Review of B and B_s decays

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XXXIII Physics in Collisions

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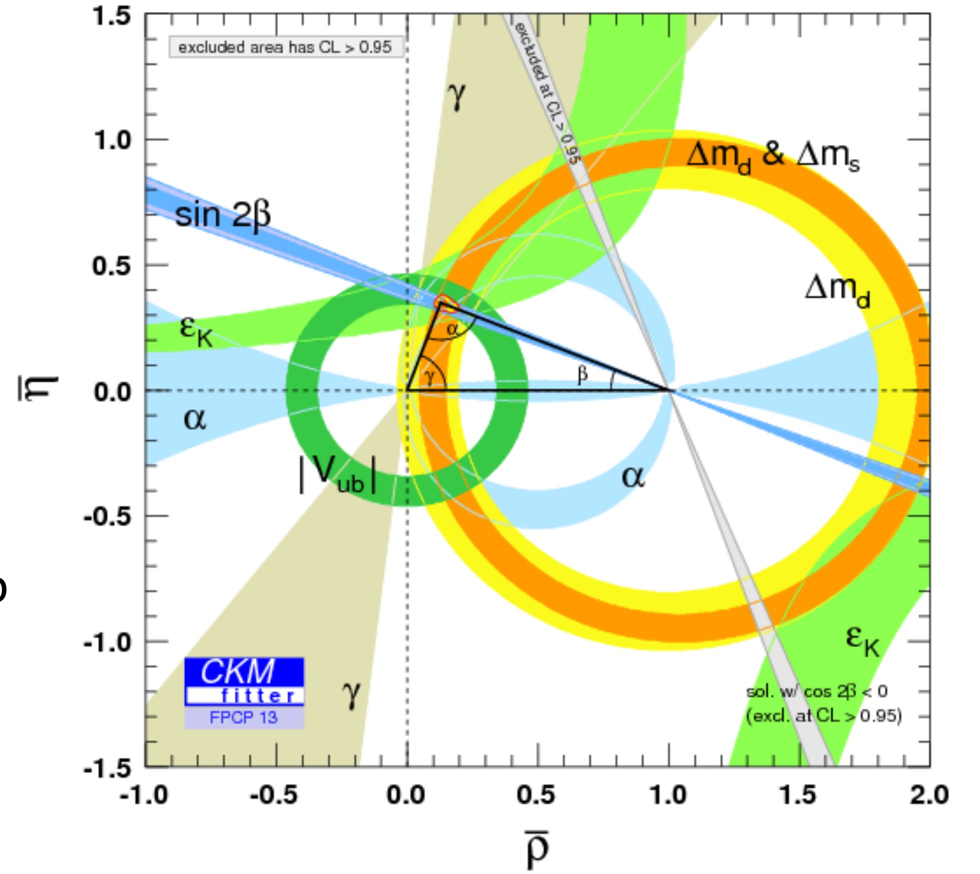
The relevance of $B_{(s)}$ decays

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



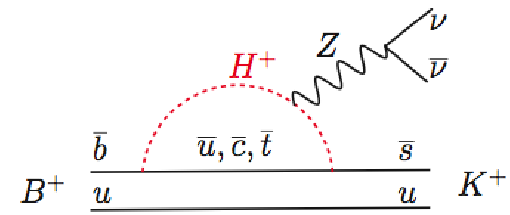
CKM unitarity triangle tested at the few percent level!

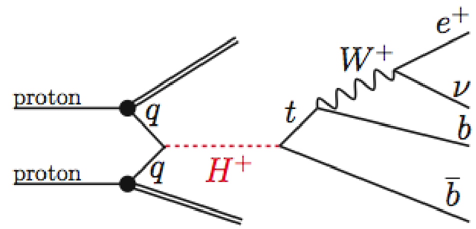
For a review of CP Violation, see talk by Stephane Monteil

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

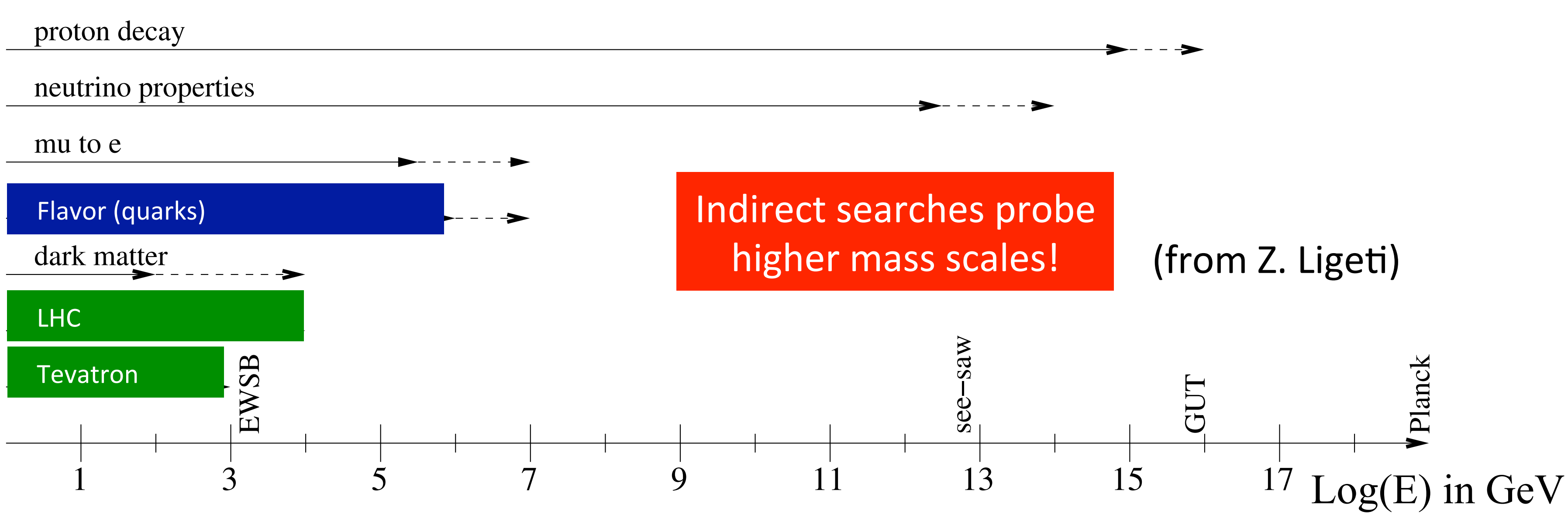
New physics might not respect the many suppressions of the SM :

- 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)

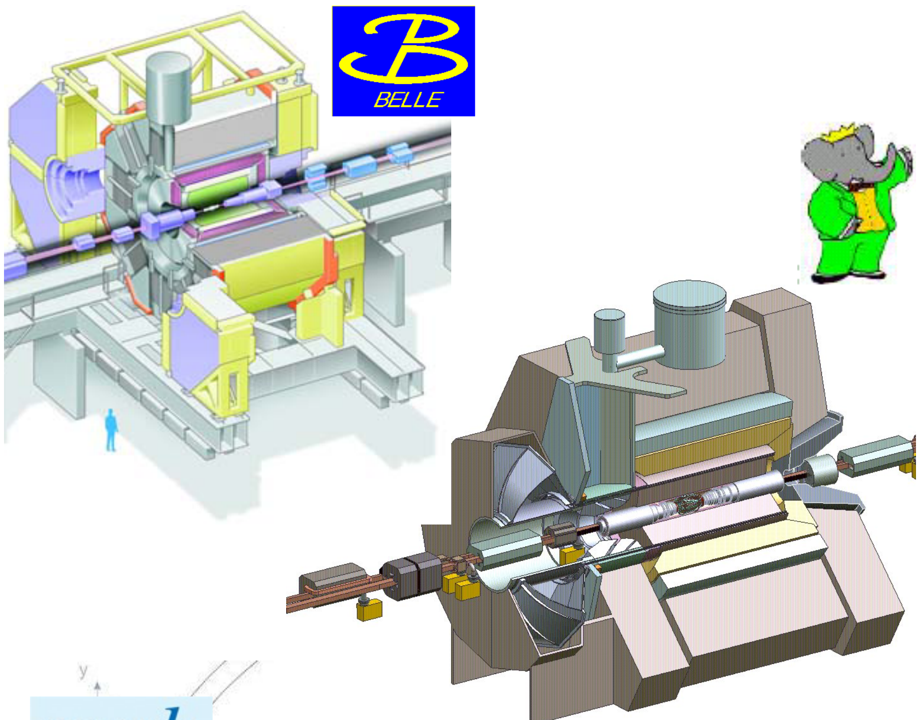


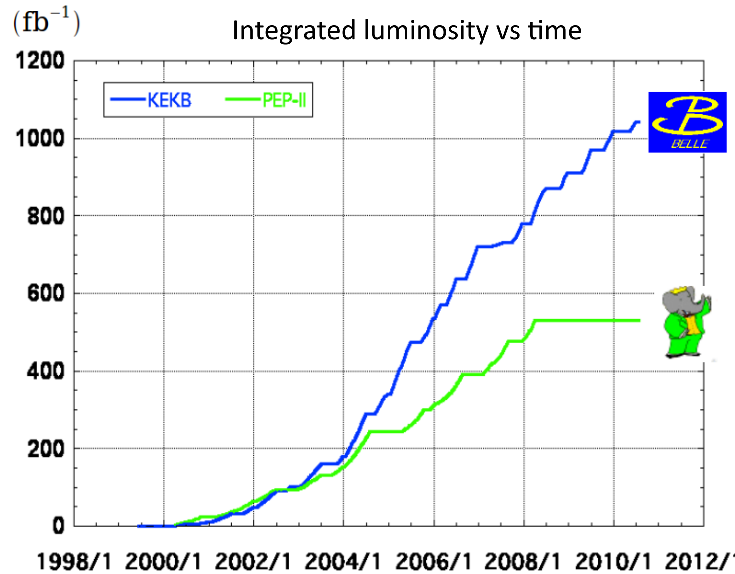
(from Z. Ligeti)

Outline

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

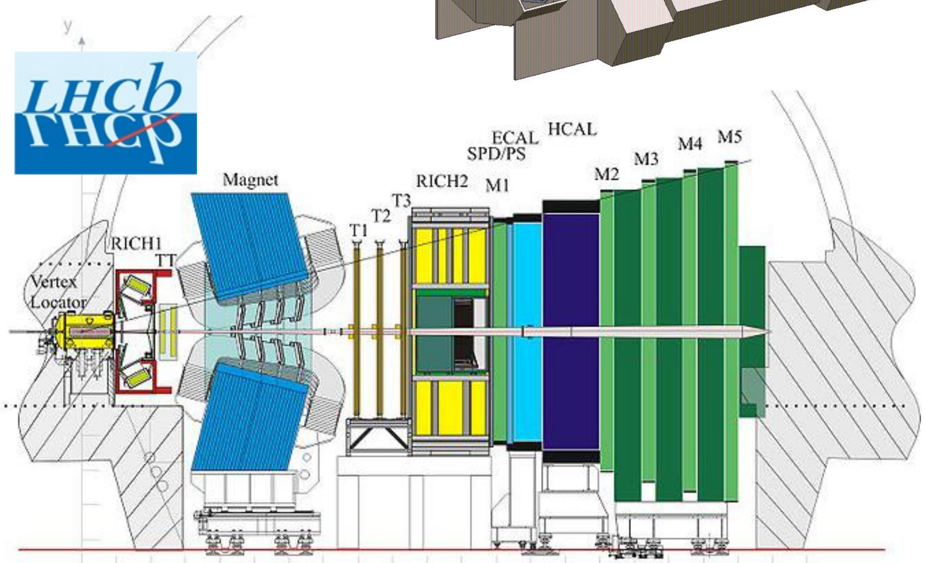
Experiments and data samples

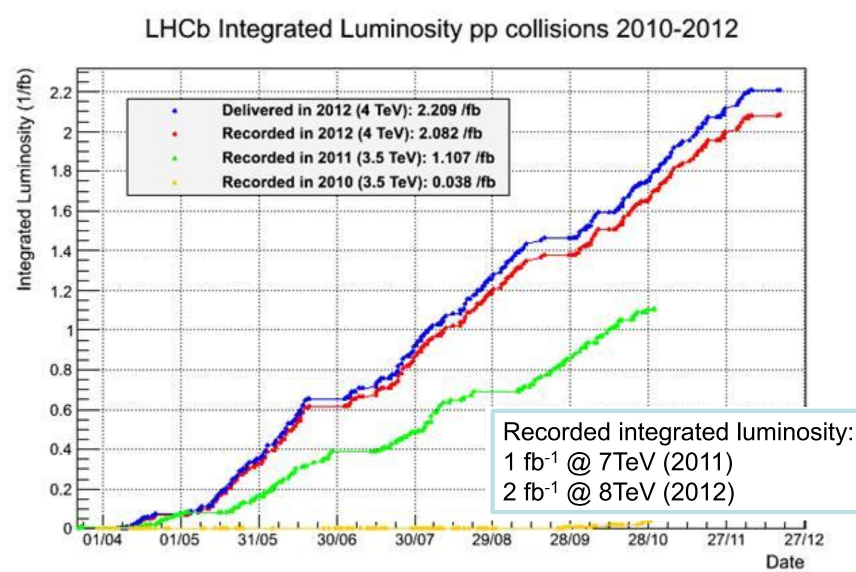




> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}





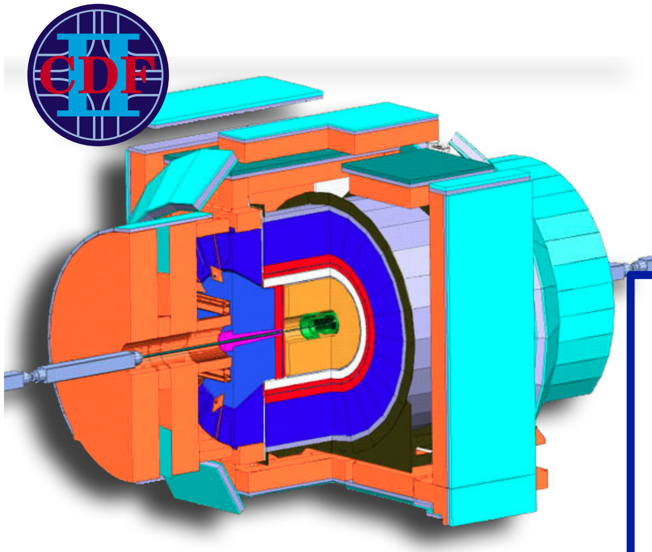
Very different energies and rates

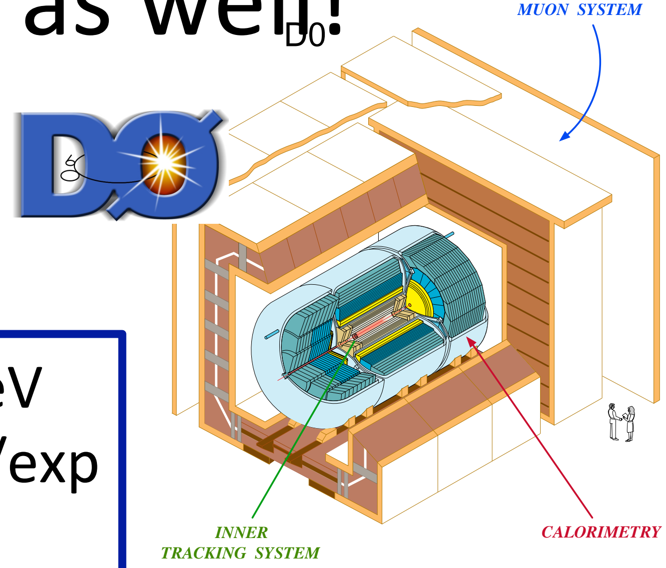
Experiment	Beams	cm Energy	Int. Lum	# Events	# Events	S/B
		[GeV]	[1/fb]	cc	bb	
BABAR/Belle	e+e-	10.58	424+711	1.2 10^9	~10^9	0.25
LHCb	pp	7000 (8000)	1.0 (2.0)	2 10^{12}	~10^{11}	~0.005

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 → 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!



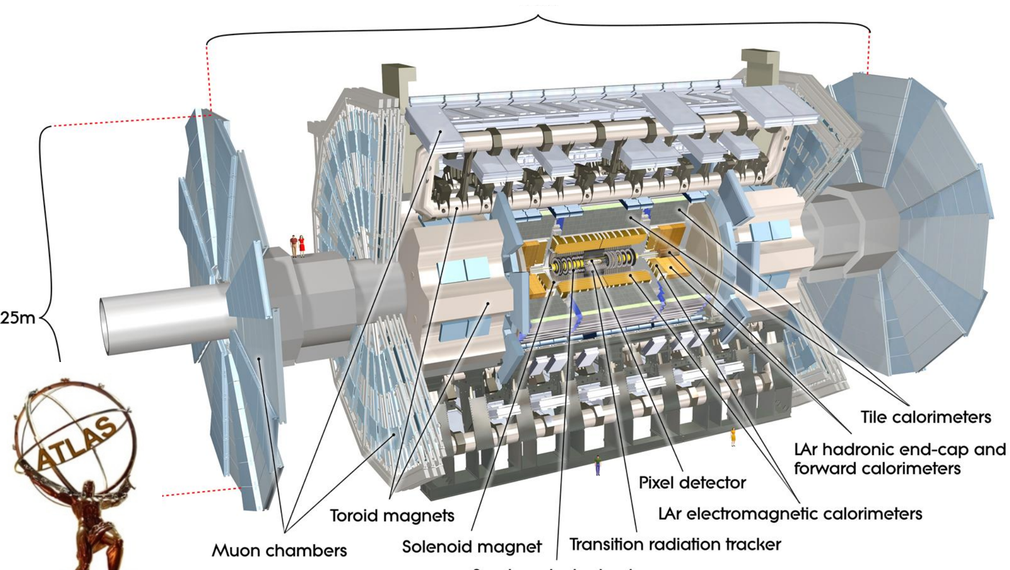


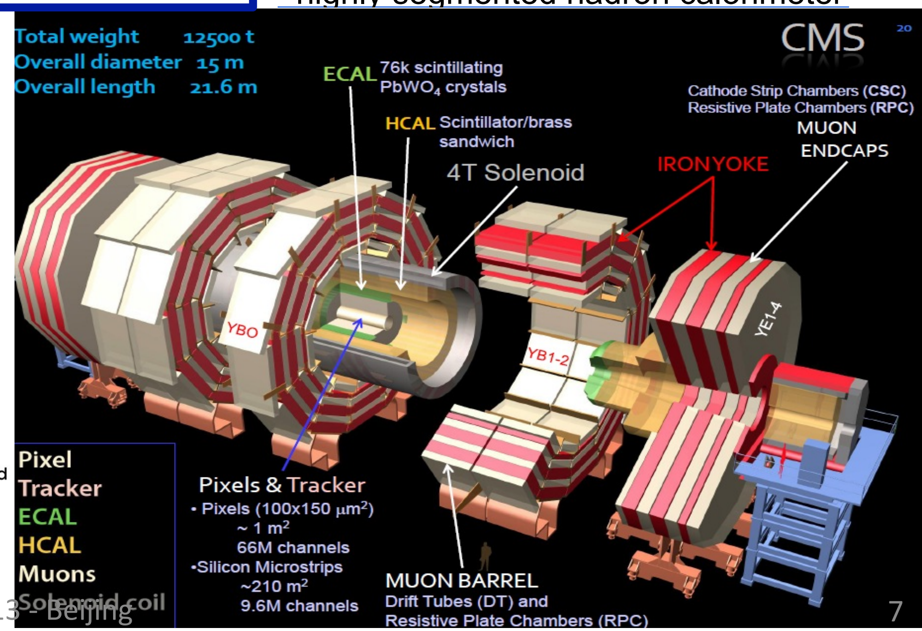
$\sqrt{s}_{TeVatron}$ = 2 TeV
$L_{TeVatron}$ ~ 10 /fb /exp

$\sqrt{s}_{LHC}$ = 7-8 TeV
L_{LHC} ~ 25 /fb /exp

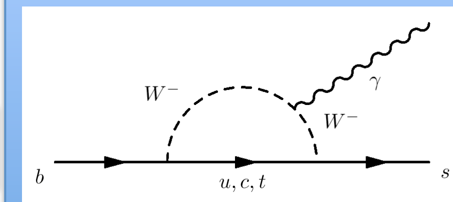
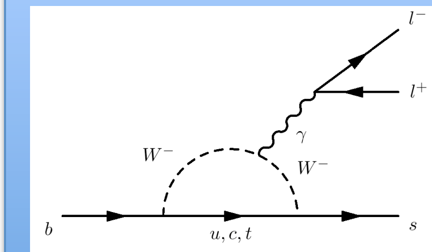
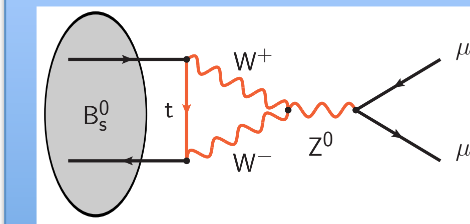
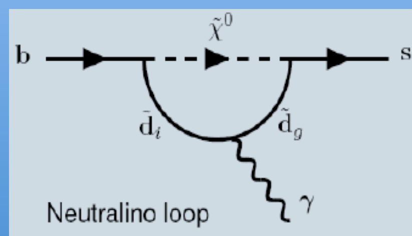
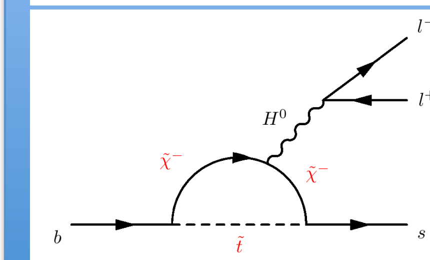
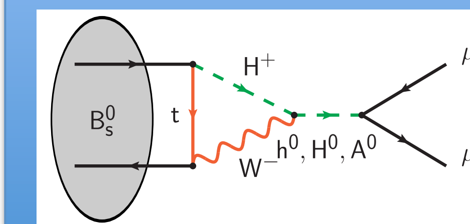
Large radius solenoid
Excellent tracking
Synchronous track trigger

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





Penguin processes

	Radiative	Electroweak	"Higgs"
SM			
SUSY			
Typical BR (SM)	$10^{-5} – 10^{-4}$	10^{-6}	10^{-9}
Observables	Br, γ polarization	Angular distributions	Branching ratios

Lorentz structure

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[\underbrace{C_i(\mu) O_i(\mu)}_{\text{Left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{Right-handed part, Suppressed in SM}} \right]$$

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

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

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

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

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

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

$B \rightarrow X_s \gamma$

Nucl. Phys. B 867 (2013), 1

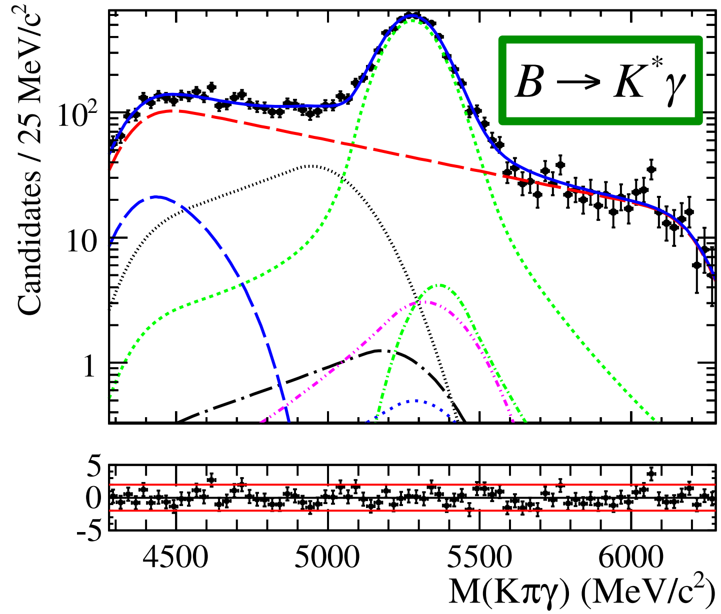
- The inclusive decay has been precisely measured at B Factories

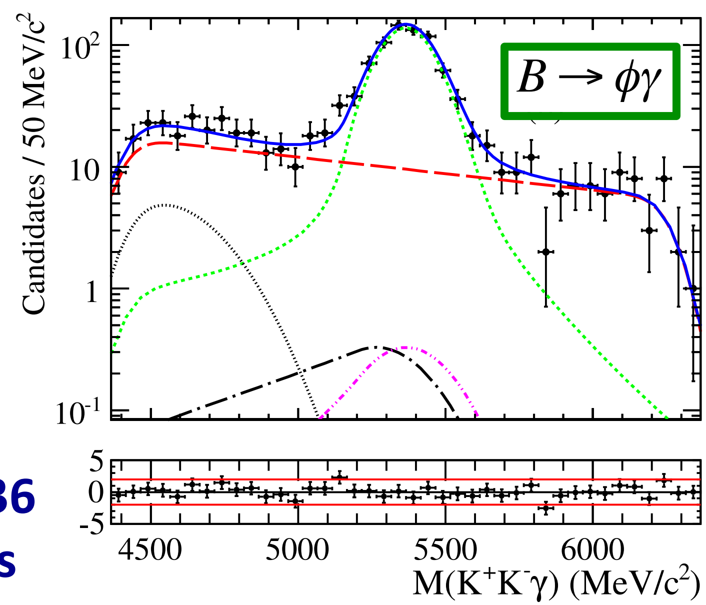
> $Br(b \rightarrow s\gamma) = (3.43 \pm 0.22) \times 10^{-4}$
> in agreement with the SM prediction
> $Br_{SM}(b \rightarrow s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$

- 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

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

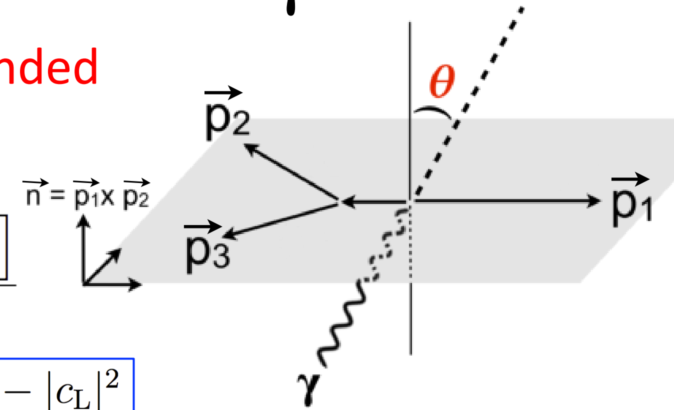
691 ± 36 events





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

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



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

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

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

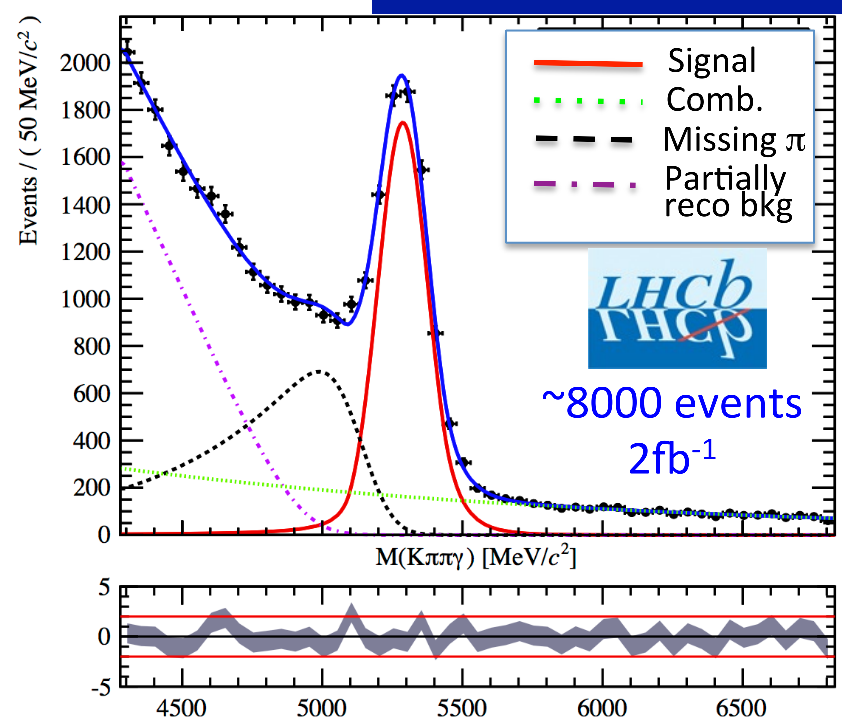
LHCB-CONF-2013-009

First measurement on a mixture of K resonances

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

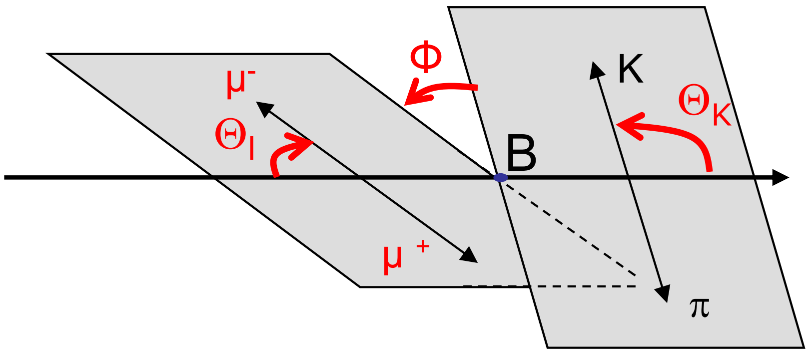
- Evidence for photon polarization in $b \to s\gamma$ decays at 4.6σ
- Difficult interpretation due to multiple resonances. If theoretical prediction existed, first measurement of λ_γ would be possible
- Also, 1st measurement of CP asymmetry

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



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 $\phi<0$, $\phi=\phi+\pi$):



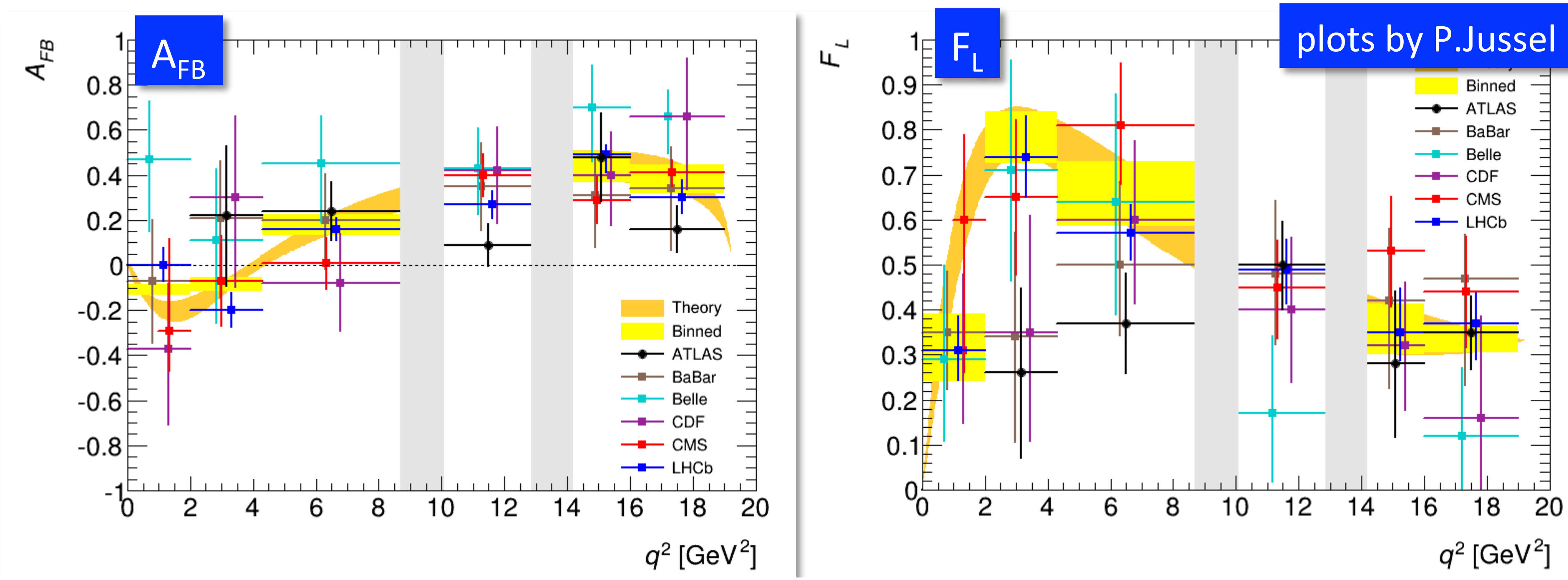
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

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: $q_0^2 = (4.36^{+0.33}_{-0.31})\, GeV^2/c^4$

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



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

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

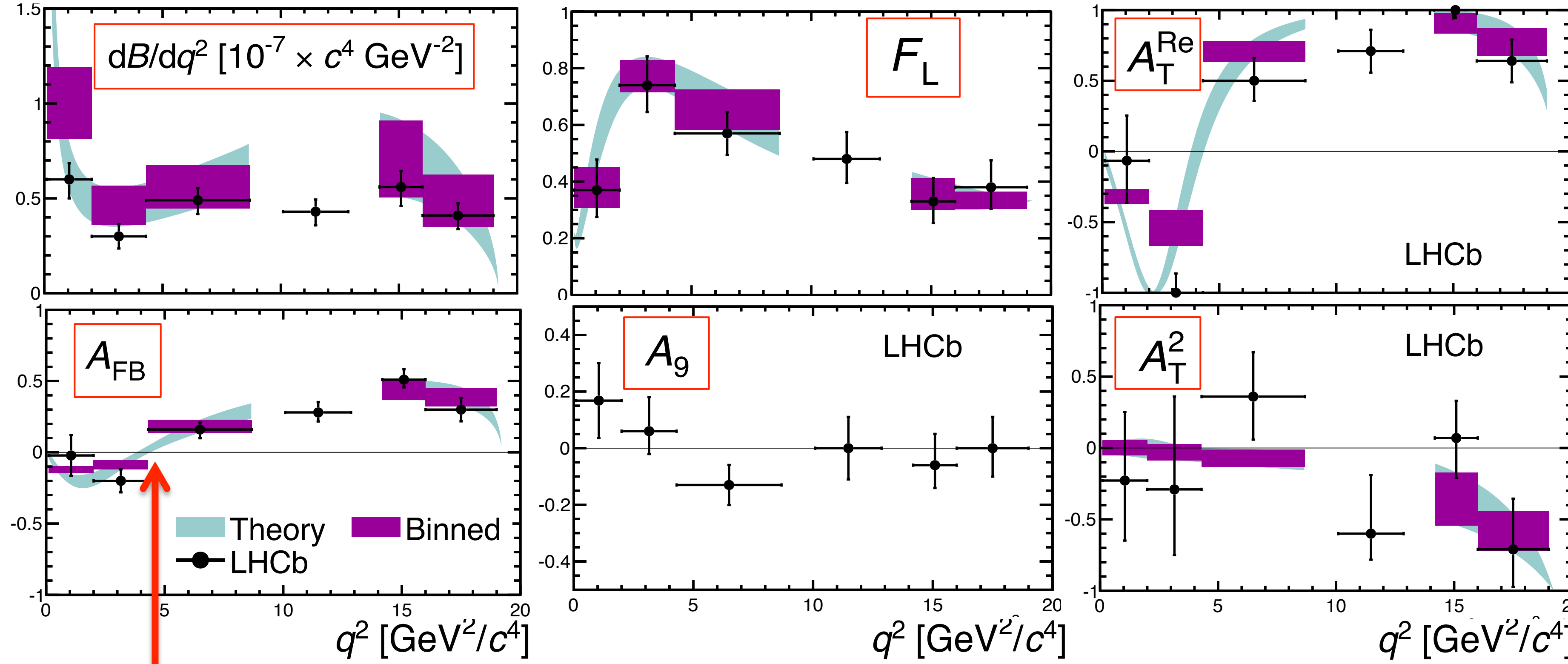
$B^0 \rightarrow K^{*0}\mu^+\mu^-$: results

arXiv:1304.6325
1 fb-1, ~900 events, 6 q^2 bins

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

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

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 :

$$q_0^2 = (4.9 \pm 0.9)\, GeV^2/c^4$$

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

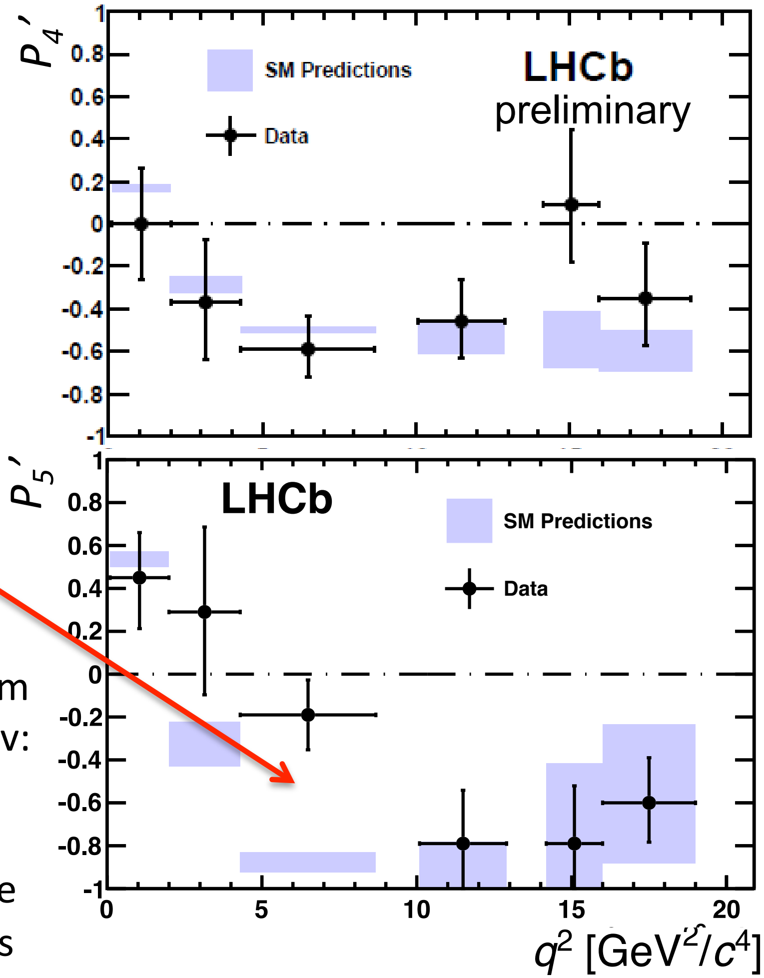
LHCb arXiv:1308.1707

- 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 ⇒ complementarity!

Good agreement for some observables

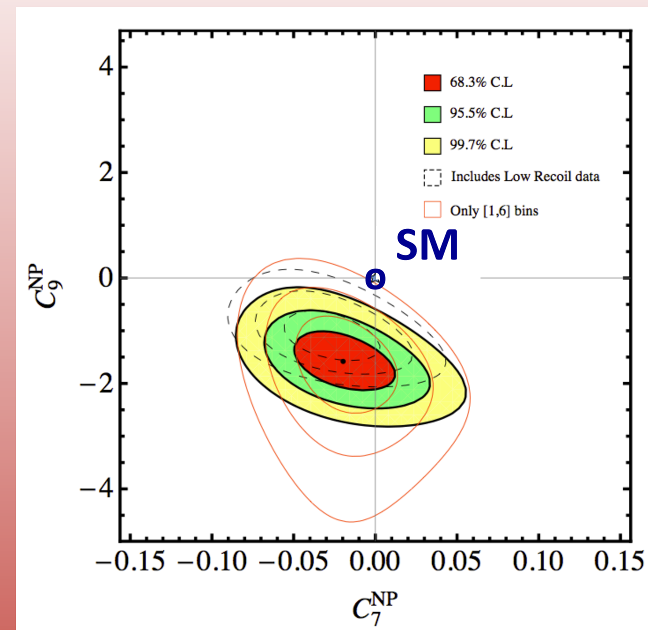
some local discrepancies for others

3.7σ



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

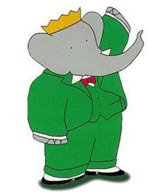
Global analysis, Descotes--Genon et al. (arXiv: 1307.5683): large New Physics contribution to the Wilson coefficient of the O_9 operator



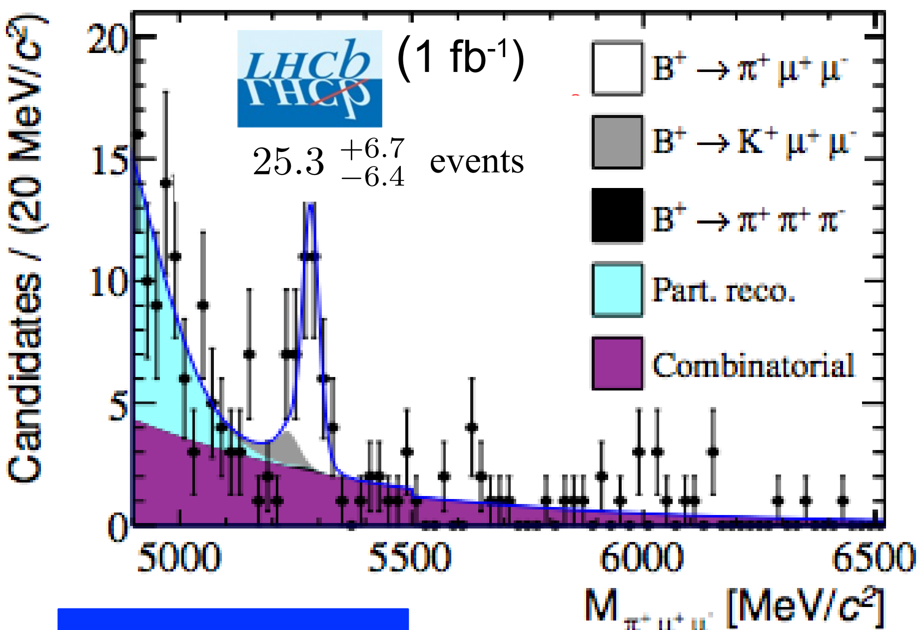
No definitive conclusion. More data and theoretical studies needed

B→h$_d$ll decays

Cabibbo-suppressed version of B→h$_s$ll, rate a factor ~25 lower



$B^+ \to \pi^+\mu^+\mu^-$ observed at 5.2σ in LHCb



JHEP 12 125 (2012)

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

Upper limits by Babar

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

Best Limits to date (red circles: 8.4, 6.9, 5.3)
First ever limits (blue circles: 10.8, 11.2, 5.9)

arXiv:1303:6010, acc. by PRD

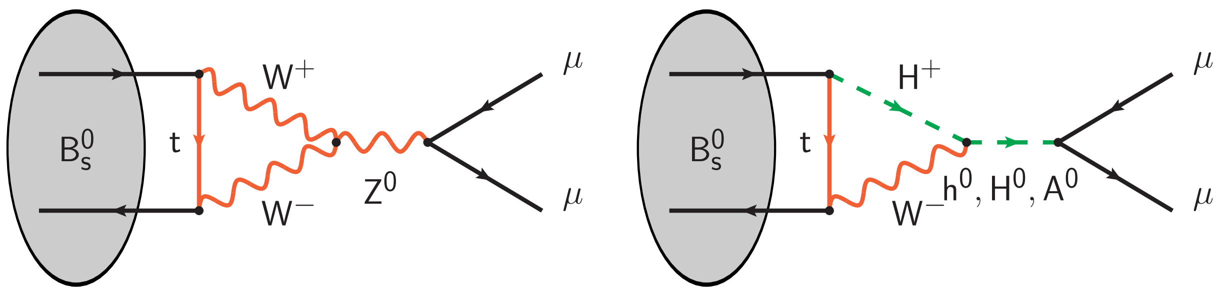
SM expected rates (excluding charmonium):

$$\mathcal{B}(B^+ \to \pi^+\ell^+\ell^-) = (1.96\text{–}3.30) \times 10^{-8}$$

$$\mathcal{B}(B^0 \to \eta\ell^+\ell^-) = (2.5\text{–}3.7) \times 10^{-8}$$

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

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



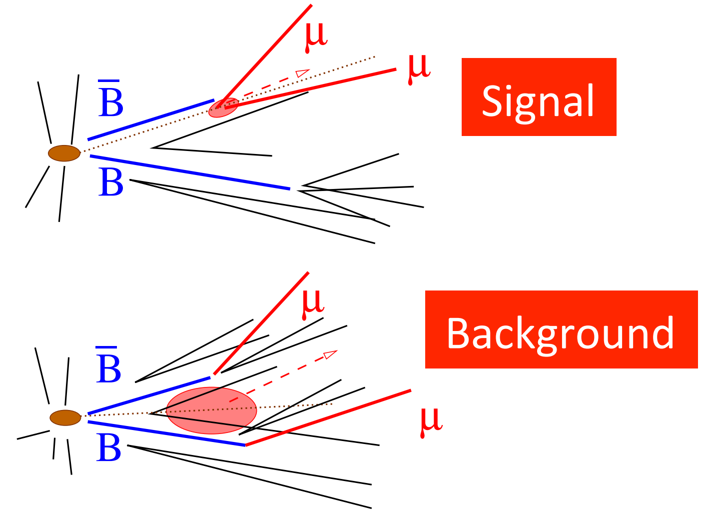
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) \propto \left(1 - \frac{4m_\mu^2}{m_B^2}\right) |C_S - C'_S|^2 + \left|(C_P - C'_P) + 2\frac{m_\mu}{m_B^2}(C_{10} - C'_{10})\right|^2$$

- 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 y_s and $A_{\Delta\Gamma}$ from HFAG:

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

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

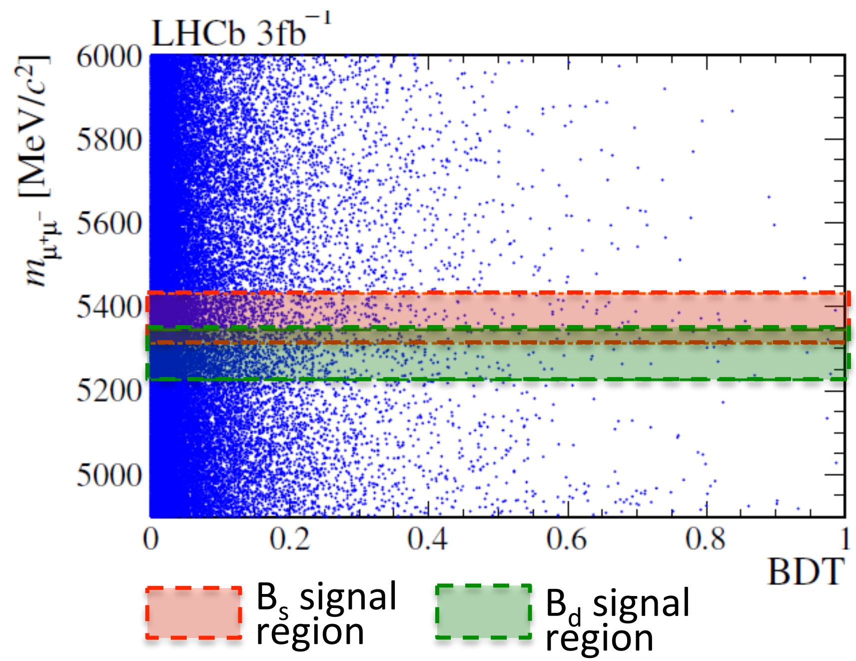
- Huge combinatorial background
- Partially reconstructed decays and particle mis-ID



$B^0_{(s)} \to h^+h'^-$ $B^0_s \to K^-\mu^+\nu_\mu$ $B^{0,+} \to \pi^{0,+}\mu^+\mu^-$

$\Lambda_b \to p\mu^-\nu_\mu$ $B^0 \to \pi^-\mu^+\nu_\mu$ $B^+_c \to J/\psi(\mu\mu)\mu^+\nu_\mu$

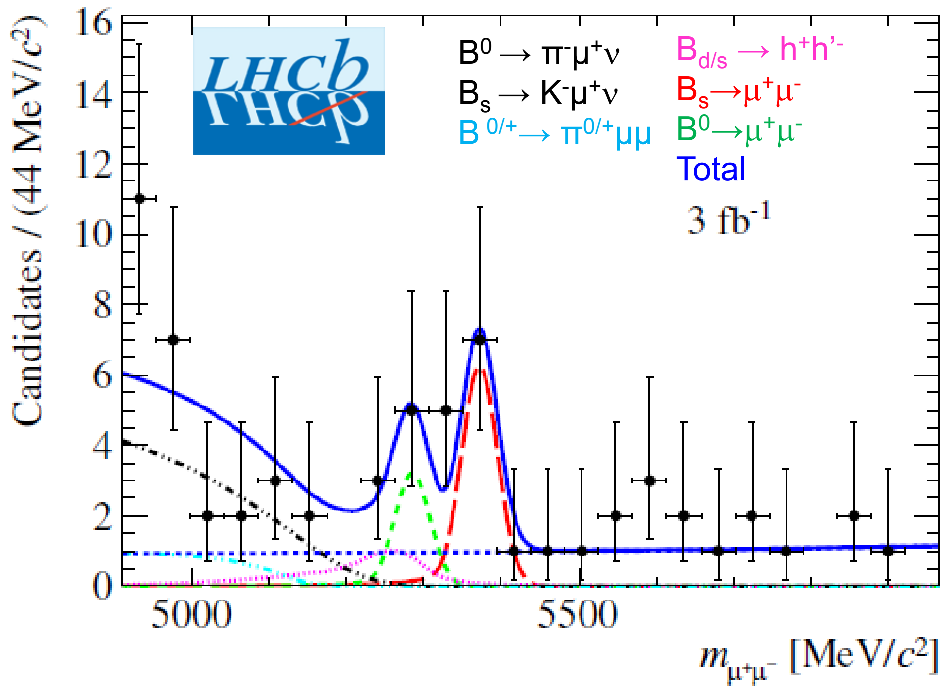
- Signal to background discrimination:
  - Loose event selection
  - classification in the plane $m_{\mu\mu}$ x BDT based on geometry and kinematics
- Background PDFs obtained with data driven methods
- BF measurement: simultaneous fit to $m_{\mu\mu}$ in BDT bins (LHCb) or categories (CMS)
- Upper limits: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



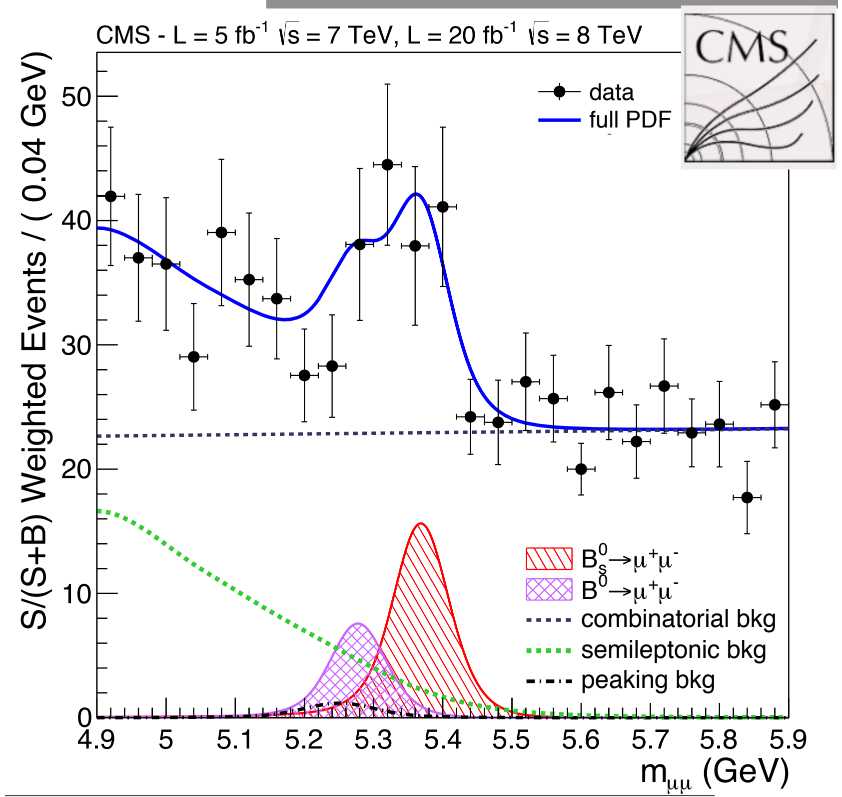
$B^0_{(s)} \to \mu^+\mu^-$: results

arXiv:1307.5024, acc. by PRL

BDT>0.7



arXiv:1307.5025, subm. to PRL



	LHCb		CMS	
$Br(B^0_s \to \mu^+\mu^-) =$	$(2.9\ ^{+1.1}_{-1.0}(stat)\ ^{+0.3}_{-0.1}(syst)) \times 10^{-9}$	4.0σ	$(3.0\ ^{+1.0}_{-0.9}) \times 10^{-9}$	4.3σ
$Br(B^0_d \to \mu^+\mu^-) =$	$(3.7\ ^{+2.4}_{-2.1}(stat)\ ^{+0.6}_{-0.4}(syst)) \times 10^{-10}$	2.0σ	$(3.5\ ^{+2.1}_{-1.8}) \times 10^{-10}$	2.0σ
	$< 7.4 \times 10^{-10}$ at 95% CL		$< 1.1 \times 10^{-9}$ 95%CL	

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

Weighed B Average (not Likelihood Combination)

Significance

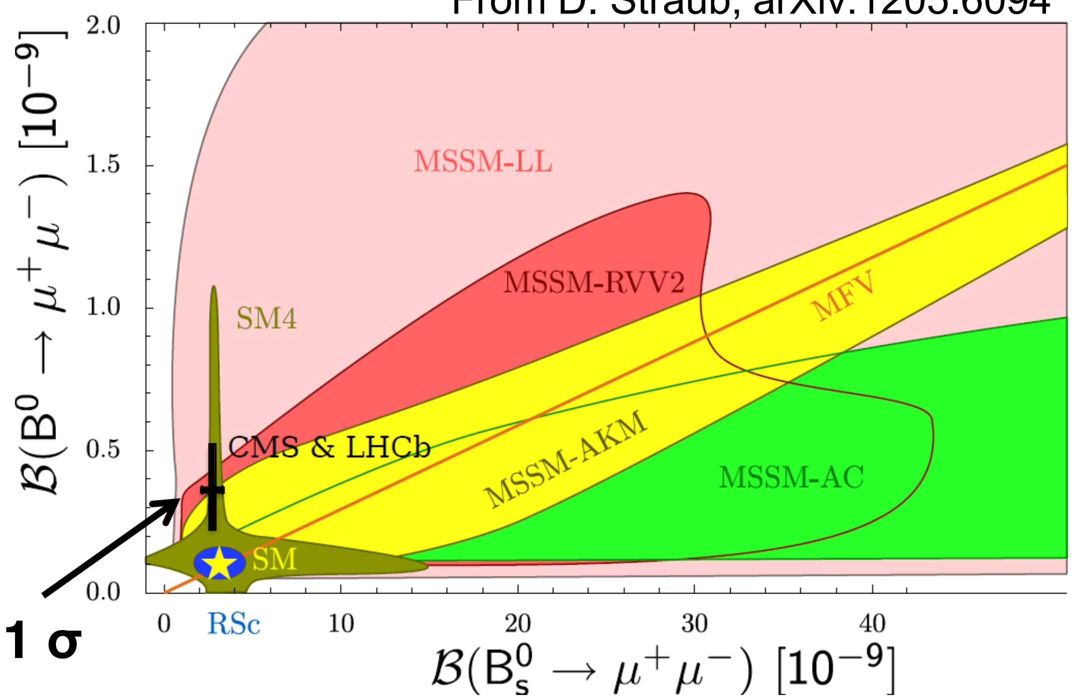
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) \stackrel{\text{LHC}}{=} (2.9 \pm 0.7) \times 10^{-9} \quad > 5\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) \stackrel{\text{LHC}}{=} (3.6^{+1.6}_{-1.4}) \times 10^{-10} \quad > 3\sigma$$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (3.56 \pm 0.30) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (1.07 \pm 0.10) \times 10^{-10}$$

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]

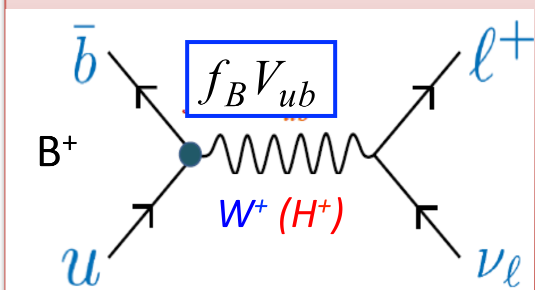
MSSM: Minimal SUSY flavour models
- AC: Agashe and Carone [Agashe and Carone, 2003]
- RVV2: Ross, Velasco-Sevilla and Vives [Ross et al., 2004]
- AKM10: Antusch, King and Malinsky [Antusch et al., 2008]
- LL11: left-handed currents only [Hall & Murayama, 1995]

(semi) leptonic decays with τ leptons

- B → τν and B → D(*)τν 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

$B \to \tau\nu$



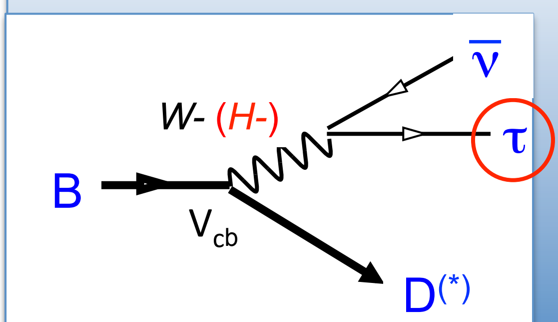
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \left(1 - \tan^2\beta \frac{m_{B\pm}^2}{m_{H\pm}^2}\right)$$

SM — Charged Higgs

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

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

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



Decays involving τ have additional helicity amplitude

Contribution from H± expected to enhance rates for B → D(*)τν

Test SM by measuring ratios (theoretically and experimentally cleaner)

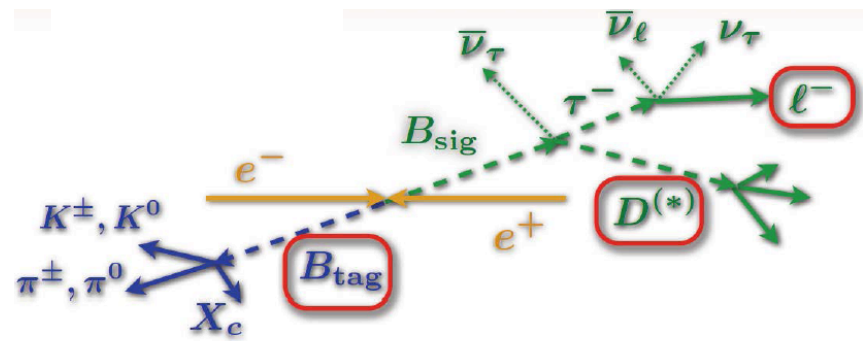
$$R(D) = \frac{\Gamma(\bar{B} \to D\tau\nu)}{\Gamma(\bar{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau\nu)}{\Gamma(\bar{B} \to D^*\ell\nu)}$$

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

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

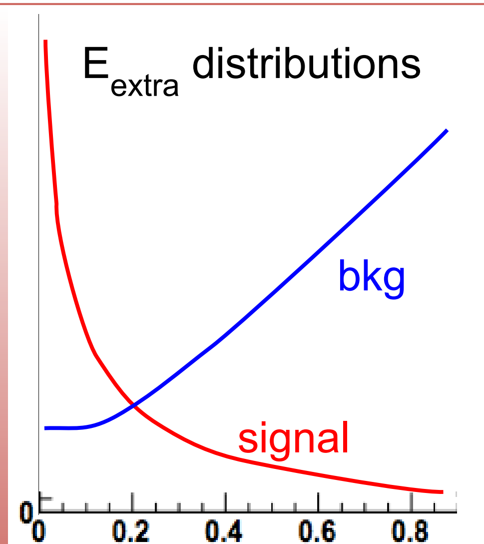
(semi) leptonic decays with taus

- 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



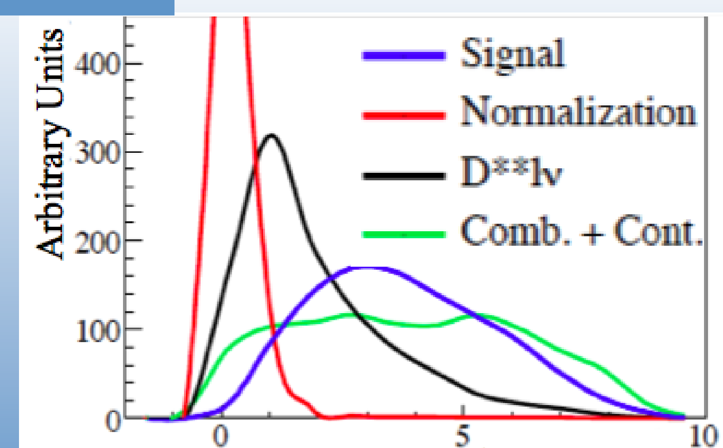
$B \to \tau\nu$

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



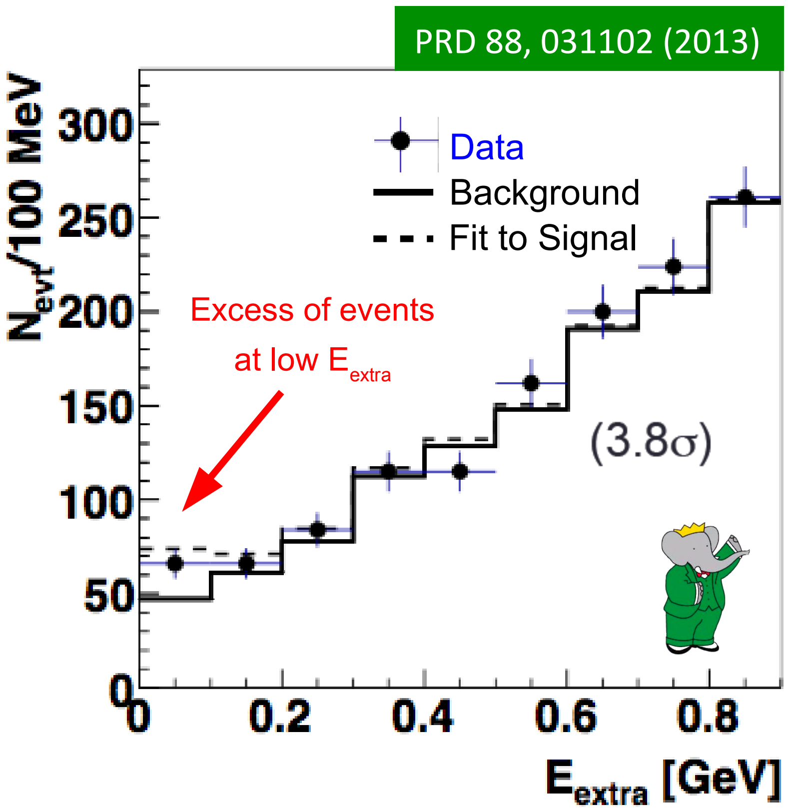
$B \to D^{(*)} \tau\nu$

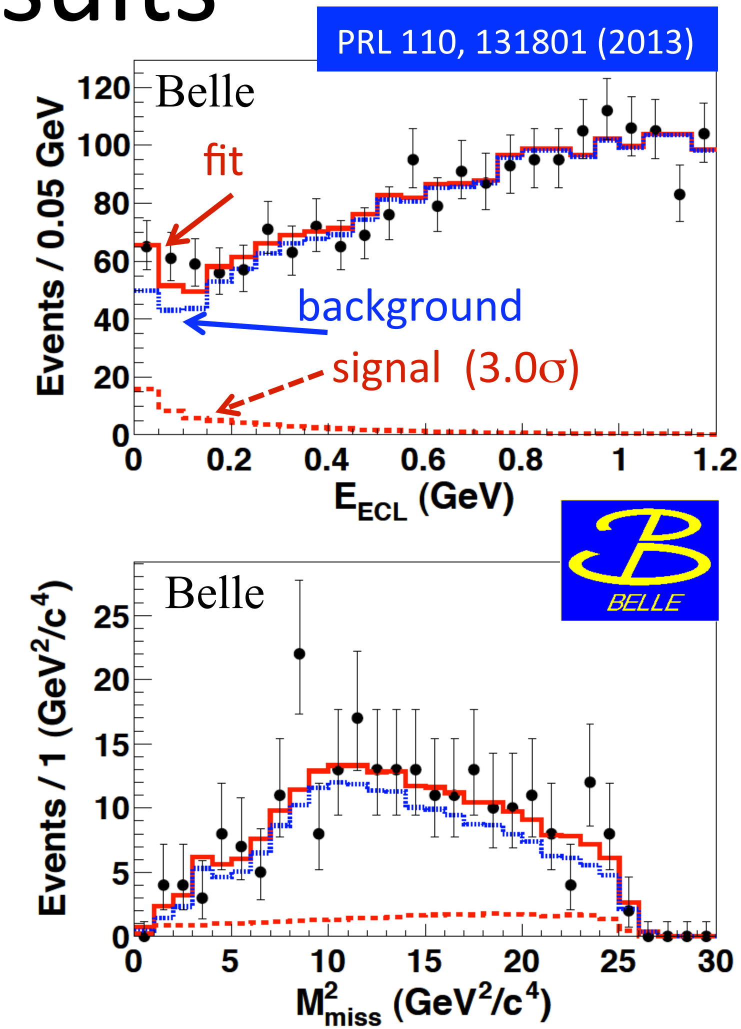
Squared missing mass



$$m^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}} - p_\ell\right)^2$$

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





62.1 ± 17.3 events, 426 fb^{-1}

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

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

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

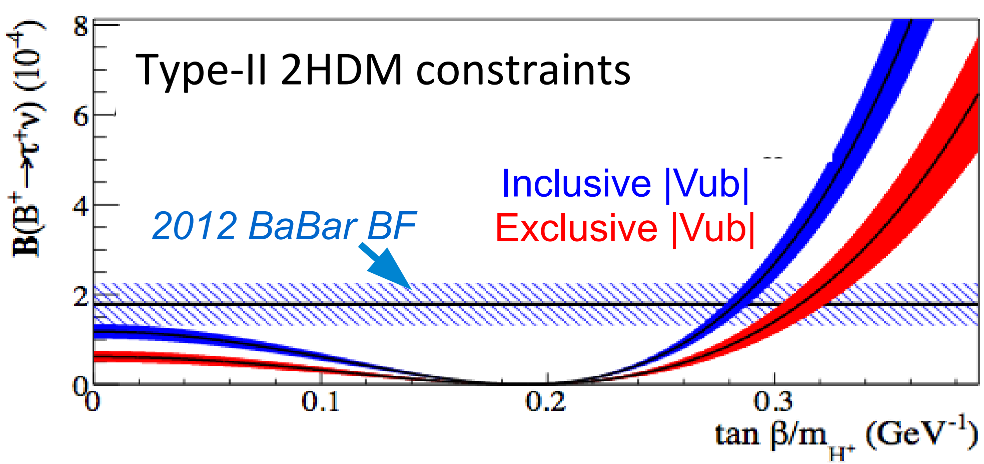
$B^+ \to \tau^+ \nu$: interpretation

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

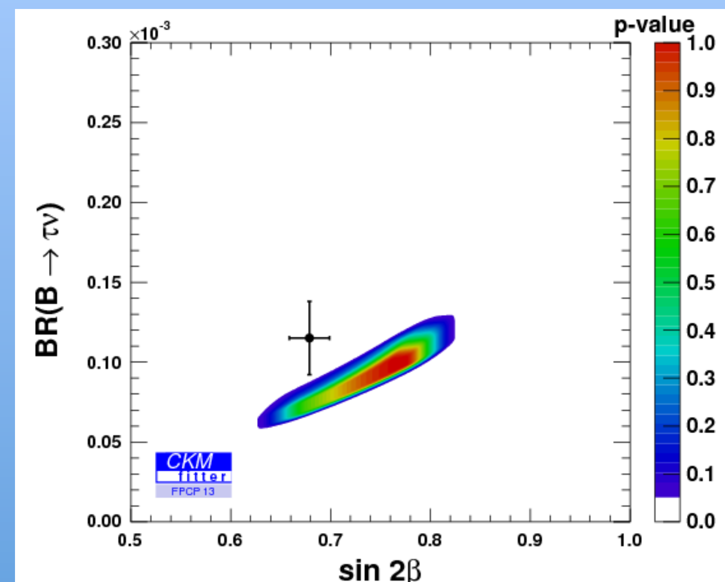
Experiment	Tag	Branching Fraction ($\times 10^{-4}$)
BABAR	hadronic	$1.83^{+0.53}_{-0.49} \pm 0.24$
BABAR	semileptonic [9]	$1.7 \pm 0.8 \pm 0.2$
Belle	hadronic	$0.72^{+0.27}_{-0.25} \pm 0.11$
Belle	semileptonic [11]	$1.54^{+0.38+0.29}_{-0.37-0.31}$

New average $\mathcal{B}(B \to \tau\nu) = (1.15 \pm 0.23) \cdot 10^{-4}$

SM $\mathcal{B}(B \to \tau\,\nu) = (1.01 \pm 0.29)$ x 10-4

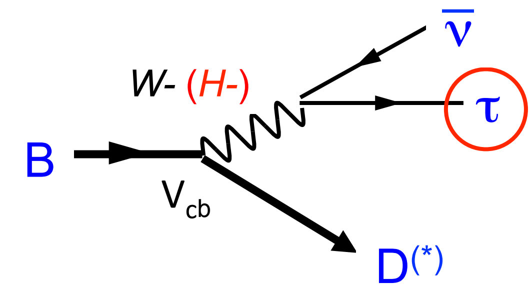


Fit to CKM parameters without $\mathcal{B}(B \to \tau\nu)$ and *sin2β* constraints



The Belle update of BR($B \to \tau\nu$) decreases the world average. Discrepancy in the CKM global fit between the world averages for $\mathcal{B}(B \to \tau\nu)$ and *sin2β* has been eased significantly.

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



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

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

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 $\mu^{\pm}$: No additional charged particles, E_{extra}<0.5GeV (no cut)
  - Background suppression by BDT (combinatorial BG and $D^{**}l\nu$)

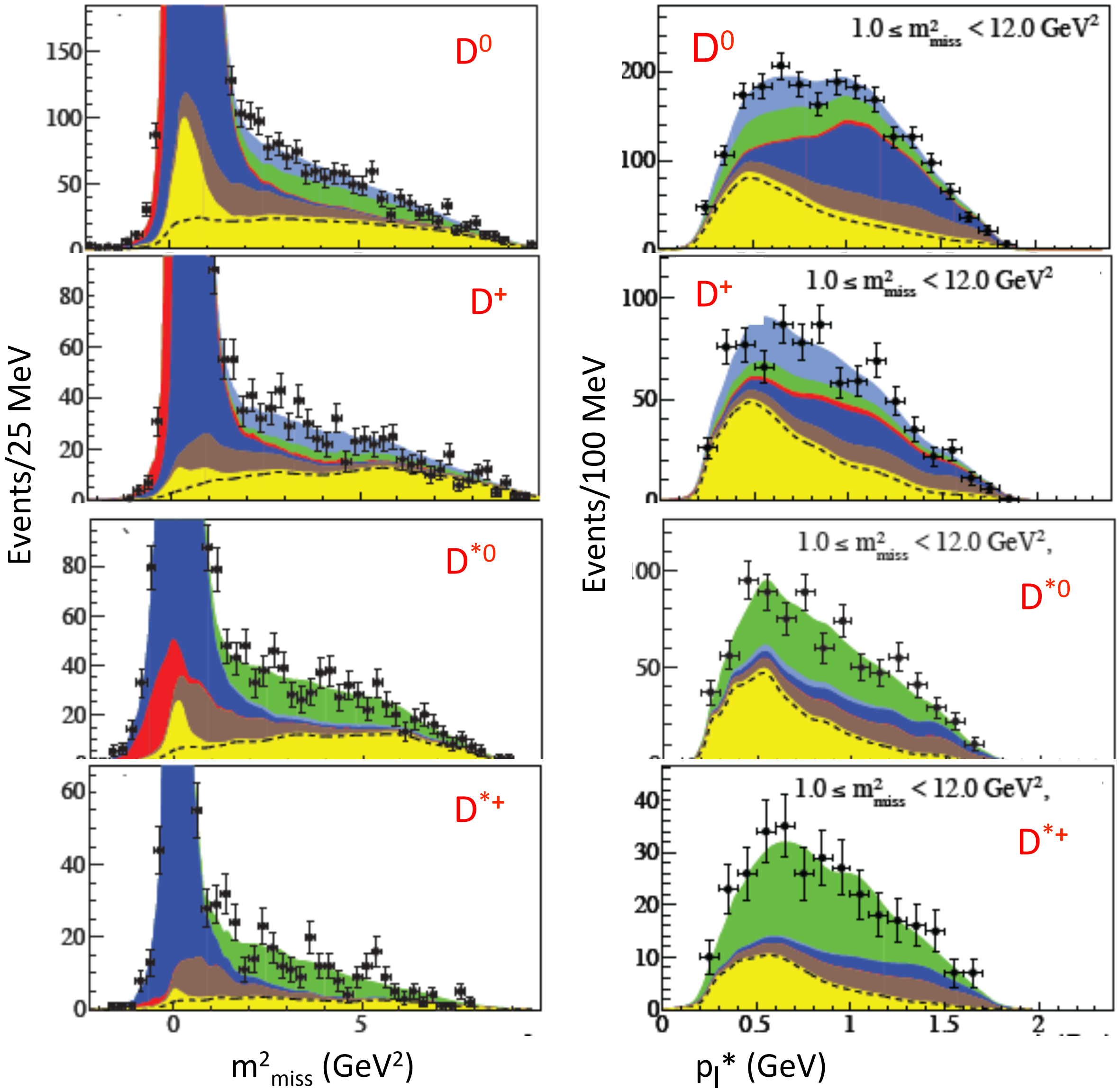
Signal extraction by unbinned M.L. fit, fully 2-dimensional: M^2_{miss} vs p^*_{lepton} ($e^{\pm}$,$\mu^{\pm}$)

D^0l, $D^{*0}l$, D^+l, $D^{*+}l$, ($e^{\pm}$ or $\mu^{\pm}$)

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

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

PRL101802 (2012)



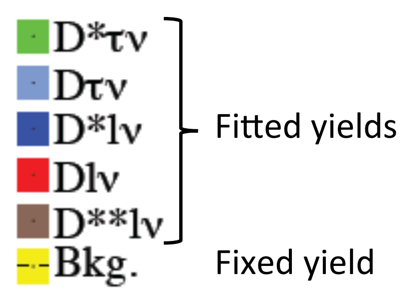
Fit results, combined using Isospin relations:

$B \rightarrow D\,\tau\,\nu$

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

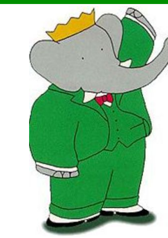


Results and implications on type-II 2HDM

$$R(D) = \begin{cases} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{cases} \Bigg\} \; 2.0\sigma$$

$$R(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{cases} \Bigg\} \; 2.7\sigma$$

PRL 101802 (2012)

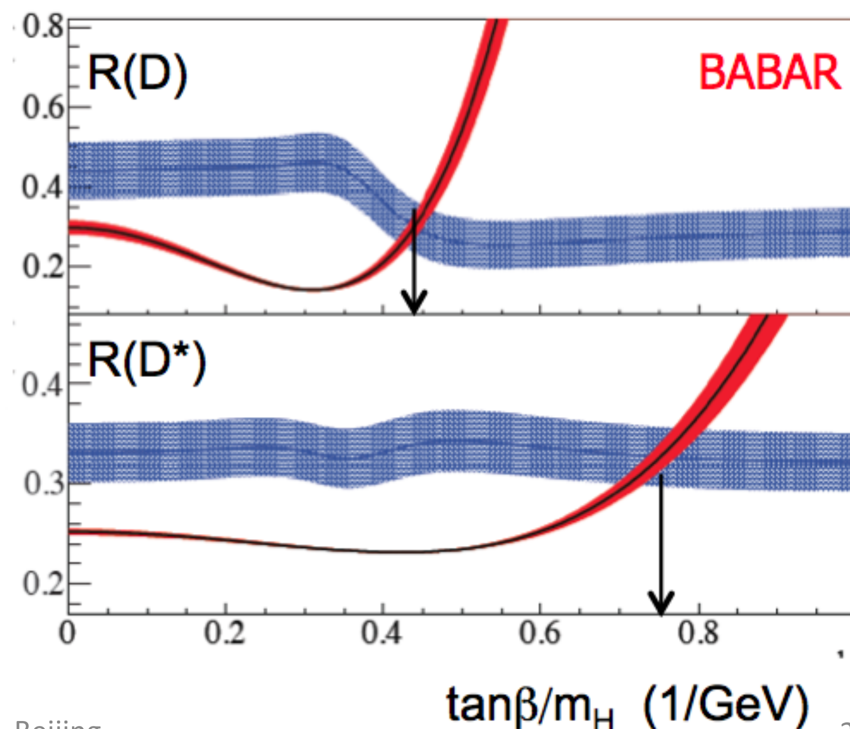


Combination of R(D) and R(D*) **excludes SM at 3.4σ**

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

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

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

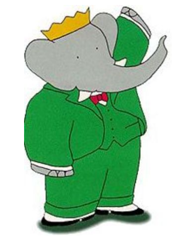


From the estimated effect of on the signal, the type II 2HDM can be excluded in the full tanβ - m_H parameter space at >99.8%, provided m_H>15 GeV.

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

arXiv:1303.0571 (2013)

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)

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

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

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

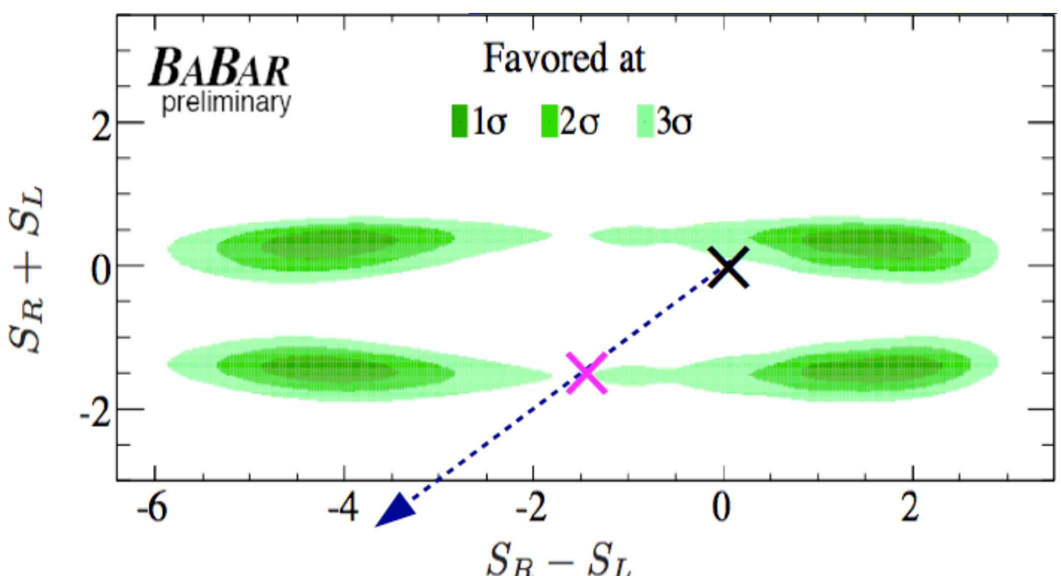
$$\mathcal{R}(D) = \mathcal{R}(D)_{\rm SM} + A'_D {\rm Re}(\boldsymbol{S_R} + \boldsymbol{S_L}) + B'_D |\boldsymbol{S_R} + \boldsymbol{S_L}|^2$$

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

- Type-II 2HDM is recovered if $S_R = -m_b m_\tau \tan^2\beta / m^2_{H+}$, $S_L = 0$.

Type III
- 4 solutions for real S_R, S_L values.
- Complex values alo allowed

Type-II has no solutions!



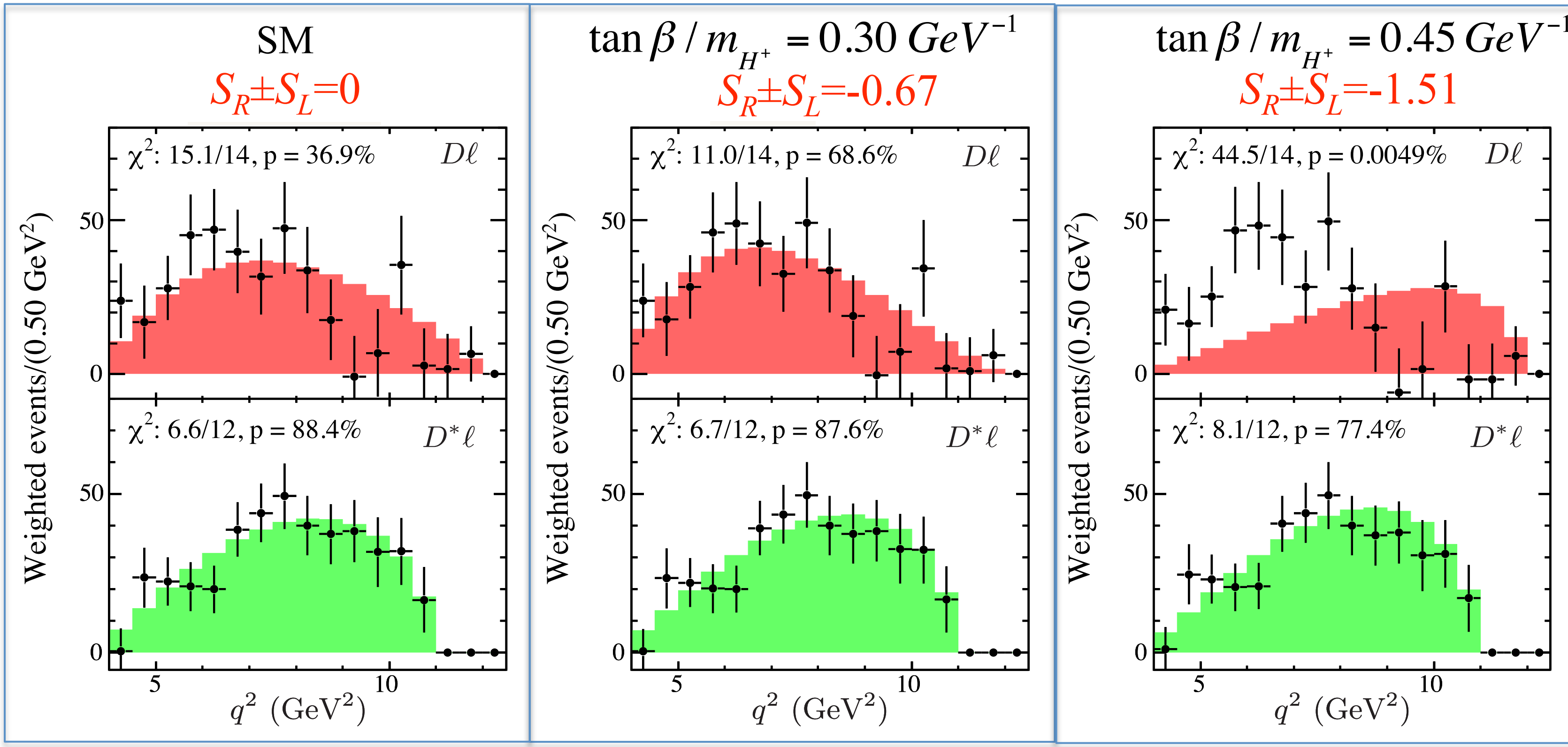
- - Type-II: $S_R + S_L = S_R - S_L$

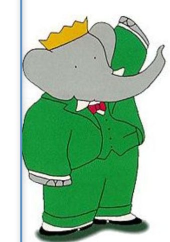
× SM value

× Measured value for R(D) in Type-II: $S_R \pm S_L$ = -1.51

Adding info from q^2 distributions

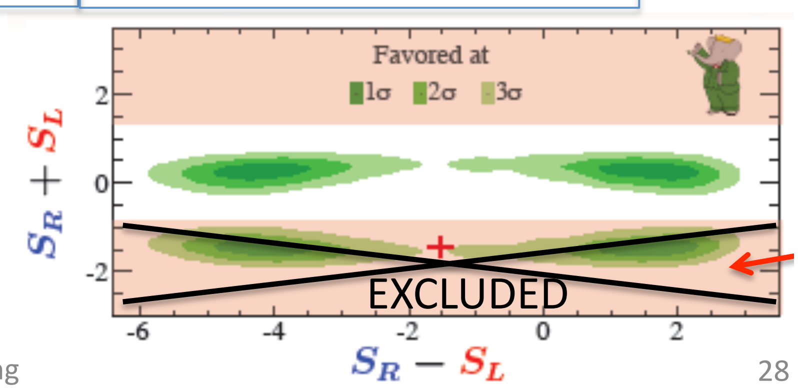
Dilepton squared invariant mass q^2 is sensitive to Higgs couplings to quarks





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

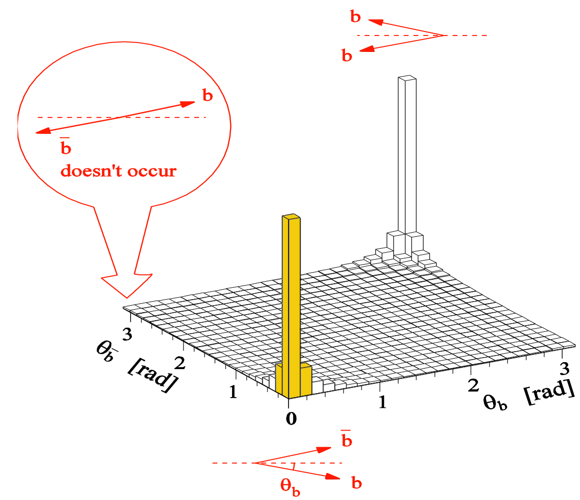


Conclusion

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

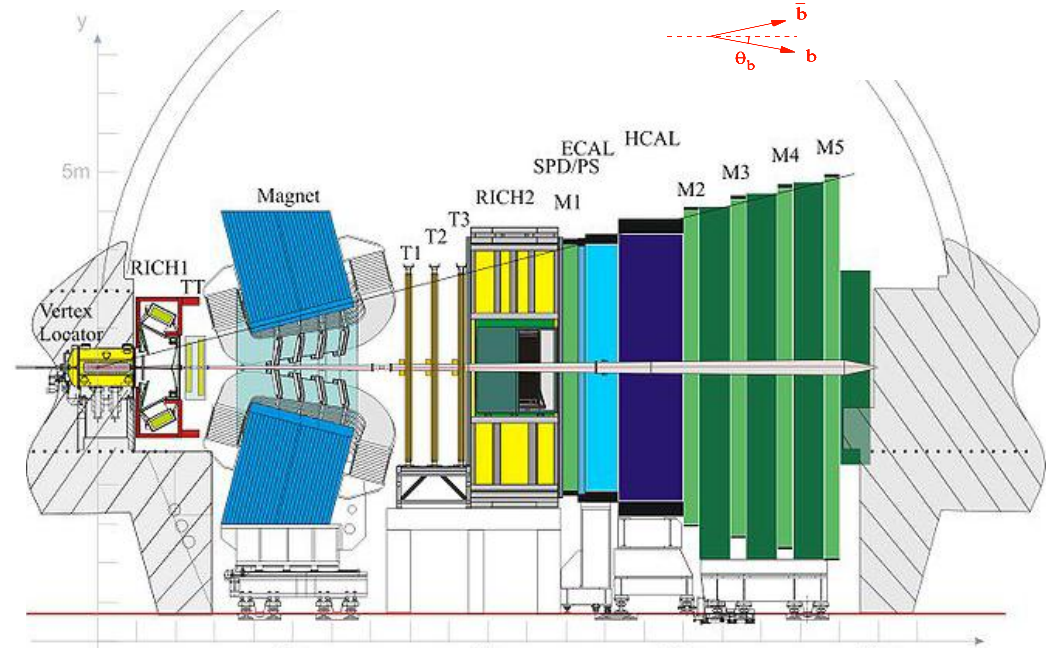
LHCb



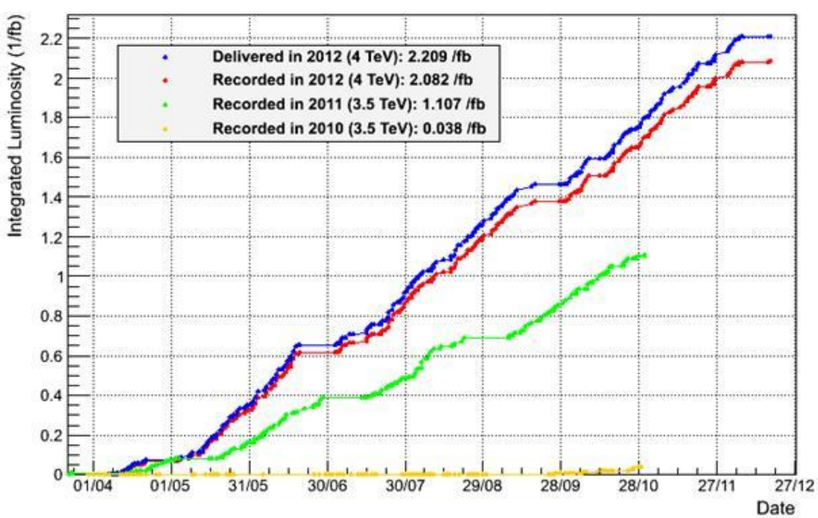
Forward spectrometer optimised for heavy flavour physics at the LHC

- Large acceptance 2<η<5
- Low trigger thresholds
- Precise vertexing
- Efficient particle identification
- Running at a constant luminosity of $4x10^{32}$ $cm^{-2}s^{-1}$, <μ>~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 ~1cm)
- Huge production cross section (~300μb)
- Small S/B ratio

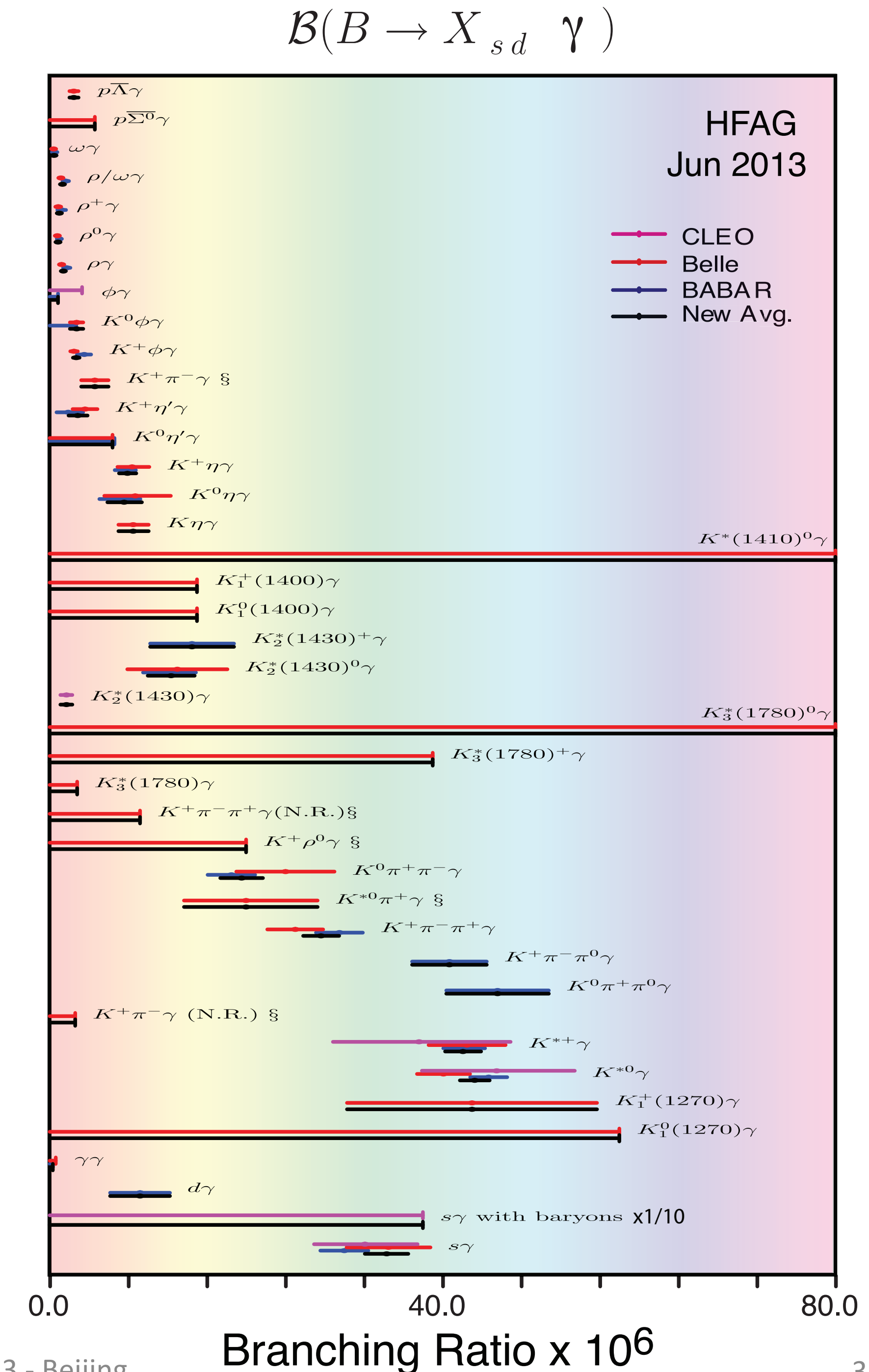
$B \to X_s \gamma$

- The inclusive decay has been precisely measured at B Factories

$BR(b \to s\gamma) = (3.43 \pm 0.22) \times 10^{-4}$
in agreement with the SM prediction
$BR_{SM}(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$

- 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

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

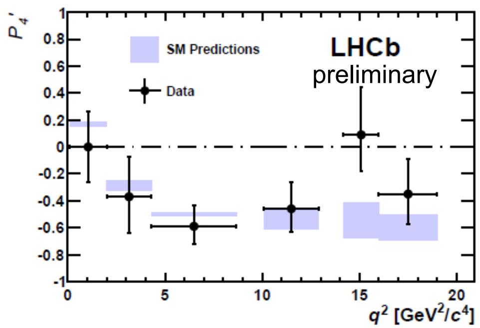


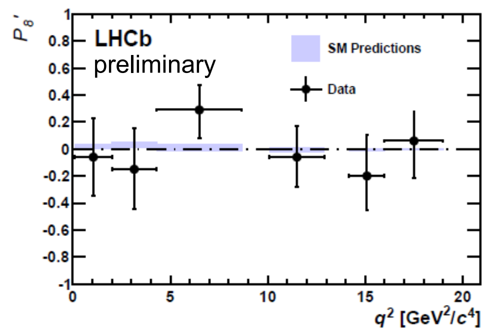
B→K*μμ: new observables

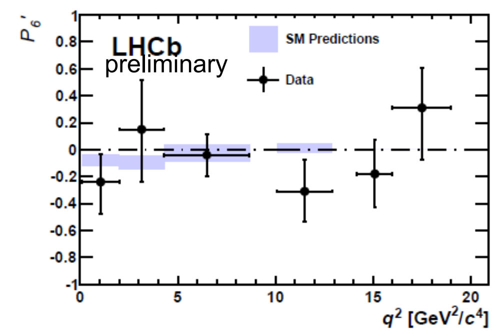
LHCb, arXiv:1308.1707

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

Good agreement for some observables

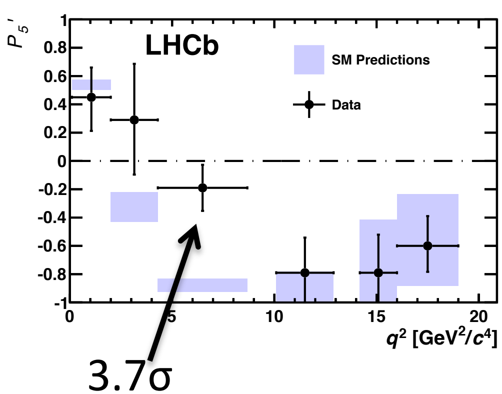


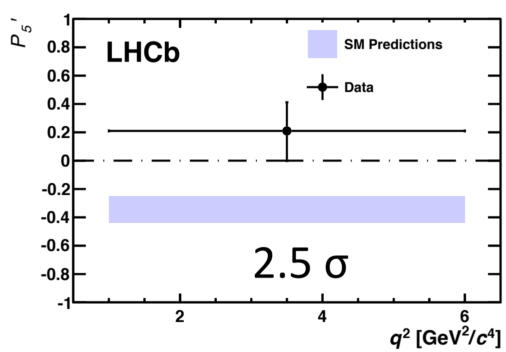


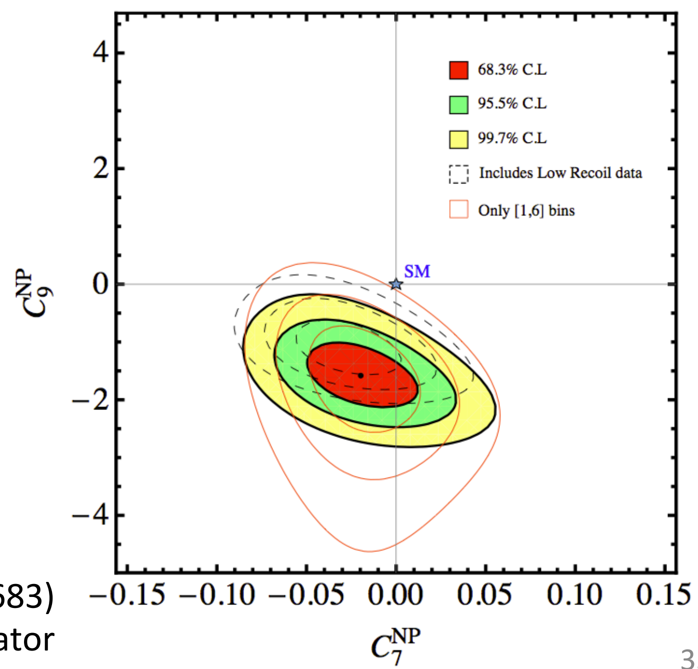


SM predictions from J. Matias et al, arXiv:1303.5794

some local discrepancies for others





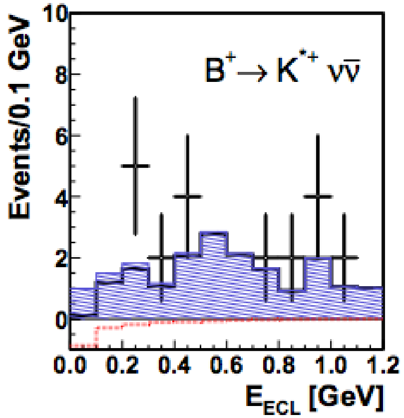


Descotes--Genon et al. (arXiv:1307.5683)

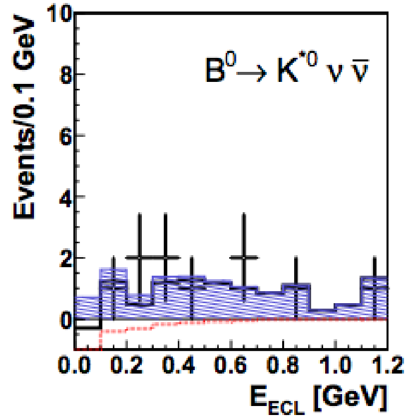
large New Physics contribution to the Wilson coefficient of the O_9 operator

B→hνν

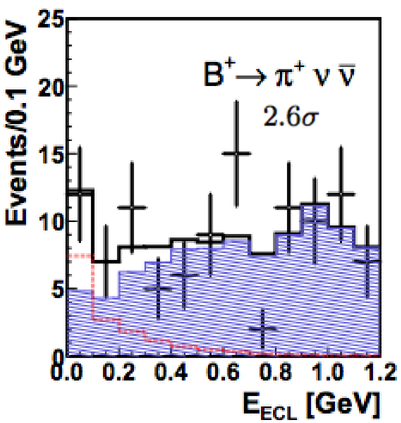
PRD 87, 111103 (2013) 772 BB



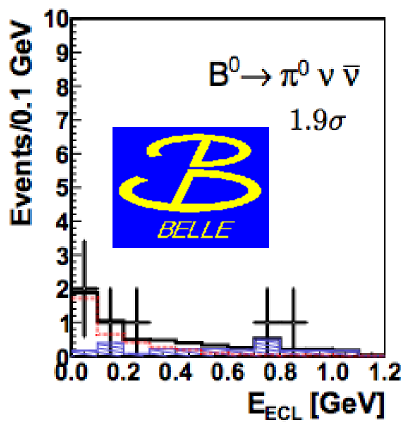
$N_{sig} = -1.7^{+1.7}_{-1.1}(\text{stat}) \pm 1.5(\text{syst})$



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



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



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

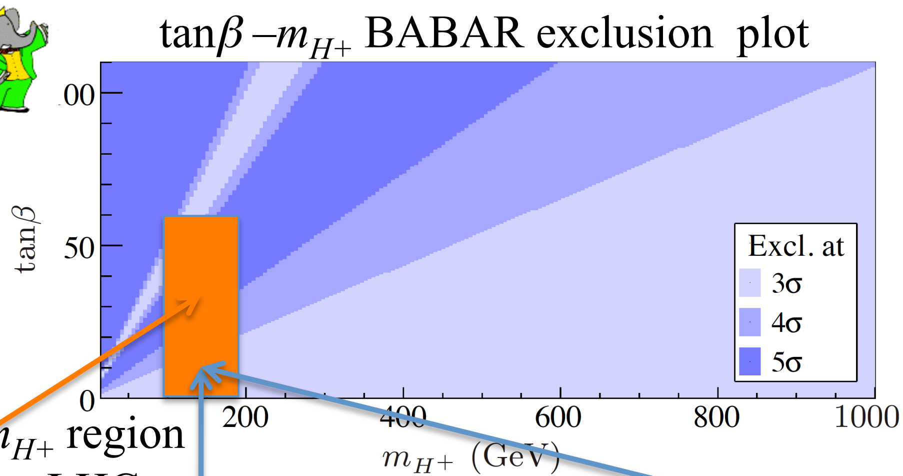
x10^{-5}

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

Best Limits to date

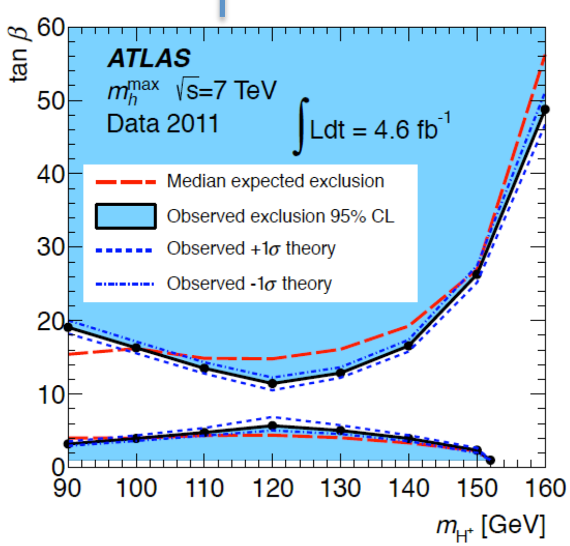
- B→K*νν limits within factor of ~5 of SM predictions (0.7-1.3x10^{-5})
- Uniquely at B Factories!
- Predict measurement with ~20% precision at Belle II with 50ab^{-1}

Type II 2HDM: compare with direct searches @ LHC

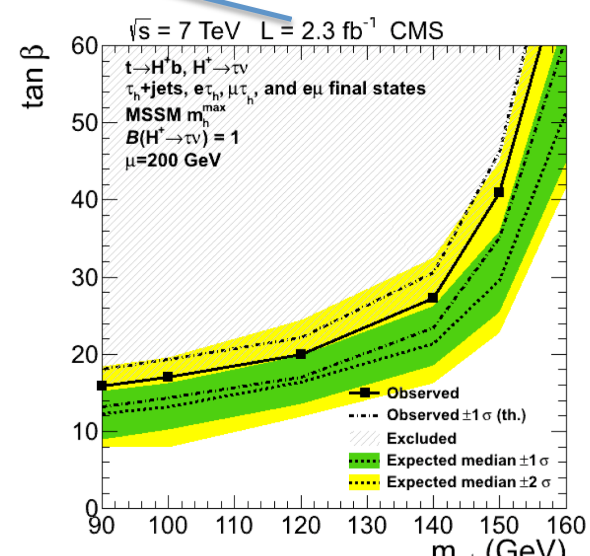


$\tan\beta - m_{H+}$ region probed at LHC

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



ATLAS: JHEP 1206, 039 (2012)



CMS: JHEP 07, 143 (2012)