LHCb highlights and future prospects

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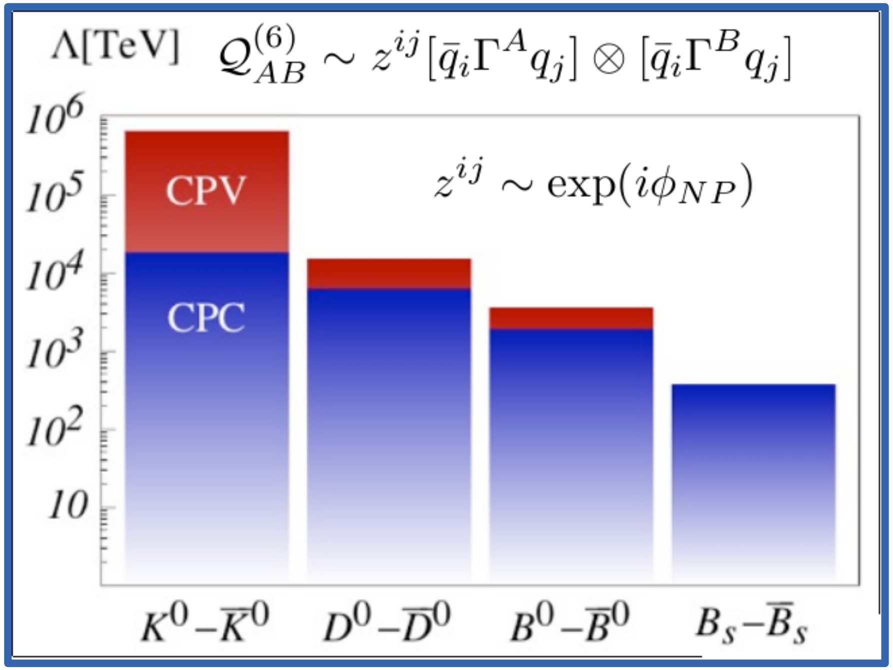
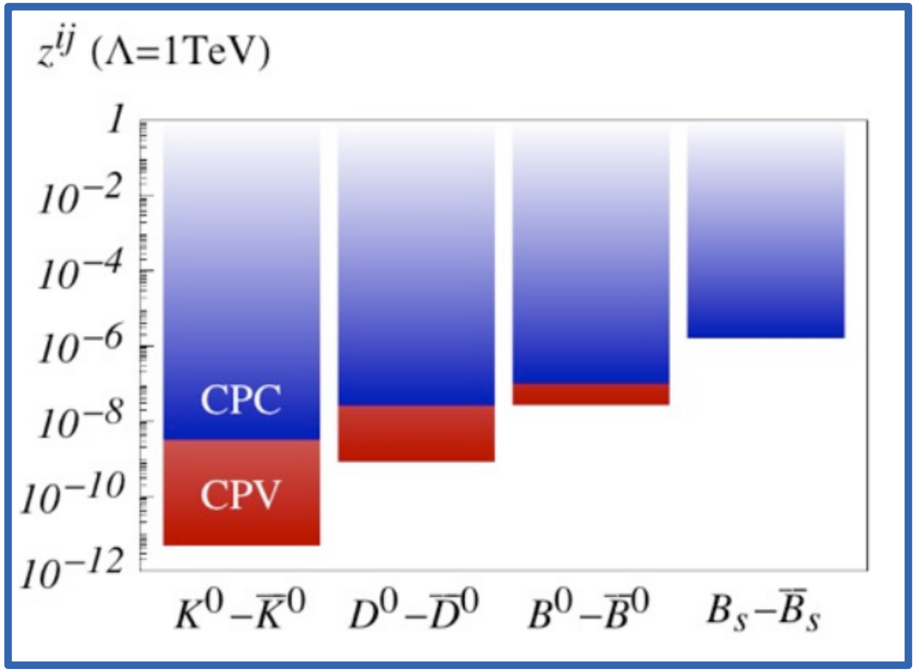
Seminar @ MIT
25th September 2017

Summary of 2016: Brexit, Trump & no NP

- The scale of new physics appears to be higher than many had expected (and all had hoped)
- Don't despair!
  - NP discovery by ATLAS/CMS still possible
  - Flavour provides another window of opportunity

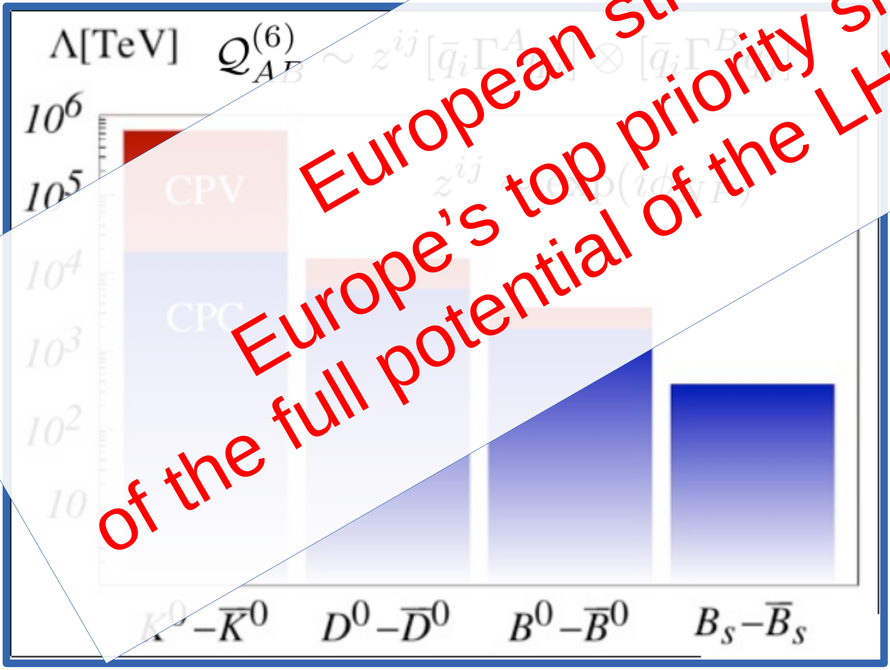


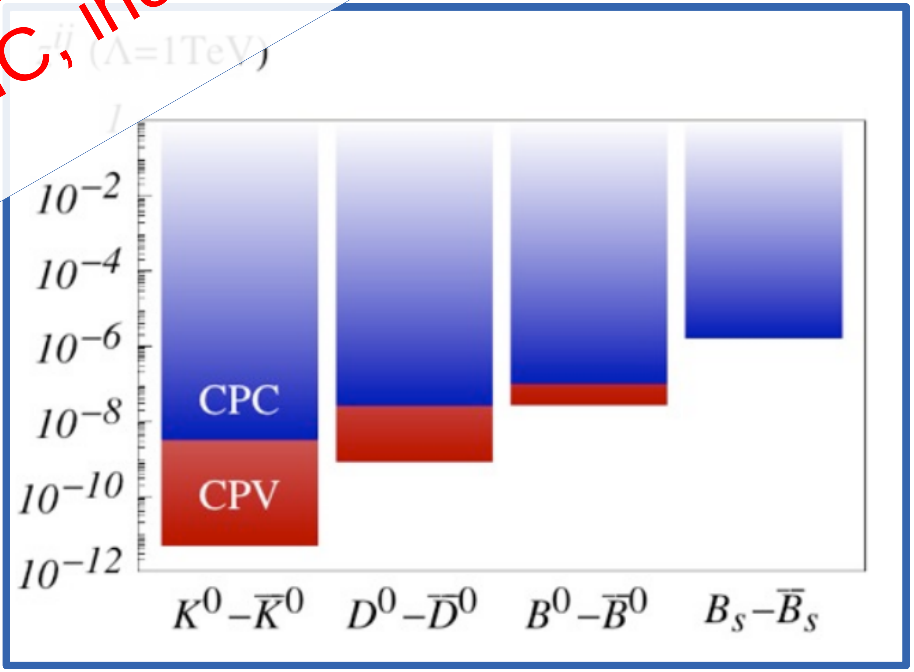


S… 6: Brexit, Trump & no NP

- T… ics appears to be higher than m… nd all had hoped)
- D…
  - – … S/CMS still possible
  - – Flavour provides another window of opportunity

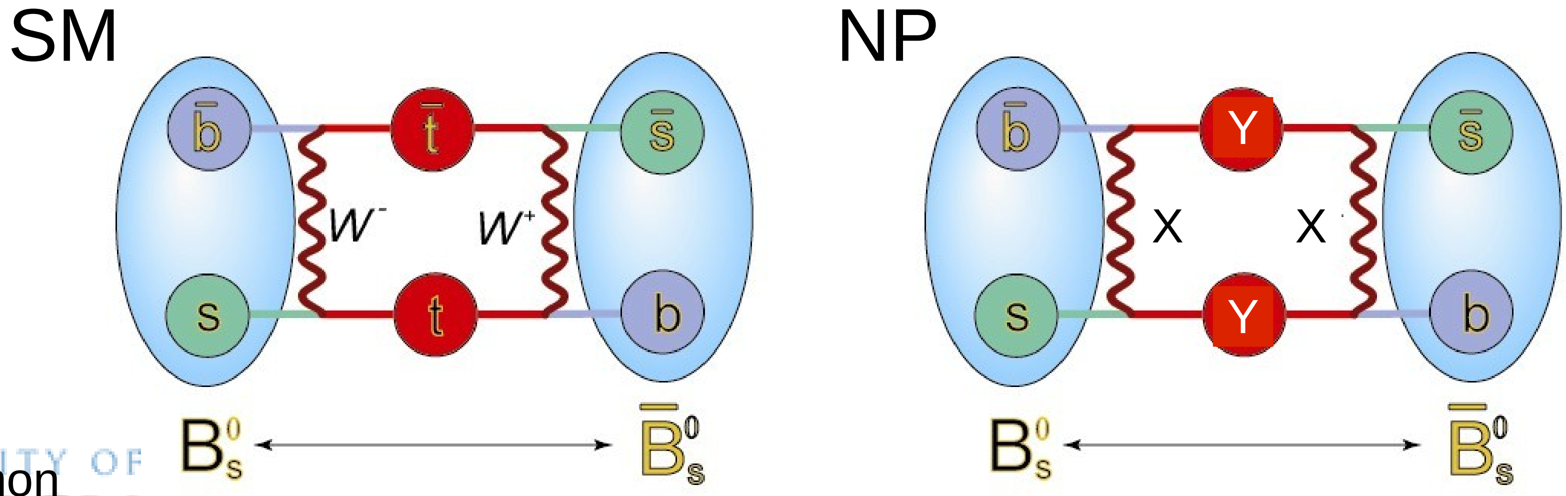
European strategy for particle physics:
Europe's top priority should be the exploitation of the full potential of the LHC, including […] flavour physics





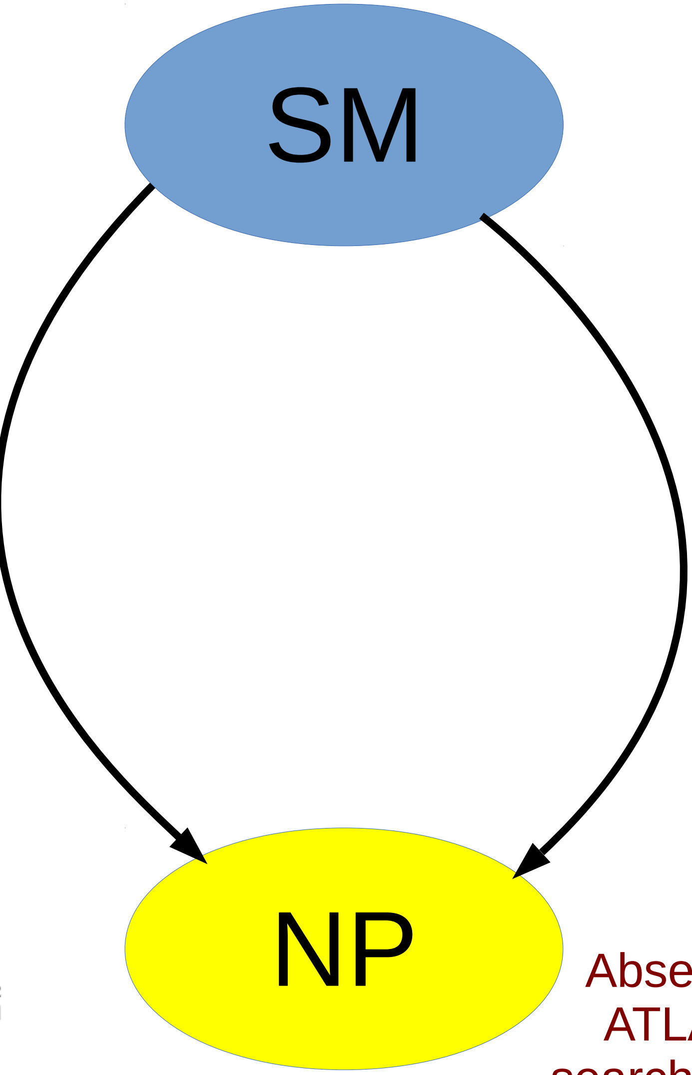
Loop diagrams for discovery

- Contributions from virtual particles in loops allow to probe far beyond the energy frontier
- History shows this approach to be a powerful discovery tool
- Interplay with high-p_T experiments:
  - NP discovered: probe the couplings
  - NP not discovered: explore high energy parameter space
- NP contributions to tree-level processes also possible in some models



Two routes to heaven

for quark flavour physics

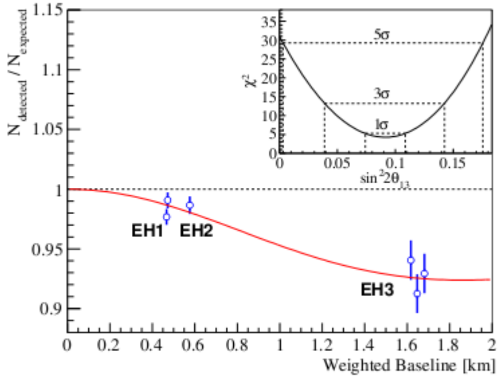

SM

NP

CP violation

(extra sources must exist)

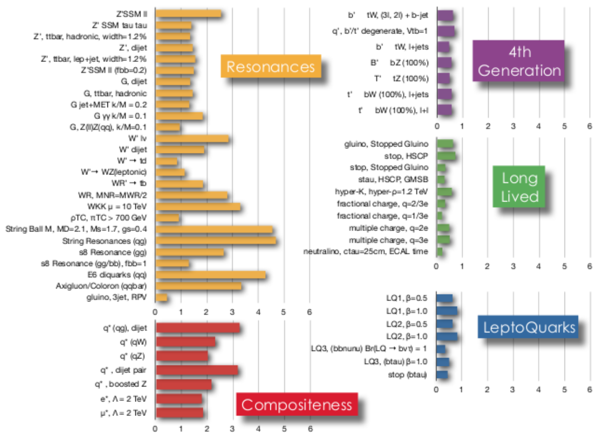
But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in νs due to large θ_{13}



Rare decays

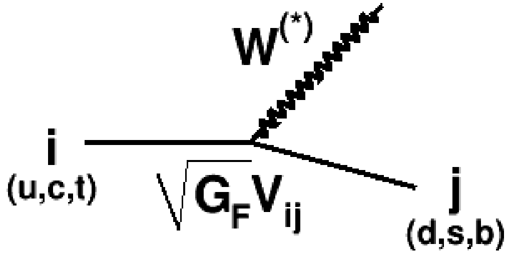
(strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?



Absence of clear NP signals at ATLAS/CMS → argument for searches via rare decays stronger

Quark flavour mixing
a.k.a. CKM phenomenology

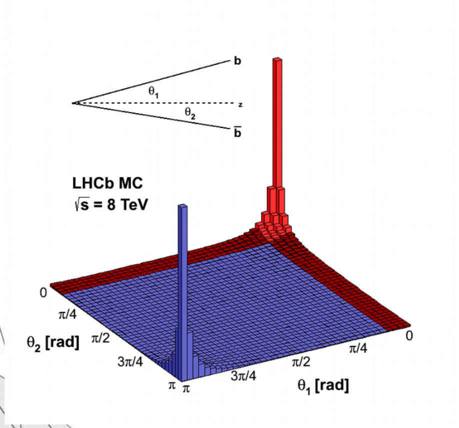


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

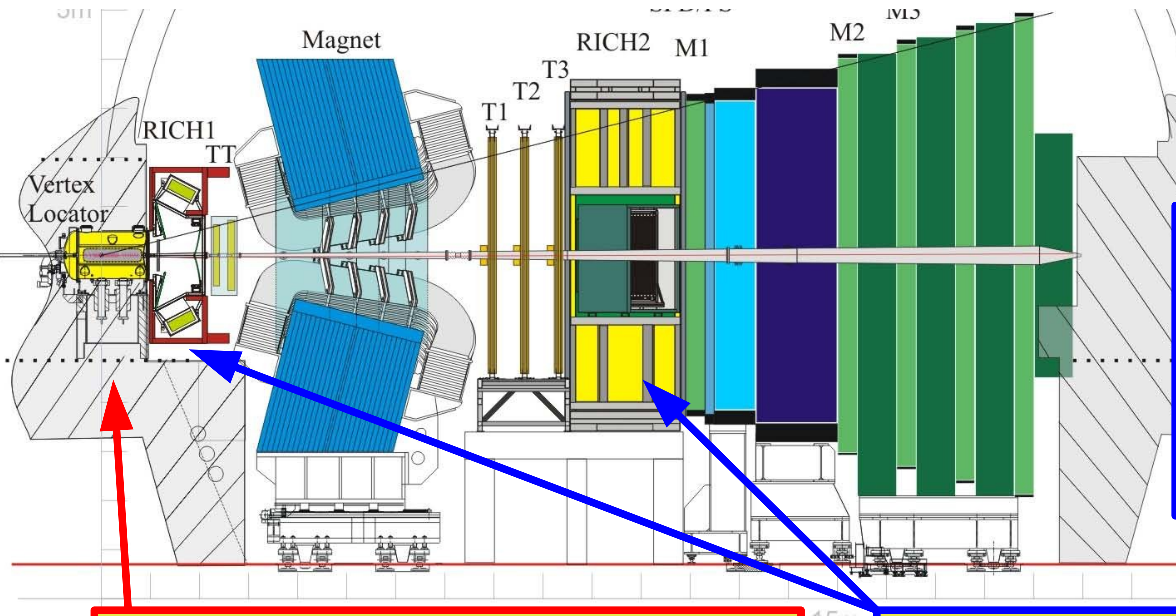
- CKM + EW theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters (+ G_F + m_q + QCD)
  - Distinctive Lorentz structure (V–A)
- CKM matrix is hierarchical
  - distinctive flavour sector of Standard Model not necessarily replicated in extended theories → strong constraints on NP models
- CKM mechanism introduces CP violation
  - only source of CP violation in the Standard Model ($m_\nu = \theta_{QCD} = 0$)

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

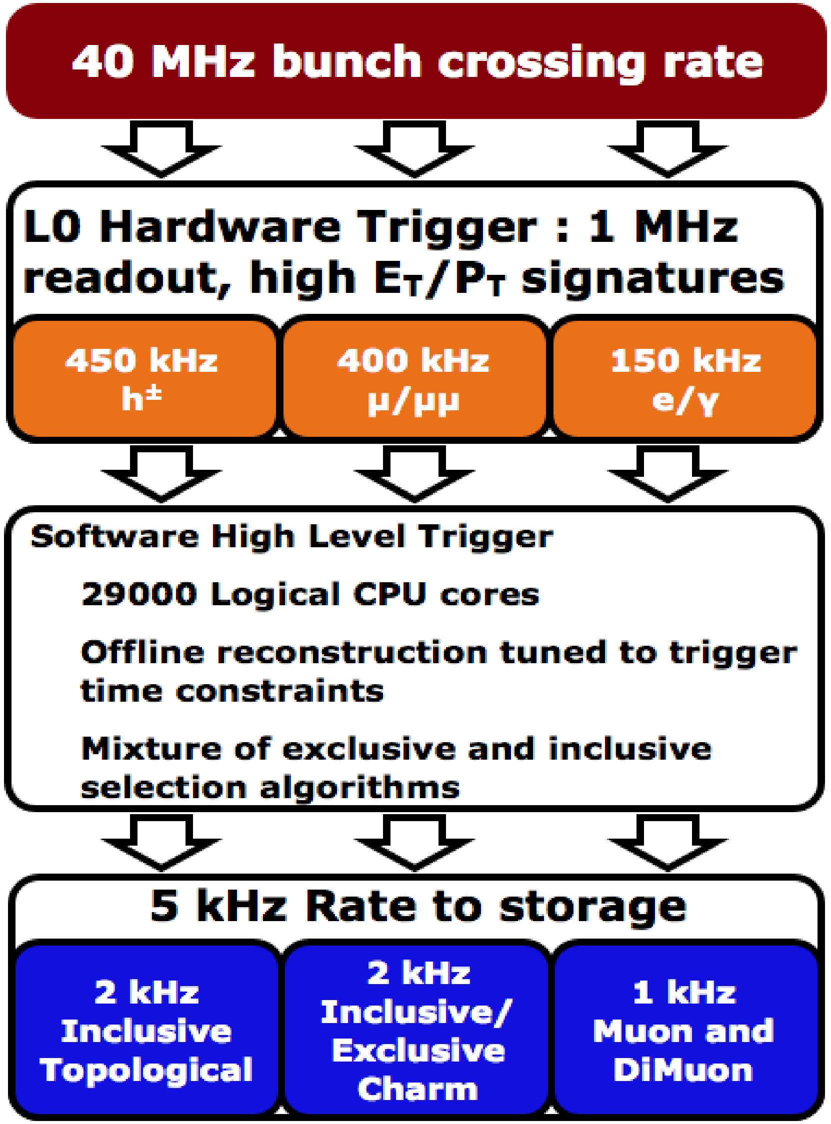
- to efficiently select most interesting events
- while maintaining manageable data rates

Main backgrounds

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

Handles

- high p_T signals (muons)
- displaced vertices



40 MHz bunch crossing rate

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

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

Software High Level Trigger

29000 Logical CPU cores

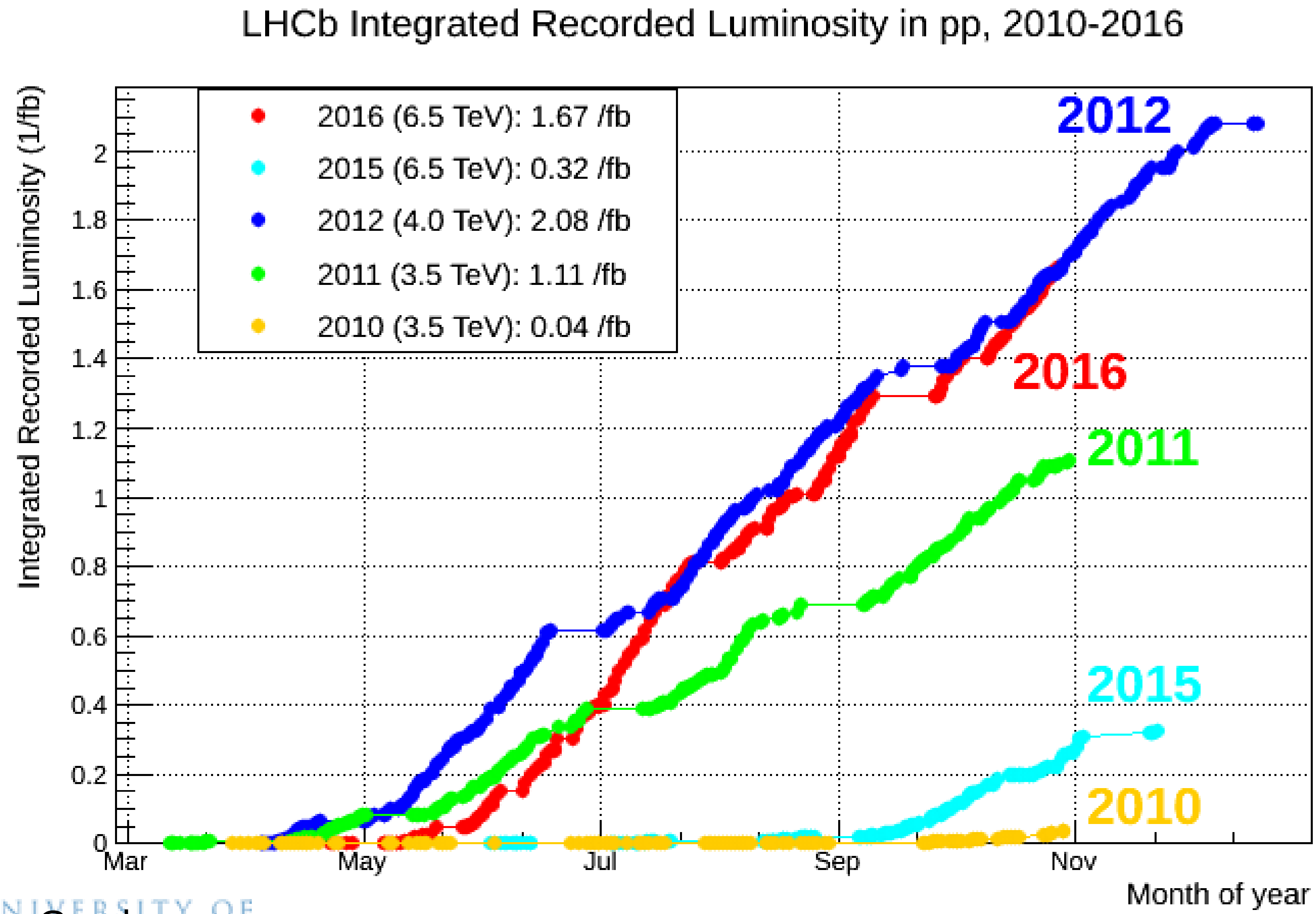
Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

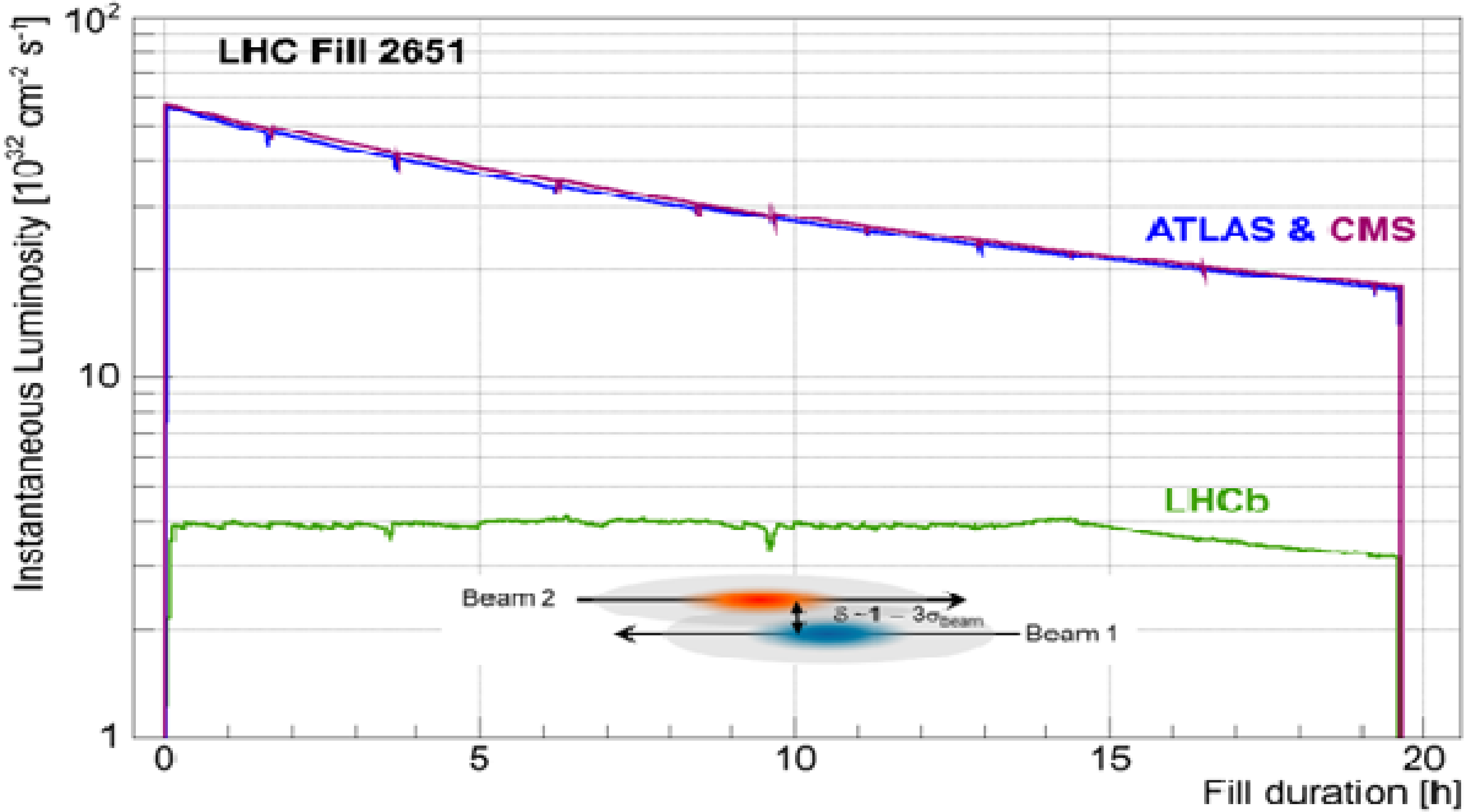
2 kHz **Inclusive Topological**	**2 kHz** **Inclusive/ Exclusive Charm**	**1 kHz** **Muon and DiMuon**

Exceptional data taking performance



+ 0.9/fb in 2017 so far; today's results mostly on Run 1 data

Luminosity levelling in LHCb



luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation
(with tilted crossing angle)

data-taking conditions ~constant throughout fill
frequent reversal of dipole magnet polarity
minimise many potential sources of systematic uncertainty

CP violation & the Unitarity Triangle

The Unitarity Triangle

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

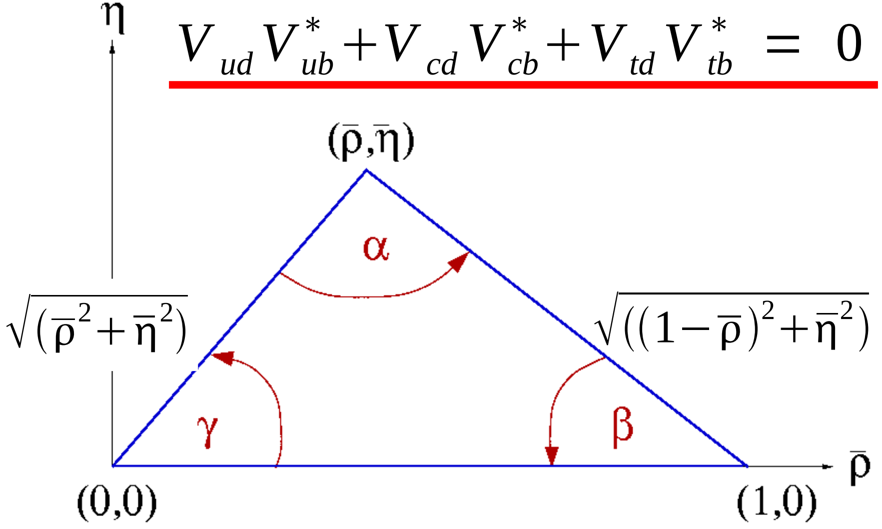
- The CKM matrix must be unitary

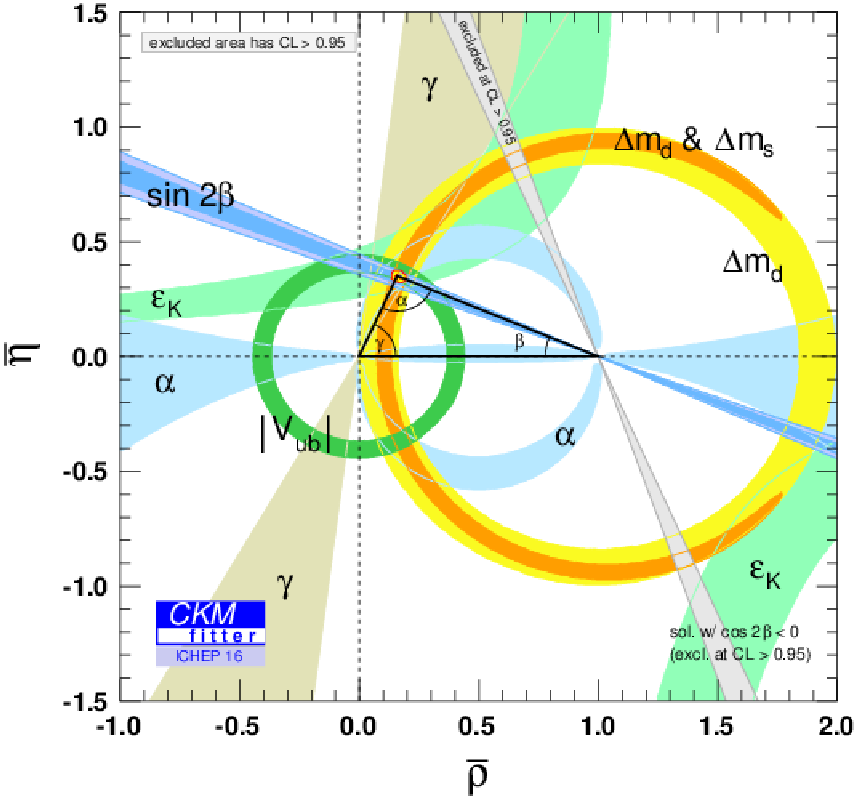
$$V^{+}_{CKM} V_{CKM} = V_{CKM} V^{+}_{CKM} = 1$$

- Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$\underline{V_{ud} V^{*}_{ub} + V_{cd} V^{*}_{cb} + V_{td} V^{*}_{tb} = 0}$$





Consistency of measurements tests the Standard Model and provides model-independent constraints on New Physics

$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

Nature Phys. 11 (2015) 743

- Long standing discrepancy between exclusive and inclusive determinations of both V_{ub} and V_{cb}

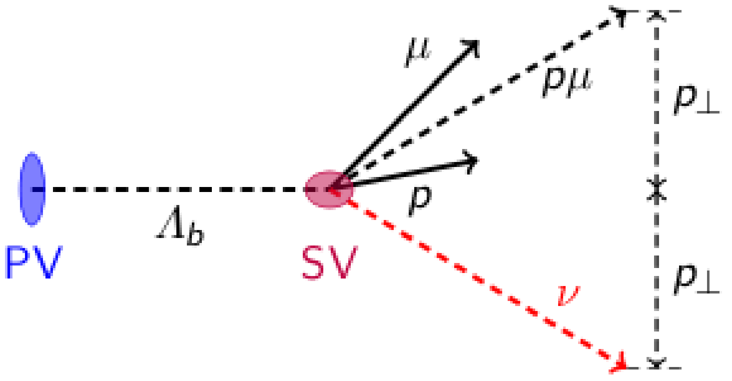
PDG 2014

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \qquad |V_{ub}| = (4.41 \pm 0.15\,^{+\,0.15}_{-\,0.17}) \times 10^{-3} \quad \text{(inclusive)},$$

$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \qquad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(exclusive)}.$$

- Use of b baryon decays provides complementary alternative to B mesons
- At LHCb, exploit displaced vertex to reconstruct corrected mass

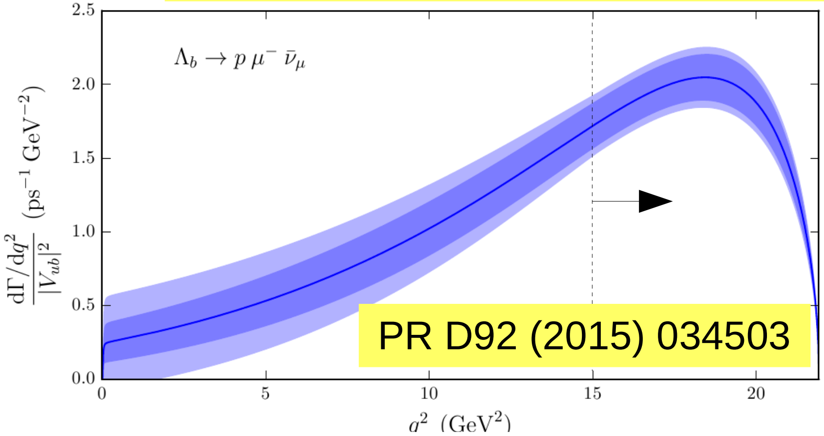
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



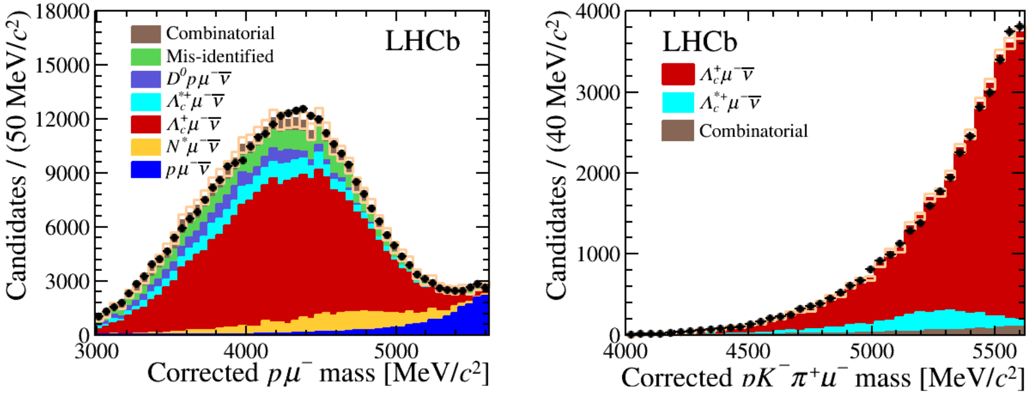
$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

Nature Phys. 11 (2015) 743

- Can then reconstruct $q^2 = m(\mu\nu)^2$
  - Select events with $q^2 > 15$ GeV^2
  - Highest rate, best resolution & most reliable theory (lattice) predictions
- Use isolation MVA to suppress background
- Fit M_{corr} to obtain signal yields



PR D92 (2015) 034503



- Rules out models with RH currents
- Compatible with UT fit (β,γ)

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\mathrm{expt}) \pm 0.004(\mathrm{lattice})$$

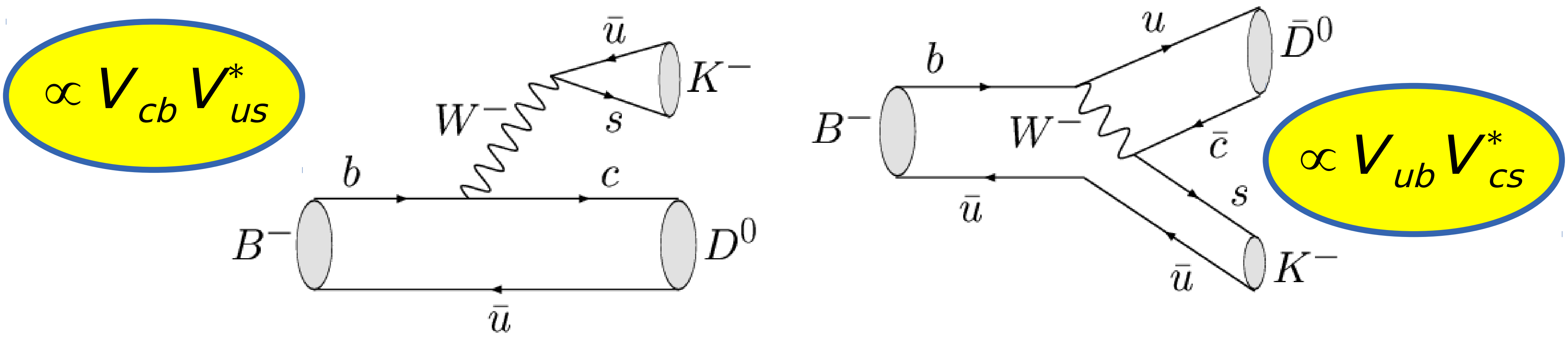
Importance of γ from B→DK

- 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



$\propto V_{cb} V^*_{us}$

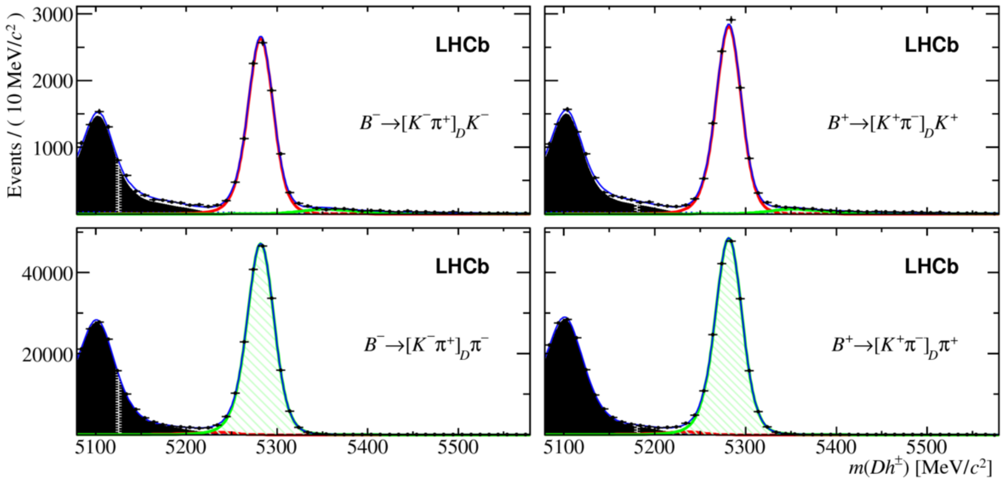
$\propto V_{ub} V^*_{cs}$

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

γ from $B^+ \to DK^+$, $D \to K\pi$

PL B760 (2016) 117

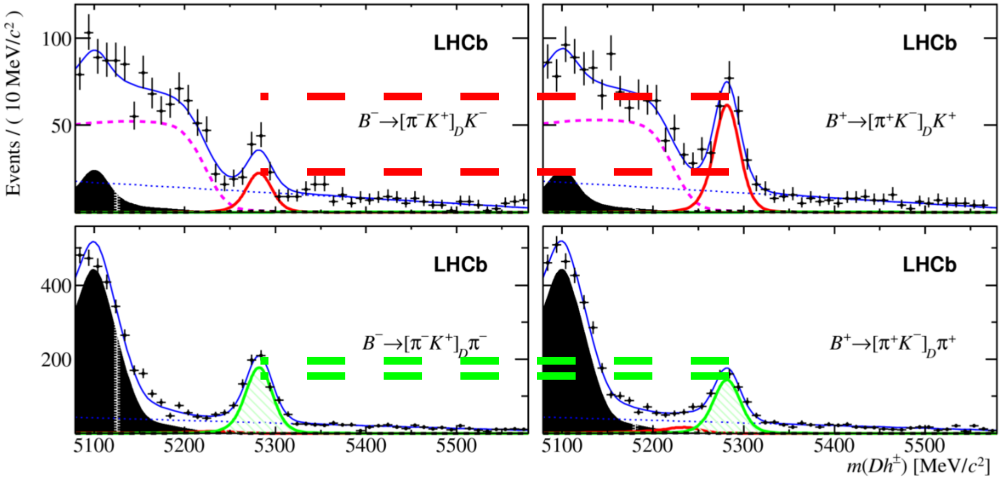
$D \to K\pi$ (favoured)



small asymmetries due to production and detection effects

$B \to D\pi$ control mode helps to separate effects

$D \to \pi K$ ("ADS" suppressed)



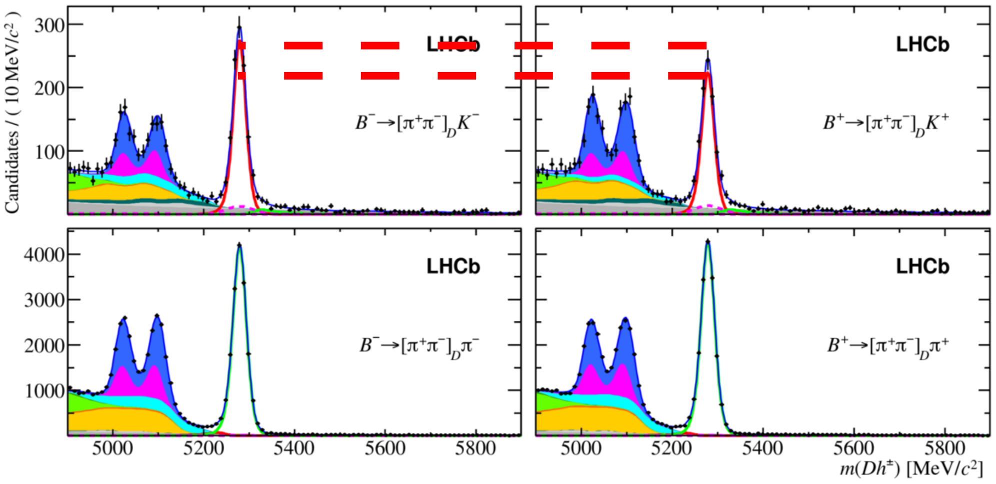
large CP violating asymmetries – first 5σ observation in a single $B \to DK$ channel

effects also possible in $B \to D\pi$

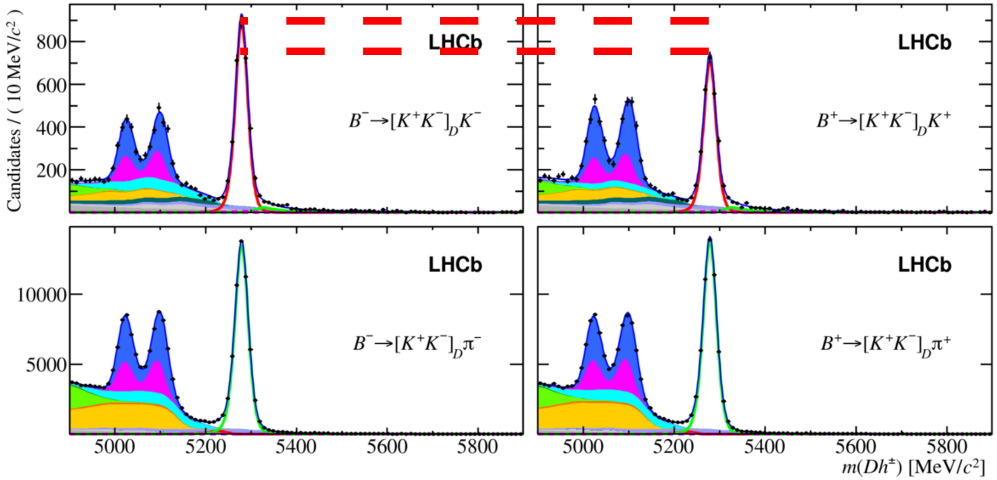
γ from $B^+ \to DK^+$, $D \to KK, \pi\pi, K\pi$

arXiv:1708.06370

$D \to \pi\pi$ ("GLW" CP+ state)

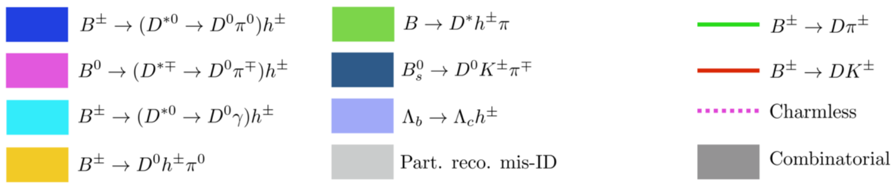


$D \to KK$ ("GLW" CP+ state)



CP violating asymmetries clearly visible

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



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

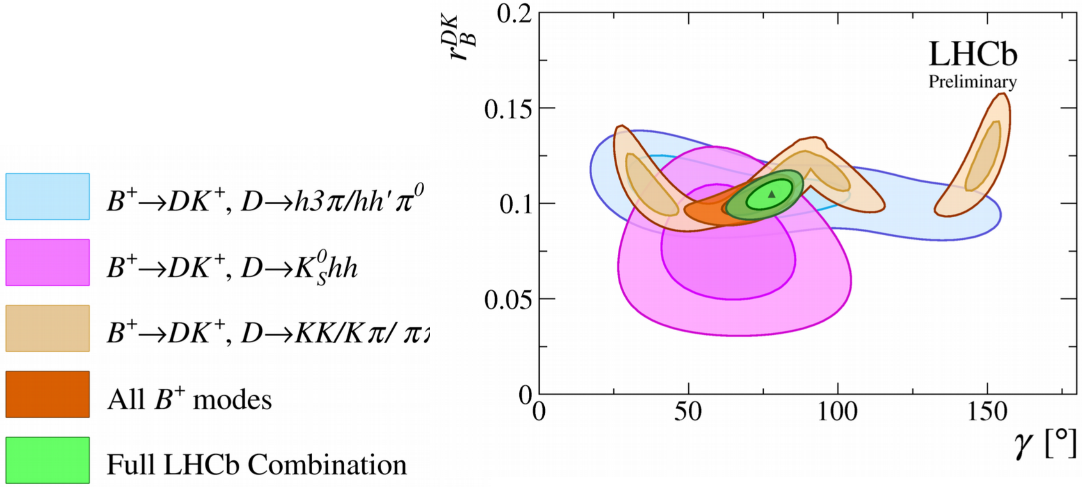
$A_{CP}(B \to D^*K;\ D^* \to D\pi^0) = -0.151 \pm 0.033\ (\text{stat}) \pm 0.011\ (\text{syst})$

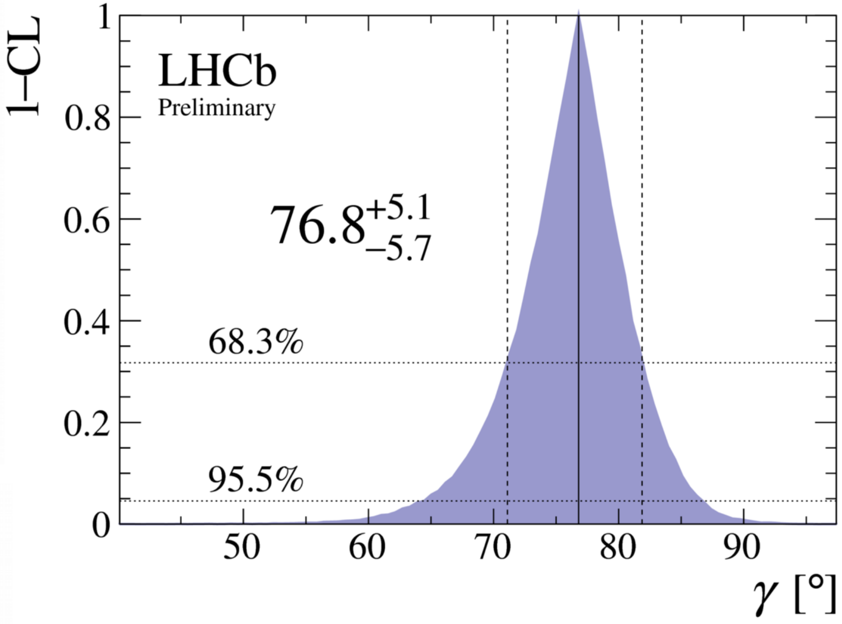
$A_{CP}(B \to D^*K;\ D^* \to D\gamma) = +0.276 \pm 0.094\ (\text{stat}) \pm 0.047\ (\text{syst})$

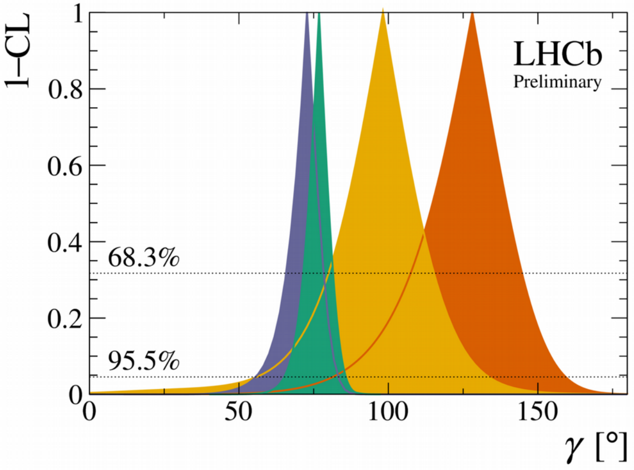
γ combination

JHEP 12 (2016) 087 &
LHCb-CONF-2017-004

Many observables with sensitivity to γ – combine them!







🟧 B_s^0 decays

🟨 B^0 decays

🟪 B^+ decays

🟩 Combination

$\gamma = (76.8^{+5.1}_{-5.7})°$

CP violation scoreboard

TG & V. Gligorov, RPP 80 (2017) 046201

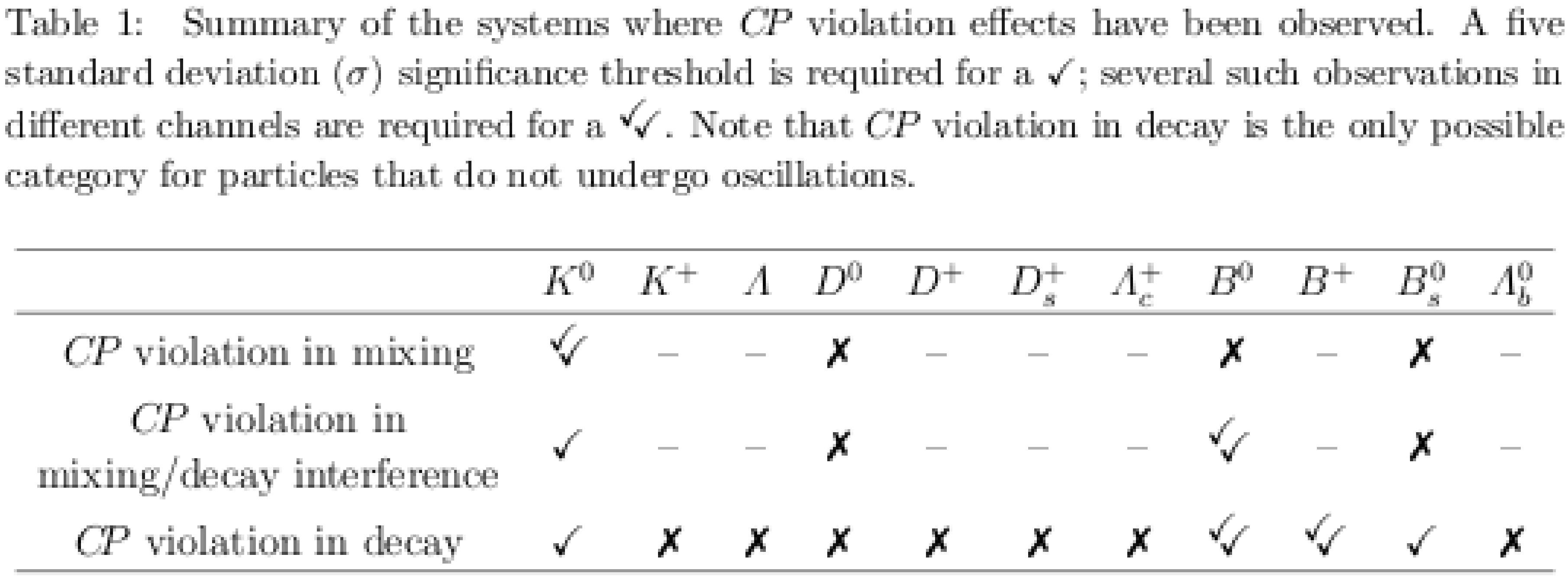
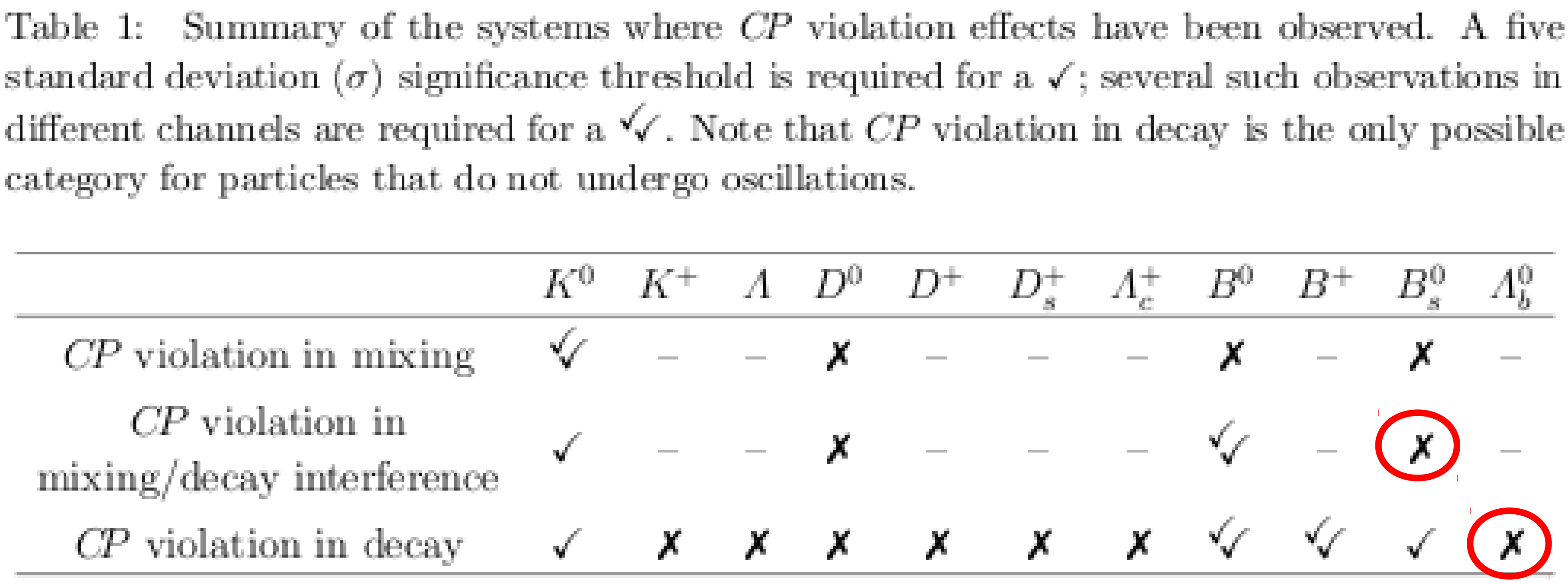


Table 1: Summary of the systems where CP violation effects have been observed. A five standard deviation (σ) significance threshold is required for a ✓; several such observations in different channels are required for a ✓✓. Note that CP violation in decay is the only possible category for particles that do not undergo oscillations.

	K^0	K^+	Λ	D^0	D^+	D_s^+	Λ_c^+	B^0	B^+	B_s^0	Λ_b^0
CP violation in mixing	✓✓	–	–	✗	–	–	–	✗	–	✗	–
CP violation in mixing/decay interference	✓	–	–	✗	–	–	–	✓✓	–	✗	–
CP violation in decay	✓	✗	✗	✗	✗	✗	✗	✓✓	✓✓	✓	✗

CP violation scoreboard

TG & V. Gligorov, RPP 80 (2017) 046201



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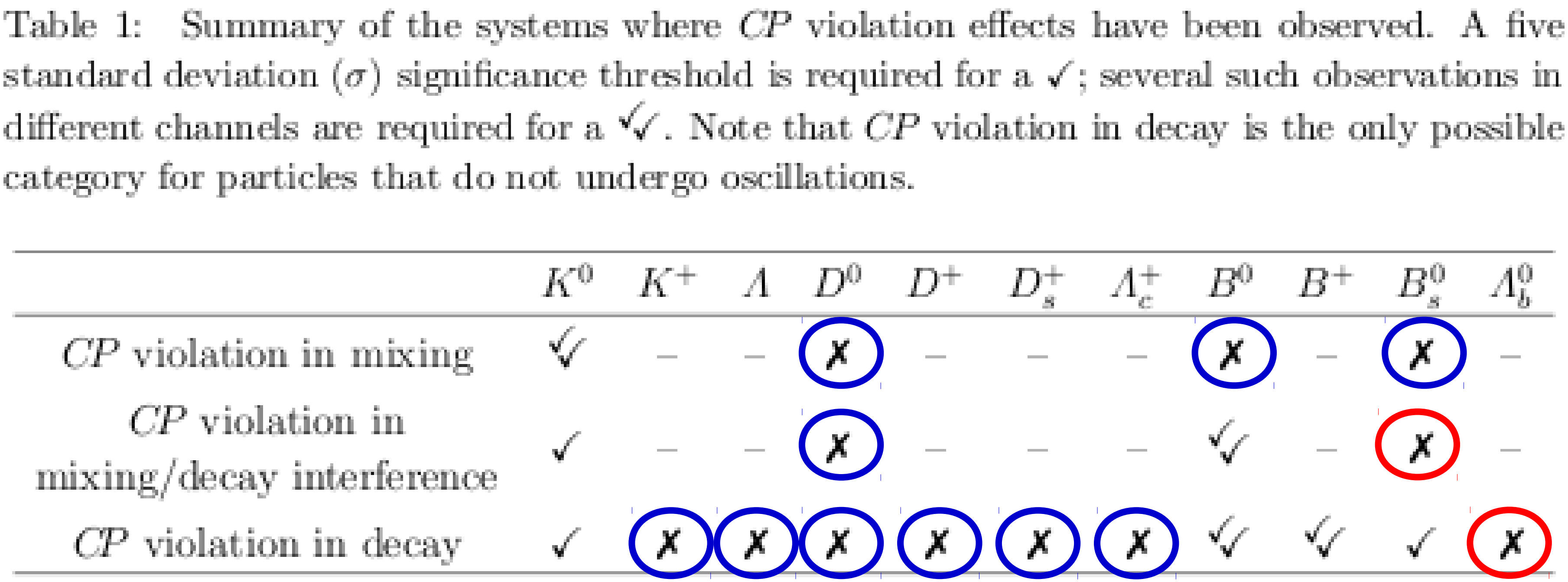
CP violation in mixing/decay interference	✓	–	–	✗	–	–	–	✓✓	–	✗	–
CP violation in decay	✓	✗	✗	✗	✗	✗	✗	✓✓	✓✓	✓	✗

First evidence, late 2016

CP violation scoreboard

TG & V. Gligorov, RPP 80 (2017) 046201



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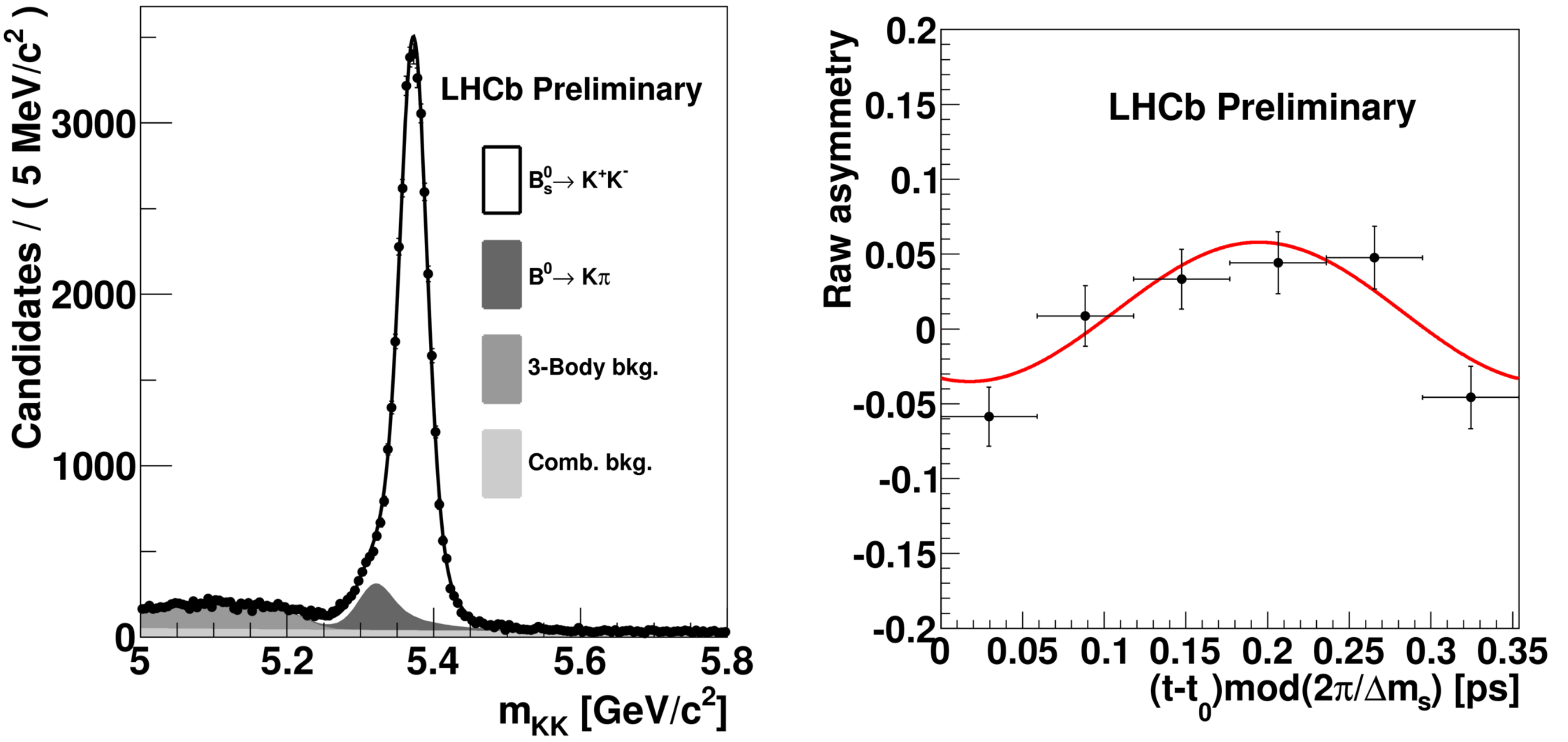
CP violation in mixing/decay interference	✓	–	–	✗	–	–	–	✓✓	–	✗	–
CP violation in decay	✓	✗	✗	✗	✗	✗	✗	✓✓	✓✓	✓	✗

First evidence, late 2016

SM CPV expected to be negligible

CP violation in $B_s^0 \to K^+K^-$

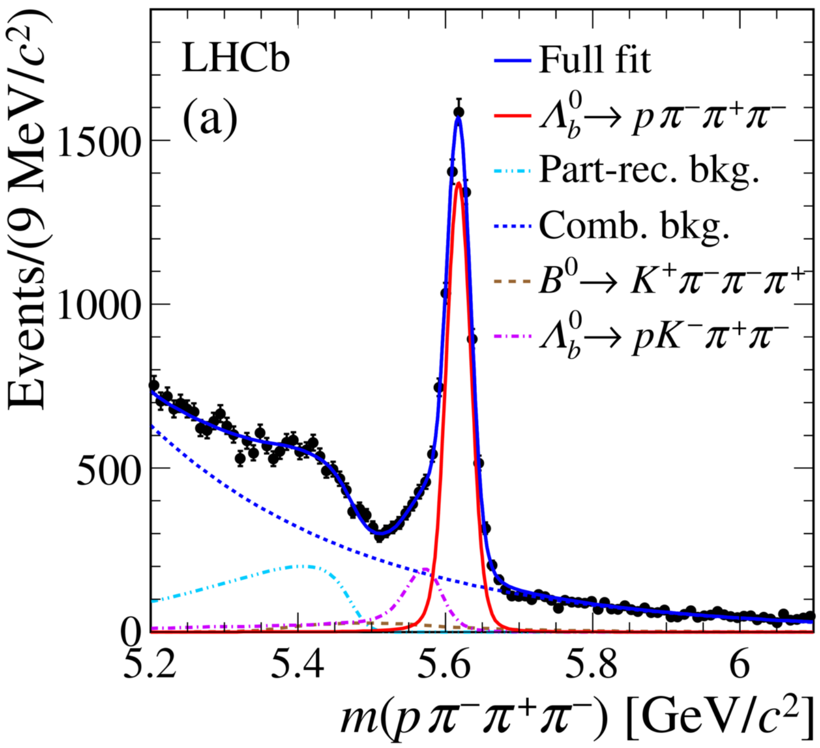
LHCb-CONF-2016-018

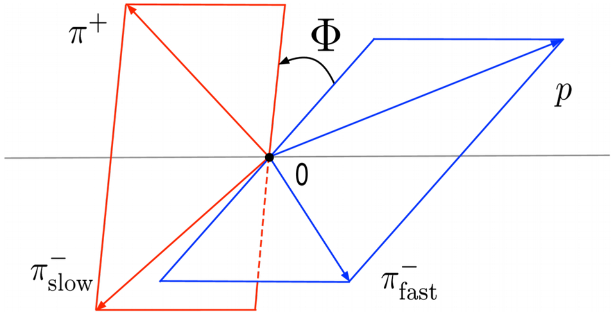


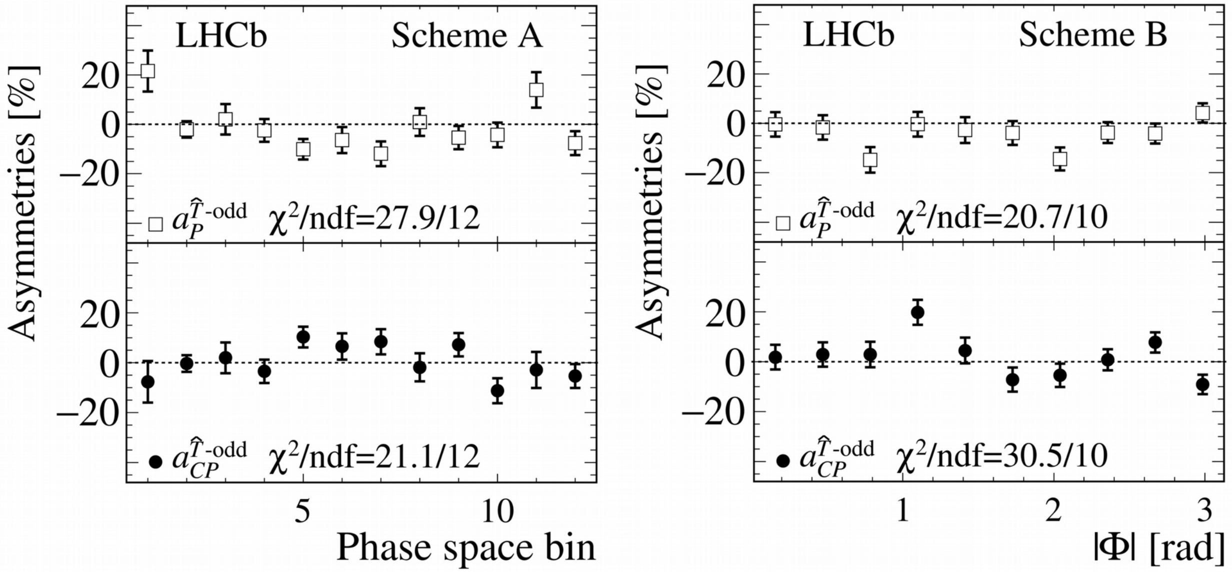
$C_{K+K-} = 0.24 \pm 0.06 \pm 0.02, \quad S_{K+K-} = 0.22 \pm 0.06 \pm 0.02$

CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Nature Phys. 13 (2017) 391







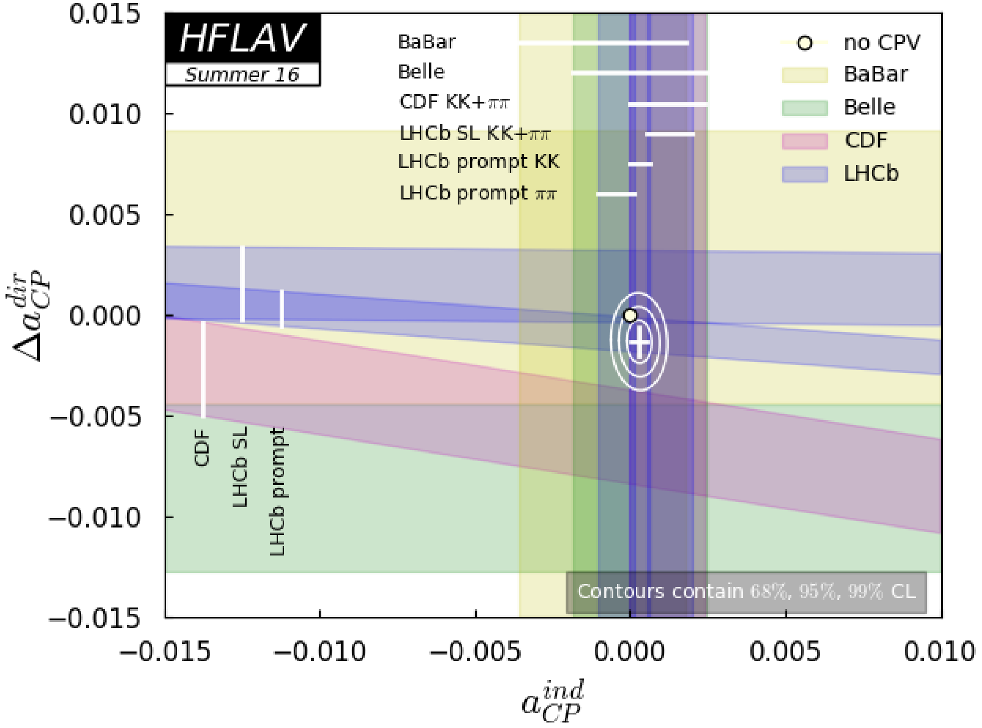
First evidence (3.3σ) for CP violation in any baryon

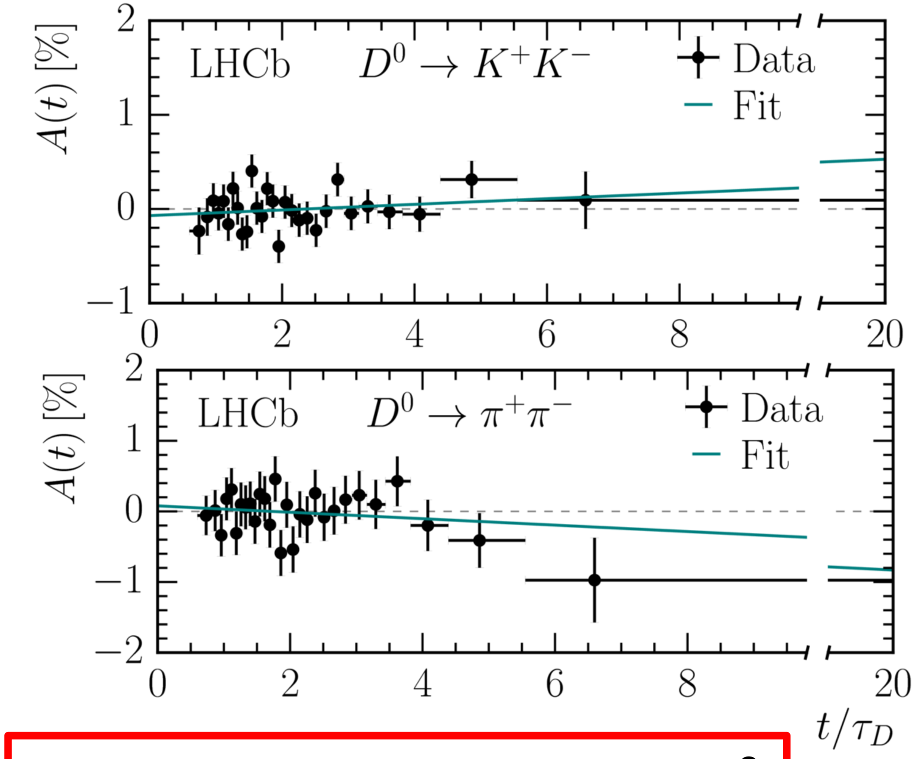
Charm CP violation

PRL 116 (2016) 191601, PRL 118 (2017) 261803

No evidence for CP violation in the charm system, whether in mixing, decay or mixing-decay interference

Latest: $\Delta A_{CP} \equiv A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi) = (-0.10 \pm 0.08 \pm 0.03)\ \%$



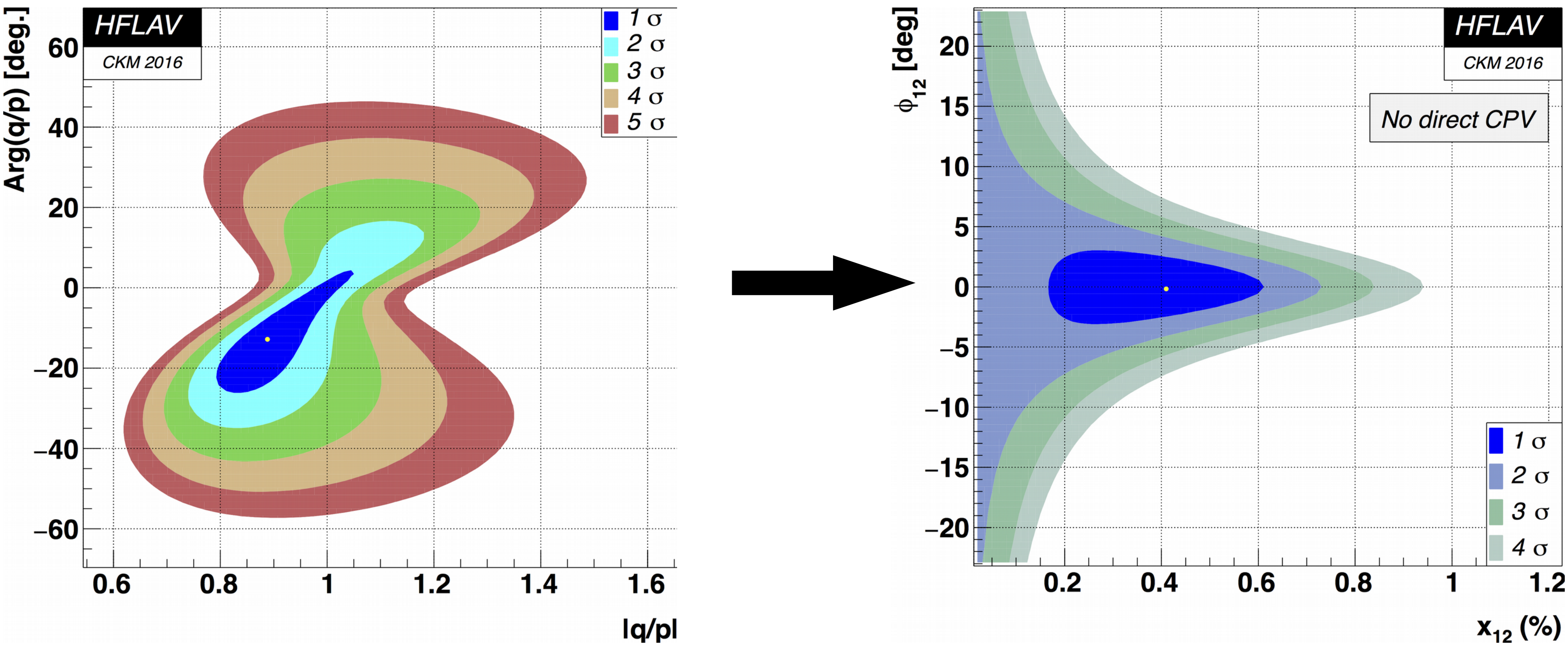


$$\boxed{A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}}$$

Charm CP violation

No evidence for CP violation in the charm system, whether in mixing, decay or mixing-decay interference

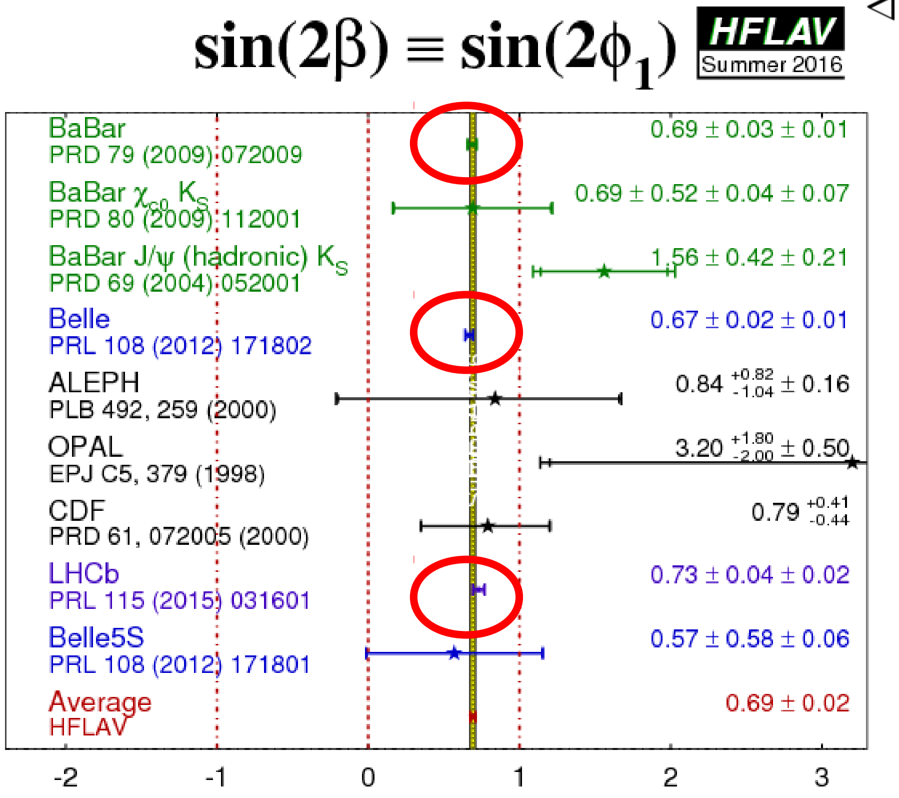
Lack of knowledge of x ≡ Δm/Γ currently limiting sensitivity … work in progress

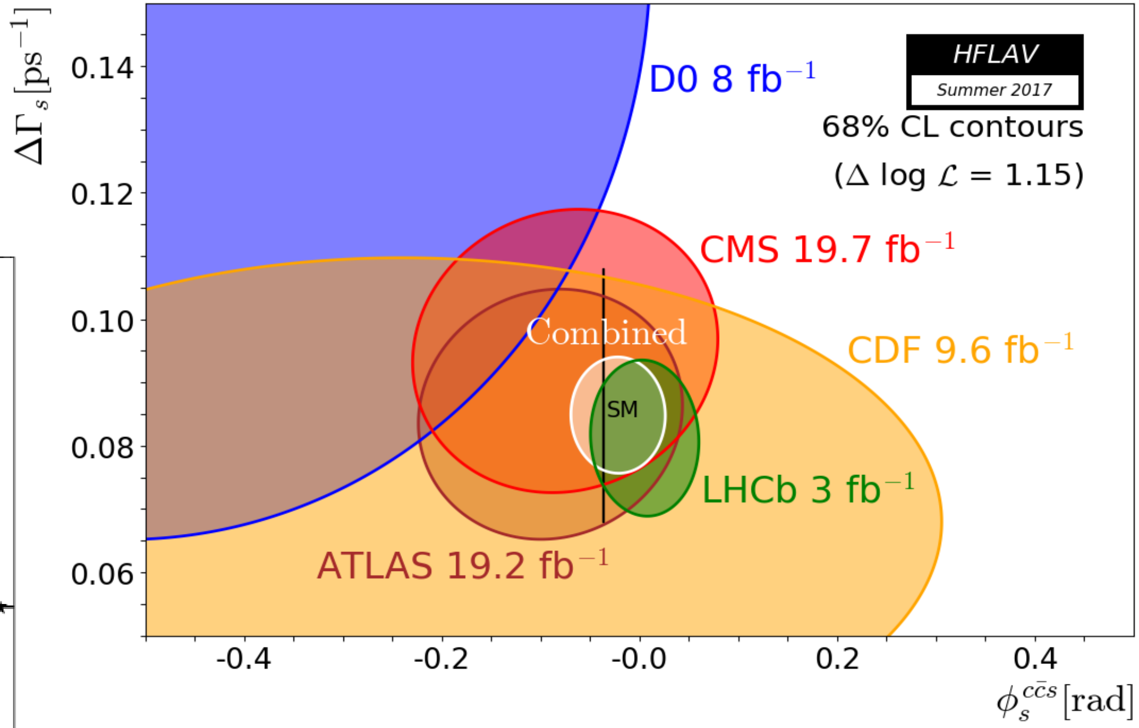


Much stronger constraints obtained with minimal assumption on CPV in decays

B^0 and B_s^0 mixing phases: $\sin(2\beta)$ & φ_s

PRL 115 (2015) 031601
& arXiv:1709.03944





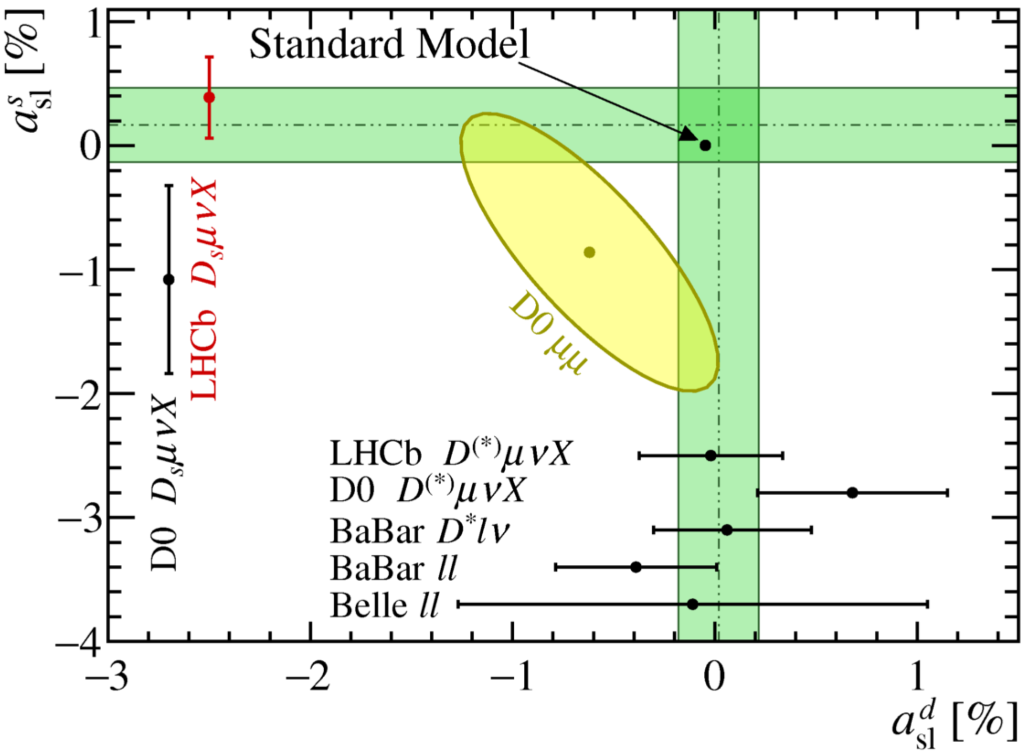
LHCb: PRL 114 (2015) 041801,
PL B736 (2014) 186 &
arXiv:1704.08217;
ATLAS: JHEP 1608 (2016) 147;
CMS: PL B757 (2016) 97

Possible penguin pollution controlled by SU(3) partners
LHCb: PL B742 (2015) 38, JHEP 11 (2015) 082

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

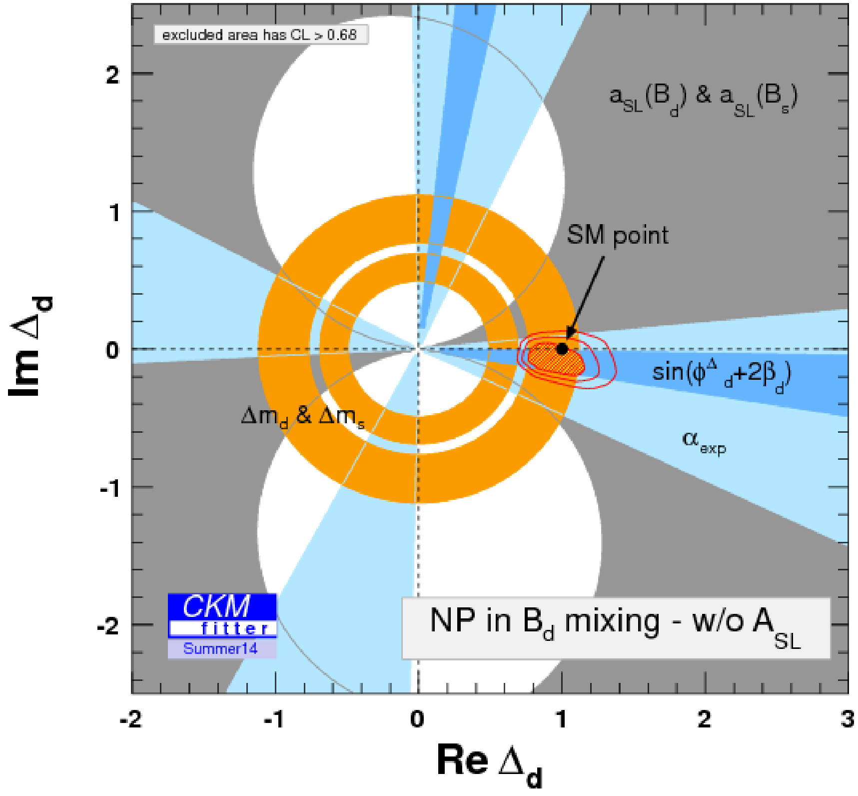


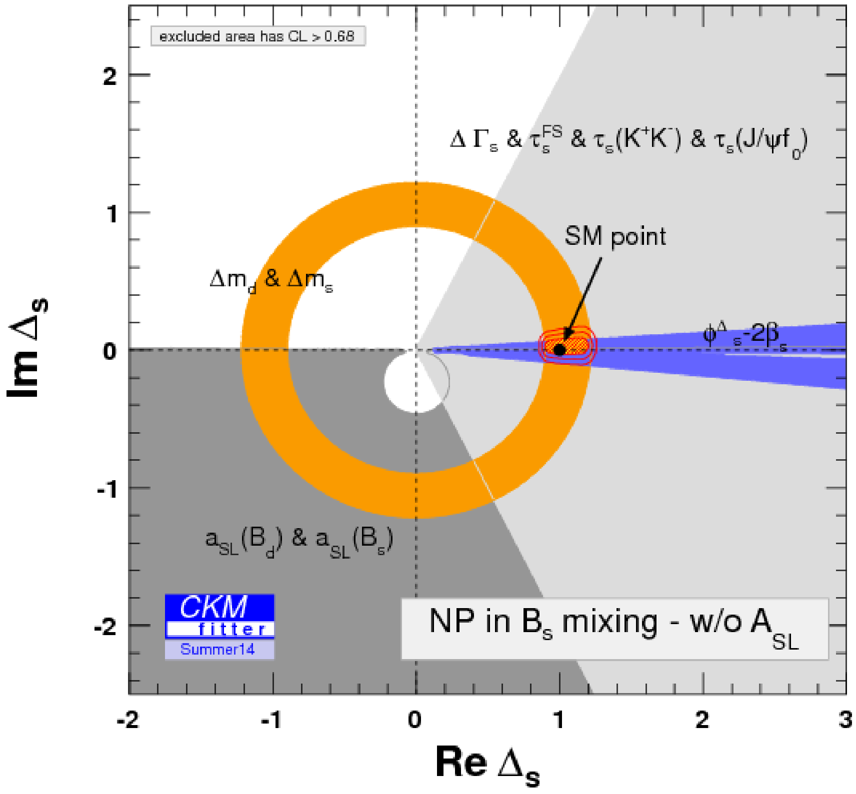
$a_{sl}(B_s^0) = (0.39\pm0.26\pm0.20)\%$

Limits on BSM contributions to ΔB=2

Define $M_{12}^{q} = M_{12}^{SM,q}\,\Delta_q$ and obtain constraints on (Re Δ_q, Im Δ_q)

(here not including anomalous D0 dimuon asymmetry result, and other recent results)





Rare (and some not so rare) decays

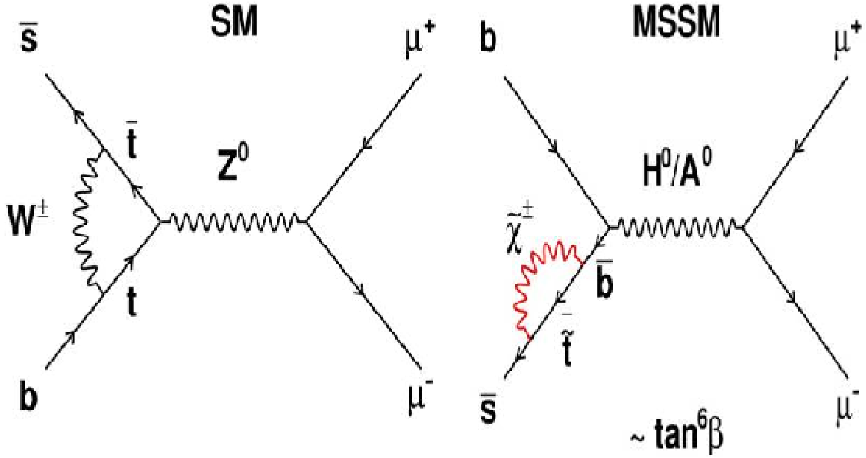
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

Very rare in Standard Model due to

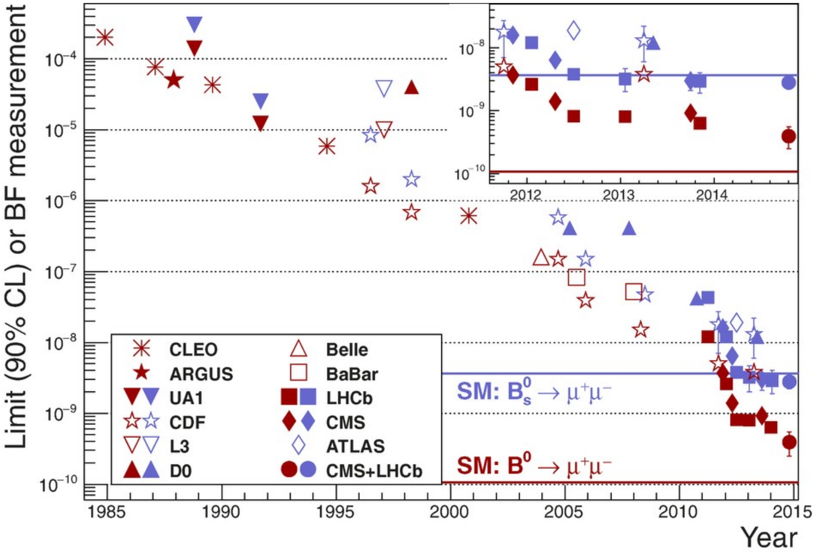
- absence of tree-level FCNC
- helicity suppression
- CKM suppression

… all features which are not necessarily reproduced in extended models



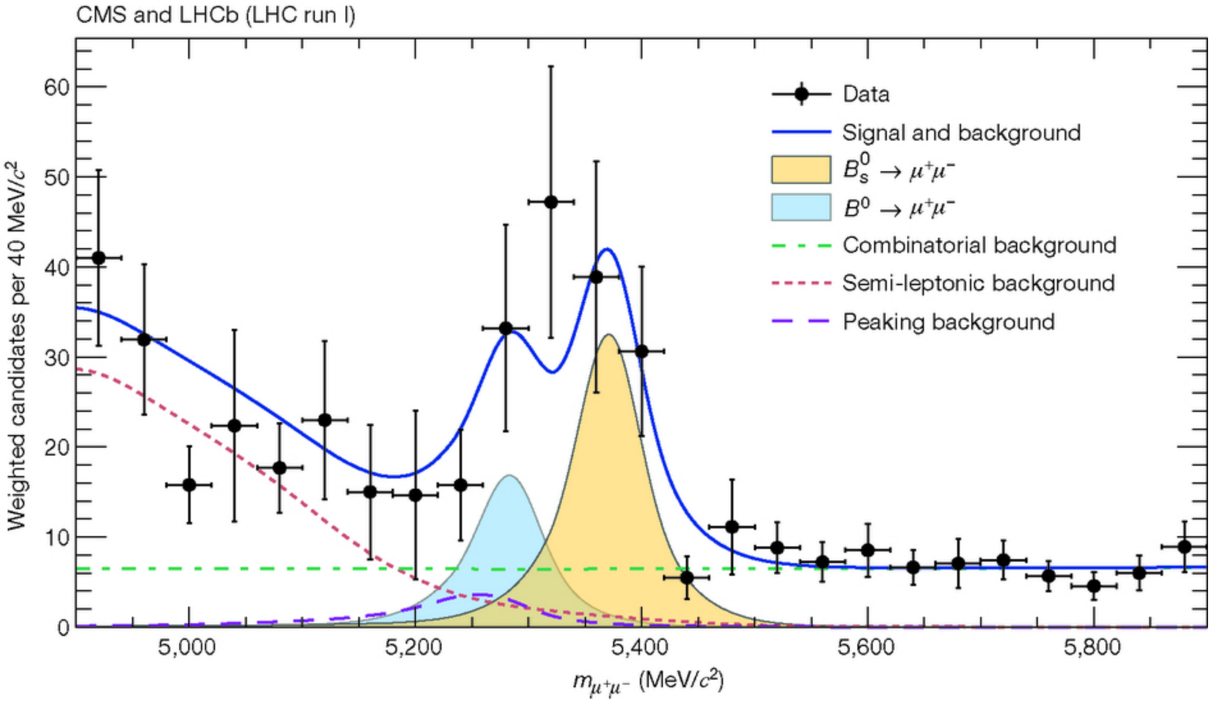
$B(B_s \to \mu^+\mu^-)^{SM} = (3.66 \pm 0.23) \times 10^{-9}$ $B(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta/M^4_{A0}$

Intensively searched for over 30 years!



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

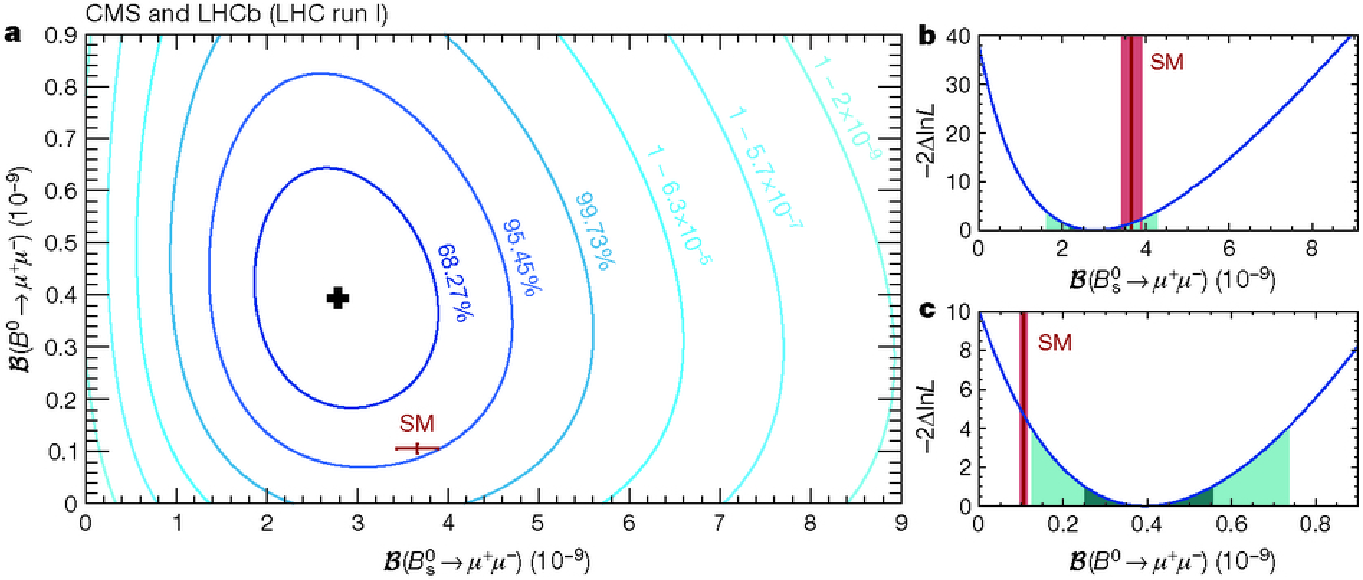
Nature 522 (2015) 68



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

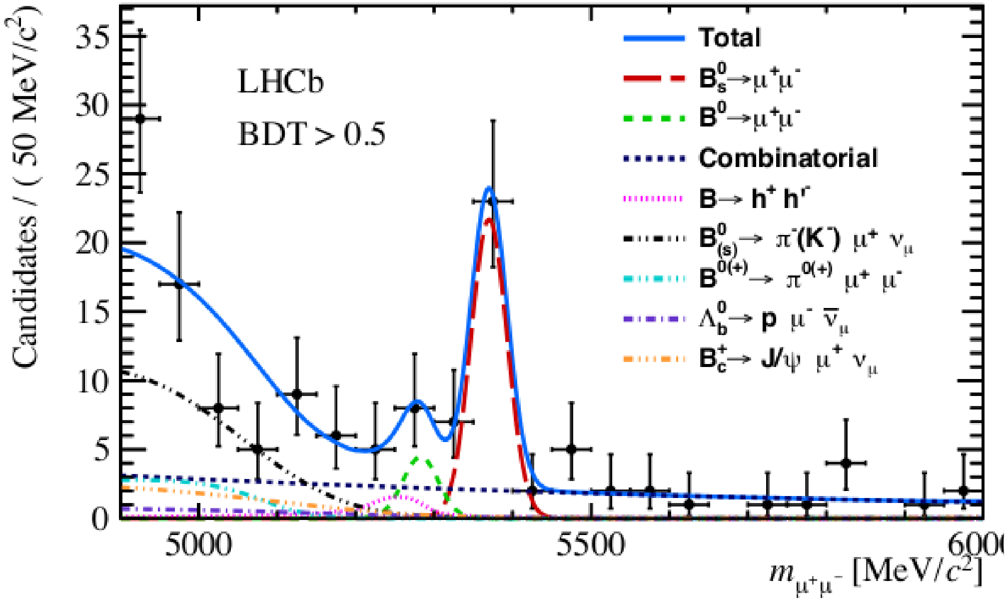
Results consistent with SM at 2σ level

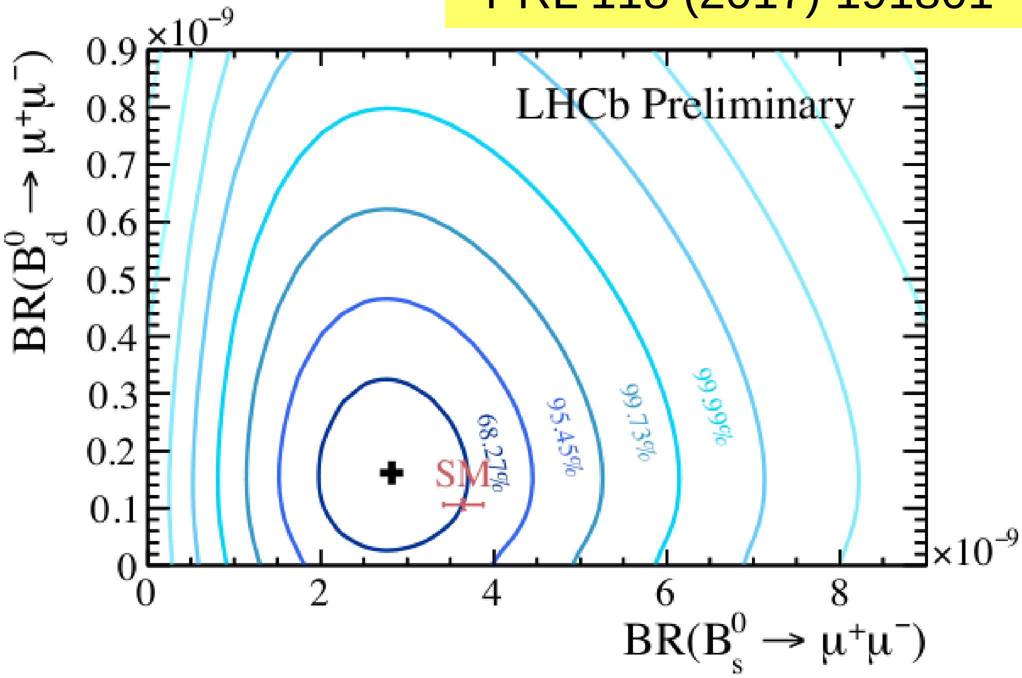
Recent results from ATLAS (not included here) have almost similar sensitivity



LHCb including Run 2 data

PRL 118 (2017) 191801





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

$$\mathcal{B}(B_s^0\to\mu^+\mu^-) = (2.8\pm0.6)\times10^{-9} \quad \mathbf{7.8\sigma}$$

$$\mathcal{B}(B^0\to\mu^+\mu^-) = (1.6^{+1.1}_{-0.9})\times10^{-10} \quad \mathbf{1.9\sigma}$$

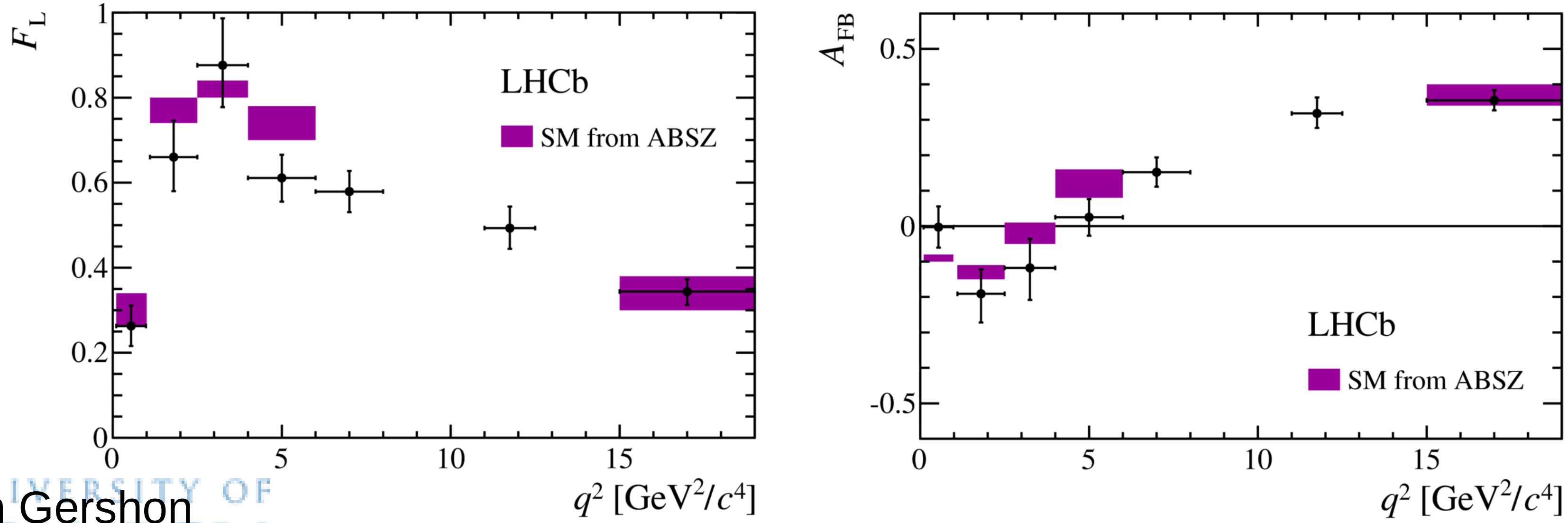
First 5σ observation by a single experiment

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

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

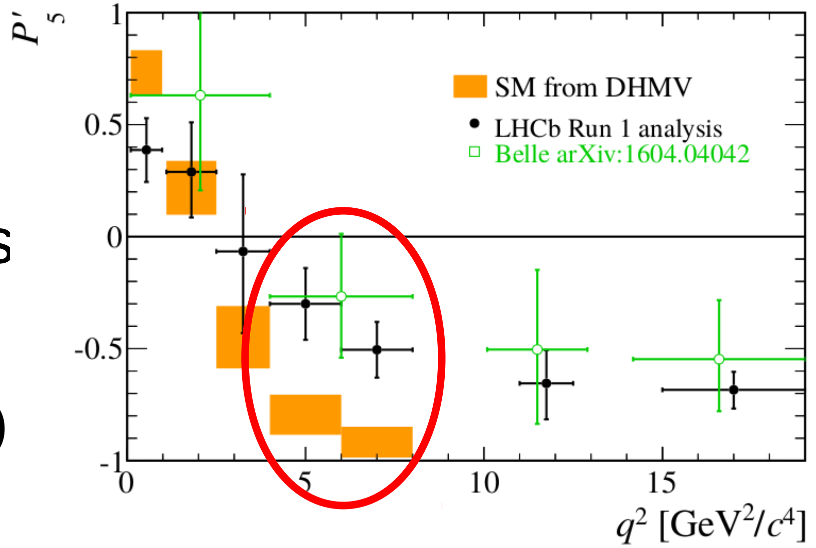
JHEP 02 (2016) 104

- $B^0 \to K^{*0}\mu^+\mu^-$ 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 (⊥) 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 $C_9^{(')}$ & $C_{10}^{(')}$)

Tension with SM in the P_5' observable

JHEP 02 (2016) 104

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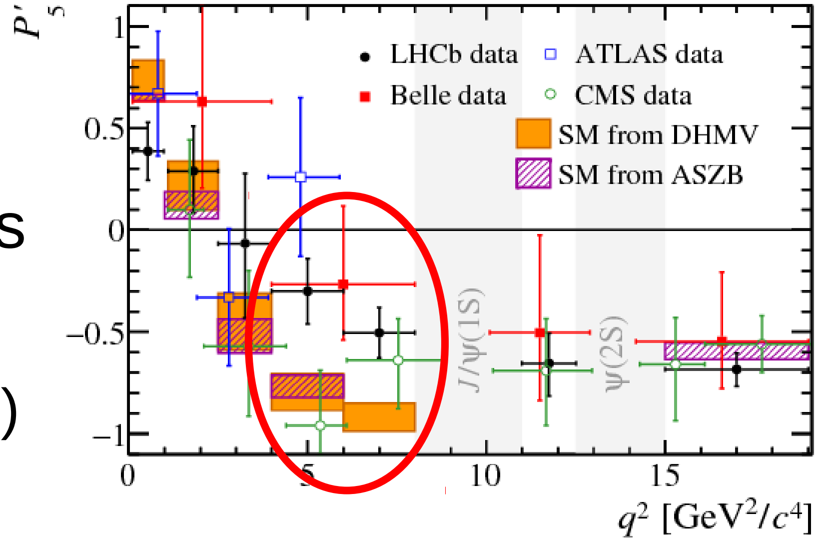

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  - constructed so as to minimise form-factor uncertainties

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

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 $C_9^{(')}$ & $C_{10}^{(')}$)

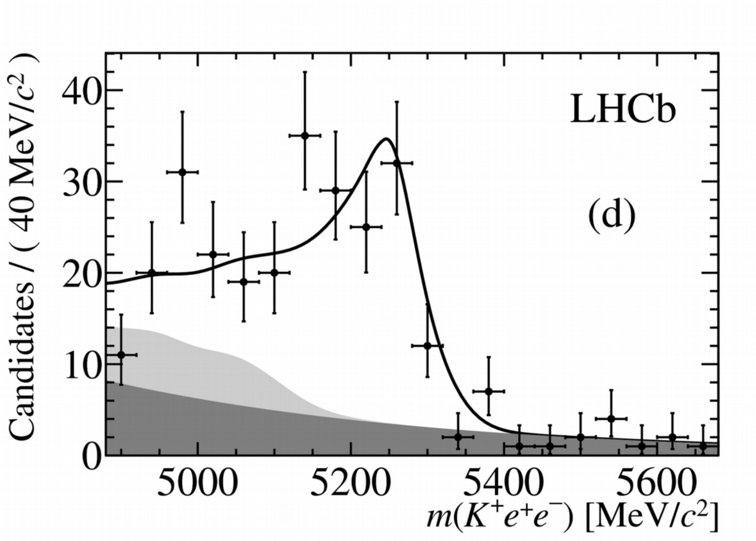
Lepton universality

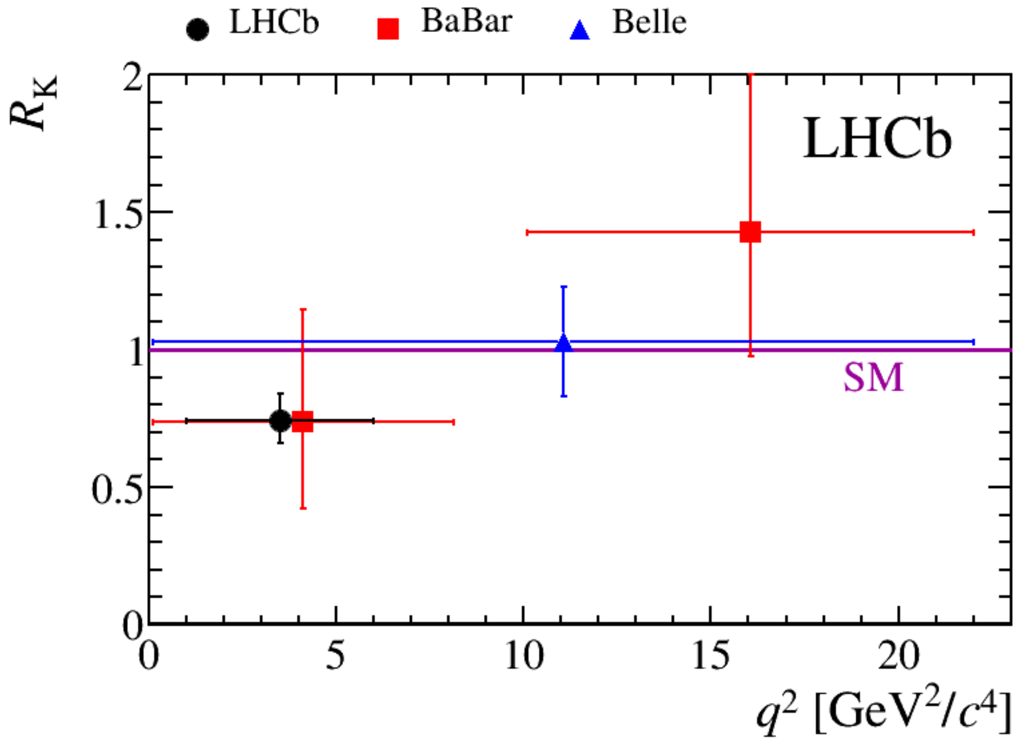
$R_K \equiv \mathcal{B}(B \rightarrow K\mu\mu)/\mathcal{B}(B \rightarrow Kee)$

PRL 113 (2014) 151601

Deficit of $B \rightarrow K\mu^+\mu^-$ 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



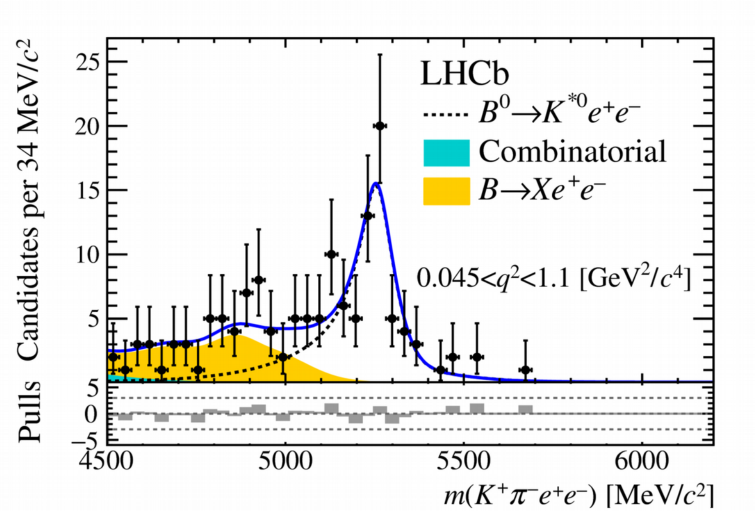


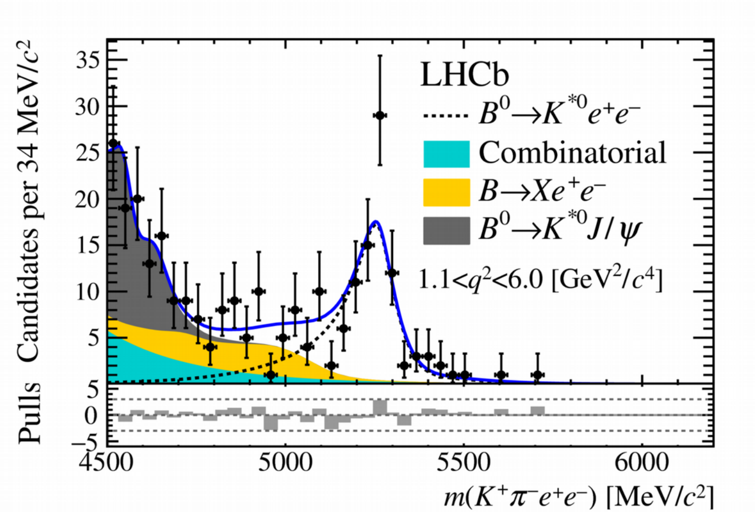
$$R_K(1 < q^2 < 6\ \text{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

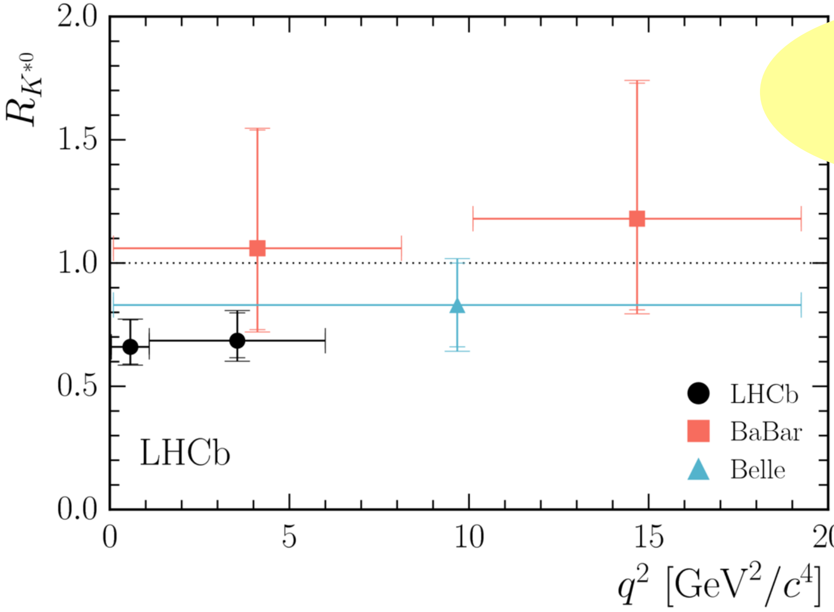
Only 2.6σ from SM but suggestive

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

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

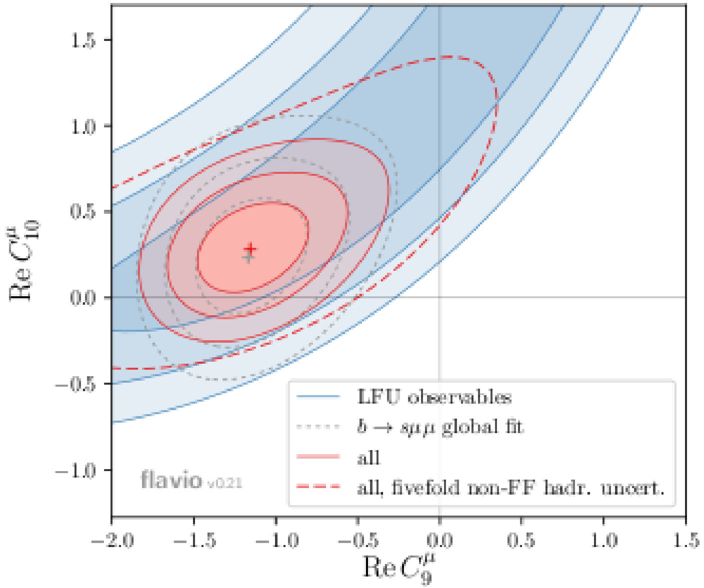
Can be explored model-independently (up to SM uncertainties) using operator product expansion

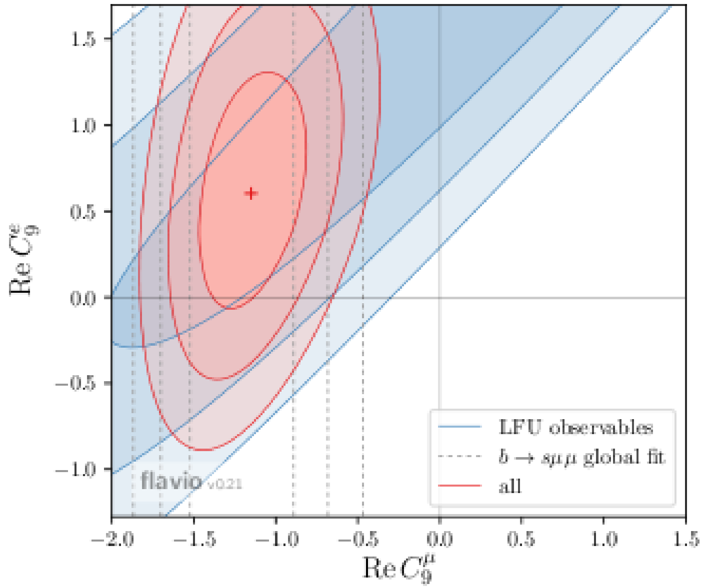
$b \to s l^+ l^-$ global fits

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





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

Many interpretations appeared on hep-ph

Plots and table shown here from arXiv:1704.05435

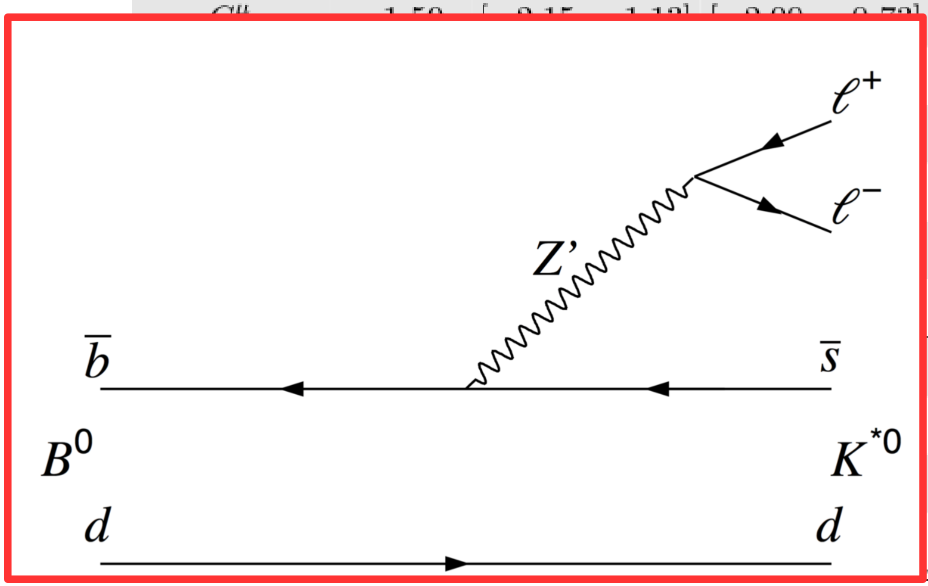
See also, e.g.,

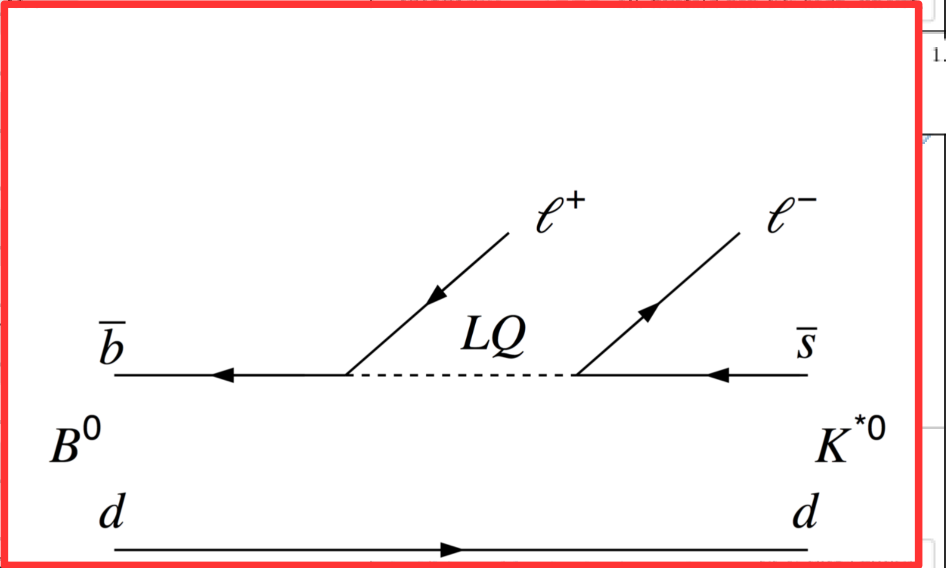
- arXiv:1704.05340 (more "optimistic")
- arXiv:1704.05447 (more "conservative")

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, …)

Coeff.	best fit	1σ	2σ	pull

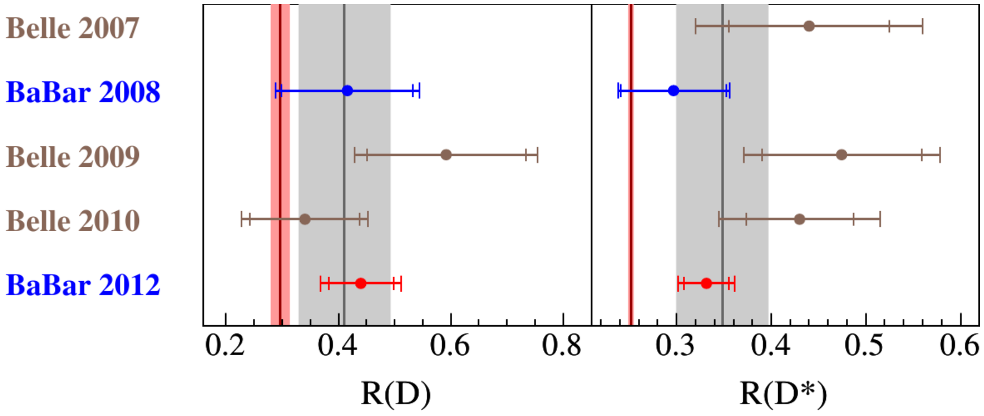


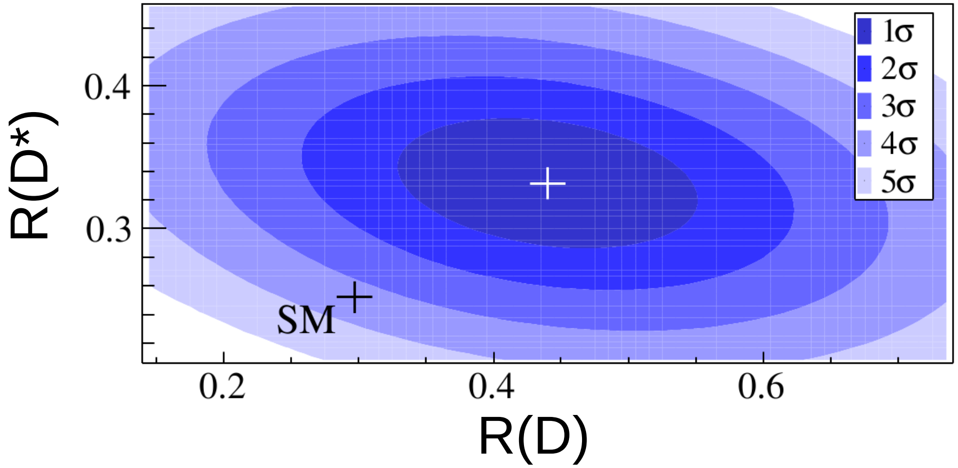


$B \to D^{(*)}\tau\nu$

- 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

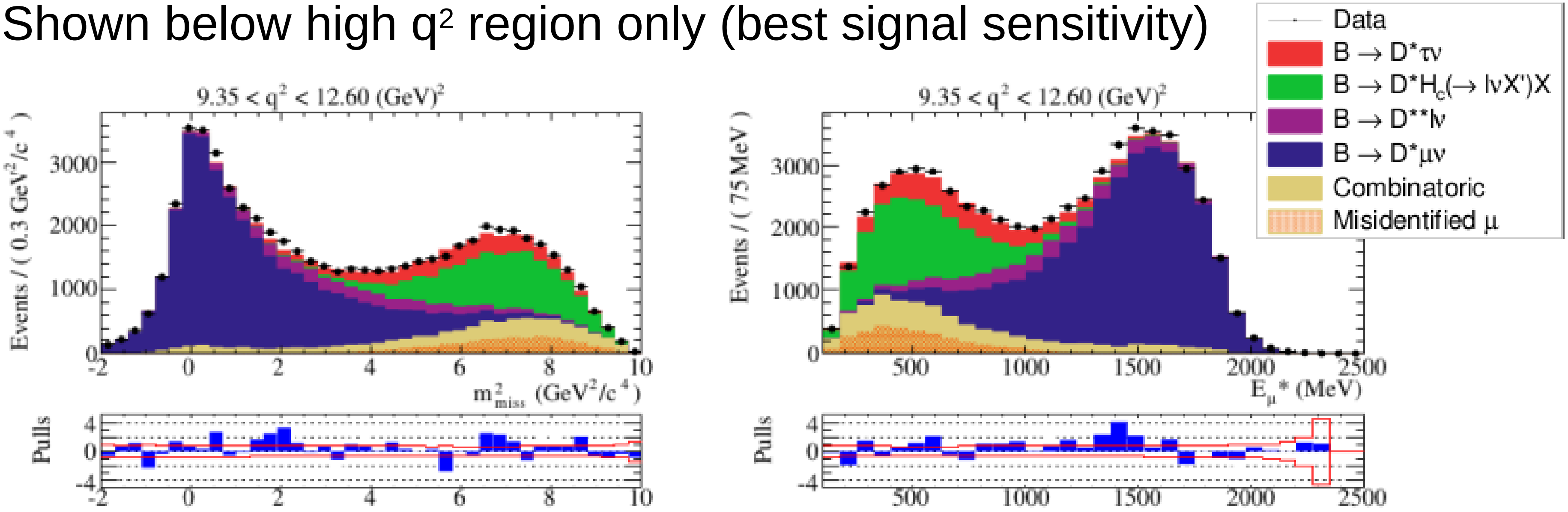




$B \to D^*\tau\nu$ at LHCb (I)

PRL 115 (2015) 112001

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



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

B→D*τν at LHCb (II)

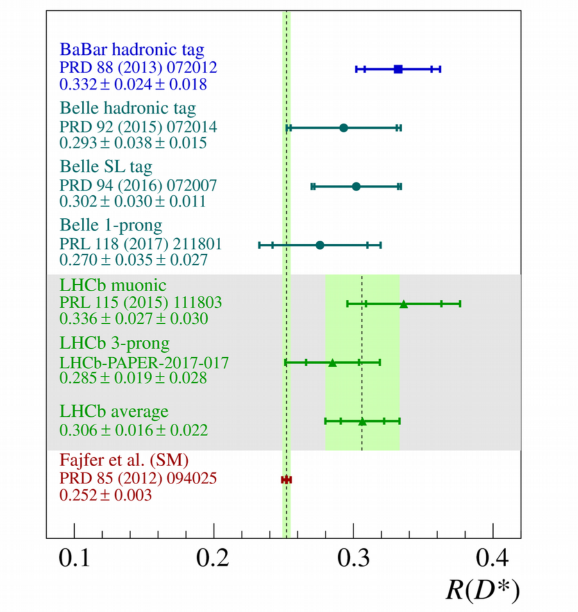
PRL 115 (2015) 112001 & LHCb-PAPER-2017-027

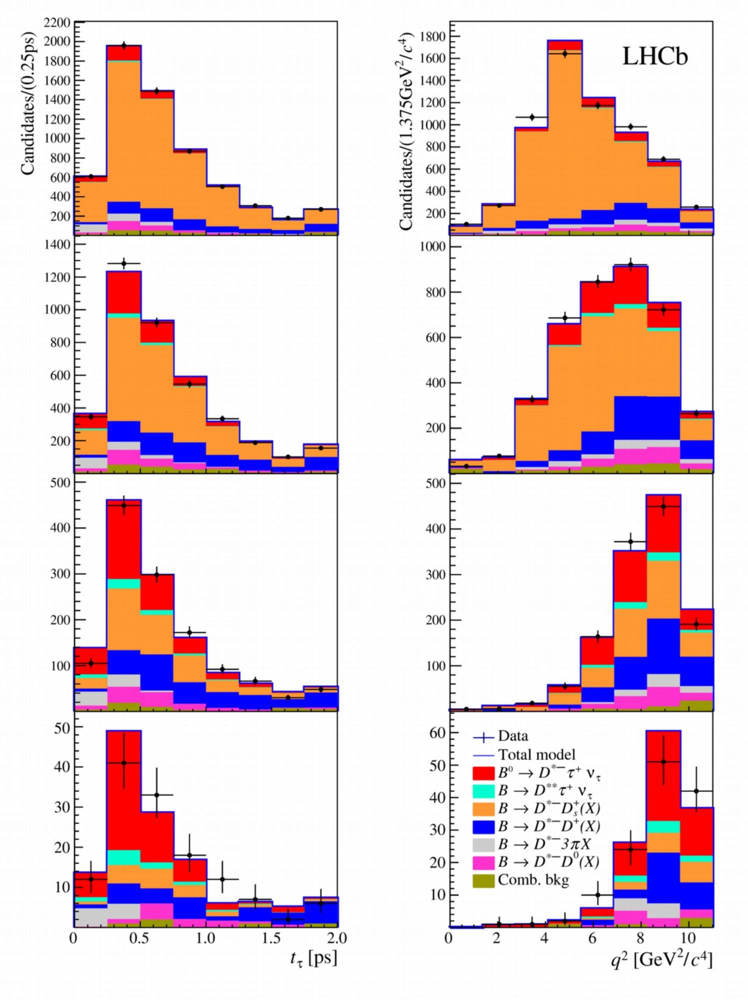
- Exploit excellent LHCb vertexing to reconstruct $\tau \to 3\pi(\pi^0)\nu$ decays
  - Background from $B \to D^*D_{(s)} \to D^*3\pi X$ controlled with MVA
- Separate signal from background by fitting
  - τ decay time & q^2
- Normalised to $B \to D^*D_{(s)} \to D^*3\pi$
  - converted to R(D*) using PDG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

Hot news:

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

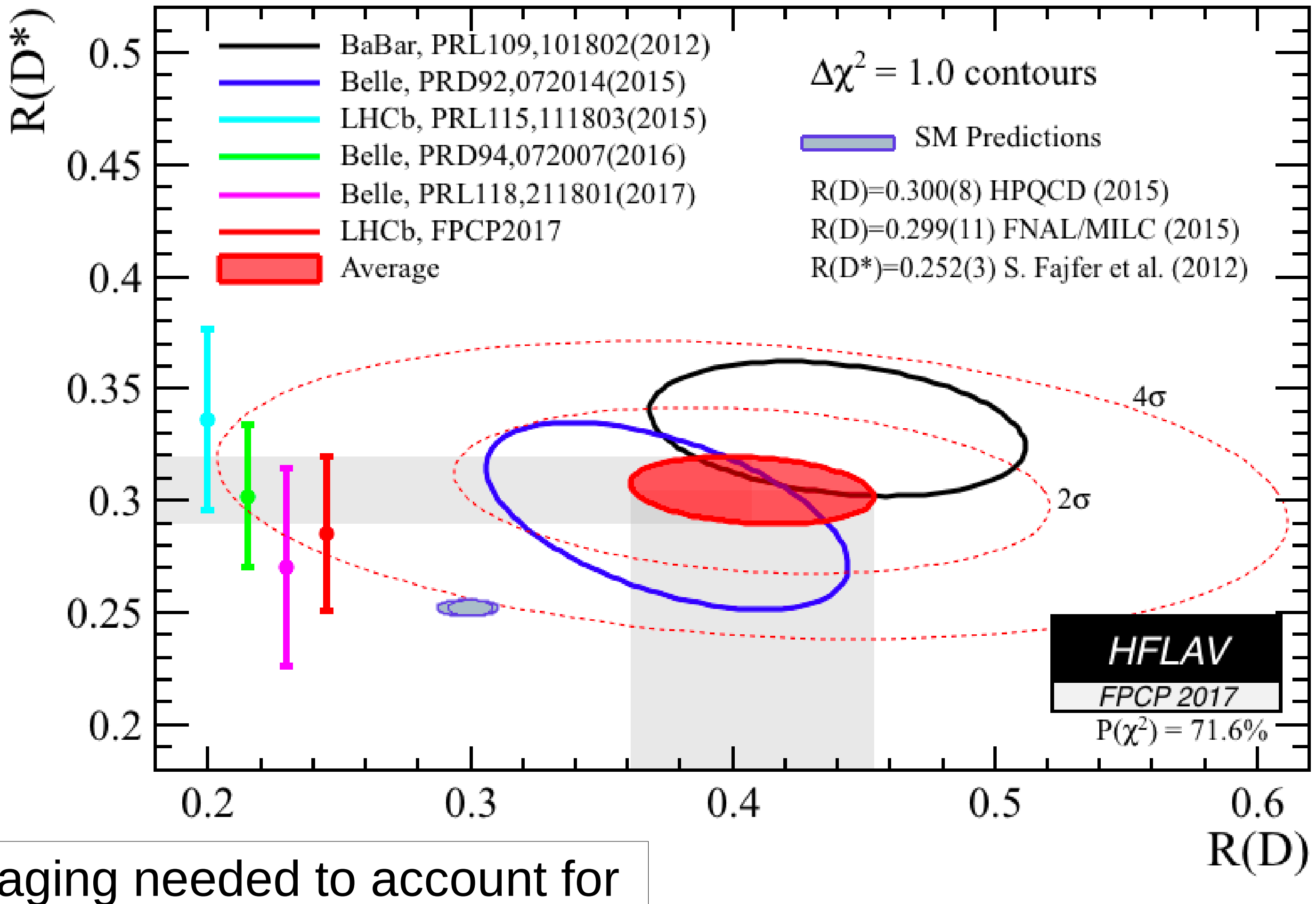
LHCb-PAPER-2017-035





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

Tension with SM at 4.1σ



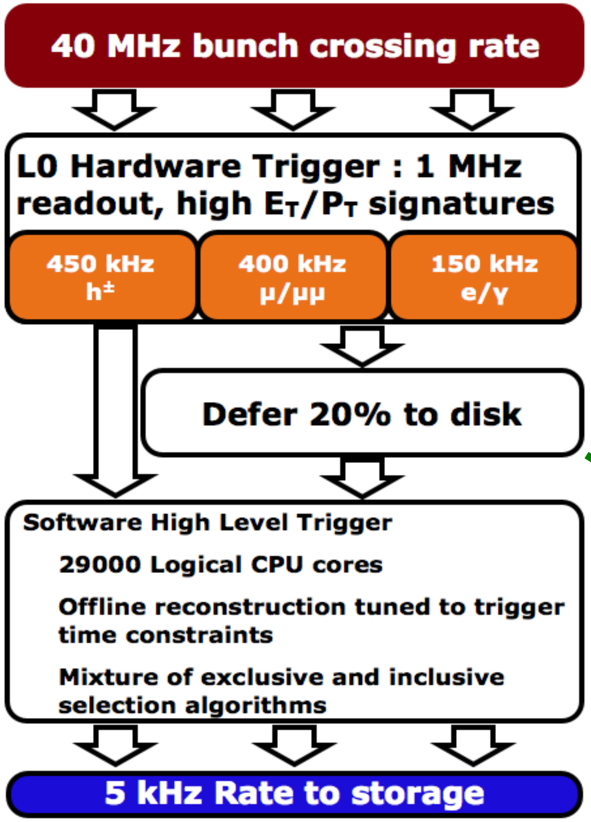
Careful averaging needed to account for statistical and systematic correlations

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

Run II data taking

- At 13 TeV, LHCb's flavour physics programme gains from higher $\sqrt{s}$ (increased production) and 25 ns bunch spacing (lower pile up)
- During LS1: some subdetector consolidation; new HERSCHEL forward shower counters; change of data flow in trigger

LHCb 2012 Trigger Diagram



40 MHz bunch crossing rate

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

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

Defer 20% to disk

Software High Level Trigger

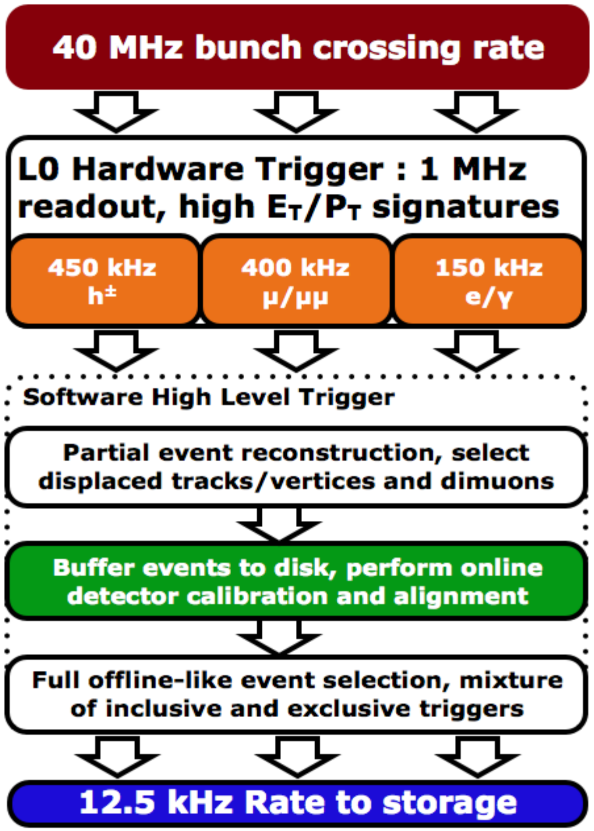
29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

LHCb 2015 Trigger Diagram



40 MHz bunch crossing rate

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

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

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

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

12.5 kHz Rate to storage

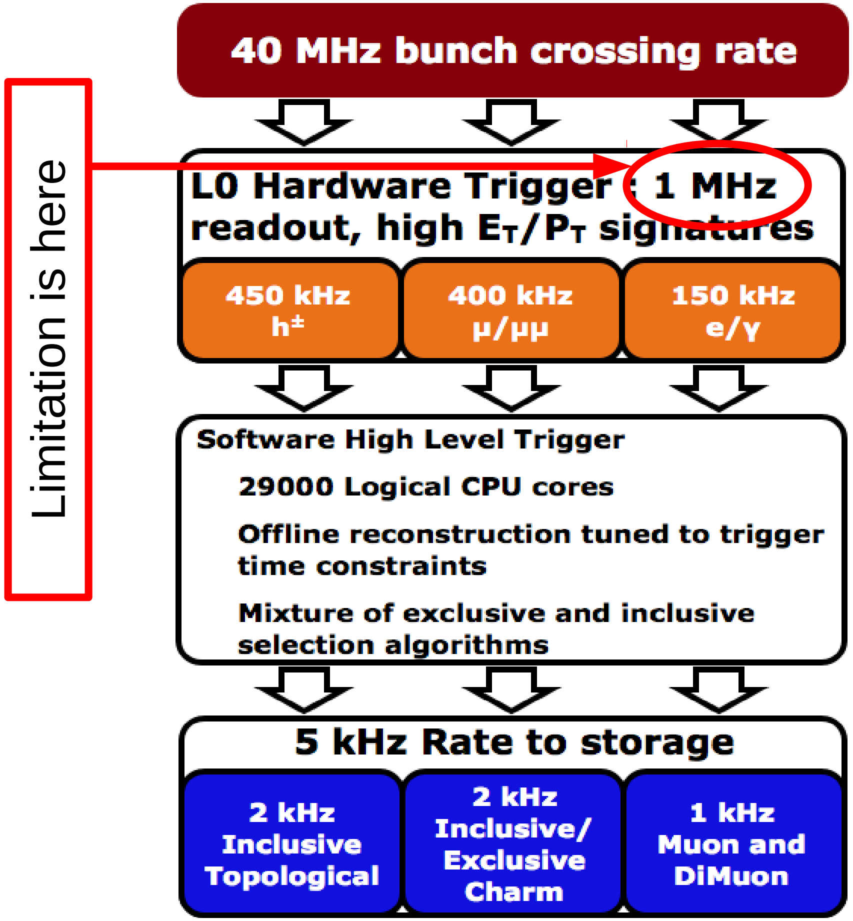
The TURBO revolution

- Buffering of data before HLT2 allows radical new possibilities for data analysis
  - Full detector calibration and alignment applied – no need to reprocess data offline
  - Physics quality data available – can perform analysis in the HLT; no need to record whole event
  - More candidates can be selected – opens possibilities for high rate analyses (similar concept at CMS referred to as “data scouting”)
- Already leading to new analyses & publications with Run 2 data
  - Charm and charmonia cross-sections (JHEP 03 (2016) 159; JHEP 10 (2015) 172)
  - Jet production and substructure (PRL 118 (2017) 192001)
  - Charm spectroscopy: Ξ_{cc}^{++} discovery (PRL 119 (2017) 112001)
  - Search for dark photon (LHCb-PAPER-2017-038)
- But this is only the beginning ...

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 $10^{33}/\mathrm{cm}^2/\mathrm{s}$
  - Upgrade detector qualified to accumulate 50/fb

LHC upgrade and the all important trigger



Limitation is here

40 MHz bunch crossing rate

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

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

Software High Level Trigger

29000 Logical CPU cores

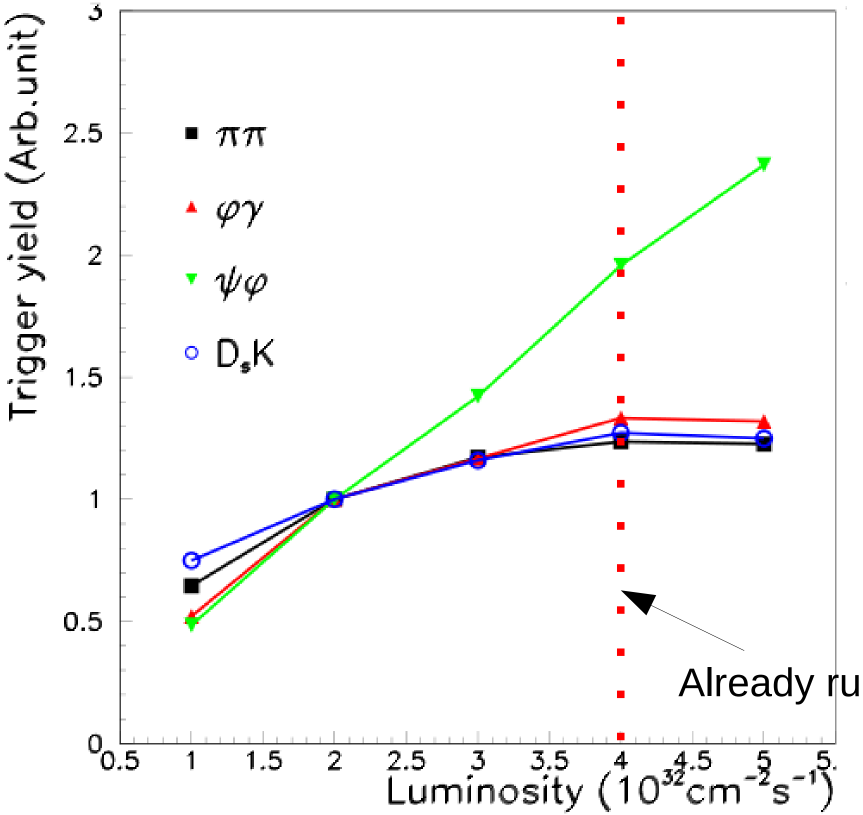
Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

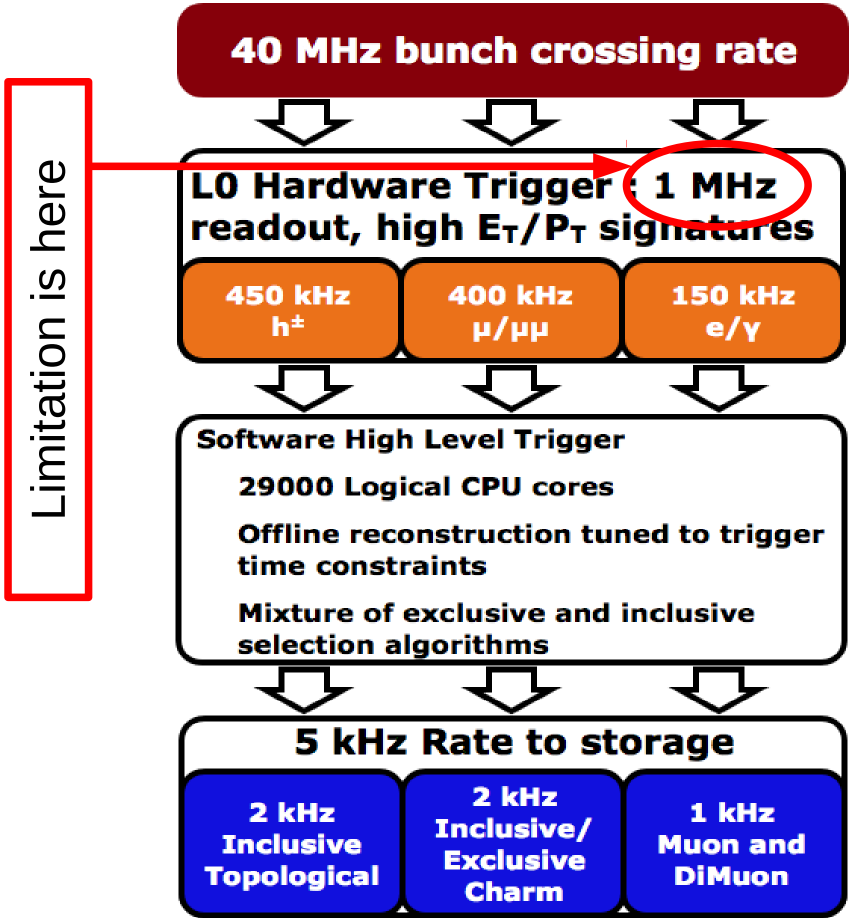
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



Already running here

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

LHC upgrade and the all important trigger



Limitation is here

40 MHz bunch crossing rate

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

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

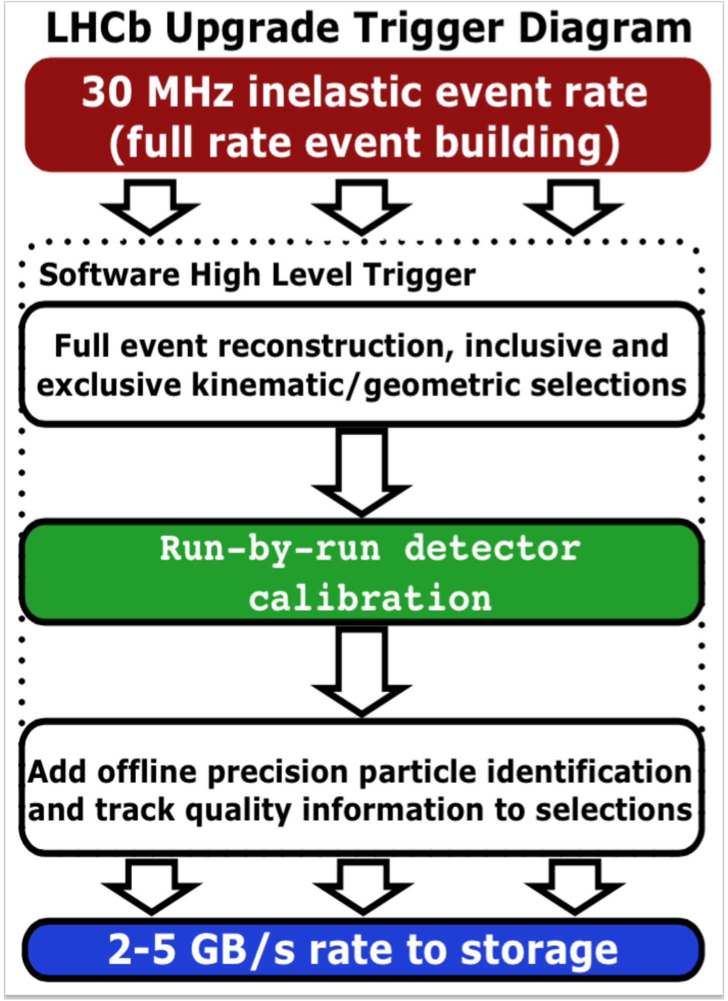
Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological

2 kHz Inclusive/ Exclusive Charm

1 kHz Muon and DiMuon



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Run-by-run detector calibration

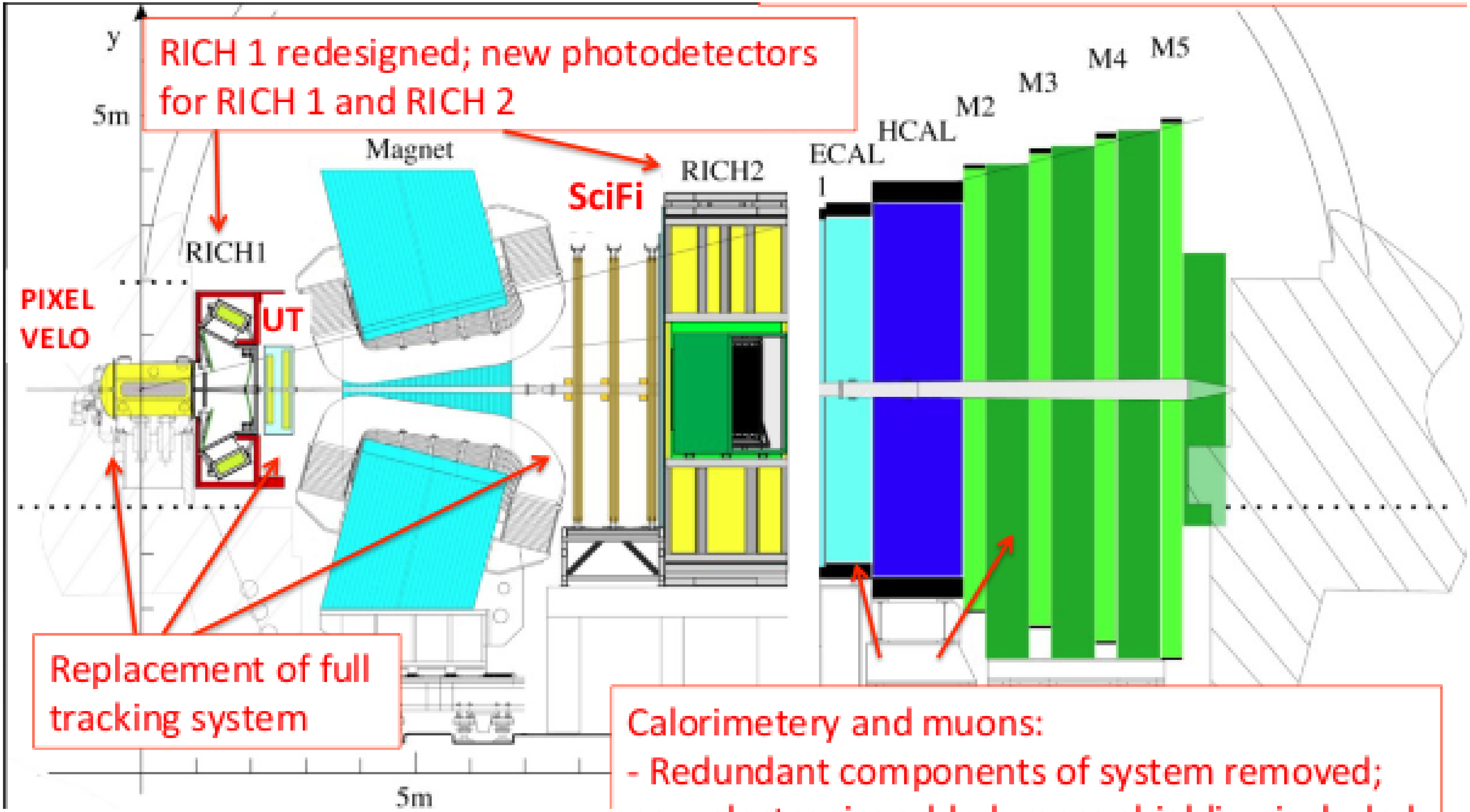
Add offline precision particle identification and track quality information to selections

2-5 GB/s rate to storage

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

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

LHCb detector upgrade



RICH 1 redesigned; new photodetectors for RICH 1 and RICH 2

Replacement of full tracking system

Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

+ novel trigger and offline data management strategies

LHCb & upgrade sensitivities

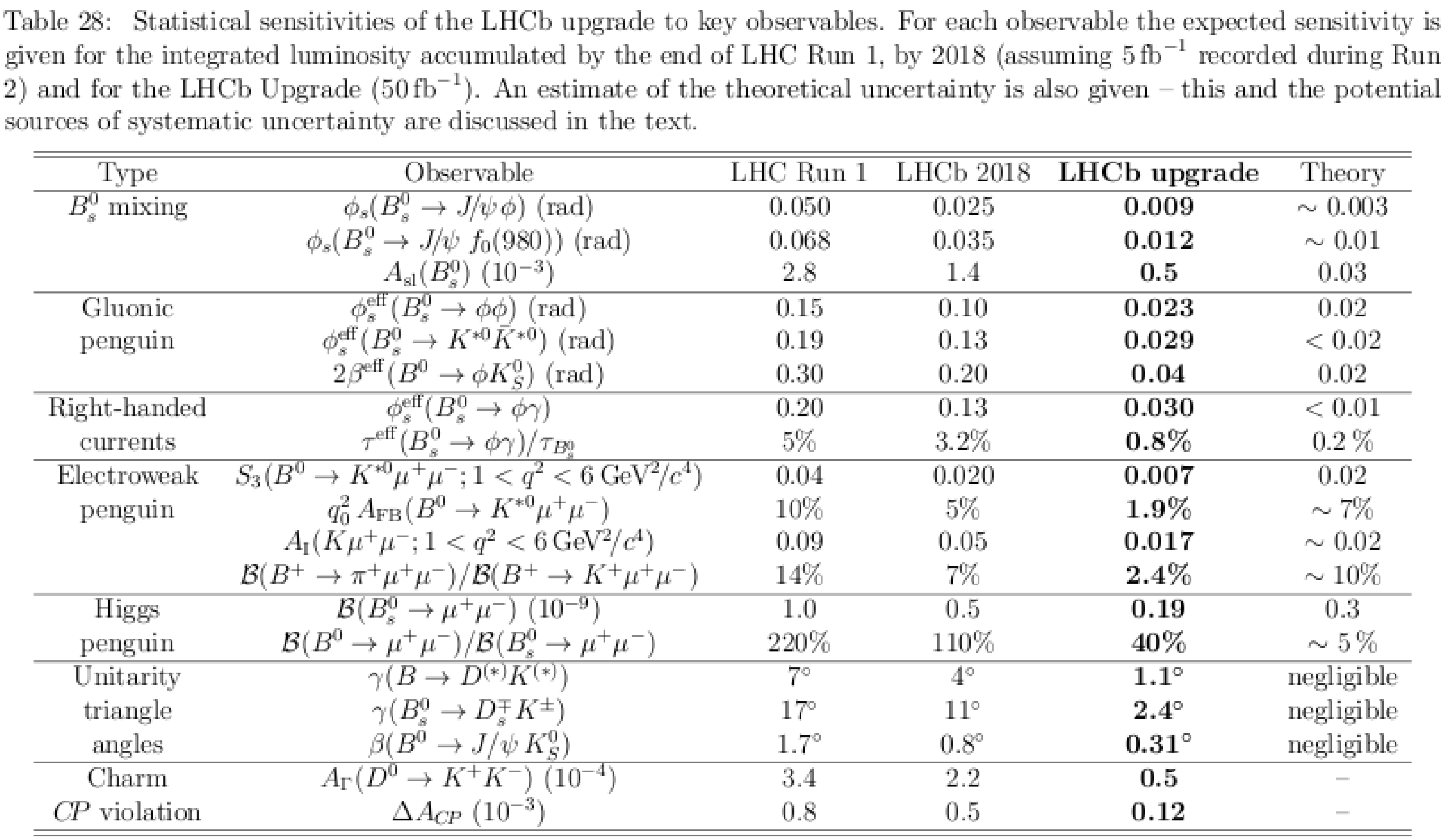


Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of 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
	$A_{\text{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\text{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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!

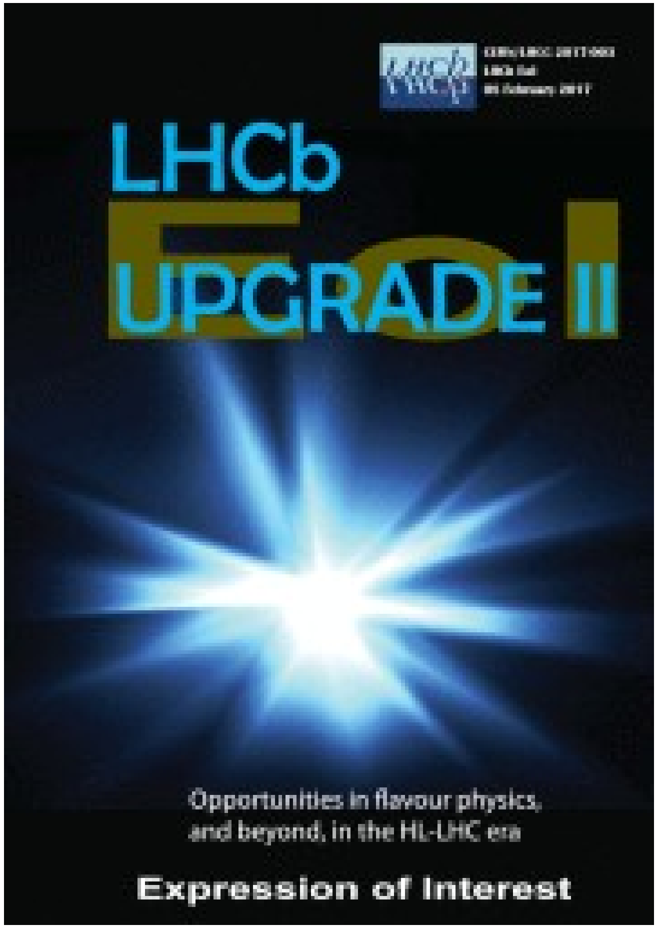
LHC long term future

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

	Run 1	2013/14	Run 2	2019/20	Run 3	2024-26	Run 4	2030/31	Run 5
		LS1		**LS2**		**LS3**		**LS4**	
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**	

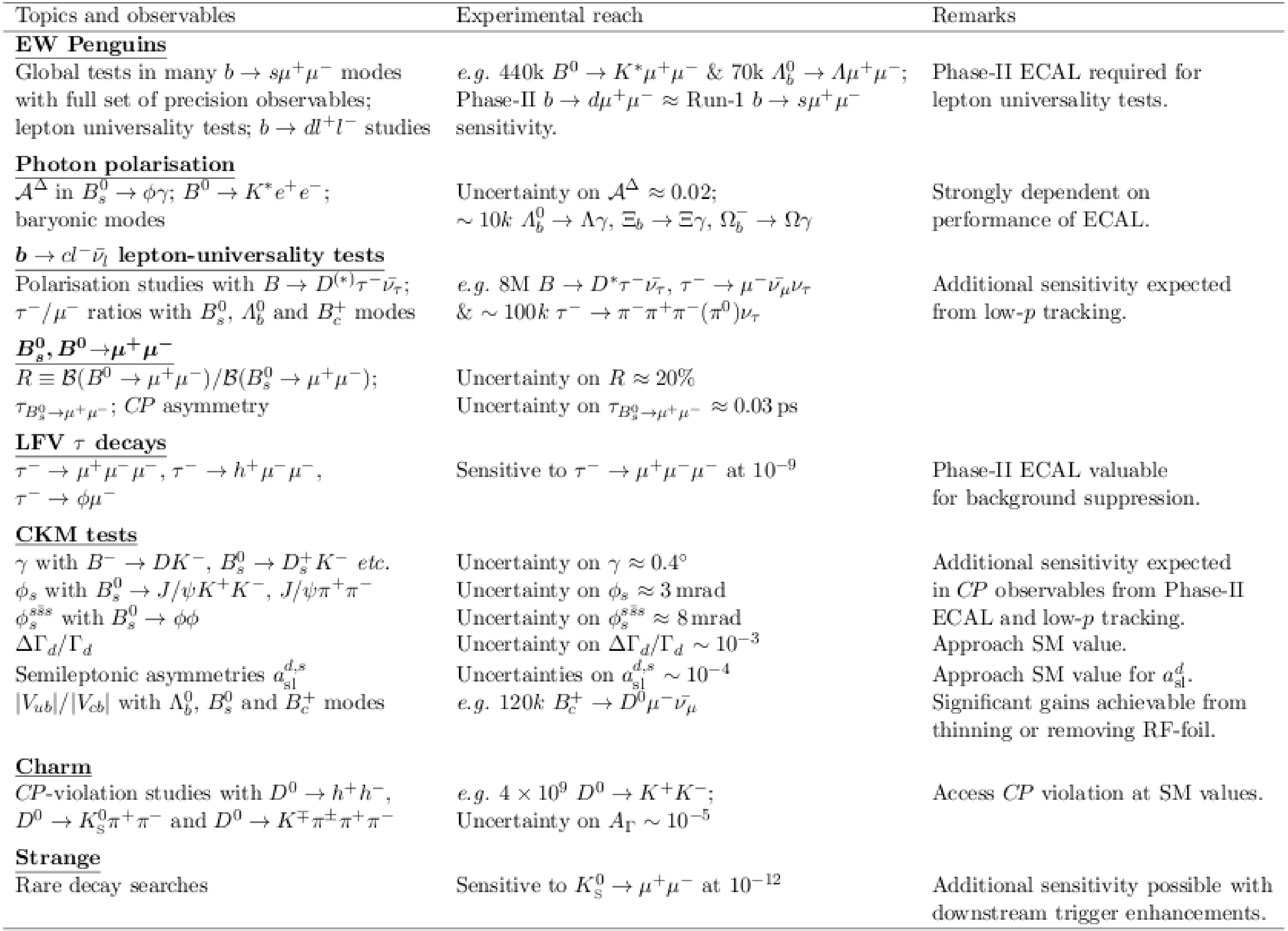
Upgrade during LS4 will allow to increase data sample
50/fb → 300/fb

Expression of interest for “Phase II” upgrade


LHCb
UPGRADE II
Opportunities in flavour physics, and beyond, in the HL-LHC era
Expression of Interest

- 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!

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.
$B_s^0, B^0 \to \mu^+\mu^-$		
$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$;	Uncertainty on $R \approx 20\%$	
$\tau_{B_s^0 \to \mu^+\mu^-}$; *CP* asymmetry	Uncertainty on $\tau_{B_s^0 \to \mu^+\mu^-} \approx 0.03\,\mathrm{ps}$	
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 in *CP* observables from Phase-II ECAL and low-p tracking.
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\mathrm{mrad}$	
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\mathrm{mrad}$	
$\Delta\Gamma_d/\Gamma_d$	Uncertainty on $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$	Approach SM value.
Semileptonic asymmetries $a_{\mathrm{sl}}^{d,s}$	Uncertainties on $a_{\mathrm{sl}}^{d,s} \sim 10^{-4}$	Approach SM value for a_{sl}^{d}.
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ 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.

Summary

- LHCb surpassed Run I performance expectations
  - huge physics output, in “core” flavour observables but also much more
  - modes with neutrinos, previously thought to be impossible
  - … and don't forget pentaquarks (and other topics not covered today)
  - several hints of BSM effects to be explored further
- Important improvements in the trigger for Run II
- Data taking going well
  - first physics papers on Run II data published; data quality is excellent
  - much to look forward to!
- Beyond Run II will install LHCb upgrade to enable even high luminosity
  - also starting to think of even longer term possibilities
  - Expression of Interest for Phase II upgrade submitted to LHCC


BACK UP!

What does $\int L\,dt = 1/\mathrm{fb}$ mean?

- Measured cross-section, in LHCb acceptance, 7 TeV

$$\sigma(pp \to b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced in 1/fb (2011 sample)

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- “B factories” BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \to c\bar{c}X) = (6.10 \pm 0.93)$ mb

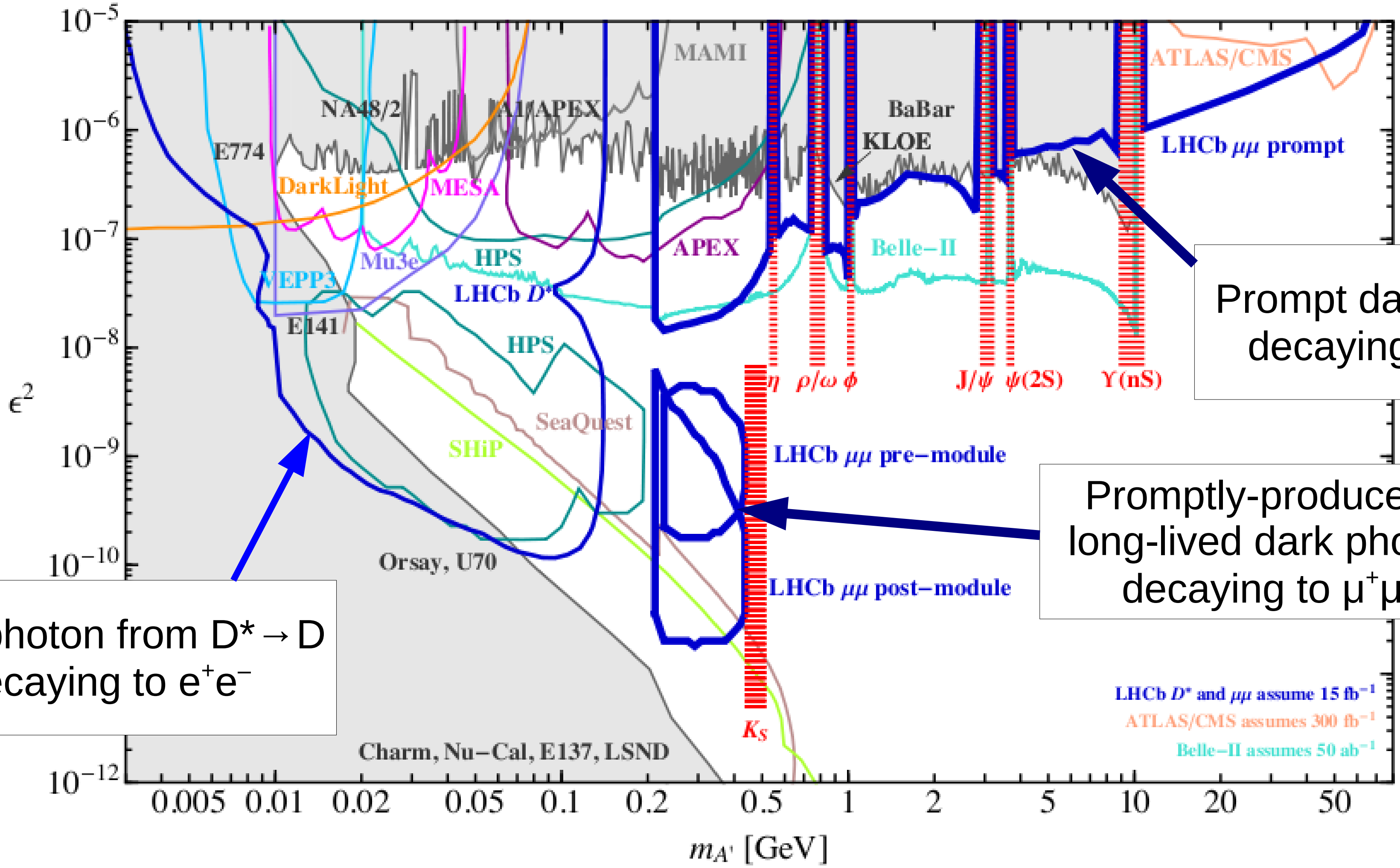
LHCb-CONF-2010-013

Not only flavour physics ...

- Most of the recent results from LHCb are on its "core" flavour physics programme
  - CP violation, the Unitarity Triangle and rare B decays
- LHCb also has unique non-flavour capability
  - Top production in the forward region (PRL 115 (2015) 112001)
  - Determination of $\sin^2\theta_W$ (JHEP 11 (2015) 190)
  - Search for hidden sector bosons (PRL 115 (2015) 161802)
  - Ideas to search for dark photons ...

Proposals for dark photon searches at LHCb

arXiv:1509.06765, arXiv:1603.08926



Prompt dark photon decaying to $\mu^+\mu^-$

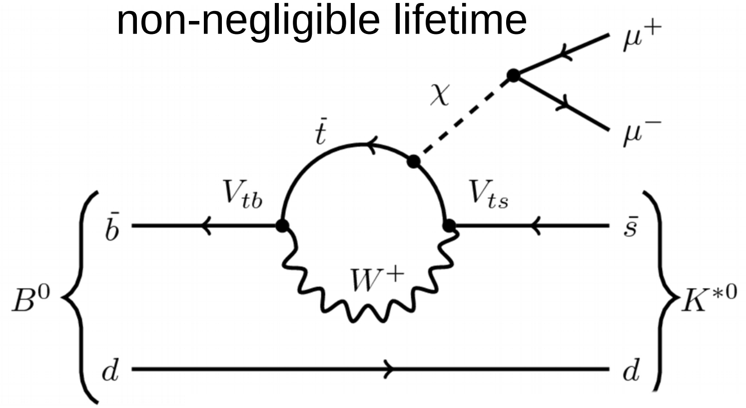
Promptly-produced, long-lived dark photon decaying to $\mu^+\mu^-$

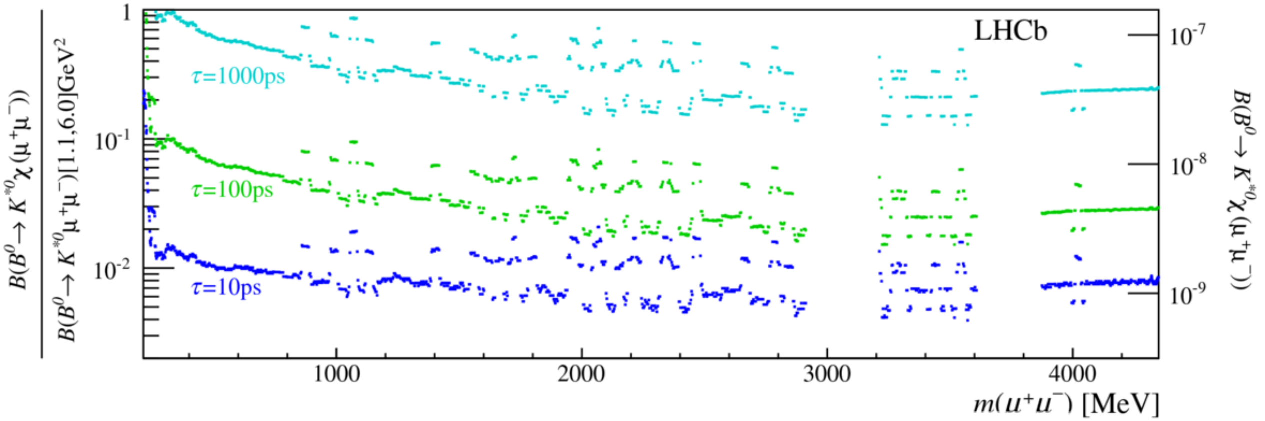
Dark photon from D* → D decaying to e^+e^-

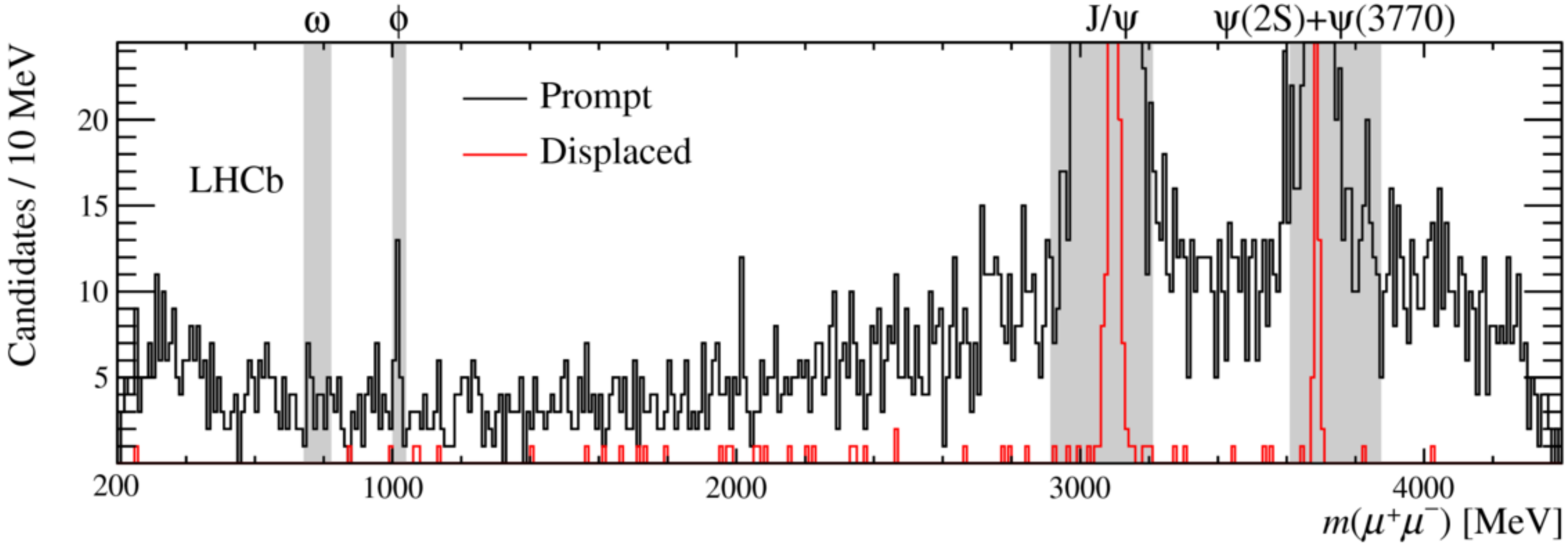
Search for hidden sector bosons

PRL 115 (2015) 161802

Search for narrow μμ peak in B → K^{*0}μμ decays corresponding to χ with either negligible or non-negligible lifetime



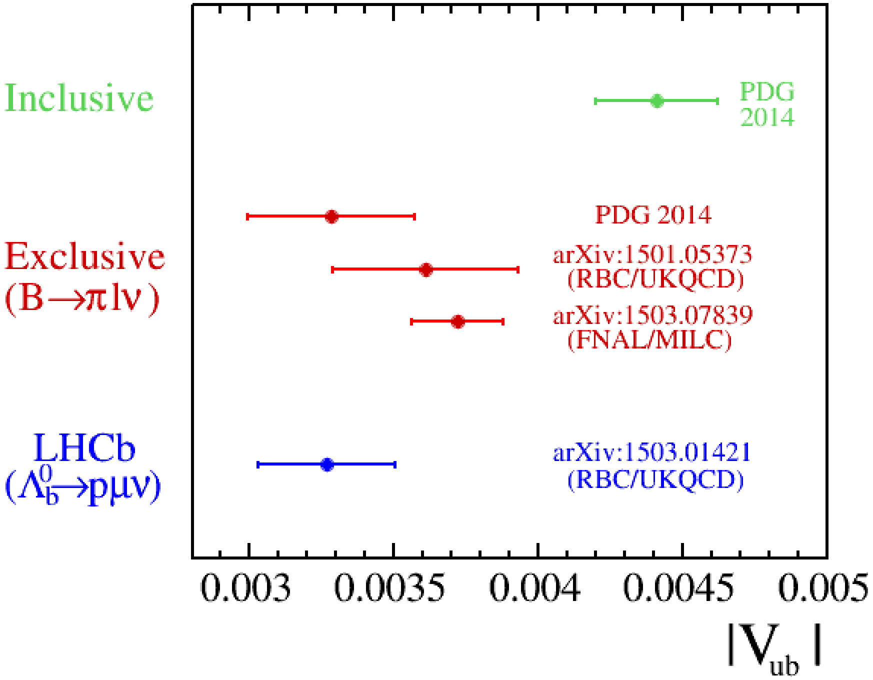


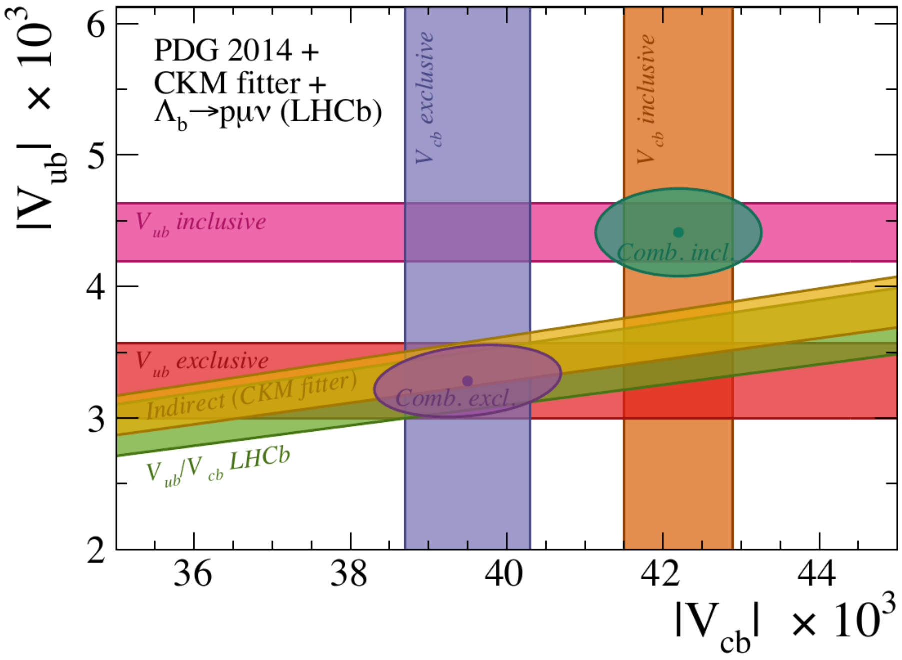


No significant peak away from known resonances

$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

Nature Phys. 11 (2015) 743





$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

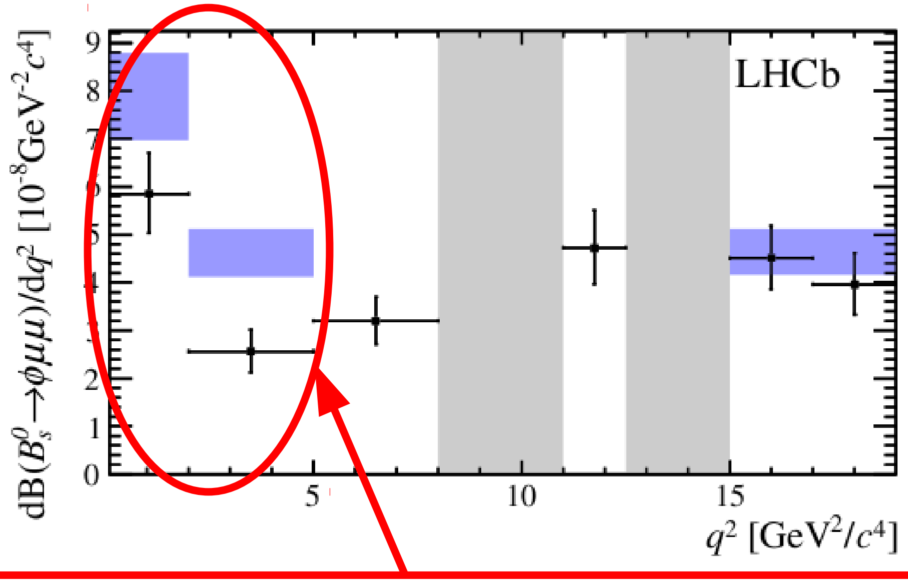
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\mathrm{expt}) \pm 0.004(\mathrm{lattice})$$

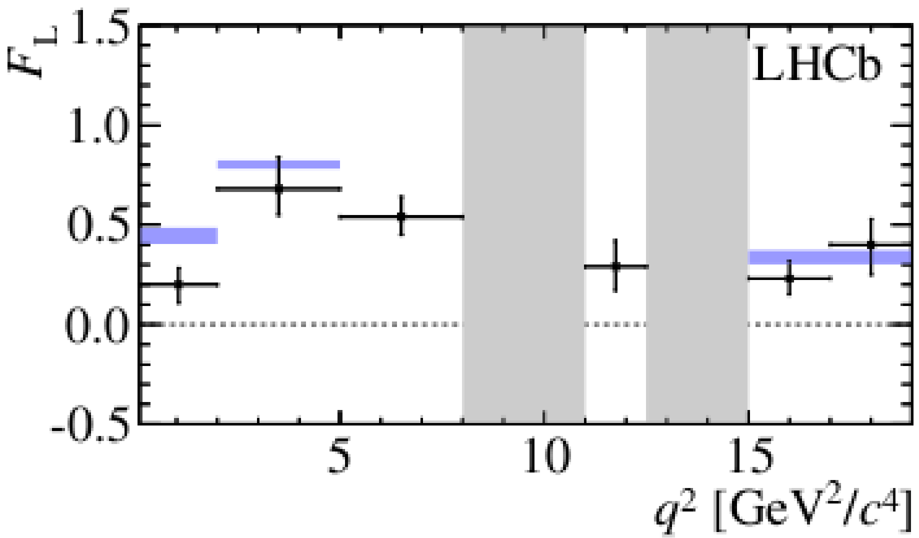
- Rules out models with RH currents
- Compatible with UT fit (β,γ)

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

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 → sl^+l^- branching fractions

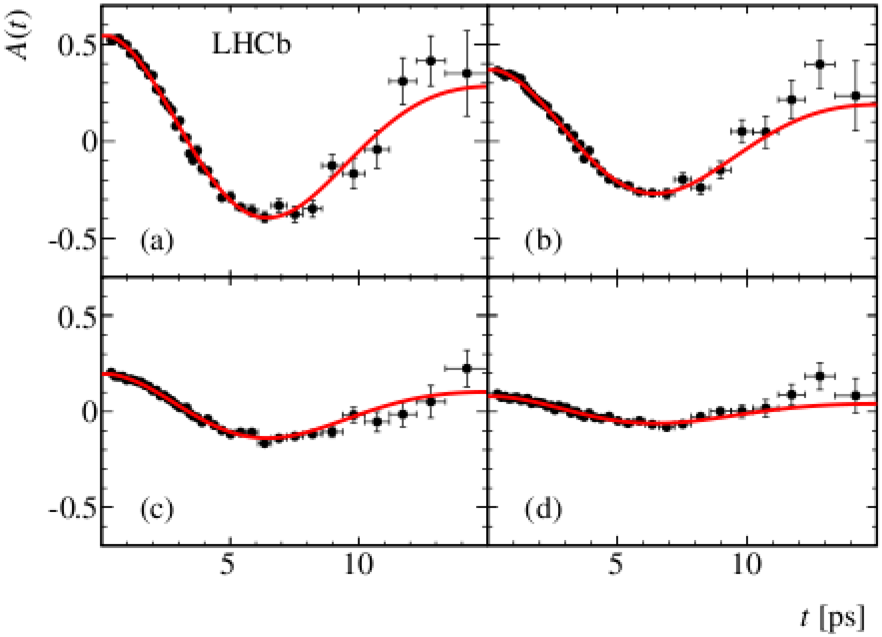
$|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$

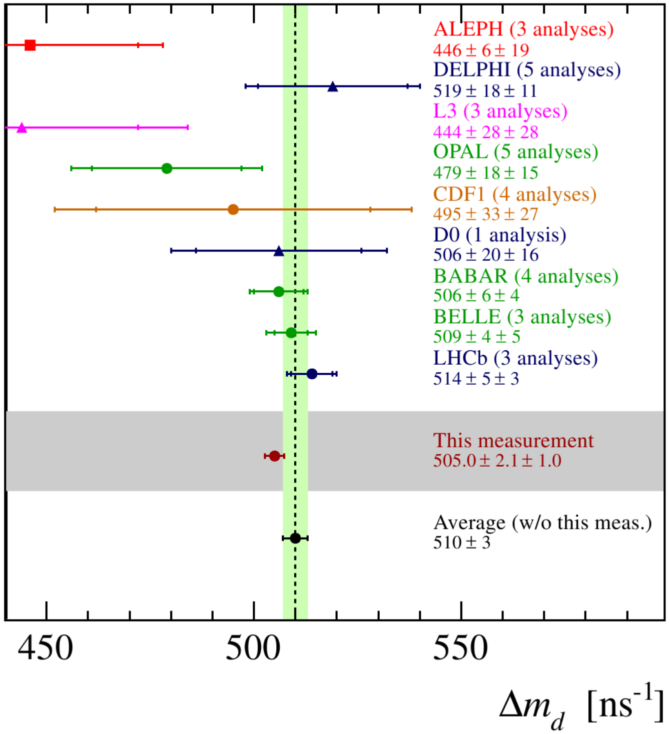
EPJC 76 (2016) 412

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$ (LHCb NJP 15 (2013) 053021)

latest lattice calculations: arXiv:1603.04306, arXiv:1602.03560

- Δm_s now precisely known
- limitation on knowledge of UT side from lattice (improving fast) and Δm_d
- new measurement uses $B^0 \to D^{(*)-}\mu\nu$ decays





only 2012 $B^0 \to D^-\mu\nu$ data shown

$\Delta m_d = (505.0 \pm 2.1\ (\mathrm{stat}) \pm 1.0\ (\mathrm{syst}))\ \mathrm{ns}^{-1}$

single most precise determination
precision of previous world average

γ from $B^0 \to DK^{*0}$, $D \to K_S\pi\pi$, K_SKK

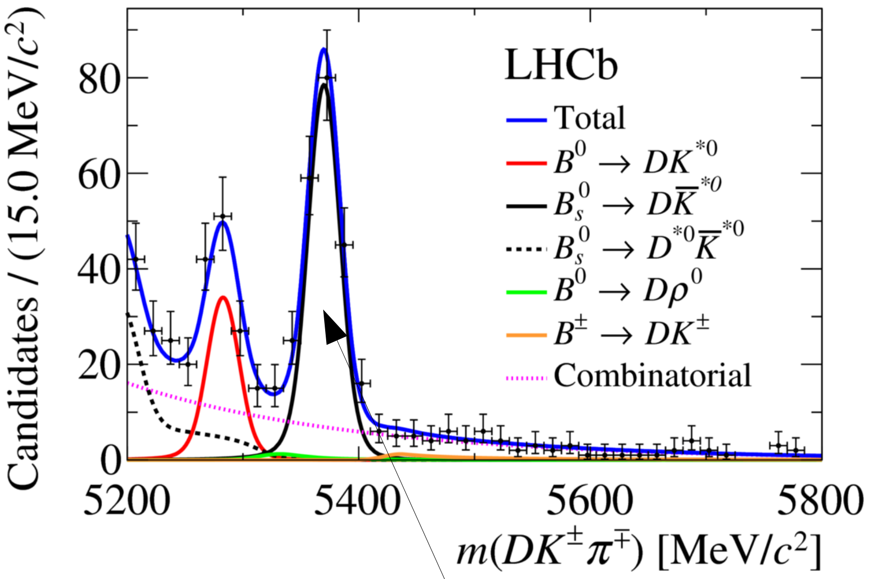
arXiv:1604.01525, arXiv:1605.01082

$B^0 \to DK^{*0}$ rarer, but with larger interference effects, than $B^+ \to DK^+$

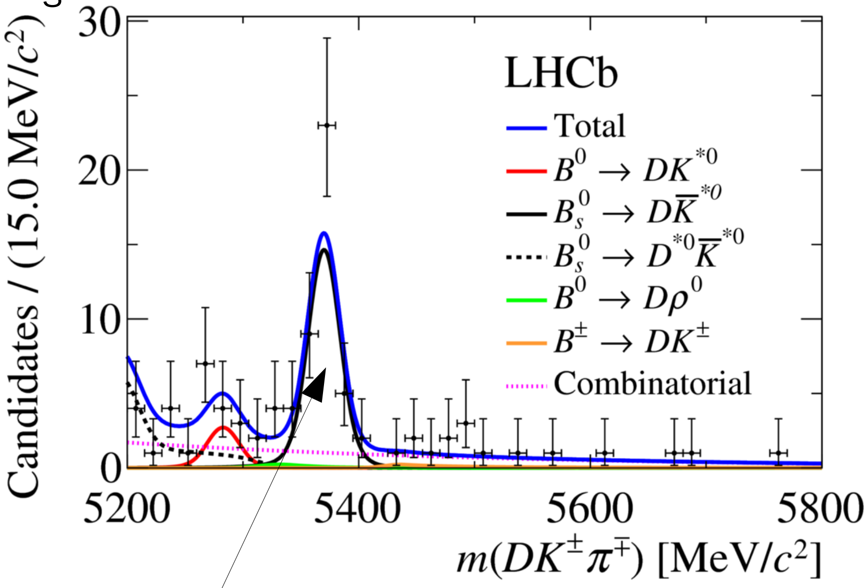
$D \to KK$, $\pi\pi$, $K\pi$ previously studied in PR D90 (2014) 112002

Now consider "GGSZ" modes with both model-independent (arXiv:1604.01525) and -dependent (arXiv:1605.01082) analyses

$D \to K_S\pi\pi$ (both MI & MD)



$D \to K_SKK$ (MI only)



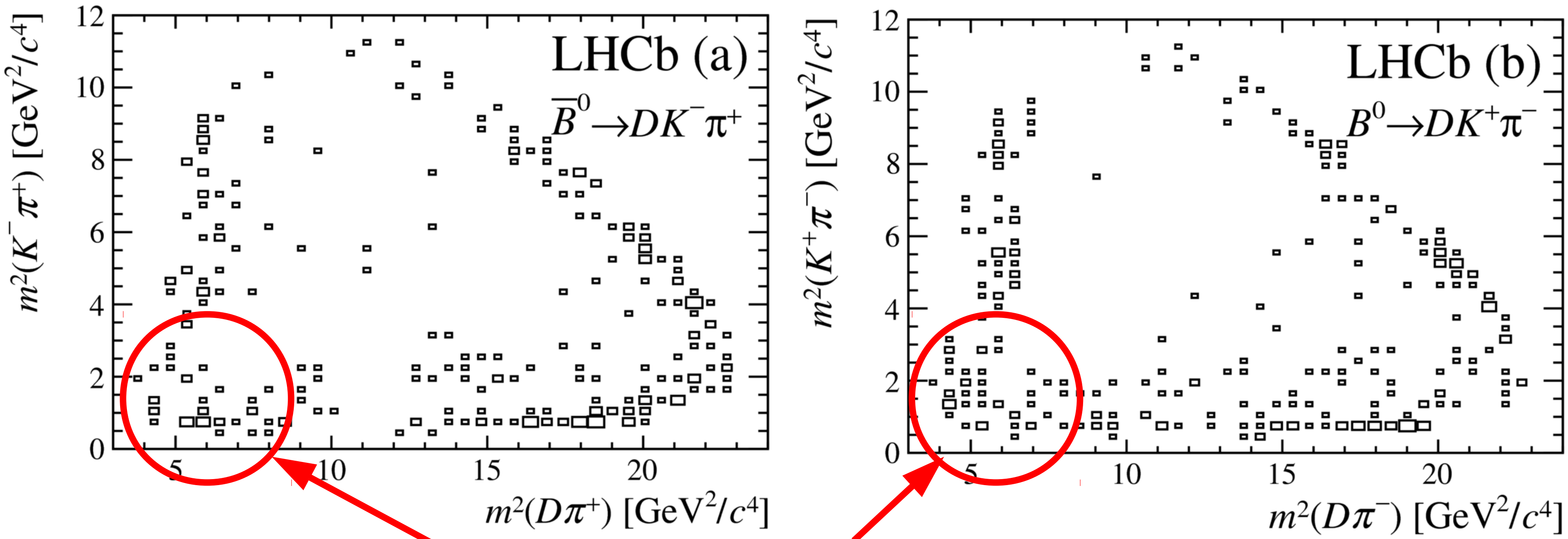
B_s^0 decays to same final states provide control channels

γ from $B^0 \to DK^{*0}$

arXiv:1604.01525, arXiv:1605.01082

For $B^0 \to DK^{*0}$, width of the K^{*0} resonance introduces a dilution factor that depends on the $B^0 \to DK^+\pi^-$ Dalitz plot

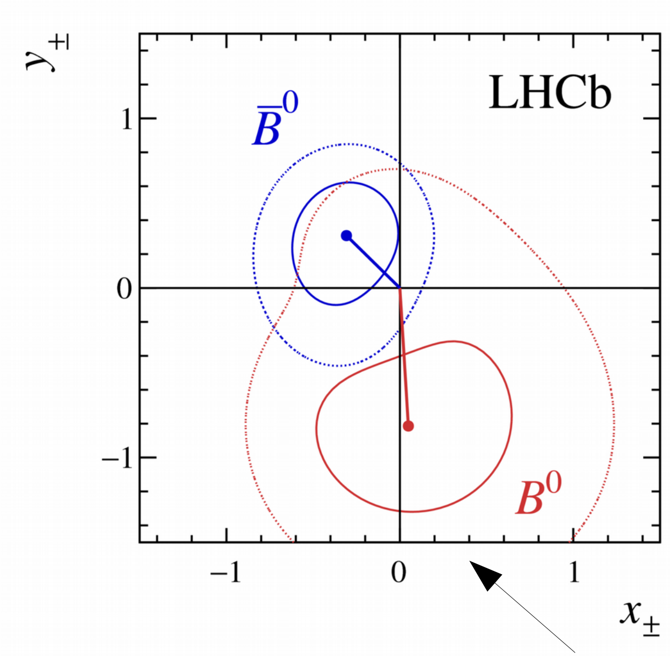
This has been studied with $D \to K\pi$ (PRD 92 (2015) 012012), KK and ππ (arXiv:1602.03455) decays



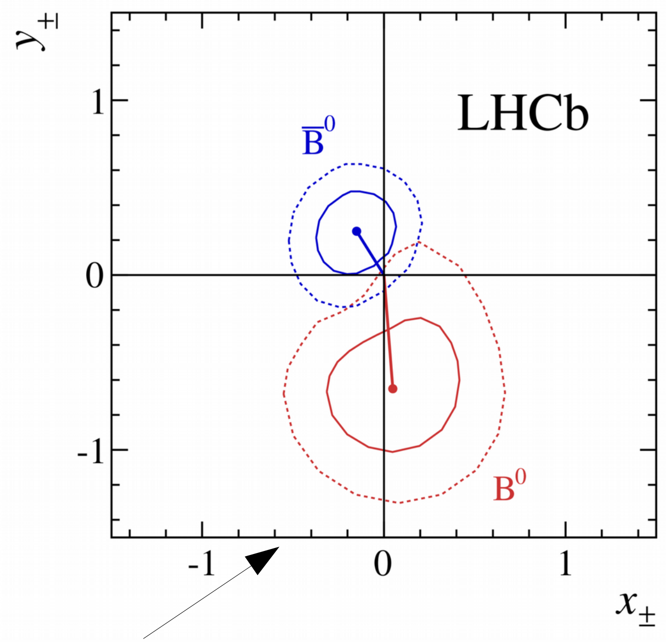
Interference effects in the D_2^*–K^* overlap region enhance sensitivity to γ

γ from $B^0 \rightarrow DK^{*0}$

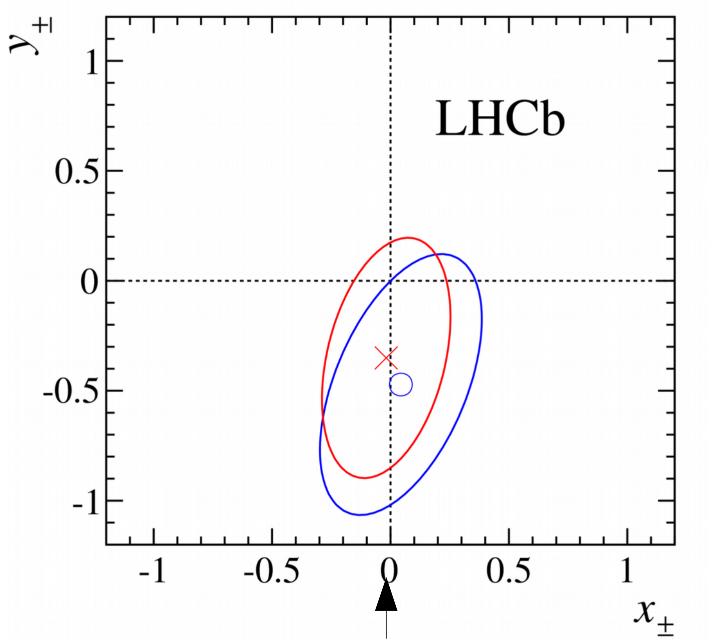
arXiv:1604.01525



arXiv:1605.01082



arXiv:1602.03455



$D \rightarrow K_S\pi\pi$

$D \rightarrow KK,\pi\pi$

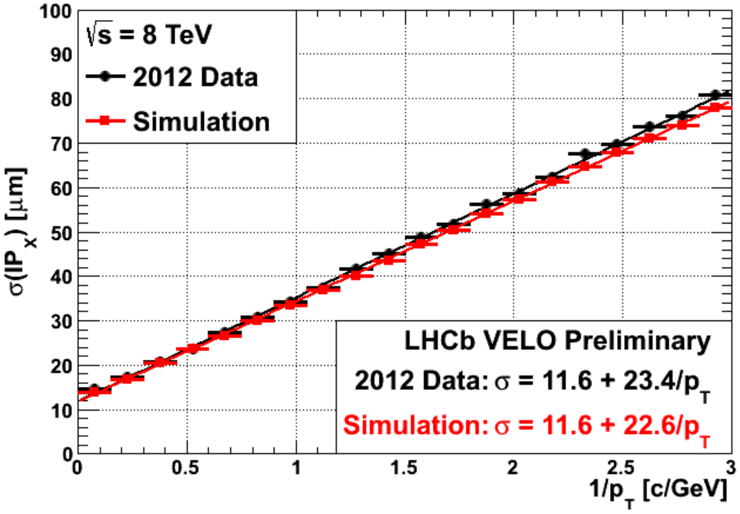
Comparison of results in terms of $x_\pm = r_B\cos(\delta_B \pm \gamma)$, $y_\pm = r_B\sin(\delta_B \pm \gamma)$

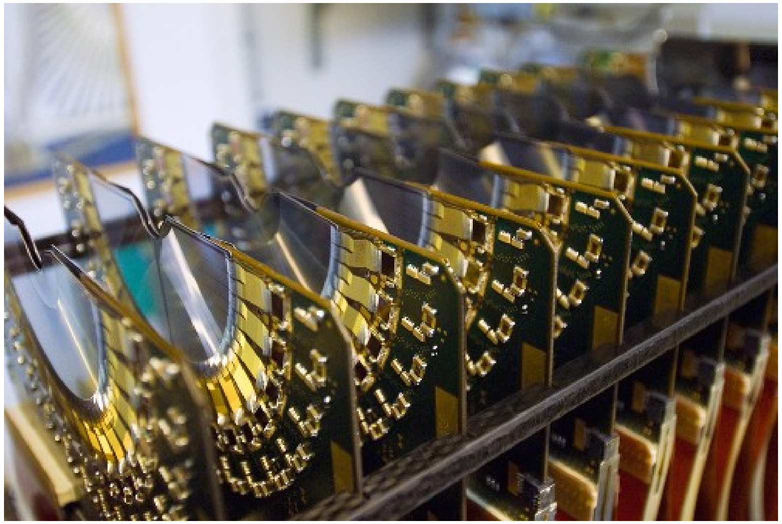
RED: (x_+,y_+), BLUE (x_-,y_-)

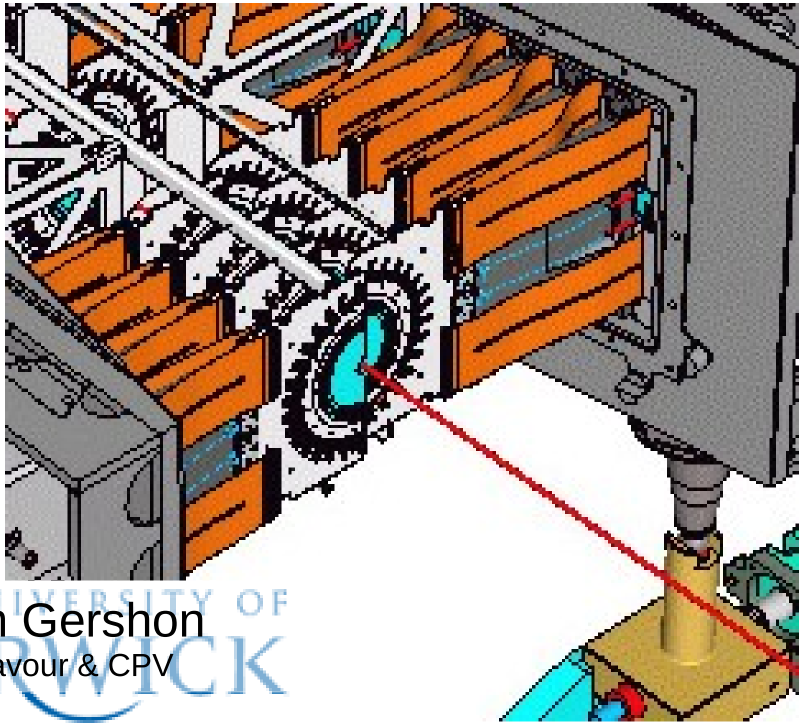
Prospects

- Data-taking progressing well
  - Expect to collect ~5/fb of 13 TeV data during Run II
  - Improve current precision by at least a factor of 2
- During LS2 (2019-20) will install upgraded detector
  - Will allow higher luminosity and improved trigger efficiency
  - Designed to accumulate 50/fb in ~5 years of operation
- Possibilities for subsequent upgrade under discussion
  - During LS3 (concomitant with HL-LHC upgrades) to extend capability (e.g. additional tracking coverage, calorimeter replacement)
  - During LS4 to allow significantly higher luminosity and/or alternative physics programme (e.g. $H \to c\bar{c}$)
  - More ideas welcome!

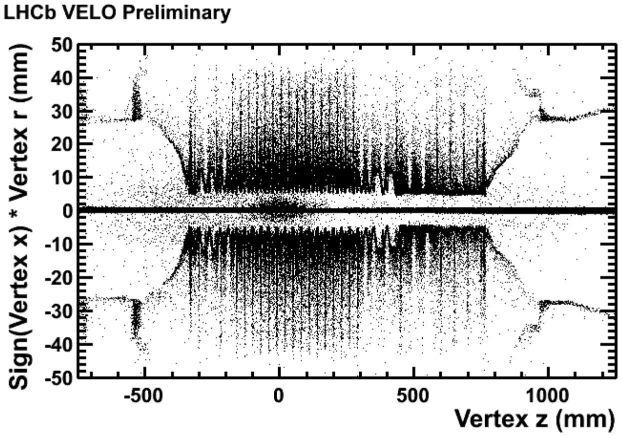
VELO

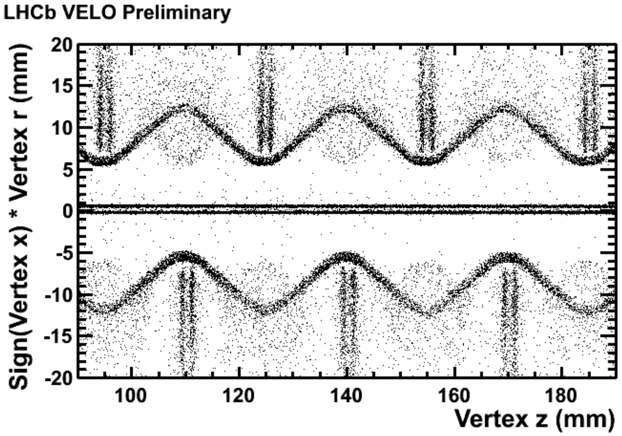




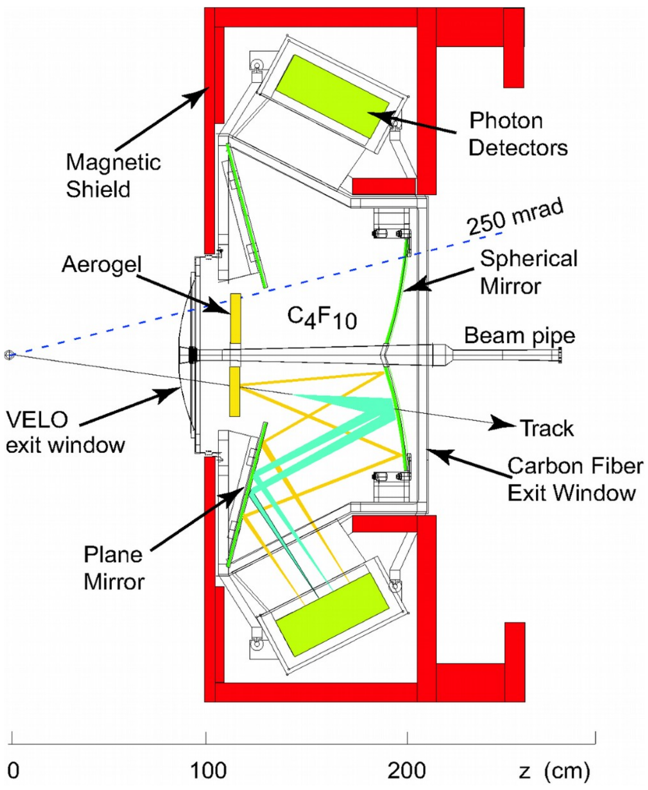


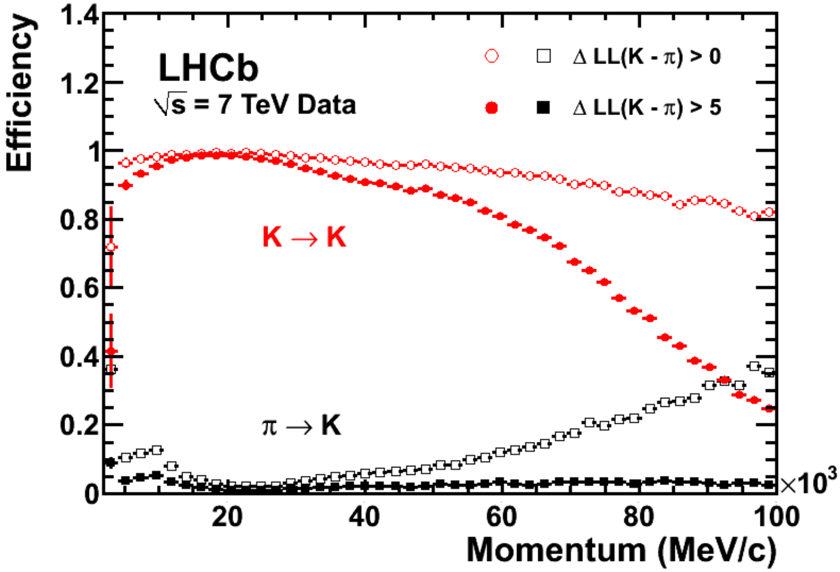
Material imaged used beam gas collisions





RICH


Magnetic Shield
Photon Detectors
250 mrad
Aerogel
C_4F_{10}
Spherical Mirror
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror
0
100
200
z (cm)


LHCb
$\sqrt{s}$ = 7 TeV Data
○ □ Δ LL(K - π) > 0
● ■ Δ LL(K - π) > 5
K → K
π → K
Efficiency
1.4
1.2
1
0.8
0.6
0.4
0.2
0
20
40
60
80
100
$\times 10^3$
Momentum (MeV/c)