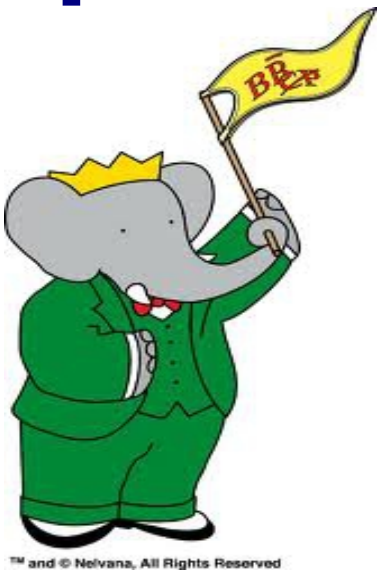
MESON 2014

Kraków Poland – 29th May - 3rd June 2014

B decays with leptons: powerful probes of New Physics with BaBar data

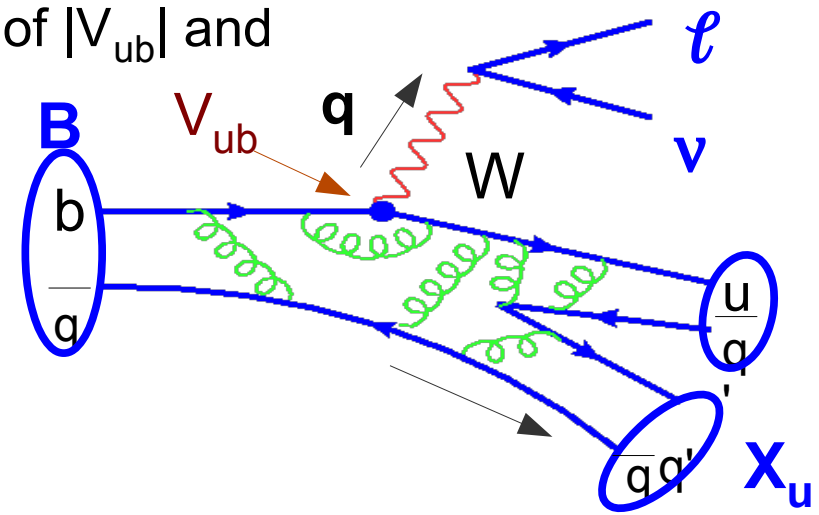


Marcello Rotondo

I.N.F.N. Padova

B decays into leptons

- B semileptonic decays allows a clean extraction of $|V_{ub}|$ and $|V_{cb}|$ that are crucial SM inputs to the CKM fits:
  - $B \to D^{(*)}\, \ell\nu$, $B \to \pi\, \ell\nu$



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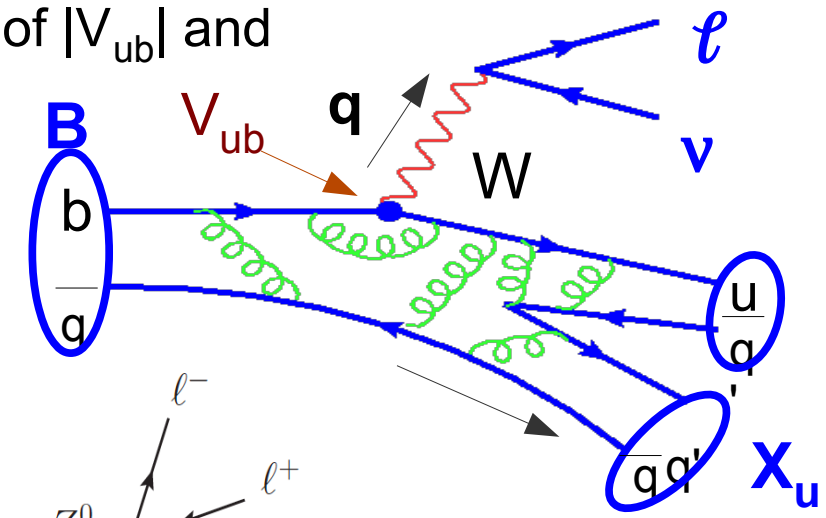
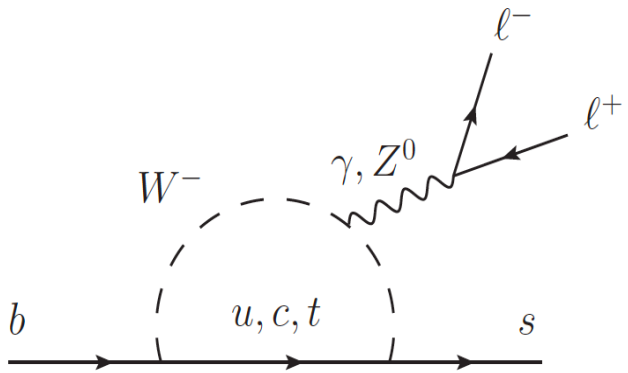


- Direct search in FCNC processes (forbidden at tree level):
  - $B \to X_s \ell^+\ell^-$



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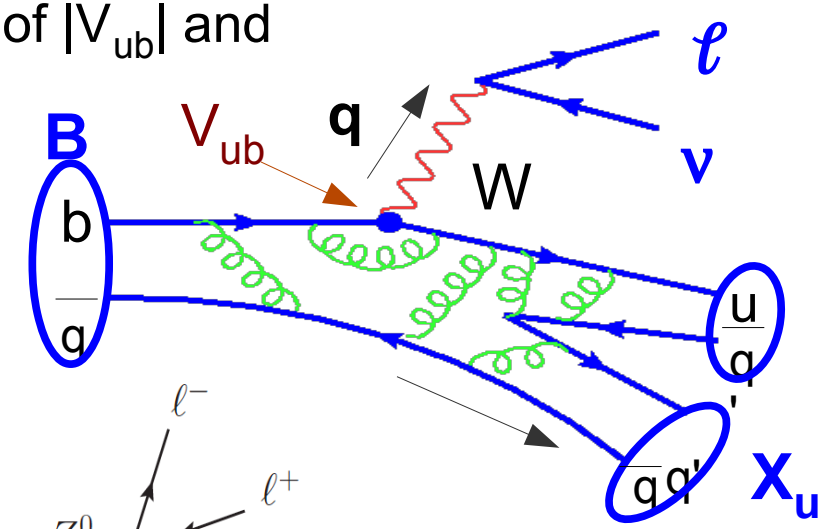

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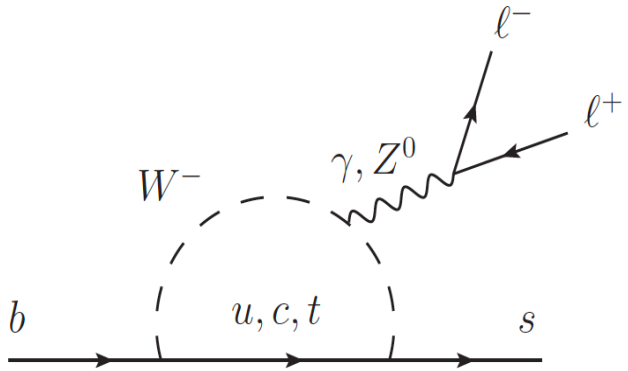


- Processes strongly suppressed in the SM
  - Lepton Number Violating processes: $B \to X\, \ell^+\ell'^+$

- Leptonic and Semileptonic decay in heavy lepton sensitive to NP couplings to heavy leptons:
  - $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$

$B \to X_s \ell^+ \ell^-$

- "Measurement of the $B \to X_s \ell^+ \ell^-$ branching fraction and search for direct CP violation from a sum of exclusive final states"

- Phys. Rev. Lett. 112, 211802 (2014)

$B \to X_s \ell^+ \ell^-$

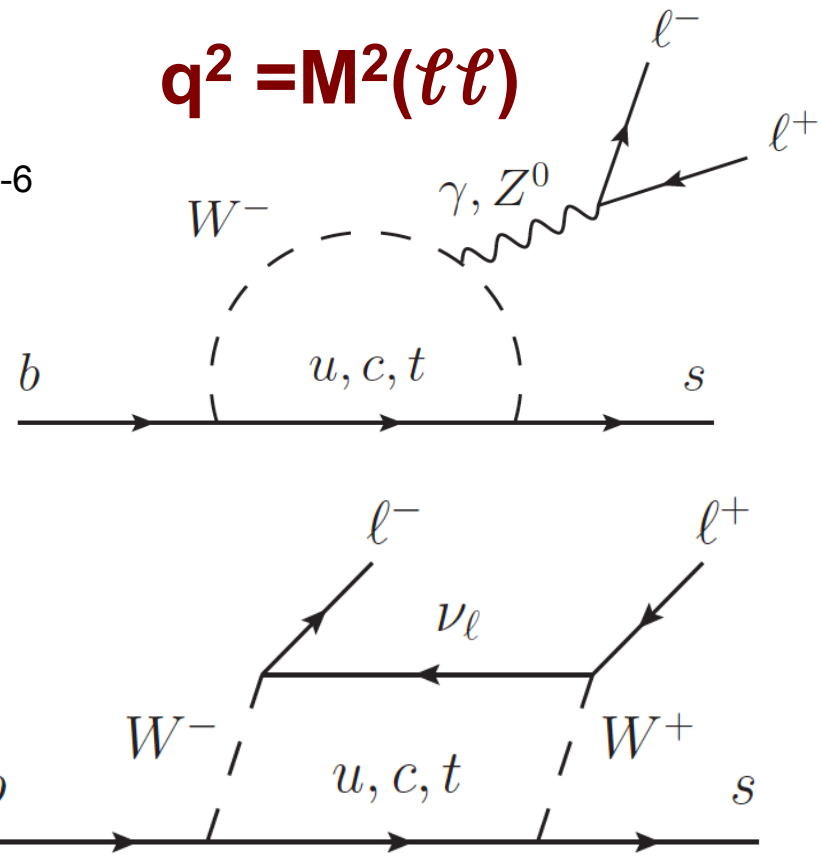
Nucl.Phys.B802,40 (2008)
Phys.Rev.D 54,882

- Sensitive to NP effects in photon, vector and axial-vector coupling
  - FCNC process forbidden at tree level: BF~10^{-6}
  - NP enter at the SM level

- $1 < q^2 < 6$ GeV^2 → $BR_{SM} = (1.59 \pm 0.11) \cdot 10^{-6}$
- $q^2 > 14.4$ GeV^2: → $BR_{SM} = (0.24 \pm 0.07) \cdot 10^{-6}$
- Direct CP violation: SM predicts $A_{CP} << 1\%$ in exclusive and inclusive transitions

- Large extend complementary to $B_s \to \mu^+\mu^-$

$q^2 = M^2(\ell\ell)$



- Decay amplitudes expressed using OPE in terms of perturbatively calculable effective coefficients:
  - Short distance Wilson coefficients: C_7^{eff}, C_9^{eff}, C_{10}^{eff}
  - Theoretical uncertainties: ~7-30% (in different q^2 regions)

$B \to X_s \ell^+ \ell^-$

- Measurement performed using a sum of 20 fully reconstructed modes
  - 0 pions: K^+, K_s
  - 1 pion: $K^+\pi^0$, $K^+\pi^-$, $K_s\pi^+$, $K_\sigma\pi^0$
  - 2 pions: $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-$, $K_s\pi^+\pi^0$, $K_s\pi^+\pi^-$
    - ℓ=e/μ

Not used in the A_{CP} measurement

- Reconstructed states account for 70% of inclusive rate: extrapolation to total rate from MC
- B decays to J/ψ (ψ') have same final state particles: explicit mass vetoes applied: vetoed events make excellent control sample

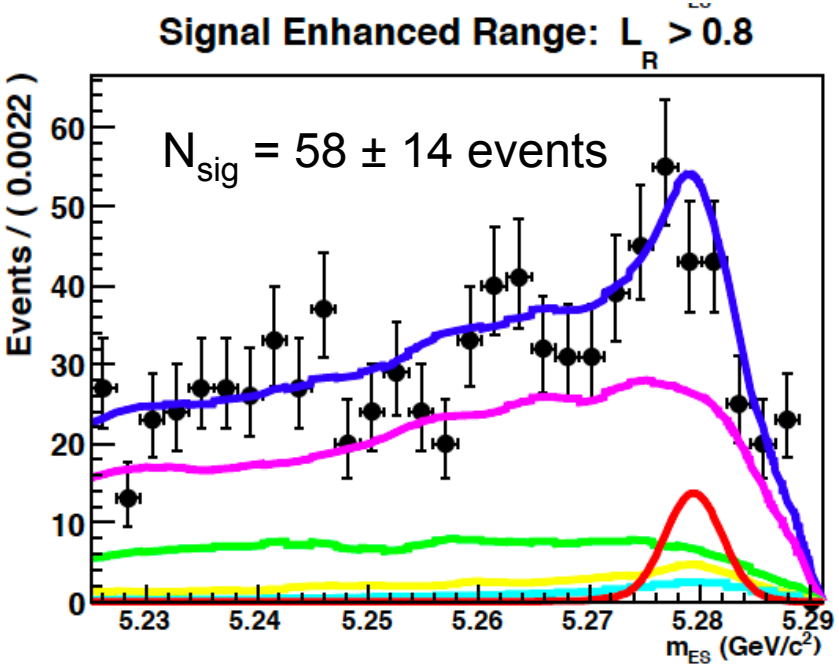
- $B \to X_s \ell^+ \ell^-$ yields extracted in hadronic mass (M_x) and q^2 bins

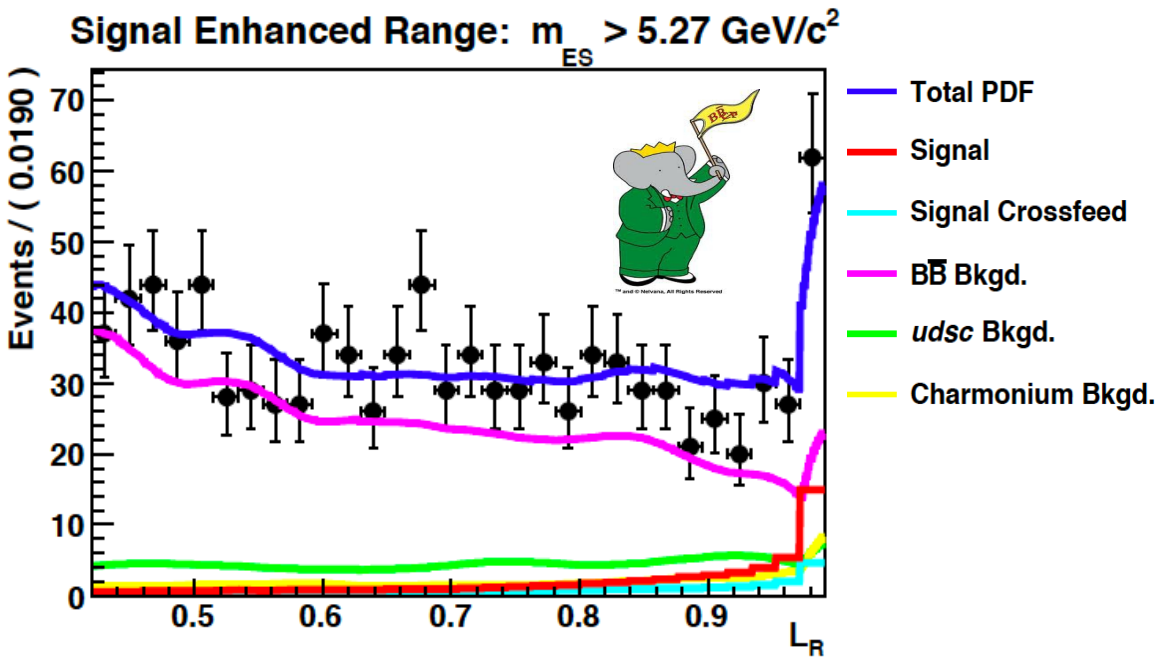
$$\frac{d\mathcal{BR}}{dq^2} \quad \frac{d\mathcal{BR}}{dM_x} \quad \mathcal{BR} \quad \frac{dA_{CP}}{dq^2}$$

$B \to X_s \ell^+ \ell^-$

- Yields extracted in various q^2 & M_x bins by 2D (m_{ES}, L_R) fit
  - $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B} \quad \Delta E = E^*_B - E^*_{beam}$
  - BB combinatorial background using a Likelihood Ratio (LR) defined from outputs of eights BDTs exploiting kinematical and topological quantities

$B \to X_s e^+ e^-$: $1 < q^2 < 6$ GeV^2





$B \to X_s \ell^+ \ell^-$

- Observed BR scaled to full rate based on simulation

$$BR = (6.73\ ^{+0.70}_{-0.64}\ ^{+0.34}_{-0.25}\ \pm 0.50) \cdot 10^{-6}$$

$$BR_{SM} = (4.6 \pm 0.8) \cdot 10^{-6}$$

Huber et al. NPB802,40 (2008)

- **I**: $1 < q^2 < 6\ GeV^2$

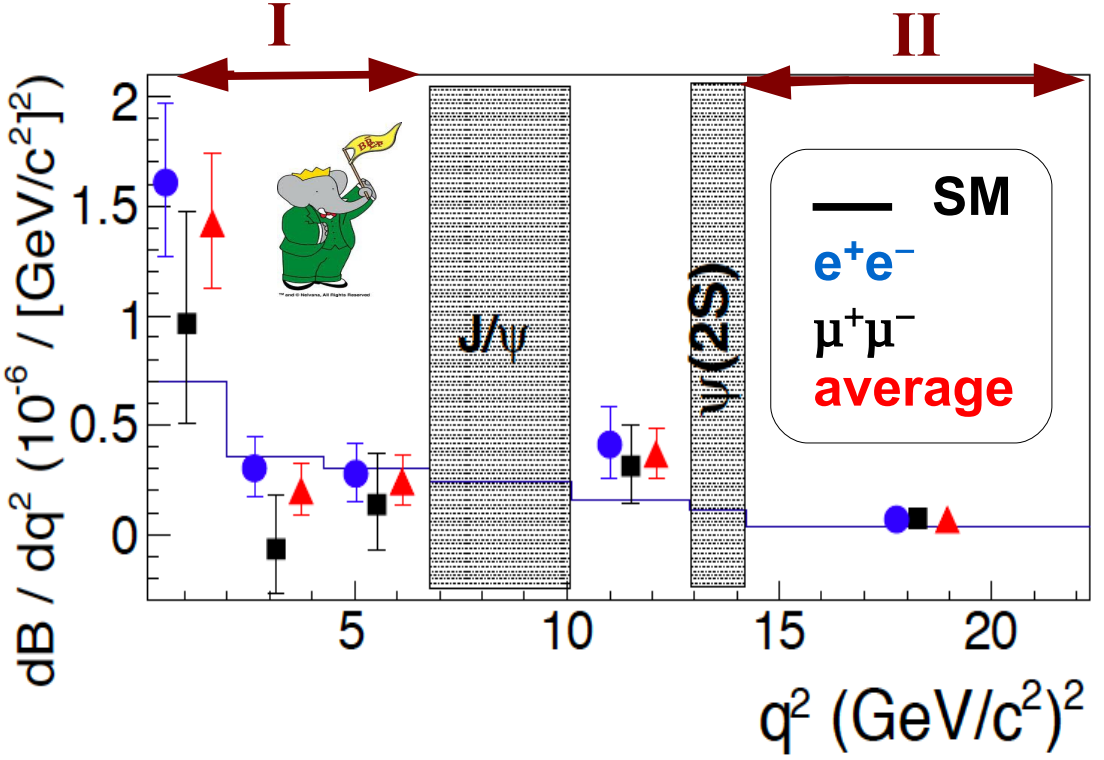
$$BR = (1.60\ ^{+0.44}_{-0.39}\ ^{+0.17}_{-0.13} \pm 0.18) \cdot 10^{-6}$$

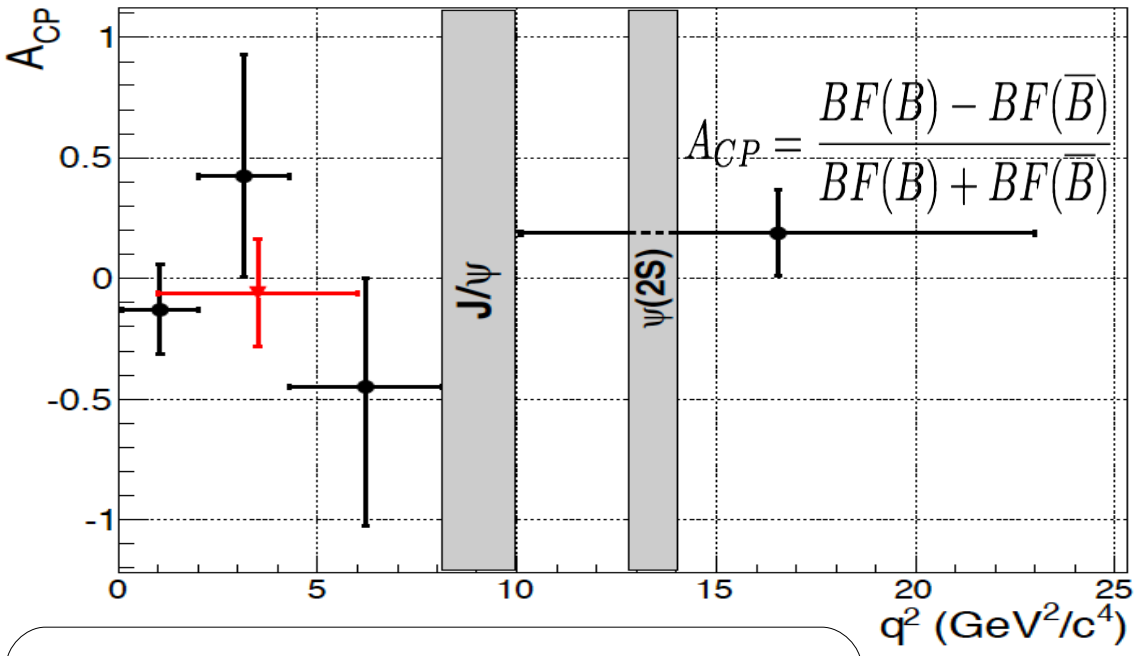
$$BR_{SM} = (1.59 \pm 0.11) \cdot 10^{-6}$$

- **II**: q^2 above $\psi(2S)$

$$BR = (0.57\ ^{+0.16}_{-0.15}\ ^{+0.03}_{-0.02} \pm 0.0) \cdot 10^{-6}$$

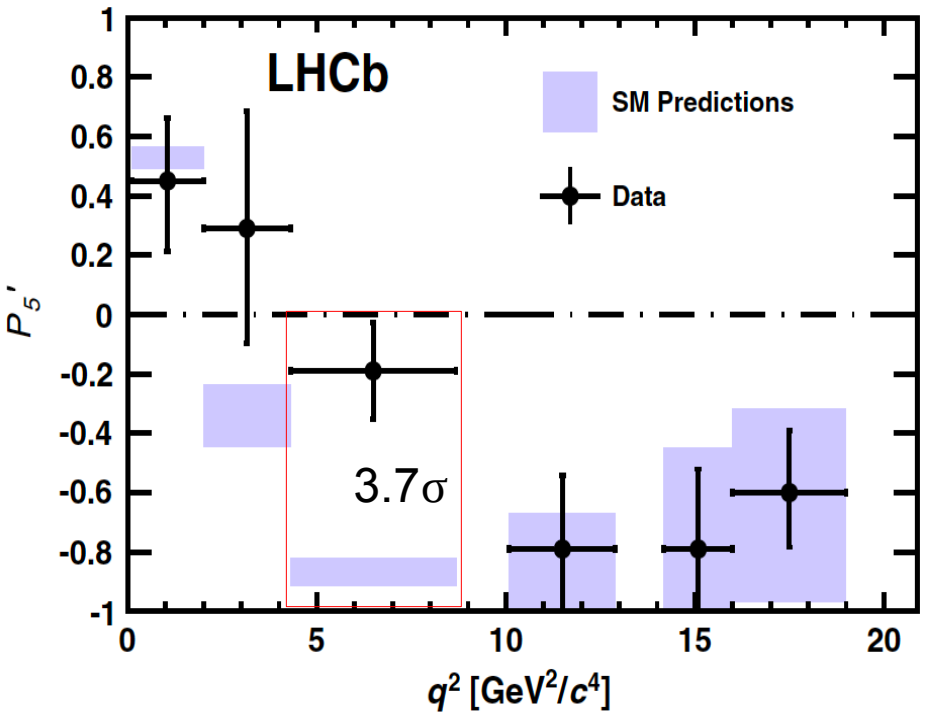
$$BR_{SM} = (0.25 \pm 0.07) \cdot 10^{-6}$$





$$A_{CP} = 0.04 \pm 0.11_{stat} \pm 0.01_{syst}$$

$B \to K \pi \ell^+ \ell^-$ & $B \to X_s \ell^+ \ell^-$



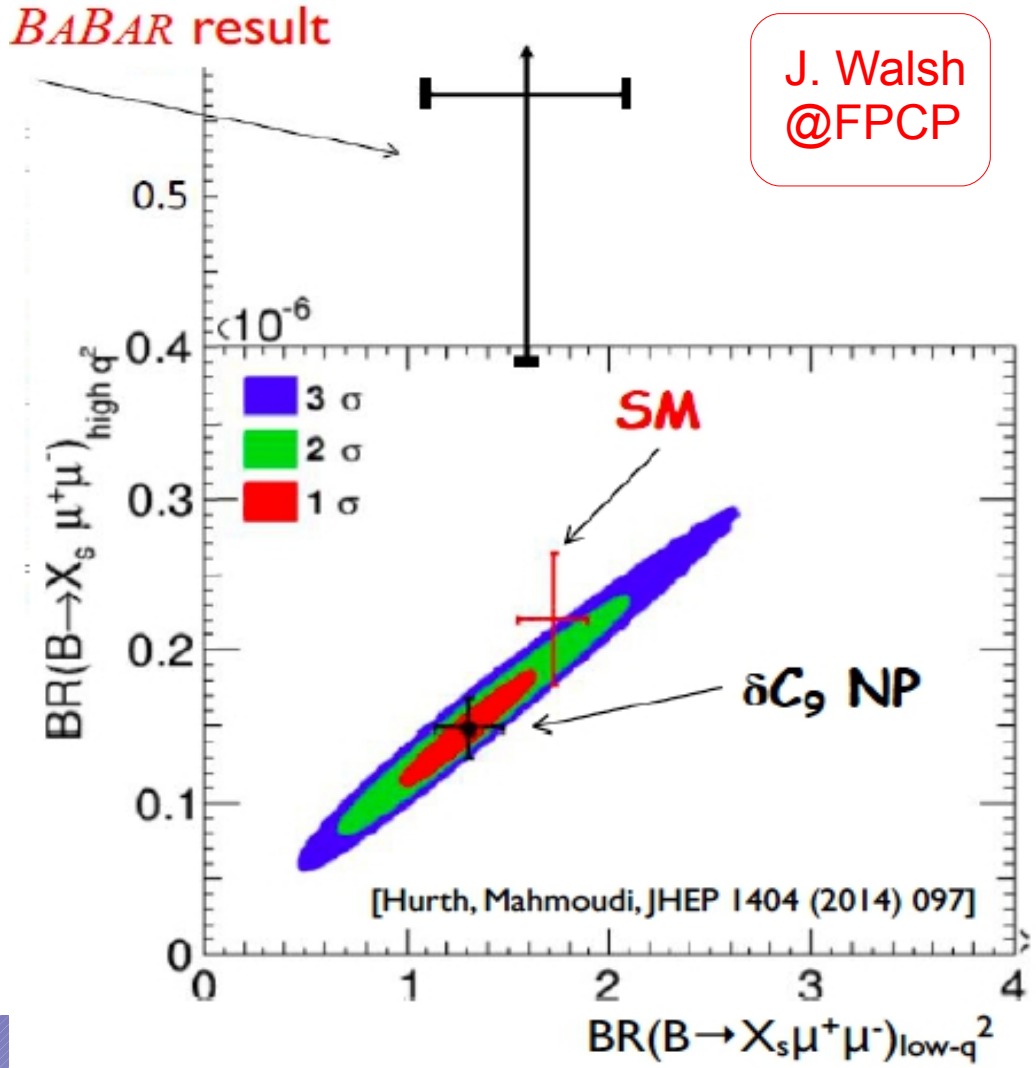
- LHCb measurement of observables free from FF contributions. One observable is not in agreement with SM

PRL111,191801(2013)

- Global fits to recent b → sll and b→ sγ data favor decreased value of Wilson coefficient $C_{9:}$: indication of NP?

JHEP1305,043 (2013), PRD88,074002(2013)

- This leads to a reduced value of inclusive $B(B \to X_s \ell^+ \ell^-)$
- However, our measurement of BF at high-q^2 does not support this hypothesis



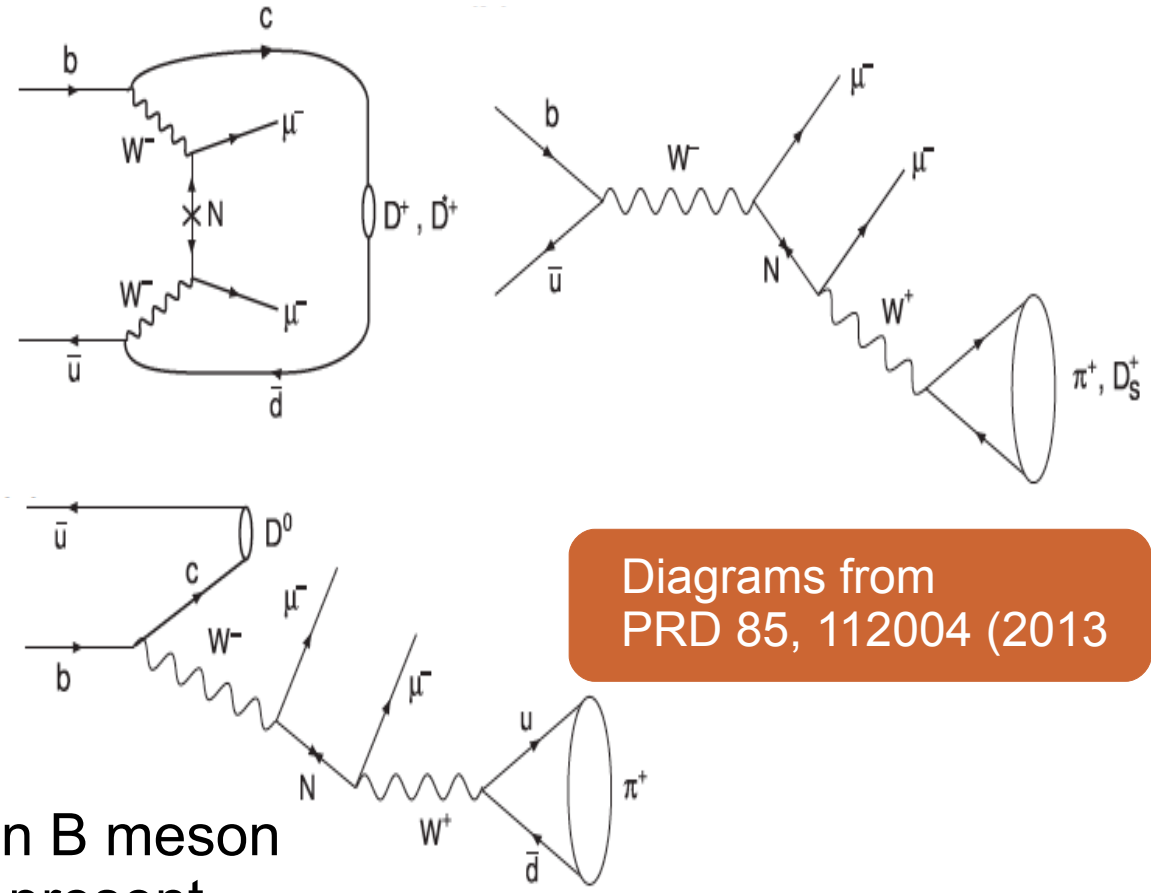
$B \to X \ell^+ \ell'^+$

- "Search for lepton-number violating $B^+ \to X \ell^+ \ell'^+$ decays"

- Phys.Rev.D (RC) 89, 011102 (2014)

$B \to X \ell^+ \ell'^+$

- Lepton-Number Violation (LNV) holds in low-energy collisions and decays
- Neutrino oscillations suggests lepton number may not be conserved
  - If neutrino are of Majorana type, LNV become possible



Diagrams from PRD 85, 112004 (2013

- Many NP models predicts LNV in B meson decays at rates detectable from present existing data: BaBar/Belle and LHCb

Klinkhamer, Manton PRD 30, 2212 (1984)
Atre, Han, Pascali, Zhang JHEP 05, 030 (2009)
Davidson, Nardi, Nir Phys.Rep.466, 105 (2008)

B→X$\ell^+\ell'^+$

- Search done in 11 B decay modes

$B^+ \to \rho^- (\to \pi^- \pi^0)\, l^+ l'^+$

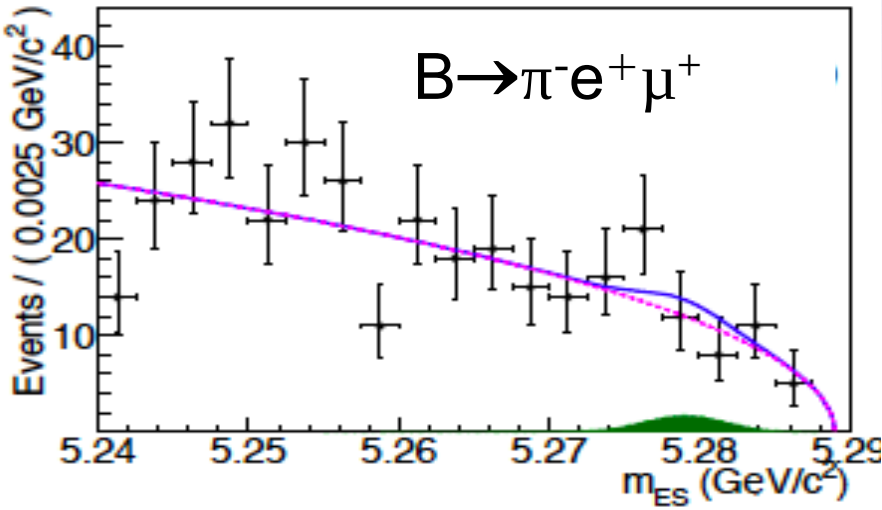
$B^+ \to K^{*-} (\to K^0_S \pi^- \text{ and } \to K^- \pi^0)\, l^+ l'^+$

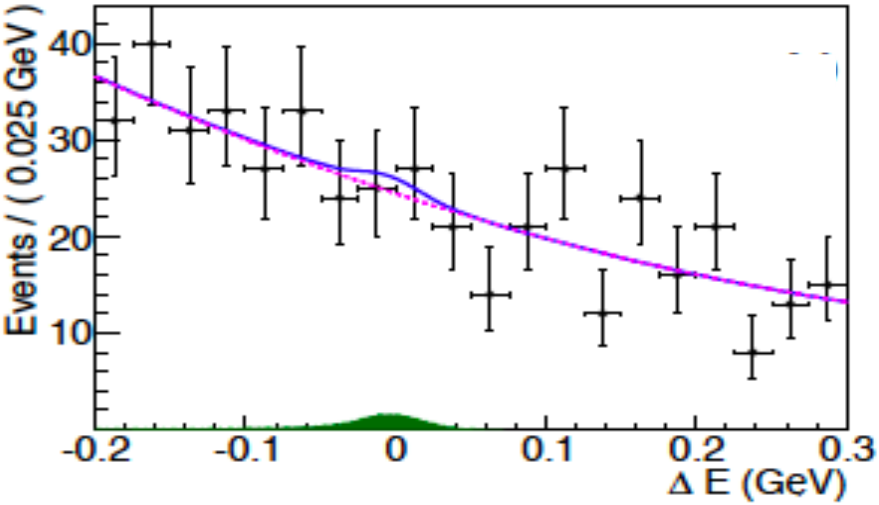
$B^+ \to D^- (\to K^- \pi^- \pi^+)\, l^+ l'^+$

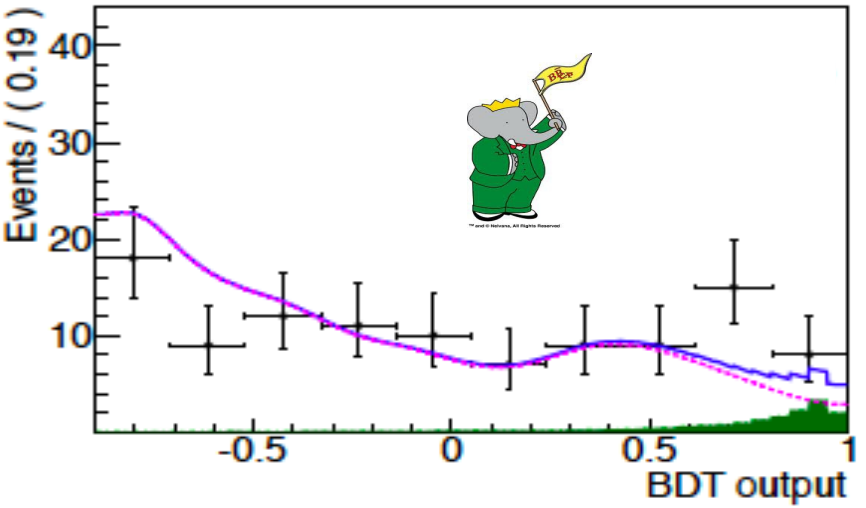
$B^+ \to K^- e^+\mu^+ ,\ \pi^- e^+\mu^+$

$(\ell^+, \ell'^+ = e^+, \mu^+)$

- Events selection requires 4 or more charged tracks (at least two leptons)
- Background (continuum and BB) using a BDT with many event-shape discriminating variables
- Signal extracted from a m_{ES}, ΔE and BDT output



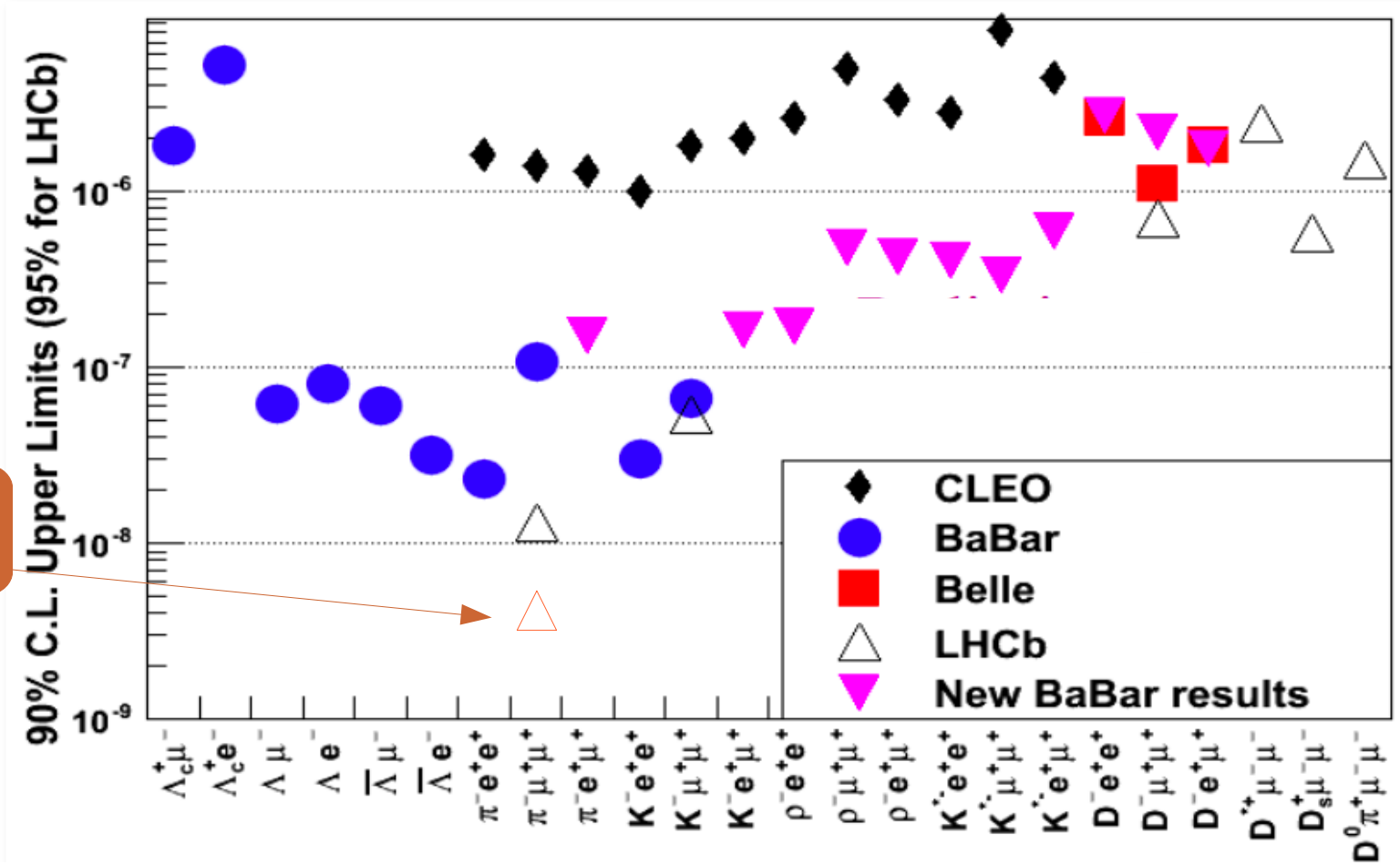




$B \to X \ell^+ \ell'^+$

- No significant yields found:
  - BF upper limits in the range $1.2 \cdot 10^{-7}$ - $26 \cdot 10^{-7}$ @90% C.L.
  - Limits are an order of magnitude more stringent than previous best results for modes with ρ, π and K

LHCb:
PRL112, 131802 (2014)



$B \rightarrow \tau \nu_\tau$

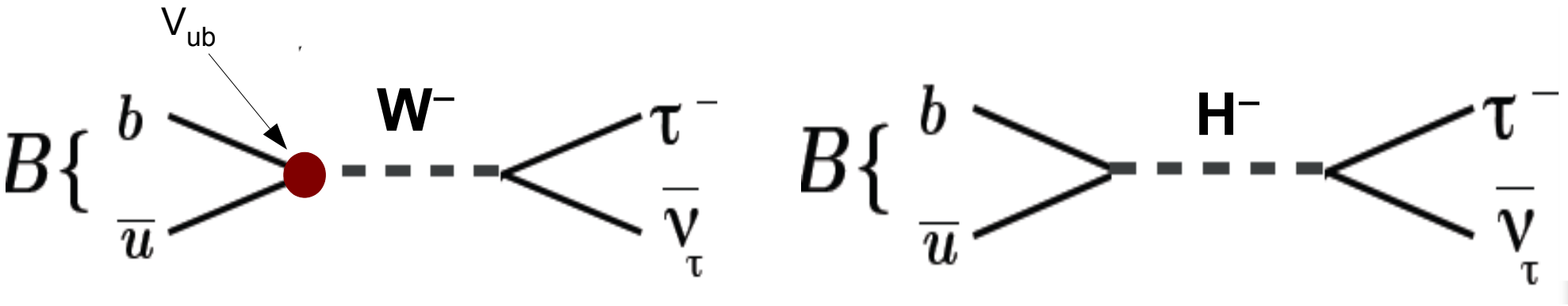
- "Evidence of decays with hadronic B tags"

PRD(RC) 88, 031102 (2013)

- After the great success of the CKM mechanism:
  - Unitarity Triangle from Tree Level processes and loop-induced processes are in agreement (a few discrepancies still present between sin 2β and $|V_{ub}|$)
  - It is true that FCNC processes are highly sensitive to NP but the Tree Level process are very good to constrain some kinds of NP

Analysis of $B \to \tau \nu_\tau$

Theoretically very clean and a sensitive probe of physics beyond the SM:



Charged Higgs exchange could modify the BR
- 2HDM is widely studied and is a model of many SM extensions that require $H^\pm$

$$\mathcal{B}_{2HDM}(B \to \tau\nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \times \left(1 - m_B^2 \frac{\tan^2\beta}{m_H^2}\right)^2$$

B(τν) In the SM

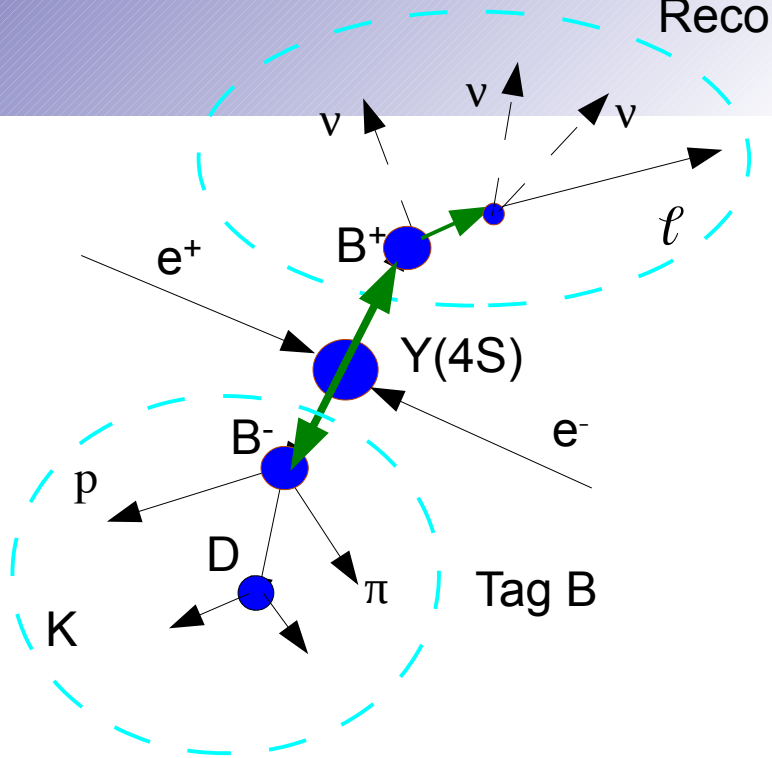
In the Type-II 2HDM

Experimentally difficult:
- helicity suppression+V_{ub} → BF(τ)~10^{-4}
- tau lepton in the final state

Only one observables: the Branching Fraction

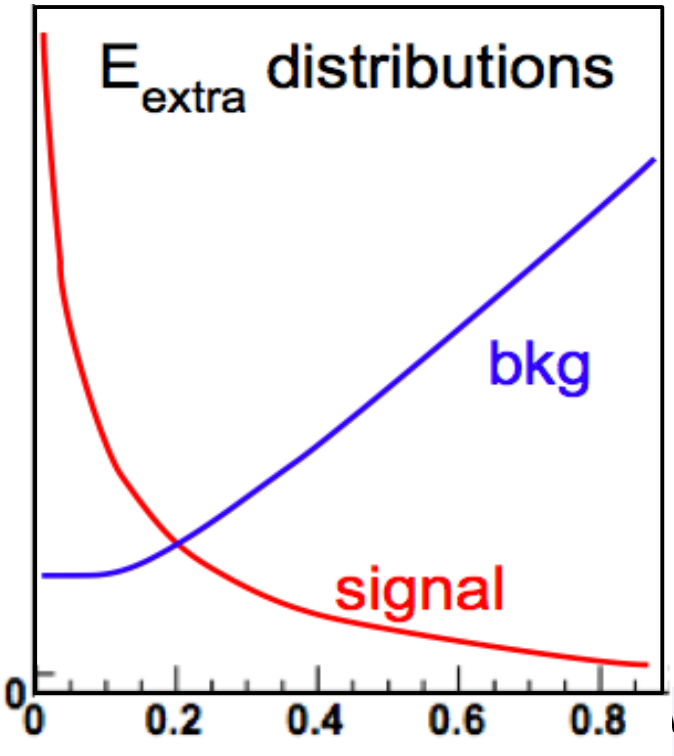
Events Reconstruction

- The experimental signature is weak due to the presence of many ν's in the final states
- Two B in the Y decay: $e^+e^- \rightarrow Y(4S) \rightarrow BB$
  - Fully reconstruct one B in hadronic decay modes (with a D, D*, D_s or a J/ψ)
  - The rest comes from the other B (B^{recoil})
- Tag efficiency ~ 0.2-0.4%
- $\vec{p}_{B^{recoil}} = -\vec{p}_{B^{tag}}$



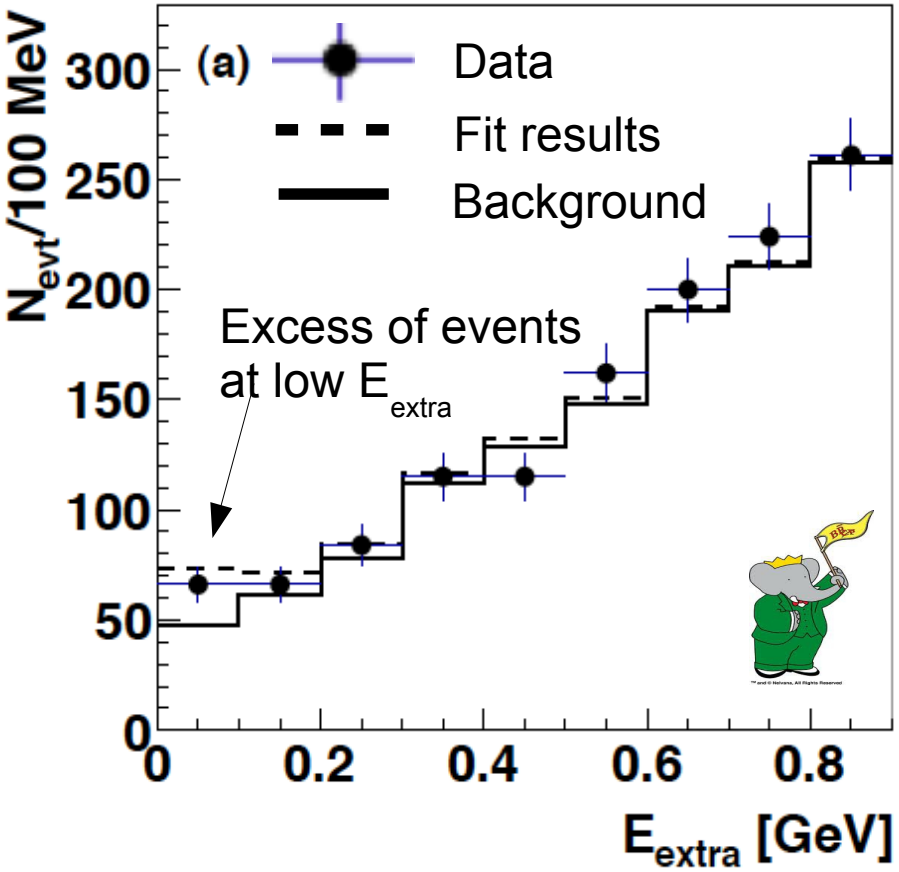
- The signal is extracted from the residual energy visible in the Calorimeter

$$E_{\mathrm{Extra}} = \sum_{\mathrm{unused}\ \gamma} E_\gamma$$



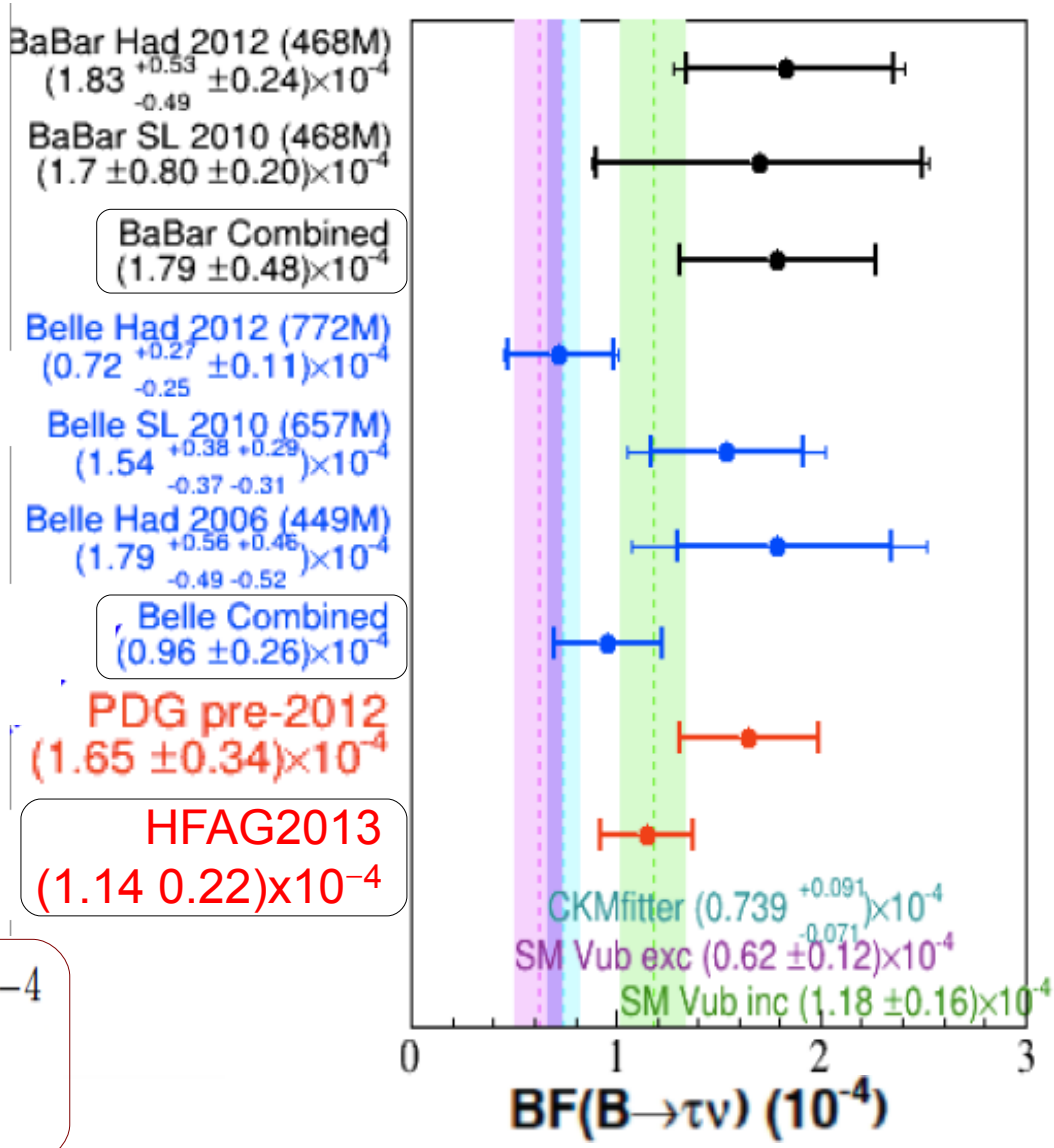
Results: $B \to \tau \nu_\tau$

- Fit together $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, $\tau \to \rho\nu$
- Combined result, compatible with BaBar-Semileptonic Tag result



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

Significance 3.8σ



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

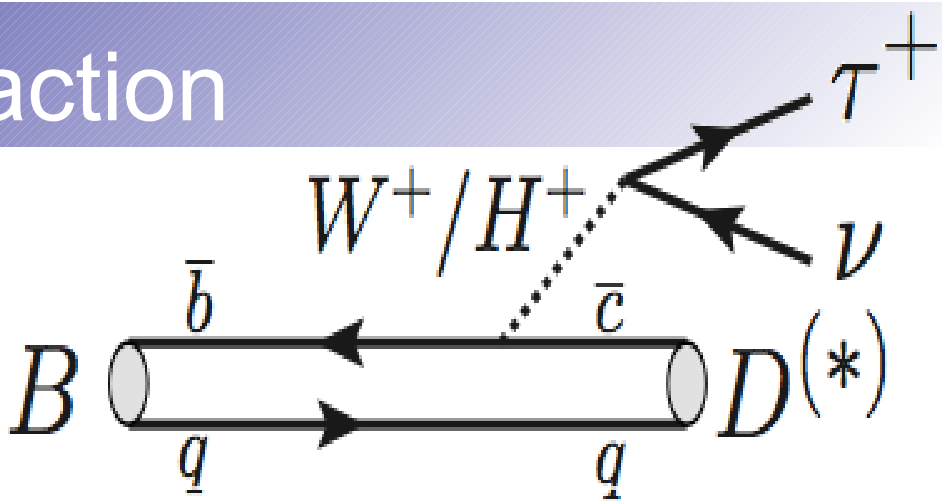
- “Evidence of an excess over the SM prediction”

Phys. Rev. Lett. 109, 101802 (2012)

Phys. Rev. D 88, 072012 (2013)

$B \to D^{(*)} \tau \nu_\tau$: Yields Extraction

- It is not a rare decay: BF~1-2%
- 3 body decay: not only the BF, many other observables can be sensitive to NP



Momentum transfer to $\tau\nu$

Helicity amplitudes common to e,μ,τ

Relevant only for tauonic decays

$$\frac{d\Gamma(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |p| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2) \left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2} |H_{0t}|^2 \right]$$

- Spin-0 Higgs does not couple to all helicity states: D and D* are affected differently

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)} \tau \nu)}{\mathcal{B}(B \to D^{(*)} \ell \nu)}$$

Normalization

Several experimental and theoretical uncertainties cancel in ratio

- D reconstruction/Particle ID...
- $|V_{cb}|$ & FFs (partially)

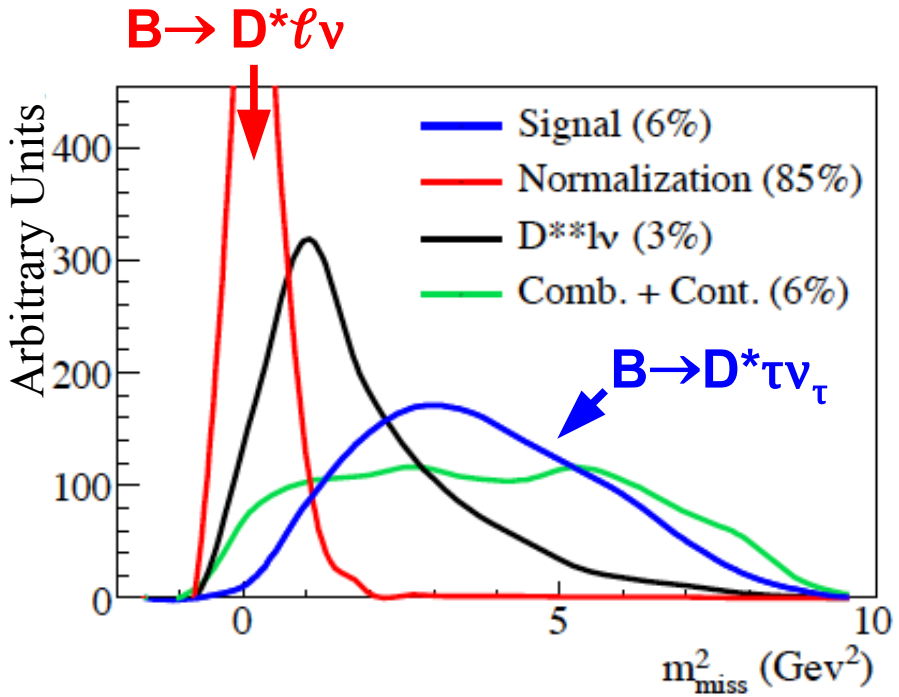
$B \to D^{(*)} \tau \nu_\tau$: Yields Extraction

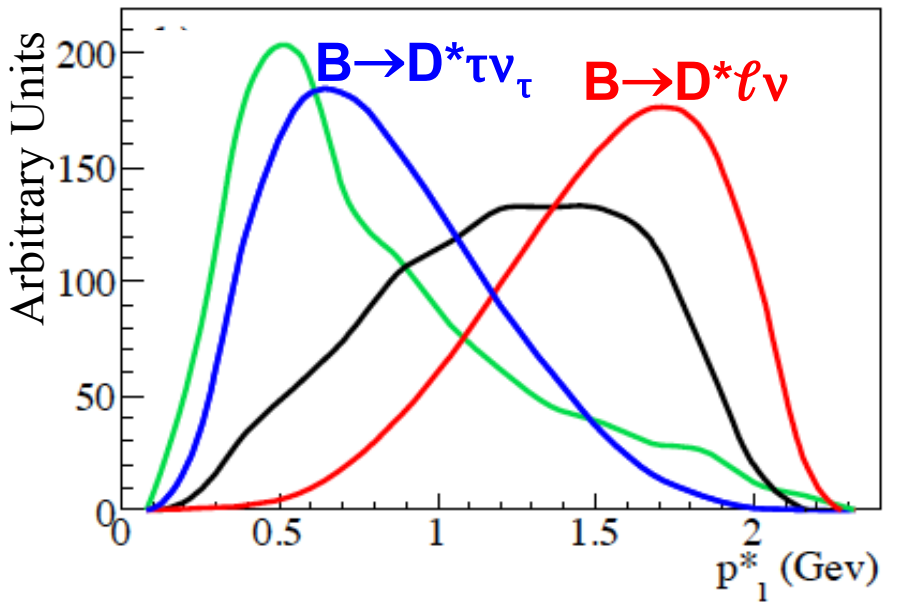
- Many neutrinos in the final state:
  - Reconstruct the hadronic B_{tag}
- Use only leptonic τ decays:
  - Similar to normalization decay
- Simultaneous un-binned M.L. Fit
  - 4 signal samples $D^0\ell$, $D^{*0}\ell$, $D^+\ell$, $D^{*+}\ell$
  - 4 $D^{(*)}\pi^0\ell\nu$ Control samples
  - 2 dimensional distributions:

$m_{miss}^2 = (p_{e+e-} - p_{tag} - p_{D(*)} - p_\ell)^2$

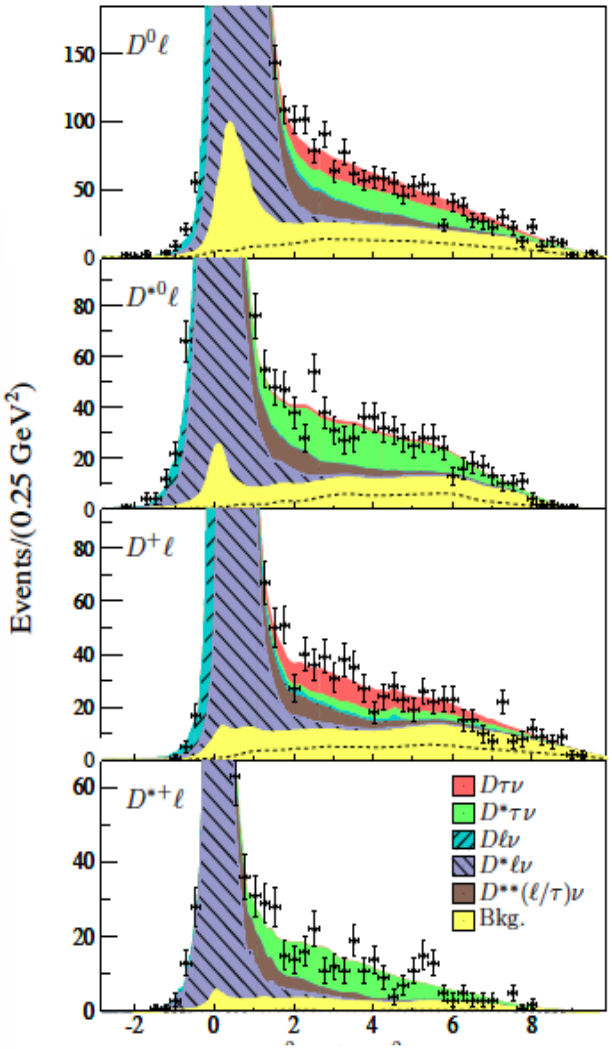
p_ℓ in the B_{sig} rest-frame

- Fitted Yields
  - 4 $D^{(*)}\tau n$ + 4 $D^{(*)}\ell n$ + 4 $D^{**}\ell n$

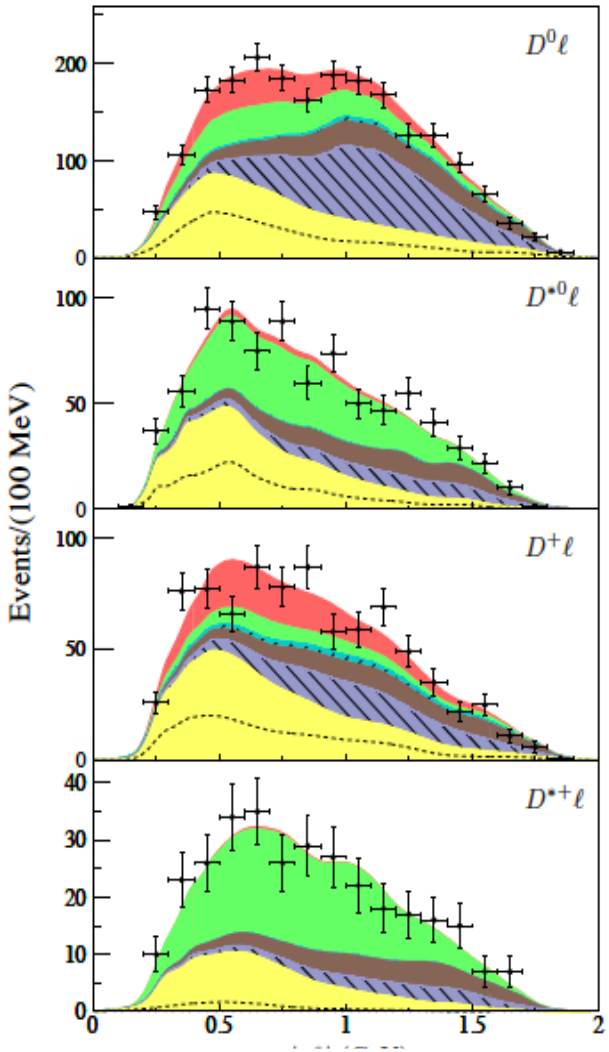




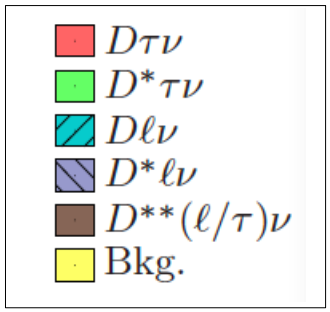
$B \to D^{(*)} \tau \nu_\tau$: Fit results



m_{miss}^2 (GeV^2)



p_ℓ (GeV)



- $B^0 \to D(*)$ and $B^+ \to D(*)$ modes observed with more than 5 sigmas
- Results between B^0 and B^+ consistent
- Largest systematics due to background PDFs
- Statistical uncertainty dominates

Isospin constrained results

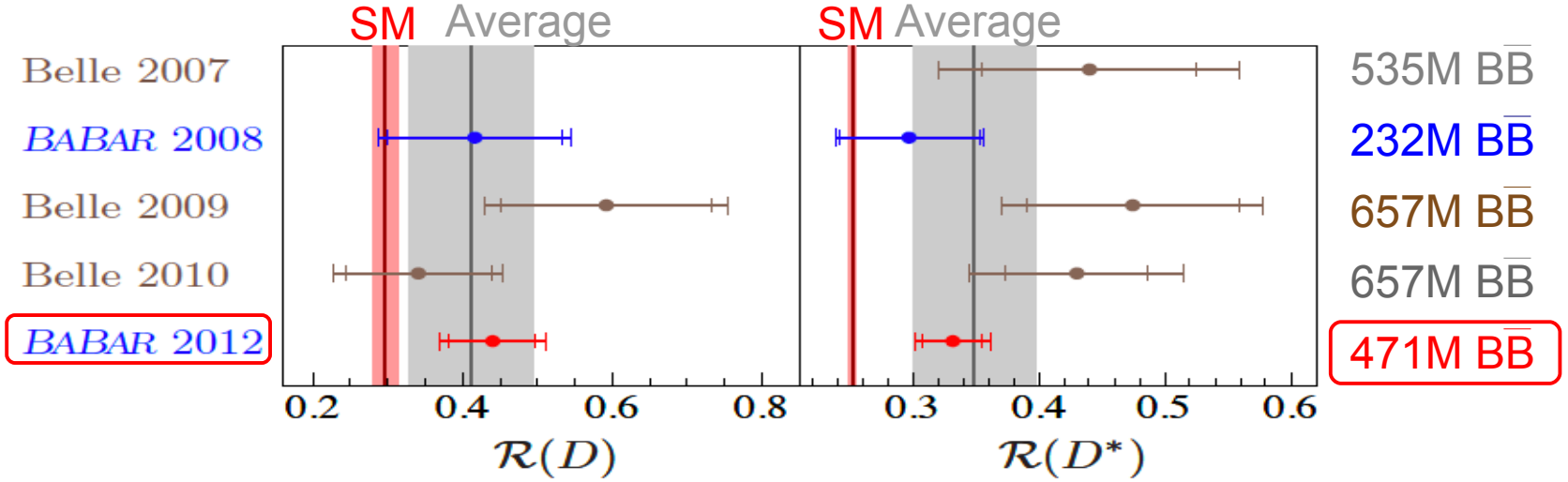
$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$$

SM Predictions of R(D) and R(D*)

[*] Kaminik Mescia 2008
Fajfer et al 2012

- The new measurements are fully compatible with earlier results from BaBar and Belle

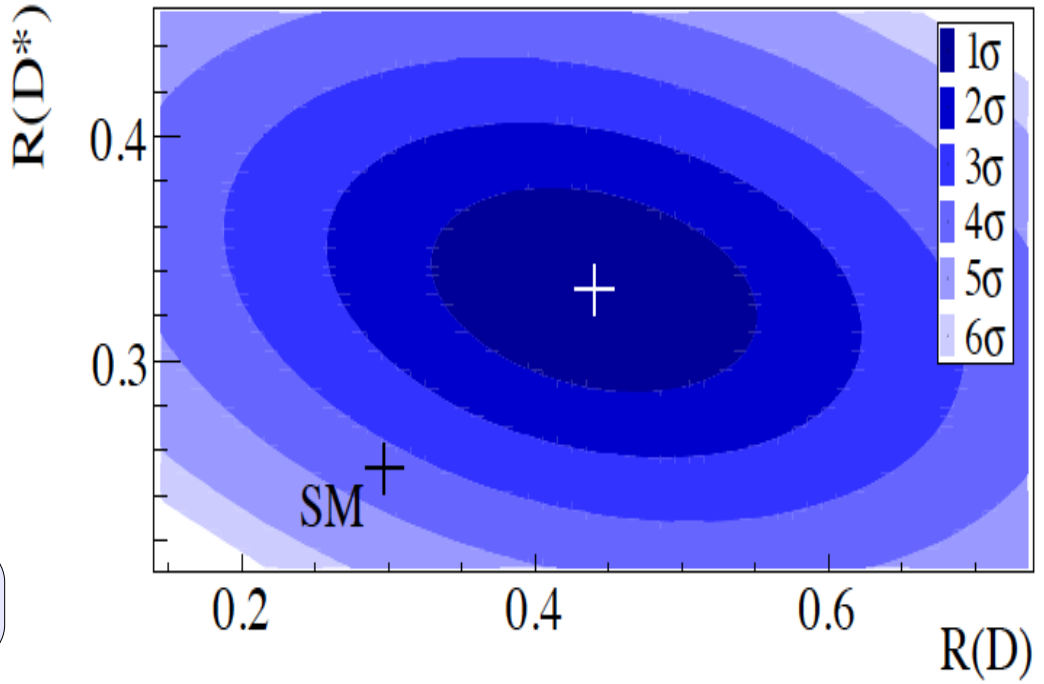
Average does not include this measurement



- And above the SM prediction!

	R(D)	R(D*)
BaBar	0.440 ± 0.071	0.332 ± 0.029
SM [*]	0.293 ± 0.017	0.252 ± 0.003
Δ	2.0σ	2.7σ

The combination of the two measurements (-0.27 correlation) yields c^2/NDF=14.6/2 -> **Prob=6.9 x 10^{-4}**



Deviation from SM is 3.4σ

Implication for 2HDM

Differential decay rate in the SM

$$\frac{d\Gamma(\overline{B} \to D^* \ell^- \overline{\nu}_\ell)}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |p| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2) \left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2} |H_{0t}|^2 \right]$$

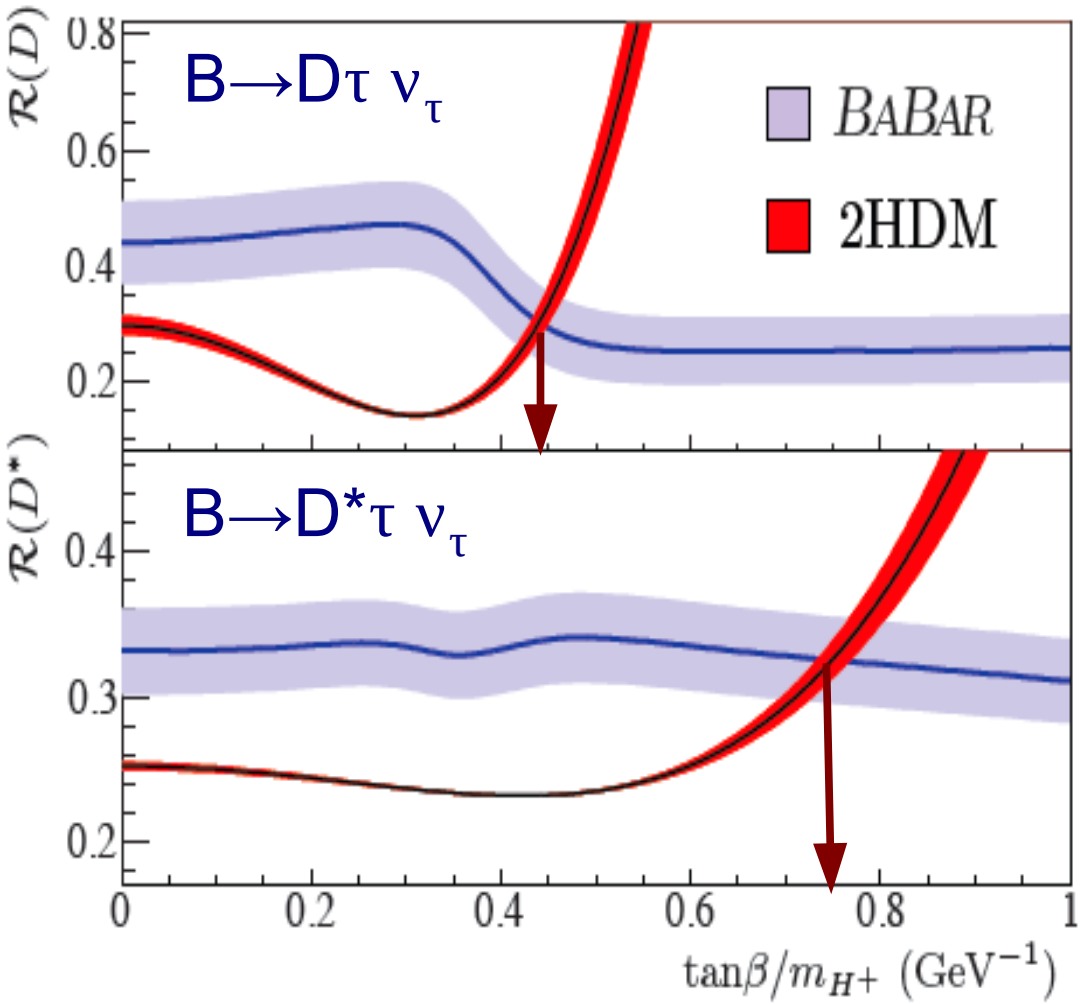
A charged Higgs (**Type-II 2HDM**) of spin 0 coupling with the τ will affects H_{0t}

$$H_{0t}^{\text{2HDM}} \approx H_{0t}^{\text{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H^+}^2} \frac{q^2}{1 \mp m_c/m_b}\right)$$

− for $B \to D\tau\,\nu_\tau$ + for $B \to D^*\tau\,\nu_\tau$

Scan the full 2HDM parameter space

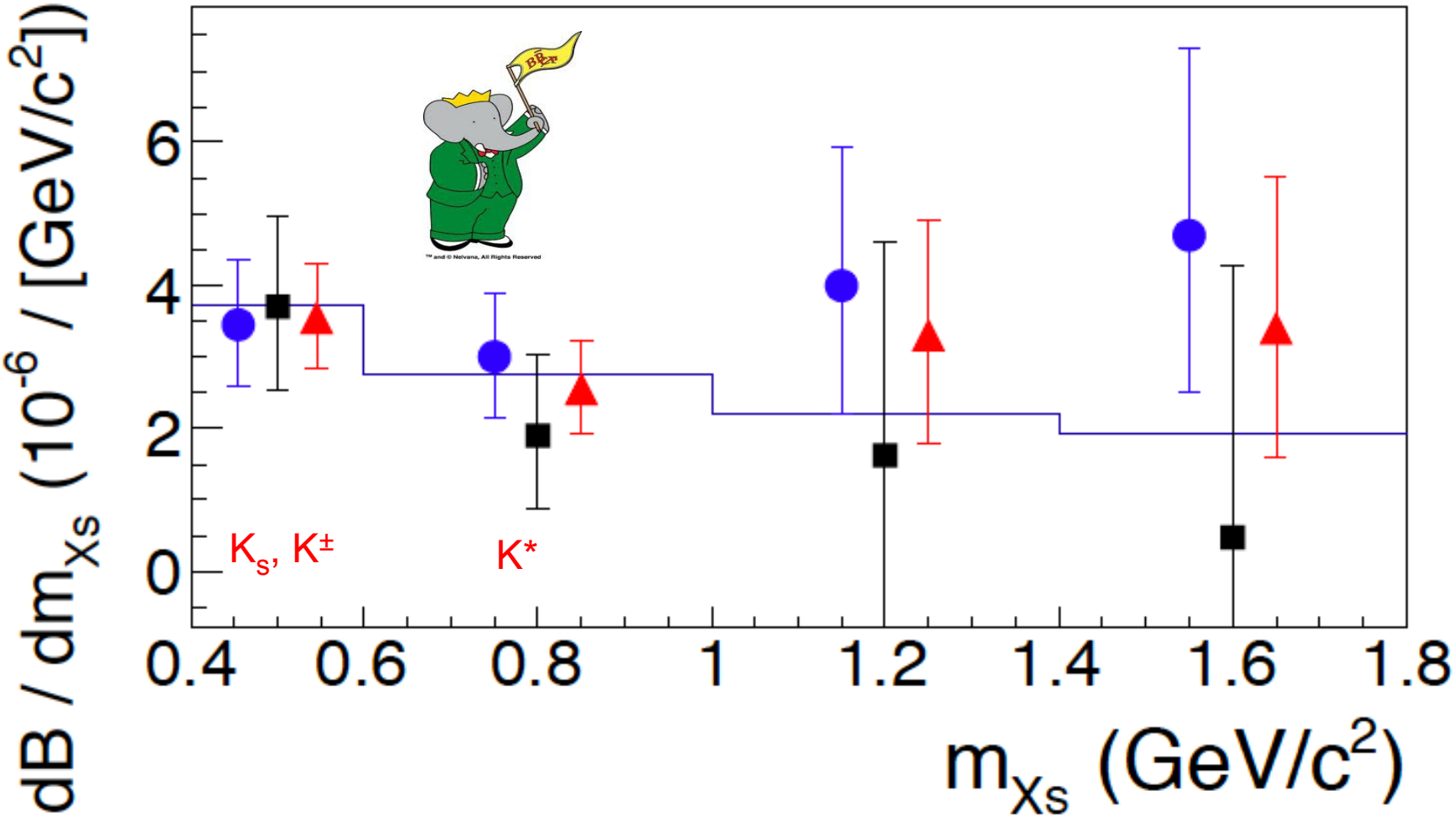
$$\mathcal{R}(D) \Longrightarrow \tan\beta/m_H = 0.44 \pm 0.02$$
$$\mathcal{R}(D^*) \Longrightarrow \tan\beta/m_H = 0.75 \pm 0.04$$



Summary

- Interesting measurements are still coming from BaBar
- Recent measurements of Inclusive $B \to X_s \ell^+ \ell^-$ continue to constrain NP models
- No evidence of NP found in LNV processes $B \to X \ell^+ \ell'^+$
- $B \to D^{(*)} \tau \nu_\tau$: not in agreement with SM prediction
  - If confirmed by Belle: look at polarization with $\tau \to \pi\nu$, D* angular distribution, FB asymmetries, Triple Products...
  - Rich physics program for LHCb and Belle-II
- $B \to \tau \nu_\tau$: reached the B-factories limits
  - Status is cloudy
  - But will be explored with high precision at Belle-II

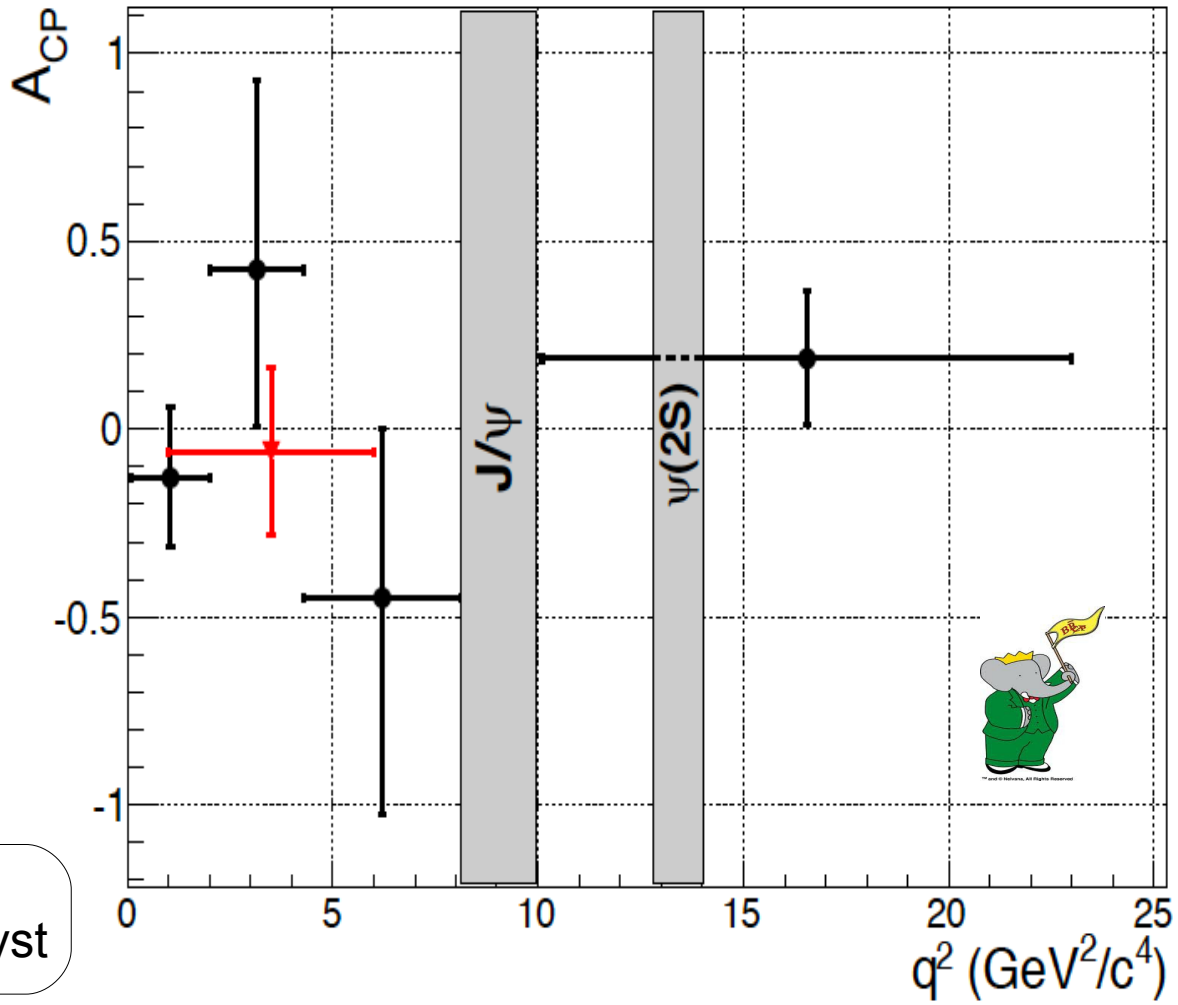
$B \to X_s \ell^+ \ell^-$ partial BF .vs. Mx



$B \to X_s \ell^+ \ell^-$ CP violation

$$A_{CP} = \frac{BF(B) - BF(\overline{B})}{BF(B) + BF(\overline{B})}$$

- Sample divided according to lepton kind and B flavor
  - Inferred from K/π charges
- No model-dependent extrapolation of signal rates performed



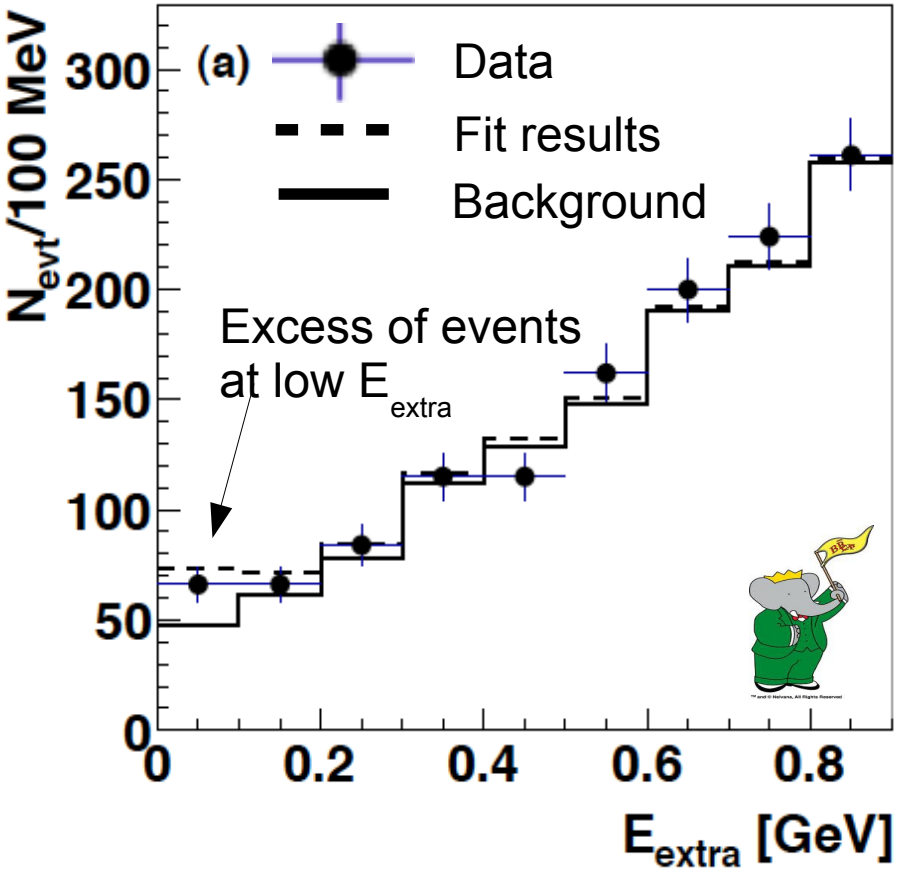
$A_{CP} = 0.04 \pm 0.11_{stat} \pm 0.01_{syst}$

- In agreement with SM predictions

Eur.Phys.JC8 619
Phys.Rev.D 54,882

Results: $B \to \tau \nu_\tau$

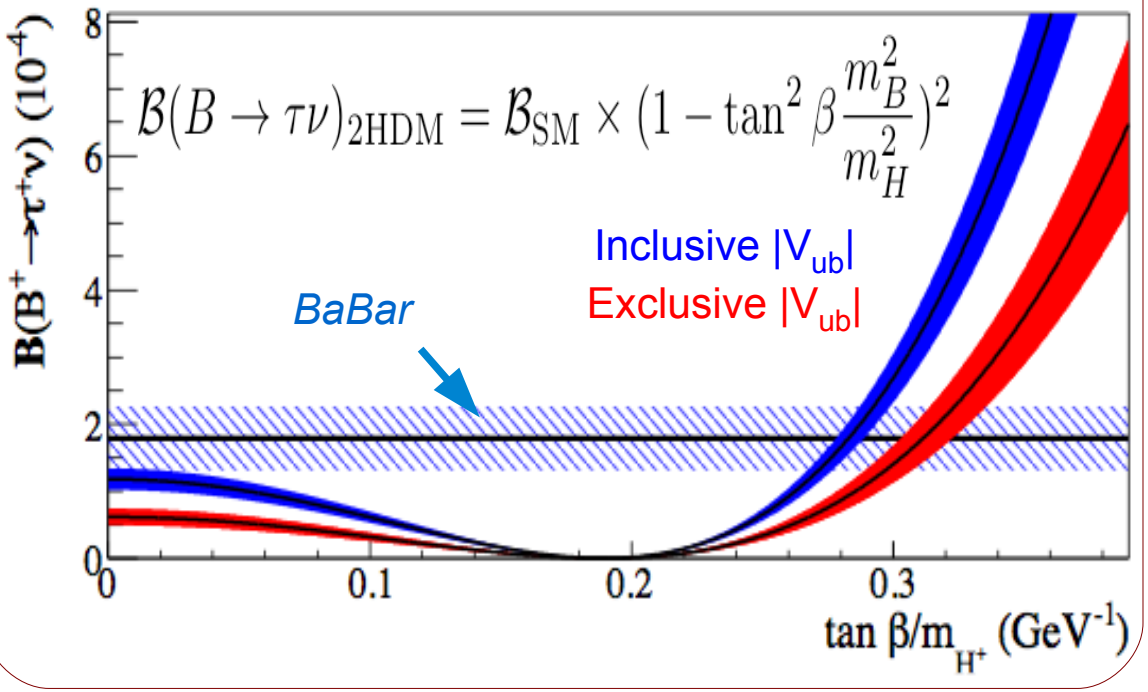
- Fit together $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, $\tau \to \rho\nu$
- Combined result, compatible with BaBar-Semileptonic result



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

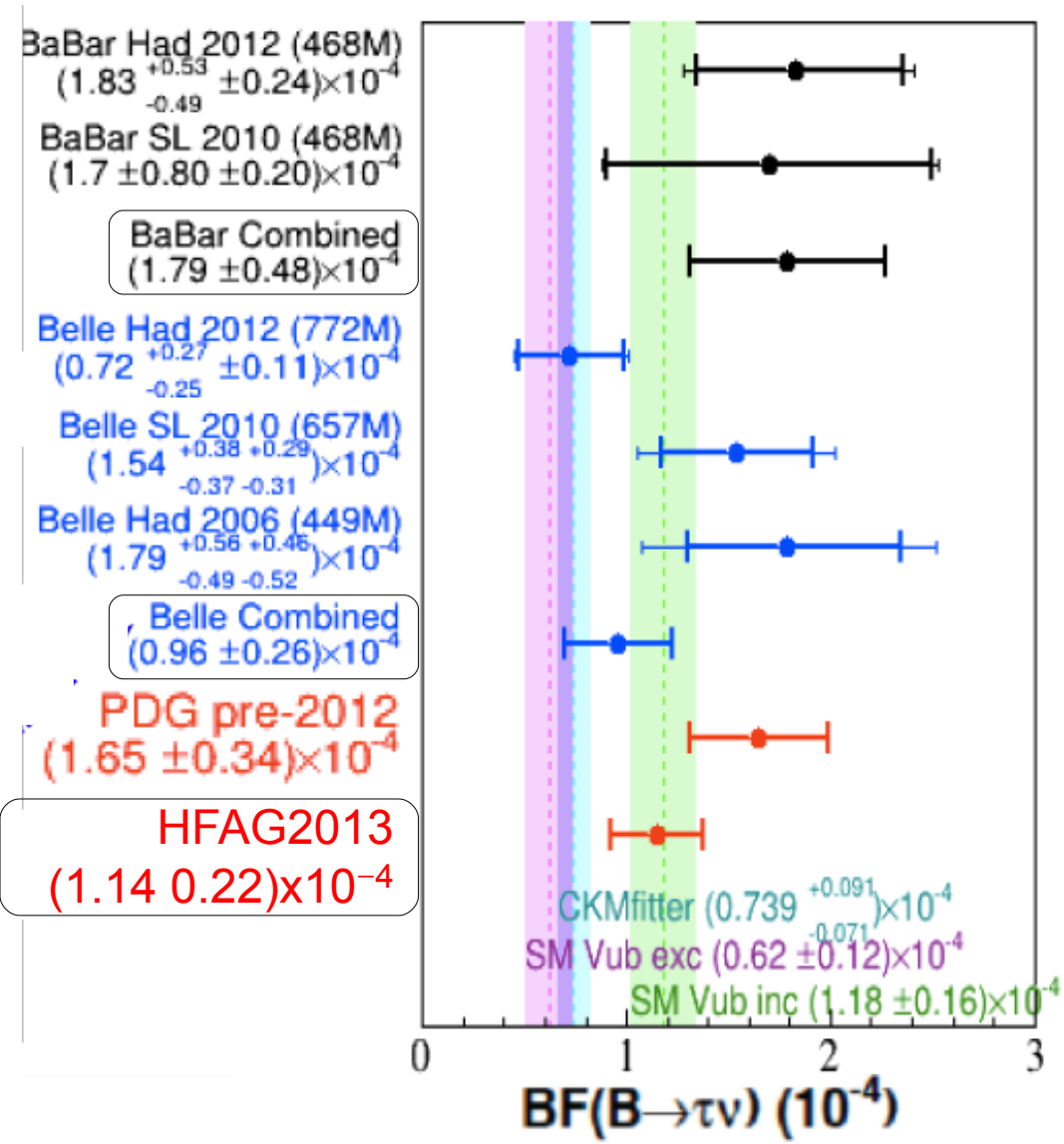
Significance 3.8σ

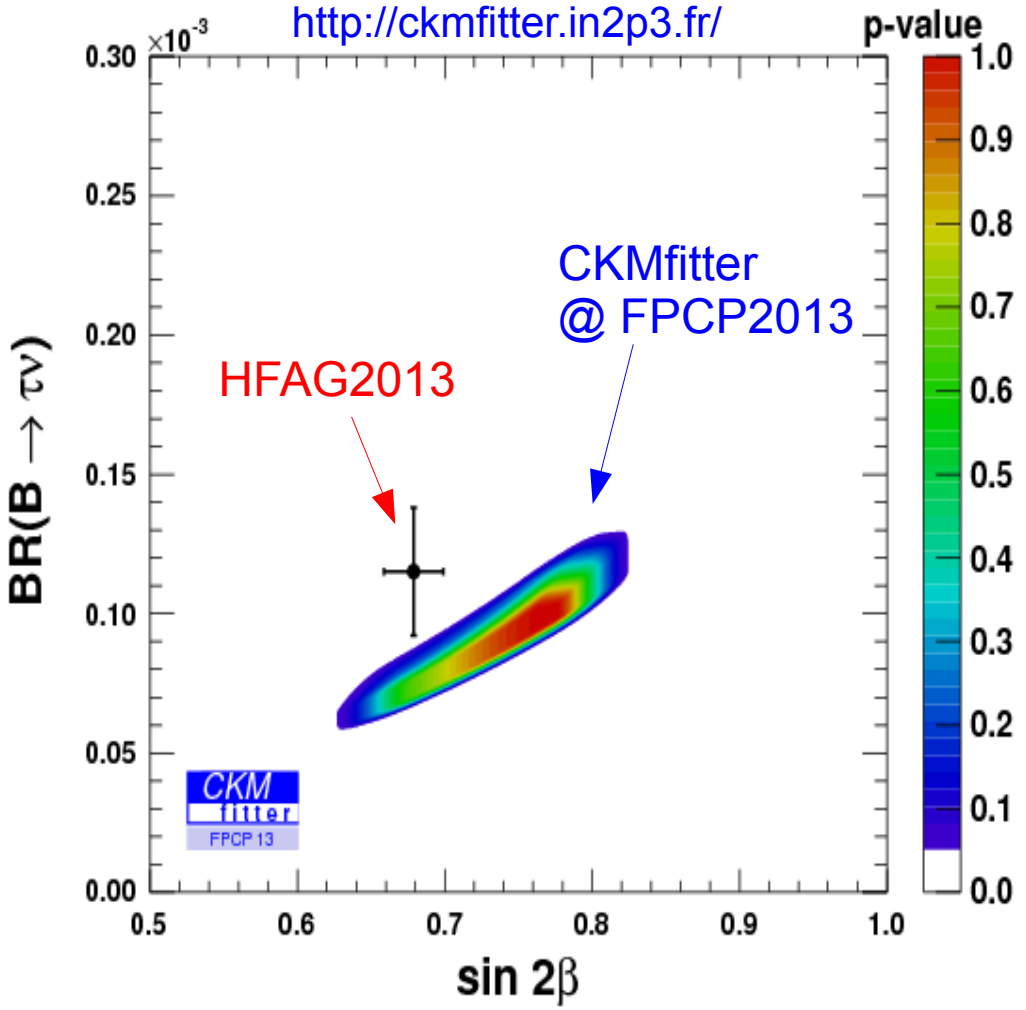
Type-II 2HDM constraints



SM & NP prediction depends on how |Vub| is obtained

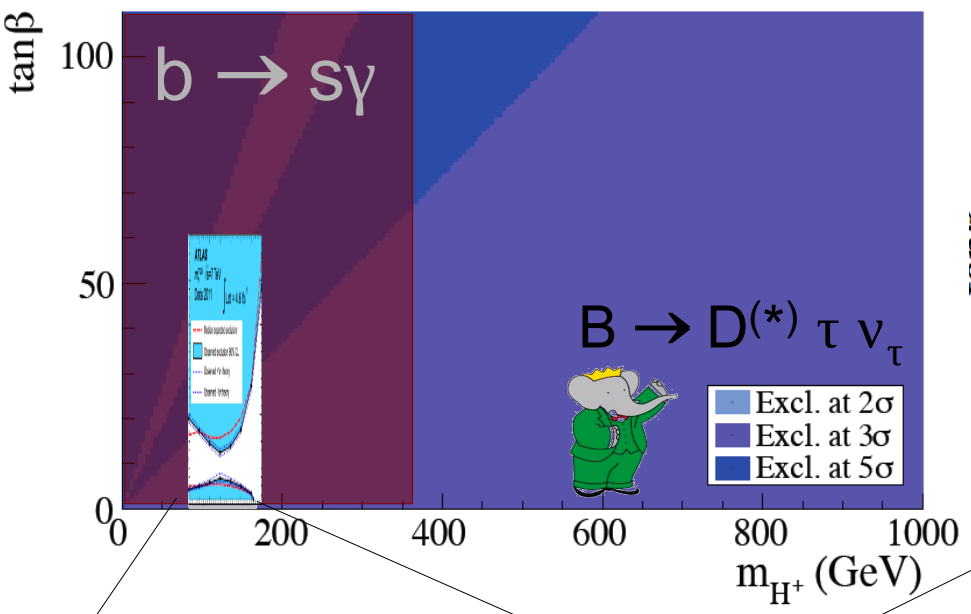
Experimental Results on $B \to \tau \nu_\tau$

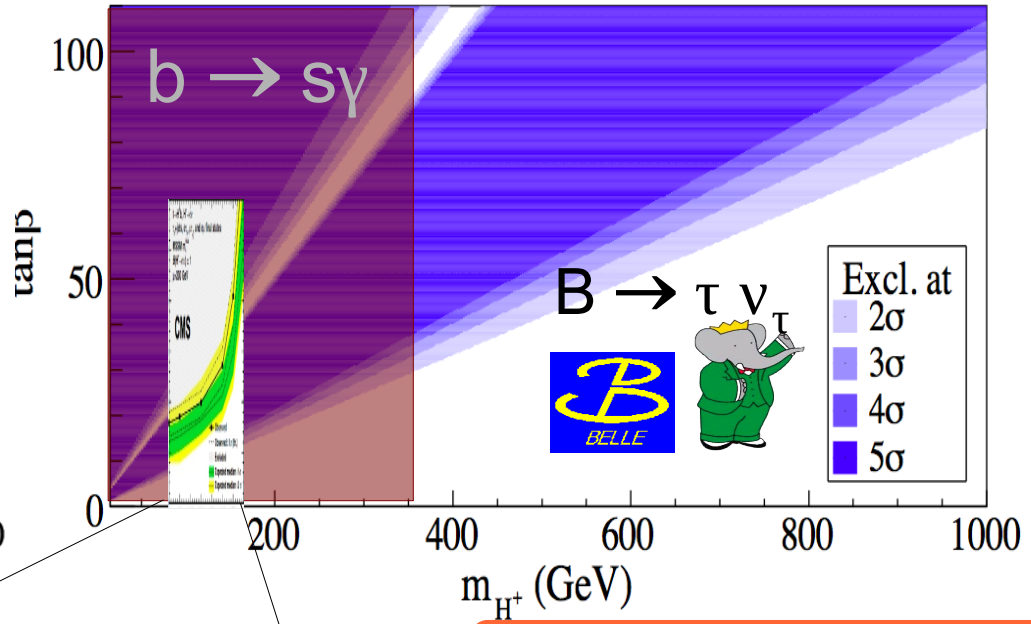


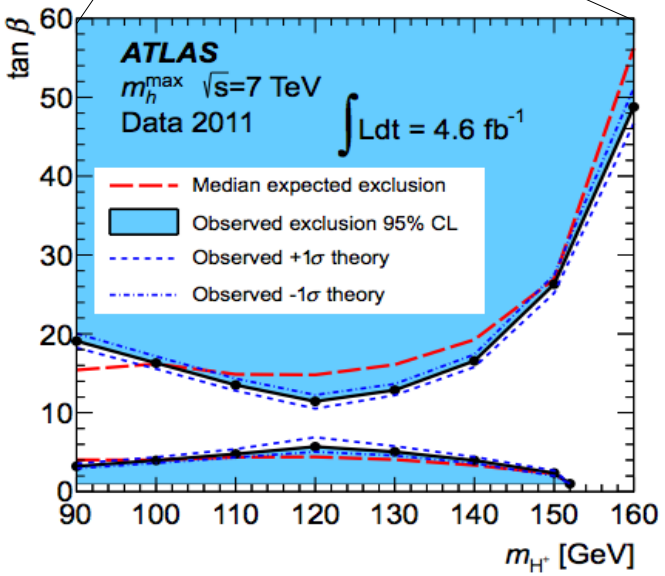


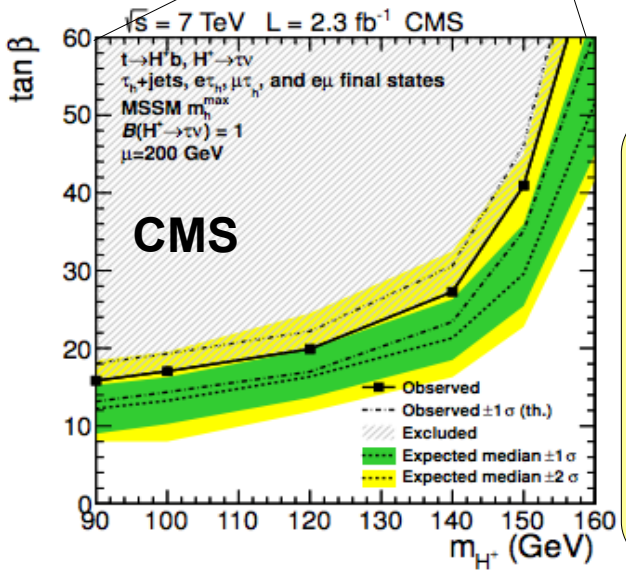
Exclusion region for 2HDM-II

Using both D – D* results: Type II 2HDM excluded at 99.8% C.L.









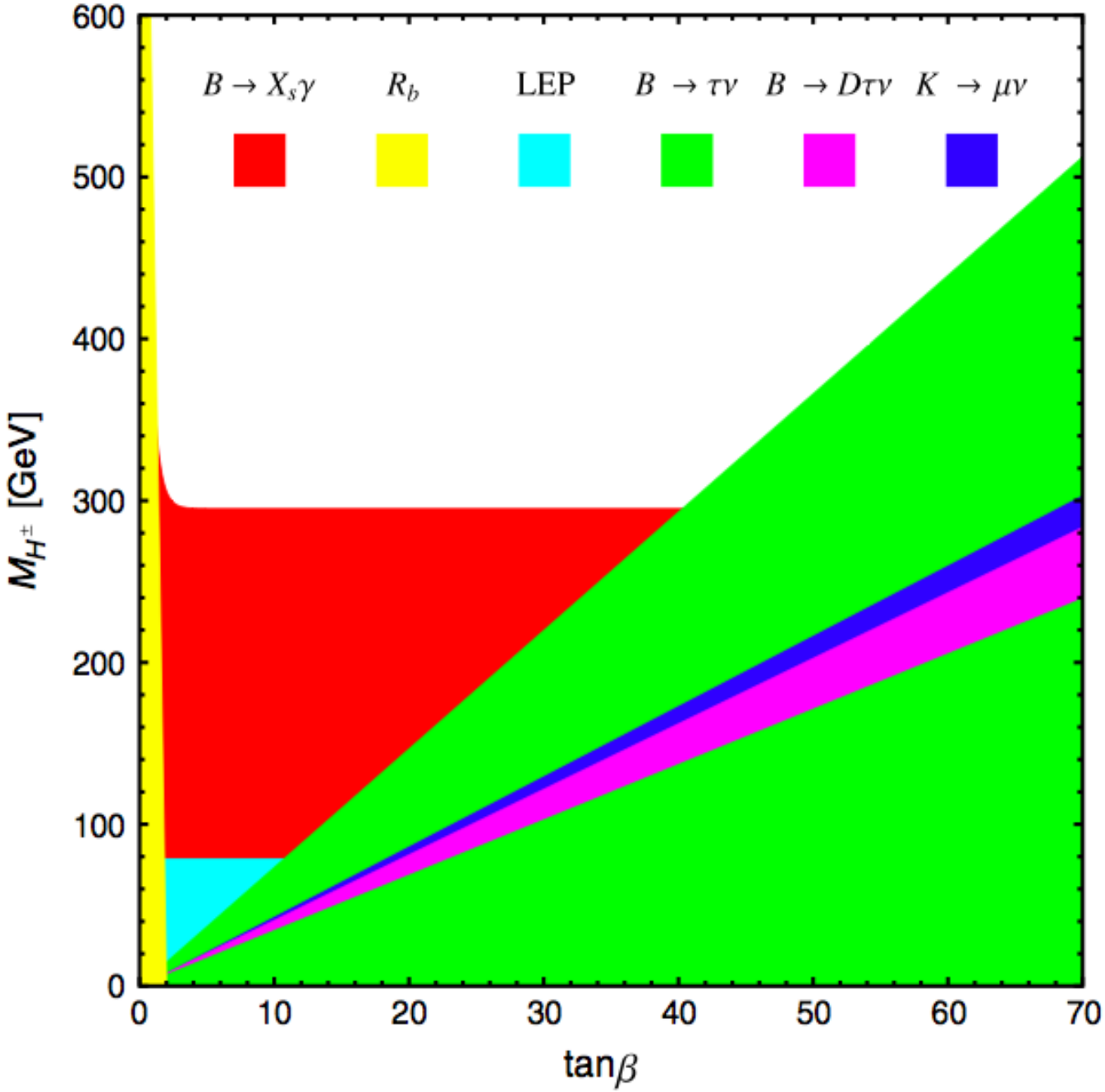
ATLAS JHEP03, 076 (2013)
CMS JHEP07, 143 (2012)

Direct search of

$t \rightarrow bH^+$

- $\tau\nu_\tau$ Large tanβ
- cs Small tanβ

B decays are <u>complementary</u> to LHC direct search!



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arXiv:0805.2141