Flavours and BSM: recent LHCb contributions.

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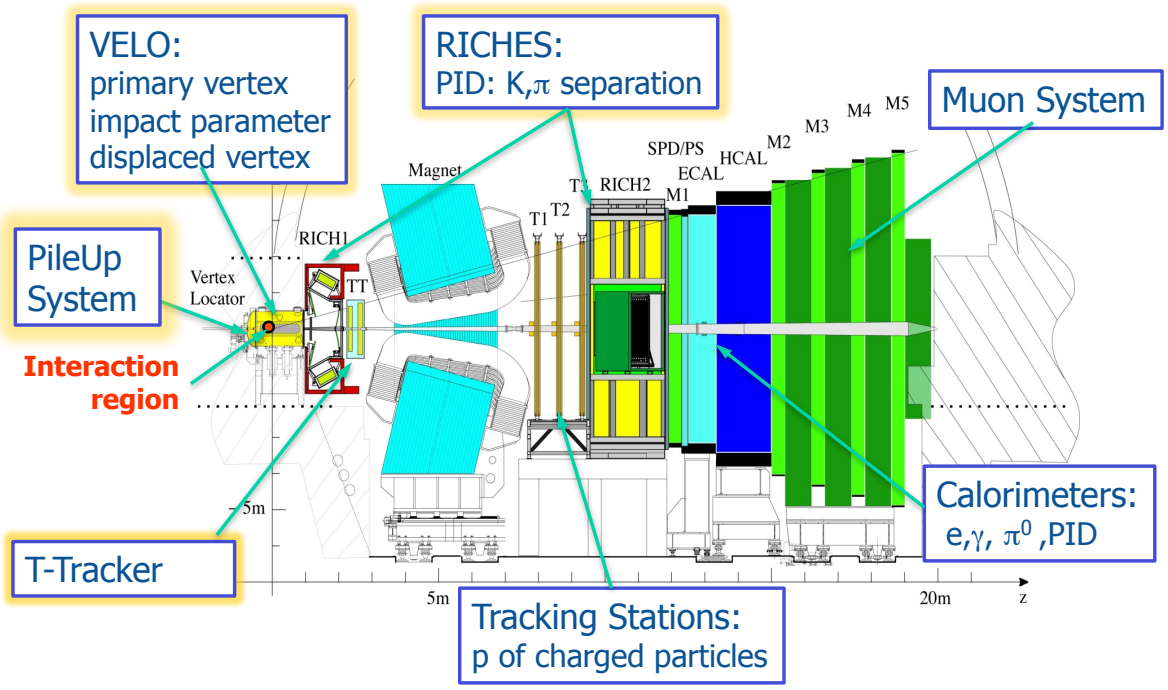
Outline of the presentation

1. The LHCb spectrometer: highlights and performance.
2. Contributions to the CKM profile.
3. Null tests of the SM and BSM constraints in $\Delta F = 2$ quark transitions.
4. Searching for BSM Physics in $\Delta F = 1$ quark transitions.
5. Searching for BSM Physics in tree-mediated processes.
6. Summary.

1. The LHCb spectrometer: highlights and performance.

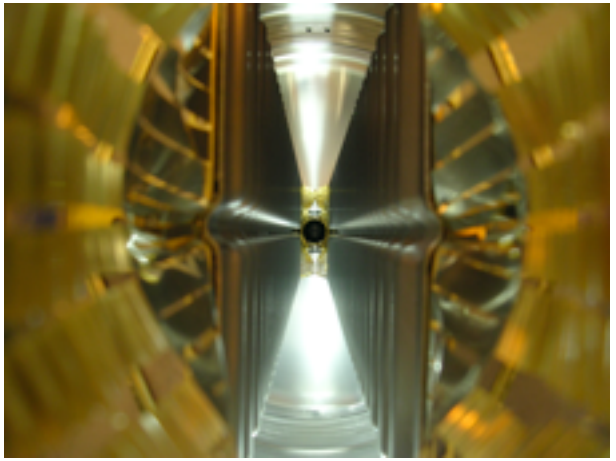
1. The LHCb spectrometer: highlights and performance.

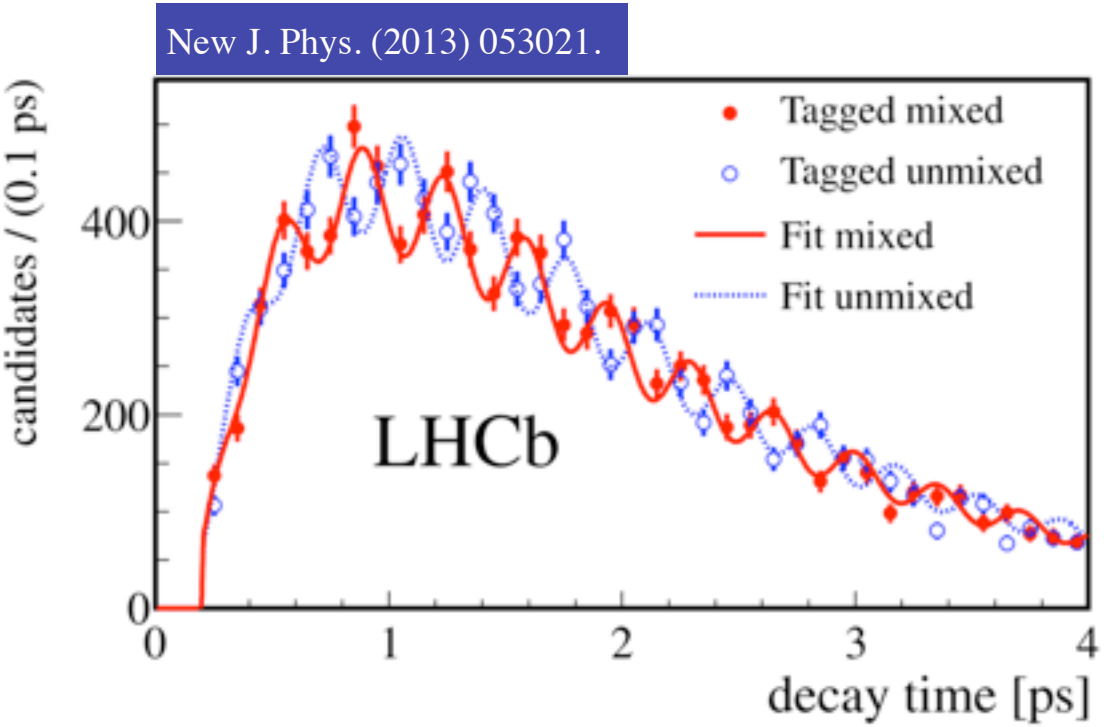
Detector- and operation-wise, the LHCb spectrometer is a success story. There is in particular a jewel for the Physics analyses: the Vertex Locator.



The excellent decay vertexing and momentum (mass) resolution is complemented by an efficient particle identification (RICHes) and a flexible and robust trigger system (hw L0 at 40 MHz, sw HLT at 1 MHz).

The vertex locator seen from the beam pipe:

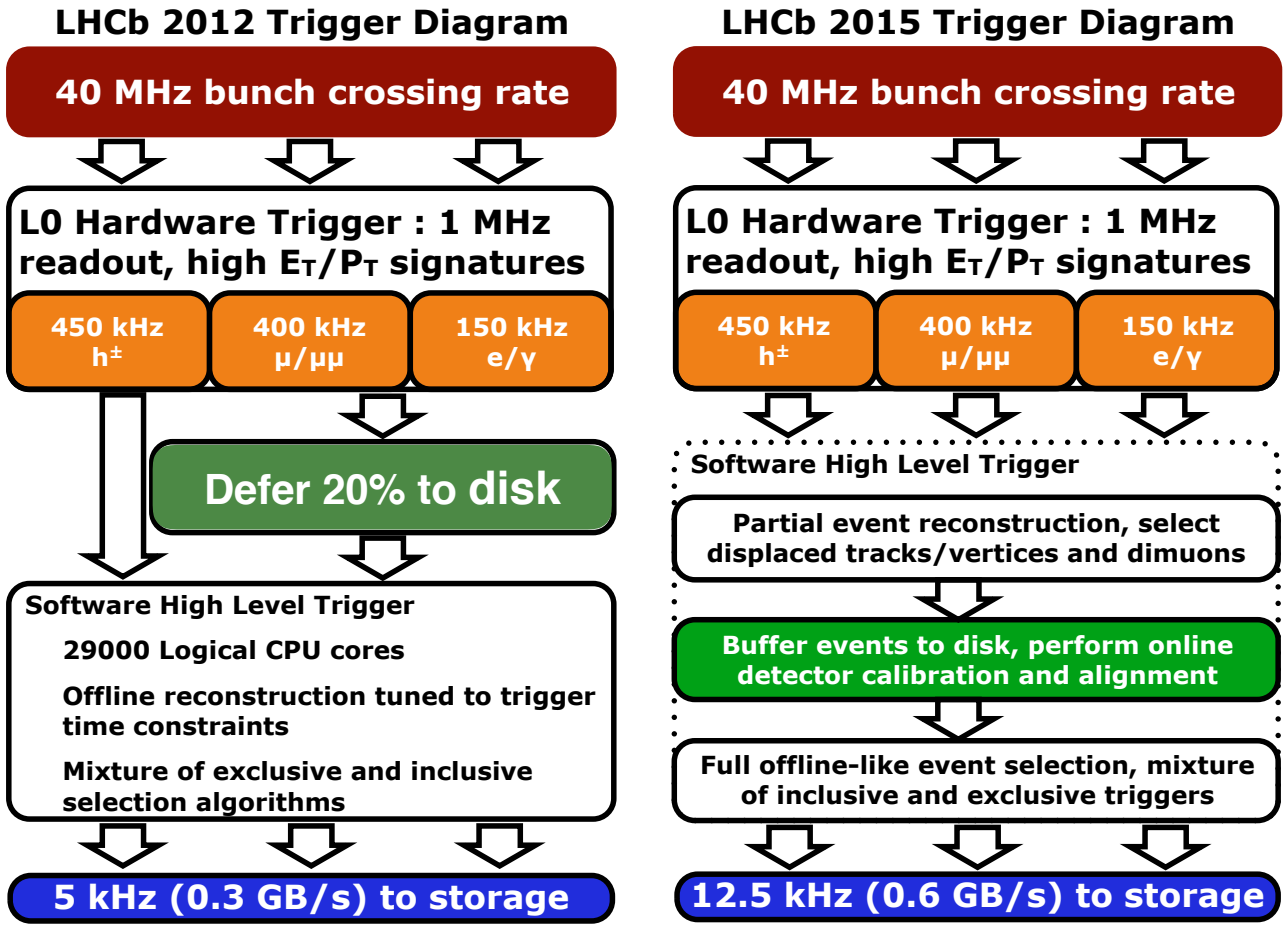




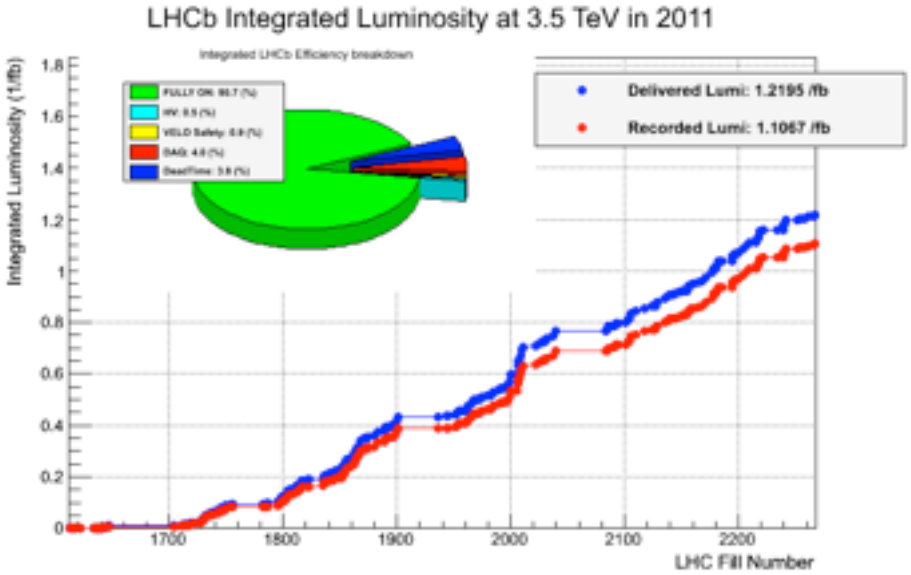
- Recontruction and flavour tagging of the decays $B_s \rightarrow D_s\pi$

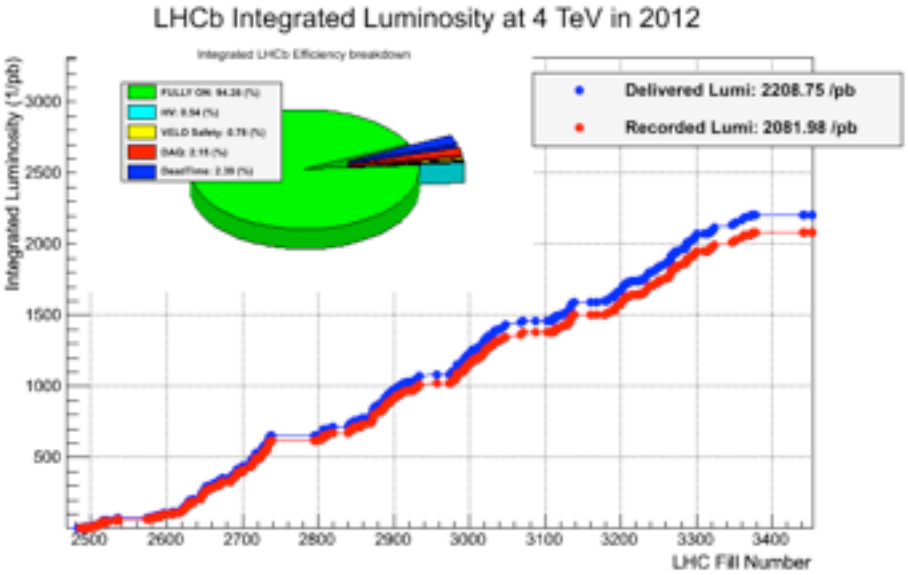
allowed to make textbook-like measurements.

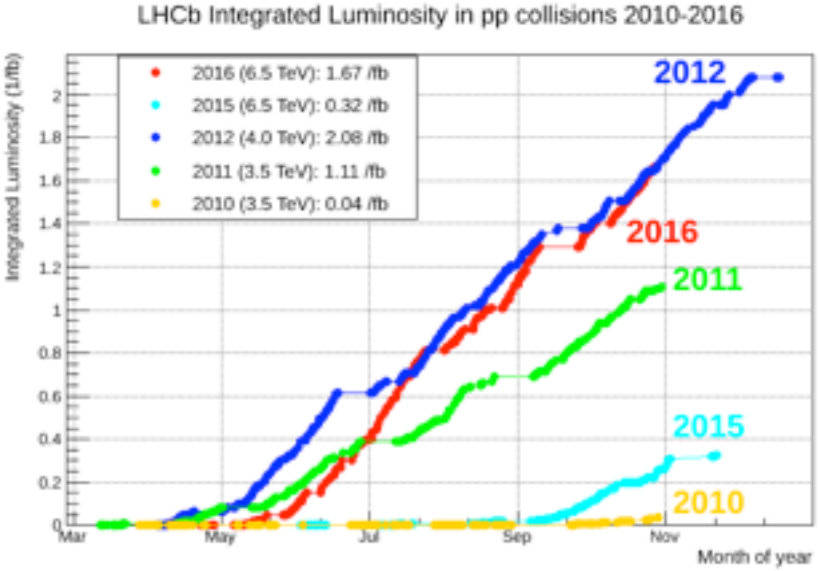
The trigger architecture and the online data flow



1. The LHCb spectrometer: highlights and performance.







The LHC Run II so far provides twice the signal recorded at Run I, thanks to the enhanced *bb* cross-section.

Inefficiencies are nowadays contained in *l'écume des jours.*

Disclaimer: all results presented here are with the LHC Run I data.

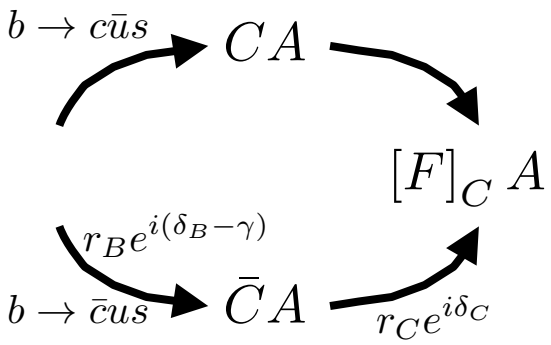
2. The CKM Profile and the constraints on the *universal* unitarity triangle.

2. The CKM Profile: the angle γ

- The angle γ is the weak phase difference between the following decay amplitudes:

$$b \to c\bar{u}s \text{ and } b \to \bar{c}us \qquad B \to [F]_C\, A$$

- accessing the very same final state:



- It can be interpreted in the SM as:

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

- with negligible theoretical uncertainty [JHEP 01 051].

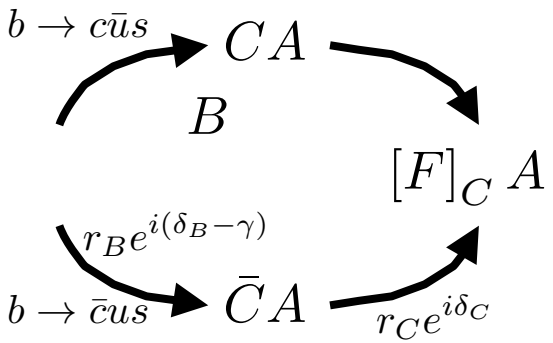
$$B \to [F]_C\, A\ ,\ e.g.\ B^{\pm} \to \left[K^{\mp}\pi^{\pm}\right]_D K^{\pm}$$

- Several techniques employed: GGSZ, GLW, ADS [PRD 63 036005, PLB253 48, PRL 78 3257], resp.

2. The CKM Profile: the angle γ

LHCb aims at searching comprehensively for the relevant final states:

B decay	D decay	Method	Ref.	Status since last combination [28]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[45]	New
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[46]	As before
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS	[47]	As before
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS	[48]	New
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[49]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[50]	New
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[51]	New
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[52]	As before



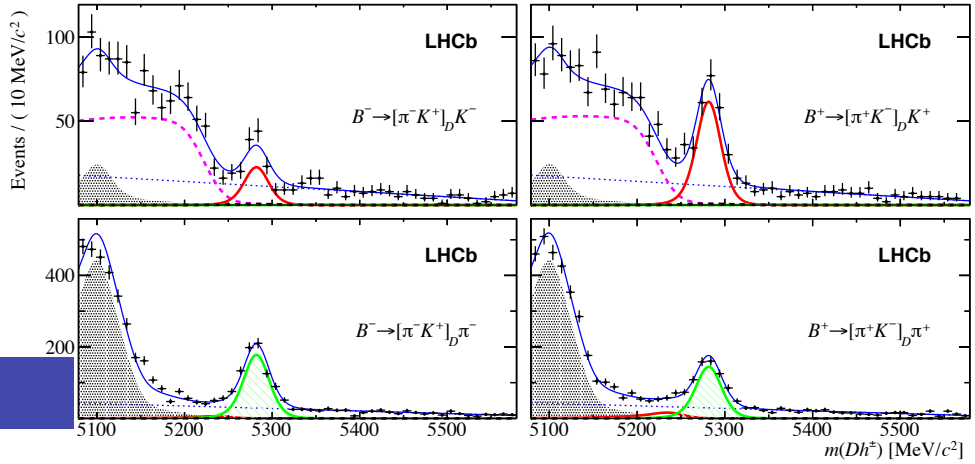
One of the most significant:

$$A^{\pi K}_{ADS}(K) = -0.403 \pm 0.056 \pm 0.011$$

First observation of CPV in a single *Dh* mode.

Phys. Lett. B760 (2016) 117.

$550_{\pm 30}$ $B^\pm \to [\pi^\pm K^\mp]K^\pm$



$1{,}360_{\pm 40}$ $B^\pm \to [\pi^\pm K^\mp]\pi^\pm$

2. The CKM Profile: the angle γ

LHCb grand combination:

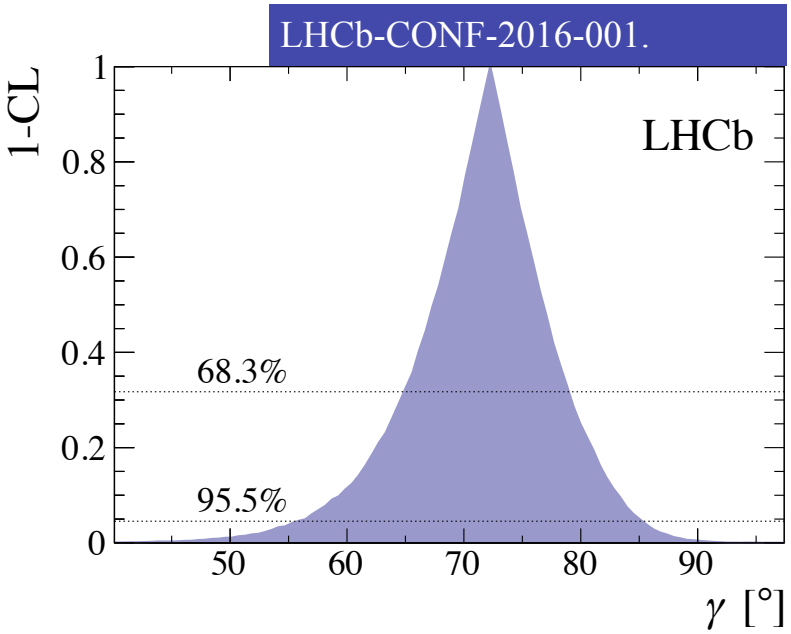
- The Run I target sensitivity is met:

$$\gamma = 72.2^{+6.8}_{-7.3}$$

- Main input nowadays to the WA. In fair agreement w/ global CKM fit prediction.

- More to come in the future. The next precision targets are 4 degrees after the LHC Run II and the degree in the LHCb upgrade era. A very promising mode to conclude this section:
Bs → DsK

LHCb-CONF-2016-015.

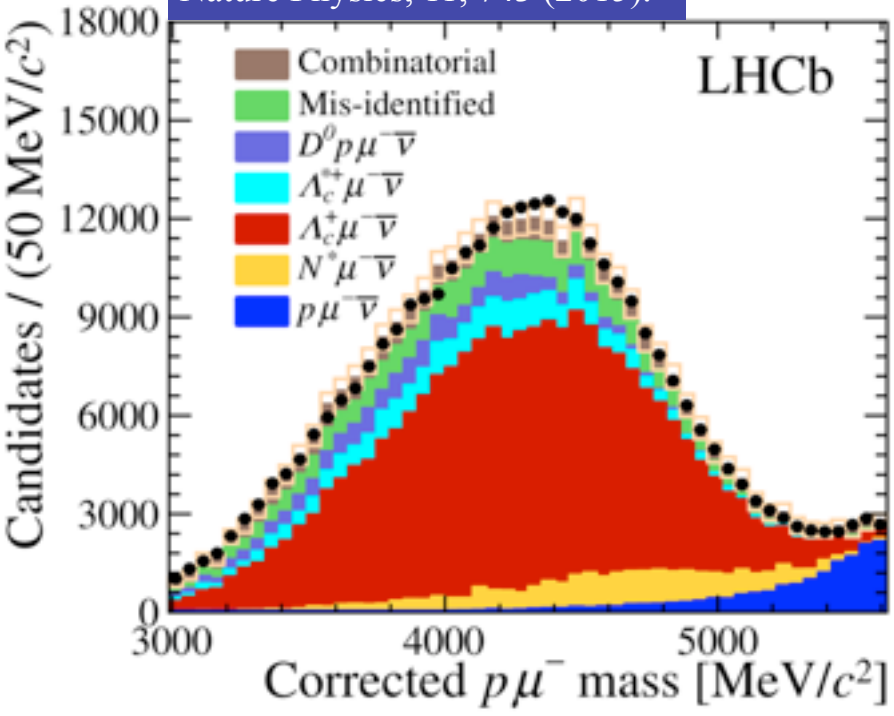


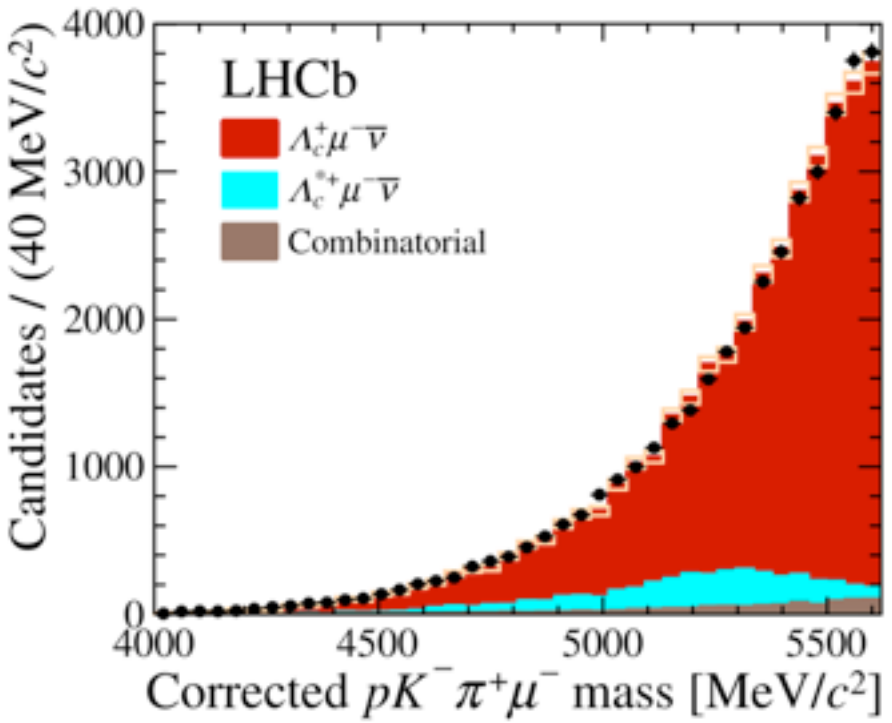
2. The CKM Profile: the modulus $|V_{ub}|$

- As the angle γ, $|V_{ub}|$ can be determined from supposedly tree-level transitions involving leptonic or semileptonic counterpart of the quark transition.
- A place where LHCb, as a spectrometer, was not expected.
- Longstanding tensions between inclusive and exclusive determinations of both $|V_{ub}|$ and $|V_{cb}|$ matrix element moduli.
- LHCb measures the branching fraction of the decay mode $\Lambda_b \to p\mu\nu_\mu$ relative to $\Lambda_b \to \Lambda_c\mu\nu_\mu$ at, where $\Lambda_c \to pK\pi$ and hence derives from the knowledge of the QCD form factors of these transitions the ratio of the matrix element moduli $|V_{ub}| / |V_{cb}|$.
- Selection of events at large q^2 to minimize the LQCD uncertainties, which dominate the error budget with the knowledge of $B(\Lambda_c \to pK\pi)$.

2. The CKM Profile: the modulus $|V_{ub}|$

Nature Physics, 11, 743 (2015).





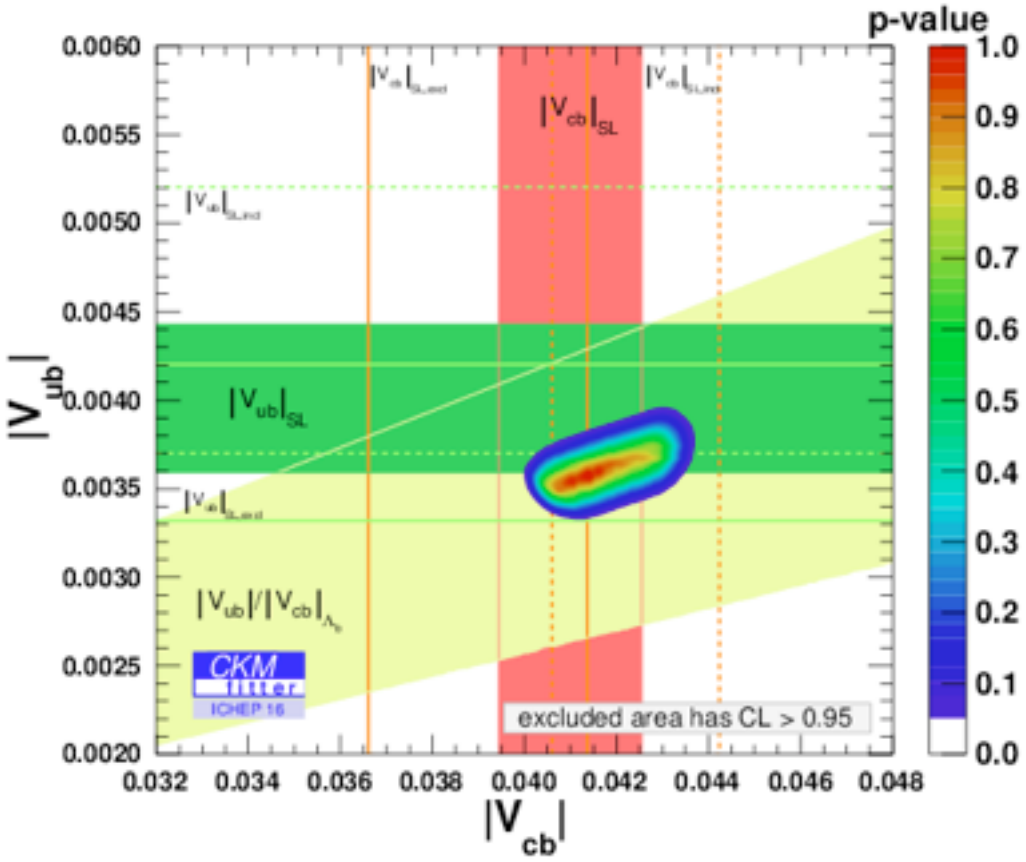
$$\frac{\mathcal{B}(\Lambda_b \to p\mu^- \bar{\nu}_\mu)_{q^2>15}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)_{q^2>7}} = (0.944 \pm 0.081)10^{-2}$$

Note: rescaled to the latest BESIII measurement of $B(\Lambda c \to pK\pi)$.

2. The CKM Profile: the modulus $|V_{ub}|$

The global picture and the LHCb contribution:

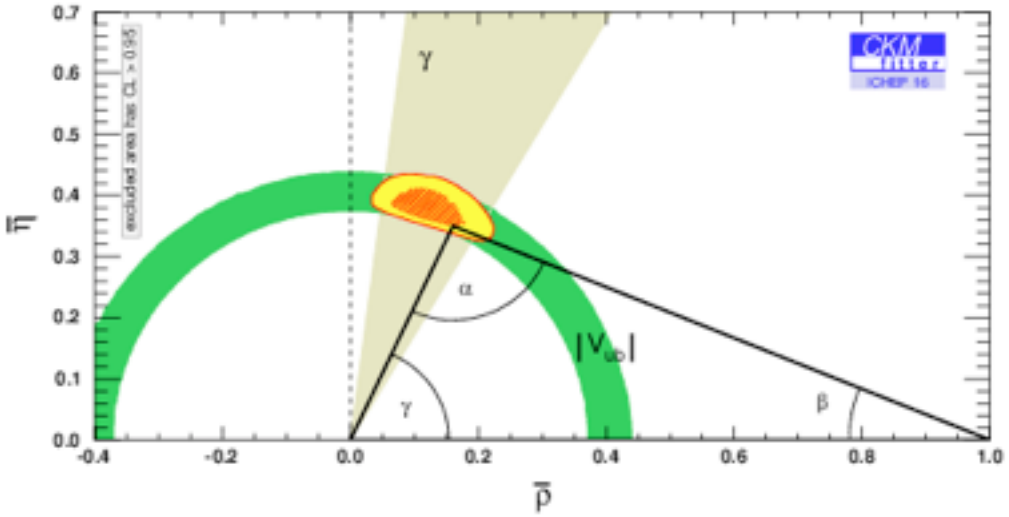
- First derivation of $|V_{ub}|$ w/ baryon decays.
- Confirms the tension between the determinations from specific and non-specific final states.
- More to come on the subject from LHCb w/meson modes, *e.g.* $B(B_s \to K\mu\nu_\mu)$



2. The CKM Profile: the angle γ and $|V_{ub}|$

- The gamma measurement is interesting per se in the comparison of its tree-level (supposedly free from BSM contributions and loop determinations).

- It is (maybe) more important when used in conjunction with the $|V_{ub}|$ measurement to fix the apex of a tree-level *universal* unitarity triangle allowing in model-independent way the exploration of BSM contributions in $\Delta F = 2$ quark transitions.

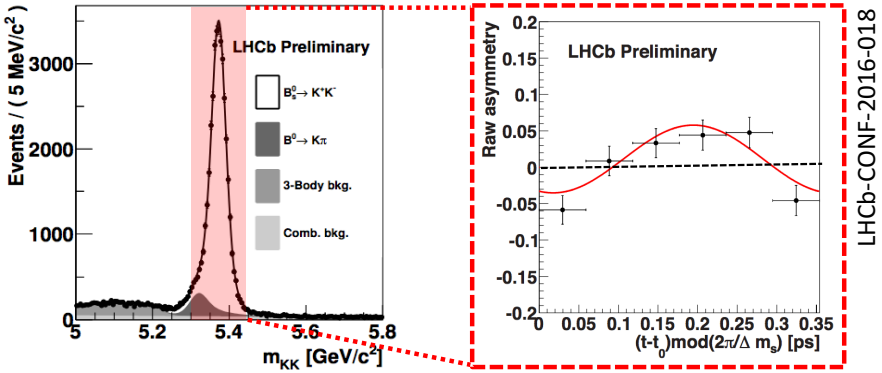


2. The CKM Profile: miscellanea

Other LHCb contributions for the global CKM picture:

- sin(2β) from $B^0 \to J/\psi K_S$ — Phys. Rev. Lett. 115 (2015) 031601
- sin(2α) from $B^0 \to \pi\pi$. — LHCb-CONF-2016-018.
- sin(2α) from $B^0 \to \rho^0\rho^0(\pi\pi\pi\pi)$. — Phys. Lett. B747 (2015) 468
- B_s oscillation frequency Δm_s — New J. Phys. (2013) 053021.

In the same analysis of the second point, the first observation of *CP* violation in the interference b/w mixing and decay of $B_s \to KK$.

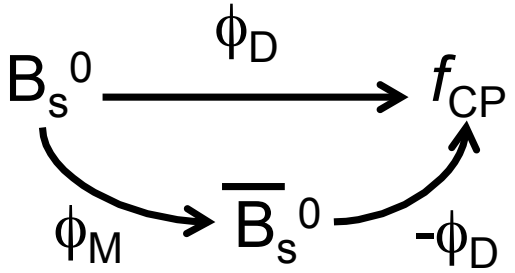


3. Null tests of the SM hypothesis and BSM constraints in $\Delta F = 2$ quark transitions.

3. Null tests of the SM in $\Delta F = 2$. $B_s \rightarrow J/\Psi\Phi$

- Study the *CP* violation in interference between decay and mixing in B_s decays in $B_s \rightarrow J/\Psi(\mu^+\mu^-)\ \Phi(K^+K^-)$ or $B_s \rightarrow J/\psi\ (\mu^+\mu^-)\ \pi\pi$ decays: *CP* violating phase $\phi_S = \phi_M - 2\phi_D$

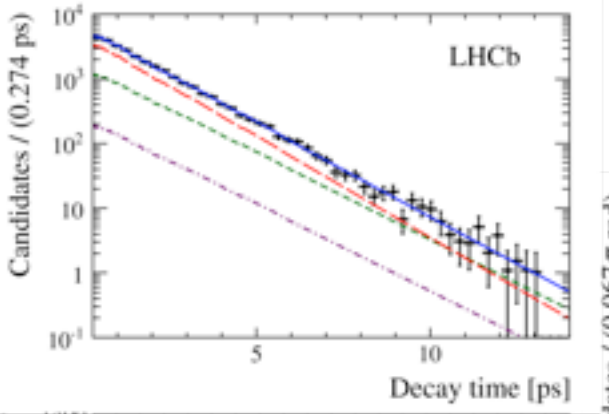
- ϕ_S is well determined in SM: $\phi_S = -2\beta_S = -0.0363 \pm 0.0017$ rad, up to penguin diagram phase contributions (10^{-4}–10^{-3}). Null test of the SM hypothesis.

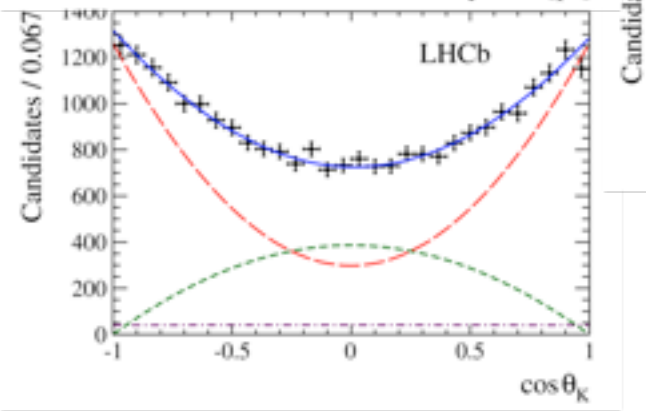


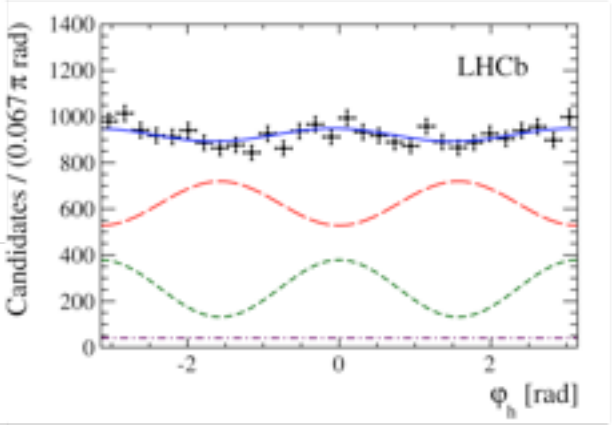
• The mixing phase, $\phi_M \approx 0$ in Standard Model can be modified by BSM contributions and hence detected by ϕ_S.

• Since the decay is P → VV, the final state is a superposition of states with different *CP* parity values: the measurement requires a tagged, time-dependent angular analysis (5 dimensions analysis).

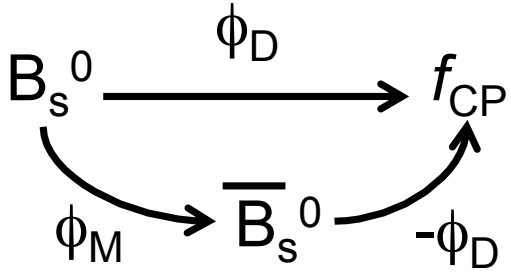
3. Null tests of the SM in $\Delta F = 2$. $B_s \rightarrow J/\Psi\Phi$



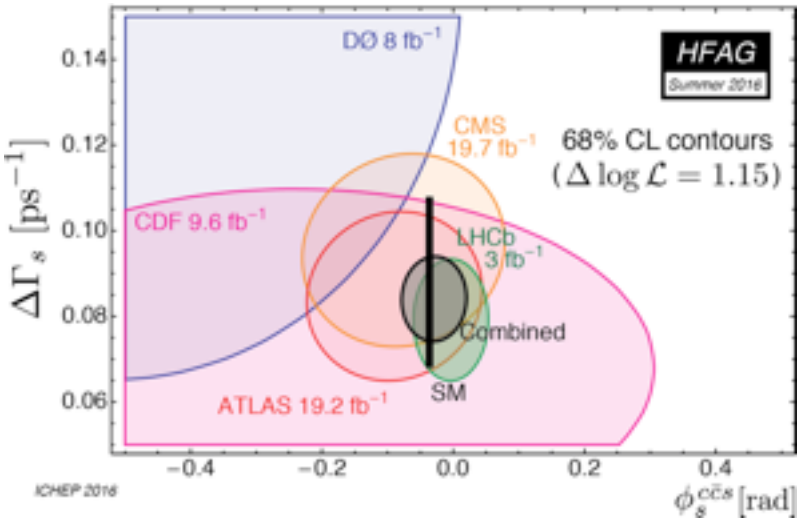




CP even
CP odd
S-wave

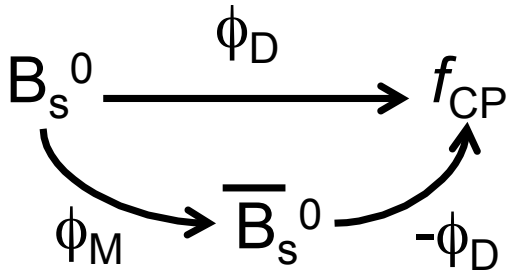


Parameter	Value
Γ_s [ps^{-1}]	$0.661 \pm 0.004 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.106 \pm 0.011 \pm 0.007$
$\lvert A_\perp \rvert^2$	$0.246 \pm 0.007 \pm 0.006$
$\lvert A_0 \rvert^2$	$0.523 \pm 0.005 \pm 0.010$
$\delta_\parallel$ [rad]	$3.32^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp$ [rad]	$3.04 \pm 0.20 \pm 0.08$
ϕ_s [rad]	$0.01 \pm 0.07 \pm 0.01$
$\lvert\lambda\rvert$	$0.93 \pm 0.03 \pm 0.02$

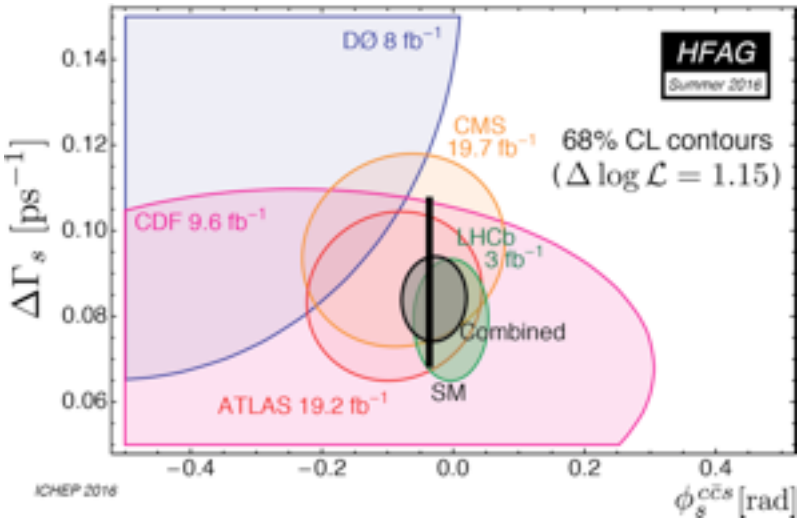


3. Null tests of the SM in $\Delta F = 2$. $B_s \rightarrow J/\Psi\Phi$

- Penguin pollution is well under control for the present available statistics
- Gathering statistics and adding modes is the key point on this subject.



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[illegible]	[illegible]
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[illegible]	[illegible]

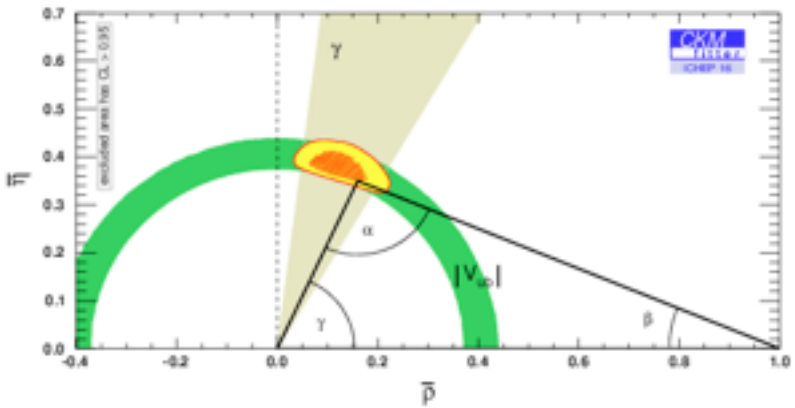


3. BSM constraints in $\Delta F = 2$ transitions.

- BSM contributions in mixing processes can be accounted for by means of new phase and modulus both in *Bd* and *Bs* system, provided that the CKM unitarity preserved.

$$\langle B_q | \mathcal{H}^{\rm SM+NP}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{\rm SM}_{\Delta B=2} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$



- Lenz, Nierste & CKMfitter PRD83:036004, following exploratory works from:

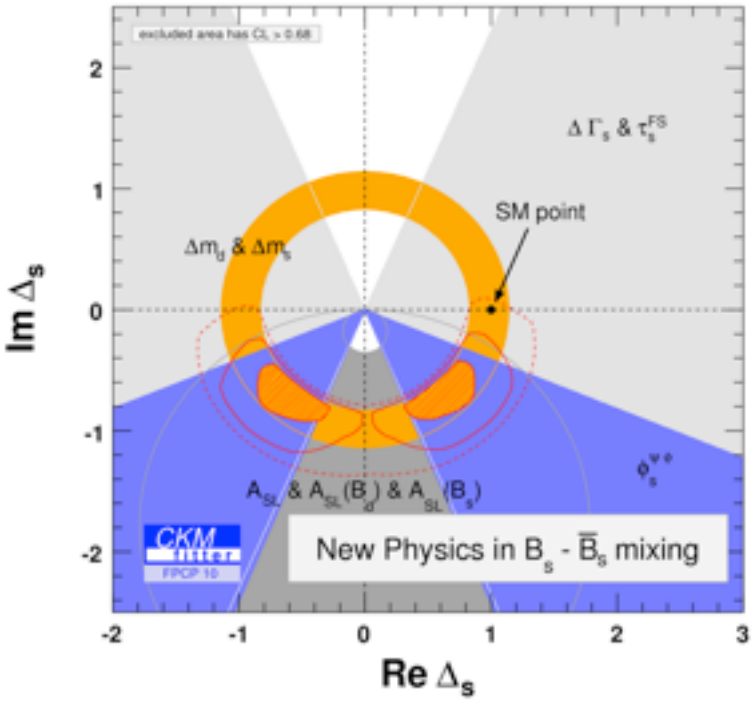
Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)

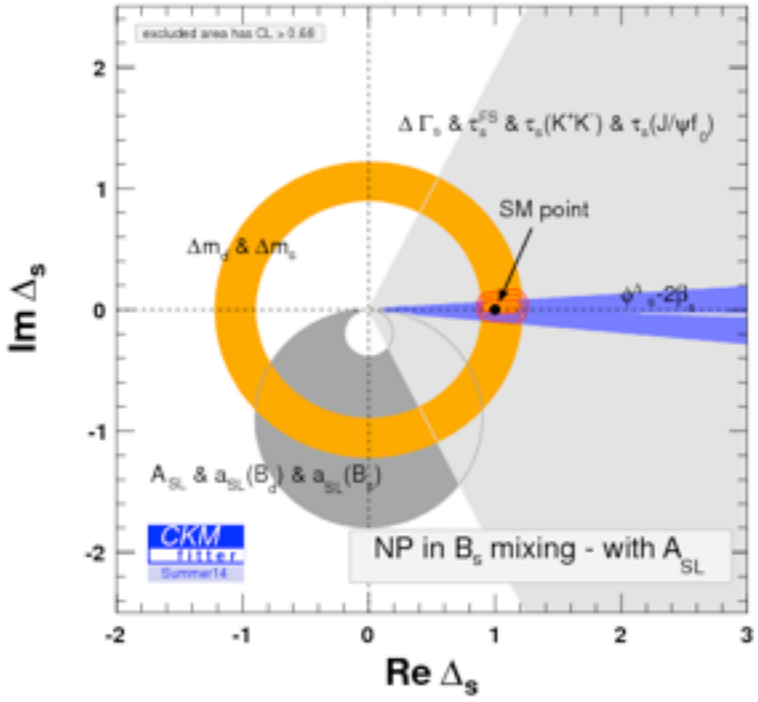
Goto et al., PRD 53, 6662 (1996)

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\rm NP}\rvert \times \Delta m_q^{\rm SM}$
2β	$2\beta^{\rm SM} + \Phi_d^{\rm NP}$
$2\beta_s$	$2\beta_s^{\rm SM} - \Phi_s^{\rm NP}$
2α	$2(\pi - \beta^{\rm SM} - \gamma) - \Phi_d^{\rm NP}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\rm SM}} \times \frac{\sin(\Phi_{12,q}^{\rm SM}+\Phi_q^{\rm NP})}{\lvert\Delta_q^{\rm NP}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP})$

3. BSM constraints in $\Delta F = 2$ transitions.

- Implications of LHCb results:





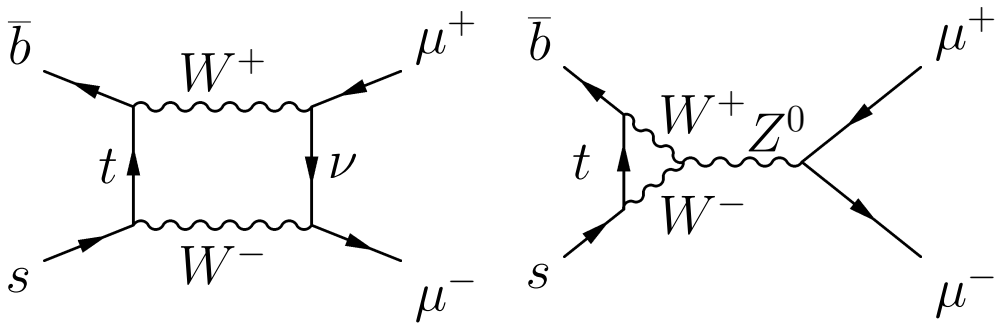
- The SM hypothesis is now (2 d.o.f.): 0.3 σ

- But don't infer a wrong statement: sizeable BSM contributions are still allowed by the LHCb constraints in both B_d and B_s mixing.

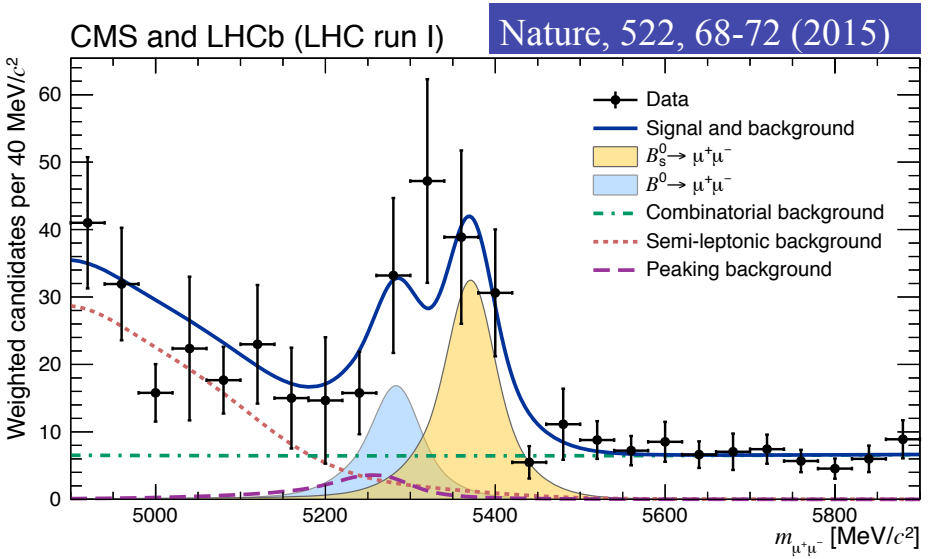
4. Searching for BSM Physics in $\Delta F = 1$ quark transitions.

4. Search for BSM in $\Delta F = 1$. $B(B^{(0)}_s \to \mu\mu)$

- Helicity-suppressed FCNC transitions, theoretically clean.
- Well-suited to search for BSM contributions in box or electroweak penguins.
- ATLAS, CMS and LHCb searched for these decays.
- Combined LHCb and CMS Run I analyses yielding the first observation of $B_s \to \mu\mu$

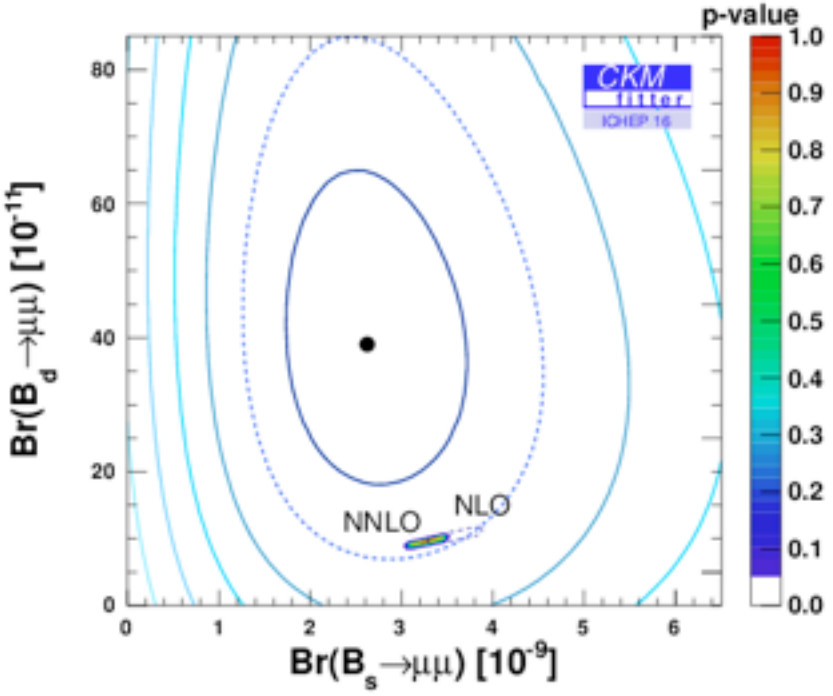


$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \cdot 10^{-10}$$



4. Search for BSM in $\Delta F = 1$. $B(B^{(0)}_s \to \mu\mu, \tau\tau)$

- So far, the measurements are consistent w/ the SM predictions.
- More to come w/ the Run II data, in particular for $B^0 \to \mu\mu$, where an excess of events is seen in its invariant mass region.
- The search for $B_s \to \tau\tau$ is another quest. Experimentally very challenging. A world best limit has been placed.
- A high luminosity Z factory can be the place for that search.



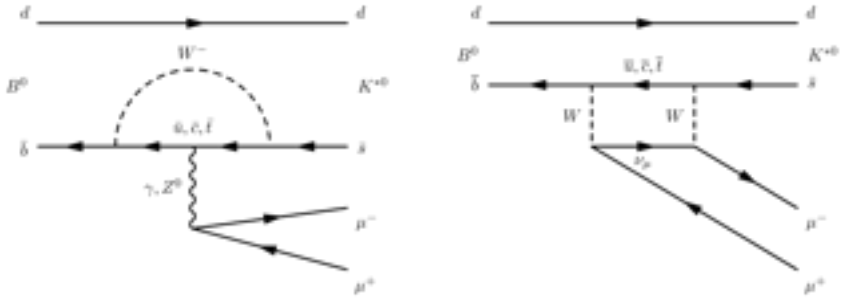
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$$

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 2.4 \cdot 10^{-3} \ @\ 90\%\ \text{C.L.}$$

4. Search for BSM in $\Delta F = 1$. $B^0 \rightarrow K^*\mu\mu$

- The decay $B^0 \rightarrow K^*\mu\mu$ proceeds solely through loop processes in the SM (box and electroweak penguin diagrams) and features interferences between the following operators / diagrams.

$$\mathcal{O}_{7,\gamma} + \mathcal{O}_{9,10}$$

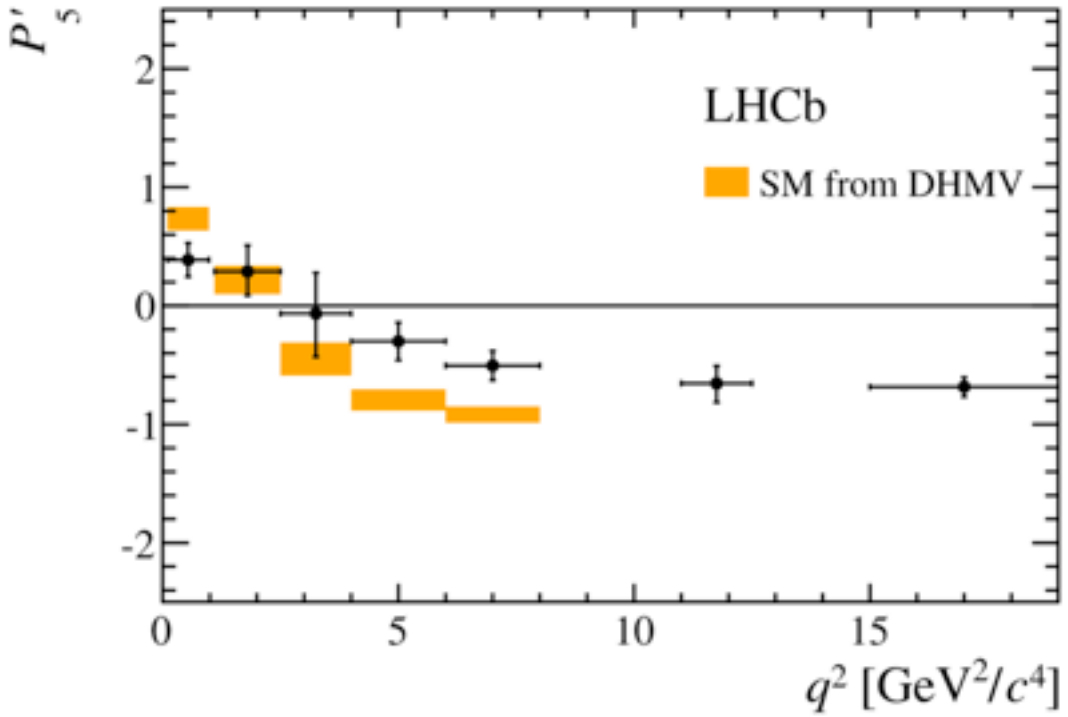


- The angular analysis of the final state $K^*\mu\mu$ brings many observables which have been designed to minimize the theoretical hadronic uncertainties.

- BSM contributions, opposite to SM, can appear at tree level, in loops and as right-handed chiralities couplings.

4. Search for BSM in $\Delta F = 1$. $B^0 \rightarrow K^*\mu\mu$

- Among the ~ten angular observables, there is this one:



- showing more than 3 standard deviations w.r.t. the SM prediction.

- The 2011 tension survived to the analysis of 2012 data. These results are supported (with less statistical power though) by Belle II measurement.

4. Search for BSM in $\Delta F = 1$. R_K

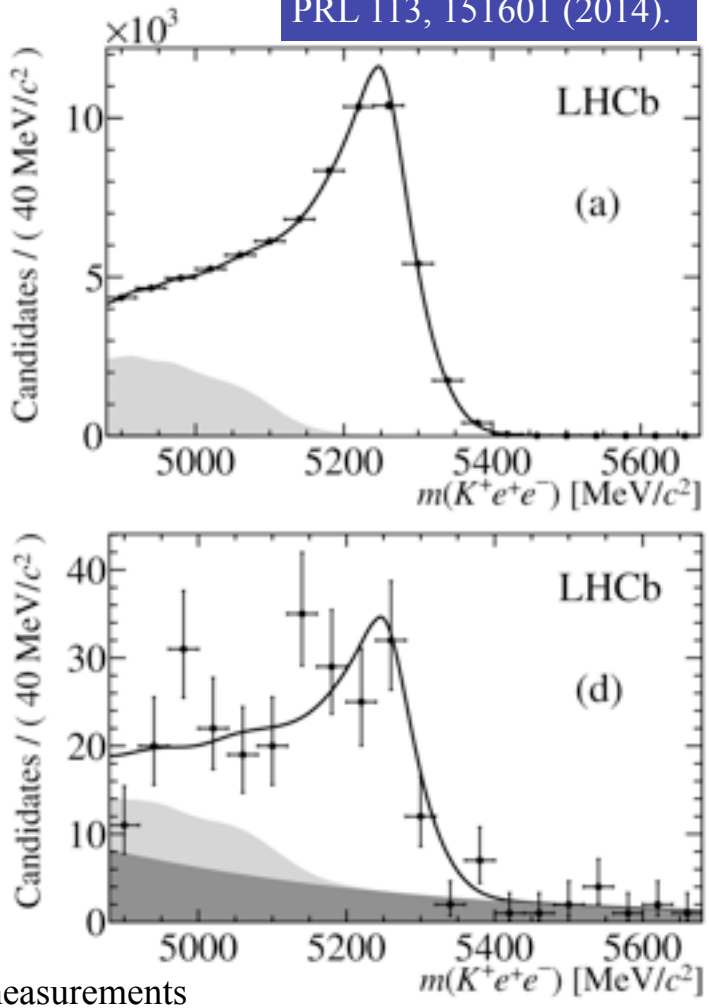
- Search for lepton universality violation in *b* quark transitions by comparing the differential branching fractions of $B^0 \to K\mu\mu$ and $B^0 \to Kee$. Tested at the few percents level with $B \to Kl\nu_l$.

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma(B^0 \to K\mu^+\mu^-)}{\mathrm{d}q^2} \cdot \mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma(B^0 \to Ke^+e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

  - $q^2 < 6$ GeV^2 explored.
  - Normalization to $B^0 \to \Psi(2S)K$
  - Challenge is the electron mode.
  - 2.6 standard deviations apart SM.

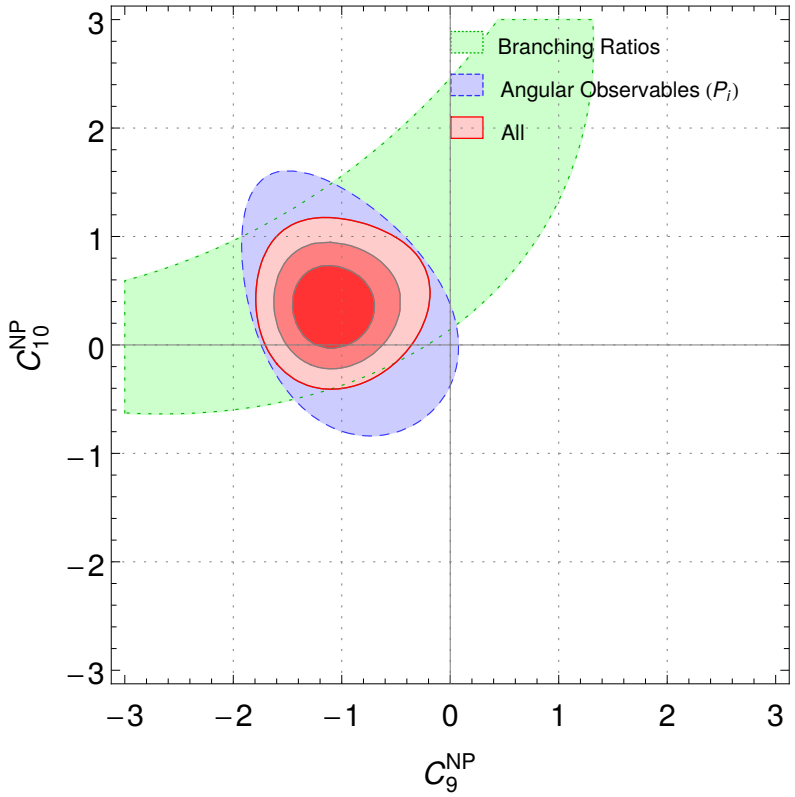
$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

PRL 113, 151601 (2014).



4. Search for BSM in $\Delta F = 1$. All EWP.

- Similar electroweak penguin modes are searched for and their differential branching fractions and angular properties are scrutinized.



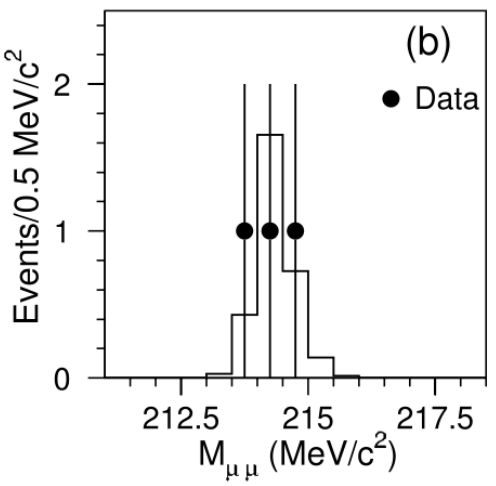
JHEP 06 (2016) 092.

- Interpretations of the tensions likely in Jean Orloff's talk.

4. Search for BSM in $\Delta F = 1$. $\Sigma^+ \to p\mu\mu$

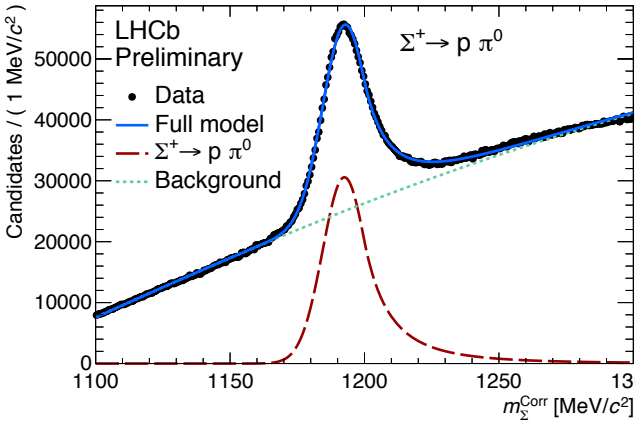
- Longstanding hint from HyperCP experiment of a low mass $\mu\mu$ resonance in the decay $\Sigma^+ \to p\mu\mu$.
- LHCb has searched for it. Experimentally challenging in reason of the Phase Space of the decay and the lifetime of the Σ^+($c\tau$ = 2.4 cm).
- Evidence for the decay has been obtained but the HyperCP result is not confirmed.

PRL, 021801 (1994).

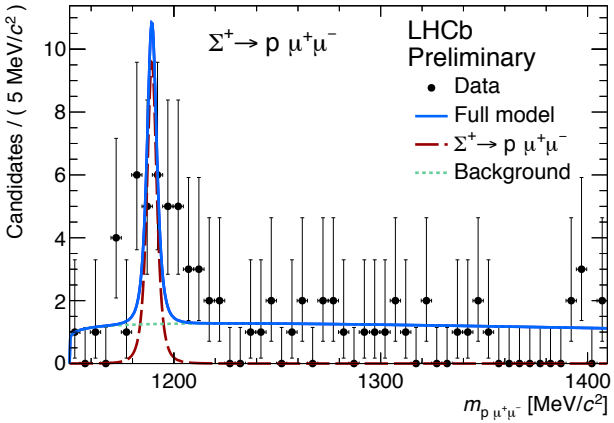


LHCb-CONF-2016-013

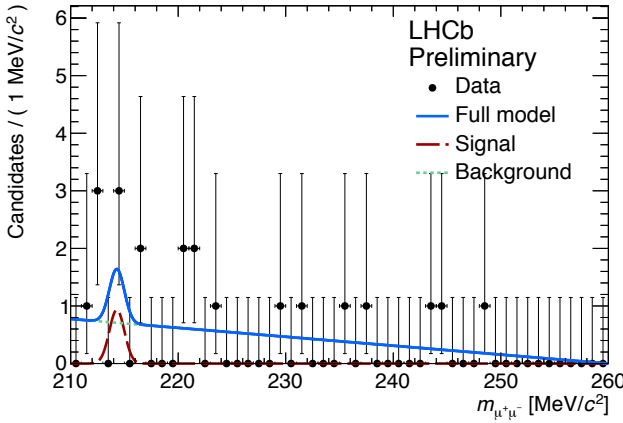
Normalization



Signal



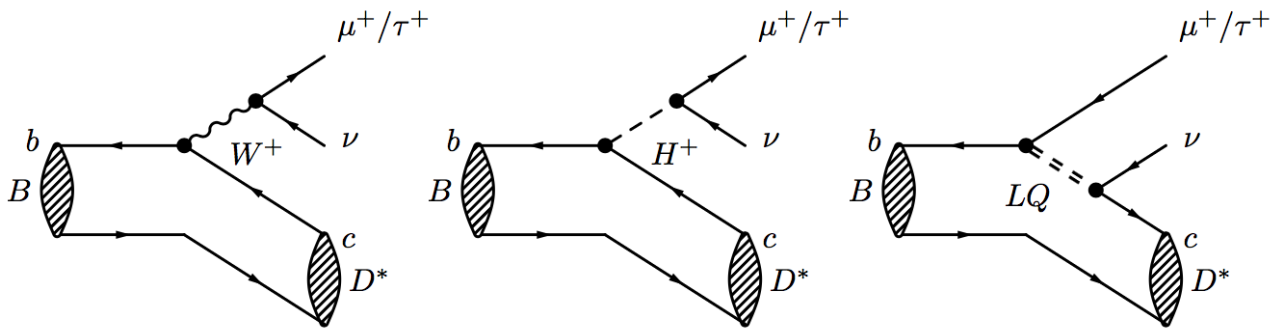
Background subtracted



5. Searching for BSM Physics in tree-mediated processes.

5. Searching for BSM Physics in trees

- Search for lepton universality violation in tree-level quark transitions by comparing branching fractions of $B^0 \to D^* \tau \nu_\tau$ and $B^0 \to D^* \mu \nu_\mu$.



- Theoretically clean:

$$R(D^*)^{SM} = \frac{BR(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = 0.252 \pm 0.003$$

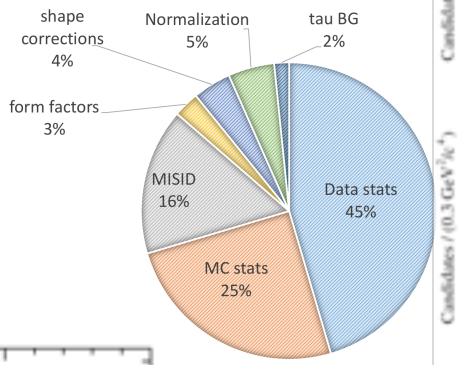
- Experimentally very challenging: large background from partially reconstructed *B* decays, missing neutrinos reconstructed w/ the direction of the *B* momentum constraint from the Velo ...

5. Searching for BSM Physics in trees

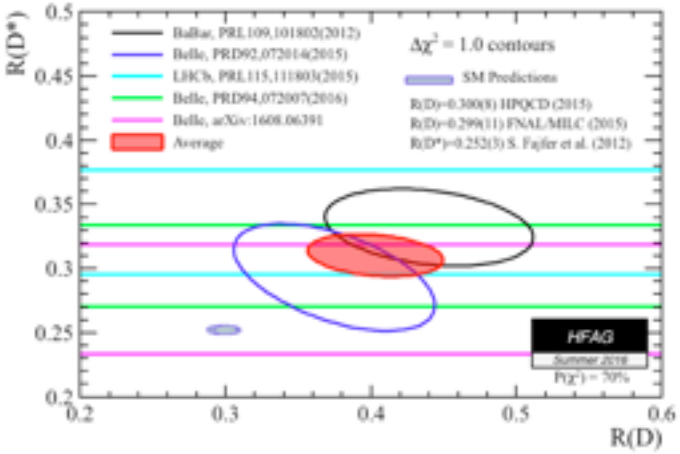
- Result:

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

- Uncertainty budget:

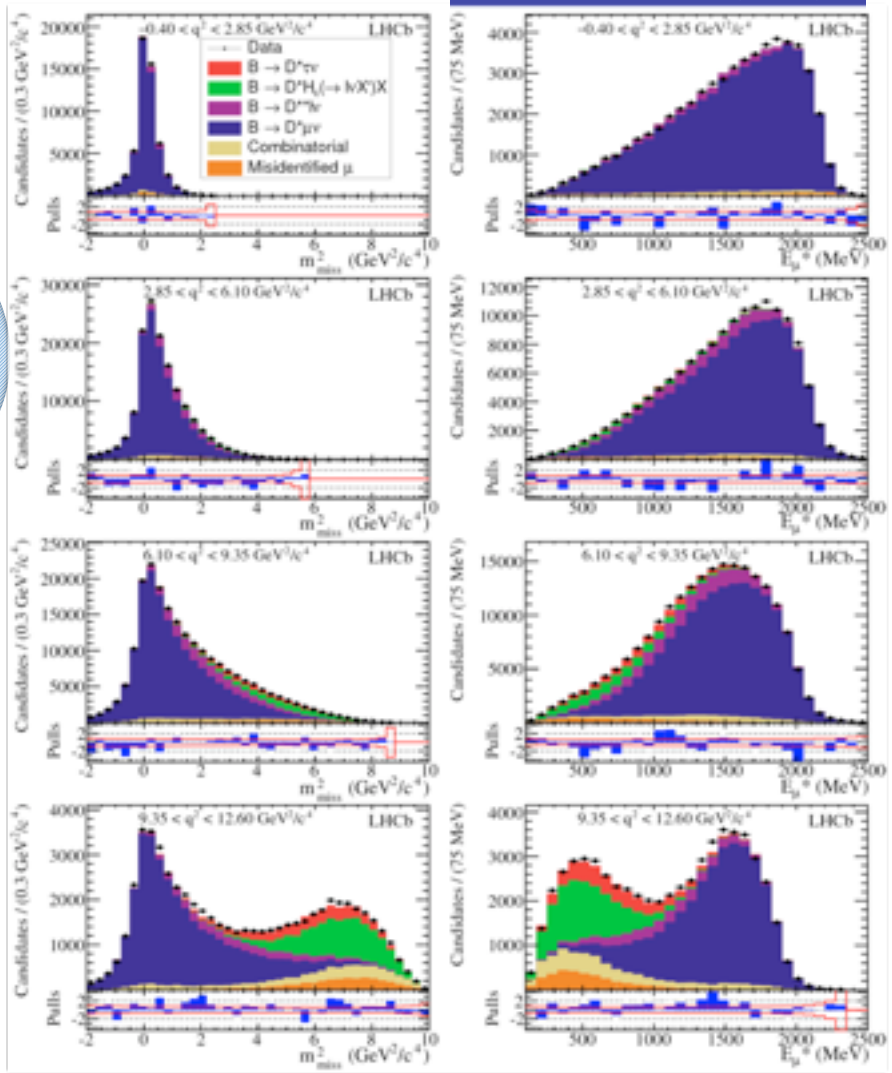


- Comparison:



- Many more ratios in preparation.

PRL 115, 111803 (2015).



X. Not covered

- Spectroscopy: *e.g.* tetra- and penta-quarks
- Charm mixing and search for *CP*V in charm
- Electroweak probes of QCD.
- Multibody hadronic charmless decays.
- Exoticas.
- ...

6. Summary

6. Summary

- LHCb provides a harvest of world best quark flavour physics measurements.
- Major contributions to the CKM profile : γ angle, $|V_{ub}|$
- No hint of BSM in clean laboratories: $B_s \to \mu^+\mu^-$, $B_s \to J/\Psi\Phi$ ...
- Some measurements are in tension with the SM at places where either QCD or experiments are challenged:

  $B^0 \to K^*(892)\mu^+\mu^-, R_K$, $B^0 \to D^*\tau\nu_\tau$ ...

- Key analyses based so far on LHC Run I data. Significant updates and new analyses with LHC Run II data to come.