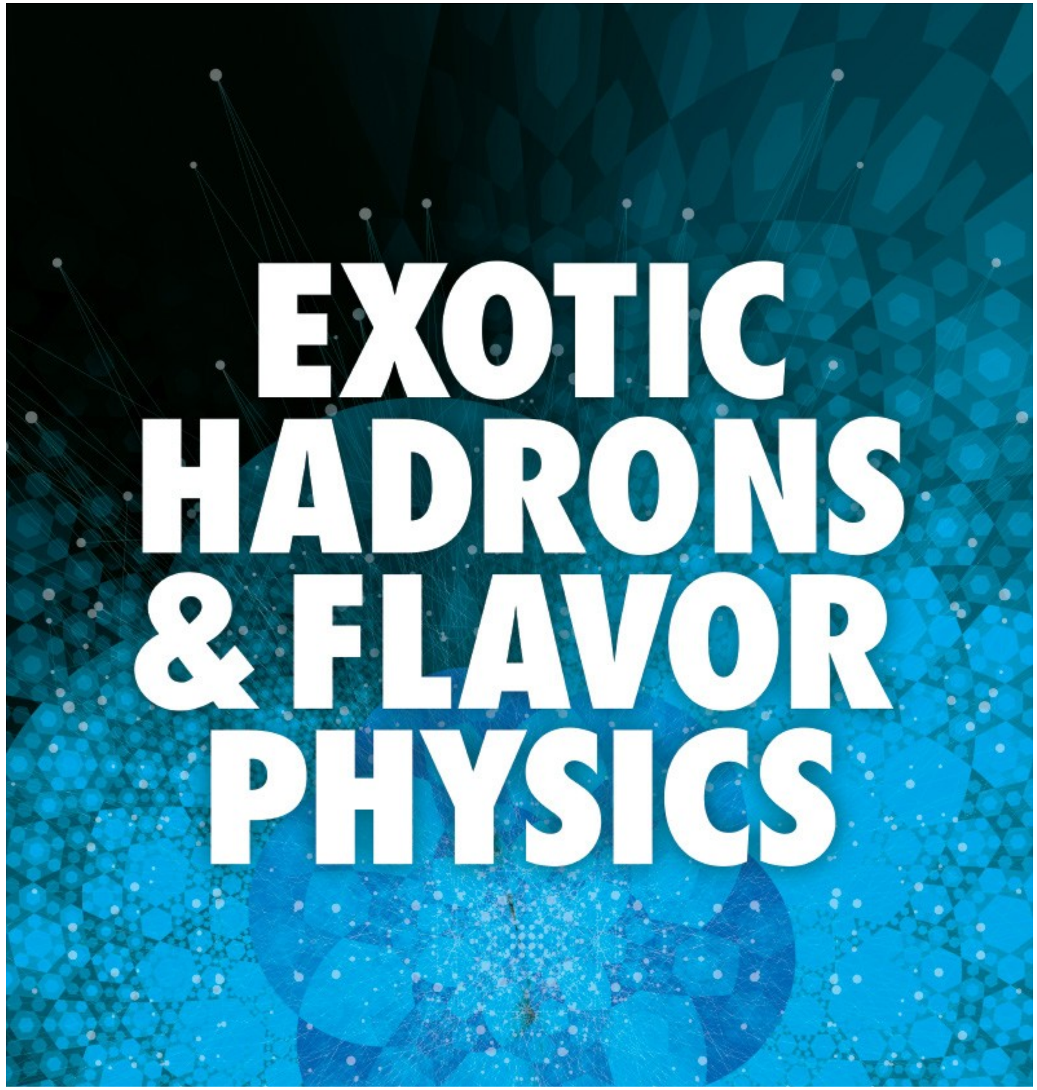
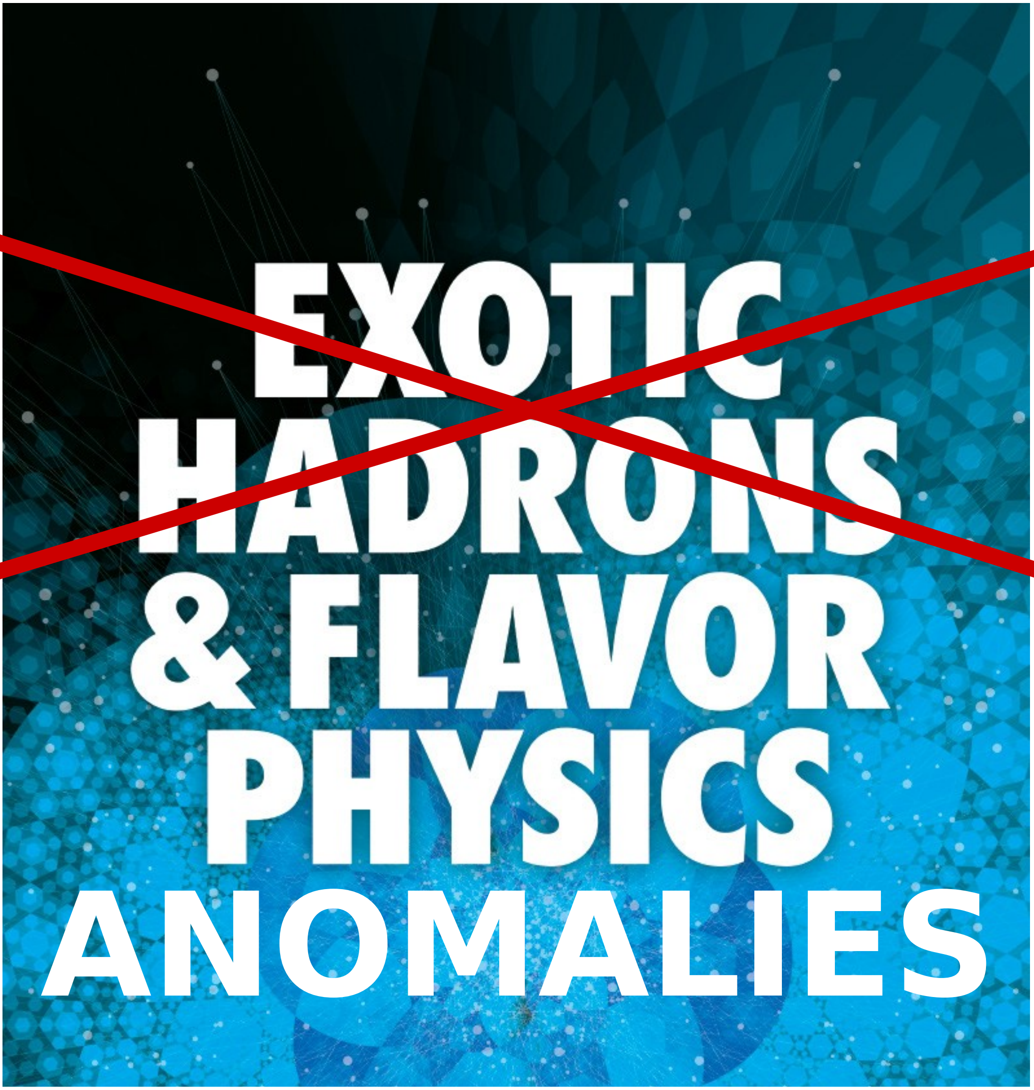


Experimental Summary

Tim Gershon
University of Warwick

1st June 2018



~~Experimental Summary~~

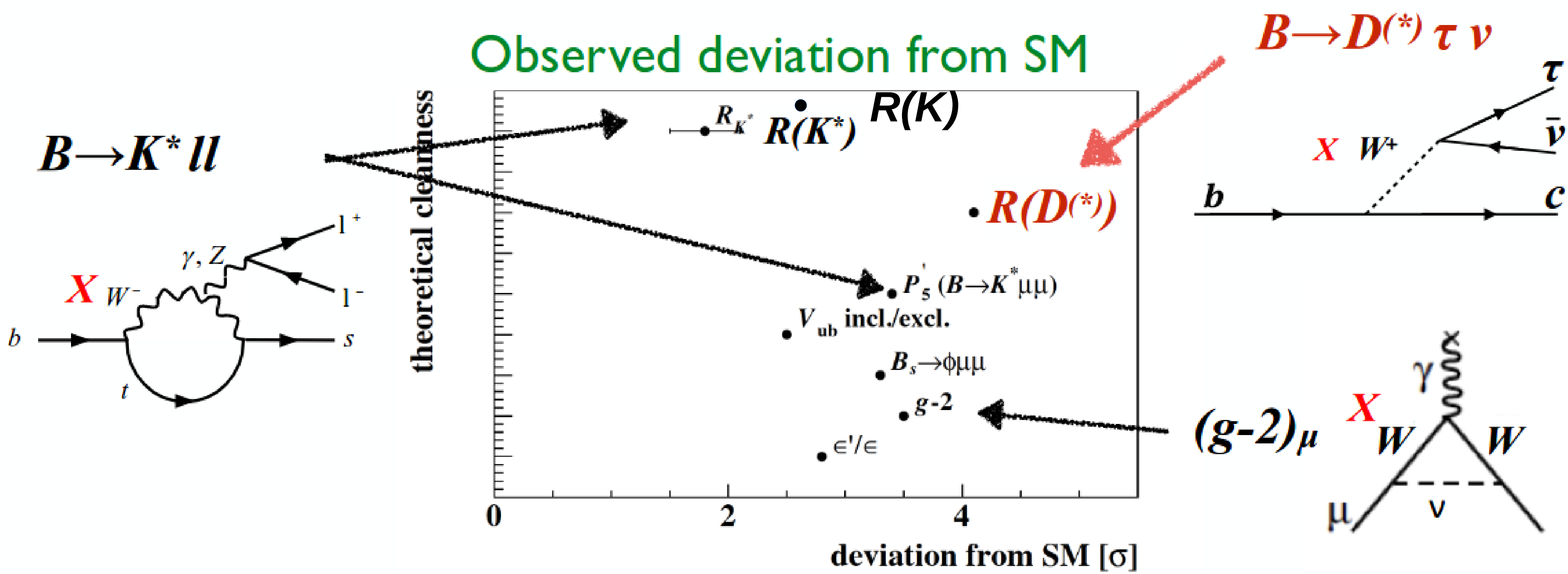
Tim Gershon
University of Warwick

1st June 2018

	RD(*), Belle status and outlook for Belle-II	Toru Iijima	13:30 - 14:00
14:00	RD(*), LHCb status and outlook, Run 1, Run 2 and beyond	Guy Wormser	14:00 - 14:30
	Status of SM predictions for RD(*)	Michele Papucci	14:30 - 15:00
15:00	coffee break		15:00 - 15:30
	RK(*), Belle status and outlook for Belle-II	Vladimir Savinov	15:30 - 16:00
16:00	RK(*), LHCb status and outlook, Run 1, Run 2 and beyond	Sheldon Stone	16:00 - 16:30
	BSM ideas on flavor anomalies	Jernej Kamenik	16:30 - 17:00

	Kaon experiments, status and outlook	Matthew Moulson	13:30 - 14:00
14:00	BSM ideas on epsilon' and other flavor anomalies	Ulrich Nierste	14:00 - 14:30
	K to pi pi and eps', status and outlook	Chris Kelly	14:30 - 15:00

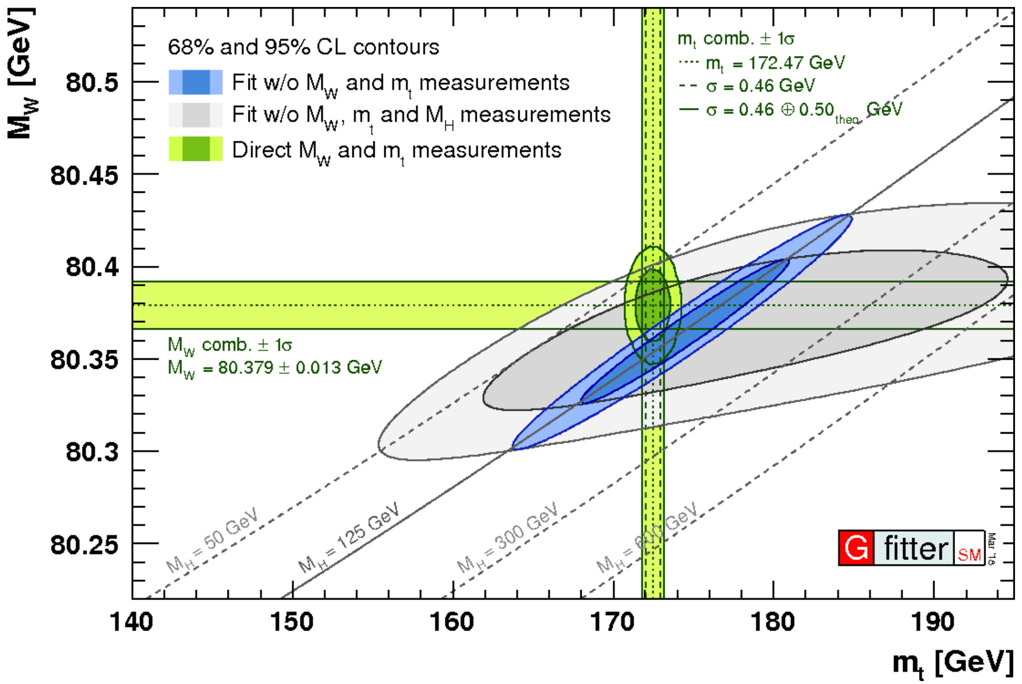
	g-2 expt status and outlook	Chris Polly, et al.	08:30 - 09:00
09:00	g-2 hadronic VP theory status and outlook, off and on the lattice	Thomas Teubner	09:00 - 09:30
	LBL contributions to g-2	Christoph Lehner	09:30 - 10:00
10:00	coffee break		10:00 - 10:30
	Status and outlook for lattice calculations for RD(*) and RK(*)	Elvira Gamiz	10:30 - 11:00
11:00	EFT analysis for flavor anomalies	Jorge Martin Camalich	11:00 - 11:30
	More BSM ideas on flavor anomalies	Gudrun Hiller	11:30 - 12:00

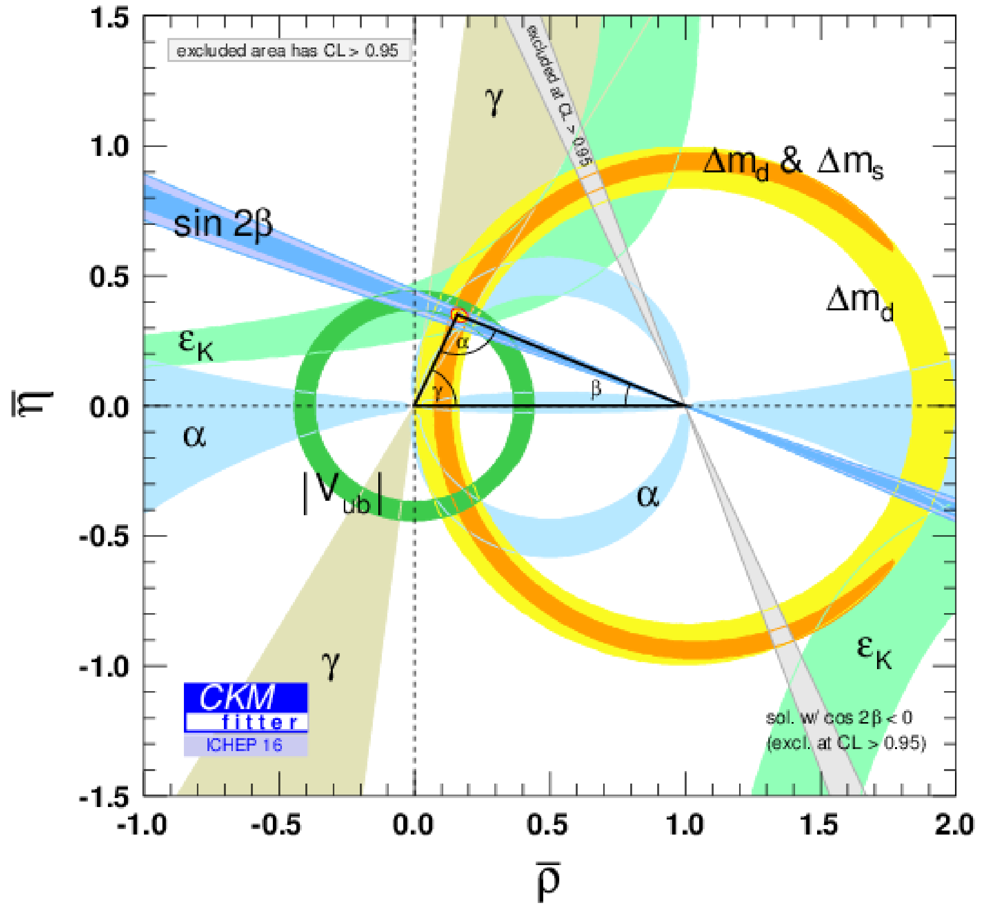


Overall consistency with the SM

http://project-gfitter.web.cern.ch/

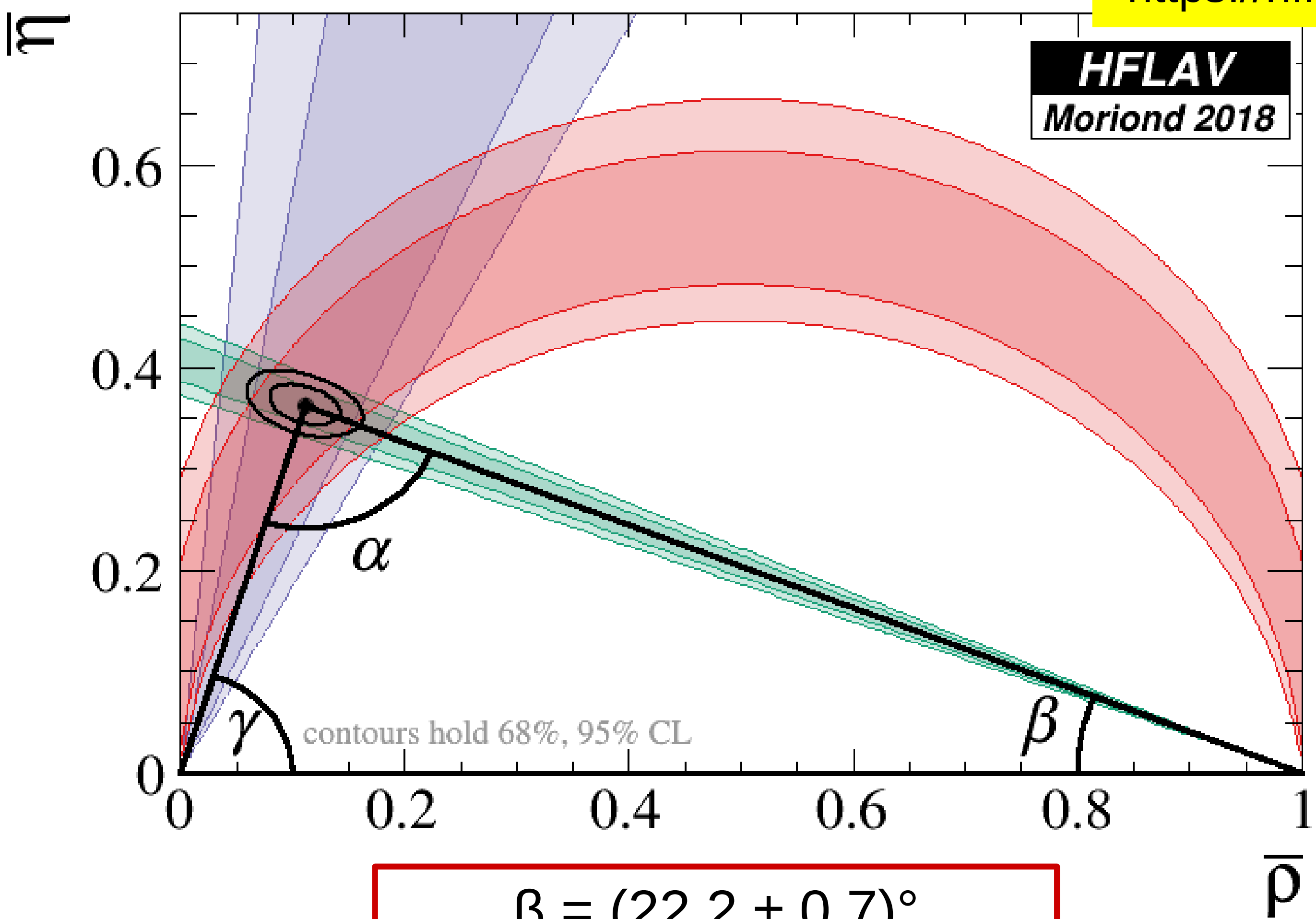
http://ckmfitter.in2p3.fr
see also http://www.utfit.org





Latest(*) UT angles

https://hflav.web.cern.ch/



$\beta = (22.2 \pm 0.7)^\circ$

$\alpha = (84.9\ ^{+5.1}_{-4.5})^\circ$

$\gamma = (73.5\ ^{+4.2}_{-5.1})^\circ$

γ no longer least well measured of the angles

(*) not including some very recent new LHCb results on γ

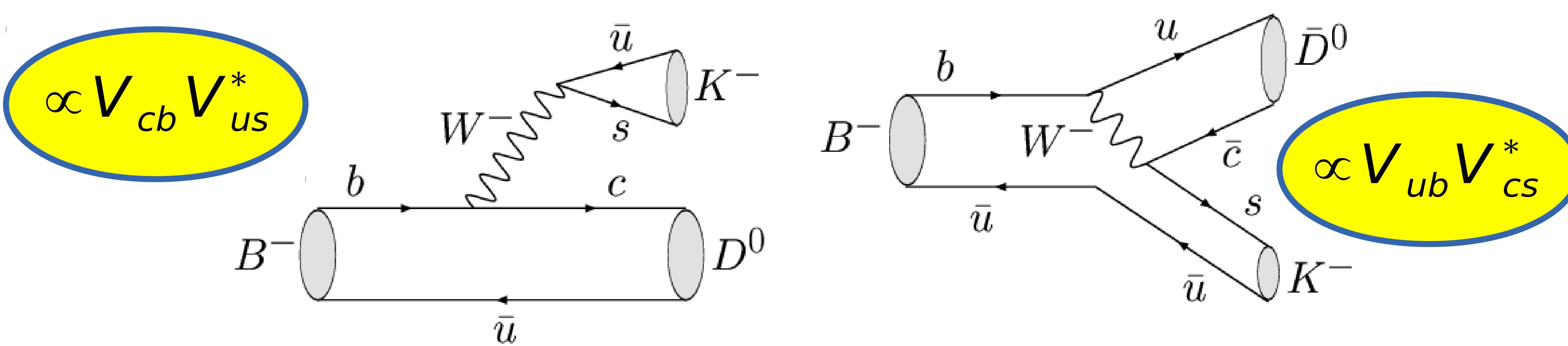
Importance of γ from B→DK

- γ plays a unique role in flavour physics

the only CP violating parameter that can be measured through tree decays (*)

(*) i.e. without uncertainty due to short distance loops

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

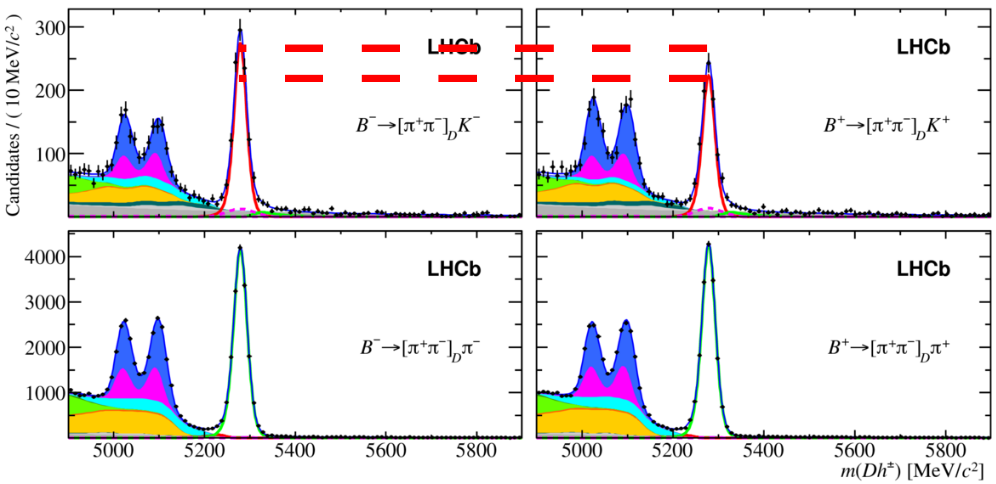


Variants use different B or D decays
require a final state common to both D^0 and $\overline{D}^0$

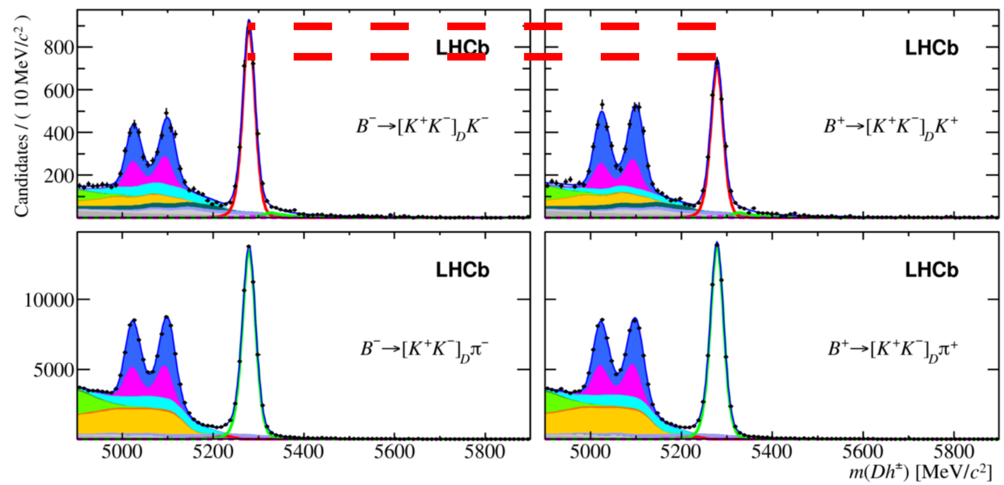
γ from $B^+ \to DK^+$, $D \to KK, \pi\pi, K\pi$

PL B777 (2018) 16

$D \to \pi\pi$ (“GLW” CP+ state)

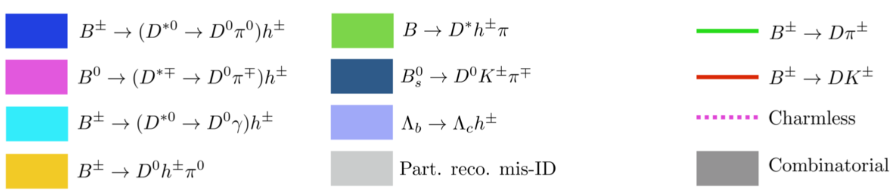


$D \to KK$ (“GLW” CP+ state)



CP violating asymmetries clearly visible

Results also for partially reconstructed $B \to D^*K$ decays



$A_{CP}(B \to DK) = +0.124 \pm 0.012$ (stat) ± 0.002 (syst)

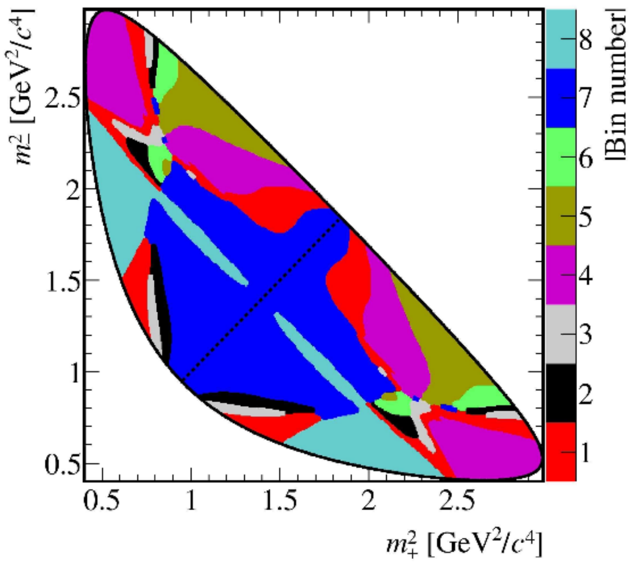
$A_{CP}(B \to D^*K;\ D^* \to D\pi^0) = -0.151 \pm 0.033$ (stat) ± 0.011 (syst)

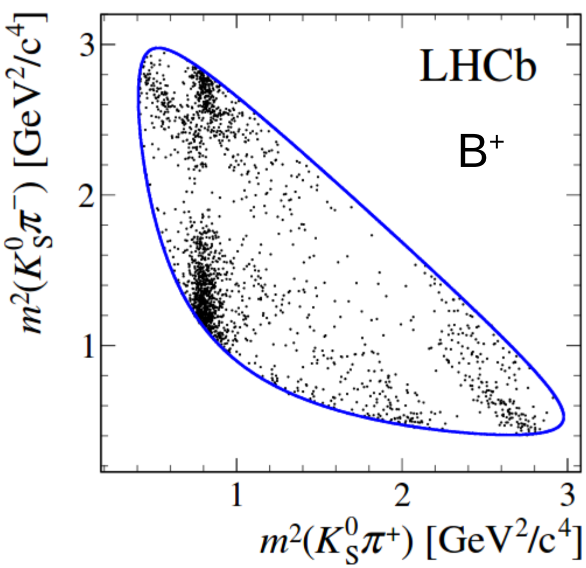
$A_{CP}(B \to D^*K;\ D^* \to D\gamma) = +0.276 \pm 0.094$ (stat) ± 0.047 (syst)

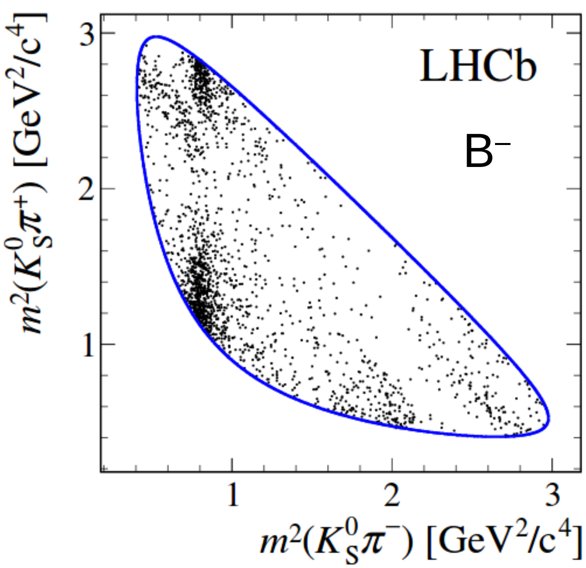
γ from $B^+ \to DK^+$, $D \to K_S\pi\pi$, K_SKK

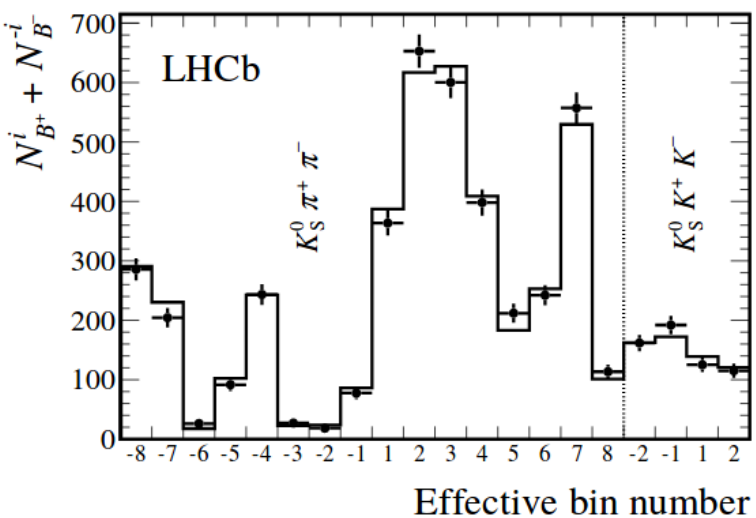
LHCb-PAPER-2018-017

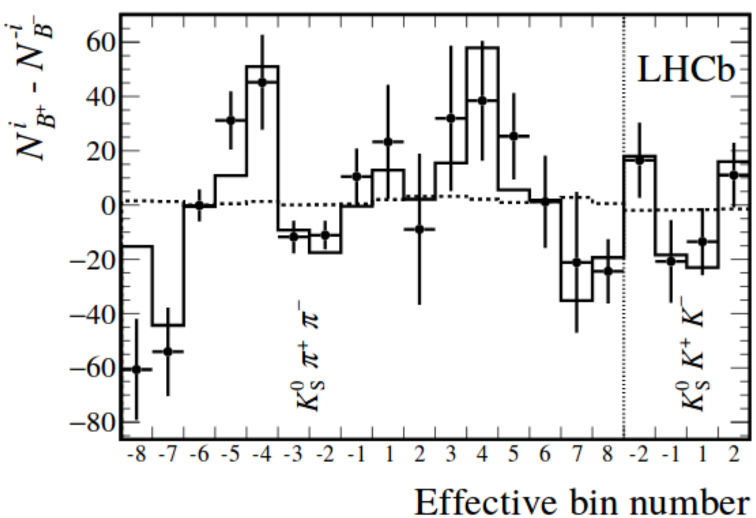
3900 signal decays selected from Run 2 data







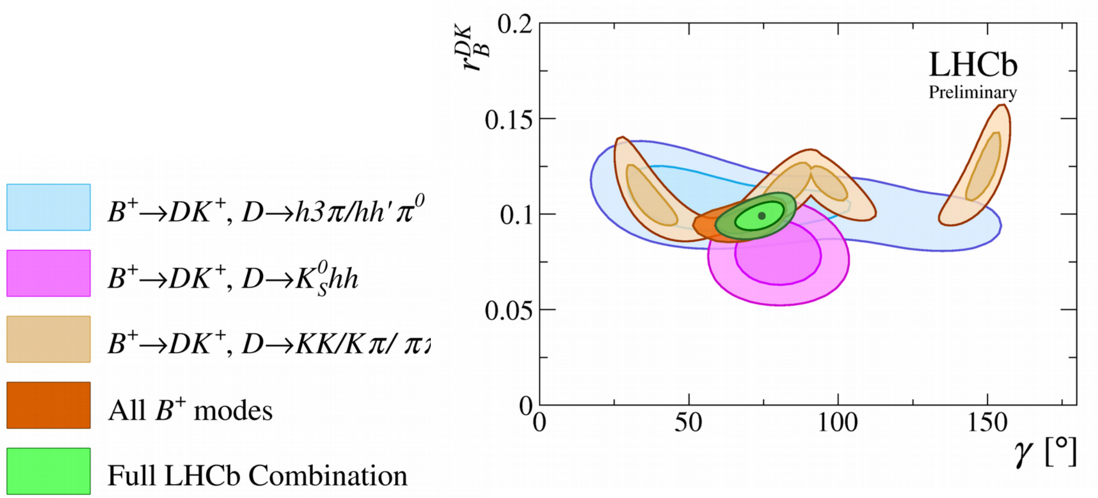


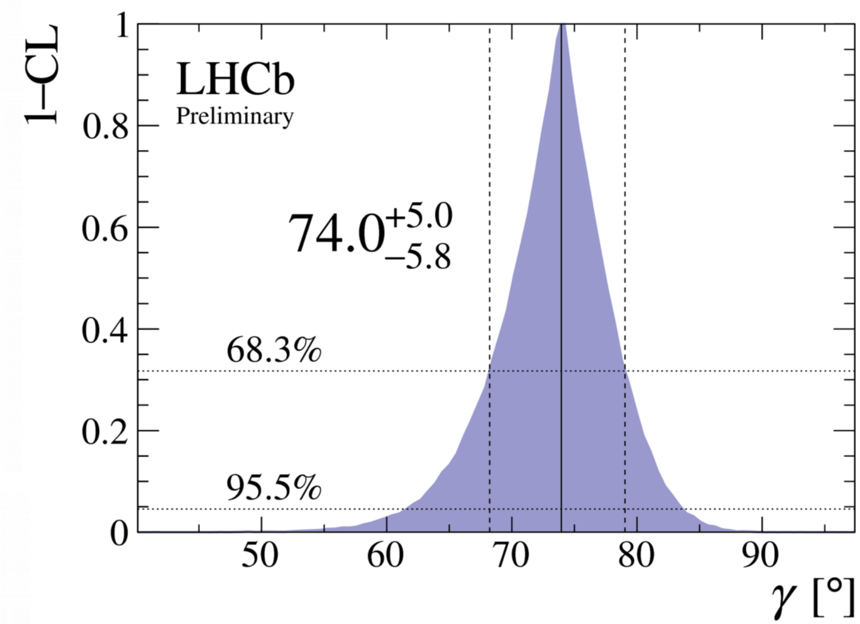


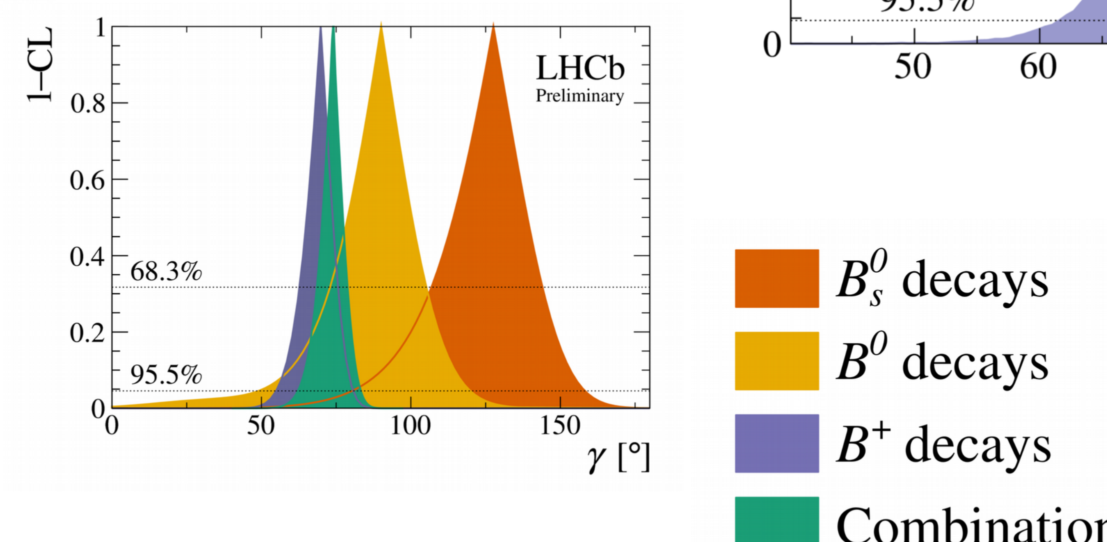
LHCb γ combination

JHEP 12 (2016) 087 &
LHCb-CONF-2018-002

Many observables with sensitivity to γ – combine them!



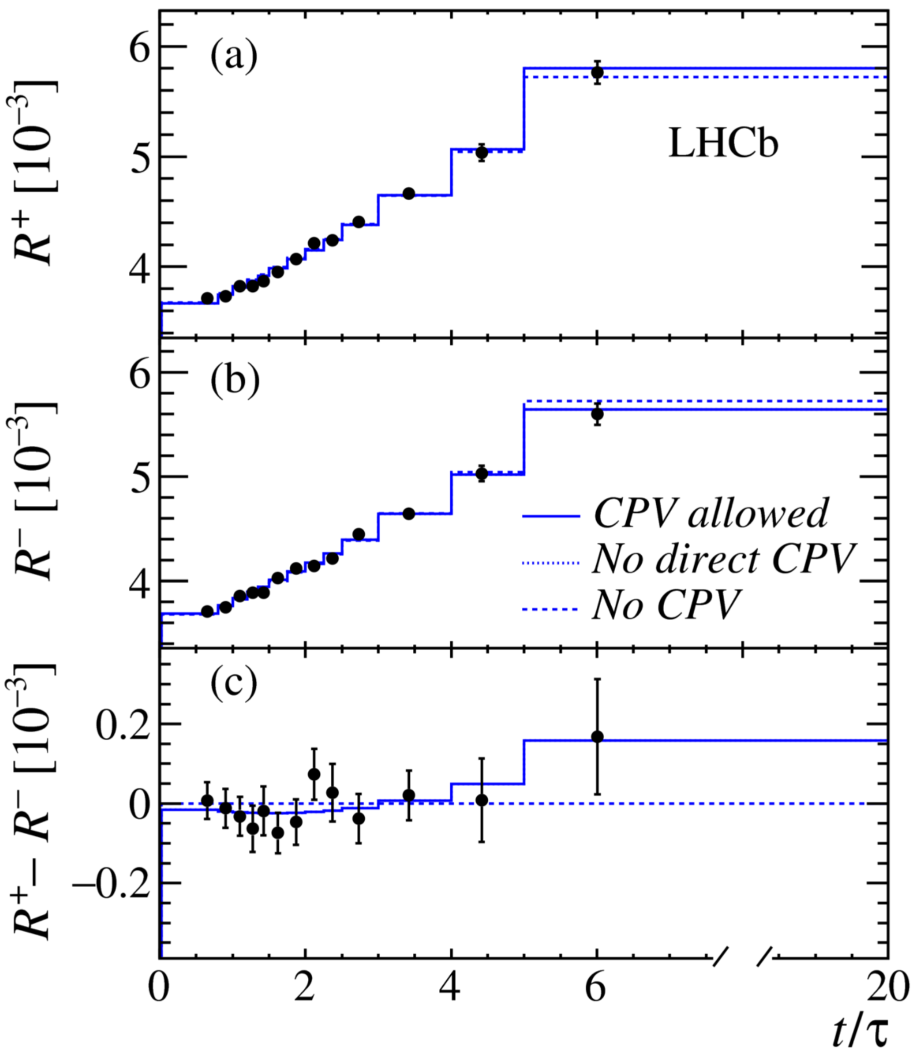




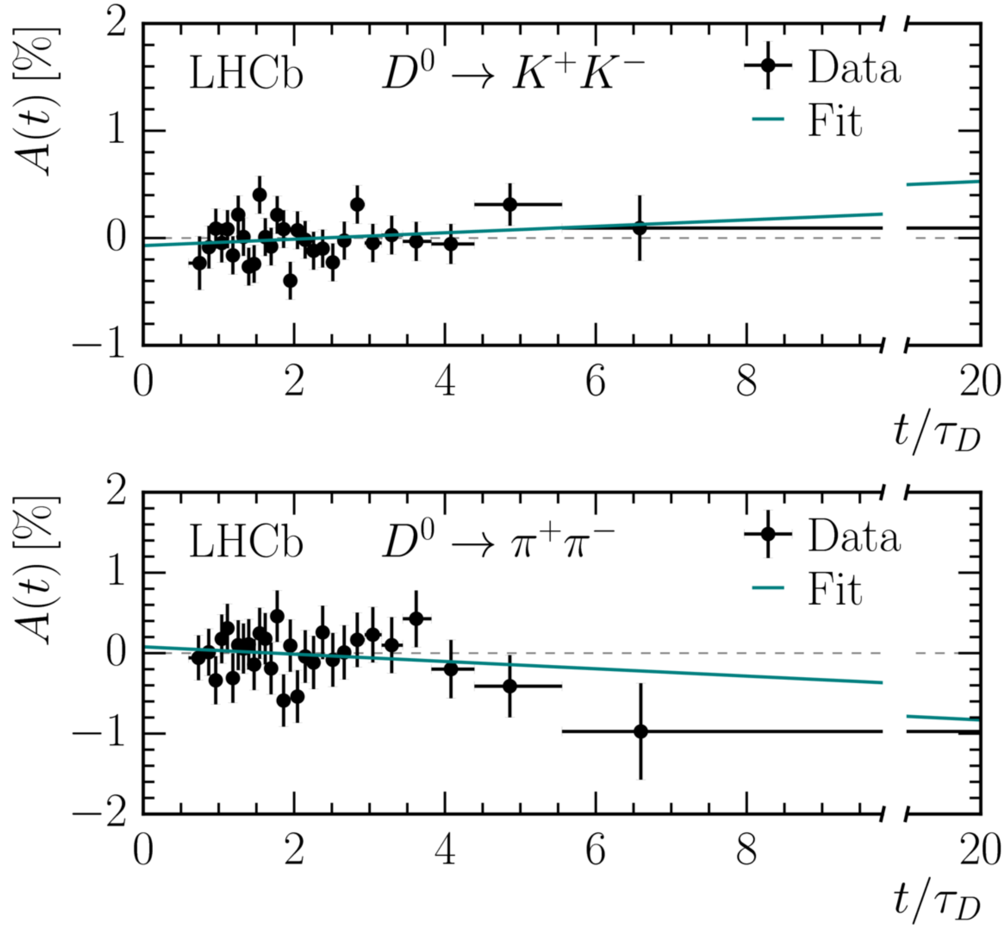
$\gamma = (74.0^{+5.0}_{-5.8})°$

No CP violation in charm, yet

D → Kπ; PR D97 (2018) 031101

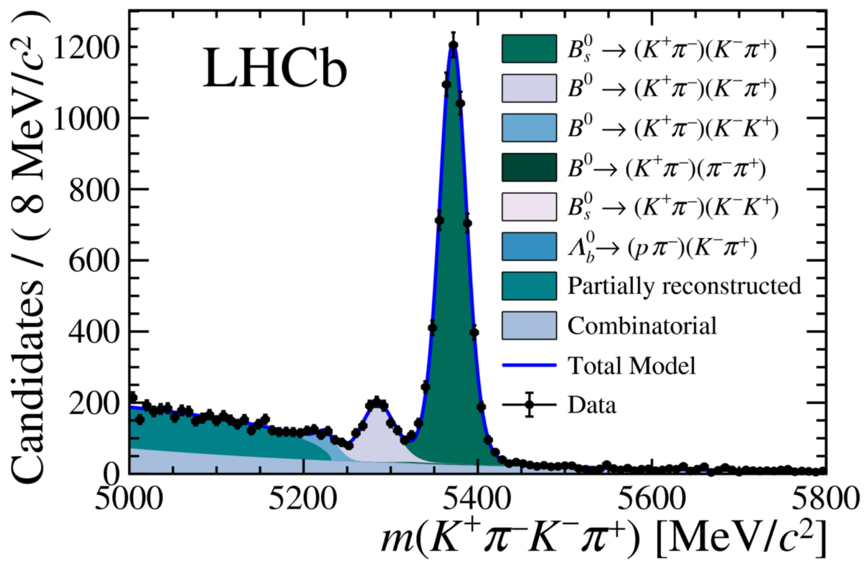


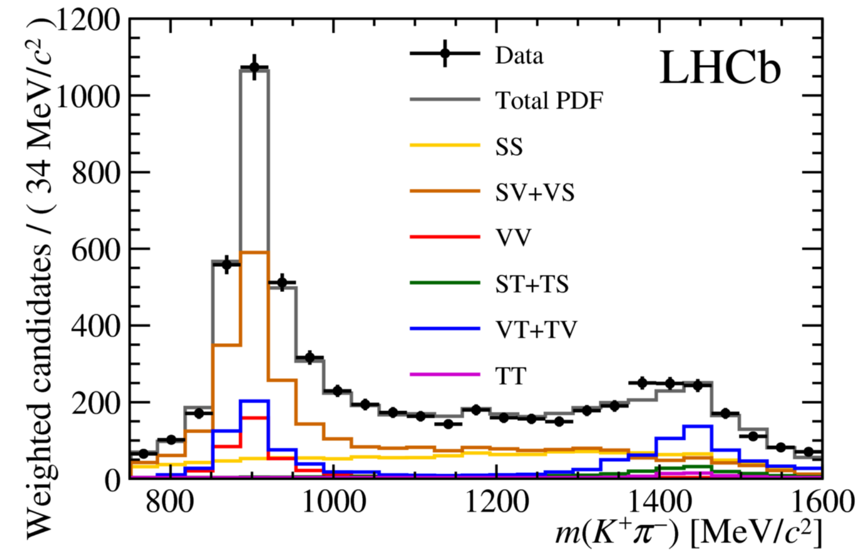
D → KK, ππ; PRL 118 (2017) 261803

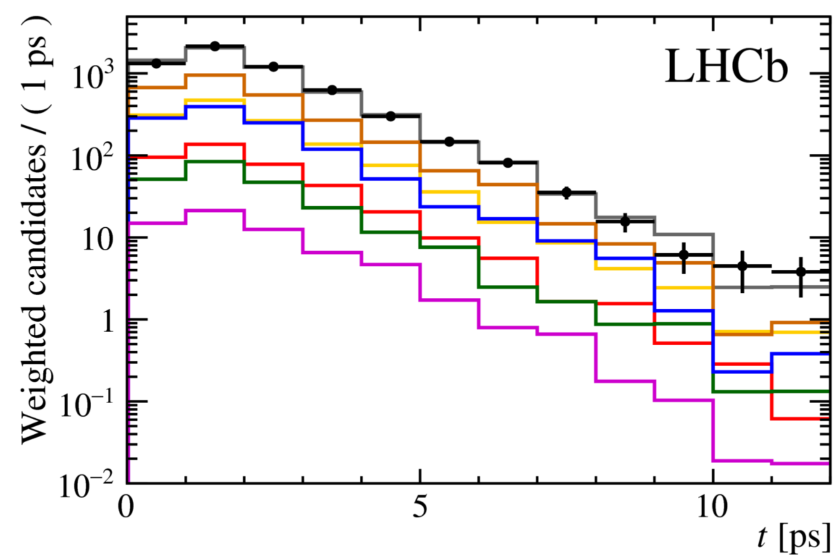


DTDCPV in charmless hadronic B decays

$\varphi_s^{d\bar{d}s}(B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+))$; JHEP 03 (2018) 140







$K^{*0}\overline{K}^{*0}$ only 7% of $(K^+\pi^-)(K^-\pi^+)$

penguin only – no tree contribution

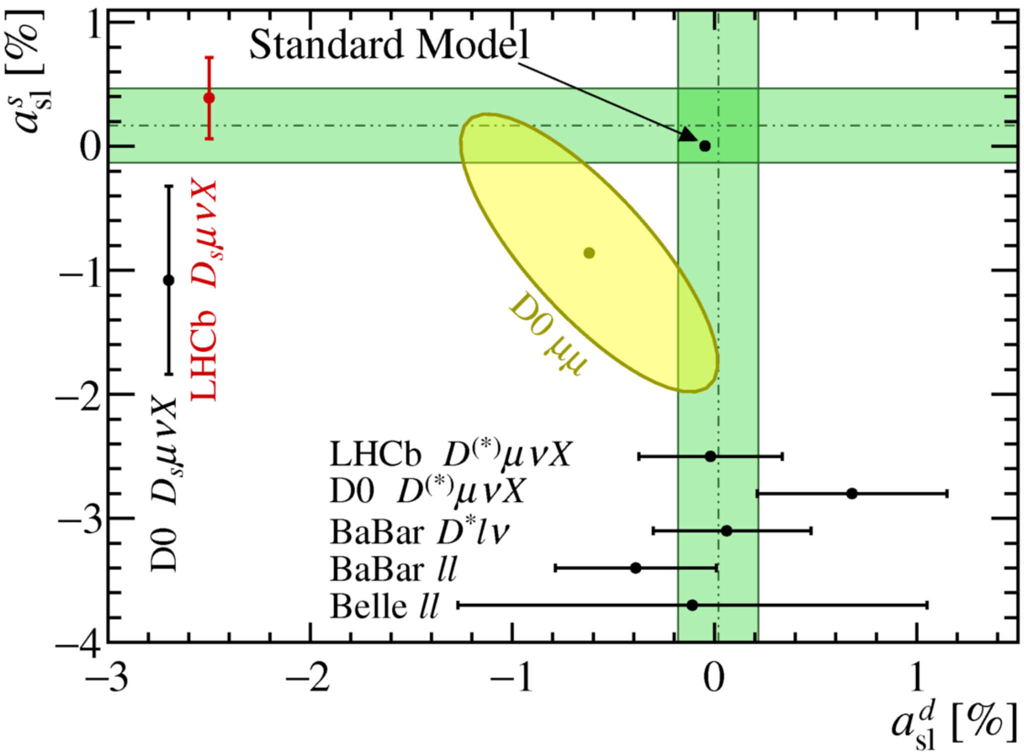
$\varphi_s^{d\bar{d}s} = -0.10 \pm 0.13$ (stat) ± 0.14 (syst) rad

consistent with SM expectation of ~0

CP violation in $B^0_{(s)}$ mixing

PRL 117 (2016) 061803

- Evidence of non-SM CP violation in inclusive dimuon asymmetry from the D0 collaboration
  - PRD 89 (2014) 012002
- Semileptonic asymmetries $a_{sl}(B^0)$ and $a_{sl}(B_s^0)$ however consistent with SM ~ (0,0)
  - $a_{sl}(B^0)$ by BaBar, Belle, LHCb, D0
  - $a_{sl}(B_s^0)$ by LHCb, D0
- Possibility of additional contributions to inclusive dimuon asymmetry under investigation
  - PR D87 (2013) 074020

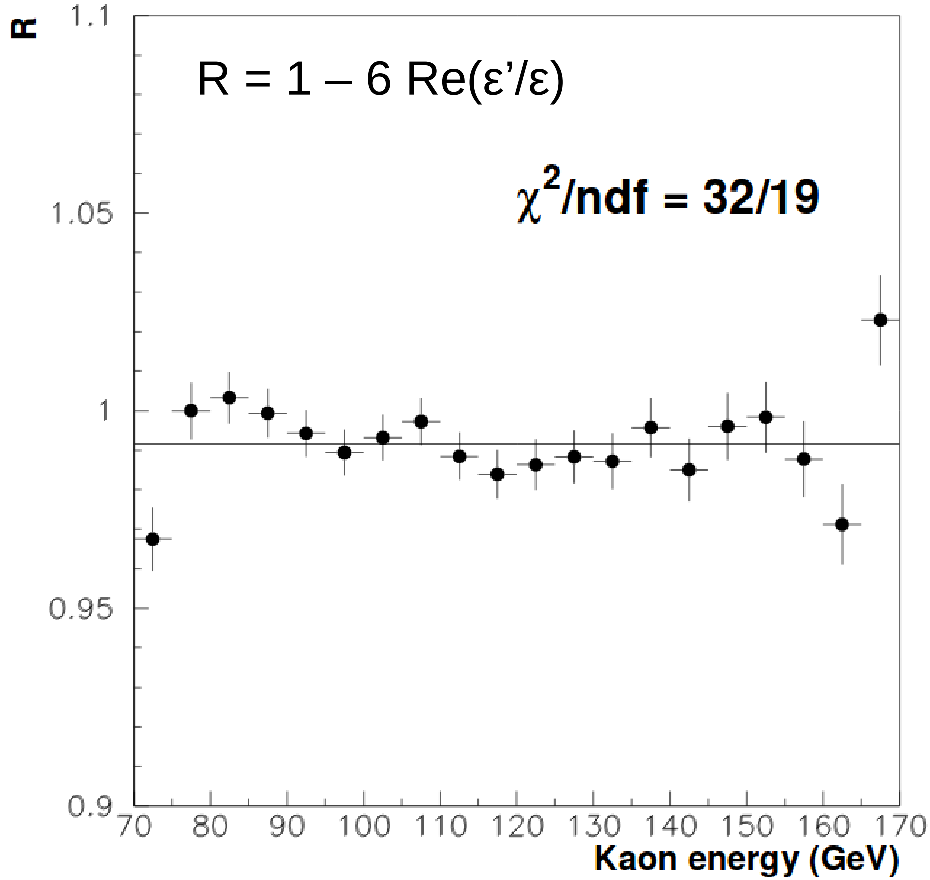


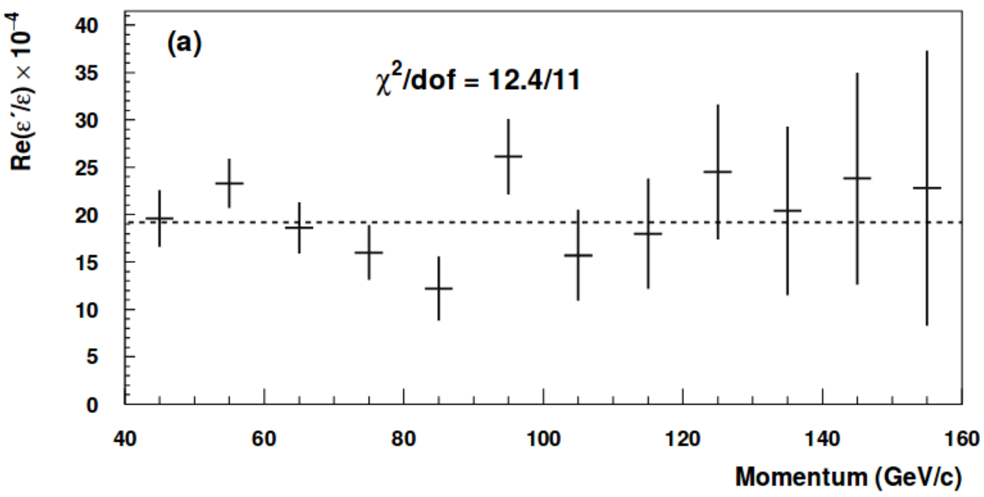
$a_{sl}(B_s^0) = (0.39\pm0.26\pm0.20)\%$

Re(ε'/ε)

NA48 PL B544 (2002) 97

KTeV PR D83 (2011) 092001





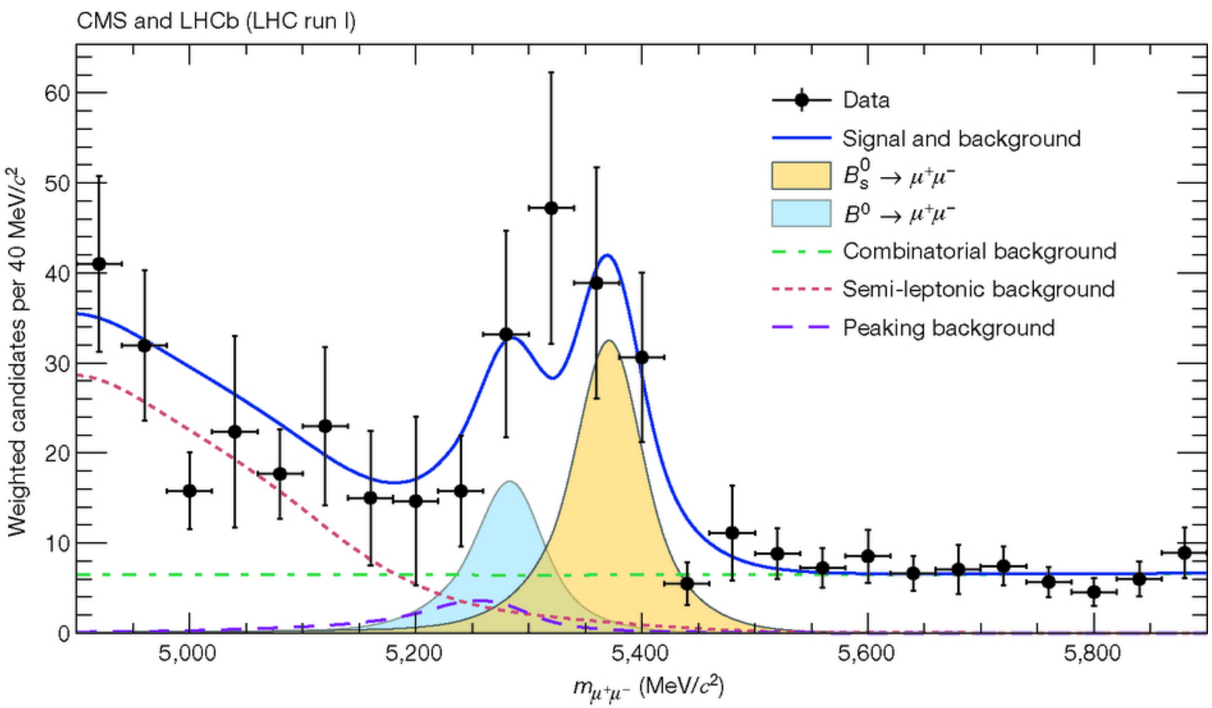
PDG Re(ε'/ε) = $(1.66 \pm 0.23) \times 10^{-3}$

Great recent progress in theory
Currently no plans for new experiments

Rare decays

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

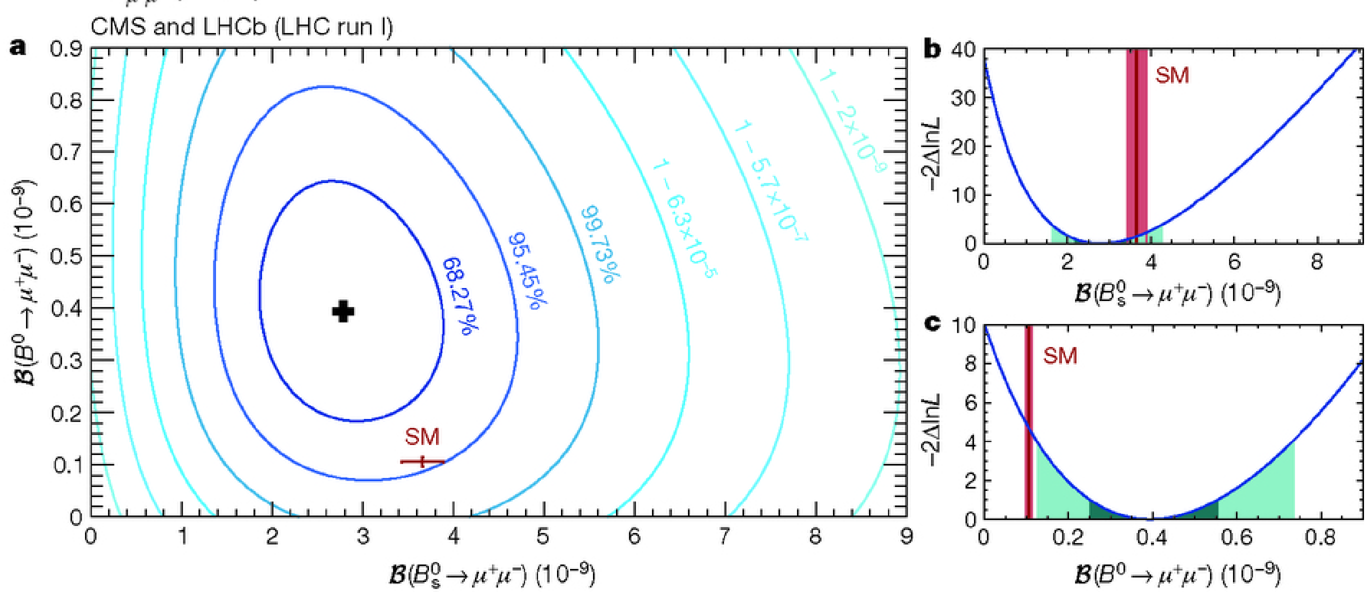
Nature 522 (2015) 68



Combination of CMS and LHCb data results in first observation of $B_s \to \mu^+\mu^-$ and first evidence for $B^0 \to \mu^+\mu^-$

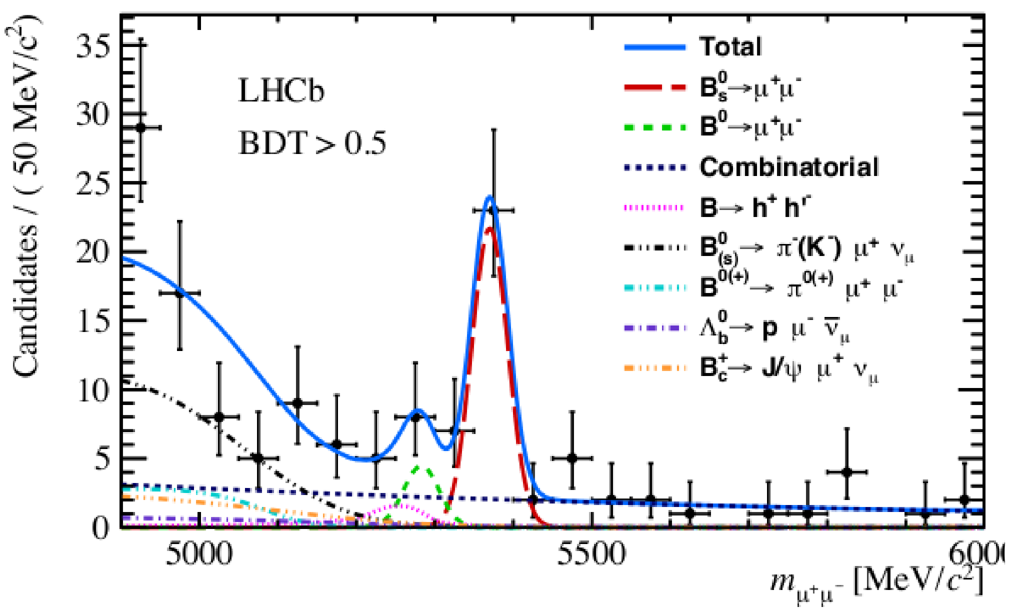
Results consistent with SM at 2σ level

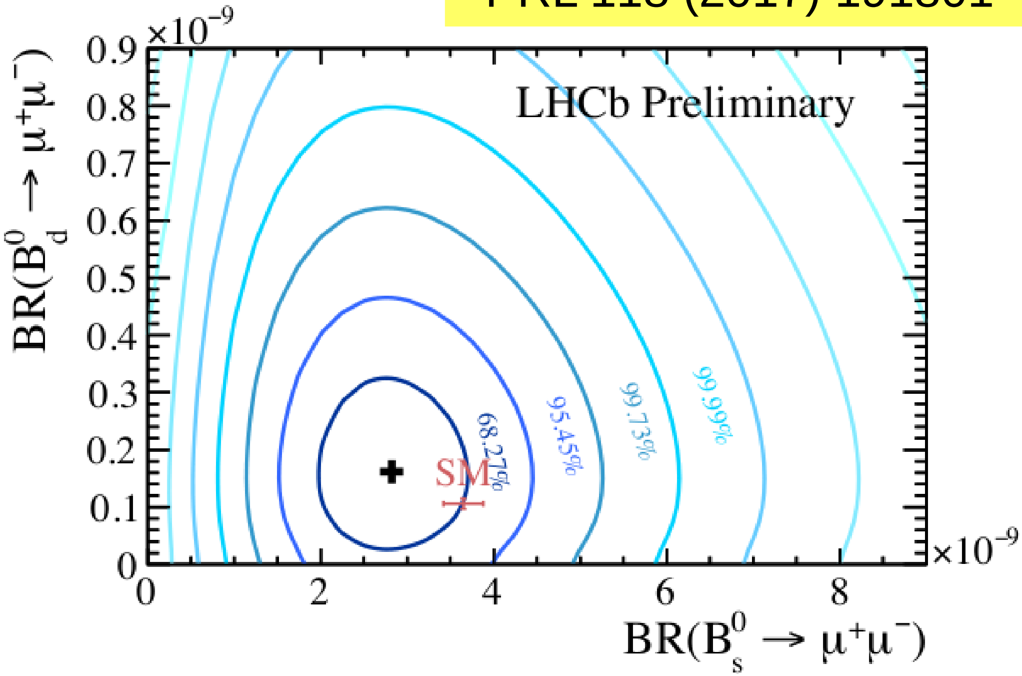
Recent results from ATLAS (not included here) have almost similar sensitivity



LHCb including Run 2 data

PRL 118 (2017) 191801





Data sample includes 1.4 fb^{-1} collected in Run 2

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.6) \times 10^{-9} \quad \textbf{7.8}\boldsymbol{\sigma}$$

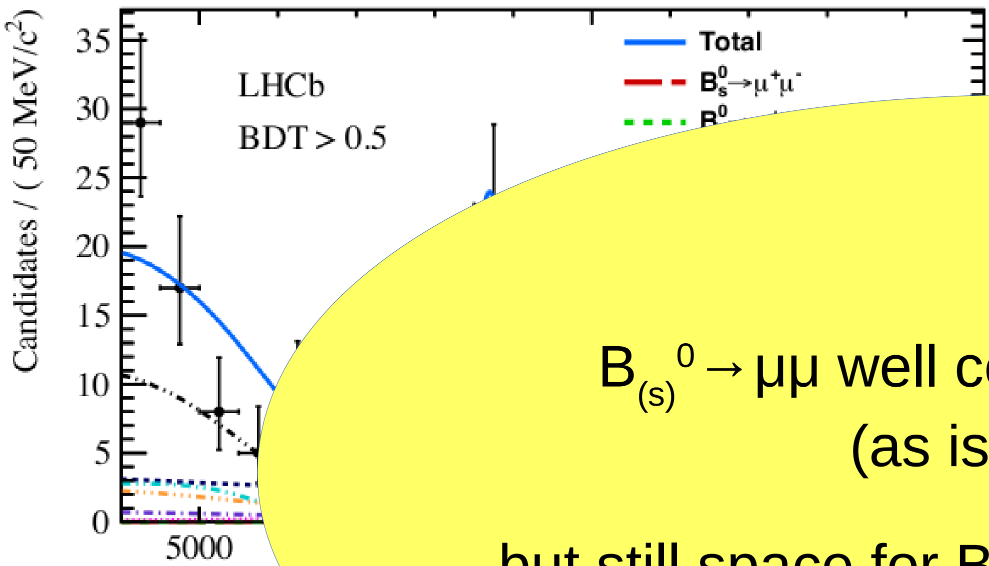
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.6^{+1.1}_{-0.9}) \times 10^{-10} \quad \textbf{1.9}\boldsymbol{\sigma}$$

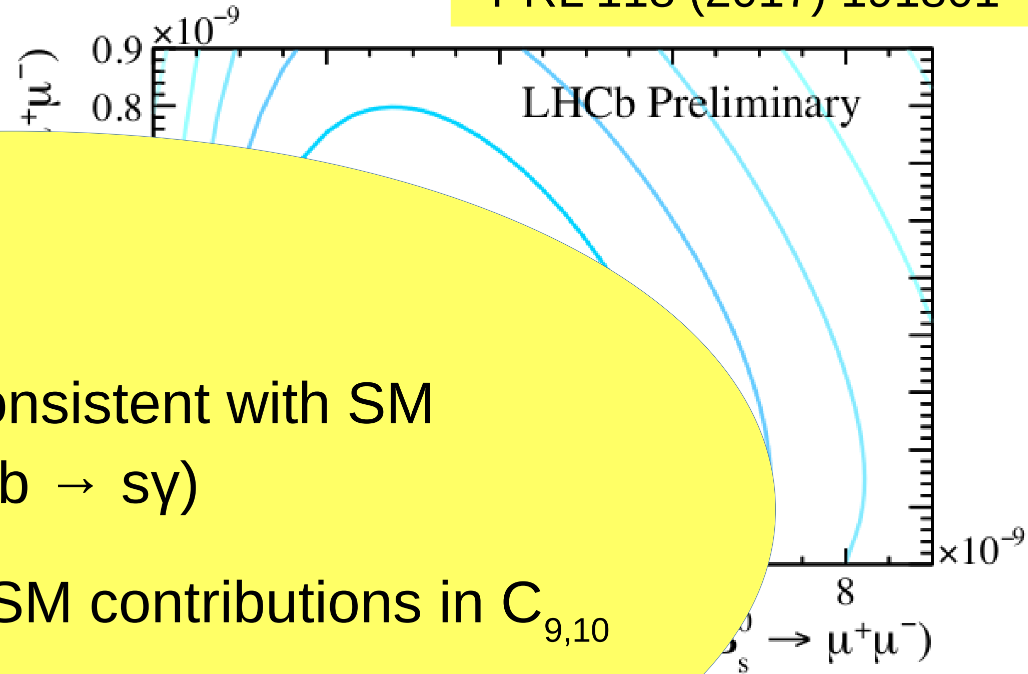
First 5σ observation by a single experiment

also best limits on $B_{(s)}^0 \to \tau^+\tau^-$ (PRL 118 (2017) 251802)

LHCb including Run 2 data

PRL 118 (2017) 191801





Data sample i

$B_{(s)}{}^0 \to \mu\mu$ well consistent with SM
(as is $b \to s\gamma$)

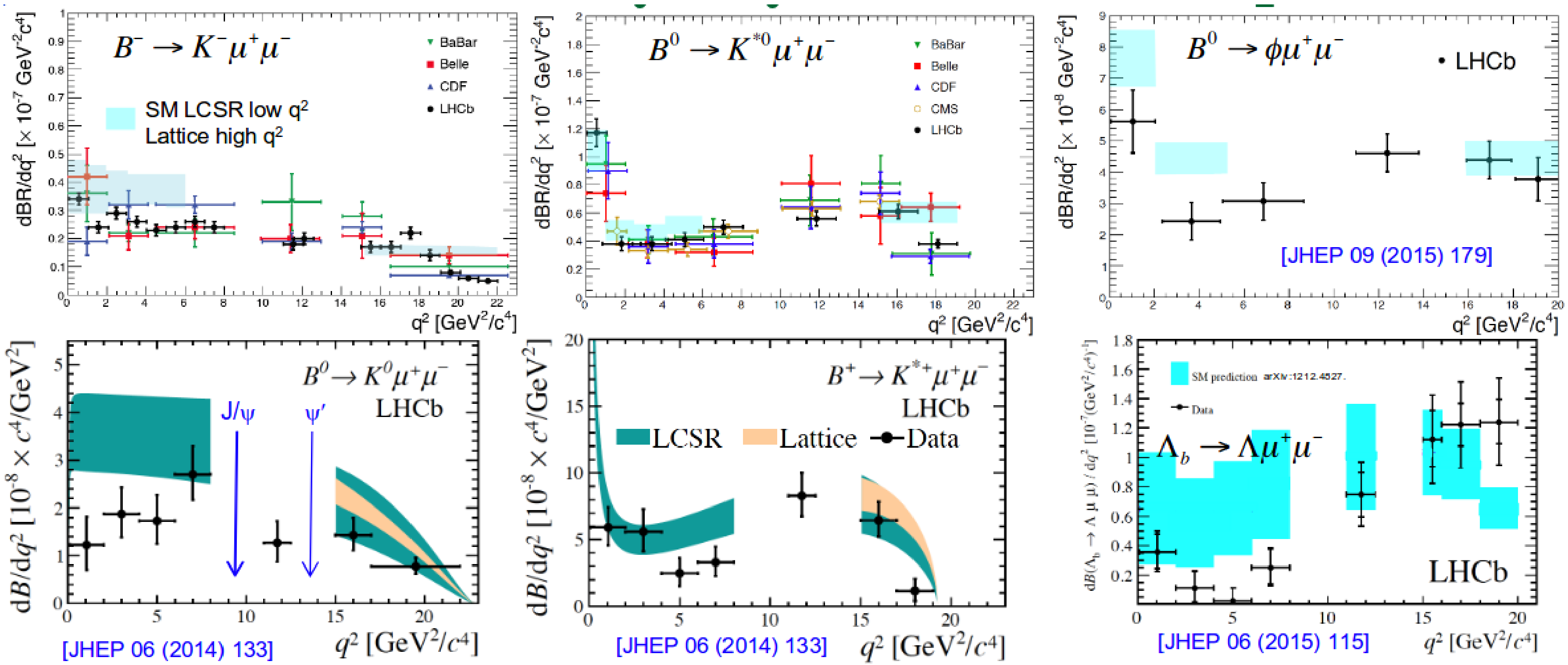
… but still space for BSM contributions in $C_{9,10}$

$\mathcal{B}(B_s^0$ …	**7.8σ**
$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.6^{+1.1}_{-0.9}) \times 10^{-10}$	**1.9σ**

First 5σ observation by a single experiment

also best limits on $B_{(s)}{}^0 \to \tau^+\tau^-$ (PRL 118 (2017) 251802)

Branching fractions of b→sμμ



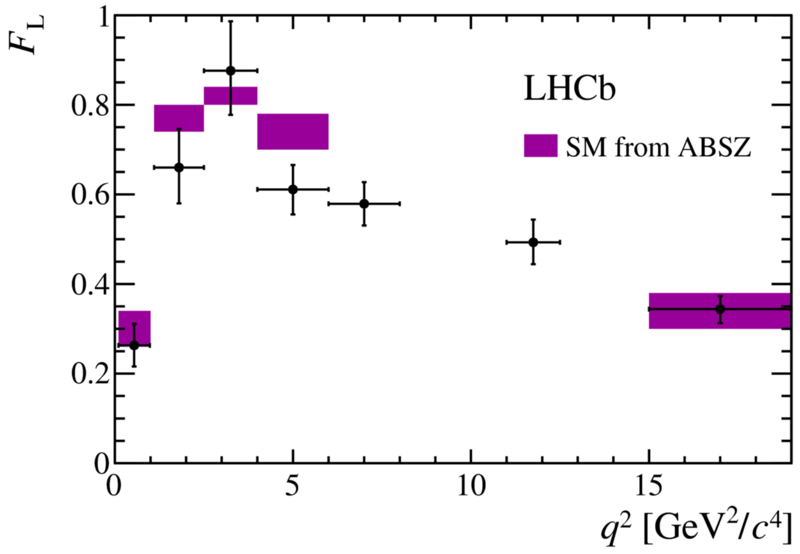
- Data generally below model predictions at low q^2
- Charmonium resonances at high q^2

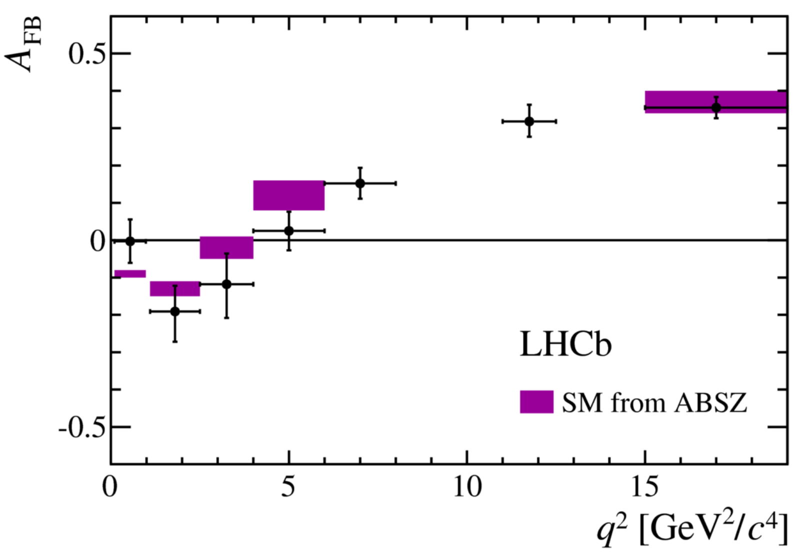
All measured relative to J/ψ control mode – low systematic uncertainties

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

JHEP 02 (2016) 104

- $B^0 \to K^{*0}\mu^+\mu^-$ provides superb laboratory to search for new physics in $b \to sl^+l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - experimentally clean signature
  - many kinematic variables … with clean(?) theoretical predictions
- Full set of observables measured – only a subset shown

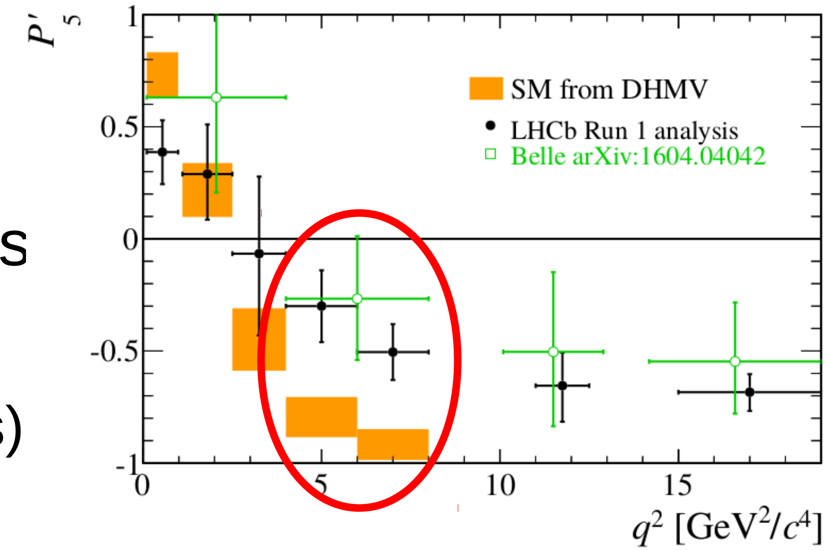




Tension with SM in the P_5' observable

JHEP 02 (2016) 104

- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA ($K^{*0}\mu^+\mu^-$)
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)



- P_5' related to difference between relative phase of longitudinal (0) and perpendicularly ($\perp$) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}} A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}} A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(\prime)}$ & $C_{10}^{(\prime)}$)

Tension with SM in the P_5' observable

JHEP 02 (2016) 104

- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
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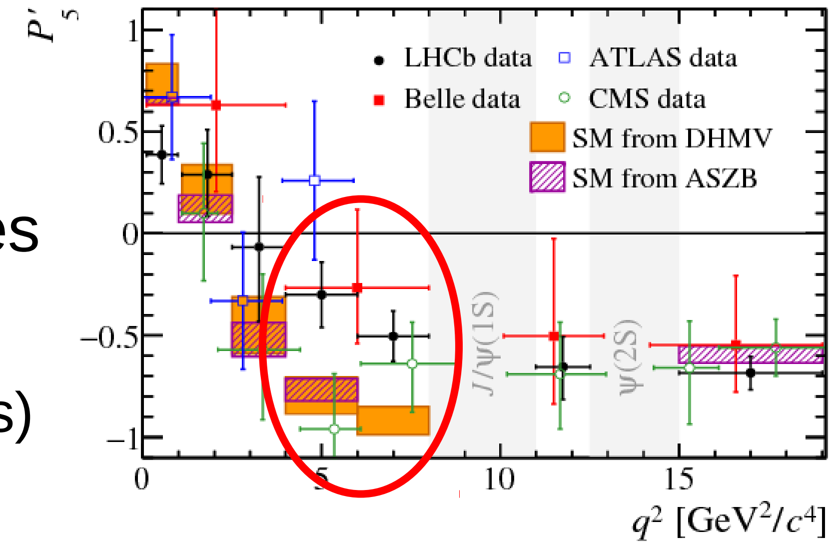
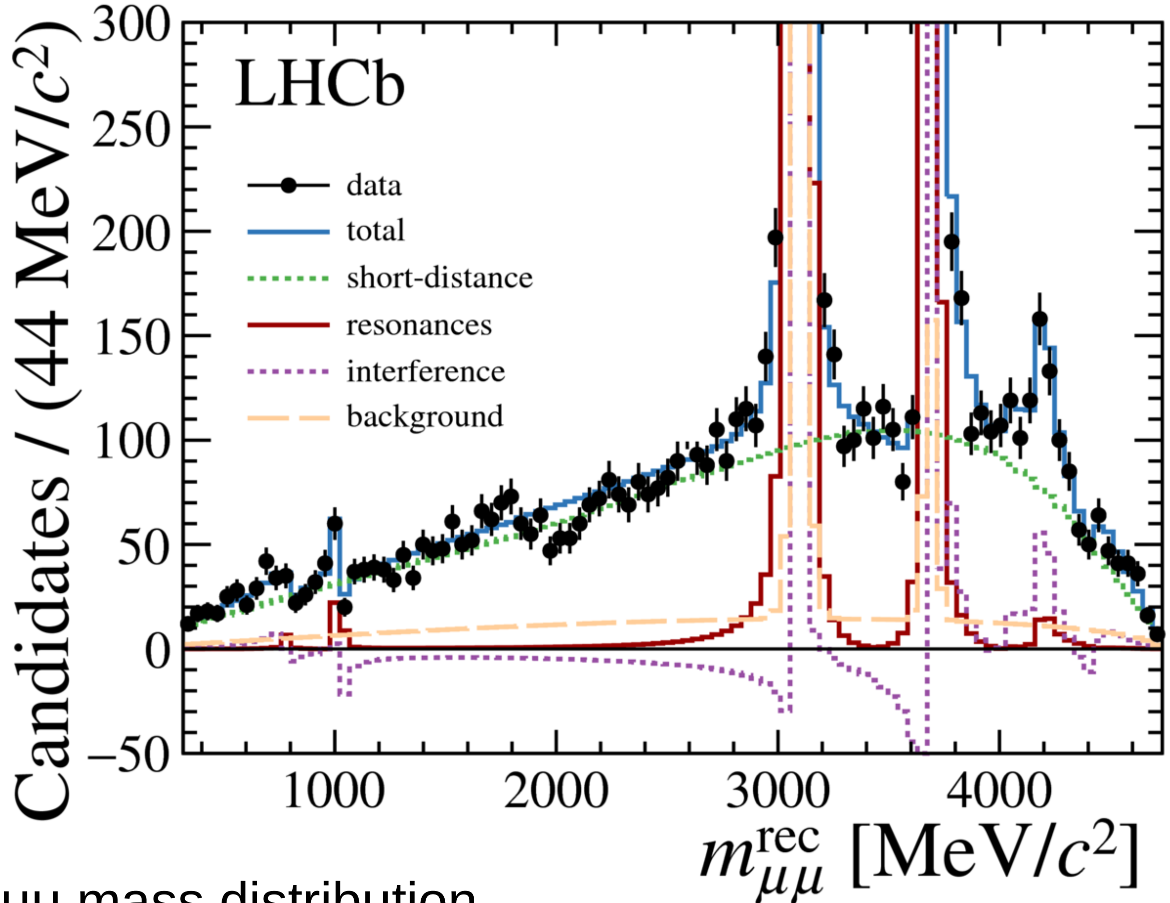


Can non-perturbative QCD effects can affect the SM prediction?
Recent theoretical progress to address this in a data-driven way
(e.g. arXiv:1707.07305, arXiv:1709.03921)
Indications that uncertainty is not significantly underestimated

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(\prime)}$ & $C_{10}^{(\prime)}$)

Towards full amplitude analysis of B → $K^{(*)}l^+l^-$

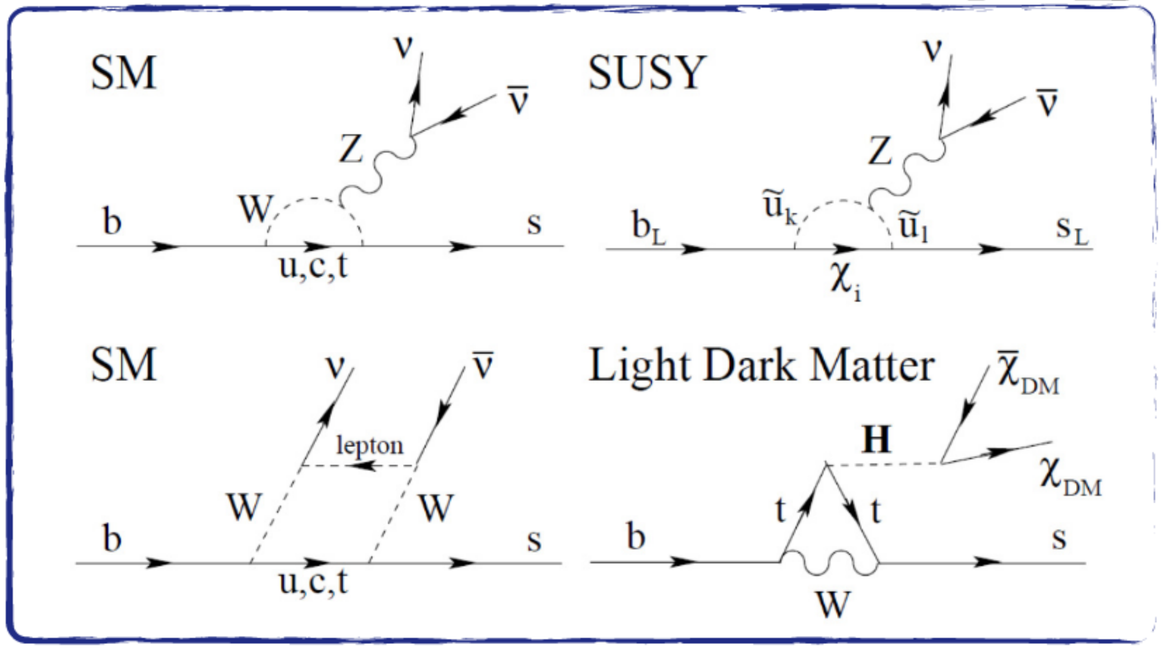
EPJ C77 (2017) 161



non-negligible hadronic contributions at low q^2

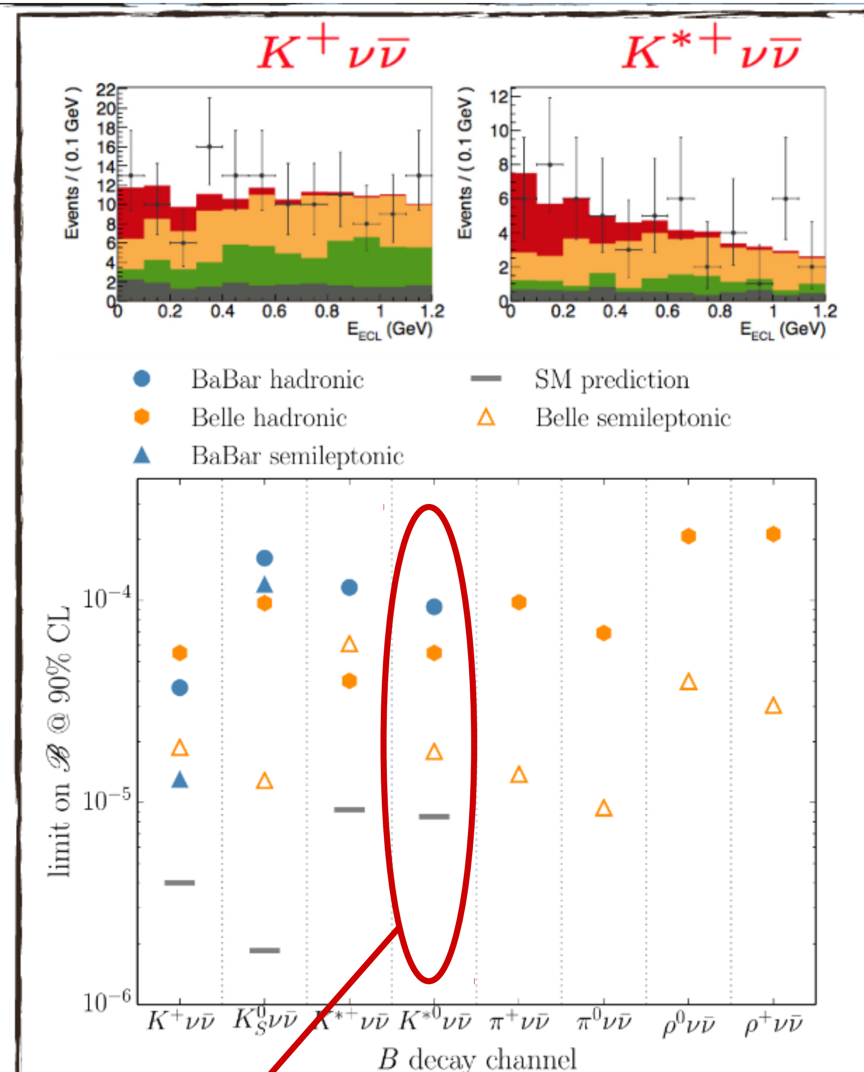
- Fit to Kμμ mass distribution
  - muon decay angle can be included in future (muon polarisation cannot)
- Working to do similar for $K^{*0}\mu\mu$
  - need to handle background contributions from exotic hadrons
  - e.g. $Z(4430)^-K^+ \to \psi(2S)\pi^-K^+ \to \mu\mu\pi^-K^+$

Fighting charm loop uncertainties: $l^+l^- \to \nu\bar{\nu}$



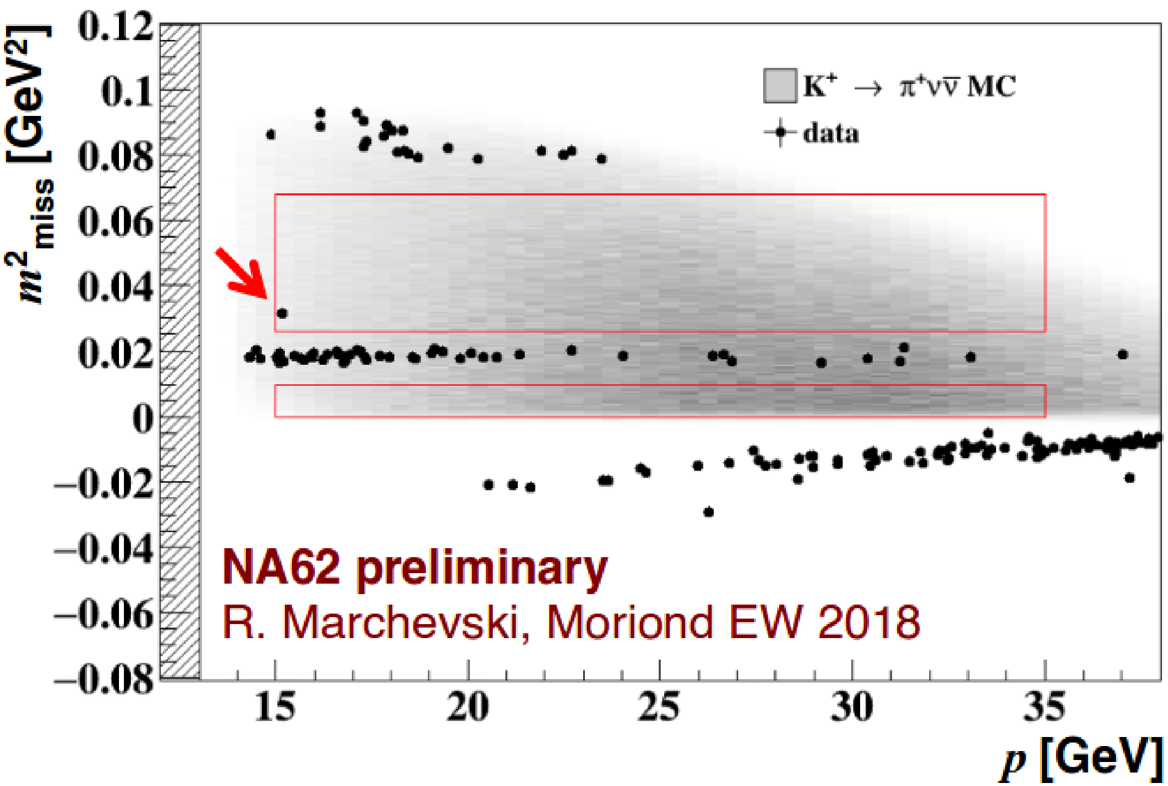
Belle II Prospects for Neutrino Electroweak Penguin Decays

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$Br(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$Br(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$Br(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$Br(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–



within a factor of ~2 … very exciting for Belle II

2016 results for $K^+ \to \pi^+ \nu\nu$



NA62 preliminary – 2016 data

1.2×10^{11} K^+ decays

SES = $(3.15 \pm 0.24) \times 10^{-10}$

Expected signal 0.267 ± 0.038

Expected background 0.15 ± 0.09

1 event observed in R2

BR($K^+ \to \pi^+\nu\nu$)

$< 14 \times 10^{-10}$ (95%CL)

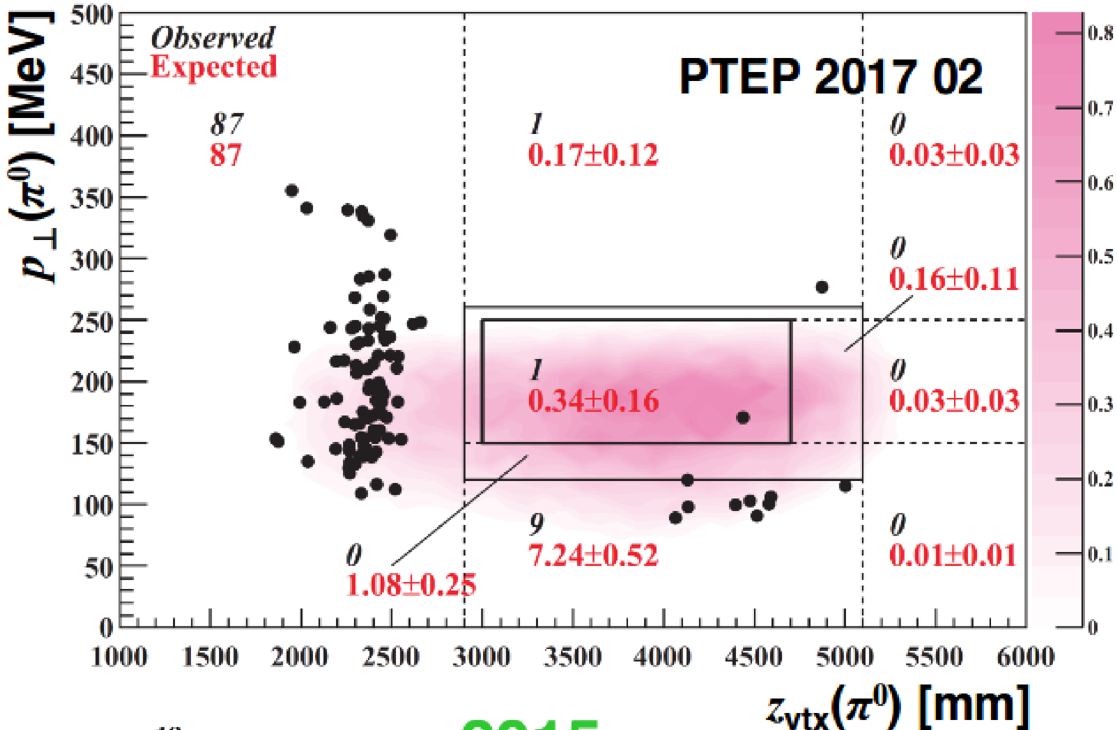
$< 10 \times 10^{-10}$ (90%CL)

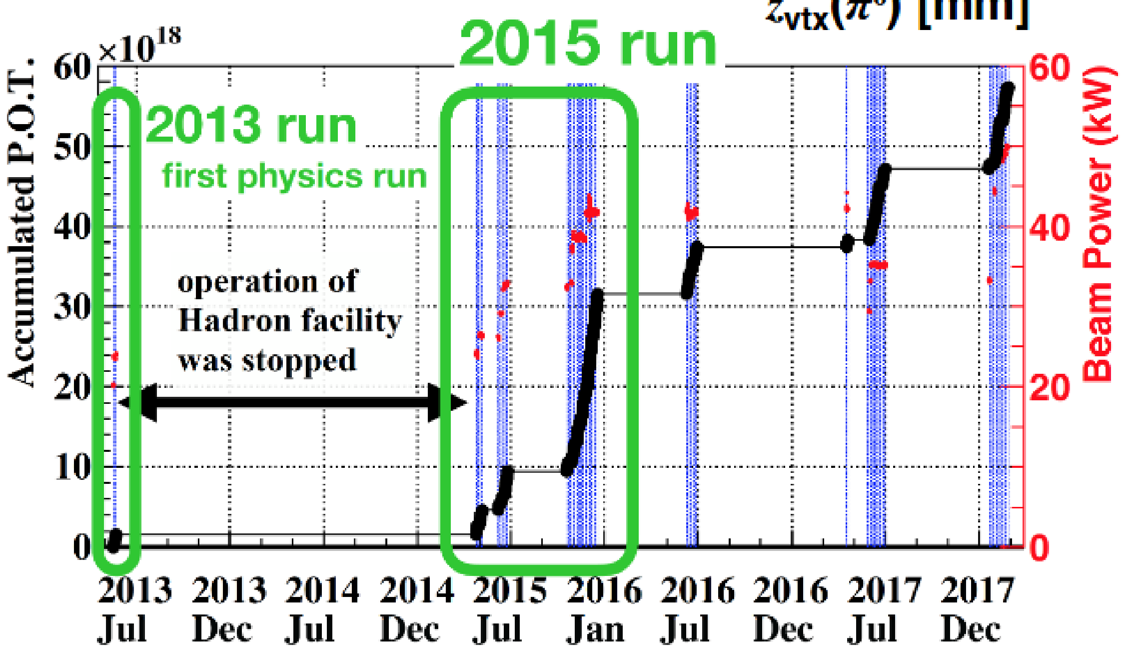
$= 28^{+44}_{-23} \times 10^{-11}$ (68% CL)

Background source	Expected events R1 + R2
$K^+ \to \pi^+\nu\nu$ (SM)	**$0.267 \pm 0.001_{stat} \pm 0.029_{sys} \pm 0.032_{ext}$**
$K^+ \to \pi^+\pi^0(\gamma_{IB})$	$0.064 \pm 0.007_{stat} \pm 0.006_{sys}$
$K^+ \to \mu^+\nu(\gamma_{IB})$	$0.020 \pm 0.003_{stat} \pm 0.003_{sys}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.018\ ^{+0.024}_{-0.017}\ {}_{stat} \pm 0.009_{sys}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{sys}$
Upstream background	$0.050 \pm\ ^{+0.090}_{-0.030}$
Total background	**$0.15 \pm 0.09_{stat} \pm 0.01_{sys}$**

Much more data on the way

$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC





KOTO is based on KEK-E391a

E391a result = current exp. value:

BR($K_L \to \pi^0 \nu\nu$) ≤ 2.6 × 10^{-8} (90%CL)

KOTO run history:

2013 pilot run (100 hrs)

BR($K_L \to \pi^0 \nu\nu$) ≤ 5.1 × 10^{-8} (90%CL)

2015 run (result coming soon)

- **40 kW** slow-extracted beam power
- 3e19 pot collected

2016-2017

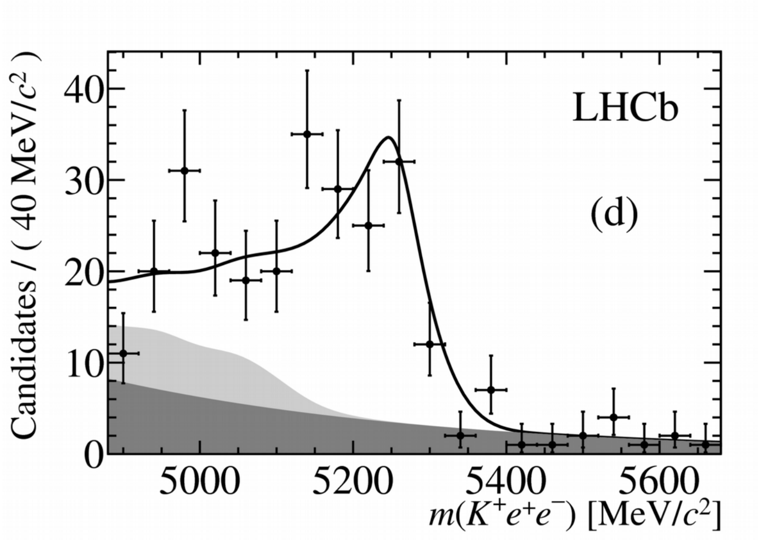
- Beam power increased to **50 kW**
- 3e19 pot collected (6e19 total)
- With all 2015-2017 data, expected sensitivity below Grossman-Nir limit

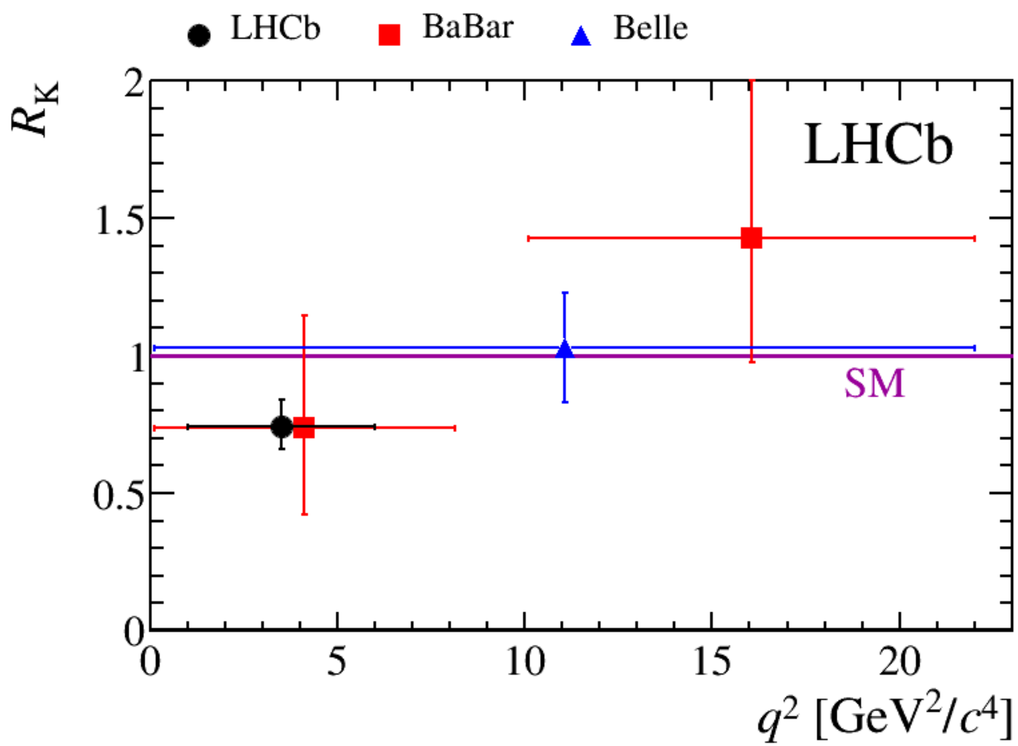
Lepton universality
$R_K \equiv B(B \to K\mu\mu)/B(B \to Kee)$

PRL 113 (2014) 151601

Deficit of $B \to K\mu^+\mu^-$ compared to expectation also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K)

Example mass fit for Ke^+e^-
Note huge tail due to energy loss





$$R_K(1 < q^2 < 6\ \text{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

Only 2.6σ from SM but suggestive

Lepton universality
$R_K \equiv \mathcal{B}(B \to K\mu\mu)/\mathcal{B}(B \to Kee)$

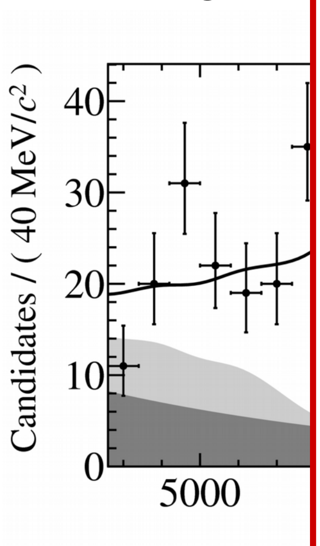
PRL 113 (2014) 151601

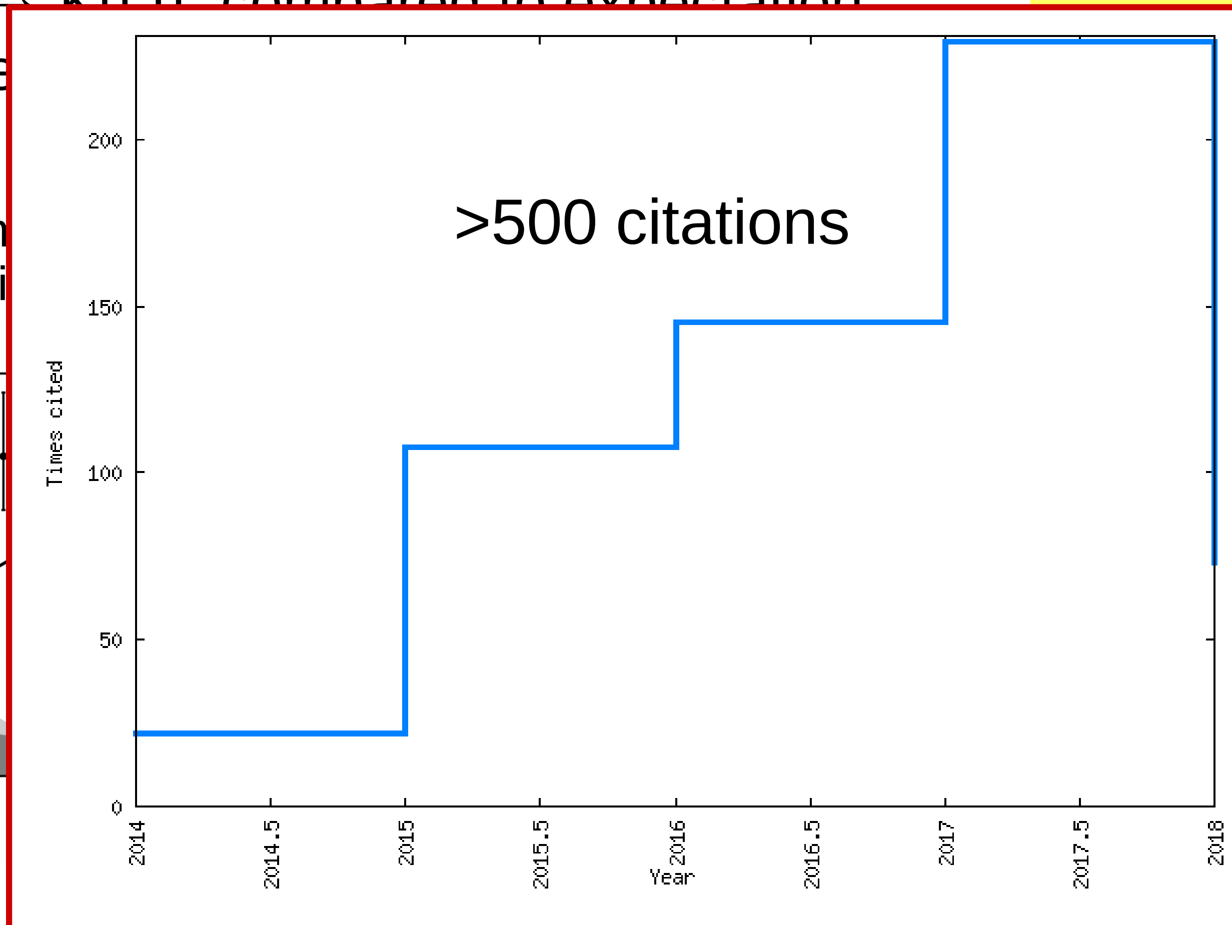
Deficit of B → $K\mu^+\mu^-$ compared to expectation

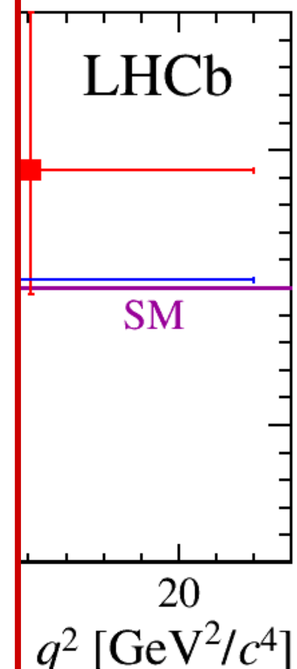
also se

Example n

Note huge tai





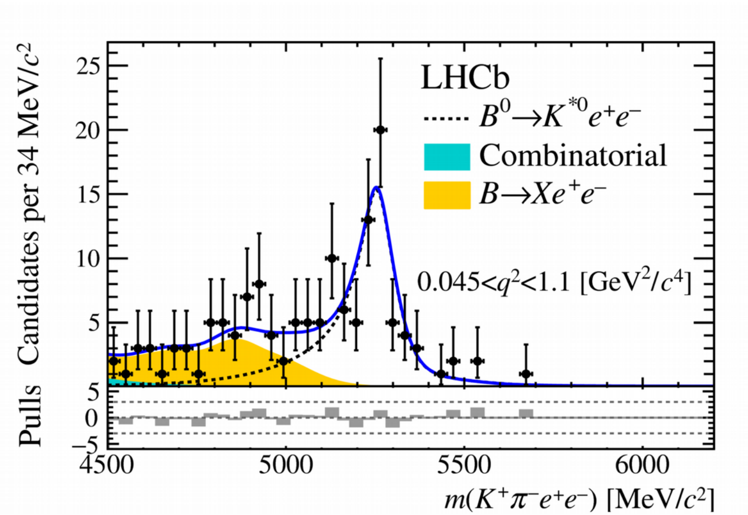


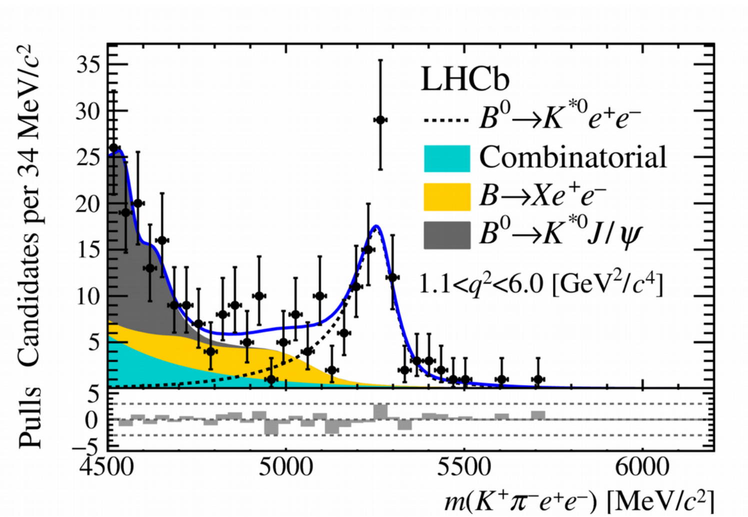
$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$

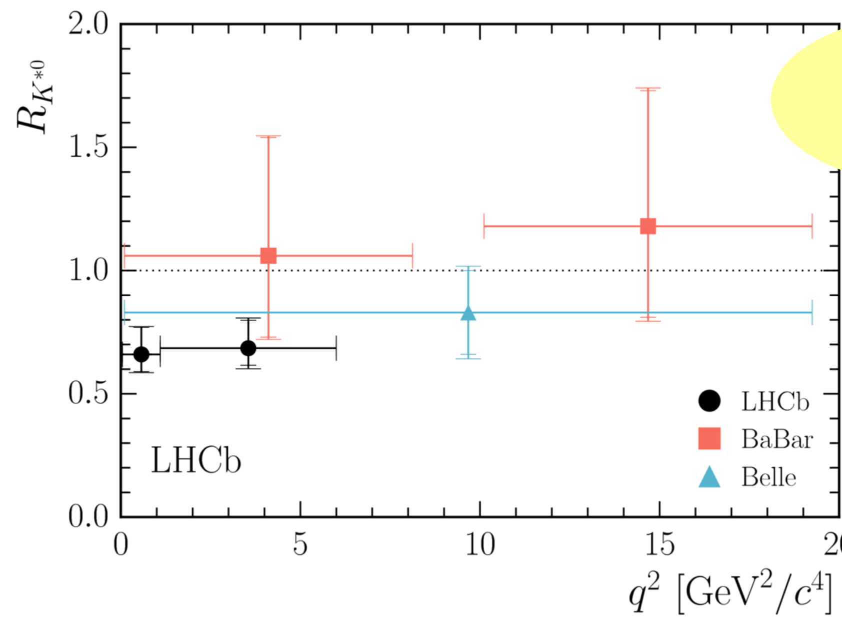
Only 2.6σ from SM but suggestive

$R_{K^*} \equiv \mathcal{B}(B \to K^*\mu\mu)/\mathcal{B}(B \to K^*ee)$

JHEP 08 (2017) 055







2 – 2.5σ
per bin

Clearly below the threshold for mass hysteria
But consistent picture with other $b \to sl^+l^-$ anomalies

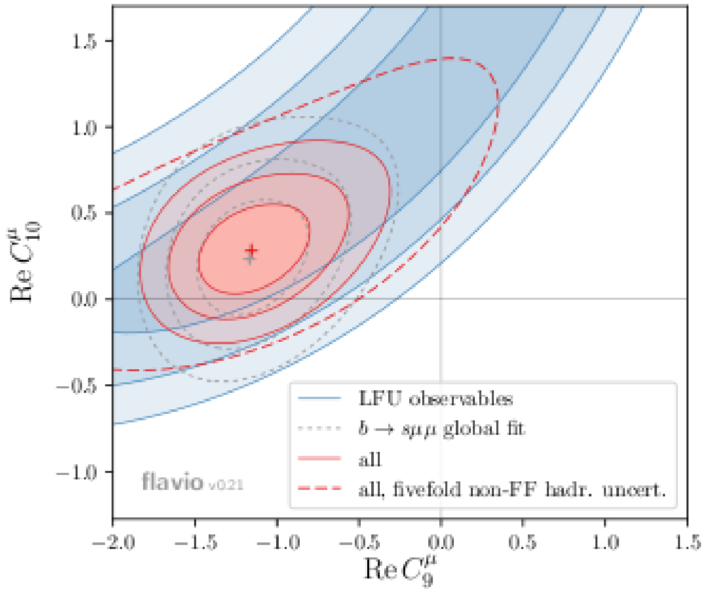
Can be explored model-independently (up to SM uncertainties) using operator product expansion

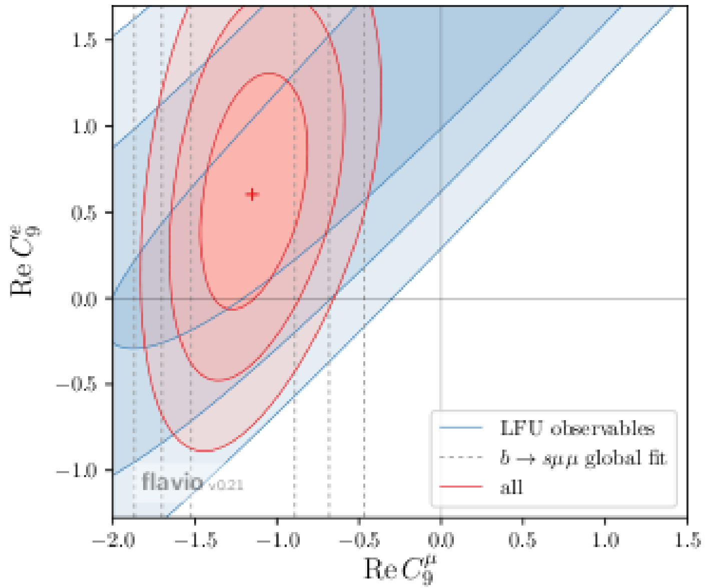
$b \to sl^+l^-$ global fits

Many interpretations appeared on hep-ph
Plots and table shown here from arXiv:1704.05435
See also, e.g.,

- arXiv:1704.05340 (more "optimistic")
- arXiv:1704.05447 (more "conservative")

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	$[-2.15, -1.13]$	$[-2.90, -0.73]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90, +1.60]$	$[+0.60, +2.04]$	4.3σ
C_9^e	$+1.58$	$[+1.17, +2.03]$	$[+0.79, +2.53]$	4.4σ
C_{10}^e	-1.30	$[-1.68, -0.95]$	$[-2.12, -0.64]$	4.4σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81, -0.48]$	$[-1.00, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.78$	$[+0.56, +1.02]$	$[+0.37, +1.31]$	4.3σ
$C_9'^\mu$	-0.00	$[-0.26, +0.25]$	$[-0.52, +0.51]$	0.0σ
$C_{10}'^\mu$	$+0.02$	$[-0.22, +0.26]$	$[-0.45, +0.49]$	0.1σ
$C_9'^e$	$+0.01$	$[-0.27, +0.31]$	$[-0.55, +0.62]$	0.0σ
$C_{10}'^e$	-0.03	$[-0.28, +0.22]$	$[-0.55, +0.46]$	0.1σ





$b \to sl^+l^-$ global fits

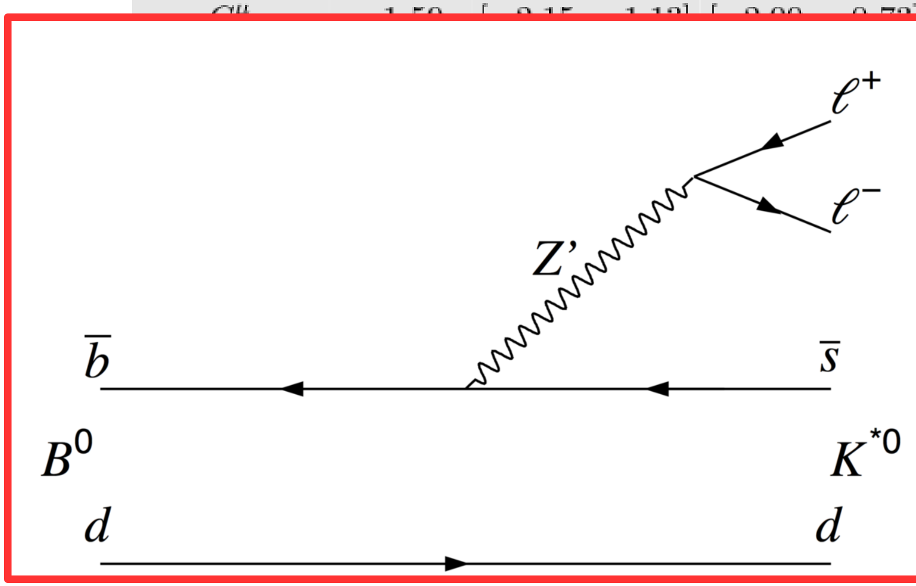
Many interpretations appeared on hep-ph

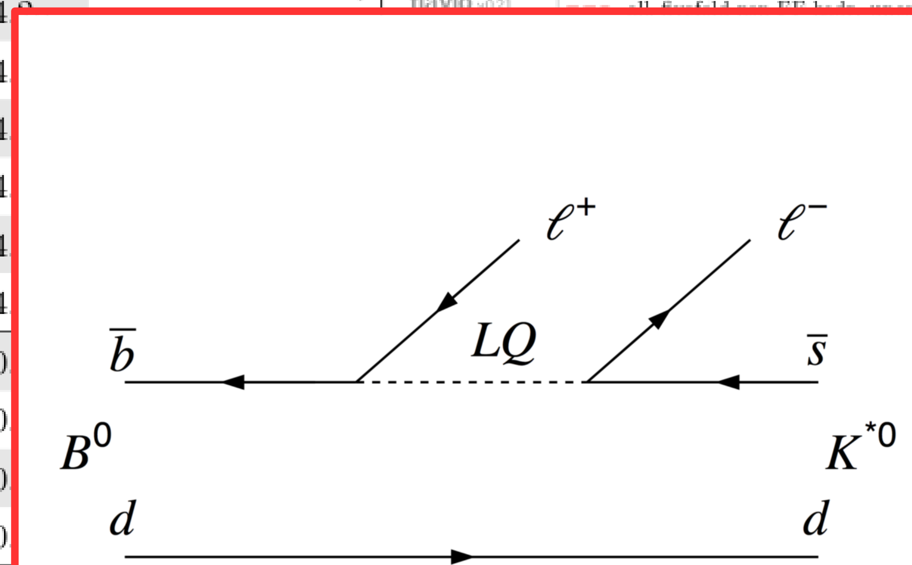
Plots and table shown here from arXiv:1704.05435

See also, e.g.,
- arXiv:1704.05340 (more "optimistic")
- arXiv:1704.05447 (more "conservative")

Favoured models to explain some or all anomalies include new vector mediators (Z') or leptoquarks

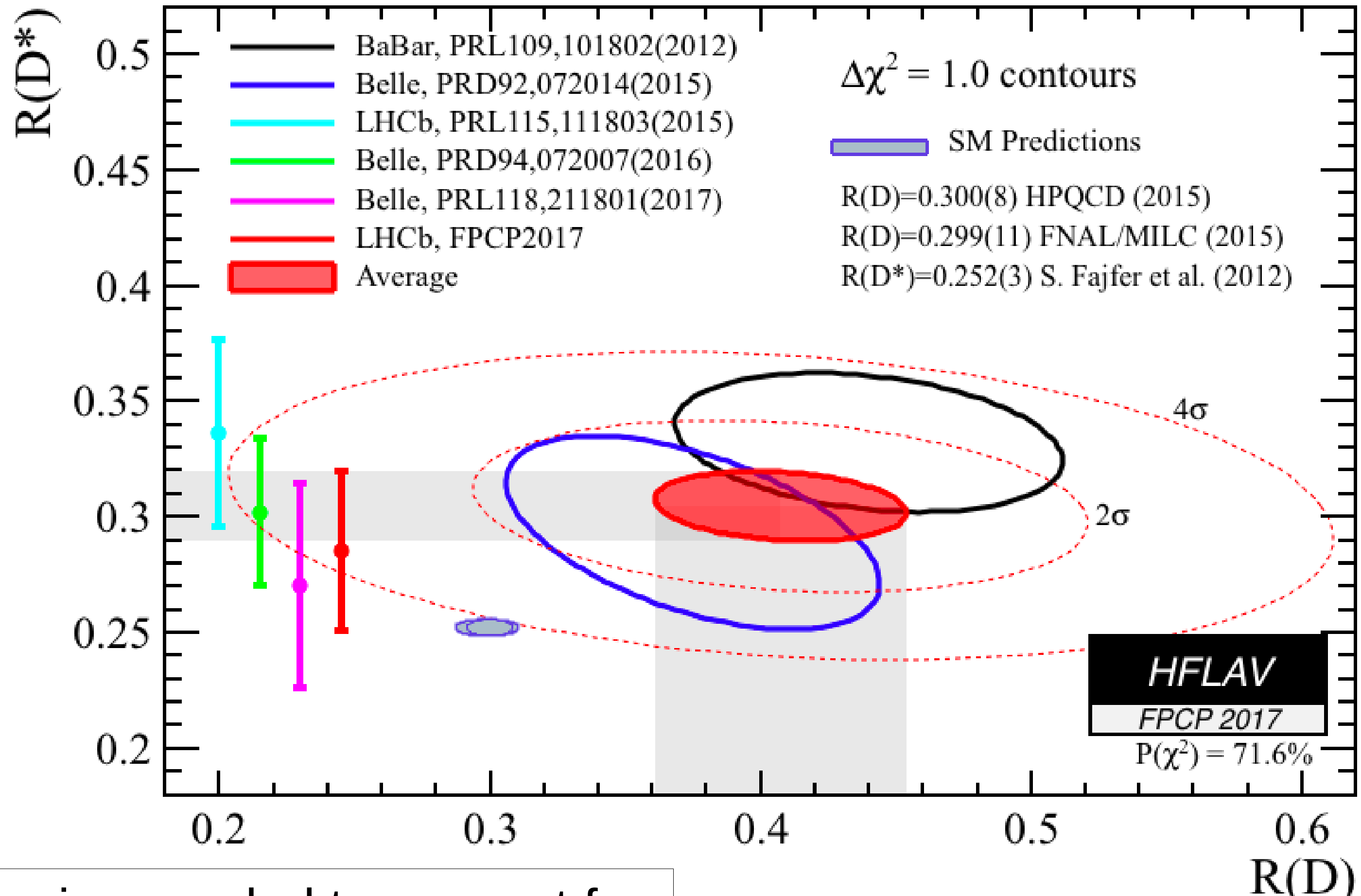
(e.g. JHEP 17 (2017) 040, arXiv:1706.02696, arXiv:1708.08450, arXiv:1709.00692, …)





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

Tension with SM at 4.1σ



Careful averaging needed to account for statistical and systematic correlations

$R(D^*) = 0.304 \pm 0.013 \pm 0.007$
$R(D) = 0.407 \pm 0.039 \pm 0.024$

Should we believe LFU violation?

Yes

- R measurements are double ratio's to J/ψ, LHCb's check with $K^*J/\psi \to e^+e^-/\mu^+\mu^-$ $=1.043\pm0.006\pm0.045$
- $\mathcal{B}(B^- \to K^- e^+ e^-)$ agrees with SM prediction puts onus on muon mode which is well measured and low
- Both R_K & R_{K^*} are different than ~1
- Supporting evidence of effects in angular distributions

No, not yet

- Statistics are marginal in each measurement
- Need confirming evidence in other experiments for R_K & R_{K^*}
- Disturbing that R_{K^*} is not ~1 in lowest q^2 bin, which it should be, because of the photon pole
- Angular distribution evidence can be effected by hadronic uncertainties

Should we believe LFU violation?

Yes

- R … le
  ra … k
  w
  =
- &
  S … n
  m
  m
- B
  th
- S
  e
  distributions

No, not yet

- St … n
  ea
- Ne … ce
  in … R_K
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  ph
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  ev … ed
  by … es

Should we believe LFU violation?

Yes

- R ... le
  ra ... k
  w
  =
- a
  S
  m
  m
- B
  th
- S
  e
  distributions

No, not yet

- St ... n
  ea
- Ne ... ce
  ... R_K
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- Ar
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When are the updates coming?

	Present effort intensity	First result precision (stat+syst)(%)	First result date	Run1+Run2 expected stat. precision (%)	Specificity
$R(\Lambda_c)$	***	7+15	Fall 2018	3	Spin 1/2
$R(J/\psi)$	***	20+10	Winter 2018	10	Bc
$R(D^0)$,$R(D^+)$	***	3+7	2019	2	Very low SM uncertainties
$R(D_s)$	*	5+10	2020	3	Sum of Ds and Ds*
R(D**)	*	15+10	2019	7	No higher level feeddown
$R(\Lambda^*_c)$	**	10+10	2019	7	No Higher level feed-down
R(p)	-	7+10	2020	5	Vub cf annihilation

Extremely optimistic, IMO

Weather forecast

	Present effort intensity	First result precision (stat+syst)(%)	First result date	Run1+Run2 expected stat. precision (%)	Specificity
$R(\Lambda_c)$	***	7+15	Fall 2018	3	Spin 1/2
$R(J/\psi)$	***	20+10	W[illegible] 2018	10	Bc
$R(D^0)$,$R(D^+)$	***	3+7	2019	2	Very low SM uncertainties
$R(D_s)$	*	5+10	20[illegible]	3	Sum of Ds and Ds*
$R(D^{**})$	*	15+10	2019	7	No higher level feeddown
$R(\Lambda^*_c)$	**	10+10	2019	7	No Higher level feed-down
$R(p)$	-	7+10	20[illegible]	5	Vub cf annihilation

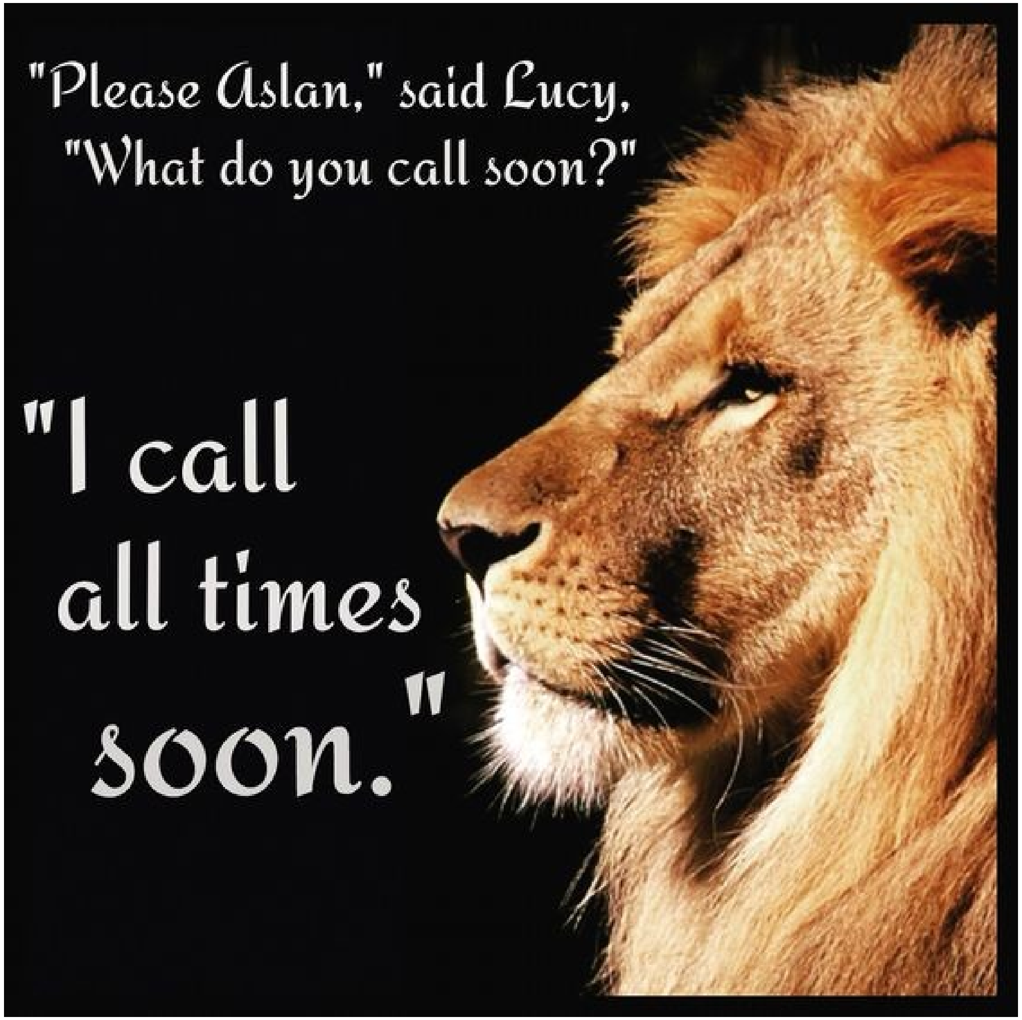
Extremely optimistic, IMO

When are the updates coming?

Soon!

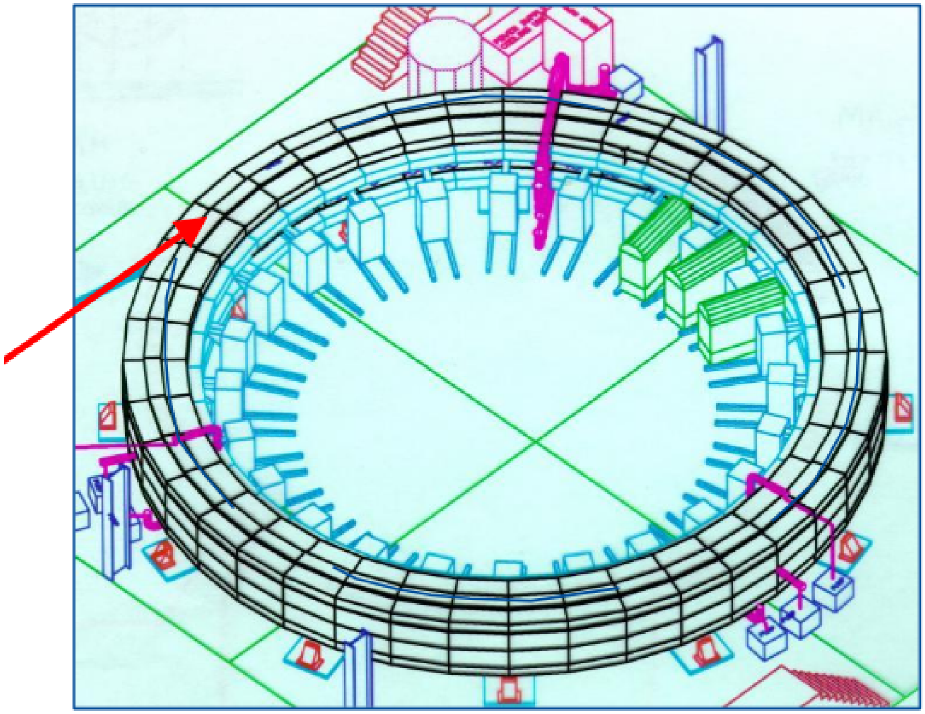
When are the updates coming?

“Do not look sad. We shall meet soon again."

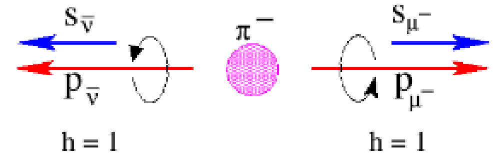


— C.S. Lewis, The Voyage of the Dawn Treader

(g-2)$_\mu$ at FNAL



1) Inject polarized muon source



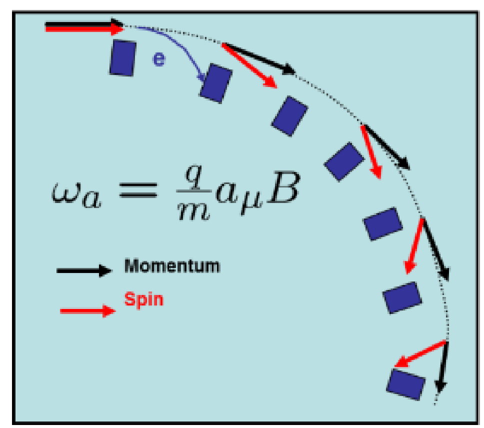
2) γ=29.3 muons allow E-field vert. focusing

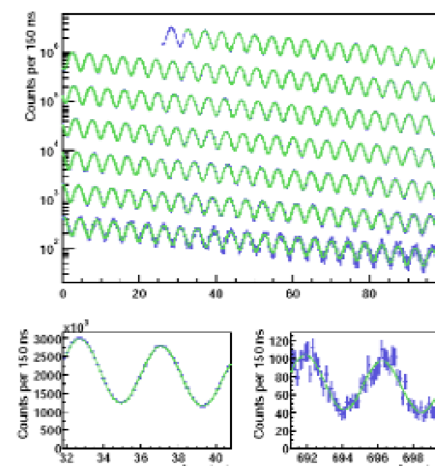
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

~0

3) Muon spin precession relative to momentum in cyclotron is directly proportional to a_μ

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$

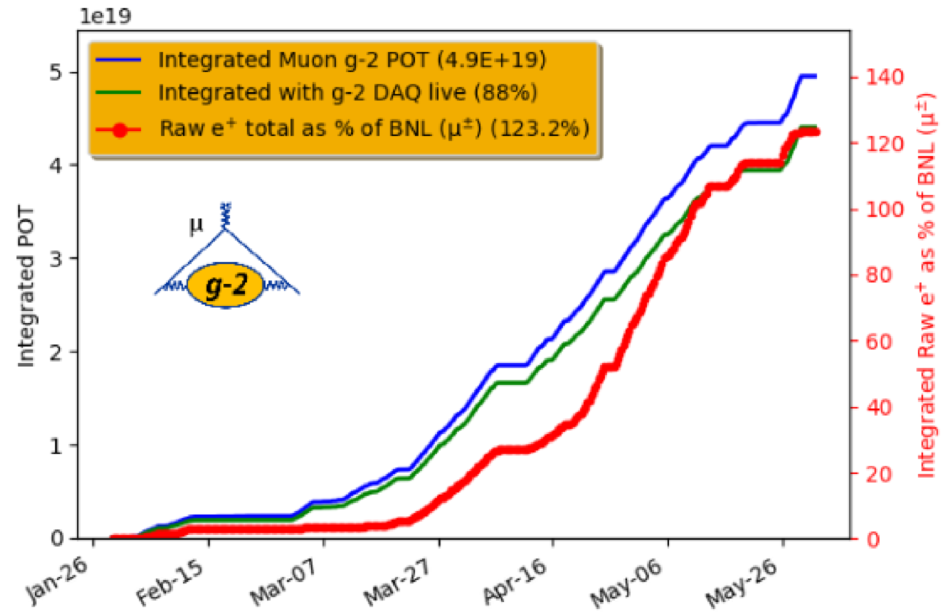




4) Highest energy decay electrons emitted when spin and momentum vectors parallel

(g-2)$_\mu$ at FNAL

- After spending most of year finalizing commissioning, started physics production running in early April
- Have > 1.2 x BNL on tape
- Collecting a BNL-sized data sample every 6 weeks!
  - 5 weeks left in this run
- Aiming to publish results exceeding BNL precision by Summer 2019



1st publication (>1 x BNL statistics)

2nd publication (5-10 x BNL statistics)

3rd publication (>20 x BNL statistics)

CY18 | CY19 | CY20 | CY21

SuperKEKB/Belle II

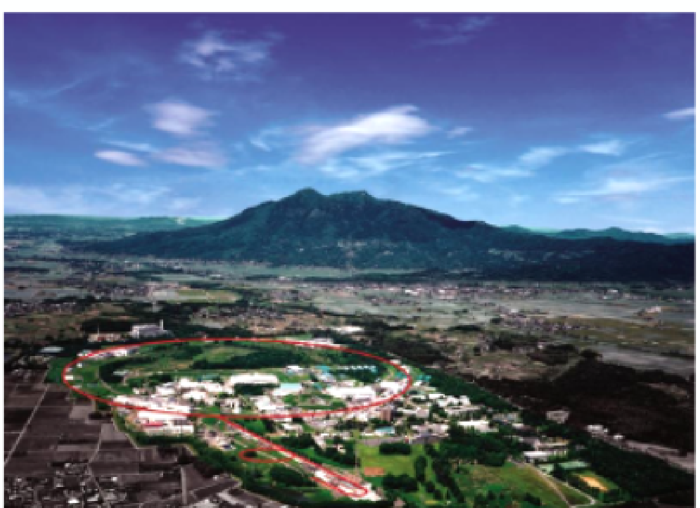
New intensity frontier facility at KEK

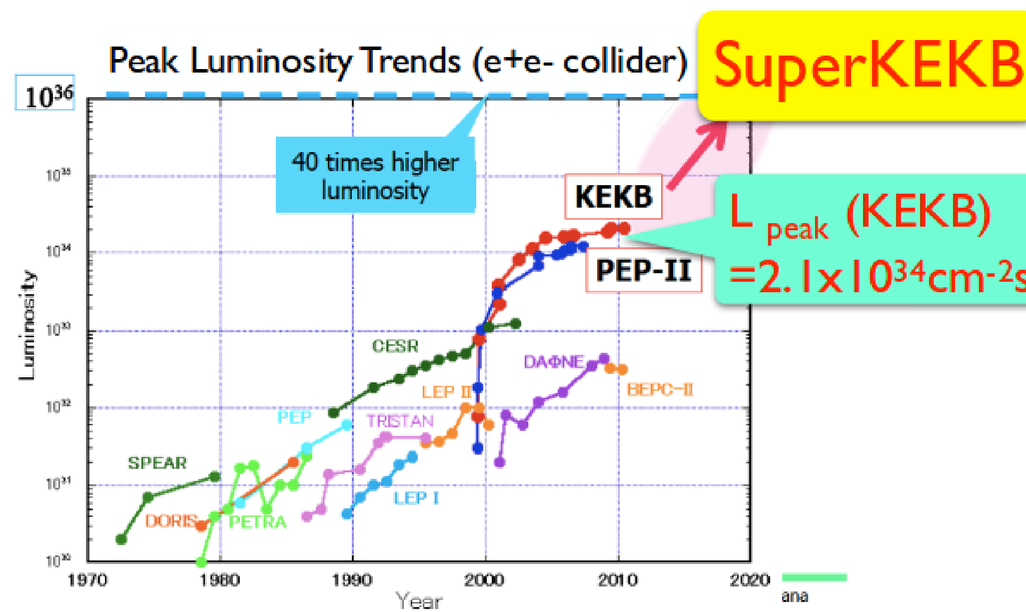
- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}$ $B\bar{B}$, $\tau^+\tau^-$ and charms per year !

  $L_{int} > 50\ ab^{-1}$

- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors) + more





The first particle collider after the LHC !

SuperKEKB Accelerator

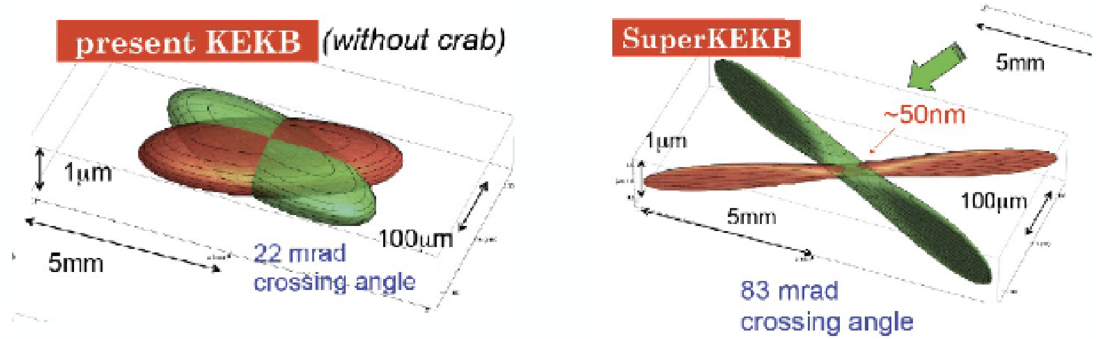
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

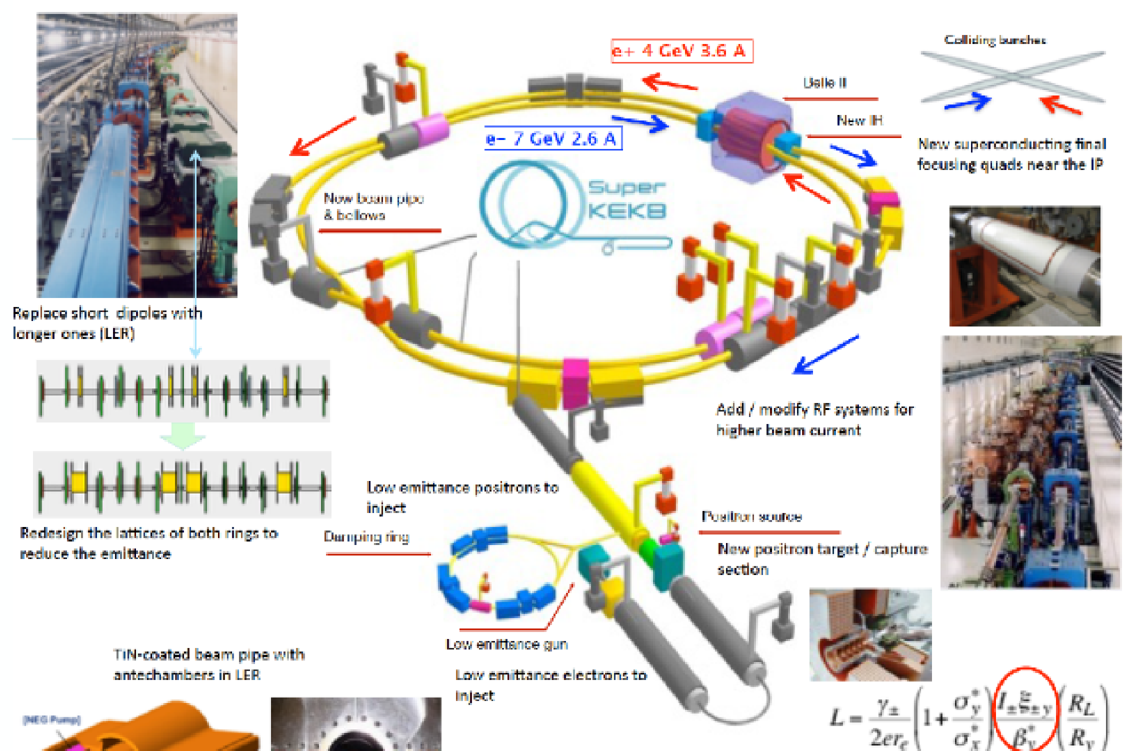
Machine parameters

	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L(cm^{-2}s^{-1})	80×10^{34}	2.1×10^{34}

x20 (β_y at IP)

x2 (I)



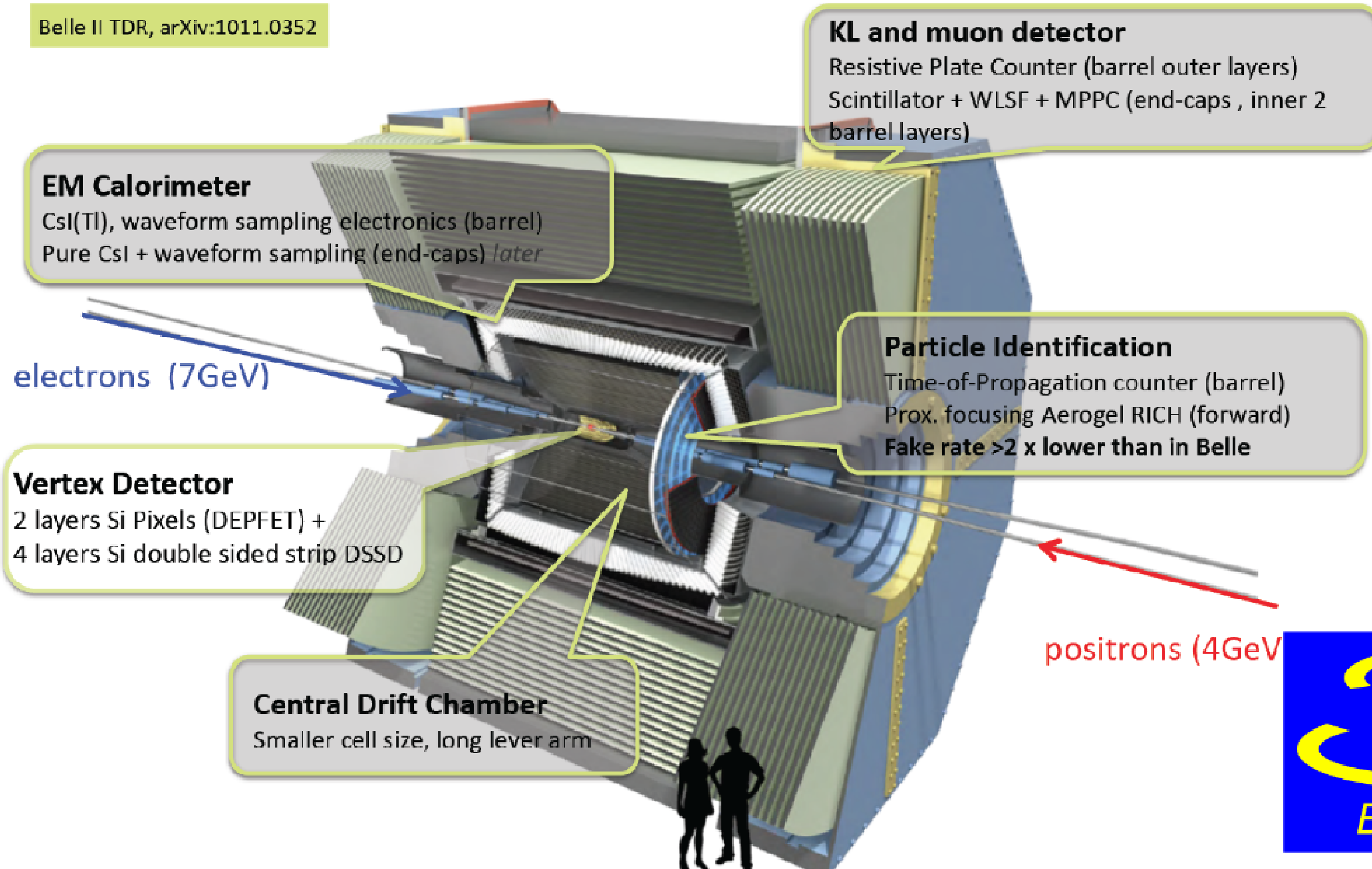


x 40 Gain in Luminosity

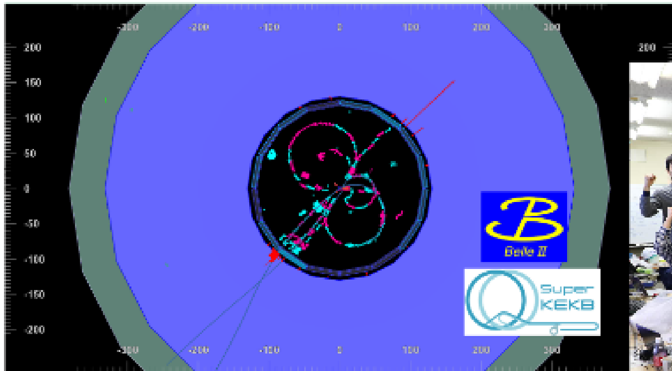
Belle II Detector

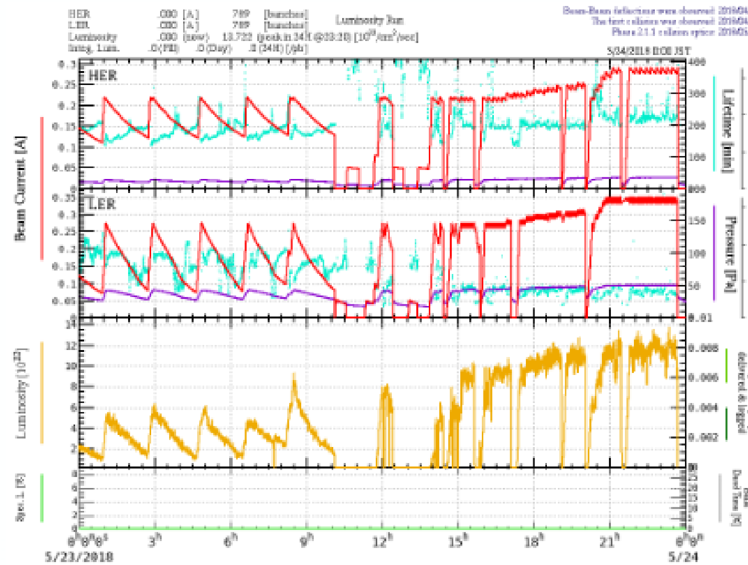
- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity

Belle II TDR, arXiv:1011.0352

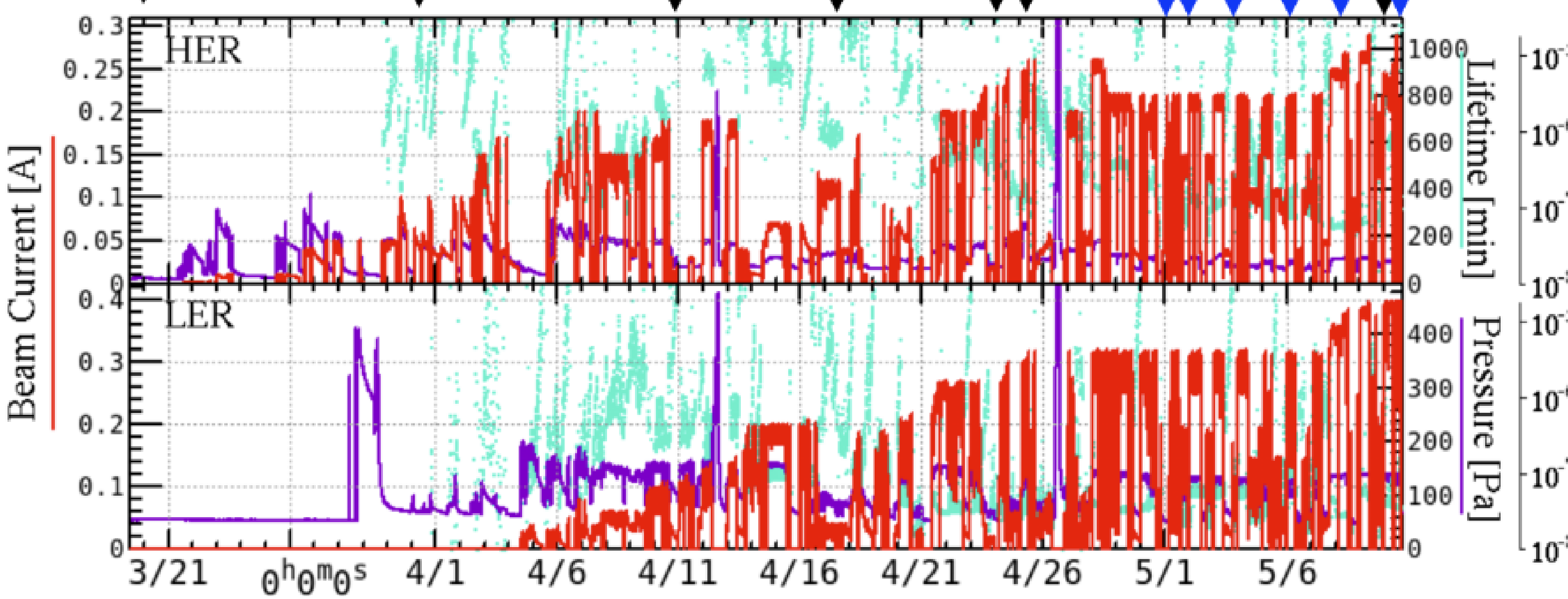


Phase 2 Commissioning



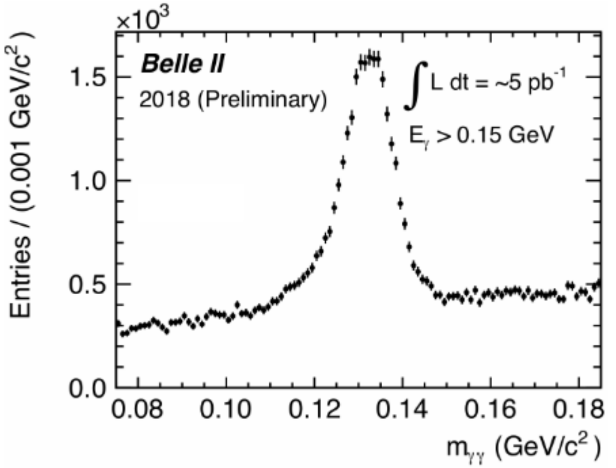


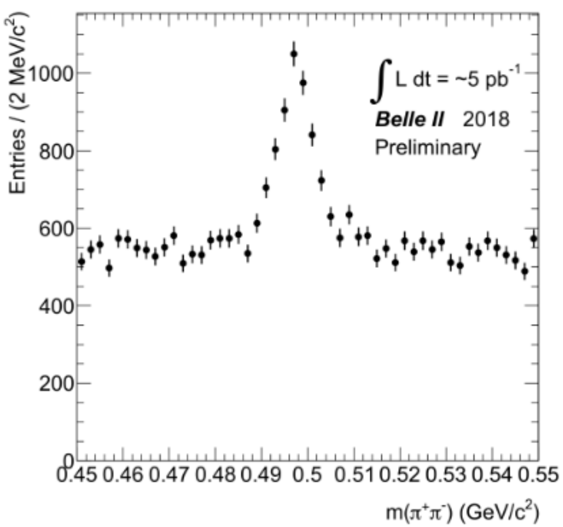
First collision

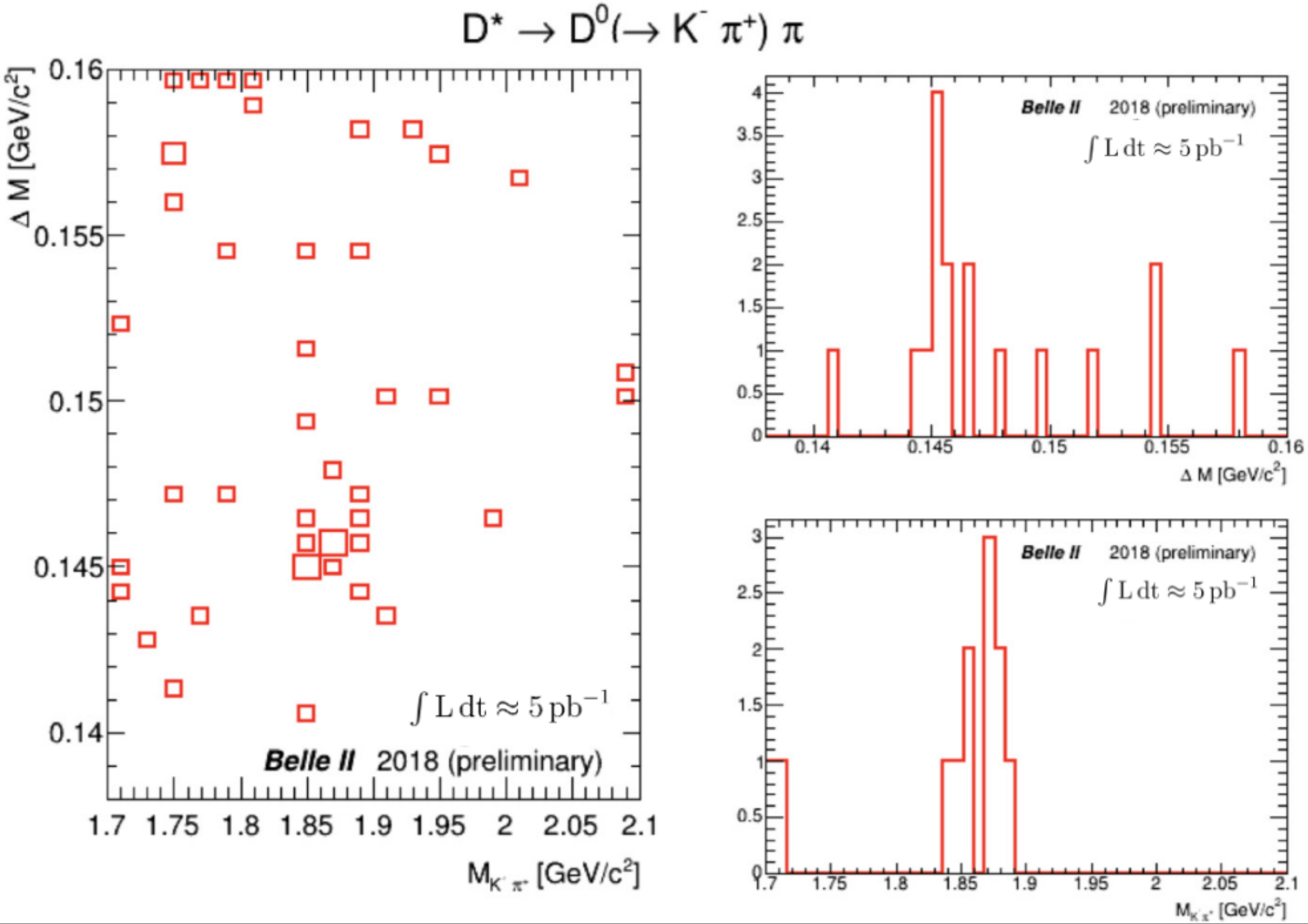


Luminosity $> 1\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

First signals appear in Belle II

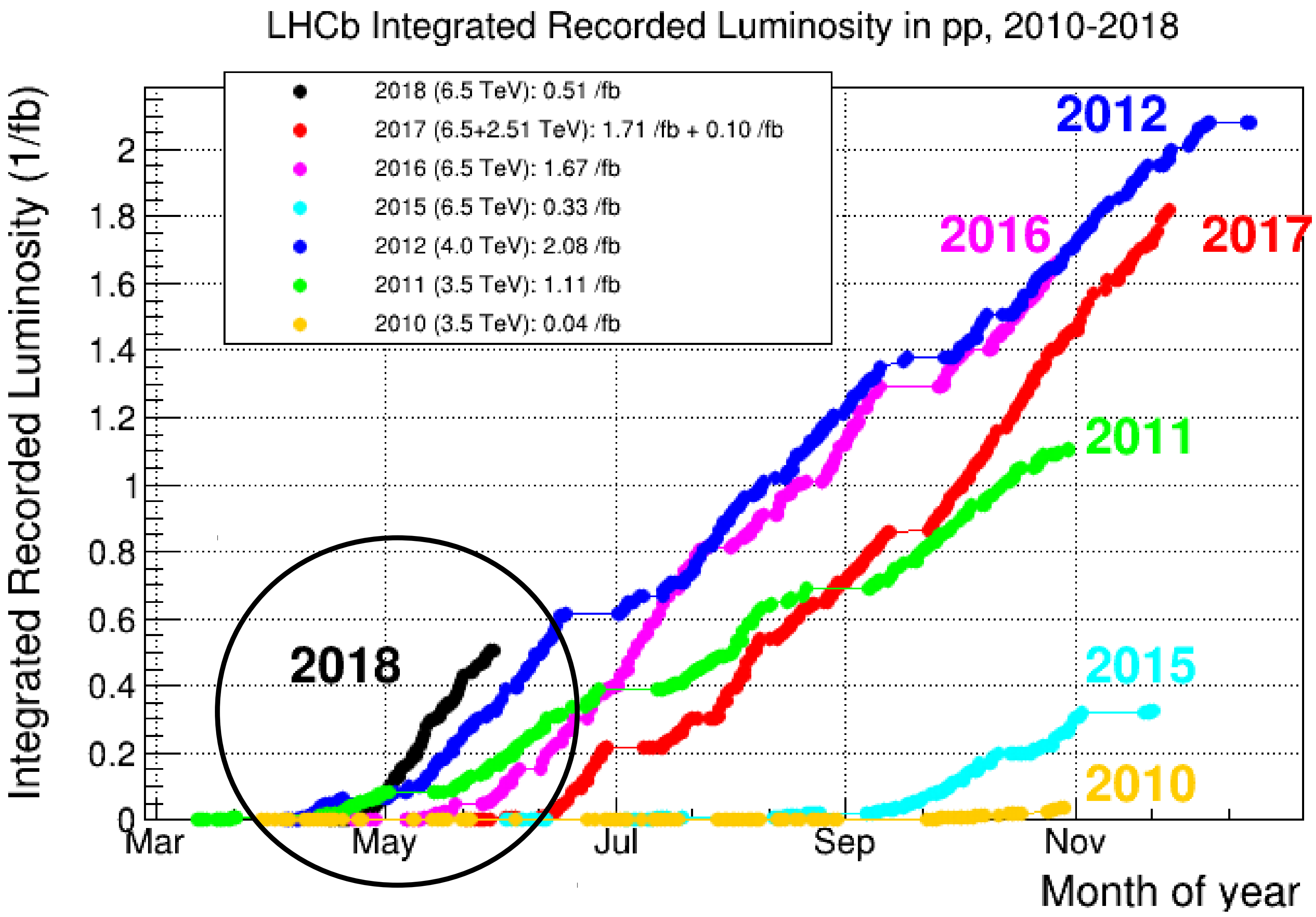






https://docs.belle2.org/collection/Belle%20II%20Notes%20%3A%20Plots?ln=en

Excellent LHC data taking

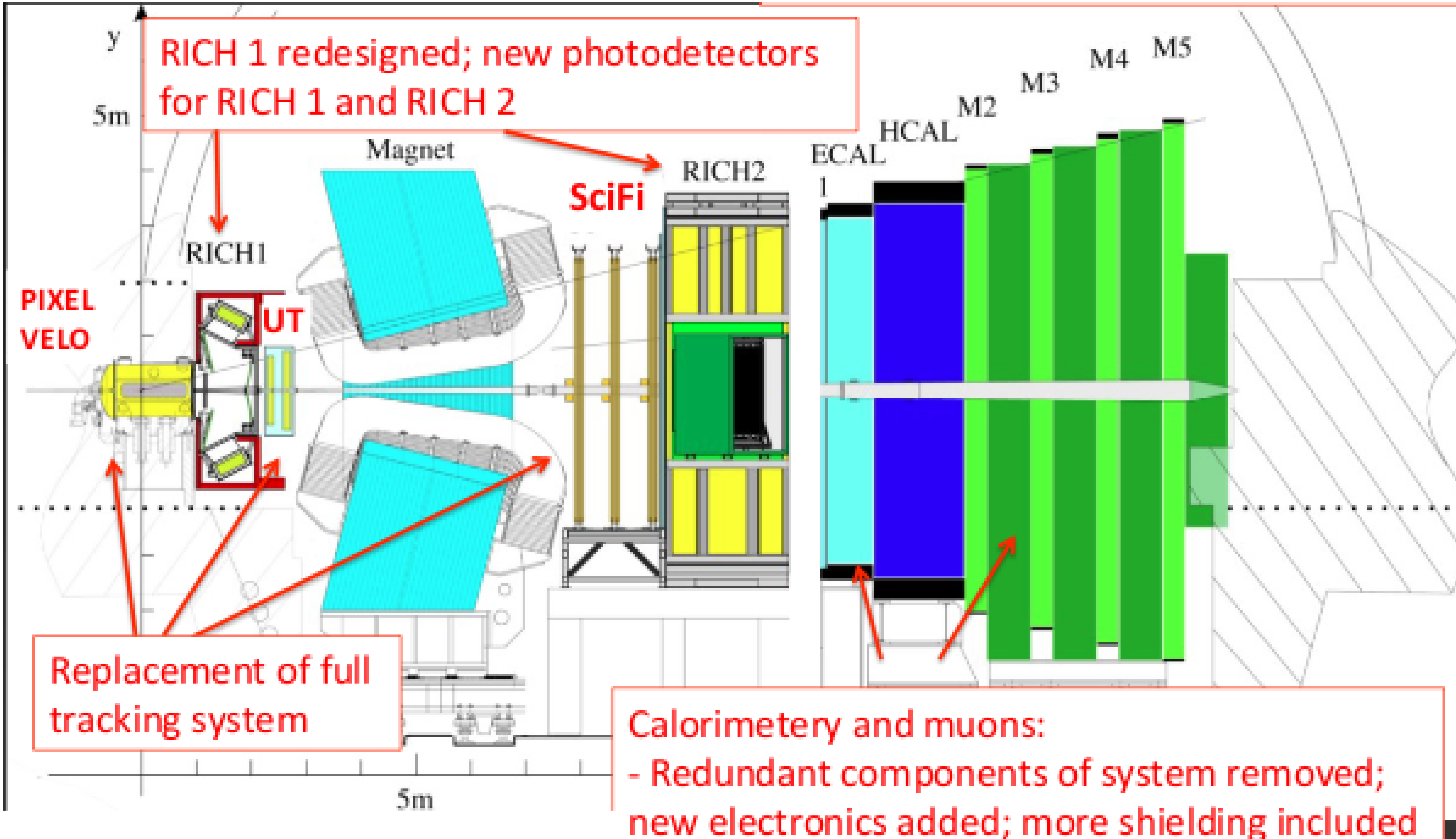


Beyond Run II – the LHCb Upgrade

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Will upgrade the LHCb detector in the LHC LS2 (2018-20)
  - Upgrade subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Operation at much higher luminosity with improved efficiency
    - order of magnitude improvement in precision (compared to today)
- Upgrade will be performed during LSII (now expected to be 2019-20)
  - Restart data taking in 2021 at instantaneous luminosity up to 2 $10^{33}/cm^2/s$
  - Upgrade detector qualified to accumulate 50/fb

LHCb-TDR-{13,14,15,16}

LHCb detector upgrade



+ novel trigger and offline data management strategies

LHCb & upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Will not reach limiting theory uncertainty!

Personal view – not an official schedule!

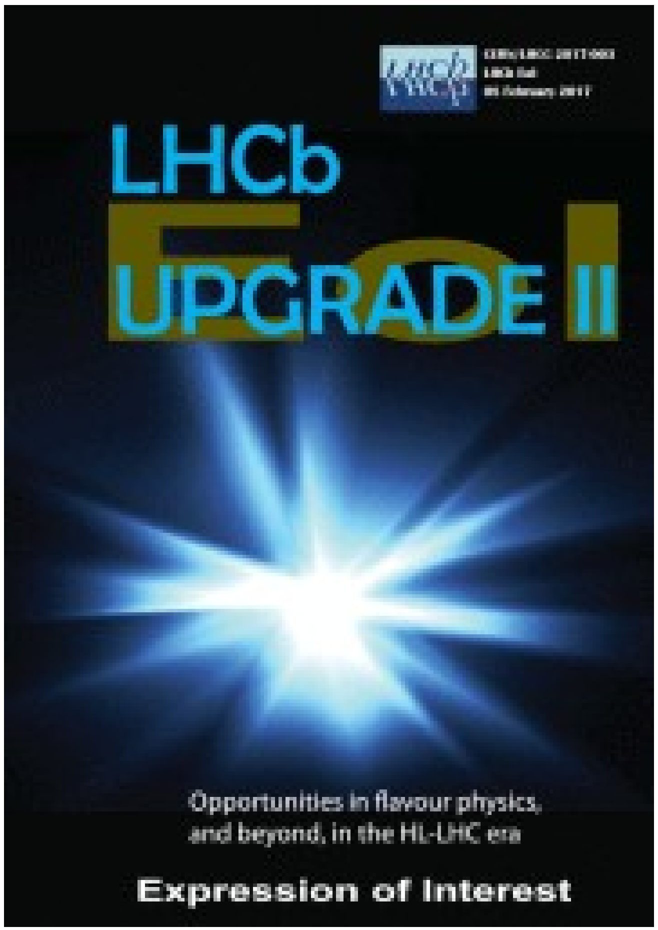
LHC long term future

Bearing in mind that “Europe’s top priority should be the exploitation of the full potential of the LHC” it seems natural to aim for a further major LHCb upgrade during LS4

		2013/14		2019/20		2024-26		2030/31	
	Run 1	**LS1**	Run 2	**LS2**	Run 3	**LS3**	Run 4	**LS4**	Run 5
LHC machine		**Energy upgrade**				**Luminosity upgrade**			
ATLAS & CMS		**Detector completion**		Consolidation		**Major upgrades to handle high lumi**		Consolidation	
LHCb		Consolidation		**40 MHz upgrade**		Consolidation		**Major upgrade to handle high lumi**	

Upgrade during LS4 will allow to increase data sample 50/fb → 300/fb

Expression of interest for “Phase II” upgrade



- Increase total integrated luminosity 50/fb → 300/fb
- Improve detector capabilities (options currently under discussion)
  - improve EM calorimetry
  - increase tracking acceptance
  - reduce material
  - add timing to control pile-up
- Enhance HL-LHC discovery potential!

Summary


I DON'T WANT TO
BELIEVE
I WANT TO
KNOW
–CARL SAGAN

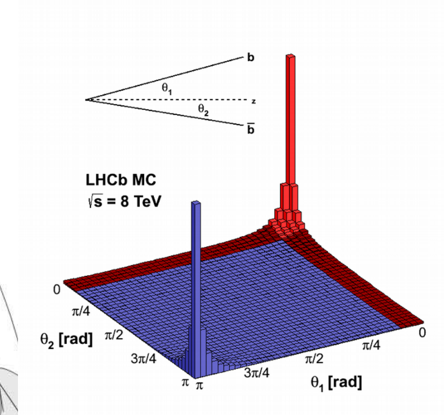

5σ
IT'S 5σ FOR A REASON.


"Please Aslan," said Lucy,
"What do you call soon?"
"I call
all times
soon."

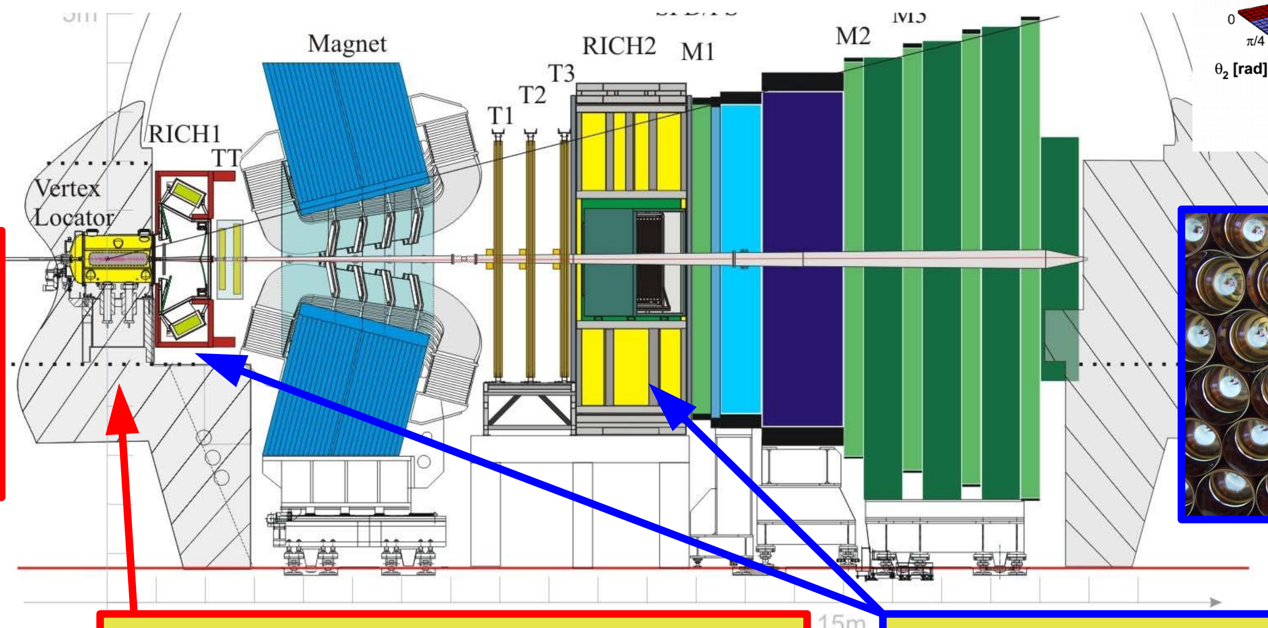

BACK UP!

The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb designed as a forward spectrometer



The LHCb Detector
JINST 3 (2008) S08005



Precision primary and secondary vertex measurements

Excellent K/π separation capability

The LHCb Run 1 trigger

JINST 8 (2013) P04022

Challenge is

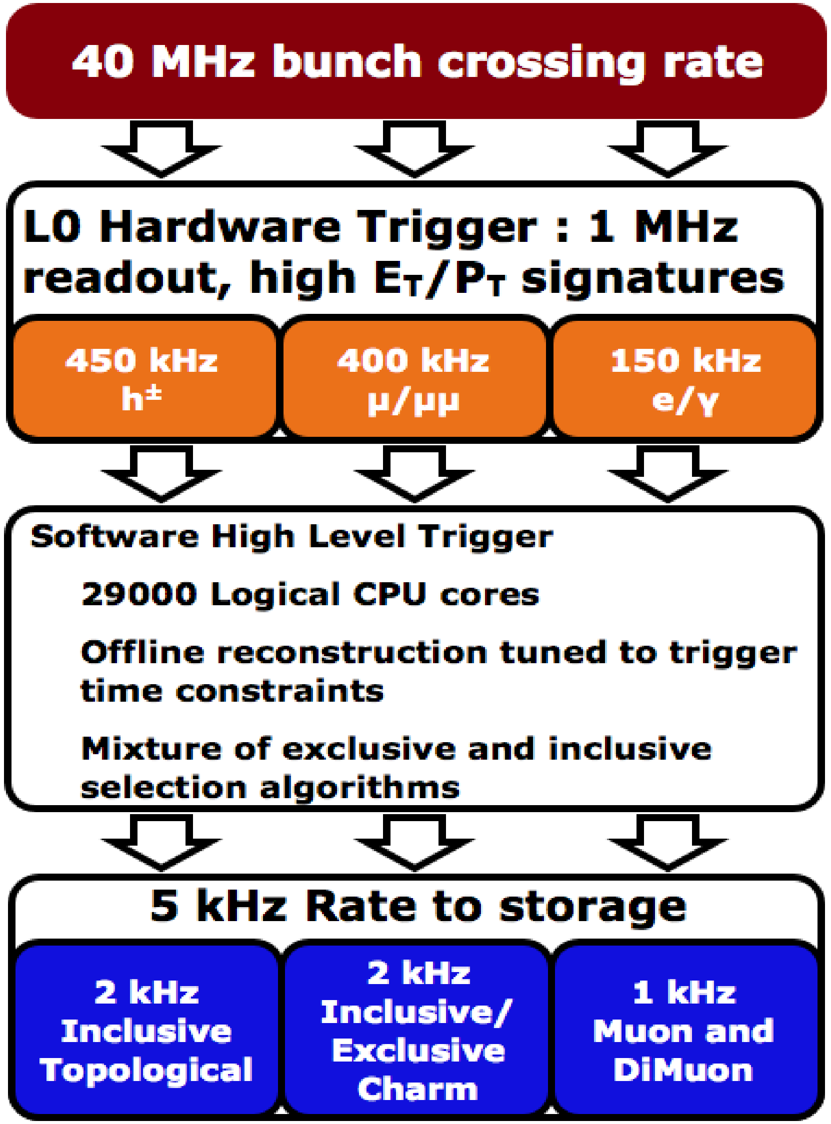
- to efficiently select most interesting events
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

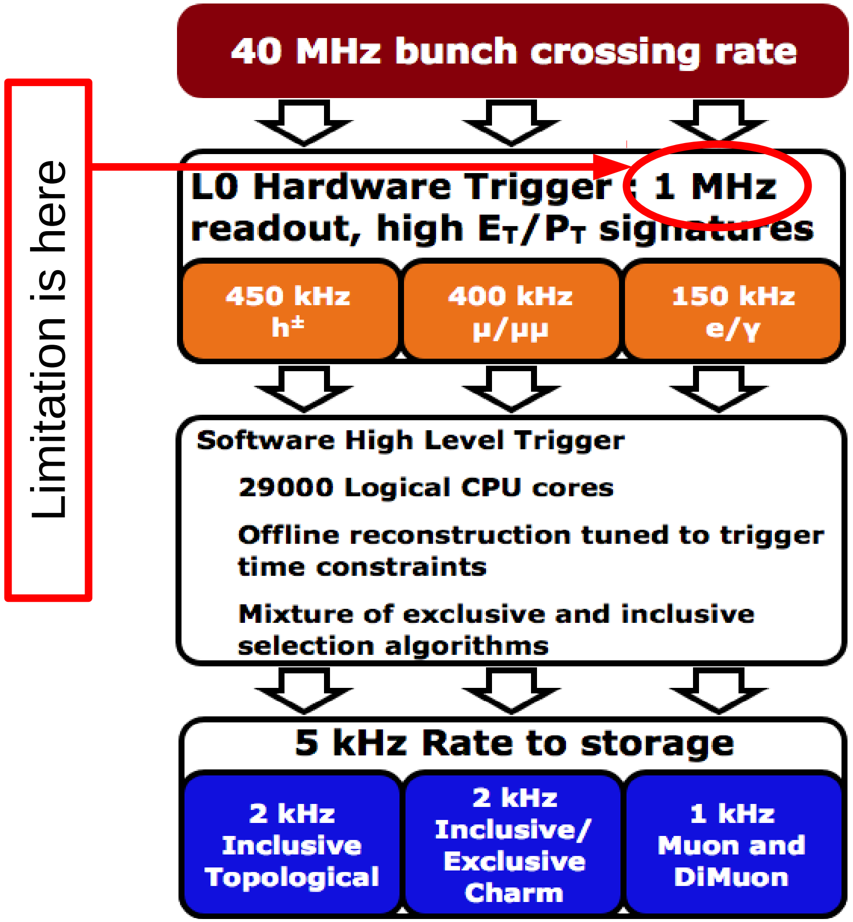
- high p_T signals (muons)
- displaced vertices



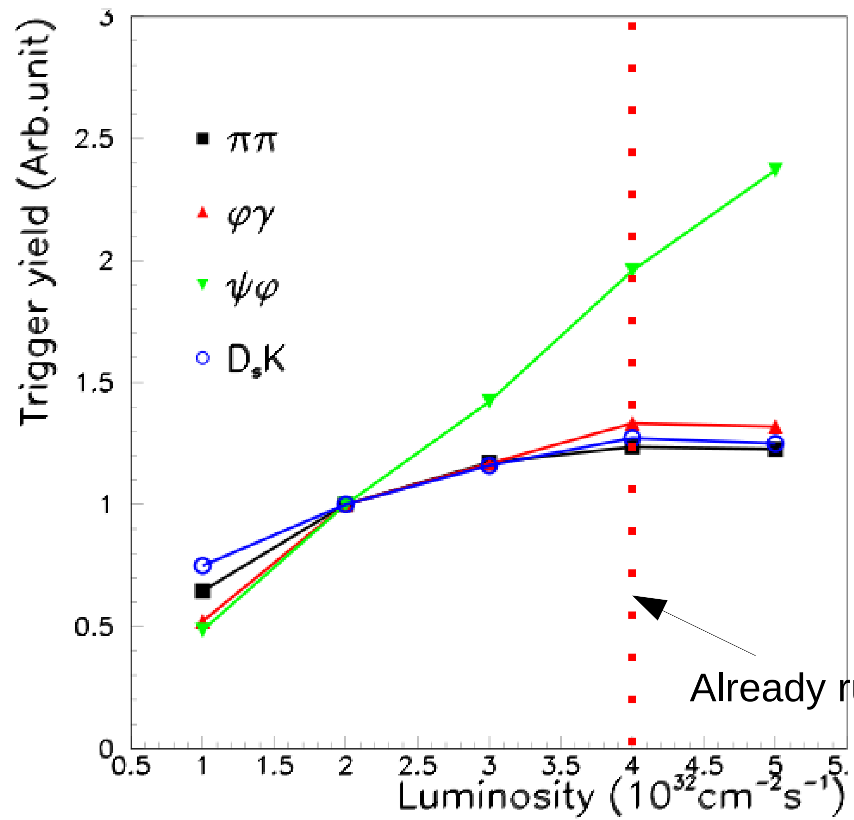
Selected physics topics

Topics and observables	Experimental reach	Remarks
EW Penguins		
Global tests in many $b \to s\mu^+\mu^-$ modes with full set of precision observables; lepton universality tests; $b \to dl^+l^-$ studies	*e.g.* 440k $B^0 \to K^*\mu^+\mu^-$ & 70k $\Lambda_b^0 \to \Lambda\mu^+\mu^-$; Phase-II $b \to d\mu^+\mu^- \approx$ Run-1 $b \to s\mu^+\mu^-$ sensitivity.	Phase-II ECAL required for lepton universality tests.
Photon polarisation		
$\mathcal{A}^{\Delta}$ in $B_s^0 \to \phi\gamma$; $B^0 \to K^* e^+e^-$; baryonic modes	Uncertainty on $\mathcal{A}^{\Delta} \approx 0.02$; $\sim 10k$ $\Lambda_b^0 \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$, $\Omega_b^- \to \Omega\gamma$	Strongly dependent on performance of ECAL.
$b \to cl^-\bar{\nu}_l$ lepton-universality tests		
Polarisation studies with $B \to D^{(*)}\tau^-\bar{\nu}_\tau$; τ^-/μ^- ratios with B_s^0, Λ_b^0 and B_c^+ modes	*e.g.* 8M $B \to D^*\tau^-\bar{\nu}_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ & $\sim 100k$ $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$	Additional sensitivity expected from low-p tracking.
$B_s^0, B^0 \to \mu^+\mu^-$		
$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$; $\tau_{B_s^0 \to \mu^+\mu^-}$; CP asymmetry	Uncertainty on $R \approx 20\%$; Uncertainty on $\tau_{B_s^0 \to \mu^+\mu^-} \approx 0.03\,\text{ps}$	
LFV τ decays		
$\tau^- \to \mu^+\mu^-\mu^-$, $\tau^- \to h^+\mu^-\mu^-$, $\tau^- \to \phi\mu^-$	Sensitive to $\tau^- \to \mu^+\mu^-\mu^-$ at 10^{-9}	Phase-II ECAL valuable for background suppression.
CKM tests		
γ with $B^- \to DK^-$, $B_s^0 \to D_s^+K^-$ *etc.*	Uncertainty on $\gamma \approx 0.4°$	Additional sensitivity expected
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\text{mrad}$	in CP observables from Phase-II
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\text{mrad}$	ECAL and low-p tracking.
$\Delta\Gamma_d/\Gamma_d$	Uncertainty on $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$	Approach SM value.
Semileptonic asymmetries $a_{\text{sl}}^{d,s}$	Uncertainties on $a_{\text{sl}}^{d,s} \sim 10^{-4}$	Approach SM value for a_{sl}^d.
$\|V_{ub}\|/\|V_{cb}\|$ with Λ_b^0, B_s^0 and B_c^+ modes	*e.g.* 120k $B_c^+ \to D^0\mu^-\bar{\nu}_\mu$	Significant gains achievable from thinning or removing RF-foil.
Charm		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; Uncertainty on $A_\Gamma \sim 10^{-5}$	Access CP violation at SM values.
Strange		
Rare decay searches	Sensitive to $K_S^0 \to \mu^+\mu^-$ at 10^{-12}	Additional sensitivity possible with downstream trigger enhancements.

LHC upgrade and the all important trigger

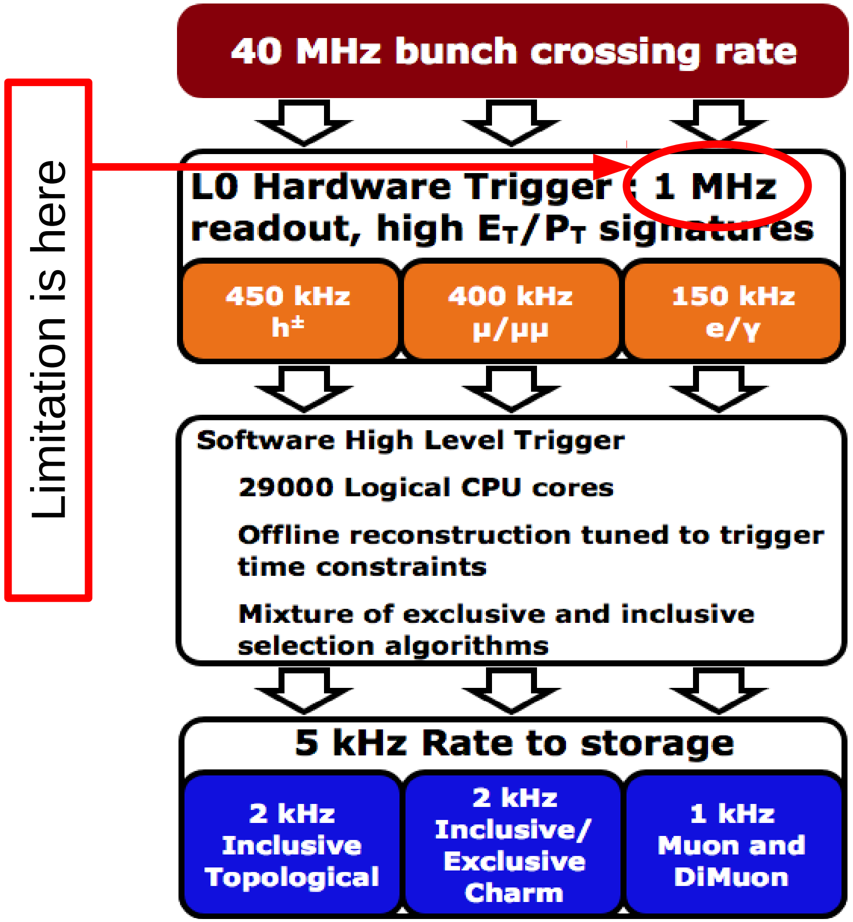


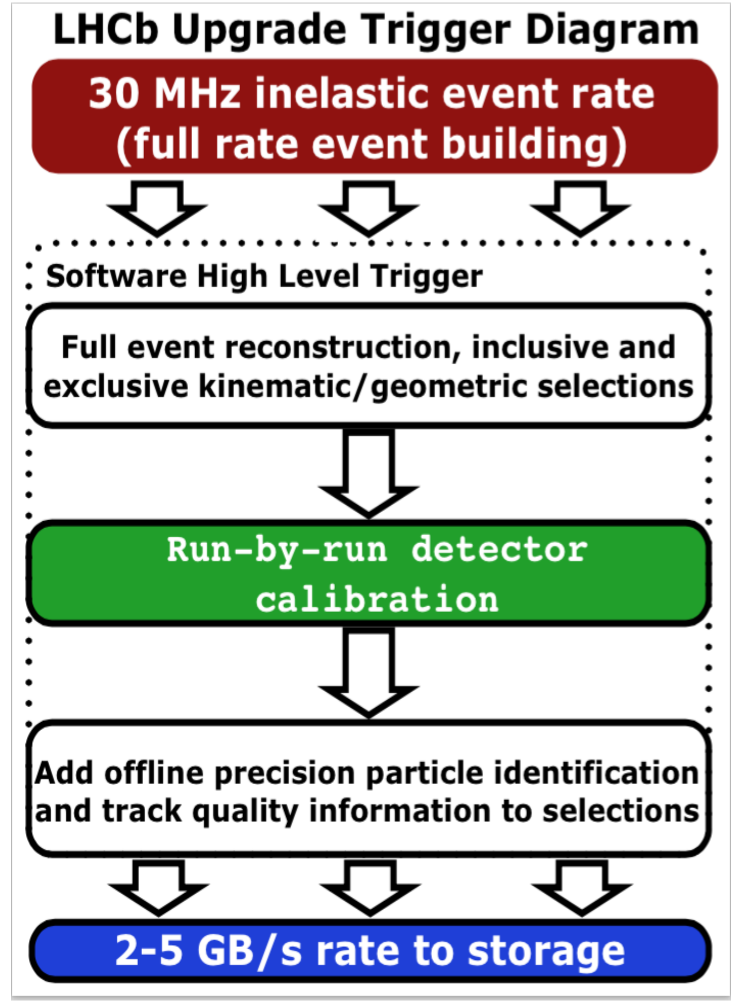
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

LHC upgrade and the all important trigger



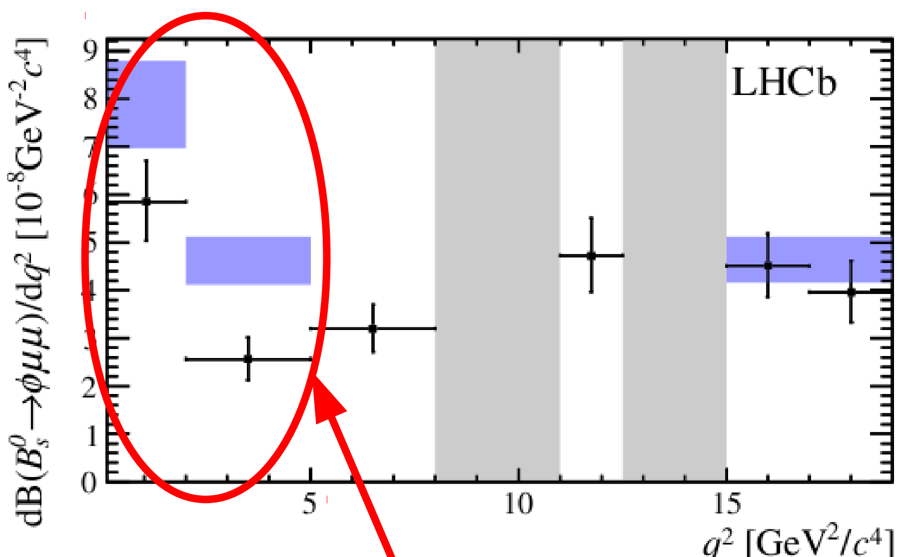


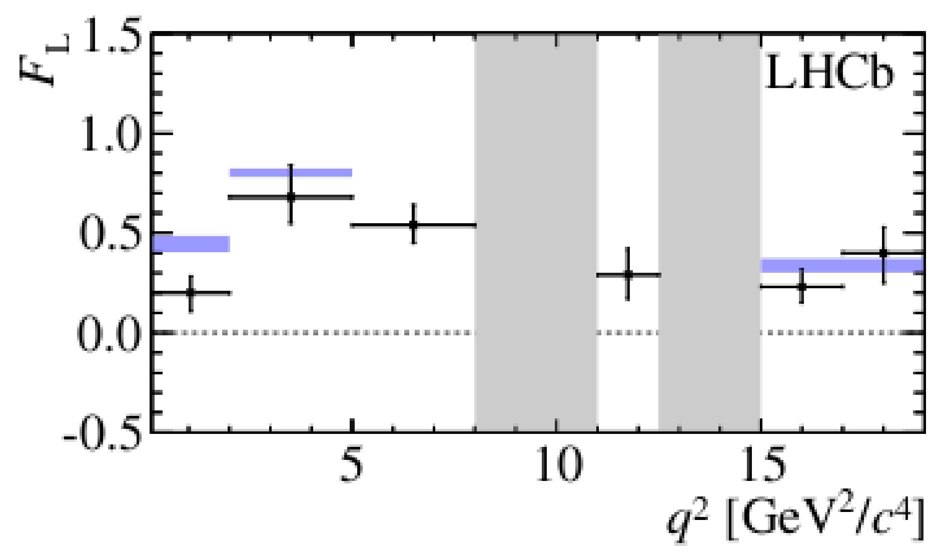
- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

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

JHEP 09 (2015) 179

- Full angular analysis performed
- Not self-tagging → complementarity to $K^{*0}\mu^+\mu^-$
  - only a subset of many observables shown





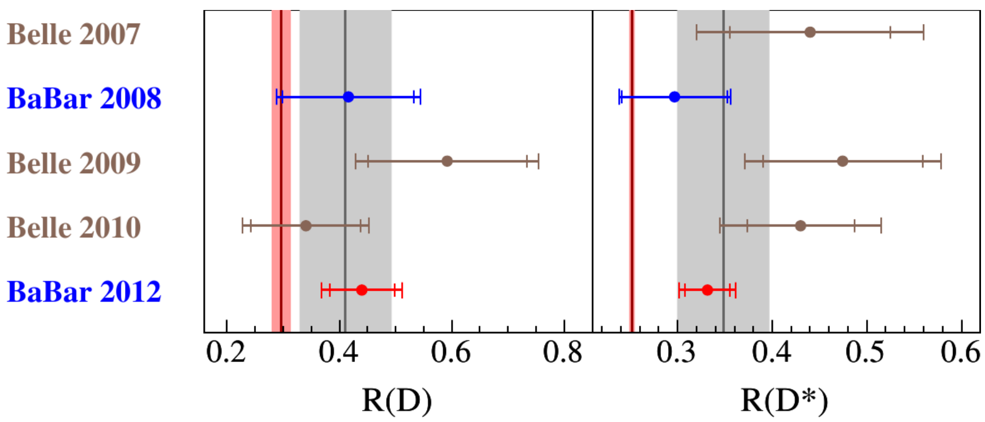
Tension in branching fraction, but angular observables consistent with SM

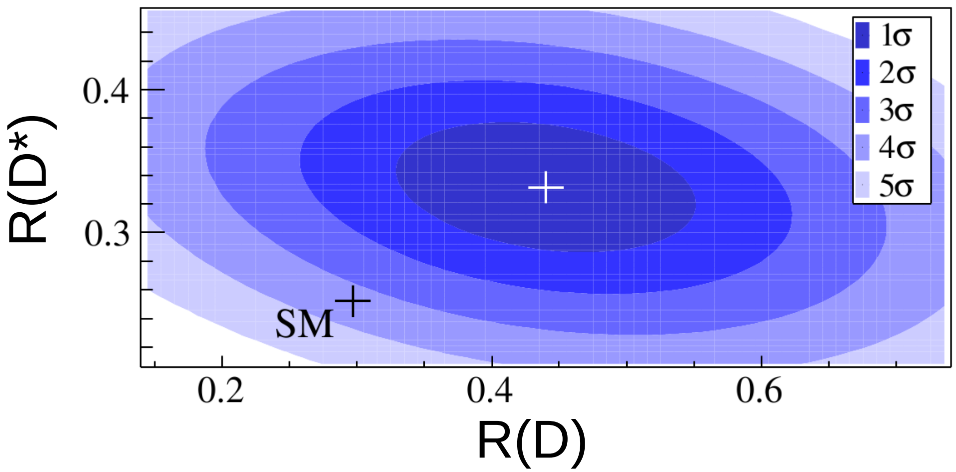
Consistent picture in $b \to sl^+l^-$ branching fractions

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

- Powerful channel to test lepton universality
  - ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ could deviate from SM values, e.g. in models with charged Higgs
- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. R_K

PRL 109 (2012) 101802
& PRD 88 (2013) 072012



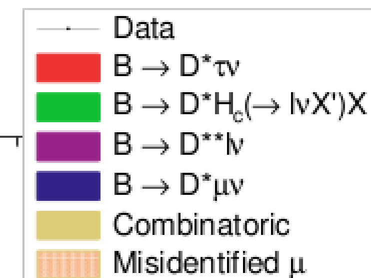


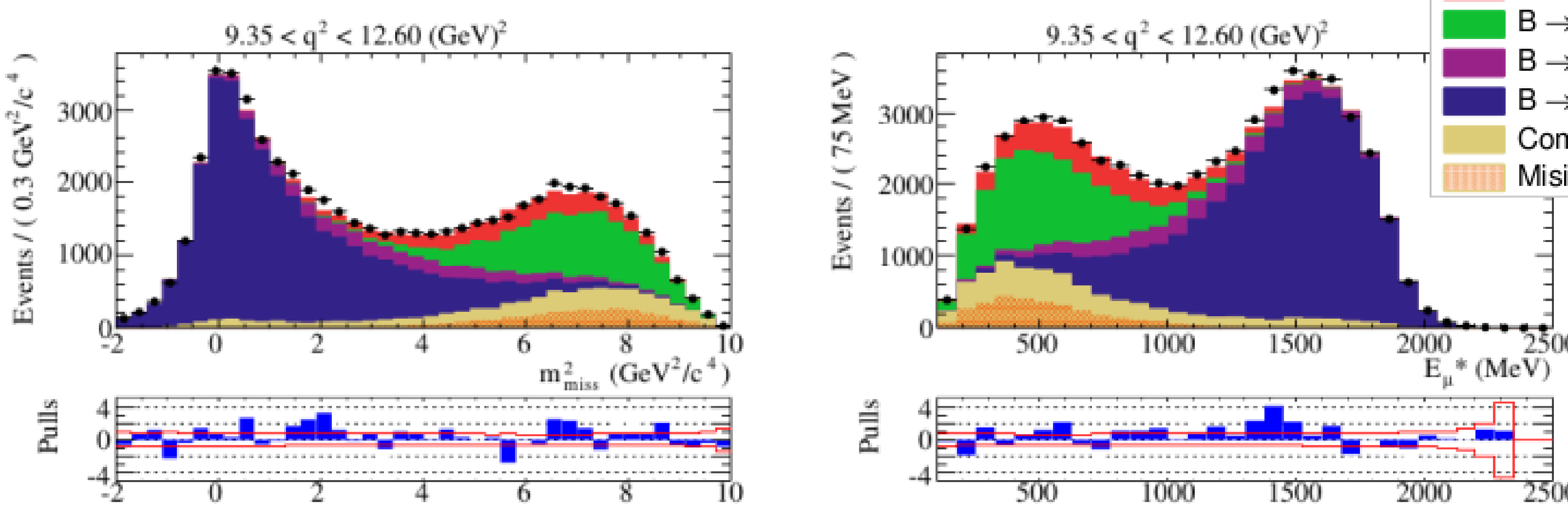
$B \to D^{*}\tau\nu$ at LHCb (I)

- Identify $B \to D^{*}\tau\nu$, $D^{*} \to D\pi$, $D \to K\pi$, $\tau \to \mu\nu\bar{\nu}$

PRL 115 (2015) 112001

  - Similar kinematic reconstruction to $\Lambda_b \to p\mu\nu$
    - Assume $p_{B,z} = (p_{D^*} + p_\mu)_z$ to calculate $M_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
  - Require significant B, D, τ flight distances & use isolation MVA
- Separate signal from background by fitting in M_{miss}^2, q^2 and E_μ
  - Shown below high q^2 region only (best signal sensitivity)



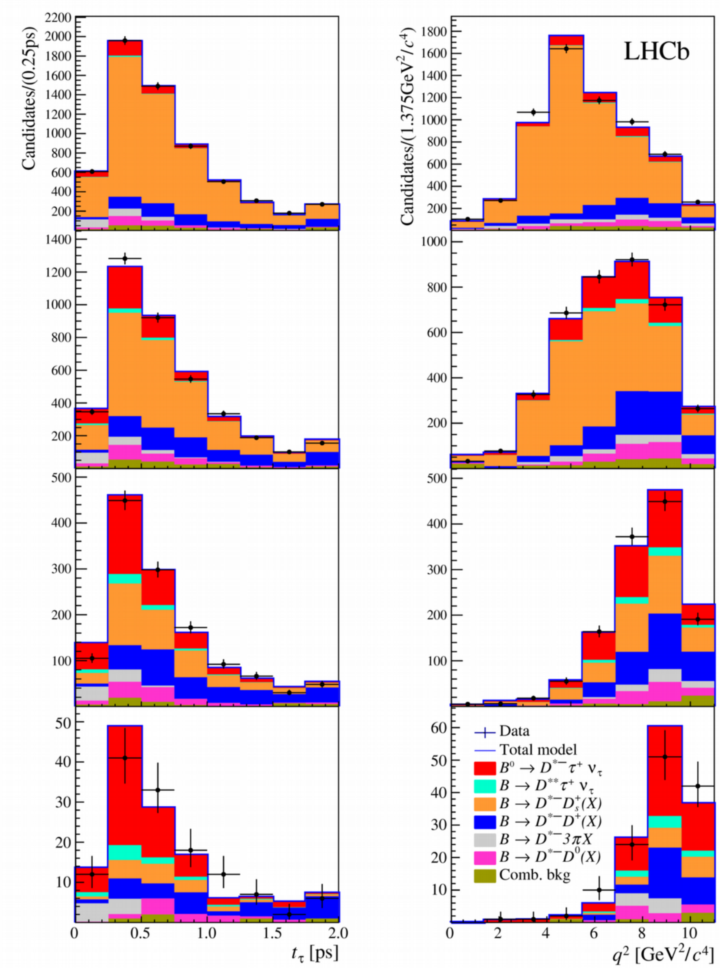


$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

$B \to D^* \tau \nu$ at LHCb (II)

PRL 120 (2018) 171802 &
PR D97 (2018) 072013

- Exploit excellent LHCb vertexing to reconstruct $\tau \to 3\pi(\pi^0)\nu$ decays
  - Background from $B \to D^* D_{(s)} \to D^* 3\pi X$ controlled with MVA
- Separate signal from background by fitting
  - τ decay time & q^2
- Normalised to $B \to D^* D_{(s)} \to D^* 3\pi$
  - converted to R(D*) using PDG BF values



LHCb has also tested lepton universality using $B_c \to J/\psi\tau\nu$ / $J/\psi\mu\nu$

PRL 120 (2018) 121801