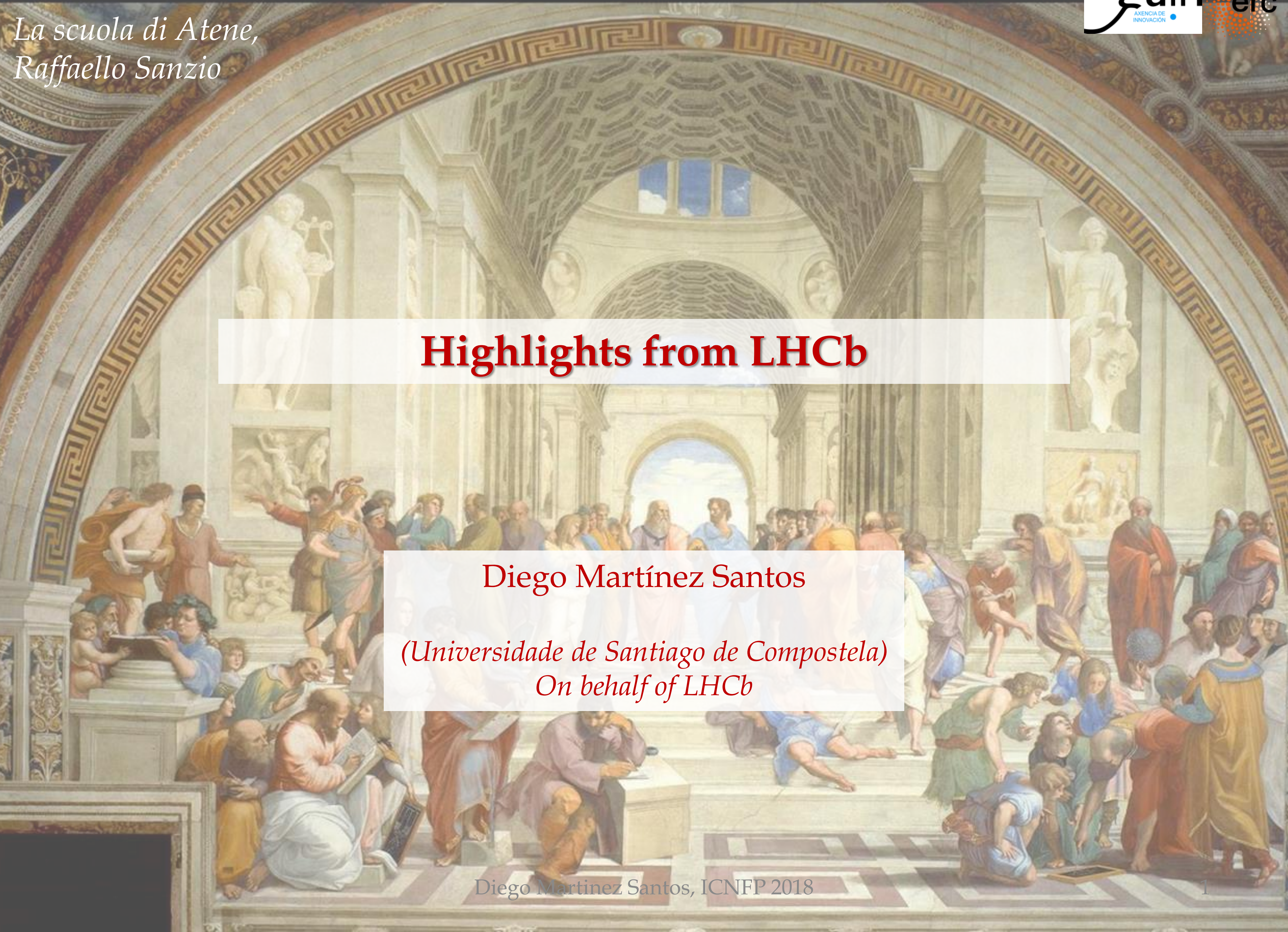


La scuola di Atene,
Raffaello Sanzio

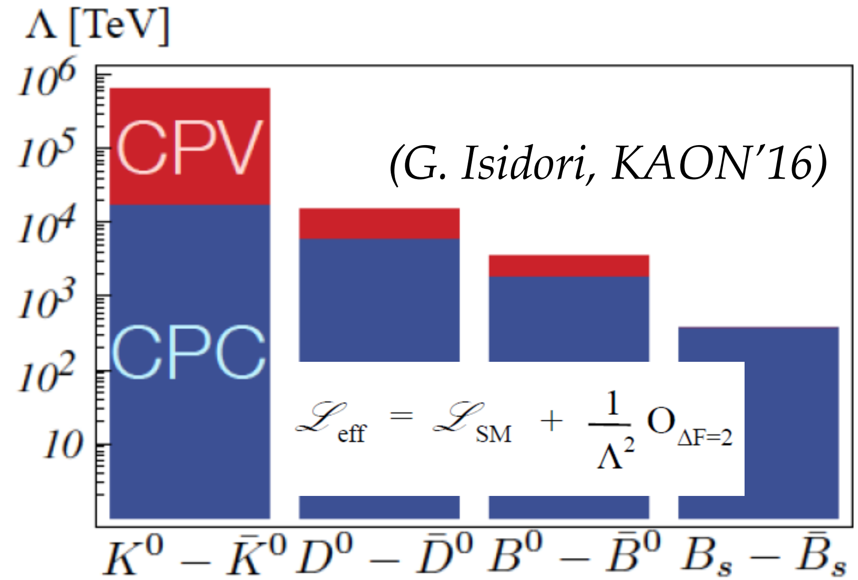
Highlights from LHCb

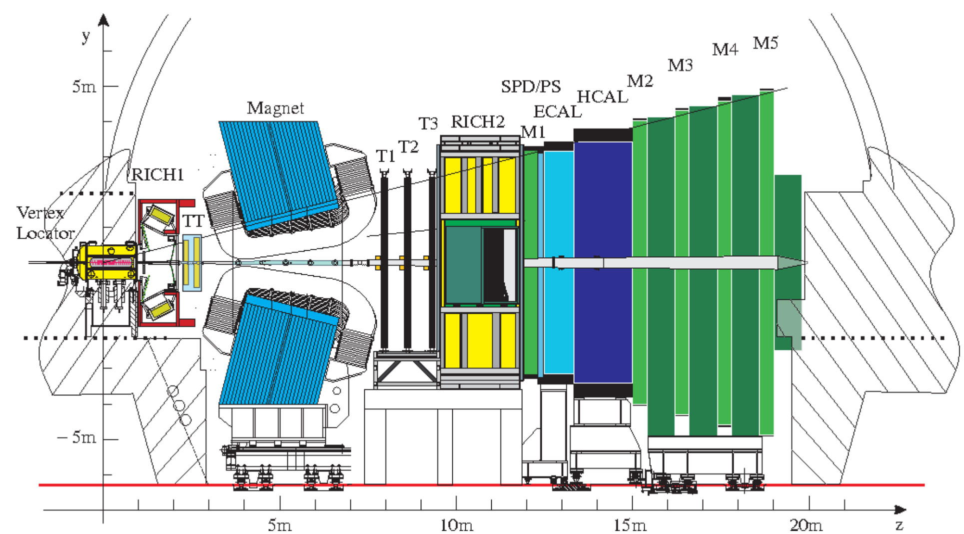
Diego Martínez Santos

(Universidade de Santiago de Compostela)
On behalf of LHCb

Introduction

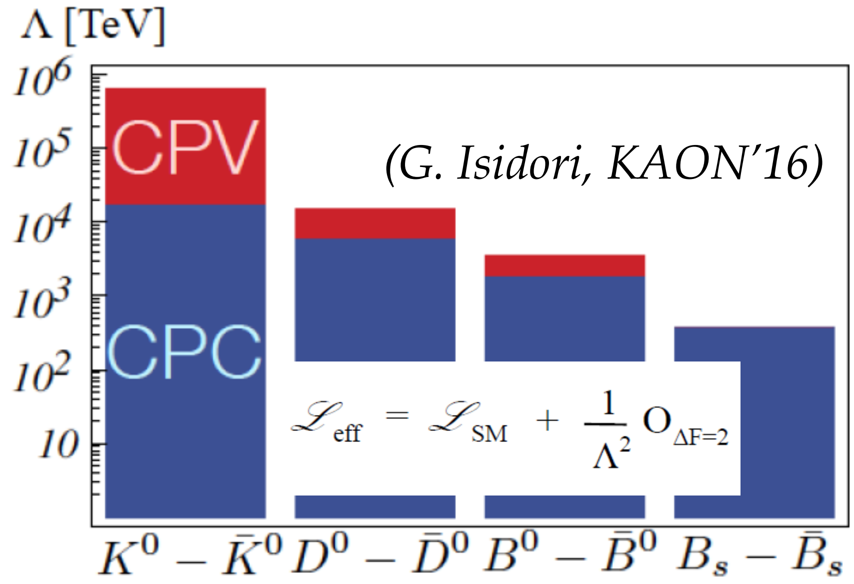
- Flavour Physics is a powerful tool to access NP beyond the reach of direct production at accelerators
- Most notably in searches for sources of FV/CPV other than CKM
- LHCb
    - Forward detector at the LHC
    - Very precise tracking and PID
- Physics goals
    - Study of CP violation and rare decays of 'light' particles (b, c, s, τ ...)
    - But also: direct searches for BSM, EW physics, soft QCD…

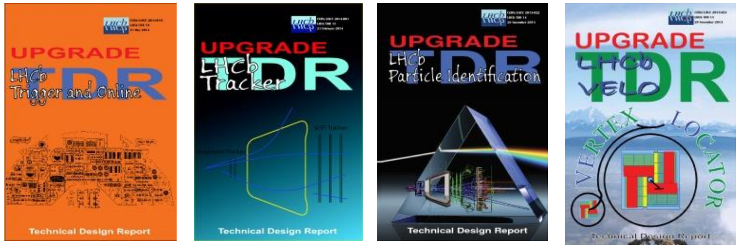




Introduction

- Flavour Physics is a powerful tool to access NP beyond the reach of direct production at accelerators
- Most notably in searches for sources of FV/CPV other than CKM
- LHCb will upgrade to continue improving our knowledge of Flavour Physics
- We speak about two upgrade phases:
    - Phase-I (2021-2029): Approved, TDR's ready, in construction





CERN-LHCC-2014-016
CERN-LHCC-2014-001
CERN-LHCC-2013-022
CERN-LHCC-2013-021

Introduction

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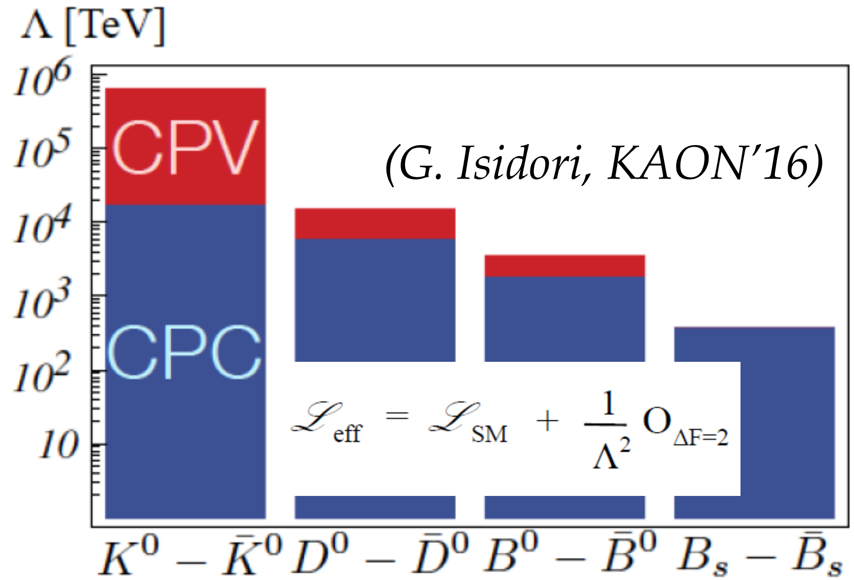
  - Phase-I (2021-2029): Approved, TDR's ready, in construction
  - Phase-II (2031->2035): Expression of Interest published



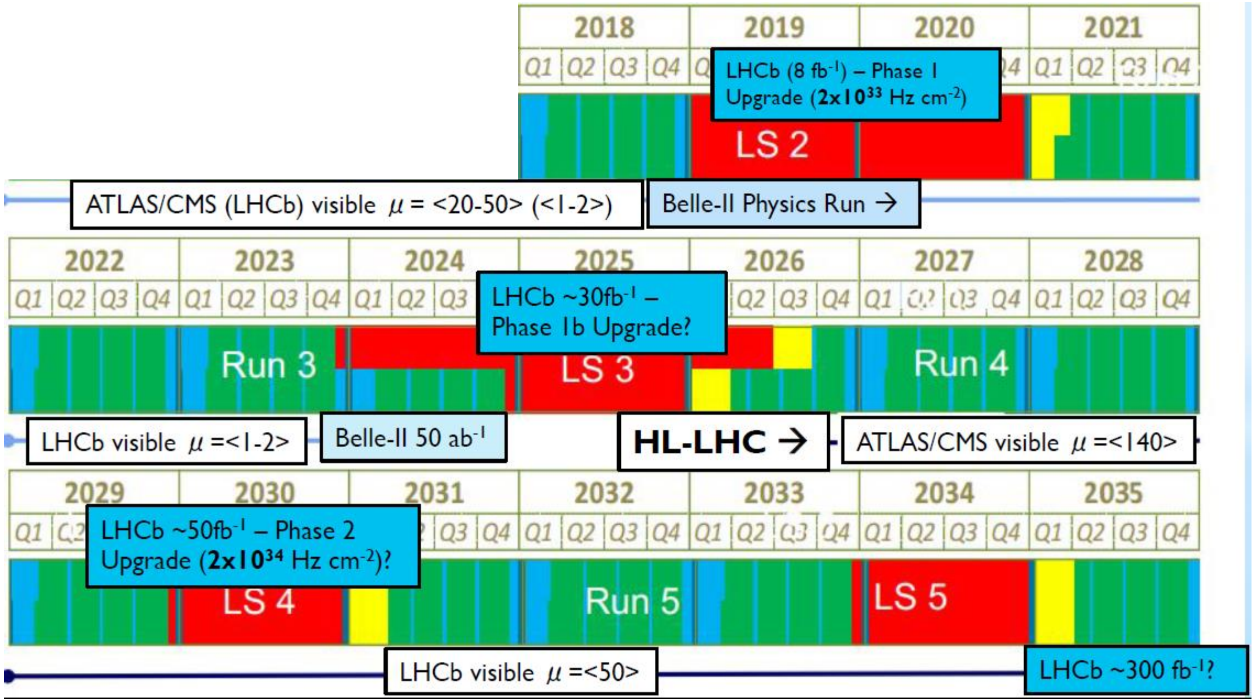
Timescale

Run-I :

- 2011: 1fb^{-1} @ 7 TeV
- 2012: 2fb^{-1} @ 8 TeV

Run-II:

- 2015: 0.3 fb-1 @13 TeV
- 2016: 1.7 @ 13 TeV
- 2017: 1.7 @ 13 TeV
- 2018: ~0.8



	LHC Run	Period of data taking	Maximum $\mathcal{L}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Cumulative $\int \mathcal{L}\,dt$ $[\mathrm{fb}^{-1}]$
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 $\rightarrow$	2031–2033, 2035 $\rightarrow$	2×10^{34}	300

$B_s \to \mu\mu$

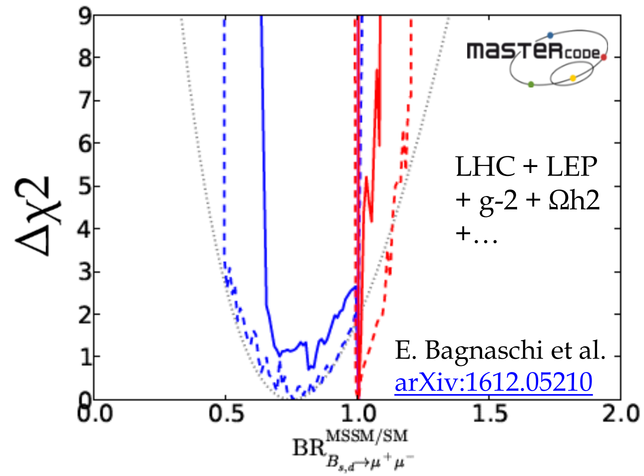
- $B_s \to \mu\mu$ is (still) a golden modes in NP searches w/ 4.4 fb^{-1} :

LHCb

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$ *LHCb, arXiv:1703.05747 PRL 118, 191801 (2017)*

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

C. Bobeth et al., arXiv:1311.0903.

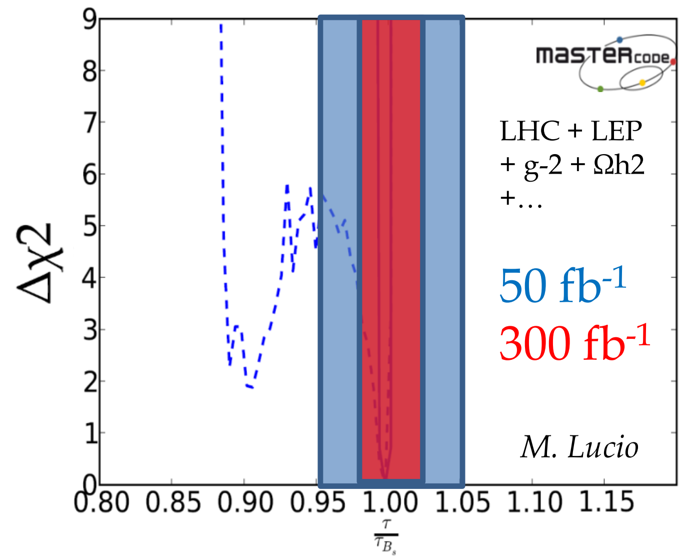


  - Deviations from SM allowed despite LHC bounds on NP
  - Expected precision

$\sigma(\mathrm{BR}(B_s \to \mu\mu))$, 50 fb^{-1} ~ 2.3×10^{-10}
$\sigma(\mathrm{BR}(B_s \to \mu\mu))$, 300 fb^{-1} ~ 1.6×10^{-10}

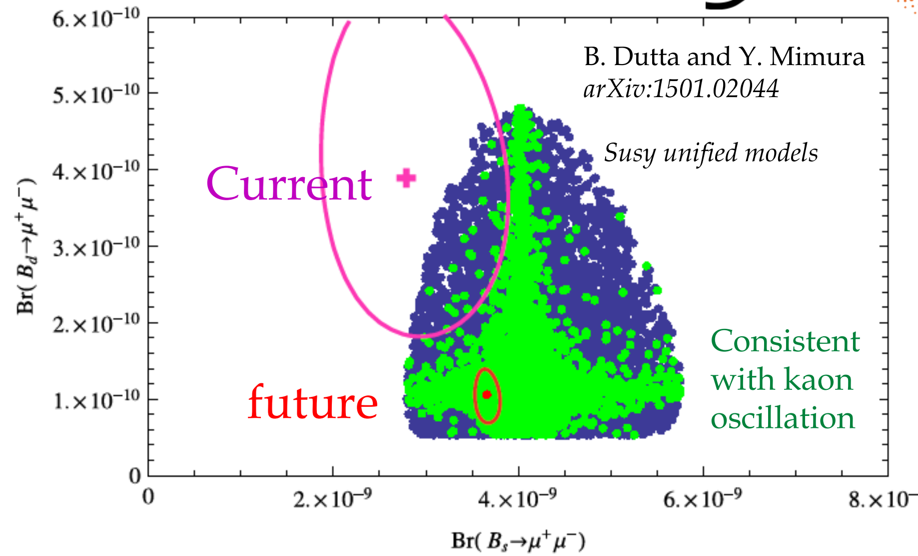
- The effective B_s lifetime in $B_s \to \mu\mu$ is also sensitive to NP for precisions of percent

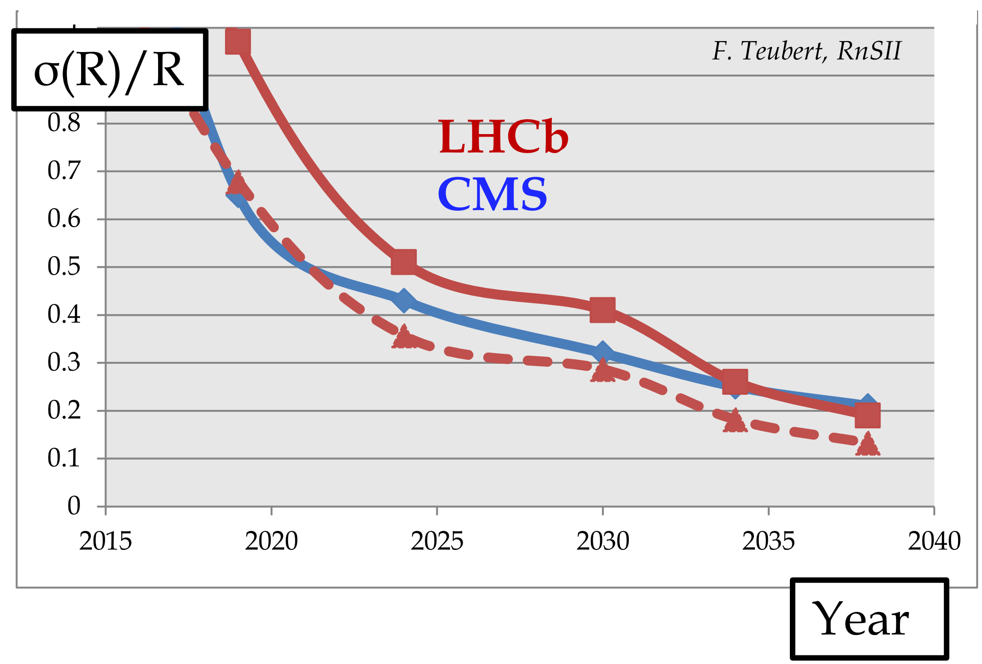
$\sigma(\tau)$, 50 fb^{-1} ~ 5%
$\sigma(\tau)$, 300 fb^{-1} ~ 2%



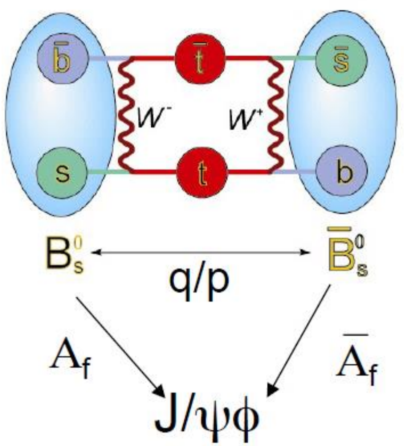
$B_s \to \mu\mu$ / $B_d \to \mu\mu$

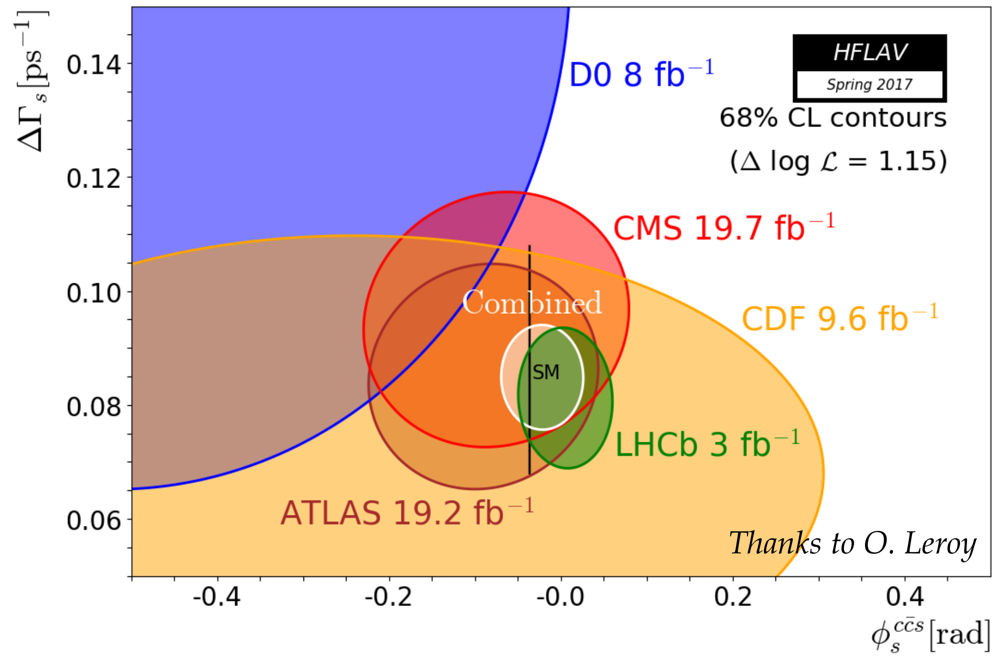
- The ratio of BR's B_d/B_s is considered a golden mode for testing new sources of flavour violation
- LHCb upgrade can reach <30% precision (stat. limited)
- Phase-II could achieve ~10% (…and still stat limited)





Bs mixing phase, Φs





CPV in interference mixing-decay:

$$\sin(\boldsymbol{\phi_s}) \equiv \sin\left(-arg\left(\frac{q}{p}\frac{A_f}{\overline{A_f}}\right)\right) \neq 0$$

$$\boxed{\phi_S^{EXP} = -0.021 \pm 0.031\,rad}$$

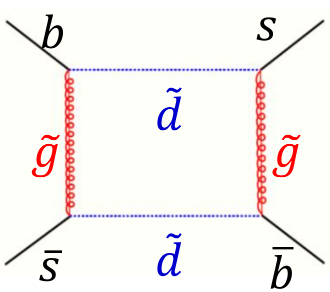
Which in b→cc decays corresponds to the mechanical phase of the Bs mixing. In SM:

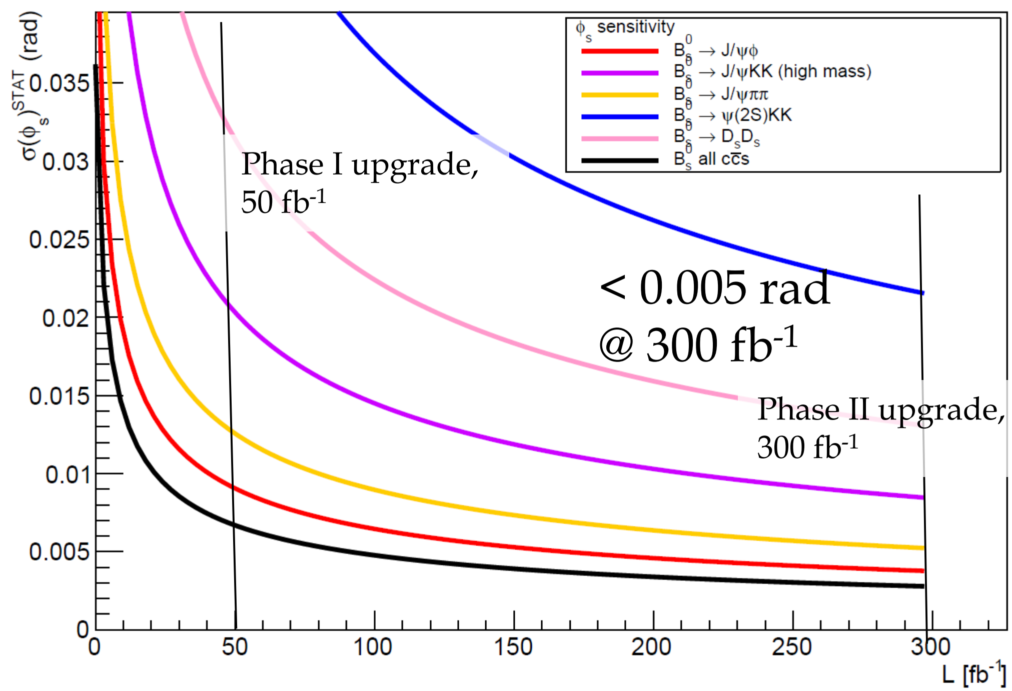
$$\phi_s \overset{\text{SM}}{=} -2\arg\left(\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) \equiv -2\beta_s = -0.0376 \pm 0.0008\,\text{rad}$$

Bs mixing phase, Φs

- Neutral meson mixing (ΔF = 2 transitions) are extremely sensitive to new source of flavour violation. eg, for O(1) couplings bounds on Λ_{NP} at 100 – 10^5 TeV

- eg, in SUSY the B mesons can mix via gluino box



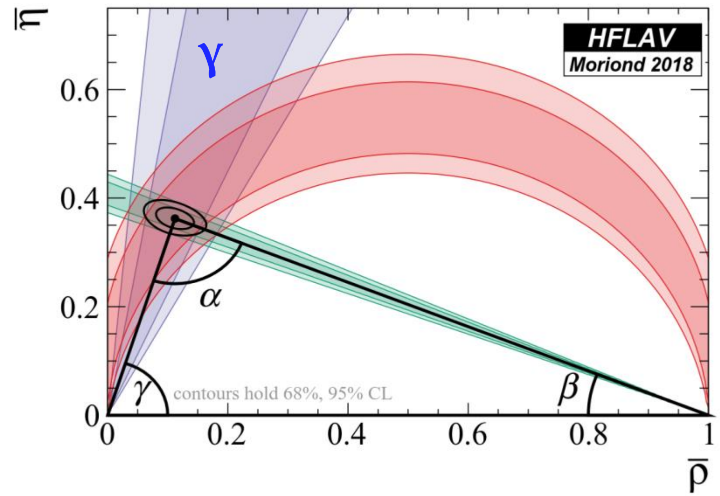


LHCb-CONF-2018-002

The CKM angle γ

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

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



B decay	D decay	Method	Ref.	Dataset
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1

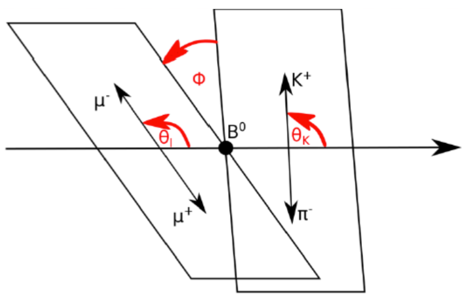
LHCb

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$
$$\gamma \in [68.2, 79.0]^\circ \quad @68.3\%\ \mathrm{CL}$$
$$\gamma \in [61.6, 83.7]^\circ \quad @95.5\%\ \mathrm{CL}$$

$B_d \to K^*\mu\mu$ angular observables

JHEP 02 (2016) 104

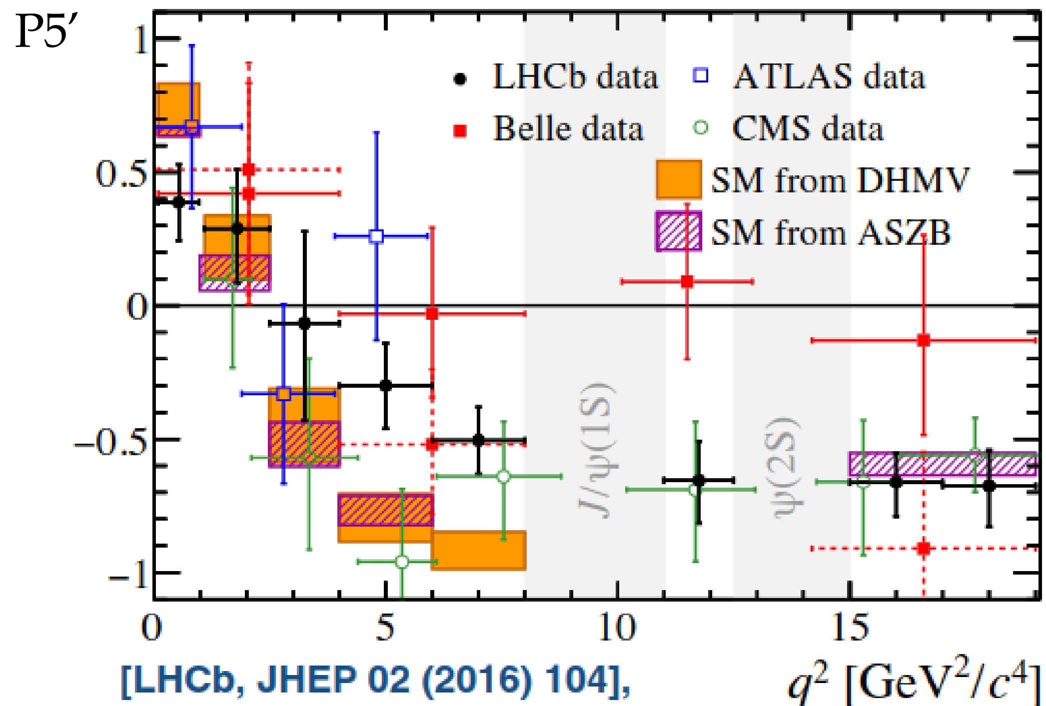
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \quad + \ldots$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell \ + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$



P_5' is one of the coefficients of the differential decay rate of the helicity angles, designed to have reduced TH uncertainties

2 bins show a ~3σ deviation (each) w.r.t SM prediction(s)

But this significance can be diluted by hadronic effects



[LHCb, JHEP 02 (2016) 104],
[Belle, PRL 118 (2017) 111801],
[ATLAS-CONF-2017-023],
[CMS, PLB 781 (2018) 517].

Lepton Universality Violation in b→sll

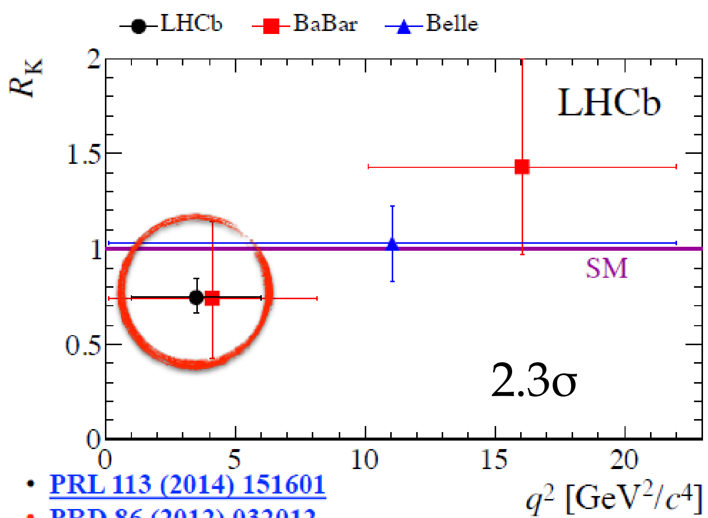
JHEP 08 (2017) 055

LHCb observed some interesting deviations in the ratios

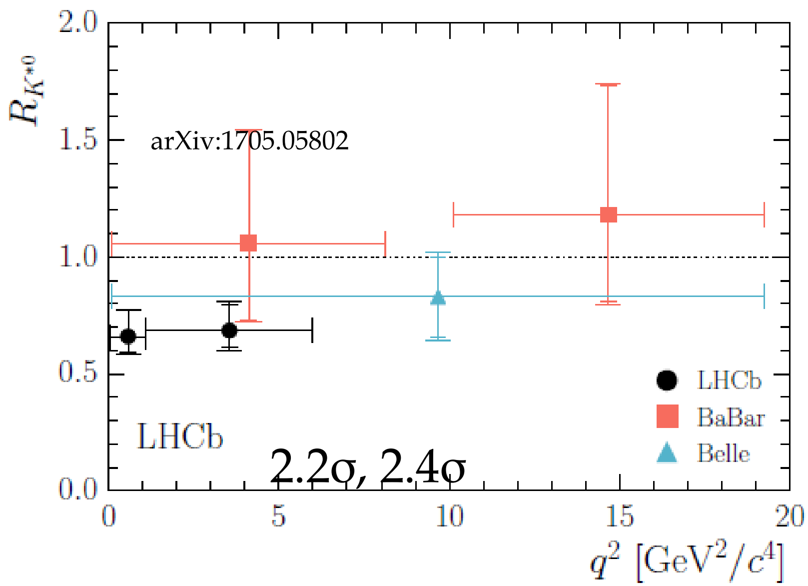
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi\,(\to e^+e^-))}$$

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

Full Run-I dataset

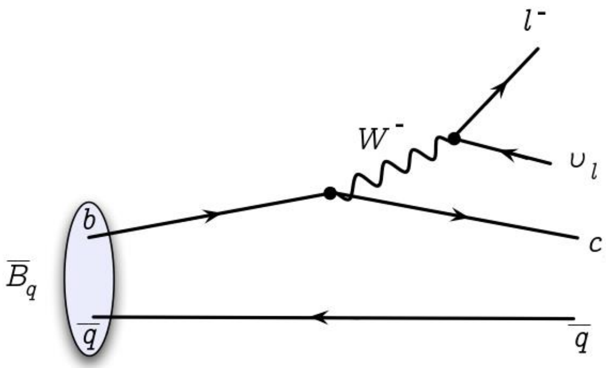


- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

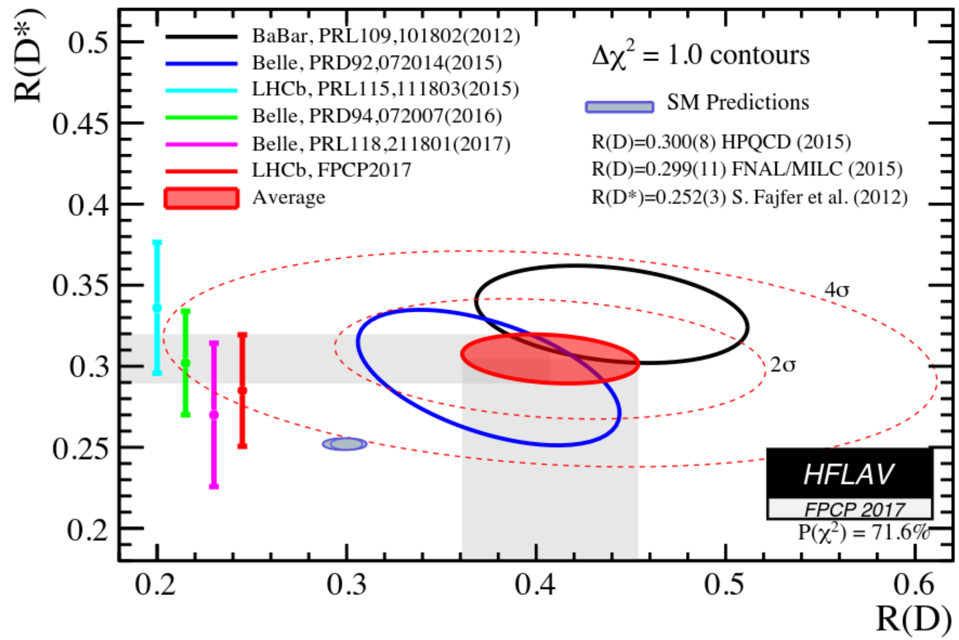


Can be "explained" by similar BSM than P_5'

LUV in semileptonic b decays



$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau \nu)}{\mathcal{B}(X_b \to X_c l \nu)}$$



LHCb, 3 fb^{-1}

Full Run-I dataset

R(D*) leptonic tau: 0.336 ± 0.027 ± 0.030 PRL 115 (2015) 111803

R(D*) hadronic: 0.291 ± 0.019 ± 0.026 ± 0.013 PRL 120 (2018) 171802

Overall (WA) ~4σ deviation w.r.t SM prediction in the R(D) vs R(D*) plane, towards larger values

→ Check it with larger stats, as well as in other channels

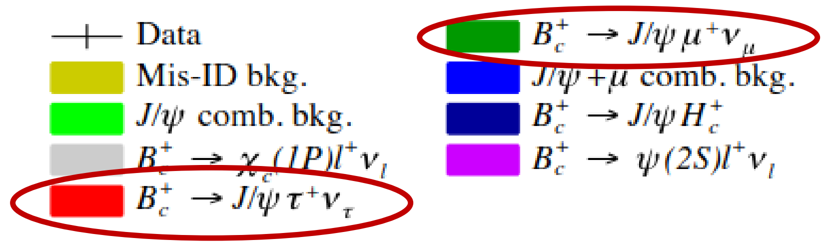
→ Recent measurement on B_c decays

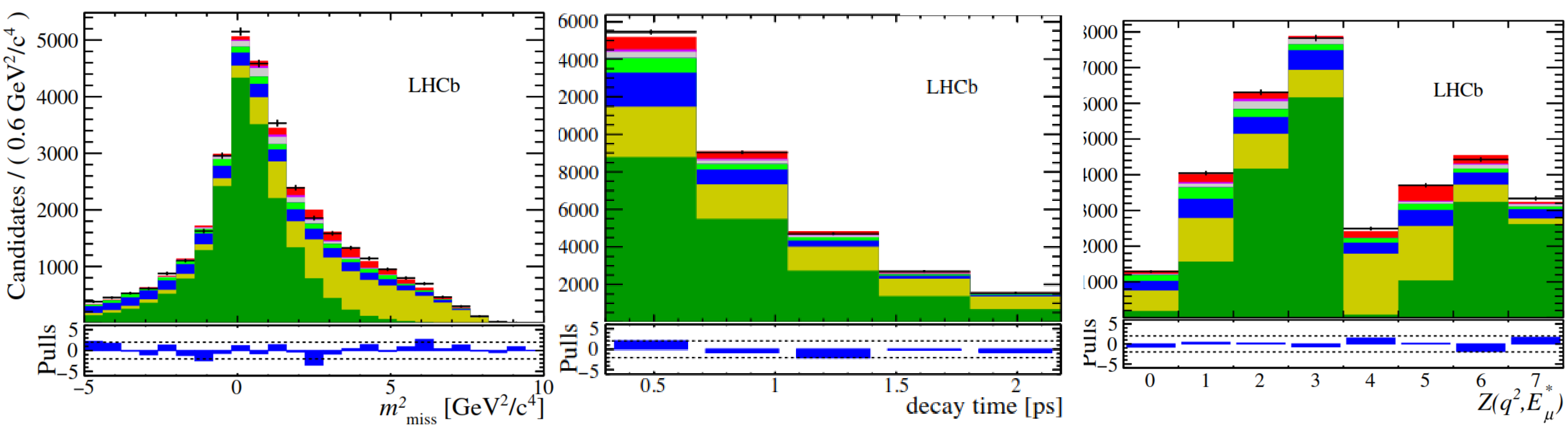
LUV in semileptonic b decays

PRL 120, 121801 (2018)

- LHCb analysis using leptonic τ decays
- 3D template fit: missing mass, estimated lifetime with kinematic constraints, and a categorical variable Z (bins of missing transverse momentum and q2)

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \bar{\nu}_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \bar{\nu}_\mu)}$$





$$\boxed{R(J/\psi) = 0.71 \pm 0.17 \pm 0.18}$$

Consistent with expectations from R(D*)
Within less than 2σ from SM (0.25-0.28)
Also first evidence for $B_c \rightarrow J/\psi\tau\nu$

Full Run-I dataset

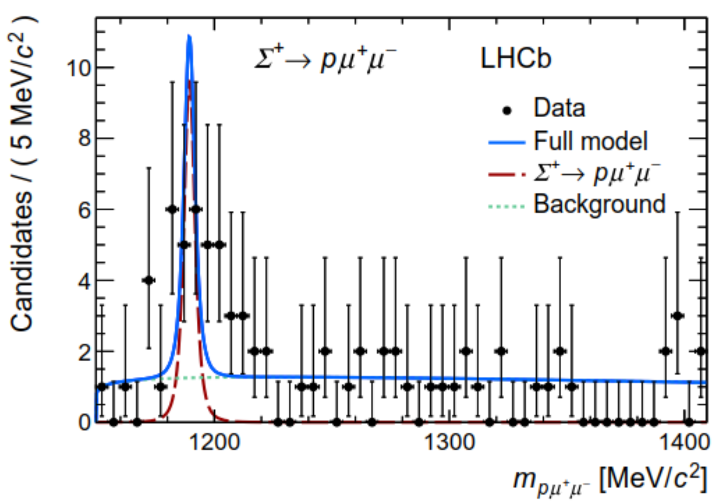
Σ→pμμ full Run-I analysis

PRL 120, 221803 (2018)

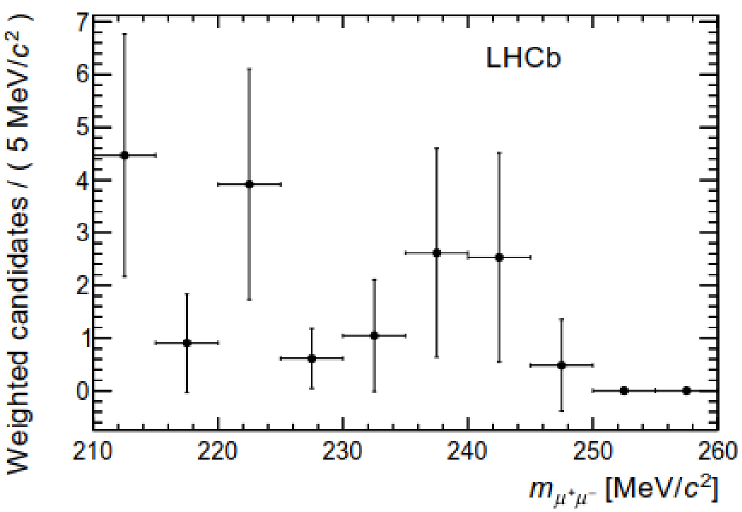
- Motivation: HyperCP experiment found evidence for Σ→pμμ decays, all with the dimuon mass of ~ 214 MeV, which suggested the possibility of a light dimuon resonance → LHCb can check this

- Σ→pμμ : Found 4σ evidence
- BR(Σ→pμμ) : $2.2^{+1.8}_{-1.3}$ x 10^{-8}

Consistent with SM as well as with HyperCP

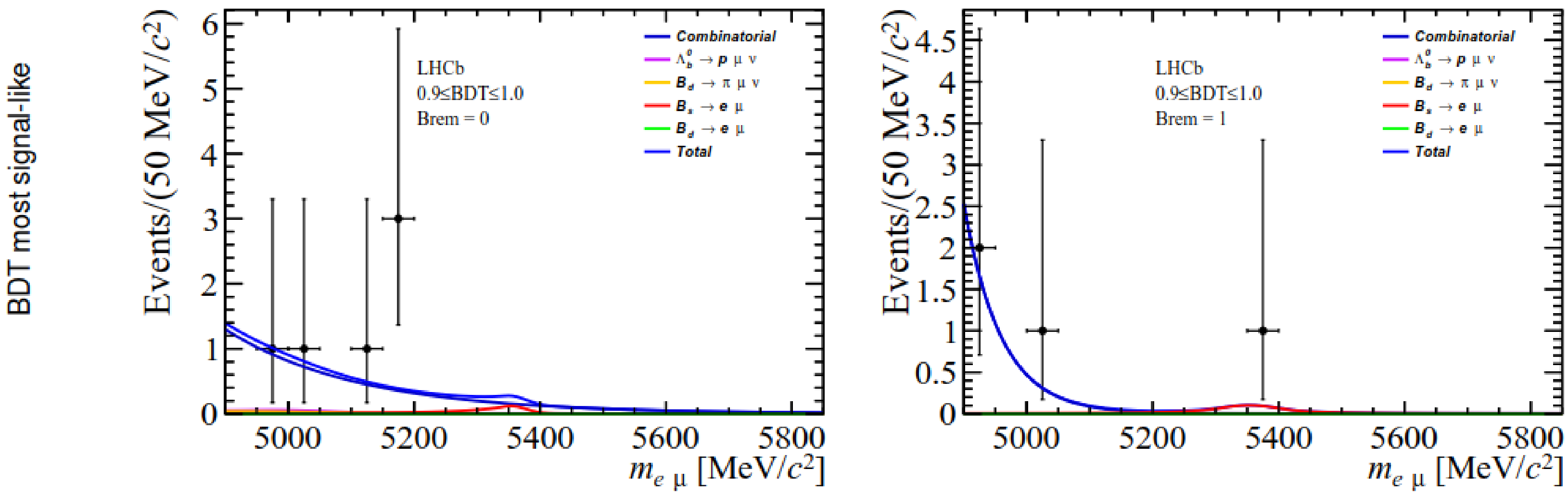


- X→ μμ : Found no evidence for the 214 MeV particle. Upper limit for the resonant channel: 1.4x10^{-8} @95% CL



LFV: $B_{(s)} \rightarrow e\mu$

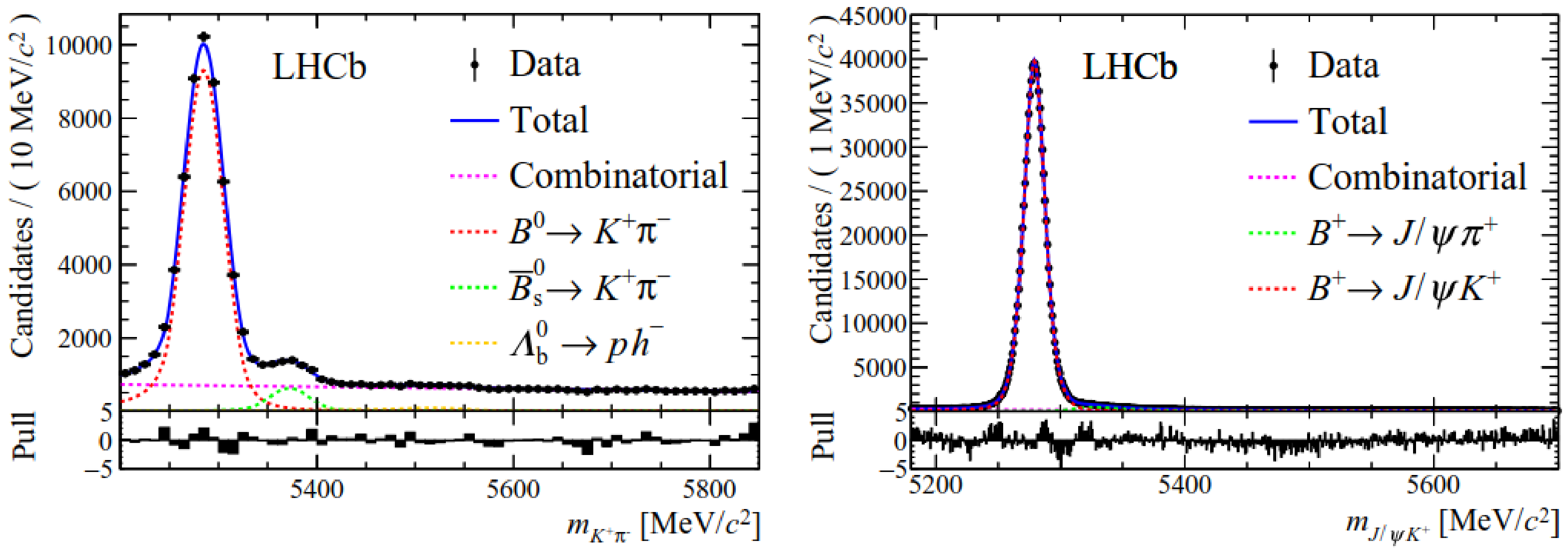
- Run-I dataset
- Used BDT to discriminate from background
- Invariant mass fit in different bremsstrahlung categories
    - Without photon recovery
    - With photon recovery



LFV: $B_{(s)} \rightarrow e\mu$

JHEP 1803 (2018) 078

- Run-I dataset
- Used BDT to discriminate from background
- Invariant mass fit in different bremsstrahlung categories
- Normalization of the signal yield to B channels with known BR: $B^+ \rightarrow J/\psi K^+$, $B_d \rightarrow K\pi$



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JHEP 1803 (2018) 078

- Run-I dataset
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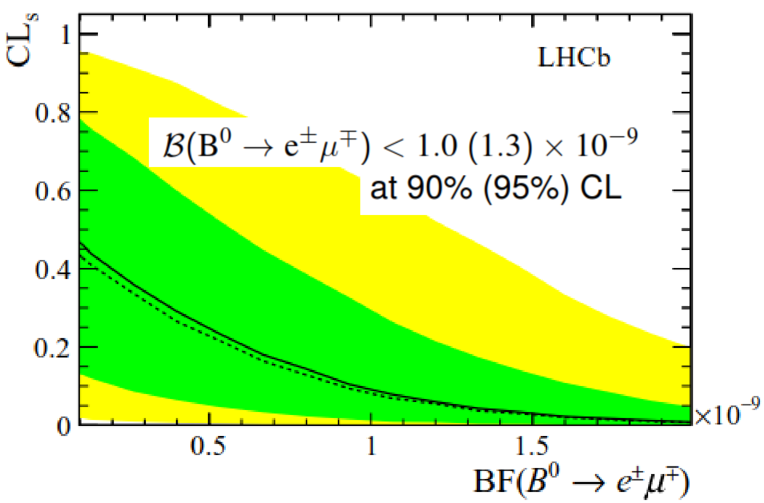
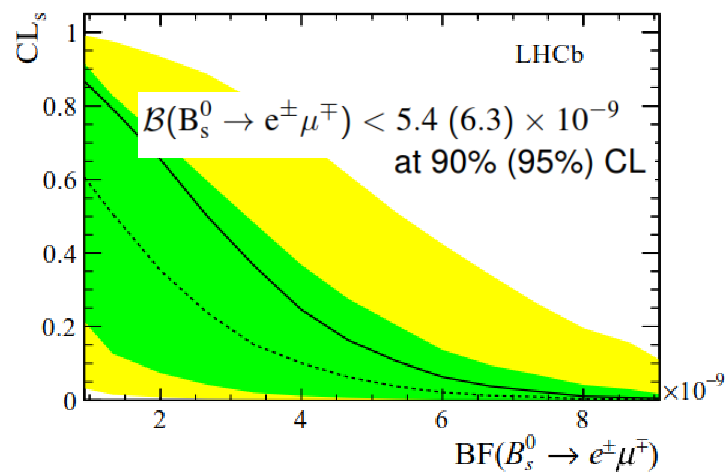
- Normalization of the signal yield to B channels with known BR: $B^+ \to J/\psi K^+$, $B_d \to K\pi$
- Upper limit set with CLs

World best upper limits:



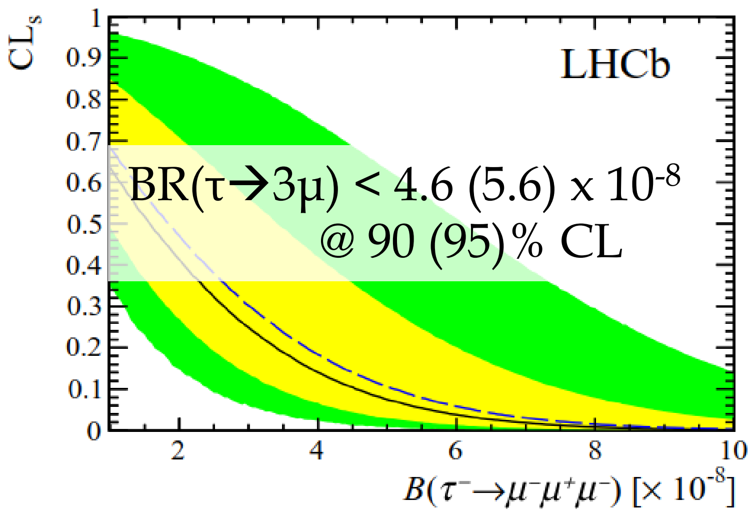


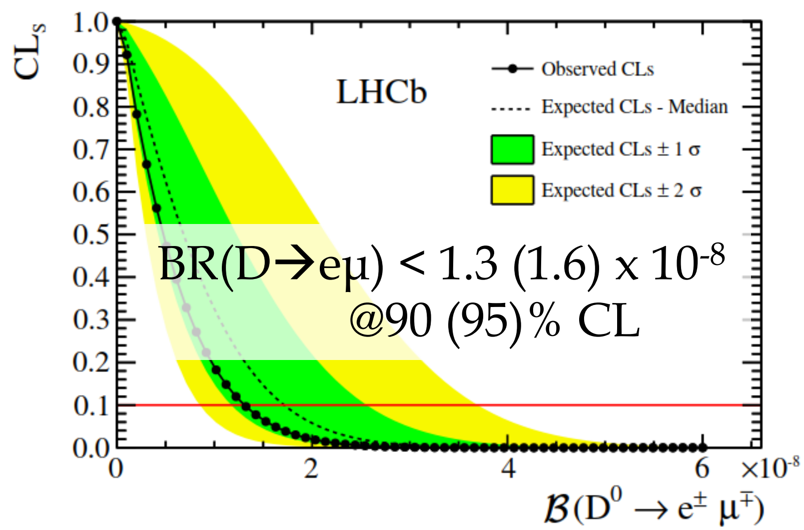
LFV: D→eμ, τ→μμμ

JHEP 02 (2015) 121
PLB 754(2016)167

Other results in LFV

- BR(τ→3μ) < 4.6 (5.6) x 10^{-8} @ 90 (95)% CL JHEP 02 (2015) 121
  - Competitive with Belle (2.1 x 10^{-8} @ 90%CL) PLB 687 (2010) 139
- BR(D→eμ) < 1.3 (1.6) x 10^{-8} @90 (95)% CL (world best) PLB 754(2016)167





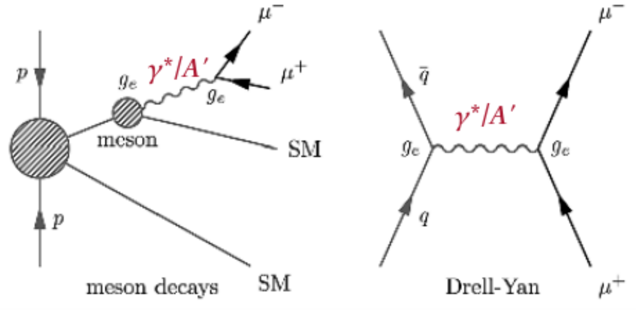
Full Run-I dataset

Dark photons

PRL 120 (2018) no.6, 061801

- Search for dark photons (A'), that mix to off-shell photons → shared production mechanism→ normalization to DY

- Uses dedicated "turbo" trigger: writes on tape only the relevant part of the event



Turbo trigger: Write on tape the relevant information of the event as measured online:

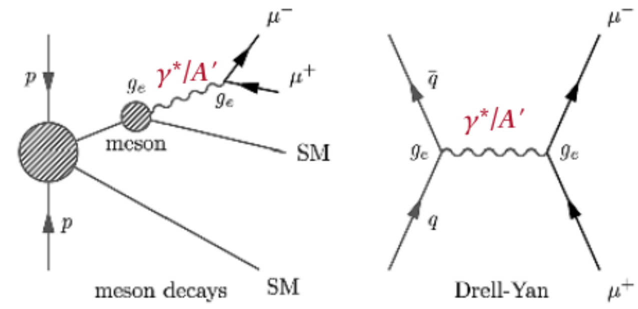
+ Advantage: Little event size → afford higher output rate and hence efficiency

+ Disadvantage: Give up offline reconstruction quality, analysis reoptimizations

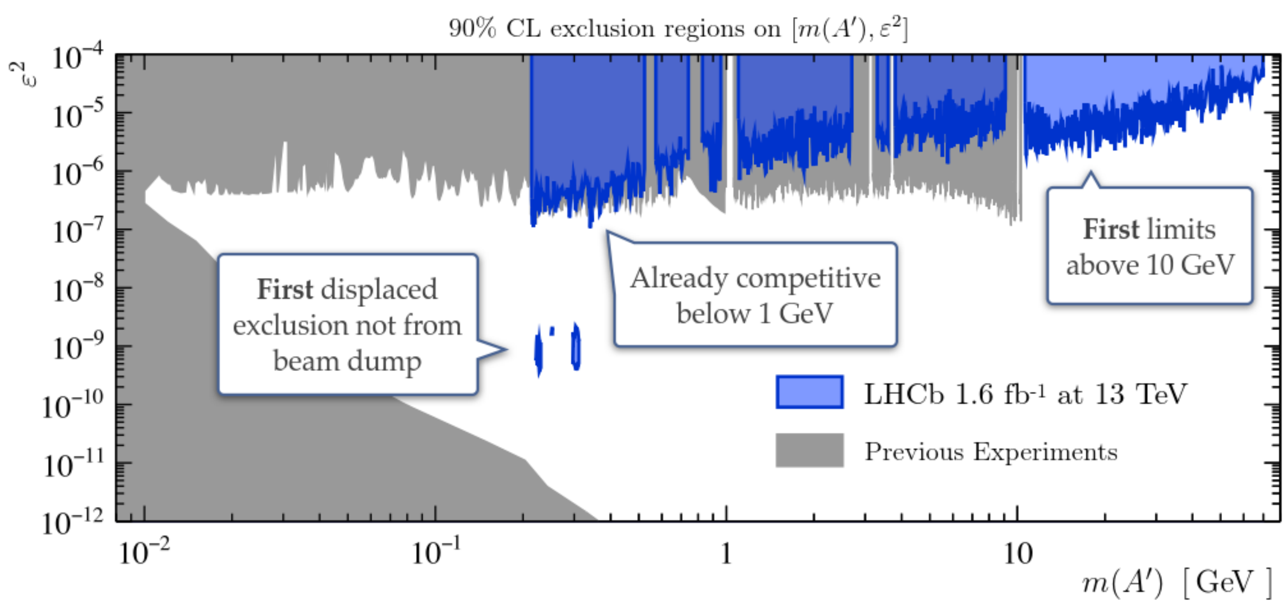
Dark photons

PRL 120 (2018) no.6, 061801

- Search for dark photons (A′), that mix to off-shell photons → shared production mechanism→ normalization to DY
- Uses dedicated "turbo" trigger: writes on tape only the relevant part of the event
- 1.6 fb^{-1} of Run-II (13 TeV) data



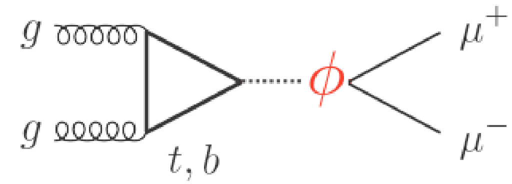
- Prompt search up to m_Z
- Displaced search up to 350 MeV

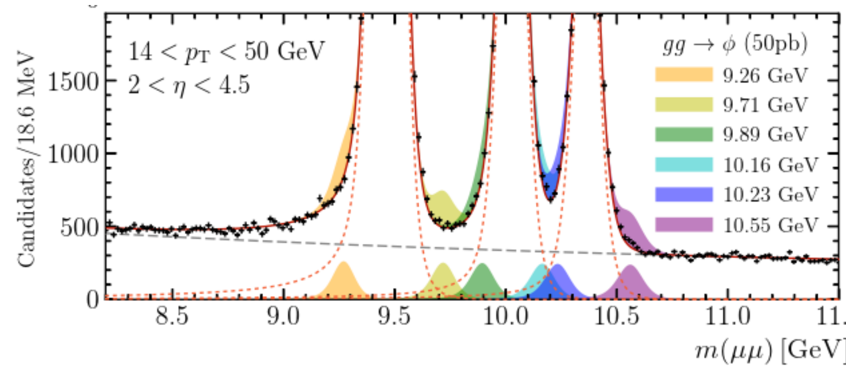


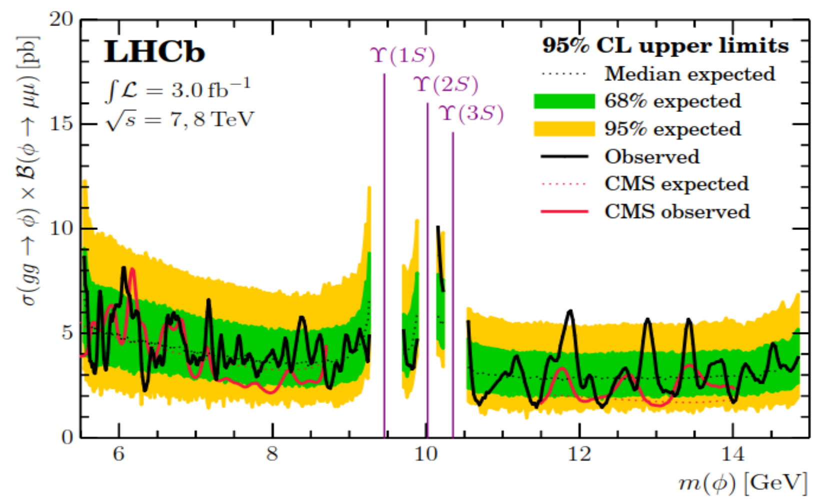
BSM bosons from gg→μμ

LHCb-PAPER-2018-008
arXiv: 1805.09820

- Search for a prompt dimuon resonance in the full Run-I data (supersedes preliminary result of Moriond EW)
- Statistically independent from the Dark Photon search → can be combined by recast searches)
- Search inspired in NMSSM, but done in bins of η, pt to easy interpretations in different models
- Good mass resolution of LHCb allows to explore closely the Υ region
- No signal found, upper limits in σ x BR set (CLs). ~ 5 pb level







Conclusions

- Presented results on beauty, charm, strange and tau decays
- Also BSM direct searches
- The HyperCP anomaly seems to vanish
- On the other hand, interesting deviations in LFU tests

Conclusions

Overall the Standard Model may look impressive, with millions of successful measurements on its side…

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… but we are not afraid

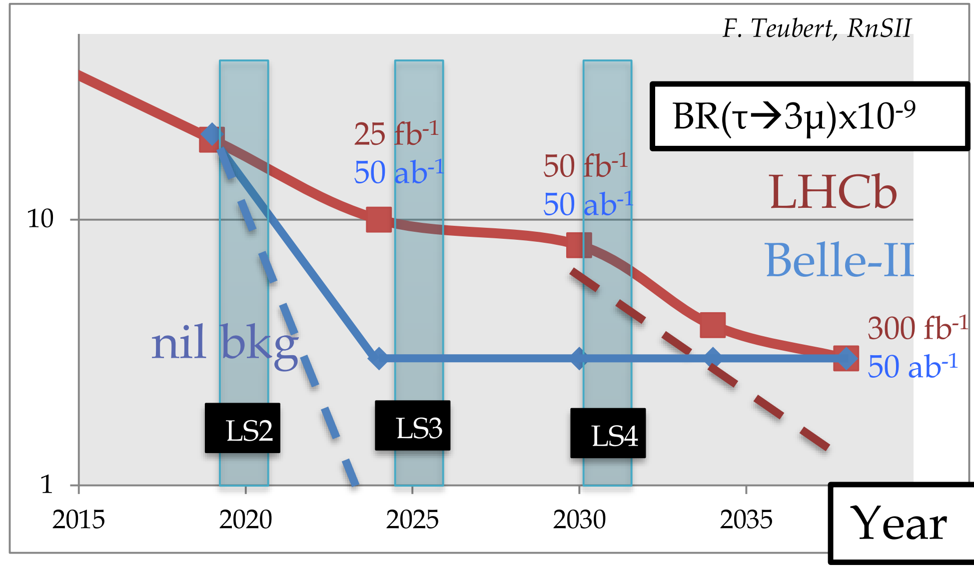
BACKUP

Lepton Flavour Violation

- LFV forbidden in SM, but allowed in BSM

  → positive signal is compelling NP discovery

- LHCb searches for LFV



Several world best results in hadron decays

τ→3μ Phase-II competitive w/ Belle II

	1fb^{-1} (Phys. Rev. Lett. 111 (2013) 141801)	3fb^{-1} (exp)	300fb^{-1} (exp)
$B_s \to e^{\pm}\mu^{\mp}$	$< 1.4\times10^{-8}$ @ 90% CL	$\sim3.8\times10^{-9}$	$\sim3\times10^{-10}$
$B \to e^{\pm}\mu^{\mp}$	$< 3.7\times10^{-9}$ @ 90% CL	$\sim1.2\times10^{-9}$	$\sim1\times10^{-10}$

B→Keμ → expected O(10^{-9}) for Phase - II

JHEP 02 (2015) 121

LFV: $\tau \to \mu\mu\mu$

- Run-I dataset
- Used BDT to discriminate from background
- Classification of events in bins of 2 BDT's and $\mu\mu\mu$ mass
- Normalization of the signal yield to $D_s \to$ □$(\to \mu\mu)\pi$
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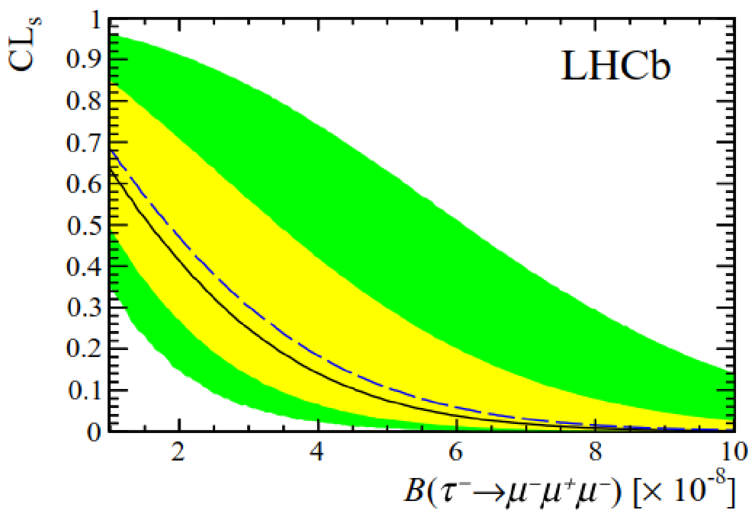
- Limit set with CLs



$BR(\tau \to 3\mu) < 4.6\ (5.6) \times 10^{-8}$
@ 90 (95)% CL

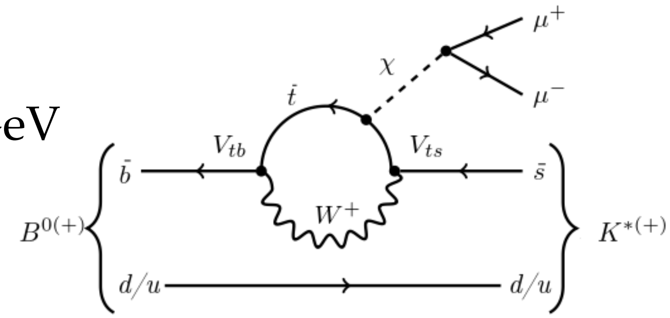
Competitive with Belle (2.1×10^{-8} @ 90%CL)
PLB 687 (2010) 139

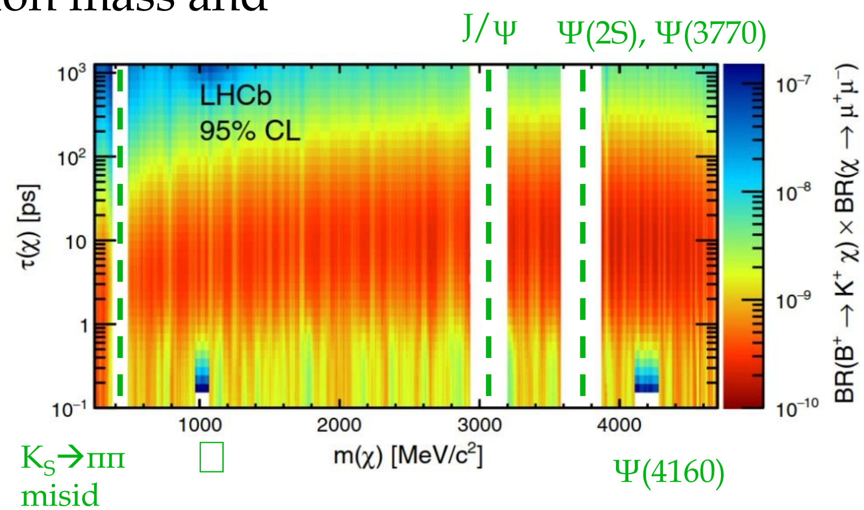
LHCb Upgrade (s) will explore the 10^{-9} region

Hidden sector bosons from flavour decays

PRL 115 161802 (2015)
PRD 95, 071101(R) (2017)

- Searches for BSM bosons (χ) in b→sμμ transitions performed in full Run-I data
- Provide sensitivity in the region ~$2m_{\mu}$ < mχ < ~4.7 GeV
- Lifetimes up to 1000 ps
- Upper limits for B→Kχ(μμ) and B→K*χ(μμ) are in the 10^{-10} – 10^{-7} range, depending on the dimuon mass and the χ lifetime (analysis reoptimized)
- See talk by Preema Pais
- Similar searches possible in s→dμμ, eg, Σ→pμμ

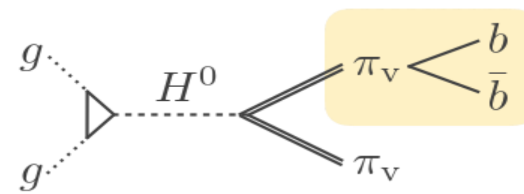


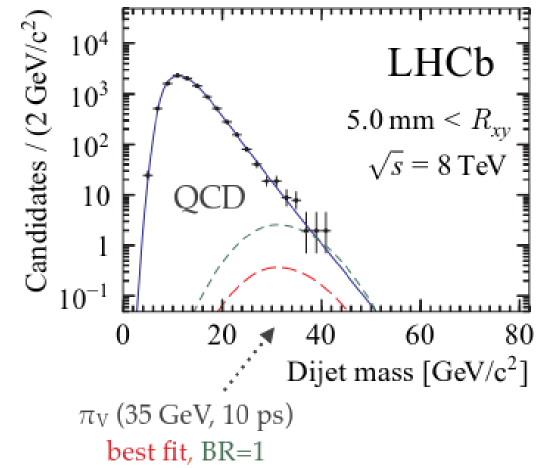


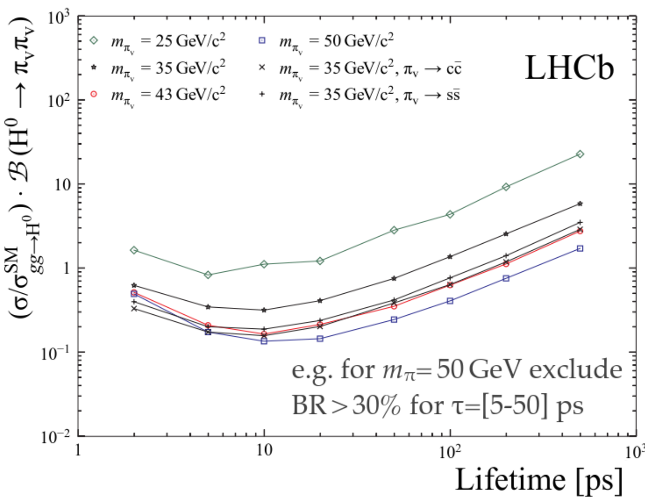
HV pions decaying to di-jets

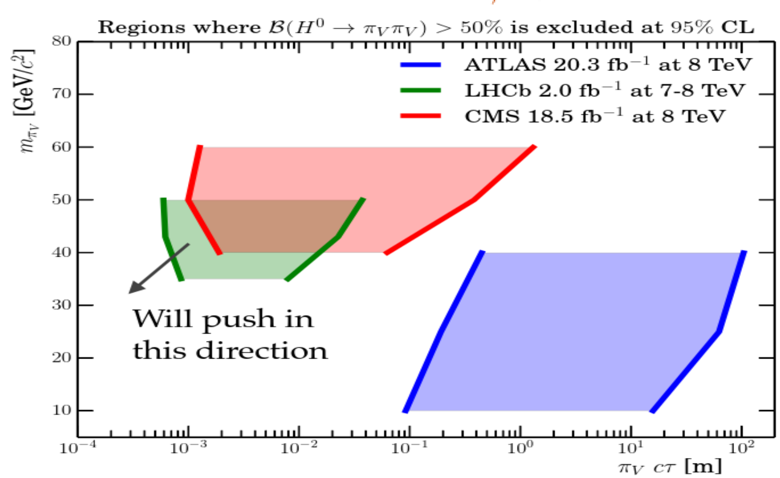
EPJC 77 (2017) 812

- Signature: search for a displaced vertex with two b-jets (low efficiency to search for all 4)
- This signature is possible in Hidden Valley pions from SM Higgs decay
- Di-jet mass fit in bins of transverse displacement
- 2 fb^{-1} of Run-I data, @7 and 8 TeV.









Trigger system: status and prospects

L0
(Hardware)

Main bottleneck for K. Can't be changed

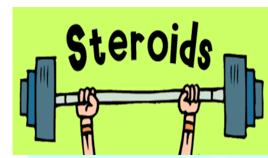
HLT1
(Software)

Not designed for K, but flexible.

HLT2
(Software)

K triggers being implemented

LHCb Upgrade



(Note: This logo may not be official)

HLT
(Software)

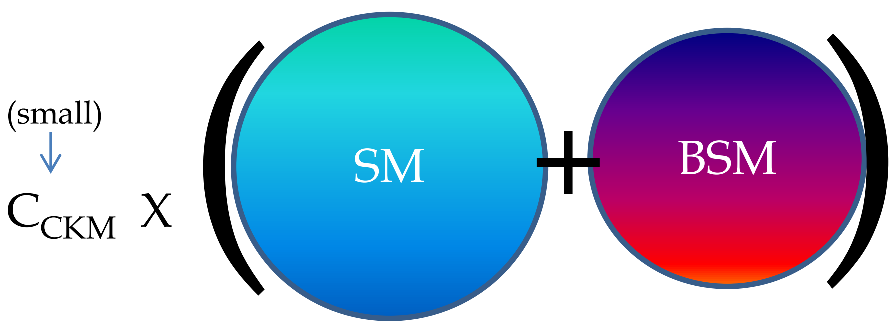
ε(2011-2012) ~ 1-2%
ε(Run-II) improved HLT1,2 ~ 18%
Maximum possible ~30% (L0 won't allow more)

ε(Upgrade) ~ 80-100%?
Simulation studies show that rate would be under control

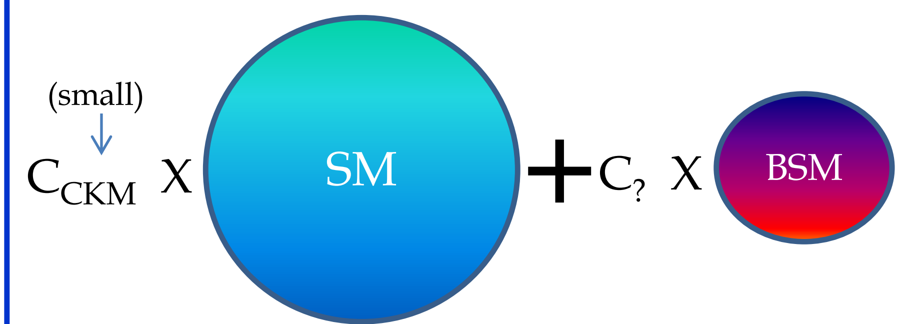
V. Chobanova et al, CERN-LHCb-PUB-2016-017

Strangeness transitions

MFV paradigm

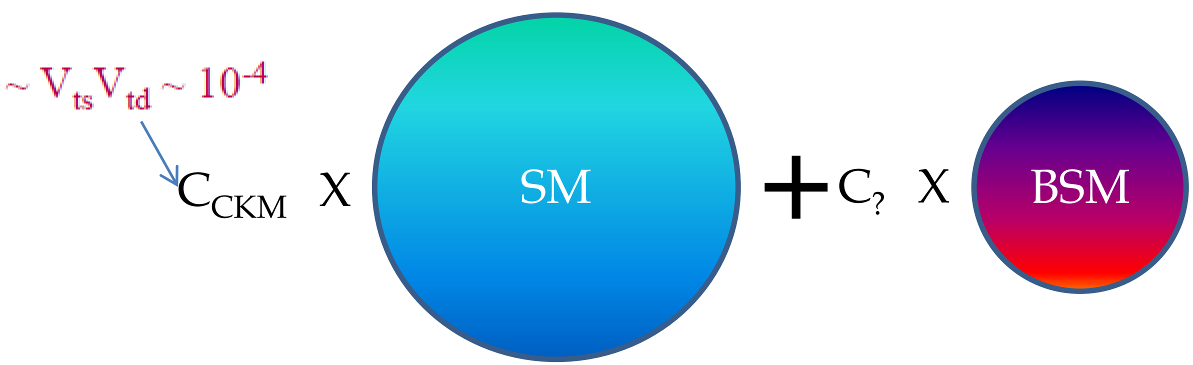


Non-MFV paradigm



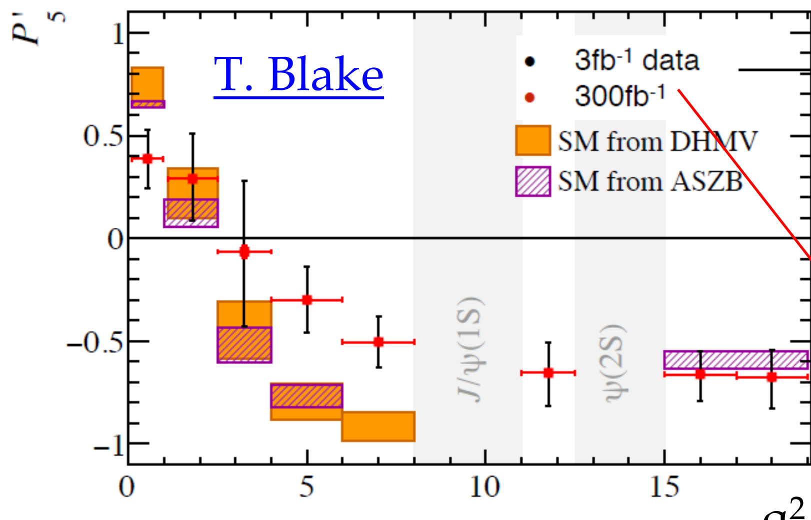
In a scenario in with BSM > few TeV, s-d transitions are central

(SM dynamics has the strongest suppression of all quark transitions)

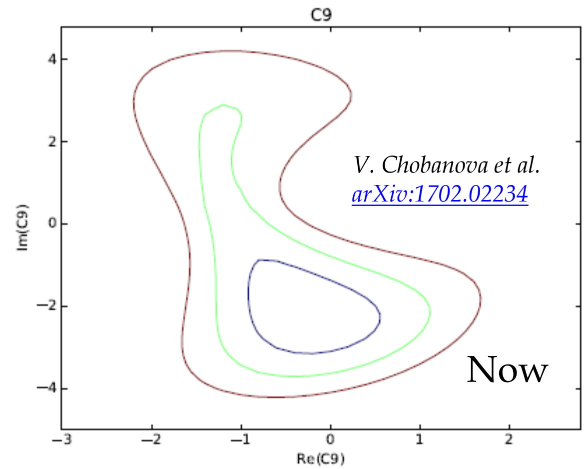


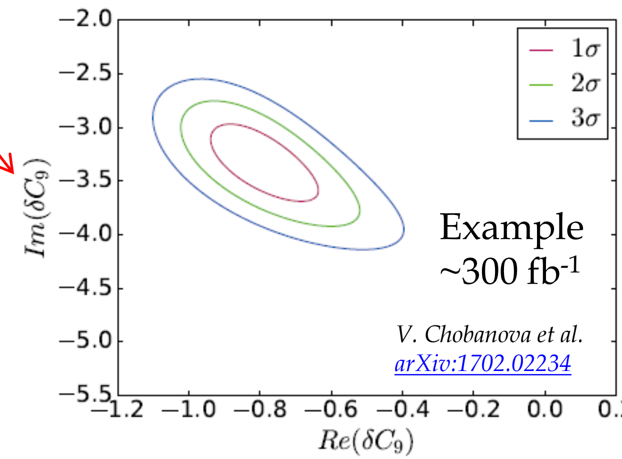
eg, for c~ 1, bounds from kaon physics go up to a scale of 10^5 TeV

$B_d \to K^* \mu\mu$ angular observables



(yes, the red points have error bars)





Moreover, the q^2 dependence will be known with high precision → very valuable input to the discussion on NP vs hadronic power corrections to SM

$B_d \to K^*\mu\mu$ angular observables

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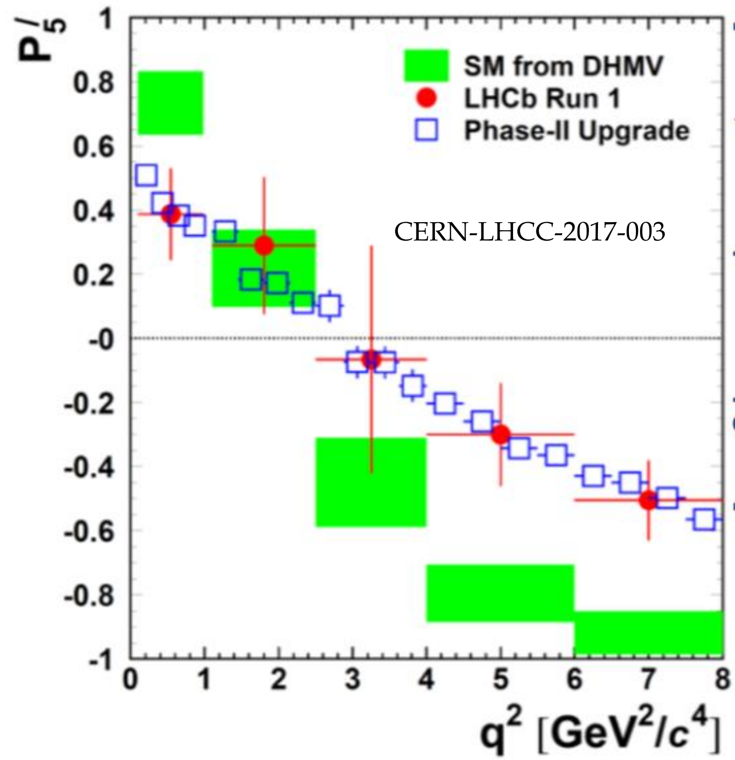
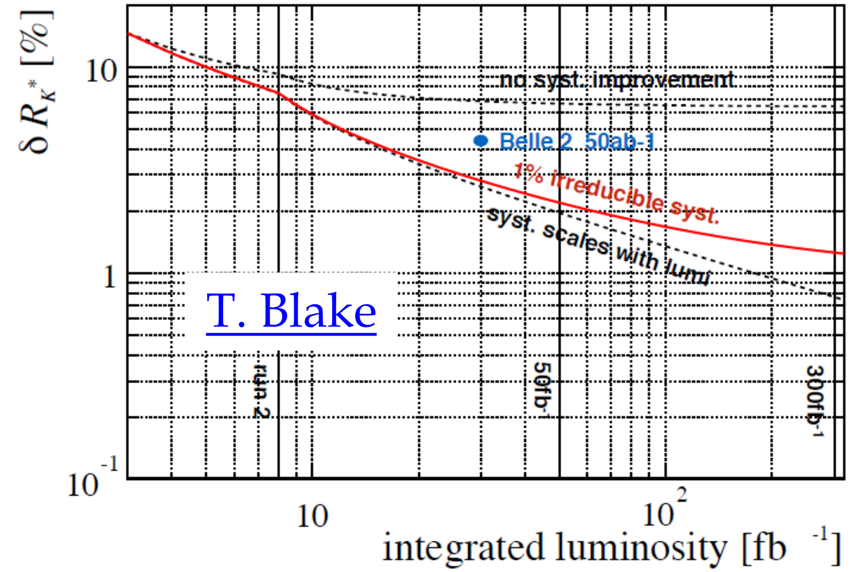


… and larger datasets would allow to make finer q^2 binning

Lepton Universality Violation in b→sll

$$R_{K^{*0}} = \begin{cases} 0.66 \,{}^{+\,0.11}_{-\,0.07}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}) \\ 0.69 \,{}^{+\,0.11}_{-\,0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}) \end{cases}$$

$$R_{K^+} = 0.745^{+0.09}_{-0.07}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$



Systematics could be ultimately reduced to ~ 1-2%

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

50 fb^{-1}	Syst./2 Pull$_{\mathrm{SM}}$	Syst./3 Pull$_{\mathrm{SM}}$
ΔC_9^μ	11.6σ	12.9σ
ΔC_9^e	12.3σ	13.6σ
ΔC_{10}^μ	12.6σ	13.9σ
ΔC_{10}^e	12.8σ	14.1σ
ΔC_{LL}^μ	12.3σ	13.6σ
ΔC_{LL}^e	12.5σ	13.8σ

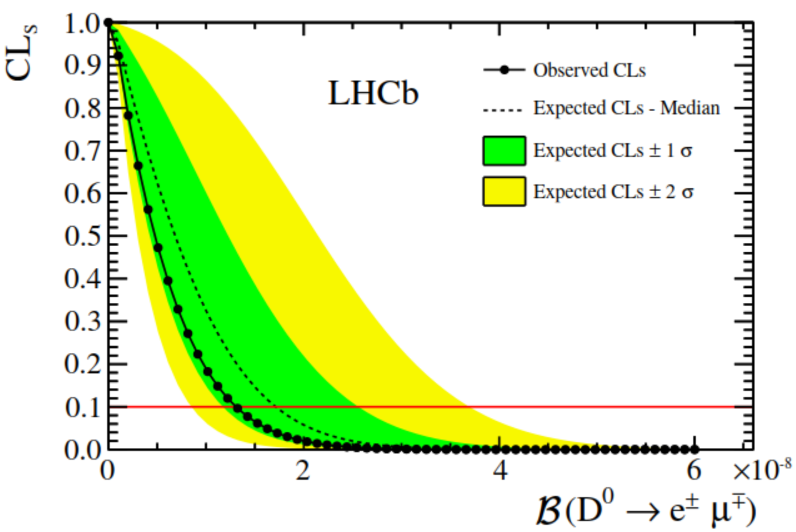
300 fb^{-1}	Syst./2 Pull$_{\mathrm{SM}}$	Syst./3 Pull$_{\mathrm{SM}}$
ΔC_9^μ	15.6σ	19.5σ
ΔC_9^e	16.6σ	20.4σ
ΔC_{10}^μ	17.0σ	20.8σ
ΔC_{10}^e	17.2σ	21.1σ
ΔC_{LL}^μ	16.6σ	20.5σ
ΔC_{LL}^e	16.9σ	20.8σ

T. Hurth et at. , arXiv:1705.06274

LFV: $D^0 \rightarrow e\mu$

PLB 754(2016)167

- Run-I dataset
- Used BDT to discriminate from background
- D^0's are tagged from $D^{*\pm} \rightarrow D^0\pi^\pm$ decays
- Invariant mass fit in different BDT categories, two mass variables: help discriminating against ~irreducible background from $D^0 \rightarrow \pi\pi$
- Normalization of the signal yield to $D^0 \rightarrow K\pi$
- Limit set with CLs



World best upper limit:

$BR(D \rightarrow e\mu) < 1.3\ (1.6) \times 10^{-8}$

@90 (95)% CL

LFV: τ→μμμ

JHEP 02 (2015) 121

- Run-I dataset
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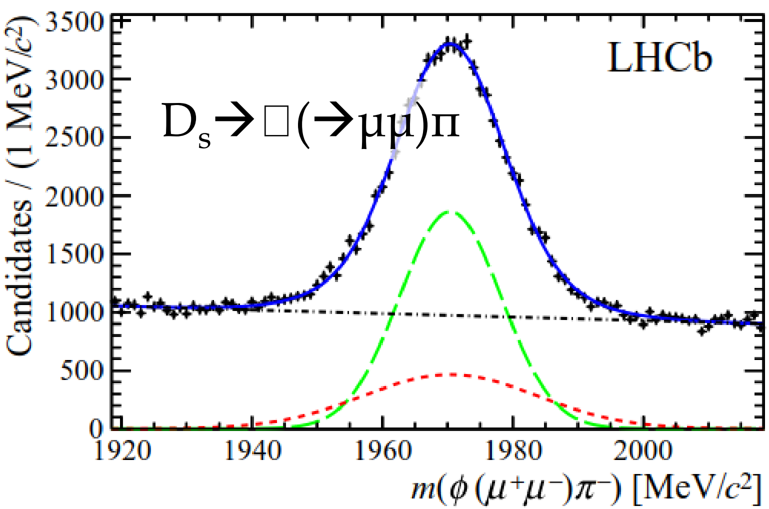
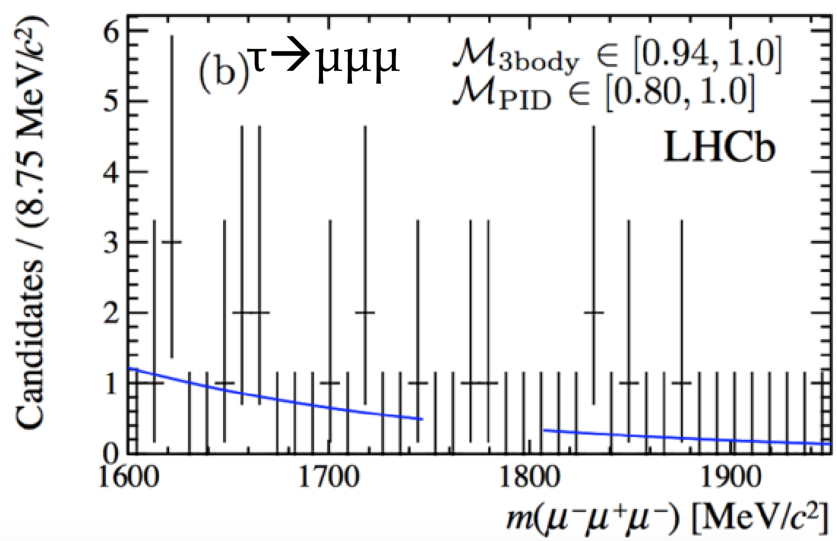
- Normalization of the signal yield to D_s→□(→μμ)π
- Background estimate from sidebands





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JHEP 02 (2015) 121

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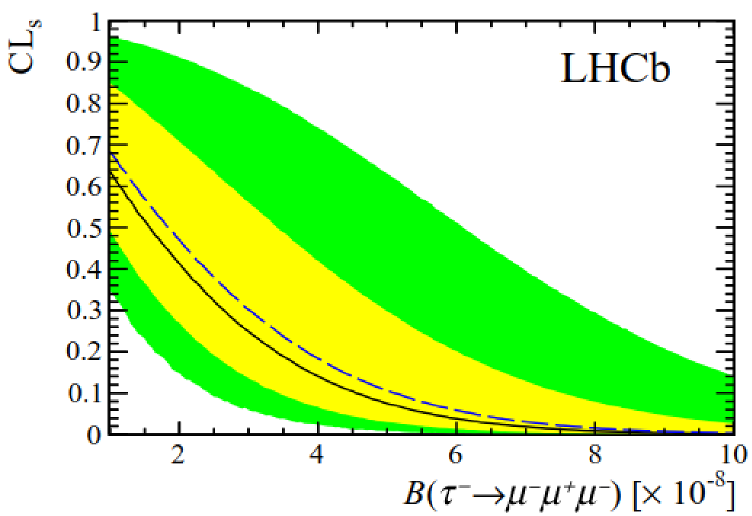

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