

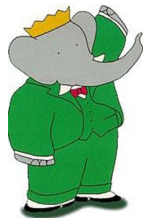
Review of B and B_s decays



Concezio Bozzi
INFN Ferrara



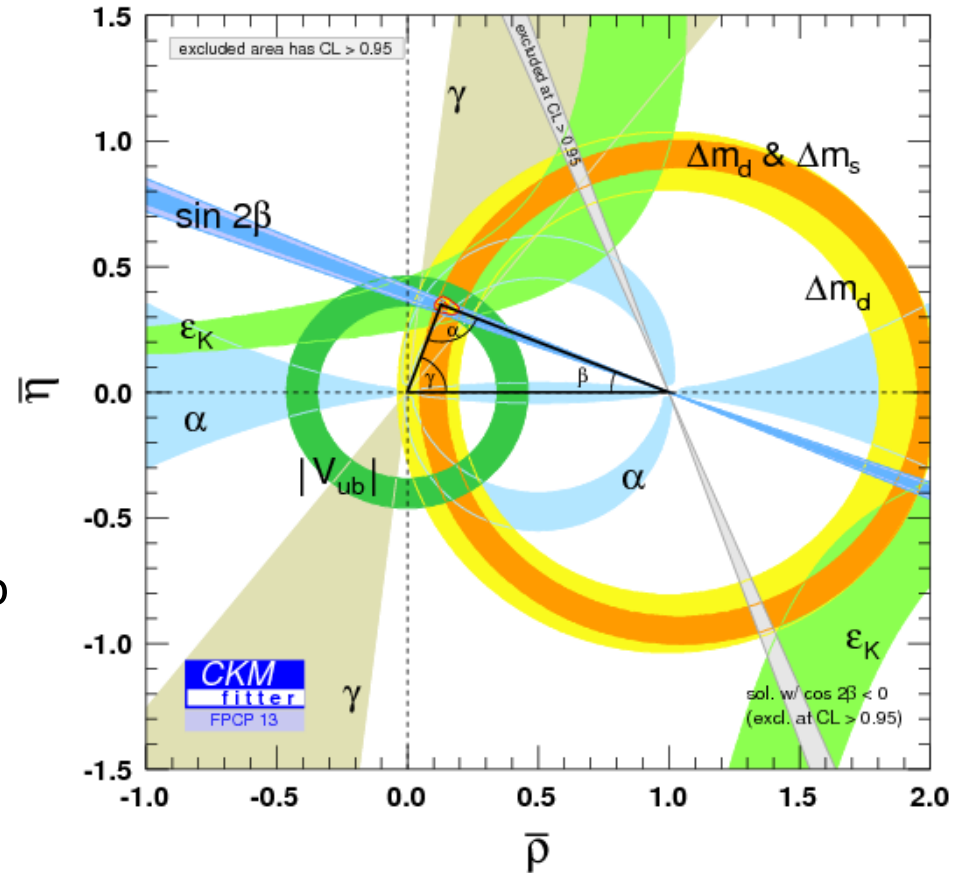
Ferrara, September 18th 2013



The relevance of $B_{(s)}$ decays

Test the **flavor sector of the SM**

- Single source of **CP violation** in **charged weak currents**
- Suppressions due to **hierarchy of CKM elements**
- Suppression of **flavor-changing neutral currents** (FCNC, loop only)
- Suppression of **chirality flips** due to small quark masses

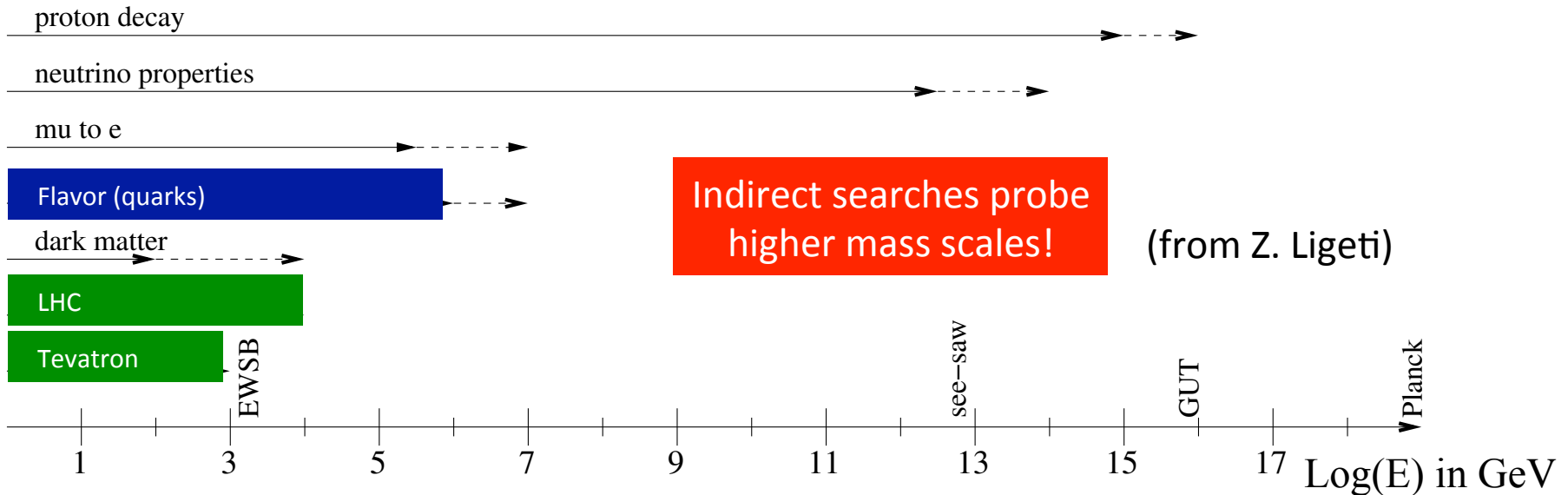
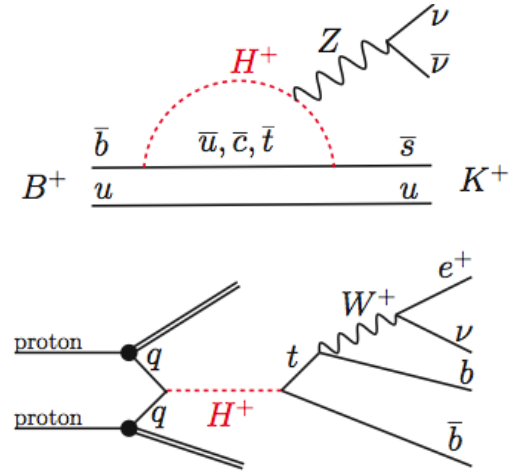


CKM unitarity triangle tested at the **few percent level!**

The relevance of $B_{(s)}$ decays

New physics **might not respect the many suppressions of the SM** :

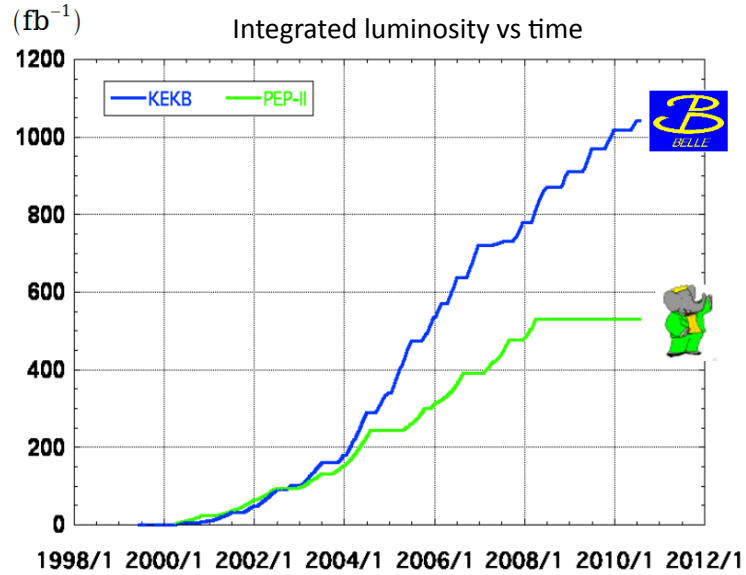
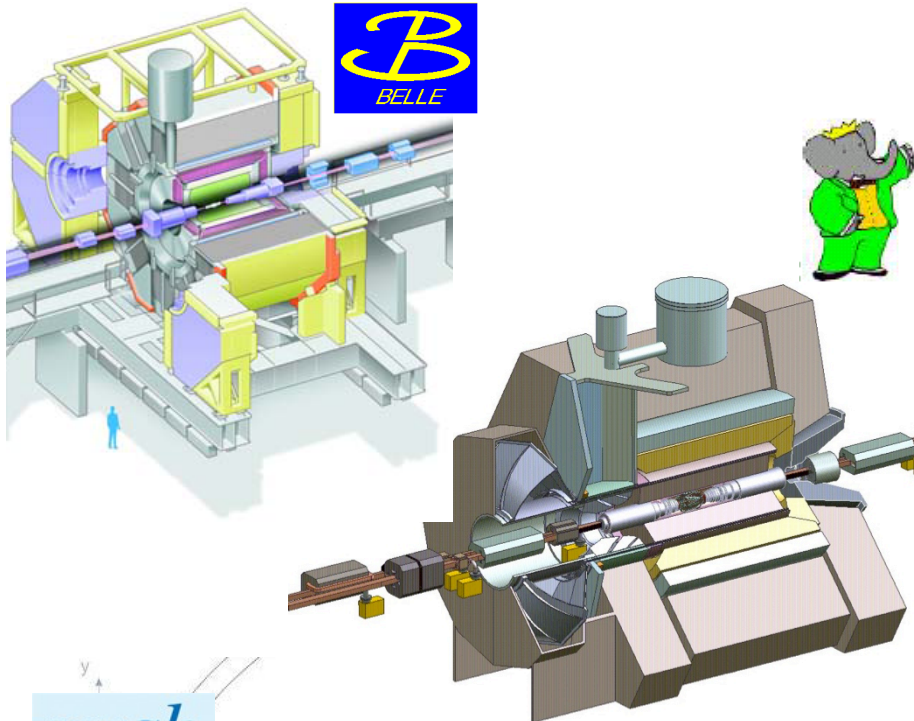
- Search for physics beyond SM in the **“quantum” way**: **increase luminosity** and look for **indirect effects** due to virtual particles
- complementary to the **“relativistic” way**: **increase energy** and look for **direct production** of new particles
- Experimental reach (with significant simplifying assumptions)



Outline

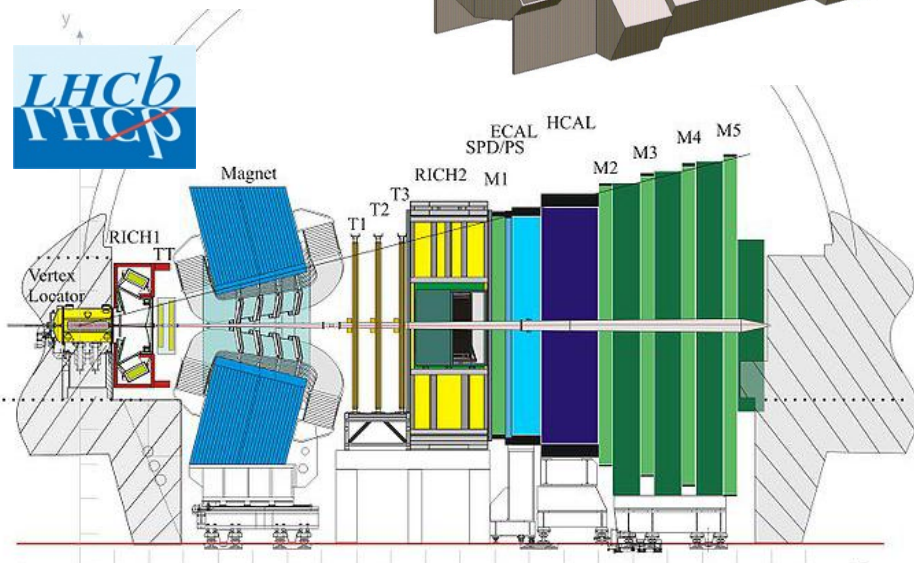
- The **experimental facilities**
- Radiative, electroweak and “Higgs” penguins
- Tree decays with τ leptons
- Conclusion

Experiments and data samples

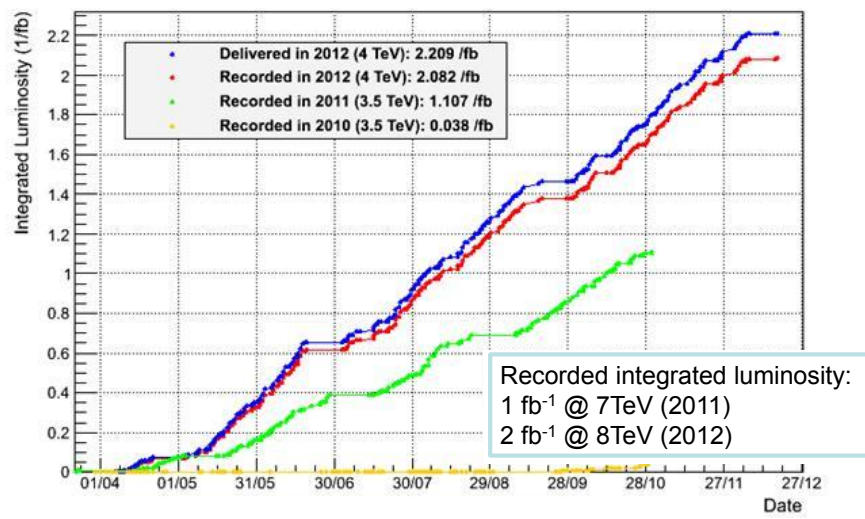


> 1 ab⁻¹
On resonance:
 Y(5S): 121 fb⁻¹
 Y(4S): 711 fb⁻¹
 Y(3S): 3 fb⁻¹
 Y(2S): 25 fb⁻¹
 Y(1S): 6 fb⁻¹
Off reson./scan:
 ~ 100 fb⁻¹

~ 550 fb⁻¹
On resonance:
 Y(4S): 433 fb⁻¹
 Y(3S): 30 fb⁻¹
 Y(2S): 14 fb⁻¹
Off resonance:
 ~ 54 fb⁻¹



LHCb Integrated Luminosity pp collisions 2010-2012



Recorded integrated luminosity:
 1 fb⁻¹ @ 7TeV (2011)
 2 fb⁻¹ @ 8TeV (2012)

Very different energies and rates

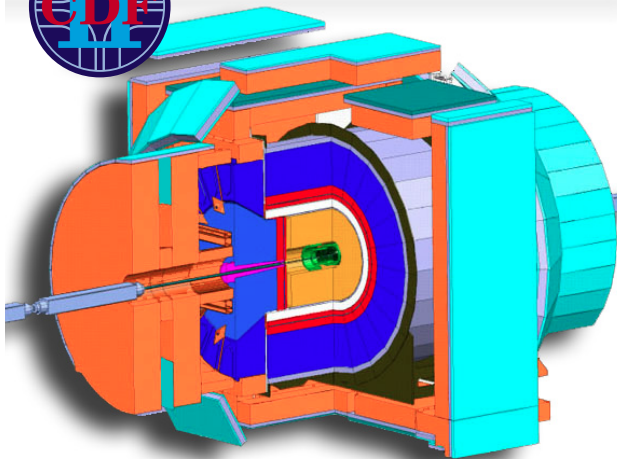
Experiment	Beams	cm Energy	Int. Lum	# Events	# Events	S/B
		[GeV]	[1/fb]	cc	bb	
BABAR/Belle	e ⁺ e ⁻	10.58	424+711	1.2 10 ⁹	~10 ⁹	0.25
LHCb	pp	7000 (8000)	1.0 (2.0)	2 10 ¹²	~10 ¹¹	~0.005



e⁺e⁻: initial state with well defined energy-momentum and quantum numbers
 simple events: exclusive 2-body or low multiplicity production
 full event reconstruction: B_tag and B_signal: full PID, $\pi^0 \rightarrow \gamma\gamma$ detection
 missing mass \rightarrow neutrino reconstruction!

pp: very high rates, all flavor mesons and baryons produced,
 high BG requires selective trigger, restricted acceptance
 long decay paths, precision charged particle tracking, PID
 complex events, normalization, relative rates! Many innovative techniques!

They play a role as well!



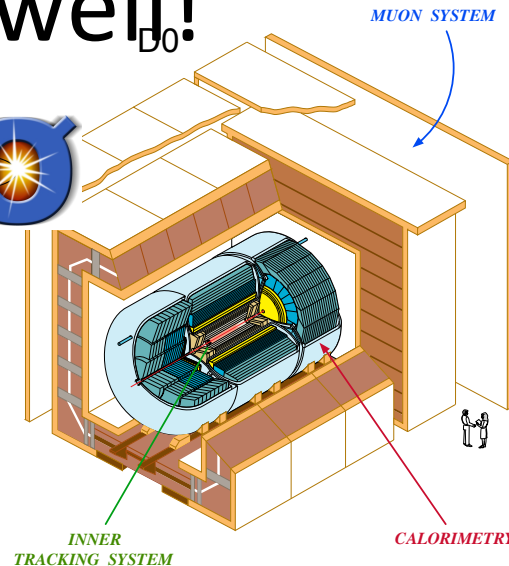
Large radius solenoid
Excellent tracking
Synchronous track trigger

$$\sqrt{s}_{\text{TeVatron}} = 2 \text{ TeV}$$

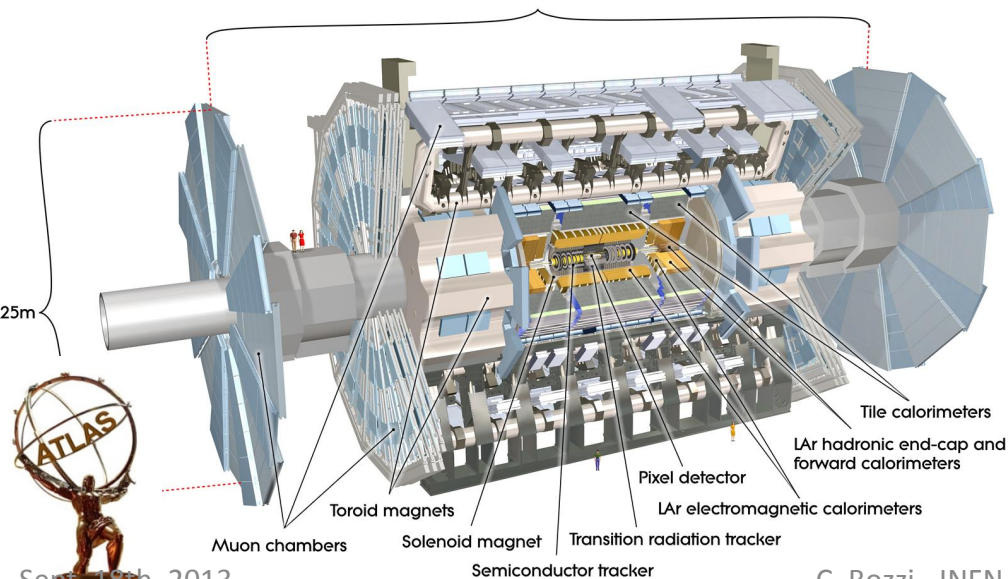
$$L_{\text{TeVatron}} \sim 10 \text{ /fb /exp}$$

$$\sqrt{s}_{\text{LHC}} = 7-8 \text{ TeV}$$

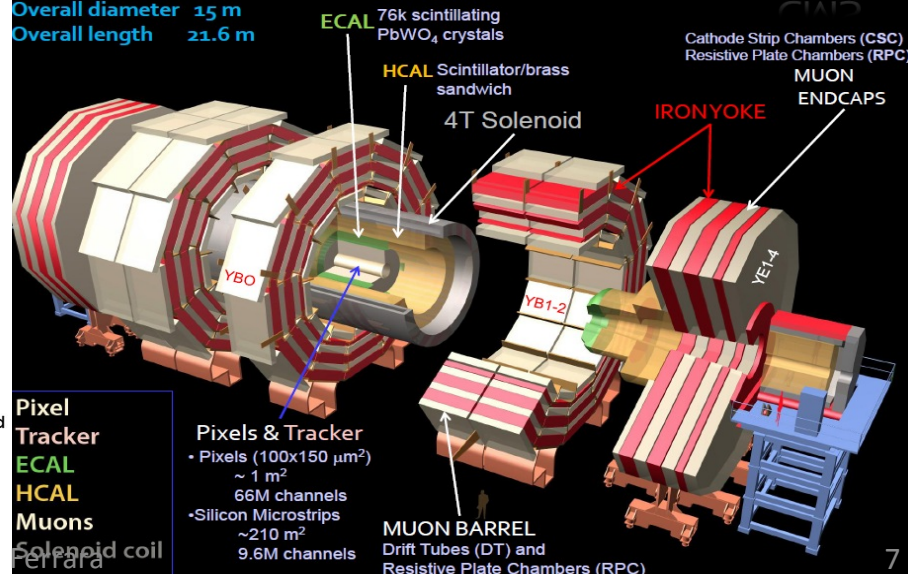
$$L_{\text{LHC}} \sim 25 \text{ /fb /exp}$$



Large muon coverage $|\eta| < 2$
Strong B field (possibility of switching polarities)
highly segmented hadron calorimeter



Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m



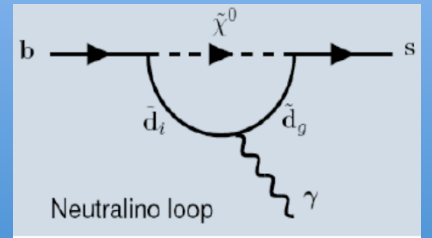
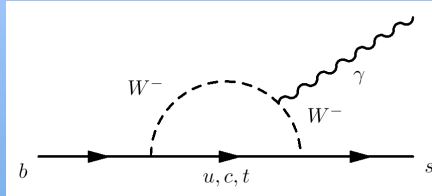


Penguin processes

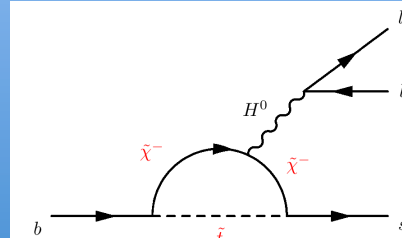
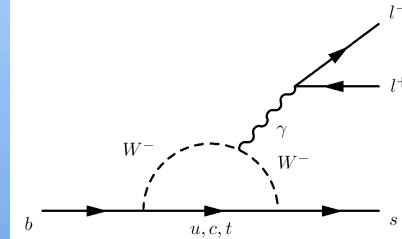
SM

SUSY

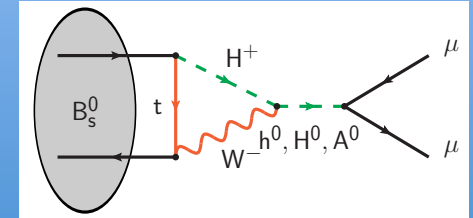
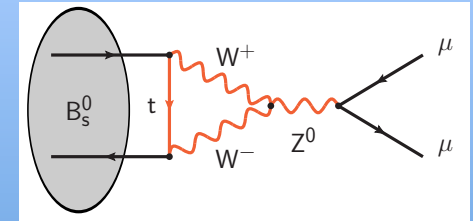
Radiative



Electroweak



“Higgs”



Typical BR (SM)

$10^{-5} - 10^{-4}$

10^{-6}

10^{-9}

Observables

Br, γ polarization

Angular distributions

Branching ratios

Lorentz structure

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu)]$$

Left-handed part
Right-handed part
Suppressed in SM

- $i=1,2$ Tree
- $i=3-6,8$ Gluon penguin
- $i=7$ Photon penguin
- $i=9,10$ EW penguin
- $i=S(P)$ (Pseudo)scalar penguin

Relevant operators

$$O_7 \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

$$O_9 \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \ell$$

$$O_S \sim \bar{s}_L b_R \bar{\ell} \ell$$

$$O_{10} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \gamma_5 \ell$$

$$O_P \sim \bar{s}_L b_R \bar{\ell} \gamma_5 \ell$$

$B \rightarrow X_s \gamma$

- The inclusive decay has been **precisely measured at B Factories**

$$Br(b \rightarrow s\gamma) = (3.43 \pm 0.22) \times 10^{-4}$$

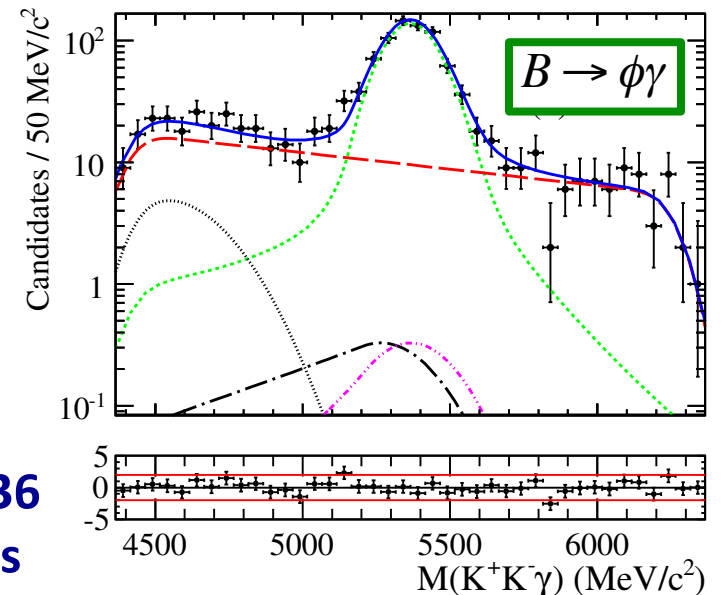
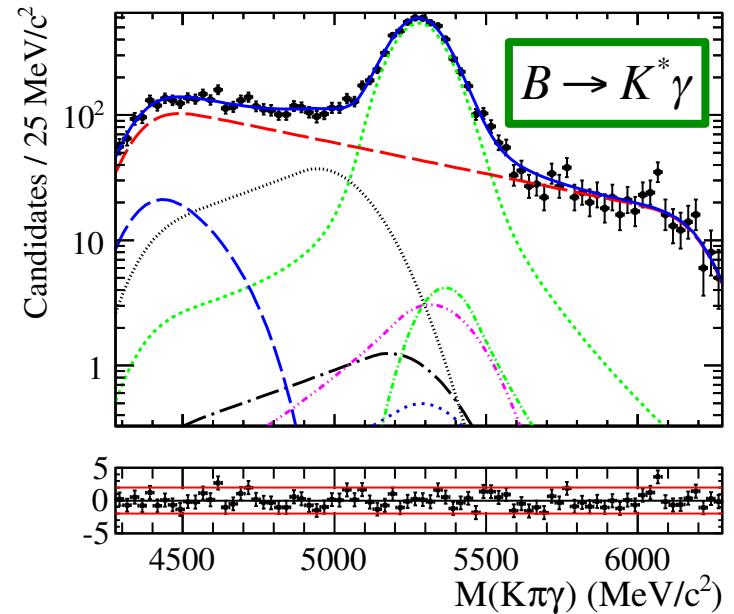
in agreement with the SM prediction

$$Br_{SM}(b \rightarrow s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

- One of the **strongest constraint in MSSM**. Given the Higgs mass, only **O(%) of the a-priory phase space left!**
- Many **exclusive modes** studied as well
- At hadron colliders, **measure exclusive decays to keep background at manageable level**
- LHCb performed **first measurements in the B_s system**

$$Br(B_s \rightarrow \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}$$

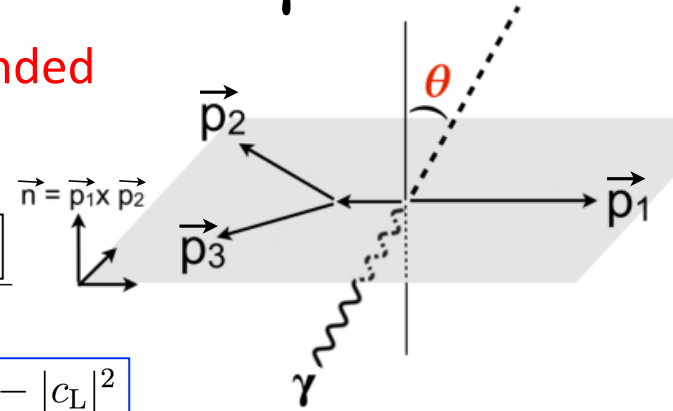
**691 ± 36
events**



Photon polarization in $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

- In SM, emitted photons are **predominantly left-handed**
- Measure **up-down asymmetry** in $K_{res} \rightarrow K\pi\pi$ decays

$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 d\cos\theta \tilde{\theta} \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \tilde{\theta} \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \tilde{\theta} \frac{d\Gamma}{d\cos\theta}} = \frac{3}{4} \lambda_\gamma \frac{\int ds ds_{13} ds_{23} \text{Im} [\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)]}{\int ds ds_{13} ds_{23} |\mathcal{J}|^2}$$



For a single intermediate resonance, A is proportional to the photon polarization

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

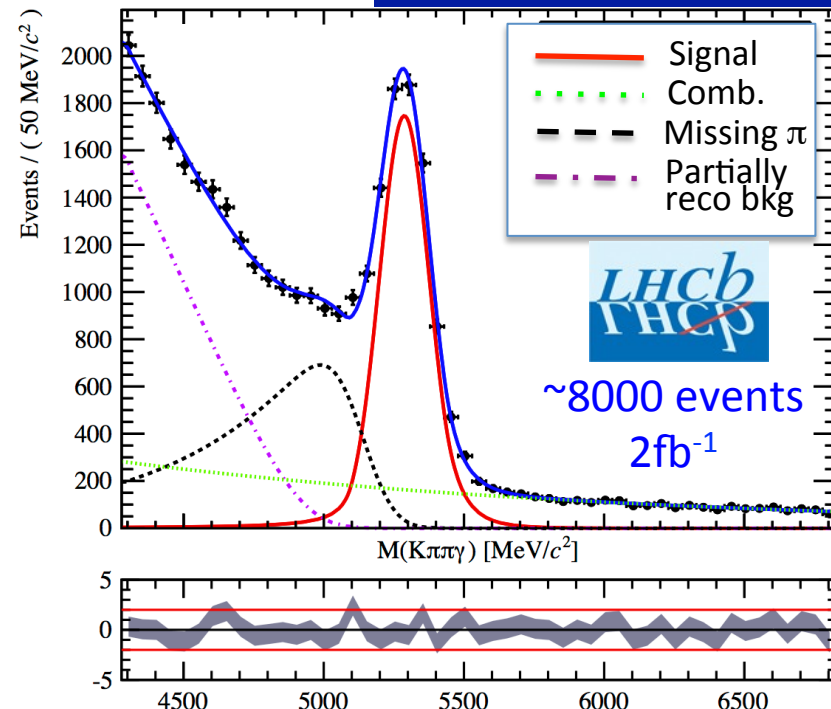
First measurement on a mixture of K resonances

$$\mathcal{A}_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.004 \text{ (syst)}$$

- Evidence for photon polarization in $b \rightarrow s \gamma$ decays at 4.6σ
- Difficult interpretation due to multiple resonances. If **theoretical prediction existed**, first measurement of λ_γ would be possible
- Also, 1st measurement of **CP asymmetry**

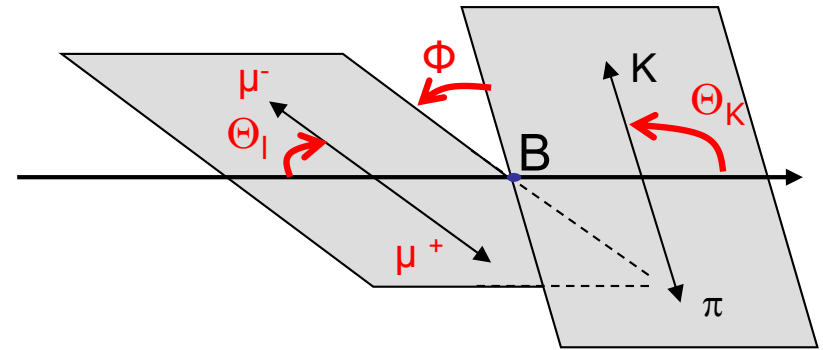
$$\mathcal{A}_{CP} = -0.007 \pm 0.015 \text{ (stat)}_{-0.011}^{+0.012} \text{ (syst)}$$

LHCb-CONF-2013-009



The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

- $B \rightarrow K^* \mu \mu$ is described by 3 angles and di-muon invariant mass squared q^2
- Number of free parameters can be reduced by folding the ϕ angle (if $\phi < 0$, $\phi = \phi + \pi$):



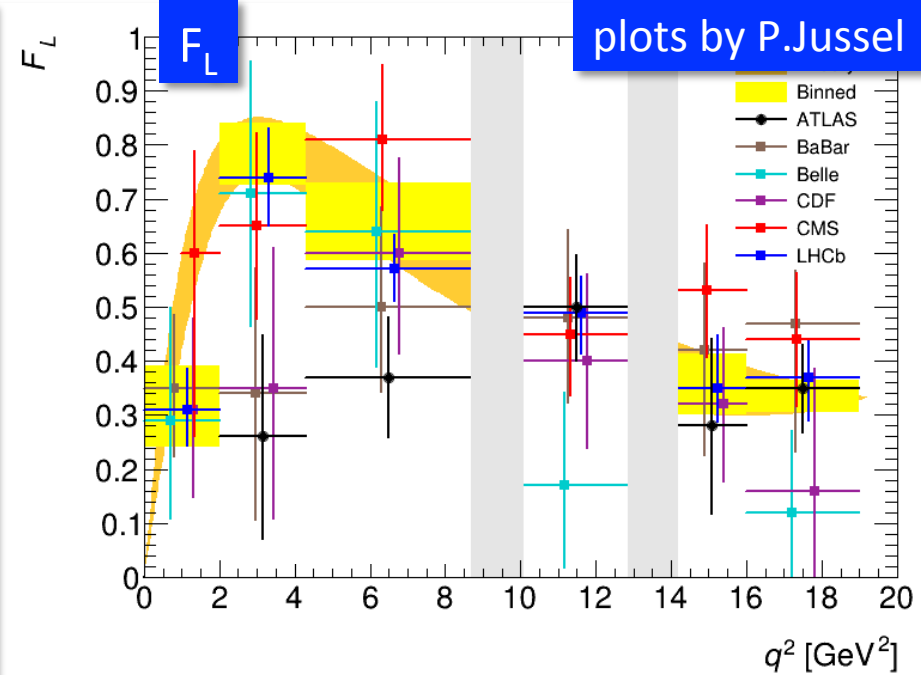
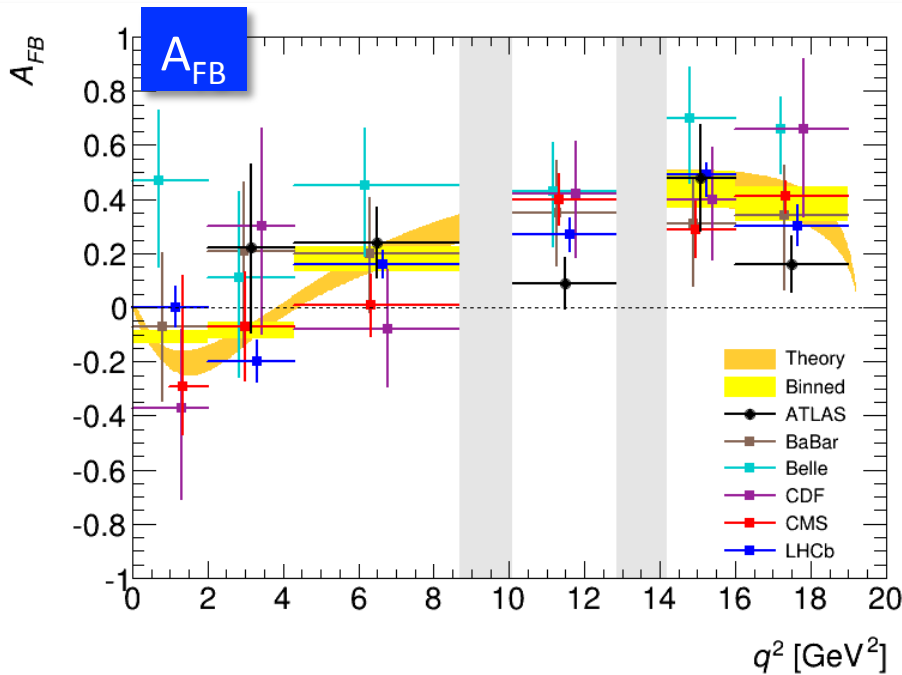
$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell d \cos \theta_K d \hat{\phi}} = \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ \left. + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \right. \\ \left. + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\hat{\phi} + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell \right. \\ \left. + 2\theta_K \sin 2\theta_\ell \sin \hat{\phi} + A_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\hat{\phi} \right]$$

A_{FB}
 forward-backward
 asymmetry
 F_L
 fraction of K^{*0}
 longitudinally polarized
 S_3
 asymmetry in K^{*0}
 transverse polarization
 A_9
 T-odd CP

Observables in blue are functions of Wilson coefficients and form factors. They depend on q^2

A_{FB} zero crossing point precisely predicted in SM: $q_0^2 = (4.36_{-0.31}^{+0.33}) GeV^2 / c^4$

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ is a hot topic!



- Results from      
- A lot of other channels being studied as well, e.g.

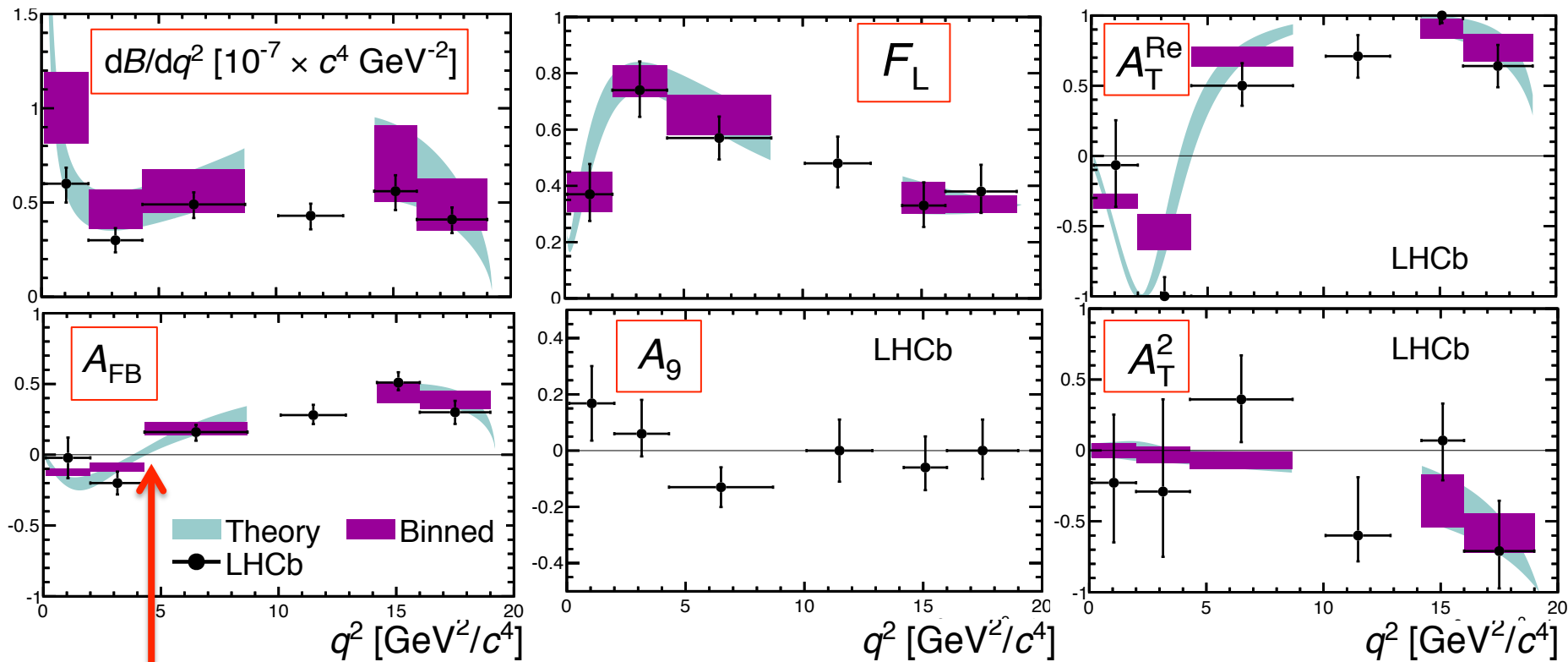
$$B_d \rightarrow K^{*0} e^+ e^-, B^+ \rightarrow K^+ \mu^+ \mu^-, B_s \rightarrow \phi \mu^+ \mu^-, \Lambda_b \rightarrow \Lambda \mu^+ \mu^-, \dots$$

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: results

Theoretically cleaner observables (reduced form factor uncertainties) can be calculated from the existing ones

$$A_T^{\text{Re}} = \frac{\frac{4}{3} A_{\text{FB}}}{(1 - F_L)} \quad A_T^2 = \frac{2S_3}{(1 - F_L)}$$

Theory from Bobeth-Hiller-Van Dyk (2011), consistent with Matias et al (2013)



Good agreement with SM predictions
 First measurement of A_{FB} zero crossing point :

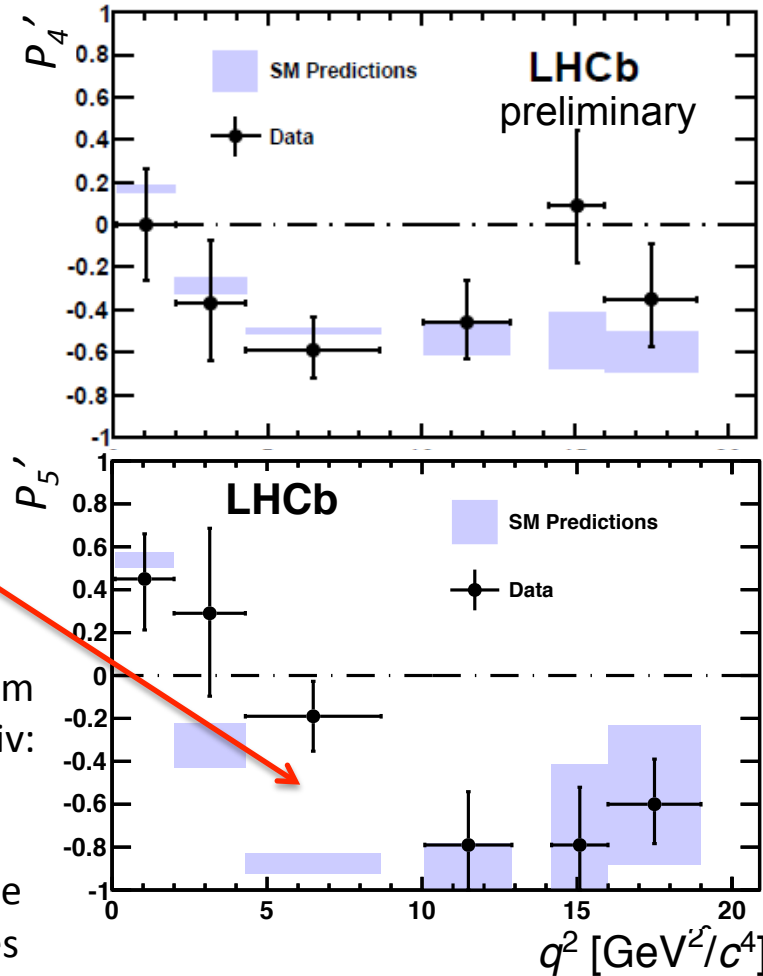
$$q_0^2 = (4.9 \pm 0.9) \text{ GeV}^2 / c^4$$

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: new observables

- Observables with **limited dependence on form-factors uncertainty** at low q^2 have been proposed by several theorists
- Different set of observables give different constraints \Rightarrow **complementarity!**

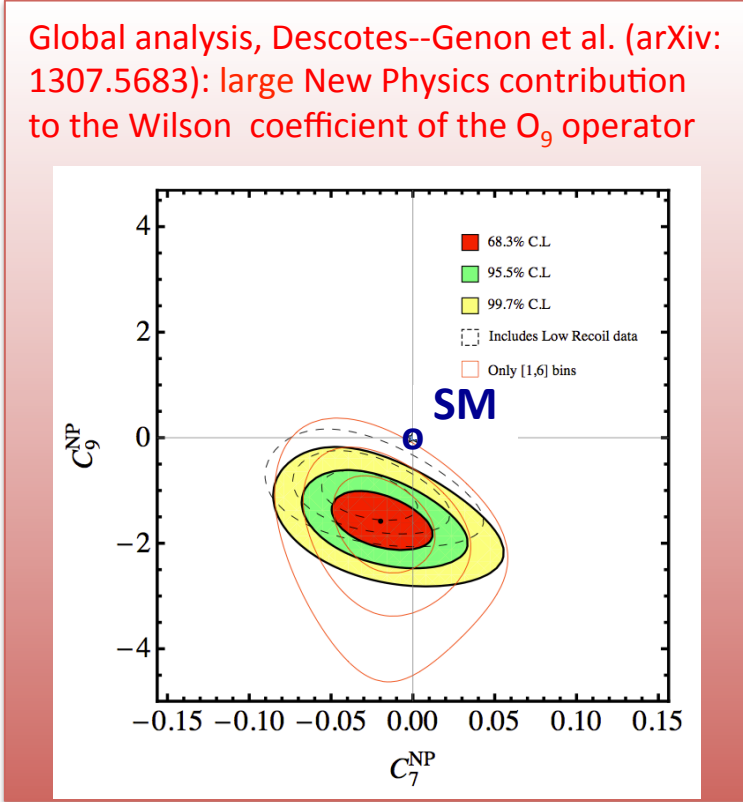
Good agreement for some observables

some local discrepancies for others



3.7 σ

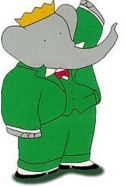
SM predictions from J. Matias et al, arXiv: 1303.5794. Jaeger et al., JHEP 05 43 (2013), quote larger uncertainties



No definitive conclusion. More data and theoretical studies needed

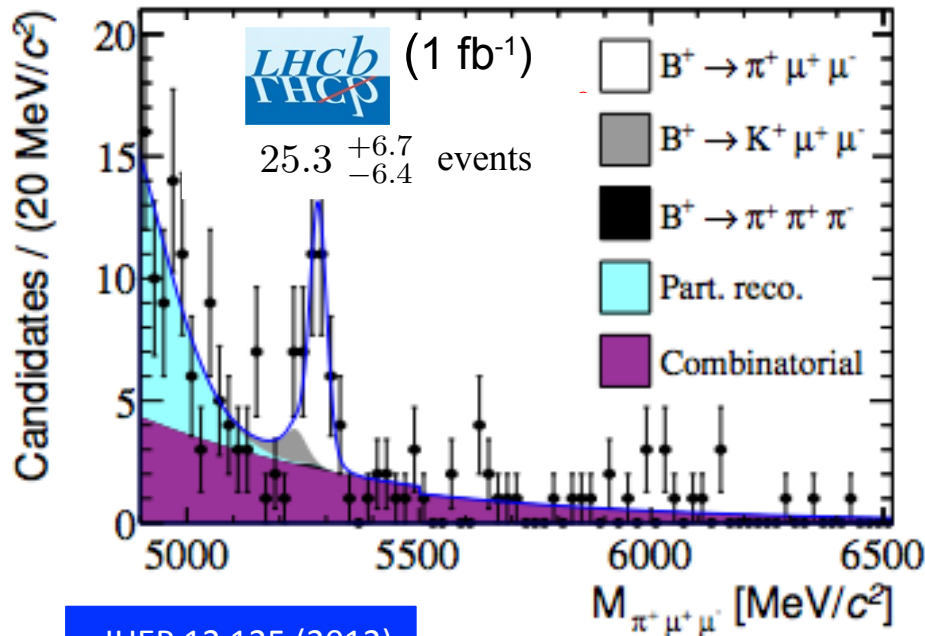
B → h_dll decays

Cabibbo-suppressed version of B → h_sll, rate a factor ~25 lower



B⁺ → π⁺μ⁺μ⁻ observed at 5.2σ in LHCb

Upper limits by Babar



Mode	\mathcal{B} (10^{-8})	Upper limit (10^{-8})
$B^+ \rightarrow \pi^+ e^+ e^-$	$4.3^{+5.9}_{-4.7} \pm 2.0$	12.5
$B^0 \rightarrow \pi^0 e^+ e^-$	$1.2^{+5.4}_{-4.0} \pm 0.2$	8.4
$B^0 \rightarrow \eta e^+ e^-$	$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$	$-0.6^{+4.4}_{-3.2} \pm 0.9$	5.5
$B^0 \rightarrow \pi^0 \mu^+ \mu^-$	$-0.3^{+5.3}_{-3.6} \pm 0.6$	6.9
$B^0 \rightarrow \eta \mu^+ \mu^-$	$-2.0^{+9.7}_{-6.6} \pm 0.4$	11.2
$B \rightarrow \pi e^+ e^-$	$4.0^{+5.1}_{-4.2} \pm 1.6$	11.0
$B \rightarrow \pi \mu^+ \mu^-$	$-0.7^{+4.1}_{-3.1} \pm 1.2$	5.0
$B^+ \rightarrow \pi^+ l^+ l^-$	$1.6^{+3.6}_{-3.0} \pm 1.2$	6.6
$B^0 \rightarrow \pi^0 l^+ l^-$	$0.5^{+3.6}_{-2.9} \pm 0.3$	5.3
$B \rightarrow \pi l^+ l^-$	$1.6^{+3.2}_{-2.7} \pm 1.0$	6.4
$B^0 \rightarrow \eta l^+ l^-$	$-2.8^{+6.6}_{-5.2} \pm 0.3$	5.9

Best Limits to date
First ever limits

JHEP 12 125 (2012)

$$Br(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.4 \pm 0.6_{stat} \pm 0.2_{syst}) \times 10^{-8}$$

arXiv:1303:6010, acc. by PRD

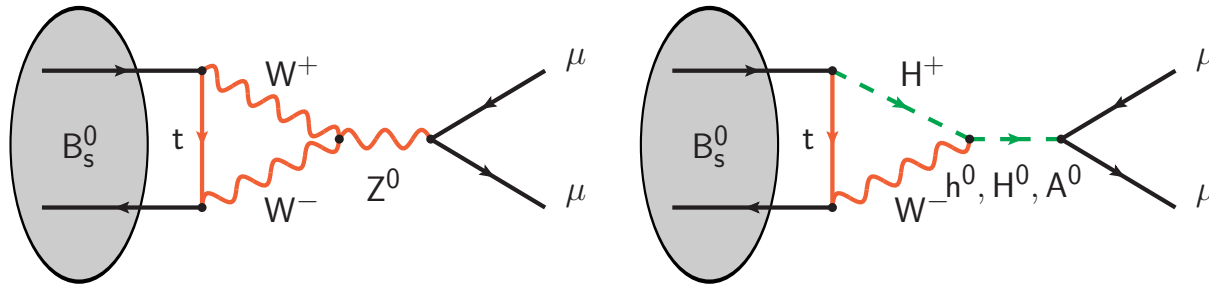
SM expected rates (excluding charmonium):

$$\mathcal{B}(B^+ \rightarrow \pi^+ l^+ l^-) = (1.96 - 3.30) \times 10^{-8}$$

$$\mathcal{B}(B^0 \rightarrow \eta l^+ l^-) = (2.5 - 3.7) \times 10^{-8}$$

Aliev & Savci, PRD 60, 014005 (1999)
Erkol & Turan, Eur. Phys. Jour. C 28, 243 (2003)

$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$



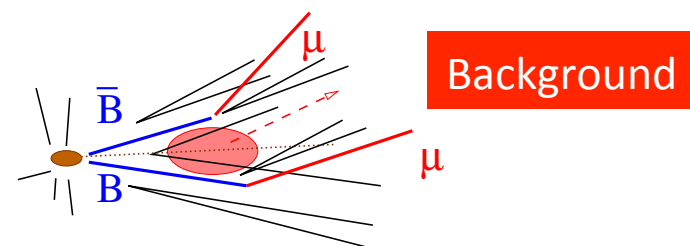
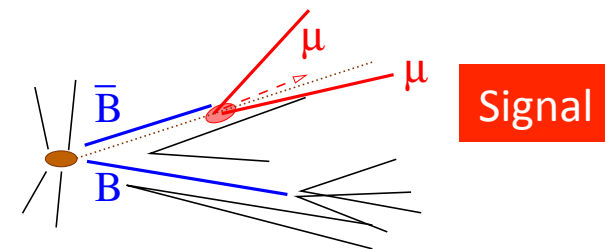
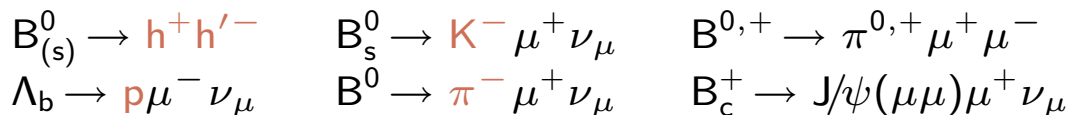
$$\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+ \mu^-) \propto \left(1 - \frac{4m_\mu^2}{m_B^2}\right) |C_S - C'_S|^2 + \left| (C_P - C'_P) + 2 \frac{m_\mu}{m_B^2} (C_{10} - C'_{10}) \right|^2$$

- Rare in SM: FCNC process, helicity suppressed
- Sensitive to scalar and pseudoscalar NP contributions
- Precise SM prediction [Buras et al., 2012]
- Time-integrated Br [Bruyn et al., 2012], with γ_s and $A_{\Delta\Gamma}$ from HFAG:

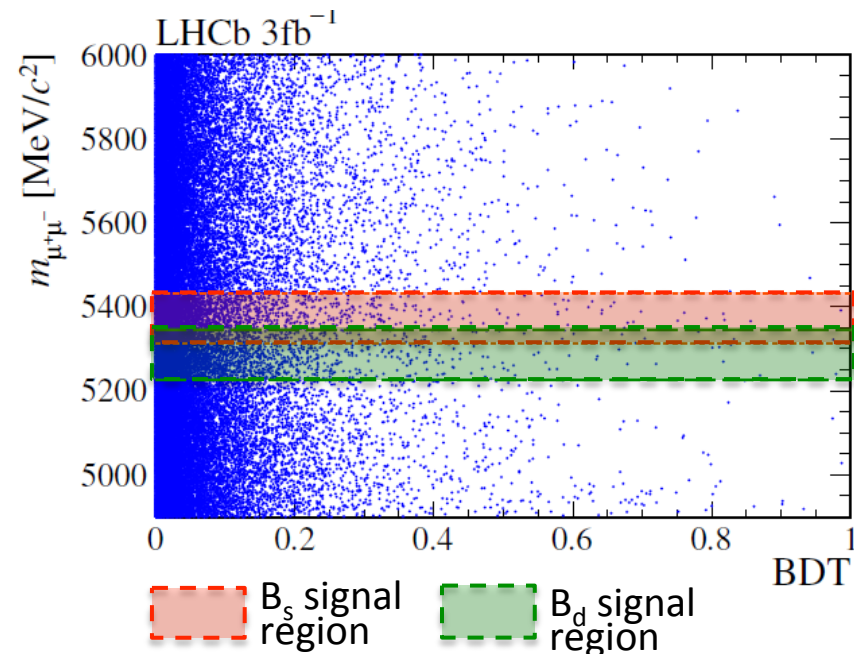
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$\stackrel{\text{SM}}{=}$	$(3.56 \pm 0.30) \times 10^{-9}$
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	$\stackrel{\text{SM}}{=}$	$(1.07 \pm 0.10) \times 10^{-10}$

$B^0_{(s)} \rightarrow \mu^+ \mu^-$: analysis strategy

- Huge combinatorial background
- Partially reconstructed decays and particle mis-ID



- Signal to background discrimination:
 - **Loose** event selection
 - classification in the plane $m_{\mu\mu} \times \text{BDT}$ based on geometry and kinematics
- Background PDFs obtained with **data driven methods**
- BF measurement: **simultaneous fit to $m_{\mu\mu}$ in BDT bins (LHCb) or categories (CMS)**
- Upper limits: CLs

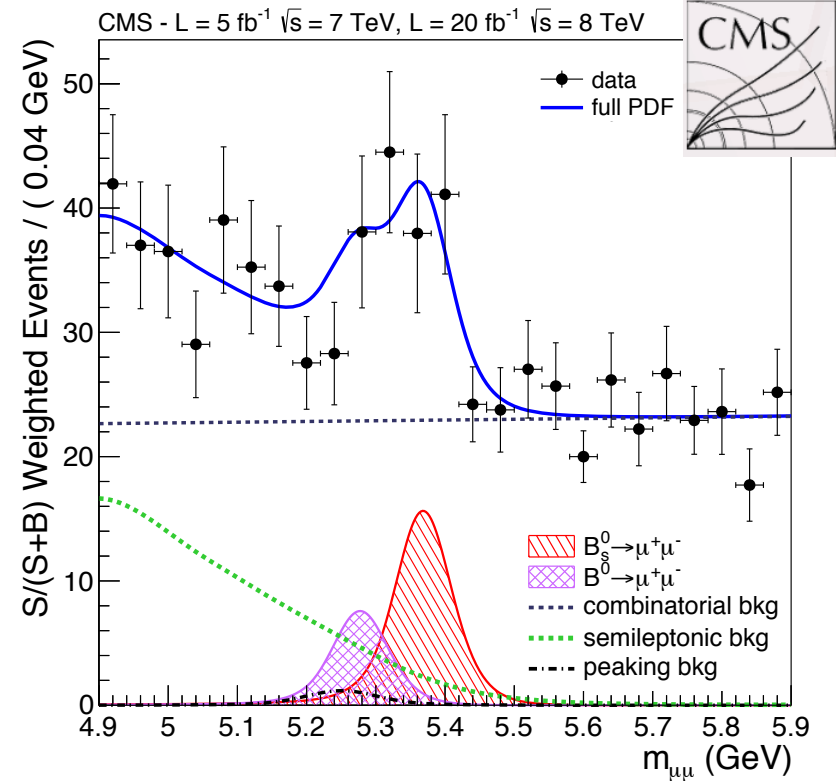
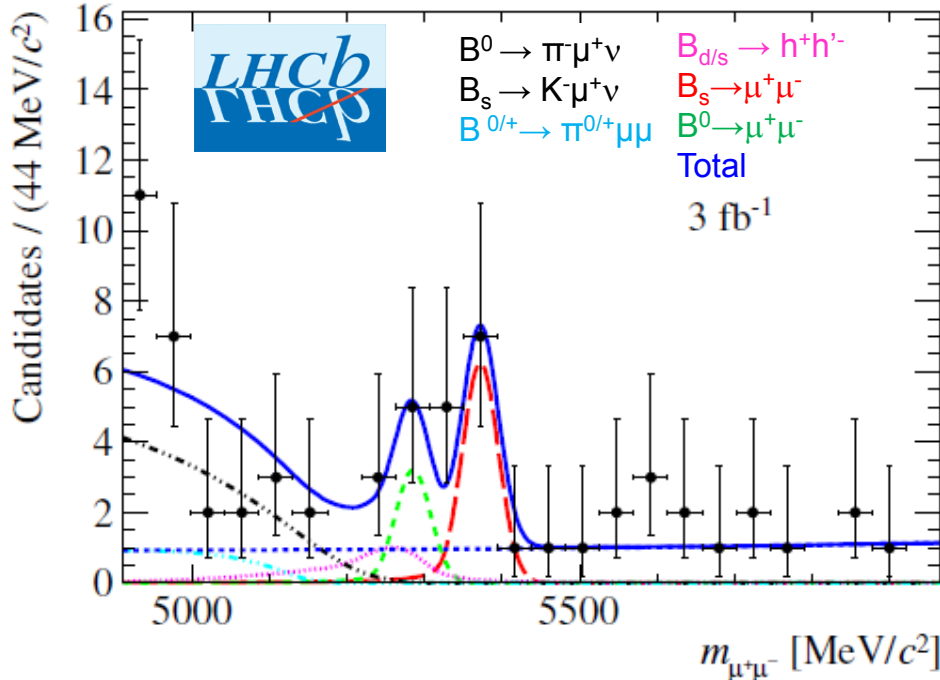


$B^0_{(s)} \rightarrow \mu^+ \mu^-$: results

PRL 111 (2013) 101804

PRL 111 (2013) 101805

BDT > 0.7



$$Br(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9} \quad 4.0\sigma$$

$$Br(B_d^0 \rightarrow \mu^+ \mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10} \quad 2.0\sigma$$

$< 7.4 \times 10^{-10}$ at 95% CL



$$(3.0^{+1.0}_{-0.9}) \times 10^{-9} \quad 4.3\sigma$$

$$(3.5^{+2.1}_{-1.8}) \times 10^{-10} \quad 2.0\sigma$$

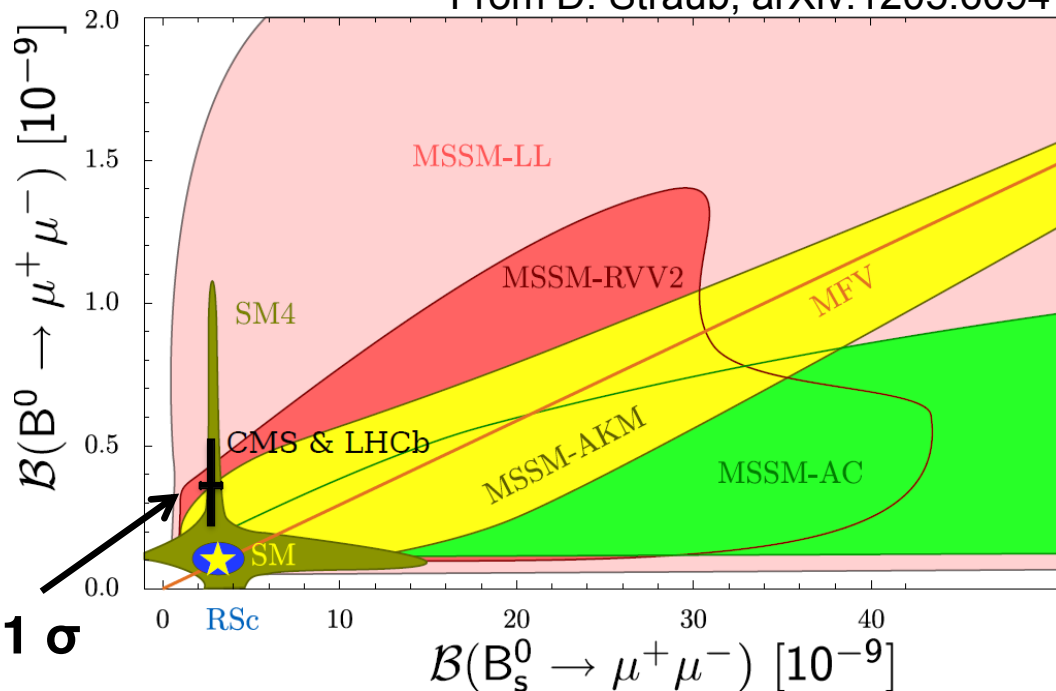
$< 1.1 \times 10^{-9}$ 95%CL

$B^0_{(s)} \rightarrow \mu^+ \mu^-$: implications

Weighed B Average (not Likelihood Combination)

			Significance
$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)$	$\underline{\underline{\text{LHC}}}$	$(2.9 \pm 0.7) \times 10^{-9}$	$> 5\sigma$
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	$\underline{\underline{\text{LHC}}}$	$(3.6^{+1.6}_{-1.4}) \times 10^{-10}$	$> 3\sigma$
$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)$	$\underline{\underline{\text{SM}}}$	$(3.56 \pm 0.30) \times 10^{-9}$	
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	$\underline{\underline{\text{SM}}}$	$(1.07 \pm 0.10) \times 10^{-10}$	

From D. Straub, arXiv:1205.6094

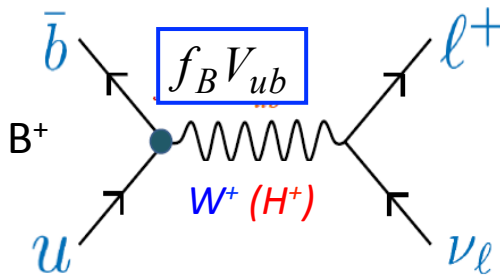


- MFV: Minimal Flavour Violation models
- SM4: SM with a fourth generation
- RSc: Randall-Sundrum model with custodial protection [Blanke et al., 2009]
- MSSM: Minimal SUSY flavour models
 - AC: Agashe and Carone [Agashe and Carone, 2003]
 - RVV2: Ross, Velasco-Sevilla and Vives [Ross et al., 2004]
 - AKM10: Antusch, King and Malinsky [Antusch et al., 2008]
 - LL11: left-handed currents only [Hall & Murayama, 1995]

(semi) leptonic decays with τ leptons

- $B \rightarrow \tau \nu$ and $B \rightarrow D^{(*)} \tau \nu$ are tree level decays mediated by a W in SM
- Lepton universality in SM, might be broken by mass-dependent couplings
- Probe SM extensions to models with enlarged Higgs sector, e.g. 2-Higgs Doublet Model (2HDM) of MSSM

$B \rightarrow \tau \nu$

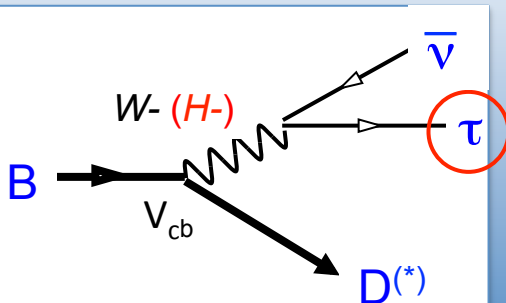


$$\mathcal{B}(B^- \rightarrow \ell^- \bar{\nu}) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \underbrace{f_B^2 |V_{ub}|^2}_{\text{SM}} \tau_B \underbrace{\left(1 - \tan^2 \beta \frac{m_{B^\pm}^2}{m_{H^\pm}^2}\right)}_{\text{Charged Higgs}}$$

SM expectation: $\mathcal{B}(B \rightarrow \tau^- \bar{\nu}_\tau)_{SM} = 1.01 \pm 0.29 \times 10^{-4}$

Based on average of incl. and excl. V_{ub}, f_B from Na et al., 2012

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



Decays involving τ have additional helicity amplitude
 Contribution from H^\pm expected to enhance rates for $B \rightarrow D^{(*)} \tau \nu$
 Test SM by measuring ratios (theoretically and experimentally cleaner)

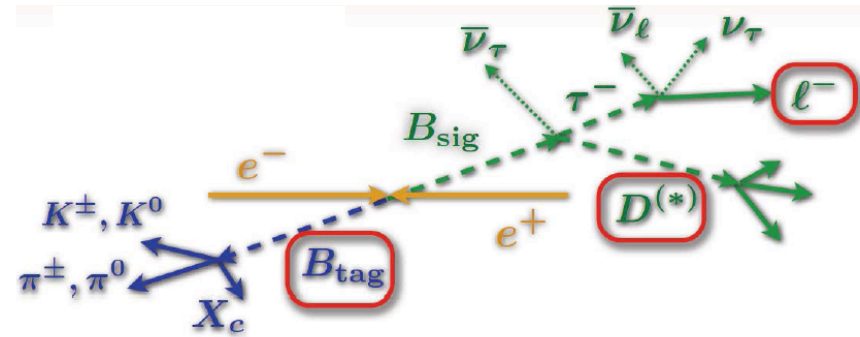
$$R(D) = \frac{\Gamma(\bar{B} \rightarrow D \tau \nu)}{\Gamma(\bar{B} \rightarrow D \ell \nu)} \quad R(D^*) = \frac{\Gamma(\bar{B} \rightarrow D^* \tau \nu)}{\Gamma(\bar{B} \rightarrow D^* \ell \nu)}$$

SM: $R(D) = 0.297 \pm 0.017$ $R(D^*) = 0.252 \pm 0.003$

Based on S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012)

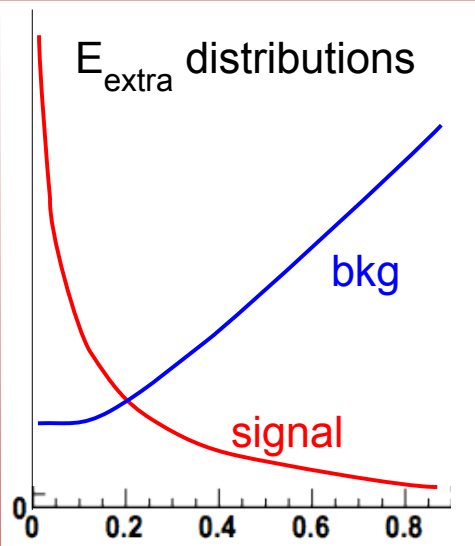
(semi) leptonic decays with taus

- Due to the presence of **at least two neutrinos** in the final state, B Factories offer **the most favorable experimental environment**
- BB events are **fully reconstructed**
 - One B decay is fully reconstructed (hadronic or semileptonic tag)
 - Look for signal decay of 2nd B meson
- Discriminating variables



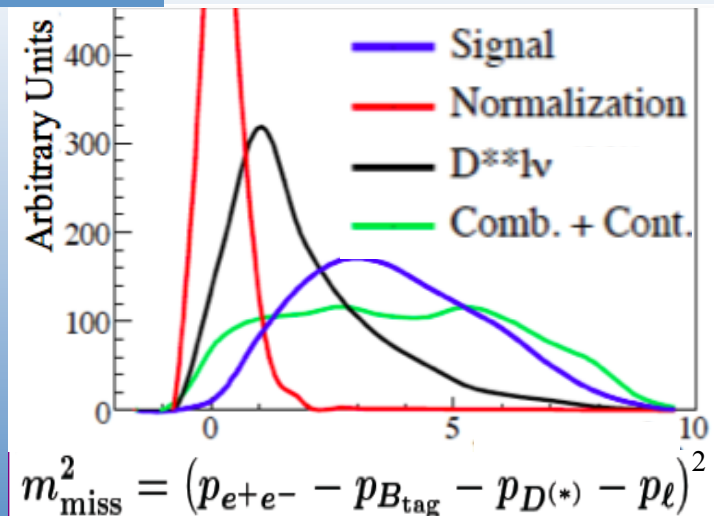
$B \rightarrow \tau \nu$

E_{extra} : sum of calorimeter energy not associated with signal or tag



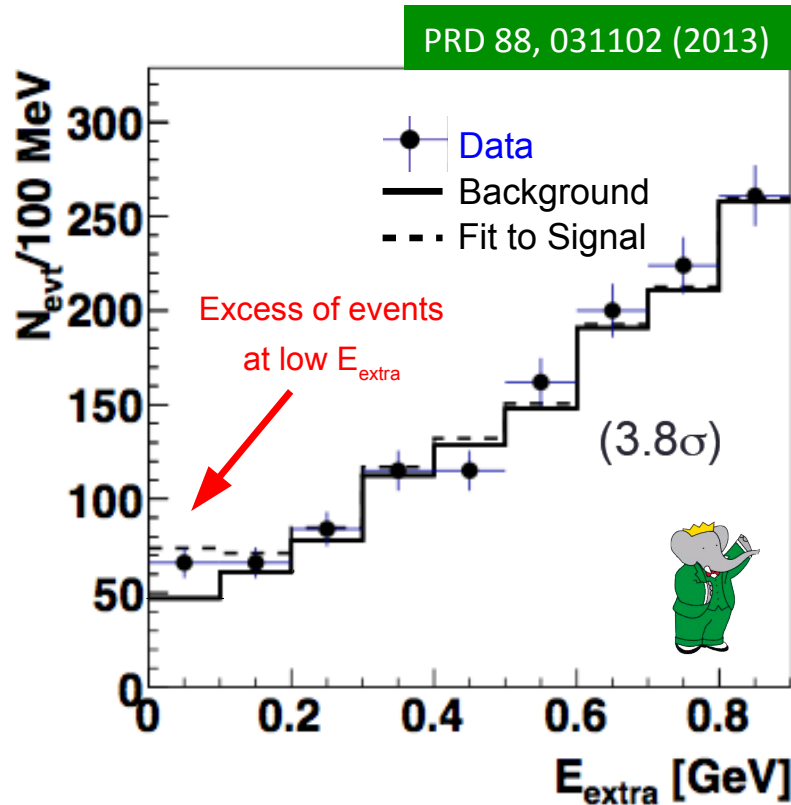
$B \rightarrow D^{(*)} \tau \nu$

Squared missing mass



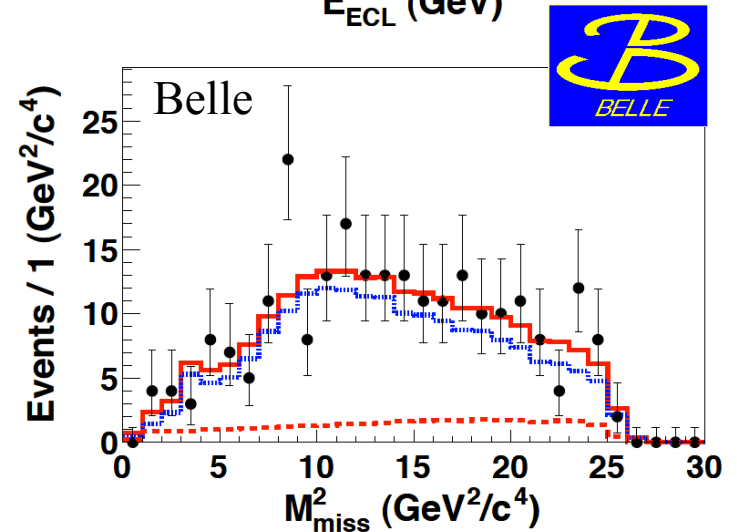
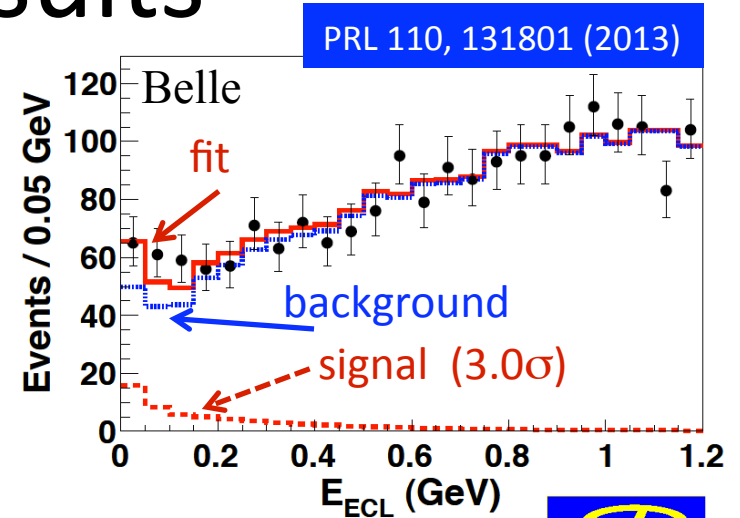
$$m_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_{\ell})^2$$

$B^+ \rightarrow \tau^+ \nu$: results



62.1 ± 17.3 events, 426 fb^{-1}

$$Br(B \rightarrow \tau \nu) = [1.83^{+0.53}_{-0.49} \pm 0.24] \times 10^{-4}$$



$62.3^{+23.1}_{-21.7}$ events, 711 fb^{-1}

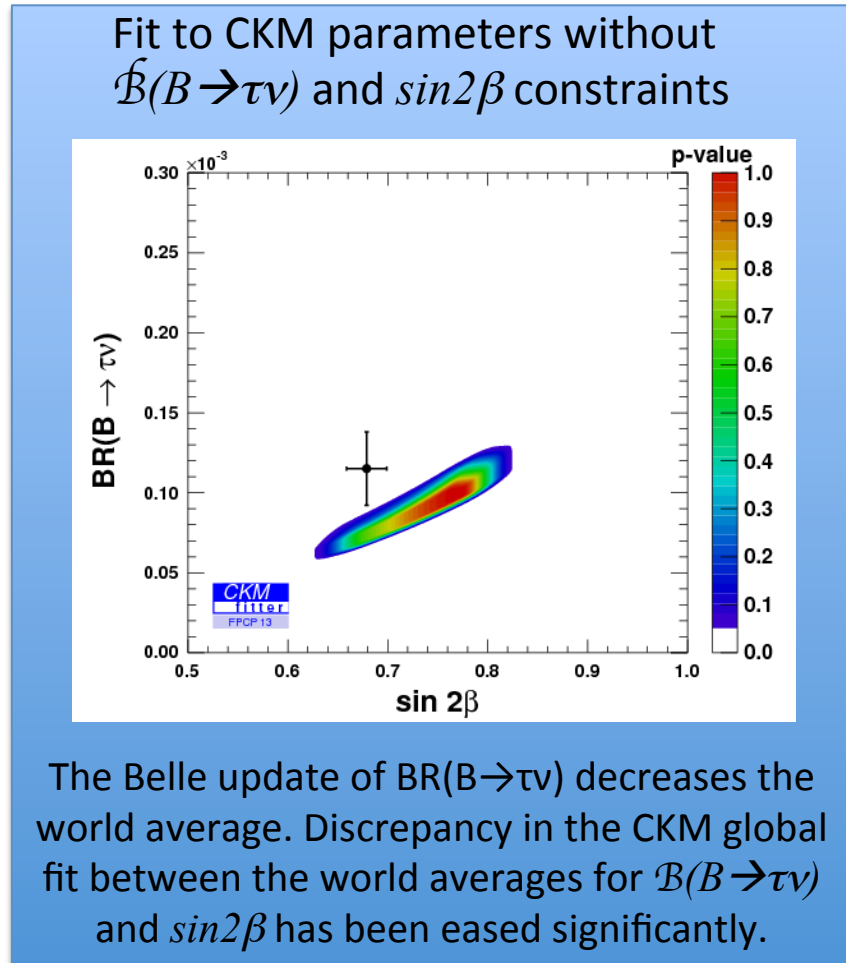
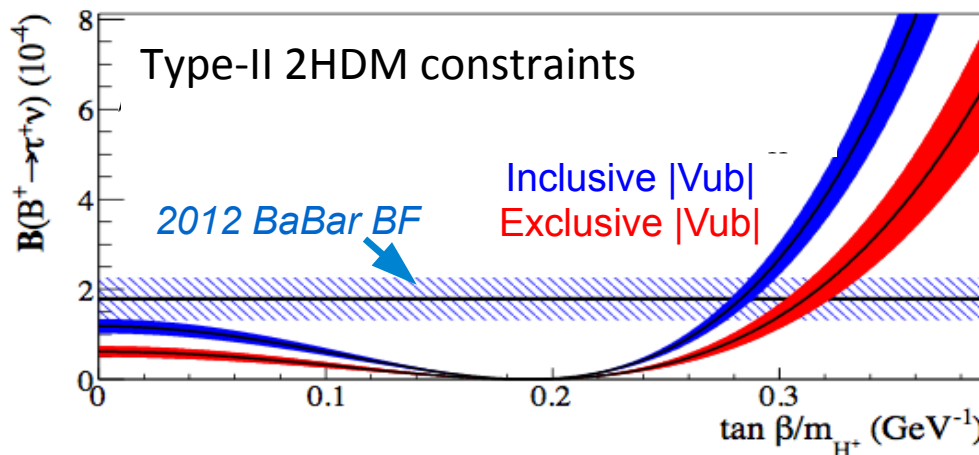
$$Br(B \rightarrow \tau \nu) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$$

$B^+ \rightarrow \tau^+ \nu$: interpretation

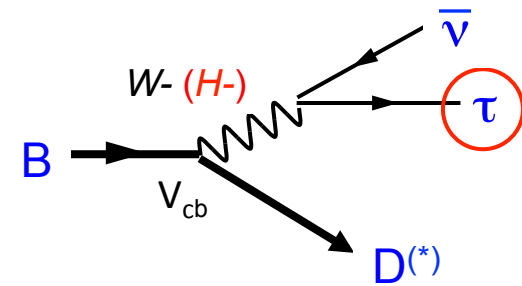
$$\mathcal{B}(B^- \rightarrow \ell^- \bar{\nu}) = \underbrace{\frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2}_{\text{SM}} f_B^2 |V_{ub}|^2 \tau_B \underbrace{\left(1 - \tan^2 \beta \frac{m_{B^\pm}^2}{m_{H^\pm}^2}\right)}_{\text{Charged Higgs}}$$

Experiment	Tag	Branching Fraction ($\times 10^{-4}$)
BABAR	hadronic	$1.83^{+0.53}_{-0.49} \pm 0.24$
BABAR	semileptonic [9]	$1.7 \pm 0.8 \pm 0.2$
Belle	hadronic	$0.72^{+0.27}_{-0.25} \pm 0.11$
Belle	semileptonic [11]	$1.54^{+0.38+0.29}_{-0.37-0.31}$

New average $\mathcal{B}(B \rightarrow \tau \nu) = (1.15 \pm 0.23) \cdot 10^{-4}$
 SM $\mathcal{B}(B \rightarrow \tau \nu) = (1.01 \pm 0.29) \times 10^{-4}$



B → D^(*)τν decays



- A simple tree process, form factors measured for $B \rightarrow D^{(*)}l\nu$, decays involving τ have additional helicity amplitude
- non-SM contribution from H^\pm expected to enhance or suppress rates for $B \rightarrow D^{(*)}\tau\nu$
- Test SM prediction by measurement of ratios:

$$R(D) = \frac{\Gamma(\bar{B} \rightarrow D\tau\nu)}{\Gamma(\bar{B} \rightarrow D\ell\nu)} \quad R(D^*) = \frac{\Gamma(\bar{B} \rightarrow D^*\tau\nu)}{\Gamma(\bar{B} \rightarrow D^*\ell\nu)}$$

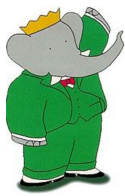
Leptonic τ
decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed (3 ν in final state!)
 - hadronic B tag
 - $D^{(*)}e^\pm$ or μ^\pm : No additional charged particles, $E_{\text{extra}} < 0.5\text{GeV}$ (no cut)
 - Background suppression by BDT (combinatorial BG and $D^{**}l\nu$)

Signal extraction by unbinned M.L. fit, fully 2-dimensional: M_{miss}^2 vs p_{lepton}^* (e^\pm, μ^\pm)
 $D^0, D^{*0}, D^+, D^{*+}, (e^\pm \text{ or } \mu^\pm)$

4 $D^{(*)}\pi^0l\nu$ control samples to assess $D^{**}l\nu$ backgrounds



$B \rightarrow D^{(*)} \tau \nu$: fit results

PRL101802 (2012)

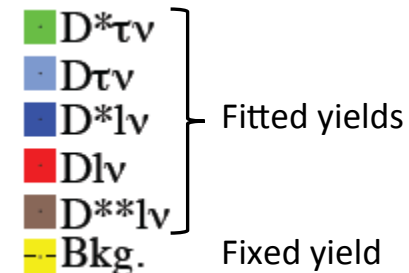
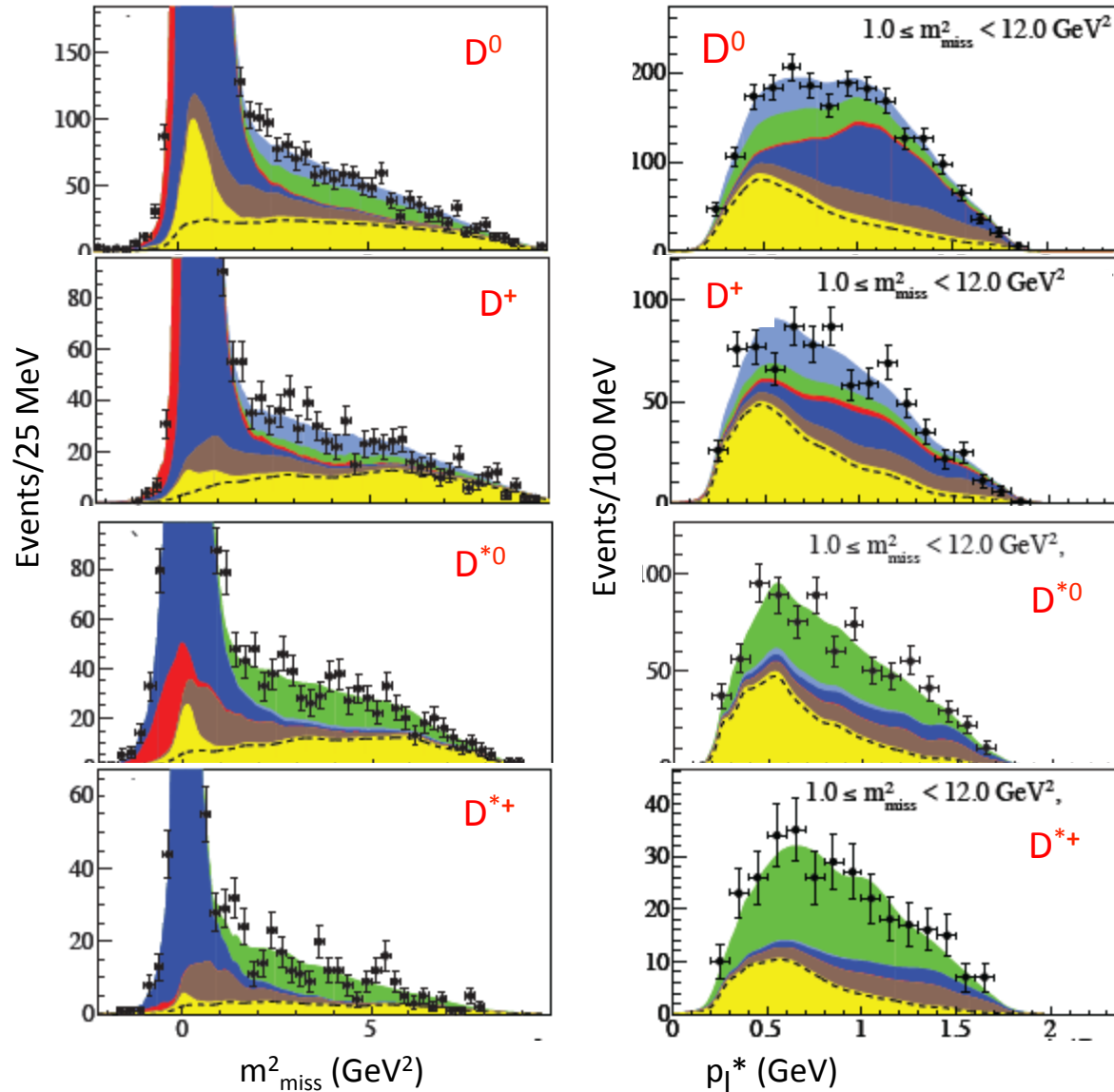
Fit results, combined using
Isospin relations:

$B \rightarrow D \tau \nu$

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

$B \rightarrow D^* \tau \nu$

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



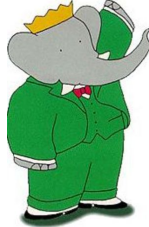
Results and implications on type-II 2HDM

$$R(D) = \left\{ \begin{array}{ll} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{array} \right\} 2.0\sigma$$

$$R(D^*) = \left\{ \begin{array}{ll} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{array} \right\} 2.7\sigma$$

PRL 101802 (2012)

Combination of $R(D)$ and $R(D^*)$ excludes SM at 3.4σ



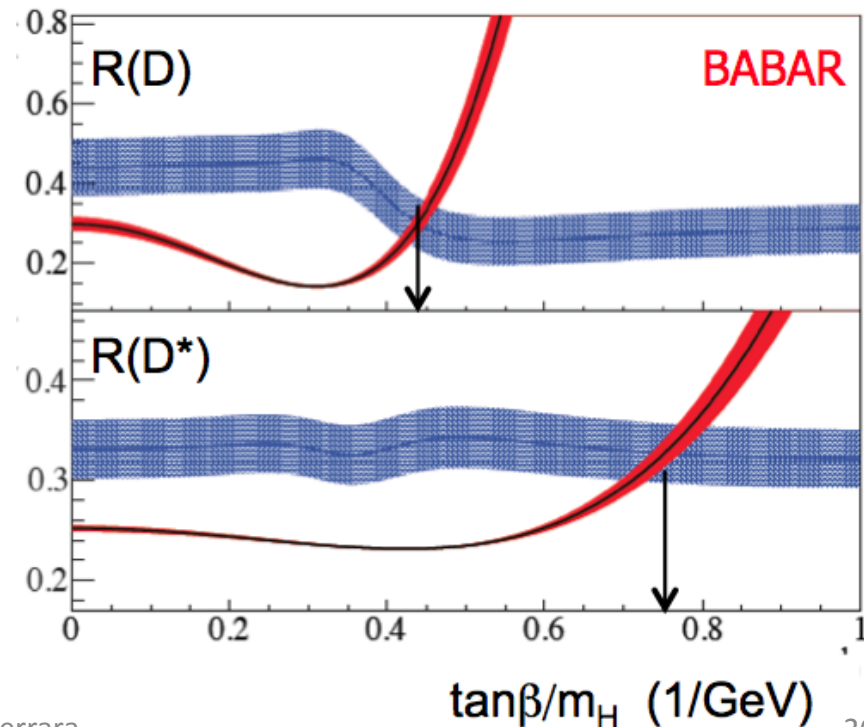
A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect scalar helicity amplitude

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

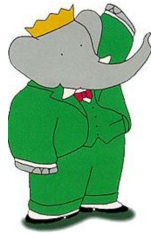
- for $D\tau V$ + for $D^*\tau V$

From the estimated effect of on the signal, the type II 2HDM can be excluded in the full $\tan\beta - m_H$ parameter space at $>99.8\%$, provided $m_H > 15$ GeV.

Earlier Belle measurements confirm this trend. Unpublished deviations from SM of Belle results presented at FPCP 2013 (A. Bozek)
 $R(D^*) : 3.0\sigma ; R(D) : 1.4\sigma$
 Waiting for final results from Belle to confirm!



Limits on type-III 2HDM



- Type-II 2HDM corresponds to a **special case**
- More general models exist, for instance **type-III HDM**,
 - e.g. Crivellin et al, arXiv:1206.2634(2012); Datta et al, PRD 86, 034027(2012)

$$\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[(\bar{c}\gamma_\mu P_L b) (\bar{\tau}\gamma^\mu P_L \nu_\tau) + \underbrace{S_L}_{\text{red circle}} (\bar{c}P_L b) (\bar{\tau}P_L \nu_\tau) + \underbrace{S_R}_{\text{blue circle}} (\bar{c}P_R b) (\bar{\tau}P_L \nu_\tau) \right]$$

S_L (S_R) parameterize complex couplings of **left-** (**right-**) handed quarks

- **Impact on $R(D^{(*)})$**

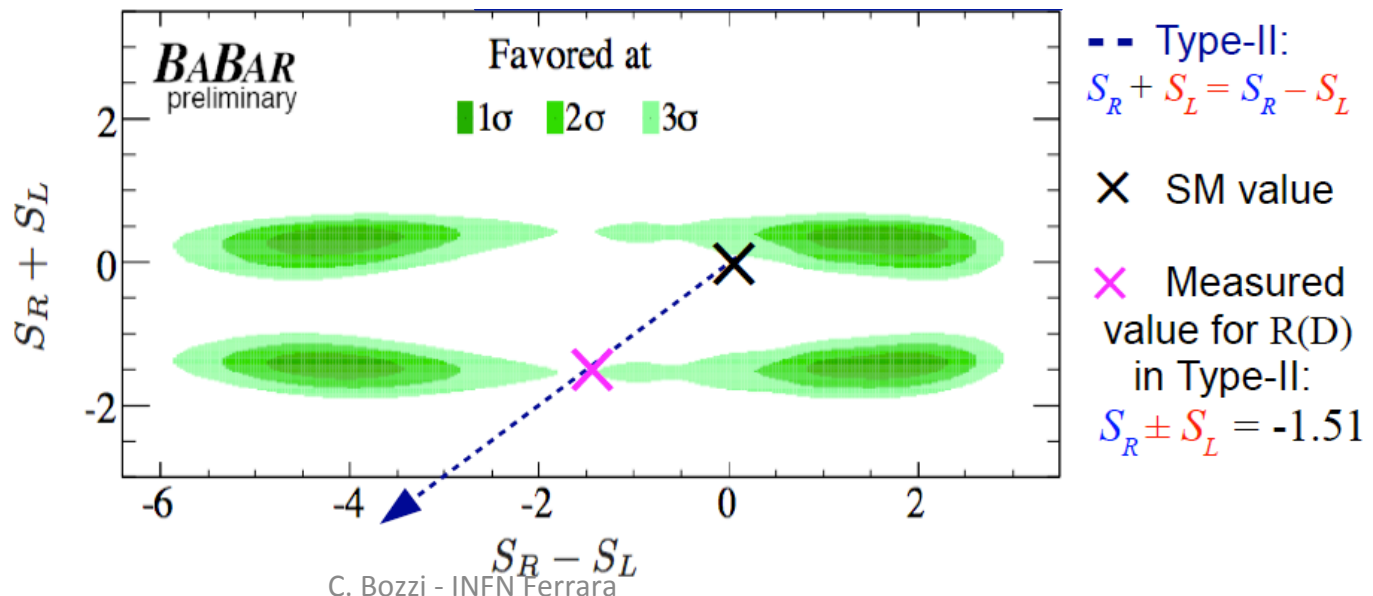
$$\mathcal{R}(D) = \mathcal{R}(D)_{\text{SM}} + A'_D \text{Re}(S_R + S_L) + B'_D |S_R + S_L|^2$$

$$\mathcal{R}(D^*) = \mathcal{R}(D^*)_{\text{SM}} + A'_{D^*} \text{Re}(S_R - S_L) + B'_{D^*} |S_R - S_L|^2$$
- Type-II 2HDM is recovered if $S_R = -m_b m_\tau \tan^2 \beta / m_{H^+}^2$, $S_L = 0$.

Type III

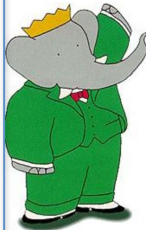
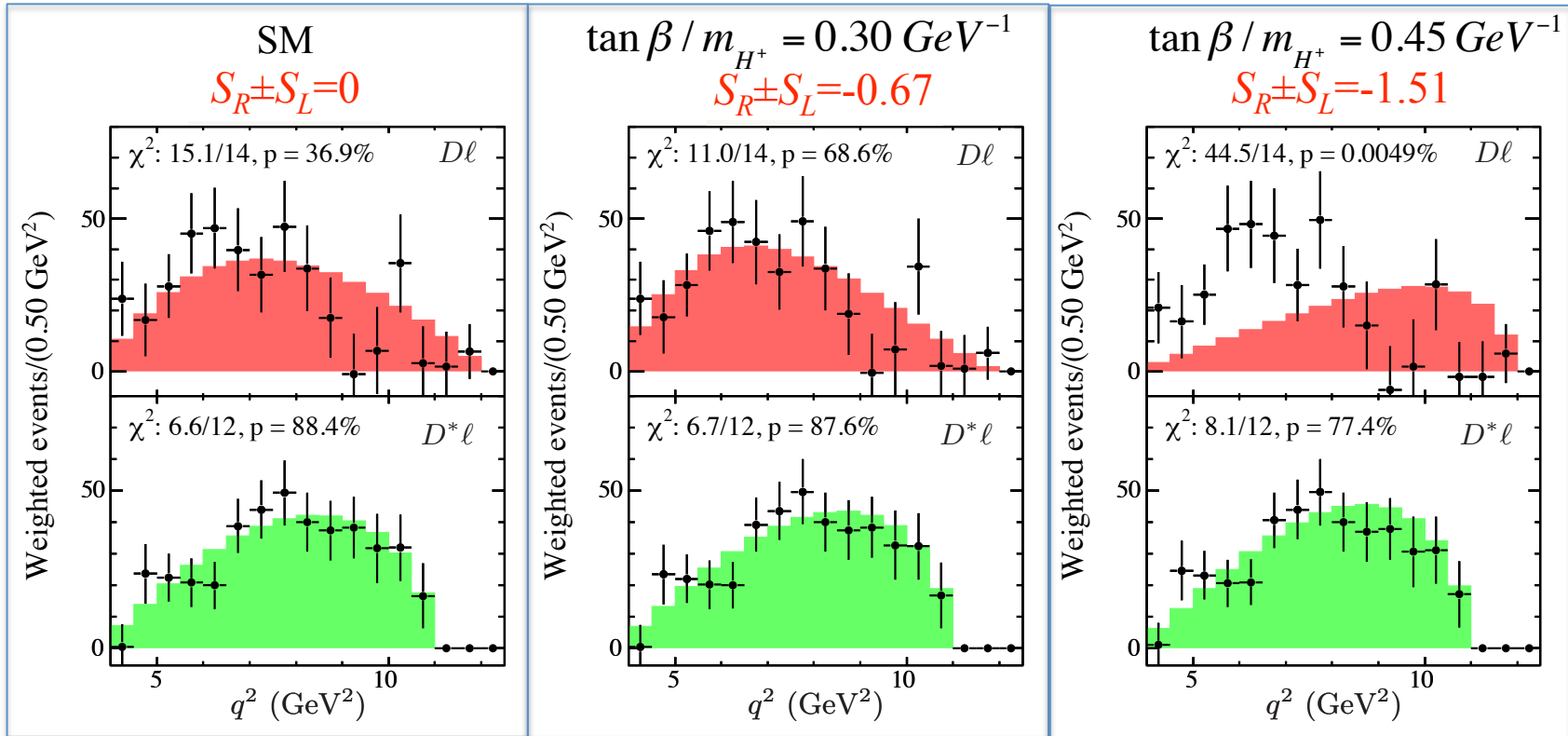
- 4 solutions for real S_R, S_L values.
- Complex values also allowed

Type-II has no solutions!



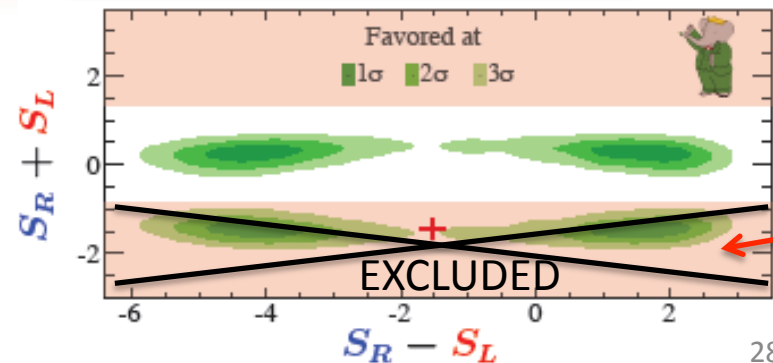
Adding info from q^2 distributions

Dilepton squared invariant mass q^2 is **sensitive to Higgs couplings to quarks**



arXiv:1303.0571 (2013)

At $S_R \pm S_L \sim -1.5$, p-value for $R(D)$ is 0.4%
 → Exclusion with significance of at least 2.9σ



Conclusion

- B and B_s decays are great probes to search for new physics effects induced by virtual particles in tree and loop diagrams
- New physics has not been discovered, however there are intriguing “tensions”
 - Angular analysis of $K^*\mu\mu$
 - Isospin analysis of $K\mu\mu$ (not discussed)
 - $B \rightarrow D^{(*)}\tau\nu$
- These should be followed up by collecting more data, analyzing other decay modes and performing more accurate theoretical studies
- B Factories and hadron colliders nicely complement each other
 - Experiments at the B Factories have nearly completed measurements on their final samples
 - LHCb is now the major driver in many channels
 - ATLAS and CMS can give substantial contributions in very rare decays with muons
 - Belle-II will enter into the game on a longer time scale

Backup

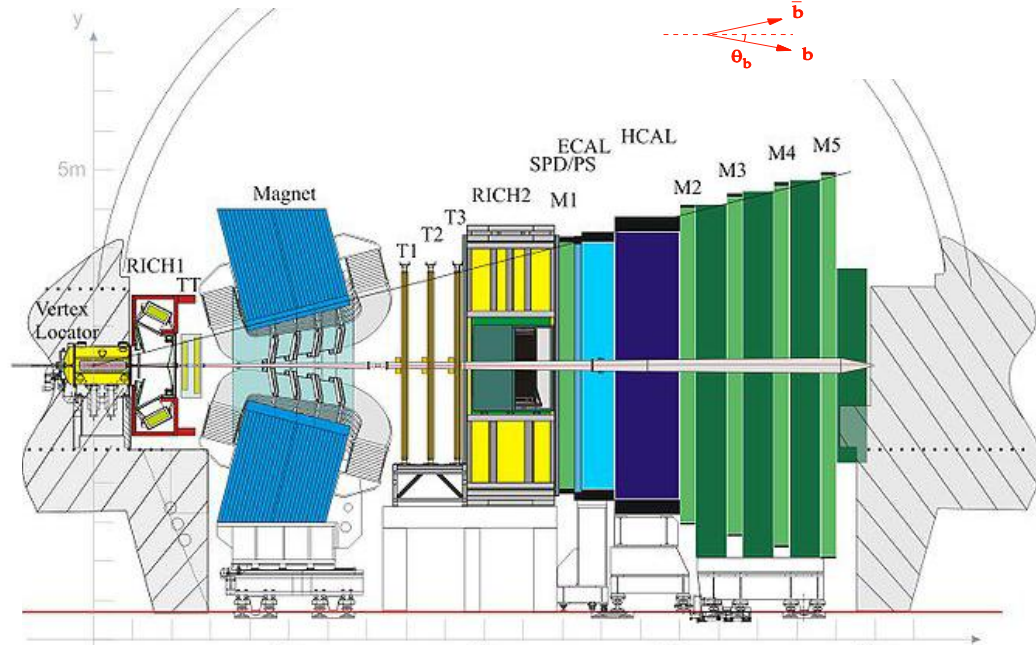
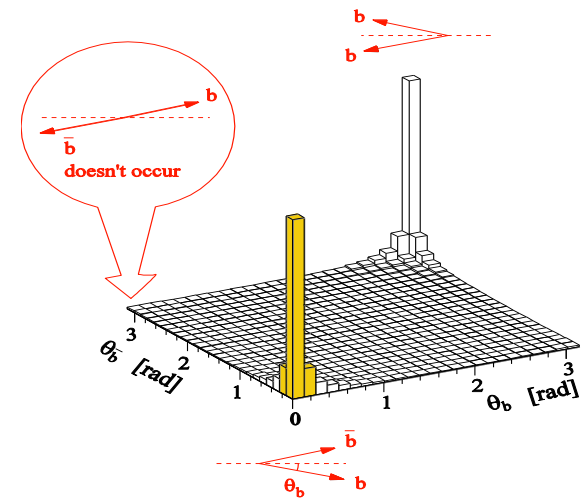
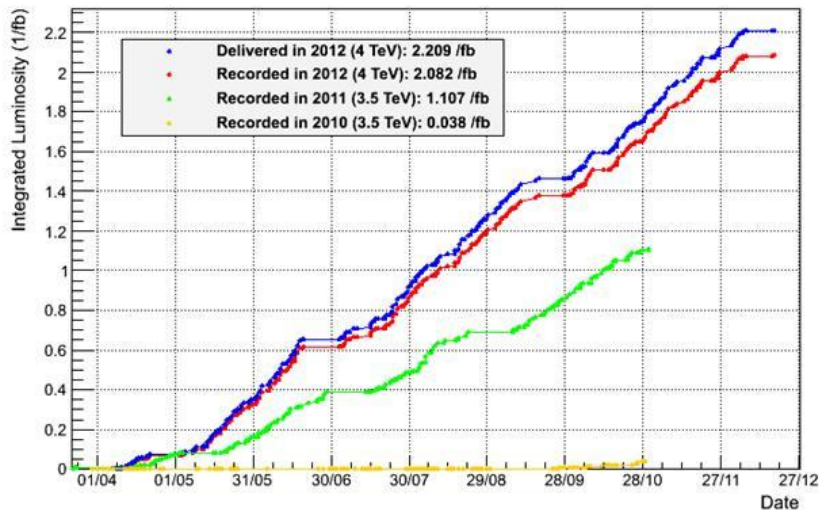
LHCb

Forward spectrometer optimised for heavy flavour physics at the LHC

- Large acceptance $2 < \eta < 5$
- Low trigger thresholds
- Precise vertexing
- Efficient particle identification
- Running at a constant luminosity of $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, $\langle \mu \rangle \sim 1.7$, 4x design

Recorded integrated luminosity:
 1 fb⁻¹ @ 7TeV (2011)
 2 fb⁻¹ @ 8TeV (2012)

LHCb Integrated Luminosity pp collisions 2010-2012



- Large boost (B mesons flight $\sim 1\text{cm}$)
- Huge production cross section ($\sim 300\mu\text{b}$)
- Small S/B ratio

$B \rightarrow X_s \gamma$

$$\mathcal{B}(B \rightarrow X_{sd} \gamma)$$

HFAG
Jun 2013

CLEO
Belle
BABAR
New Avg.

The inclusive decay has been precisely measured at B Factories

$$\mathcal{BR}(b \rightarrow s \gamma) = (3.43 \pm 0.22) \times 10^{-4}$$

in agreement with the SM prediction

$$\mathcal{BR}_{SM}(b \rightarrow s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

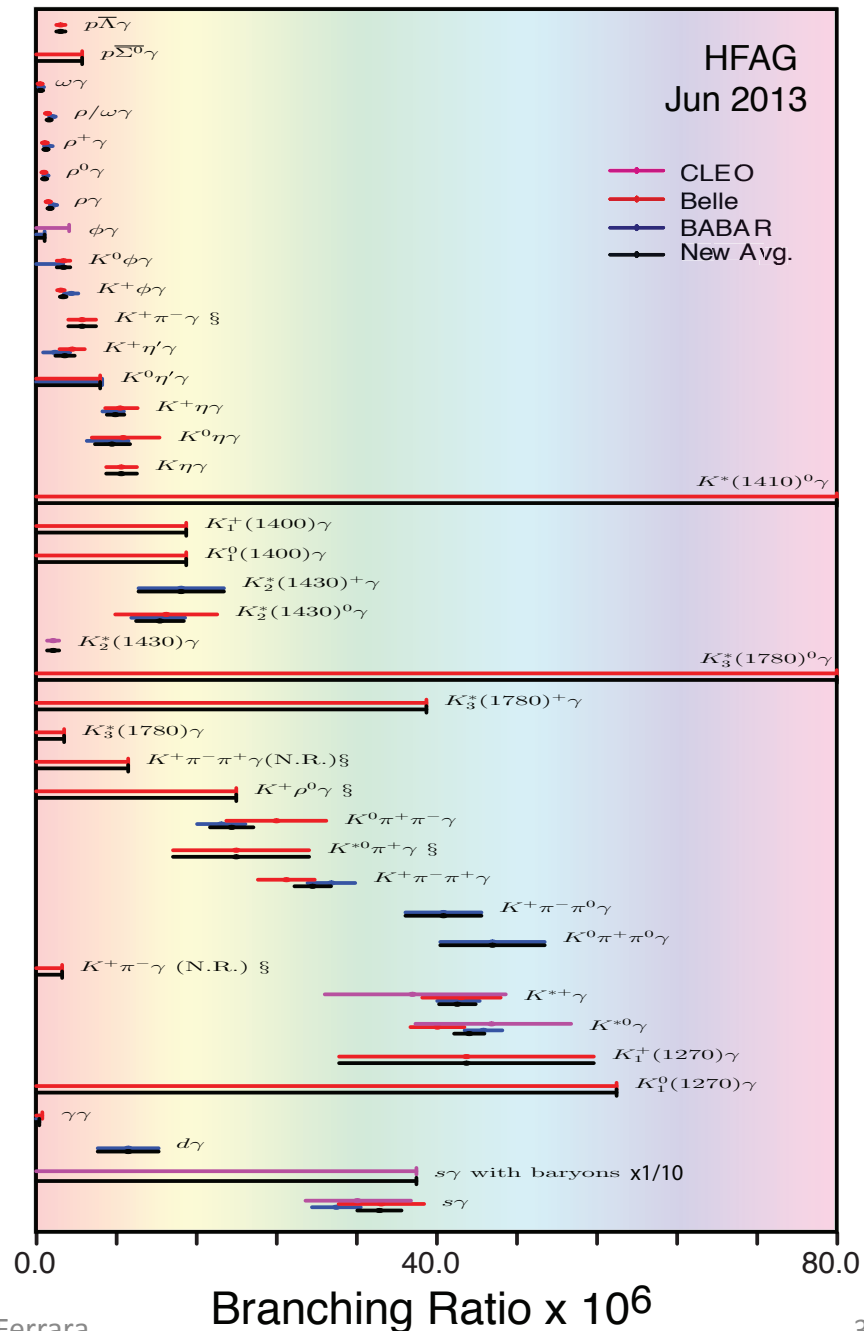
Known as one of the strongest constraint in MSSM. Together with the Higgs mass measurement, only O (%) of the a-priory phase space left!

Many exclusive modes studied as well

At hadron colliders, measure exclusive decays to keep background at manageable level

LHCb performed first measurements in the B_s system; now starting measuring photon polarization

$$\mathcal{BR}(B_s \rightarrow \Phi \gamma) = (3.5 \pm 0.4) \times 10^{-5}$$

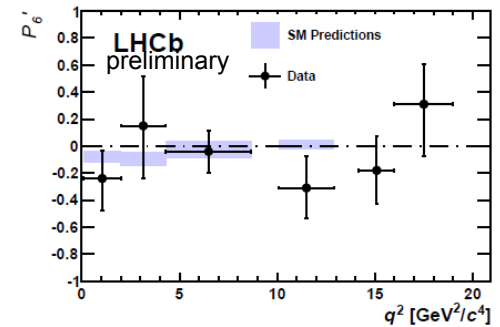
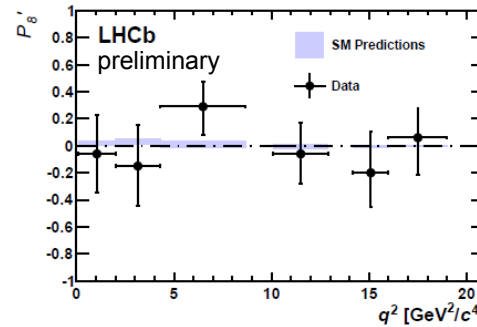
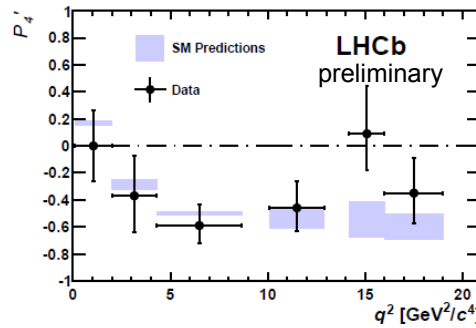


$B \rightarrow K^* \mu\mu$: new observables

LHCb, arXiv:1308.1707

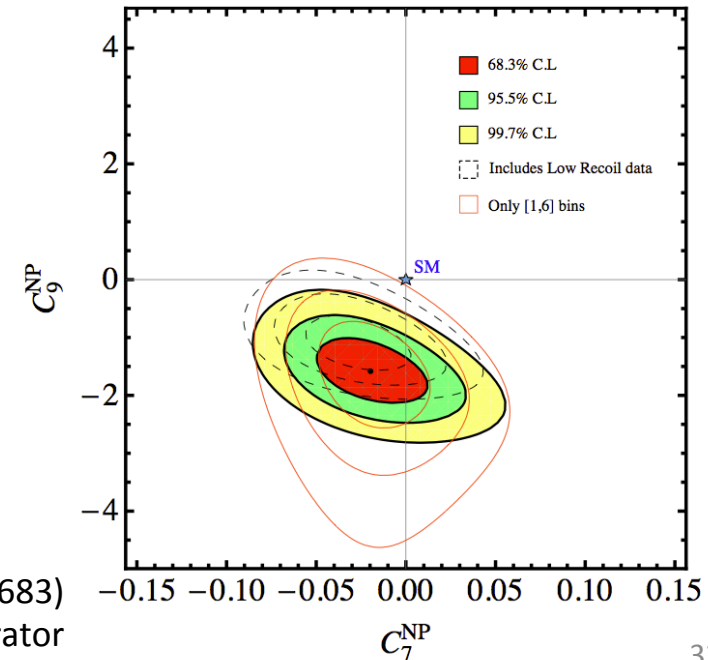
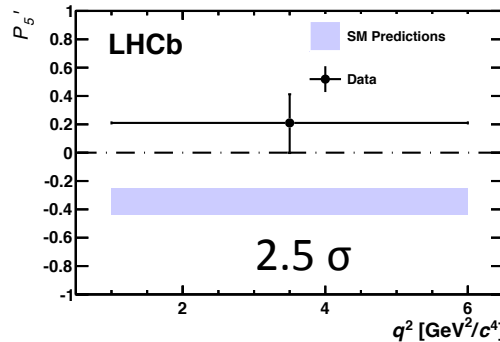
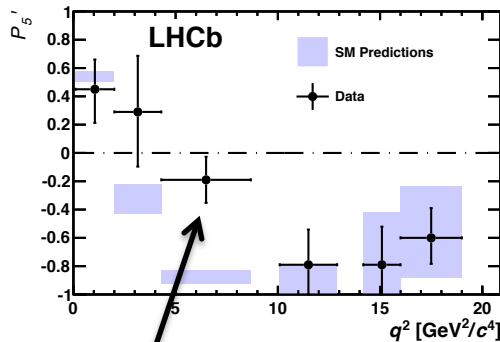
- Observables with limited dependence on form-factors uncertainty have been proposed by several theorists
- Different set of observables give different constraints \Rightarrow complementarity!

Good agreement for some observables



SM predictions from J. Matias et al, arXiv:1303.5794

some local discrepancies for others

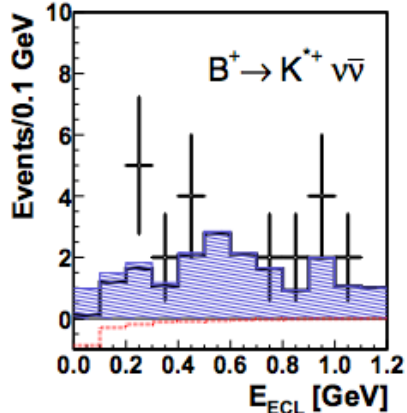


Descotes-Genon et al. (arXiv:1307.5683)

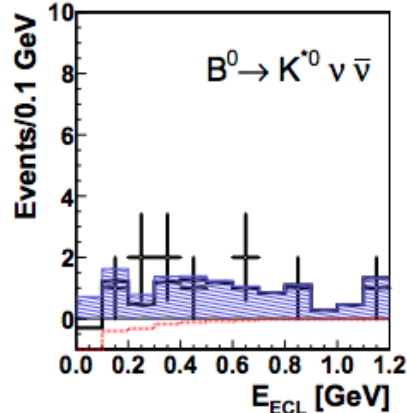
large New Physics contribution to the Wilson coefficient of the O_9 operator

B → hvv

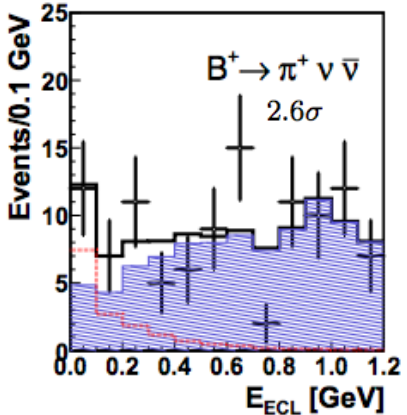
PRD 87, 111103 (2013) 772 BB



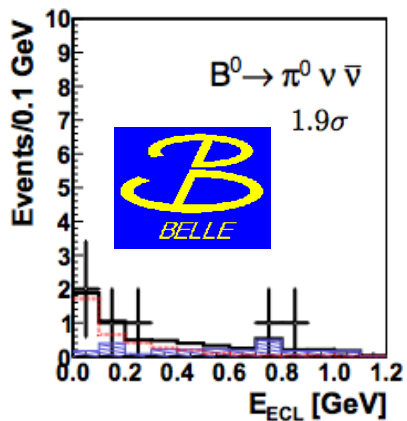
$$N_{\text{sig}} = -1.7^{+1.7}_{-1.1}(\text{stat}) \pm 1.5(\text{syst})$$



$$N_{\text{sig}} = -2.3^{+10.2}_{-3.5}(\text{stat}) \pm 0.9(\text{syst})$$



$$N_{\text{sig}} = 15.2^{+7.1}_{-6.2}(\text{stat}) \pm 1.4(\text{syst})$$



$$N_{\text{sig}} = 3.5^{+2.6}_{-1.9}(\text{stat}) \pm 0.6(\text{syst})$$

Mode	$\times 10^{-5}$	
	BF Upper Limit 90%CL	Previous Belle/BaBar
$B^+ \rightarrow K^+ \nu \bar{\nu}$	< 5.5	1.3
$B^0 \rightarrow K_s^0 \nu \bar{\nu}$	< 9.7	5.6 (x0.5)
$B^+ \rightarrow K^{*+} \nu \bar{\nu}$	< 4.0	8
$B^0 \rightarrow K^{*0} \nu \bar{\nu}$	< 5.5	12
$B^+ \rightarrow \pi^+ \nu \bar{\nu}$	< 9.8	10
$B^0 \rightarrow \pi^0 \nu \bar{\nu}$	< 6.9	22
$B^+ \rightarrow \rho^+ \nu \bar{\nu}$	< 21.3	15
$B^0 \rightarrow \rho^0 \nu \bar{\nu}$	< 20.8	44
$B^0 \rightarrow \phi \nu \bar{\nu}$	< 12.7	5.8

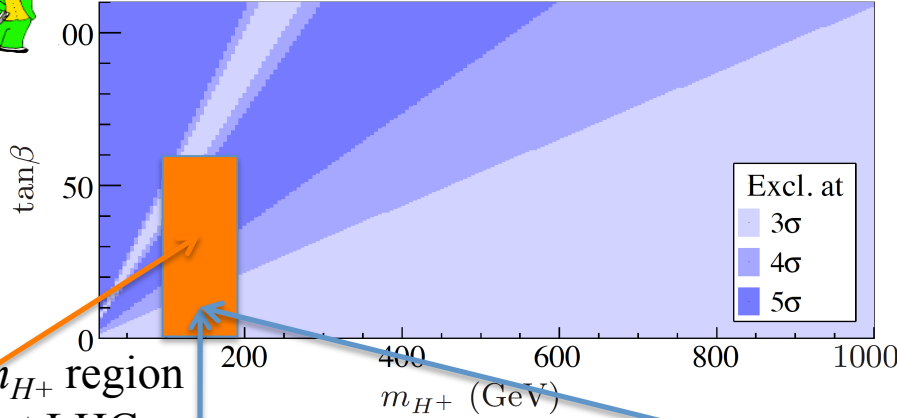
Best Limits to date

- B → K* νν limits within factor of ~5 of SM predictions (0.7-1.3x10⁻⁵)
- Uniquely at B Factories!
- Predict measurement with ~20% precision at Belle II with 50ab⁻¹

Type II 2HDM: compare with direct searches @ LHC

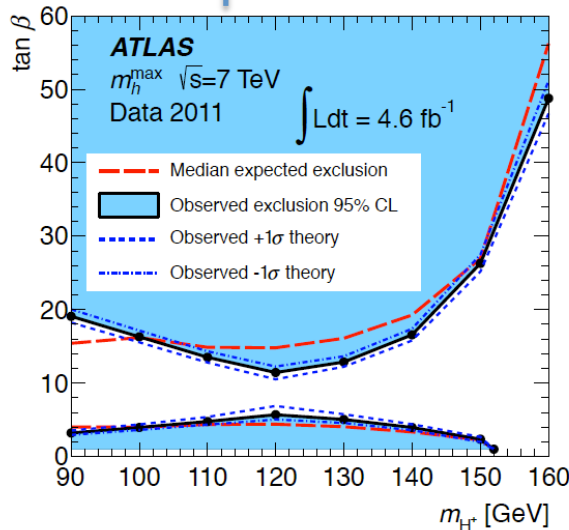


$\tan\beta - m_{H^+}$ BABAR exclusion plot

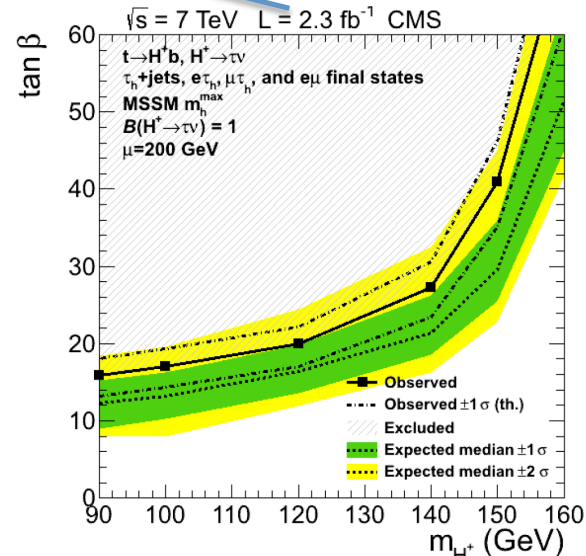


$B \rightarrow D^{(*)} \tau \nu$ and $B \rightarrow \tau \nu$ searches at B factories are complementary to direct searches at LHC in $t \rightarrow b H^+ \rightarrow \tau \nu$

$\tan\beta - m_{H^+}$ region probed at LHC



ATLAS: JHEP 1206, 039 (2012)



CMS: JHEP 07, 143 (2012)