Beyond-SM searches in $\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau$ and rare decays at BaBar

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on behalf of the BaBar collaboration

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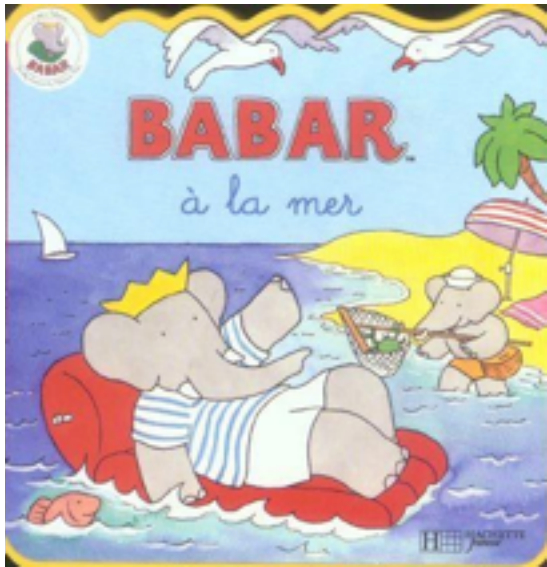
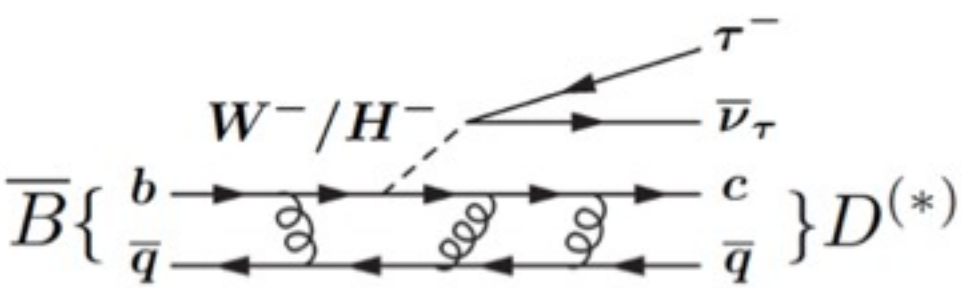
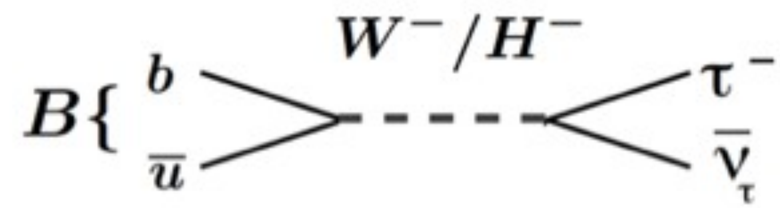


The third generation leptons couple more strongly to the electroweak symmetry breaking sector. Their decays, therefore, are suitable to probe physics beyond the Standard Model (SM).



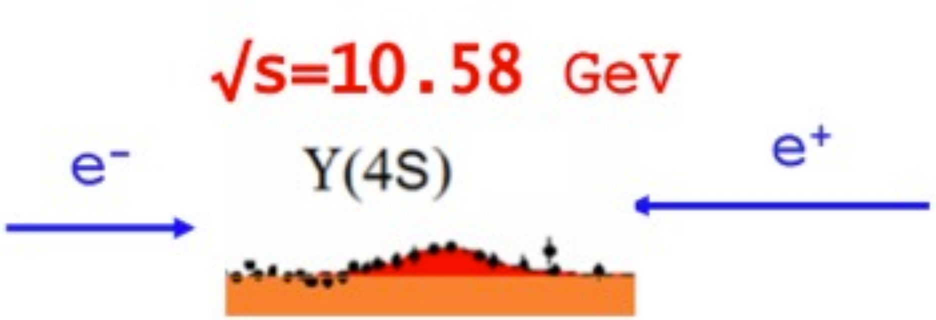


One popular scenario for New Physics is the two Higgs doublet model (2HDM). It can enhance or decrease the decay rates of $B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$ through the contribution of a charged Higgs boson.

We can also study other decay modes like $B \to K^{(*)}\nu\nu$ to further limit the NP effects

We can use the unique environment of B-factories to study these decays in detail.

The boost enables to perform the time-dependent analysis.

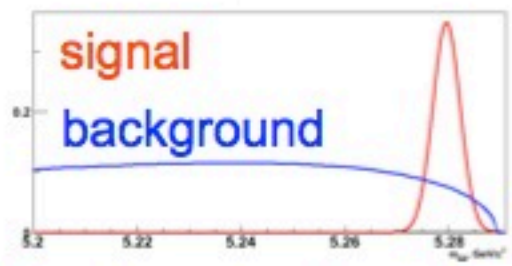


BaBar $9\ \mathrm{GeV}/c^2$ $3.1\ \mathrm{GeV}/c^2$

Belle $8\ \mathrm{Gev}/c^2$ $3.5\ \mathrm{Gev}/c^2$

Energy substituted mass

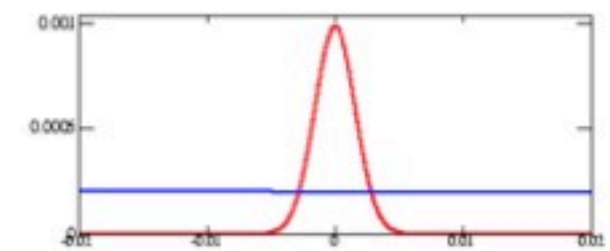
$$m_{ES} = \sqrt{E_{\text{beam}}^2 - p_B^2}$$



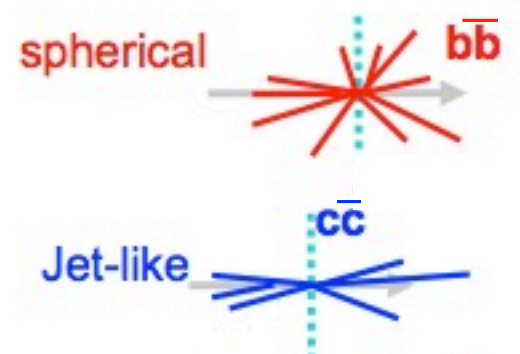
Typical experimental resolution ~2.6 MeV/c²

Beam-energy difference

$$\Delta E = E_B - E_{\text{beam}}$$

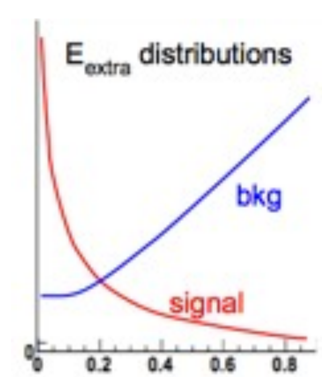


Typical experimental resolution [15-20] MeV

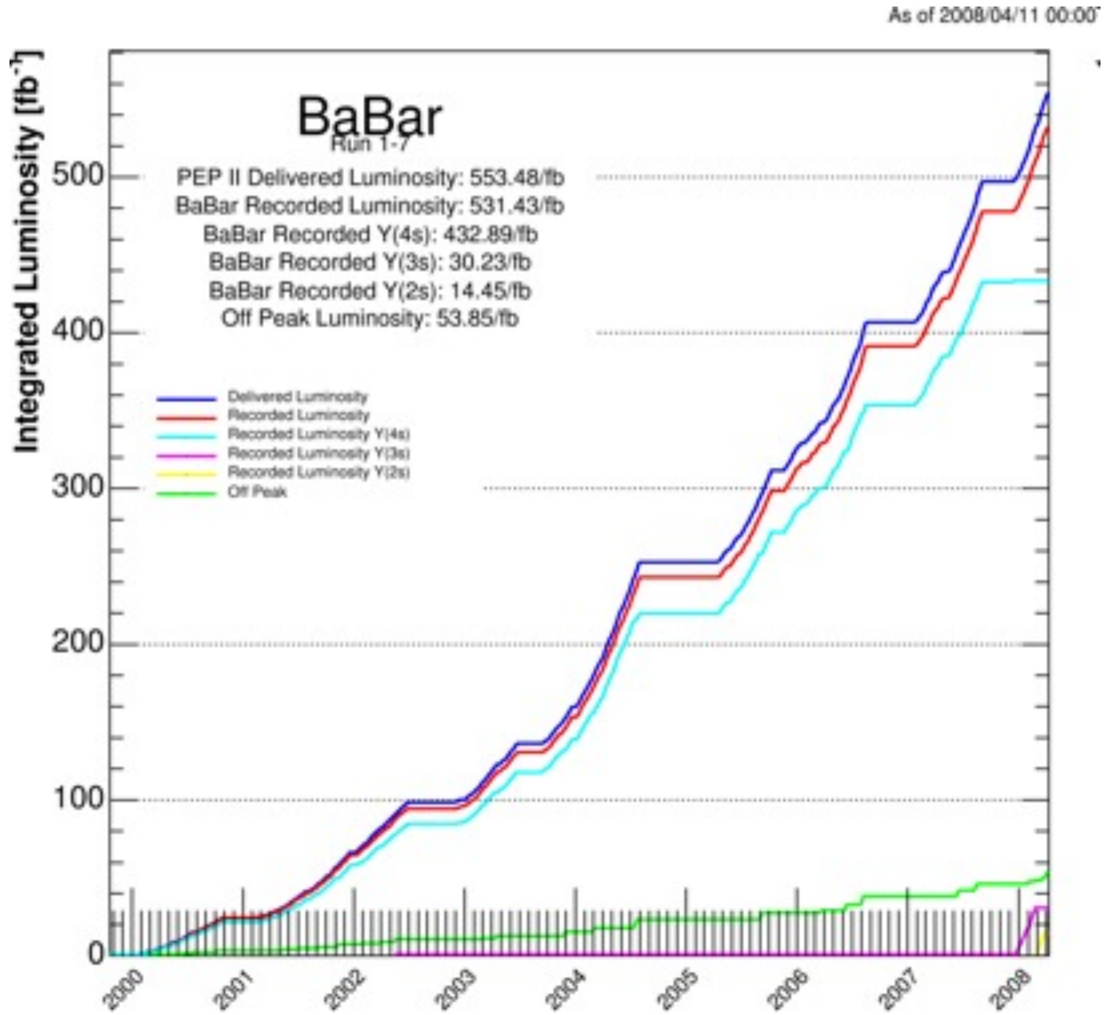


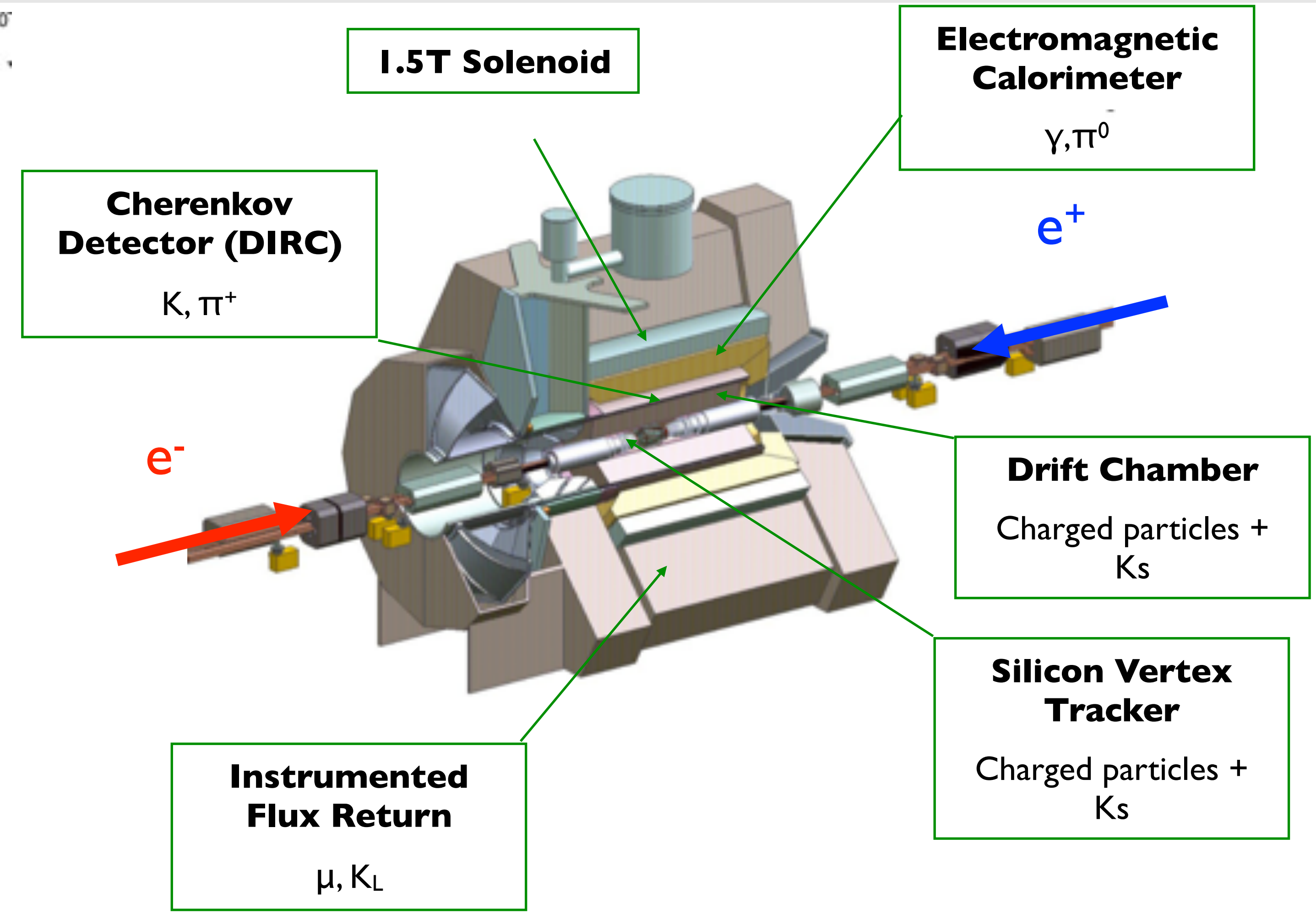
event shape moments
angles of thrust axes

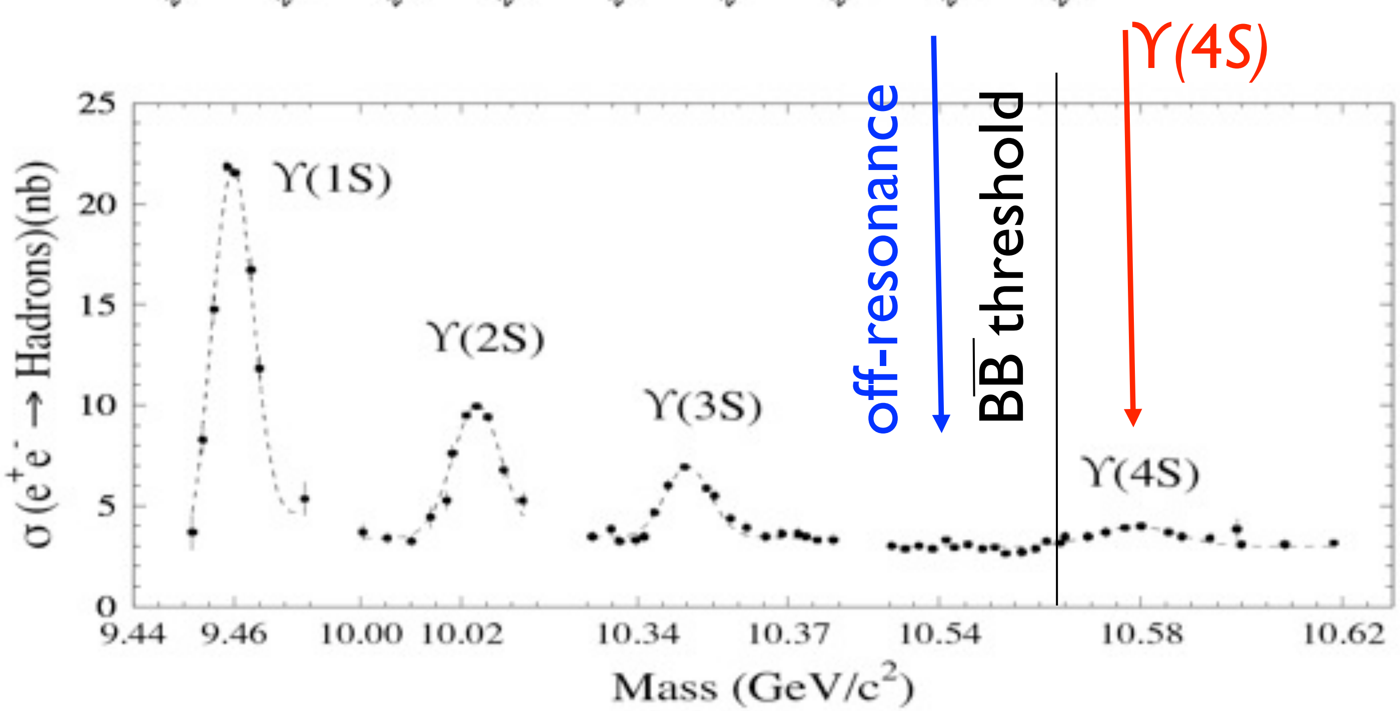
E_{extra} : sum of the energies of all photons that are not associated with the reconstructed $B\bar{B}$ pair.



BaBar detector and recorded luminosity







3.1 GeV e^+ & 9 GeV e^- beams

$\mathscr{L} = 1.2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

$\int \mathscr{L}dt \sim 430\ \mathrm{fb^{-1}}$ @ Υ(4S) + off-resonance (~10%)

with >96% Υ(4S)→BB

(coherent production L=1)

$\mathscr{L}$ = 426 fb^{-1}

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

PRL 109, 101802 (2012)
More detailed studies accepted by PRD, arXiv:1303.0571

Analysis strategy

This decay channel is interesting due to the large rates.
3 body decay permits study of other observables sensitive to NP (like, q^2 distributions)

Differential decay rates can be written:

Momentum of $D^{(*)}$ in CM frame

momentum transfer to τν

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

Helicity amplitudes common to e, μ, τ
Only H_0 affects D(l/τ)ν

Helicity amplitude only relevant for τ

Spin-0 Higgs does not couple to all helicity states and thus affects D and D* differently

We measure:

signal mode

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B\to D^{(*)}\tau\nu)}{\mathcal{B}(B\to D^{(*)}\ell\nu)} = \frac{\int_{m_\tau^2}^{q^2_{\rm max}} \frac{d\Gamma_\tau}{dq^2}\,dq^2}{\int_{m_\ell^2}^{q^2_{\rm max}} \frac{d\Gamma_\ell}{dq^2}\,dq^2}$$

, with $\tau^\pm$ reconstructed into $\ell^\pm \nu_\ell \nu_\tau$

normalisation mode

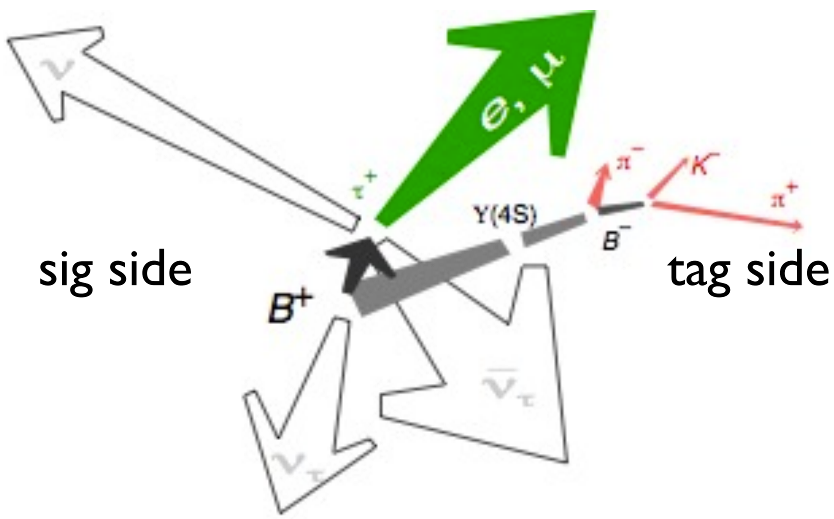
Reduces theoretical uncertainties:
- independent of $|V_{cb}|$
- mostly independent of form factor parameterization.

Reduces experimental uncertainties:
- Cancels multiplicative uncertainties; e.g., lepton PID, detection and reconstruction efficiencies.

TABLE X. Previous measurements of $\mathcal{R}(D^{(*)})$.

Measurement	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Belle 2007 [13]	—	$0.44 \pm 0.08 \pm 0.08$
BABAR 2008 [14]	$0.42 \pm 0.12 \pm 0.05$	$0.30 \pm 0.06 \pm 0.02$
Belle 2009 [15]	$0.59 \pm 0.14 \pm 0.08$	$0.47 \pm 0.08 \pm 0.06$
Belle 2010 [16]	$0.34 \pm 0.10 \pm 0.06$	$0.43 \pm 0.06 \pm 0.06$

arXiv:1303.0571
accepted by PRD



We reconstruct both B mesons produced in the event. This gives us the possibility to estimate the missing energy and momentum.

First step: reconstruct $B_{tag} \rightarrow SX^{\pm}$
S - seed meson (D, D*, D_s, D_s*, J/ψ)
$X^{\pm}$ - charged state comprised of up to five hadrons, pions or kaons, among them up to two neutral mesons, π^0 or K_s^0

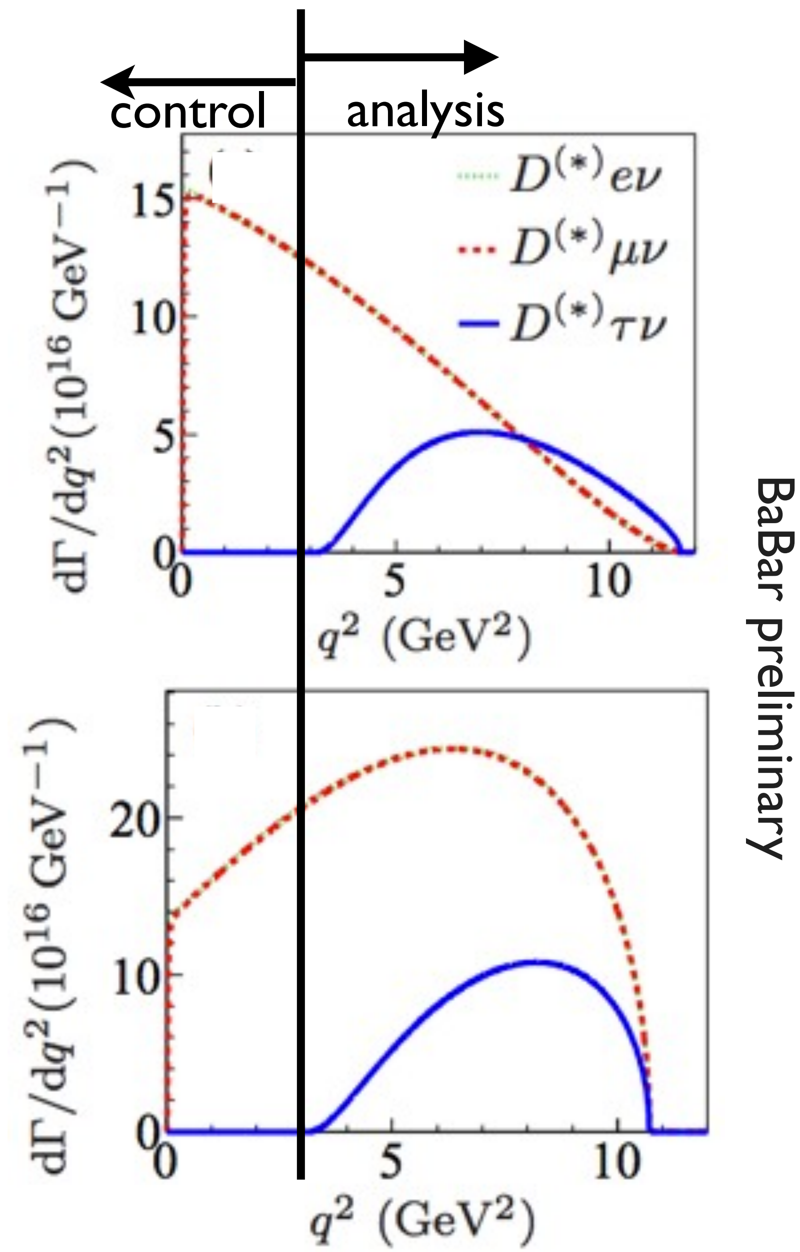
Thus, we reconstruct 1680 different decay modes for B_{tag}

Only events with B_{tag} m_{ES}> 5.27 GeV and |ΔE| < 0.072 GeV are considered. To further reduce the background, we select tag modes based on the reconstruction quality on Monte Carlo.

We than search for a signal D meson:
$D^0 \rightarrow K^-\pi^+, K^-K^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+, K^0_S\pi^+\pi^-$
$D^+ \rightarrow K^-\pi^+\pi^+, K^-\pi^+\pi^+\pi^0, K^0_S\pi^+, K^0_S\pi^+\pi^+\pi^-, K^0_S\pi^+\pi^0, K^0_SK^+$
and an electron or muon.

We use the selection on missing momentum and momentum transfer to discriminate signal region: $|p_{miss}|$>200 MeV, q^2>4 GeV^2

q^2<4 GeV^2 region is used for MC studies

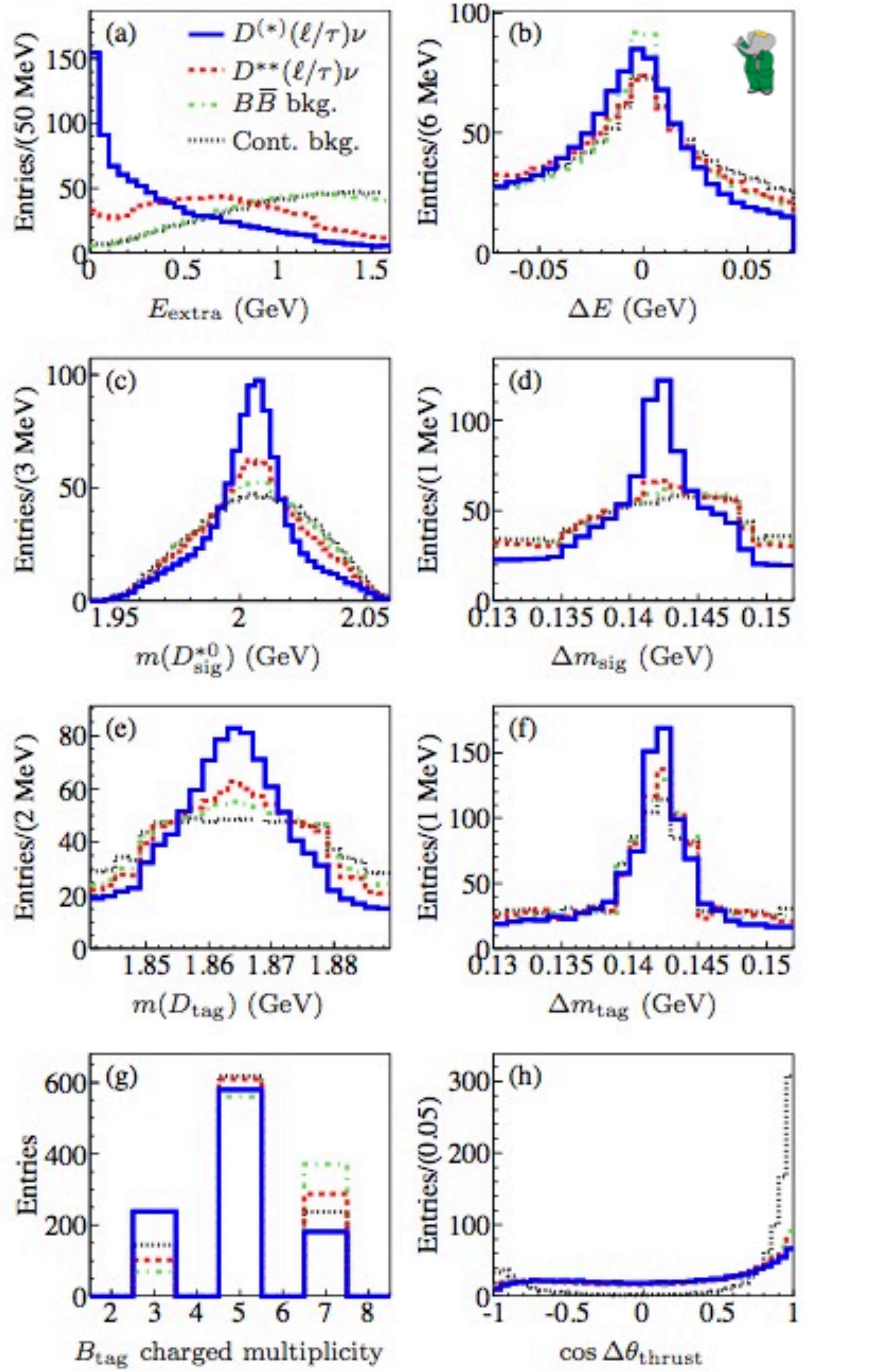


arXiv:1303.0571
accepted by PRD

In order to constrain the large D** background, we also reconstruct $D^0\pi^0\ell$, $D^{*0}\pi^0\ell$, $D^+\pi^0\ell$, and $D^{*+}\pi^0\ell$ samples.

We train Boosted Decision Tree on 8 observables for signal and D** backgrounds from simulated events. We use:

(a) E_{extra}, the sum of the energies of all photons that are not associated with the reconstructed BB pair;
(b) ΔE;
(c) the reconstructed mass of the signal $D^{(*)}$ meson;
(d) the mass difference for the reconstructed signal D*: $\Delta m = m(D\pi) - m(D)$;
(e) the reconstructed mass of the seed meson of the B_{tag};
(f) the mass difference for a D* originating from the B_{tag}, $\Delta m_{tag} = m(D_{tag}\pi) - m(D_{tag})$;
(g) the charged particle multiplicity of the B_{tag} candidate;
(h) $\cos\Delta\theta_{thrust}$, the angle between the thrust axes of the B_{tag} and of the rest of the event.



arXiv:1303.0571
accepted by PRD

Selection efficiencies are included in the final ratio:

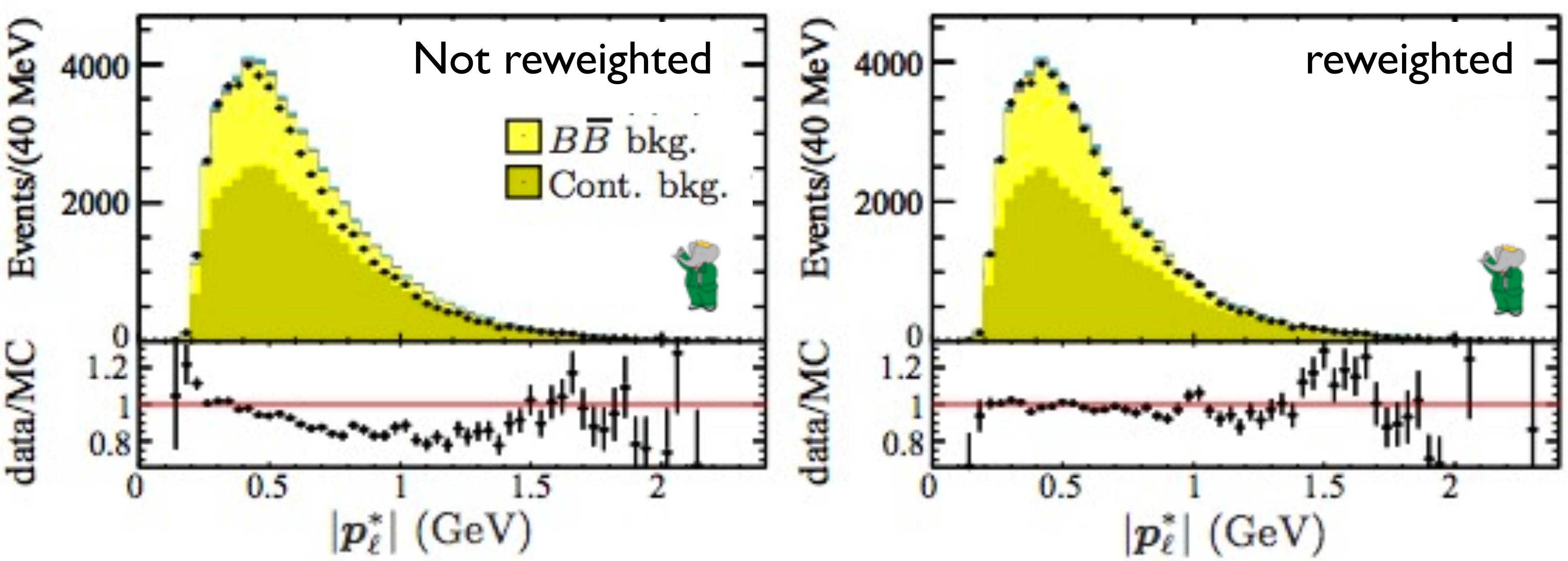
$$\mathcal{R}(D^{(*)}) = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}$$

The efficiency is taken from the simulated events. We perform the reweighting using lepton momentum from control samples in data, yield of combinatorial events etc.

Control samples to correct MC distributions:

- $e^+e^- \to q\bar{q}(\gamma)$: Off-peak data (40 MeV below $\Upsilon(4S)$)
- Normalization decays: q^2 sidebands
- $B\bar{B}$ Combinatorial: m_{ES} and E_{extra} sidebands
- Incorrectly reconstructed decay: events that fail BDT selection

example for intermediate E_{extra} region:



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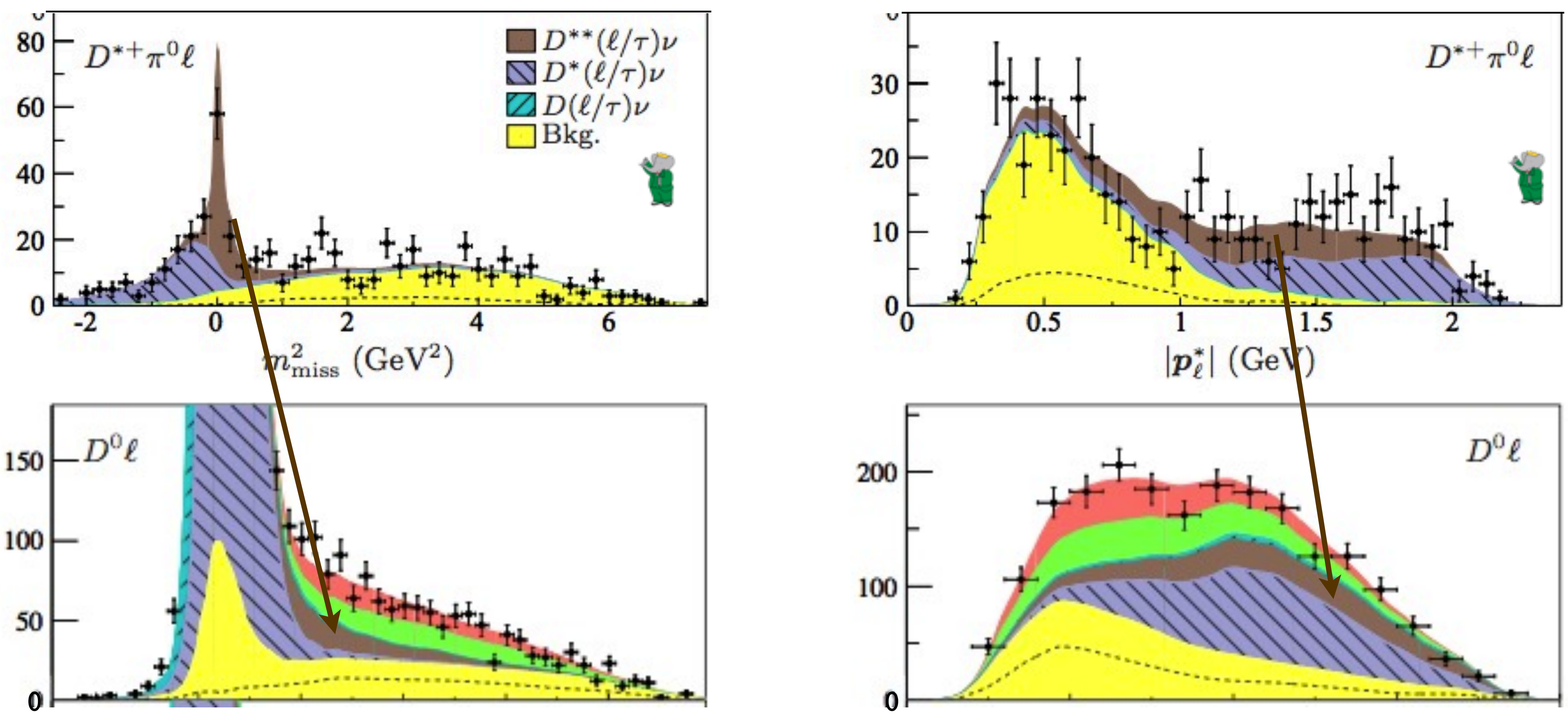
2D unbinned maximum likelihood fit (missing mass x lepton momentum) is performed on all D$\ell\nu$, D*$\ell\nu$ and D**$\ell\nu$ samples simultaneously

Each sample has contribution from all event types. For each such contribution, we estimate its distribution in missing mass and lepton momentum using non-parametric kernel estimators.

Example of D** fit projection



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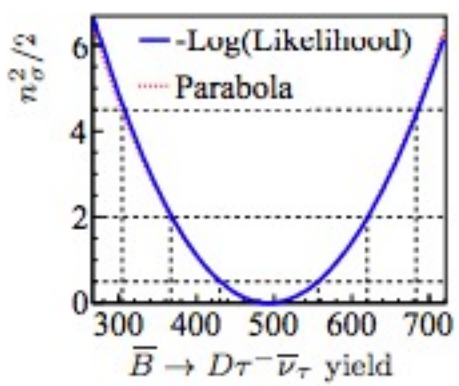
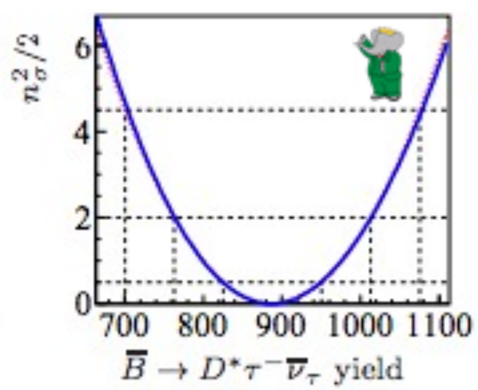
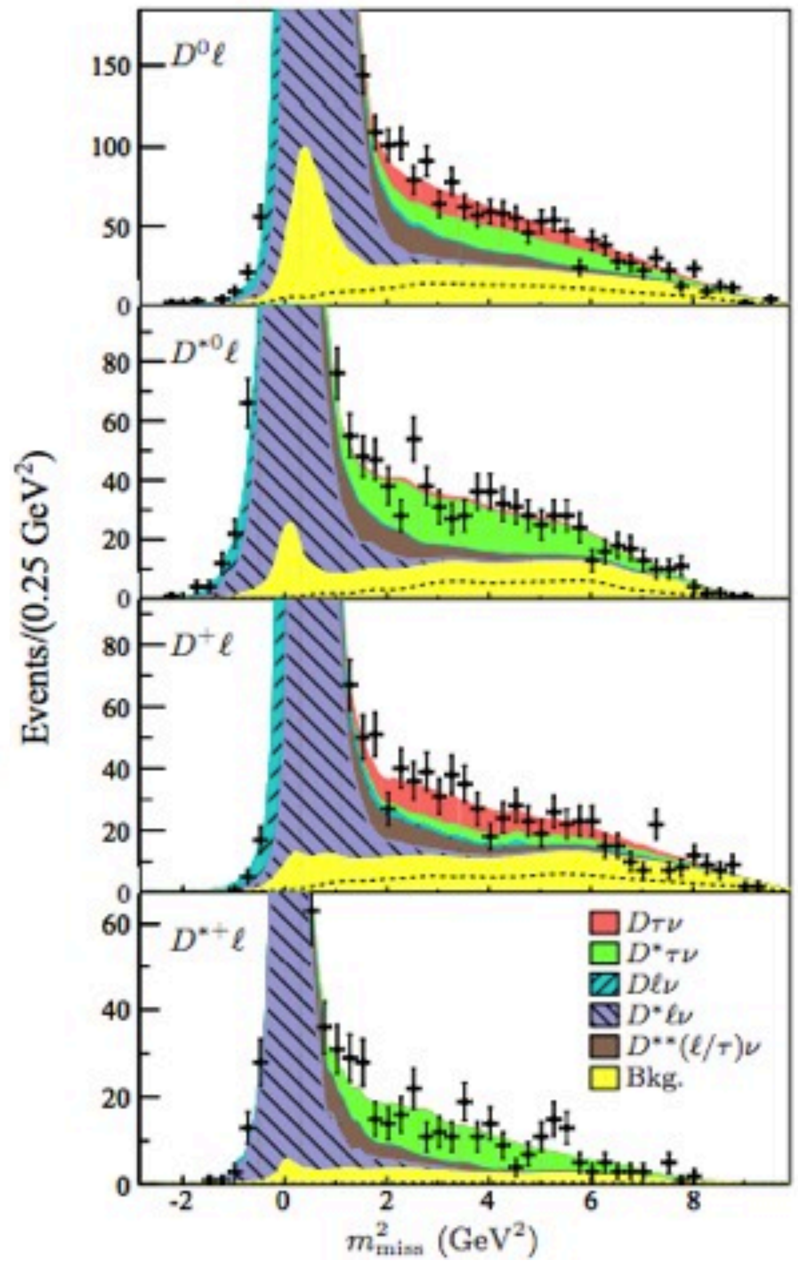
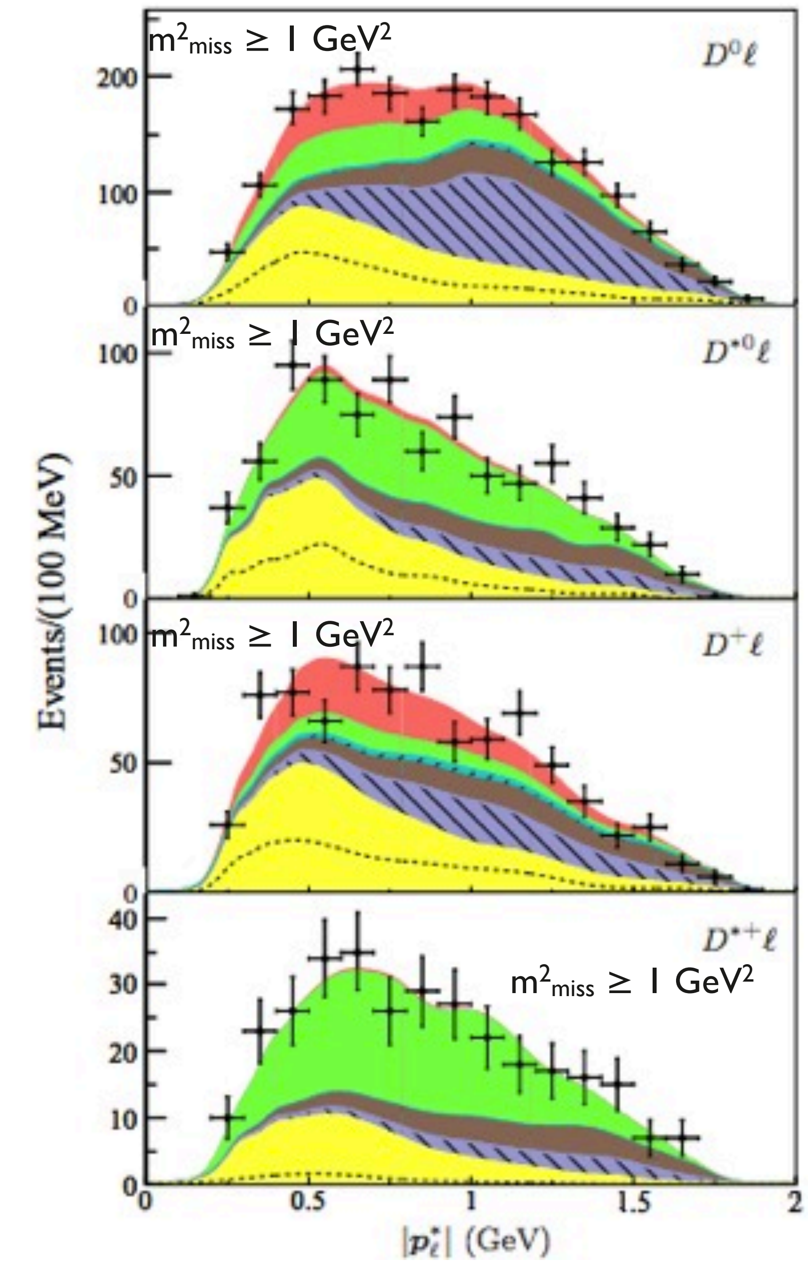
The fit is performed in two ways:
- isospin unconstrained
- isospin constrained

Likelihoods are gaussian









Isospin constrained results:

Decay	N_{sig}	N_{norm}	$\varepsilon_{sig}/\varepsilon_{norm}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	Σ_{stat}	Σ_{tot}
$\overline{B} \to D\tau^-\overline{\nu}_\tau$	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

Largest systematic due to background Probability Density Functions
Statistical uncertainty dominates
First measurement of $B \to D^{(*)}\tau^-\nu_\tau$

significance

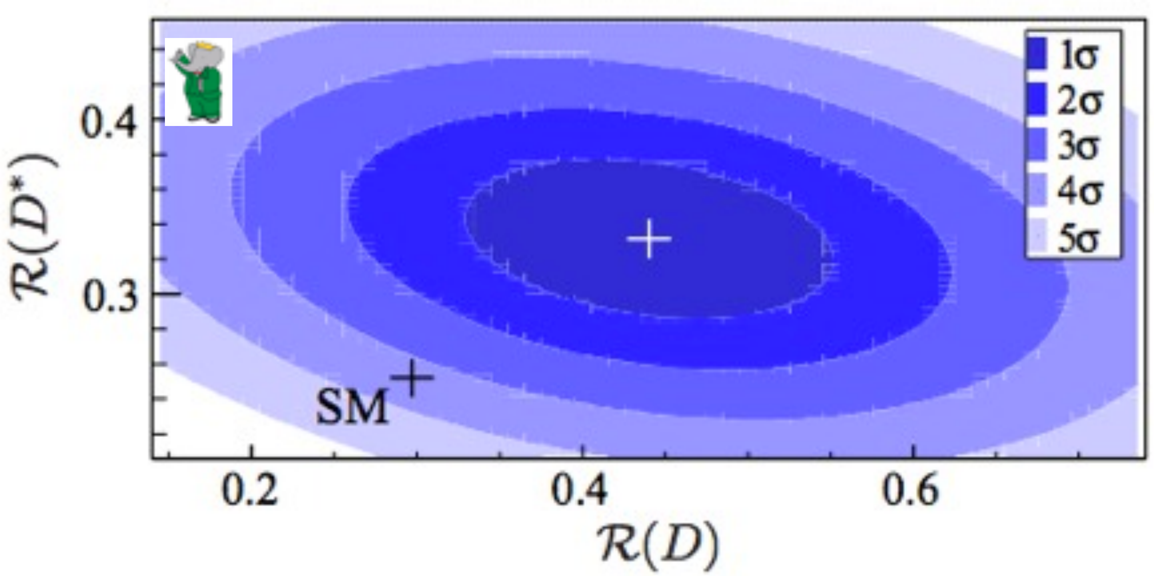
arXiv:1303.0571
accepted by PRD

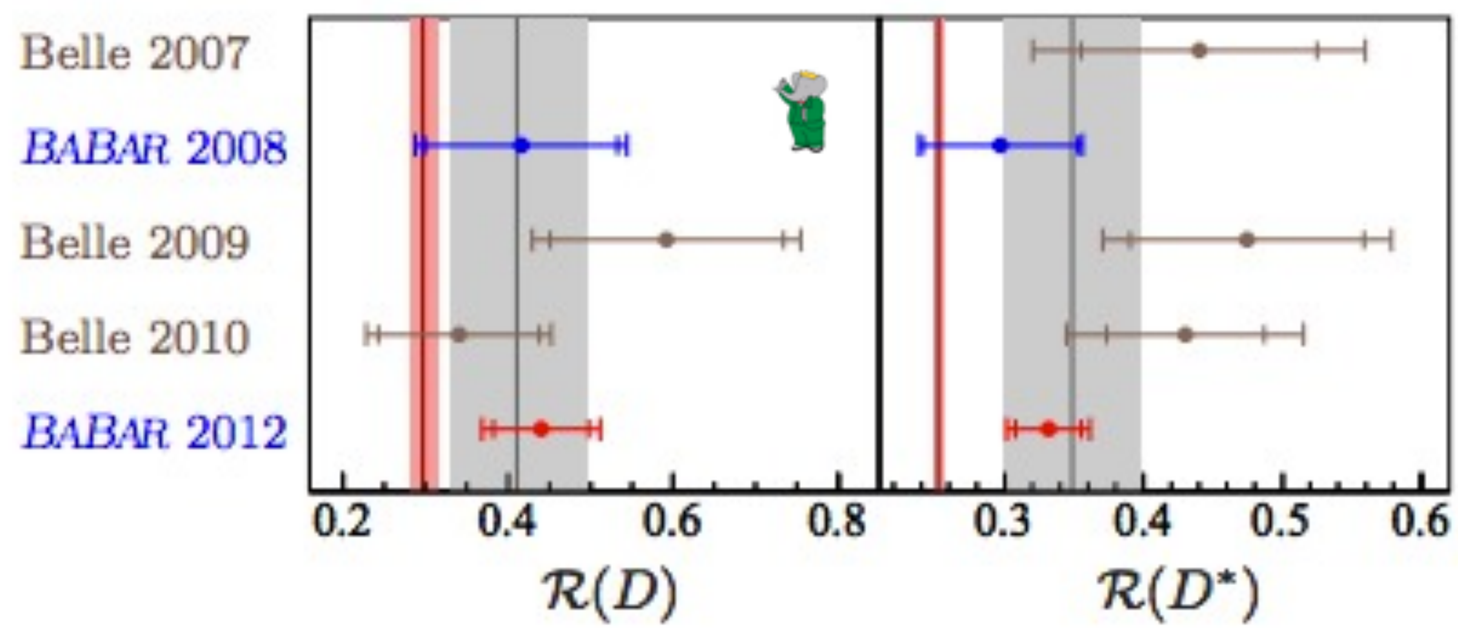
We compare our results to those predicted in the Standard Model (SM)

$$\mathcal{R}(D)_{\text{exp}} = 0.440 \pm 0.072 \quad \mathcal{R}(D^*)_{\text{exp}} = 0.332 \pm 0.030$$
$$\mathcal{R}(D)_{\text{SM}} = 0.297 \pm 0.017 \quad \mathcal{R}(D^*)_{\text{SM}} = 0.252 \pm 0.003$$

Calculations from: Fajfer et al. Phys.Rev. D85 (2012) 094025
Tanaka and R. Watanabe, PRD82, 0340276 (2010)
Tanaka, Z. Phys. C 67, 321 (1995)

R(D) and R(D*) are in excess over the SM predictions at the level of 2.0σ and 2.7σ respectively.
We perform a χ^2 test between the theory and experimental result using the covariance matrices.





R(D) and R(D*) not independent due to D*→D feed-down:-27% correlation

The possibility of both measurements agreeing with the SM is excluded at the 3.4σ level

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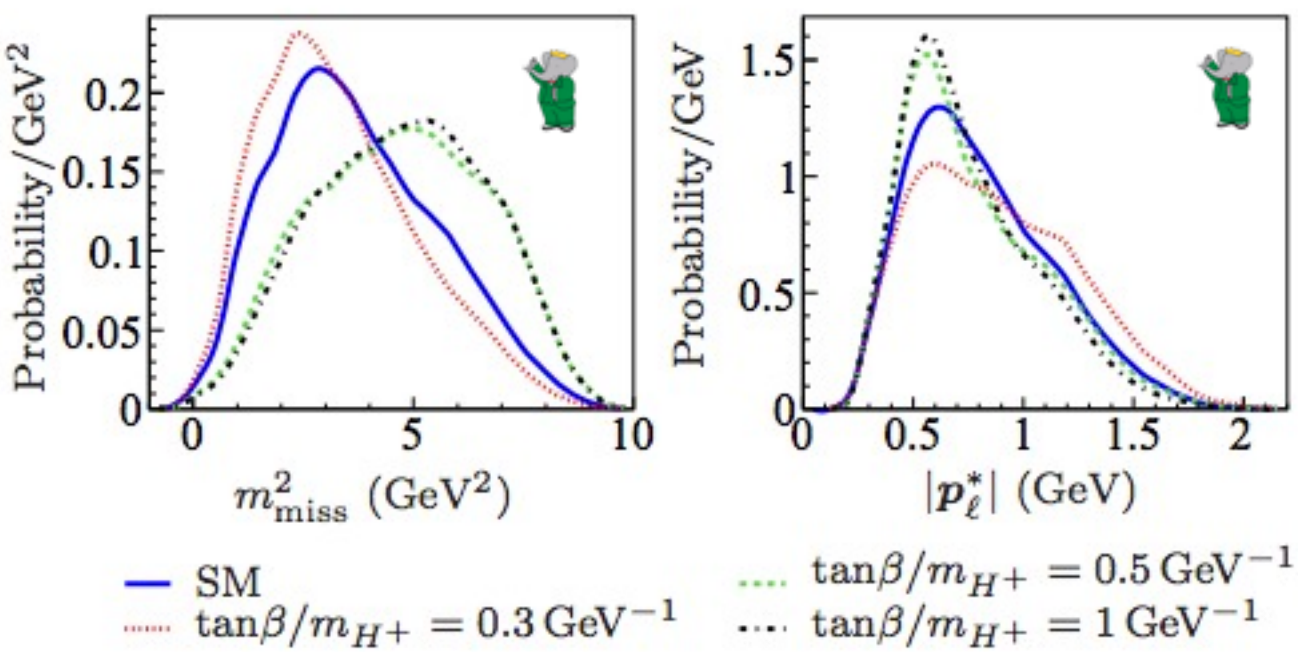
Type-II 2HDM: one of the two Higgs doublets couples to up-type quarks, while the other doublet couples to down- type quarks and leptons.

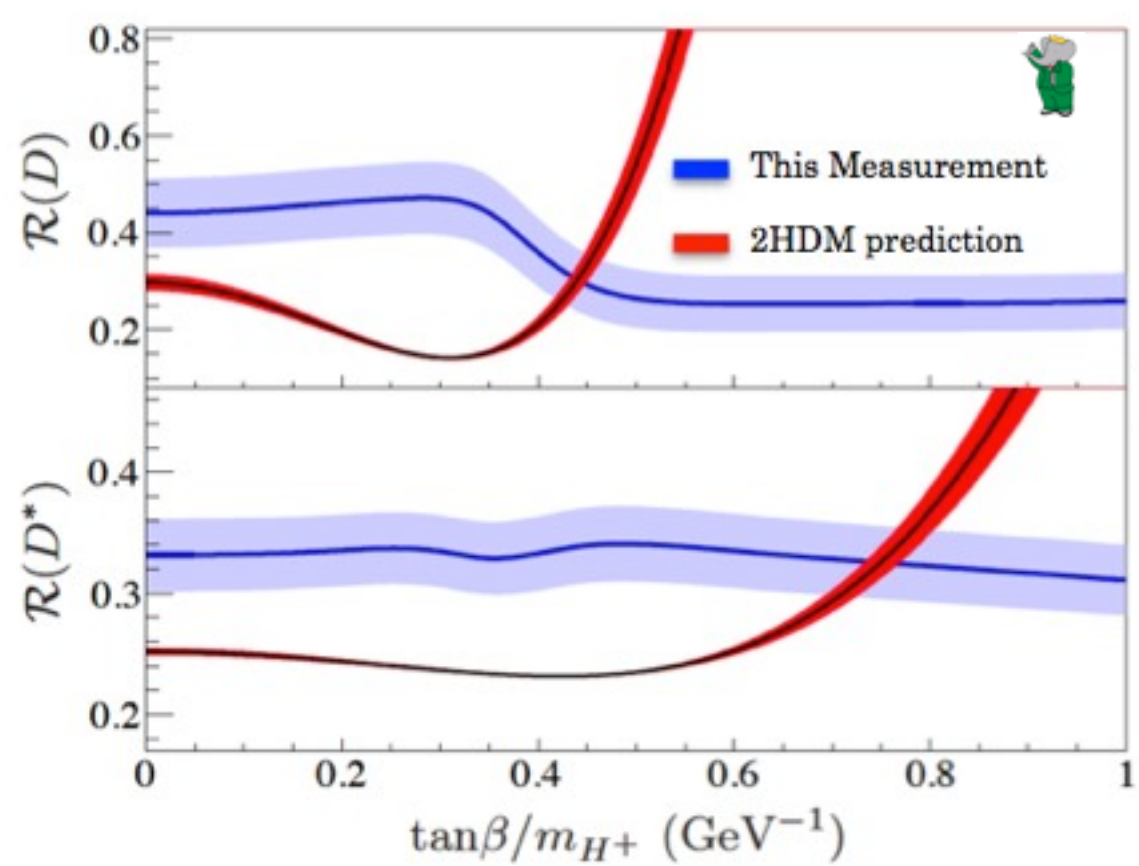
Here, R(D) is dependent on tan(β) and mass of the Higgs boson (m_{H+}):

$$\mathcal{R}(D^{(*)})_{2\mathrm{HDM}} = \mathcal{R}(D^{(*)})_{\mathrm{SM}} + A_{D^{(*)}} \frac{\tan^2\beta}{m_{H+}^2} + B_{D^{(*)}} \frac{\tan^4\beta}{m_{H+}^4}$$

The presence of a charged Higgs can affect the missing mass and lepton momentum signal distributions significantly. We assess and account for its impact as a function of tan(β)/m_{H+} in order to examine whether the observed excess is consistent with the type-II 2HDM

	$\overline{B} \to D\tau^-\overline{\nu}_\tau$	$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$
$\mathcal{R}(D^{(*)})_{\mathrm{SM}}$	0.297 ± 0.017	0.252 ± 0.003
$A_{D^{(*)}}$ (GeV^2)	-3.25 ± 0.32	-0.230 ± 0.029
$B_{D^{(*)}}$ (GeV^4)	16.9 ± 2.0	0.643 ± 0.085





Together with the b→sɣ measurements, we exclude the type-II 2HDM at 99.8% confidence level in the full parameter space

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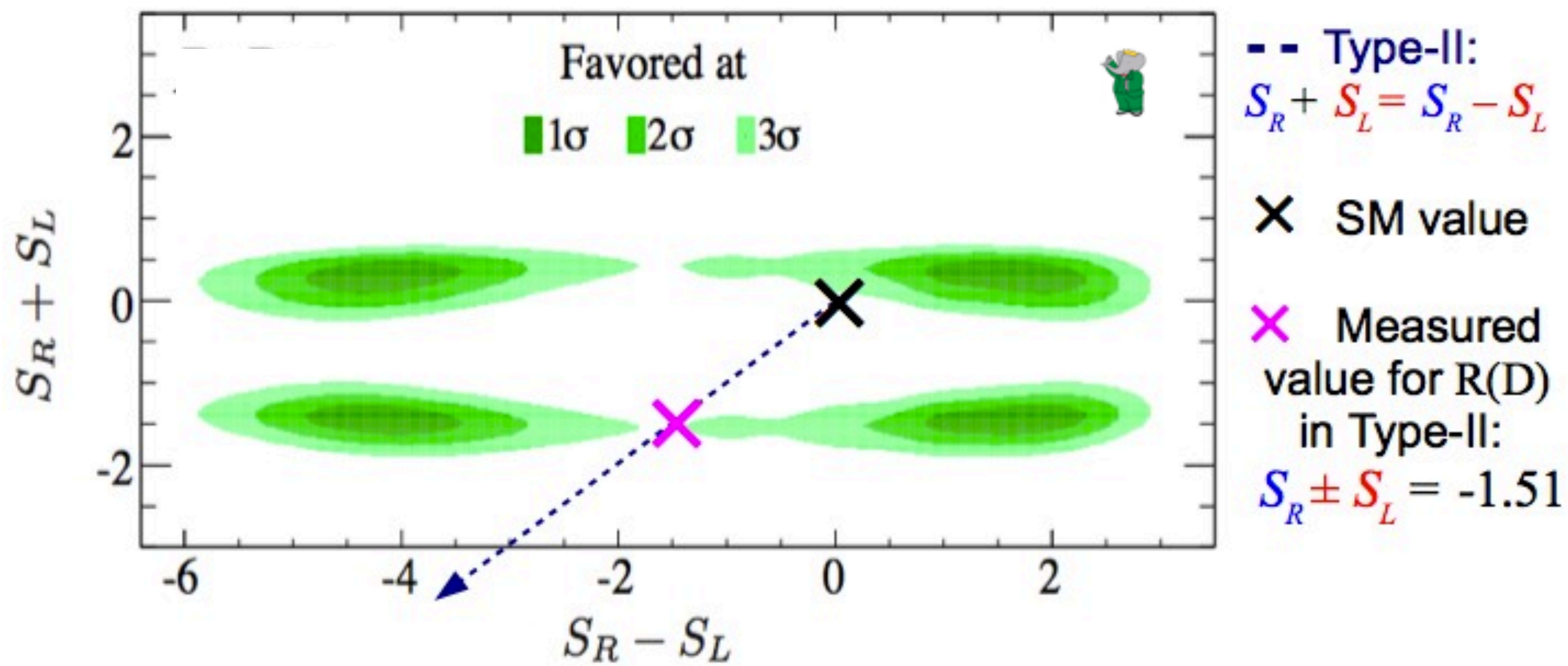
Type-III 2HDM: More general charged Higgs model, type-II being subset of type III

R(D) and R(D*) depend on 2 independent NP parameters *($S_R \pm S_L$)*

$$\mathcal{R}(D) = \mathcal{R}(D)_{\rm SM} + A'_D {\rm Re}(S_R + S_L) + B'_D |S_R + S_L|^2,$$
$$\mathcal{R}(D^*) = \mathcal{R}(D^*)_{\rm SM} + A'_{D^*} {\rm Re}(S_R - S_L) + B'_{D^*} |S_R - S_L|^2.$$



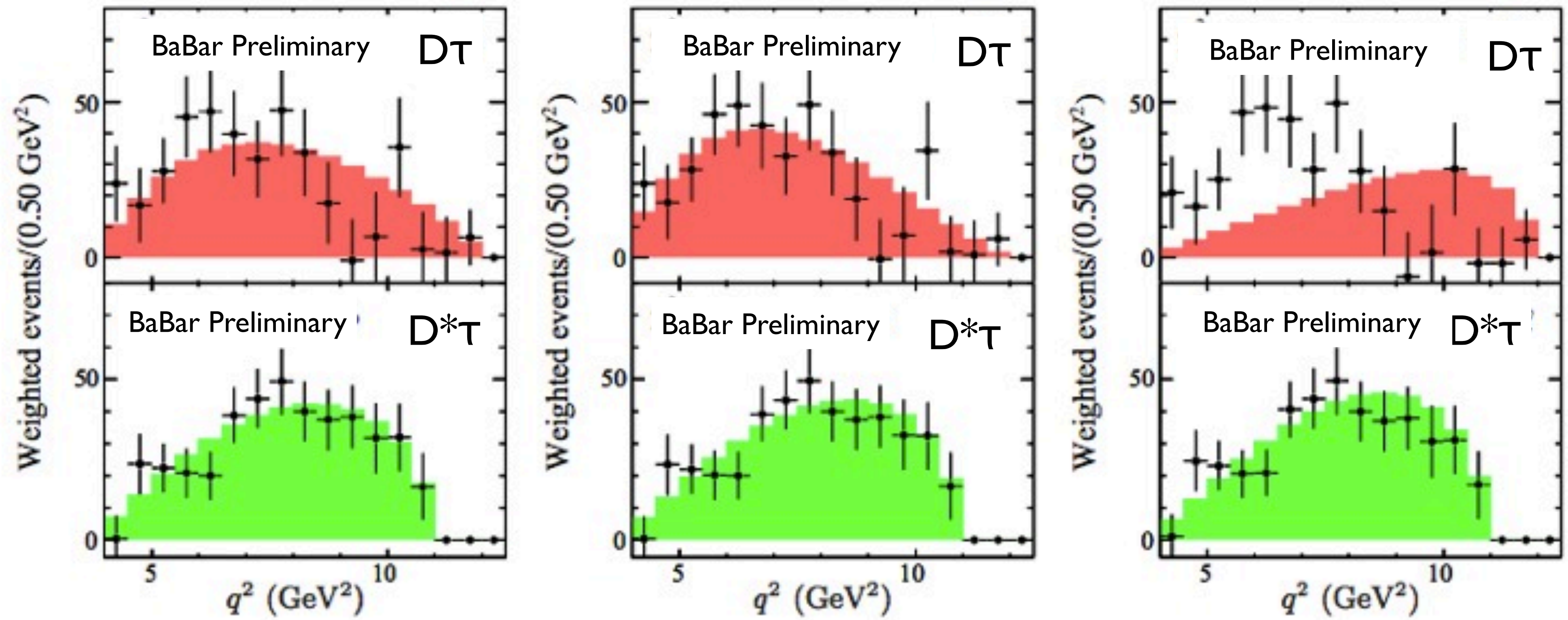
We also study the signal ($D^{(*)}\tau\nu$) yield dependence on the q^2.

We compare the predicted distributions to the background subtracted events.

SM ($S_R \pm S_L = 0$)

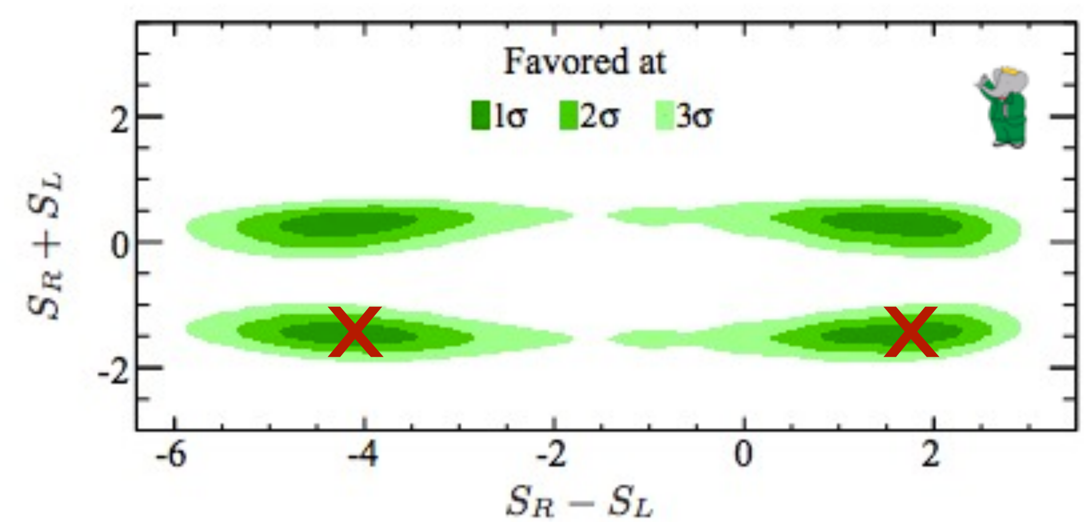
$\tan(\beta)/m_{H+} = 0.30\ \mathrm{GeV}^{-1}$ ($S_R \pm S_L = -0.67$)

$\tan(\beta)/m_{H+} = 0.45\ \mathrm{GeV}^{-1}$ ($S_R \pm S_L = -1.51$)



	$\overline{B} \to D\tau^-\overline{\nu}_\tau$	$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$
SM	83.1%	98.8%
$\tan\beta/m_{H^+} = 0.30\,\mathrm{GeV}^{-1}$	95.7%	98.9%
$\tan\beta/m_{H^+} = 0.45\,\mathrm{GeV}^{-1}$	0.4%	97.9%

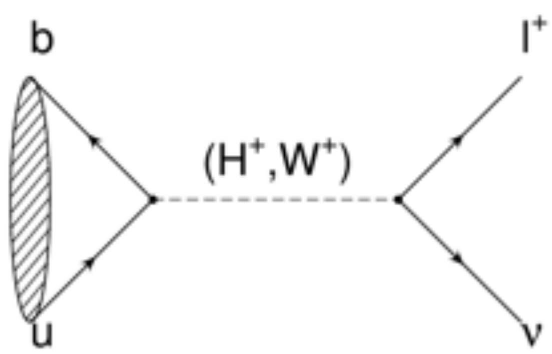
This study excludes the lower solutions of plot in previous page at 2.9σ



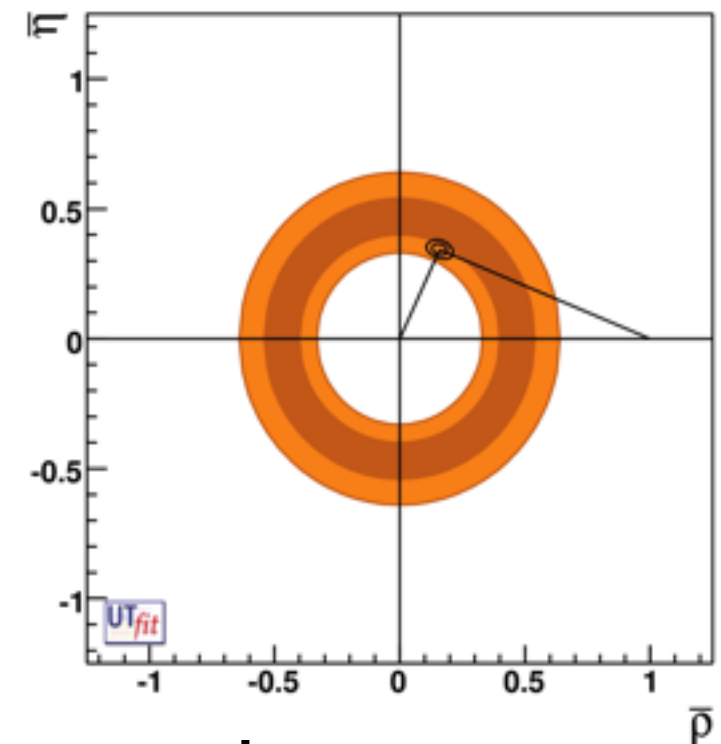
$\mathscr{L}$= 426 fb^{-1}

$B \to \tau\nu$

Hadronic tag: PRD 88, 031102 (2013)
Leptonic tag: PRD 81, 051101(R) (2010)



This branching fraction can give another important constraint on the New Physics scenarios

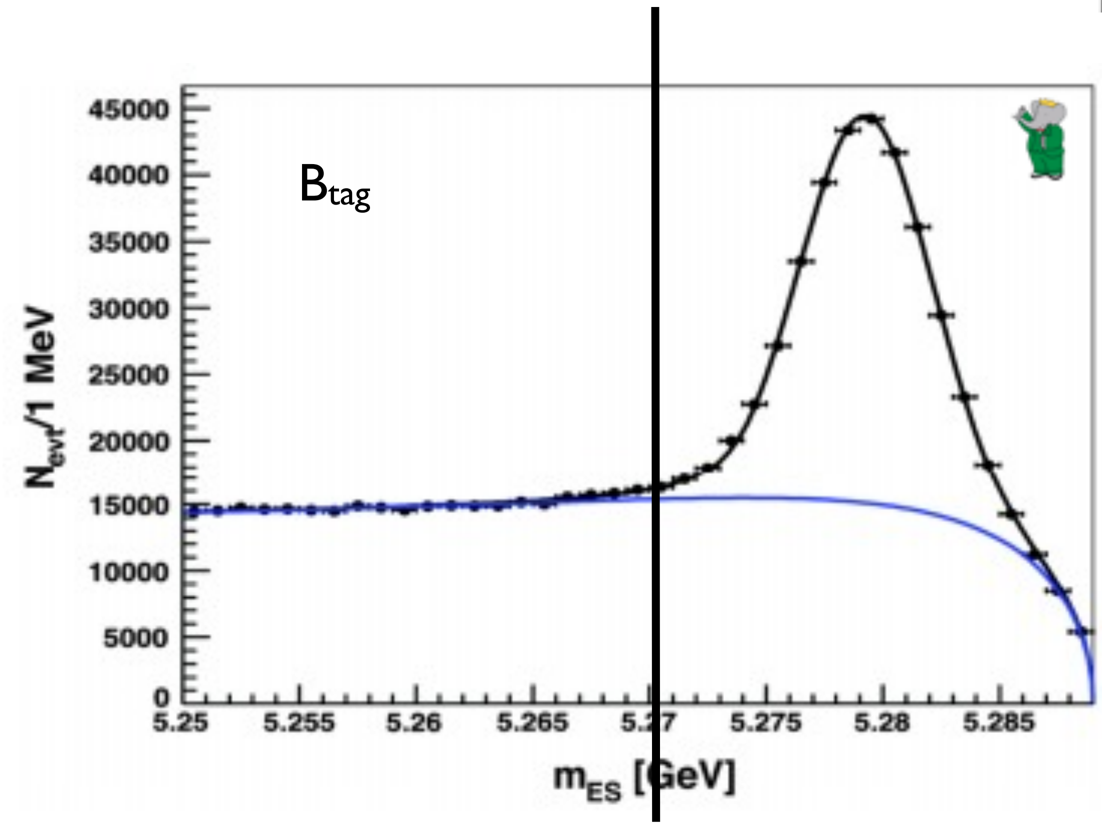


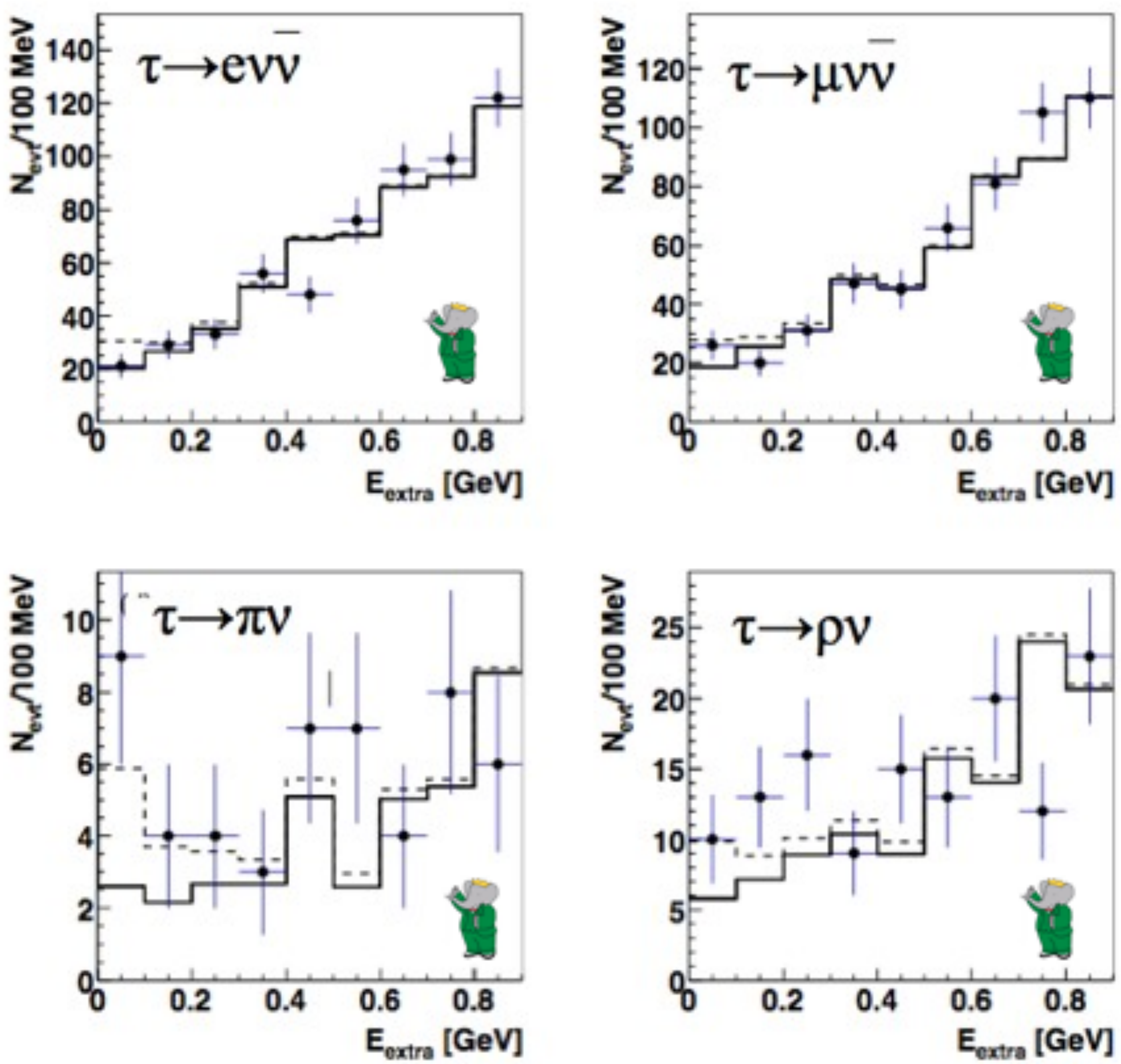
$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

New physics can enhance or suppress SM rate.

We use the same technique as in previous analysis, with reconstruction of B_{tag}

τ decay modes used ($e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, and $\rho\nu \to \pi^+\pi^0\nu$) comprise ~70% of total τ decay modes

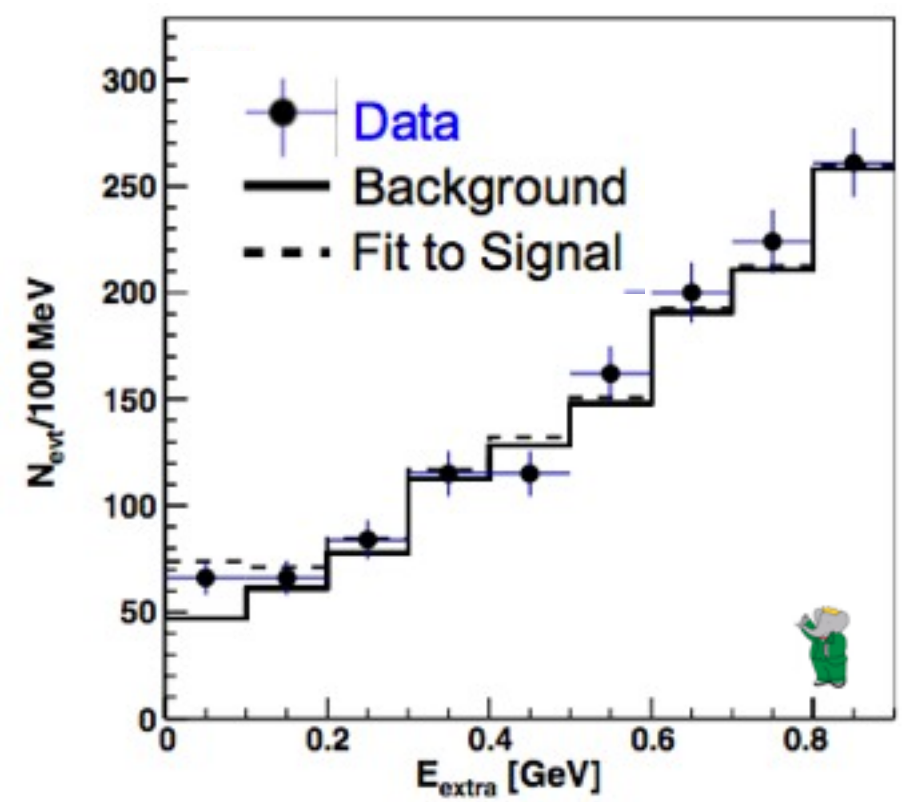




We perform the 1D Maximum likelihood fit.
Signal and peaking background PDFs taken from MC
Combinatorial background PDF taken from m_{ES} sidebands in data.

Decay mode	$\epsilon_k(\times 10^{-4})$	Signal yield	$\mathcal{B}(\times 10^{-4})$
$\tau^+ \to e^+ \nu \bar{\nu}$	2.47 ± 0.14	4.1 ± 9.1	$0.35^{+0.84}_{-0.73}$
$\tau^+ \to \mu^+ \nu \bar{\nu}$	2.45 ± 0.14	12.9 ± 9.7	$1.12^{+0.90}_{-0.78}$
$\tau^+ \to \pi^+ \nu$	0.98 ± 0.14	17.1 ± 6.2	$3.69^{+1.42}_{-1.22}$
$\tau^+ \to \rho^+ \nu$	1.35 ± 0.11	24.0 ± 10.0	$3.78^{+1.65}_{-1.45}$
Combined		62.1 ± 17.3	$1.83^{+0.53}_{-0.49}$

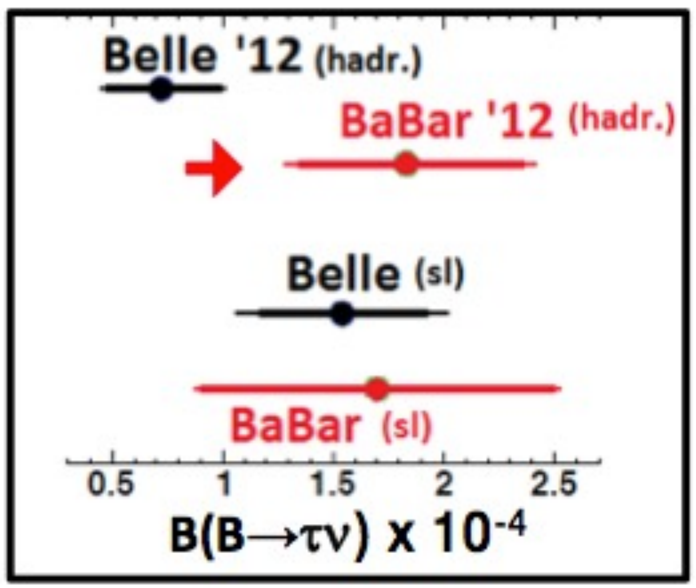
We then fit all τ modes simultaneously.

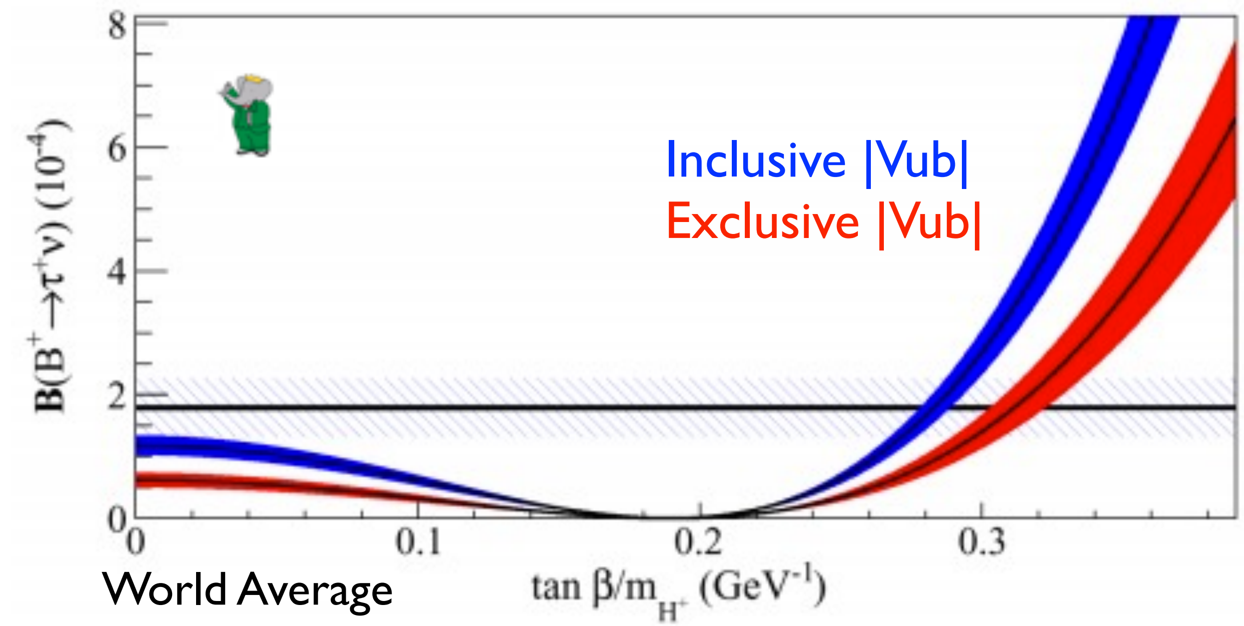


$$\mathcal{B}(B^+ \to \tau^+ \nu) = (1.83^{+0.53}_{-0.49}(\text{stat.}) \pm 0.24(\text{syst.})) \times 10^{-4}$$

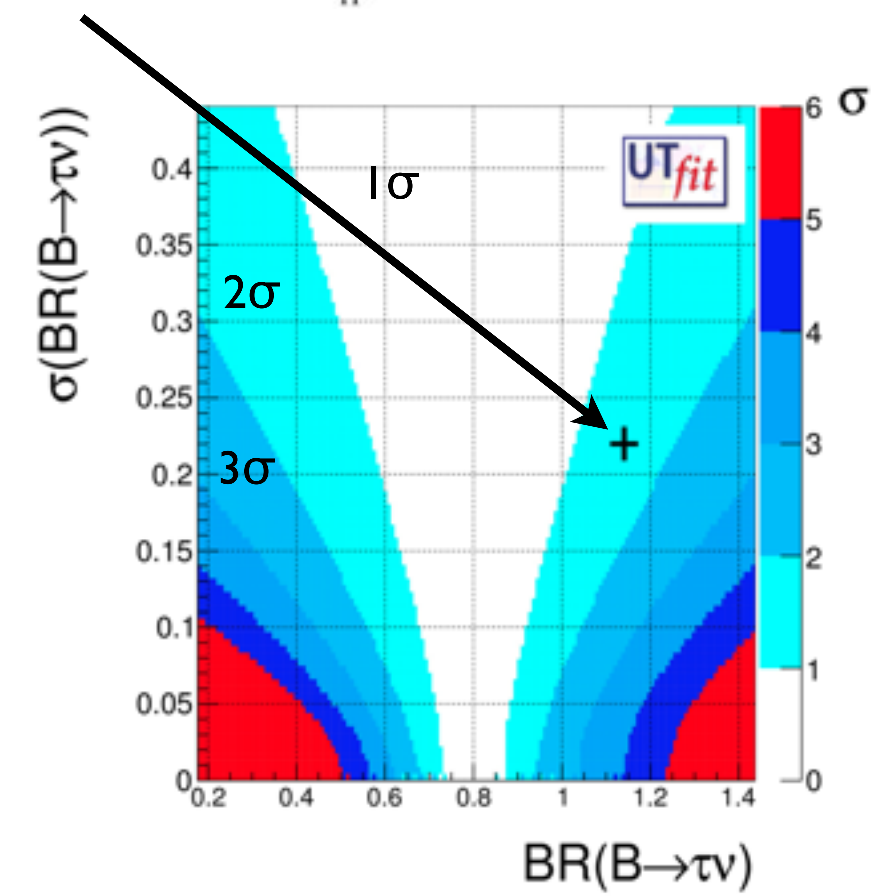
We evaluate the results and compare to 2HDM in a similar way, like previous analysis. We do it for exclusive and inclusive $|V_{ub}|$ measurements separately.

Other results are available from BaBar and Belle:





World Average



HFAG average gives:

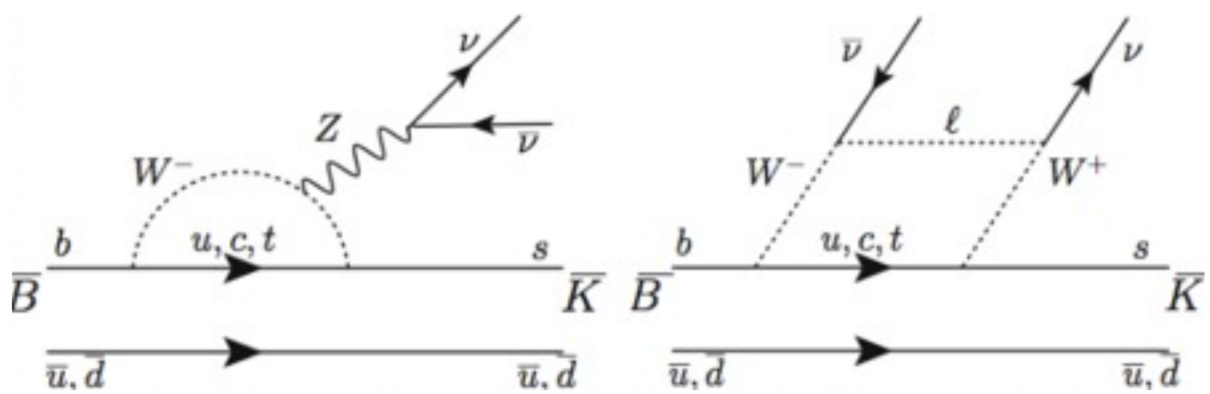
$$B(B \to \tau\nu) = (1.14 \pm 0.22) \cdot 10^{-4}$$

Which is compatible with SM expectation (exclusive and inclusive $|V_{ub}|$ combined)

$\mathcal{L}$= 429 fb^{-1}

Search for $B\rightarrow K^{(*)}\nu\bar{\nu}$

PRD 87, 112005 (2013)



Flavor-Changing Neutral Current processes are not allowed at tree-level in SM.

The decay is dominated by top-quark exchange, thus suppressed by $|Vts|^2$, the expected BF($B \rightarrow K^{(*)}\nu\bar{\nu}$) is $\sim 10^{-6}$

Altmannshofer, et al JHEP 0904, 022 (2009)

New Physics can enhance Branching Fraction at leading order:
- entering in loops;
- modifying Z or Z' couplings;
- adding "invisible" contributions to neutrinos.

Once decay is discovered, the observables of interest will be:
- angular/momentum distributions
- lepton flavor ratios
- CP asymmetries

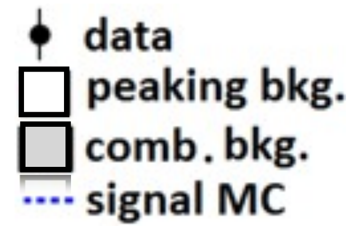
We reconstruct 4 channels and hadronic tag in the recoil B:

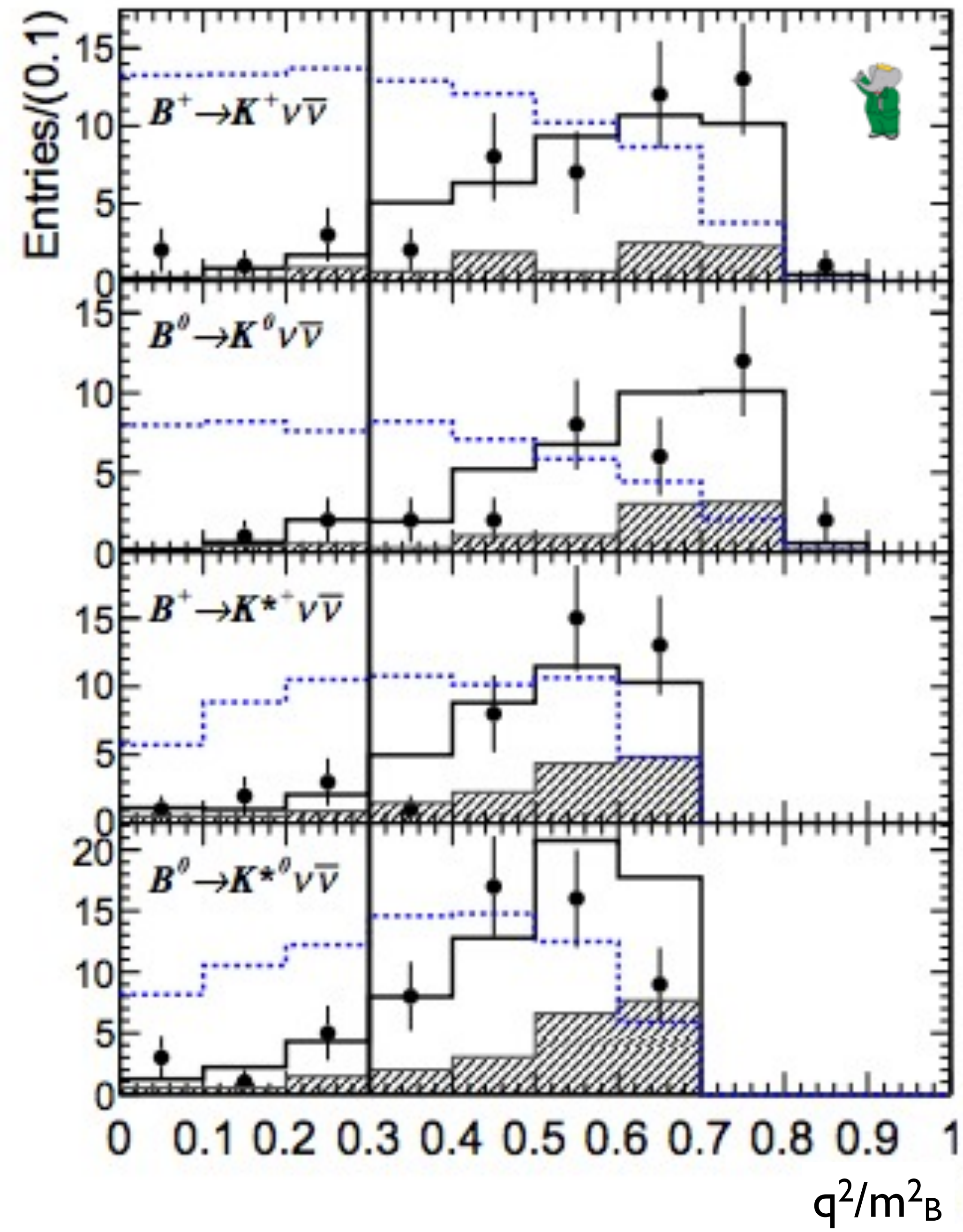
$B^+ \to K^+ \nu\bar{\nu}$

$B^0 \to K_s^0 \nu\bar{\nu}$ ($K_s^0 \to \pi^+\pi^-$)

$B^+ \to K^{*+} \nu\bar{\nu}$ ($K^{*+} \to K^+\pi^0, K_s^0\pi^+$)

$B^0 \to K^{*0} \nu\bar{\nu}$ ($K^{*0} \to K^+\pi^-, K_s^0\pi^0$)





No additional tracks

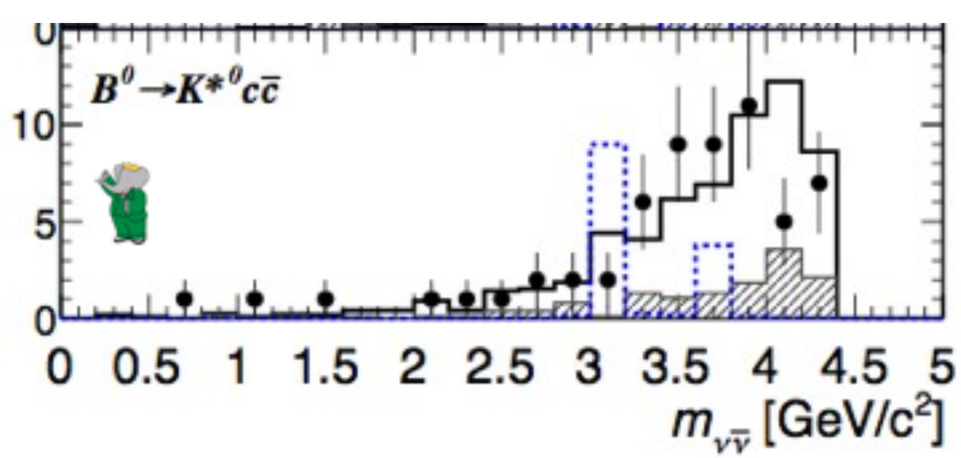
Suppress continuum background using event-shape variables

Restrict to low values of E_{extra}

Correct MC to data using m_{ES} sidebands

We study the observable q^2/m^2_B, where q^2 is the squared magnitude of the four-momentum transferred from the B meson to the neutrino pair, and m_B is the B meson mass.

We also look for very suppressed charmonium decays: J/ψ and ψ(2S) to $\nu\bar{\nu}$.

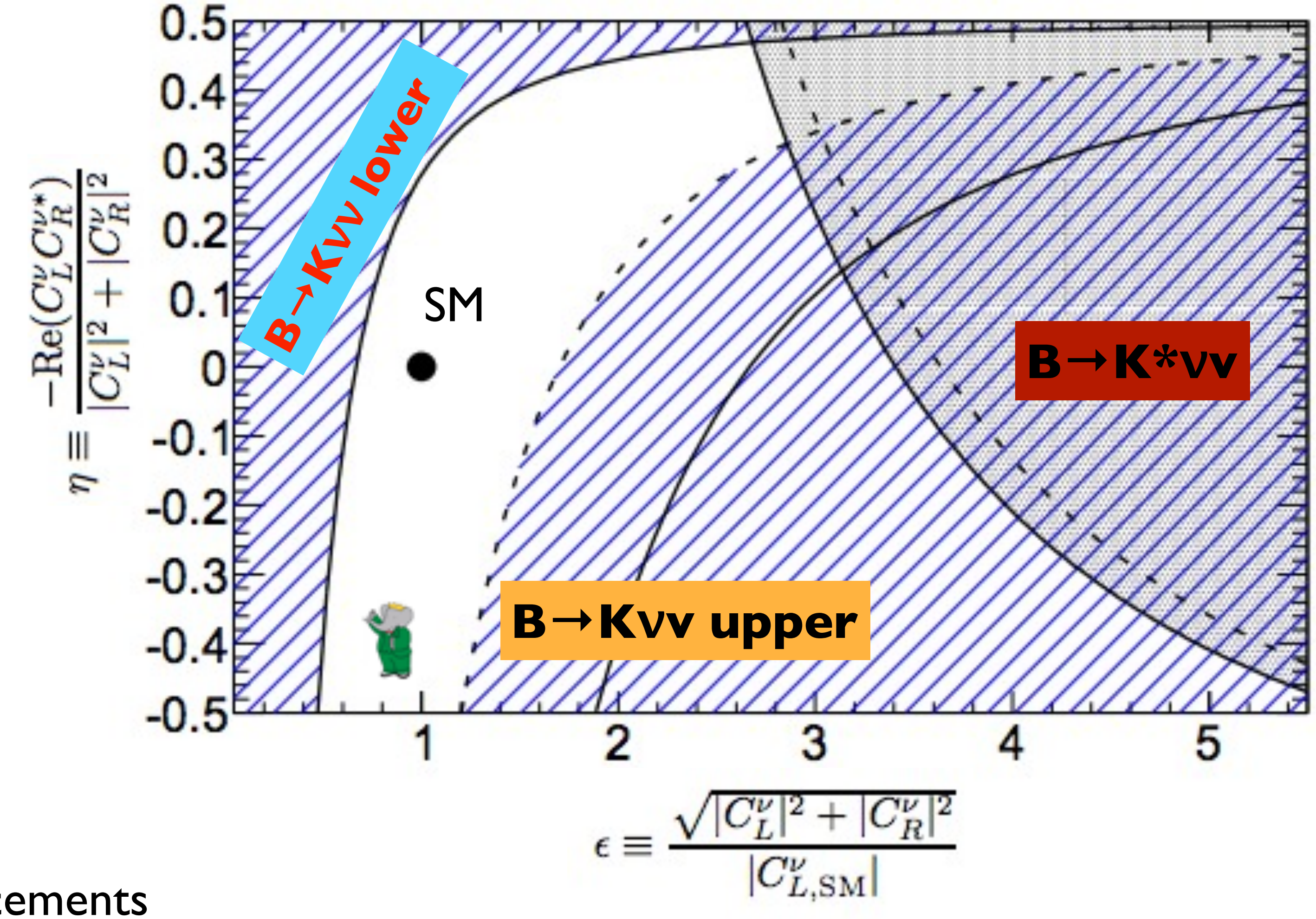


Branching fraction upper limits at 90% CL

$K^+\nu\bar{\nu}$	$K^0\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$	
$(>0.4, <3.7)$	<8.1	<11.6	<9.3	$\times 10^{-5}$

First lower limit on $B^+ \to K^+\nu\bar{\nu}$

New Physics scenario (e. g. with invisible scalar contributions) can modify the Wilson coefficients for the decays (Altmannshofer et al. JHEP 0904:022 (2009)). We check it using isospin constrained results.



—— these constraints

- - - - SL-tag constraints

We also set the world's first limit on the neutrino pair decay:

$B(\psi(2S) \to \nu\bar{\nu}) < 1.55 \times 10^{-3}$

Since certain new-physics models suggest that enhancements are possible at high q^2 values, we also report model-independent partial branching fractions (ΔB_i) over the full spectrum.

$\mathscr{L} = 428\ fb^{-1}$

$B \to \pi/\eta \ell\ell$

PRD 88 (2013) 032012

The theoretical motivation is similar to the previous analysis

Fully reconstructable final state (no B_{tag} reco necessary) Lepton pair + π or η candidate

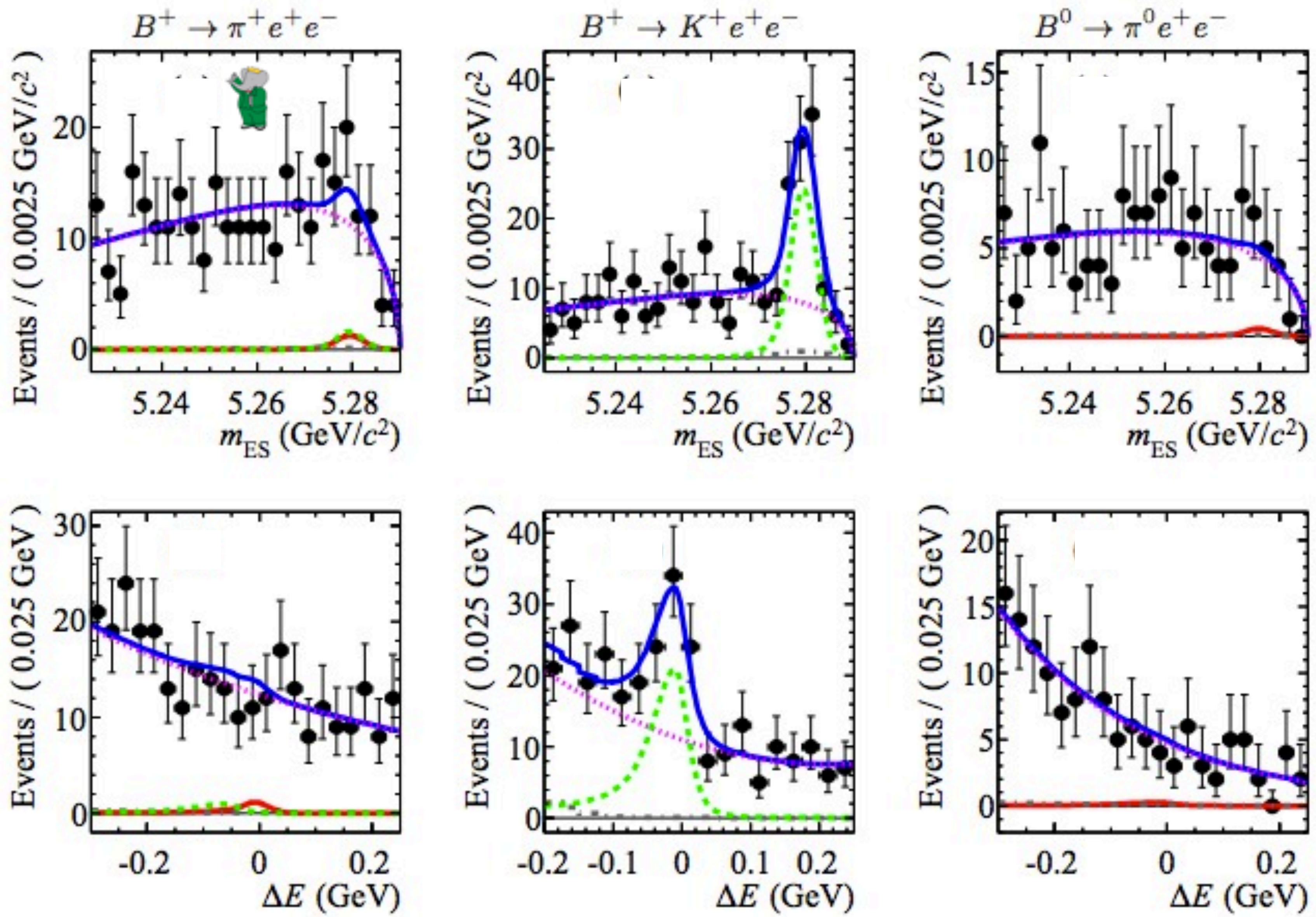
6 channels (where l = e or μ) are reconstructed:

- $B^0 \to \pi^0 l^+ l^-$
- $B^+ \to \pi^+ l^+ l^-$
- $B^0 \to \eta l^+ l^-$ ($\eta \to \pi^+\pi^-\pi^0$ or $\eta \to \gamma\gamma$)

After some fiducial cuts and charm veto, we perform a 2D Maximum likelihood fit to m_{ES} and ΔE simultaneous for π and K, in order to fix the cross-feed.

We also perform lepton-flavor and/or isospin-constrained fits to combine channels.

Combinatoric background
Signal
B→K+l+l-



We put the limit using a scan on the yield

Mode	ε	Yield	$\mathcal{B}\,(10^{-8})$	Upper Limit (10^{-8})
$B^+ \to \pi^+ e^+ e^-$	0.199	$4.2^{+5.7}_{-4.6}$	$4.3^{+5.9}_{-4.7} \pm 2.0$	12.5
$B^0 \to \pi^0 e^+ e^-$	0.163	$1.0^{+3.2}_{-1.1}$	$1.2^{+5.4}_{-4.0} \pm 0.2$	8.4
$B^0 \to \eta e^+ e^-$			$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^0 \to \eta_{\gamma\gamma} e^+ e^-$	0.164	$-1.2^{+3.1}_{-2.4}$		
$B^0 \to \eta_{3\pi} e^+ e^-$	0.115	$-0.5^{+1.2}_{-1.0}$		
$B^+ \to \pi^+ \mu^+ \mu^-$	0.140	$-0.5^{+3.1}_{-2.3}$	$-0.6^{+4.4}_{-3.2} \pm 0.9$	5.5 *
$B^0 \to \pi^0 \mu^+ \mu^-$	0.115	$-0.2^{+2.0}_{-0.7}$	$-1.0^{+5.0}_{-3.4} \pm 0.6$	6.9
$B^0 \to \eta \mu^+ \mu^-$			$-2.0^{+9.7}_{-6.6} \pm 0.4$	11.2
$B^0 \to \eta_{\gamma\gamma} \mu^+ \mu^-$	0.102	$-0.4^{+1.7}_{-1.3}$		
$B^0 \to \eta_{3\pi} \mu^+ \mu^-$	0.063	$-0.1^{+0.7}_{-0.4}$		
$B \to \pi e^+ e^-$			$4.0^{+5.1}_{-4.2} \pm 1.6$	11.0
$B \to \pi \mu^+ \mu$			$-0.9^{+3.9}_{-3.0} \pm 1.2$	5.0
$B^+ \to \pi^+ \ell^+ \ell^-$			$2.5^{+3.9}_{-3.3} \pm 1.2$	6.6
$B^0 \to \pi^0 \ell^+ \ell^-$			$1.2^{+3.9}_{-3.3} \pm 0.2$	5.3
$B^0 \to \eta \ell^+ \ell^-$			$-2.8^{+6.6}_{-5.2} \pm 0.3$	6.4
$B \to \pi \ell^+ \ell^-$			$2.5^{+3.3}_{-3.0} \pm 1.0$	5.9

Best Limits to date

First ever limits

Constrained

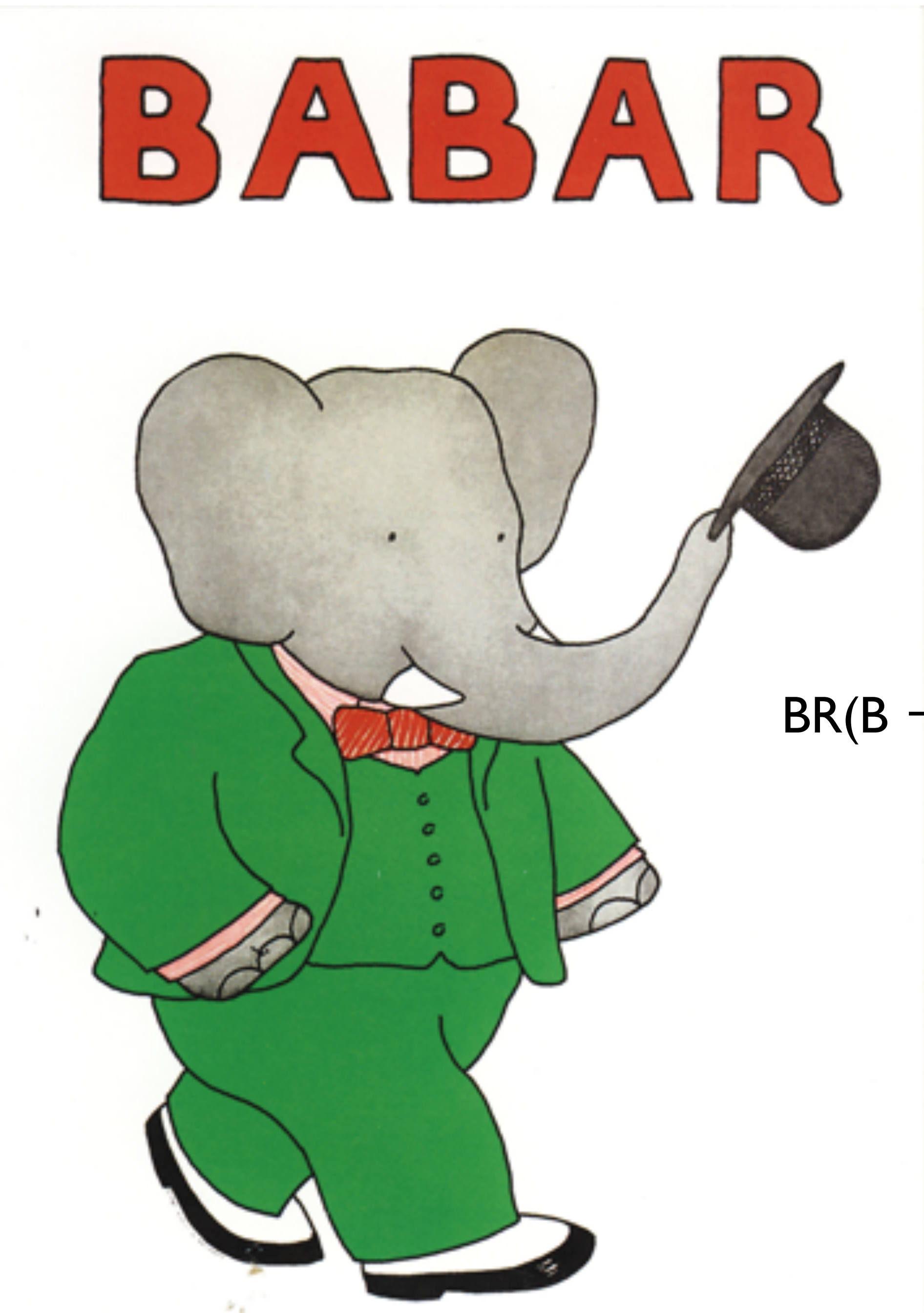
isospin

lepton flavor

both

We are getting very close to SM expectations in some modes

* Recent LHCb result $(2.4\pm0.6\pm0.2)\times10^{-8}$
J. High Energy Phys. 12 125 (2012).



New results from BaBar on B decays sensitive to New Physics

$R(D^{(*)})$ from $B \to D^{(*)}\tau\nu$ are inconsistent with SM by 3.4σ

	R(D)	R(D*)	R(D)&R(D*)	q^2 spectrum
SM	✗ (2.0 σ)	✗ (2.7 σ)	✗ (3.4 σ)	✓
Type II 2HDM	✓	✓	✗ (3.1 σ)	✗
Type III 2HDM	✓	✓	✓	~

$BR(B \to \tau\nu)$ observed at 3.8σ, this also gives some constraints on 2HDM type II model

First lower limits for $B \to K\nu\bar{\nu}$

First search for $B \to \eta\ell^+\ell^-$

All the results from this talk are from 2013 analyses by BaBar