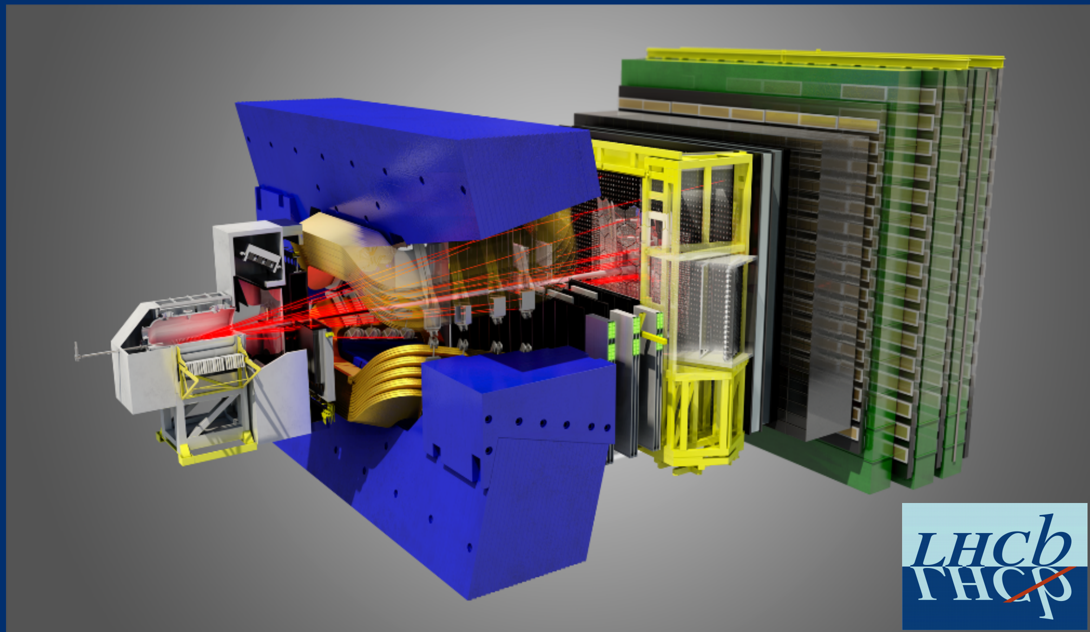
Rare decays at the *L*arge *H*adron *C*ollider *b*eauty experiment



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On behalf of the LHCb collaboration

LISHEP 2013, 17-24 March - Rio de Janeiro (Brazil)

WHY RARE DECAYS?

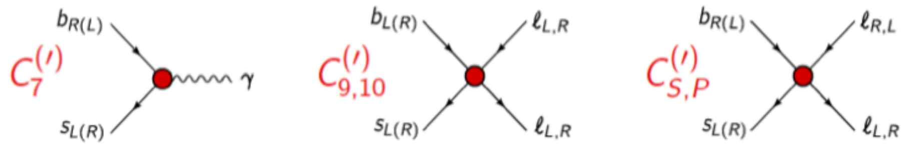
- Part of *LHCb* program is to perform **indirect searches of New Physics.**
  Complementary to direct searches at LHC

$$H_{eff}^{\Delta F=1} = -\frac{4G}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum (C_i O_i + C_i^I O_i^I)$$

Wilson coeffs. (short-dist. interactions)

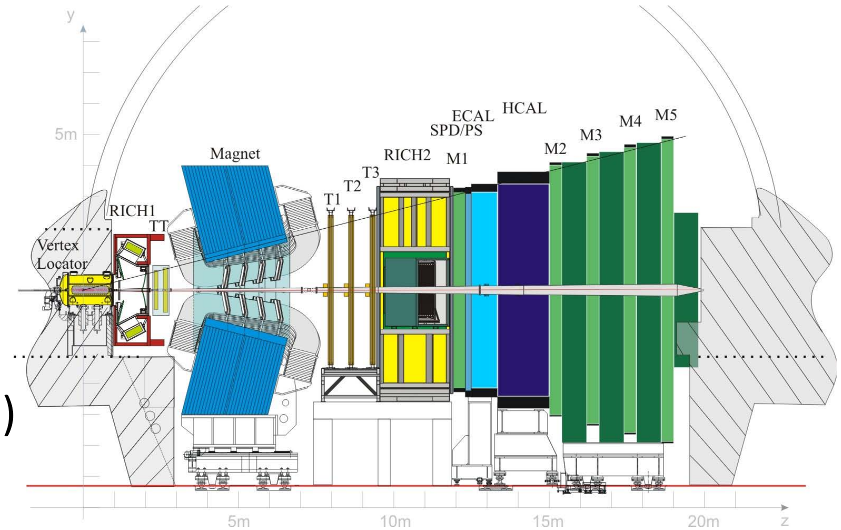
Operators (long-dist. interactions)

- **Rare decays are** perfectly suited:
  - **suppressed of forbidden** in Standard Model
  - **highly sensitive to new physics** effects!
  - **set constraints on the Wilson coefficients**



mag. dipole operator | semileptonic operators | scalar operators

- ***LHCb* is designed for this purpose**!
  - High trigger efficiency
  - Excellent tracking system (time, impact parameter, mass resolutions)
  - Excellent Particle Identification

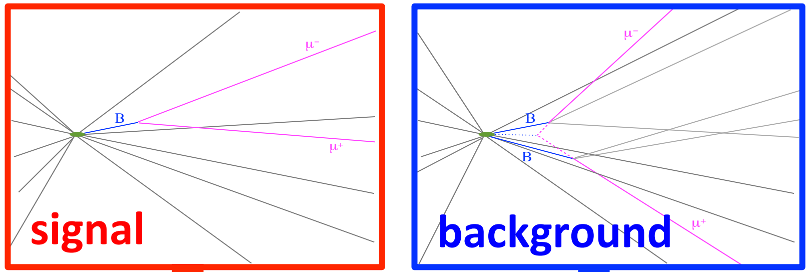


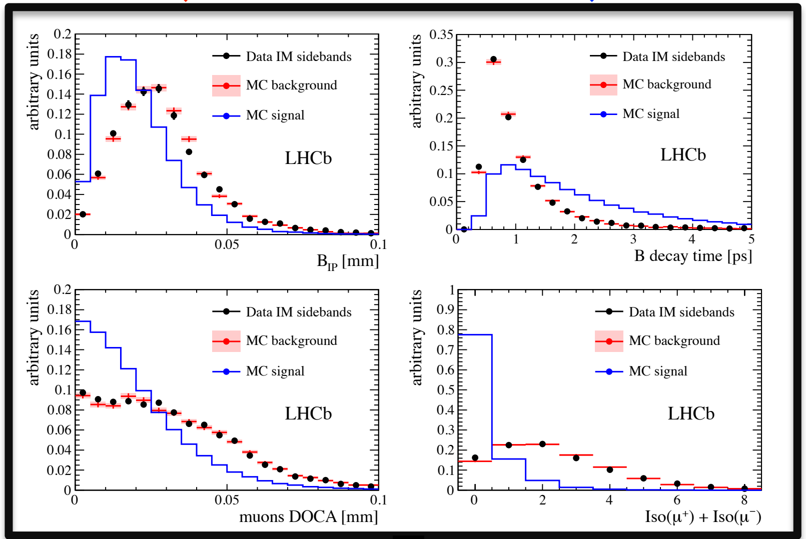
- ***LHCb*** has collected lots of data to:
  - push further current limits (ex: $K_s \to \mu\mu$)
  - observe some of the rarest decays (ex: $B_s \to \mu\mu$ *first evidence*, see Alberto Correa Dos Reis's talk)
  - study their properties (ex: $B \to K^* \mu\mu$)

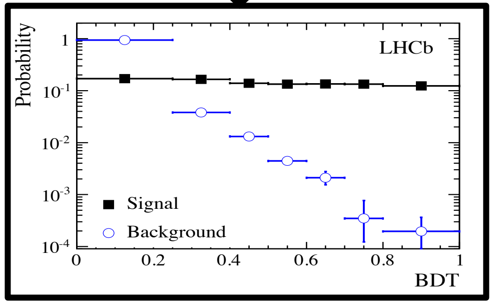
ANALYSIS GENERALITIES

Common features of many of rare decays analysis at *LHCb*:

- **muons** in the final state: clean signature, easy to trigger on.
- Combinatorial background suppression based on **multivariate techniques** exploiting information from kinematic variables
- **Specific vetoes** to remove or reduce peaking backgrounds
- Particle **Id**entification requirements
- **Control channels** whenever possible to not rely on simulations only
- **Normalization channels** to reduce systematics
- **CLs method** to set upper limits when no signal is observed





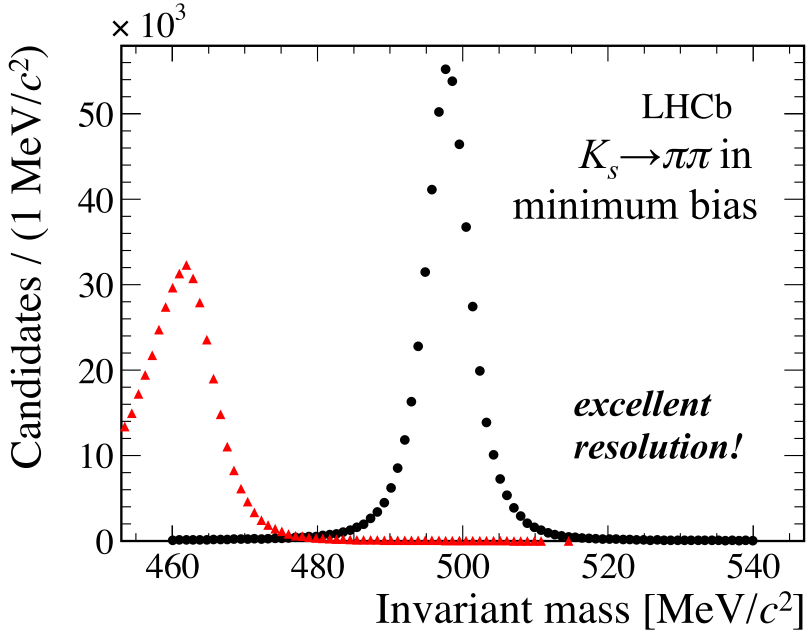


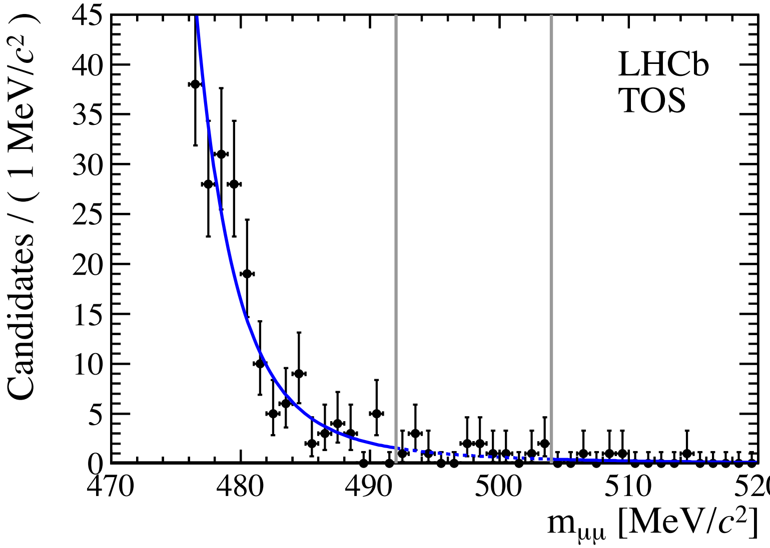
All analysis here are based on
1.0 fb^{-1} @ $\sqrt{s}$=7TeV (2011 dataset)

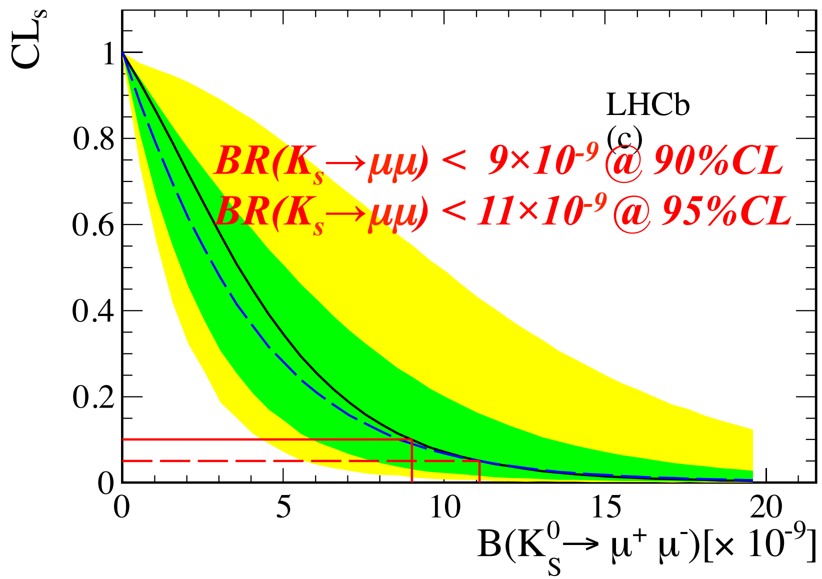
$K_S \to \mu\mu$

JHEP 01 (2013) 090

- In SM: ***BR(K$_s$→μμ) =(5.0±1.5) ×10^{-12}***
- Inside *LHCb* acceptance: ***10^{13} K$_s$* per *fb^{-1}***
- ***K$_s$→ππ*** is used to train the BDT and as normalization sample
- Specific backgrounds:
  - - μ from interactions with VELO
  - - $K_s \to \pi\pi$ with π misID as μ
- Candidates classified in bins of BDT, compared to signal and background expectation
- **Thirty times better than previous measurement!**



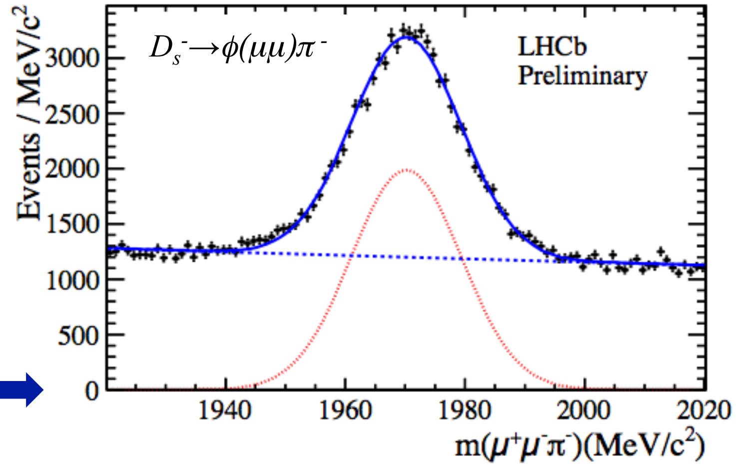




$\tau \to \mu\mu\mu$

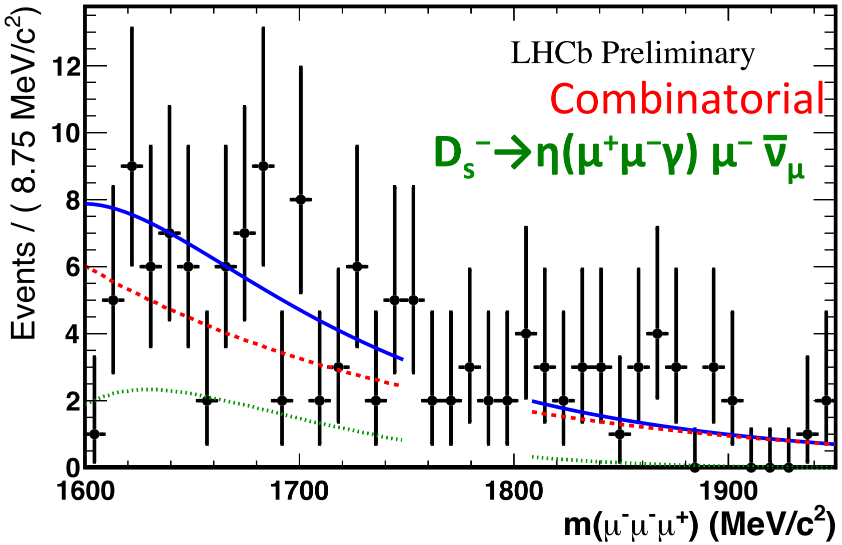
LHCb-CONF-2012-015

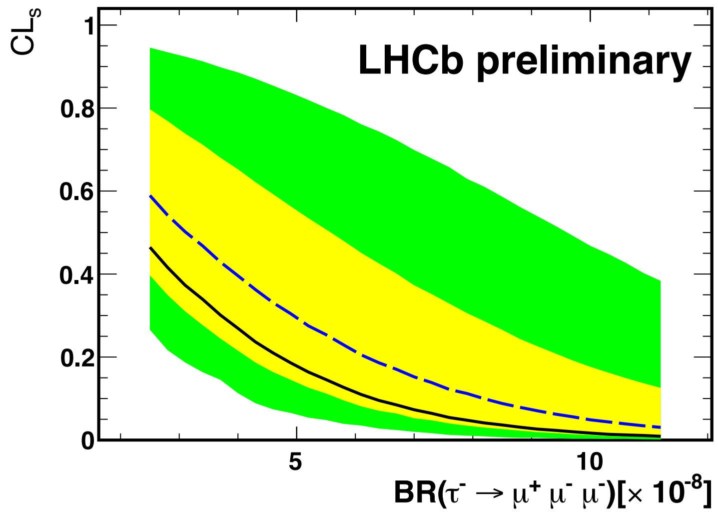
- **Lepton flavor violating process**
- Inclusive τ production @ LHCb **~80 μb**:
- τ dominantly from B (~20%) *and* D_s^- (~80%)
- Clear signature expected.
- Normalization and control channel: $D_s^- \to \phi(\mu\mu)\pi^-$



- Signal/background discrimination operated by a likelihood based on M_{3body}, M_{PID}, $m(\mu\mu\mu)$

Preliminary limit: BR($\tau \to \mu\mu\mu$)<7.8(6.3)*10-8 @ 95% (90%) CL

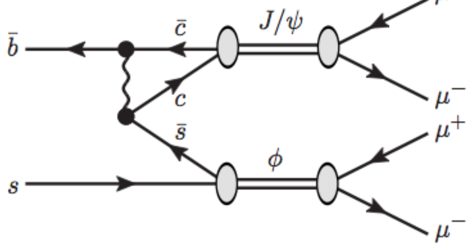




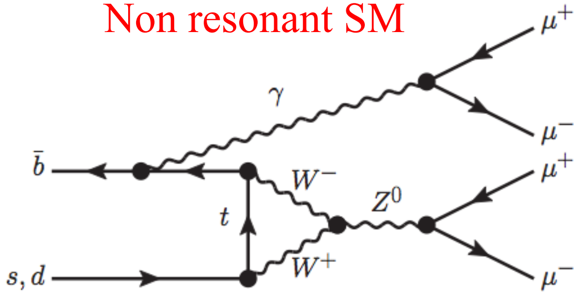
$B_{(s)}^{0} \to \mu^+\mu^-\mu^+\mu^-$

arXiv:1303.1092

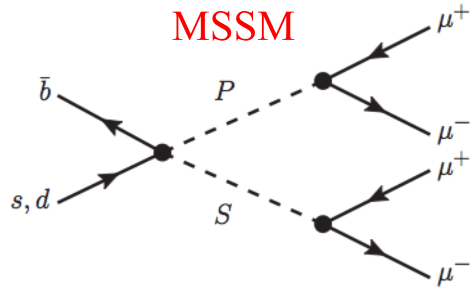
Resonant SM



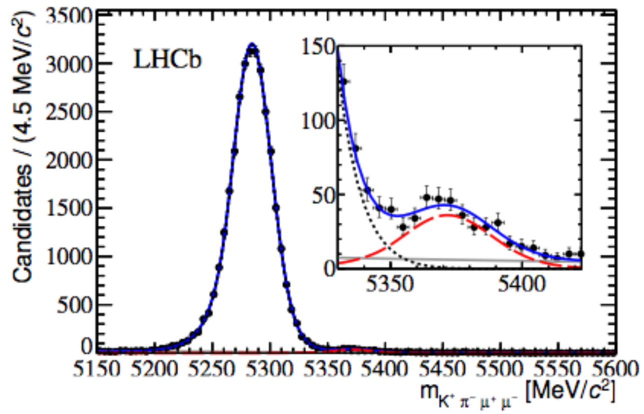
Non resonant SM



MSSM



- **Strongly suppressed in SM**. Two contributions:
  - resonant $(2.3\pm0.9)\times10^{-8}$
  - non resonant $< 10^{-10}$
- **Enhanced in MSSM models via sgoldstino**: a new scalar S and a new pseudo scalar P
- Resonant removed from analysis and used as control sample
- Normalization channel: $B^0 \to J/\psi\, K^*$
- Backgrounds: only combinatorial (peaking negligible)



Results:

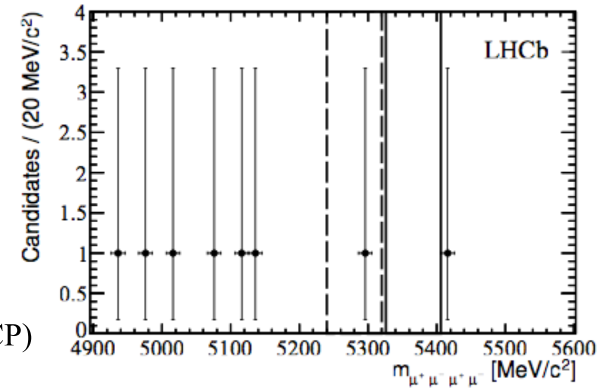
For SM → $\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.6\ (1.2) \times 10^{-8}$,

$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.6\ (5.3) \times 10^{-9}$.

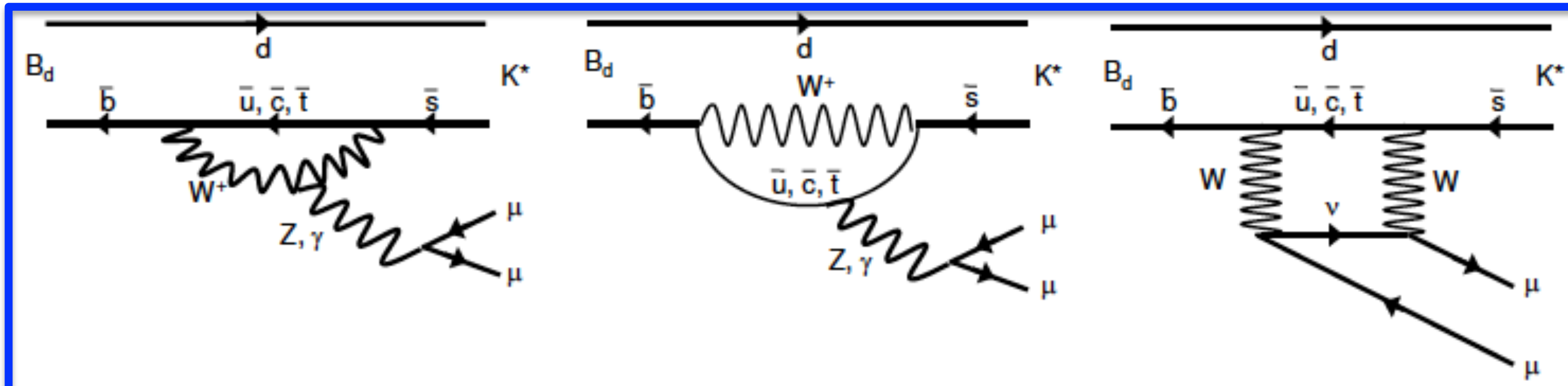
For MSSM → $\mathcal{B}(B_s^0 \to SP) < 1.6\ (1.2) \times 10^{-8}$,

$\mathcal{B}(B^0 \to SP) < 6.3\ (5.1) \times 10^{-9}$.

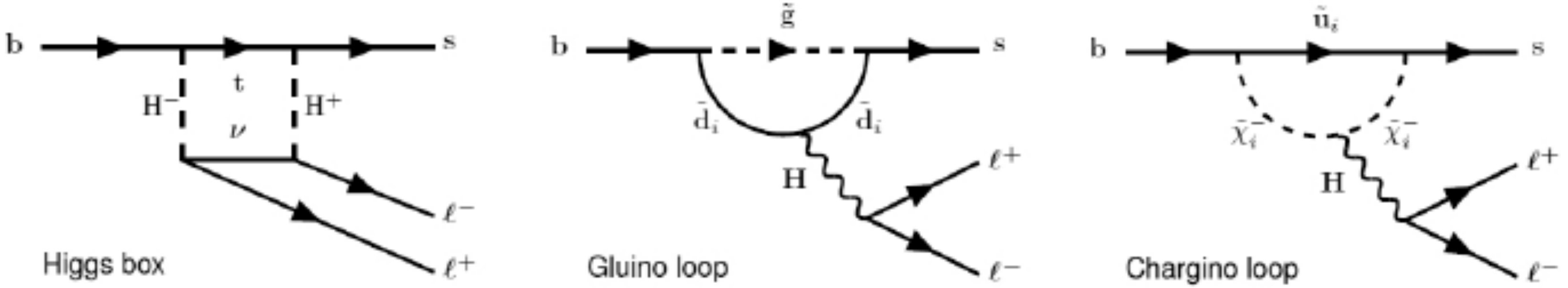
(assuming m_S=2.5GeV/c² and m_P=214MeV/c² from Hyper CP)



Tests of the Lorentz structure



SM



NP

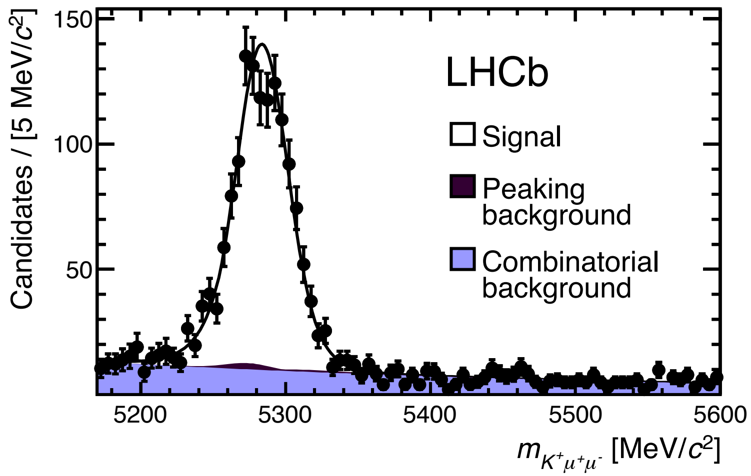
- **FCNC *b->s(d)* transition** mediated by electroweak penguin and box diagram in SM
- **Possible new physics contribution in the loops** from right-handed currents and new scalar/pseudo-scalar operators.
- Rich category of decays with **many observables**

$B^+ \to K^+ \mu^+ \mu^-$

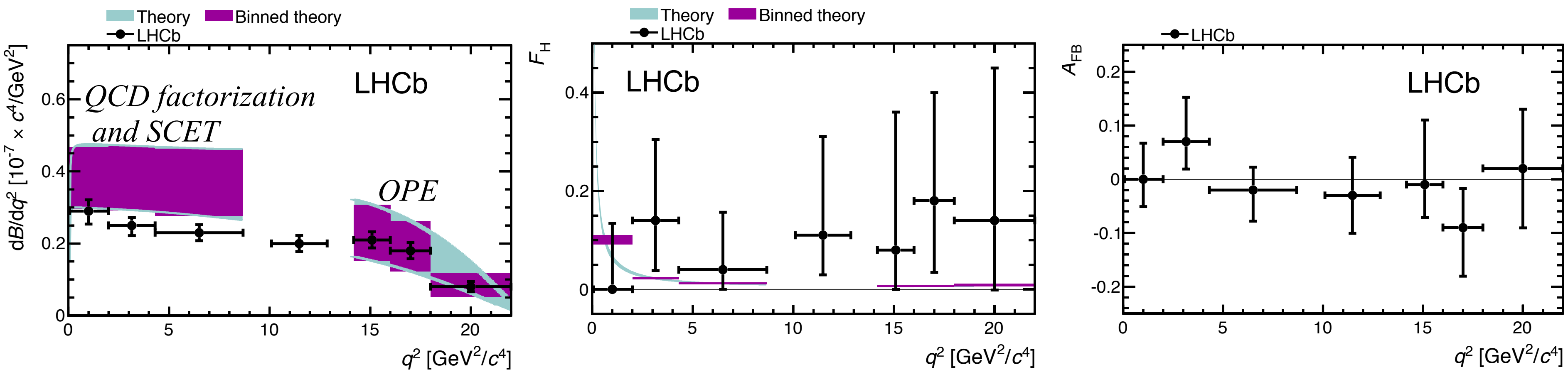
arXiv:1209.4284 [hep-ex], JHEP 02 (2013) 105

- **FCNC $b \to s$** transition
- Analysis range: $0.05 < q^2 < 22\ GeV^2/c^4$ (with $q^2 = m_{\mu\mu}^2$)
- Normalization and BDT training sample: $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$
- Specific vetoes for:
  - $B^+ \to K^+ J/\psi$, $B^+ \to K^+ \psi(2s)$, $B^+ \to \bar{D}^0(\to K\pi)\ \pi^+$
  - Small residual peaking: $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to \pi^+\mu^+\mu^-$
- Measurements: **- differential and total branching fractions**
  - A_{FB} and F_H via angular analysis:

$$\frac{1}{\Gamma}\frac{d\Gamma\left[B^+ \to K^+\mu^+\mu^-\right]}{d\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$



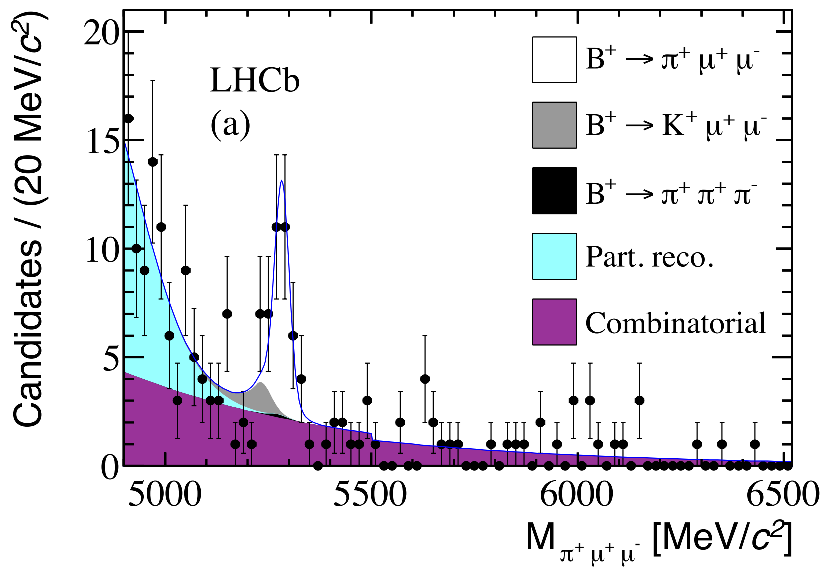
Results: $BR(B^+ \to K^+\mu^+\mu^-) = (4.36 \pm 0.15 \pm 0.18)\times 10^{-7}$



$B^+ \rightarrow \pi^+ \mu^+ \mu^-$

LHCB-PAPER-2012-020, subm. to JHEP

- **FCNC $b \rightarrow d$** transition
- IN SM: $\boldsymbol{BR(B \rightarrow \pi\mu\mu) = (2.0 \pm 0.2) \times 10^{-8}}$
- Alternative measurement of $|V_{td}|/|V_{ts}|$ in SM: $R = BR(B \rightarrow \pi\mu\mu) / BR(B \rightarrow K\mu\mu) = (|V_{td}| / |V_{ts}|)^2 f^2$ (alternative to radiative decays and mixing processes determination)
- $B^+ \rightarrow K^+ J/\psi(\rightarrow \mu^+\mu^-)$ used to control the signal shape, the misID $B \rightarrow K\mu\mu$ shape and as normalization sample
- Backgrounds: - $B^+ \rightarrow K^+\mu^+\mu^-$ (with misID K)
  - $B^+ \rightarrow \pi^+\pi^+\pi^-$
- Simultaneous fit of $B^+ \rightarrow K^+\mu^+\mu^-$, $B^+ \rightarrow \pi^+\mu^+\mu$, $B^+ \rightarrow K^+ J/\psi$, $B^+ \rightarrow K^+ J/\psi$ with kaon attributed as pion



Results:

- **First observation of $b \rightarrow dll$ transition: 5.2σ**
- $BR(B \rightarrow \pi\mu\mu) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$
- $R = 0.053 \pm 0.014 \pm 0.001 \Rightarrow |V_{td}|/|V_{ts}| = 0.266 \pm 0.035 \pm 0.003$

$B \to K^{(*)}\mu^+\mu^-$ isospin asymmetry

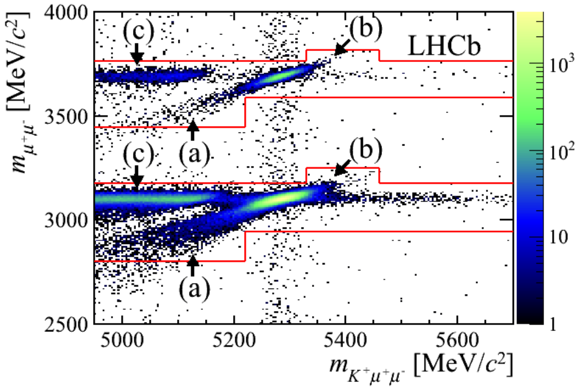
arXiv:1205.3422

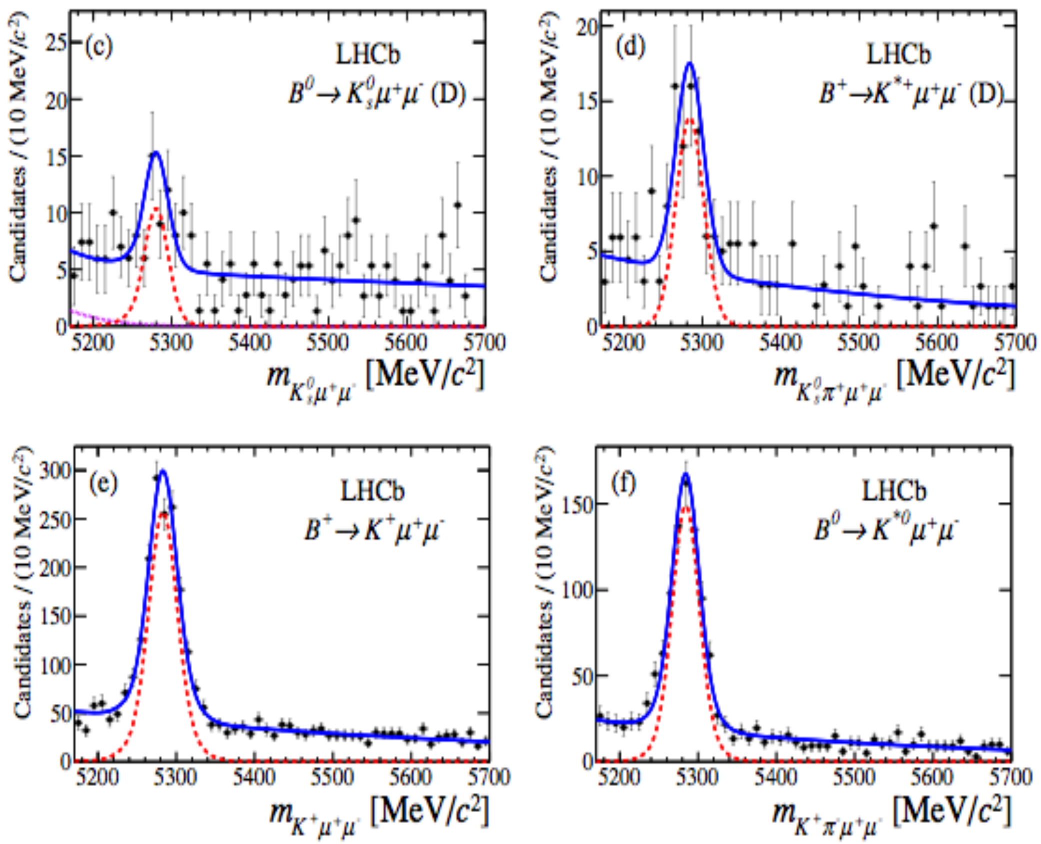
- The CP averaged isospin asymmetry is theoretically clean: not leading form factor uncertainties

$$A_{\rm I} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

- Small in SM, mainly due to initial state radiation for the different spectator quark
- Babar found A_I negative at 3.9σ

- Normalization, control of shape: $\boldsymbol{B^0 \to J/\psi\, K^{(*)}}$
- *S*imultaneous fit to all channels
- Specific backgrounds:
  - Vetoes against $\boldsymbol{\Lambda \to p\pi^-}$ (mistaken as K_s)
  - For $\boldsymbol{B \to K^*\mu\mu}$ **:**
    $\boldsymbol{B_s^0 \to \phi\mu\mu}$ **,** $\boldsymbol{B^0 \to J/\psi\, K^{*0}}$**,** $\boldsymbol{B \to K^*\mu\mu}$ (misID)
  - For $\boldsymbol{B \to K\mu\mu}$ **:**
    $\boldsymbol{B^+ \to J/\psi\, K^+}$**,** $\boldsymbol{B^+ \to \psi(2s)}$ (swap K, μ)
  - For $\boldsymbol{B \to K\mu\mu}$ **:** partially reconstructed *B*



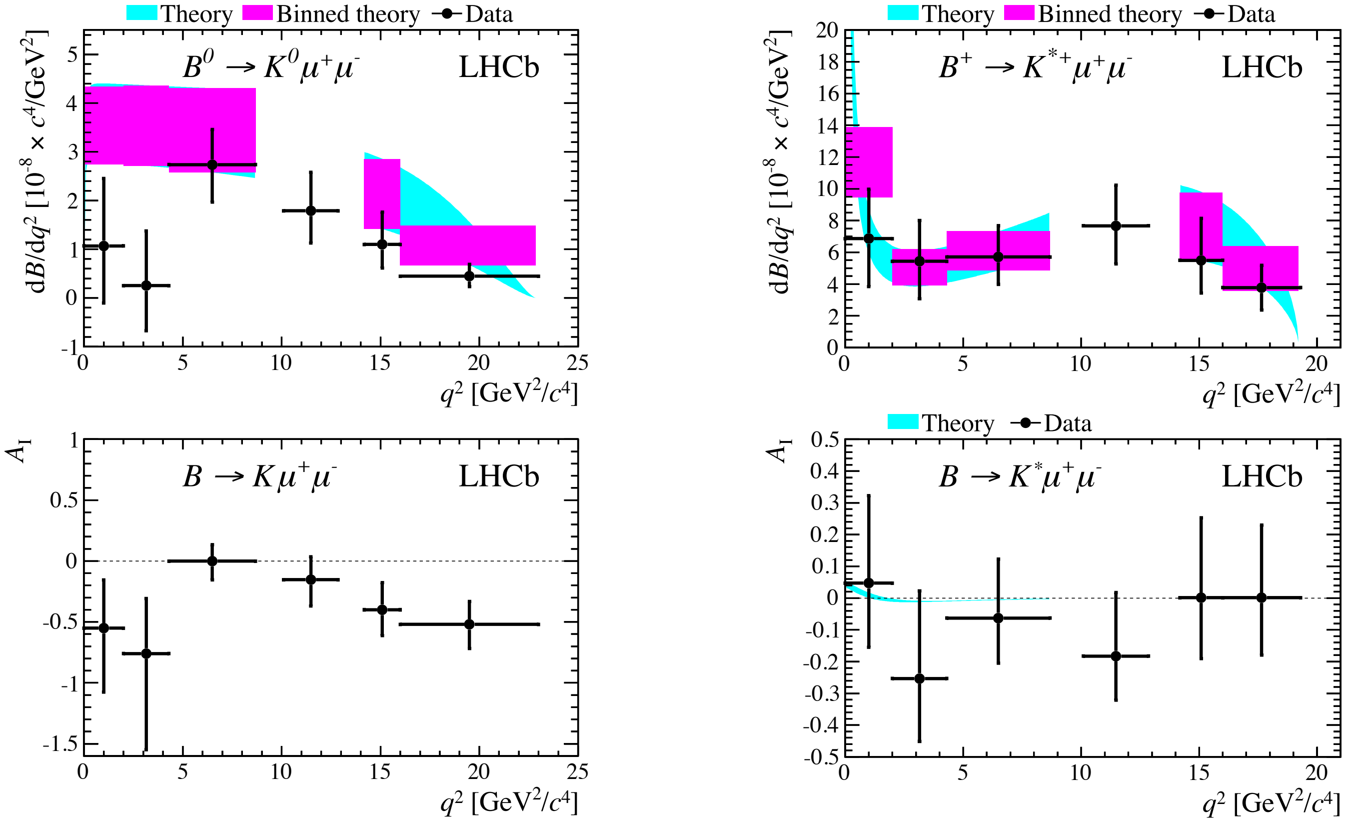


$B\to K^{(*)}\mu^+\mu^-$ isospin asymmetry

arXiv:1205.3422

Results:

- ***B→Kμμ* negative isospin asymmetry integrated over *q^2*: deviation from 0 by 4.4 *σ***
- This is dominated by a deficit in $B^0\to K_s^0\mu\mu$
- **$B^0\to K_s^0\mu\mu$ observed with 5.7σ**
- ***B→K*μμ* isospin asymmetry consistent with negligible as predicted in SM**
- $BR(B^0\to K^0\mu\mu) = (0.31^{+0.07}_{-0.06})10^{-6}$ and $BR(B\to K^*\mu\mu) = (1.16+/-0.19)10^{-6}$
- Small systematics: 4-8% respect to the ~40% statistical error



A_{CP} in $B^0 \to K^* \mu^+ \mu^-$

arXiv:1210.4492 [hep-ex], Phys.Rev.Lett 110, 031801 (2013)

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$

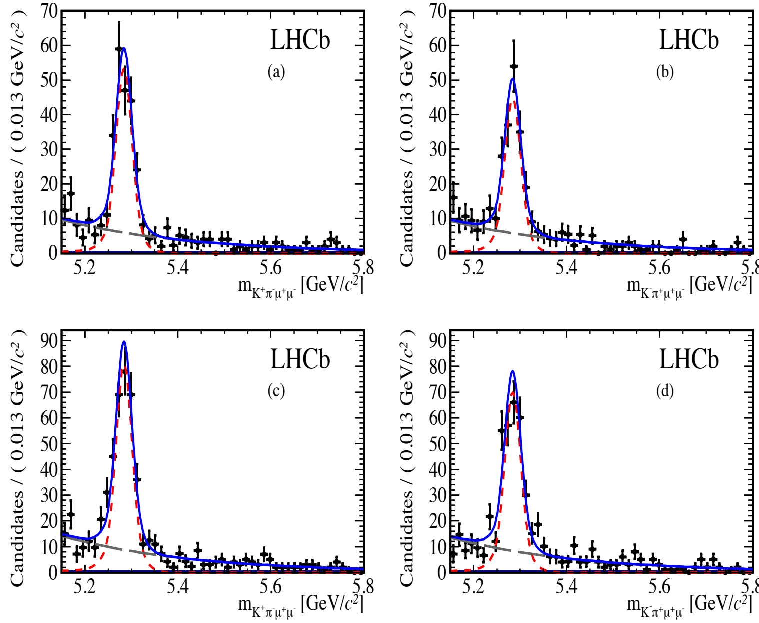
- SM predicts 10^{-3}, no leading form factor uncertainties

- Measure by a simultaneous fit: $A_{RAW} = A_{CP} + kA_P + A_D$
  - *B* production asymmetry A_P as in ***B⁰→J/ψ K**** (~1%)
  - detection asymmetry A_D:
    1) for left-right detector asymmetries
       => average measurements with magup and magdown;
    2) for different charge interaction of particles with material
       => same as in ***B⁰→J/ψ K****

- $\mathcal{A}_{CP} = \mathcal{A}_{\mathrm{RAW}}(B^0 \to K^{*0}\mu^+\mu^-) - \mathcal{A}_{\mathrm{RAW}}(B^0 \to J/\psi K^{*0})$

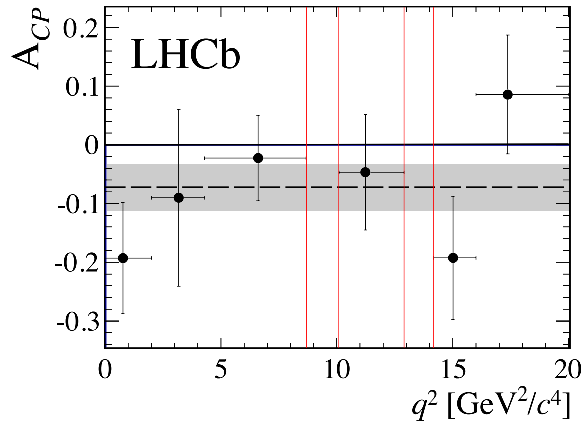
- Differences in ***B→K*μμ*** and ***B⁰→J/ψ K**** kinematics accounted in systematics by reweighting

- Different momentum distributions of μ^+ and μ^- due to A_{FB} studied with a ***J/ψ*** control sample



Results:

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040 \pm 0.005$$

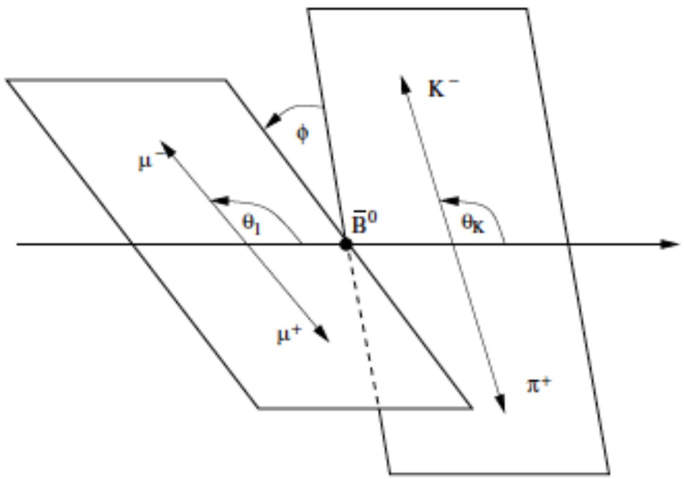


$B^0 \to K^* \mu^+ \mu^-$ angular analysis

LHCb-CONF-2012-008

- **Test of the helicity structure** of the decay through the angular observables distributions of θ_L θ_K ϕ
- *Experimental challenges:* - **Control backgrounds** that could pollute the angular distributions
  - Understand the **biases induced by the geometrical acceptance** on angles

$$\frac{d\Gamma}{d\cos\Theta_K d\cos\Theta_L \phi} = \varepsilon(\cos\Theta_K)\times\varepsilon(\cos\Theta_L)\times[I_1(\cos\Theta_K)+I_2(\cos\Theta_K)(2\cos^2\Theta_L-1)+I_3(\cos\Theta_K)(1-\cos^2\Theta_L)\cos 2\phi + I_6(\cos\Theta_K)\cos\Theta_L + I_9(\cos\Theta_K)(1-\cos^2\Theta_L)\sin 2\phi]$$



$$I_{1s} = \frac{3}{4}(1-F_L)\times\left(1+\frac{1}{3}\cdot\frac{4m_\ell^2}{q^2}\right) \qquad I_{1c} = F_L\times\left(1+\frac{4m_\ell^2}{q^2}\right)$$

$$I_1 = I_{1s}\times(1-\cos^2\Theta_K) + I_{1c}\times\cos^2\Theta_K$$

$$I_{2s} = \frac{1}{4}(1-F_L)\times\left(1-\frac{4m_\ell^2}{q^2}\right) \qquad I_{2c} = -F_L\times\left(1-\frac{4m_\ell^2}{q^2}\right)$$

$$I_2 = I_{2s}\times(1-\cos^2\Theta_K) + I_{2c}\times\cos^2\Theta_K$$

$$I_3 = \frac{1}{2}(1-F_L)\times A_T^{(2)}\times\left(1-\frac{4m_\ell^2}{q^2}\right)\times(1-\cos^2\Theta_K)$$

$$I_6 = 2\sqrt{1-4\frac{m_\ell^2}{q^2}}A_T^{(\mathrm{Re})}(1-F_L)\times(1-\cos^2\Theta_K)$$

$$I_9 = \frac{1}{2}(1-F_L)\times A_T^{(\mathrm{Im})}\times\left(1-\frac{4m_\ell^2}{q^2}\right)\times(1-\cos^2\Theta_K)$$

Phys. Lett. B273 (1991) 505
JHEP 01 (2009) 019

- **Fraction of longitudinal K^{*0} polarization**:

$$F_L = \frac{|A_0|^2}{|A_0|^2+|A_\perp|^2+|A_\parallel|^2}$$

- **Transverse asymmetry**:

$$A_T^2 = \frac{|A_\perp|^2-|A_\parallel|^2}{|A_\perp|^2+|A_\parallel|^2} = \frac{2S_3}{1-F_L} \approx -2\frac{A_R}{A_L}$$

- $A_T^{(Im)}$

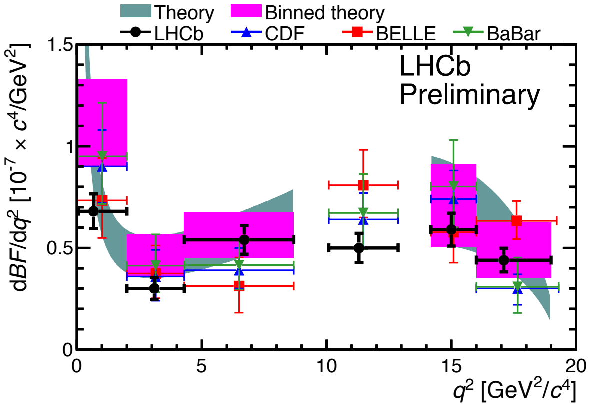
$$= 2*\frac{\mathrm{Im}(A_{\parallel L}^* A_{\perp L}) - \mathrm{Im}(A_{\parallel R}^* A_{\perp R})}{|A_\perp|^2+|A_\parallel|^2} = \frac{2A_{\mathrm{Im}}}{1-F_L}$$

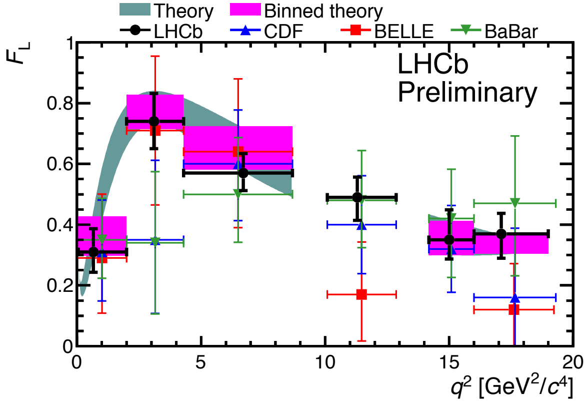
- **Forward-backward asymmetry** of θ_L distribution:

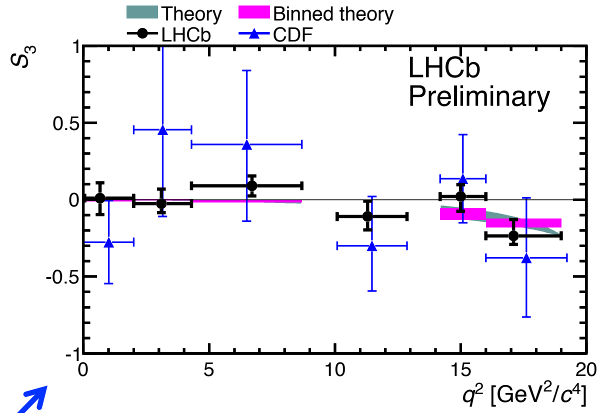
$$A_T^{(\mathrm{Re})} = 2*\frac{\mathrm{Re}(A_{\parallel L}^* A_{\perp L}) - \mathrm{Re}(A_{\parallel R}^* A_{\perp R})}{|A_\perp|^2+|A_\parallel|^2} = \frac{4}{3}\frac{A_{FB}}{1-F_L}$$

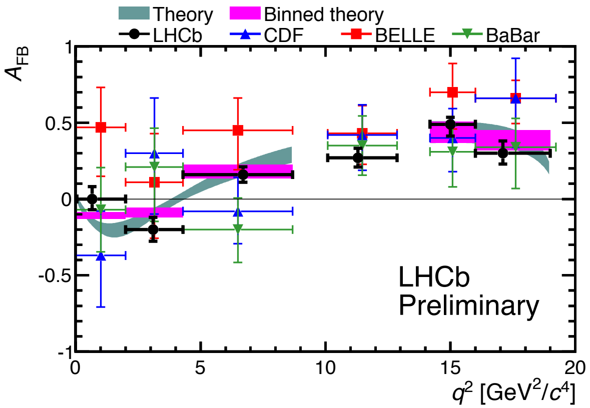
$B^0 \to K^* \mu^+ \mu^-$ angular analysis

LHCb-CONF-2012-008, paper in preparation





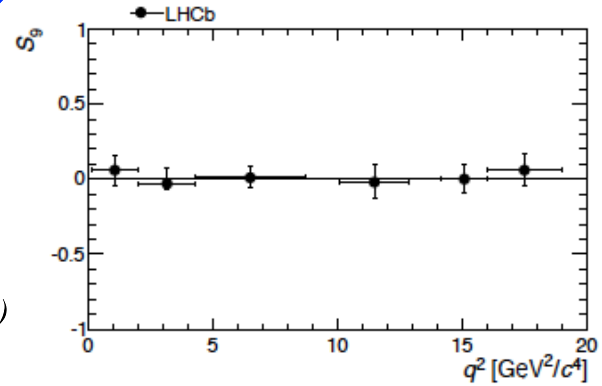




$$A_{FB} = \frac{3}{4}(1 - F_L)A_T^{\mathrm{Re}}$$

$$S_3 = \frac{1}{2}(1 - F_L)A_T^2$$

Theory predictions: Bobeth et al. (arXiv:1111.2558)



- *LHCb* has already the most precise measurements of all observables.
- New observable accessible!
- All measurement are in agreement with the SM predictions.
- Results are used to put constraints on new physics in theory papers (ex: arXiv:1206.0273)

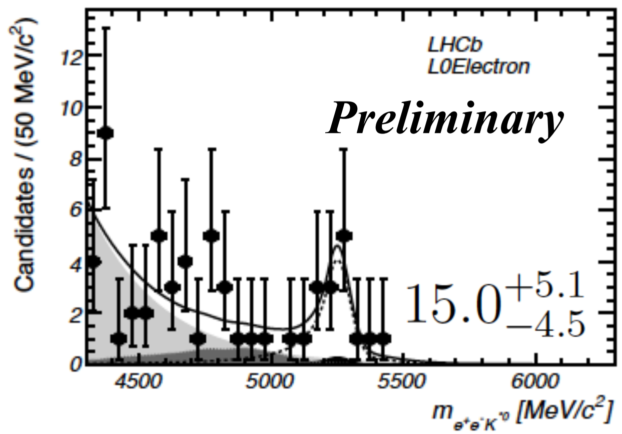
Comparison with $B \to K^* \mu^+ \mu^-$:

✓ higher sensitivity to the photon polarization (left-handed in SM) as lower q^2 ($= m_{ee}^2$)

✓ complementary since more sensitivity to C7' than C9'

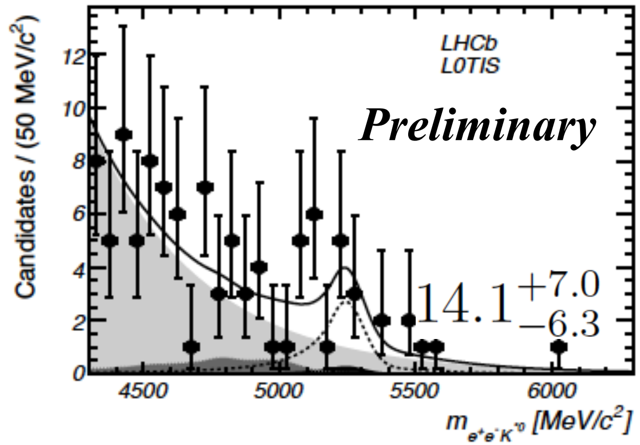
✓ easier formalism, since lepton mass is negligible

x - worst resolution because of bremsstrahlung effects



- Analysis range $0.03 < q^2 < 1$ GeV^2/c^4 avoids:
  - high contamination of $B \to K^* \gamma$
  - degradation of *ee* plane measurement due to multiple scattering

- Trigger on one of the electrons (L0Electron) or another particle in the event (L0TIS)



- ***$B \to K^* J/\psi(\to ee)$*** to control the signal shape and as normalization

- Backgrounds specific cuts:
  - ***$B^0 \to D^- e \nu$*** with ***$D^- \to e^- \bar{\nu} K^*$ (require $m(K^*e) > 1.9$ GeV/c^2)***
  - ***$B^0 \to K^* \gamma$*** with photon converting (cut on conversion vertex)

Preliminary results: $\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1^{+0.9}_{-0.8}\,{}^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$

- ***4.6σ*** observation
- Angular analysis to come with full dataset

$B \to K^{(*)}\gamma / B_s \to \phi\gamma$

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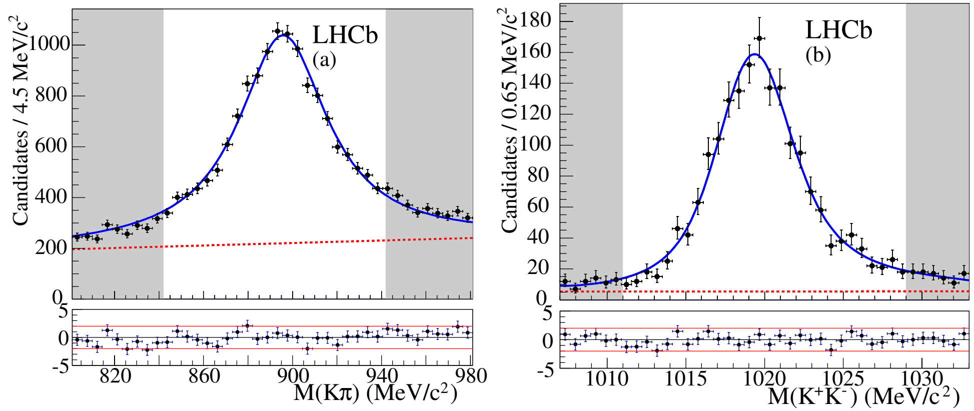
- SM predictions (NNLO using soft-collinear effective theory):
  BR($B^0 \to K^*\gamma$) = BR($B_s \to \phi\gamma$) = $(4.3 +/- 1.4)10^{-5}$
  BR($B^0 \to K^*\gamma$)/BR($B_s \to \phi\gamma$)=(1.0+/−0.2)
  $A_{CP}(B^0 \to K^*\gamma)$=(−0.61+/−0.43)%

- Specific selections:
  - $E_T(\gamma)$>2.6GeV
  - cut on helicity angle to kill $B \to V\pi^0$ (going as $\cos^2\theta_H$ instead of $\sin^2\theta_H$)



$B^{+(0)} \to \phi K^{+(0)}\gamma$

$B^{+(0)} \to K^{*0}\pi^{+(0)}\gamma$

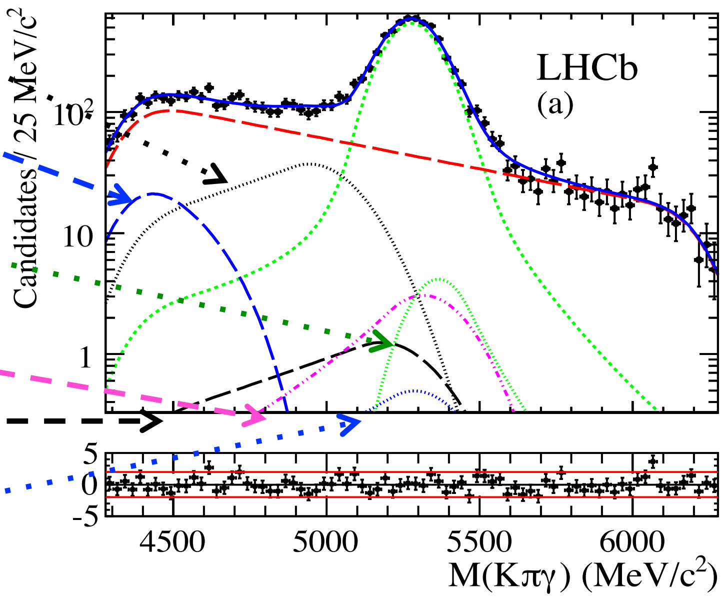
$B \to K^{*0}(\phi)\pi^0 X$

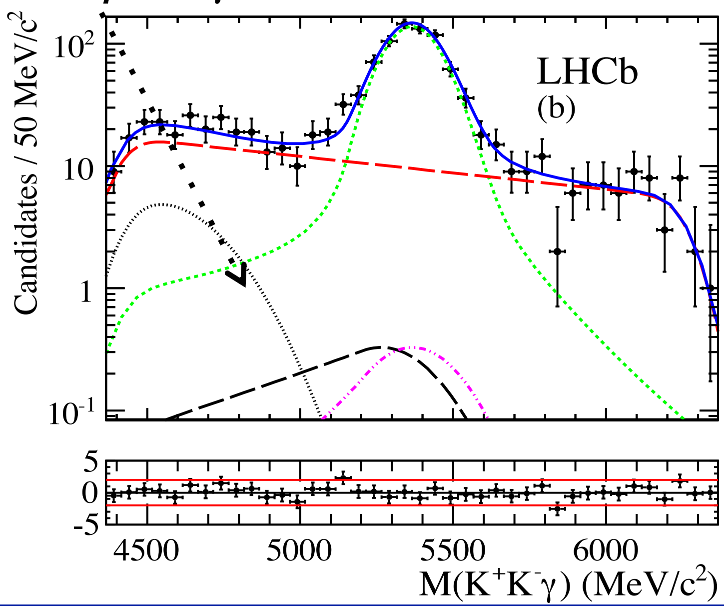
$B_s^0 \to K^{*0}\gamma$

$\Lambda_b^0 \to \Lambda^*\gamma$

$B^0 \to K^+\pi^-\pi^0$

$B_s^0 \to K^+\pi^-\pi^0$





$B \to K^{(*)}\gamma / B_s \to \phi\gamma$

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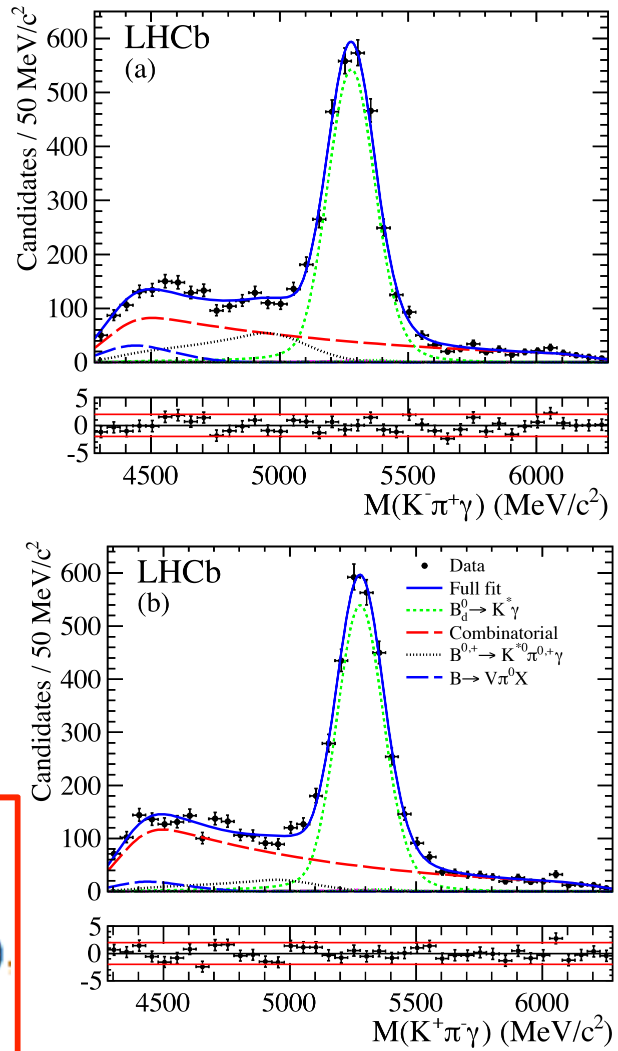
Decay	Branching fraction ($\times 10^6$)	Relative contribution to $B^0 \to K^{*0}\gamma$	Relative contribution to $B_s^0 \to \phi\gamma$
$\Lambda_b^0 \to \Lambda^*\gamma$	estimated from data	$(1.0 \pm 0.3)\%$	$(0.4 \pm 0.3)\%$
$B_s^0 \to K^{*0}\gamma$	1.26 ± 0.31 (theo. [25])	$(0.8 \pm 0.2)\%$	$\mathcal{O}(10^{-4})$
$B^0 \to K^+\pi^-\pi^0$	$35.9^{+2.8}_{-2.4}$ (exp. [4])	$(0.5 \pm 0.1)\%$	$\mathcal{O}(10^{-4})$
$B_s^0 \to K^+\pi^-\pi^0$	estimated from SU(3) symmetry	$(0.2 \pm 0.2)\%$	$\mathcal{O}(10^{-4})$
$B_s^0 \to K^+K^-\pi^0$	estimated from SU(3) symmetry	$\mathcal{O}(10^{-4})$	$(0.5 \pm 0.5)\%$
$B^+ \to K^{*0}\pi^+\gamma$	20^{+7}_{-6} (exp. [4])	$(3.3 \pm 1.1)\%$	$< 6 \times 10^{-4}$
$B^0 \to K^+\pi^-\pi^0\gamma$	41 ± 4 (exp. [4])	$(4.5 \pm 1.7)\%$	$\mathcal{O}(10^{-4})$
$B^+ \to \phi K^+\gamma$	3.5 ± 0.6 (exp. [4])	3×10^{-4}	$(1.8 \pm 0.3)\%$
$B \to V\pi^0X$	$\mathcal{O}(10\%)$ (exp. [4])	a few%	a few%



- Systematics:
  1) hadron reconstruction efficiency
  2) Simulation reliability
  3) PID efficiency from $D^* \to D^0(K\pi)\,\pi$

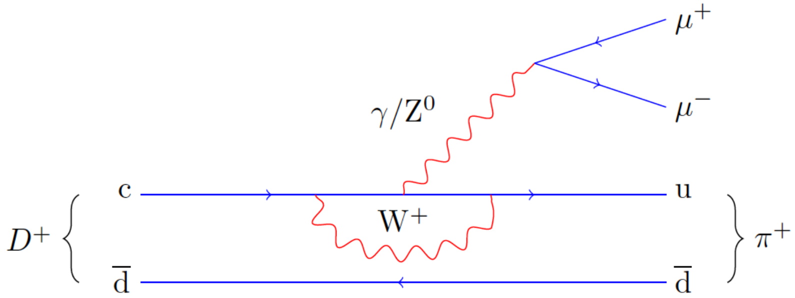
Results:

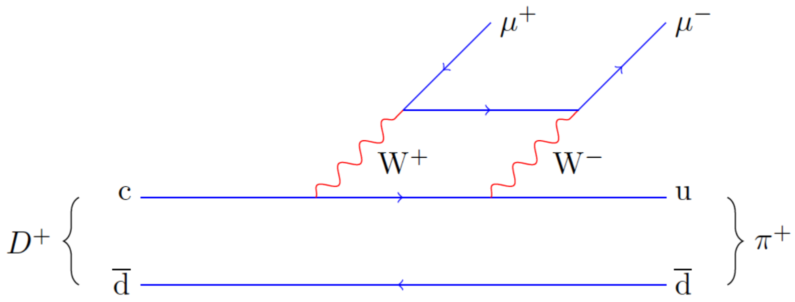
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%$$

$D_{(s)}{}^{+}\to\pi^{+}\mu^{+}\mu^{-}$ and $D_{(s)}{}^{+}\to\pi^{-}\mu^{+}\mu^{+}$

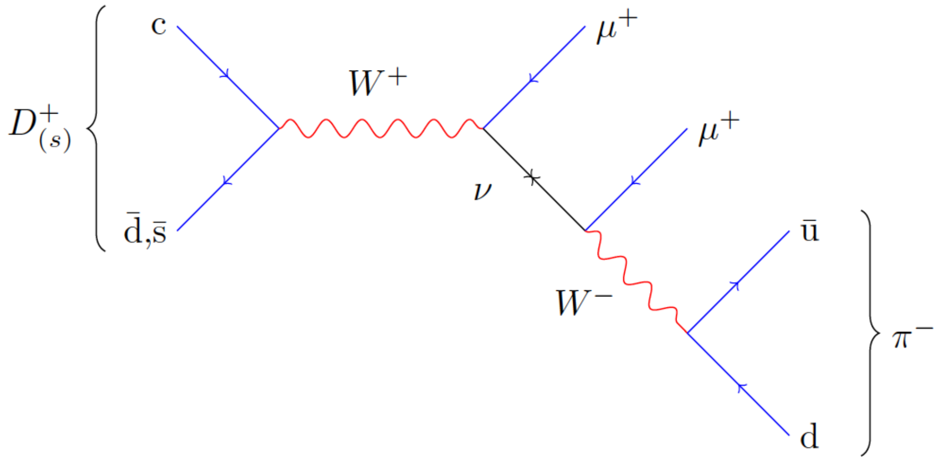
$D_{(s)}{}^{+}\to\pi^{+}\mu^{+}\mu^{-}$: c → u FCNC process





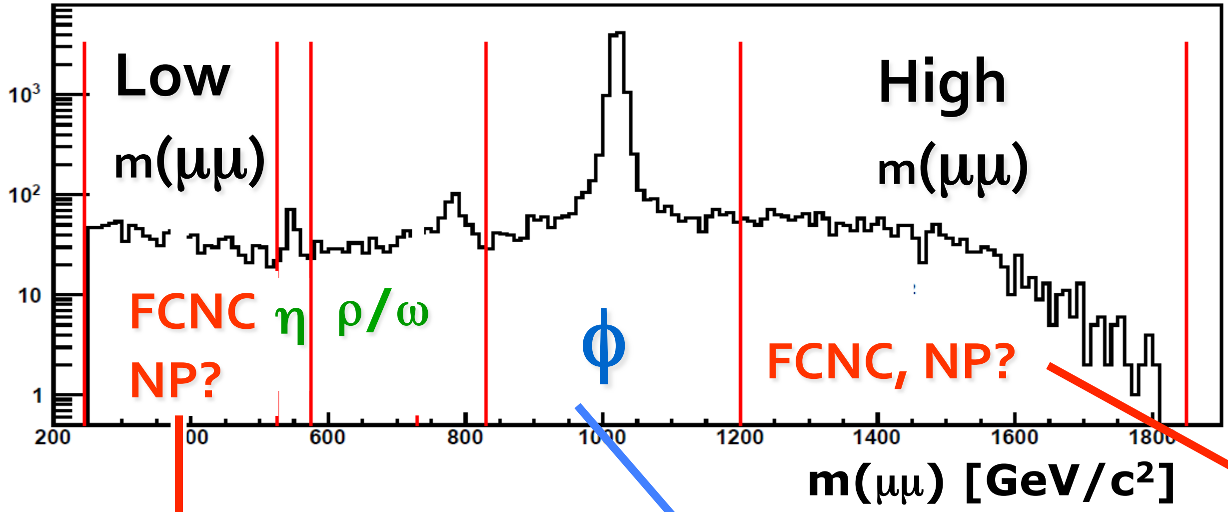
$D_{(s)}{}^{+}\to\pi^{+}\mu^{+}\mu^{+}$: Lepton-number violating

- Forbidden in the SM
- May occur by, e.g., Majorana neutrinos
- Similar searches with *B* mesons ***(PRD85 (2012) 112004)***



$D_{(s)}^{+} \to \pi^{+}\mu^{+}\mu^{-}$ and $D_{(s)}^{+} \to \pi^{-}\mu^{+}\mu^{+}$

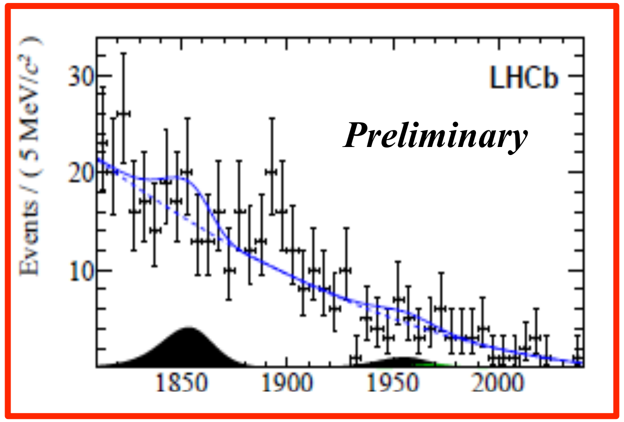
Five regions of the dimuon spectrum studied simultaneously



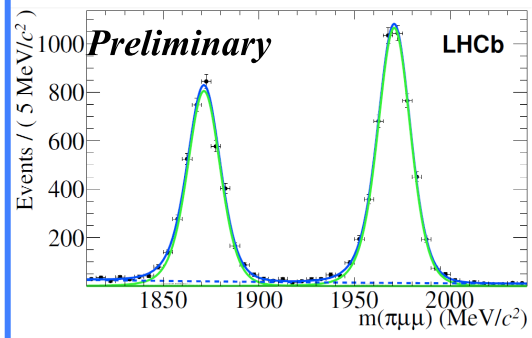
LHCb preliminary

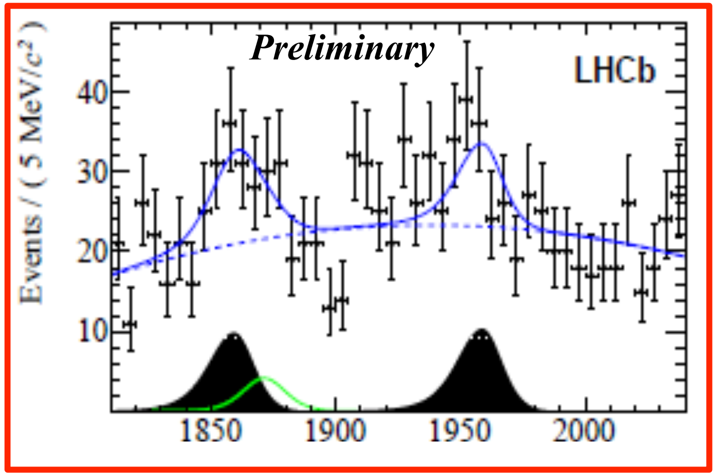
To be submitted to Phys. Lett. B

- Signal
- Comb. background
- **Peaking backgrounds:** $D^{+}_{s} \to \pi^{+}\pi^{+}\pi^{-}$



$D^{+}_{(s)} \to \pi^{+}\,\phi(\mu^{+}\mu^{-})$ used as standard candles





$D_{(s)}^+ \to \pi^+\mu^+\mu^-$ and $D_{(s)}^+ \to \pi^-\mu^+\mu^+$

$D_{(s)}^+ \to \pi^+\mu^+\mu^-$: Preliminary upper limits $\times 10^{-8}$ @ 90% (95%) C.L.

Region	$B(D^+ \to \pi^+\mu^+\mu^-)$	$B(D_S \to \pi^+\mu^+\mu^-)$
Low m(μμ)	2.0 (2.5)	6.9 (7.7)
High m(μμ)	2.6 (2.9)	16.0 (18.6)
Total [1]	7.3 (8.3)	41.0 (47.7)

- Total non resonant BF, extrapolated from the high m(μμ) region (phase space model)
  - **50 to 100 times better than previous measurements** (D0, Babar)
  - Still above largest theory predictions ($\sim 10^{-8}$)

$D_{(s)}^+ \to \pi^-\mu^+\mu^+$: (the analysis uses a similar approach to $D_{(s)}^+ \to \pi^+\mu^+\mu^-$)

- No sign of LFV
- Limits of the order of a few 10^{-8} (10^{-7}) for D^+ (D_S) decays
- **100 times better than previous measurement** (Babar)

CONCLUSIONS

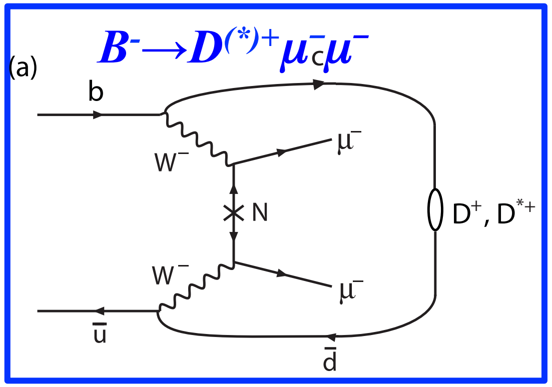
- ✓ ***Rare decays are a sensitive probe for new physics***
- ✓ ***LHCb has performed many measurements pushing further current limits, observing new decays, studying rare decays properties***
- ✓ ***All measurements are the most precise to date***
- ✓ ***At the moment no evidence of new physics can be claimed***
- ✓ ***But more data are being analyzed and new channels are being explored!***

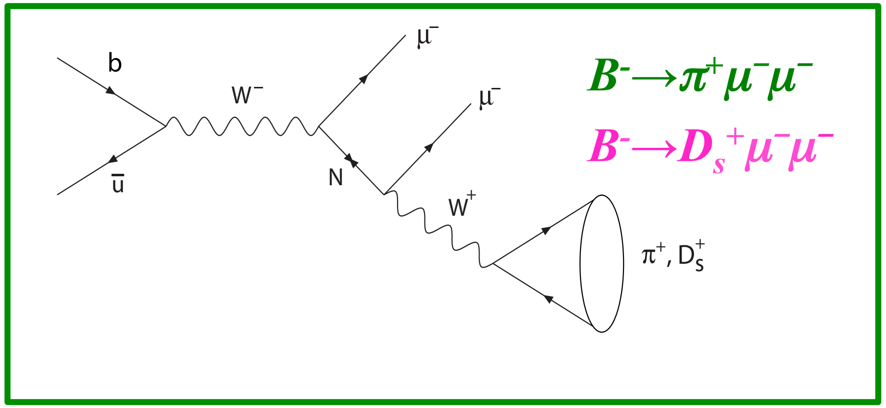
BACKUP

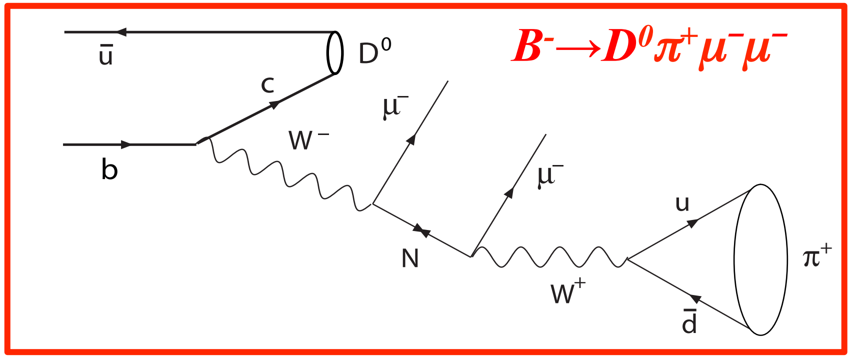
Majorana neutrinos

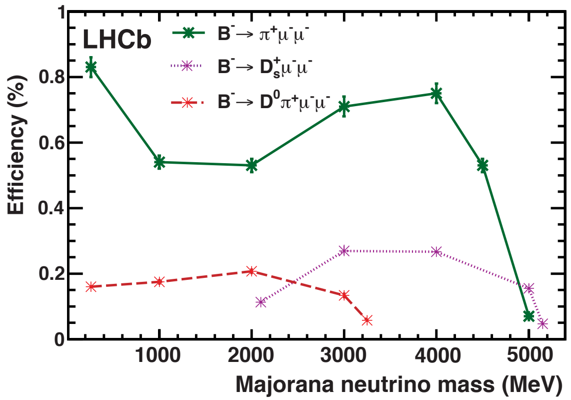
PRD85 (2012) 112004

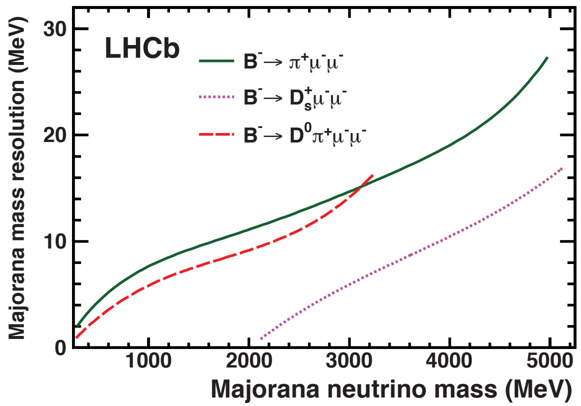
- If neutrinos are Majorana particles, they are **their own antiparticles**.
- Then the following processes, where the **neutrino acts as virtual particle**, are allowed.
- They can be on-shell → enhanced expected BR











Majorana neutrinos

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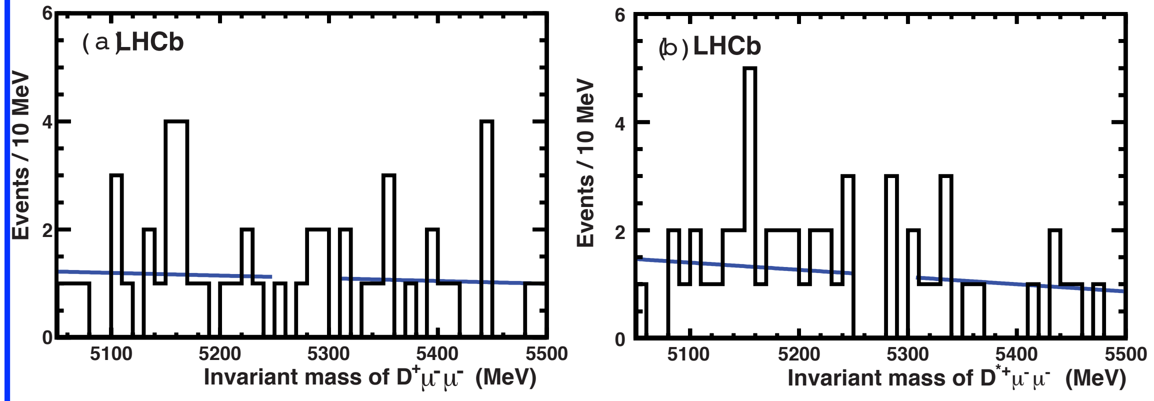
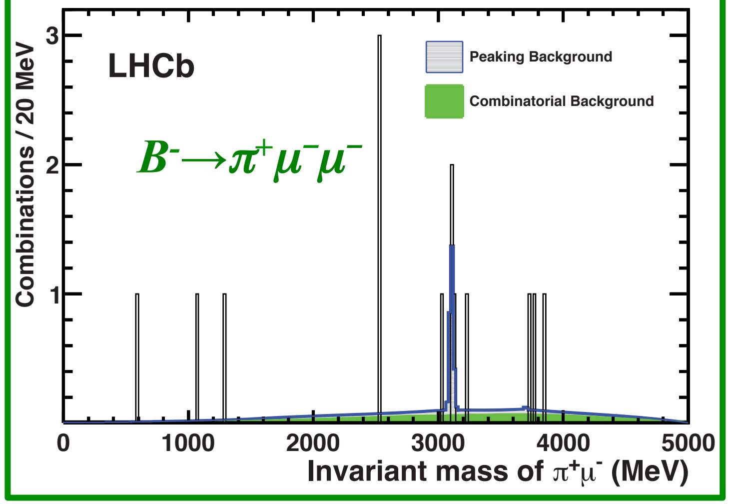
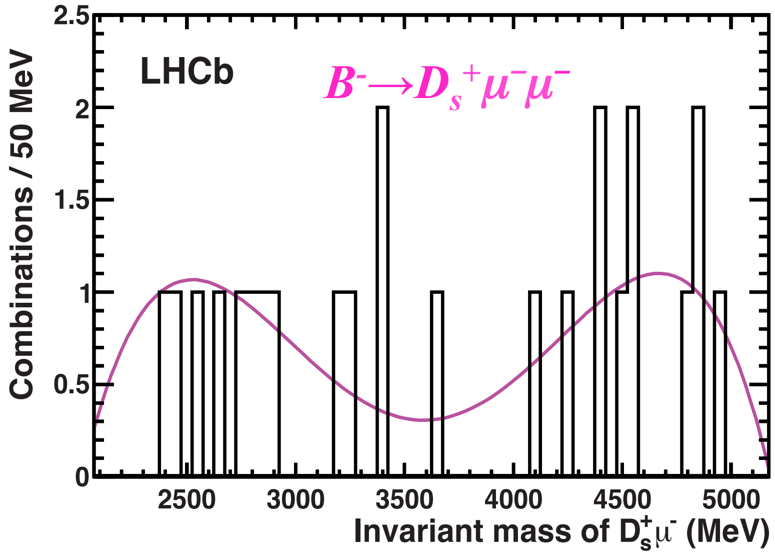
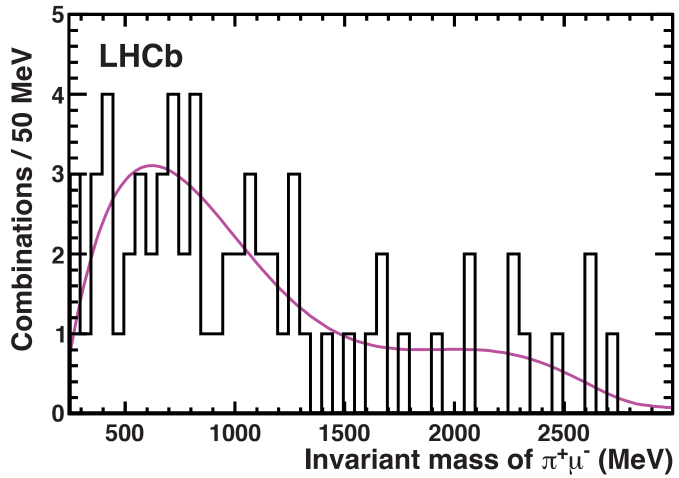
$B^- \to D^{(*)+}\mu^-\mu^-$







$B^- \to D^0\pi^+\mu^-\mu^-$



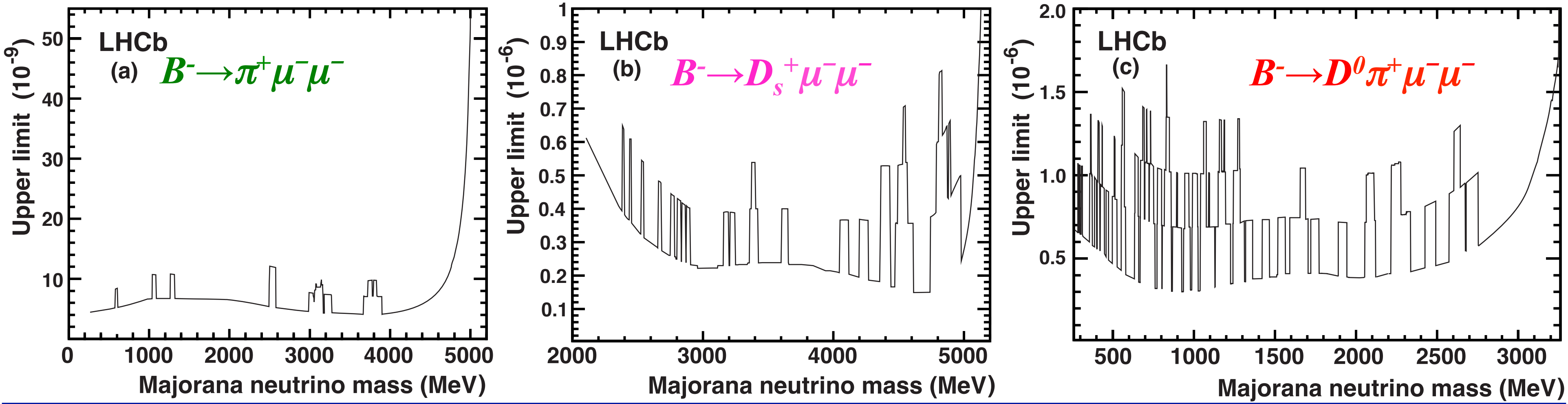
Majorana neutrino

PRD85 (2012) 112004

- Normalization channels: $B^- \to J/\psi K^-$ and $B^- \to \psi(2s) K^-$ (with $\psi(2s) \to J/\psi\pi\pi$)
- No observation: 95%CL are set:

Mode	$\mathcal{B}$ upper limit	Approximate limits as function of M_N
$D^+\mu^-\mu^-$	6.9×10^{-7}	
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}	
$\pi^+\mu^-\mu^-$	1.3×10^{-8}	$(0.4 - 1.0) \times 10^{-8}$
$D_s^+\mu^-\mu^-$	5.8×10^{-7}	$(1.5 - 8.0) \times 10^{-7}$
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}	$(0.3 - 1.5) \times 10^{-6}$

0.4 fb^{-1}



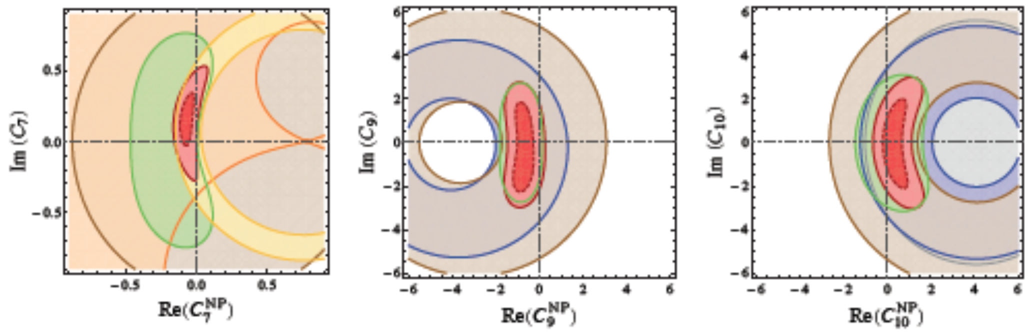


Figure 1: Individual 2σ constraints on the unprimed Wilson coefficients from $B \to X_s \ell^+ \ell^-$ (brown), BR$(B \to X_s \gamma)$ (yellow), $A_{CP}(b \to s\gamma)$ (orange), $B \to K^* \gamma$ (purple), $B \to K^* \mu^+ \mu^-$ (green), $B \to K \mu^+ \mu^-$ (blue) and $B_s \to \mu^+ \mu^-$ (gray) as well as combined 1 and 2σ constraints (red).

arXiv:1206.0273v2 [hep-ph] 10 Aug 2012

Wolfgang Altmannshofer[a] and David M. Straub[b]

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}\ .$$

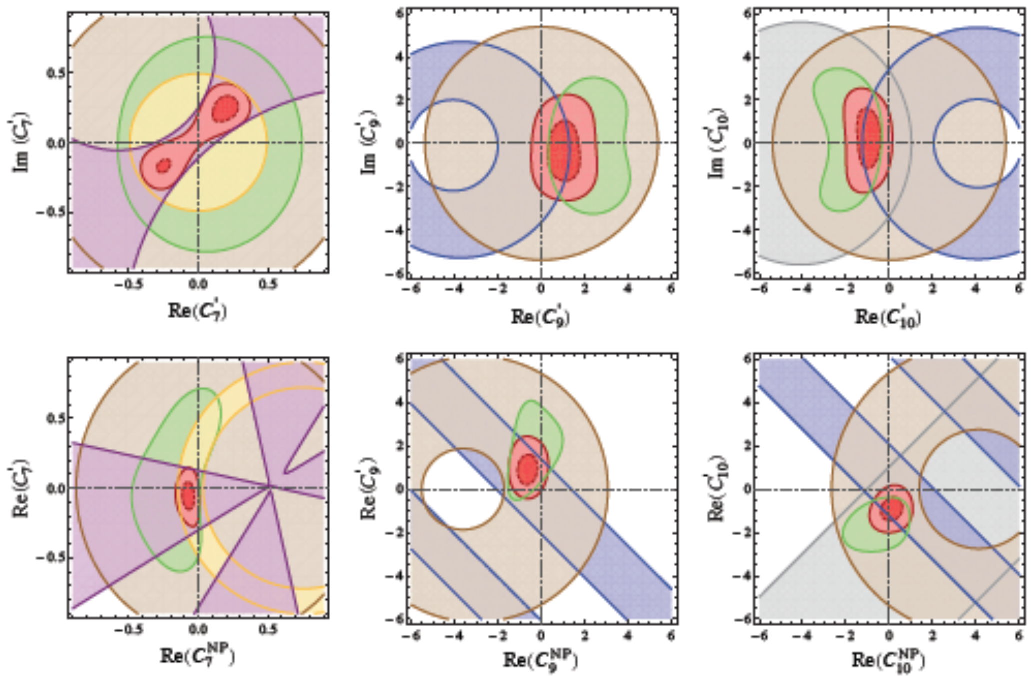


Figure 2: Individual 2σ constraints on the primed Wilson coefficients as well as combined 1 and 2σ constraints. Same colour coding as in figure 1.