Physics of Flavour

- Off-shell searches
- LHCb
- Anomalies
- Fits

(Picture from November 2005)

06/11/2019 — Imperial College HEP Seminar

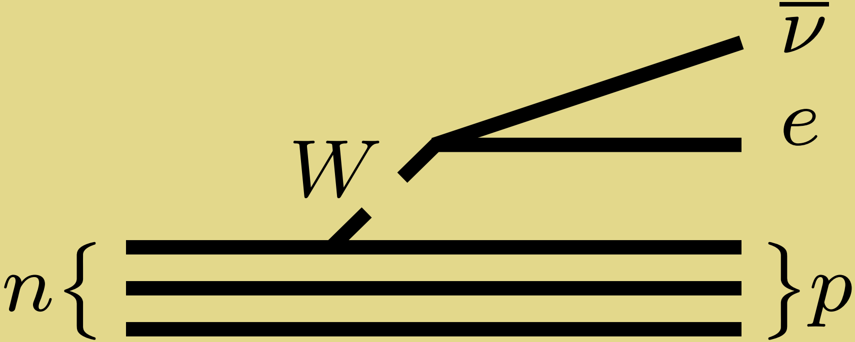
Patrick Koppenburg

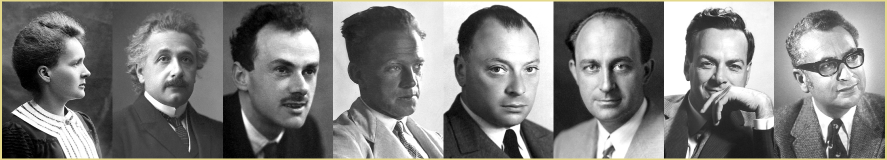
Nikhef

BLUF — Bottom Line Up Front

- ✗ **Lepton flavour violation is not seen**
- ✔ **There is a pattern of 2–4σ deviations in lepton flavour universality tests**
  - **Hints of something new?**
  - **Something else not understood?**
  - → **Upgraded LHCb and Belle II will check**

Nuclear β decay

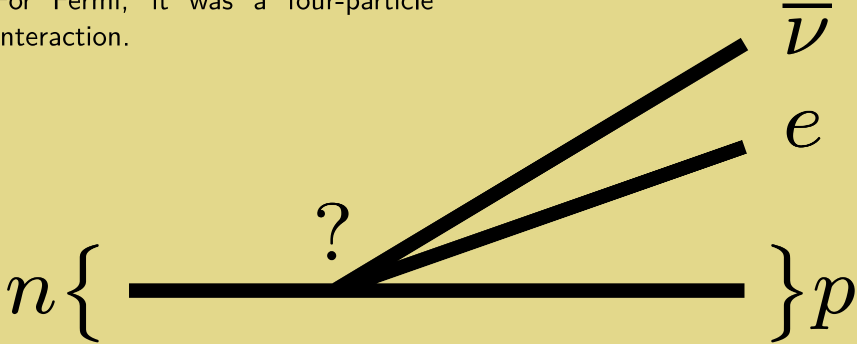


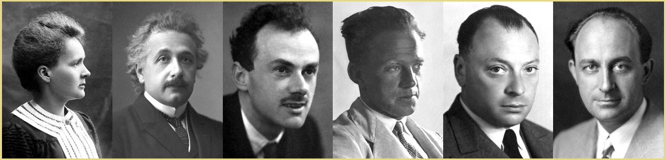


Curie Einstein Dirac Heisenberg Pauli Fermi Feynman Gell-Mann

Nuclear β decay

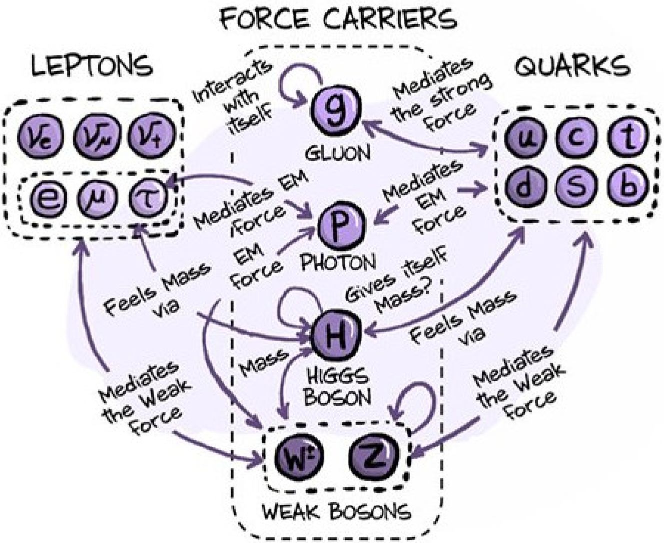
For Fermi, it was a four-particle interaction.





Curie Einstein Dirac Heisenberg Pauli Fermi

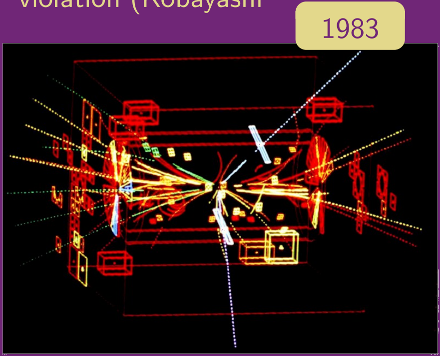
Particle Interactions



Precision Measurements

Sensitive to "New" Physics effects off-shell

- When was the Z discovered?
  - 1973 from $\nu N \to \nu N$
  - 1983 at SpS collider?
- c quark needed to explain $K^0_\mathrm{L} \to \mu^+\mu^-$ (GIM)
- Third family (b,t) to explain CP violation (Kobayashi & Maskawa)



Generic New Physics Amplitude:

$$\mathcal{A} = \mathcal{A}_0 \left(\frac{C_\mathrm{SM}}{M_W^2} + \frac{C_\mathrm{NP}}{\Lambda^2} \right)$$

➜ Sensitive to very high NP scales Λ

Precision Measurements

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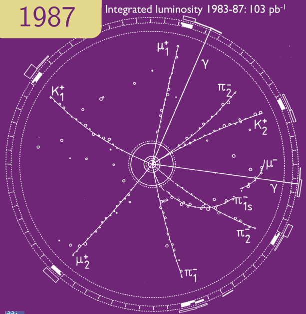
✔ Estimate masses
  - t quark from $B\overline{B}$ mixing
  - ✔ Much larger mass coverage than $\sqrt{s}$

✔ Get phases of couplings
  - Half of new parameters
  - Needed for a full understanding

- Look in lepton and **flavour** sectors
  - ➜ CP asymmetry in the Universe

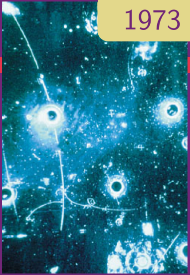
1973

1987



Precision Measurements

1973

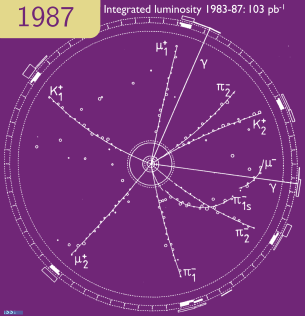


Where to look?

Need three ingredients:

1. **Precise SM prediction**
2. **(desirable) Precise beyond-SM predictions**
3. **Good experimental precision**

1987



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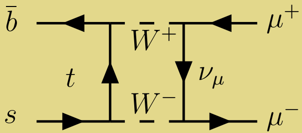
Check out my Scholarpedia article on Rare Decays. [Scholarpedia 32643]

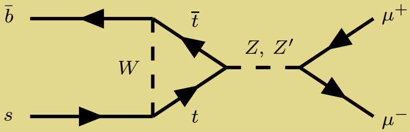
$B_s^0 \to \mu^+\mu^-$

Very rare decay, well described in the SM

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (3.57 \pm 0.17) \cdot 10^{-9}$$

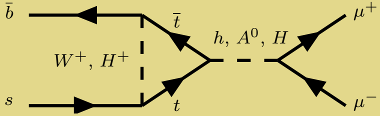
[Beneke, Bobeth, Szafron], [Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser, PRL 112, 101801 (2014)], [De Bruyn, Fleischer, Knegjens, PK, Merk, Pellegrino, Tuning, PRL 109, 041801 (2012)] ...



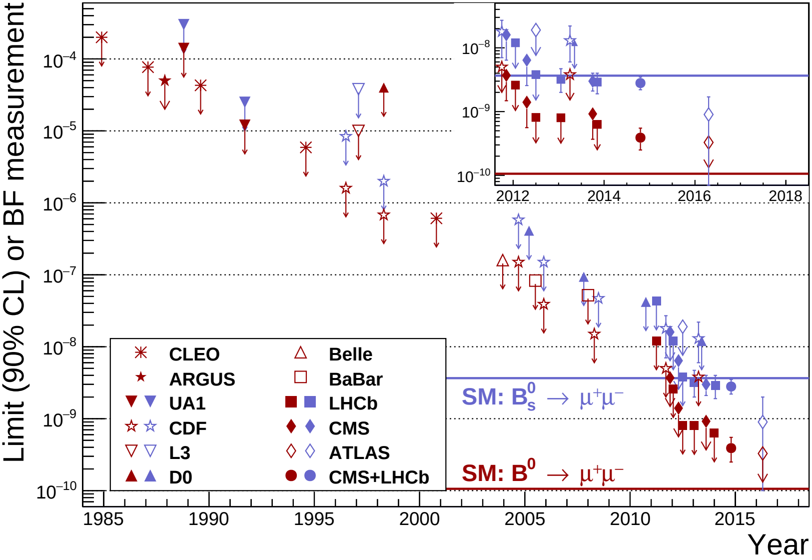


Very sensitive to NP, e.g. Minimal supersymmetric Models:

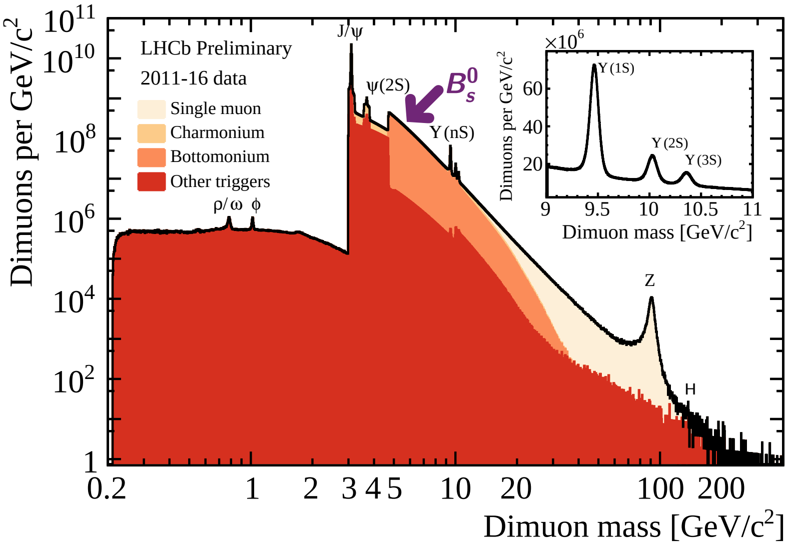
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{MSSM}} \propto \frac{m_b^2 m_\ell^2 \tan^6\beta}{m_A^4}$$



$B_s^0 \to \mu^+\mu^-$ Limits History

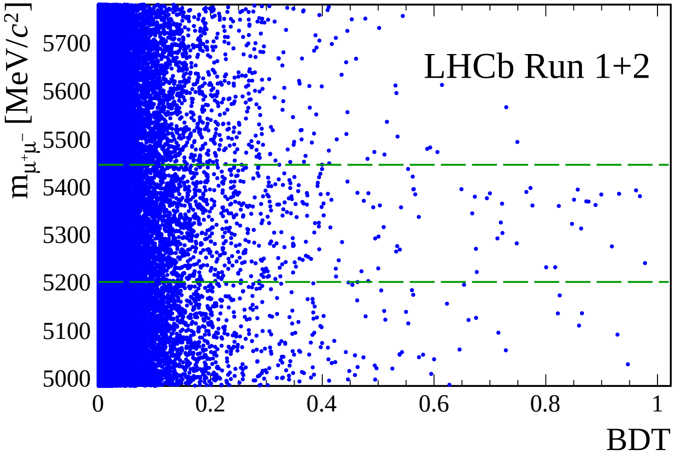


Dimuon mass distribution



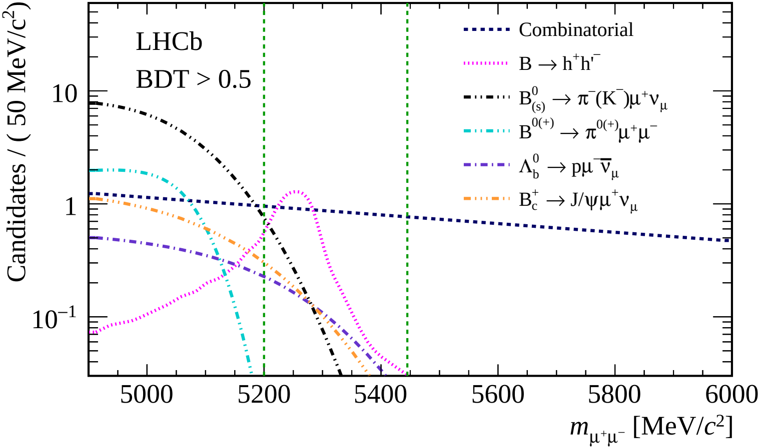
[LHCb, Phys. Rev. Lett. 118 (2017) 191801, arXiv:1703.05747]

Observation of the decay $B_s^0 \to \mu^+\mu^-$



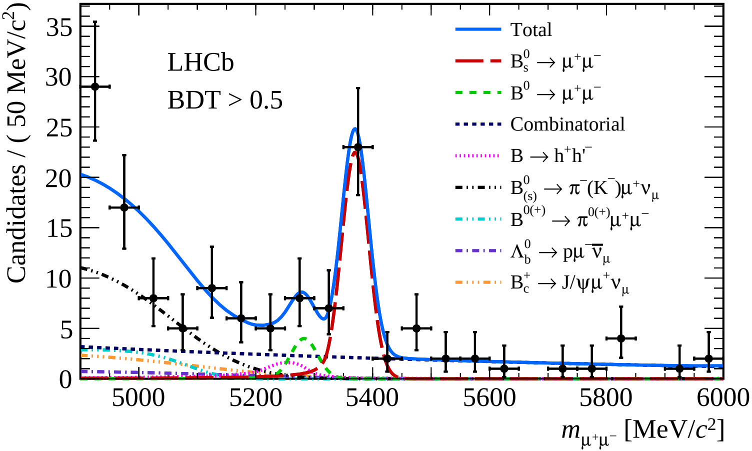
A $B \to \mu^+\mu^-$ search using 2011–2016 data ($4.4\,\text{fb}^{-1}$) is done with a mass fit in bins of BDT output.

Observation of the decay $B_s^0 \to \mu^+\mu^-$



The BDT is optimised to fight combinatorial and specific backgrounds.

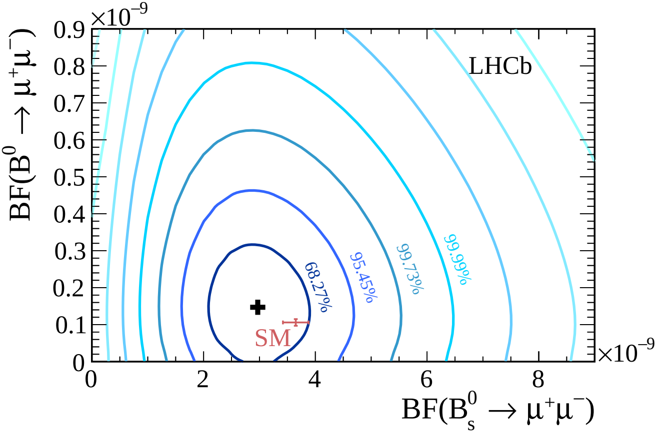
Observation of the decay $B_s^0 \to \mu^+\mu^-$



Mass plot shows candidates with BDT>0.5.

The significances are 7.8σ for $B_s^0 \to \mu^+\mu^-$ and 1.6σ for $B^0 \to \mu^+\mu^-$.

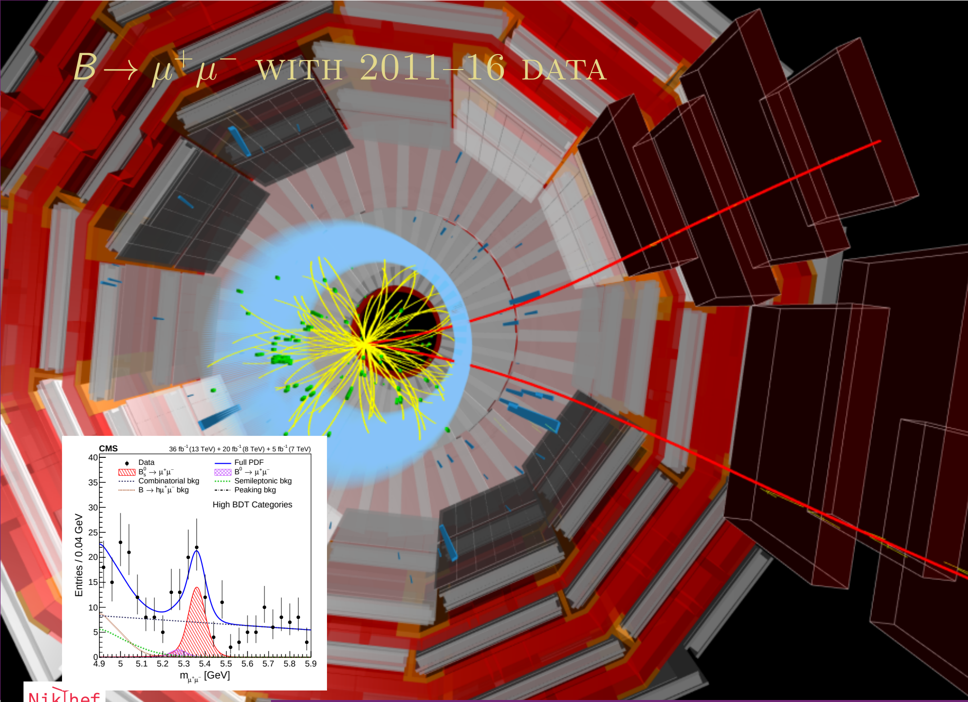
Observation of the decay $B_s^0 \to \mu^+\mu^-$



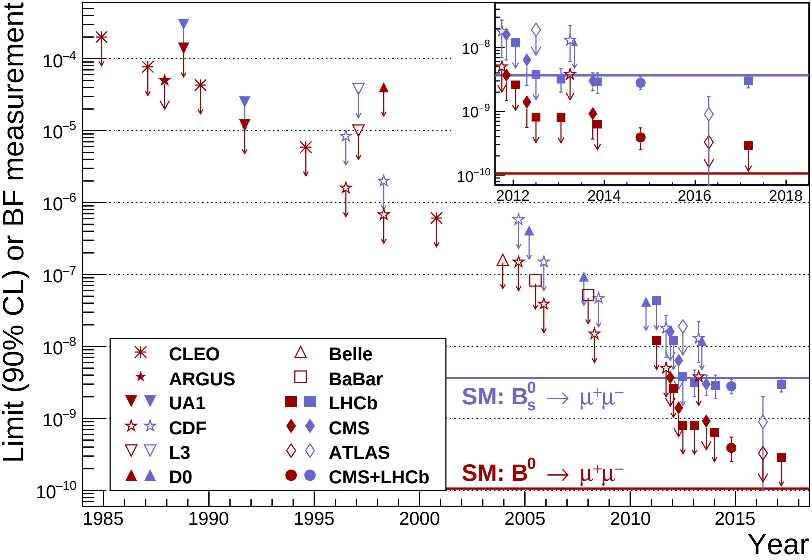
The results $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$ are consistent with the SM.

[Bobeth et al., PRL 112 101801 (2014)]

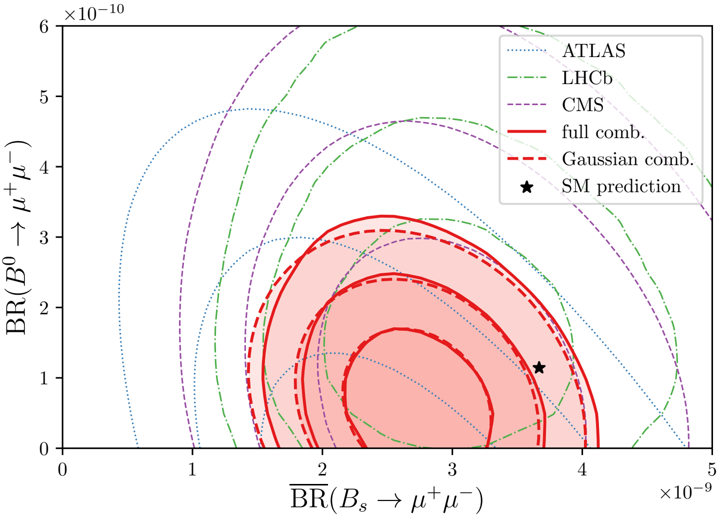
$B \to \mu^+\mu^-$ WITH 2011–16 DATA



$B_s^0 \to \mu^+\mu^-$ RACE TOWARD THE SM



$B \to \mu^+\mu^-$ after Summer 2019



Thanks to David Straub for the updated plot

[PRL 118 (2017) 191801] [ATLAS JHEP 04 (2019) 098] [CMS, arXiv:1910.12127]

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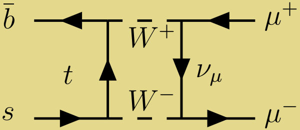

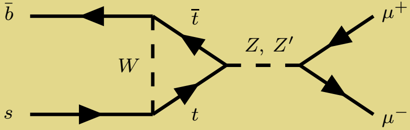

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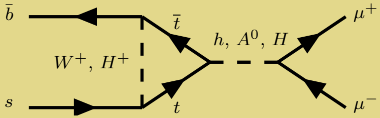
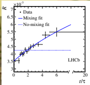
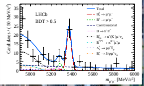


LHCb Physics Programme

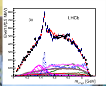
CKM and *CP* violation with *b* and *c* hadrons

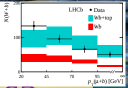


Rare decays of *b* hadrons and *c* hadrons

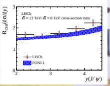


Spectroscopy in *pp* interactions and *B* decays

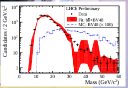




Electroweak and QCD measurements in the forward acceptance



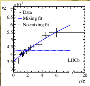
Heavy quark production



Exotica searches

LHCb Physics Programme

CKM and *CP* violation with *b* and *c* hadrons



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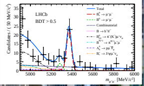

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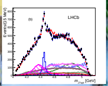

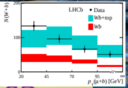

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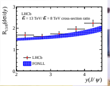

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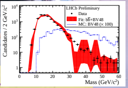
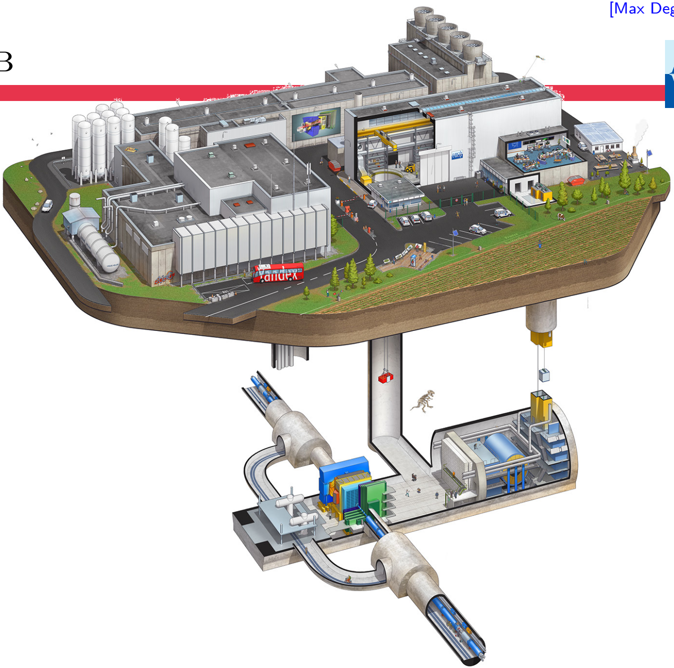


Exotica searches

[Max Degtyarev (2019)]

LHCb



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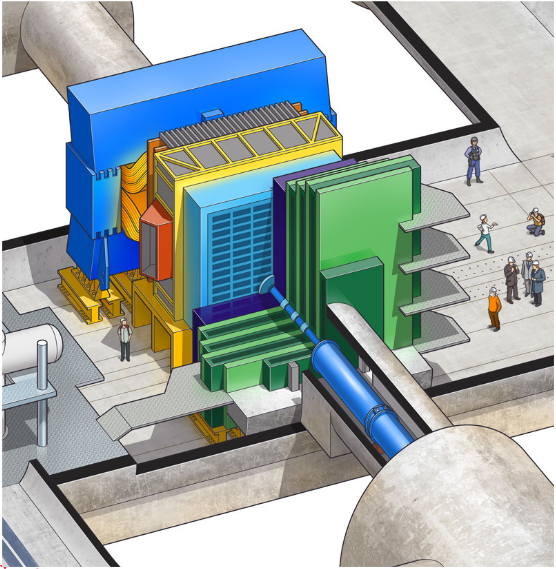

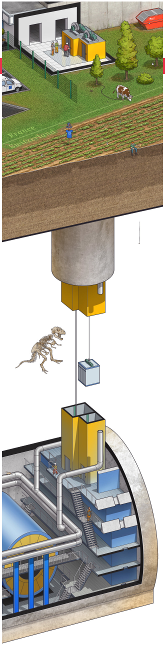

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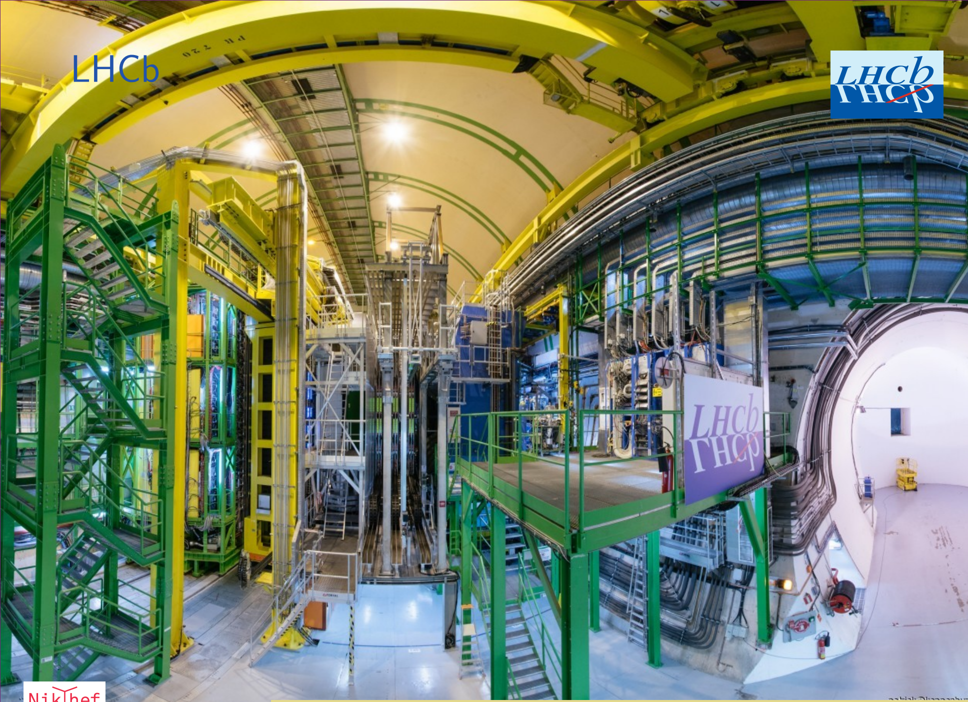

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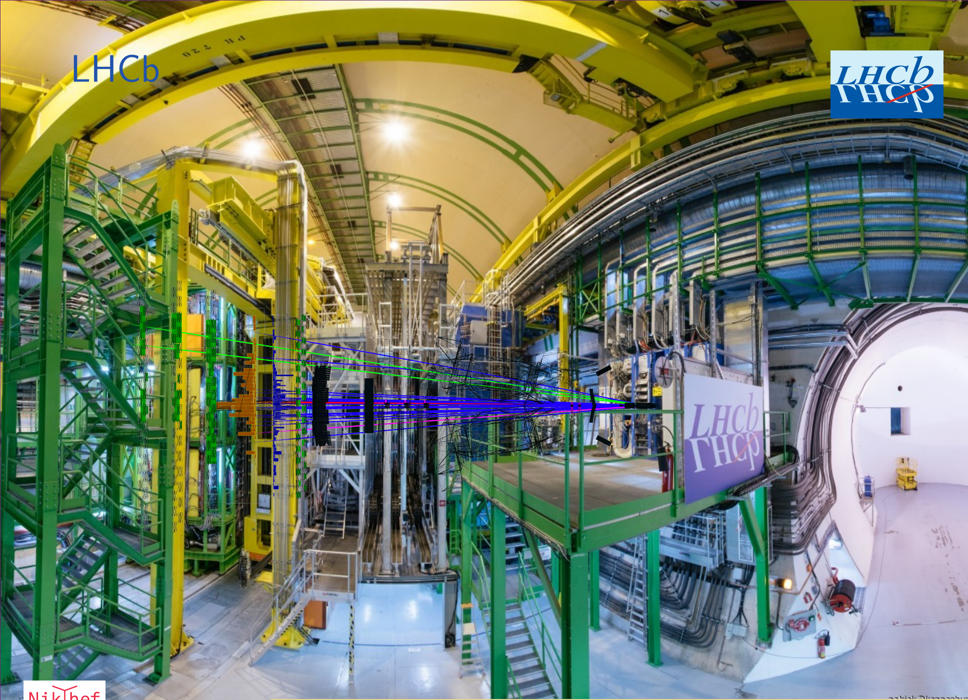
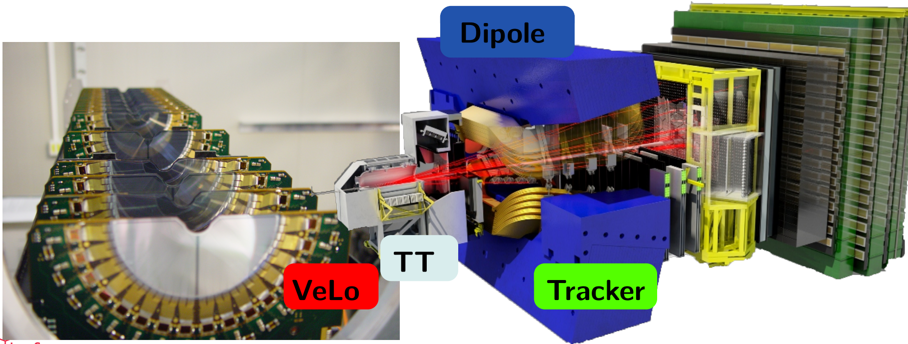


LHCb Detector

Forward detector: many b hadrons produced forward at LHC, $(144 \pm 1 \pm 21)$ μb in acceptance at 13 TeV [PRL 118 (2017) 052002]

- Warm dipole magnet. Polarity can be reversed
- ✔ Good momentum and position resolution
  - Vertex detector gets 8mm to the beam



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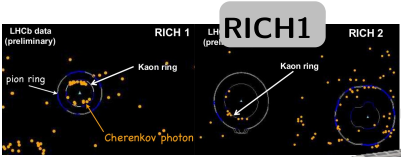
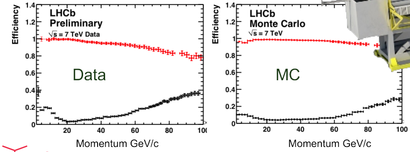
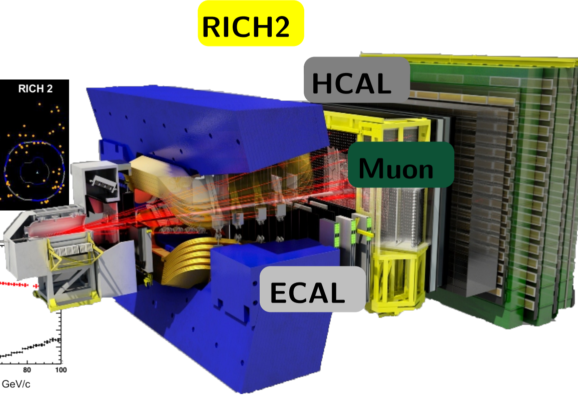
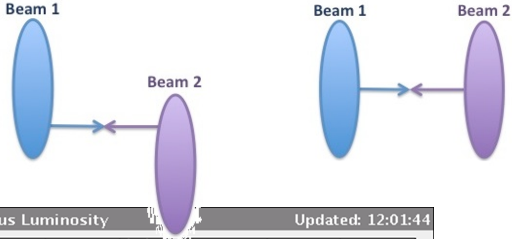
- Warm dipole magnet. Polarity can be reversed
- ✔ Good momentum and position resolution, high efficiency
- ✔ Excellent Particle ID

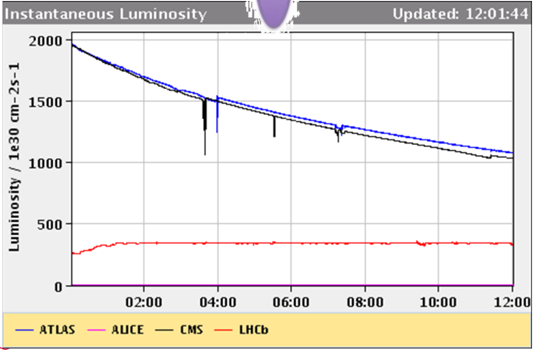




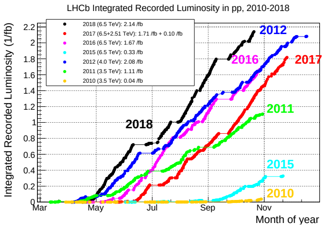


Luminosity levellling

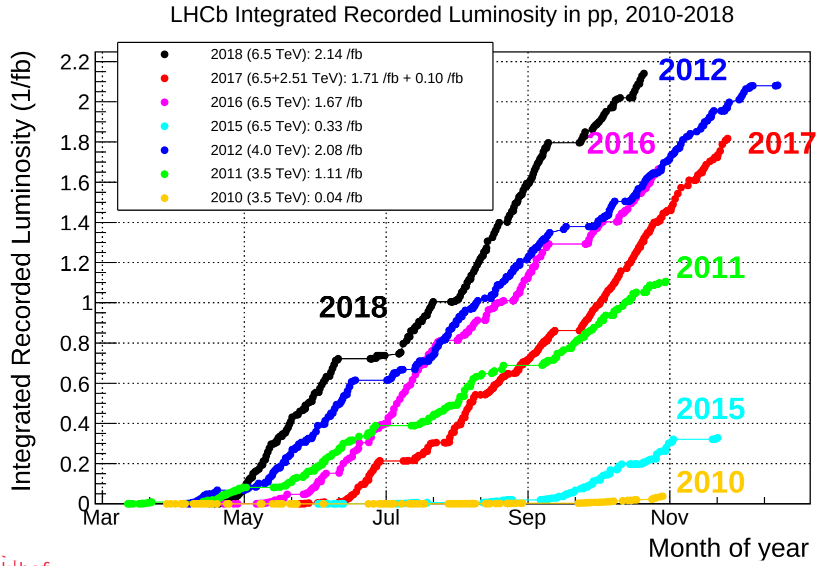




Beams are offset in real time to keep a constant luminosity



Integrated luminosity



LHCb Trigger in Run 2

LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Defer 20% to disk

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

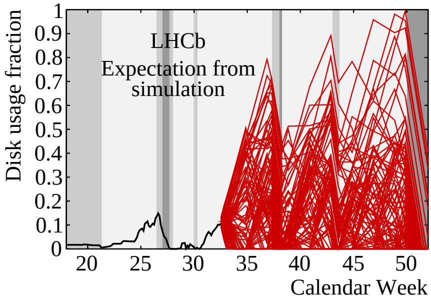
12.5 kHz (0.6 GB/s) to storage

LHCb Trigger in Run 2

Events are buffered on disk (10 PB) while calibrations are being run.

➜ Offline-quality trigger objects available for analysis.

- Disk ➜ more CPU. The full reconstruction can also be run during LHC downtime.



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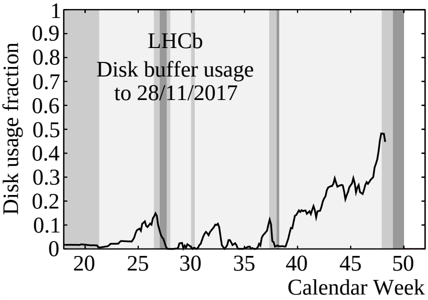
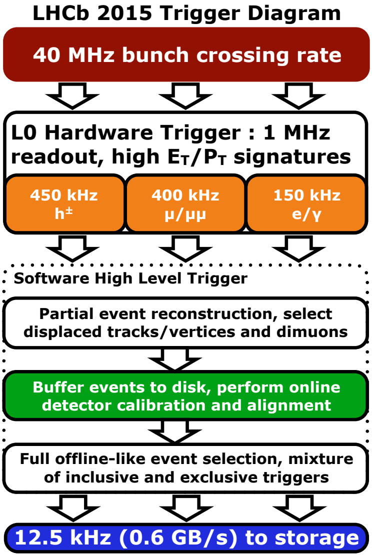
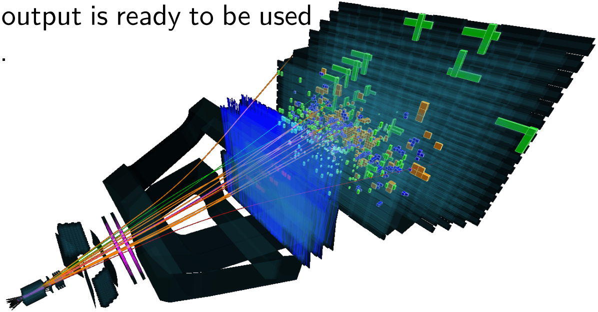




TURBO

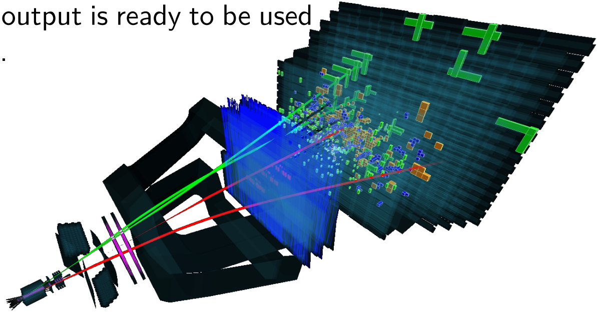
We perform a full calibration in real time. The output is ready to be used for physics.



Plenty of collision events discarded, while the interesting are kept.

TURBO

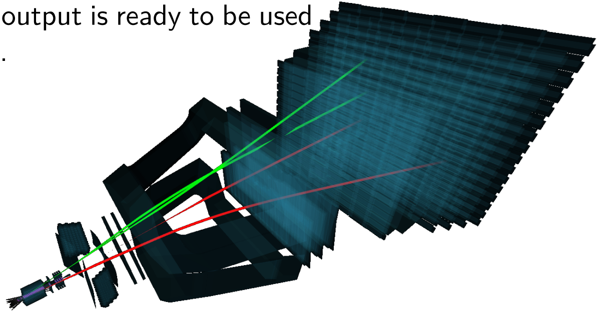
We perform a full calibration in real time. The output is ready to be used for physics.



TURBO then stores only the information needed for the analysis
➜ Huge savings in time and cost

TURBO

We perform a full calibration in real time. The output is ready to be used for physics.



TURBO then stores only the information needed for the analysis
➜ Huge savings in time and cost

Flavour Anomalies

Most Cited hep-ex 2019 preprints

1. **Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$**
(95) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Apr 8, 2019. 11 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.22, 222001**
LHCb-PAPER-2019-014 CERN-EP-2019-058
DOI: 10.1103/PhysRevLett.122.222001
e-Print: **arXiv:1904.03947 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to SYMMETRY; Link to Fulltext from Publisher; Link to Article from SCOAP3
Data: INSPIRE | HepData
Detailed record - Cited by 95 records 50+

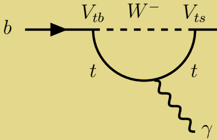
2. **Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays**
(89) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Mar 21, 2019. 13 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.19, 191801**
LHCb-PAPER-2019-009, CERN-EP-2019-043, LHCb-PAPER-2019-009 CERN-EP-2019-043
DOI: 10.1103/PhysRevLett.122.191801
e-Print: **arXiv:1903.09252 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Fulltext from Publisher; Link to Article from SCOAP3
Detailed record - Cited by 89 records 50+

3. **Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method**
(58) Belle Collaboration (A. Abdesselam (Tabuk, Coll. Technol.) *et al.*). Apr 18, 2019. 12 pp.
e-Print: **arXiv:1904.08794 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 58 records 50+

4. **Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report**
(47) J. Beacham (Ohio State U., Columbus (main)) *et al.*. Jan 20, 2019. 150 pp.
CERN-PBC-REPORT-2018-007
e-Print: **arXiv:1901.09966 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 47 records

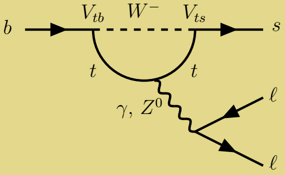
5. **Test of lepton flavor universality in $B \to K^*\ell^+\ell^-$ decays at Belle**
(46) Belle Collaboration (A. Abdesselam (Tabuk, Coll. Technol.) *et al.*). Apr 4, 2019. 8 pp.
BELLE-CONF-1901
e-Print: **arXiv:1904.02440 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 46 records

$b \to s\ell^+\ell^-$



- Start with $b \to s\gamma$, the first observed penguin decay

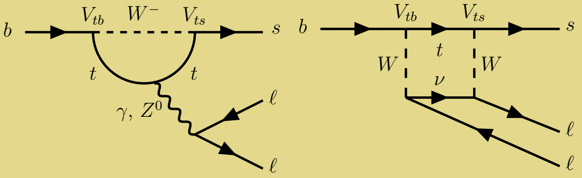
$b \to s\ell^+\ell^-$



- Start with $b \to s\gamma$, pay a factor α_{EM}
  - ➜ Decay the γ into 2 leptons

See e.g. [PK, Scholarpedia, arXiv:1606.00999]

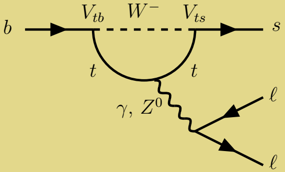
$b \to s\ell^+\ell^-$

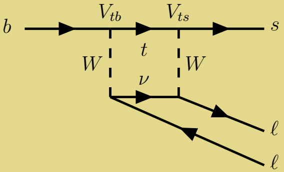


- Start with $b \to s\gamma$, pay a factor α_{EM}
  - ➜ Decay the γ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to s\ell^+\ell^-$, very rare in the SM
    $\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.8 \pm 0.2) \cdot 10^{-6}$

    [Huber et al., Nucl.Phys.B802:40-62,2008]

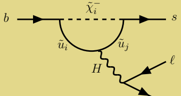
$b \to s\ell^+\ell^-$

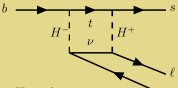


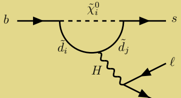


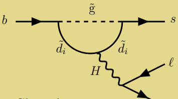
- Start with $b \to s\gamma$, pay a factor α_{EM}
  - ➜ Decay the γ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to s\ell^+\ell^-$, very rare in the SM
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Leptoquarks, Axions . . .

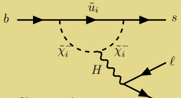
✔ Ideal place to look for new physics


Chargino loop

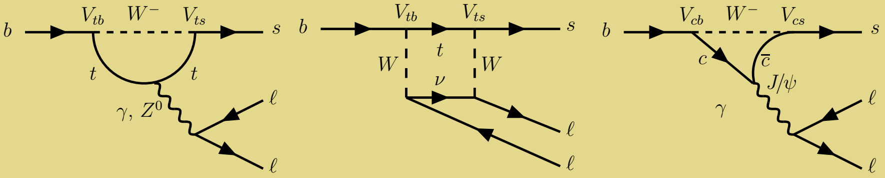

Higgs box


Neutralino loop

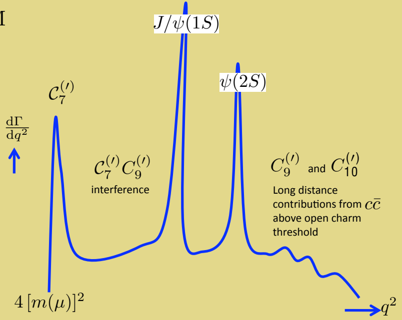

Gluino loop


Chargino loop

$b \to s\ell^+\ell^-$



- Start with $b \to s\gamma$, pay a factor α_{EM}
  - ➜ Decay the γ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to s\ell^+\ell^-$, very rare in the SM
- ✗ But beware of long-distance effects:
  - Tree $b \to c\overline{c}s$, $(c\overline{c}) \to \ell\ell$
  - ✔ Can be removed by mass cuts
  - ✗ ✔ Interferes elsewhere



(c) Jaeger

Flavour Anomalies

Search for lepton flavour universality violation in $B^+ \to K^+\ell^+\ell^-$ decays

Paula Álvarez Cartelle

HEP seminar,
Imperial College London

June 26, 2019

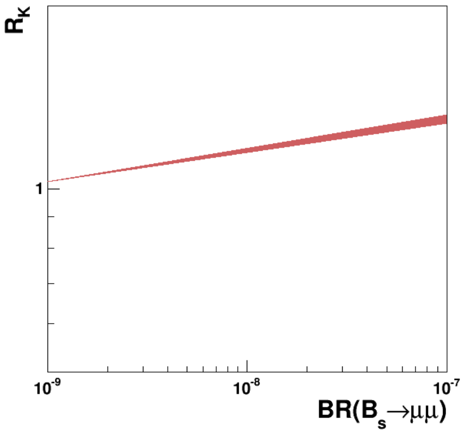
Lepton Universality in $b \to s\ell^+\ell^-$

$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \mathrm{d}q^2 \frac{d\Gamma\left(B\to X\mu^+\mu^-\right)}{\mathrm{d}q^2}}{\int_{q^2_{min}}^{q^2_{max}} \mathrm{d}q^2 \frac{d\Gamma(B\to Xe^+e^-)}{\mathrm{d}q^2}}$$

$$\boxed{R_K - 1 \propto \mathcal{B}(B^0_s \to \mu^+\mu^-)}$$

Assuming:

- Right-handed currents negligible
- (Pseudo-)scalar couplings $\propto m_\ell$,
- No *CP* phases beyond the SM

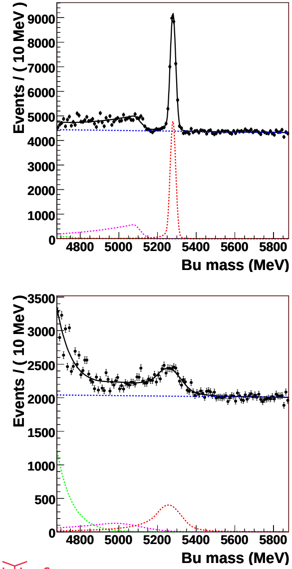


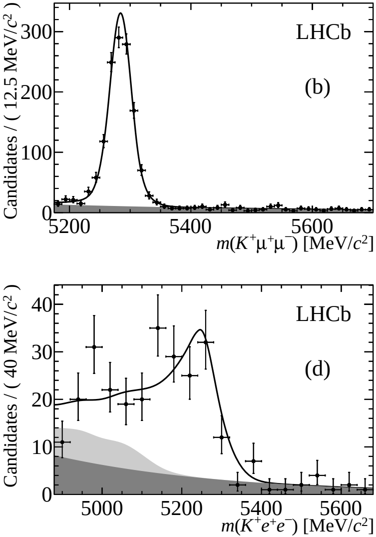
[Hiller & Krüger, PRD69 (2004) 074020]

[LHCb, Phys. Rev. Lett. 113 (2014) 151601, arXiv:1406.6482]

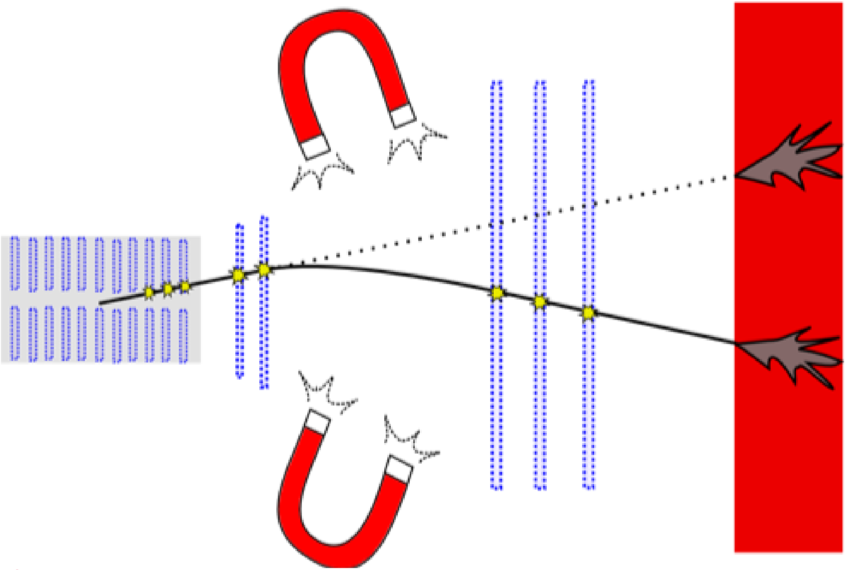
R_K History

[Note LHCb-2007-034]





Bremsstrahlung correction



Lepton Universality in $B^+ \to K^+\ell^+\ell^-$

Using 2011–12 and 2016 data we get

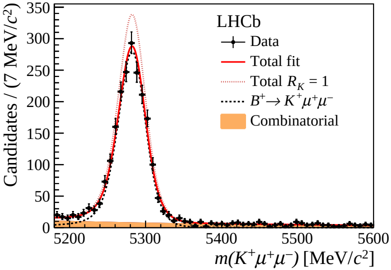
$$R_K = 0.846\,^{+\,0.060}_{-\,0.054}\,^{+\,0.016}_{-\,0.014}$$

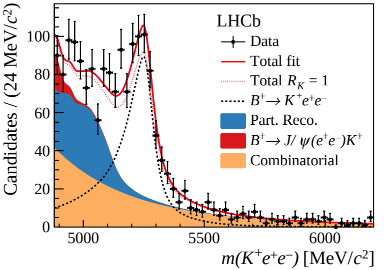
(2.5σ from the SM)

The Run 1 result is consistent with $0.745\,^{+\,0.090}_{-\,0.74} \pm 0.036$ [PRL 113 (2014) 151601]

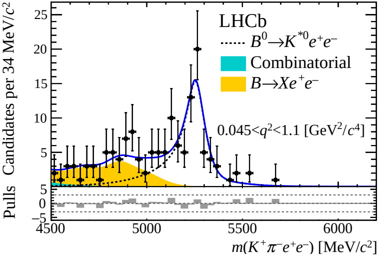
$$R_K^{7\text{–}8\,\text{TeV}} = 0.717\,^{+\,0.083}_{-\,0.071}\,^{+\,0.017}_{-\,0.016}$$
$$R_K^{13\,\text{TeV}} = 0.928\,^{+\,0.089}_{-\,0.076}\,^{+\,0.020}_{-\,0.017}$$

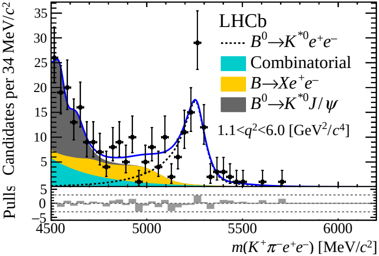
The BF of $B^+ \to K^+e^+e^-$ in $1.1 < q^2 < 6\,\text{GeV}^2/c^4$ is $(28.6\,^{+\,2.0}_{-\,1.7} \pm 1.4) \times 10^{-9}$





Lepton universality in $B^0 \to K^{*0}\ell^+\ell^-$

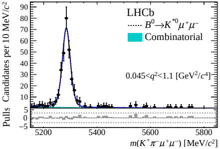


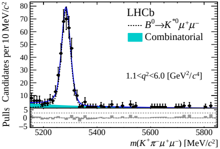


Measure ratio R_{K^*} of $B^0 \to K^{*0}\mu^+\mu^-$ to $B^0 \to K^{*0}e^+e^-$ in $0.045 < q^2 < 1.1$ and $1.1 < q^2 < 6$ GeV^2

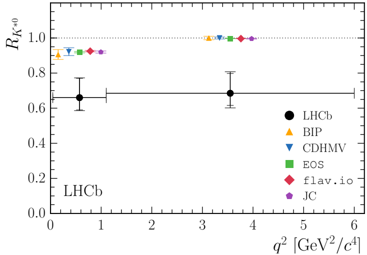
- ✔ Signal clearly visible in $K^{*0}\mu^+\mu^-$
- Yields entering the double ratio:

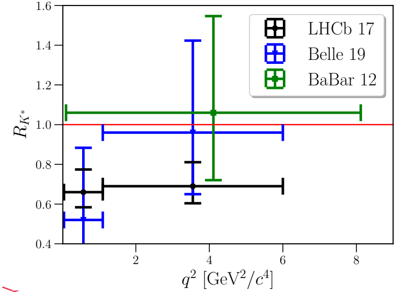
	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to J/\psi K^{*0}$
	low- q^2	central- q^2	
$\mu^+\mu^-$	285 ± 18	353 ± 21	$274416 ^{+602}_{-654}$
e^+e^-	$89 ^{+11}_{-10}$	$111 ^{+14}_{-13}$	43468 ± 222





Lepton universality in $B^0 \to K^{*0}\ell^+\ell^-$





Measure ratio R_{K^*} of $B^0 \to K^{*0}\mu^+\mu^-$ to $B^0 \to K^{*0}e^+e^-$ in $0.045 < q^2 < 1.1$ and $1.1 < q^2 < 6$ GeV^2

- ✔ Signal clearly visible in $K^{*0}\mu^+\mu^-$
- Yields entering the double ratio:

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to J/\psi\, K^{*0}$
	low- q^2	central- q^2	
$\mu^+\mu^-$	285 ± 18	353 ± 21	$274416\,^{+602}_{-654}$
e^+e^-	$89\,^{+11}_{-10}$	$111\,^{+14}_{-13}$	43468 ± 222

Build a double ratio $R_K =$

$$\left(\frac{\mathcal{N}_{K^{*0}\mu^+\mu^-}}{\mathcal{N}_{K^{*0}e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^{*0}}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^{*0}}}\right)$$

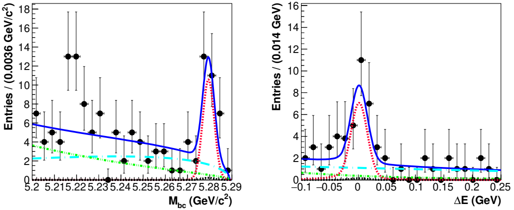
$$= \begin{cases} 0.66\,^{+0.11}_{-0.07} \pm 0.03 & 0.045 < q^2 < 1.1 \\ 0.69\,^{+0.11}_{-0.07} \pm 0.05 & 1.1 < q^2 < 6.0 \end{cases}$$

This about 2 to 2.5σ from the SM, depending on predictions. [BIP, EPJC 76 440] [CDHMV, JHEP04(2017)016] [EOS, PRD 95 035029] [flav.io, EPJC 77 377] [JC, PRD93 014028]

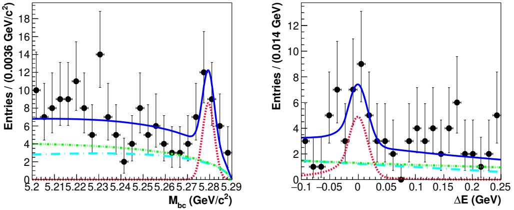
R_K at Belle

Using the full sample of 772×10^6 $B\overline{B}$ pairs Belle selects $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^0_{\rm S}\ell^+\ell^-$ decays

- 137 ± 14 $B^+ \to K^+\mu^+\mu^-$ and 138 ± 15 $B^+ \to K^+e^+e^-$ decays found
- 27 ± 6 $B^0 \to K^0_{\rm S}\mu^+\mu^-$ and 22 ± 7 $B^0 \to K^0_{\rm S}e^+e^-$ decays found



$B^0 \to K^0_{\rm S}\mu^+\mu^-$

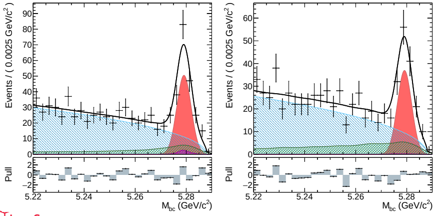


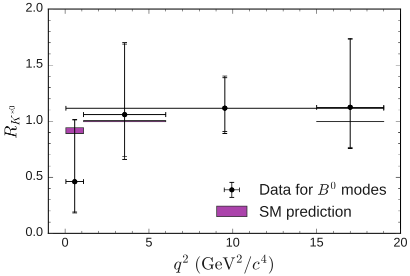
$B^0 \to K^0_{\rm S}e^+e^-$

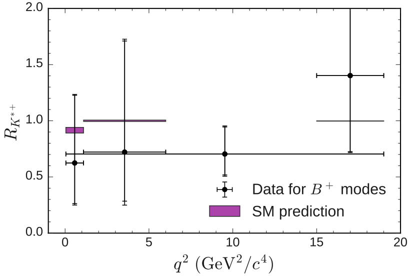
R_{K^*} at Belle

Using 711fb^{-1} data, Belle measure R_{K^*}

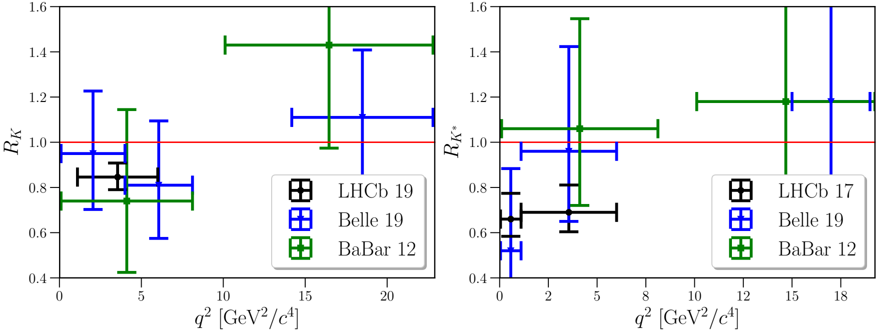
- Find 103 ± 13 $B \to K^* e^+ e^-$ and 140 ± 16 $B \to K^* \mu^+ \mu^-$ decays, adding B^0 and B^+
- Cross-check $r_{J/\psi} = 1.015 \pm 0.025 \pm 0.038$
- Results, split by B^0 and B^+ ➜







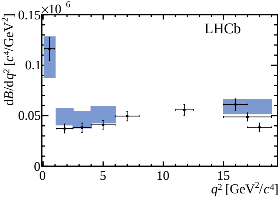
R_K AND R_{K^*}



LHCb [JHEP 08 (2017) 055] [PRL 122 (2019) 191801]. Belle [arXiv:1904.02440] [arXiv:1908.01848].
BaBar [PRD 86 (2012) 032012].

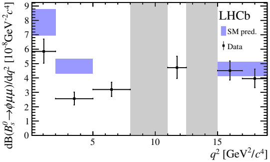
[B]

BFs too low in $b \to s\mu^+\mu^-$ decays?



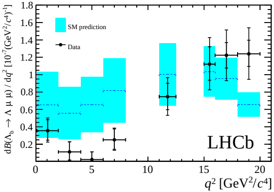
$B^0 \to K^{*0}\mu^+\mu^-$

[JHEP 11 (2016) 047]



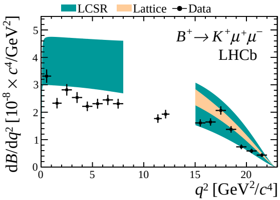
$B_s^0 \to \phi\mu^+\mu^-$

[JHEP 09 (2015) 179]



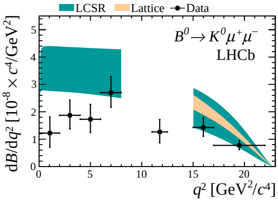
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

[JHEP 06 (2015) 115]



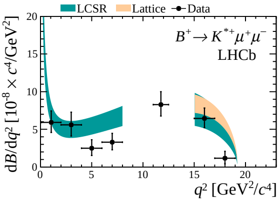
$B^+ \to K^+\mu^+\mu^-$

[JHEP 06 (2014) 133]



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

[JHEP 06 (2014) 133]

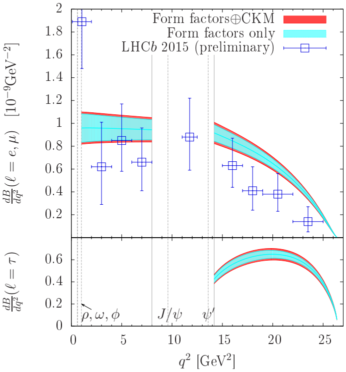


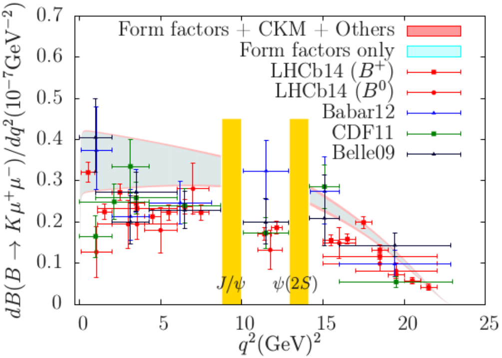
$B^+ \to K^{*+}\mu^+\mu^-$

[JHEP 06 (2014) 133]


Lattice
LHCb
Sum Rules

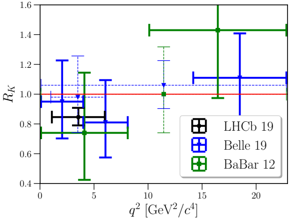
$B \to h\ell^+\ell^-$ form factors from MILC



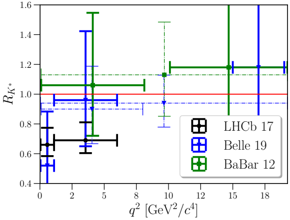


$B^+ \to \pi^+\ell^+\ell^-$ [JHEP 10 (2015) 034] and $B \to K\ell^+\ell^-$ [JHEP 06 (2014) 133] are all below the lattice computations.

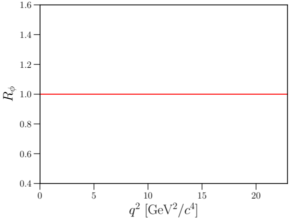
R_X: It's only the beginning



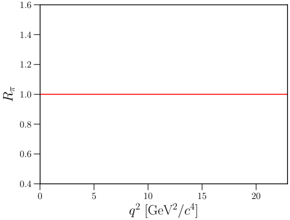
$B \to K\ell^+\ell^-$



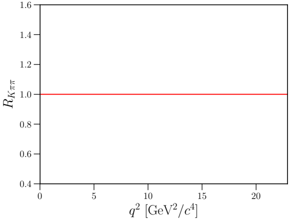
$B \to K^*\ell^+\ell^-$



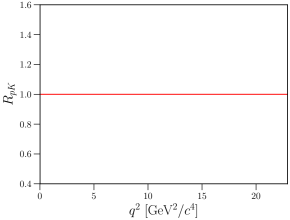
$B^0_s \to \phi\ell^+\ell^-$



$B^+ \to \pi^+\ell^+\ell^-$



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



$\Lambda^0_b \to pK^-\ell^+\ell^-$

Flavour Anomalies

Angular (P'_5)

$b \to s\ell^+\ell^-$ FCNC

Flavour anomalies

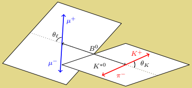
BFs

e–μ universality

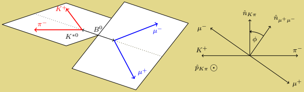
$B^0 \to K^+\pi^-\ell^+\ell^-$ Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

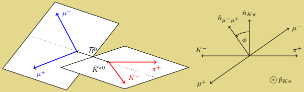
$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \right.$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos2\theta_\ell$$
$$+ S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi$$
$$+ S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin2\theta_K\sin2\theta_\ell\sin\phi$$
$$\left. + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi \right]$$



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



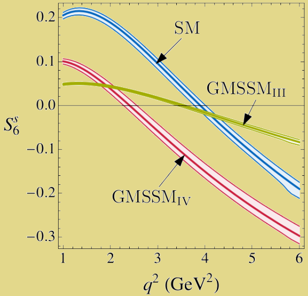
(c) ϕ definition for the $\overline{B}^0$ decay

→ Many observables depending on $q^2 = m^2_{\ell\ell}c^4$

$B^0 \to K^+\pi^-\ell^+\ell^-$ Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \right.$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+ S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$\left. + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \right]$$



→ **Forward-backward asymmetry**
$S_6 = \frac{4}{3}A_{\mathrm{FB}}$

[Altmannshofer et al., JHEP 0901:019,2009] [Krüger & Matias, Phys.Rev.D71:094009] [Egede et al., JHEP 0811:032,2008] [Ali et al., Phys.Rev.D61:074024]

$B^0 \to K^+\pi^-\ell^+\ell^-$ Angular Distributions

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+ S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
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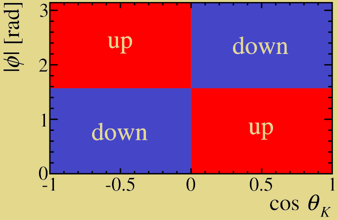
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+ S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



Definition of S_5

[Altmannshofer et al., JHEP 0901:019,2009] [Krüger & Matias, Phys.Rev.D71:094009] [Egede et al., JHEP 0811:032,2008] [Ali et al., Phys.Rev.D61:074024]

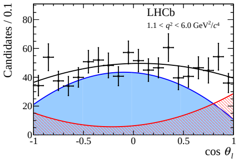
➜ $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

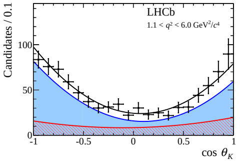
[Descotes-Genon et al., JHEP, 1305 137]

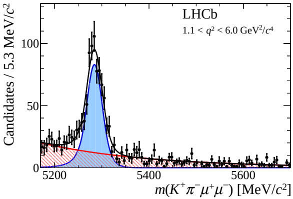
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

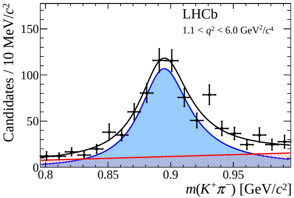
Update of [JHEP 08 (2013) 131] and [PRL 111 (2013) 191801] to 3 fb^{-1}. S-wave is taken into account, we have finer bins, and no φ folding is needed.

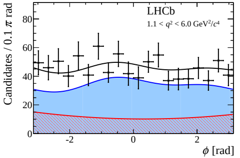
- Angular acceptance obtained from MC and validated on $B^0 \to J/\psi K^*$ decays.
- **Max Likelihood fit:** 4D fit to $m(K^+\pi^-)$ and three angles in bins of q^2.
  - Here $1.1 < q^2 < 6$ GeV$^2/c^4$ is shown.
  - 2398 ± 57 decays found in total.











[LHCb, JHEP 02 (2016) 104, arXiv:1512.04442]

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

Update of [JHEP 08 (2013) 131] and [PRL 111 (2013) 191801] to 3 fb^{-1}. S-wave is taken into account, we have finer bins, and no φ folding is needed.

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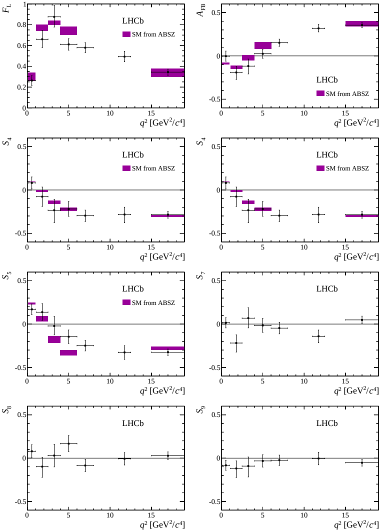
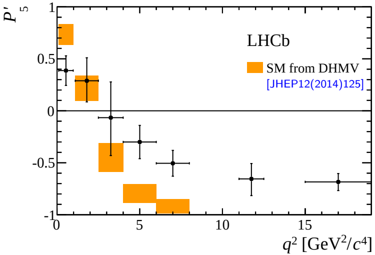
- **Max Likelihood fit:** 4D fit to $m(K^+\pi^-)$ and three angles in bins of q^2.
- Observables consistent with SM, except S_5

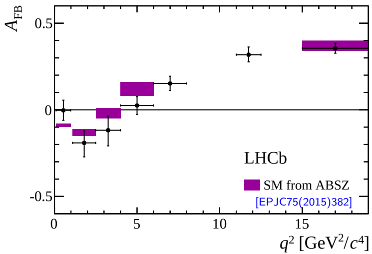


ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

Update of [JHEP 08 (2013) 131] and [PRL 111 (2013) 191801] to 3 fb^{-1}. S-wave is taken into account, we have finer bins, and no φ folding is needed.

- **Max Likelihood fit:** 4D fit to $m(K^+\pi^-)$ and three angles in bins of q^2.
- Observables consistent with SM, except S_5
- $P_5' = S_5/\sqrt{F_L(1-F_L)}$ has a local discrepancy in two bins
- A_{FB} seems to show a trend, but is consistent with SM



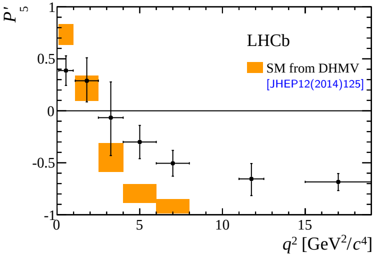


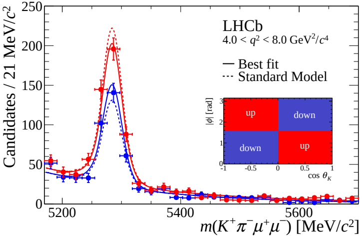
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

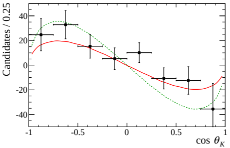
What is P_5'?

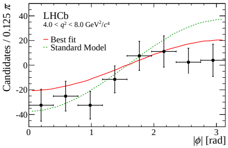
It is an asymmetry built with $\cos\theta_K$ and $|\phi|$, shown in the sketch. (integrating over one of the two gets zero).

The discrepancy with the SM prediction is visible in both angular distributions.

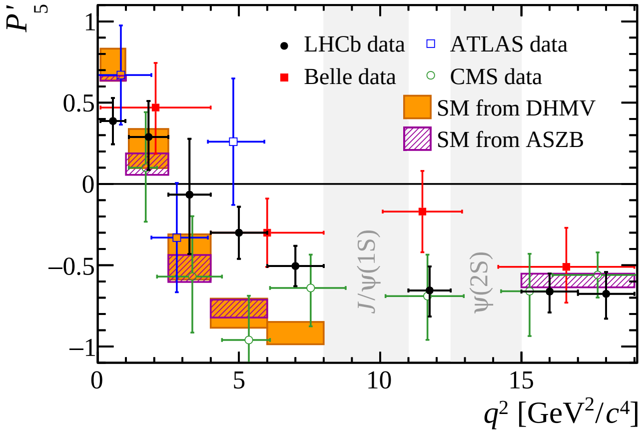






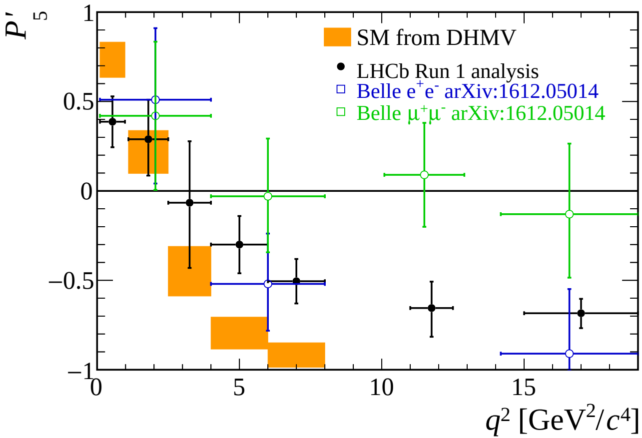


All P_5' measurements



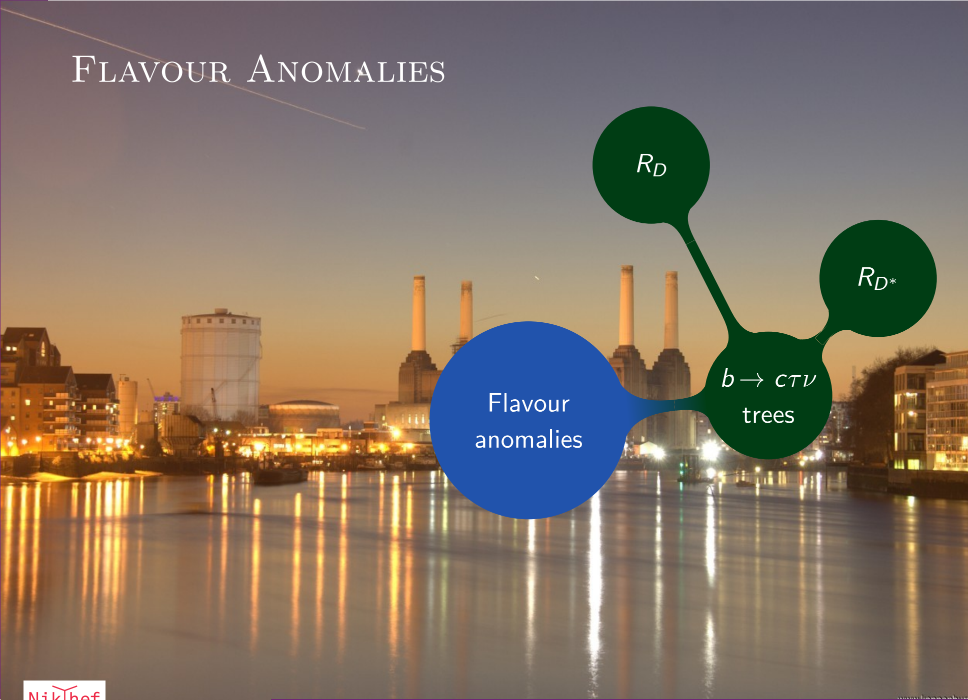
LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801]
CMS [PLB 781 (2018) 517], ATLAS [arXiv:1805.04000]

All P_5' measurements

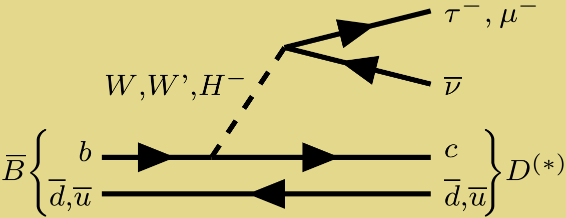


LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801]

Flavour Anomalies



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



τ versus μ,e lepton universality can be tested with

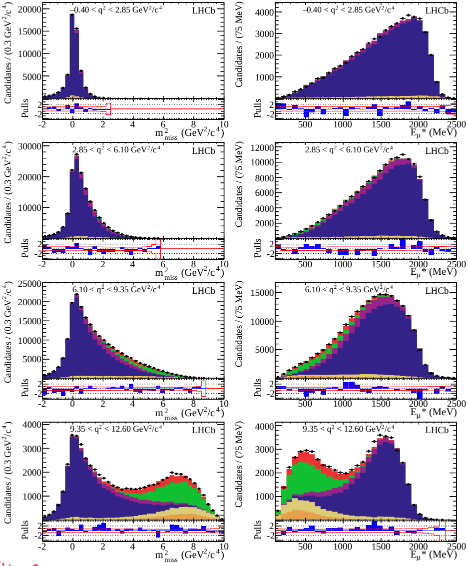
$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)} \quad \ell = \mu, e,$$

which is well predicted in the SM ($\neq 1$ due to phase-space, etc. . .)

$$R(D^*) \stackrel{\text{SM}}{=} 0.252 \pm 0.003, \qquad R(D) \stackrel{\text{SM}}{=} 0.297 \pm 0.017$$

[Kamenik et al., PRD 78 014003], [Fajfer et al., PRD 85 094025], [BABAR, PRD 88 072012]

$\overline{B}^0 \to D^{*+}\tau\nu$ AT LHCb

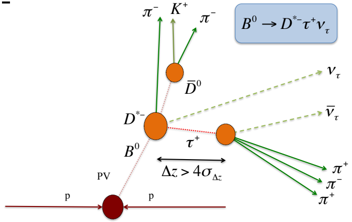


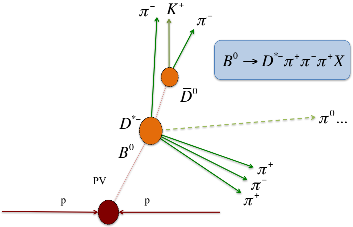
- Select D^* with $D^0 \to K^-\pi^+$ and μ^-, forming a good vertex separated from PVs, and isolated using dedicated MVA
- $B^0 \to D^{*+}\tau^-\overline{\nu}$ with $\tau^- \to \mu^-\nu\overline{\nu}$ and $B^0 \to D^{*+}\mu^-\overline{\nu}$: same final state.
- Disentangled by kinematical variables : q^2, E^*_μ, m^2_{miss}.
  - The B momentum is approximated from the boost of the reconstructed system.
- A template fit in q^2 bins determines signal yields

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

The ratio $\mathcal{R}(D^*) = \frac{\mathcal{B}(B\to D^*\tau^+\nu_\tau)}{\mathcal{B}(B\to D^*\mu^+\nu_\mu)}$ is measured above the SM.

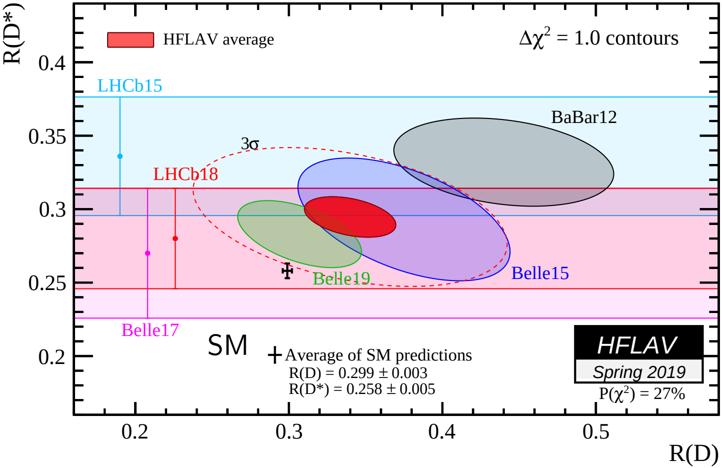
- So far all measurements used $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$, which provides the same final state as $B \to D^*\mu^+\nu_\mu$
- Here for the first time, $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$ is used.
- The main background is $B^0 \to D^{*-}\pi^+\pi^-\pi^-$. The two are separated exploiting the τ^+ lifetime.
- A BDT is used for that purpose





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

HFLAV



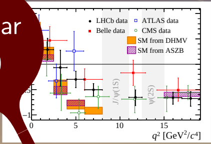
BABAR [PRL 109 101802 (2012)] [PRD 88 072012 (2013)] Belle [PRD 92 072014 (2015)] [PRL 118 211801 (2017)] [PRD 97 012004 (2018)] [arXiv:1904.08794] LHCb [PRL 115 (2015) 111803] [PRL 120 (2018) 171802]. Theory [FLAG EPJC77 (2017) 112], [Faijfer et al., PRD 85 094025 (2012)]

Flavour Anomalies

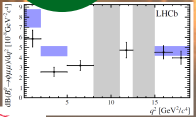
Flavour anomalies

$b \to s\ell^+\ell^-$ FCNC

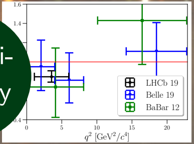
Angular (P_5')



BFs



e–μ universality

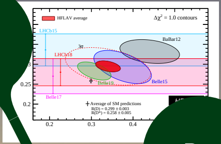


$b \to c\tau\nu$ trees

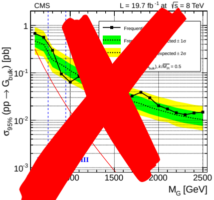
R_D

R_{D^*}

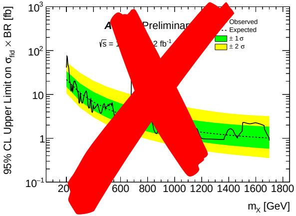
$R_{J/\psi}$



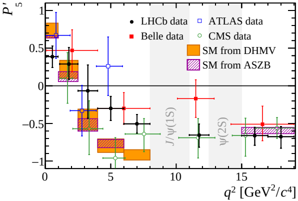
Are we already seeing New Physics?



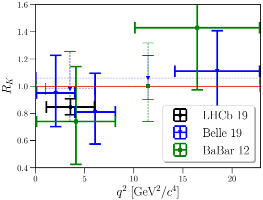
ess at 2 TeV [CMS, JHEP 08 (2014) 174]



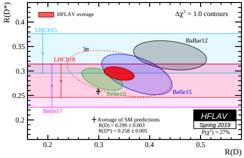
Excess at 750 GeV [ATLAS-CONF-2015-081]



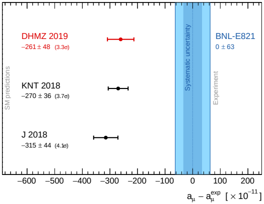
P_5' in $B \to K^* \mu^+ \mu^-$ [JHEP 02 (2016) 104]



Lepton universality [PRL 122 (2019) 191801] ...



$b \to c\tau\nu$ [HFlav, arXiv:1909.12524]



Muon $g-2$ [Davier, Hoecker, Malaescu, Zhang]

There is a handful of intriguing 3–4σ anomalies


LIVE
breakyourownnews.com
BREAKING NEWS
CERN REPORTS NEW PHYSICS
15:32
THERE'S SOMETHING FISHY WITH MUONS SAYS DR. MITESH PATEL OFTHE LHCB EXPE

Patrick Koppenburg @PKoppenburg · 2j
While preparing for 2 seminars, let's ask the vox populi. The flavour anomalies are

Flukes	**43%**
Leptoquarks	21%
Supersymmetry	7%
Something else (discuss)	28%

67 votes • Résultats finaux

3 2 3

Paul de Jong @DeJong1001 · 1j
So, what do you make of the outcome of the poll?

2 1

Monica Vazquez
@monicavatworld

En réponse à @DeJong1001 et @PKoppenburg

I think the outcome deserves to be part of the seminar content

Beware of. . .

τ DECAYS LEPTON UNIVERSALITY

HFLAV

$$\Gamma(L \to \nu_L \ell \overline{\nu}_\ell(\gamma)) = g_L^2 g_\ell^2 \times f(m_L, m_\ell, m_W)$$ [HFAG]

Using PDG BFs [PDG 2014, Chin. Phys. C38 090001]:

$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0010 \pm 0.0015, \quad \left(\frac{g_\tau}{g_e}\right) = 1.0029 \pm 0.0015$$

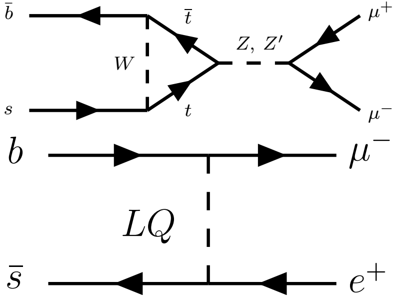
$$\left(\frac{g_\mu}{g_e}\right) = 1.0019 \pm 0.0014$$

Similarly, using $\tau \to h\nu_\tau$ and $h \to \mu\overline{\nu}_\mu$ decays

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9961 \pm 0.0027, \quad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9860 \pm 0.0070$$

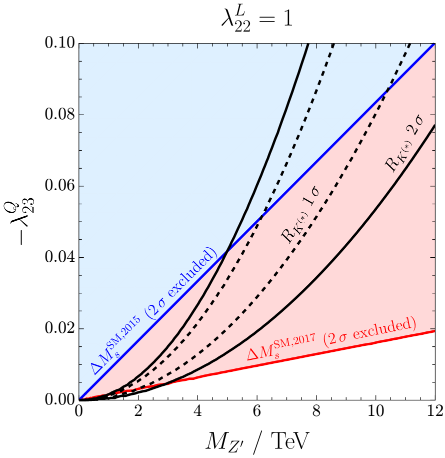
This is obviously work for electron machines, including BESIII.

B_s^0 MIXING AND $b \to s\ell^+\ell^-$ ANOMALIES



New physics in $b \to s\ell^+\ell^-$ transitions, this is $(\bar{b}s)(\ell^+\ell^-)$ necessarily affects B_s^0 mxing at some level.

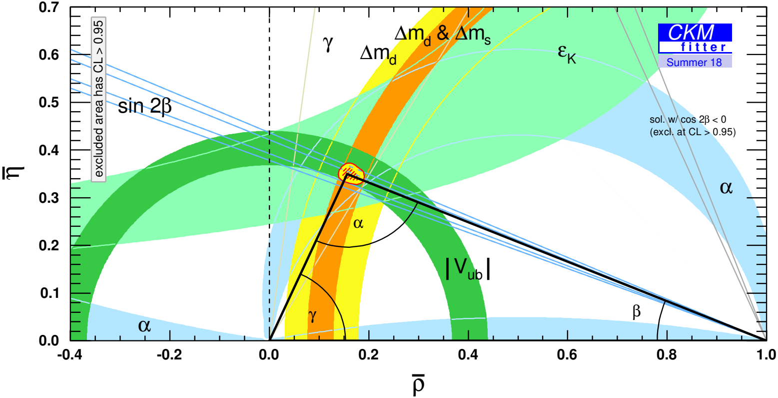
But the constraints are the wrong way.



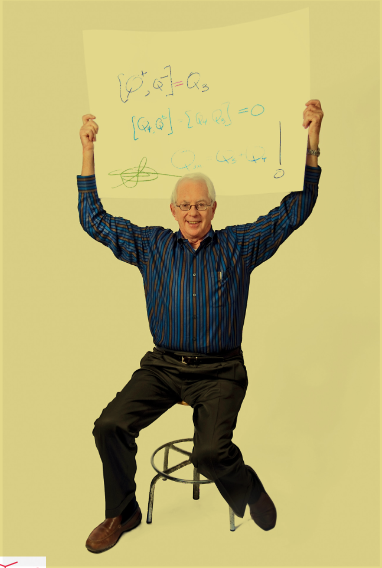
Constraints from B_s^0 mixing and R_K on Z' mass and coupling.

Unitarity Triangle

The data agree very well!



Lepton-universality violation in B decays?



[...] any departure from lepton universality is necessarily associated with the violation of lepton flavor conservation. **No known symmetry principle can protect the one in the absence of the other.**

Thus, LHCb's reported value of R_K implies, e.g., that $B \to K^{(*)}\mu^\pm e^\mp$ and $B \to K^{(*)}\mu^\pm\tau^\mp$ must occur at rates much larger than would occur in the SM due to tiny neutrino masses. We urge that these and other lepton flavor violations (LFV) be sought with renewed vigor in LHC Run II and elsewhere.

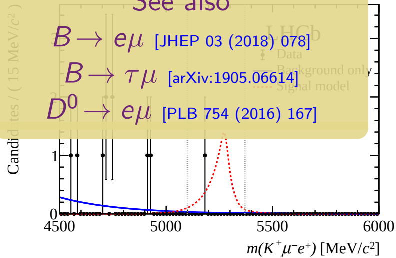
SEARCH FOR $B^+ \to K^+\mu^\pm e^\mp$

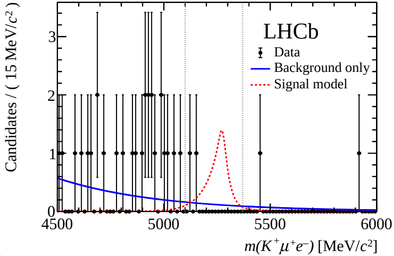
See also

$B \to e\mu$ [JHEP 03 (2018) 078]

$B \to \tau\mu$ [arXiv:1905.06614]

$D^0 \to e\mu$ [PLB 754 (2016) 167]





If lepton universality is violated, lepton-number conservation may be too

- LHCb search for $B^+ \to K^+\mu^\pm e^\mp$ with Run 1 ($3\,\text{fb}^{-1}$) data
- After full (BDT) selection, combinatorial background dominates
- No signal found

Limits (90%) set as

$$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 7.0 \times 10^{-9}$$
$$\mathcal{B}(B^+ \to K^+\mu^-e^+) < 6.4 \times 10^{-9}$$

More than a factor 10 better than previous limit [BaBar, PRD73:092001,2006]

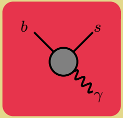
Fits

[Buchalla, Buras, Lautenbacher, Rev. Mod. Phys.68 (1996) 1125]

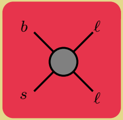
Operators

Operator

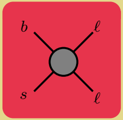
$\mathcal{O}_{7\gamma}$



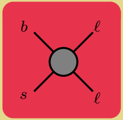
$\mathcal{O}_{9V}$



$\mathcal{O}_{10A}$



$\mathcal{O}_{S,P}$



Effective Hamiltonian $\mathcal{H}$

$$A(M \to F) = \langle F \left| \mathcal{H}_{\text{eff}} \right| M \rangle$$

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

- Operators $\mathcal{O}_i$: Long-distance effects
- Wilson coefficients C_i: Short-distance effects (masses above μ are integrated out)

New physics can show up in new operators or modified Wilson coefficients

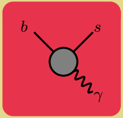
[Buchalla, Buras, Lautenbacher, Rev. Mod. Phys.68 (1996) 1125]

Operators

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

Operator

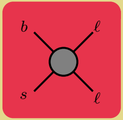
$\mathcal{O}_{7\gamma}$



$b \to s\gamma$

$$\mathcal{O}_{7\gamma} = \sqrt{\frac{\alpha_{\mathrm{EM}}}{64\pi^3}}\, m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

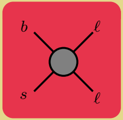
$\mathcal{O}_{9V}$



$b \to s\ell^+\ell^-$

$$\mathcal{O}_{9V} = \frac{\alpha_{\mathrm{EM}}}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$$

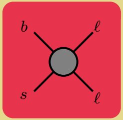
$\mathcal{O}_{10A}$



$b \to s\ell^+\ell^-$

$$\mathcal{O}_{10A} = \frac{\alpha_{\mathrm{EM}}}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$

$\mathcal{O}_{S,P}$



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

$$\mathcal{O}_{S,P} = \frac{\alpha_{\mathrm{EM}}}{4\pi}(\bar{s}_L b_R)(\bar{\ell}\gamma^5\ell)$$

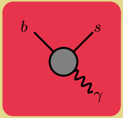
(Add primed operators for right-handed currents)

[Buchalla, Buras, Lautenbacher, Rev. Mod. Phys.68 (1996) 1125]

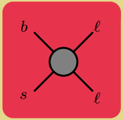
Operators, separately for e and μ

Operator

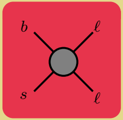
$\mathcal{O}_{7\gamma}$



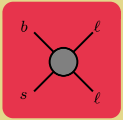
$\mathcal{O}_{9V}$



$\mathcal{O}_{10A}$



$\mathcal{O}_{S,P}$

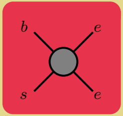


- All C_i calculated at NLO if not NNLO in SM
- We need to measure all coefficients
- Any discrepancy is a sign of New Physics

Operators

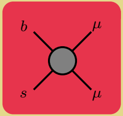
Operator

$\mathcal{O}_{9V}^{e}$



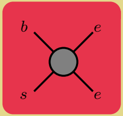
$b \to s e^+ e^-$

$\mathcal{O}_{9V}^{\mu}$



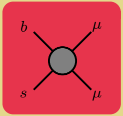
$b \to s \mu^+ \mu^-$

$\mathcal{O}_{10A}^{e}$



$b \to s e^+ e^-$

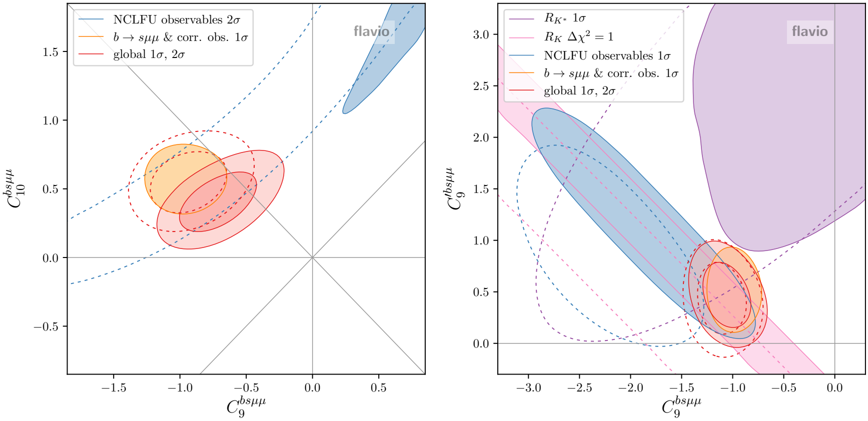
$\mathcal{O}_{10A}^{\mu}$



$b \to s \mu^+ \mu^-$

So far operators assumed to be lepton-universal. What if not?

B-decay discrepancies after Moriond



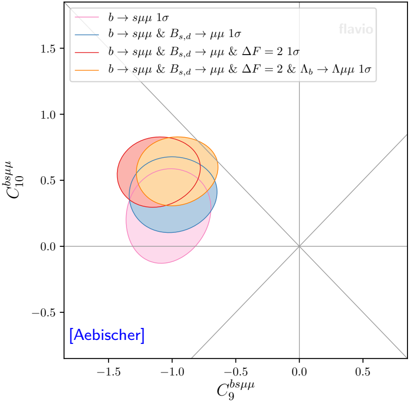
After the R_K [PRL 122 (2019) 191801] and R_{K*} updates, the best fit is still away from the SM. But there's little room for right-handed currents.

Fits to recent $b \to s\ell^+\ell^-$ data

NP hypothesis		[Algueró]	[Aebischer]	[Alok]	[Arbey]	[D'Amico]	[Kowalska]
Vector:	$C_{9\mu}^{\mathrm{NP}}$	5.6σ	5.9σ	6.2σ	5.3σ	6.5σ	4.7σ
$V-A$:	$C_{9\mu}^{\mathrm{NP}} = -C_{10\mu}^{\mathrm{NP}}$	5.2σ	6.6σ	6.4σ	4.5σ	5.9σ	4.8σ
RH :	$C_{9\mu}^{\mathrm{NP}} = -C_{9'\mu}^{\mathrm{NP}}$	5.5σ		6.4σ			

They differ by

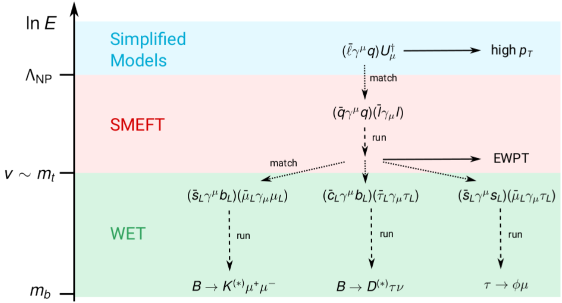
- Uncertainties of QCD-related quantities (form-factors)
- External constraints used (Oscillation frequencies $\Delta m_{d,s}$)
- Some of the data ($\Lambda_b^0 \to \Lambda\mu^+\mu^-$ only in [Aebischer])
- Statistical treatment (frequentist versus Bayesian)



SM Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D>4} \sum_i \frac{1}{\Lambda_{\text{NP}}^{D-4}} C_i^{(D)} O_i^{(D)}$$

- Describes low-energy processes, EW and Higgs, top, high-p_{T} (as long as $E \ll \Lambda_{\text{NP}}$)
- Asssumes large Λ_{NP}, no other light particles. . .



[Straub, Lyon 2019]

- Broader scope as weak effective theories, but is less general
- Studies correlations between CC, NC, EW phase transitions. . .

SM Effective Field Theory

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- Describes low-energy processes, EW and Higgs, top, high-p_{T} (as long as $E \ll \Lambda_{\mathrm{NP}}$)
- Asssumes large Λ_{NP}, no other light particles...

But a single generic operator like

$$\frac{1}{\Lambda^2} [C_{lq}]^{ij\alpha\beta} (\bar{Q}_i \gamma_m u Q^j)(\bar{L}_\alpha \gamma^\mu L_\beta)$$

with Q and L left-handed quark and lepton fields with generation indices i, j, α, β in 1–3 has 3^4 complex coefficients ➜ 162 reals.

[Bordone, Catà, Feldmann, arXiv:1910.02641]

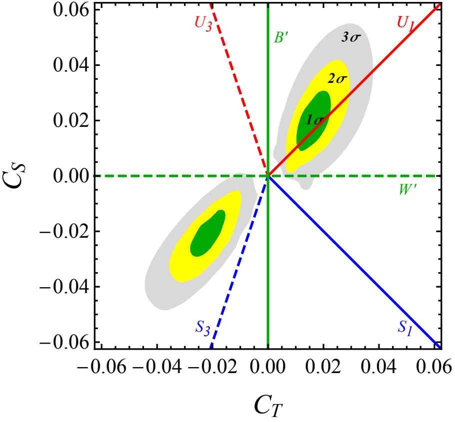
- Broader scope as weak effective theories, but is less general
- Studies correlations between CC, NC, EW phase transitions...

Guide to combined explanations

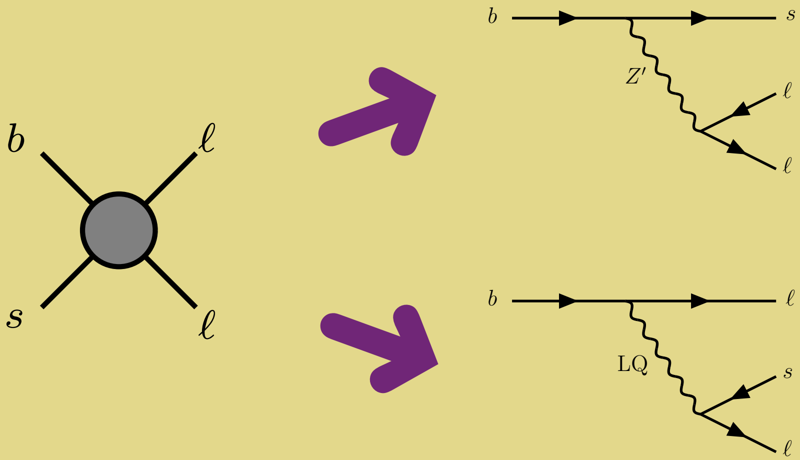
EFT fit to flavour data

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

- Assuming $U(2)_q \times U(2)_\ell$ flavour symmetry and minmal breaking
- Two regions preferred by fit, one nicely matching vector leptoquarks $[U_1^\mu = (3, 1, 2/3)]$.
  - Escapes contraints from B mixing
- Options with scalar leptoquarks (S_1, S_3) or new bosons W' are less favoured.

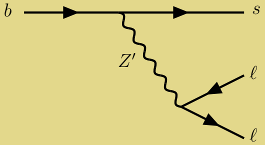


Opening Up the Operators



New Physics

- $b \to s\ell^+\ell^-$ hints toward a new vector current (C_9) ➜ a Z' ?



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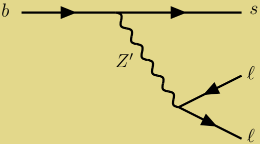
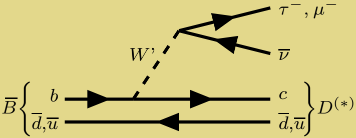
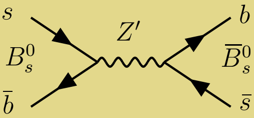
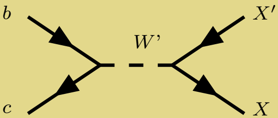




- Won't do $b \to c\tau^-\nu$ ➜ W', Z' triplet? Or $H^\pm$?
  - ✎ Beware of B mixing and of the B_c^+ lifetime





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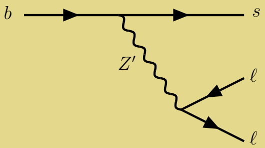

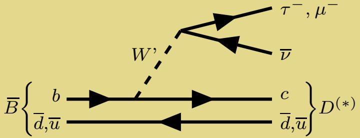

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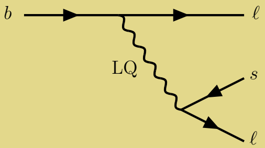
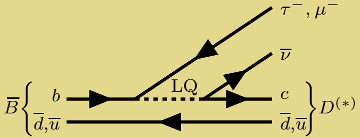
➜ Leptoquarks?





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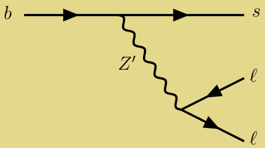

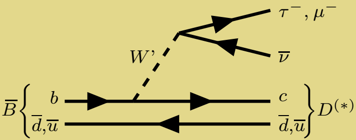

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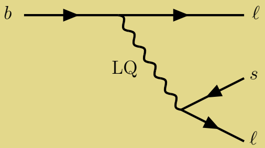
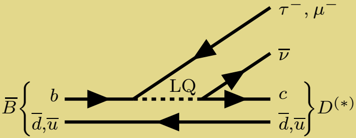


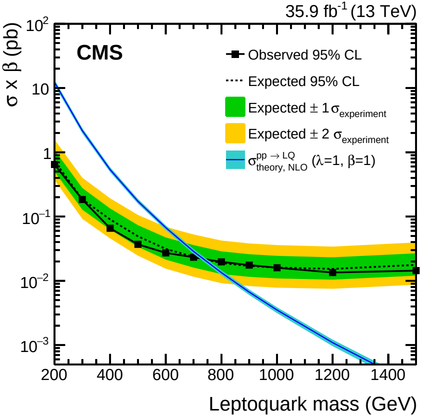


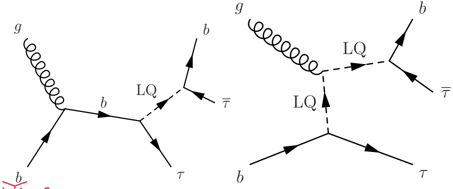
† It's tough for supersymmetry, but susy never dies. . .

Search for scalar leptoquark to $b\tau$

Using $36\,\mathrm{fb}^{-1}$ 13 TeV data, CMS search for $b\tau^+\tau^-$ signatures

- Single production of third-generation leptoquarks
- ✗ No excess found
- Excluded for masses below $740\,\mathrm{GeV}/c^2$





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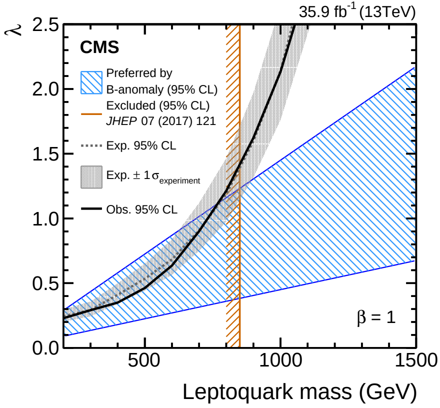
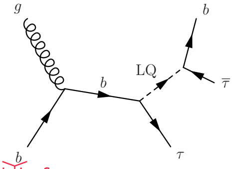
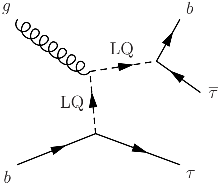
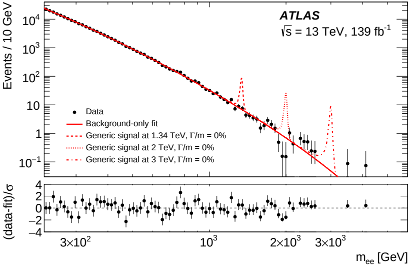
- Most of the phase space preferred by $R(D^{(*)})$ is still allowed

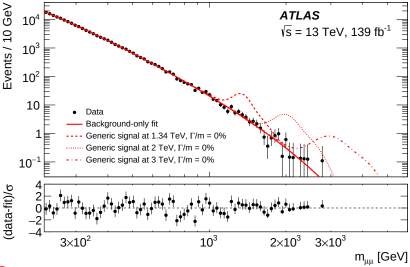






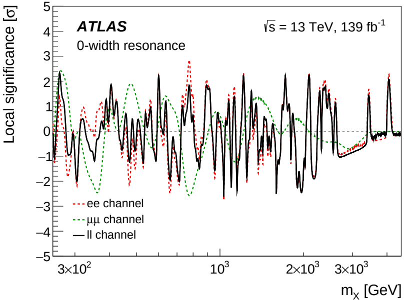
Search for $Z' \to \ell^+\ell^-$ resonances





Search for narrow dilepton ($\mu^+\mu^-$ and e^+e^-) resonances with 139 fb^{-1} Run-2 data.

- ✗ No local excess found
- Limits set on $\sigma(Z') \times \mathcal{B}$



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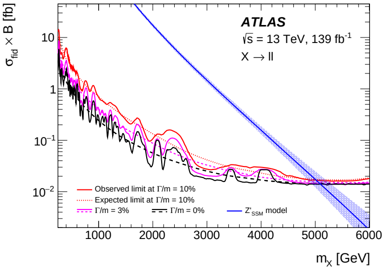

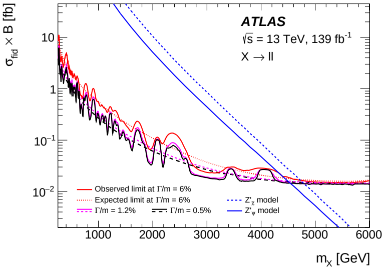

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- Can be turned into mass limits for benchmark scenarios: 4.5–5.1 TeV

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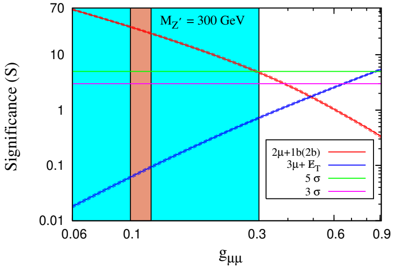

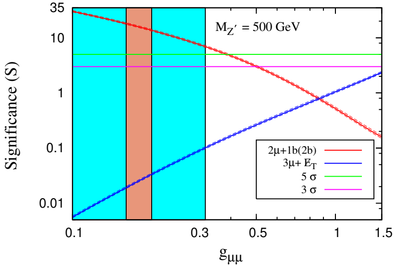

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- ✗ No local excess found
- Limits set on $\sigma(Z') \times \mathcal{B}$
- Can be turned into mass limits for benchmark scenarios: 4.5–5.1 TeV
- and recast into limits for models that could explain flavour anomalies. Here $b\overline{b} \to Z'\ell^+\ell^-$ [Falkowski, Kumar Ghosh et al., arXiv:1908.03031]

Flavour Anomalies

We need better precision in QCD.

Flavour anomalies

QCD

Lattice

Sum rules

Flavour Anomalies

It could be new vector bosons (but beware of $B\overline{B}$ mixing)

Z', W'

Flavour anomalies

QCD

Lattice

Sum rules

Flavour Anomalies

It could be new vector bosons, or leptoquarks

Flavour anomalies

Z', W'

QCD

Lattice

Sum rules

Lepto-quarks

Flavour Anomalies

Why is there no CP violation beyond the CKM matrix?

Flavour anomalies

Z', W'

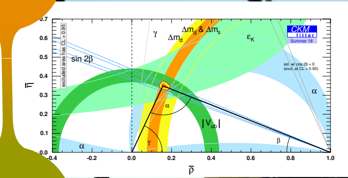
CPV?

Lepto-quarks

QCD

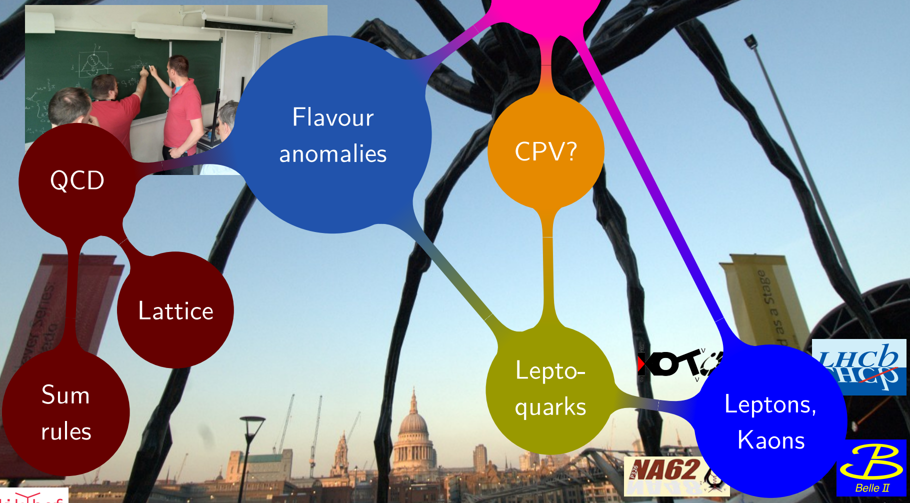
Lattice

Sum rules



Flavour Anomalies

They are likely to generate charged-lepton flavour violation.

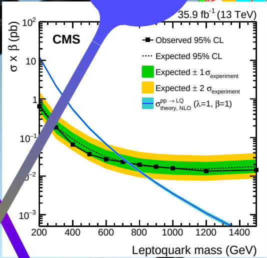


Flavour Anomalies

Can we see the bosons or leptoquarks at ATLAS and CMS?

Z', W'

LHC



Flavour anomalies

CPV?

QCD

Lattice

Sum rules

Lepto- quarks

Leptons, Kaons

Flavour Anomalies

Throw all data at a big fit of everything

QCD

Lattice

Sum rules

Flavour anomalies

Z', W'

CPV?

LHC

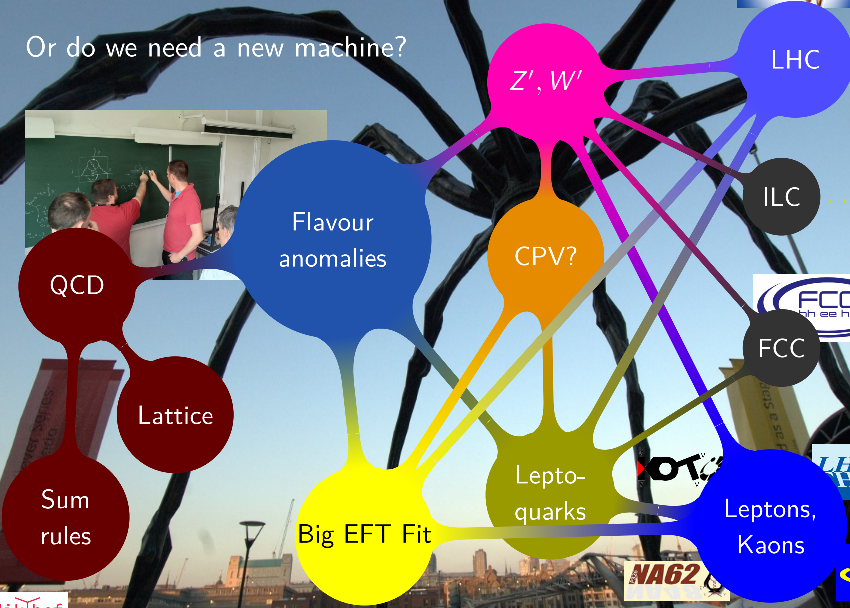
Lepto-quarks

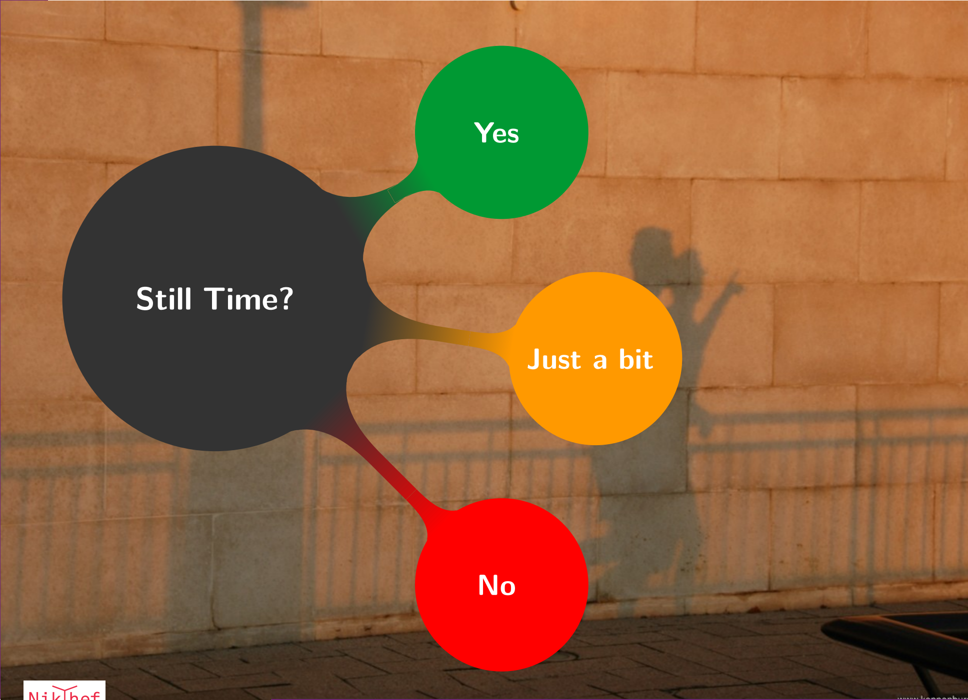
Leptons, Kaons

Big EFT Fit

Flavour Anomalies

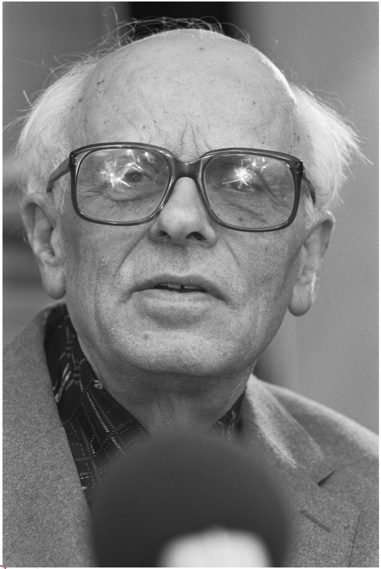
Or do we need a new machine?




Still Time?
Yes
Just a bit
No

CP violation

Sakharov Conditions



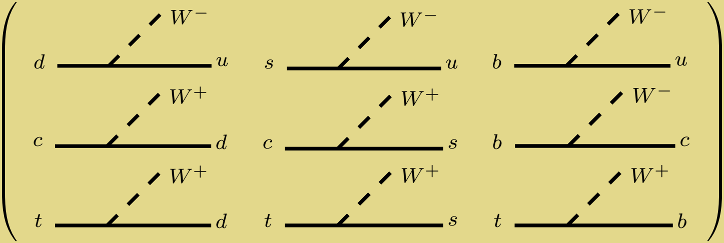
Necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates:

1. Baryon number B violation
2. **C-symmetry and CP-symmetry violation ($CP\,|q\rangle = \pm\,|q\rangle$)**
3. Interactions out of thermal equilibrium

[Kobayashi, Maskawa, Progr. Theo. Phys. 49 (1973) 652]

CKM Matrix Elements

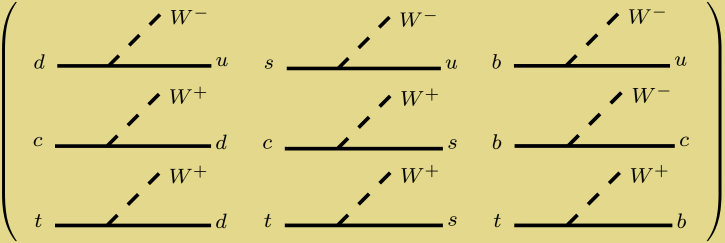
$V_{\mathrm{CKM}} =$



$$= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM Matrix Elements

$V_{\text{CKM}} =$



This matrix is

Unitary: as much gets in as gets out

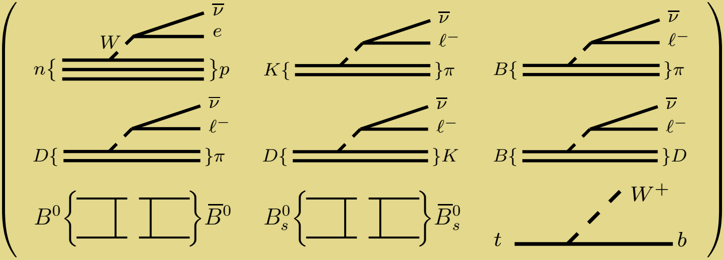
Complex: it's quantum mechanics

➜ A single phase cannot be rotated away. It is the source of all known experimental *CP* violation effects.

CKM Matrix Elements

... and how they are actually measured

$V_{\mathrm{CKM}} =$



Only the top-quark row is somewhat complicated

[Kobayashi, Maskawa, Progr. Theo. Phys. 49 (1973) 652]

The CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation in $\lambda = 0.23 \sim \theta_c$ at order $\mathcal{O}(\lambda^3)$:

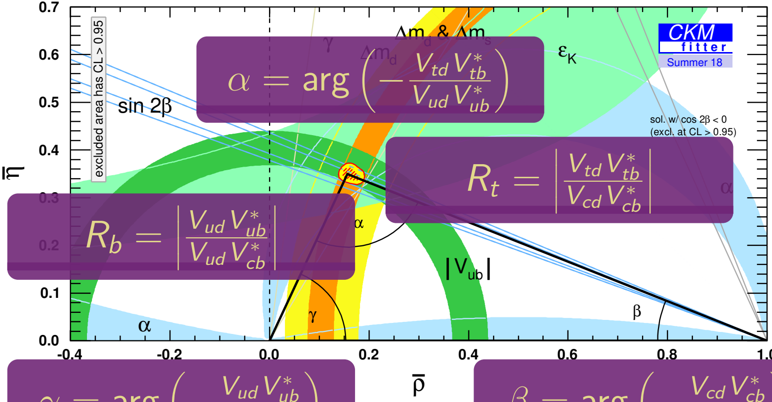
$$\begin{pmatrix} 1 -\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 -\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho - i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix}$$

[Wolfenstein, PRL 51 (1983) 1945]

Unitarity Triangle

"The" unitarity triangle exploits the relation

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



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$$

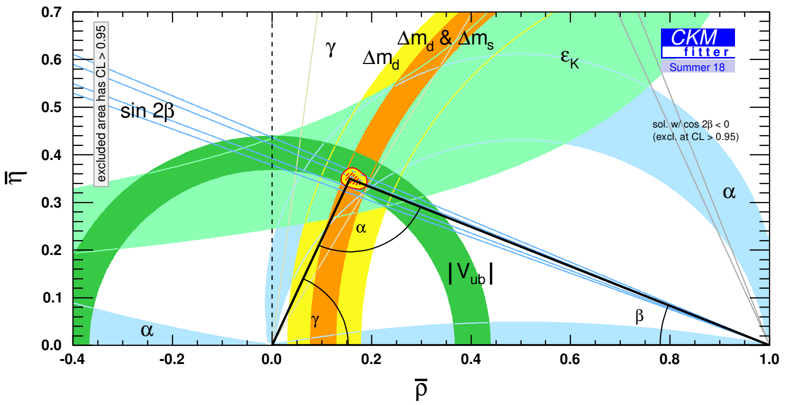
$$R_b = \left|\frac{V_{ud}V_{ub}^*}{V_{ud}V_{cb}^*}\right|$$

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

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

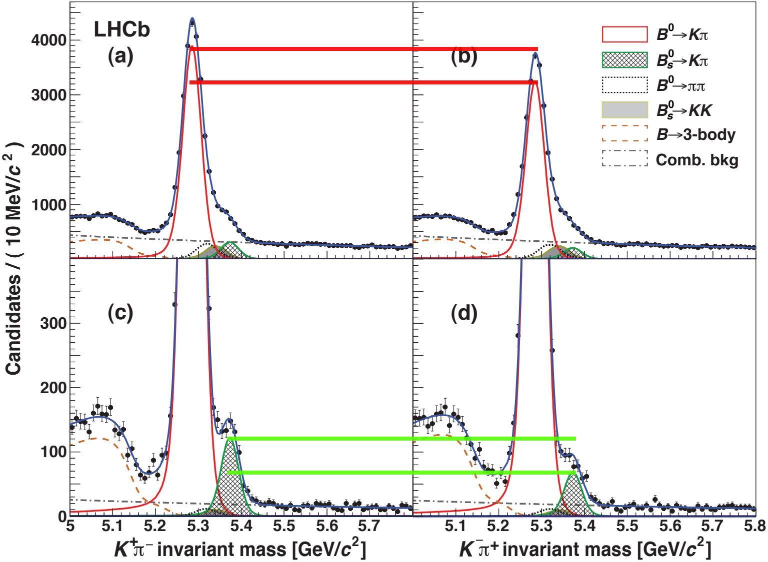
Unitarity Triangle

The data agree very well!

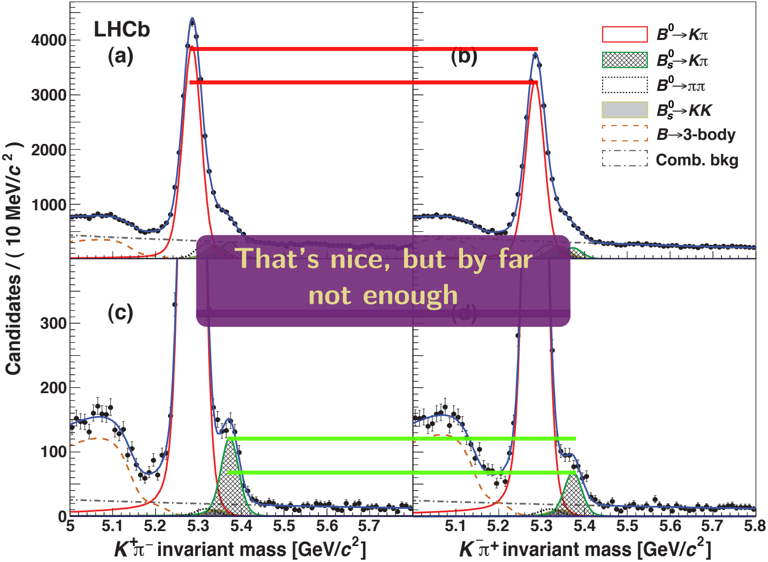


[LHCb, Phys. Rev. Lett. 110 (2013) 221601, arXiv:1304.6173]

CPV IN $B^0 \to K^+\pi^-$ AND $B_s^0 \to K^-\pi^+$

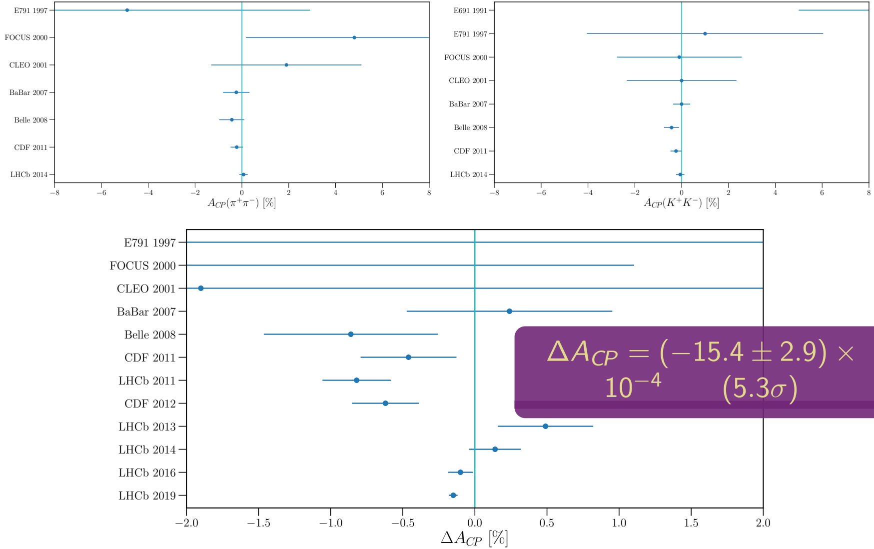


CPV IN $B^0 \to K^+\pi^-$ AND $B_s^0 \to K^-\pi^+$



That's nice, but by far not enough

ΔA_{CP} History



$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \quad (5.3\sigma)$$

Just a bit

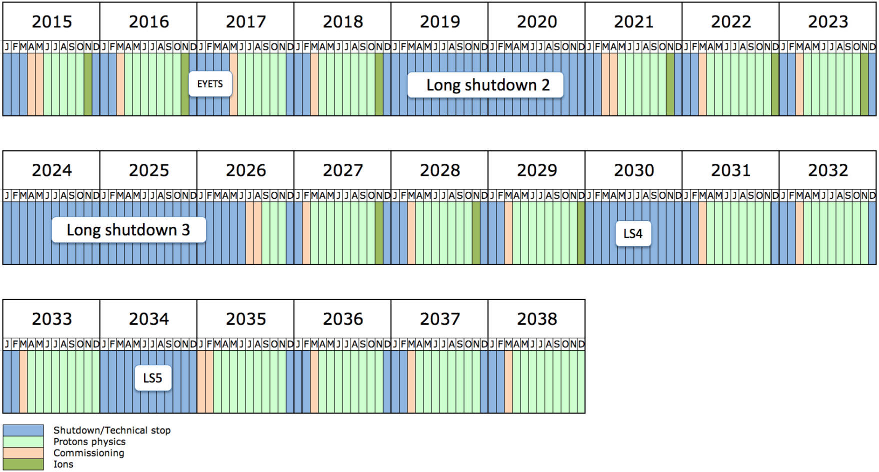
Still Time?

No

Outlook

[LHC web]

LHC schedule



LHCb Upgrade

$\mathcal{L} = 2{\cdot}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ requires some new detectors and 40 MHz read-out clock new electronics

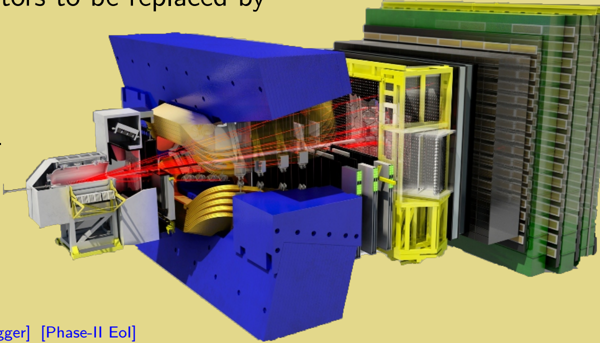
VELO: New pixel vertex detector

TRACKERS: New scintillating fibre tracker. The upstream tracker is also replaced

PID: Hybrid photodetectors to be replaced by multi-anode PMTs

➜ 50 fb^{-1} by Run 4.

✔ We are preparing another upgrade for Run 5
➜ 300 fb^{-1}



[Upgrade TDR] [Velo] [PID] [Sci-Fi] [Trigger] [Phase-II EoI]

LHCb Trigger in Run 3

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

⇓ ⇓ ⇓

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz	400 kHz	150 kHz
$h^\pm$	$\mu/\mu\mu$	e/γ

⇓ ⇓ ⇓

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons

⇓

- Buffer events to disk, perform online detector calibration and alignment

⇓

- Full offline-like event selection, mixture of inclusive and exclusive triggers

⇓ ⇓ ⇓

12.5 kHz (0.6 GB/s) to storage

→

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

⇓ ⇓ ⇓

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections

⇓

- Buffer events to disk, perform online detector calibration and alignment

⇓

- Add offline precision particle identification and track quality information to selections

  Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

⇓ ⇓ ⇓

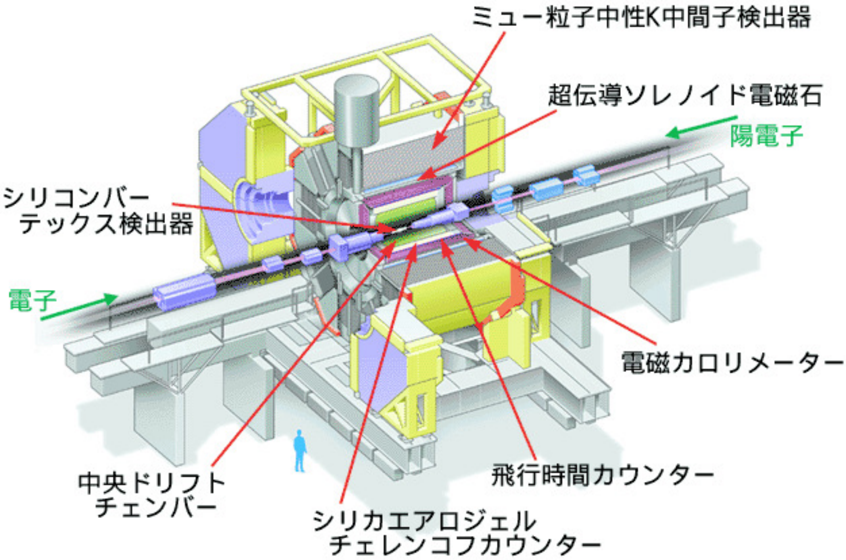
2-5 GB/s to storage


LHCb
YCMM01
UX85

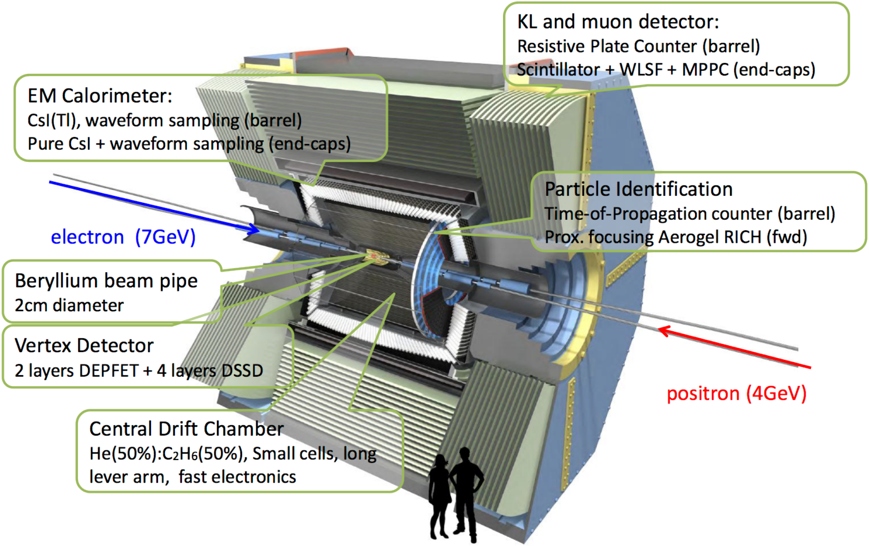
Hackathon

[Belle, NIM A479 (2002) 117]

The Belle Experiment

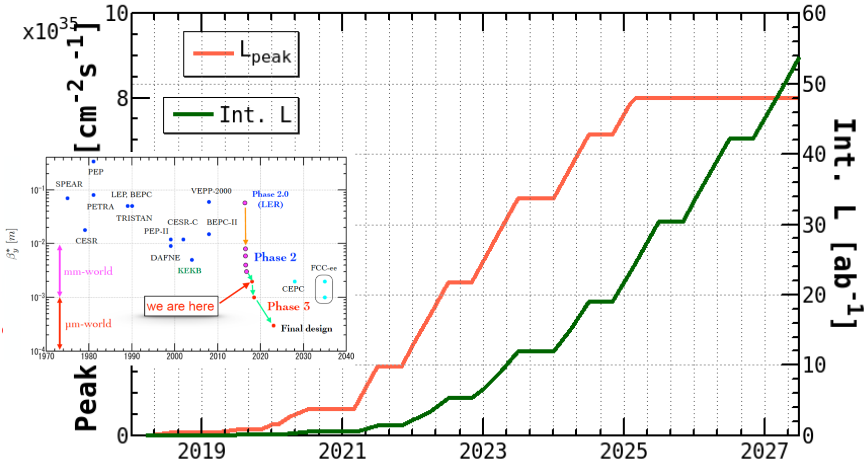


Belle II

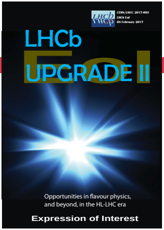


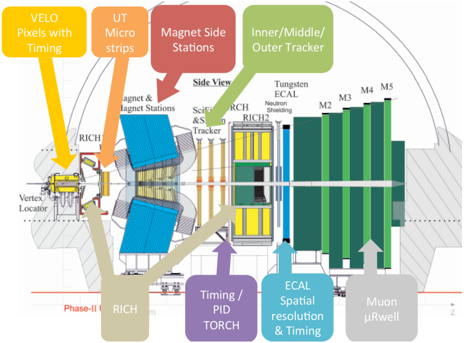
KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)
EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)
electron (7GeV)
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)
Beryllium beam pipe
2cm diameter
Vertex Detector
2 layers DEPFET + 4 layers DSSD
positron (4GeV)
Central Drift Chamber
He(50%):C2H6(50%), Small cells, long lever arm, fast electronics

Belle II Schedule



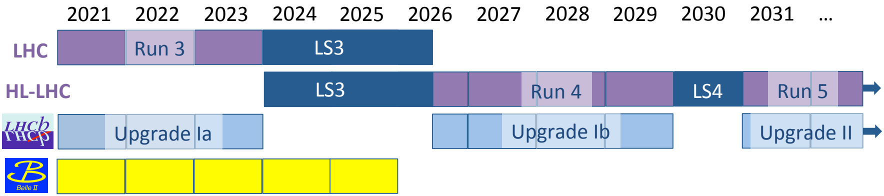
EoI for Phase-II Upgrade





We have expressed an interest for a Phase-II upgrade [CERN-LHCC-2017-003] .

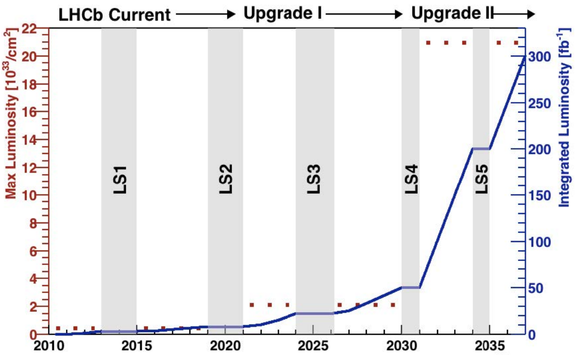
The physics case is [arXiv:1808.08865].



LHCb Phase-II Upgrade

The plan is to record 300 fb^{-1} by the end of Run 5.

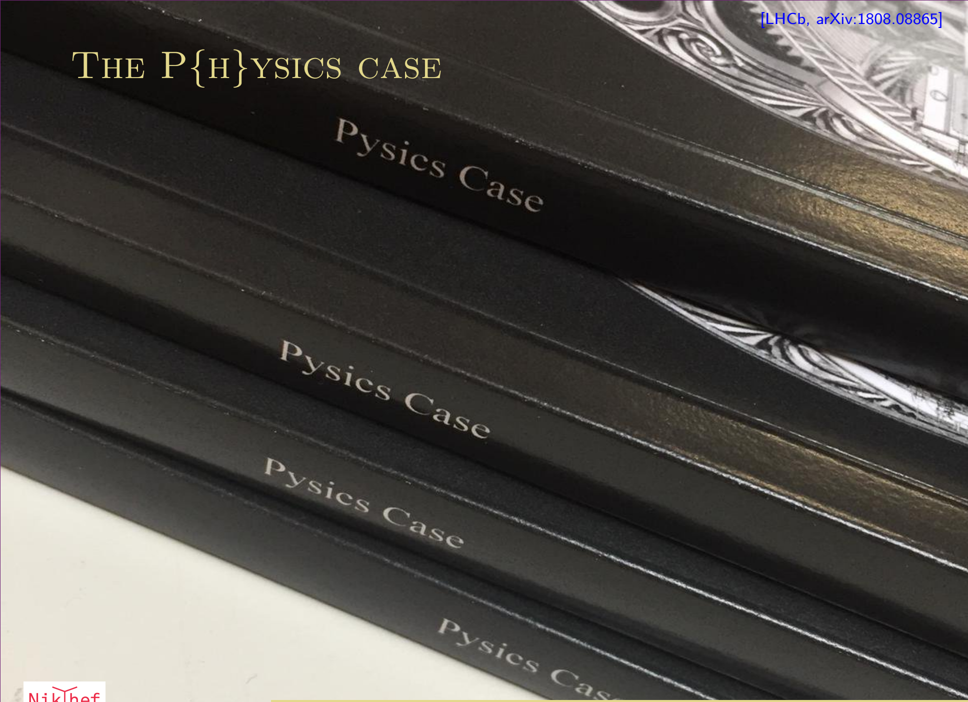
1. EoI [CERN-LHCC-2017-003]
2. Physics case [LHCb, arXiv:1808.08865]
3. LHCC has approved LHCb to proceed to a framework TDR (2021)



Join us at the open Upgrade-II meeting in Spring 2020 in Barcelona!

- Possibility to join as technical associate group.

The P{h}ysics case



Conclusion

- ✗ Lepton flavour violation is not seen
- ✔ There is a pattern of 2–4σ deviations in lepton flavour universality tests
  - Hints of something new?
  - Something else not understood?
  - → Upgraded LHCb and Belle II will check

Backup

B_s^0 MIXING AND $b \to s\ell^+\ell^-$ ANOMALIES

$$\Delta M_s \equiv M_H^s - M_L^s = 2\left|\frac{G_F^2}{12\pi^2}\lambda_t^2 M_W^2 S_0(x_t) B f_{B_s}^2 M_{B_s}\hat{\eta}_B\right|$$

gets [Artuso, Borissov, Lenz, RMP88 (2016) 045002]

$$\Delta M_s^{\mathrm{SM},\,2015} = (18.3 \pm 2.7)$$

and experiment [HFlav]

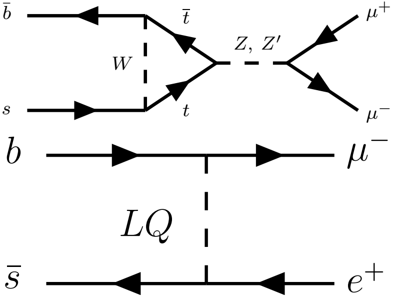
$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

but with latest lattice [FermiLab/MILC, PRD93, 113016 (2016)]

$$\Delta M_s^{\mathrm{SM},\,2017} = (20.01 \pm 1.25)\ \mathrm{ps}^{-1}$$

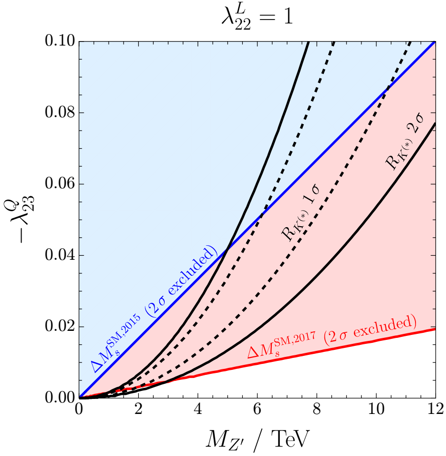
which is 1.8σ away. Could the same NP explain this and the B anomalies?

B_s^0 MIXING AND $b \to s\ell^+\ell^-$ ANOMALIES



New physics in $b \to s\ell^+\ell^-$ transitions, this is $(\bar{b}s)(\ell^+\ell^-)$ necessarily affects B_s^0 mxing at some level.

But the constraints are the wrong way.



Constraints from B_s^0 mixing and R_K on Z' mass and coupling.

Lepton Universality in $B^+ \to K^+\ell^+\ell^-$

Using 2011–12 and 2016 data we get

$$R_K = 0.846\,^{+\,0.060}_{-\,0.054}\,^{+\,0.016}_{-\,0.014}$$

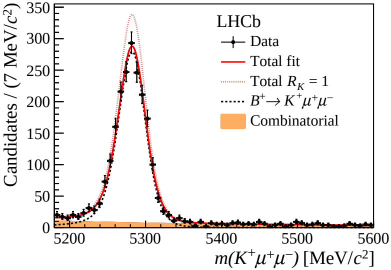
(2.5σ from the SM)

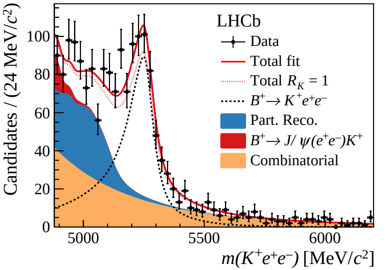
The Run 1 result is consistent with $0.745\,^{+\,0.090}_{-\,0.74} \pm 0.036$ [PRL 113 (2014) 151601]

$$R_K^{7\text{–}8\,\text{TeV}} = 0.717\,^{+\,0.083}_{-\,0.071}\,^{+\,0.017}_{-\,0.016}$$

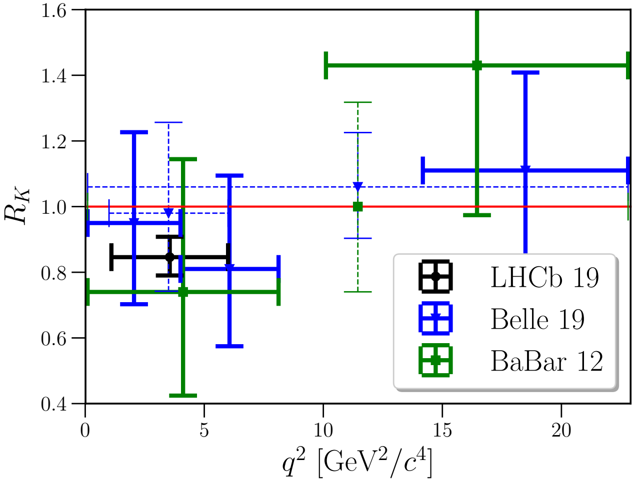
$$R_K^{13\,\text{TeV}} = 0.928\,^{+\,0.089}_{-\,0.076}\,^{+\,0.020}_{-\,0.017}$$

The BF of $B^+ \to K^+e^+e^-$ in $1.1 < q^2 < 6\,\text{GeV}^2/c^4$ is $(28.6\,^{+\,2.0}_{-\,1.7} \pm 1.4) \times 10^{-9}$



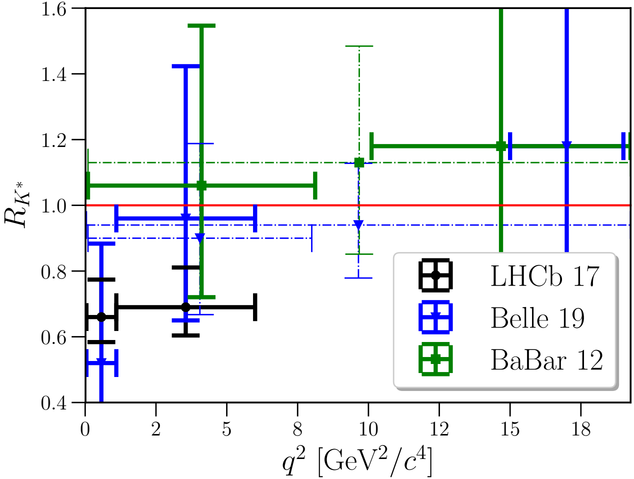


R_K



LHCb [PRL 122 (2019) 191801]. Belle [arXiv:1908.01848]. BaBar [PRD 86 (2012) 032012].

R_{K^*}



LHCb [JHEP 08 (2017) 055] . Belle [arXiv:1904.02440] . BaBar [PRD 86 (2012) 032012].

Parked B sample at CMS

DAQ capacity exceeds computing capacity
→ park some data for later use

- CMS collected 10^{10} B events.
- Similar to LHCb's 2011 sample (caveats apply)

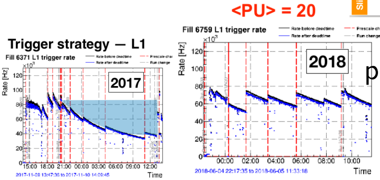
What we Have on Tape

Mode	N_{2018}	f_B [17]	$\mathcal{B}$
Generic B hadrons			
B_d^0	4.99×10^9	0.4	1.0
$B^\pm$	4.99×10^9	0.4	1.0
B_s	1.56×10^9	0.1	1.0
b baryons	1.56×10^9	0.1	1.0
B_c	1.25×10^7	0.001	1.0
B hadrons total	1.25×10^{10}	1.0	1.0
Interesting B decays			
$B^0 \to K^*\ell^+\ell^-$	3290	0.4	$\frac{2}{3} \times 9.9 \times 10^{-7}$ [14]
$B^\pm \to K^\pm\ell^+\ell^-$	2250	0.4	4.51×10^{-7} [15]

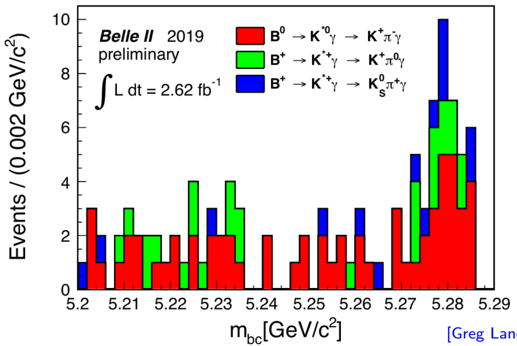
More than 20x the entire BaBar B sample collected in just 6 months!

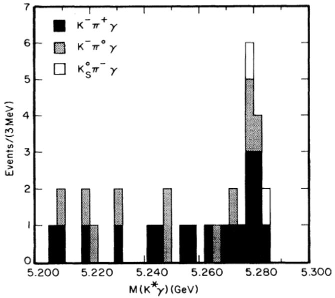
For other physics, the integrated luminosity of this sample is ~50 fb^{-1}

Greg Landsberg - Flavor Anomalies in CMS - Lyon September 2019 Slide 16



Approximate sample of b hadrons in parked sample **before** reconstruction and selection



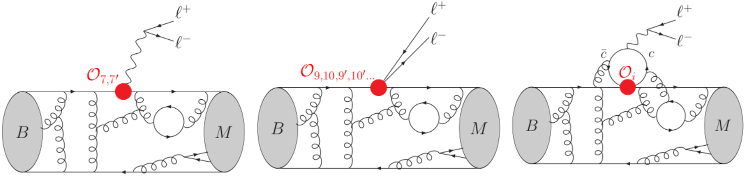


[Greg Landsberg, Lyon 4/9/19][CLEO, PRL 71 (1993) 674]

	signal yield (statistics only)	significance
$B^0 \to K^{*0}(\to K^+\pi^-)\gamma$	19.1 ± 5.2	4.4 σ
$B^+ \to K^{*+}(\to K^+\pi^0)\gamma$	9.8 ± 3.4	3.7 σ
$B^+ \to K^{*+}(\to K^0_S\pi^+)\gamma$	6.6 ± 3.1	2.1 σ

Two sources of hadronic uncertainties

$$A(B \to K^* \ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu)\bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



Form factors (local) Charm loop (non-local)

- Local contributions (here with SM $\mathcal{C}_i$): 7 form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s}\sigma_{\mu\nu} P_R b | B \rangle + \mathcal{C}_9 \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle$$

$$B_\mu = \mathcal{C}_{10} \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle \qquad \lambda : \ K^* \text{ helicity}$$

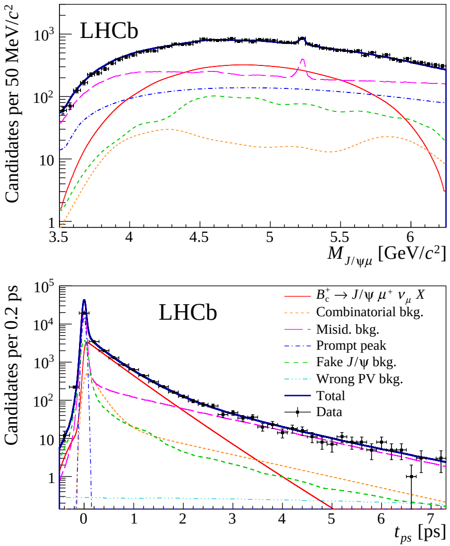
- Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

B_c^+ LIFETIME USING $B_c^+ \to J/\psi\, \mu\nu X$ DECAYS

Measurement of B_c^+ lifetime using semileptonic decays

- Use 2fb^{-1} 2012 data
- The difficulty is of course to understand the background shapes. . . but signal too
- Hence a systematically limited result $\tau = 509 \pm 8 \pm 12\,\text{fs}$, improving by more than a factor two compared to the world average

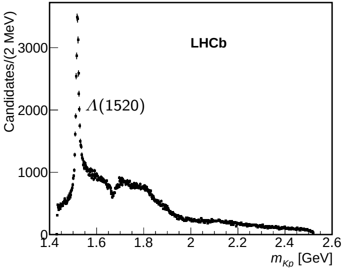


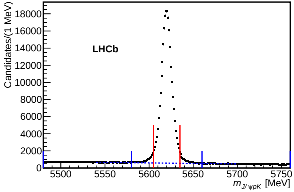
Observation of narrow pentaquarks

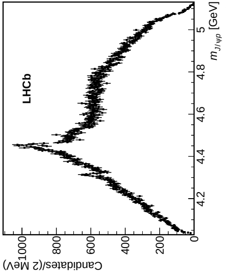
Update of Run 1 analysis [PRL 115 (2015) 072001]

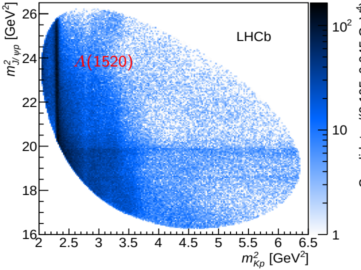
➜ Revisit this channel with an updated BDT: 246 000 $\Lambda_b^0 \to J/\psi\, pK^-$ decays (10 times Run 1) and 6.4% background.

- Reflections from B_s^0 vetoed
- Re-optimised BDT including PID (new)









Observation of narrow pentaquarks

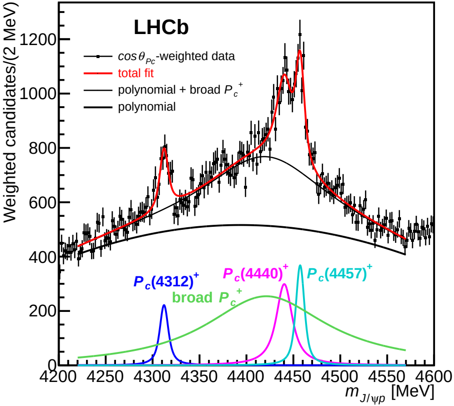
Three states are observed:

$P_c(4312)^+$ $\Gamma \sim 10\,\text{MeV}$ (7σ), which we could not see with $3\,\text{fb}^{-1}$

$P_c(4440)^+$ $\Gamma \sim 20\,\text{MeV}$ and

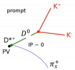
$P_c(4457)^+$ $\Gamma \sim 6\,\text{MeV}$. The significance of the 2-peak structure is 5.4σ

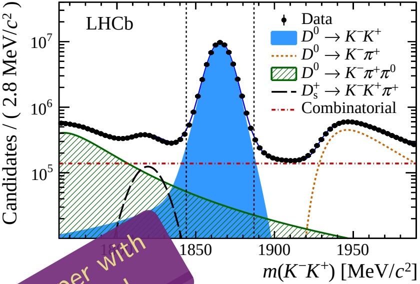
✗ No sensitivity to the wide $P_c(4380)^+$

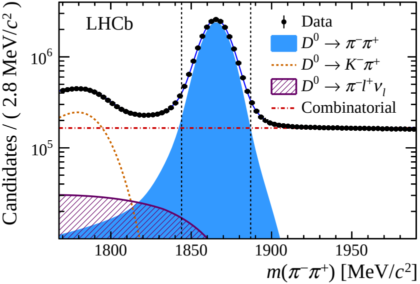


State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7\,^{+6.8}_{-0.6}$	$9.8 \pm 2.7\,^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07\,^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3\,^{+4.1}_{-4.7}$	$20.6 \pm 4.9\,^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33\,^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6\,^{+4.1}_{-1.7}$	$6.4 \pm 2.0\,^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16\,^{+0.15}_{-0.13}$

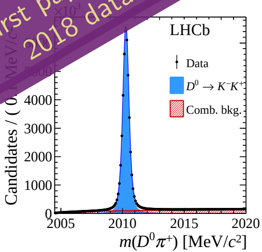
PROMPT $D^0 \to K^- K^+$ AND $D^0 \to \pi^-\pi^+$





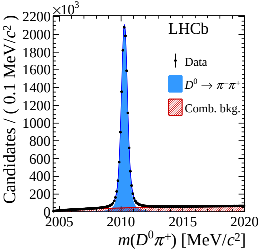


First paper with 2018 data!

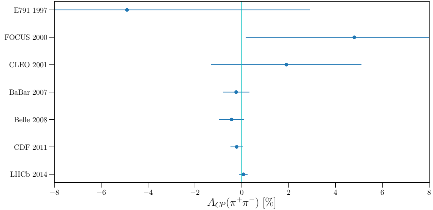


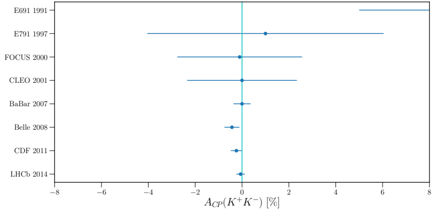
Combine $D^0 \to h^+h^-$ with a slow pion, both from a PV.

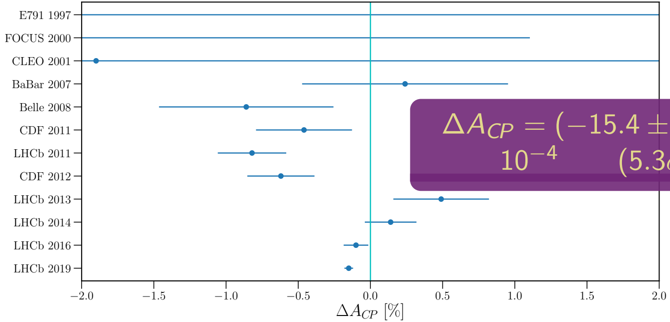
Find 44 million tagged $D^0 \to K^-K^+$ and 14 million $D^0 \to \pi^-\pi^+$ in 2015–18 data.



ΔA_{CP} History







$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \quad (5.3\sigma)$$