Flavour Anomalies & Rare Decays

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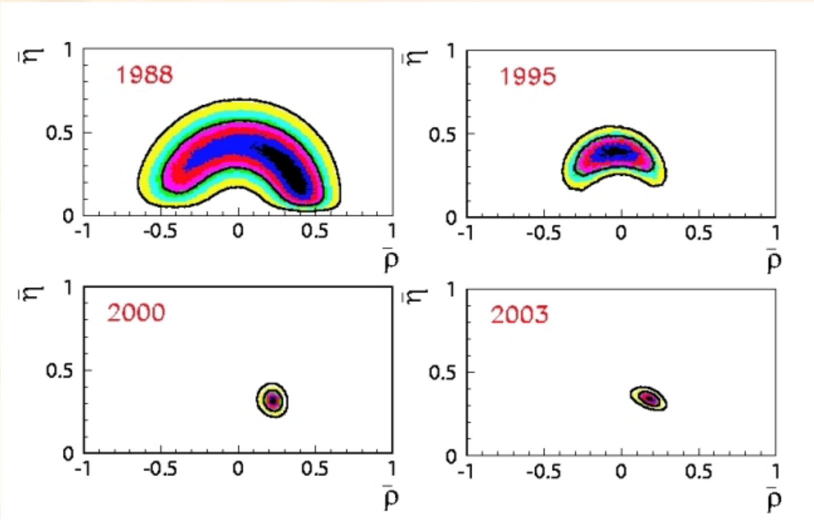
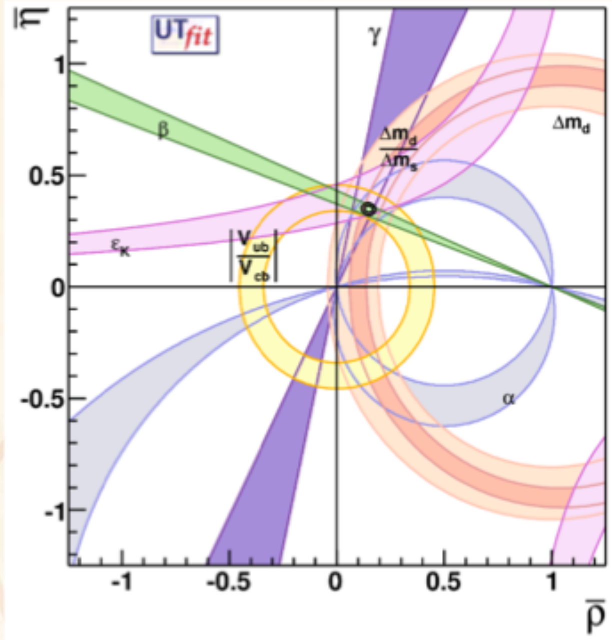
Introduction

- Preface
- Anomalies
  - What anomalies?
  - How large?
- Where from?
- What developments in the near future?
- What implications for the future?

Preface (caveat emptor?)

- Flavour has become a precision domain in the last 20-30 years

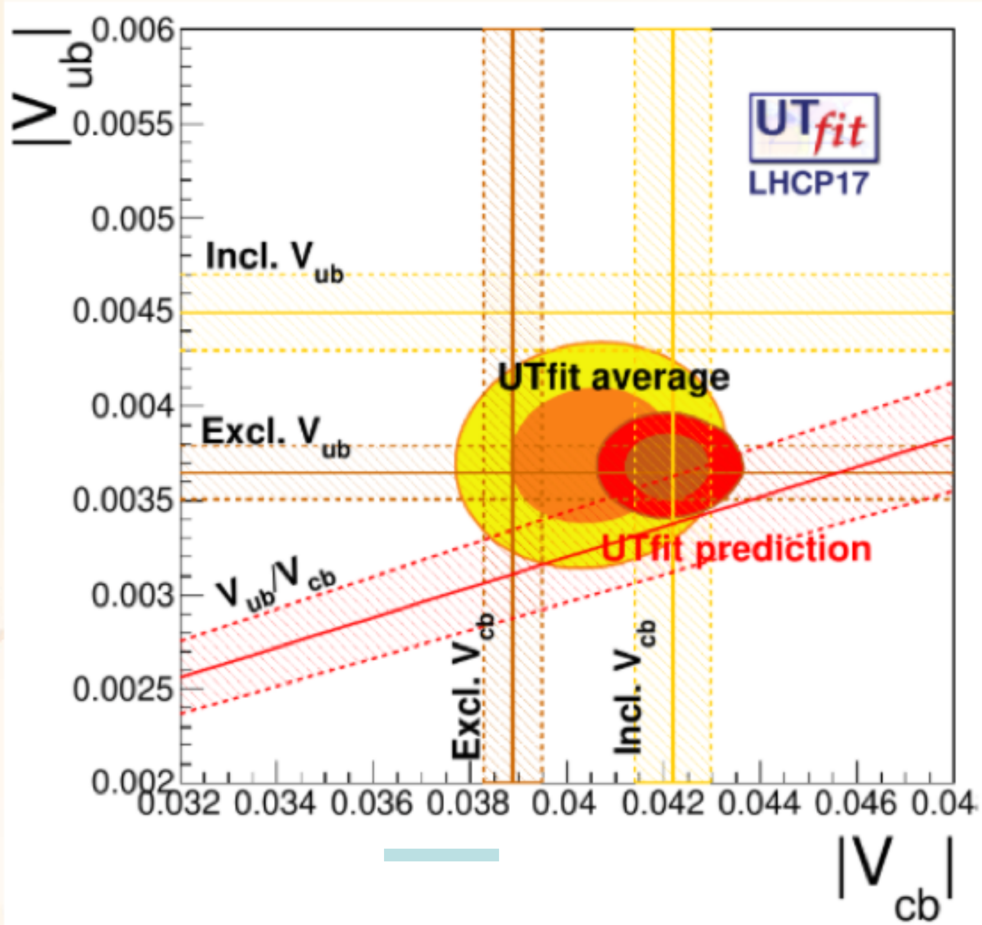




- Many fluctuations & neglected systematic effects have been inevitably seen

V_{ub} and V_{cb}

- Long-standing discrepancy btw inclusive and excl. determinations
- Disagreement is still there
- Promising new developments hint at forgotten systematics



Latest Belle 2 result [1702.01521]

V_{ub} and V_{cb}

- Long-standing discrepancy btw inclusive and excl. determinations
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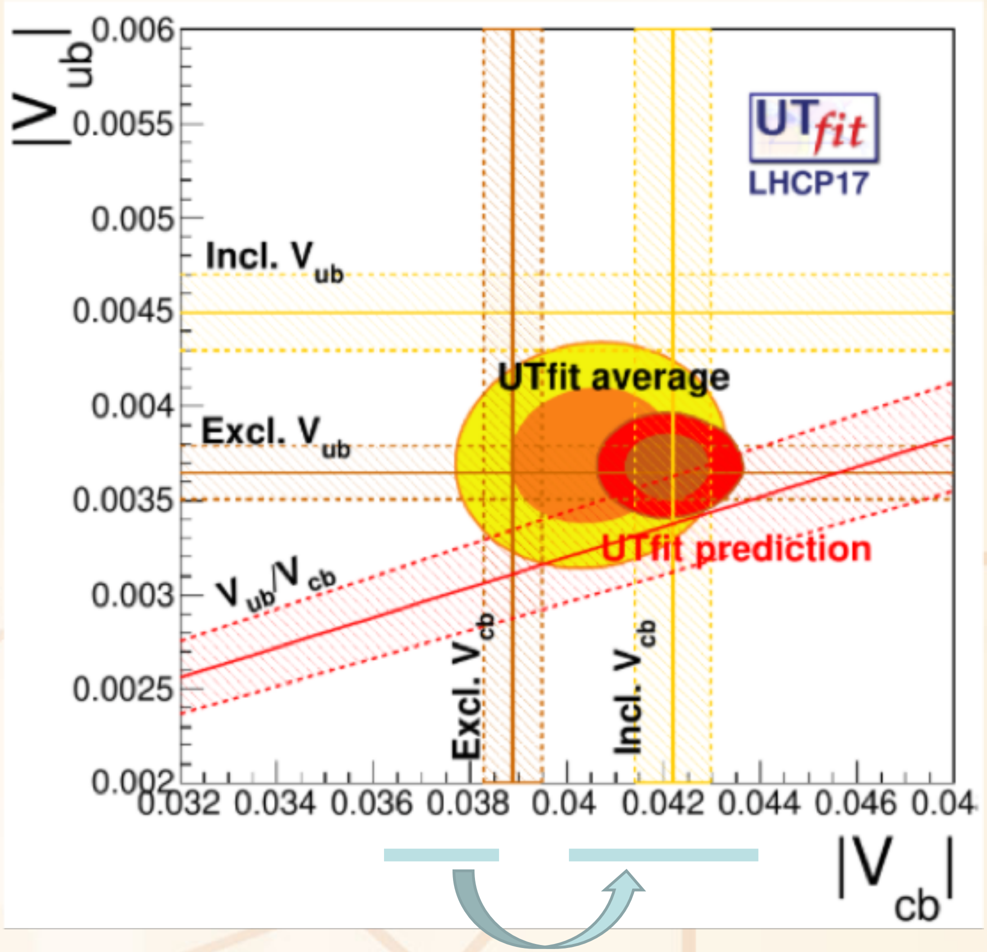
- Promising new developments hint at forgotten systematics

Grinstein, Kobach, arXiv:1703.08170
Bigi, Gambino, Schacht, arXiv:1703.0612



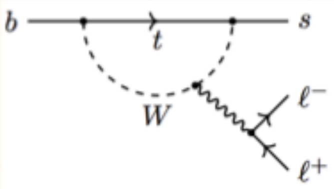
Latest Belle 2 result [1702.01521]

The Moral of the Story

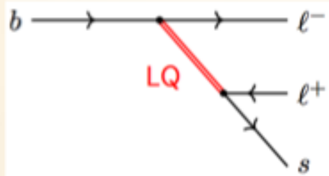
- Precision gives more stringent tests
- More opportunities to look for new physics
- …housekeeping is essential!
- High statistics (of results) → fluctuations are bound to happen
- Until confirmed we should not easily dismiss nor make incommensurate jumps

What are these Flavour Anomalies?

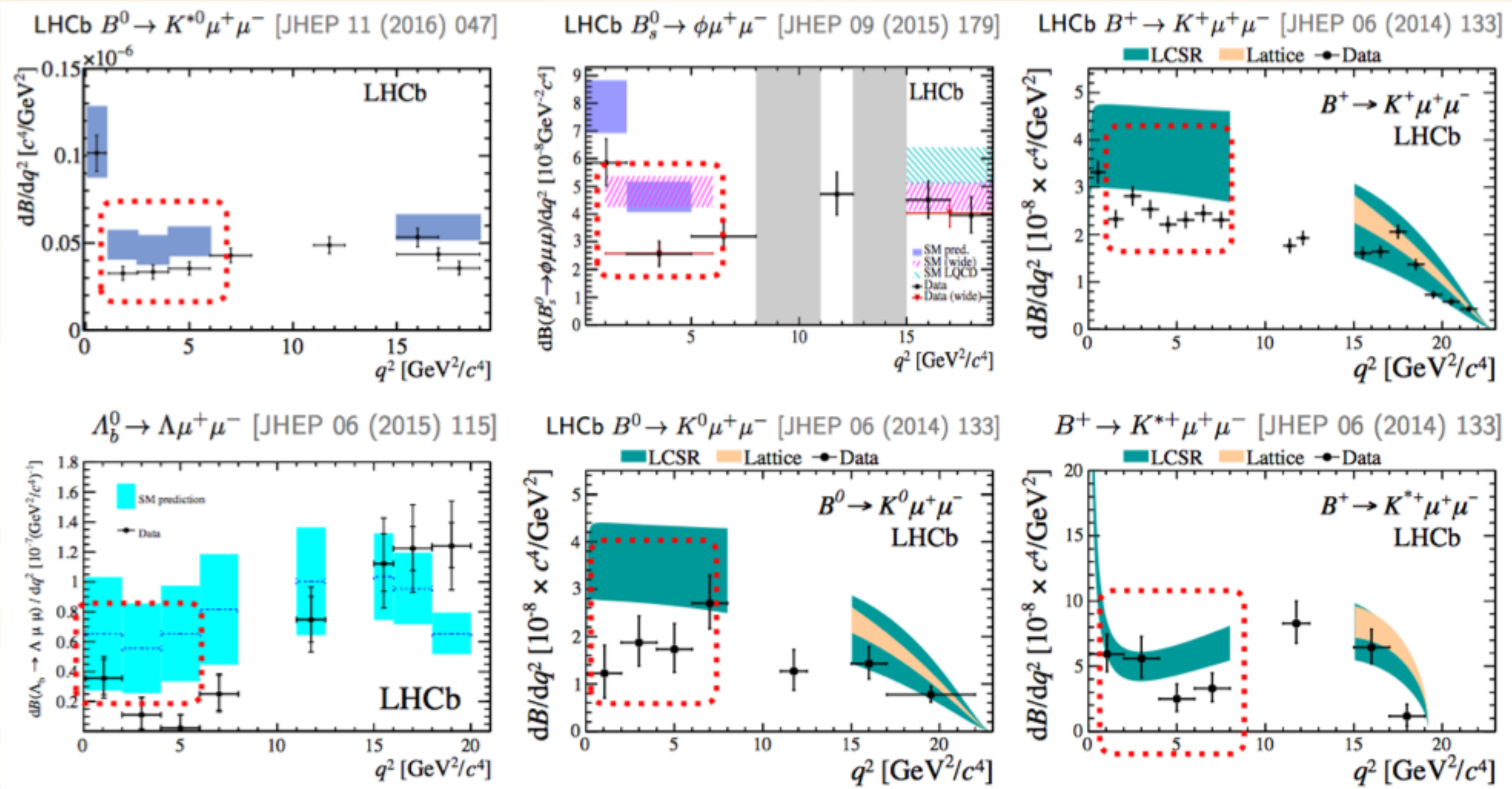
- Two broad categories:
  - "semi-rare" b decays
    - Two anomalies
    - ..plus some LFU troubles
  - Tree-level LFU tests
    - Somewhat of a LEP legacy

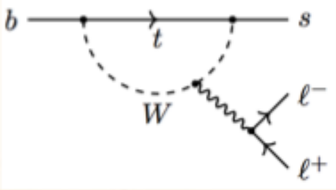


Semi-rare B decays

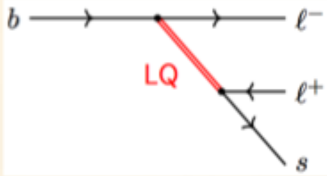


- b→sμμ processes, loop-suppressed
- Potential contribution from new heavy particles → angles & BR





Semi-rare B decays



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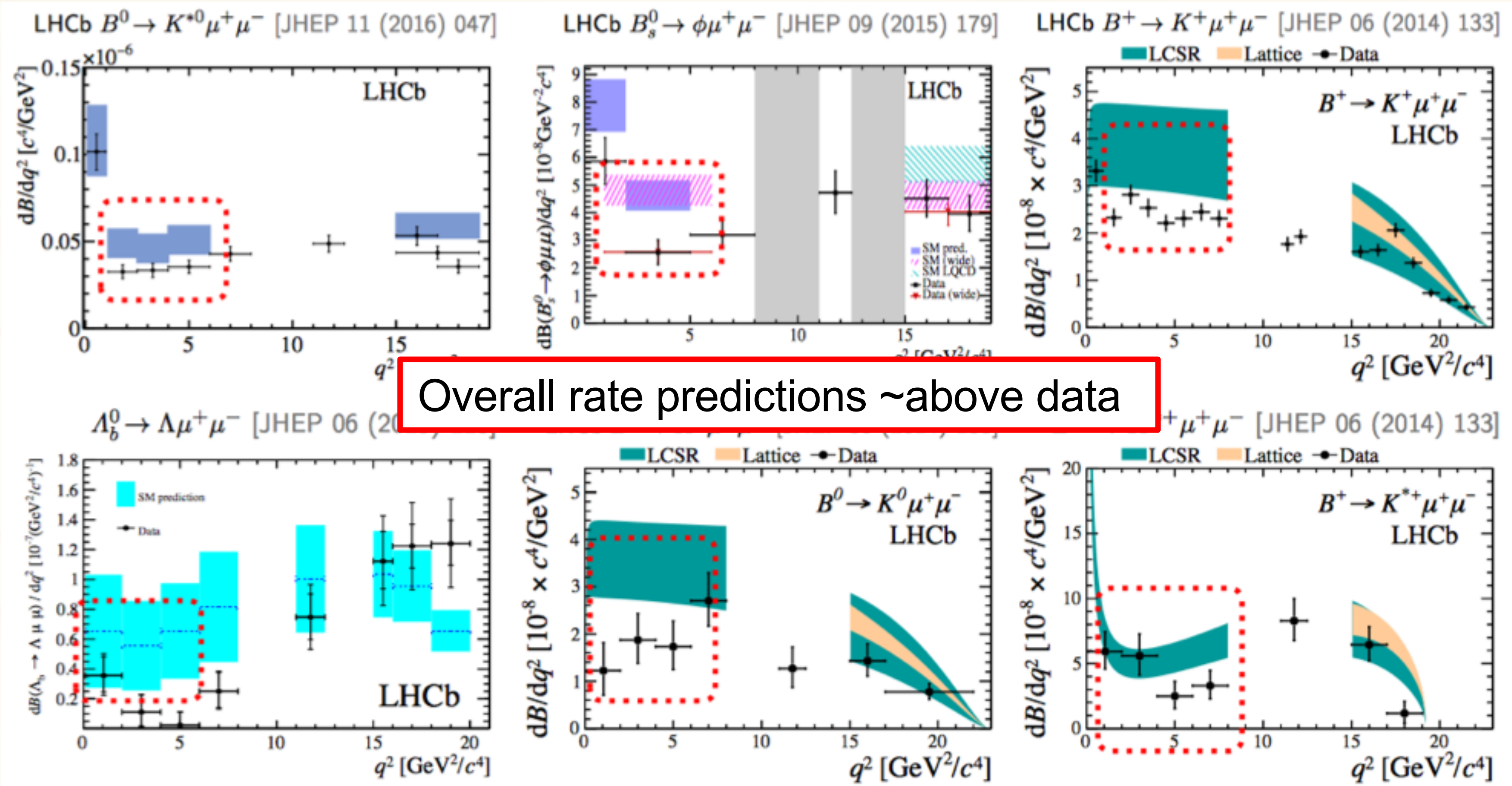
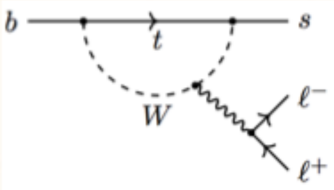
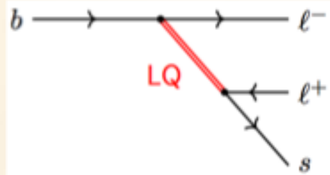




Semi-rare B decays



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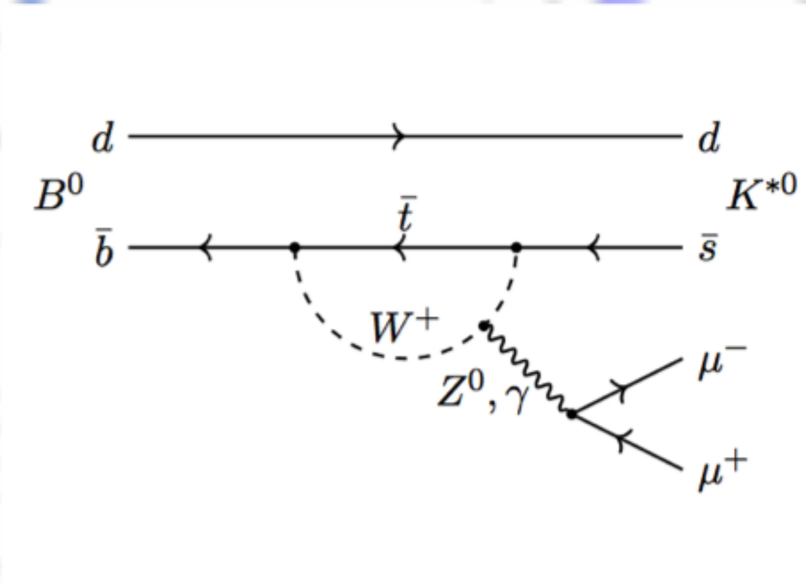
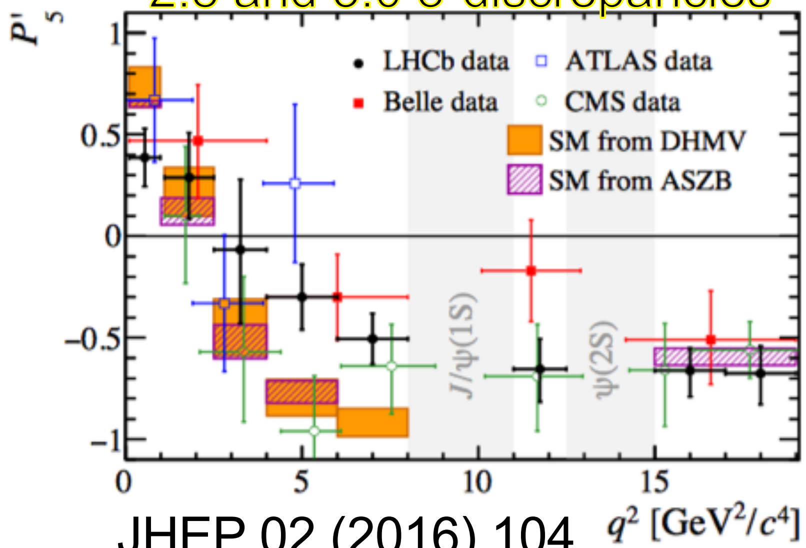


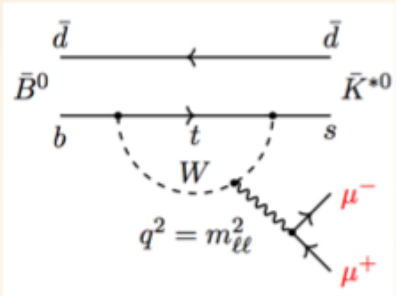
2.8 and 3.0 σ discrepancies



JHEP 02 (2016) 104
PRL 118 (2017) 111801
PLB 781 (2018) 517
arXiv:1805.04000

LFU Trouble

- R_K/R_{K^*}:
  - SM: 1 at the % level
  - QED O(10^{-2}) [EPJC 76 (2016) 8440]
  - Form factors mostly cancel



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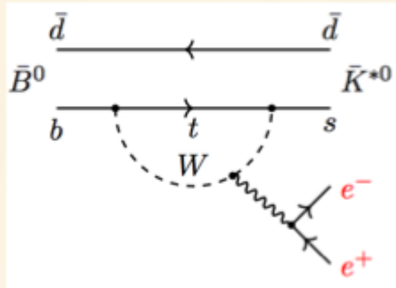
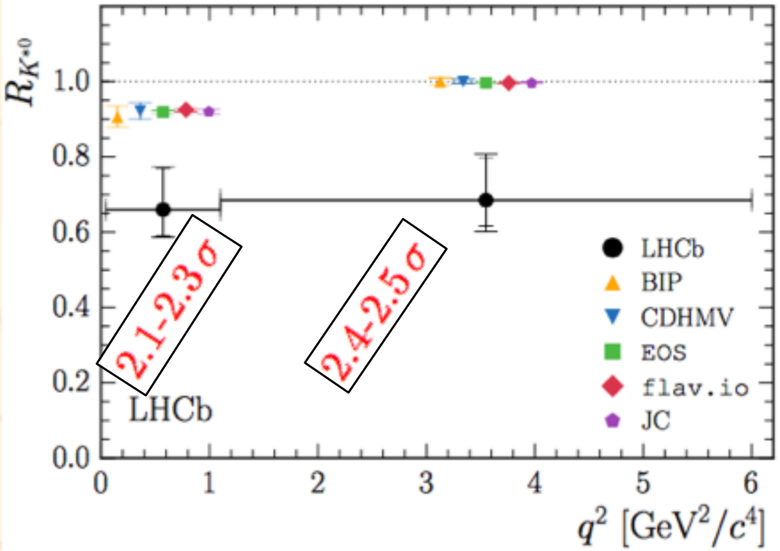
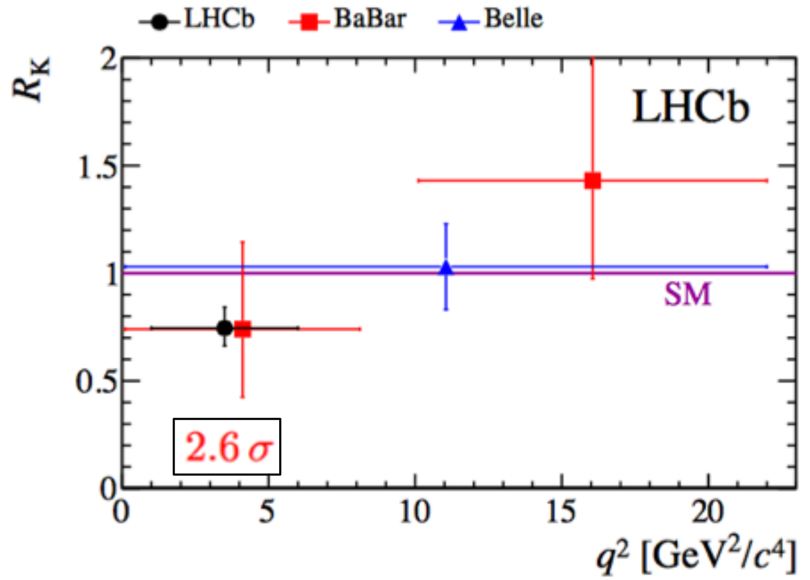


[JHEP 08 (2017) 055]



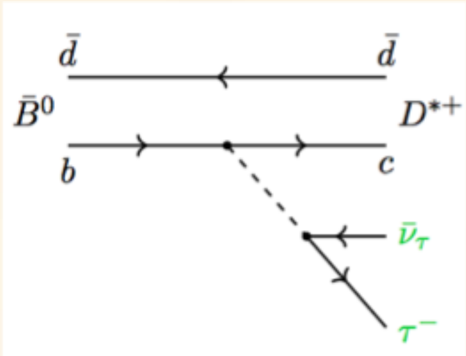


- BIP [EPJC 76 (2016) 440]
- CDHMV [JHEP 04 (2017) 016]
- EOS [PRD 95 (2017) 035029]
- flav.io [EPJC 77 (2017) 377]
- JC [PRD 93 (2016) 014028]

- LHCb [PRL 113 (2014) 151601]
- Belle [PRL 103 (2009) 171801]
- BaBar [PRD 86 (2012) 032012]

Tree Level Troubles

- ...enter R_D R_{D*}:



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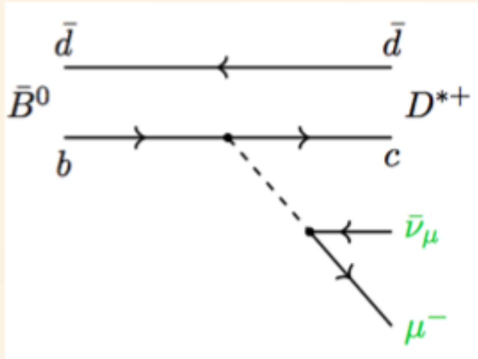
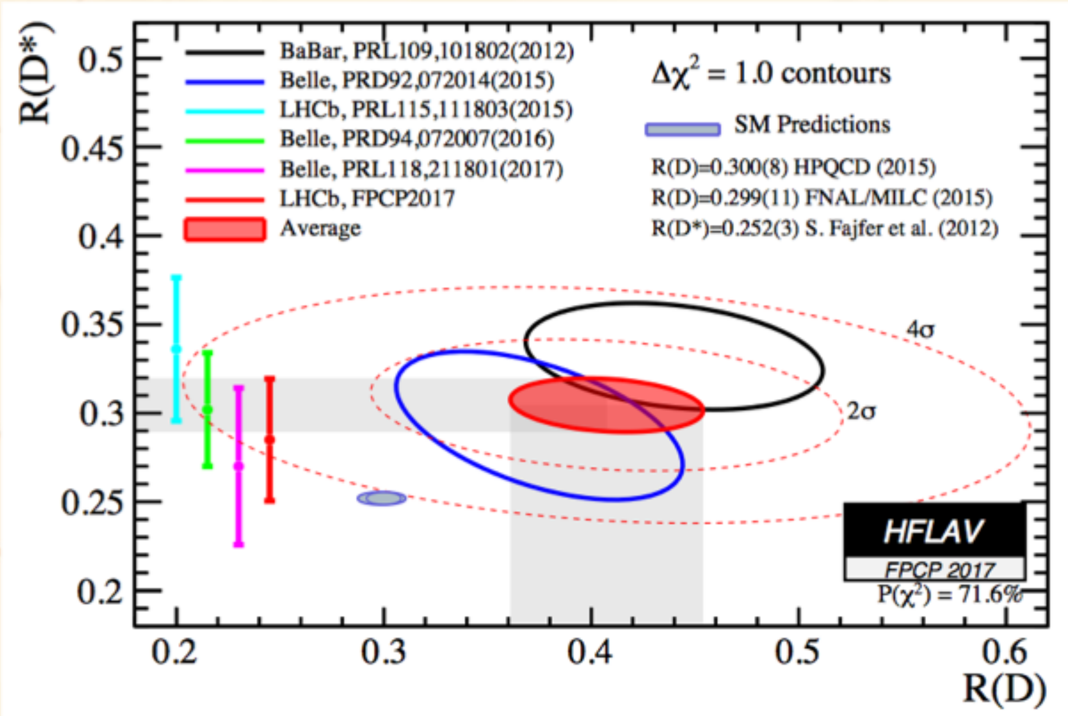
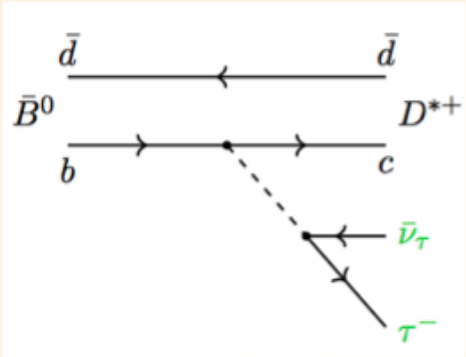




- All exp. Results above SM expectation
- Combined tension ~4.1σ
- Theory inputs reduce tension [JHEP 11 (2017) 061]

Tree Level Troubles

- …enter R_D R_{D^*}:



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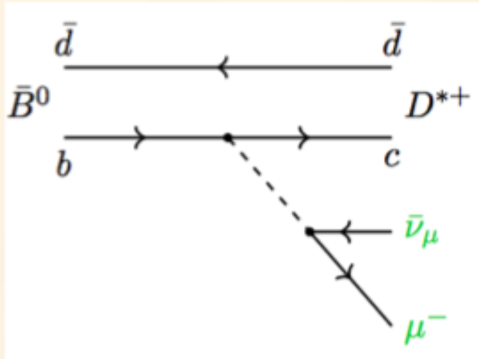
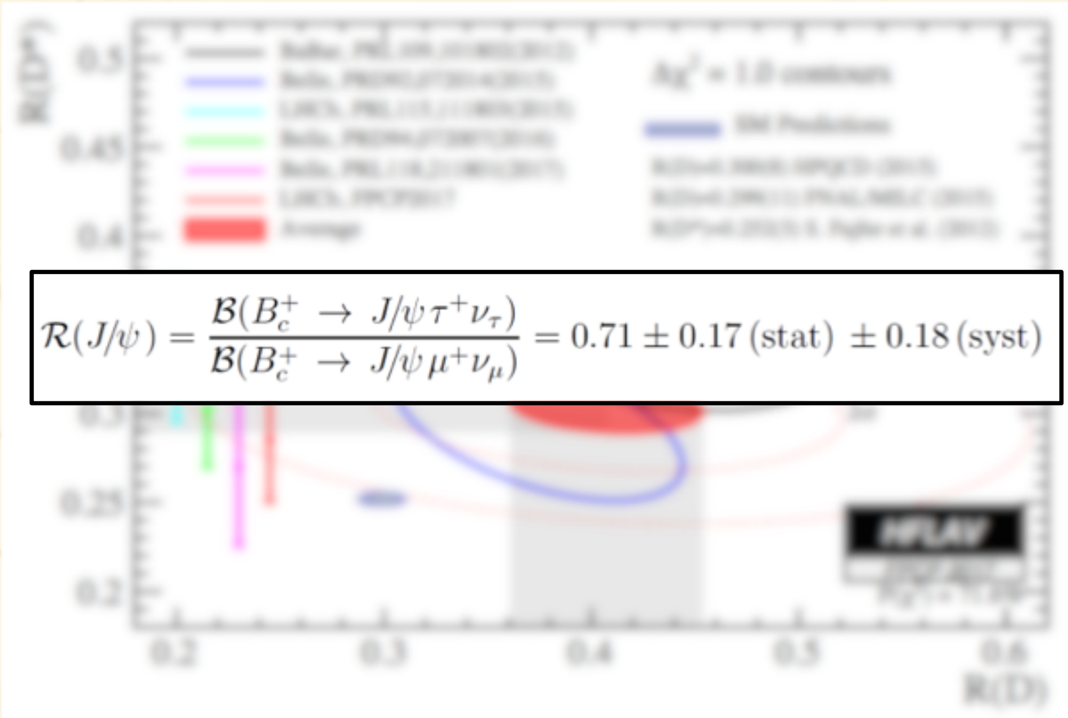




$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

- All exp. Results above SM expectation
- Combined tension ~4.1σ
- Theory inputs reduce tension [JHEP 11 (2017) 061]
- Bc decays show tension too (2σ-ish)

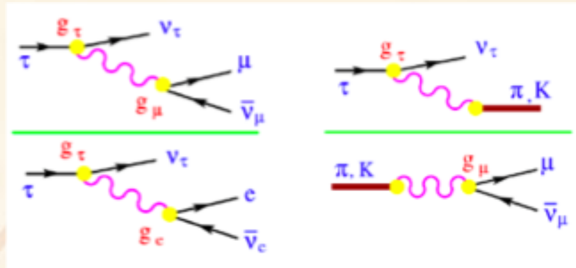
…other legacies:

- B→τν (Belle 2006, BaBar 2008, 2010, 2013)

$$BR(B \to \tau\nu) = \left(1.7^{+0.56+0.46}_{-0.49-0.51}\right) \cdot 10^{-4}$$

Later Belle measurement relaxed the tension, except with BaBar

- LEP II CC universality tests:



	$\lvert g_\mu / g_e \rvert$
$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.996 ± 0.010

	$\lvert g_\tau / g_\mu \rvert$
$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

2.6 σ

	$\lvert g_\tau / g_e \rvert$
$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0029 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.031 ± 0.013

2.4 σ

…however g anomaly cannot be accommodated with EFT
[Filippuzzi et al. 1203.2092]

Stolen from A. Pich, Mass 2018

…other legacies:

- B→τv (Belle 2006, BaBar 2008, 2010, 2013)

$$BR(B \to \tau v) = \left(1.7^{+0.56+0.46}_{-0.49-0.51}\right) \cdot 10^{-4}$$

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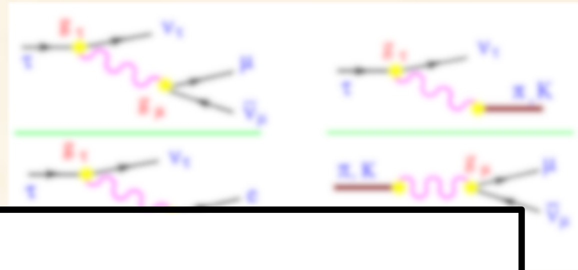
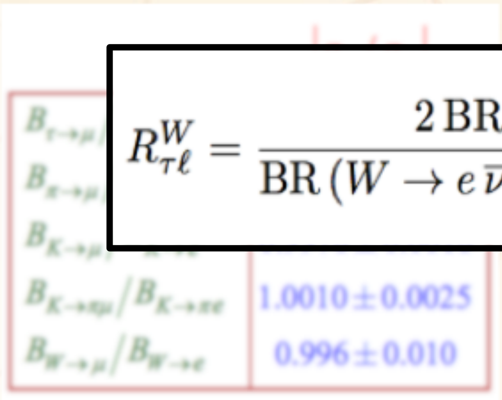
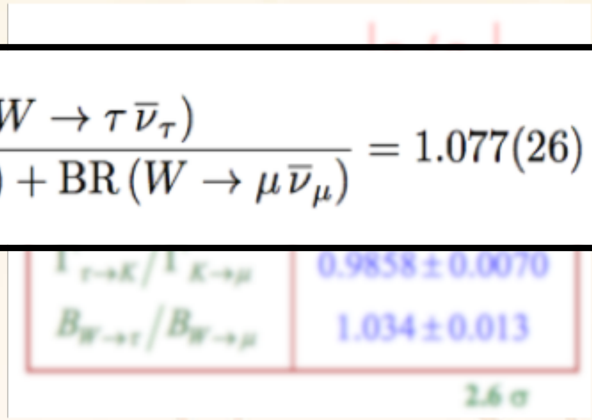
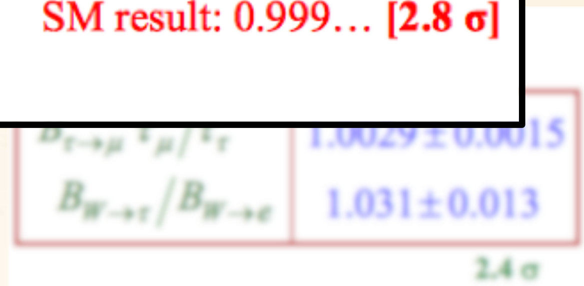


- LEP II CC universality tests:







$$R^{W}_{\tau\ell} = \frac{2\,\mathrm{BR}(W \to \tau\bar{\nu}_\tau)}{\mathrm{BR}(W \to e\bar{\nu}_e) + \mathrm{BR}(W \to \mu\bar{\nu}_\mu)} = 1.077(26)$$

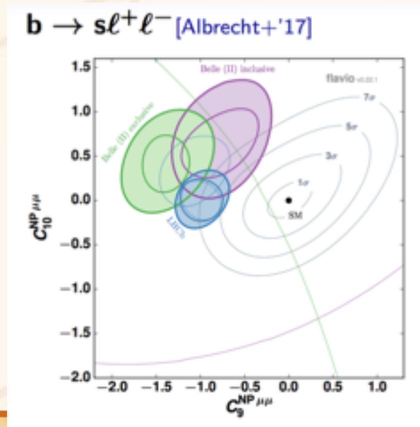
SM result: 0.999… **[2.8 σ]**

…however g anomaly cannot be accommodated with EFT

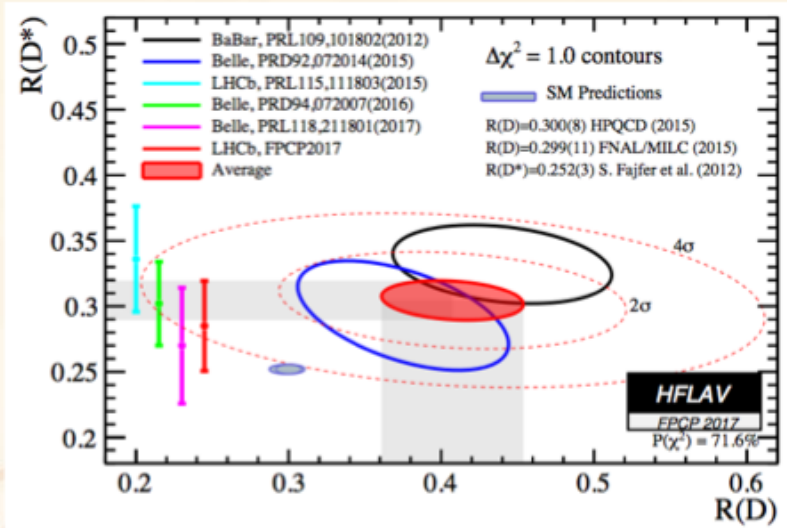
[Filippuzzi et al. 1203.2092]

Flavour Anomalies: Summary

- Neutral Current
- b→sμμ
  - <4σ Angular observables in K*μμ
  - 3.5σ BR
  - 2.6σ LFU violation in R_K
  - (2.3⊕2.6)σ LFU violation in R_{K^*}
- Several discrepancies, some debate…



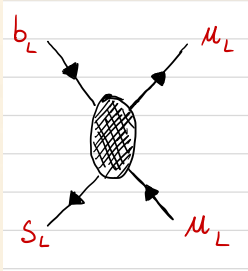
- Charged Current
- b→cτν



- Long standing tension

New Physics, at what scale?

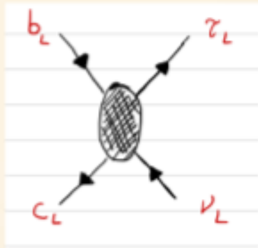
- NC



$$\mathcal{L}_{eff} = \frac{1}{\Lambda_{R_K}^2} \bar{s}_L \gamma^\mu b_L \bar{u}_L \gamma_\mu u_L + h.c.$$

$$\Lambda_{R_K} \sim 30\ TeV$$

- CC



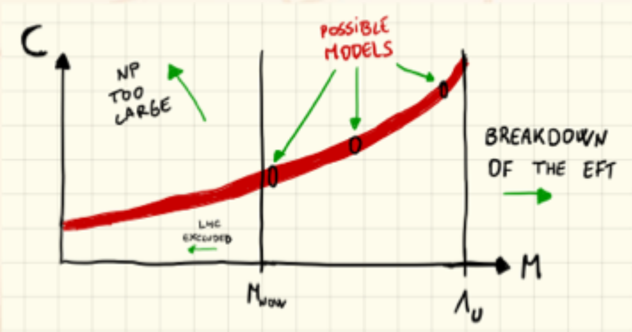
$$\mathcal{L}_{eff} = \frac{2}{\Lambda_{R_K}^2} \bar{c}_L \gamma^\mu b_L \bar{\tau}_L \gamma_\mu \upsilon_L + h.c.$$

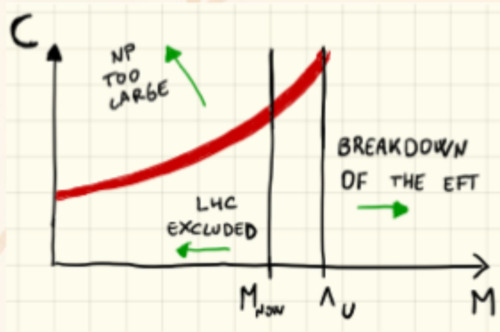
$$\Lambda_{R_K} \sim 3\ TeV$$

REM: $\frac{1}{\Lambda} \sim \frac{C}{M^2}$

- C→ model dependent (loops, coupling, flavour structure)
- M→ NP on shell…

Unitarity → upper bound



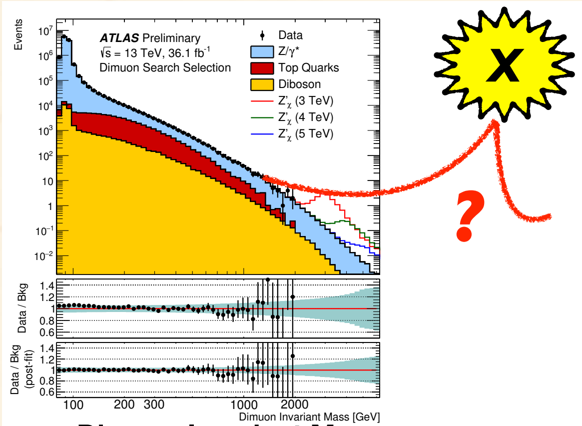


M. Nardecchia – HL/HE-LHC workshop

EFT and GPD

Off-shell (now-ish) ?→On-shell (future)

[1704.09015,1805114402]

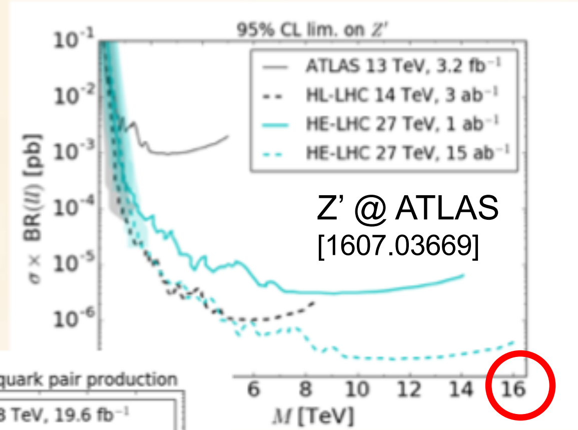


Dimuon Invariant Mass

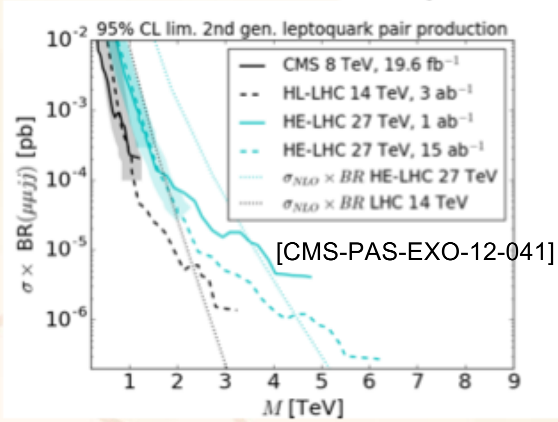
- μμ, $\tau\tau$ [1609.07138]
- Better gauged at CC anomalies, since for NC:

$$\frac{1}{(30\ \mathrm{TeV})^2}\,(\bar{b}\Gamma s)\,(\bar{\mu}\Gamma\mu)$$

27 TeV… maybe?

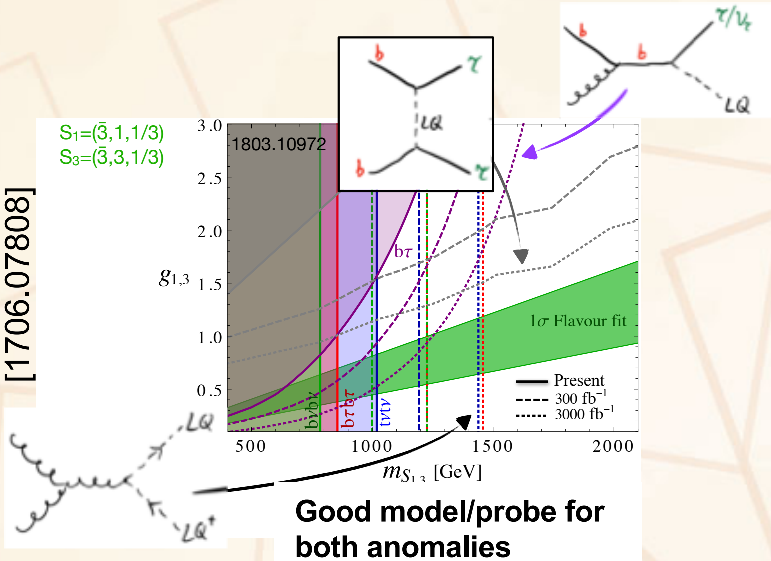


Z' @ ATLAS [1607.03669]

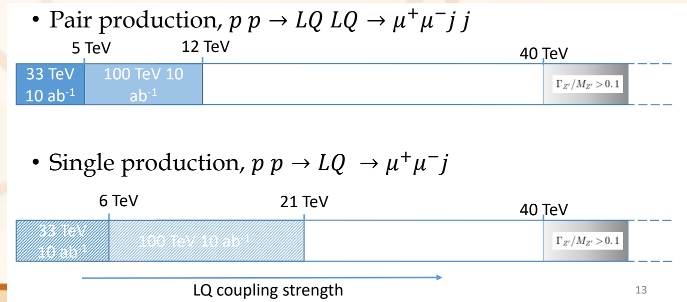


[CMS-PAS-EXO-12-041]

[1706.07808]



Good model/probe for both anomalies



Based on CMS 1703.03995, 1803.02864, CMS-PAS-SUS-18-001, CMS-PAS-EXO-17-029

M. Nardecchia – HL/HE-LHC workshop

EFT and GPD

Off-shell (now-ish) ?→ On-shell (future)

- Non-exhaustive picture, but hopefully conveying the importance of these anomalies – if confirmed – for GPD searches
- Didn't distinguish EFT and concrete motivated models addressing SM 'issues':
  - Naturalness
  - Origin of flavour
  - Renormalizability
  - …

  - (…maybe we shouldn't even start by trying to catch too many experimental birds with the same stone)

[1704.09015,1805111402]

[1706.07808]

Good model/probe for both anomalies

Based on CMS 1703.03995, 1803.02864, CMS-PAS-SUS-18-001, CMS-PAS-EXO-17-029

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EFT and GPD

Off-shell (now-ish) ?→On-shell (future)

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- Didn't dist ... odels addressin
  - Natur
  - Origin
  - Renor
  - …
  - (…ma ... catch too many ...)
  - OTOH EFT predictions may overlook obvious direct signatures….

[1704.09015,1805511402]

[1706.07808]

Good model/probe for both anomalies

Based on CMS 1703.03995, 1803.02864, CMS-PAS-SUS-18-001, CMS-PAS-EXO-17-029

M. Nardecchia – HL/HE-LHC workshop

What are the next steps?

- Are these anomalies real?
  - Run 2 data and Belle 2 hold the verdict!
  - Everyone and their sibling in the flavour community are waiting for R_D, R_{D^*}, R_K, R_{K^*} from LHCb & Belle 2
  - Additional input from related observables in B_c, b-baryons, $\tau \rightarrow \mu\mu\mu$ and co.
  - Are there any hints in GPD of EFT mediators?
- If they are real and they stay where they are, new physics might be within reach!
- …however there's no guaranteed 'threshold'

Near Future

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	3%	1%	1%
$B_s^0, B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c l^- \bar{\nu}_l$ LUV studies				
$R(D^*)$	9% [199, 202]	3%	2%	1%
$R(J/\psi)$	25% [202]	8%	–	2%

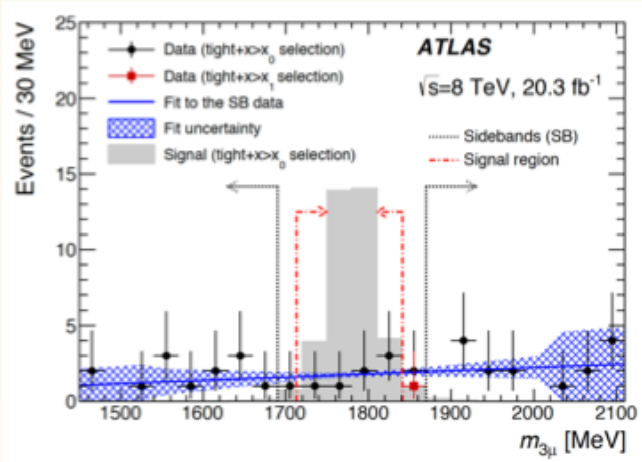
C. Langenbruch – HL/HE-LHC workshop

Great potential from LHCb, but definitely not the only player in probing these NP effects!

Other things to keep an eye on:

- **$\tau \rightarrow 3\mu$**
  - SM (through ν osc.): ~10^{-14}
  - BSM: up to 10^{-8}

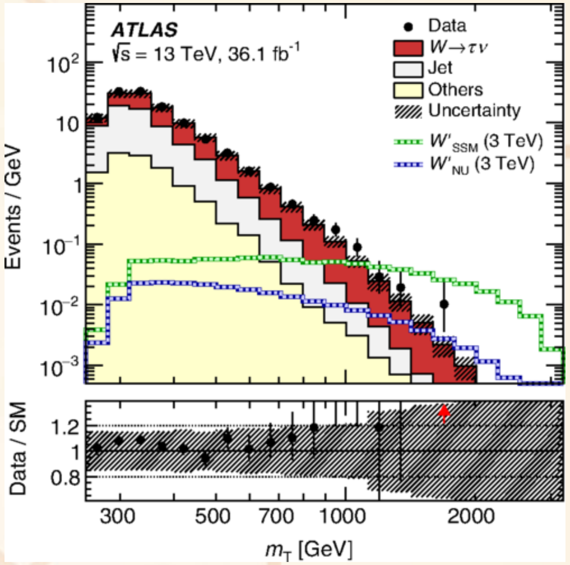
Expt.	Limit [10^{-8}]		Ref.	
	Now	HL	Now	HL
Belle/Belle 2	**2.1**	**0.04**	PLB687(2010)139	PoS FPCP2015 (2015) 049
BaBar	**3.3**	**-**	PRD81(2010)11101	-
LHCb Hadronic	**4.6**	**0.6**	JHEP02(2015)121	Extr. From Run 1 @ 3fb^{-1}
ATLAS $W \rightarrow \tau\nu$ Run 1	**38**	**0.9**	EPJC76(2016)5,232	Naïve Extr. From Run 1
CMS Run 2	**Soon**	**0.4**	-	Simulated $D_s \rightarrow \tau\nu$



Eur. Phys. J. C76 (2016) 5, 232

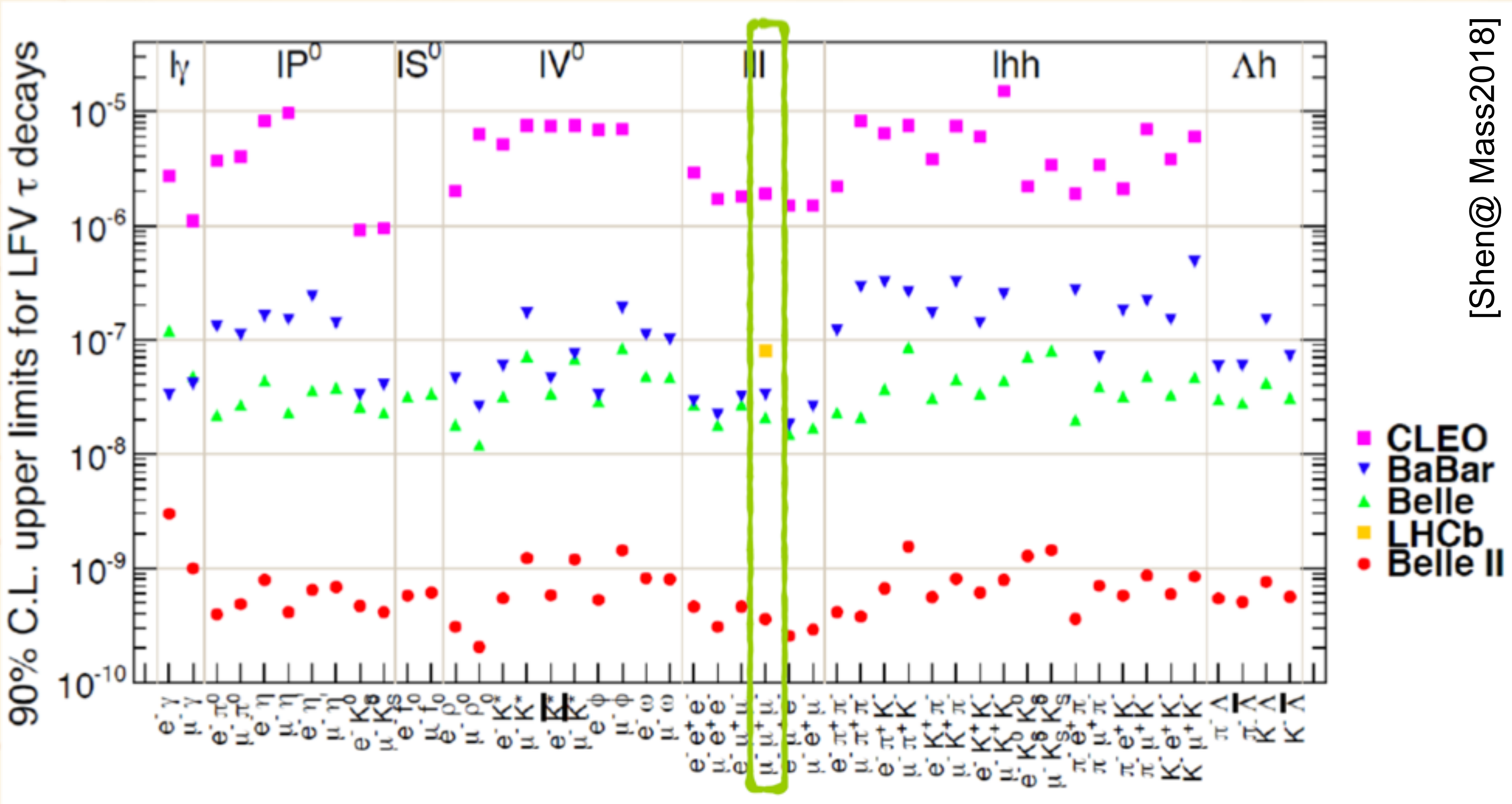
- **$\tau \rightarrow \pi/K\ \nu$**
  - Possible direct searches!

- **$Z \rightarrow \tau l$**
  - $\tau\mu$: <1.2/1.3 10^{-5} [Delphi'97, ATLAS 1804.09568]
  - τe: <10^{-5}, <5.8×10^{-5} 2.3σ excess
    [Opal'95], [ATLAS 1804.09568]



ATLAS, PRL 120 (2018) 161802

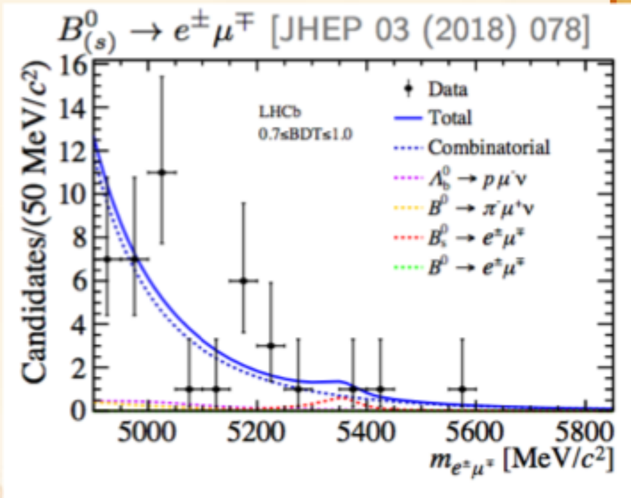
Belle 2 and τ LFV

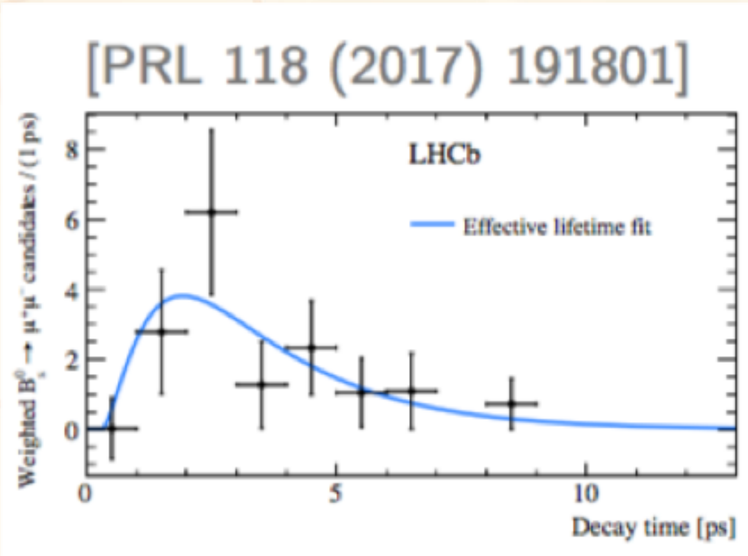


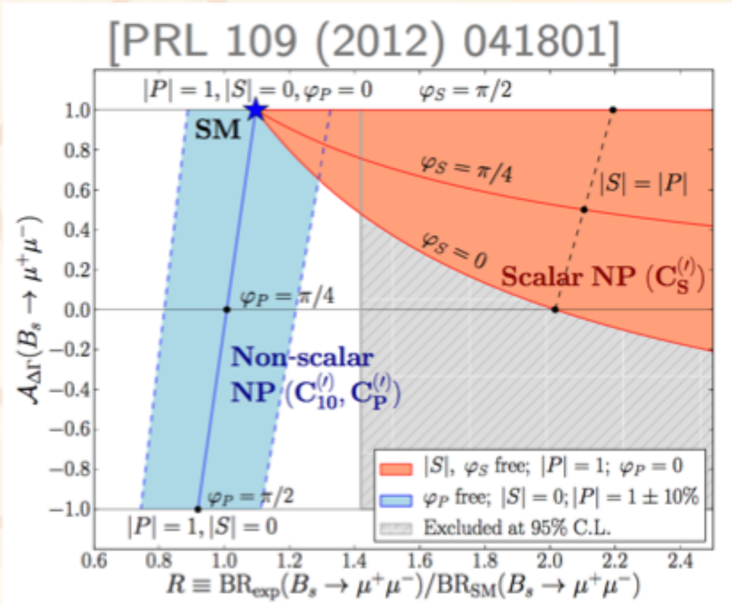
HFLAV summary of τ LFV with Belle 2 reach (0-background assumed)

Other things to keep an eye on:

- Rare B decays (μμ, ee, μe)
  - Probe axial component→complement vector term of b→sμμ
  - Probe directly LFU through e.g. eμ
  - With lifetime: Probe NP structure
  - Clean observables accessible also to GPE



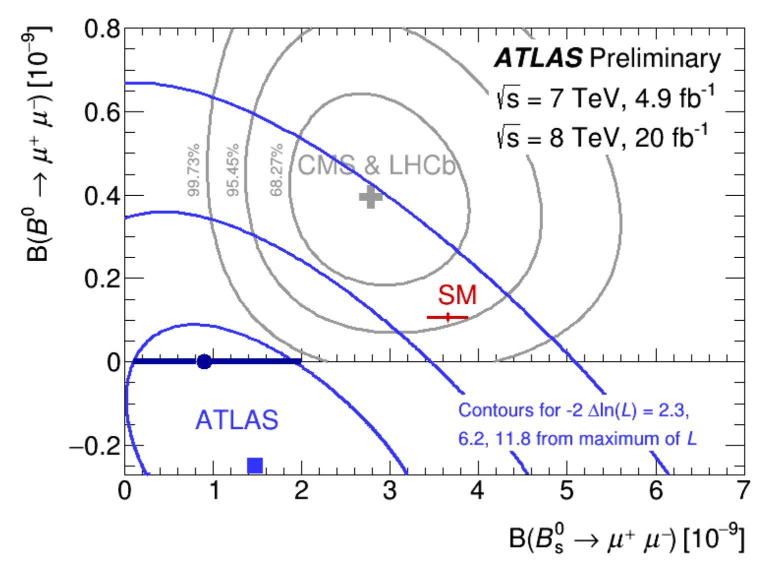




Rare B Decays

- Both LHCb and GPE contribute
  - BR
  - BR ratio: Bs/Bd has clean predictions
  - Lifetime: no reason GPE shouldn't perform well

Now



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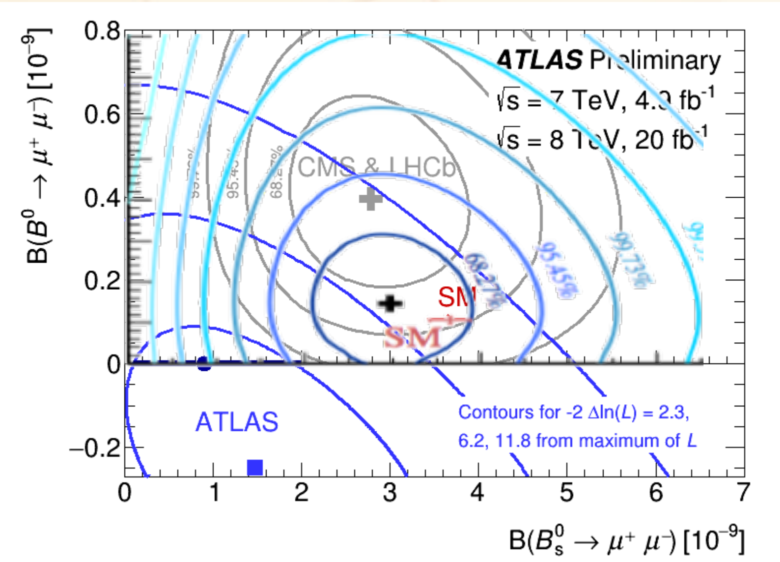

[EPJ C (2016) 76: 513, PRL118, 191801 (2017)]

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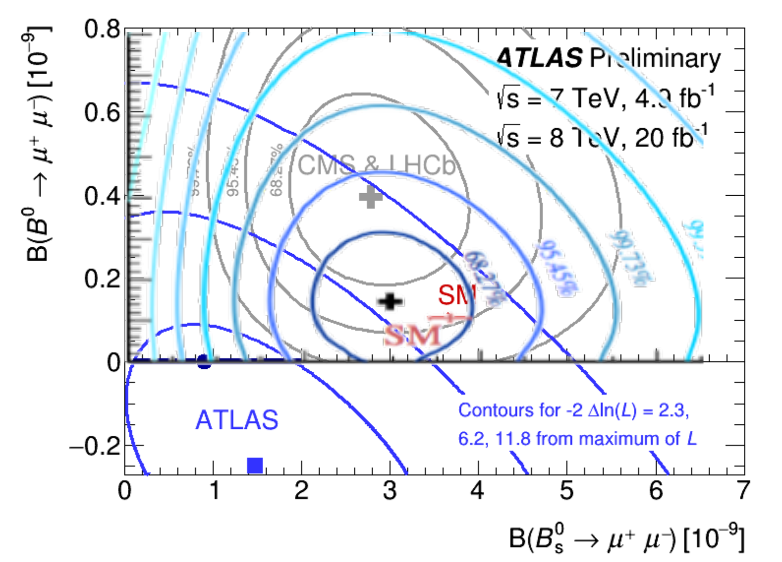
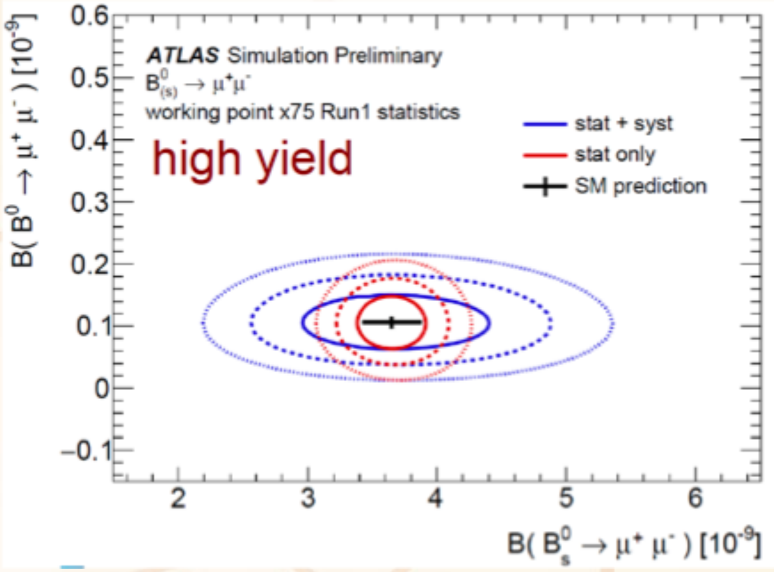


[EPJ C (2016) 76: 513, PRL118, 191801 (2017)]

Future?



[ATL-PHYS-PUB-2018-005]

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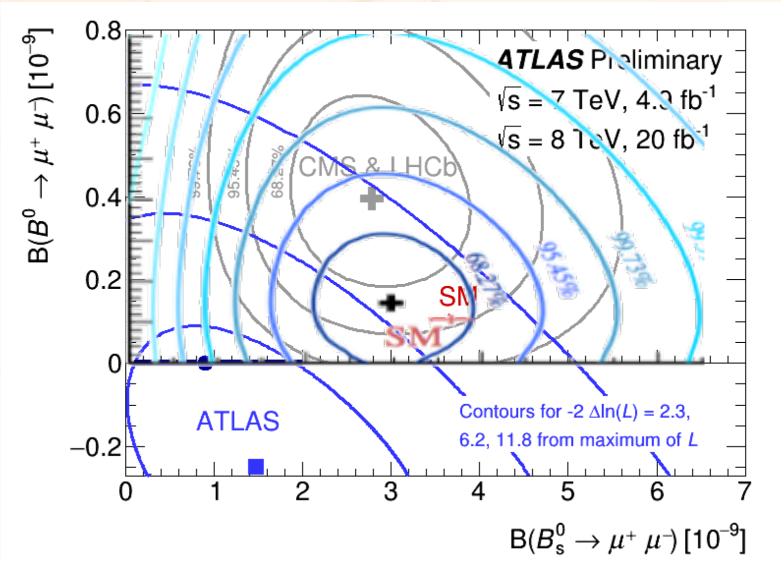
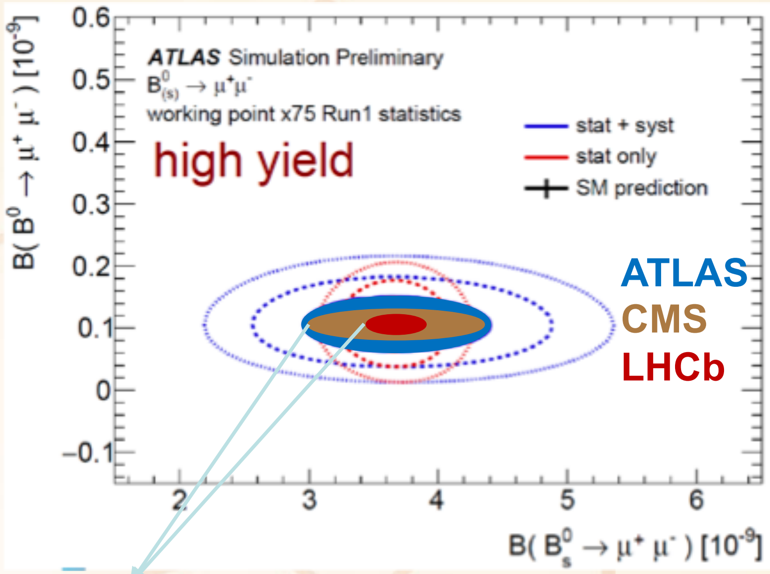


[EPJ C (2016) 76: 513, PRL118, 191801 (2017)]

Future?



My Naïve calculations, based on HL extrapolations
[CMS-PAS-FTR-14-015, C.Langenbruch@HL/HE-LHC workshop]

Summary

- Heavy Flavour studies are the prime probe of the flavour structure of NP at colliders
- Significant combined anomalies
  - “Long standing fluctuations”?
  - Systematic effects?
  - New physics?
  - The jury is still out, but due back in soon
- If confirmed
  - NP *could* be near
  - GPE can contribute to the on-going investigation
  - GPE in an excellent position to probe new physics scenarios
  - Strong implications for future colliders
- Else… next talk!