LHCb highlights

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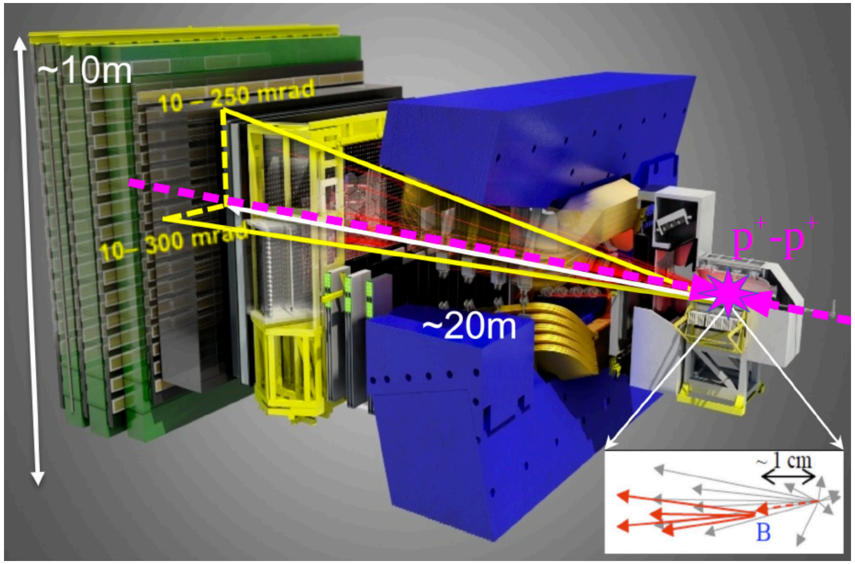
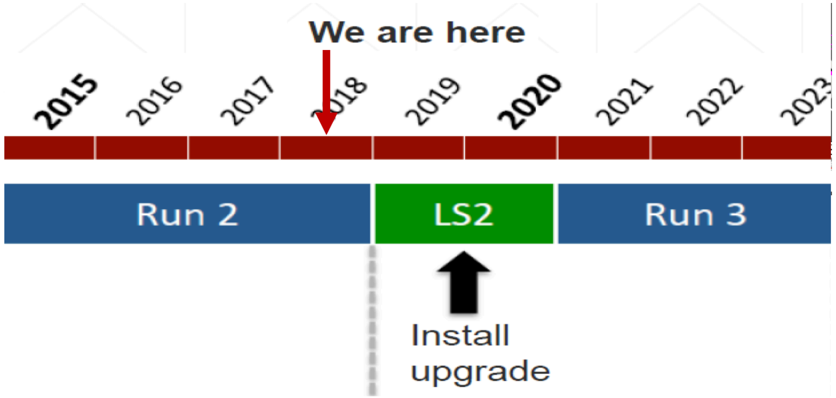
LHCb Upgrade

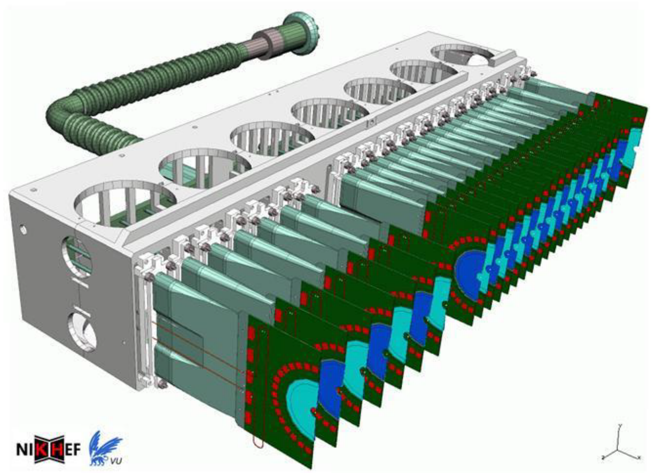
- Run experiment at a luminosities 5 times greater than presently.
- Greatly improve trigger efficiency on hadronic channels and on rare decays.
- Expand scope to the lepton flavor sector, electroweak physics, QCD and exotics searches.
- Current 1 MHz L0 trigger output is a severe limitation.
    - Remove the L0 hardware trigger and readout an event at every bunch crossing (40 MHz). Use an efficient fully software trigger.
    - New front-end electronics and New DAQ system.

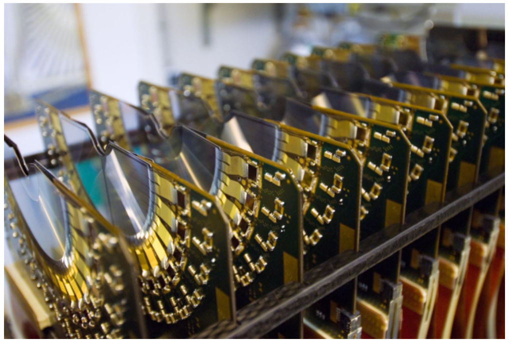


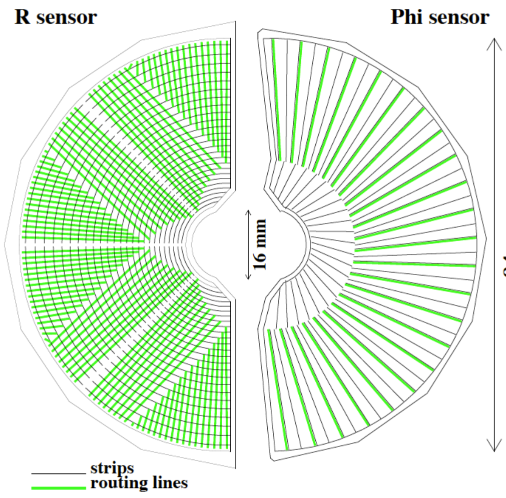


Current VELO

- Silicon strip detector 84 sensors (R + φ measurements per module). 2048 channels (strips per sensor).
- Capable of 1 MHz readout.
- Exists in 2 retractable halves and can move. The closest distance of the active silicon to the LHC beam is 8.2 mm.
- Radiation hard,7×10^{14} $1MeVn_{eq}cm^{-2}$ for full lifetime.
- CO_2 cooling.

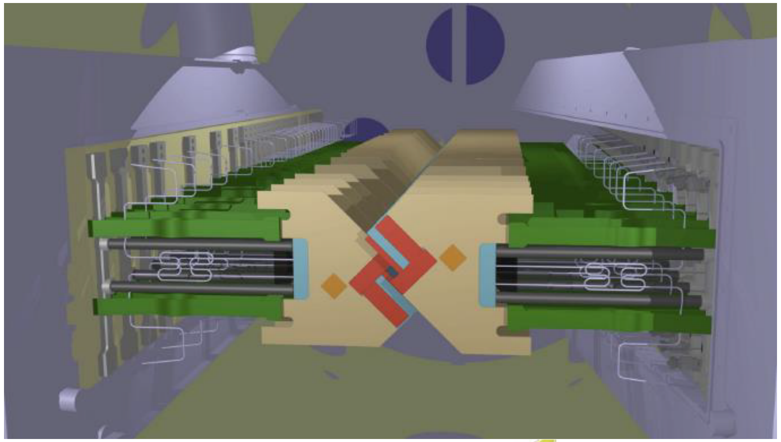


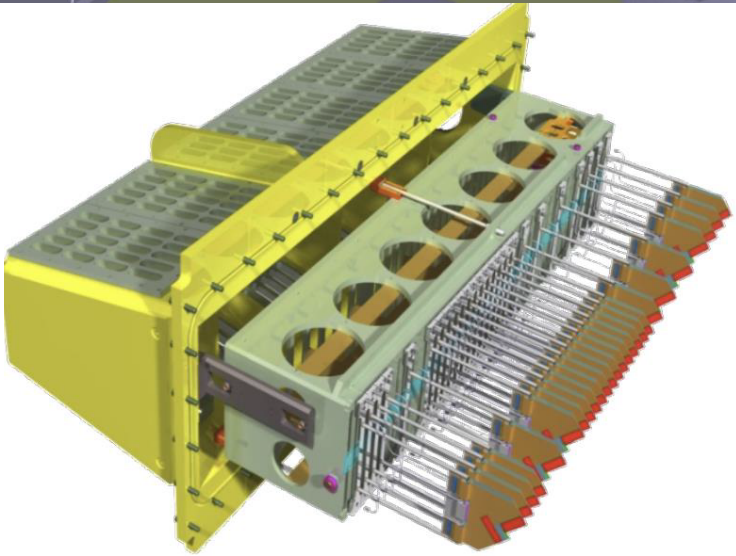




VELO Upgrade

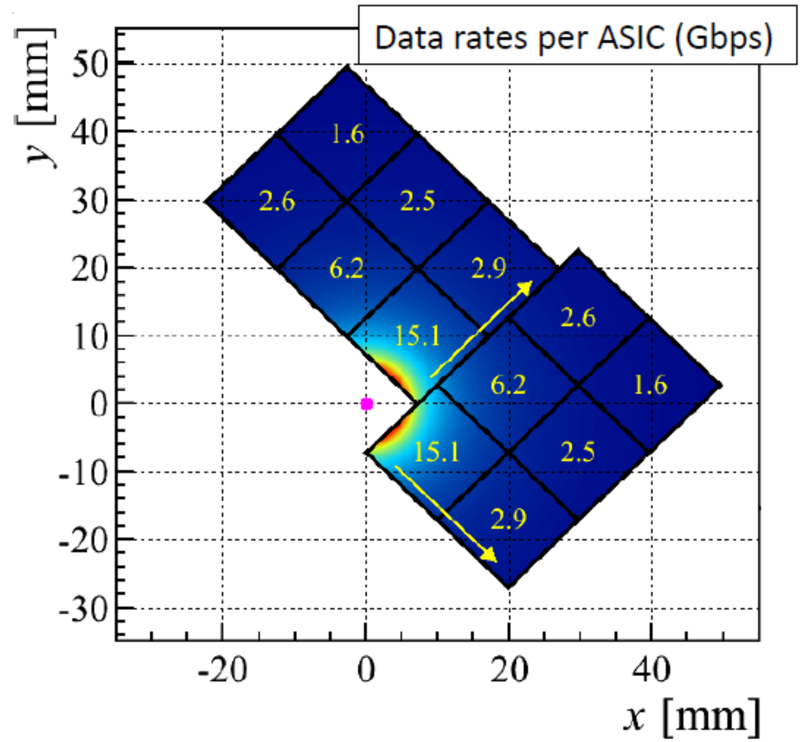
- Moving from Silicon Strips to Pixels.
- Sensors are thinner, 300 µm to 200 µm.
- 41M pixels (current:172k strips).
- High readout rate, up to 40 MHz.
- Large number of modules, 42 to 52.
- Reducing distance from beam, 8.2mm to 5.1mm
- Sensor temperature < -20 ºC
- Power dissipation / module ~ 28 W.





VELO Upgrade

- Improved Radiation Hardness.
- Huge data bandwidth: up to 20 Gbit/s for central ASICs and ~ 3 Tbit/s in total.
- New microchannel evaporative CO_2 cooling.
- Thinner RF foil, 300 μm to 250 μm.
- High tracking efficiency.
- Measure the impact parameter with high precision.
- High granularity.



All prototypes have been delivered and are undergoing testing:

- Qualification of sensors.
- Velopix testing.
- Test of the readout electronic chain.
- Test of the cooling system.

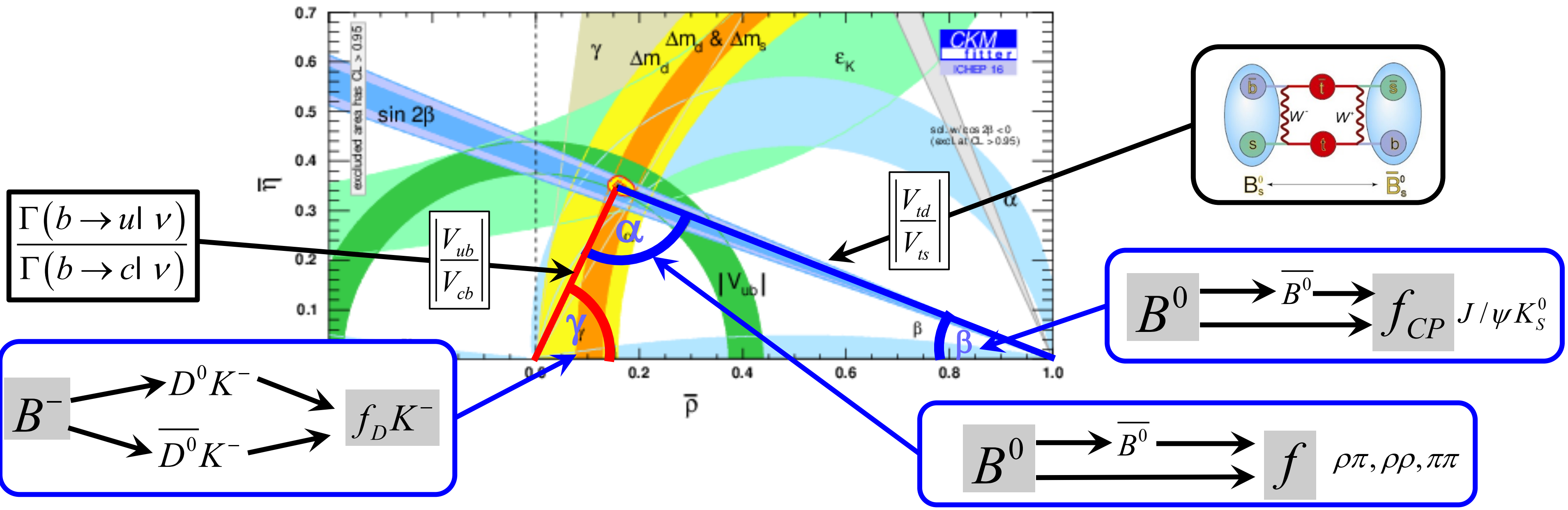
Production, reception, qualification and assembly steps move in parallel. Schedule is tight.

CP violation in the SM

- Weak interaction is the only source of CP violation in the SM.
  - Explained by CKM matrix.
  - CKM matrix: unitary, 3*3 describing quark-flavour changing charged-current Ws.
- Unitarity matrix→Unitarity triangles.
- Probing the unitarity triangle.
  - Deviations would indicate BSM Physics.
  - If SM is correct all measurements must agree on the apex of the triangle.

$$\begin{array}{cccc} & d & s & b \\ \begin{matrix} u \\ c \\ t \end{matrix} & \multicolumn{3}{c}{\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}} \end{array}$$

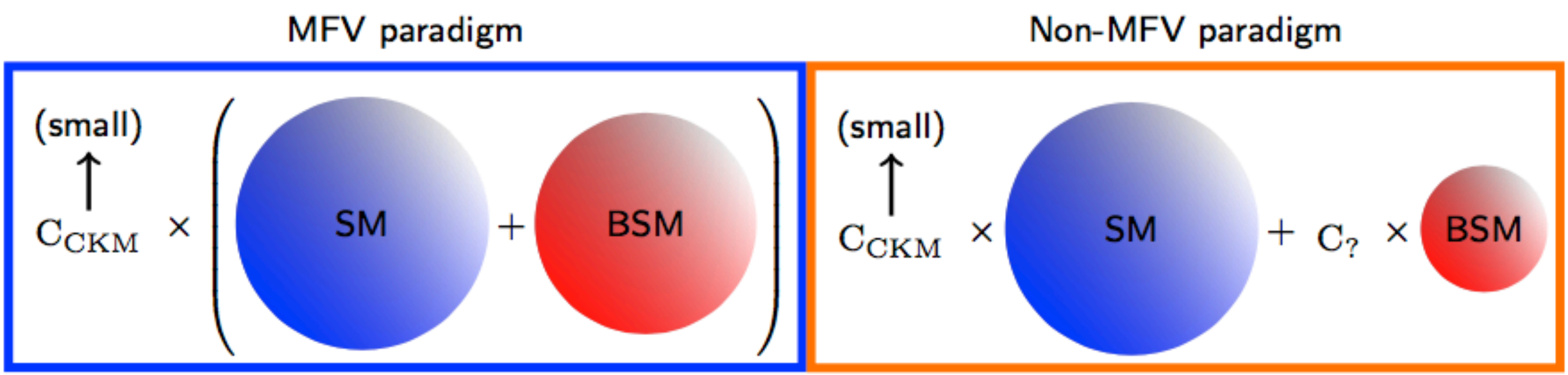
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



CP violation in the strange sector

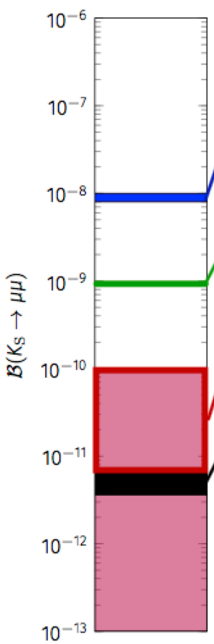
Strange decays play a major role in particle physics:

- For BSM at $\mathcal{O}$(TeV), it might only be seen if there are new sources of flavour violation
- $s \to d$ transitions have the strongest suppression in the SM: $V_{td}V_{ts}^{*} \sim 10^{-4}$
- In a Non-Mininimal-Flavour-Violating (Non-MFV) paradigm, they have the highest sensitivity



$K_s^0 \to \mu^+\mu^-$

- Flavour-changing neutral current (FCNC) transition
- Dominated by long distance contributions through $K^0_{S/L} \to \gamma\gamma$
- Notably new light scalars can affect K^0_S exclusively
- Model-independent bounds on the CP-violating phase of the $s \to dl^+l^-$ amplitude
- SM prediction: $\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) = (5.0 \pm 1.5) \times 10^{-12}$ [Nucl. Phys. B366 (1991) 189][JHEP 01 (2004) 009]



Old LHCb limit
$\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) < 9(11) \times 10^{-9}$ at 90(95)% of CL
[JHEP 01 (2013) 090]

New limit!
$\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) < 0.8(1.0) \times 10^{-9}$ at 90(95)% of CL
[EPJ C, 77 10 (2017) 678]

Theoretically more interesting region

Standard Model prediction

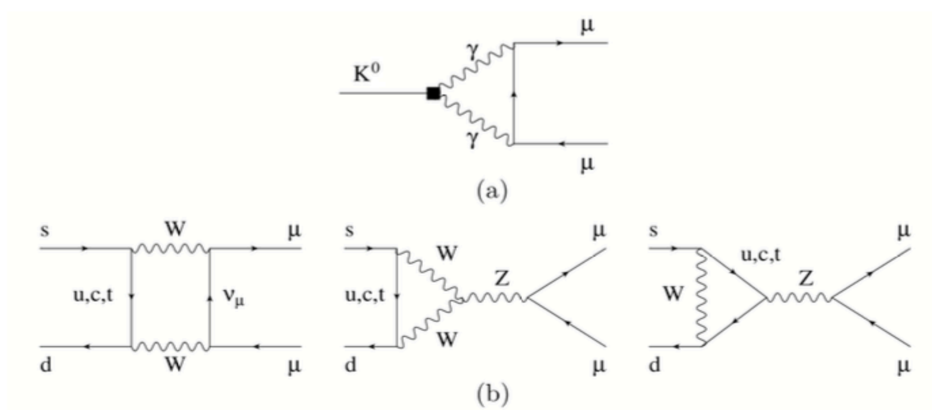
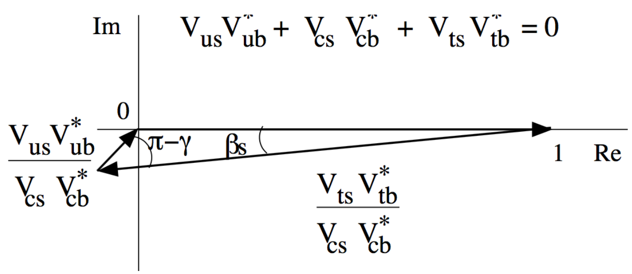


Figure: (a): Long distance contribution. (b) Short distance contributions. [JHEP 01 (2004) 009]

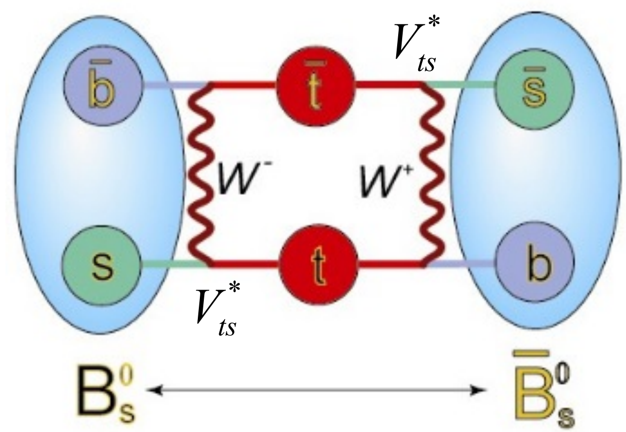
The second triangle

- Despite of its flatness there is a second triangle that, given the reached precision measurements, allows to perform CKMetrics.
- Its main parameter is the β_s angle.



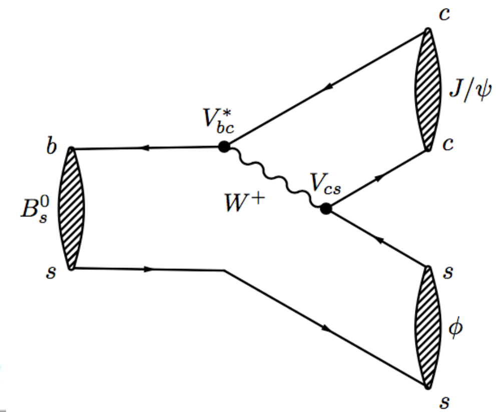
$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

- Can be measured in B_s^0 meson oscillations.
  - In time dependent analysis of $B_s^0 \to J/\psi\phi$ and similar decays.



$B_s^0 \to J/\psi\phi$

The time dependent asymmetry of $B_s^0 \to (c\bar{c})(s\bar{s})$ decays is given by:

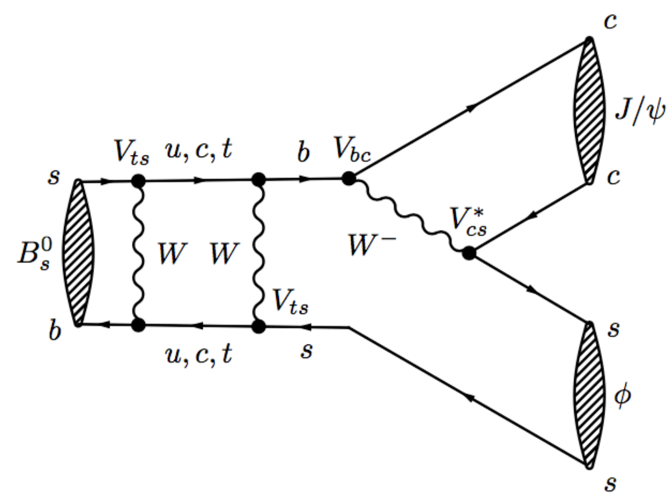


$$A_{CP}(t) = \frac{\Gamma_{B_s^0(t)\to J/\psi\phi} - \Gamma_{\bar{B}_s^0(t)\to J/\psi\phi}}{\Gamma_{B_s^0(t)\to J/\psi\phi} + \Gamma_{\bar{B}_s^0(t)\to J/\psi\phi}} = \frac{-\Im\lambda_{J/\psi\phi}\sin\Delta m t}{\cosh\frac{1}{2}\Delta\Gamma t + \Re\lambda_{J/\psi\phi}\sinh\frac{1}{2}\Delta\Gamma t}$$

Where

$$\lambda_{J/\psi\phi} = \left(\frac{q}{p}\right)_{B_s^0}\left(\eta_{J/\psi\phi}\frac{\bar{A}_{J/\psi\phi}}{A_{J/\psi\phi}}\right) = (-1)^l\left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\right)\left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)$$

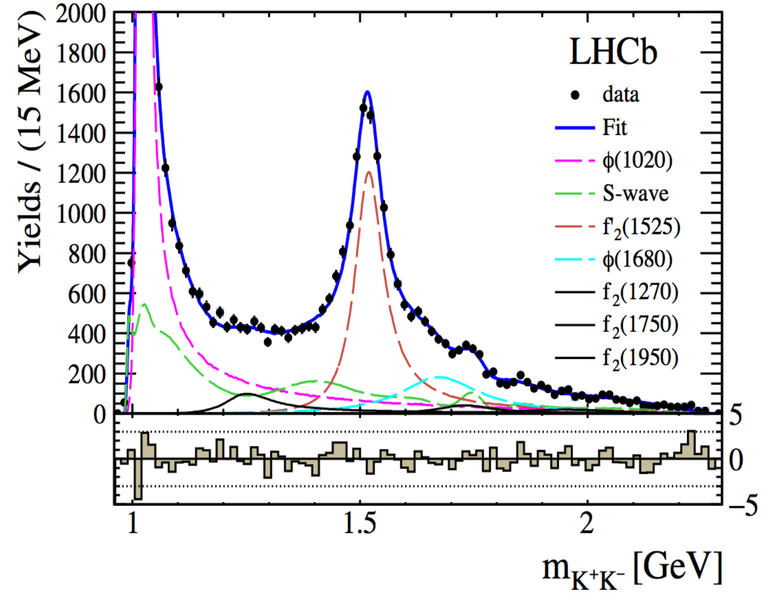
$$\Im\lambda_{J/\psi\phi} = (-1)^l\sin(-2\beta_s)$$



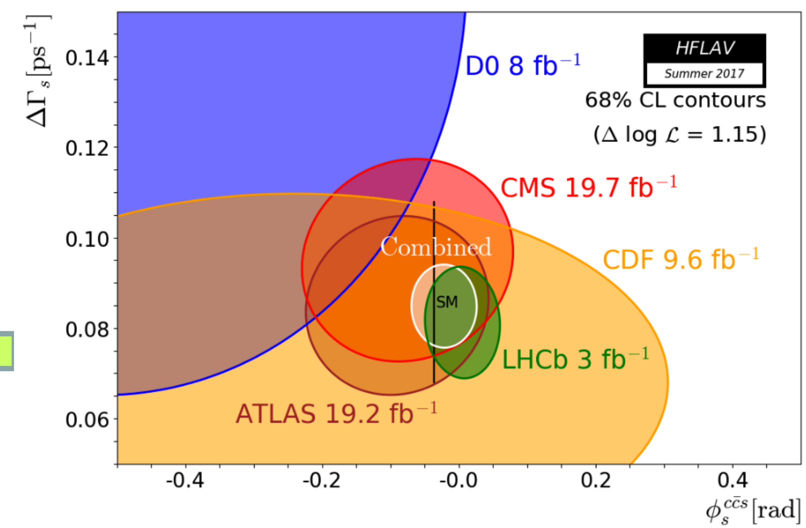
Which means we can access to β_s in time dependent analyses of these modes.

$\phi^{c\bar{c}}_s = -2\beta_s$

- Global fit: ϕ^{cc}_s = −21 ± 31 mrad [HFLAV] dominated by LHCb [PRL 114, 041801 (2015)].
  - In agreement with the SM value $\phi^{cc}_s{}^{SM}$ = 0.0376 ± 0.0008
- Penguin pollution under control [JHEP 1503 (2015) 145].
- LHCb measurement of ϕ^{cc}_s in $B_s^0 \to J/\psi K^+K^-$ above the ϕ(1020) region [JHEP 08 (2017) 037].
  - 1st time ϕ^{cc}_s measured in tensor final states.
- New LHCb average (including J/ψφ and J/ψππ): ϕ^{cc}_s = 1 ± 37 mrad.

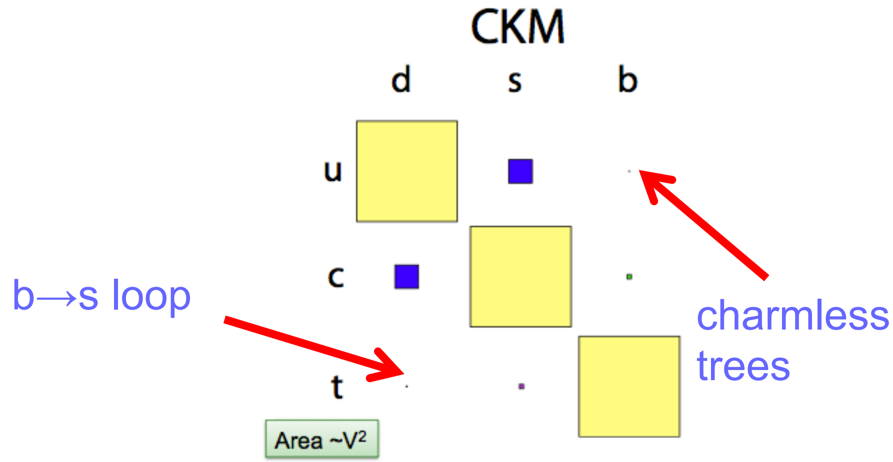


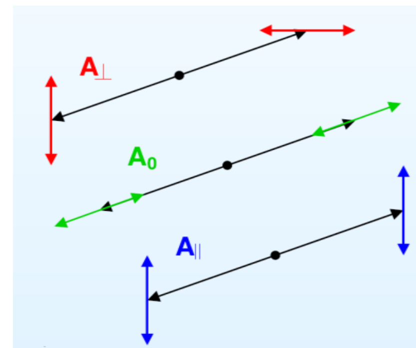
Exp.	Mode	Lumi	ϕ_s [rad]	
LHCb	$J/\psi KK$	3 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	[PRL 114, 041801 (2015)]
	$J/\psi KK$ HM	3 fb^{-1}	$+0.119 \pm 0.107 \pm 0.034$	[arXiv:1704.08217] 2017
	$J/\psi \pi\pi$	3 fb^{-1}	$-0.070 \pm 0.068 \pm 0.008$	[PLB 736 (2014) 186]
	$\psi(2S)\phi$	3 fb^{-1}	$+0.23^{+0.29}_{-0.28} \pm 0.02$	[PLB 762 (2016) 253]
	$D_s^+D_s^-$	3 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	[PRL 113, 211801 (2014)]
ATLAS	$J/\psi\phi$	19.2 fb^{-1}	$-0.098 \pm 0.084 \pm 0.040$	[JHEP 1608 (2016) 147] 2016
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	[PLB 757 (2016) 97] 2016
Average	-	-	-0.021 ± 0.031	[HFLAV]
Theory	-	-	-0.0376 ± 0.0008	[CKMFitter]

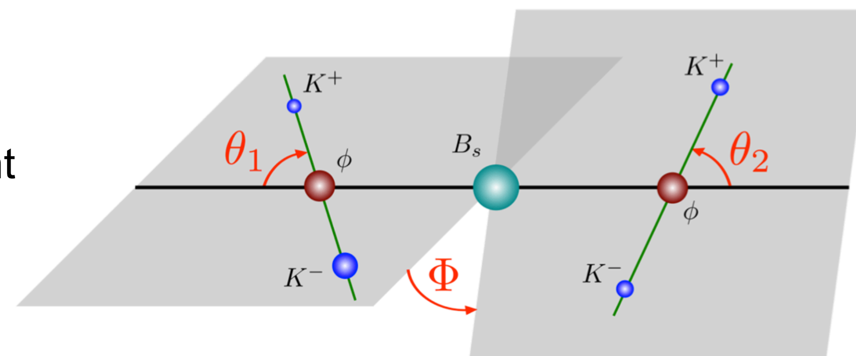


Charmless $B \to V_1 V_2$

- Suppressed compared to charmed:
  - $b \to u$ tree.
  - $b \to s$, $b \to d$ loops.
- More sensitive to NP.
- Mediated by three smallest CKM matrix elements.
- V_1 and V_2: angular momentum L = 0,1,2.
- High longitudinally polarization expected:
  - Additional effects (rescattering) could produce smaller polarizations.
- Angular pdf depends on:
  - Polarization fractions: $|A_0|^2$, $|A_{||}|^2$, $|A_\perp|^2$
  - Strong phases: $\delta_{||}$, $\delta_\perp$
  - If final state is common to B_s^0 and $\bar{B}_s^0$:
    - CP–violating phase: $\phi_{(s)}$ in time dependent analyses.
  - If final state is not common to the B mesons CP: asymmetries.



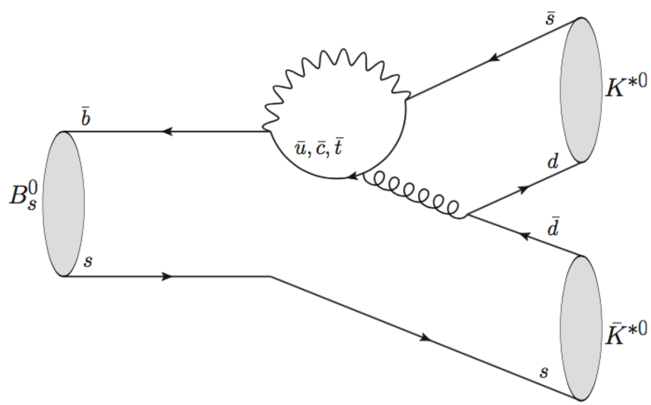


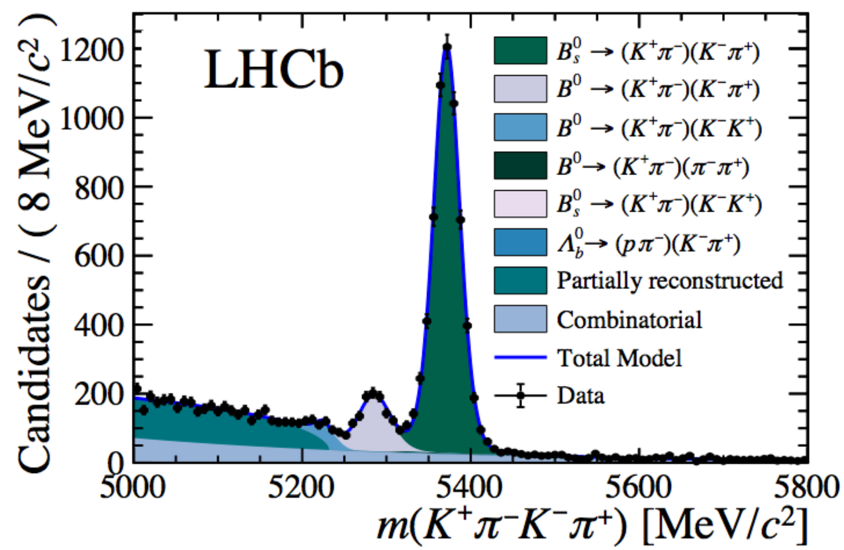


$B_s^0 \to K^{*0}\bar{K}^{*0}$

- Time dependent analysis.
- Paradigm: new particles may enter the loop.
- Original approach:
  - Extended m($K\pi$) range: 750−1600 MeV/c^2 :
    - Scalar: $K_0^*(1430)^0$ + Non Res
    - Vector: $K^*(892)^0$
    - Tensor: $K_2^*(1430)^0$
- 3×3=9 decay channels. Common $\phi_s^{d\bar{d}}$ phase assumed. **SM predicts it to be 0**.
- Tagged, time-dependent, angular and 2-body invariant mass analysis.
- More than 6000 candidates with Run-1 data.

Channel	Decay	Polarization amplitudes
Channel #1	$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
Channel #2	$B_s^0 \to (K^+\pi^-)_0^*\bar{K}^*(892)^0$	SV
Channel #3	$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
Channel #4	$B_s^0 \to (K^+\pi^-)_0^*\bar{K}_2^*(1430)^0$	ST
Channel #5	$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
Channel #6	$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	VVo, VV‖, VV⊥
Channel #7	$B_s^0 \to K^*(892)^0\bar{K}_2^*(1430)^0$	VTo, VT‖, VT⊥
Channel #8	$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	TVo, TV‖, TV⊥
Channel #9	$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	TTo, TT‖1, TT⊥1, TT‖2, TT⊥2





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$B_s^0 \rightarrow K^{*0}\overline{K}^{*0}$

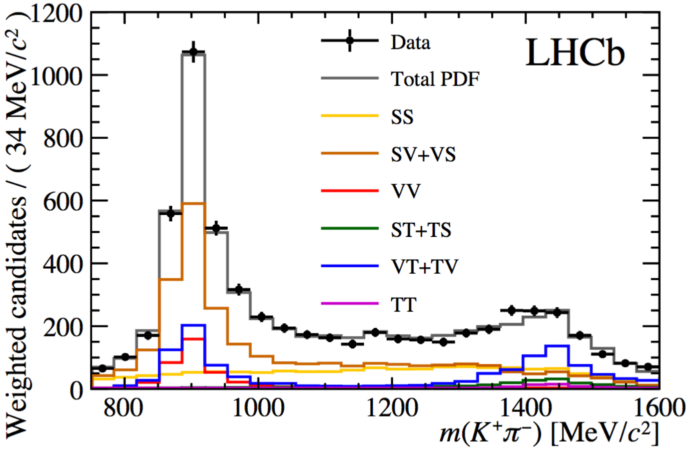
- First measurement of $\phi_s^{d\bar{d}}$, using $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ decays (including $B_s^0 \rightarrow K^{*0}\overline{K}^{*0}$), $\phi_s^{d\bar{d}}$ = **−0.10 ± 0.13 ± 0.14 rad**. [JHEP 1803 (2018) 140]

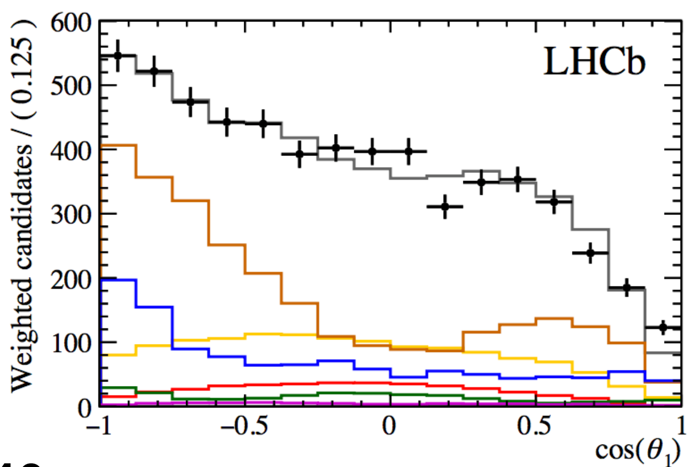
- CP-asymmetry determination: $|\lambda|$ = **1.035 ± 0.034 ± 0.089**.

- Compatible with SM.

- Additional 37 observables, including polarization amplitudes. Confirmed low longitudinal VV polarization:

$$f_L = 0.208 \pm 0.032 \pm 0.046$$





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Polarization Summary of $B \to V_1V_2$

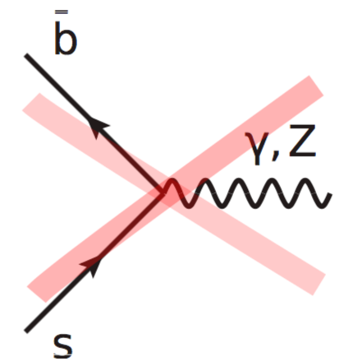
- Large Longitudinal polarization confirmed in $b \to u$ tree dominated decays ($f_L \sim 1$) .
- Penguin decays show intermediate-small longitudinal polarization fractions.
  - Exception in $B^0 \to K^{0*}\overline{K}^{*0}$.
  - Polarization puzzle.
  - Would $b \to d\bar{q}q$ show higher f_L than $b \to s\bar{q}q$ penguins?

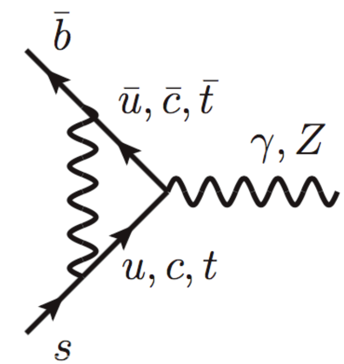
Decay	$B^0 \to \rho^+\rho^-$ BaBar	$B^0 \to \rho^0\rho^0$ BaBar-Belle-LHCb	$B^0 \to \rho^0 K^{*0}$ BaBar	$B_s^0 \to \phi\phi$ LHCb-CDF	$B_s^0 \to K^{*0}\overline{K}^{*0}$ LHCb	$B^0 \to K^{0*}\overline{K}^{*0}$ BaBar	$B^0 \to \phi K^{*0}$ BaBar-Belle-LHCb	$B_s^0 \to \phi \overline{K}^{*0}$ LHCb
f_L	$0.978^{+0.025}_{-0.022}$	$0.714^{+0.055}_{-0.062}$ **USC**	0.40±0.14 **Soon USC**	0.361±0.022	0.201±0.070 **USC**	$0.80^{+0.12}_{-0.13}$ Soon **USC**	0.497±0.017 **USC**	0.51±0.16 **USC**

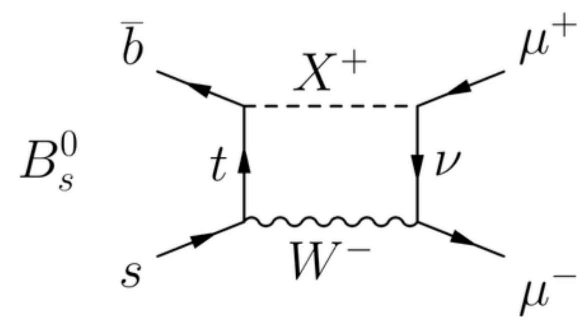
$b \to d\bar{q}q$ penguin contribution

Rare decays

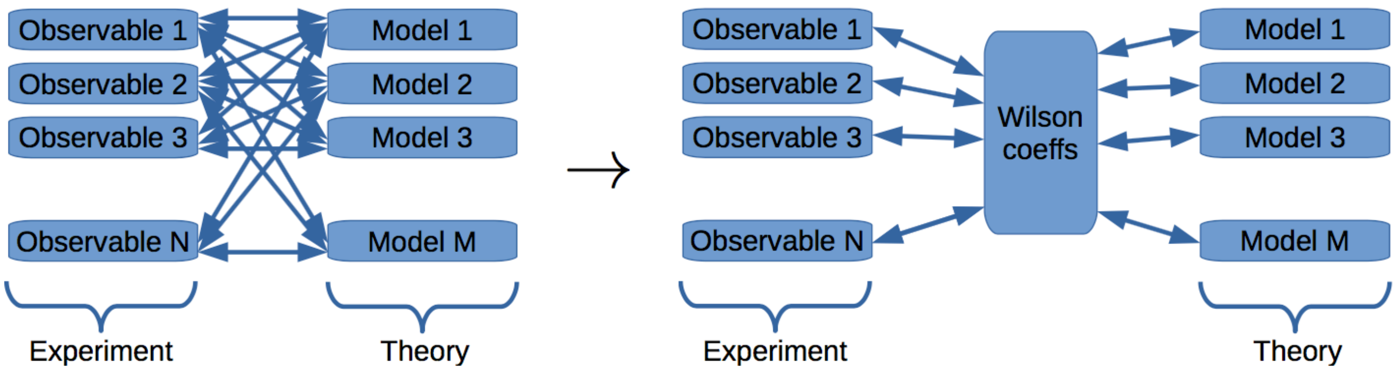
- SM predicts very small branching fractions ~10^{-9}.
- Physics BSM can compete with sizeable effects.
  - In BF and other observables.
- Three main categories:
  - Flavor changing neutral currents.
    - Suppressed by weak loop In the SM.
    - Signatures: lepton pair (γ^*, $Z^0 \rightarrow \mu^+\mu^-$) hard photon ($B \rightarrow K^*\gamma$).
  - Lepton flavor violating decays
    - E.g. $B \rightarrow e^{\pm}\mu^{\mp}$. Strongly forbidden in the SM.
  - Flavor (non-)universality
    - Lepton couplings in SM are the same for the three generations of leptons (e,μ,τ). Possible NP if deviations e.g. in $B \rightarrow Ke^+e^-$ and $B \rightarrow K\mu^+\mu^-$.







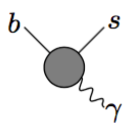
How it works?

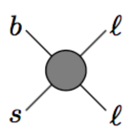


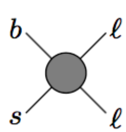
Model-independent description in an effective theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators





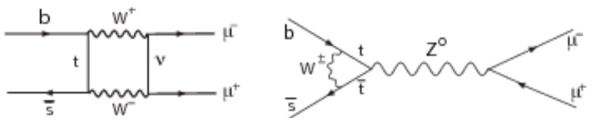


	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

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

Relevant channel for BSM searches

Highly suppressed in the SM.

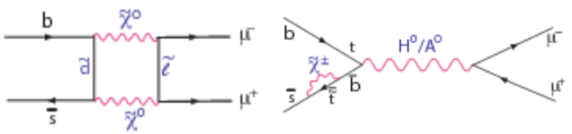


$$B_{SM}(B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

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

[Bobeth et. al, PRL112, 101801 (2014)]

Sensitive to NP in C_{10} & $C_{S,P}$.



Combined data of LHCb+CMS

[Nature 522 (2015) 68]

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

Also ATLAS [Eur.Phys.J. C76 (2016) no.9, 513]

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ [95\% CL]}$$

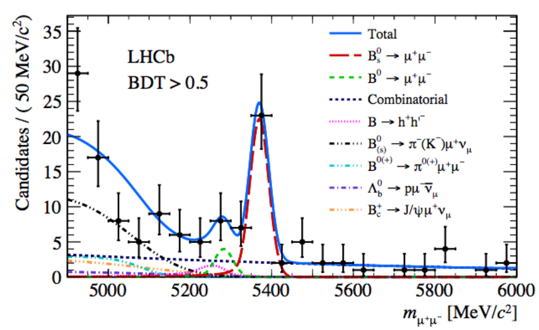
LHCb published an update of the BF including part of LHC Run 2 data. [LHCb, PRL 118, 191801 (2017)]

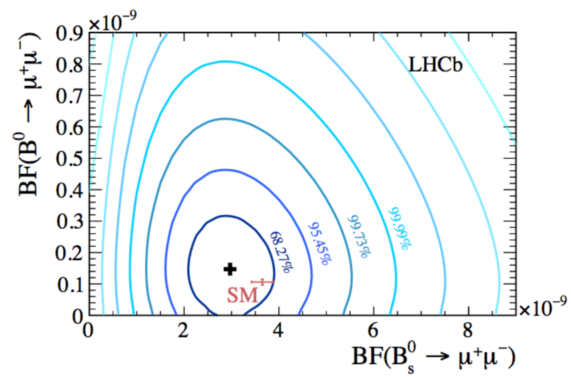
- Again compatible with SM.
- First observation of $B^0_s \rightarrow \mu^+\mu^-$ in a single experiment. 7.8σ significance.

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

- $B^0 \rightarrow \mu^+\mu^-$ consistent with absence of signal (1.6σ significance).

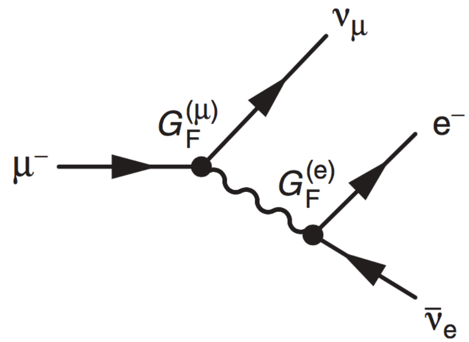
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.5^{+1.2+0.2}_{-1.0-0.1}) \times 10^{-10}$$

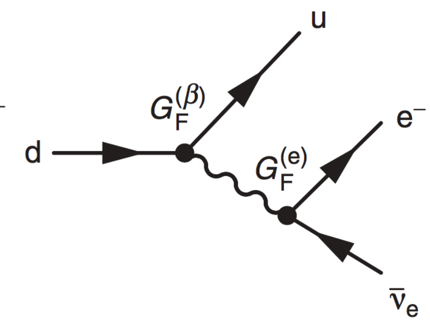


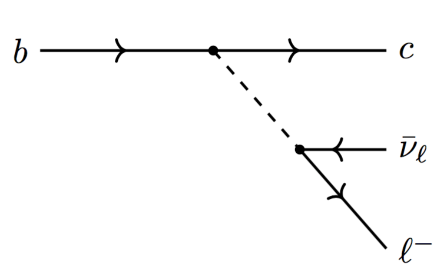


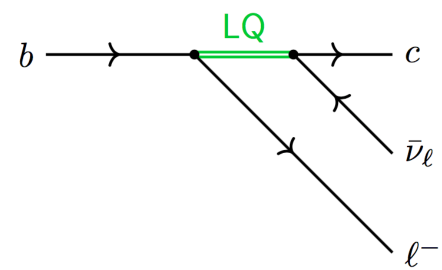
Lepton Flavor Universality

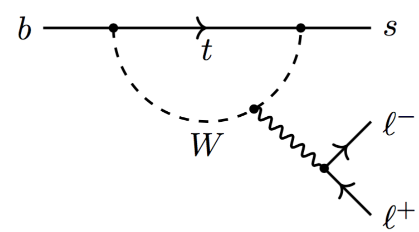
- In the SM the weak interaction to charged leptons and the corresponding neutrino is universal ($G^{(e)} = G^{(\mu)} = G^{(\tau)}$).
  - Confirmed with high precision in $Z^0 \rightarrow l^+ l^-$
- NP: Could violate lepton universality.
  - Charged Higgs.
  - Heavy W (W′).
  - Leptoquarks…
- Lepton universality tests in **tree-level decays**.
  - Abundant b → clν semileptonic decay.
  - Well known in the SM.
  - Possible NP coupling mainly to 3rd family.
- Lepton universality tests in **rare (loop-level) decays.**
  - b → sll
  - Forbidden at tree-level in SM
  - Sensitive to NP contributions in loops

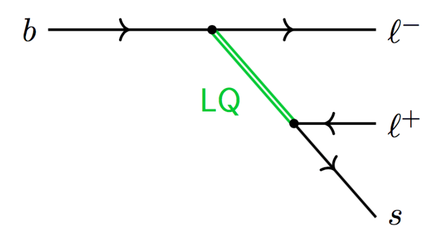






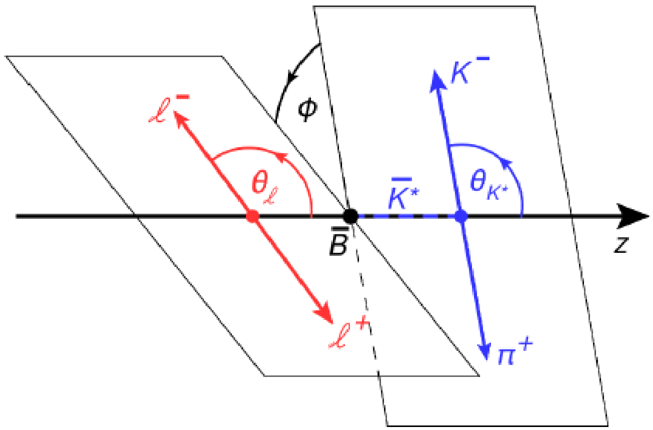






Angular analysis of $B^0 \rightarrow K^* l^+ l^-$

- Decay described by 3 angles $W=(\theta_l, \theta_{K^*}, \phi)$ and q^2.



$$\frac{1}{\mathrm{d}(\Gamma+\bar\Gamma)/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar\Gamma)}{\mathrm{d}q^2\,\mathrm{d}\vec\Omega} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_\mathrm{L}})\sin^2\theta_K + \boxed{F_\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-\boxed{F_\mathrm{L}})\sin^2\theta_K\cos 2\theta_l - \boxed{F_\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}\boxed{A_\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

19

Fraction of longitudinal polarisation of the K*

Forward-backward asymmetry of the dilepton system

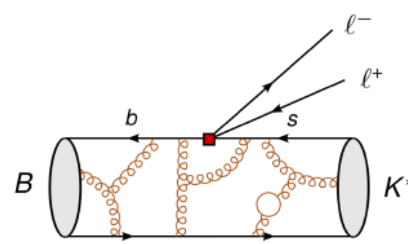
- F_L , A_{FB} , S_i combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors.
- Less sensitive observables where form factors cancel at leading order:

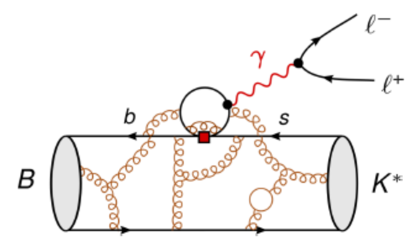
eg: $$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[Descotes-Genon, JHEP 05 (2013) 137]

B→K* form factors (LQCD)

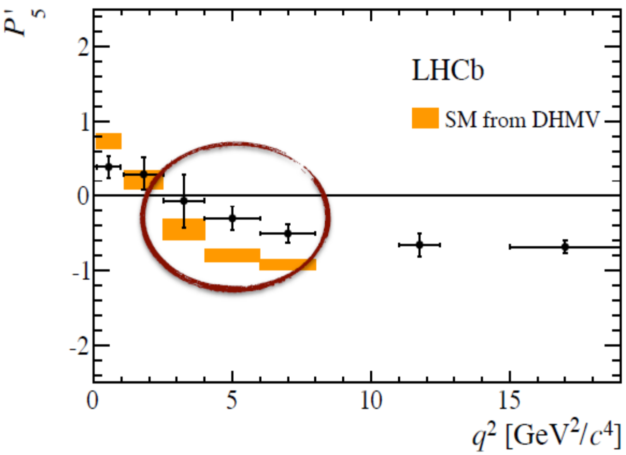
Non-factorizable corrections (charm loops, broad *cc* resonance)



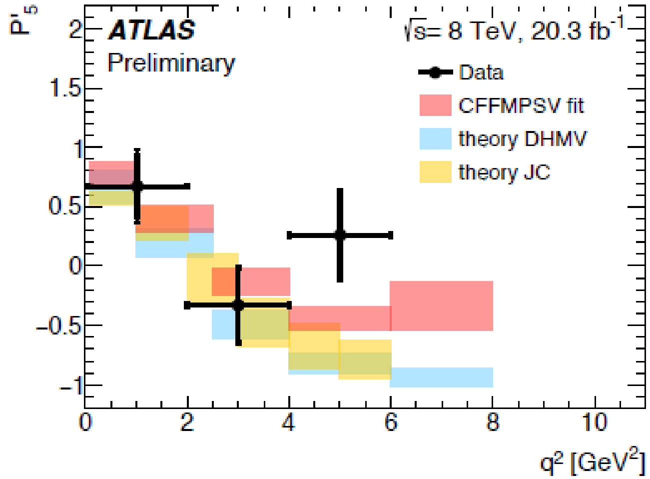


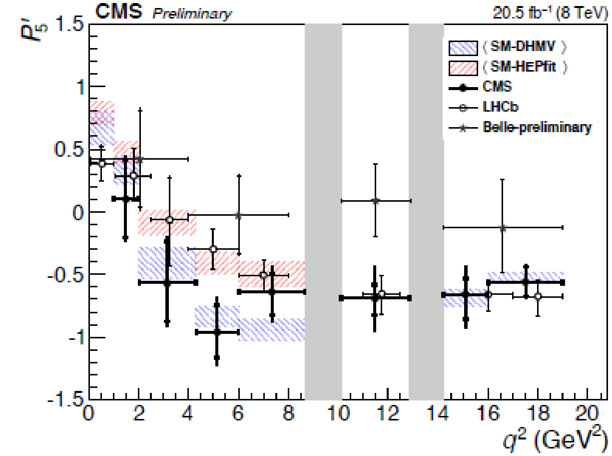
Angular analysis of $B^0 \rightarrow K^* l^+ l^-$

[JHEP 02 (2016) 104]



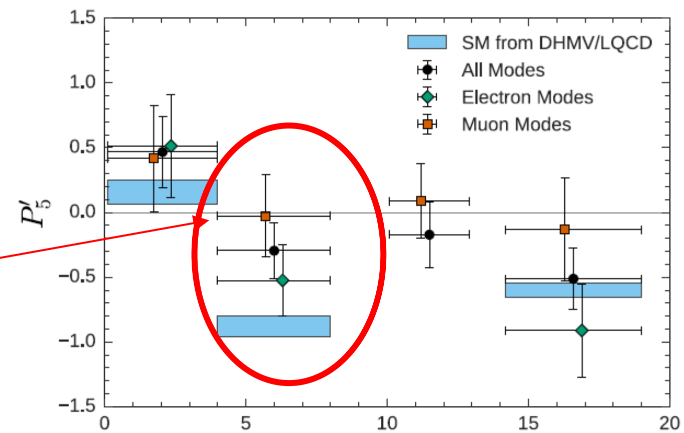
[ATLAS-CONF-2017-023]





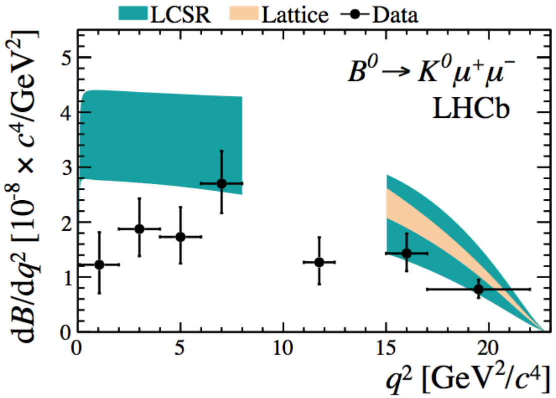
- Measure angular observables F_L, A_{FB}, $S_{3\ldots9}$, P_5' in bins of q^2.
- LHC*b* ATLAS, Belle show tension in P_5' with SM predictions.
- New analysis by Belle, separately for *e* and μ.
  2.6σ deviation for $K^*\mu\mu$
  1.1σ deviation for K^*ee

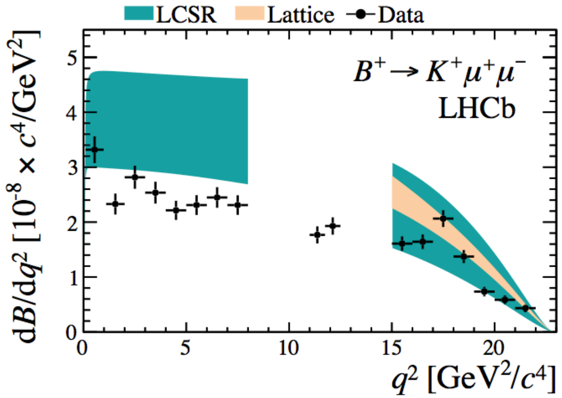
Belle, PRL, 118, 111801 (2017)

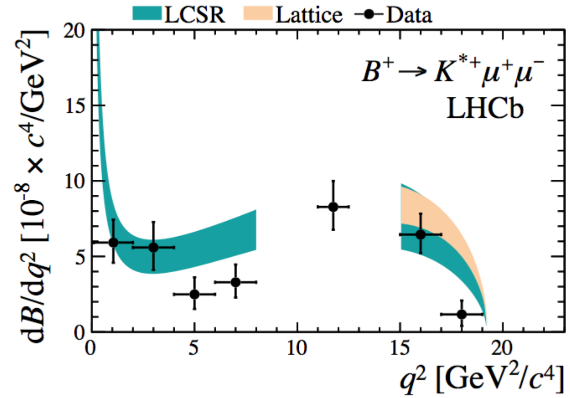


Differential x-section in b→sl⁺l⁻ decays

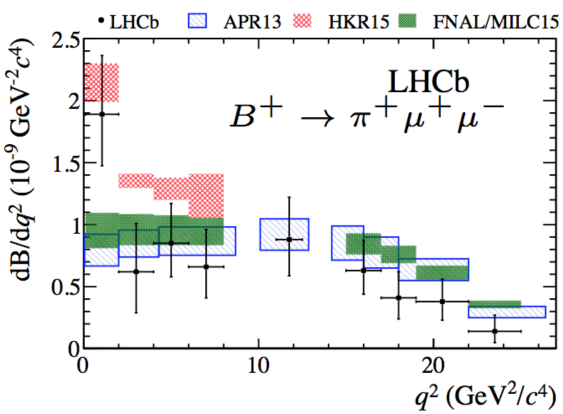
[JHEP 06 (2014) 133]



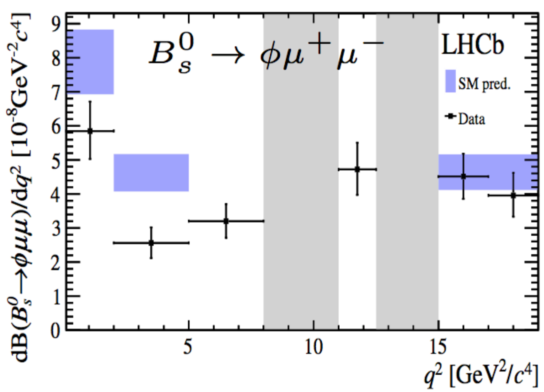




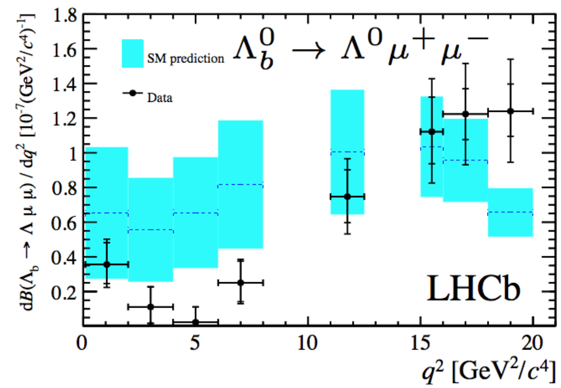
[JHEP 10 (2015) 034]



[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]



Cross-sections consistently lower than SM in low-q^2 region.

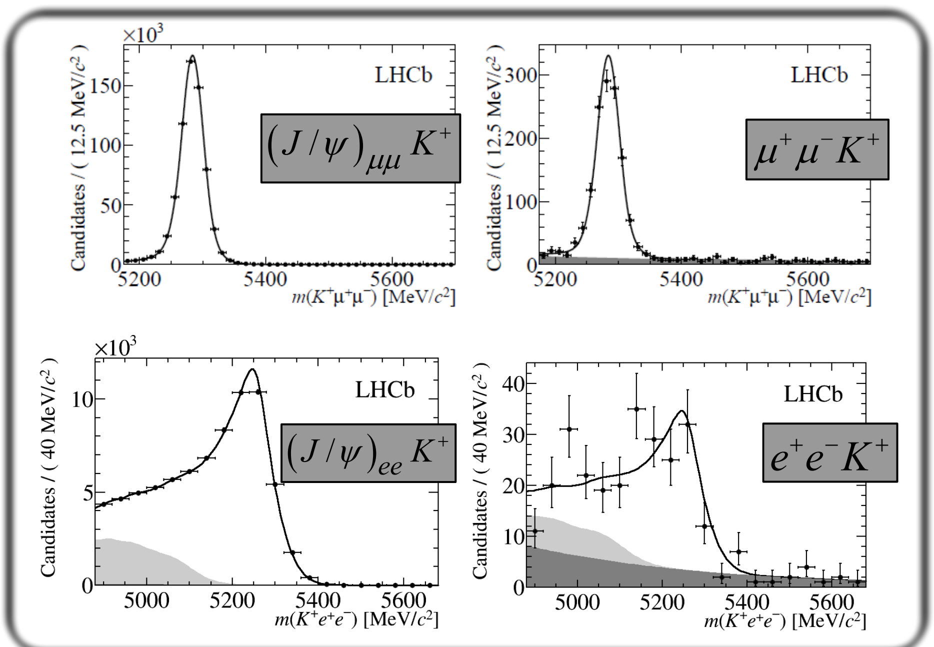
Lepton Universality in rare decays, R_K

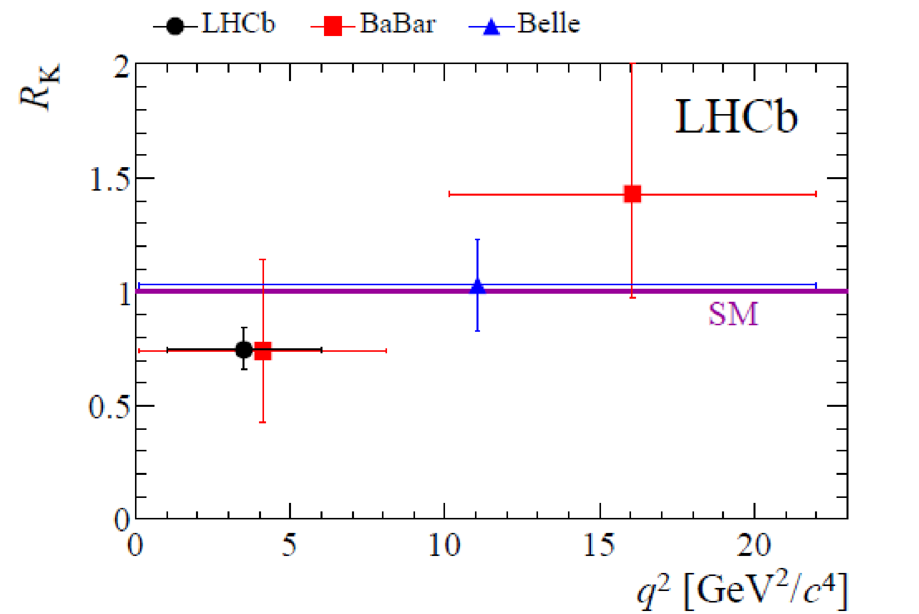
$$R_K \equiv \frac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to K^+e^+e^-)}$$

- **Theoretically clean**
- **Stringent test of LFU**

LHCb: PRL 113, 151601 (2014)
BaBar: PRD 86, 032012 (2012)
Belle: PRL 103, 171801 (2009)

LHCb: PRL 113, 151601 (2014)

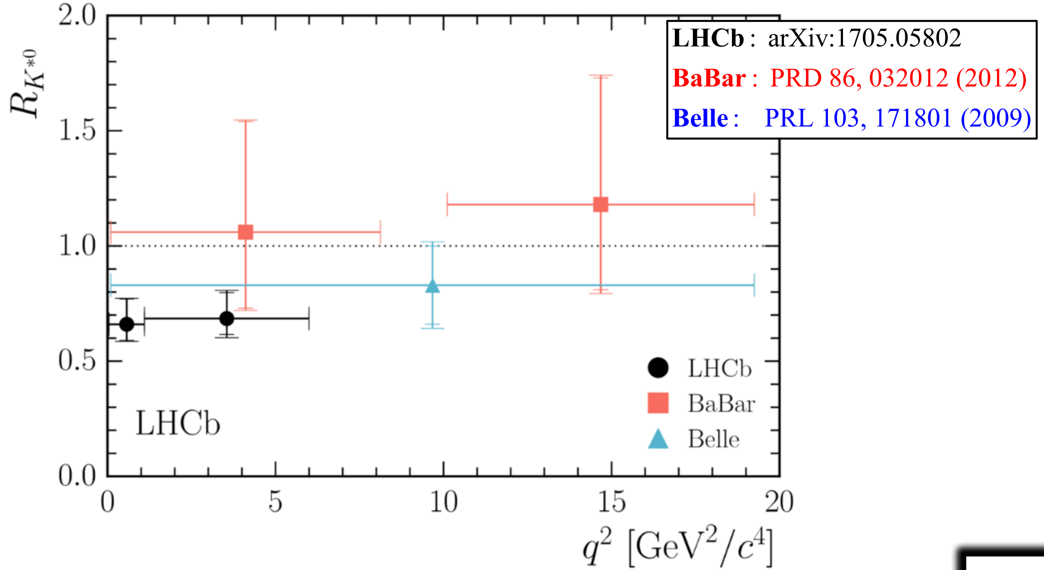




$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ **LHCb**
2.6 standard deviations from the SM prediction

Lepton Universality in rare decays, R_{K^*}

$$R_{K^*} \equiv \frac{B(B^0 \to K^{*0}\mu^+\mu^-)}{B(B^0 \to K^{*0}e^+e^-)}$$



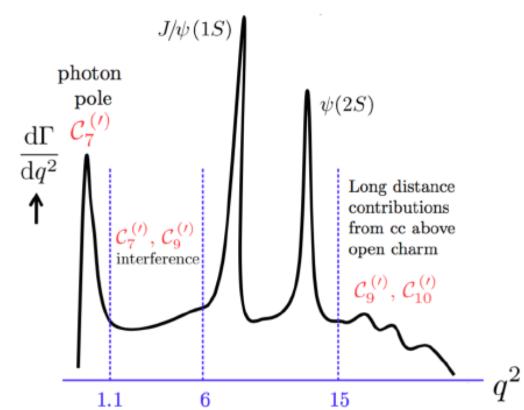
	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05$

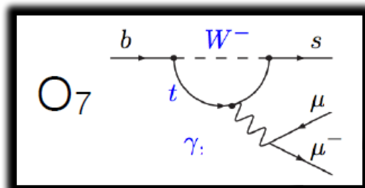
- Compatibility with the SM prediction(s):
  - Low-q^2: 2.1 - 2.3 standard deviations
  - Central-q^2: 2.4 - 2.5 standard deviations

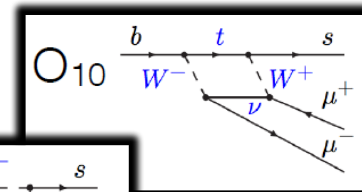
- Similar to R_K
- Double-ratio, wrt $B^0 \to J/\psi\, K^{*0}$

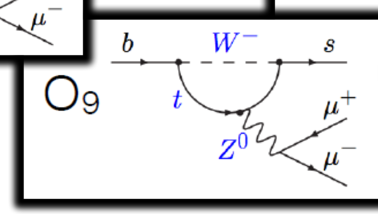
$$R_{K^*} = \frac{\mathcal{B}(B \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B \to K^{*0}e^+e^-)}{\mathcal{B}(B \to K^{*0}J/\psi\,(\to e^+e^-))}$$

- Measured in two q^2 intervals
  - q^2 is the $\mu^+\mu^-$ or e^+e^- invariant mass squared, q^2

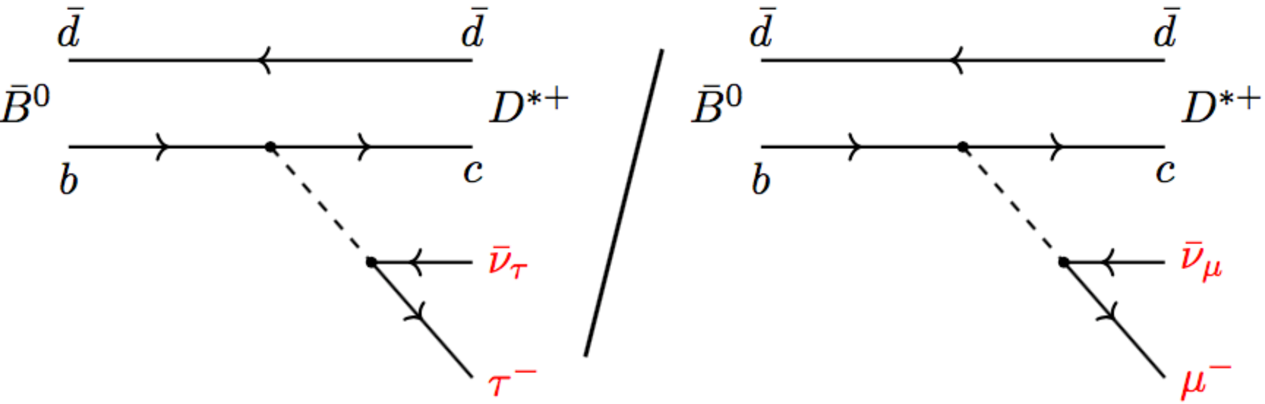








Lepton universality in semileptonic decays: R_{D*}

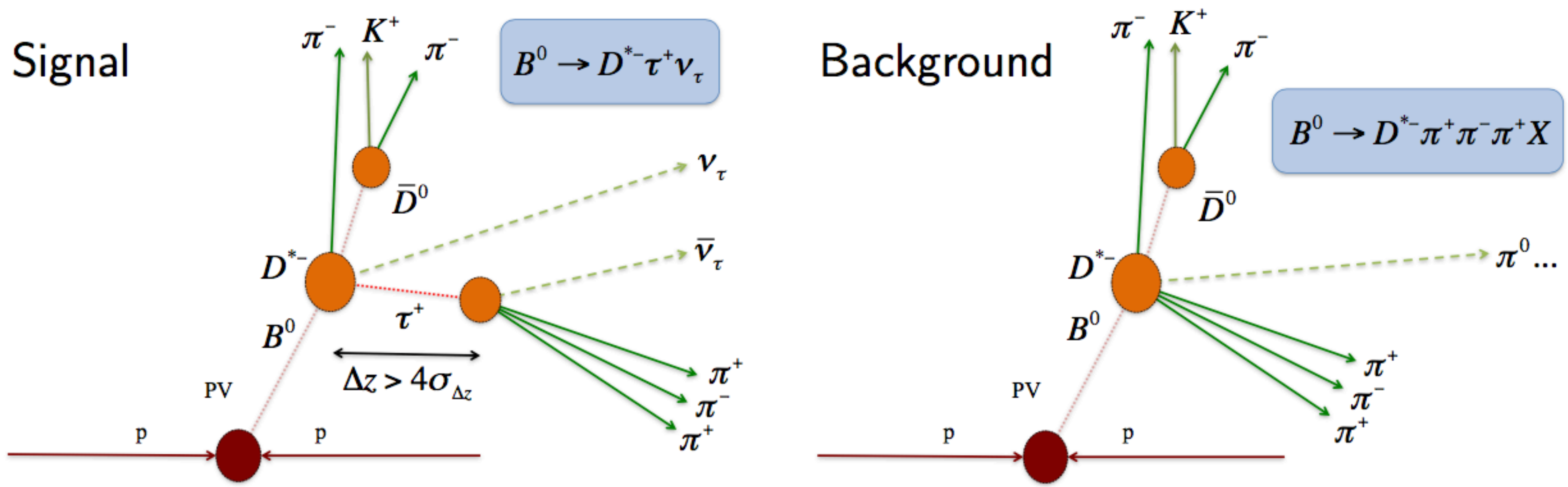


decay mode	$\mathcal{B}[\%]$ [PDG2017]
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	17.39 ± 0.04
$\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$	9.31 ± 0.05
$\tau^- \to \pi^+\pi^-\pi^-\pi^0\nu_\tau$	4.62 ± 0.05

$$R_{D^*} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \stackrel{\text{SM}}{=} 0.252 \pm 0.003$$ [PRD 85 (2012) 094025]

- Accurate SM prediction (hadronic uncertainties cancel).
- R_{D*}<1 because of phase space.
- Two LHCb analyses:
  - Leptonic $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decay [PRL 115 (2015) 111803]
  - Hadronic $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$ decays [PRL 120 (2018) 17]
- Experimental challenges:
  - Final state neutrinos
  - Large backgrounds from partially reconstructed and misidentified decays

R_{D*} with $\overline{B}^0 \to D^{*+}\tau^-(\to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau)\overline{\nu}_\tau$ decays



- Normalize to $B^0 \to D^{*-}3\pi$ with the same final state suppressing systematics:

$$R_{D^*} = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+(\to 3\pi(\pi^0)\overline{\nu}_\tau)\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^- \to D^{*-}\mu^+\nu_\mu)}$$

- Main background from hadronic $B \to D^*3\pi X$ decays suppressed by exploiting τ lifetime
  – (no bkg. from $B^0 \to D^{*-}\mu^+\nu_\mu$)
- BDT to suppress $B \to DD_{(s)}X$ background

[PRL 120 (2018) 17]

R_{D*} with $\overline{B}^0 \to D^{*+}\tau^-(\to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau)\overline{\nu}_\tau$ decays

- 3D binned template fit to q^2, τ-lifetime and BDT.
- Templates from simulation, validated using control samples

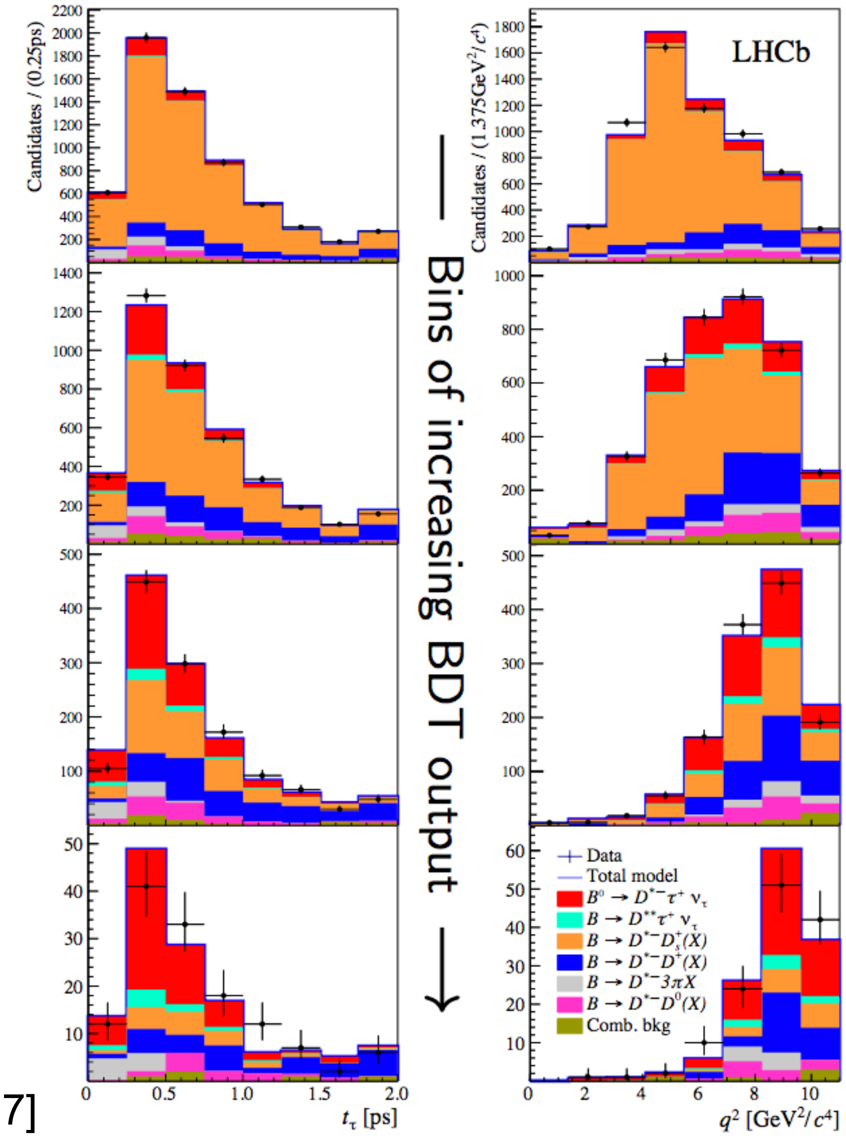
$$R_{D^*} = 0.286 \pm \underbrace{0.019}_{\text{stat.}} \pm \underbrace{0.025}_{\text{syst.}} \pm \underbrace{0.021}_{\text{ext.}}$$

- External inputs [PRD 87 (2013) 092001] [arXiv:1612.07233]

$$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.23 \pm 0.51) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$

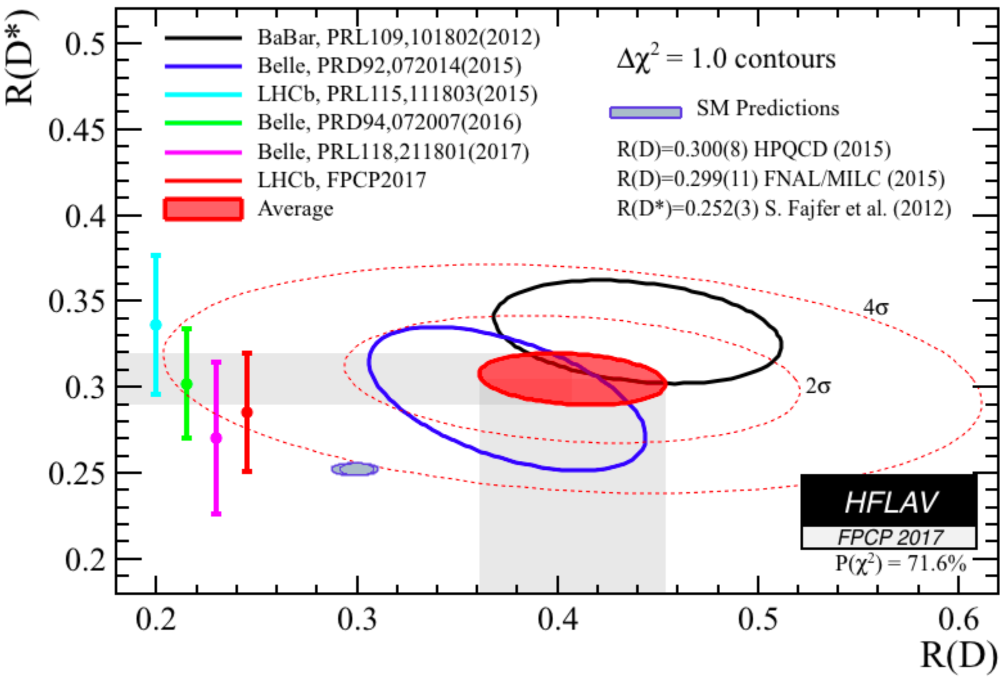
- Dominant systematic uncertainty: Size of simulated samples

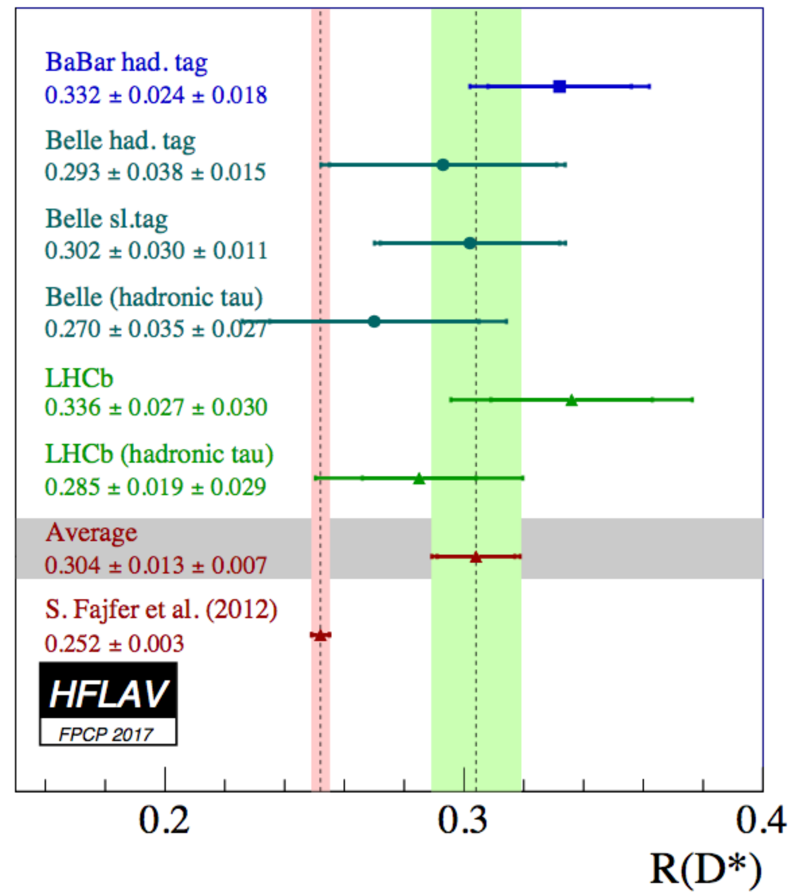


[PRL 120 (2018) 17]

Summary of R_D and R_{D*}

- Average of different final states an experiments.
- Including additional measurements, discrepancy of **4.1σ**. With SM.
- Possible BSM scenarios (H^+, W', LQs).



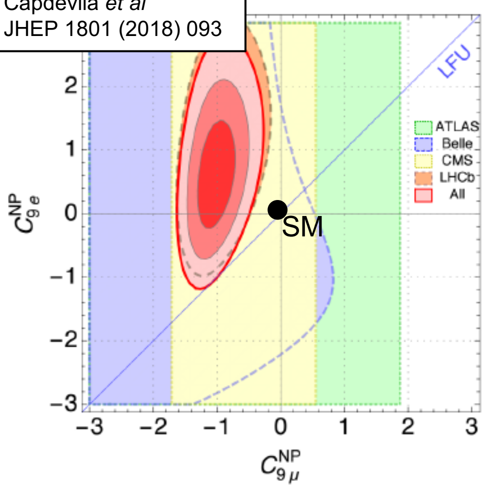


Global fits to b → sll data

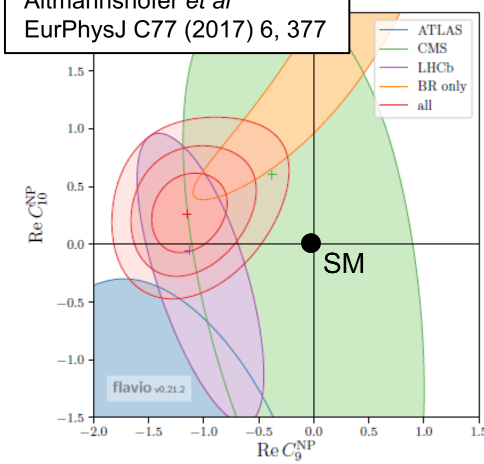
- Several global analyses performed to rare *b* decay data, assuming NP in one or more of the C_i's.
- Tension in SM fits at 4-5σ level if no NP allowed.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left[\left[C_i^{SM} + C_i^{\text{l}} \right] O_i(\mu) + \left[C_i'^{SM} + C_i'^{\text{l}} \right] O_i'(\mu) \right]$$

Capdevila *et al*
JHEP 1801 (2018) 093



Altmannshofer *et al*
EurPhysJ C77 (2017) 6, 377



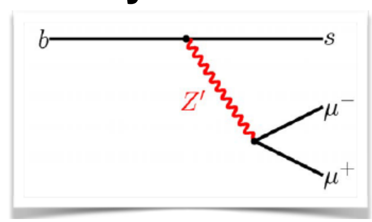
$C_9^{(')}$ & $C_{10}^{(')}$ are Wilson coefficients for EW penguins

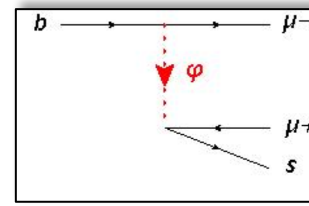
$$O_9^{(l)} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{\text{l}}\gamma^\mu \text{l}\right), \qquad O_{10}^{(l)} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{\text{l}}\gamma^\mu\gamma_5 \text{l}\right)$$

Vector **Axial vector**

Fits favor NP contribution to C_9 possibly C_{10}

Possibly NP in the vector couplings?





Z′, Leptoquarks, composite models, …

Problem in our understanding of QCD contributions?

More data required.

Capdevila *et al*
JHEP 1801 (2018) 093

- Hypotheses "NP in some C_i only" (1D, 2D, 6D) to be compared with SM

All				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{SM}$
$C_{9\mu}^{NP}$	**-1.11**	[−1.28, −0.94]	[−1.45, −0.75]	5.8
$C_{9\mu}^{NP} = -C_{10\mu}^{NP}$	-0.62	[−0.75, −0.49]	[−0.88, −0.37]	5.3
$C_{9\mu}^{NP} = -C_{9\mu}'$	-1.01	[−1.18, −0.84]	[−1.34, −0.65]	5.4
$C_{9\mu}^{NP} = -3C_{9e}^{NP}$	-1.07	[-1.24,-0.90]	[-1.40,-0.72]	5.8

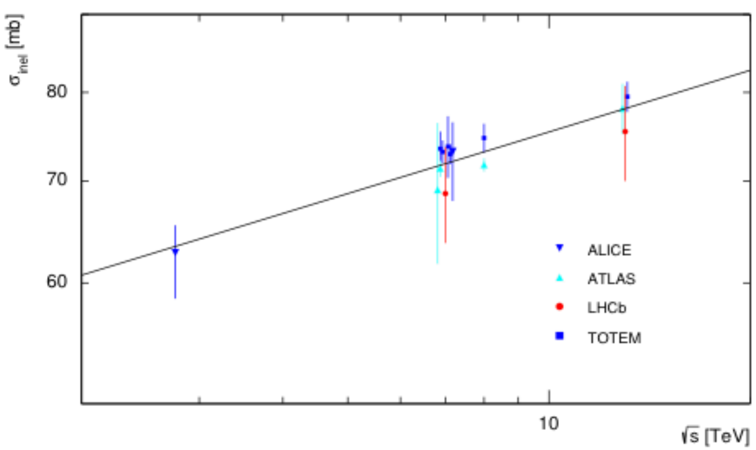
LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{SM}$
$C_{9\mu}^{NP}$	**-1.76**	[−2.36, −1.23]	[−3.04, −0.76]	3.9
$C_{9\mu}^{NP} = -C_{10\mu}^{NP}$	-0.66	[−0.84, −0.48]	[−1.04, −0.32]	4.1
$C_{9\mu}^{NP} = -C_{9\mu}'$	-1.64	[−2.13, −1.05]	[−2.52, −0.49]	3.2
$C_{9\mu}^{NP} = -3C_{9e}^{NP}$	-1.35	[−1.82, −0.95]	[−2.38, −0.59]	4.0

p-p inelastic cross section

- Other than flavor physics, LHCb slowly increasing its scope to other areas
  - QCD (soft, heavy ions, spectroscopy, exotic states)
  - EW and top physics
  - Higgs and BSM direct searches

***USC involved**

- **QCD physics: example**



arXiv:1803.10974
(submitted to JHEP)
also, PhD thesis **A. Dosil**

- Measurement of the pp inelastic xsection at 13 TeV **σ_{inel}=75.4±3.0±4.5 mb**
- Main challenge: determination of integrated luminosity!

Nuclear modification factor for charged particles at LHCb

- Nuclear effects on single particle production evaluated with the nuclear modification factor:

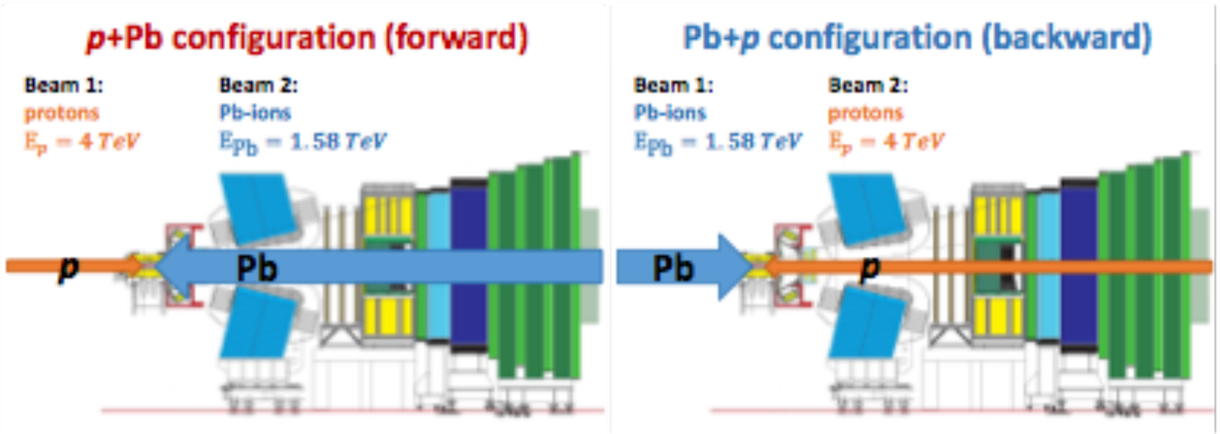
$$R_{p\text{Pb}} = \frac{\frac{d^2 N_{p\text{Pb}}}{dp_T d\eta}}{\langle T_{pPb}\rangle \frac{d^2\sigma_{pp}}{dp_T d\eta}} = \frac{\frac{d^2\sigma_{p\text{Pb}}}{dp_T d\eta}}{A\frac{d^2\sigma_{pp}}{dp_T d\eta}}$$

- Incoherent superposition of nucleon-nucleon collisions would yield $R_{p\text{Pb}} = 1$.
- Measurement of charged particle multiplicities can unravel the puzzle of Cold Nuclear Matter effects in p-Pb collisions
  - Due to LHCb asymmetry three different observables can be measured in different unexplored ranges:

$$R_{p\text{Pb}}, \quad 1.5 < \eta < 4.5$$

$$R_{\text{Pb}p}, \quad 2.5 < \eta < 5.5$$

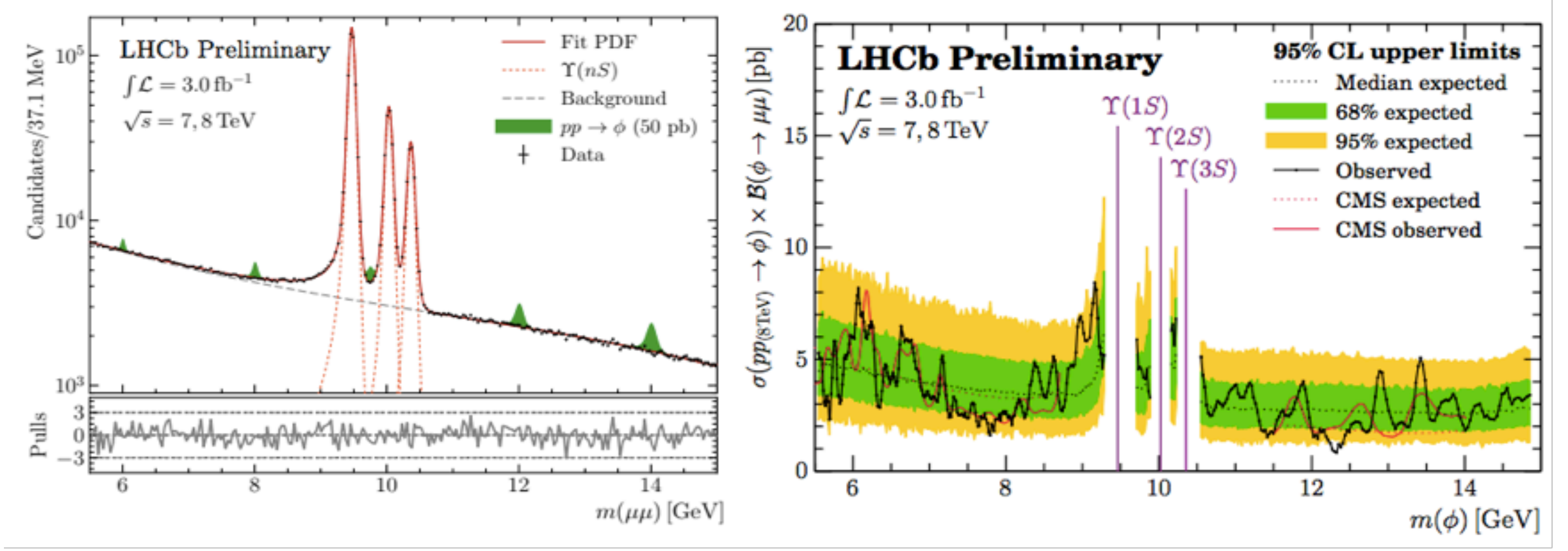
$$R_{\text{FB}} = \frac{R_{p\text{Pb}}}{R_{\text{Pb}p}}, \quad 2.5 < \eta < 4.5$$



BSM searches

- **BSM direct searches: example**
  - Search for a dimuon resonance in the Υ region. Sensitive to several models NMSSM, dark photons, …
  - First search that manages to look between the Υs and also goes closer to them than anyone else! (excellent mass resolution at LHCb)

LHCb-PAPER-2018-008
also PhD thesis **C. Vazquez**



Summary

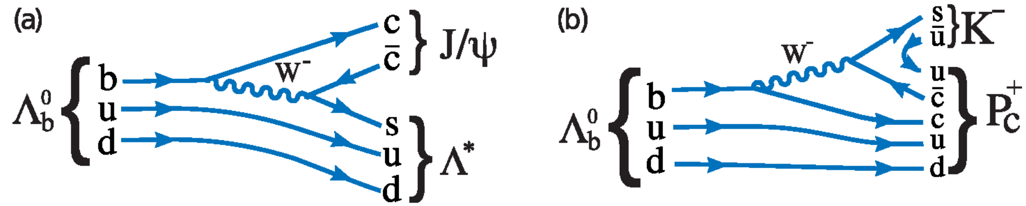
- The flavor sector has produced some of the most successful recent results in particle physics.
- The indirect approach could lead us to the discovery of NP.
- For that a new upgraded detector is required.
- In the meanwhile... stringent tests and the discovery of new exotic particles have been achieved.

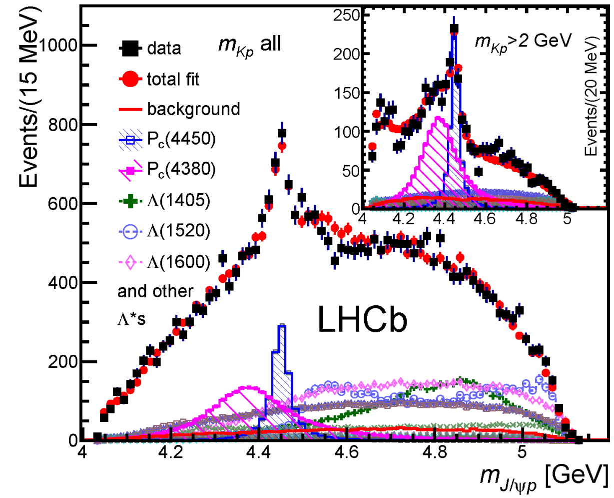
Exotic Spectroscopy

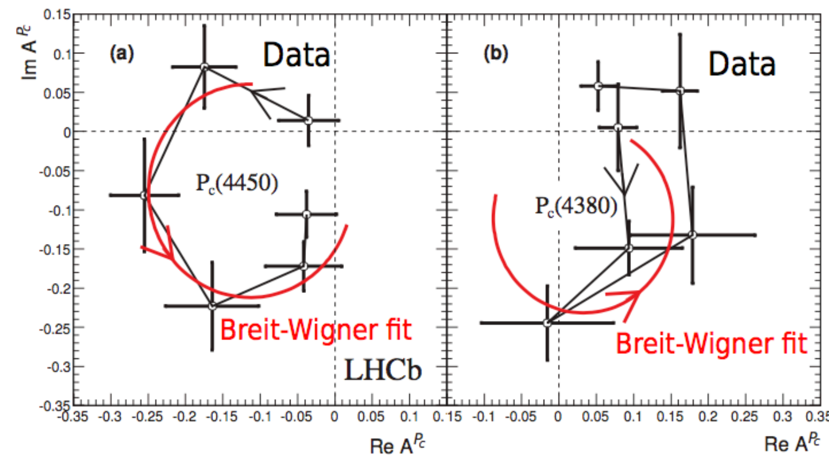
- Quarks form colorless objects:
  - mesons ($q\bar{q}$)
  - baryons (qqq)
- Angular, spin and radial excitations $\Rightarrow$ spectroscopy.
- Exotic spectroscopy: beyond 2- and 3-quark systems: tetraquarks ($q\bar{q}q\bar{q}$), pentaquarks ($qqqq\bar{q}$)

Pentaquarks

- 14 July 2015: LHCb reported the observation of two particles **P_c^+(4450) and P_c^+(4380) analyzing** 26 000 $\Lambda_b^0 \to J/\psi p K^-$ decays.
- 9σ < significance.
- Argand plot favors interpretation of these resonances as pentaquarks.
  - Interference with Λ^* states allows to extract the phase in bins of $m_{J/\psi p}$.
  - Clear phase rotation for P_c(4450), direction consistent with Breit-Wigner amplitude Not conclusive for P_c(4380), need more statistics.







Parameters of the pentaquark states

$P_c(4380)$:

$M = 4380 \pm 8 \pm 29\,\text{MeV},$

$\Gamma = 205 \pm 18 \pm 86\,\text{MeV}$

$\mathcal{F} = (8.4 \pm 0.7 \pm 4.2(\text{syst}))\%$

$P_c(4450)$:

$M = 4449.8 \pm 1.7 \pm 2.5\,\text{MeV}$

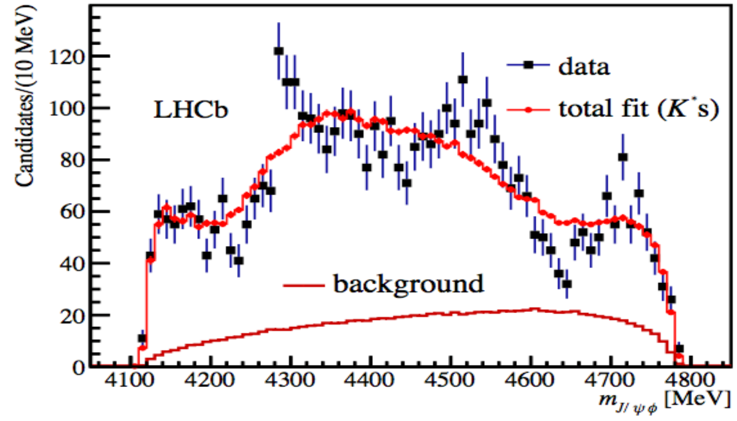
$\Gamma = 39 \pm 5 \pm 19\,\text{MeV}$

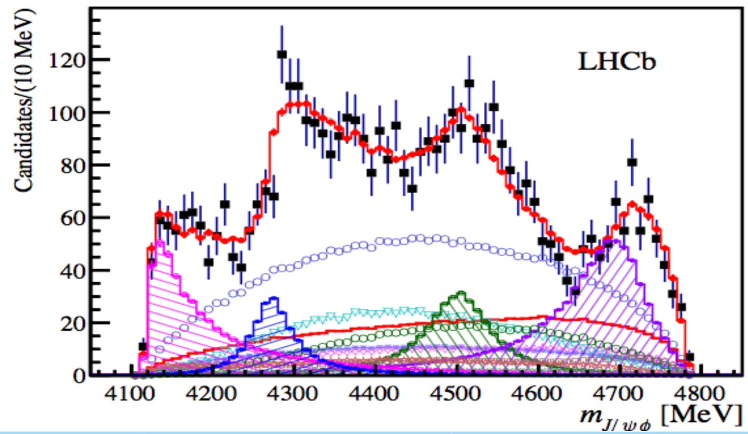
$\mathcal{F} = (4.1 \pm 0.5 \pm 1.1(\text{syst}))\%$

Tetraquarks

[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]

- 28 June 2016: LHCb reported observation of three new "exotic" particles X(4274), X(4500) and X(4700) and confirmation of existence of X(4140) (already seen by CDF) in the analysis of final J/ψφ states.
- Seem to be formed by two quarks and two antiquarks (tetraquark).
  - Alternative interpretation: strange charm charged meson pairs $D_s\, D_s^*$ bouncing off each other and rearranging their quark content to emerge as a J/ψφ system.

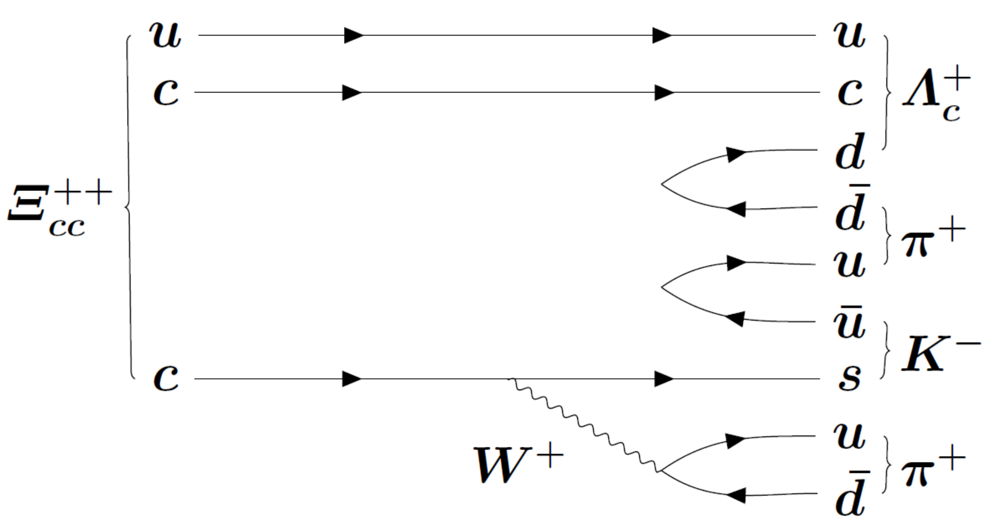


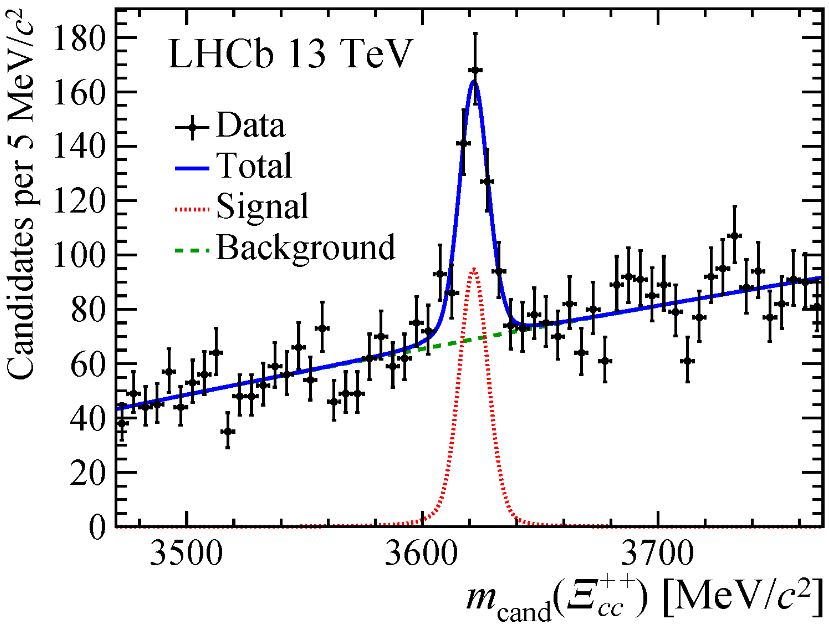


Contribution	J^{PC}	Significance	M_0 [MeV]	Γ_0 [MeV]	FF %
$X(4140)$	1^{++}	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.8}_{-2.0}$
$X(4274)$	1^{++}	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ \ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
$X(4500)$	0^{++}	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	0^{++}	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$

Discovery of Ξ_{cc}^{++}

- 6th July 2017. The Ξ_{cc}^{++}baryon identified by LHCb in its decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- Obtained in the analysis of 1.7 fb^{-1} 2016 LHCb data.
- $M_{\Xi cc++}$ =3621.40± 0.78 MeV
- Discovery opens a new field
  - Family of doubly charmed baryons related to Ξ_{cc}^{++} predicted and will be searched for.



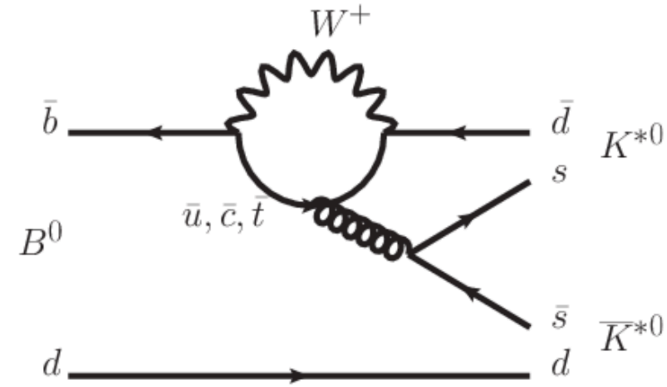


$B^0 \to K^{*0}\overline{K}^{*0}$

- U-spin partner of $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay.
  - Controls its penguin pollution from subleading amplitudes
- First LHCb analysis of $B^0 \to K^{*0}\overline{K}^{*0}$.
  - Evidence by BaBar with

$$\mathcal{B} = (1.28\,^{+\,0.35}_{-\,0.30} \pm 0.11) \times 10^{-6} \qquad f_L = 0.80\,^{+\,0.10}_{-\,0.12} \pm 0.06$$

  - Also analyzed by Belle



- Longitudinal polarization very high compared with $B_s^0 \to K^{*0}K^{*0}$.
- LHCb untagged and time-integrated analysis.
  - Assuming $\Delta\Gamma \sim 0$ and negligible CPV.
  - Data sample seven times larger than the precedent ones.

$$\frac{d^5\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi dm_1 dm_2} = \frac{9}{8\pi}\sum_{i=1}^{6}\sum_{j\geq i}\mathcal{R}e[A_i A_j^* F_{ij}\delta_{\eta_i\eta_j}]$$

$$F_{ij} = \Phi_4(m_1, m_2) f_i f_j^* (2 - \delta_{ij})$$

- Statistical precision of 0.053 achieved in f_L.

Parameter	Value
f_L	$x.xxx \pm 0.053$

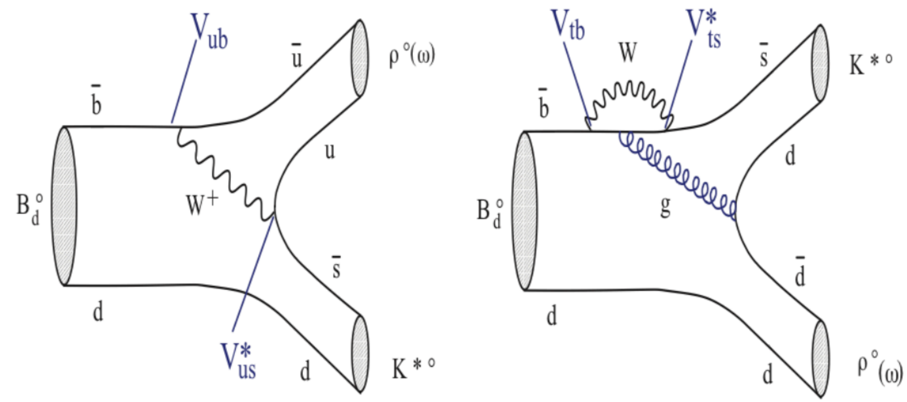
i	A_i	f_i
1	A_0	$\cos\theta_1 \cos\theta_2 \mathcal{M}_1(m_1)\mathcal{M}_1(m_2)$
2	$A_\parallel$	$\frac{1}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \cos\phi \mathcal{M}_1(m_1)\mathcal{M}_1(m_2)$
3	$A_\perp$	$\frac{i}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \sin\phi \mathcal{M}_1(m_1)\mathcal{M}_1(m_2)$
4	A_S^+	$-\frac{1}{\sqrt{6}}(\cos\theta_1 \mathcal{M}_1(m_1)\mathcal{M}_0(m_2) - \cos\theta_2 \mathcal{M}_0(m_1)\mathcal{M}_1(m_2))$
5	A_S^-	$-\frac{1}{\sqrt{6}}(\cos\theta_1 \mathcal{M}_1(m_1)\mathcal{M}_0(m_2) + \cos\theta_2 \mathcal{M}_0(m_1)\mathcal{M}_1(m_2))$
6	A_{SS}	$-\frac{1}{3}\mathcal{M}_0(m_1)\mathcal{M}_0(m_2)$

- Decay branching fraction determined improving the previous statistical uncertainty by a factor of 2:

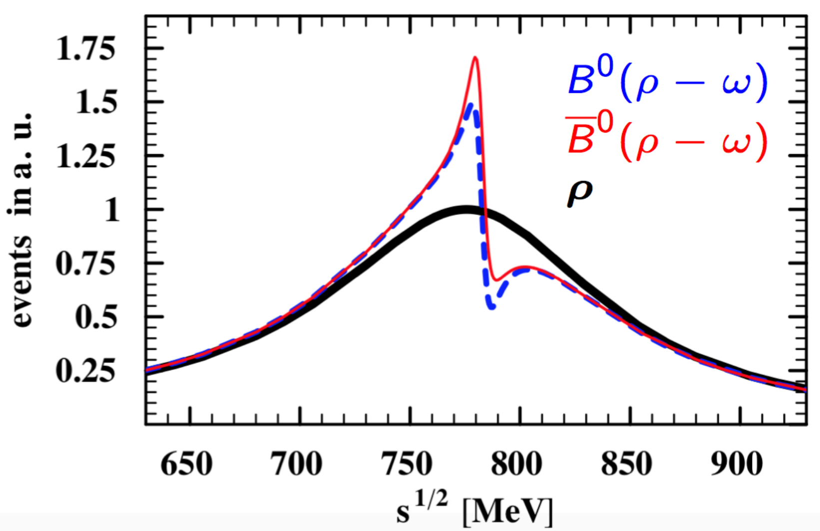
$$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (x.x \pm 1.9(\text{stat})) \times 10^{-7}$$

$B^0 \to \rho^0 K^{*0}$

- Proceeds either via:
  - Doubly Cabibbo suppressed tree
  - Gluonic b → s penguin
- Vector partner of $B^0 \to K\pi$
- Similar amplitudes! (good for a_{CP} search)
- $\rho \to \omega$ interplay may enhance CP violating effect
- A model accounting for 10 decay channels (14 waves) is considered.
  - $[K^{*0}+(K\pi)]\times[\rho^0+\omega+f_0(500)+f_0(980)+f_0(1370)]$
  - And the corresponding CP conjugated.
- World largest data sample. More than one order of magnitude increase.
- Triple products very sensitive to BSM.



i	Type	A_i	$g_i(\theta_1,\theta_2,\phi)$	$M_i(m_1,m_2)$
1		$A^0_{\rho K^*}$	$\cos\theta_1\cos\theta_2$	$M_\rho(m_1)M_{K^*}(m_2)$
2	V_1V	$A^{\parallel}_{\rho K^*}$	$\frac{1}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\phi$	$M_\rho(m_1)M_{K^*}(m_2)$
3		$A^{\perp}_{\rho K^*}$	$\frac{i}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\phi$	$M_\rho(m_1)M_{K^*}(m_2)$
4		$A^0_{\omega K^*}$	$\cos\theta_1\cos\theta_2$	$M_\omega(m_1)M_{K^*}(m_2)$
5	V_2V	$A^{\parallel}_{\omega K^*}$	$\frac{1}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\phi$	$M_\omega(m_1)M_{K^*}(m_2)$
6		$A^{\perp}_{\omega K^*}$	$\frac{i}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\phi$	$M_\omega(m_1)M_{K^*}(m_2)$
7	V_1S	$A^0_{\rho(K\pi)}$	$\frac{1}{\sqrt{3}}\cos\theta_1$	$M_\rho(m_1)M_{(K\pi)}(m_2)$
8	V_2S	$A^0_{\omega(K\pi)}$	$\frac{1}{\sqrt{3}}\cos\theta_1$	$M_\omega(m_1)M_{(K\pi)}(m_2)$
9	S_1V	$A^0_{f_0(500)K^*}$	$\frac{1}{\sqrt{3}}\cos\theta_2$	$M_{f_0(500)}(m_1)M_{K^*}(m_2)$
10	S_2V	$A^0_{f_0(980)K^*}$	$\frac{1}{\sqrt{3}}\cos\theta_2$	$M_{f_0(980)}(m_1)M_{K^*}(m_2)$
11	S_3V	$A^0_{f_0(1370)K^*}$	$\frac{1}{\sqrt{3}}\cos\theta_2$	$M_{f_0(1370)}(m_1)M_{K^*}(m_2)$
12	S_1S	$A^0_{f_0(500)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(500)}(m_1)M_{(K\pi)}(m_2)$
13	S_2S	$A^0_{f_0(980)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(980)}(m_1)M_{(K\pi)}(m_2)$
14	S_3S	$A^0_{f_0(1370)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(1370)}(m_1)M_{(K\pi)}(m_2)$



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arXiv:hep-ph/0502139

CP violation and matter-antimatter balance

- Excess of matter over anti-matter in the universe.
- Sakharov's conditions (1967):
  - Unstable Proton: no baryon conservation.
  - Interactions violating C conjugation and CP symmetry: initial matter-antimatter balance upset.
  - Universe: phase of extremely rapid expansion. Prevents restoration of balance due to CPT symmetry.
- Standard Model. Two ways to break CP:
  - QCD: unobserved.
  - Weak force: verified. Accounts for a small portion. Net mass ~ only a single galaxy ☹.
- Physics beyond SM?
  - Flavor physics: excellent playground to search for BSM physics.