# Rare and Radiative Penguin B Decays: Experimental Status

Flavour Working Group

LTS1 2014
Long Term Strategy of INFN-CSN1
Elba
22/5/2014

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INFN, Pisa

# Outline

Very selective…

- $B \to X_s l^+ l^-$
- $B_s, B^0 \to \mu\mu$
- $B \to X_s \gamma$
- Brief mention of a few other interesting channels
- Projections

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

# $B \to K^* l^+ l^-$: Observables

## "Traditional"

- The more complex final state leads to additional observables:
  - $A_{FB}$, the forward-backward lepton asymmetry
  - $s_0$, the $A_{FB}$ zero crossing: this observable has particularly low theoretical uncertainties, thanks to cancellations
  - $R_{K(*)}$, the ratio of $B \to K(*)\mu\mu / B \to K(*)ee$
  - $F_L$, the K* longitudinal polarization fraction in $B \to K^* ll$

## "Optimized"

- Optimized for K*μμ physics (LHCb):
  - based on full angular analysis of K*μμ decay
  - ratios of coefficients such that form factor uncertainties cancel
  - several versions have been proposed, *P*$_i$' have been measured experimentally

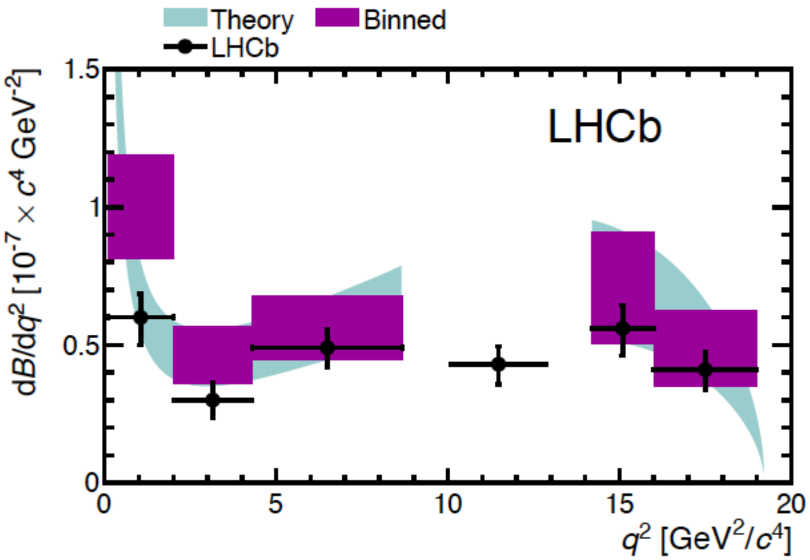
Differential decay rate for $B \to K^* l^+ l^-$

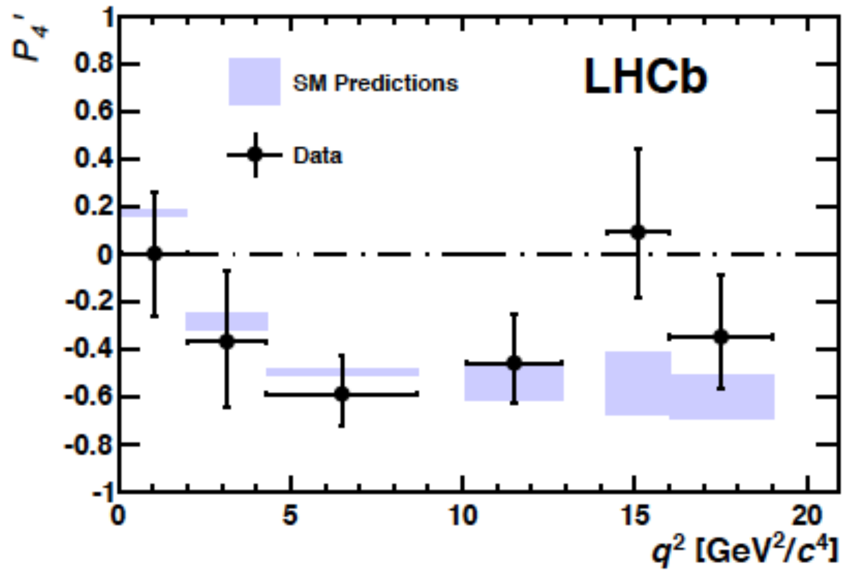
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

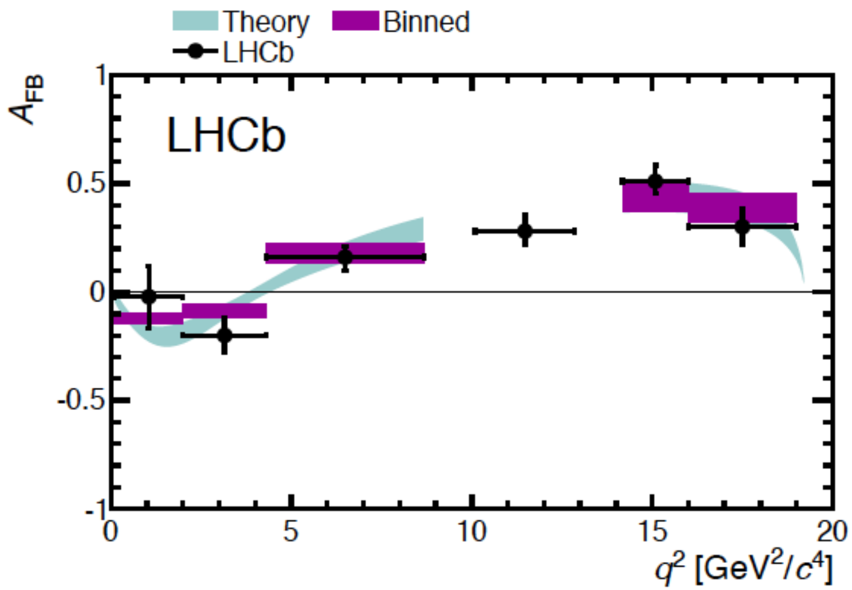
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

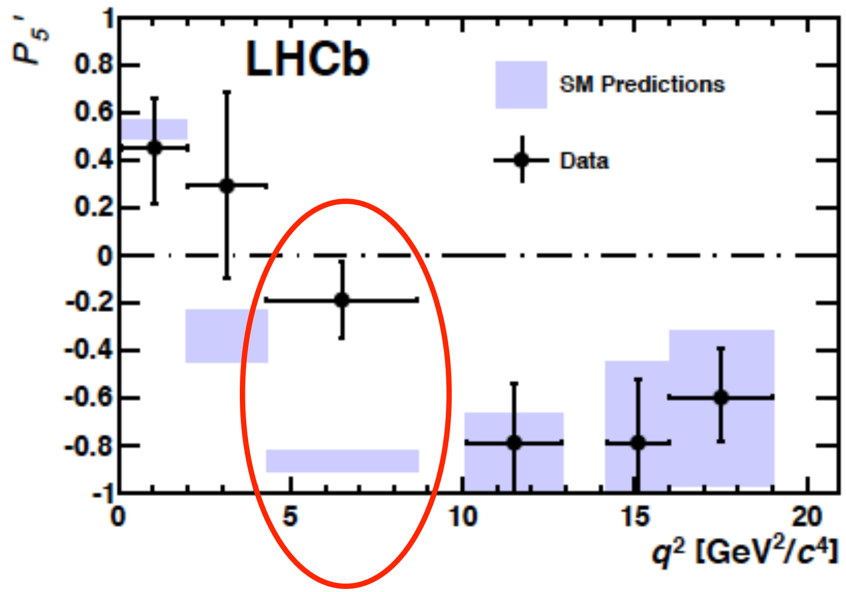
# $B \to K^* \mu^+ \mu^-$ @ LHCb

based on 1 $fb^{-1}$



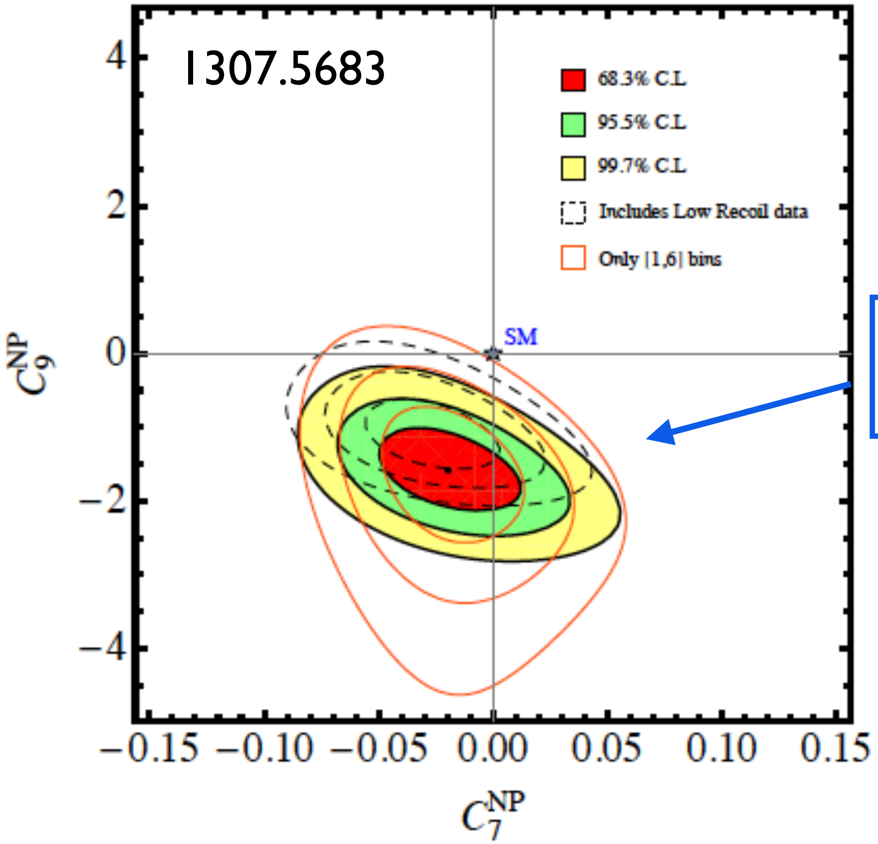



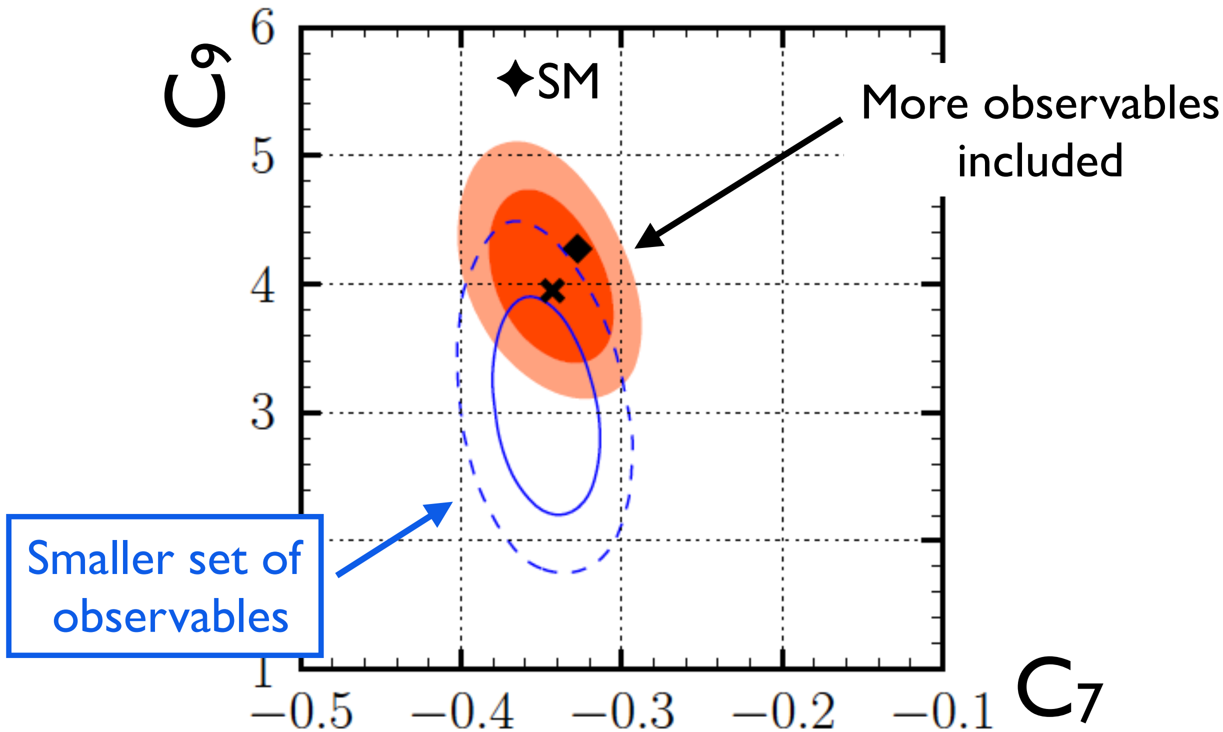




*3.7σ anomaly*

# Global fits to Wilson coefficients

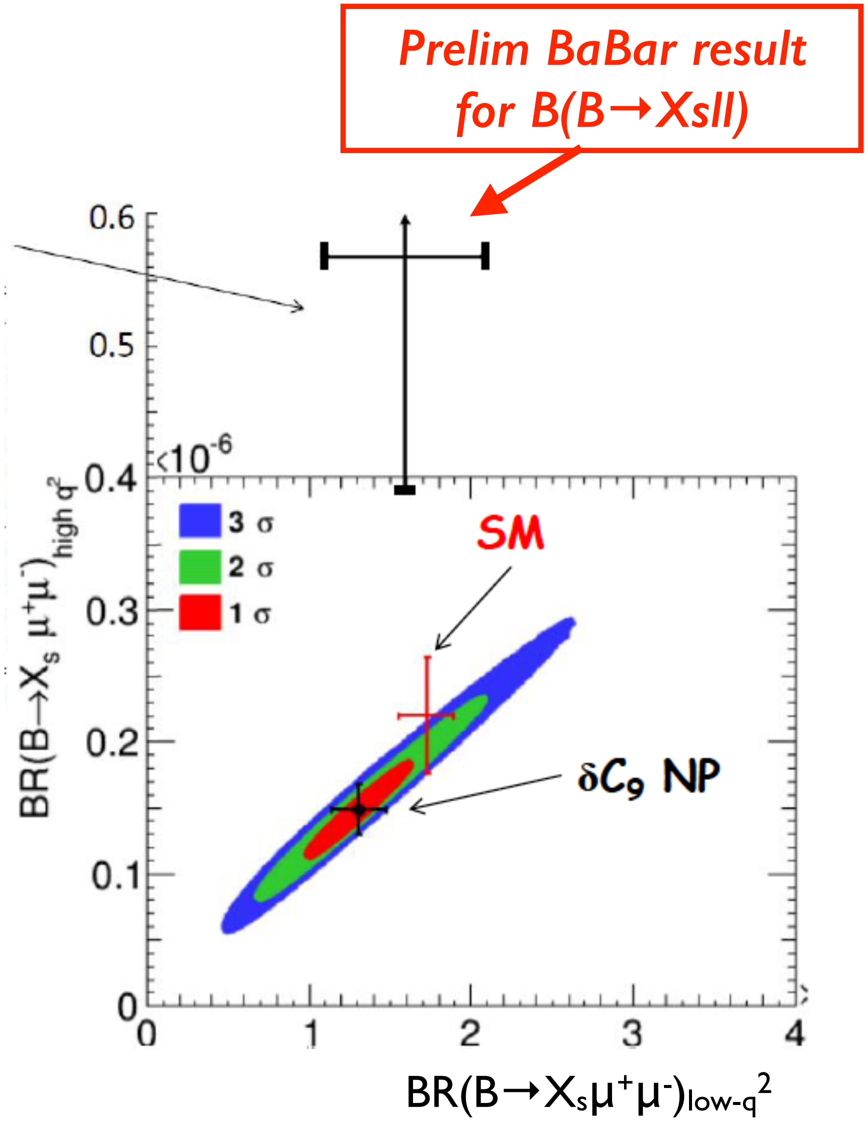



| Channel | Constraints | Kinematics | Source | Selection |
|---|---|---|---|---|
| $B \to X_s\gamma$ | $\mathcal{B}$ | $1.8\,\text{GeV} < E_\gamma$ | [1, 2] | ✓ |
| $B \to X_s\ell^+\ell^-$ | $\mathcal{B}$ | $q^2 \in [1, 6]\ \text{GeV}^2$ | [3, 4] | ✓ |
| $B_s \to \mu^+\mu^-$ | $\int d\tau\mathcal{B}(\tau)$ | – | [5, 6] | ✓ |
| $B \to K^*\gamma$ | $\mathcal{B}$, $S$, $C$ | – | [7–11] | ✓ |
| $B \to K\ell^+\ell^-$ | $\mathcal{B}$ | $q^2 \in [1, 6], [14.18, 16], [> 16]\ \text{GeV}^2$ | [12–14] | — |
| | | $q^2 \in [1, 6], [14.18, 16], [16, 18], [18, 22]\ \text{GeV}^2$ | [15] | — |
| $B \to K^*\ell^+\ell^-$ | $\mathcal{B}$ | $q^2 \in [1, 6], [14.18, 16], [> 16]\ \text{GeV}^2$ | [12–14, 16, 17] | — |
| | $F_L$ | –"– | [12–14, 16–18] | — |
| | $A_{FB}$ | –"– | [12–14, 16–18] | † |
| | $A_T^{(2)}$ | –"– | [14, 16] | † |
| | $A_T^{re}$, $P'_{4,5,6}$ | –"– | [16, 19] | † |
| $B$ properties | $M_{B^*} - M_B$ | – | [54] | ✓ |
| $B \to K$ form factor | $f_+$ | $q^2 = 17, 20, 23\ \text{GeV}^2$ | [50] | — |
| $B \to K^*$ form factors | $V/A_1$ | $q^2 = 0\ \text{GeV}^2$ | large energy limit | ✓ |
| | $A_0$ | $q^2 = 0\ \text{GeV}^2$ | [35] | ✓ |
| | $V$, $A_1$, $A_{12}$ | $q^2 = 15, 19.21\ \text{GeV}^2$ | [51] | — |

# Inclusive $B \to X_s l^+ l^-$ can help…

- Inclusive BF of $B \to X_s l^+ l^-$ also depends on $C_9$
- Plot BF in high $q^2$ region vs. BF in low $q^2$ region
  - Colored ellipses: from global fit to K*ll data
  - Red cross: SM calculation
  - Black cross: central value of global fit but error bars from expected results from current B-factories
- Preliminary Babar result does not favor $\Delta C_9$ from global fit



# More $B \to X_s l^+ l^-$ observables

- Besides the observables derived from an angular analysis of $K^* \mu\mu$, there are others that are important as well:
  - Isospin asymmetry $A_I$
  - $s_0$ the $A_{FB}$ zero-crossing point
  - $R_{K(*)}$ the ratio of $B \to K(*)\mu\mu$ to $B \to K(*)ee$
  - direct $A_{CP}$
- Relevant also for the exclusive K ($B \to K\mu\mu$) and electron ($B \to K^{(*)}ee$) modes, as well as the inclusive process, $B \to X_s l^+ l^-$

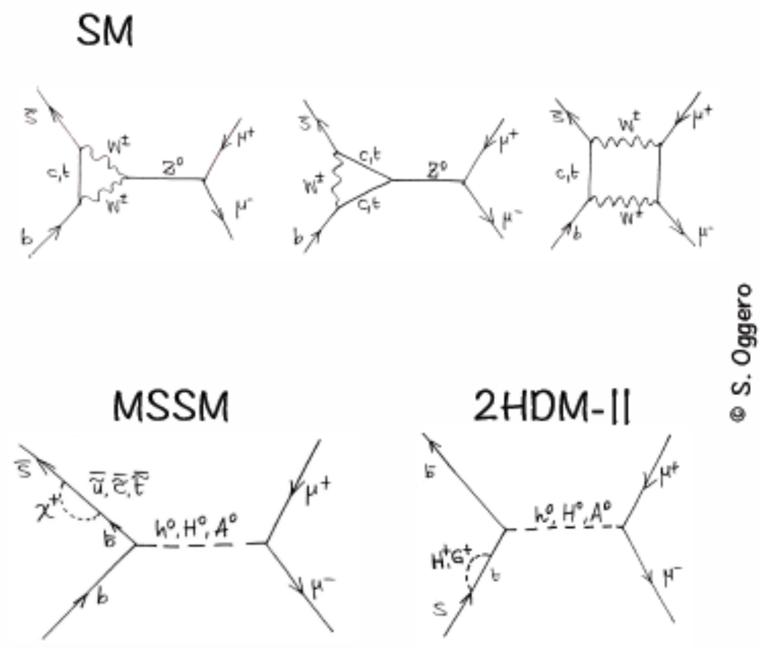
# $B_s^0, B^0 \rightarrow \mu\mu$

# $B_s \to \mu\mu$ and $B_d \to \mu\mu$

Very rare decays in SM:

- no tree-level FCNC
- helicity suppression
- CKM suppresion

... none of which is necessarily true in NP!




Precise SM predictions

- $Br(B_d \to \mu\mu) = (1.1 \pm 0.2)\ 10^{-10}$
- $Br(B_s \to \mu\mu) = (3.5 \pm 0.2)\ 10^{-9}$

Buras et al, EPJ C72 (2012) 2172; see also PRL109 (2012) 041801

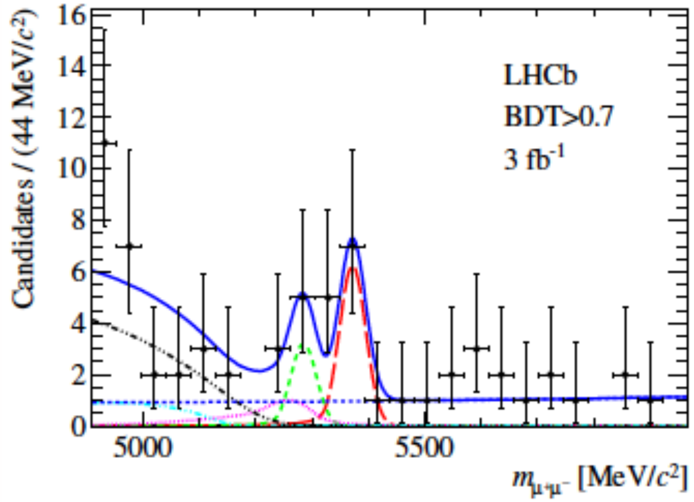
Strong enhancement in e.g. MSSM: $Br \propto \tan^6\beta$

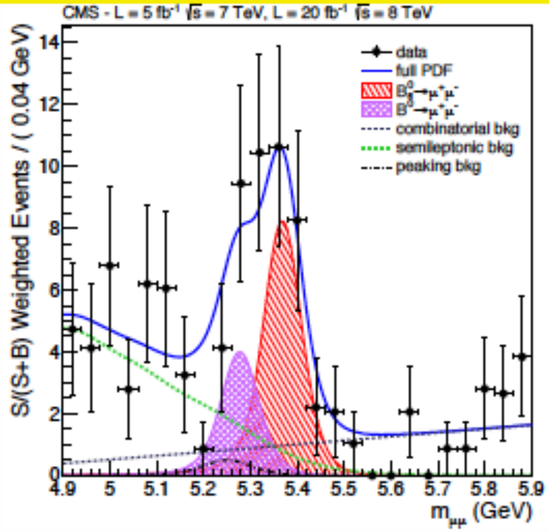
Previously known as the “golden channel” for NP discovery ... more recently named the “SUSY killer”!

# EPS2013: LHCb/CMS joint discovery of $B_s \to \mu^+\mu^-$

LHCb: arXiv:1307.5024, PRL.111.101805 (2013)

CMS: arXiv:1307.5025, PRL. 111.101804 (2013)




$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}) \times 10^{-10}$$

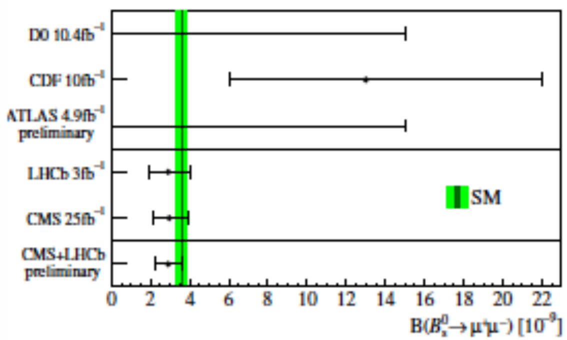
--> 4.0σ

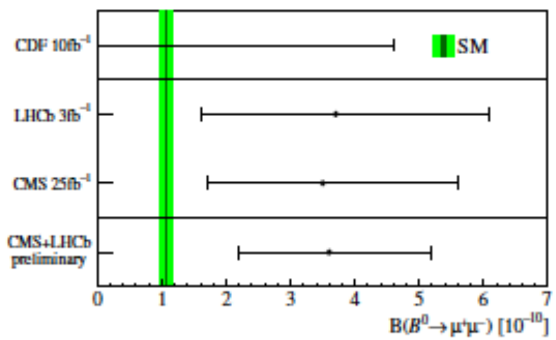
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8}) \times 10^{-10}$$

--> 4.3σ

combination:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathrm{BR}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}$$

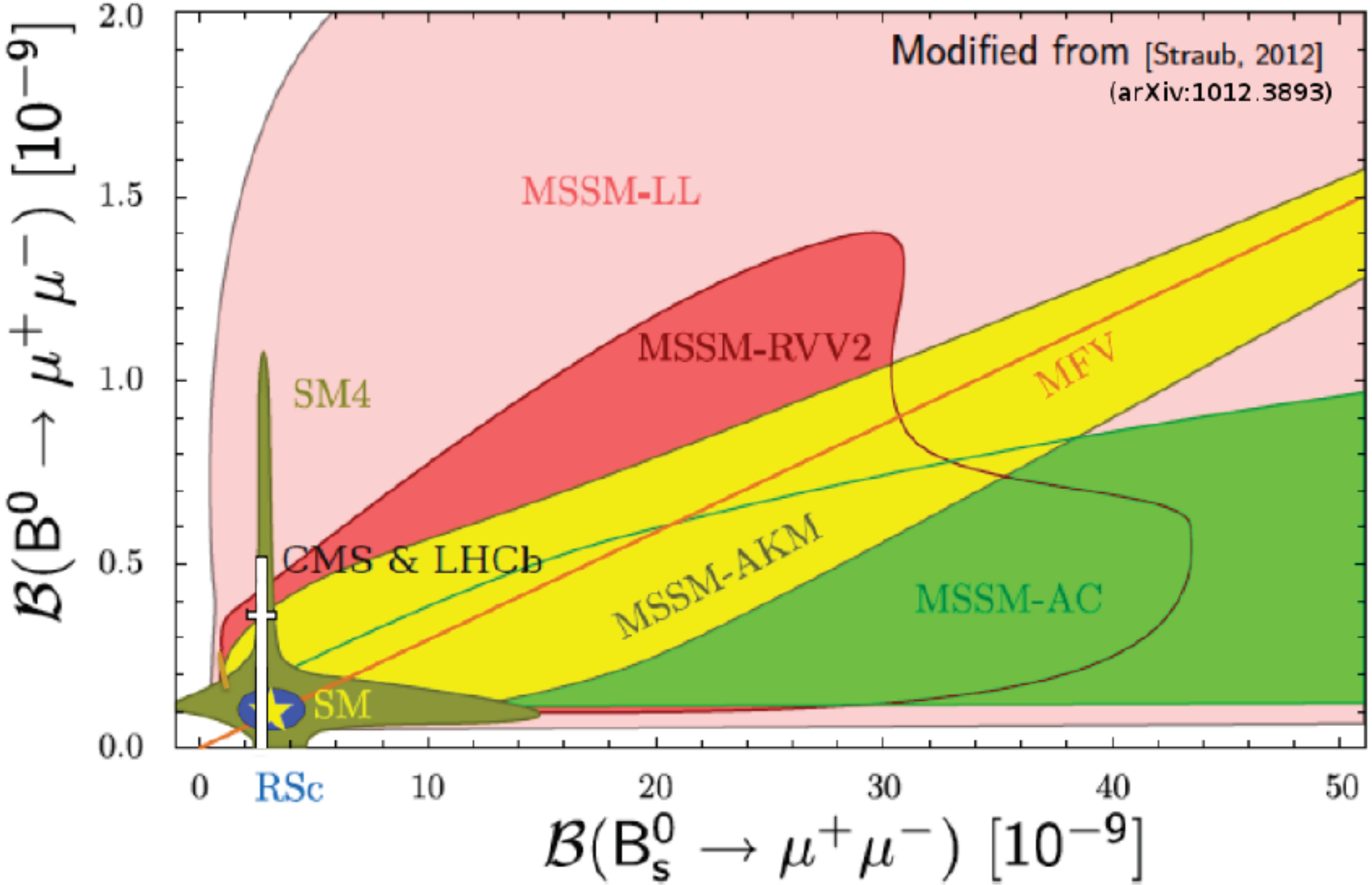



CMS-PAS-BPH-13-007 ; LHCb-CONF-2013-012

*W. Hulsbergen*
*Dec 2013, Puri, India*

# $B^0/B^0_s \to \mu\mu$, the golden ratio




*V.V. Gligorov*
*Jan 2014*

# $B \to X_s \gamma$

# $B \to X_s \gamma$: Inclusive BF: general observations

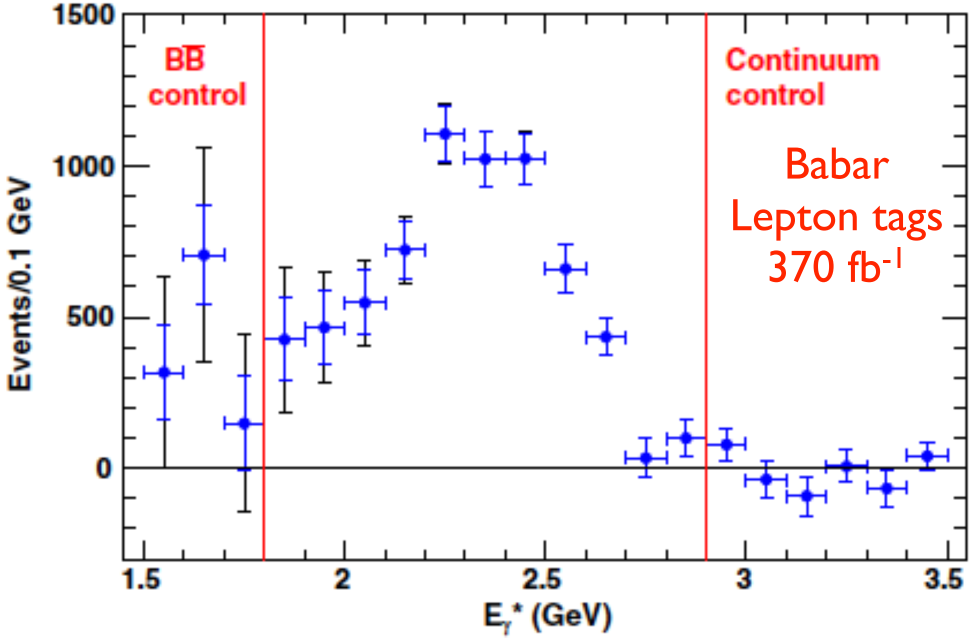
- SM calculation at NNLO (~10k diagrams) [hep-ph/0609232]. Quite precise (~7%):

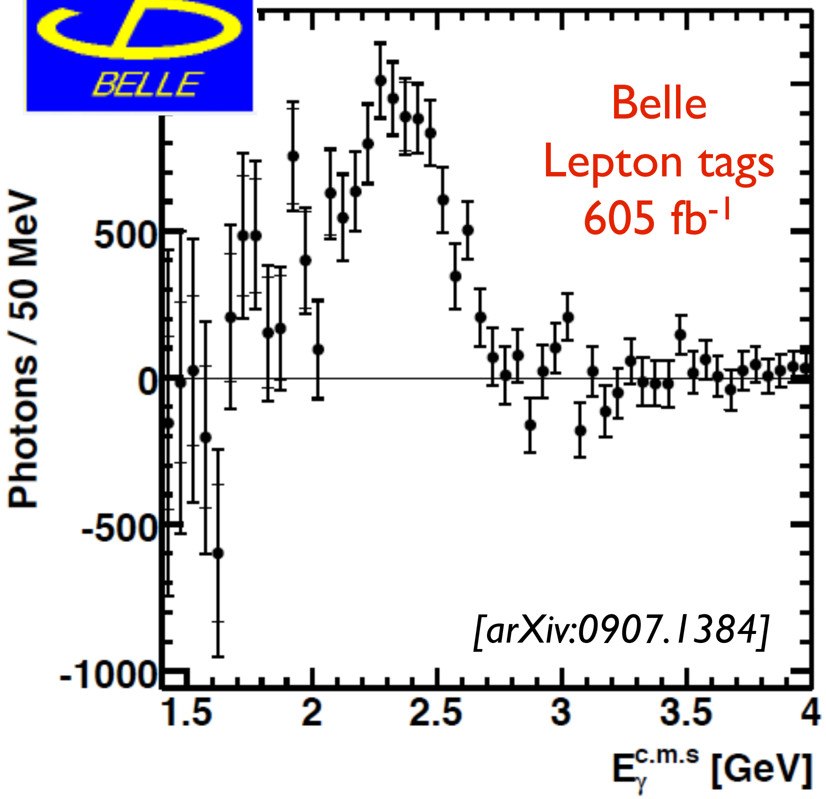
$$\mathcal{B}(B \to X_s\gamma)|_{E_\gamma > 1.6\ \mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$

- Very powerful in constraining NP models, historically and still very relevant.
- Inclusive measurement is preferred → allows comparison with precise SM prediction for inclusive rate
- Experimentally challenging:
  - fully inclusive: large irreducible background from $B \to X\pi^0(\to\gamma\gamma)$
  - sum-of-exclusive technique: problem of missing channels
- Current status of uncertainties: comparable statistical and systematic errors
  - but a large fraction of systematic error is statistical in nature (for some measurements)

# $B \to X_s\gamma$: Inclusive BF

[PRD 86, 112008 (2012)]




*HFAG experimental average:*

$$\mathcal{B}(B \to X_s\, \gamma) = (3.42 \pm 0.21_{\text{exp}} \pm 0.07_{\text{model}}) \times 10^{-4}$$

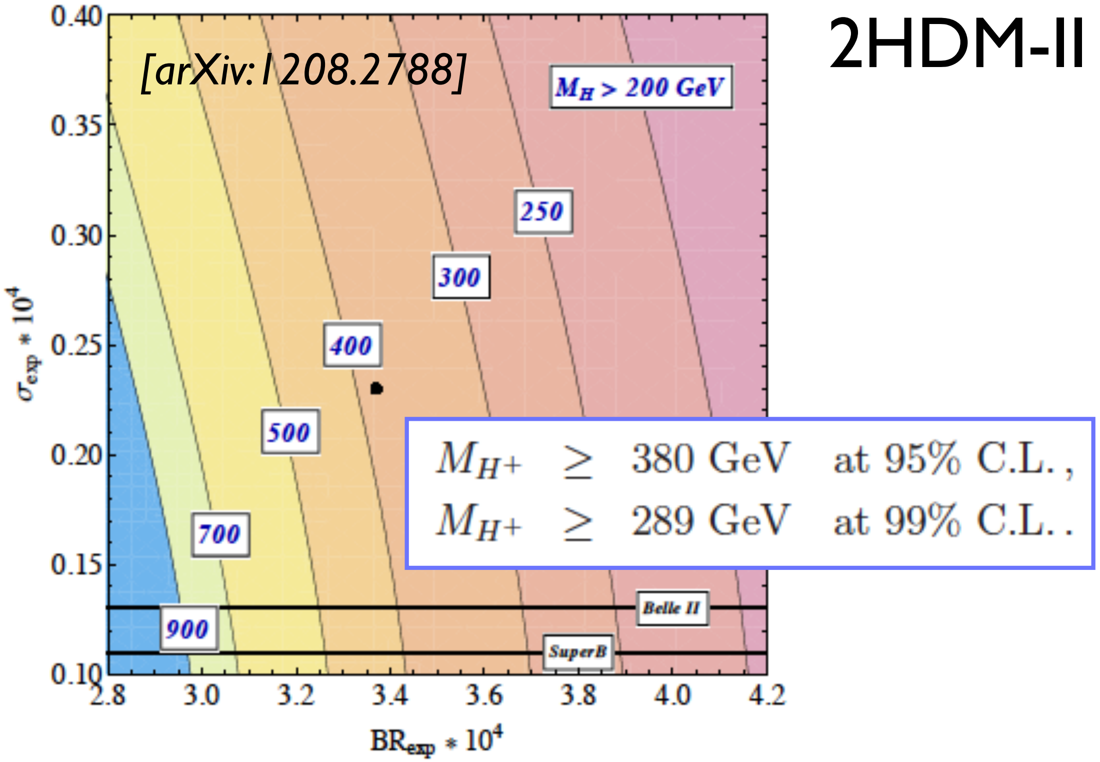
*Standard Model theory:*

$$\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

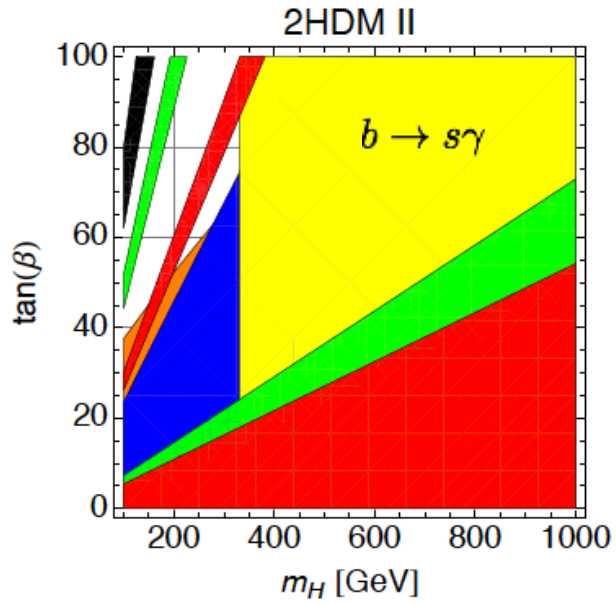
*B-factories only*

- Other inclusive observables:
  - isospin asymmetry
  - direct CP asymmetry
  - isospin/CP asymmetry
  - $B(B\to X_d\gamma)/B(B\to X_s\gamma)$

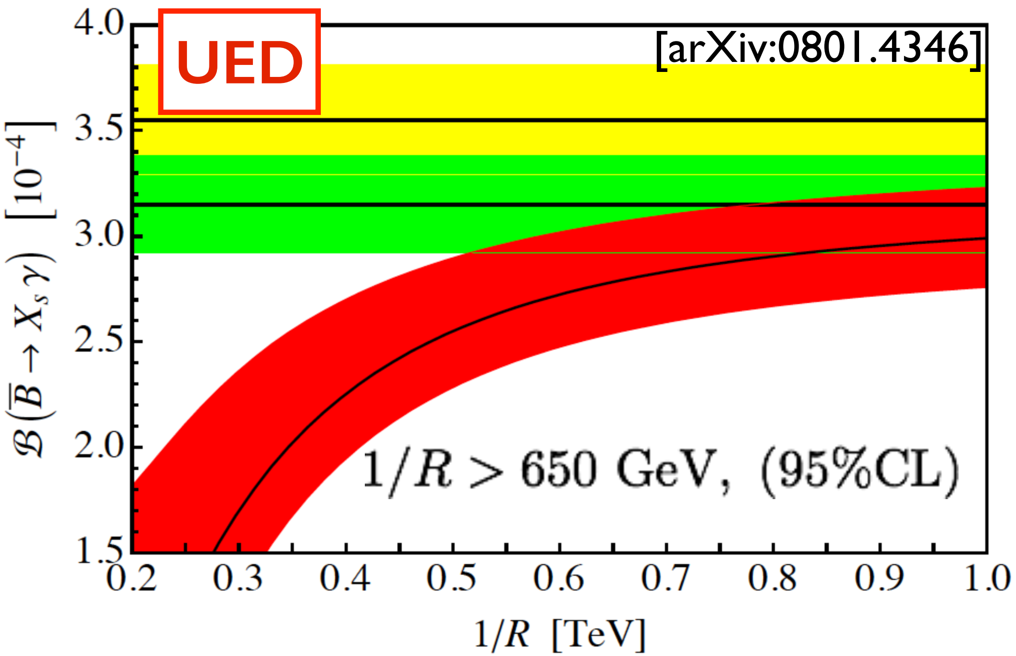
# B→$X_s\gamma$: Inclusive BF → contraints



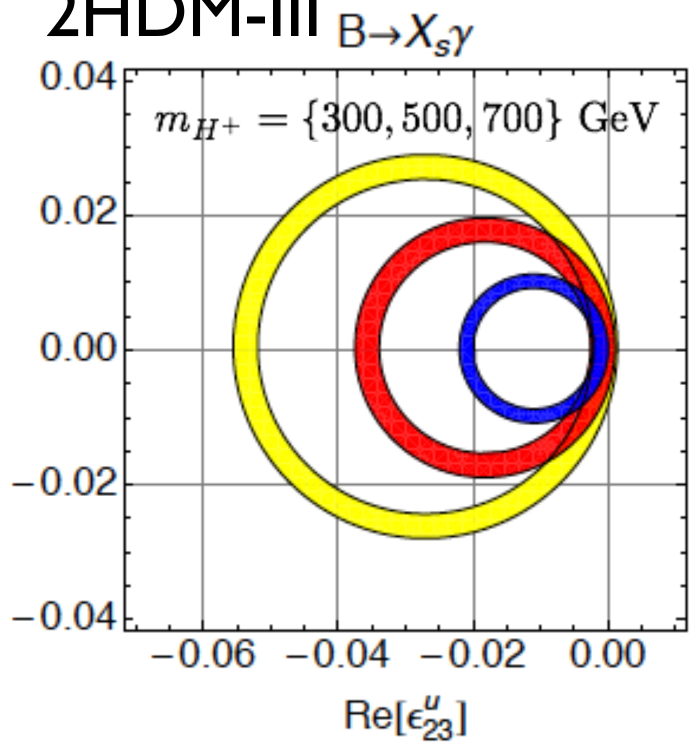

2HDM-II




[arXiv:1303.5877]

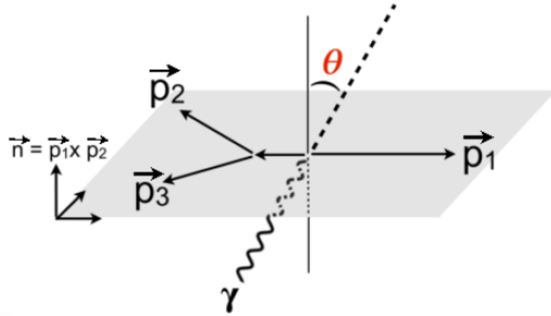



2HDM-III

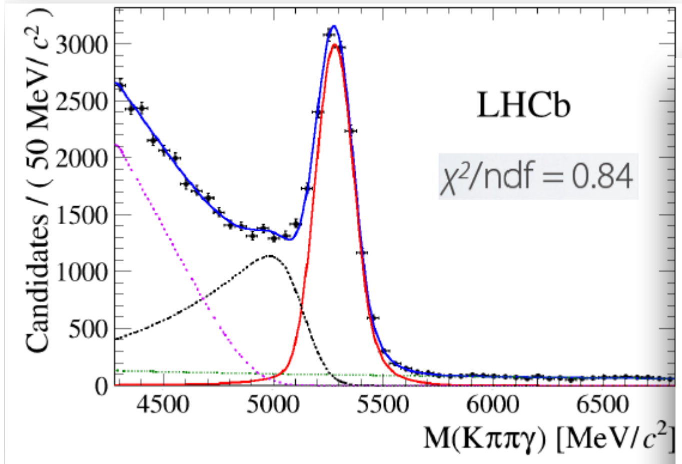


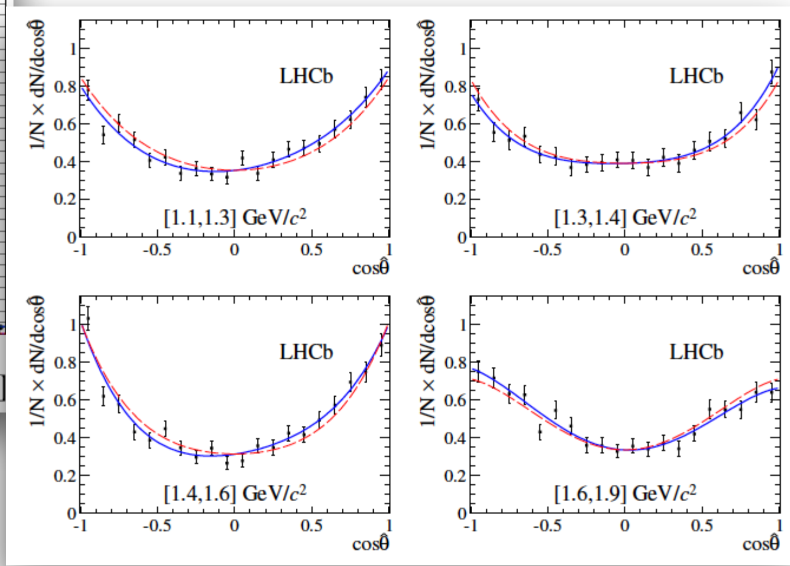
# B→$X_s\gamma$: Exclusive modes

- Generally, larger theoretical uncertainties make exclusive decays less useful
- Exception: where one can access photon polarization → looking for NP in LeftRight models




## Up/Down asymmetry in $B^+ \to K^+\pi^+\pi^-\gamma$




- Non-zero up/down asymmetry determined at 5.2σ

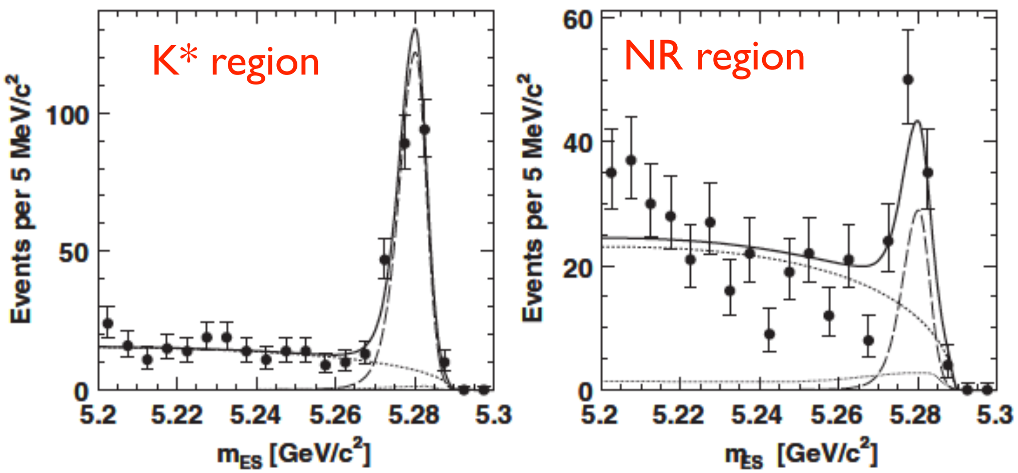
$$\mathcal{A}_{ud} = C\lambda_\gamma$$

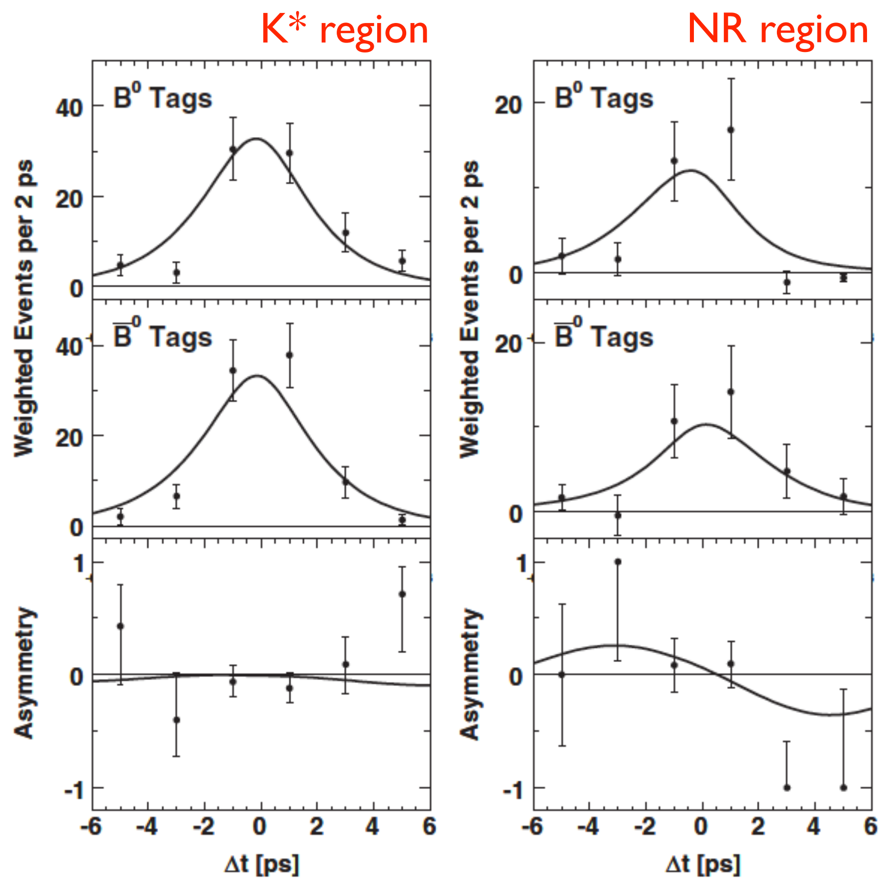
- Full amplitude analysis or theory progress needed to determine photon polarization.

| | | | | |
|---|---|---|---|---|
| $\mathcal{A}_{ud}$ | 6.9±1.7 | 4.9±2.0 | 5.6±1.8 | −4.5±1.9 |

# $B \to X_s \gamma$: Exclusive modes

- Another approach to photon polarization: time-dependent CP violation measurement in $B^0 \to K_S^0 \pi^0 \gamma$



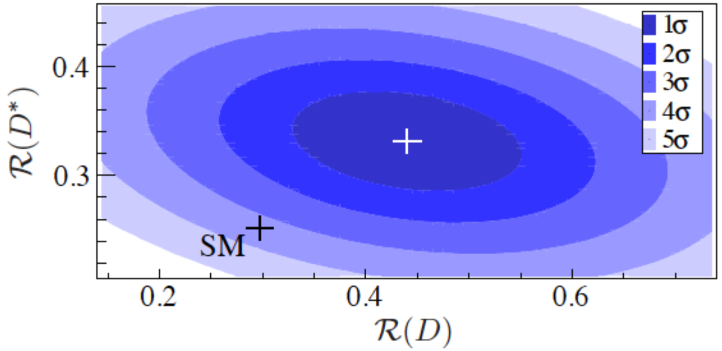

***Combined Belle and Babar***

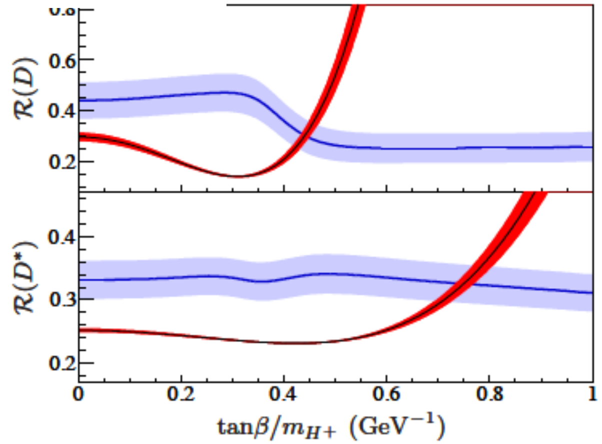
$$S_{CP} = -0.15 \pm 0.20$$
$$C_{CP} = -0.07 \pm 0.12$$

error completely dominated by statistics

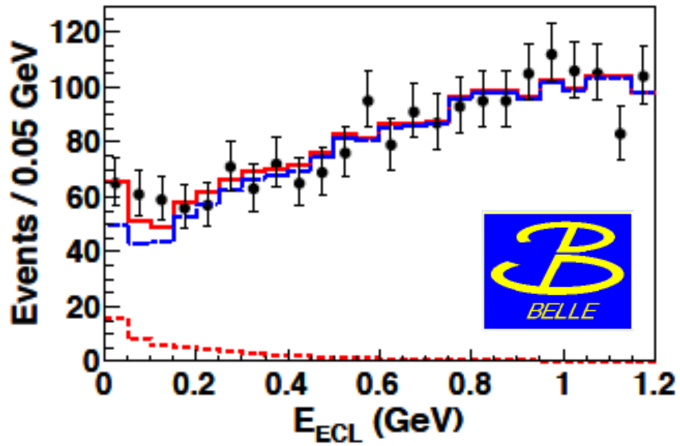
# Some more interesting channels:

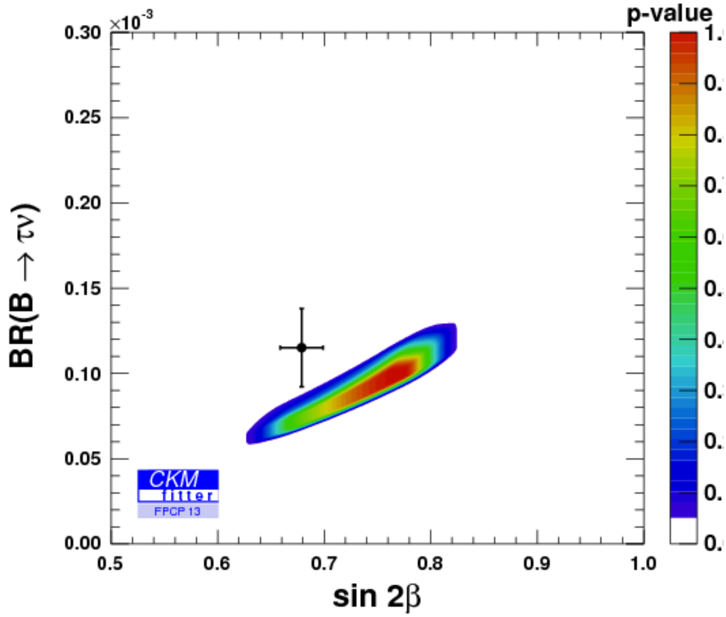
$$B \to D^{(*)}\tau\nu$$




$$B^- \to \tau^- \bar{\nu}_\tau$$




*Many others:*

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ $\quad B_s \to \gamma\gamma$ $\quad B_s^0 \to \tau^+\tau^-$ $\quad B \to X_d\gamma$

$B^+ \to \pi^+\mu^+\mu^-$ $\quad B_s \to \phi\gamma$ $\quad$ *etc.*

# Projections: LHCb

*Integrated luminosity*

| | LHC era | | | HL-LHC era | |
|---|---|---|---|---|---|
| | Run 1 (2010–12) | Run 2 (2015–17) | Run 3 (2019–21) | Run 4 (2024–26) | Run 5+ (2028–30+) |
| | $3\,\text{fb}^{-1}$ | $8\,\text{fb}^{-1}$ | $23\,\text{fb}^{-1}$ | $46\,\text{fb}^{-1}$ | $100\,\text{fb}^{-1}$ |

| | LHC era | | | HL-LHC era | |
|---|---|---|---|---|---|
| | Run 1 | Run 2 | Run 3 | Run 4 | Run 5+ |
| $\phi_s(B^0_s \to J/\psi\phi)$ | 0.05 | 0.025 | 0.013 | 0.009 | 0.006 |
| $\phi_s(B^0_s \to \phi\phi)$ | 0.18 | 0.12 | 0.04 | 0.026 | 0.017 |
| $\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$ | 220% | 110% | 60% | 40% | 28% |
| $q^2_0\ A_{\text{FB}}(K^{*0}\mu^+\mu^-)$ | 10% | 5% | 2.8% | 1.9% | 1.3% |
| $\gamma$ | 7° | 4° | 1.7° | 1.1° | 0.7° |
| $A_\Gamma(D^0 \to K^+K^-)$ | $3.4 \times 10^{-4}$ | $2.2 \times 10^{-4}$ | $0.9 \times 10^{-4}$ | $0.5 \times 10^{-4}$ | $0.3 \times 10^{-4}$ |

- *Projections are probably optimistic: use as a rough guide, not as gospel truth*
- *Point of departure for discussion*

- Exclusive modes (*mostly* with muons, charged final state)

$$B_s \to \mu^+\mu^-$$
$$B^0 \to \mu^+\mu^-$$
$$B \to K^{(*)}\mu^+\mu^-$$

- Some exclusive radiative decays

$$B^0_s \to \phi\gamma$$
$$B^+ \to K^+\pi^-\pi^+\pi^-\gamma$$

# Projections: Belle-II

2019 2023

| | Observables | Belle (2014) | Belle II 5 ab$^{-1}$ | Belle II 50 ab$^{-1}$ |
|---|---|---|---|---|
| UT angles | $\sin 2\beta$ | $0.667 \pm 0.023 \pm 0.012$ [64] | 0.012 | 0.008 |
| | $\alpha$ [°] | $85 \pm 4$ (Belle+BaBar) [24] | 2 | 1 |
| | $\gamma$ [°] | $68 \pm 14$ [13] | 6 | 1.5 |
| Gluonic penguins | $S(B \to \phi K^0)$ | $0.90^{+0.09}_{-0.19}$ [19] | 0.053 | 0.018 |
| | $S(B \to \eta' K^0)$ | $0.68 \pm 0.07 \pm 0.03$ [65] | 0.028 | 0.011 |
| | $S(B \to K^0_S K^0_S K^0_S)$ | $0.30 \pm 0.32 \pm 0.08$ [17] | 0.100 | 0.033 |
| | $\mathcal{A}(B \to K^0 \pi^0)$ | $-0.05 \pm 0.14 \pm 0.05$ [66] | 0.07 | 0.04 |
| UT sides | $\lvert V_{cb}\rvert$ incl. | $41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8] | 1.2% | |
| | $\lvert V_{cb}\rvert$ excl. | $37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$ [10] | 1.8% | 1.4% |
| | $\lvert V_{ub}\rvert$ incl. | $4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$ [5] | 3.4% | 3.0% |
| | $\lvert V_{ub}\rvert$ excl. (had. tag.) | $3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7] | 4.7% | 2.4% |
| Missing $E$ decays | $\mathcal{B}(B \to \tau\nu)$ [$10^{-6}$] | $96(1 \pm 27\%)$ [26] | 10% | 3% |
| | $\mathcal{B}(B \to \mu\nu)$ [$10^{-6}$] | $< 1.7$ [67] | 20% | 7% |
| | $R(B \to D\tau\nu)$ | $0.440(1 \pm 16.5\%)$ [29]$^\dagger$ | 5.2% | 2.5% |
| | $R(B \to D^*\tau\nu)^\dagger$ | $0.332(1 \pm 9.0\%)$ [29]$^\dagger$ | 2.9% | 1.6% |
| | $\mathcal{B}(B \to K^{*+}\nu\bar\nu)$ [$10^{-6}$] | $< 40$ [30] | $< 15$ | 30% |
| | $\mathcal{B}(B \to K^{+}\nu\bar\nu)$ [$10^{-6}$] | $< 55$ [30] | $< 21$ | 30% |
| Rad. & EW penguins | $\mathcal{B}(B \to X_s\gamma)$ | $3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$ | 7% | 6% |
| | $A_{CP}(B \to X_{s,d}\gamma)$ [$10^{-2}$] | $2.2 \pm 4.0 \pm 0.8$ [68] | 1 | 0.5 |
| | $S(B \to K^0_S \pi^0 \gamma)$ | $-0.10 \pm 0.31 \pm 0.07$ [20] | 0.11 | 0.035 |
| | $S(B \to \rho\gamma)$ | $-0.83 \pm 0.65 \pm 0.18$ [21] | 0.23 | 0.07 |
| | $C_7/C_9$ $(B \to X_s\ell\ell)$ | ~20% [36] | 10% | 5% |
| | $\mathcal{B}(B_s \to \gamma\gamma)$ [$10^{-6}$] | $< 8.7$ [42] | 0.3 | – |
| | $\mathcal{B}(B_s \to \tau\tau)$ [$10^{-3}$] | – | $< 2$ [44]$^\ddagger$ | – |

- Inclusive processes

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

- Modes with neutrinos

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

- Specific modes with neutrals

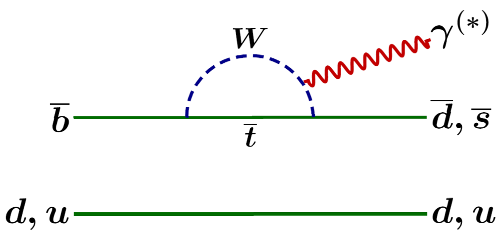
$$B \to K_S \pi^0 \gamma$$

- *Projections are probably optimistic: use as a rough guide, not as gospel truth*
- *Point of departure for discussion*

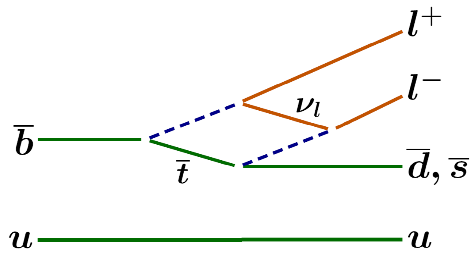
# Backup slides

# Introduction/Motivations

- Flavour-changing neutral current process: prohibited at tree level in the Standard Model → New Physics contributions enter at same order as SM physics




`radiative penguin'




`WW box'

- In many NP models, the SM particles in the loops are replaced by new heavy particles, new masses, new couplings → modify quantities that we can measure
  - Branching Fractions, CP and Isospin asymmetries, observables from angular distributions

# Effective Hamiltonian

- Effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} [C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)],$$

- Relevant operators for this physics:

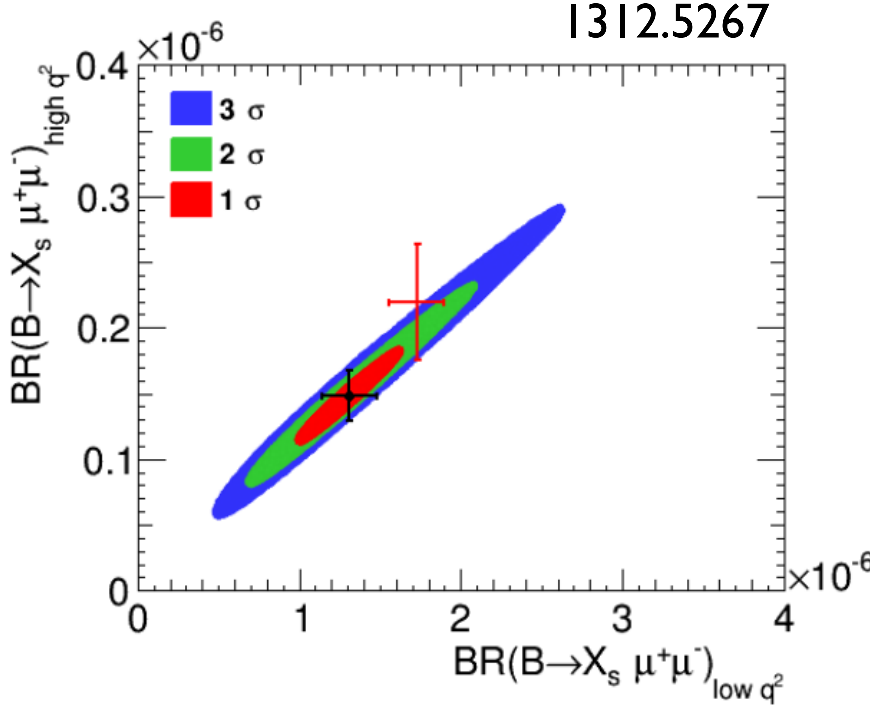
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \quad \mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l), \quad \mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l),$$

- The $C_i$ are the Wilson coefficients, which are calculable perturbatively in SM and NP models
- $C_7$: coefficient of dipole operator. $|C_7|$ determined by $B(B \to X_s \gamma)$
- $C_7$, $C_9$, $C_{10}$ all affected by $B \to X_s l^+ l^-$

# Inclusive $B \to X_s l^+ l^-$ can help…

- Inclusive BF of $B \to X_s l^+ l^-$ also depends on $C_9$
- Plot BF in high $q^2$ region vs. BF in low $q^2$ region
  - Colored ellipses: from global fit to K*ll data
  - Red cross: SM calculation
  - Black cross: central value of global fit but error bars from expected results from current B-factories

1312.5267

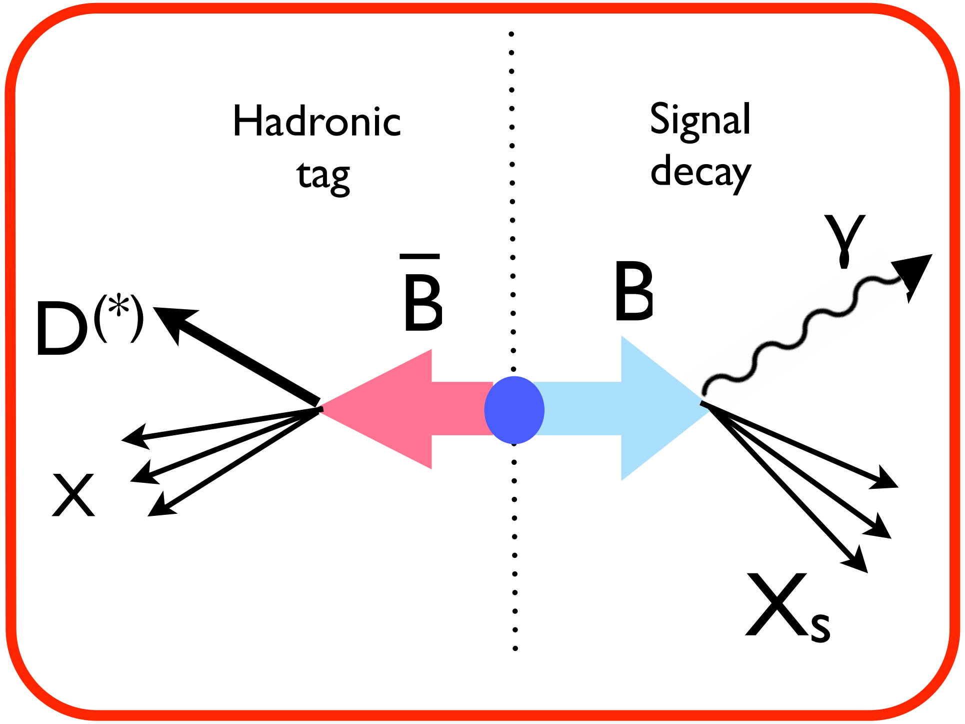


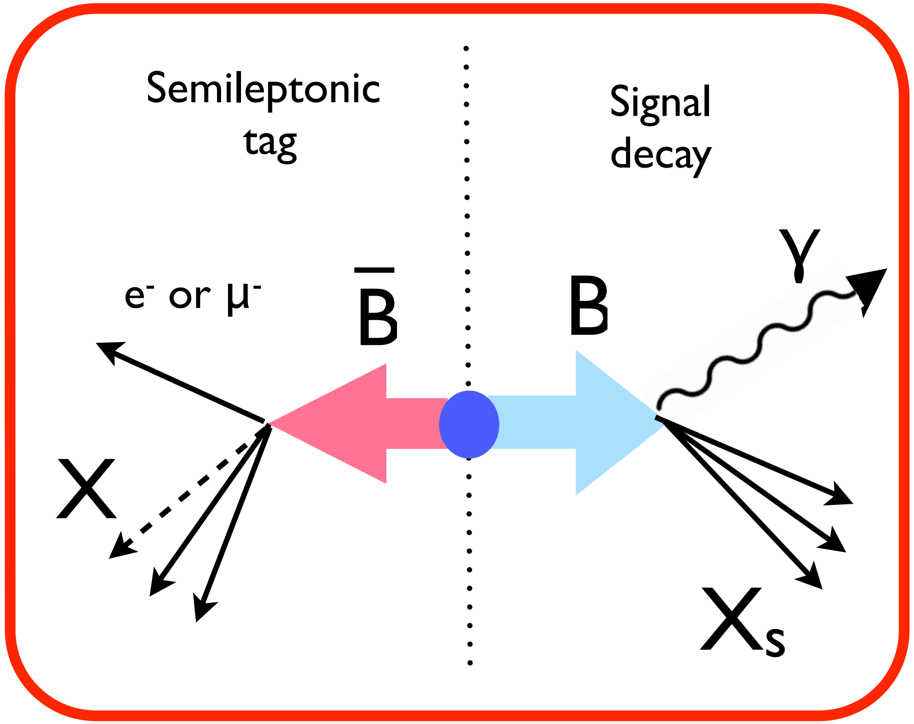
# $B \to X_s l^+ l^-$: General characteristics

- Lepton pair in final state offers many more observables (compared to $B \to X_s \gamma$, for example)
- Theory predicts observables as function of $q^2 \equiv m_{\ell\ell}^2$, so experiment aims to measure as function of $q^2$ → strong tool for revealing NP
- Very small BF: ~ $1.5 \times 10^{-6}$ → need high statistics
- Most exp. focus has been on exclusive states: $B \to K^{(*)} l^+ l^-$k
- Inclusive measurements will be valuable in the future:
  - theoretical calculations under good control
  - only at $e^+e^-$ machines: Belle-II

# $B \to X_s \gamma$: Tagging strategies

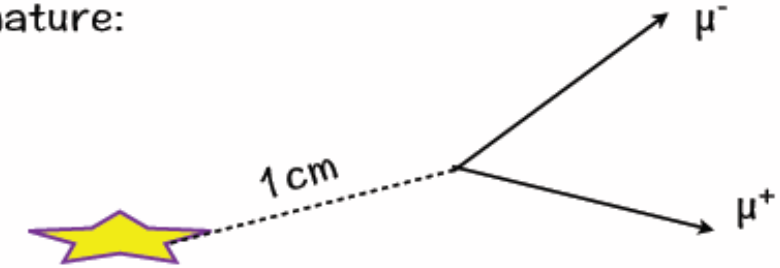
- Requiring tag on "other B" in event can greatly reduce background
- **Fully-reconstructed hadronic decay** is most powerful but low efficiency (~ 0.5%)
- **High-p lepton with missing $E_T$** selects semileptonic B decays, reducing continuum background significantly, with eff ~ 10%



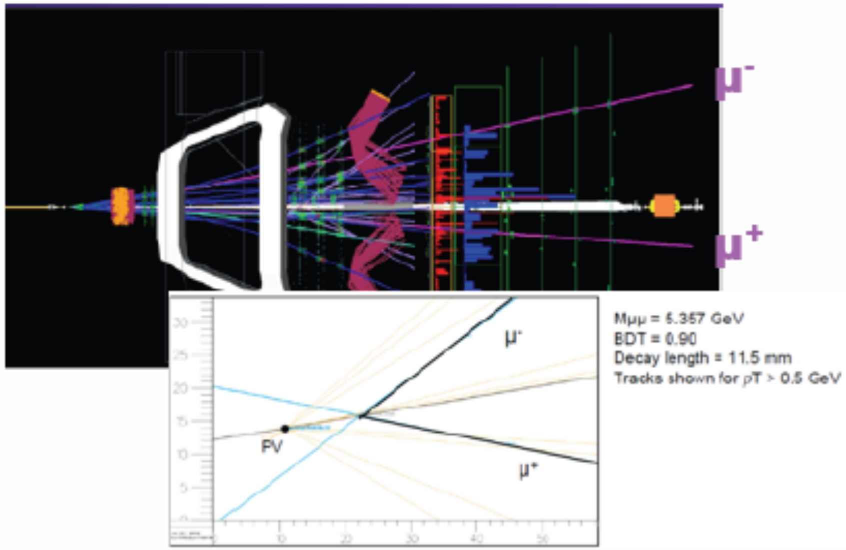



# The quest for $B_q \rightarrow \mu\mu$

Signature:

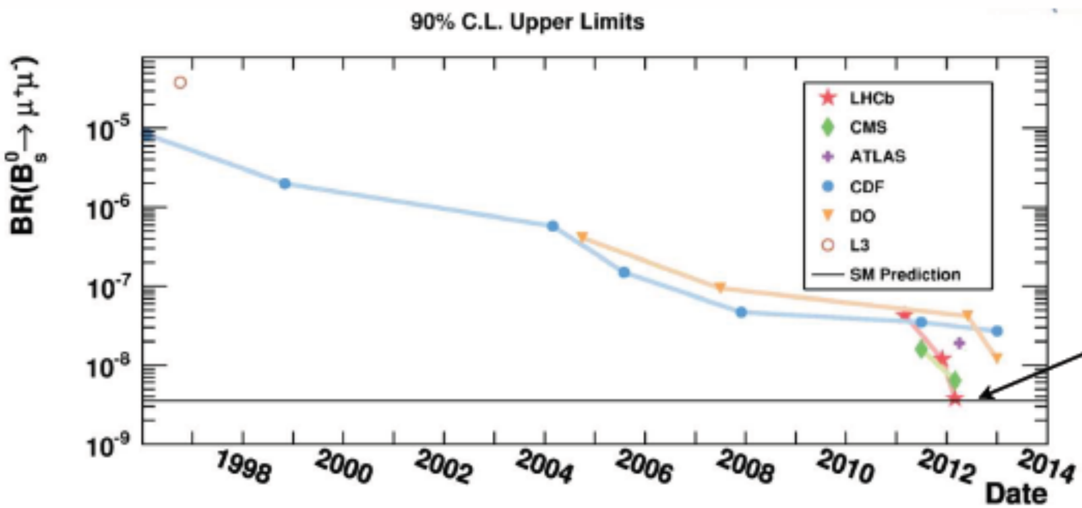



Actual candidate in LHCb data




Complicated measurement: large backgrounds from B->hh and double B->Xμ

Searches started as early as 1984 (CLEO)!
Evolution of limit as function of time:




first hints by LHCb and CMS

*W. Hulsbergen*
*Dec 2013, Puri, India*

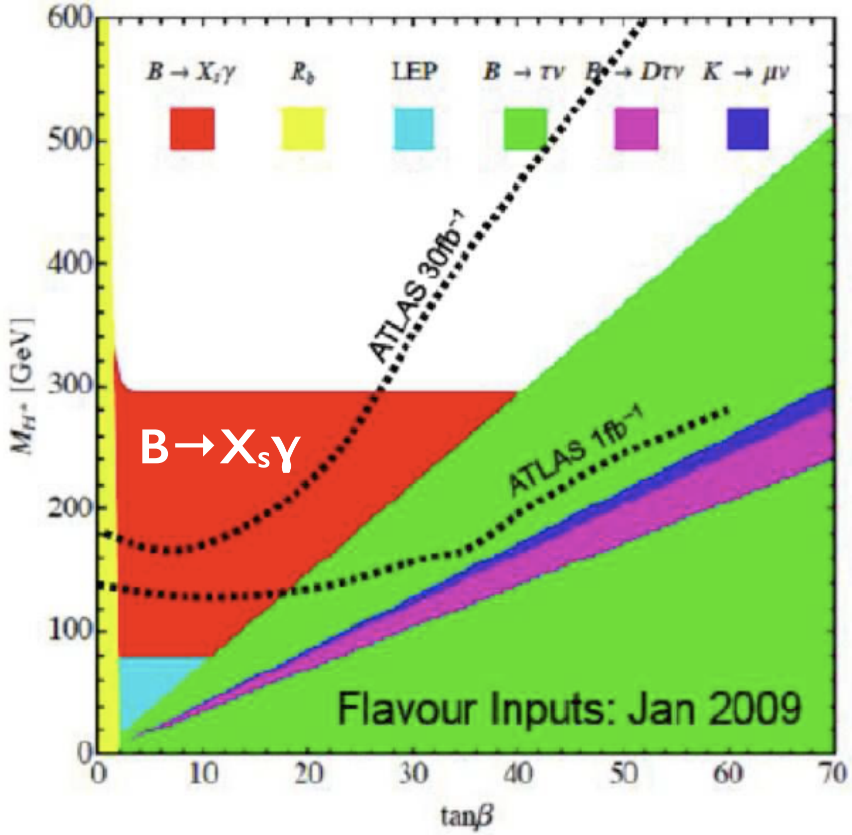
# B→X$_s$γ: NP Constraints

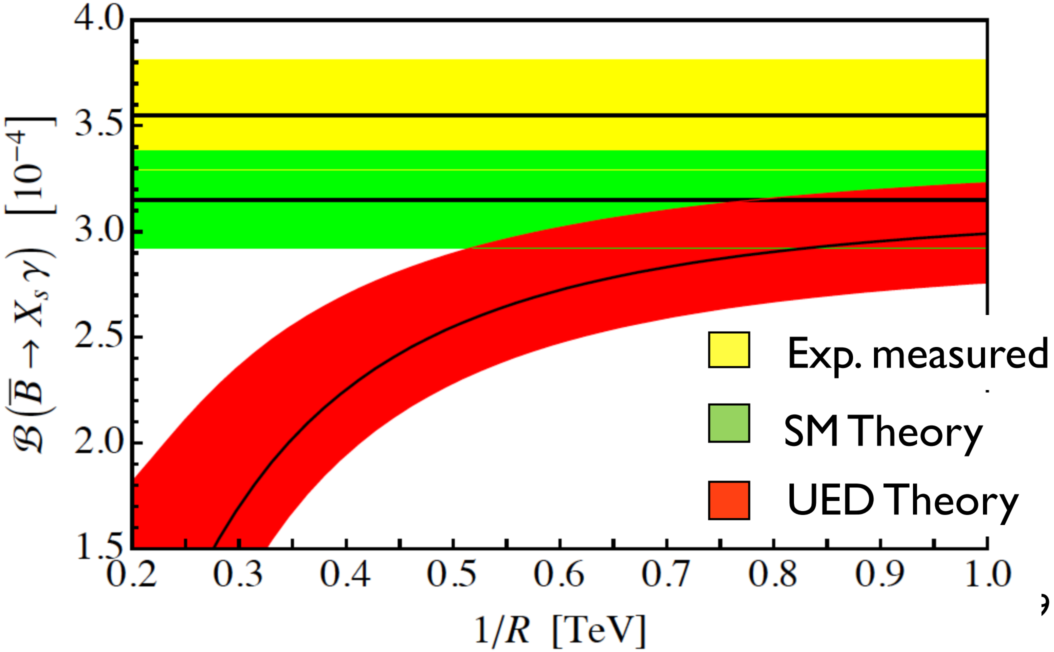
- B→X$_s$γ can be used directly to constrain NP models
- Two Higgs doublet model (type 2)

$$m_{H^+} > 295 \text{ GeV}, \ (95\%\text{CL})$$

- Independent of tan β

[arXiv:1104.5123]




## Universal extra dimensions

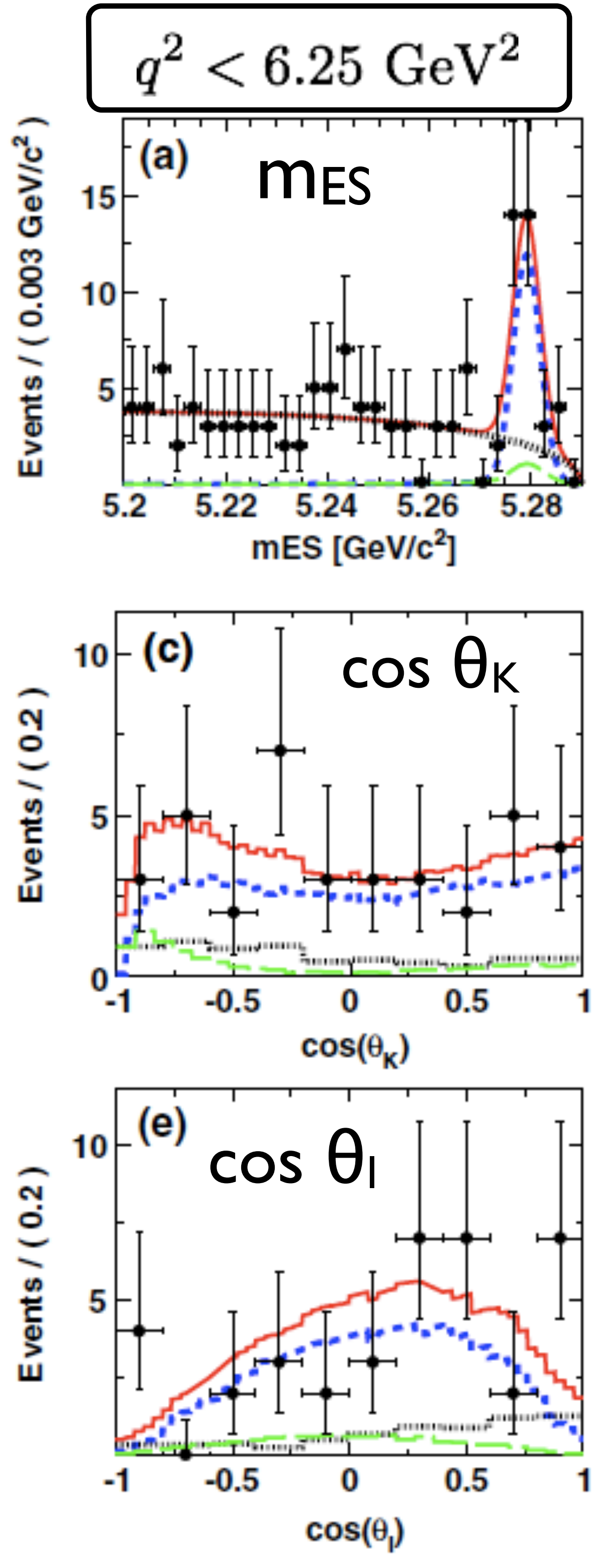
Direct constraint on compactification radius:

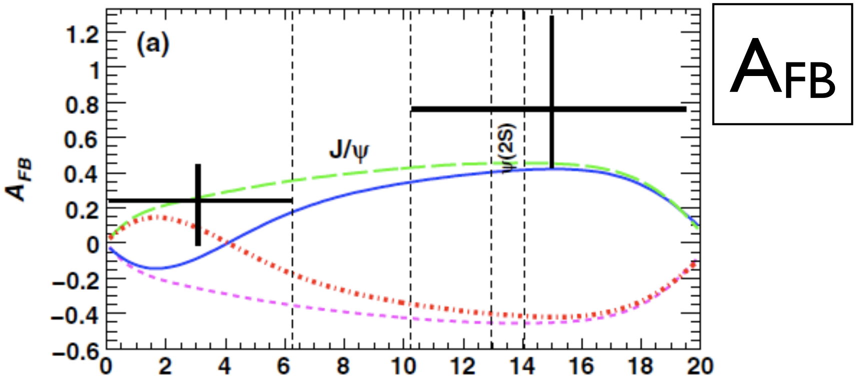
$$1/R > 650 \text{ GeV}, \ (95\%\text{CL})$$

[arXiv:0801.4346]

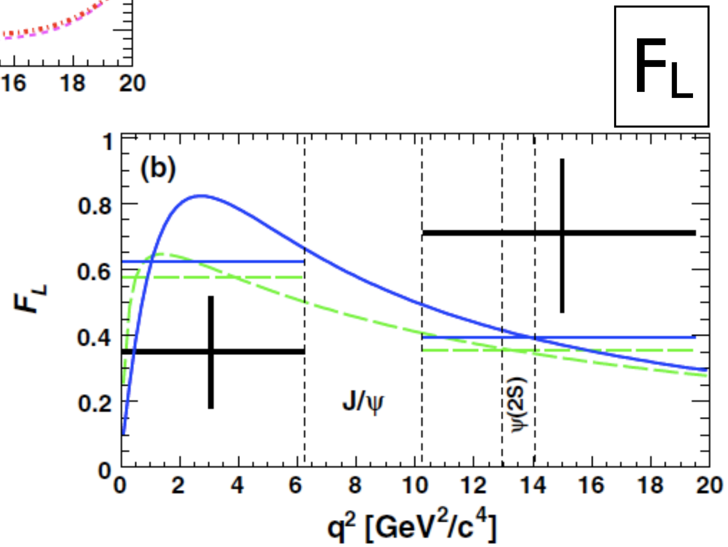
# $B \to K^{(*)}ll$: Experimental analysis

- Reconstruct 10 $B \to K(*)ll$ states:
  - $K^+$, $K_s^0$, $K^+\pi^-$, $K^+\pi^0$, $K_s^0\pi^+$ with $e^+e^-$ ($p_e$>0.3 GeV) or $\mu^+\mu^-$ ($p_\mu$>0.7 GeV)
- Good PID for e, μ, K, π, $K_s^0 \to \pi^+\pi^-$
- Neural net classifiers to suppress background from double semileptonic B and D decays
- Kinematical variables, $m_{ES}$ and ΔE
- Veto charmonium events → control sample




*[PRD 79 031102(R) (2009)]*

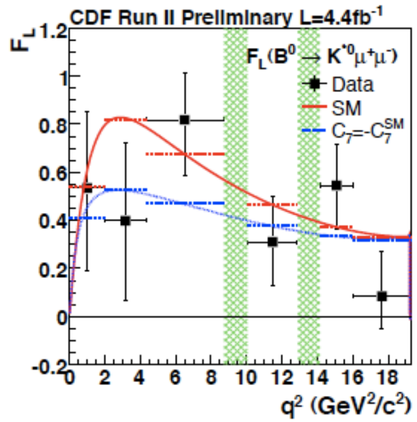


# Combining results:

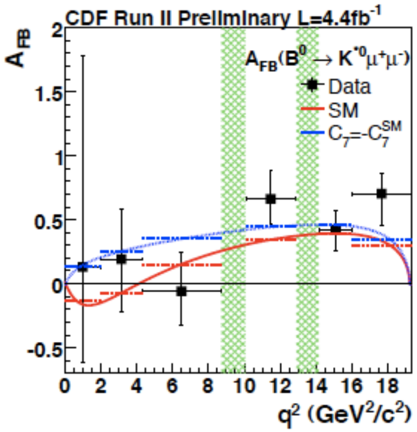
*[arXiv:1006.5013]*

## *CDF*

$F_L$

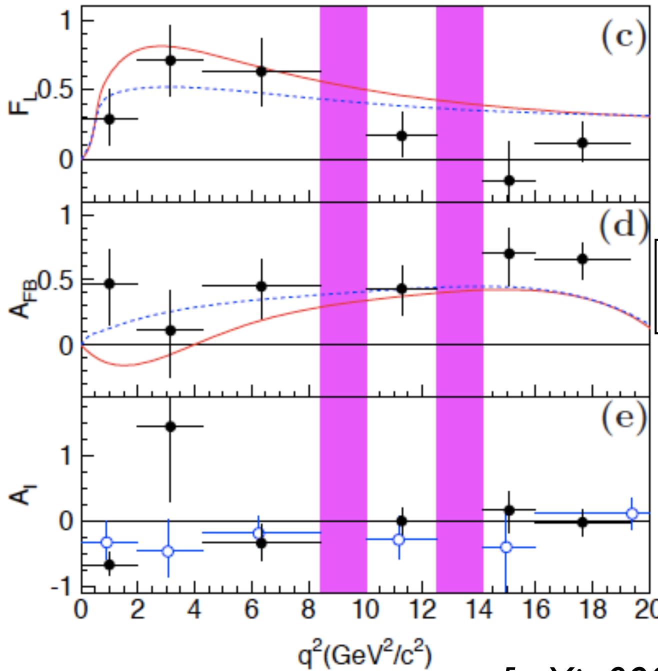



$A_{FB}$




*[CDF-PUB-10047]*

## *Belle*



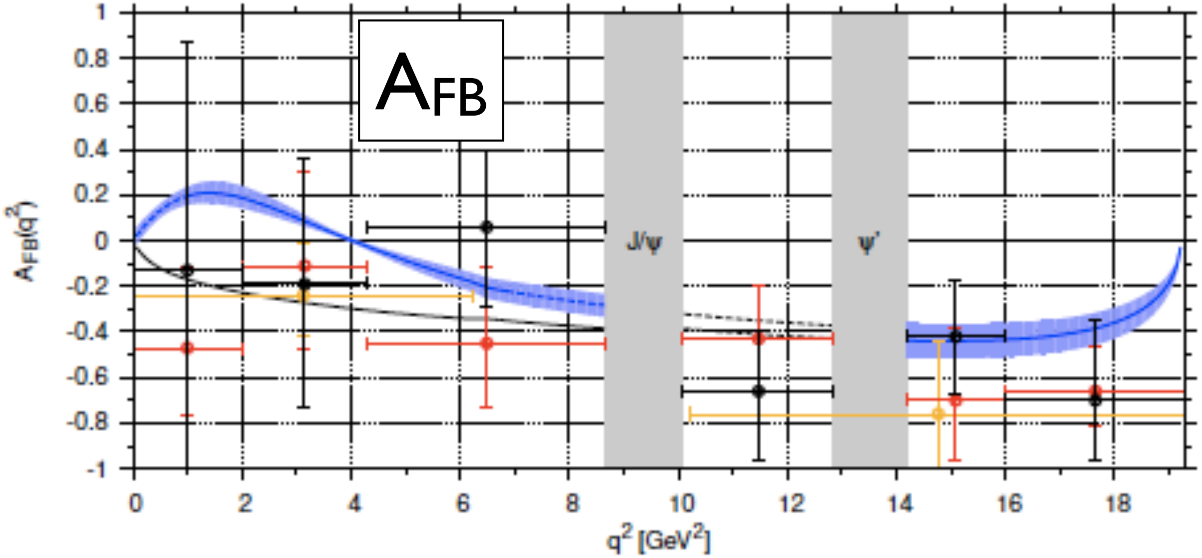

$F_L$

$A_{FB}$

*[arXiv:0904.0770]*

## *All data + SM prediction*

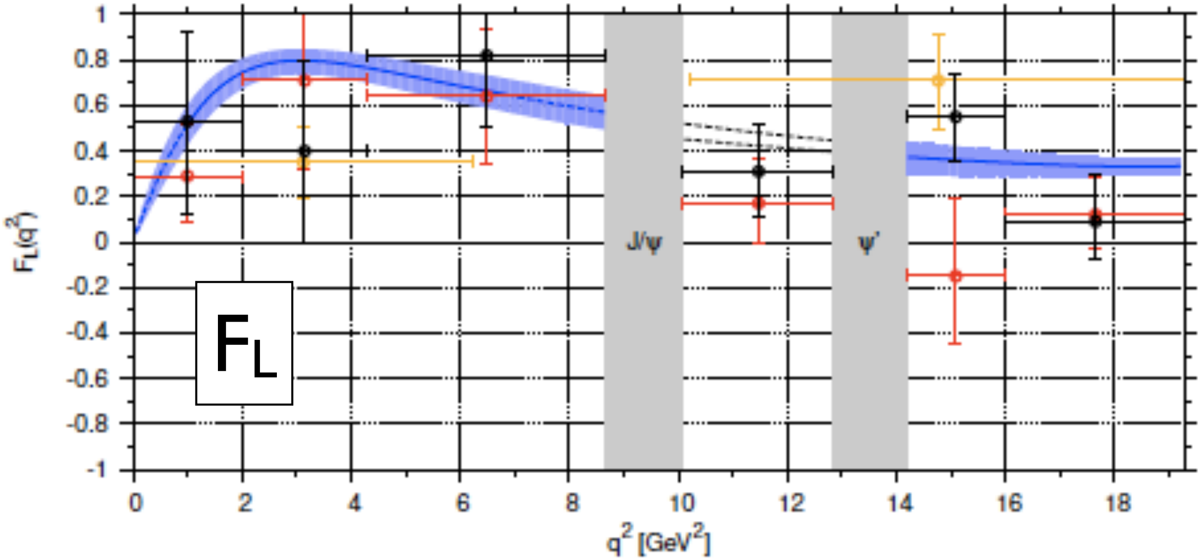
$A_{FB}$




(b)

Belle, Babar, CDF

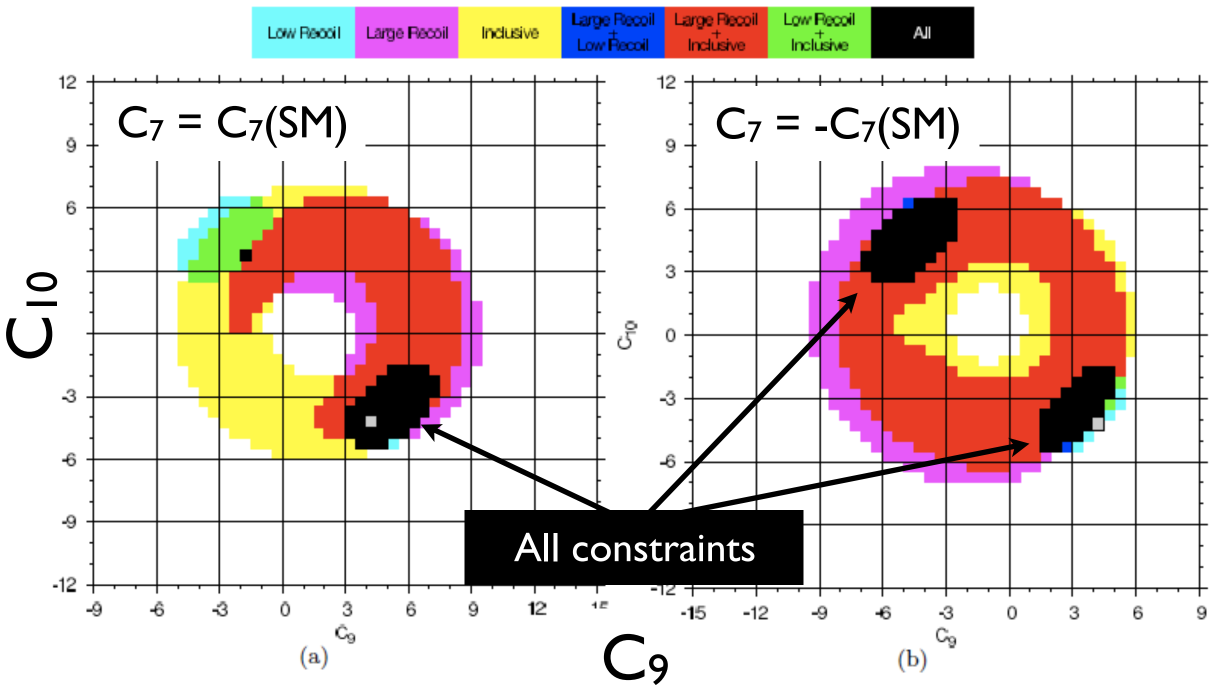
$F_L$

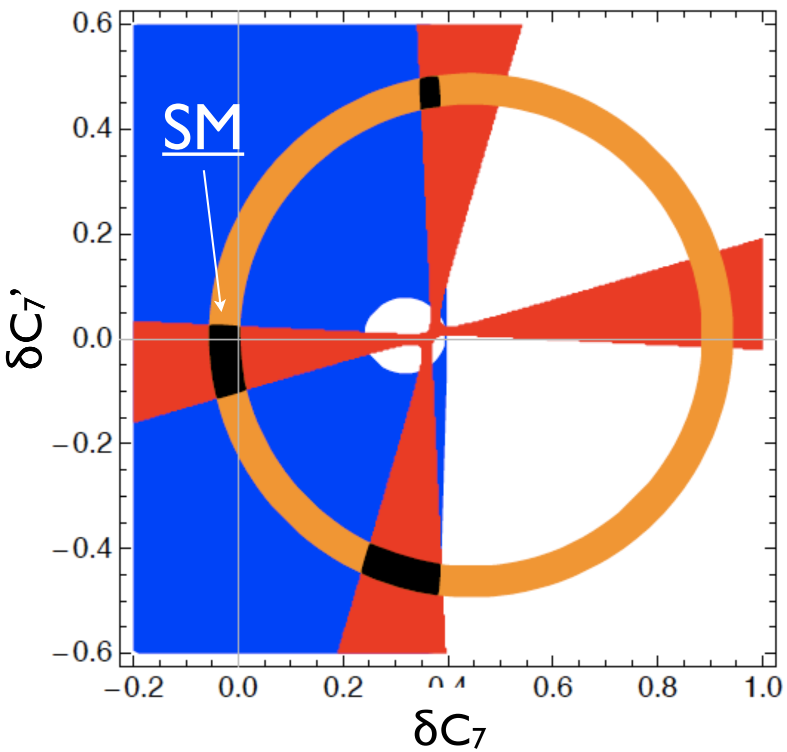


# Constraining Wilson coefficients

- $C_{10}$ vs. $C_9$ plane
- Use exclusive and inclusive $B \rightarrow X_s l^+ l^-$ data
- Two cases: $C_7 = C_7(SM)$ and $C_7 = -C_7(SM)$

[arXiv:1006.5013]




- $\delta C_7'$ vs $\delta C_7$ plane: variations from SM prediction

[arXiv:1104.3342]