Challenging the Standard Model with LHCb data

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25. & 26. October 2016

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Deutsche Forschungsgemeinschaft DFG

erc

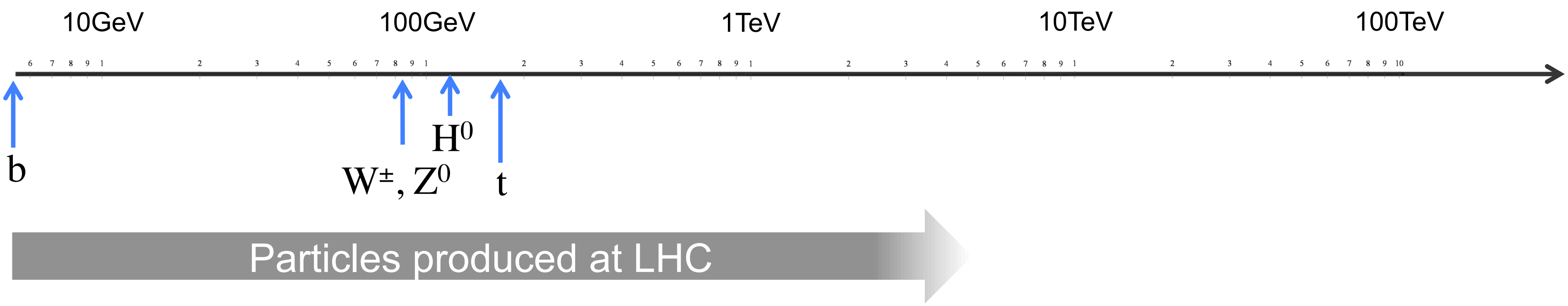
Indirect searches for New Physics

- High **energy**:
  “real” new particles can be produced and discovered via their decays
  - Discovery of the Higgs boson at the LHC → completion of the SM
  - **Tested scale : <10TeV**

- High **precision**:
  “virtual” new particles can be seen in quantum loops
  - Higher mass scale reachable (up to **~100TeV**)

Direct and indirect searches are both needed, both equally important, and complement each other

Searches for New Physics in Flavour



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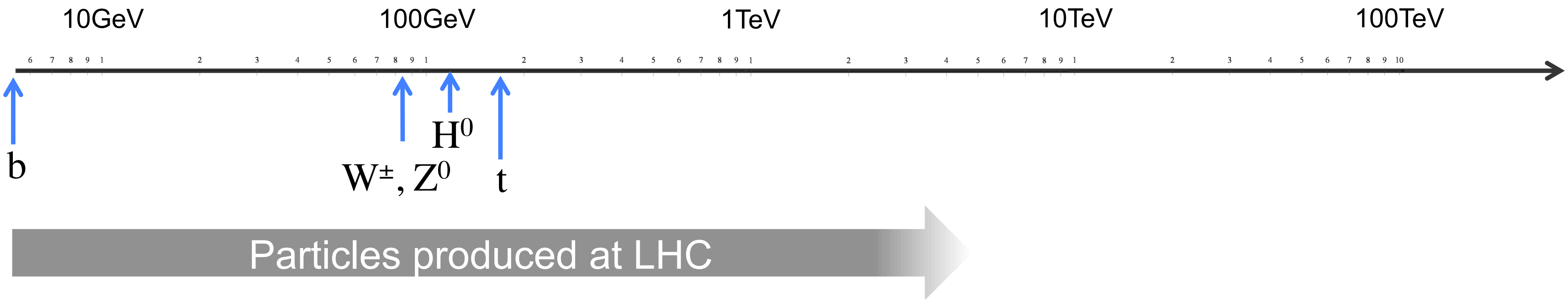
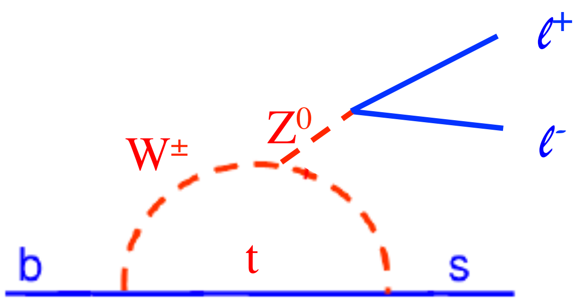
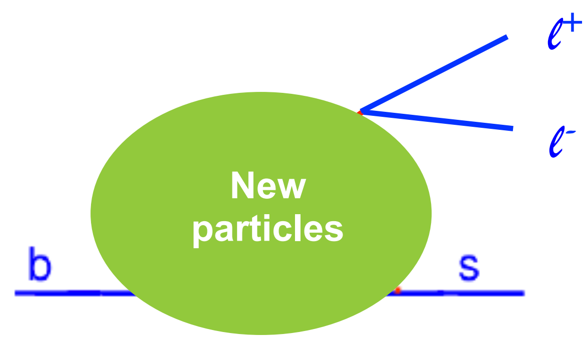
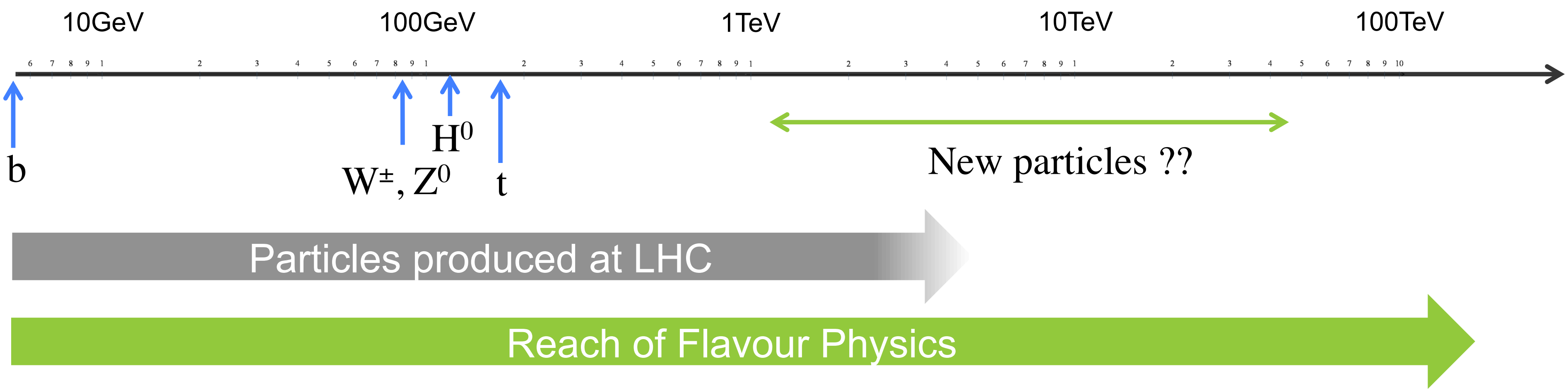


Flavour physics: Search for new heavy particles in precision measurements of quantum effects

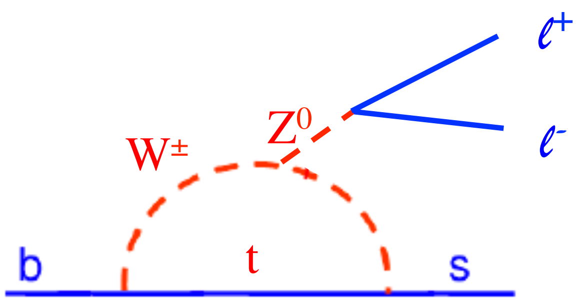


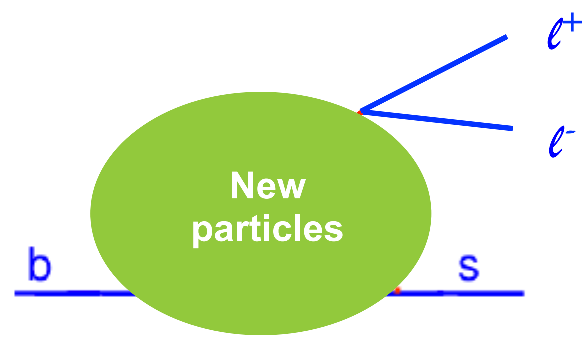


Searches for New Physics in Flavour



Flavour physics: Search for new heavy particles in precision measurements of quantum effects





Precision data is sensitive to new particles of masses up to **~100TeV**

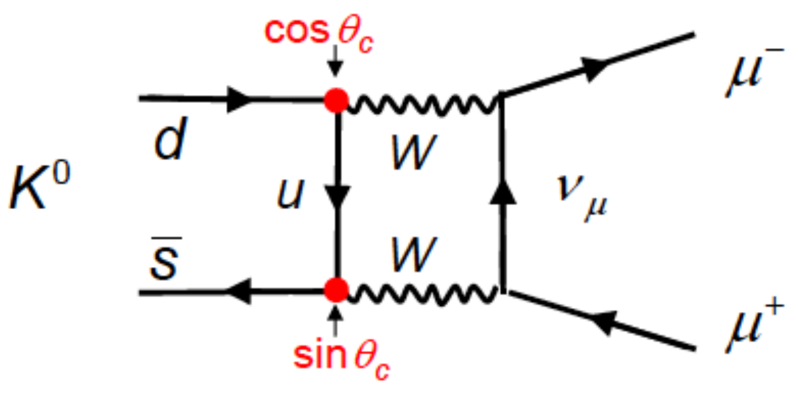
[A. Buras et al, JHEP1411(2014)121]

GIM Mechanism (1970)

Observed branching ratio $K^0 \to \mu\mu$

$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

In contradiction with theoretical expectation in the 3-Quark Model



$M \sim \sin\theta_c \cos\theta_c$

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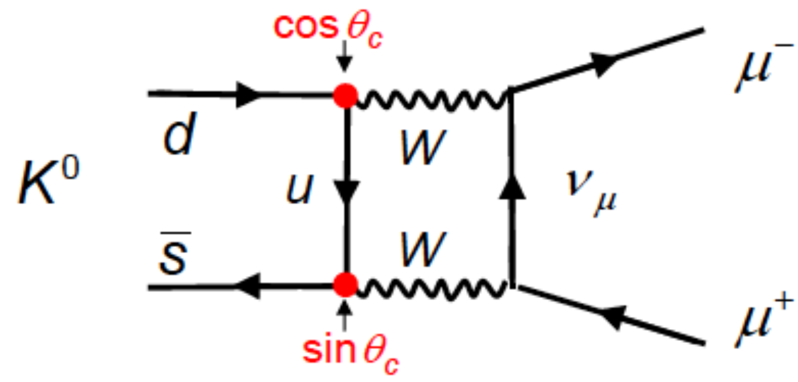
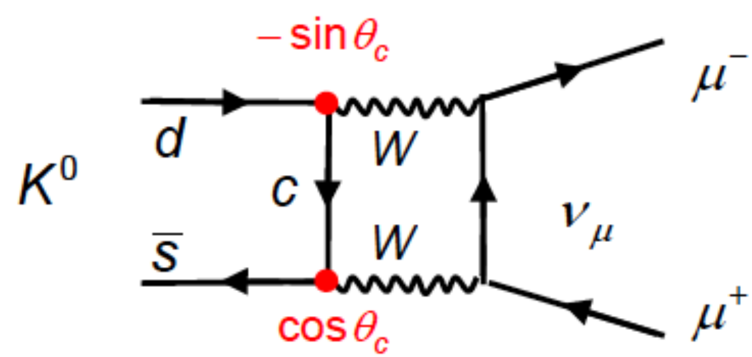
⬇

Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up-type quark, additional Feynman graph cancels the "u box graph".



$M \sim \sin\theta_c \cos\theta_c$



$M \sim -\sin\theta_c \cos\theta_c$

Examples from the past II

- The way to the top quark
  - 1972 Kobayashi & Maskawa: expect third generation 
  - 1977 Fermilab discovers b-quark → expect top as partner
  - 1987 Argus: B-mixing implies m_t > 50 GeV
  - before the top quark was discovered (< 1995):
    indirect mass determination → $m_t = 178 \pm 8\ ^{+17}_{-20}$ GeV

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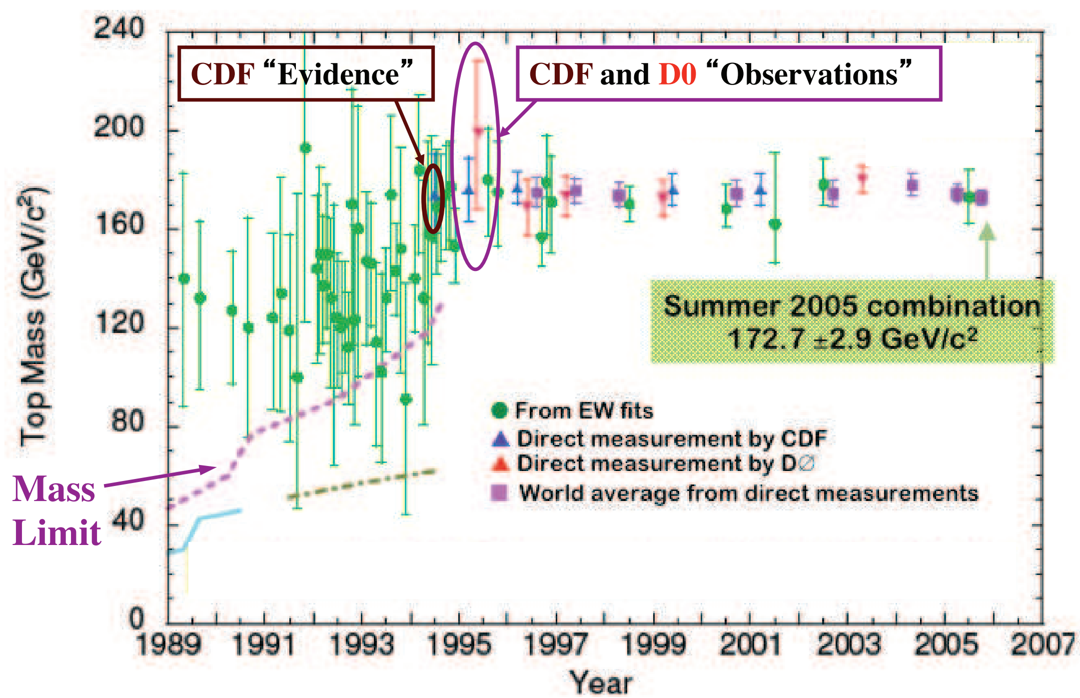
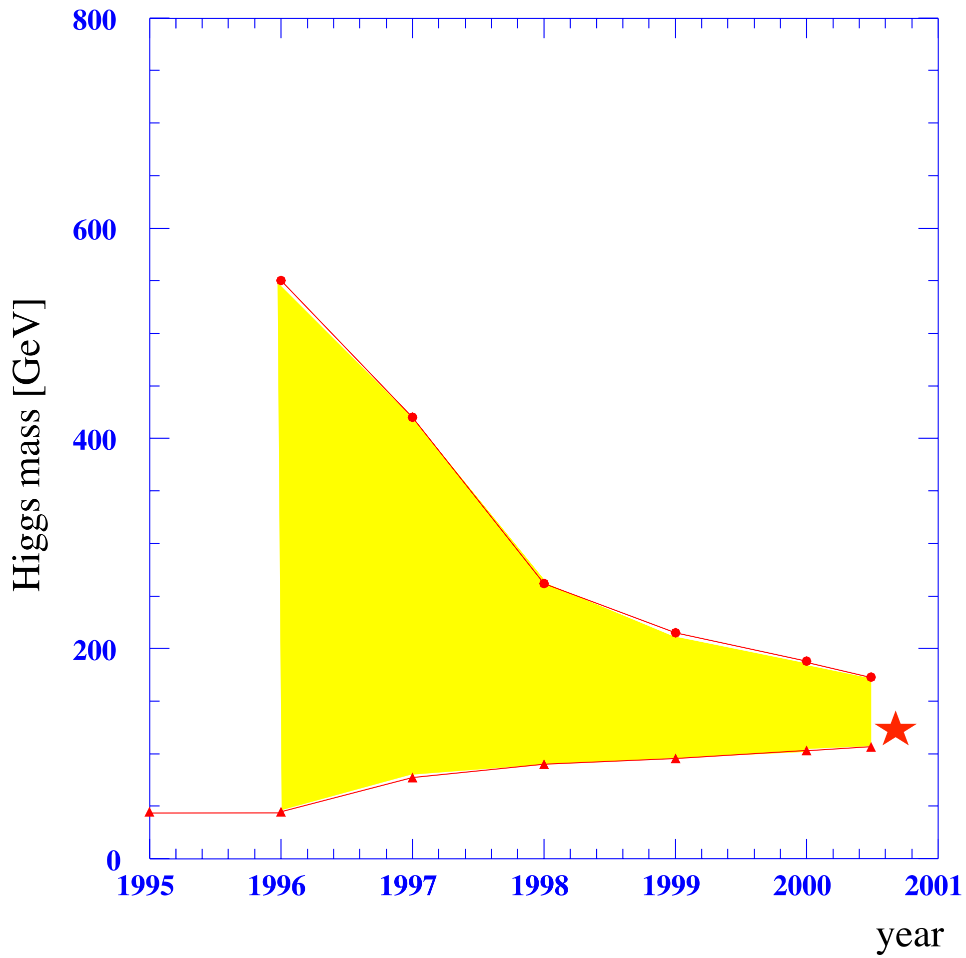
  - Top discovery Fermilab 1995: $m_t = 180 \pm 12$ GeV
  - Today: $m_t = 173.2 \pm 0.8$ GeV [PDG16]



Examples from the past III

- The way to the Higgs Boson:
  - You know all the details!

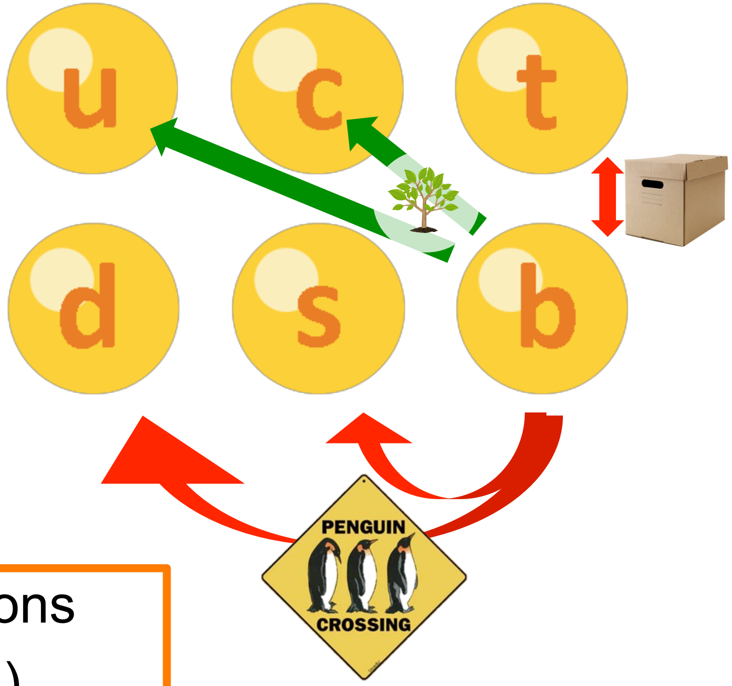


Pre-discovery (2011)
$m_H = 94^{+29}_{-24}$ GeV

ATLAS & CMS (2016):
$m_H = 125.09 \pm 0.24$ GeV

Beauty quarks: ideal for precision studies

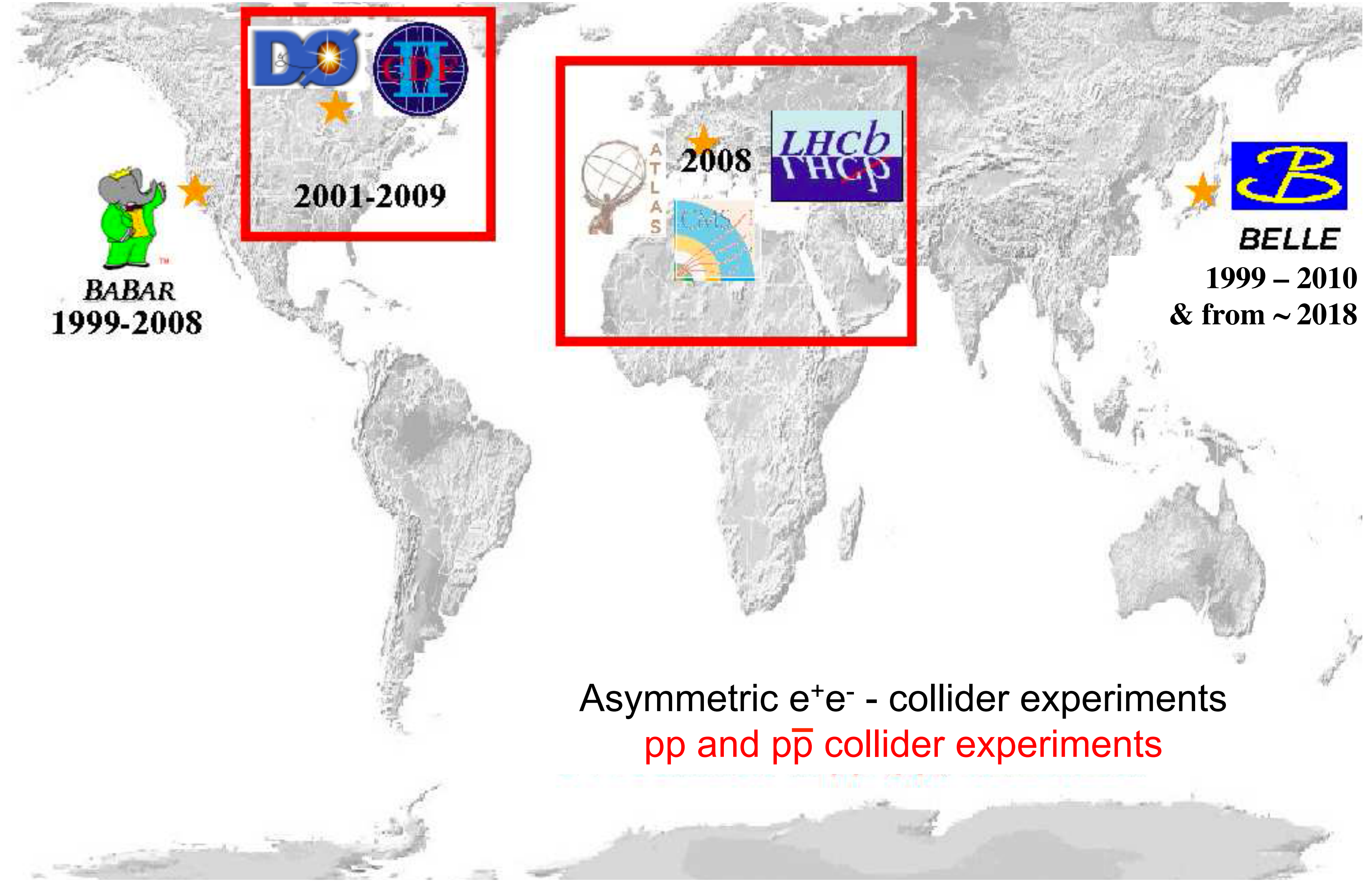
- The beauty quark …
  - Is the heaviest quark that forms hadronic bound states
    → high mass: many accessible final states
  - Must decay outside the 3rd family
    - All decays are CKM suppressed
    - Long lifetime (~1.6ps)



- Beauty-decays:
  - Dominant decay process: "tree"
    b→c transition
  - Very suppressed "tree" b→u transition
  - FCNC "penguin" b-> s and b→ d transitions
  - Flavour oscillations (b→t "box" diagrams)
  - CP violation

Focus of todays seminar

B–Physics Around the World



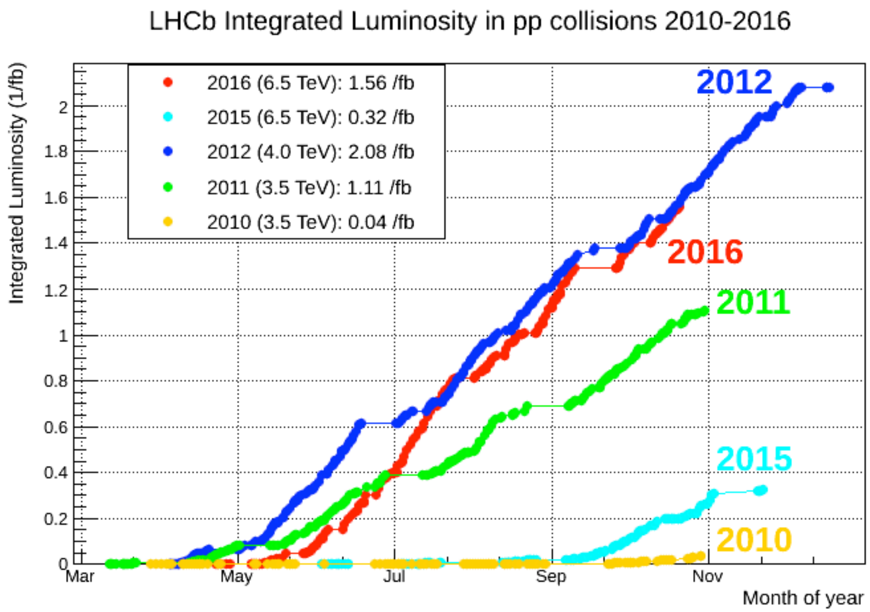
Asymmetric e^+e^- - collider experiments

pp and $p\bar{p}$ collider experiments

Large Hadron Collider

LHCb and beauty production

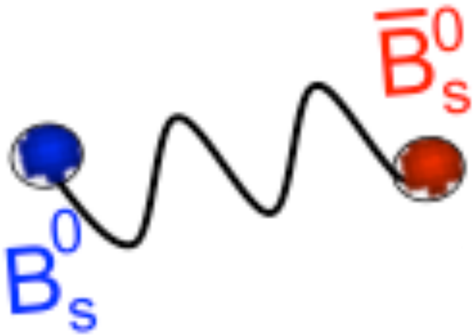
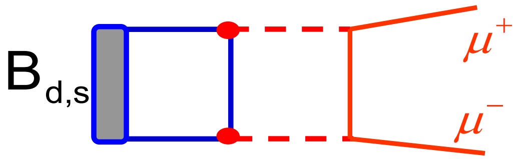
- Proton collisions at 7-13TeV: huge heavy flavour production cross sections
  - In LHCb acceptance: 75kHz bb and 1.5MHz cc
  - ~1/10 events contains b or c signal



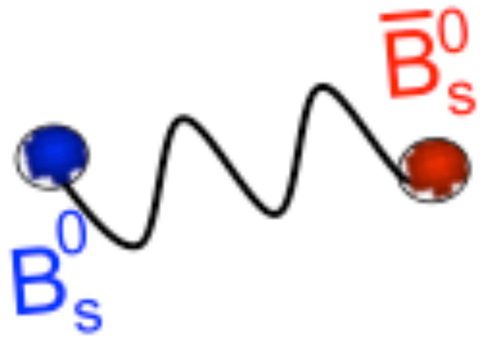
Experiment	$\int \mathcal{L}\, dt$ [fb^{-1}]	σ_{beauty} [μb]	End of life
BaBar	530 (total)	0.001 [e^+e^- at $\Upsilon(4S)$]	2008
Belle	1040 (total)	0.001 [e^+e^- at $\Upsilon(4S)$]	2010
CDF/D0	12 (total)	100 [$p\bar{p}$ at 2 TeV]	2011
ATLAS/CMS	55 (so far)	250-500 [pp at 7-13 TeV]	> 2030
LHCb*	>5 (so far)	250-500 [pp at 7-13 TeV]	> 2030

Test of fundamental interactions

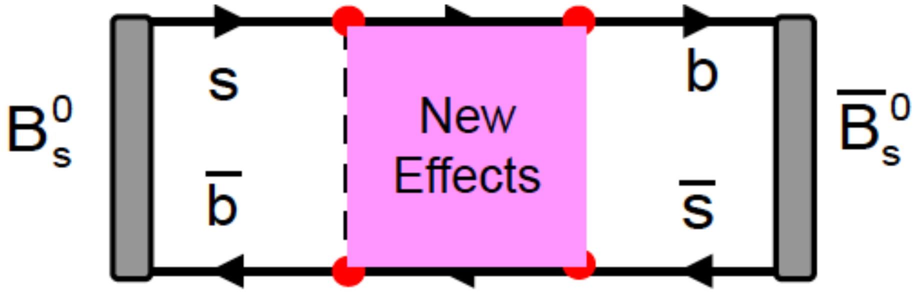
- A few selected highlights

CP violation	Rare decays	Future outlook
 B_s mixing and CP violation	 (Semi-) leptonic beauty decays	

CP violation



B_s mixing and
CP violation



$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \left(\mathbf{M} + i\frac{\mathbf{\Gamma}}{2} \right)\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Flavor states B_s & $\bar{B}_s$ $\neq$ mass states B_H & B_L

Observables:

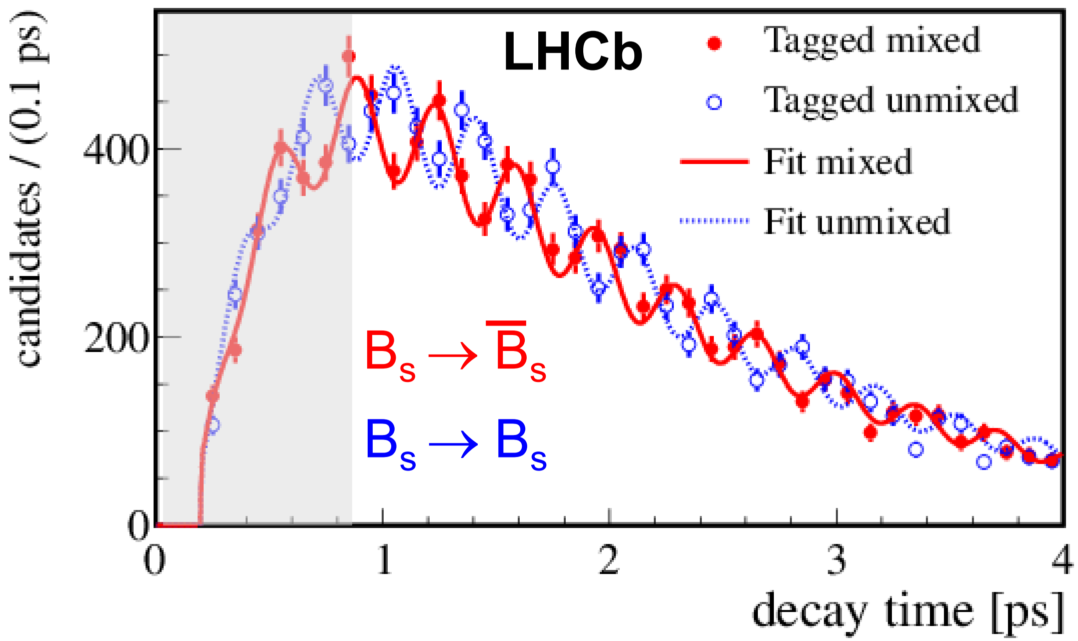
Δm_s = Mixing frequency

$\Delta\Gamma_s$ = Decay width (lifetime) difference between B_H and B_L

ϕ_s = Phase: $A_{mix} = |A_{mix}|\, e^{-i\phi_s}$ $\rightarrow$ $\not{CP}$

Measurement of B_s mixing

New J. Phys. 15 (2013) 053021



$\Delta m_s = 17.768 \pm 0.023^{stat} \pm 0.006^{syst}\ ps^{-1}$

Standard Model: $\Delta m_s = 17.3 \pm 1.5$
(U. Nierste, 2012)

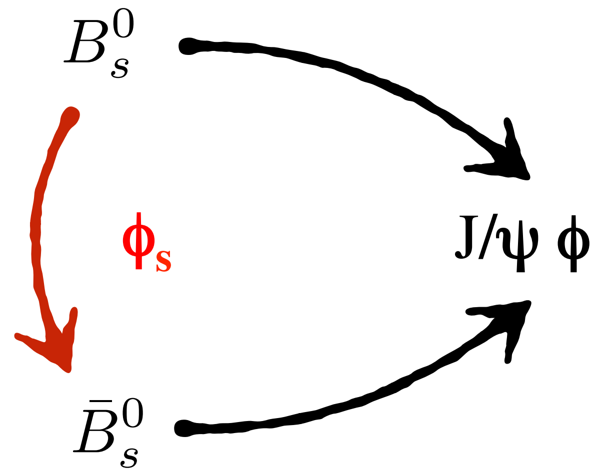
CP-violating phase ϕ_s

- Measure CP violating phase in $B_s \rightarrow J/\psi\ \phi$ decays

- Standard Model prediction:

$$\phi_s = -0.036 \pm 0.003$$

→ basically a NULL test



CP-violating phase ϕ_s

LHCb $\phi_s = 0.010 \pm 0.039$ PRL 114 (2015) 041801

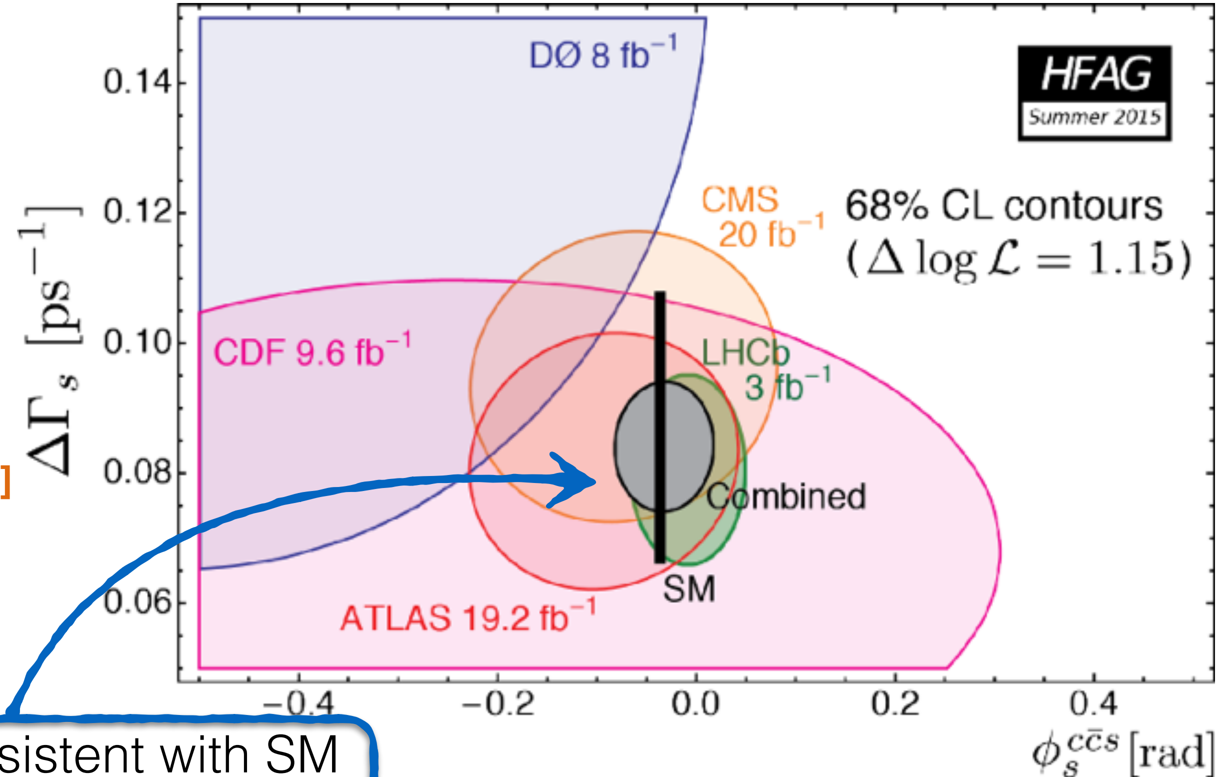
[D0, PRD 85 (2012) 032006]

[CDF, PRL 109 (2012) 171802]

[LHCb, PRL 114 (2015) 041801]

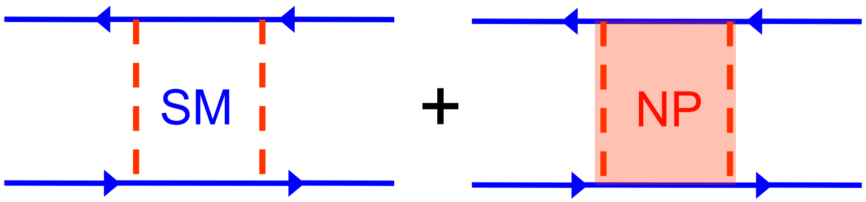
[CMS, CMS-BPH-13-012]

[ATLAS, EPS 2015]



results are consistent with SM

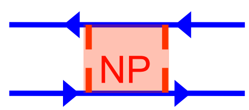
Still room for new physics



$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP}$$
$$= \mathcal{A}_{mix}^{SM} \cdot \Delta$$

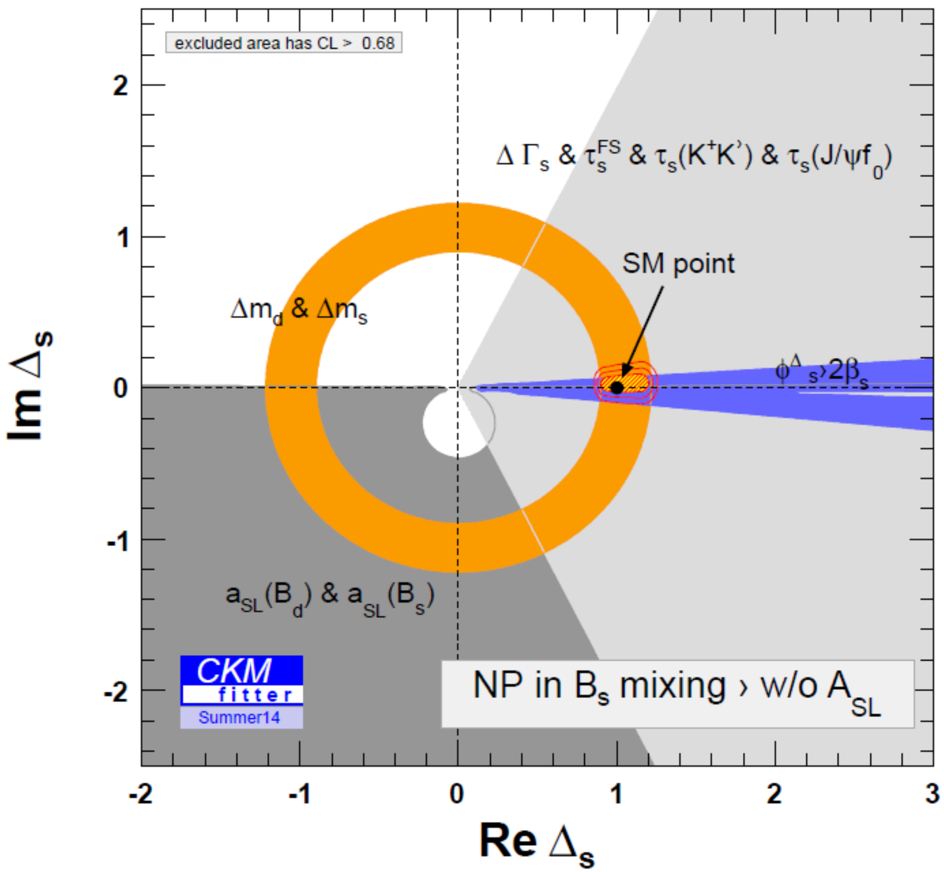
$B_s^0\ (\bar{b}s)$ < 20%

$B_d^0\ (\bar{b}d)$ < 30%



U. Nierste

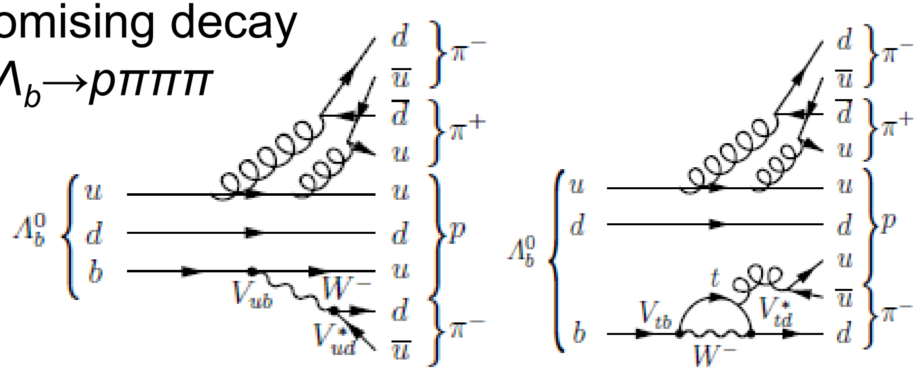
ckmfitter.in2p3.fr

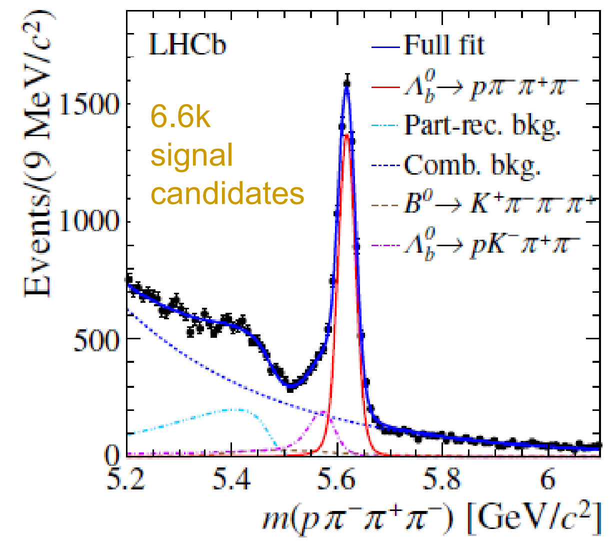


NEW: CPV with Baryons

CP violation in baryons has never been observed In the lab, although the universe manifests it very clearly - we are made of protons, not antiprotons !

One promising decay mode: $\Lambda_b \to p\pi\pi\pi$

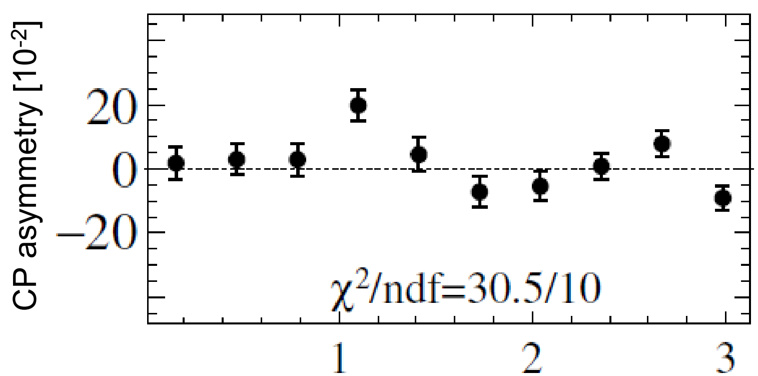




Search for *CP*-violating asymmetries in decay angle distributions of final state.

Study asymmetry in different configurations of final-state distribution (*e.g.* different bins of an angle between two decay planes)

Not compatible with horizontal line at 0



First ever evidence for *CP* violation in baryons; run-2 data can provide a clear discovery !

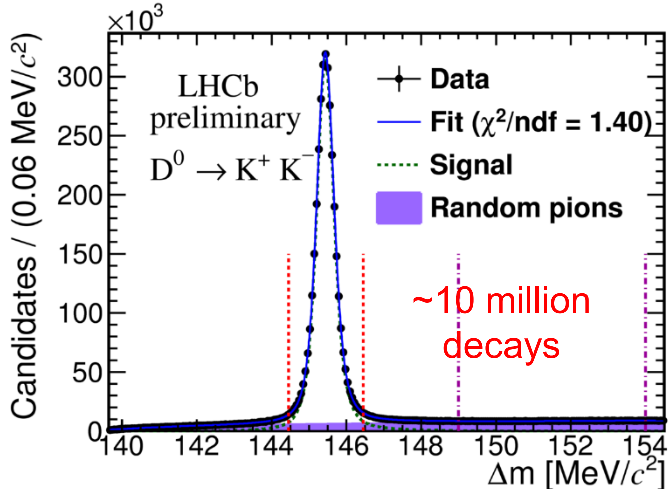
arXiv:1609.05216, submitted to Nature Physics

CP Violation in charm

LHCb has much larger samples in charm decays to charged tracks than any previous facility (and its supremacy here will remain unchallenged by Belle II).

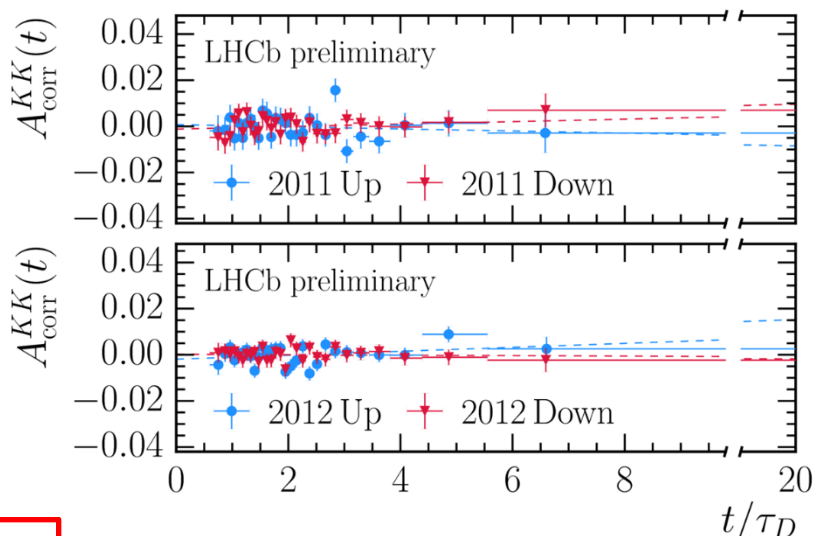
A key task is the search for indirect *CP*-violation in charm, so far undiscovered and predicted to be tiny in the SM. Look for time-dependent CP asymmetry, expressed in A_Γ parameter, in decay to *CP* eigenstate, such as $D^0 \rightarrow KK$ or $\pi\pi$.

Massive, clean & well-understood data sets.



$$A_\Gamma(D^0 \rightarrow K^+K^-) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$$
$$A_\Gamma(D^0 \rightarrow \pi^+\pi^-) = (\ \ 0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$$

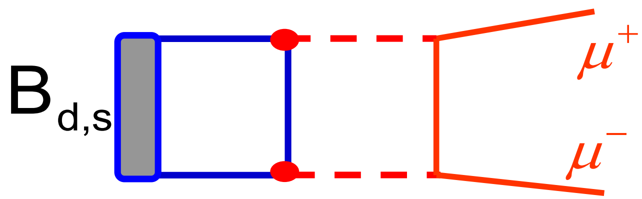
Results split by different years and magnet polarities (up, down)



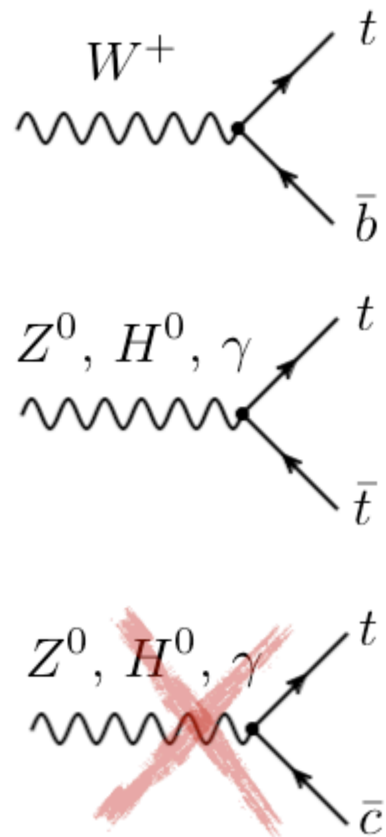
[LHCb-CONF-2016-009; LHCb-CONF-2016-010]

Consistent behaviour; no slope, which means no *CP* violation (yet !)

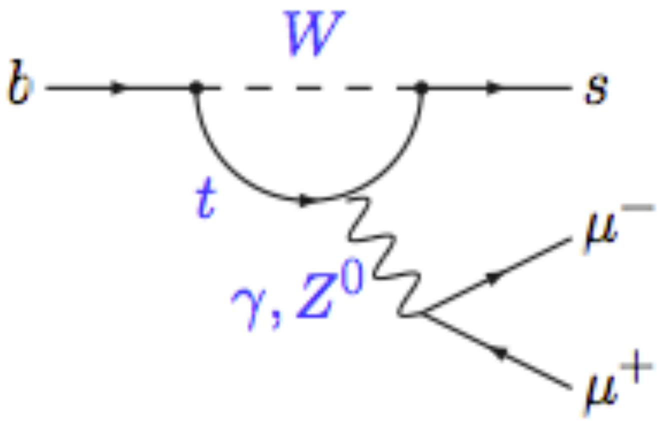
Rare decays

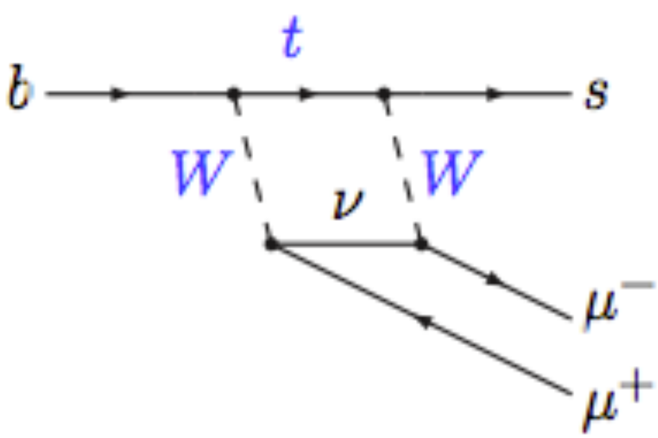


1) Leptonic decays
2) Semileptonic decays



$b \to s\, \mu^+\mu^-$ base diagram





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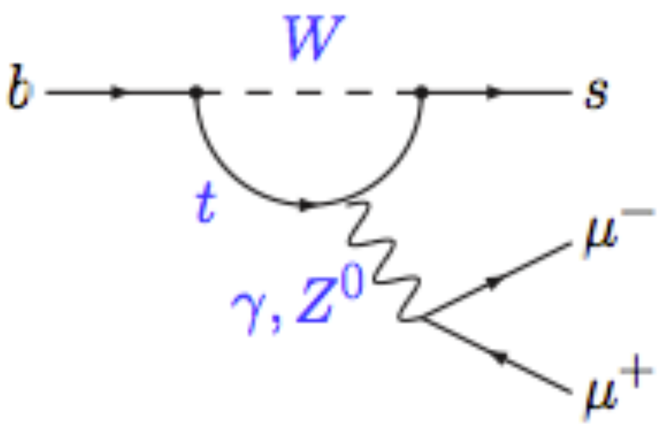
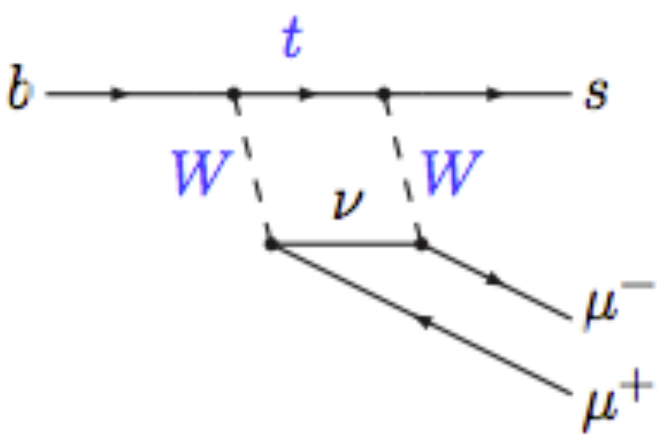




- Purely leptonic
  - "add nothing"
- Semileptonic
  - add d quark as spectator
    → $B^0 \to K^{*0}\, \mu^+\mu^-$
  - add s quark as spectator
    → $B_s \to \phi\, \mu^+\mu^-$
  - add u quark as spectator
    → $B^+ \to K^+\, \mu^+\mu^-$
- Ratios:
  - Compare muons to electrons

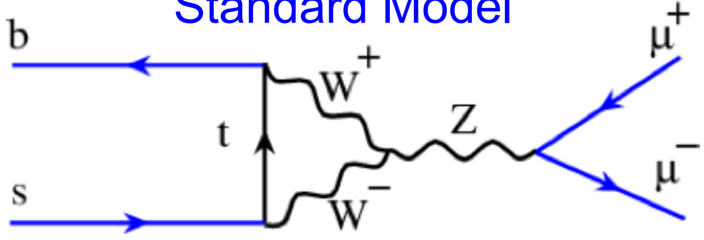
Golden channel: $B_{s,d} \to \mu^+\mu^-$

Theory prediction: Standard Model

decay	SM
$B_s \to \mu^+\mu^-$	$3.5 \pm 0.3 \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$1.1 \pm 0.1 \times 10^{-10}$

SM: Buras, Isidori et al: arXiv:1208.0934
Mixing effects: Fleischer et al, arXiv:1204.1737

Standard Model

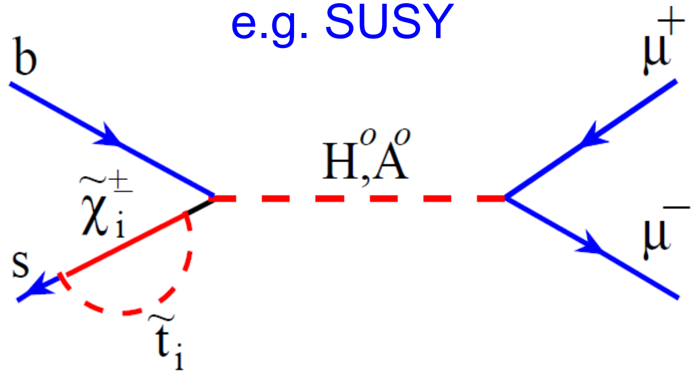


Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

➔ Very **sensitive to an extended scalar sector**
(e.g. extended Higgs sectors, SUSY, etc.)

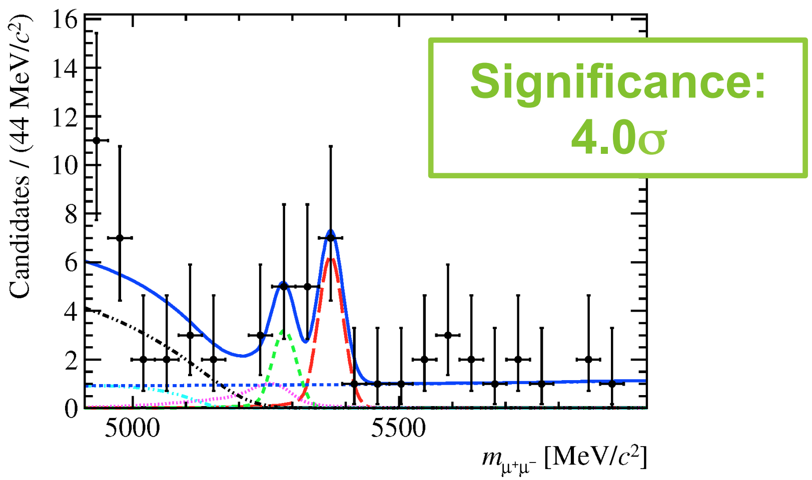
e.g. SUSY



New results for $B \to \mu^+\mu^-$

- **Nov 2012: LHCb found the first evidence for $B_s \to \mu^+\mu^-$ using 2.1fb^{-1}**
- Update: full dataset: 3fb^{-1}
  - Improved BDT
  - Expected sensitivity: 5.0σ

arXiv:1307.5024



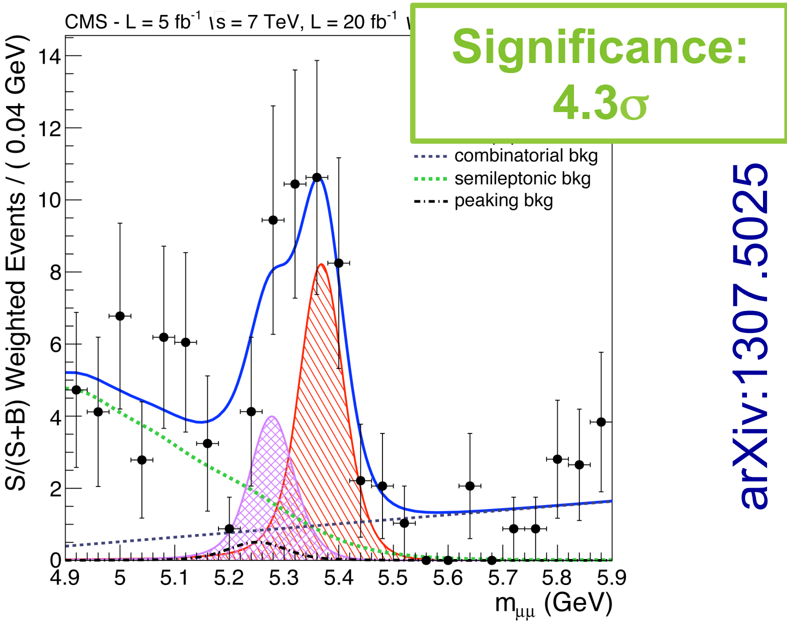
$$BR(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) < 0.7 \times 10^{-9} @ 95\%CL$$

- Update to 25fb^{-1}
  - Cut based → BDT based
  - Improved variables
  - Expected sensitivity: 4.8σ

arXiv:1307.5025



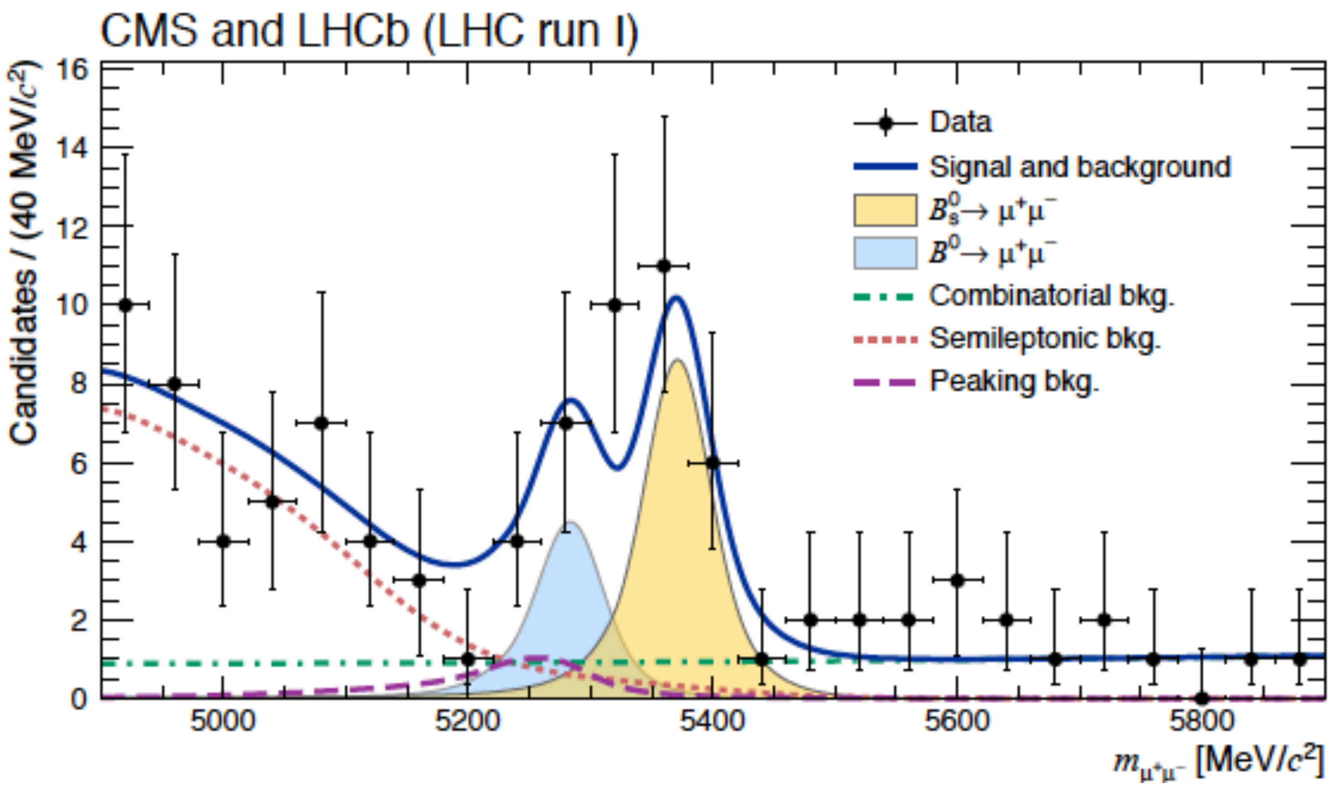
$$BR(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9} @ 95\%CL$$

First observation of $B_s \to \mu^+\mu^-$

OPEN
doi:10.1038/nature14474



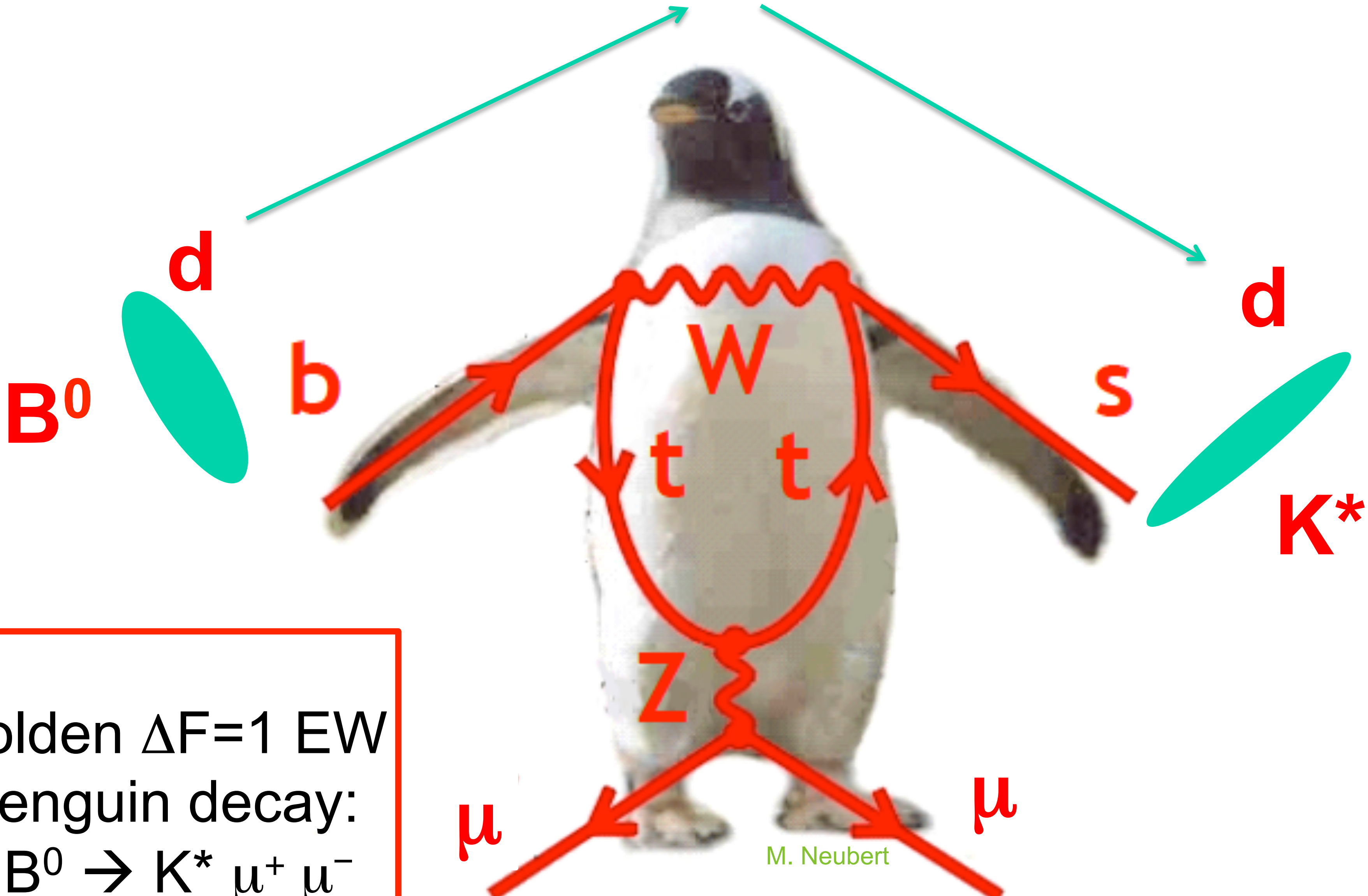
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \cdot 10^{-9}$$

6.2σ significance → first observation
- compatible with SM at 1.2σ

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

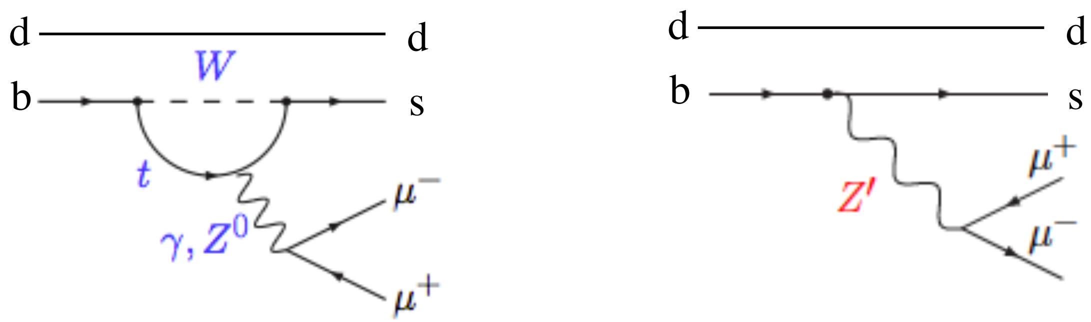
3.0σ significance → first evidence
- compatible with SM at 2.2σ

ΔF=1 Electroweak Penguins



Golden ΔF=1 EW penguin decay:
$B^0 \rightarrow K^* \mu^+ \mu^-$

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



$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}}\bigg|_P = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

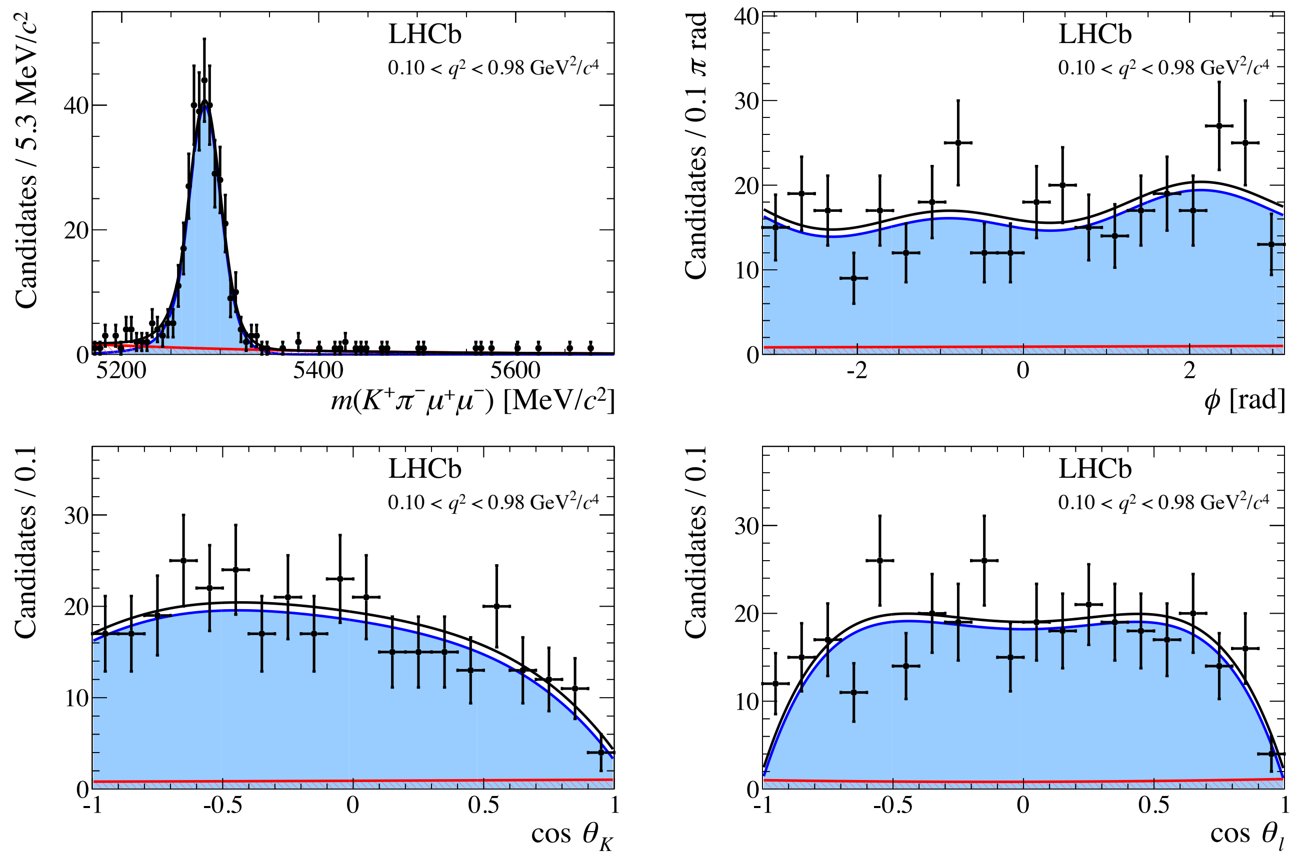
Observables depend on B→K* form factors and on short distance physics

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

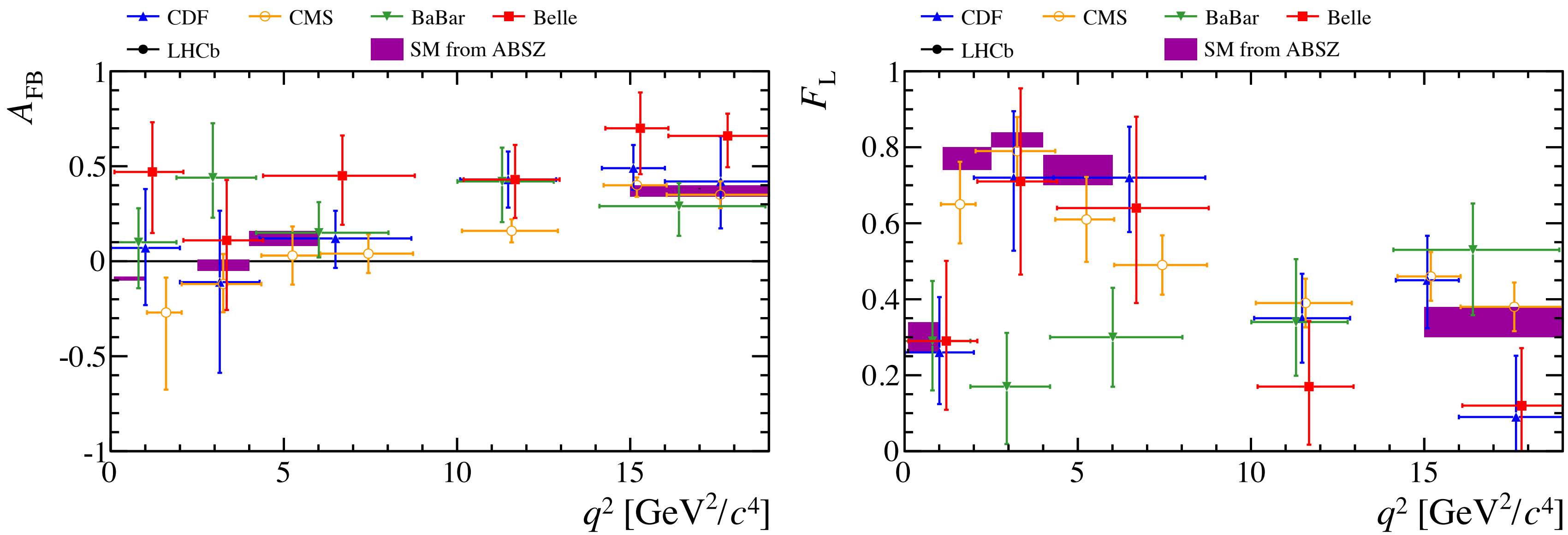
- LHCb published the first full angular analysis of the decay
  - Unbinned maximum likelihood fit to $K\pi\mu\mu$ mass and three decay angles
  - Simultaneously fit $K\pi$ mass to constrain s-wave configuration
  - Efficiency modelled in four dimensions
  - Binned in $q^2 = m_{\mu\mu}^2$

JHEP02(2016)104

Example fit projections in low q^2 bin

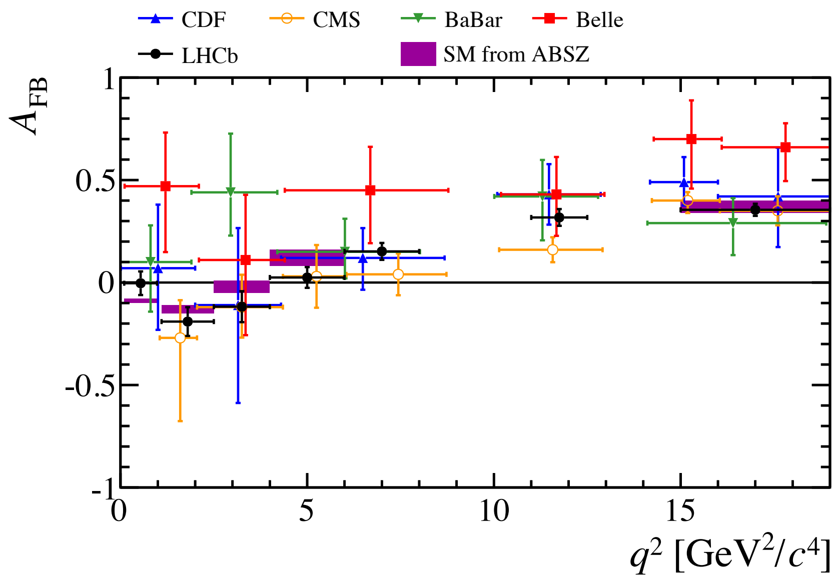


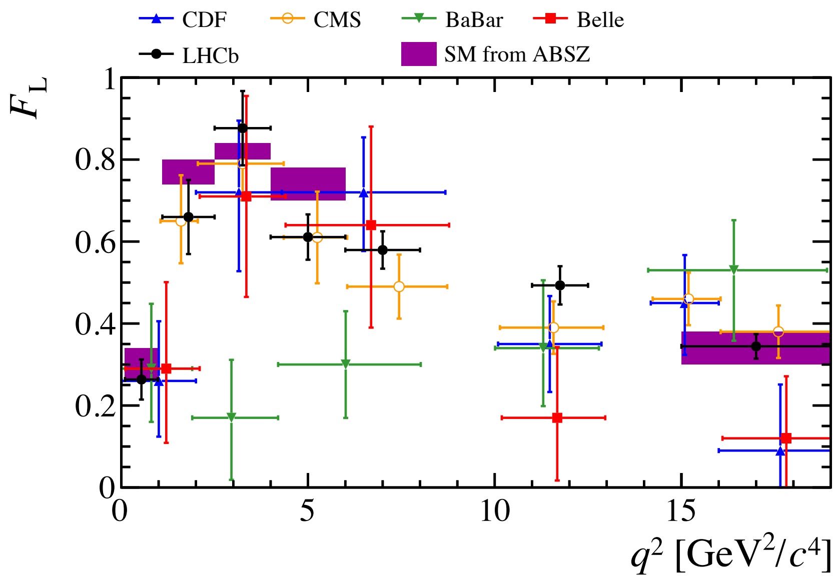
Results



References:
LHCb [JHEP 02 (2016) 104] ,
CMS [PLB 753 (2016) 424]
BaBar [arXiv:1508.07960]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801].

Results

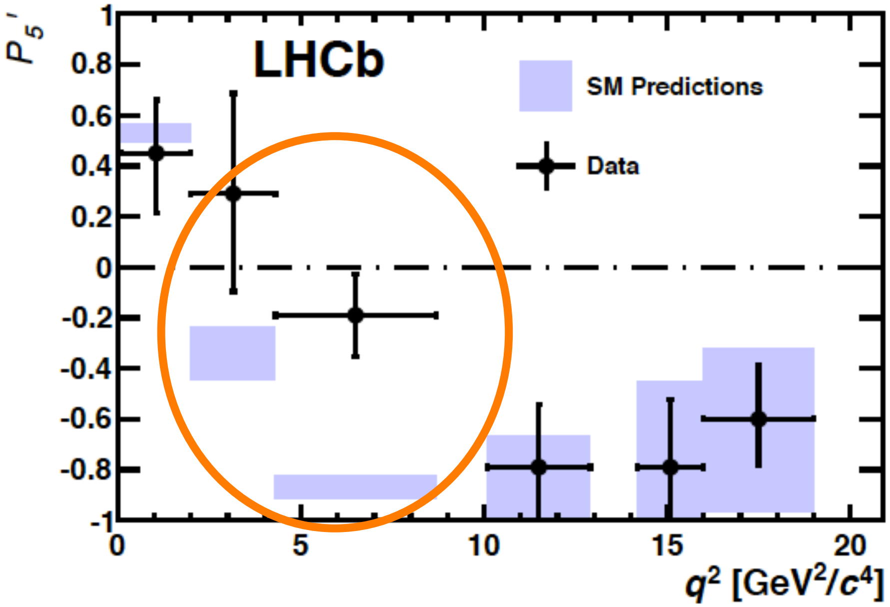




References:
LHCb [JHEP 02 (2016) 104] ,
CMS [PLB 753 (2016) 424]
BaBar [arXiv:1508.07960]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801].

- 2013, LHCb has observed a deviation in angular observables in $B^0 \rightarrow K^{*0} \mu^+\mu^-$ decays

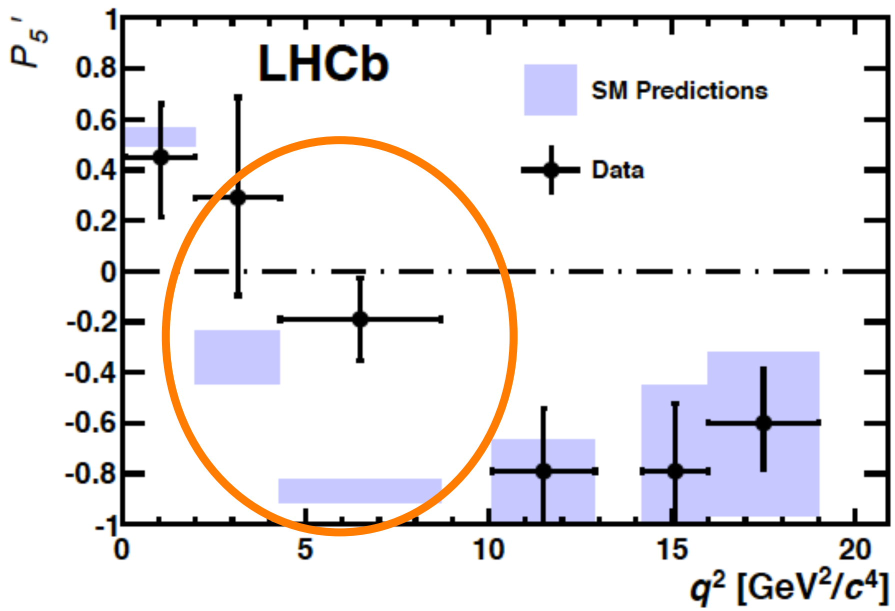
LHCb, Phys.Rev.Lett. 111 (2013) 191801

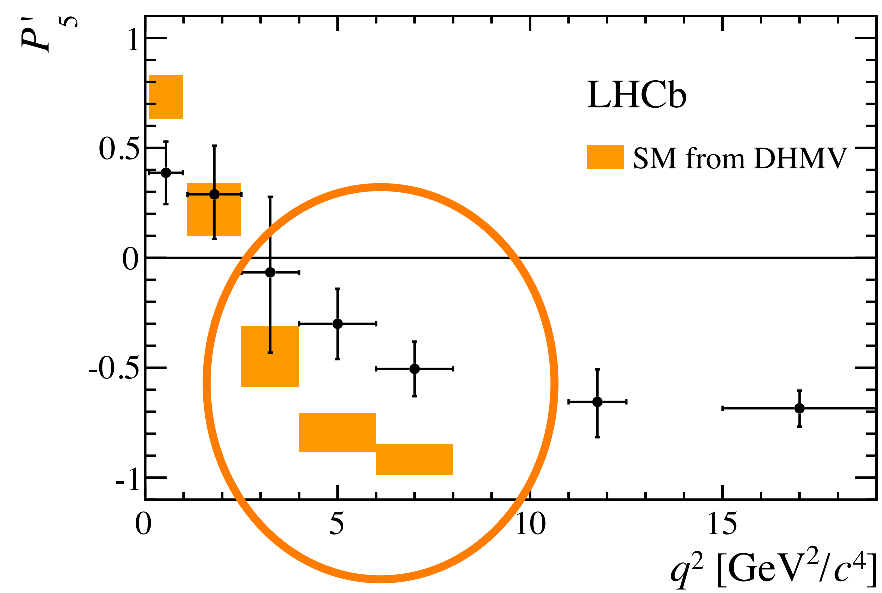


Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys.Rev.Lett. 111 (2013) 191801



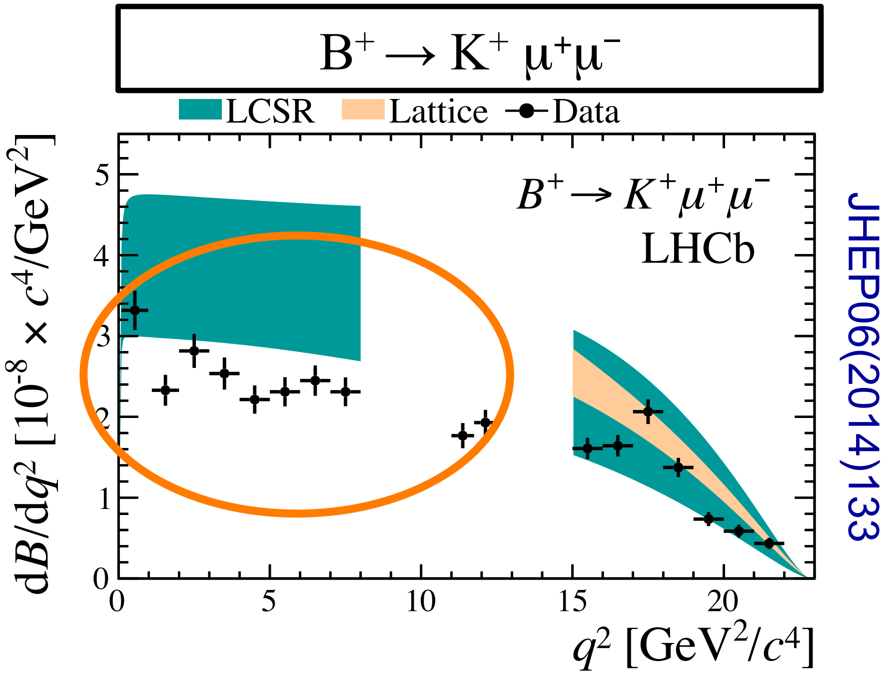


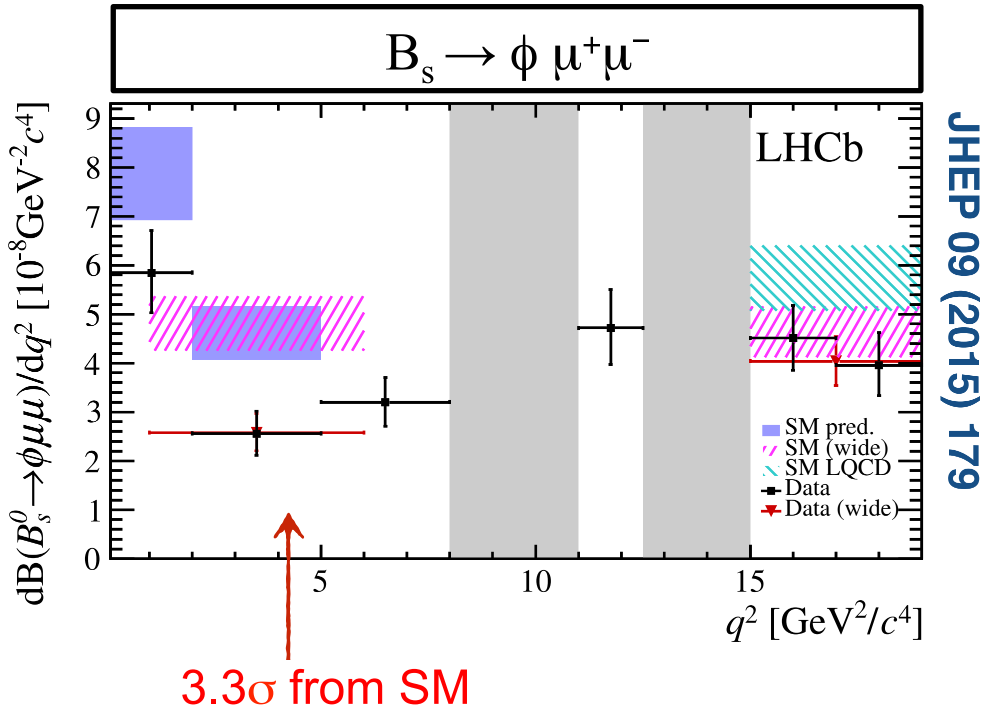
[LHCb, JHEP 02 (2016) 104]

- Full Run 1 analysis confirms effect

- If real, expect discrepancies in **other $b \to s$ decays** ..

Branching fractions of $b \rightarrow s\ \mu^+\mu^-$





- Analysis of large class of $b \rightarrow s\ \mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate

→ Perform global analysis

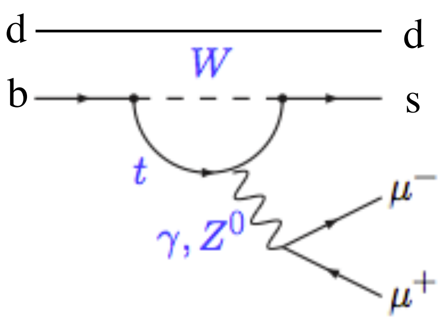
… later

SM predictions based on
[Altmannshofer & Straub, arXiv:1411.3161]
[LCSR form-factors from Bharucha et al. arXiv:1503.05534]
[Lattice prediction from Horgan et al. arXiv:1310.3722]

Lepton universality

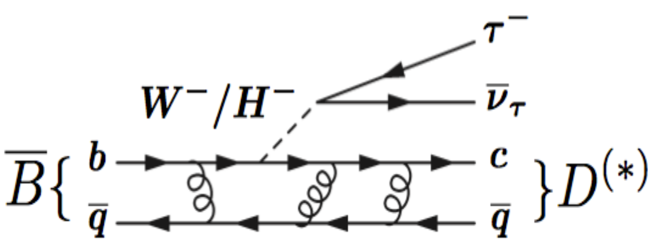
- In the SM, leptons couple universal to $W^{\pm}$ and Z^0
  → test this in ratios of semileptonic decays

<u>electrons / muons</u>



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

<u>tau / muons</u>



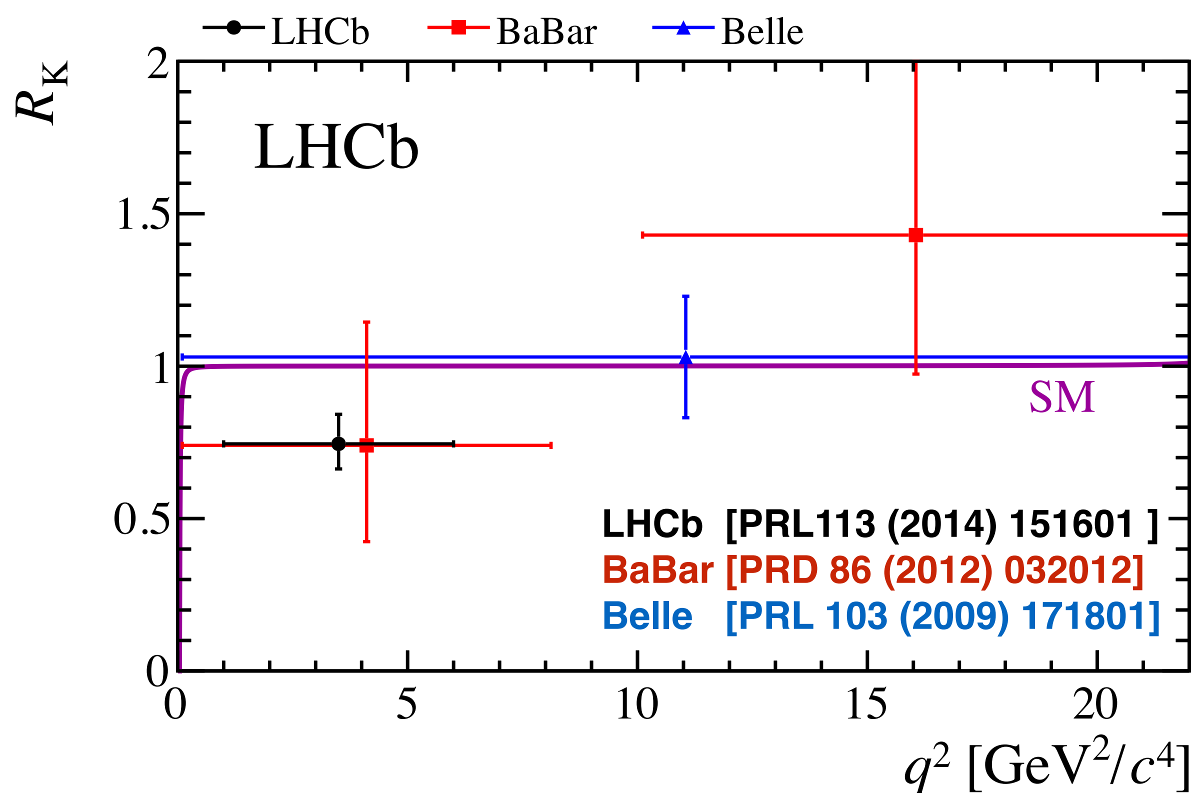
$$R_{D*} = \frac{BR(B^0 \to D^{*+} \tau^- \bar{\nu})}{BR(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

- Ratios differ from unity only by phase space
  → hadronic uncertainties cancel in the ratio

LHCb measures with $3fb^{-1}$

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745 \begin{matrix} +0.090 \\ -0.074 \end{matrix} (stat) \pm 0.036 (syst)$$

(SM: R_k=1.0, consistent at 2.6σ)



R(D) and R(D*)

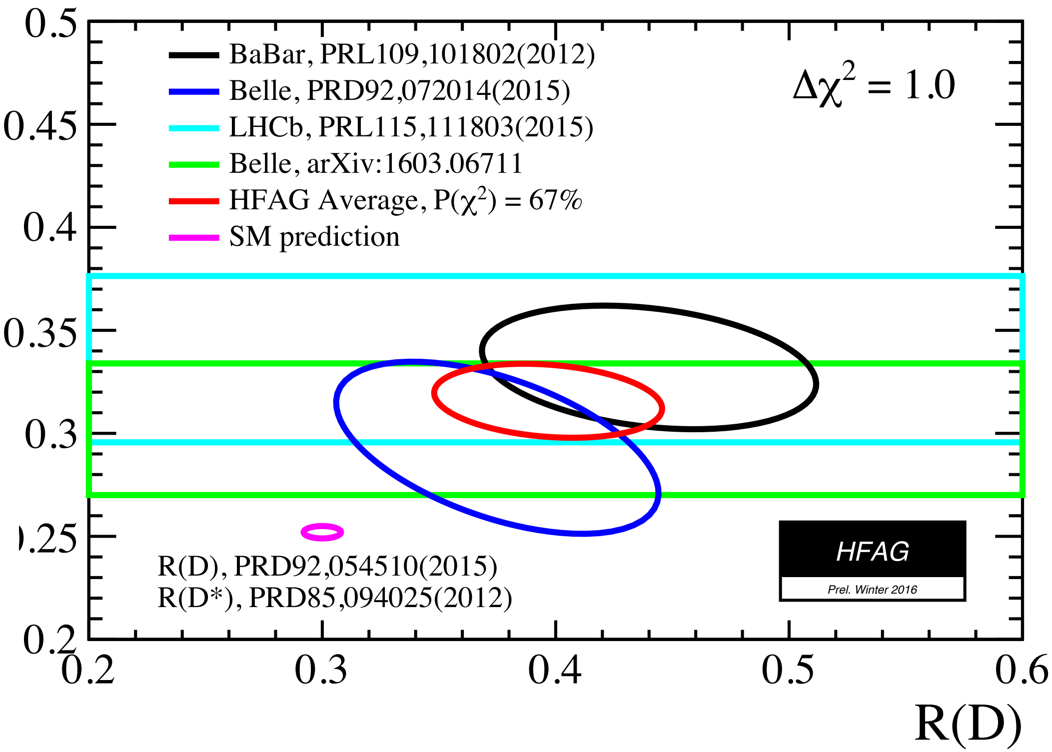
$$R_{D*} = \frac{BR(B^0 \to D^{*+} \tau^- \bar{\nu})}{BR(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

Belle

$$\mathbf{R(D) = 0.375 \pm 0.064 \pm 0.026}$$
$$\mathbf{R(D^*) = 0.293 \pm 0.038 \pm 0.015}$$

LHCb

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



- Combination is **3.9**σ from the SM expectation:

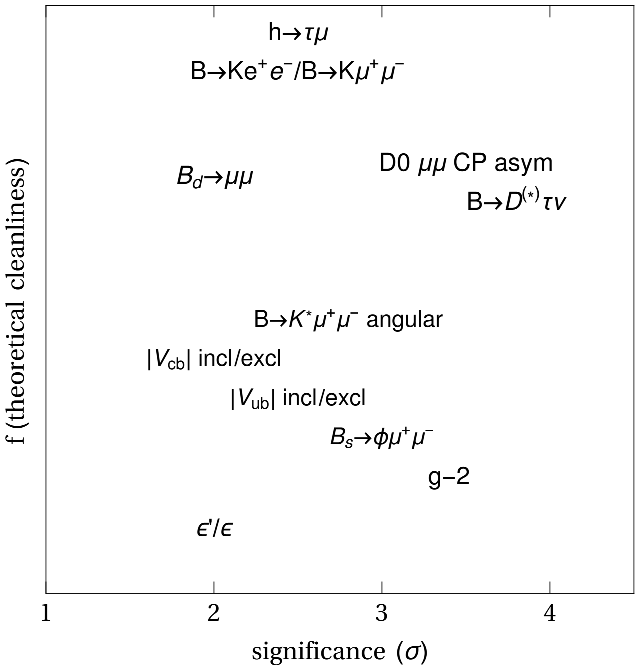
$$R(D) = 0.297 \pm 0.017 \quad , \quad R(D^*) = 0.252 \pm 0.003$$

[Kamenik et al. Phys. Rev. D78 014003 (2008), S. Jajfer et al. Phys. Rev. D85 094025 (2012)]

[3.9σ do not include newest Belle measurement]

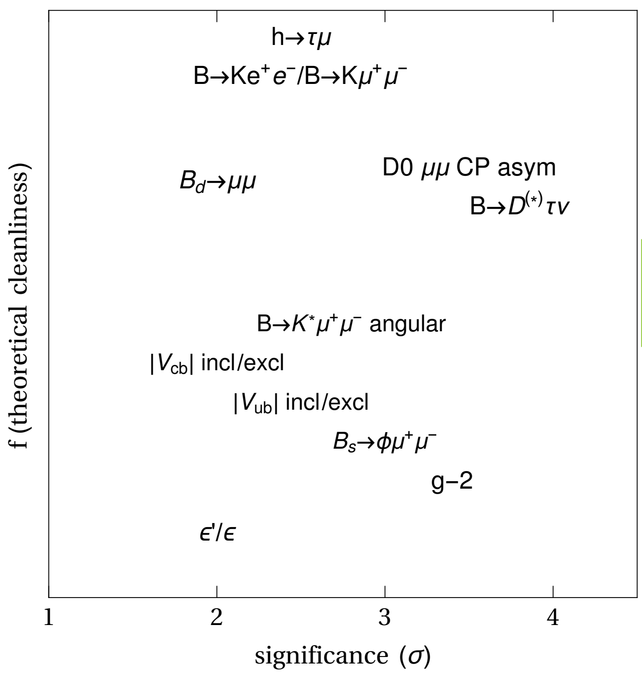

I LIKE
IT.
WHAT
IS IT?
Anthony Burrill

Observed tensions



Summary talks of Z. Ligeti and C. Bobeth, Moriond QCD 2016

Observed tensions



global fit

Large effort to perform global fit

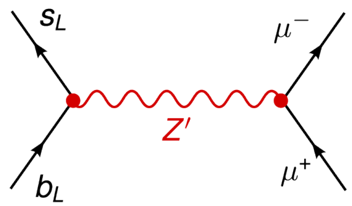
year	arXiv:	group	authors	method
2013	1307.5683	DMV	Descotes-Genon/Matias/Virto	$\Delta\chi^2$
	1308.1501	AS	Altmannshofer/Straub	$\Delta\chi^2$
	1310.2478	EOS	Beaujean/CB/van Dyk	bayesian
	1310.3887	HLMW	Horgan/Liu/Meinel/Wingate	$\Delta\chi^2$
	1312.5267	SuperISO	Hurth/Mahmoudi	$\Delta\chi^2$
2014	1408.4097	GNR	Ghosh/Nardecchia/Renner	bayesian
	1410.4545	SuperISO	Hurth/Mahmoudi/Neshatpour	$\Delta\chi^2$
	1411.3161	AS	Altmannshofer/Straub	$\Delta\chi^2$
2015	1503.06199	AS	Altmannshofer/Straub	$\Delta\chi^2$
	1508.01526	EOS	Beaujean/CB/Jahn	bayesian
	1510.04239	DHMV	Descotes-Genon/Hofer/Matias/Virto	$\Delta\chi^2$
	1512.07157	HEPfit	Ciuchini/Fedele/Franco/Mishima/Paul/Silvestrini/Valli	$\Delta\chi^2$
2016	1603.00865	SuperISO	Hurth/Mahmoudi/Neshatpour	$\Delta\chi^2$
	1603.02974	EOS	Meinel/van Dyk	bayesian

Summary talks of Z. Ligeti and C. Bobeth, Moriond QCD 2016

Results consistent (significance of 4-5σ):
Reduce strength of left handed EW penguin processes by ~25%

Current Flavour data hints at new particles

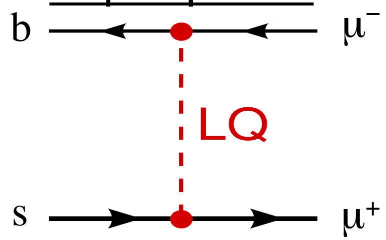
Z' boson



Additional U(1) vector boson, mass 1-10 TeV

e.g.Altmannshofer1308.1501,1411.3161, 1403.1269,Buras:1309.2466,1311.6729, 1409.4557, Celis:1505.03079,Crivellin: 1501.00993,1503.03477,1505.02026, Gauld: 1308.1959,1310.1082,Glashow:1411.0565, Niehoff:1503.03865

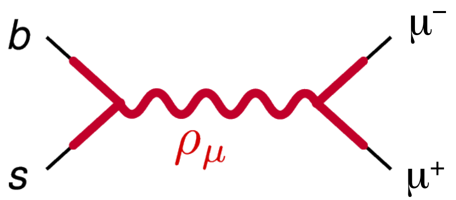
Leptoquarks



couples to quarks and leptons, mass ~TeV

e.g. Alonso:1505.05164, Bauer:1512.06828,1511.01900, Becirevic:1503.09024, Biswas:1409.0882, Buras:1409.4557, Hiller: 1408.1627,1411.4773, Sahoo:1501.05193

Composite models



Some particles might not be fundamental

e.g. Carmona:1510.07658, Gripaios: 1412.1791, Isidori:1604.03940, Niehoff: 1503.03865,1508.00569

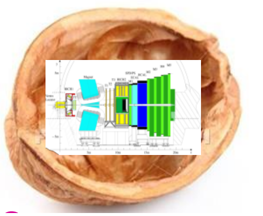
[I stopped collecting references in summer, apologies if I missed yours]

The coming years of LHCb running, together with inputs from the Belle2 experiment, will illuminate if we see fluctuations or exciting hints of something new

Heavy Flavour Future

Heavy quark flavour physics experiments

LHCb upgrade in a nutshell



Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond run 2 requires significant changes.

The LHCb Upgrade

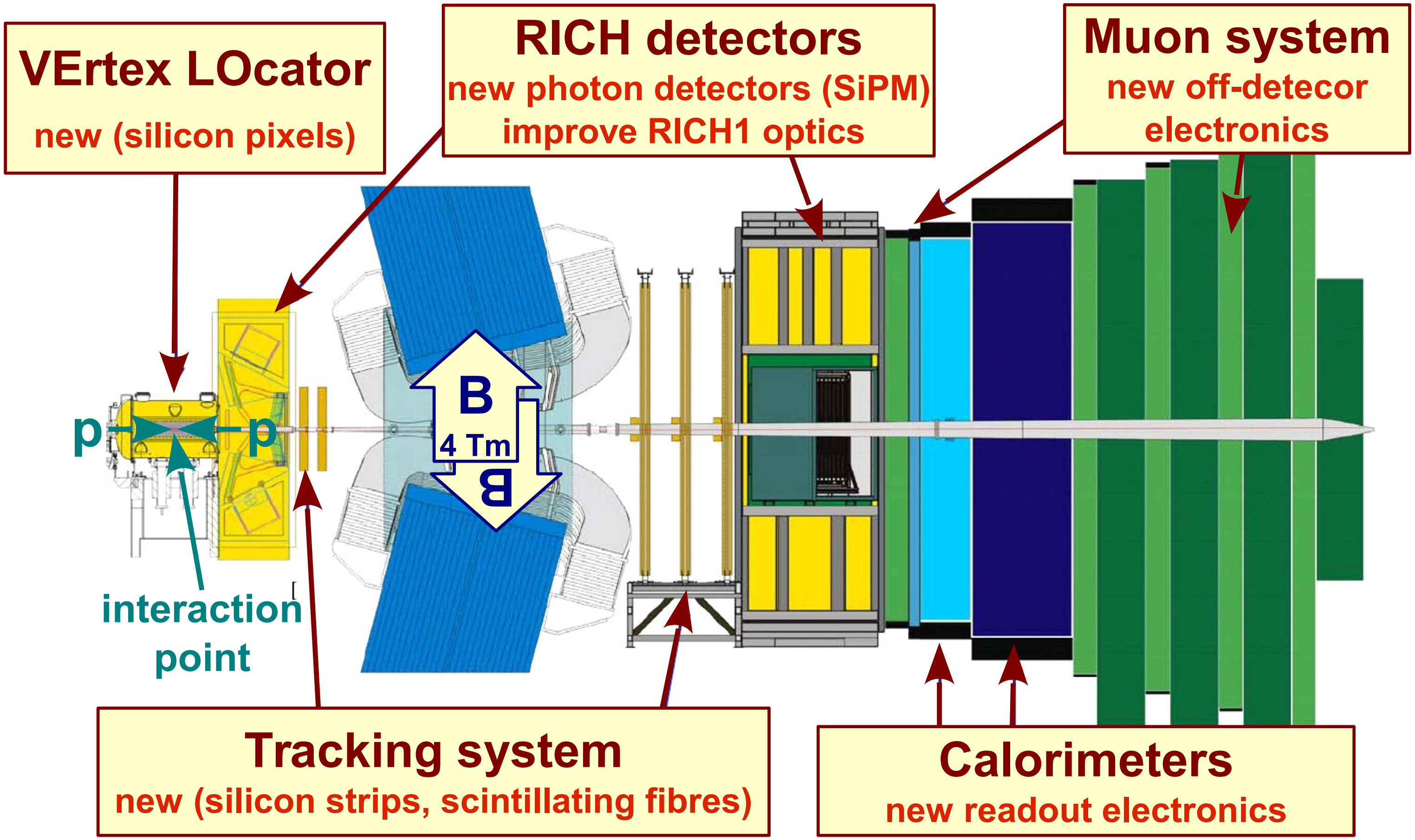
1) Full software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1}

Necessitates redesign of several sub-detectors & overhaul of readout

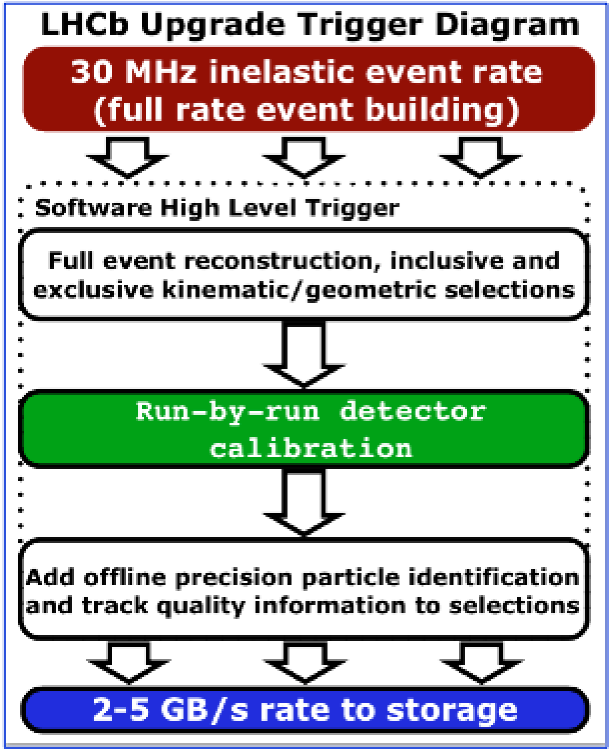
Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies *beyond the reach of the current detector*.

Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region')



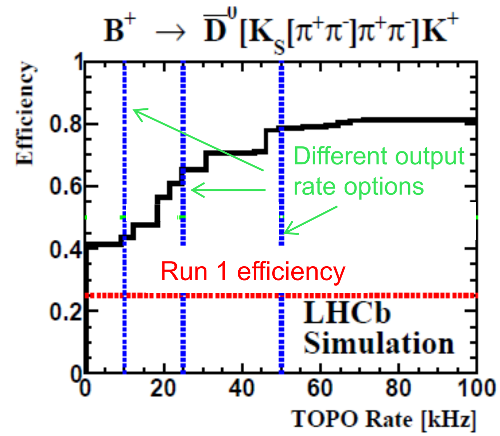
- 40 MHz readout → replace sub-systems with embedded front-end electronics
- 5 × higher luminosity → adapt detector technology where needed to maintain excellent performance

LHCb upgrade DAQ



Upgrade software trigger

Full event information → much improved efficiency



NB: many of run-2 innovations can also be considered as R&D for the Upgrade trigger !

- Detector readout and trigger at 40 MHz + higher rate to storage will be the drivers to handle 5x luminosity and collect larger samples
- Based on new front-end electronics, large PC-based event-builder network, and large expansion of online CPU farm
- Real-time data calibration and reconstruction

Complementarity LHCb – Belle 2

- B_s System
  - CPV in $J/\psi\phi$, $\phi\phi$,
  - CPV in Mixing
- $B \rightarrow \mu\mu$
- CKM phase γ in $B \rightarrow DK$
- CPV in B_d
- $B \rightarrow X_s\, ll$ (exclusive)
- $B \rightarrow X\gamma$ (exclusive)
- Charm physics
- Semi-leptonic B decays
- τ - physics: LFV
- $B \rightarrow D, D^* \tau\nu$
- $B \rightarrow X_s\, ll$ (inclusive)
- $B \rightarrow X\gamma$ (inclusive)
- $B \rightarrow \tau\nu$, $\mu\nu$
- $B \rightarrow K^*\nu\nu$, $B \rightarrow \nu\nu$

"B_s & charged tracks"

Important overlap: sporty competition!

"inclusive & neutrals "

Summary

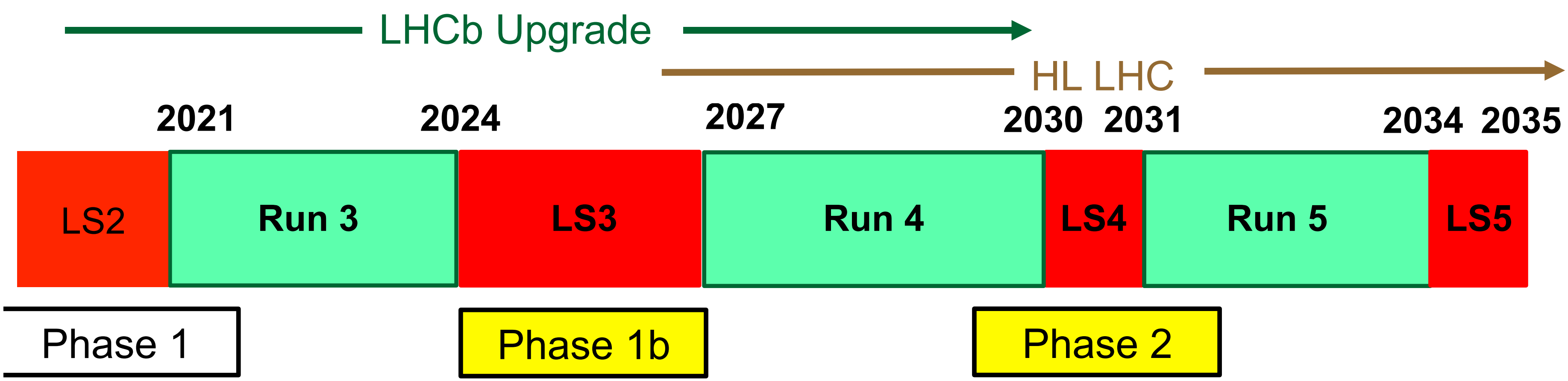
- The Standard Model is tested in a variety of channels
  → many measurements consistent with predictions
  → **significant deviations in of $b \rightarrow s\, \ell^{+}\ell^{-}$ channels**
  → **need for data to conclude**

- Interesting flavour data coming soon
  - LHCb Run 2 → tripling the dataset (~factor 2 already!)
  - LHCb Upgrade – record data with „Trigger-less Readout“
  - Belle2 in the stating blocks

Backup

LHC(b) long term plan

The current long-term schedule of LHC looks like this:



- HL-LHC funded until 2035!
- Thinking now underway for evolution beyond the current upgrade:
  - Consolidation activities and modest improvements during LS3 ('Phase 1b')
  - Longer term luminosity upgrade, probably in LS4 ('Phase 2')

	Integrated luminosity	
	LHCb	GPD
Run 1	3	25
Run 2	10	100
Run 3	25	300
Run 4	50	+300/a
Run 5	**300**	

LHCb Upgrade Projections

	Observable	Current precision	LHCb (5 fb^{-1})	Upgrade (50 fb^{-1})	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s\to\mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7^\circ$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

$b \to s\, \ell^+ \ell^-$ as test bench for high scales

- $b \to s\, \ell^+ \ell^-$ decays allow precise tests of Lorentz structure
  - Sensitive to new phenomena via non-standard couplings
  - Best described with effective field theory, allows to extract potential New Physics amplitudes

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

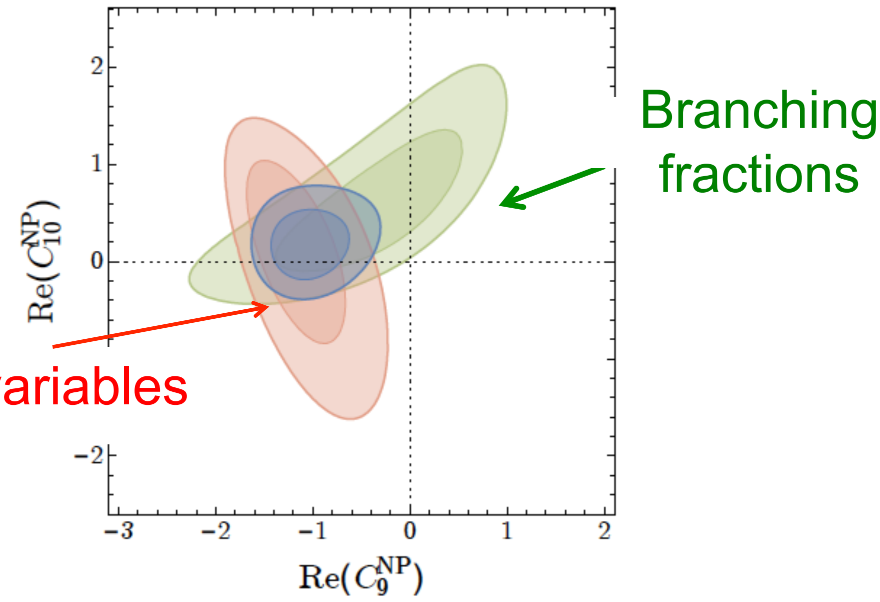
- Menu for this talk:
  - Purely leptonic decays: $B_s \to \mu^+\mu^-$
    → sensitive to $C_{S,P}$ and C_{10}
  - Recent measurements of $b \to s\, \ell^+\ell^-$, dominantly $B^0 \to K^* \mu^+\mu^-$
    → sensitive to $C_{7,9}$ and C_{10}
  - Lepton flavour universality
    → sensitive to C^e vs C^μ

Combine all $b \to s$ data in global fit

Effective Hamiltonian:

$$H = \sum_i \left(C_i^{SM} + C_i^{NP} \right) O_i$$

Altmannshofer & Straub, 1503.06199



- Global fit to all $b \to s$ data prefers a deviation from the Standard Model in a vector-like interaction
- Interpretation:
  - "clearly New Physics", or ..
  - Not well understood QCD contribution

→ Understanding needs more data and theoretical work

Experimental overview of $b \rightarrow s\ (d)\ \ell^+\ell^-$

- FCNC decays $b \rightarrow s\ (d)\ \ell^+\ell^-$: large variety of final states
  - Allows detailed test of the structure of the underlying interaction
  - Effects in one decay can be cross checked in others

# of events	BaBar 433fb^{-1}	Belle 605fb^{-1}	CDF 9.6fb^{-1}	LHCb 1 / 3 fb^{-1}	ATLAS 5fb^{-1}	CMS 5fb^{-1}
$B^0 \rightarrow K^{*0}\ \ell^+\ell^-$	137±44*	247±54*	288±20	2361±56	466±34	415±29
$B^+ \rightarrow K^{*+}\ \ell^+\ell^-$			24±6	162±16		
$B^+ \rightarrow K^+\ \ell^+\ell^-$	153±41*	162±38*	319±23	4746±81		
$B^0 \rightarrow K^0_s\ \ell^+\ell^-$			32±8	176±17		
$B_s \rightarrow \phi\ \ell^+\ell^-$			62±9	174±15		
$\Lambda_b \rightarrow \Lambda\ \ell^+\ell^-$			51±7	78±12		
$B^+ \rightarrow \pi^+\ \ell^+\ell^-$		limit		25±7		

Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012
ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]
LHCb arxiv:1403.8044 +1305.2168 +1306.2577 +JHEP12(2012)125

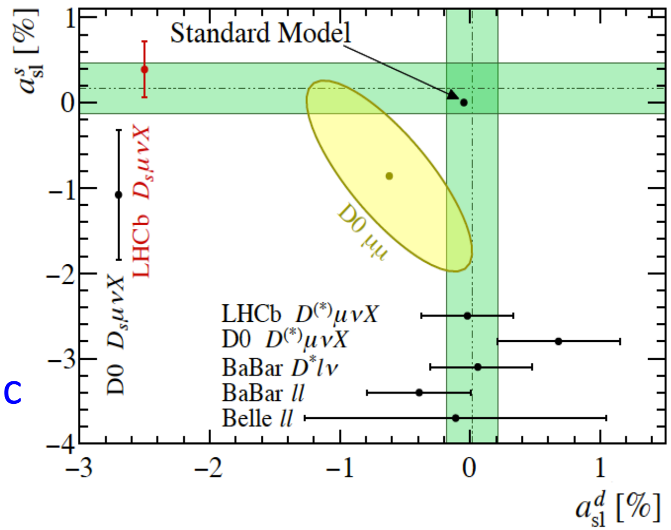
*mixture of B^0 and $B^{\pm}$ and $\ell = e,\mu$
other experiments: $\ell = \mu$ only

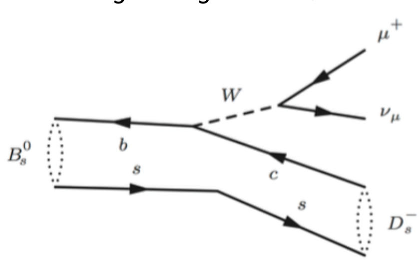
CP violation in B_s-$\bar{B}_s$ mixing

- *CP* violation in neutral *B*-meson mixing manifests itself if

$$\mathcal{P}(B_q \to \bar{B}_q) \neq \mathcal{P}(\bar{B}_q \to B_q)$$

- Interest triggered by a measurement from D0 yielding an anomalous like-sign dimuon asymmetry
  - PRD 89 (2014) 012002
- Precise measurements of semileptonic asymmetries from LHCb do not confirm the anomaly
- Latest measurement of $a_{sl}(B_s)$ using $B_s \to D_s(KK\pi)\mu\nu X$ decays





$$\frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)}$$

Note: $a_{sl}(B_d)$ and $a_{sl}(B_s)$ are very small in the SM

$a^s_{sl} = (2.22 \pm 0.27) \times 10^{-5}$ for B^0_s

$a^d_{sl} = (-4.7 \pm 0.6) \times 10^{-4}$ for B^0

Artuso, Borissov, Lenz [arXiv:1511.09466]

PRL 117 (2016) 061803

$$a^s_{sl} = (0.39 \pm 0.26(\text{stat}) \pm 0.20(\text{syst}))\%$$

9

DESY
Physics Seminar

Gemeinde Zeuthen
Wald. Wasser. Leben.

Challenging the Standard Model with LHCb data

Johannes Albrecht

25. & 26. October 2016

technische universität dortmund

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

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