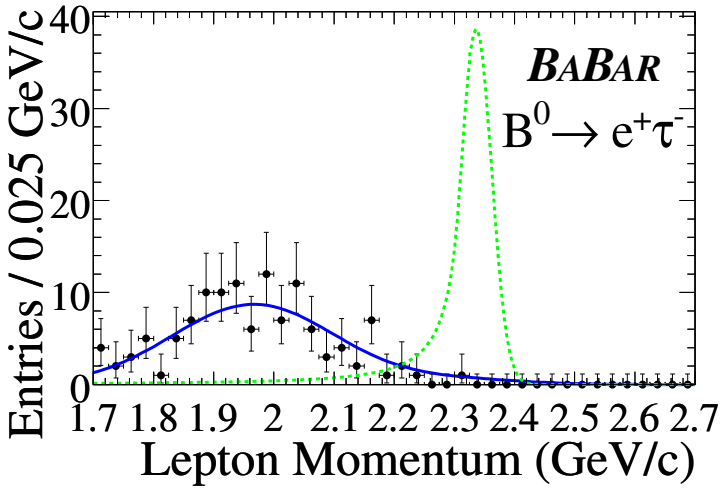
- First two generations less challenging than τ.
  - But the third generation is most sensitive to NP
  - Usually published along with LFC analyses of $B \to \ell^+\ell^-$ and $B \to K\ell^+\ell^-$ (where $\ell = e, \mu$)
- Both analyses use very similar methodology based on hadronic tag reconstruction.

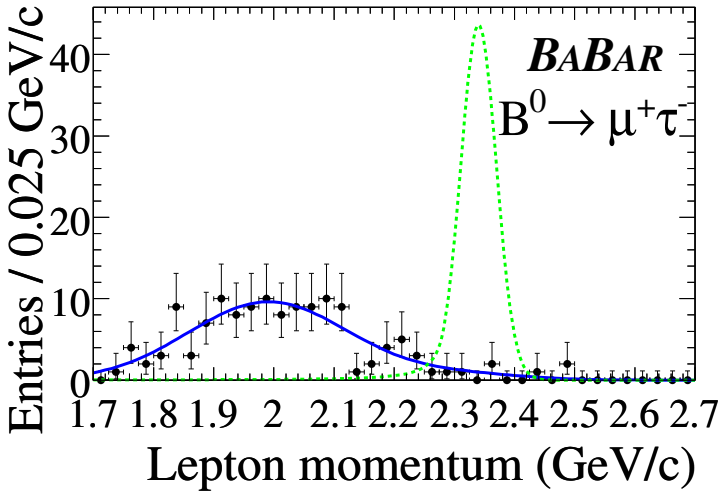
PRD 77,091104 (2008) arXiv:0801.0697 378×10^6 *$B\bar{B}$ pairs*

PRL 99,201801 (2007) arXiv:0708.1303 383×10^6 *$B\bar{B}$ pairs*

$B \to \ell\tau(\ell = e, \mu)$ WITH HADRONIC TAGS RESULTS

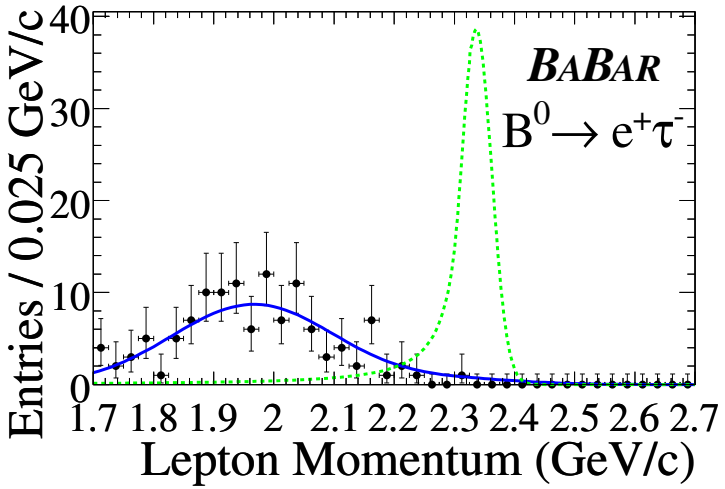
- Well established methodology.
  - Same as $B \to \ell\nu$

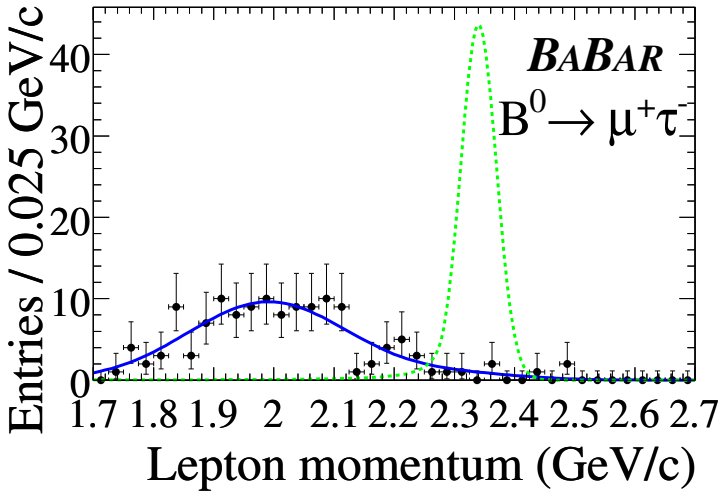




$B \to \ell\tau(\ell = e, \mu)$ WITH HADRONIC TAGS RESULTS

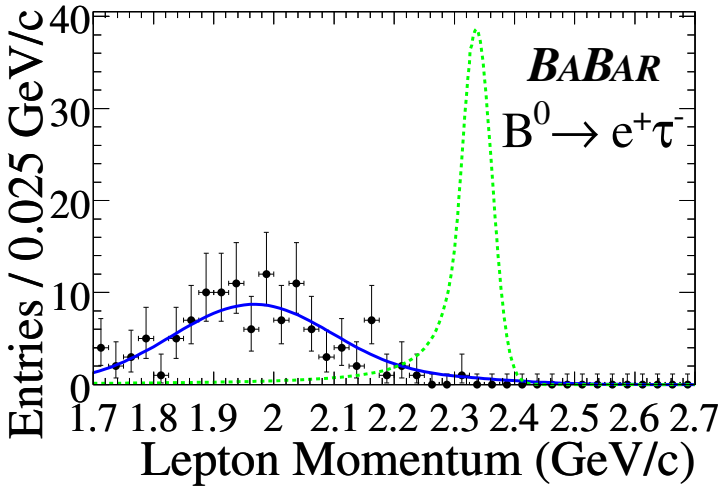
- Well established methodology.
  - Same as $B \to \ell\nu$
- Hadronic B tag

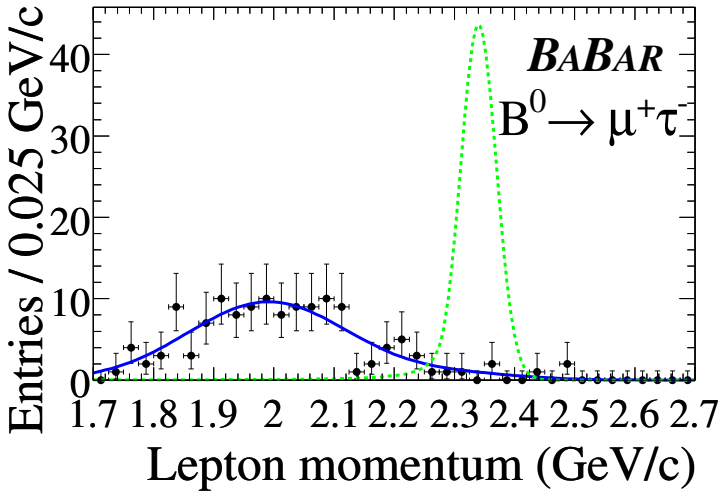




$B \to \ell\tau(\ell = e, \mu)$ WITH HADRONIC TAGS RESULTS

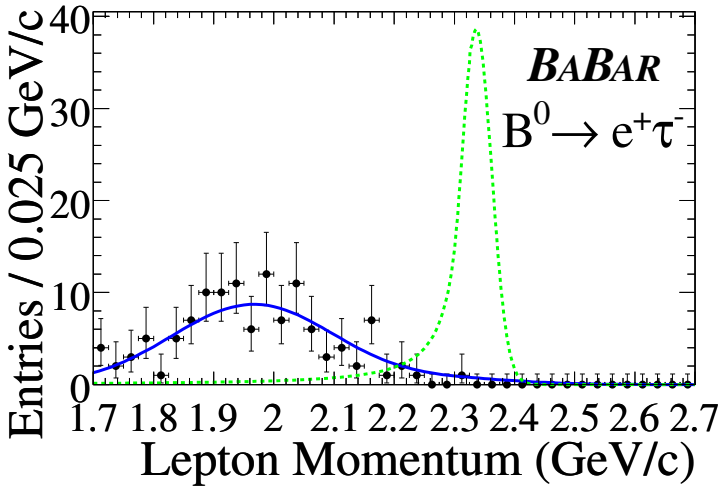
- Well established methodology.
  - Same as $B \to \ell\nu$
- Hadronic B tag
- Lepton monochromatic in the B rest frame.
  - Very clear signature.

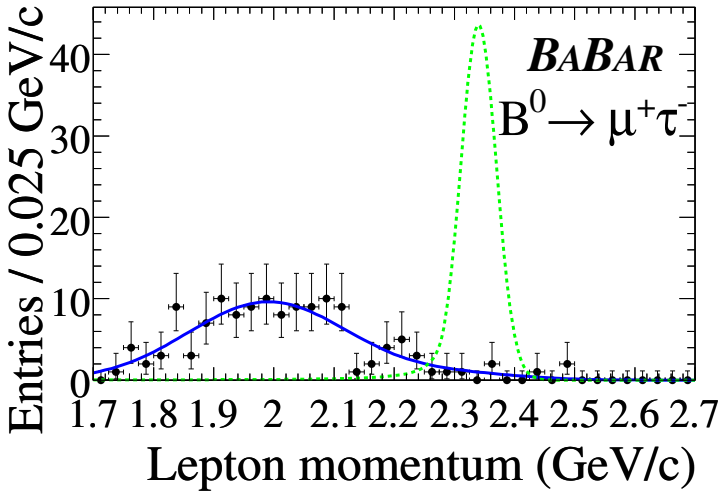




$B \to \ell\tau(\ell = e, \mu)$ WITH HADRONIC TAGS RESULTS

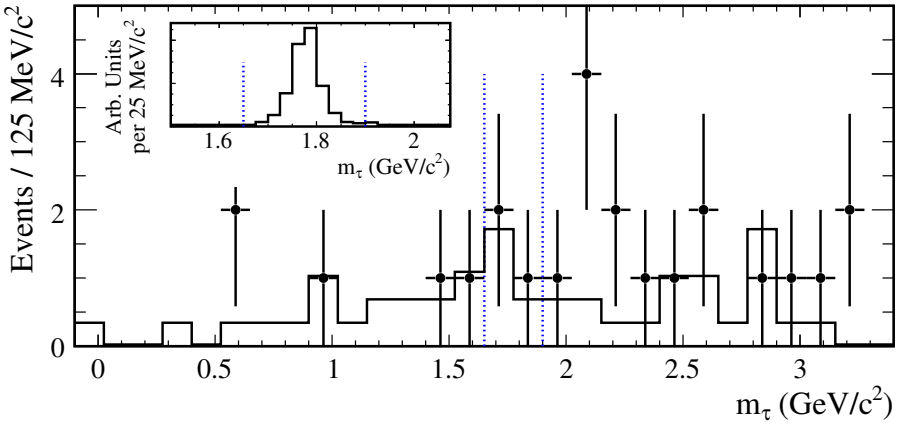
- Well established methodology.
  - Same as $B \to \ell\nu$
- Hadronic B tag
- Lepton monochromatic in the B rest frame.
  - Very clear signature.
- Straightforward reconstruction of the τ
  - Full 4-momenta
- 90% CL upper limits.
  - $\mathcal{B}(B^0 \to e\tau) < 2.8 \times 10^{-5}$
  - $\mathcal{B}(B^0 \to \mu\tau) < 2.2 \times 10^{-5}$
  - $\mathcal{B}(B^0 \to K^+\mu\tau) < 7.7 \times 10^{-5}$





$B \to K^+ \mu \tau$

- Potentially the most sensitive LFV channel to NP.
- Hadronic B tag
- Signal side completely reconstructed.
- τ mass defines the signal.
- Main background (and control sample) from $b \to c\ell\nu$



M.Sher and Y.Yuan,PRD44,1461 (1991) T.P.Cheng and M.Sher,PRD35,3484 (1987)

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- Belle is still running and BaBar is still analyzing.
- **Next generation B-factories could be very exciting!**
- Thanks for your time!