FLAVOUR PHYSICS AT LHCb

ICNFP 2015 : 4th International Conference on New Frontiers in Physics

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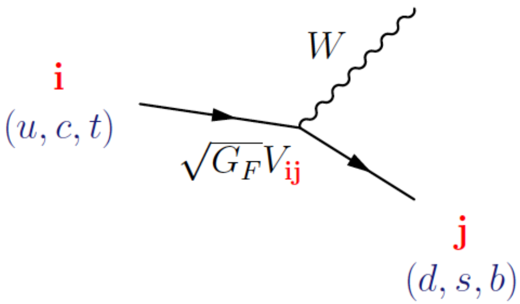
on behalf of the LHCb Collaboration

Quark flavour mixing



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

V_{CKM} originates from MISALIGNMENT between UP and DOWN quark couplings to the Higgs boson

$$-\mathcal{L}_Y^q = Y^D \bar{Q}_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_R + Y^U \bar{Q}_L \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix} U_R + H.C. \qquad Y^U \neq Y^D \qquad V_{CKM} = U_L^{U+} U_L^D$$

- KM theory is highly predictive
  - huge range of phenomena, over many orders of magnitude in energy with only 4 independent parameters (not including quark masses)
- CKM matrix has minimal flavour violation
  - extended theories do not replicate in general such flavour structure
- KM mechanism introduces CP violation
  - it is THE standing theory of CP violation, in absence of neutrino masses or θ_{QCD}

The Unitarity Triangles

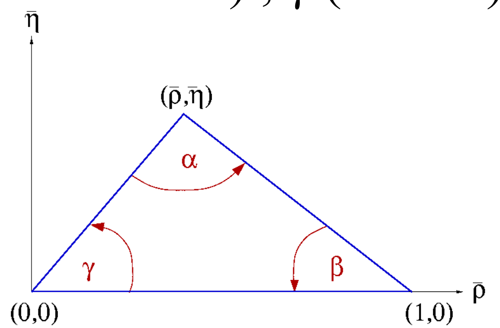
- CKM matrix must be UNITARY for a given number of quark generations (3) : $V_{CKM}^{+} = V_{CKM}$
- which provides many relationships, prominently:

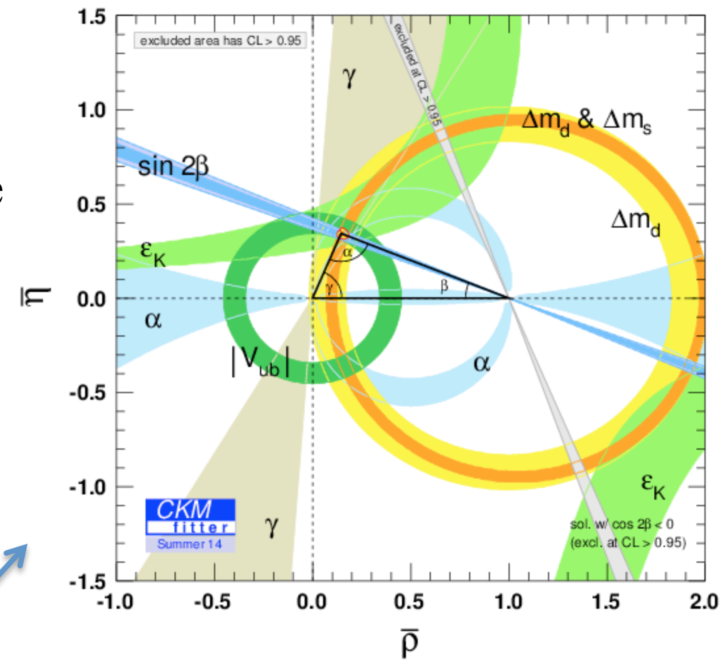
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- only one independent phase, but 4 measurable combinations can be formed of the type $V_{\alpha i}V_{\alpha j}^{*}V_{\beta j}V_{\beta i}^{*}$ such as β (BaBar, Belle 2001, *this talk*), β_s (LHCb 2013) , γ (*this talk*)

http://ckmfitter.in2p3.fr
see also http://www.utfit.org





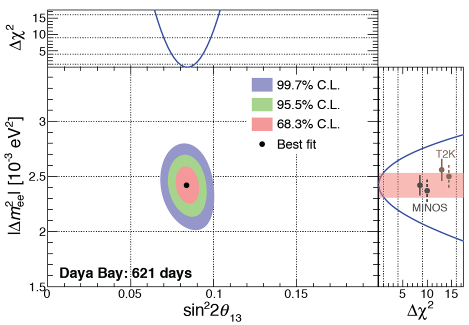
- consistency of measurements *are* tests of the Standard Model and provide model-independent constraints on New Physics

Two roads to travel the same path

in quark flavour physics

is KM theory perturbed ?

- not necessarily in quark sector
- unpredicted scale
- CPV in NEUTRINOS now realistic, with sizable θ_{13}

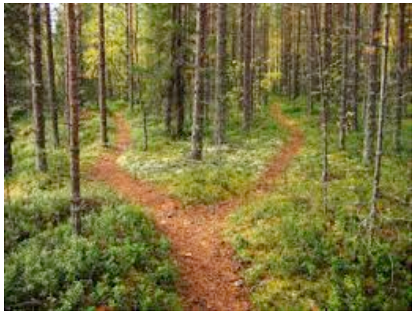


CP VIOLATION

extra sources must be there for baryogenesis

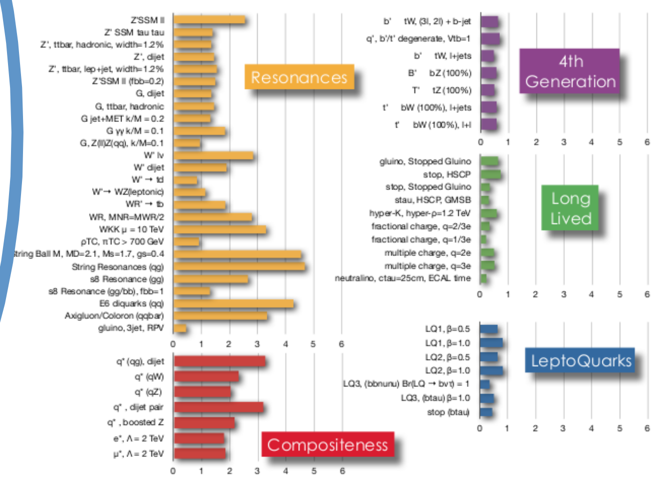
NP territory

leaky **SM**



Non appearence at ATLAS/CMS *makes the case more compelling*

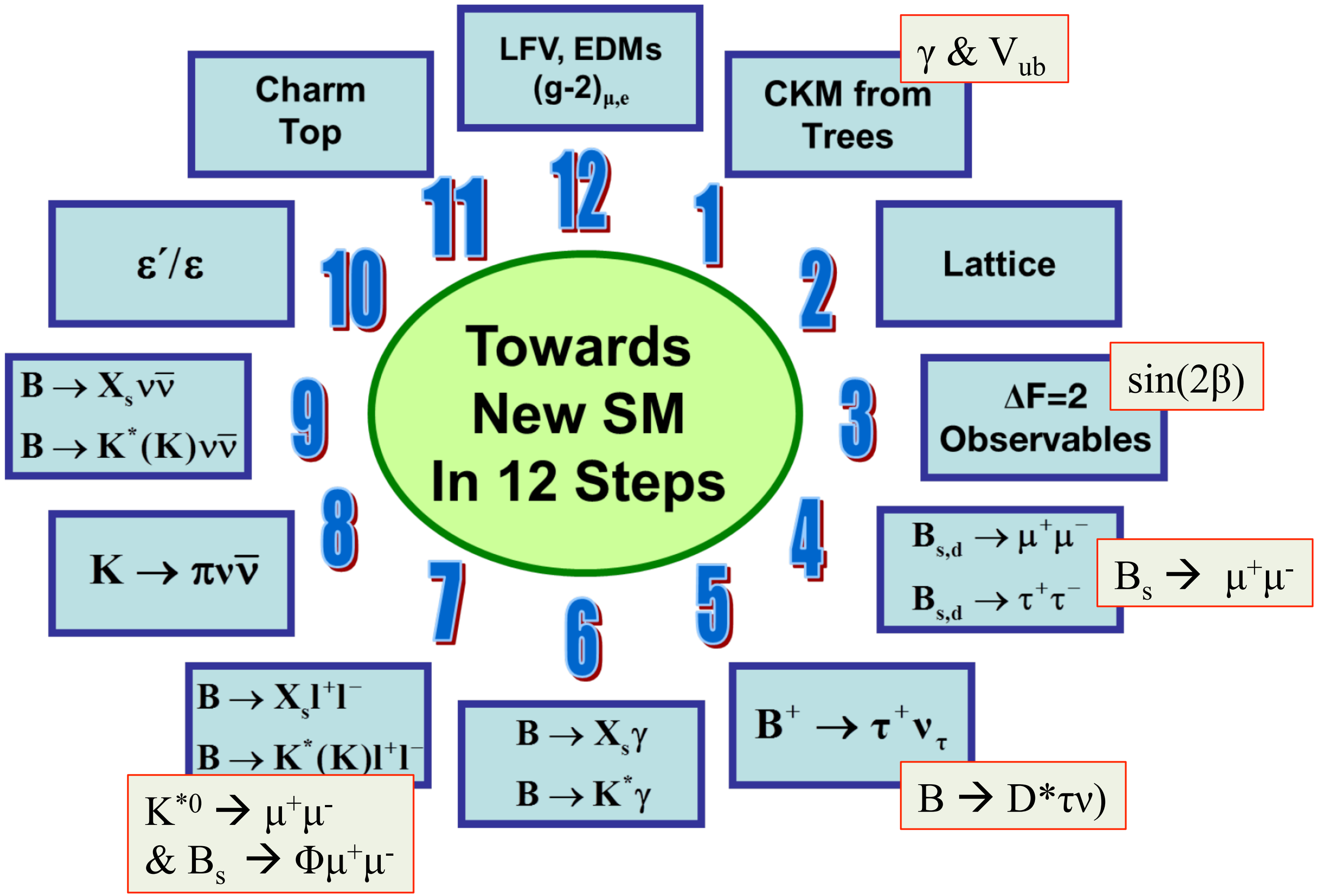
can be seen in RARE DECAYS *through quantum loops*



NEW HEAVY PARTICLES

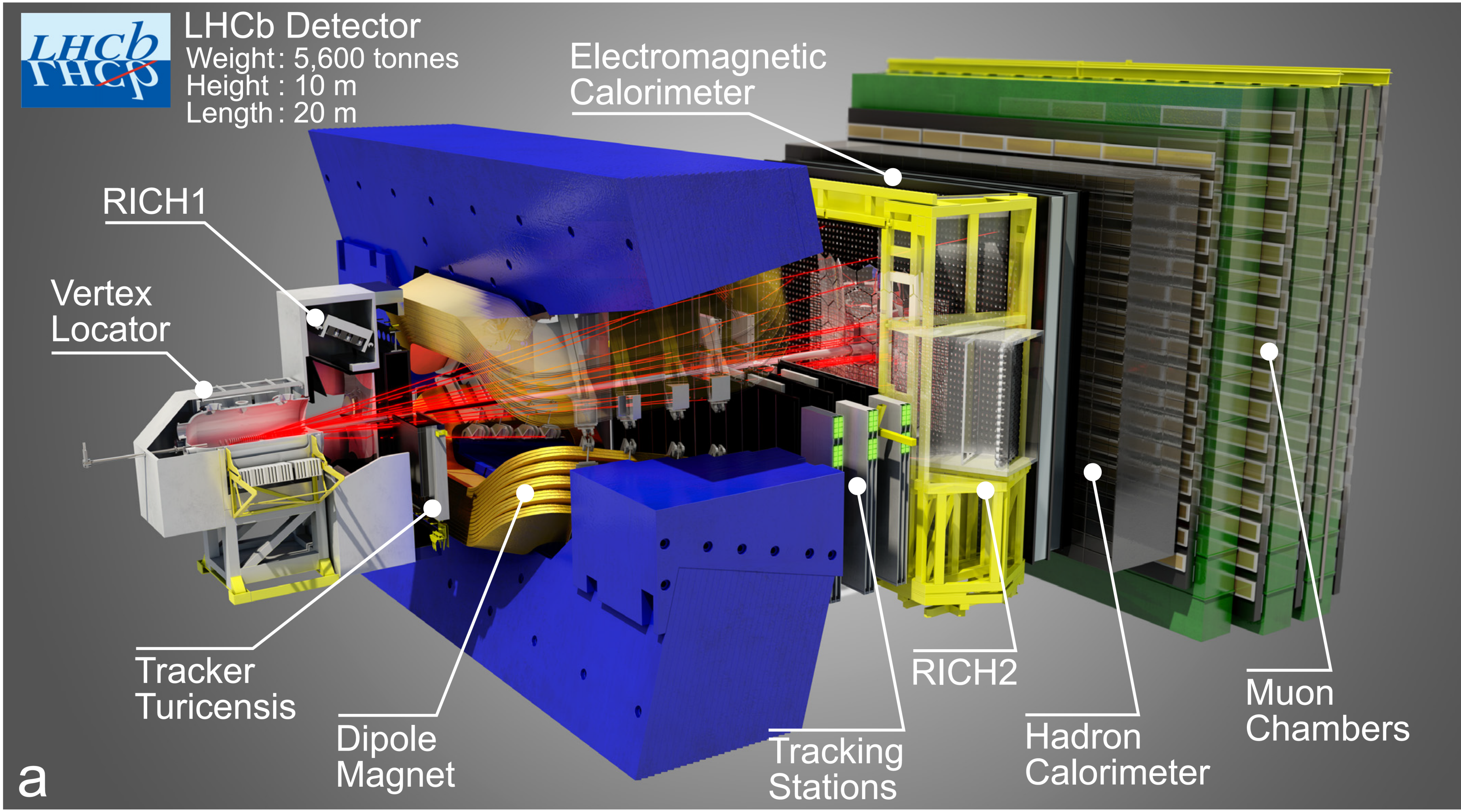
theoretically favoured

Topics covered in this talk



Clock from Buras & Girbach, RPP (2014) 086201

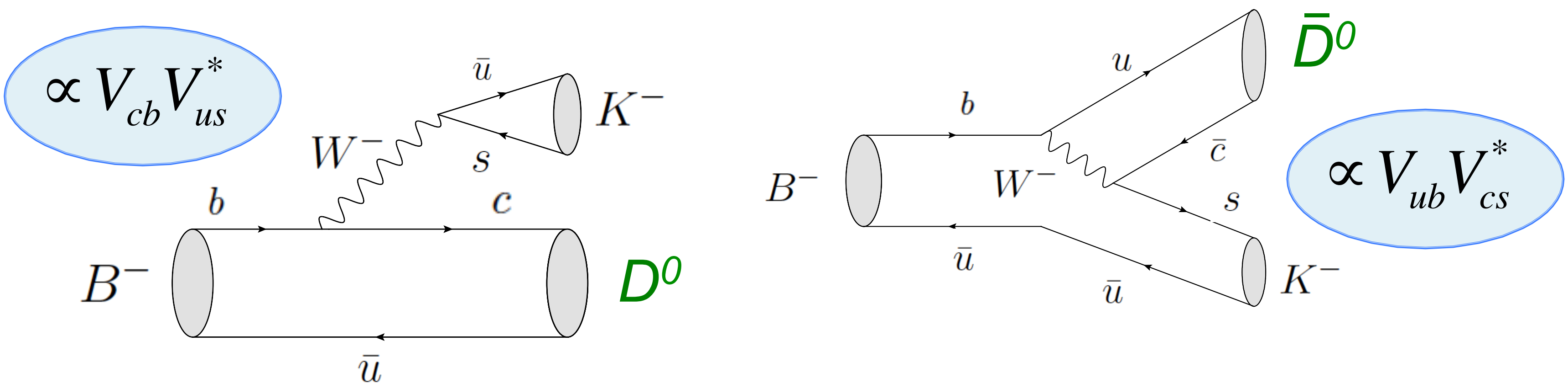
The LHCb apparatus



CP VIOLATION

Why γ from B → DK is important

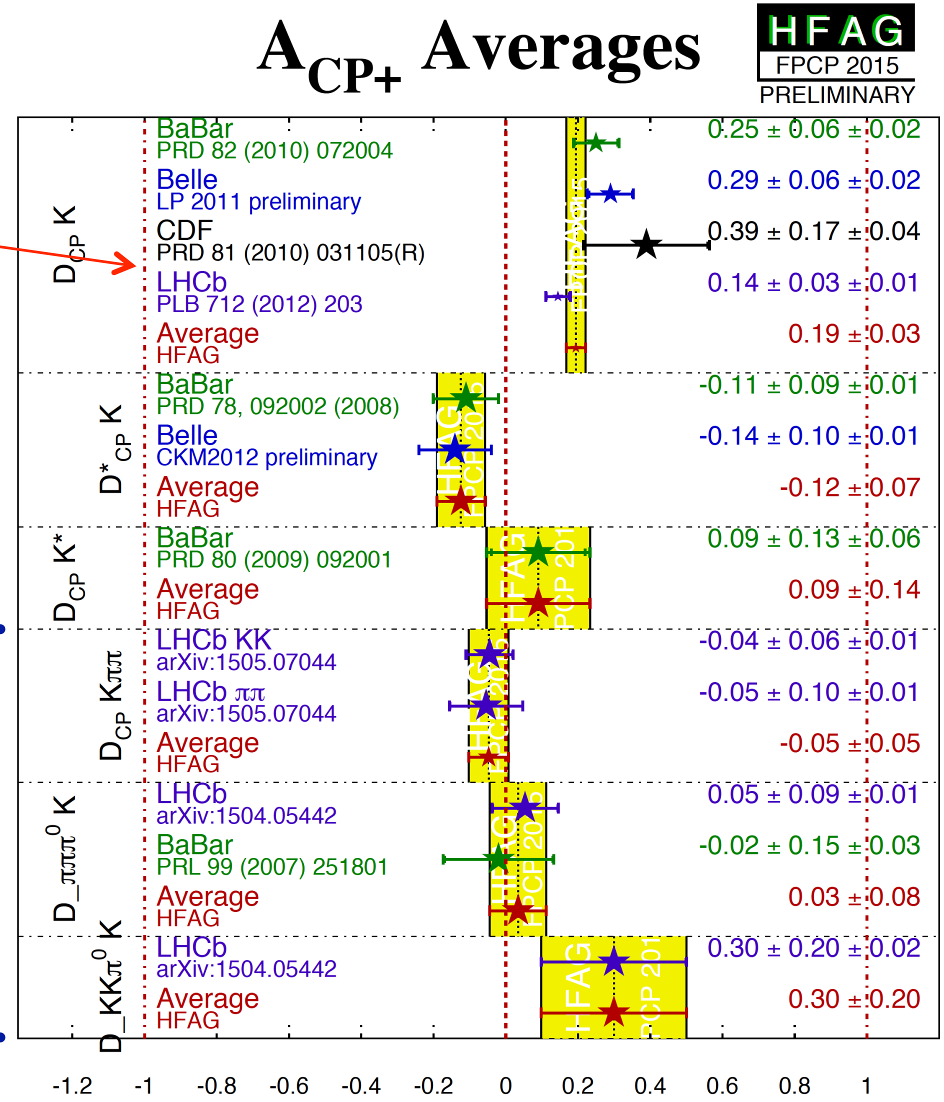
- γ plays a unique role in flavour physics
  - it can be measured from tree diagrams alone (probably the only such CP violating parameter)
- Therefore a reference point for the Standard Model
  - particularly important after New Physics is discovered



- A final state COMMON to D^0 and $\bar{D}^0$ is required. Different possibilities are characterized in the literature (GLW,ADS,GGSZ)

γ status

- Most precise channel is $D_{CP}K$ (awaiting LHCb update with full Run 1 data sample)
  - LHCb only combination, without latest results (but including measurements on DK^{*0} and time dependent $D^{\pm}_{s}K^{\pm}$) gives $\gamma = (73^{+9}_{-10})^{o}$, best single-experiment result (CKM2014 update)
- New LHCb measurements with competitive sensitity



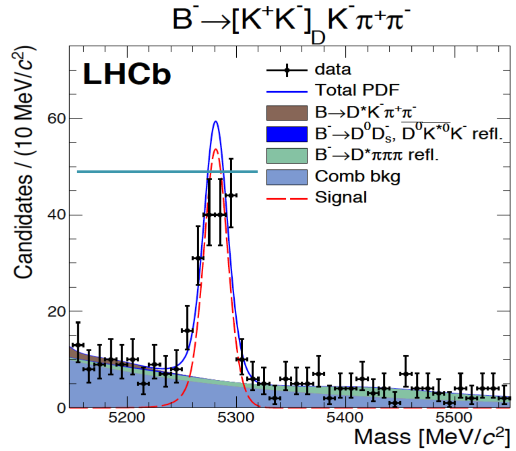
New decays modes for γ at LHCb

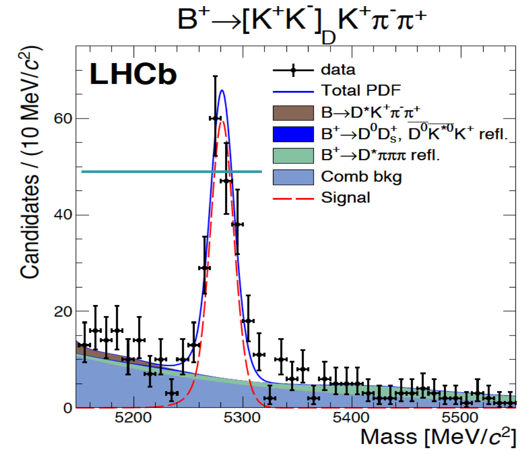
- Highly significant signals in CP modes $B^- \rightarrow DK^-\pi^+\pi^-$, $D \rightarrow K^+\pi^-, K^+K^-, \pi^+\pi^-$
- New independent, additional LHCb measurement:

$$\gamma = \left(74^{+20}_{-18}\right)^o$$

arXiv:1505.07044 , submitted to PRD

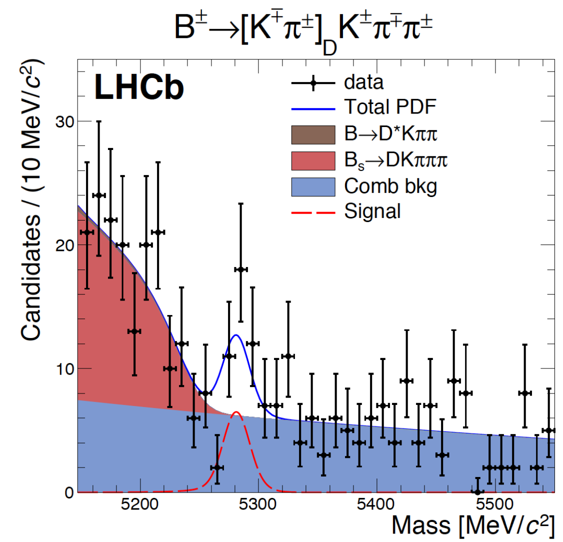
- First observation of the suppressed ADS mode $B^- \rightarrow (K^+\pi^-)_D K^-\pi^+\pi^-$, very sensitive to γ





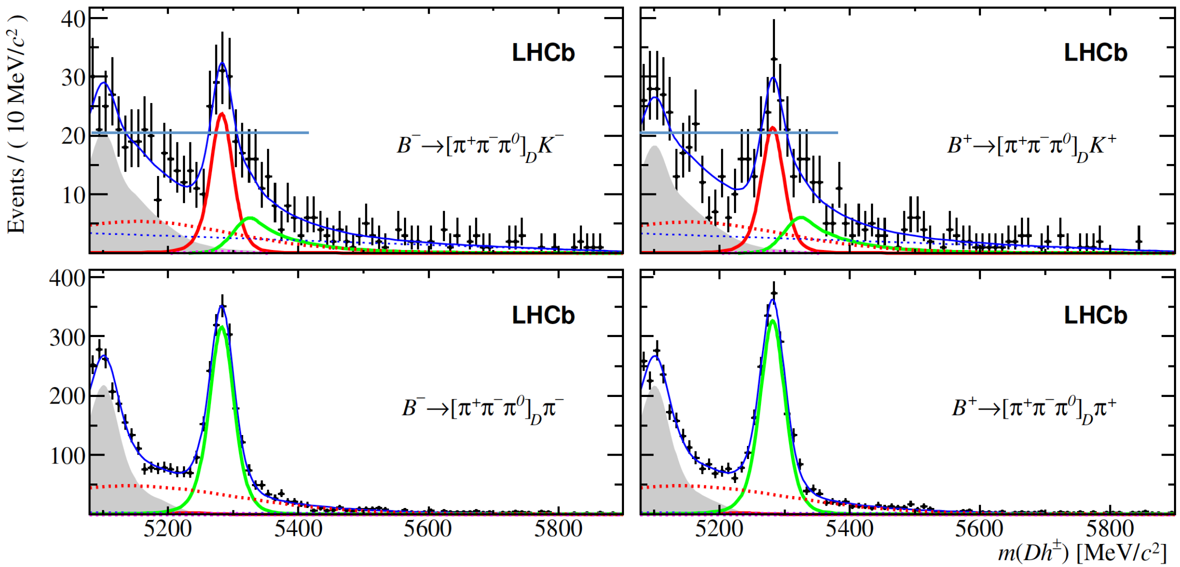
$B^- \rightarrow [\pi^+\pi^-]_D K^-\pi^+\pi^-$

$B^+ \rightarrow [\pi^+\pi^-]_D K^+\pi^-\pi^+$



New decays modes for γ at LHCb

- Further analysis strategies by LHCb on the neutral modes $B^- \rightarrow DK^-$ with $D \rightarrow \pi^+\pi^-\pi^0$, $D \rightarrow K^+K^-\pi^0$ and $D \rightarrow K^-\pi^+\pi^0$ (ADS)



Phys. Rev. D91 112014 (2015) , arXiv:1504.05442

- Recent analysis of coherently produced $D\bar{D}$ at ψ(3770) has shown that $D \rightarrow \pi^+\pi^-\pi^0$ is very close to a CP-even eigenstate (CP-even fraction $F_+ = 0.968 \pm 0.017$), which makes it particularly suitable for γ analysis (so called quasi-GLW) PLB 740 (2015) 1 arXiv:1410.3964.
- No evidence of CP violation has been obtained yet at LHCb, but good consistency with other measurements has been shown

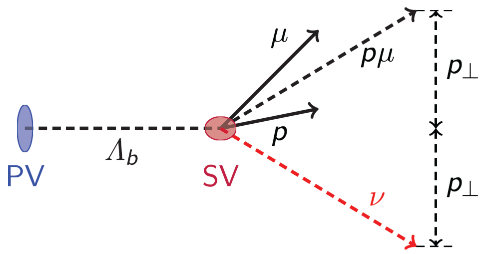
V_{ub}/V_{cb} from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$

- $|V_{ub}|$ governs the most sensitive misalignment between up/down quark flavor couplings to the Higgs boson
- Excellent measurements from $B^- \to \pi^0 l^- \bar{\nu}$ and $B^0 \to \pi^+ l^- \bar{\nu}$ at B-factories, but long standing discrepancy between exclusive and inclusive (containing all $b \to u l^- \bar{\nu}$ transitions) measurements, at 3.8σ level:

$$|V_{cb}| = (42.4 \pm 0.9)\times 10^{-3} \quad |V_{ub}| = (4.41 \pm 0.15 \,{}^{+0.15}_{-0.17})\times 10^{-3} \quad \textit{(incl.)}$$
$$|V_{cb}| = (39.5 \pm 0.8)\times 10^{-3} \quad |V_{ub}| = (3.23 \pm 0.31)\times 10^{-3} \quad \textit{(excl.)}$$

- LHCb at a hadron collider uses the corrected mass:

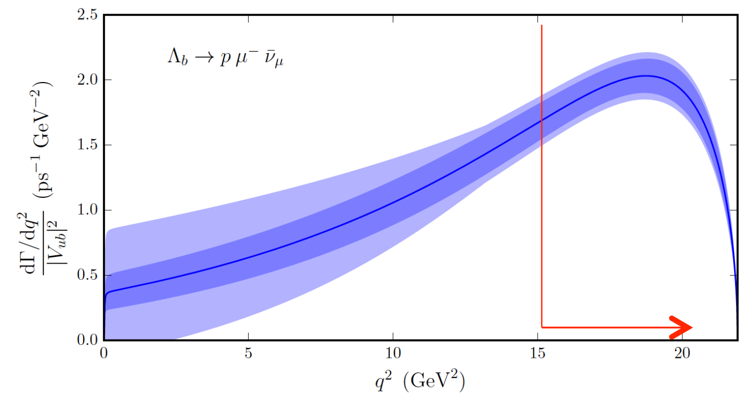
$$M_{corr} = \sqrt{M_{h\mu}^2 + p_\perp^2} + p_\perp$$



and directly compares $\Lambda_b \to p\mu^-\bar{\nu}$ with $\Lambda_b \to \Lambda_c^+(pK^-\pi^+)\mu^-\bar{\nu}$

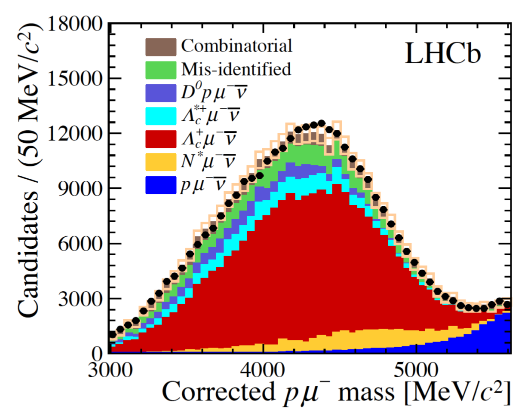
V_{ub}/V_{cb} from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$

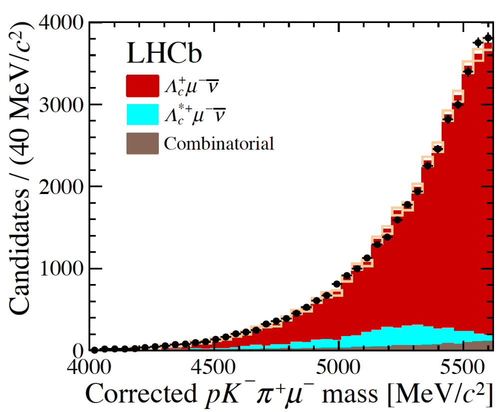
arXiv: 1503.01421



Nature Physics 10.1038 arXiv:1504.01568

- Lattice QCD form factors, needed in the calculation of $|V_{ub}|$, are most precise at high q^2 ($\mu\nu$), select $q^2 > 15$ GeV^2
- q^2 can be determined using Λ_b flight direction and mass, up to a two-fold ambiguity
- vertex isolation is used, $\Lambda_c^+ \to pK^-\pi^+$ cross-feed is the main background
- fit M_{corr} to get the signal yields





V_{ub}/V_{cb} from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$

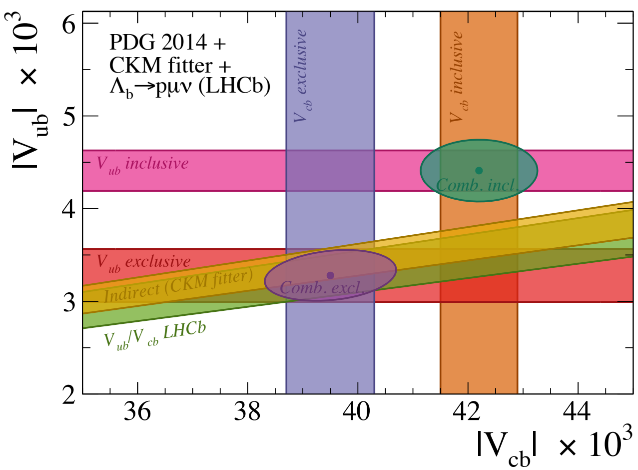
- New physics claimed to explain the puzzle with extra RH currents

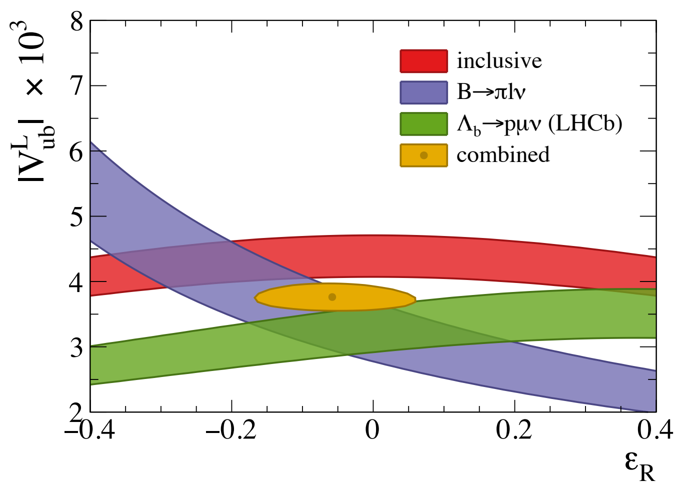
$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \left(\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b\right)\left(\bar{\nu}\gamma^\mu P_L l\right) + h.c.$$

F. Bernlochner et al. PRD 90, 094003 (2014)

$$\text{LHC}b: \quad \frac{B(\Lambda_b \to p\mu^-\bar{\nu}_\mu)_{q^2>15GeV^2/c^4}}{B(\Lambda_b \to \Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7GeV^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

Nature Physics 10.1038 arXiv:1504.01568





$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\exp) \pm 0.004(lattice)$$

- LHCb results do not support RH currents, agree with exclusive

$\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_s$

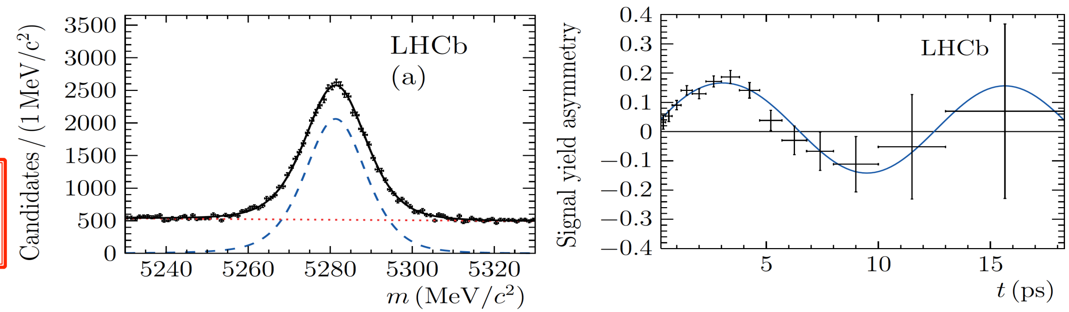
LHCb-PAPER-2015-004 arXiv:1503.07089

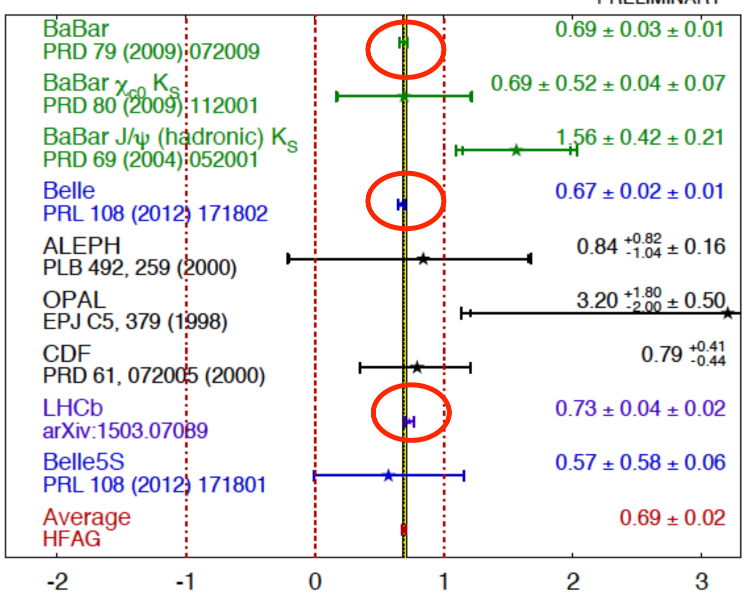
- time evolution of $B^0/\overline{B}^0$ asymmetry, 41500 decays
- LHCb is now competitive:

  $\sin(2\beta)=0.731\pm0.035\pm0.020$

  similar statistical precision to B-factories
- result consistent with world averages and with other measurements constraing $\sin(2\beta)$:

  $0.771^{+0.017}_{-0.041}$ CKMfitter arXiv:1501.05013
- significant improvement will require understanding of higher-order contributions





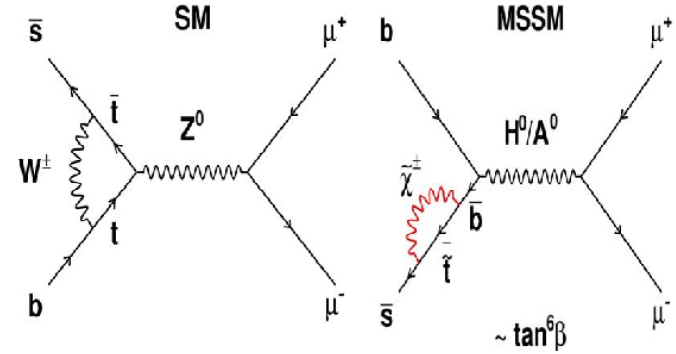
RARE AND SEMI-RARE DECAYS

$B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

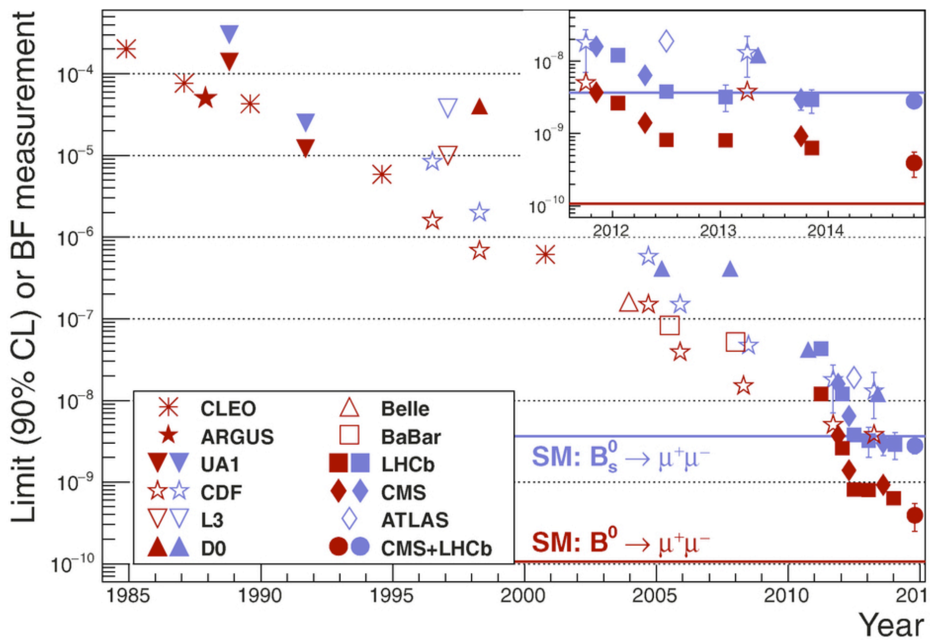
- $B \to \mu^+\mu^-$ decays are an *acid test* for New Physics models

  Very suppressed (10^{-9}-10^{-10}) in SM due to:
  - GIM mechanism (Z^0)
  - chirality of $W^\pm$
  - minimal flavor violation (H^0)

  Features not generally respected by generic extensions !



Painstakingly searched for over 30 years …



- Predictions are sharp:

  $B(B_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.23)\times 10^{-9}$

  $B(B^0 \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09)\times 10^{-10}$

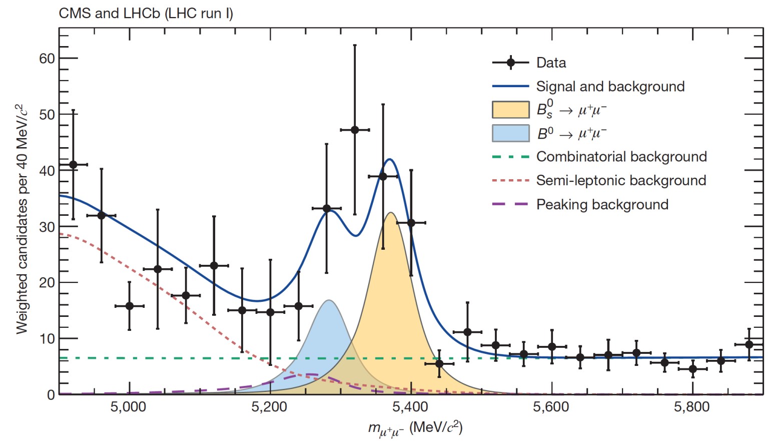
- Exemplary sensitivity for SUSY:

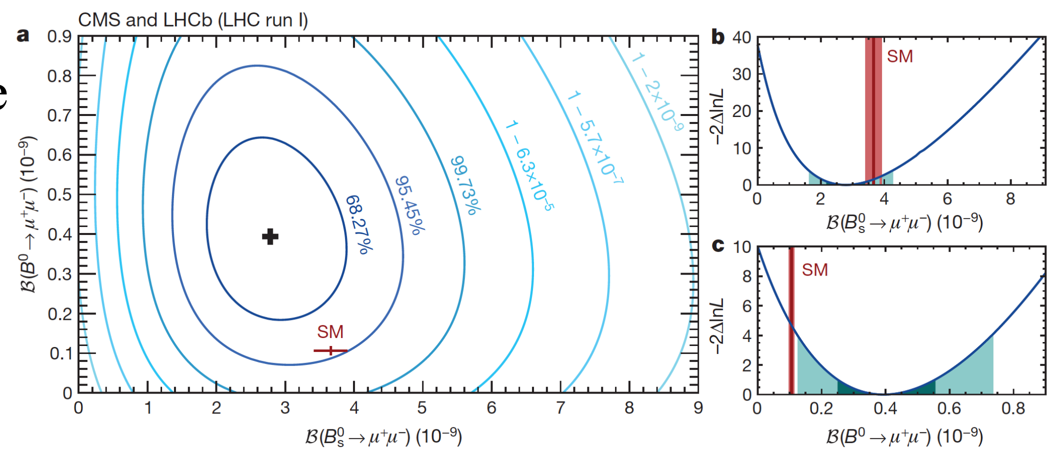
  $B(B_s \to \mu^+\mu^-) \approx (\tan\beta)^6/M_{A0}$

$B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

Nature Letter 522 (2015) 68

- LHCb / CMS collaborative upshot
  - complementary angular regions with respect to LHC beams
  - designed for different purposes: higher instantaneous $\mathcal{L}$ compensates lower $B \rightarrow \mu\mu$ efficiency (CMS)
  - dimuon mass resolution different: uniform ≈ 25 MeV/c^2 for LHCb and angle dependent ranging from 32-76 MeV/c^2 for CMS
- Combination of CMS and LHCb data results in conclusive evidence for $B_s \rightarrow \mu^+\mu^-$, and in a 3σ effect for $B^0 \rightarrow \mu^+\mu^-$
- Results consistent with SM at 2σ level: A NEW PHASE OF PRECISION MEASUREMENTS IS INITIATED





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

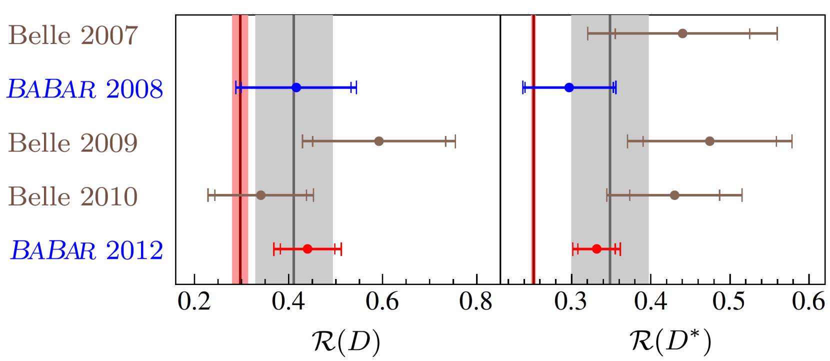
- Lepton universality can be broken by new physics with τ lepton, and ratios like $R(D^*)=\mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ are sensitive to it
  - in two Higgs doblet models (2HDM), the D/D* helicity amplitudes H_s become:

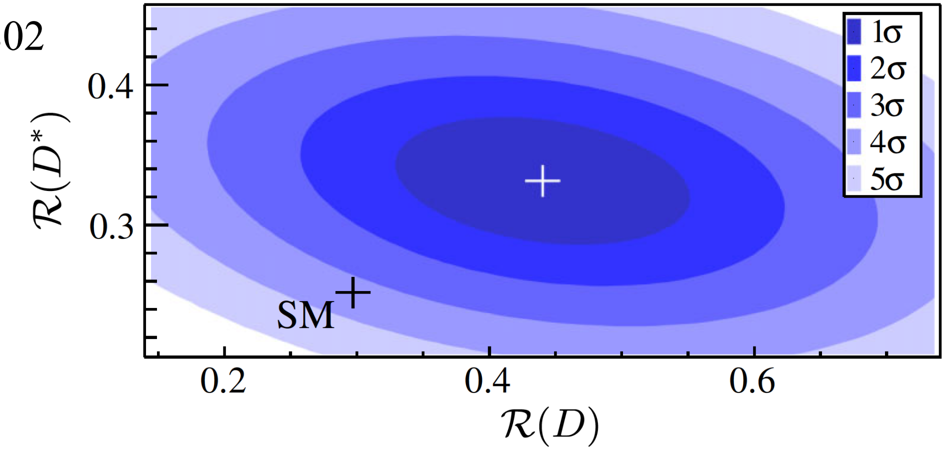
$$H_s^{2HDM} \approx H_s^{SM}\left(1 + (S_R \pm S_L)\frac{q^2}{m_\tau(m_b \mp m_c)}\right)$$

with scalar NP contributions $S_{L,R}$ proportional to $(\bar{c}P_{L,R}b)\,(\bar{\tau}P_L\nu_\tau)$ $\quad P_{L,R} = (1 \mp \gamma_5)/2$

- BaBar reported anomalous high values of $R(D^*)$ and $R(D)$:

PRD 88 (2013) 072012, also PRL 109 101802

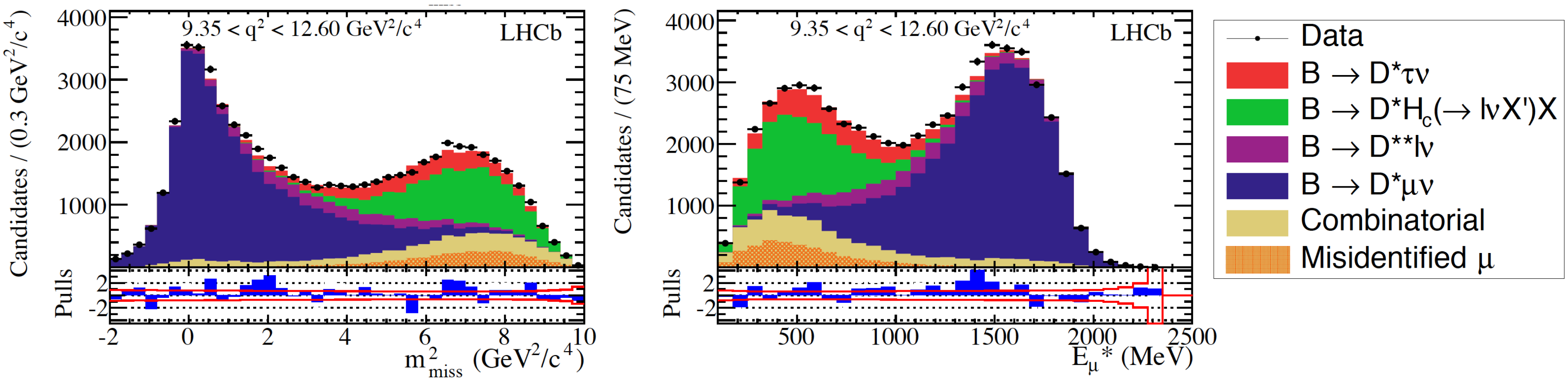




- Those exclude 2HDM where $S_L= 0$ (type II, minimal SUSY) in the full tanβ-$m_{H\pm}$ plane, but are compatible with general 2HDM having $|S_R+S_L|<1.4$

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

- First b → τ reco at a hadron collider : $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ and $B^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ identical final state topologies with $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\,\pi^+$ and $\tau^- \rightarrow \mu^- \bar{\nu}_\mu\, \nu_\tau$



R(D*) = 0.336 ± 0.027± 0.030

arXiv:1504.01568, submitted to PRL

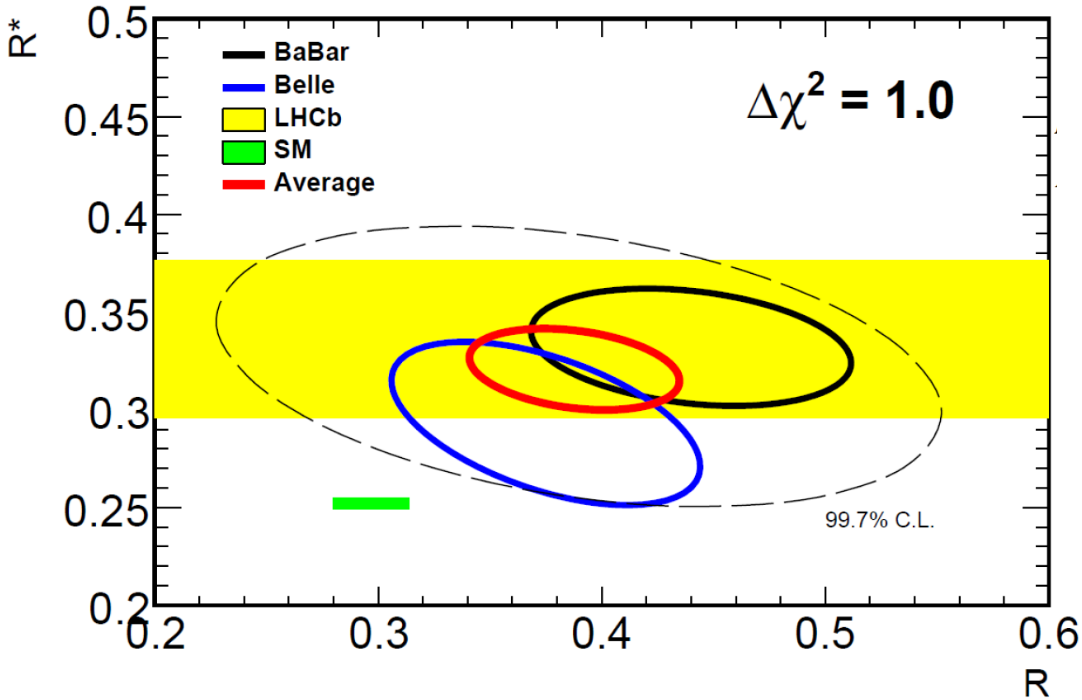
- LHCb result *confirms* the excess to the SM value 0.252±0.003. Fit also extracts form factor parameters, which appear to agree with world averages.
  - B^0 rest-frame variables (m_{miss}^2, E_μ^*, q^2) are measured with (15-20)% resolution thanks to $\vec{p}_B$ estimation with charged particles
  - Control samples of various backgrounds allow precise corrections
    - → good prospects for Run 2 , systematics expected to scale with sample sizes

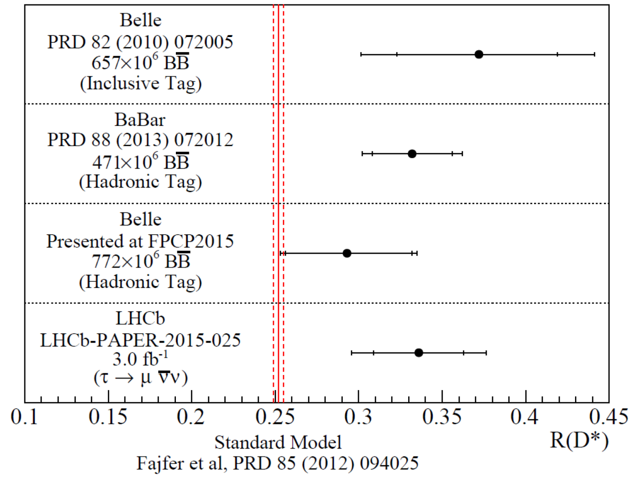
$B \rightarrow D^{(*)}\tau\nu$

- Tension with SM seems to persist

unofficial average, very preliminary

$R(D^*) = 0.322 \pm 0.021$
$R(D) = 0.390 \pm 0.047$





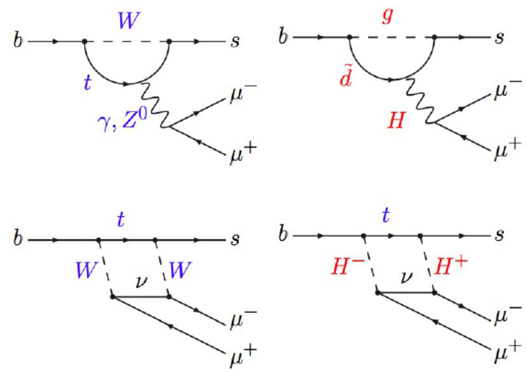
SM prediction from
PRD 85 (2012) 094025

statistical or systematic correlations not accounted for

thanks to M. Rotondo

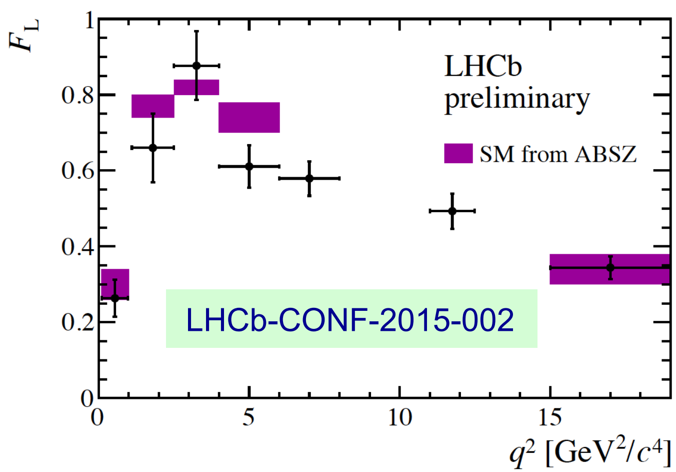
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

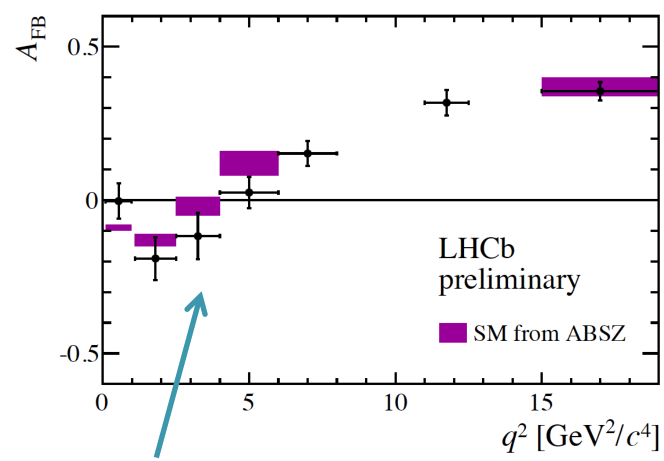
- $b \rightarrow s\, \mu^+\mu^-$ FCNC transition allowed in SM via electroweak penguin and box diagrams, subject to contamination by new heavy particles (Z', extra H...)



- angular observables in $K^{*0}(K^+\pi^-)\mu^+\mu^-$ characterized by 6 amplitudes: $A^{L,R}_{0,\|,\perp}$
  for K^{*0} helicities and $\mu^+\mu^-$ chiralities (L,R)
- full set of 8 observables analised (3 fb^{-1}) as function of $q^2(\mu^+\mu^-)$, only some are shown

largely in agreement with SM, however ... see next

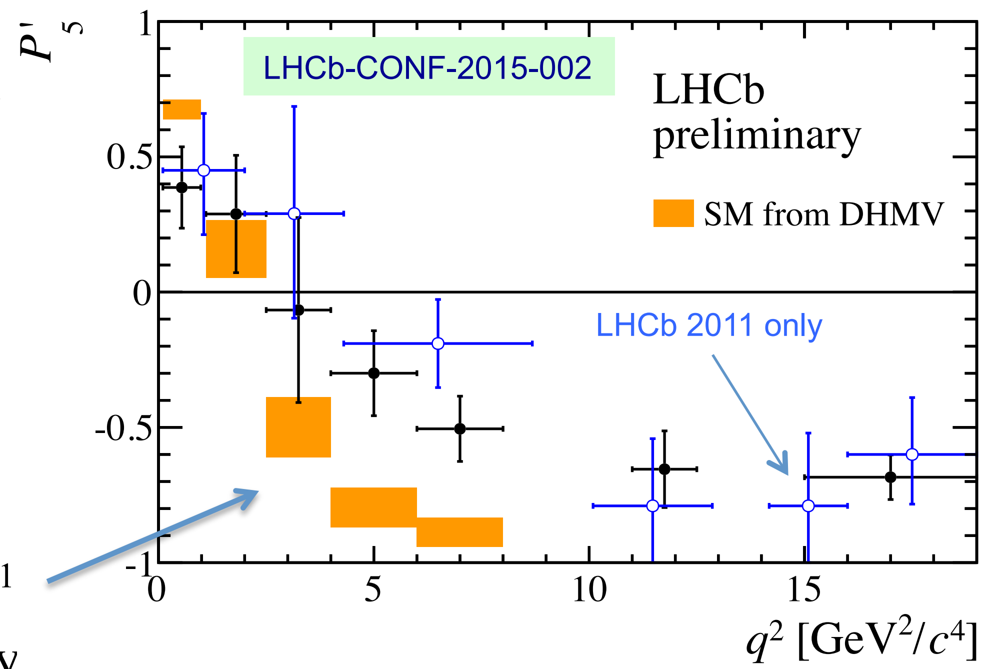




Zero crossing point q_0^2 OK with SM, very sensitive to some MSSM models arXiv:0811.1214

$B^0 \rightarrow K^{*0} \mu^+\mu^-$ & tension in P'_5

- Earlier publication by LHCb with 2011 dataset PRL 111 (2013) 191801 found a local deviation from SM prediction with 3.7σ significance in one particular observable: P'_5
- Possible interpretations of this discrepancy was widely discussed in the literature (over 13 papers in 2014). The full datasample with 3 fb^{-1} *confirms* a 3.7σ statistical discrepancy
- P'_5 is related to the L/R asymmetry of the interference between A_0 and $A_\perp$:



sensitive to NP in VV or VA
(Wilson coefficient C_9)

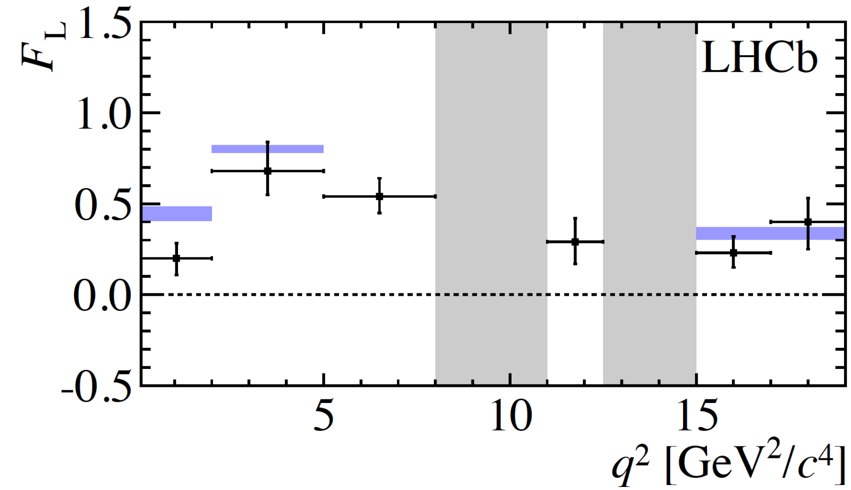
$$P_5' = \sqrt{2} Re\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right) / \sqrt{F_L(1-F_L)} = S_5/\sqrt{F_L(1-F_L)} \qquad F_L = |A_0^L|^2 + |A_0^R|^2$$

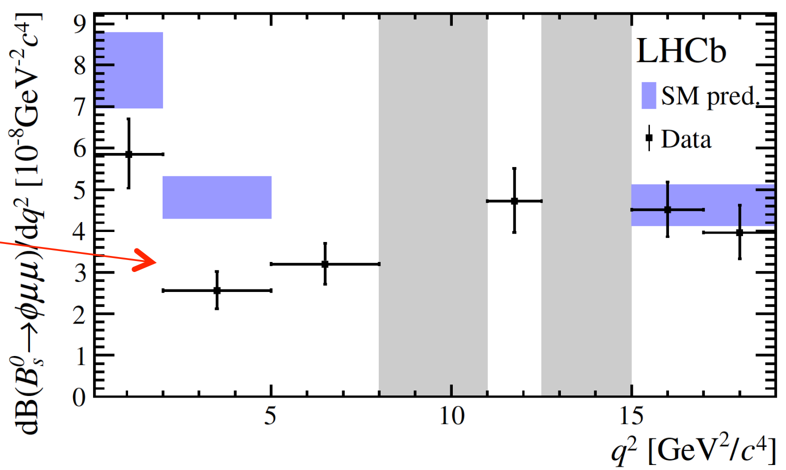
S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, arXiv:1407.8526

$B_s \to \Phi \mu^+\mu^-$

- Contrary to $B^0 \to K^{*0} \mu^+\mu^-$, $B_s \to \Phi(K^+K^-)\mu^+\mu^-$ is not self-tagging. Good complementarity (yield ≈ 1/6)
- Full angular analysis as function of $q^2(\mu^+\mu^-)$, all of the 8 observables are determined for the first time
  - physics-wise, the observables are different from K* μμ (new CP-violating asymmetries, no S_5 or A_{FB})
- All angular observables are *consistent with the SM*, but tension seen in the branching fraction
  - a similar trend is also seen for the branching fractions of other $b \to s \mu^+ \mu^-$ decays at LHCb ($B^0 \to K^{(*)} \mu^+\mu^-$, JHEP 06 (2014) 133, $B^+ \to K^+ \pi^+ \pi^- \mu^+\mu^-$, JHEP 10 (2014) 064.

LHCb-PAPER-2015-023, submitted to JHEP





Summary

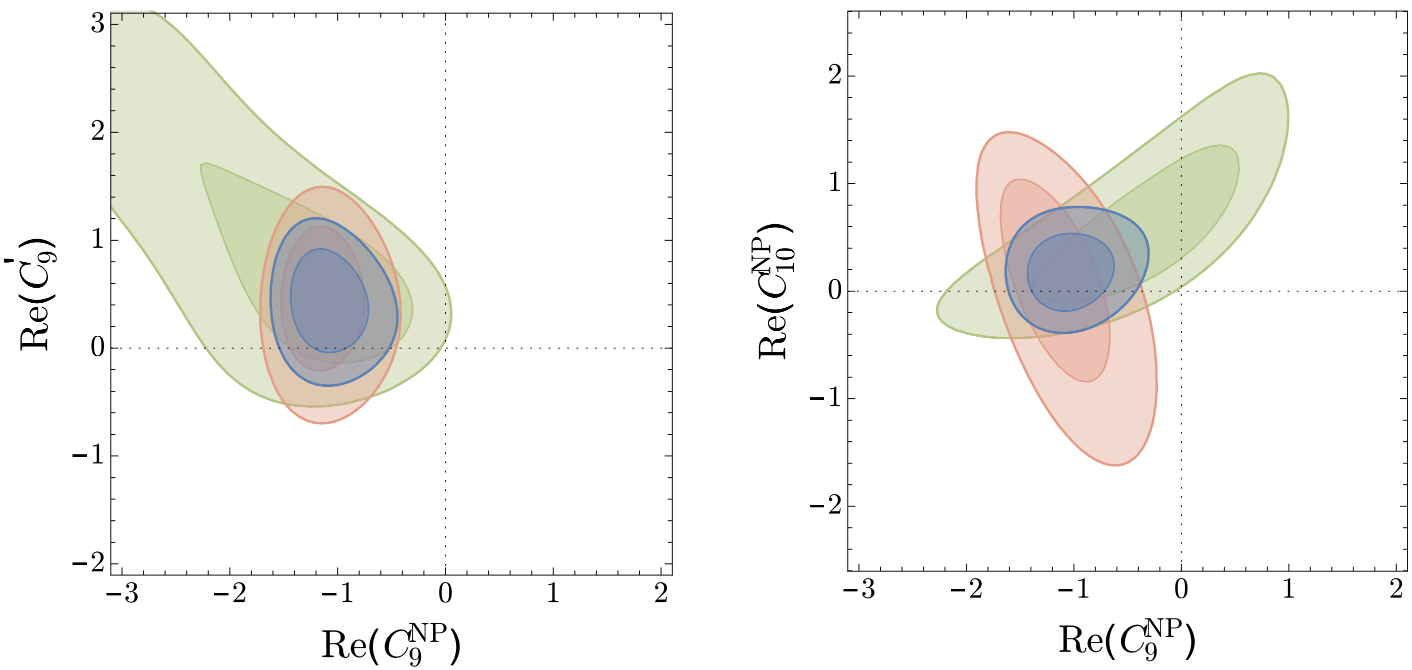
- Appreciable amount of Flavour Physics results by LHCb this year, not everything has been covered in this talk (absent were charm CPV, other rare decays, B → no charm, etc)
- Sensitivity to $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ has reached the 10^{-10} level and will continue to improve
- A few interesting "tensions" with the SM to follow up very closely:
  - hints on τ-lepton non-universality in $R(D^*)$ and $R(D)$
  - S_5 observable in $B \to K^{*0}\mu\mu$ deviated from SM , also $b \to s\mu\mu$ rates too low.
  - inclusive/exclusive tension in $|V_{ub}|$ still there, although RH currents are not supported
- Much to know in the short and longer terms:
  - Run 2 has just started at LHC (LHCb & ATLAS &CMS)
  - LHCb upgrade & Belle II will take over from 2018 on

THE END

Global fits $B^0 \rightarrow K^{*0} \mu^+\mu^-$

Global fits performed on the new LHCb $B^0 \rightarrow K^{*0} \mu^+\mu^-$ data

J. Matias and D. Straub, Moriond EW 2015 arXiv:1503.06199



Angular observables, branching fractions and combination

Consistently, data favour $C_9^{NP} \neq 0$ at 3-4 σ