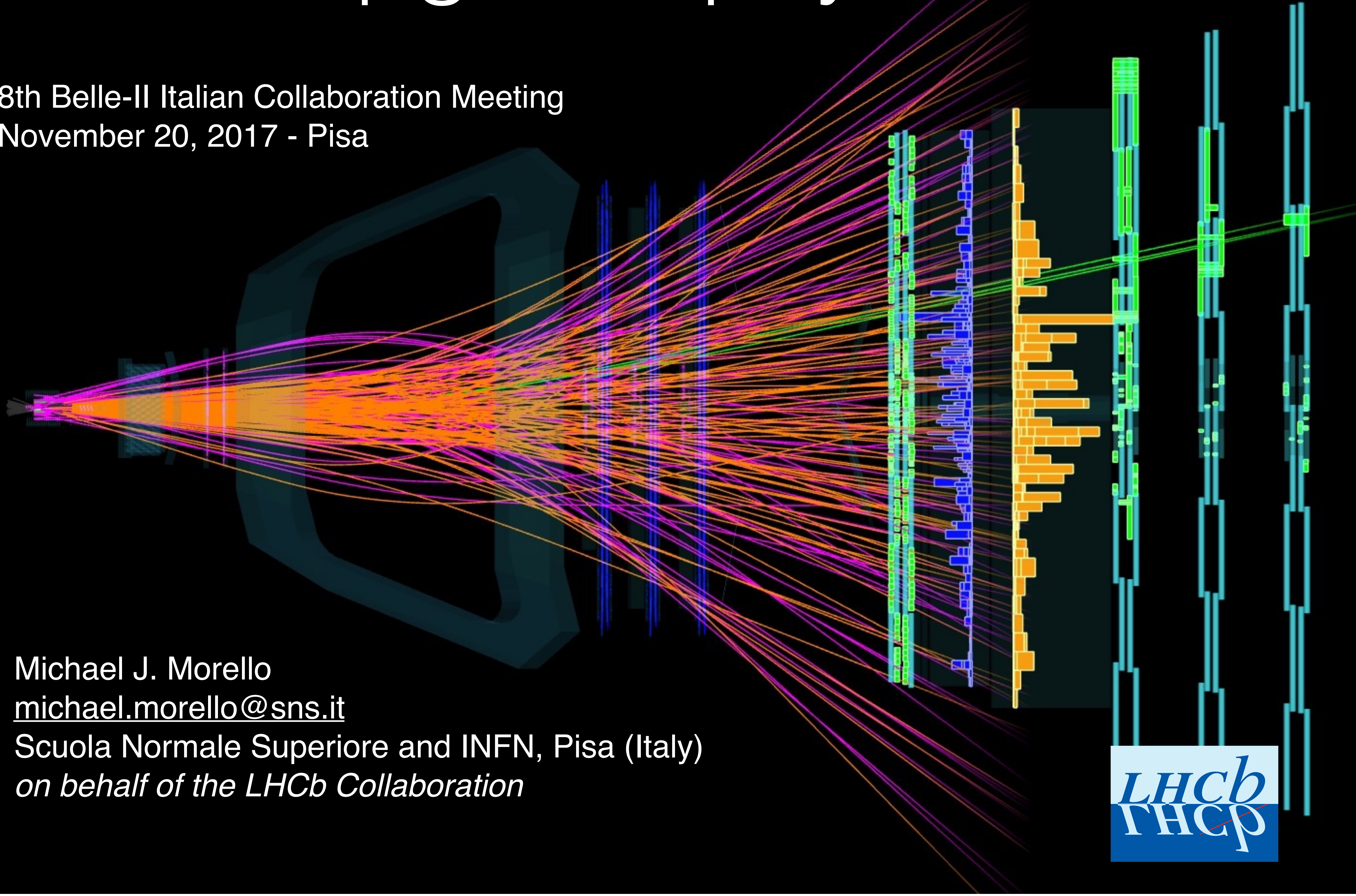
LHCb-Upgrade physics reach

8th Belle-II Italian Collaboration Meeting
November 20, 2017 - Pisa



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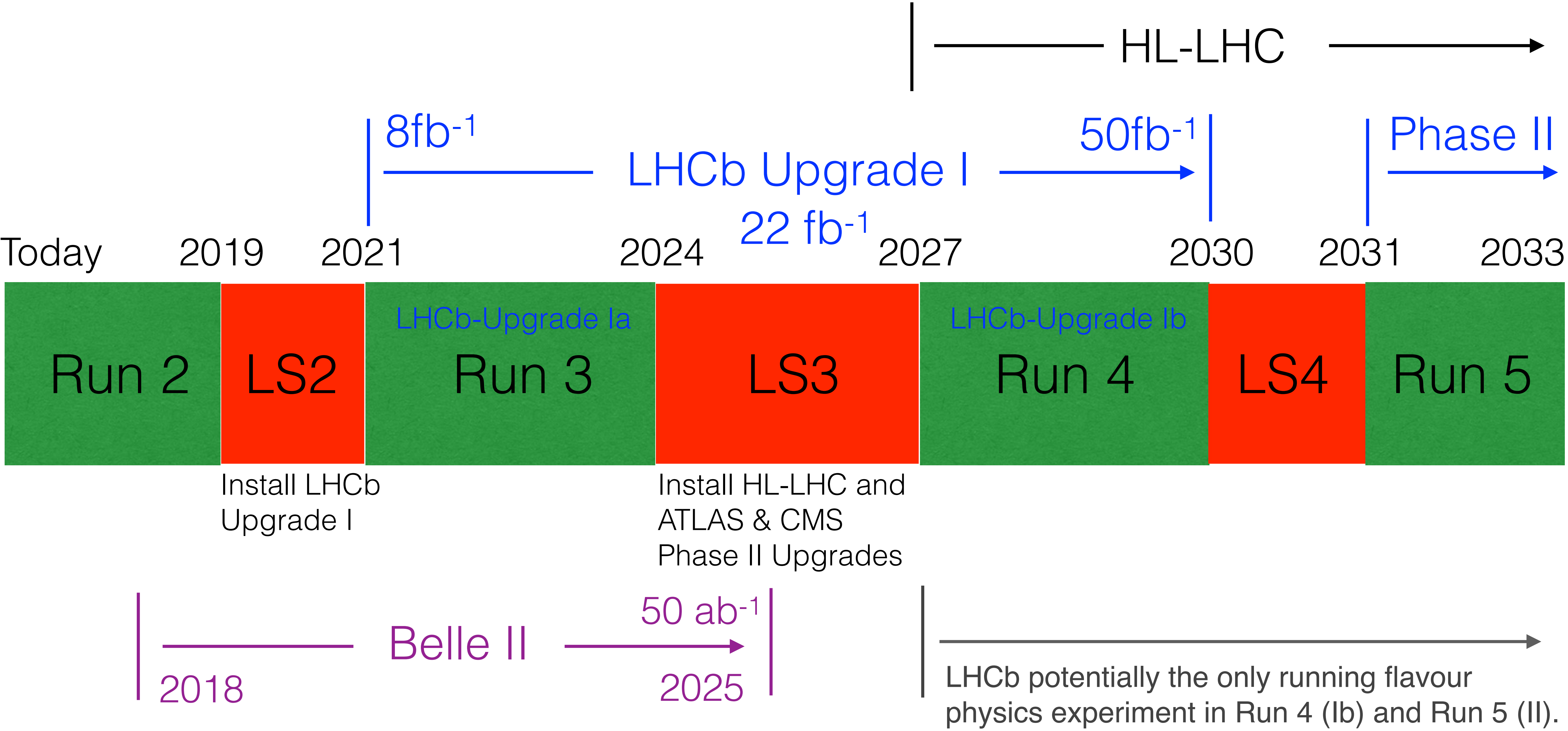
on behalf of the LHCb Collaboration

LHCb timeline in the next decades



HL-LHC

8fb^{-1} LHCb Upgrade I 50fb^{-1}

Phase II

22 fb^{-1}

Today 2019 2021 2024 2027 2030 2031 2033

Run 2 | LS2 | LHCb-Upgrade Ia Run 3 | LS3 | LHCb-Upgrade Ib Run 4 | LS4 | Run 5

Install LHCb
Upgrade I

Install HL-LHC and
ATLAS & CMS
Phase II Upgrades

Belle II 50 ab^{-1}

2018 2025

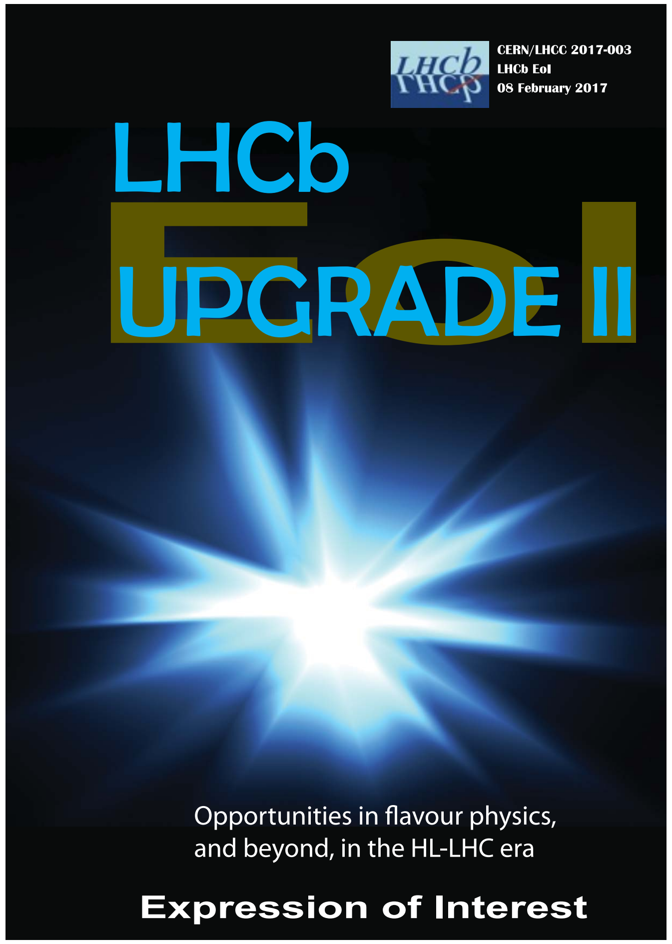
LHCb potentially the only running flavour physics experiment in Run 4 (Ib) and Run 5 (II).

The LHCb Upgrade I will enable to integrate about 22 fb^{-1} by end of Run 3 and 50 fb^{-1} by end of Run 4.

Proposal for future LHCb upgrades

- LHCb Upgrade I in Run-3, Run-4 (2021-2023, 2026-2029)
  - L_{inst}= 2 x 10^{33} cm^{-2} s^{-1}, integrate 50 fb^{-1} by the end of Run 4.
  - Profit from LS3 for a “consolidation” of Upgrade I in Run 4 (1b).
- LHCb Upgrade II in Run 5 (2031-2033) and beyond.
  - New experiment to be installed in LS4
  - L_{inst} = 2 x 10^{34} cm^{-2} s^{-1}, integrate > 300 fb^{-1}.
  - May be the only general heavy flavour experiment on this timescale.

CERN-LHCC-2017-003



CERN/LHCC 2017-003
LHCb EoI
08 February 2017

LHCb
UPGRADE II
EoI

Opportunities in flavour physics,
and beyond, in the HL-LHC era

Expression of Interest

“It is proposed to upgrade the LHCb experiment in order to take full advantage of the flavour-physics opportunities at the High Luminosity LHC (HL-LHC).

.....

This project will extend the HL-LHC's capabilities to search for physics beyond the Standard Model, and implements the highest-priority recommendation of the European Strategy for Particle Physics (Update 2013), which is to exploit the full potential of the LHC for a variety of physics goals, including flavour.”

LHCb Upgrade I (Run 3)

VErtex LOcator

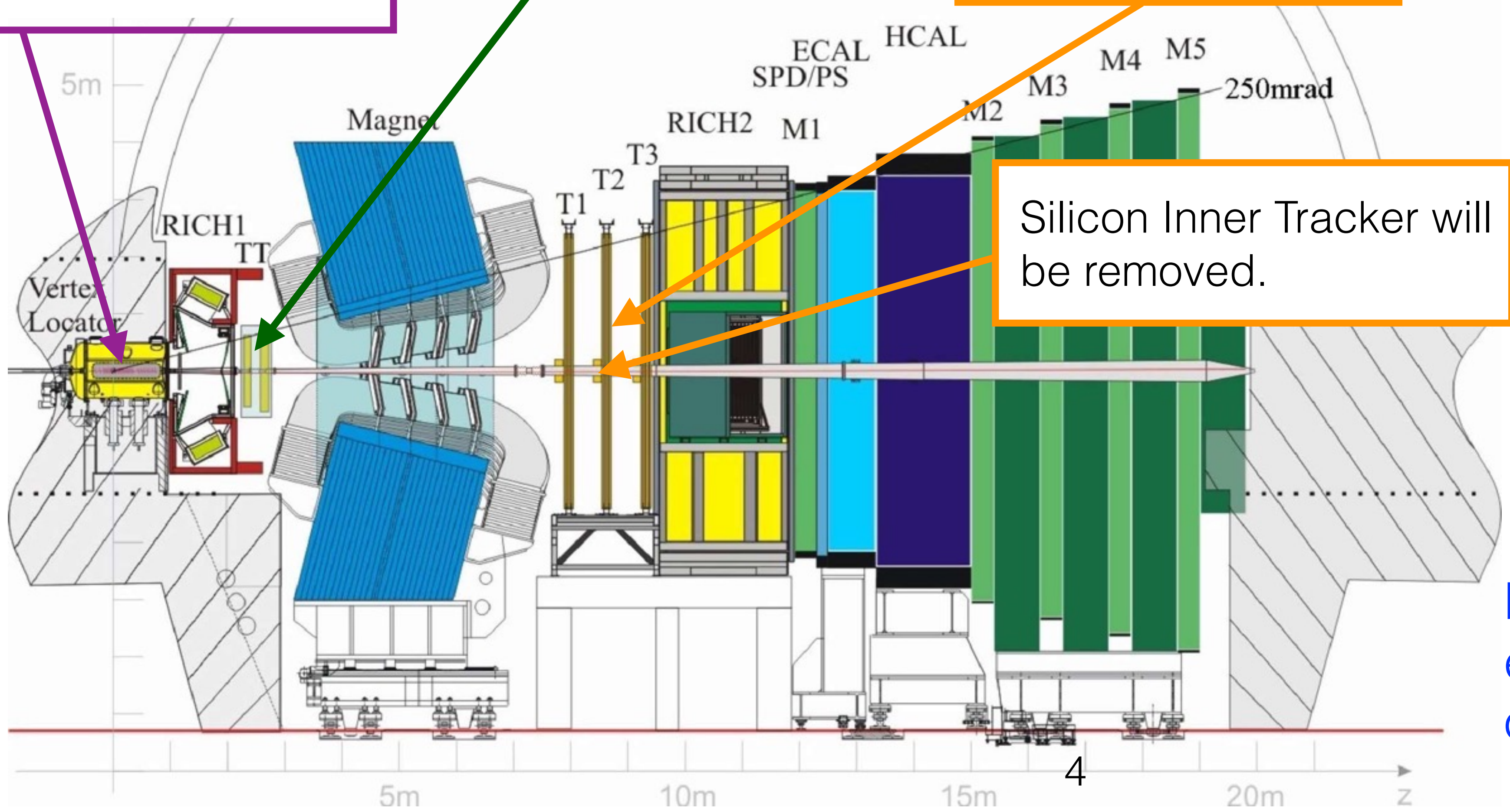
- From strip sensors to hybrid pixel detectors
- Closer to the beam (from 8.2 mm to 5.1 mm)
- CO_2 cooling in micro-channel substrate
- New RF box
- Fluence in the innermost region 8×10^{15} MeV n_{eq} cm^{-2}

Upstream Tracker

- 4 planes (x-u-v-x) of Si strips sensors
- Staves staggered: overlap in x
- Closer to the beam pipe
- Finer granularity
- Bi-phase CO2 cooling in stave support

SCIntillating FIbres

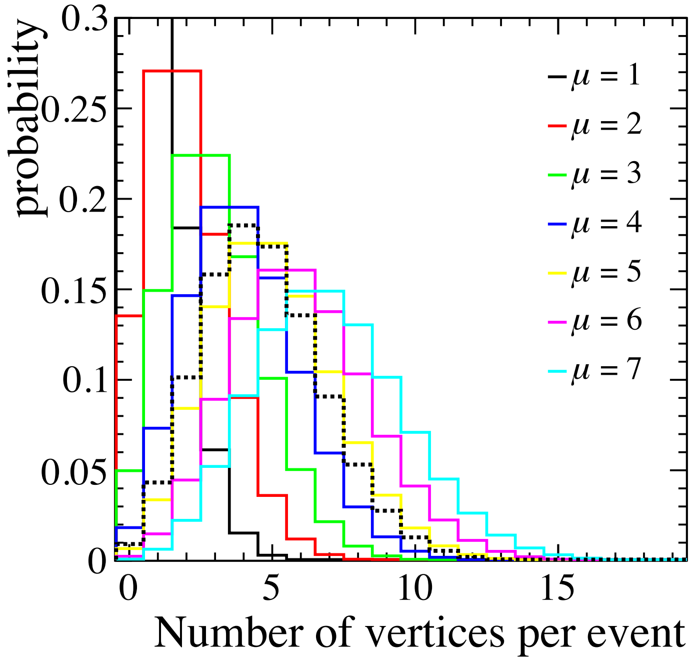
- Scintillating fibres as active detector elements
- 3 stations with 4 detection layers (x-u-v-x)
- 2 x 2.5 m long modules with mirror in the middle
- Readout with SiPMs at the outer edge



Silicon Inner Tracker will be removed.

Upgrade (current) Conditions

- visible interactions=5.5 (1.1)
- $\sqrt{s}$=14 TeV (13 TeV)
- lumi: 2×10^{33} cm^{-2} s^{-1} (4×10^{32} cm^{-2} s^{-1})
- expected integrated lumi: 50 fb^{-1} (8 fb^{-1})



LHCB-TDR-013

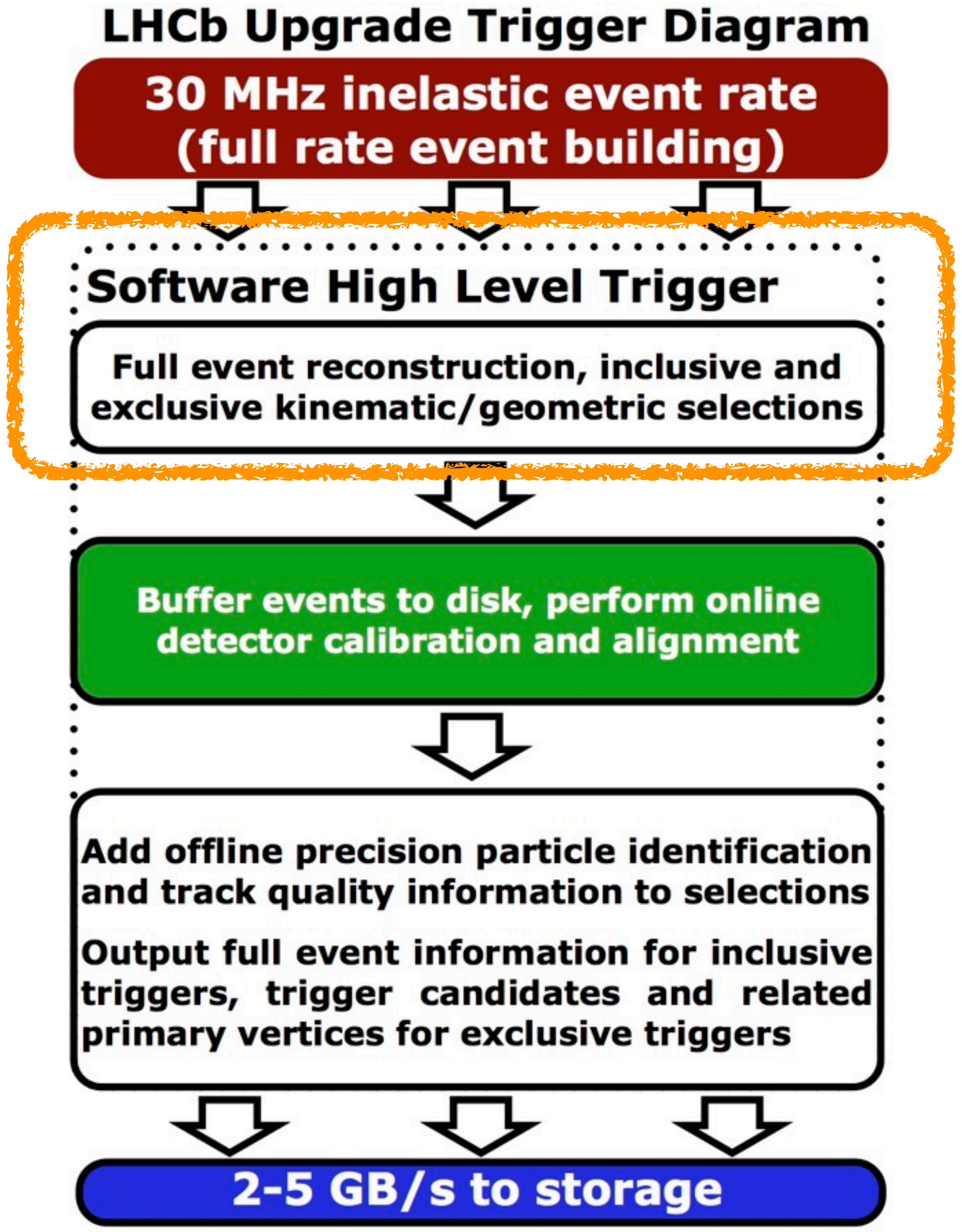
Major upgrade of the electronics to allow the read-out of all sub-detectors at 40MHz.

LHCb Upgrade Trigger

- Detector read-out at 40 MHz (30 MHz of visible pp collisions).

- From CERN-LHCC-2014-016: "*The main challenge for the trigger-less readout is to build a cost-effective system that can handle the sizable bandwidth of 4 TBytes/s.*" and "*In 2019 we expect to be able to run 400 instances of the Moore application on a server. Therefore, the CPU time budget for each Moore application is 13 ms assuming a farm of 1000 servers, and an input rate of 30 MHz.*" Estimated cost in 2014 was 2.8 MCHF.

- 30 MHZ of events (at L=2 x10^{33}) must be fully reconstructed in realtime with an excellent quality.



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

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

Event (today full size) 70 KB → 70kHz

Event (today turbo size) 5 KB → 1000kHz

LHCb Upgrade Trigger

- No possible any further offline data processing.
  - Physics output will entirely rely on the real-time analysis. Signal and control mode selections for a given measurement must be fully prepared in advance.
  - Control of systematics will be crucial.
- Physics not reconstructed in the trigger is lost. For instance, downstream tracks (essential to increase acceptance and efficiency of long-lived particles K_S,K_L,Λ) are not in the Run 3 base plan at the moment. Computing power not sufficient.
- Evolution of computing power and costs estimates were assumed to be too optimistic in 2013 (CERN-LHCC-2014-016). It may be possible to have some “safety knob” (LLT, GEC cuts, prescaling) in order to reduce the input rate to the EFF.

LHCb-Upgrade: physics reach

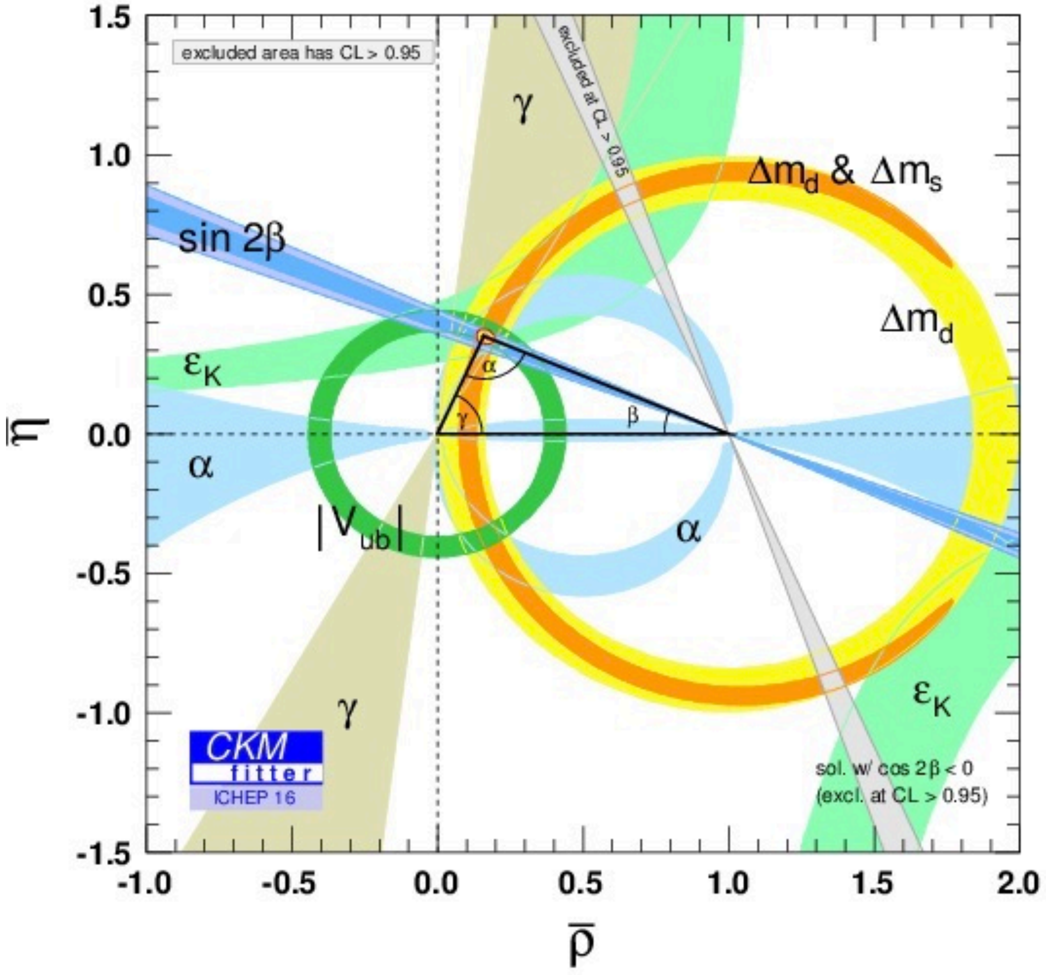
- Classic broad-range measurements
  - CKM physics and search for very rare decays
- Measurements in specific sectors where anomalies are emerging in recent years.
  - Lepton-flavour universality in b → s $\ell^+\ell^-$ transitions, and related b → s $\ell^+\ell^-$ picture of decay rates.
  - Lepton-flavour universality in semi-leptonic b-hadron decays.
- Spectroscopy (not covered here)
  - While primarily looking for BSM physics, the LHC is also a unique laboratory to better understand QCD in the low-energy regime.

I am not going to cover all items, but just a small set of observables of common interest to LHCb and Belle II. I will focus on the LHCb-Upgrade Phase I, but you can easily project from 50 fb^{-1} to 300 fb^{-1}, assuming the 1/sqrt(S) behavior (that is our best guess at the moment) .

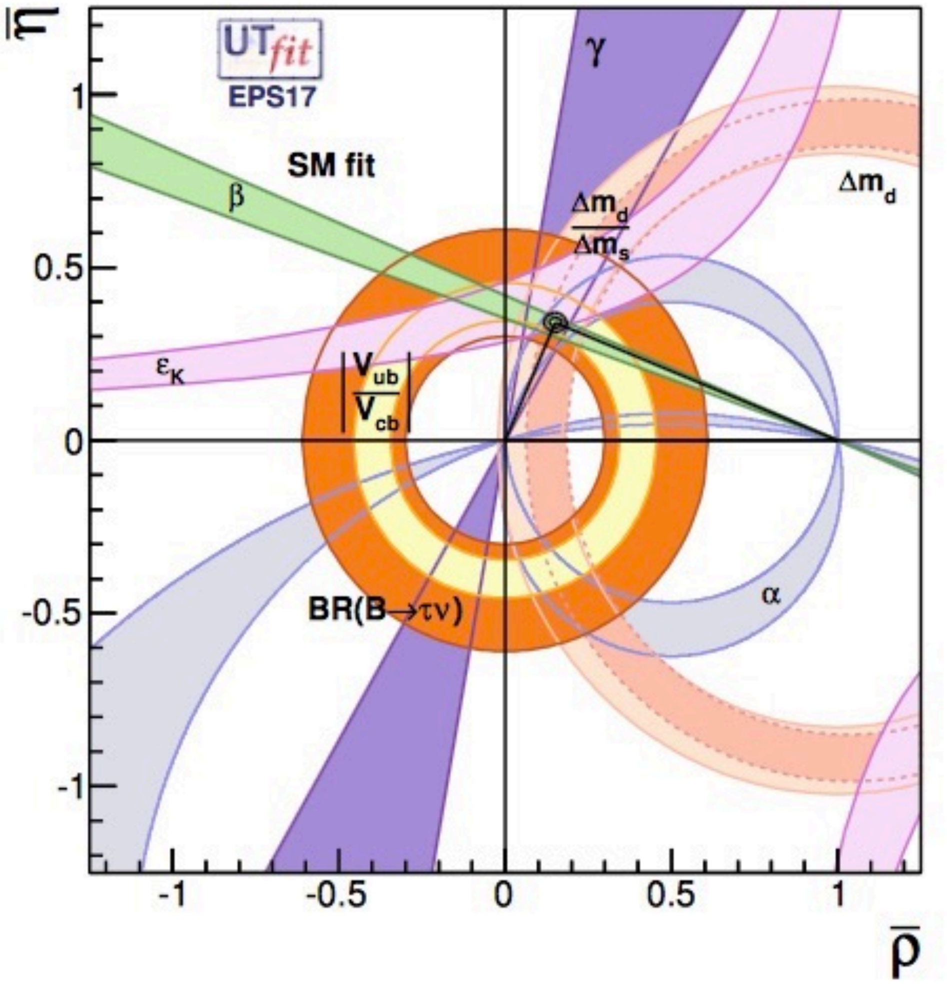
Classic program

Global UT fits today

http://ckmfitter.in2p3.fr



http://www.utfit.org

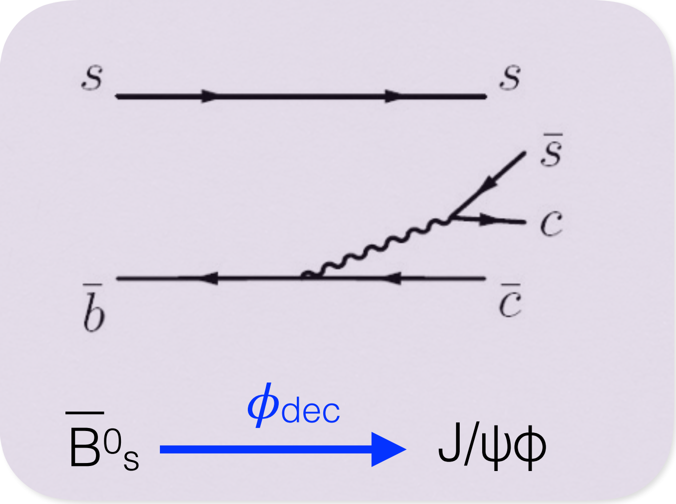


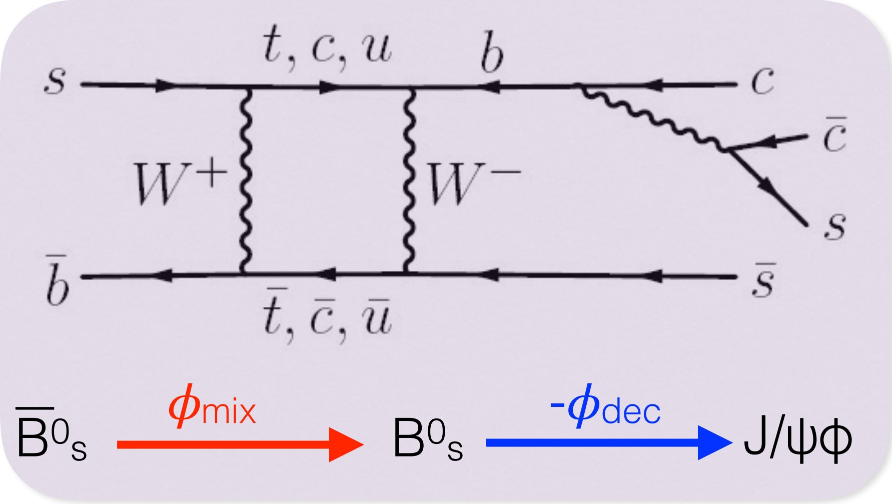
Great success of the Standard Model CKM picture, but there is still room for new physics at the 10%-15% level. Still far from EW precision tests. Relevant inputs from Lattice QCD and flavour theory to make strong statements.

ϕ_s from $b \to c\bar{c}s$ transitions

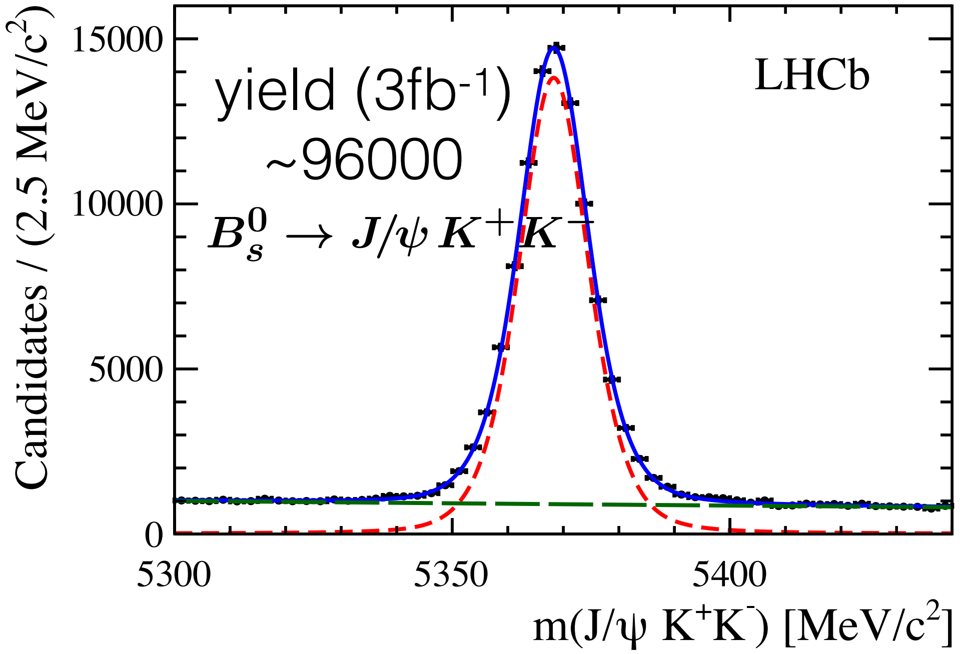
- Golden mode $B_s \to J/\psi\phi$ proceeds (mostly) via a $b \to c\bar{c}s$ tree diagram

- Interference between Bs mixing and decay graphs:





Phys. Rev. Lett. 114, 041801 (2015)



- Measures the phase-difference ϕ_s between the two diagrams, Precisely predicted from global CKM fits in the SM to be $\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad can be altered by NP.

- A small pollution (~5%) of sub-leading SM amplitudes must be accurately taken under control via subsidiary measurements (i.e. $B^0 \to J/\psi\pi\pi$).

ϕ_s, $\Delta\Gamma_s$ and $\Delta\Gamma_d$

http://www.slac.stanford.edu/xorg/hflav/

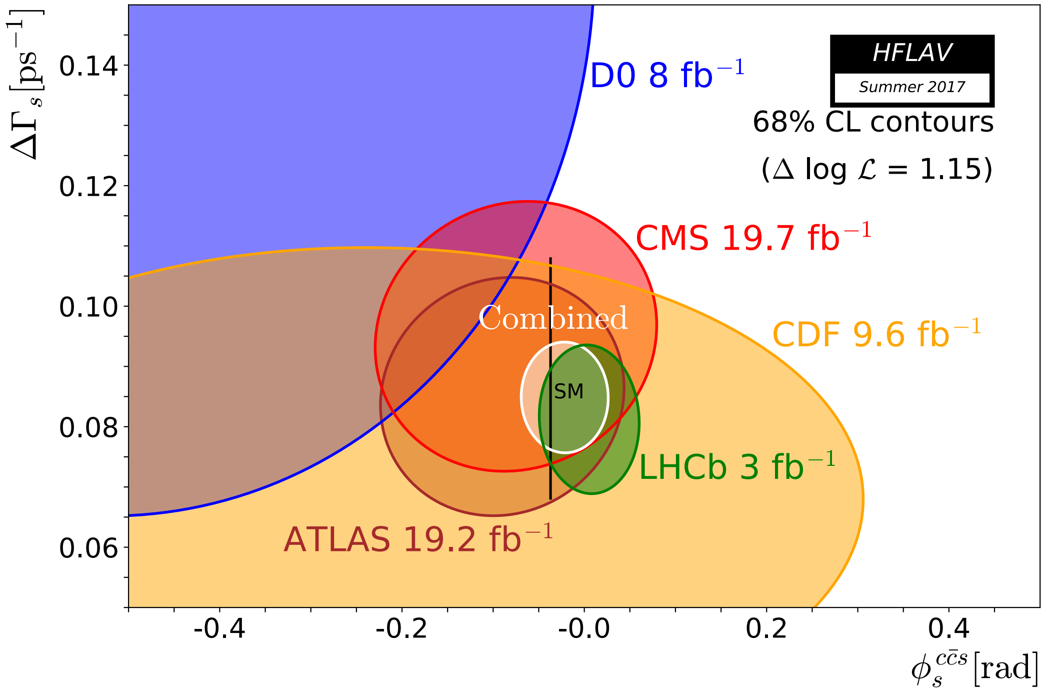


Table 1: Direct experimental measurements of $\phi_s^{c\bar{c}s}$, $\Delta\Gamma_s$ and Γ_s using $B_s^0 \to J/\psi\,\phi$, $J/\psi\,K^+K^-$, $\psi(2S)\phi$, $J/\psi\,\pi^+\pi^-$ and $D_s^+D_s^-$ decays. Only the solution with $\Delta\Gamma_s > 0$ is shown, since the two-fold ambiguity has been resolved in Ref. [1]. The first error is due to statistics, the second one to systematics. The last line gives our average.

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\,\phi$	9.6 fb^{-1}	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\,\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\,\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\,\phi$	14.3 fb^{-1}	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$	[5]
ATLAS	above 2 combined		$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	[5]
CMS	$J/\psi\,\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi\,K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$	[7]
LHCb	$J/\psi\,\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	$J/\psi\,K^+K^{-a}$	3.0 fb^{-1}	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$	[9]
LHCb	above 3 combined		$+0.001 \pm 0.037$(tot)	$+0.0813 \pm 0.0073 \pm 0.0036$	[9]
LHCb	$\psi(2S)\phi$	3.0 fb^{-1}	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	[10]
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	[11]
All combined			-0.021 ± 0.031	$+0.085 \pm 0.006$	

[a] $m(K^+K^-) > 1.05$ GeV/c^2.

- ϕ_s precision mostly driven by LHCb, but ATLAS and CMS also contribute significantly to the global endeavor. Systematic uncertainties much lower than statistical ones.
  - HFLAV 2017 world average $\phi_s = -21 \pm 31$mrad,
  - SM prediction [CKM fitter]: $\phi_s = -37.6 \pm 0.8$ mrad.
- Compatible with the SM at the present level of precision.
- Most precise measurement of $\Delta\Gamma_d/\Gamma_d$ by ATLAS, by comparing decay-time distributions of $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}$ decays:

$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\,(\text{stat.}) \pm 0.9\,(\text{syst.})) \times 10^{-2}$$

JHEP 06 (2016) 081

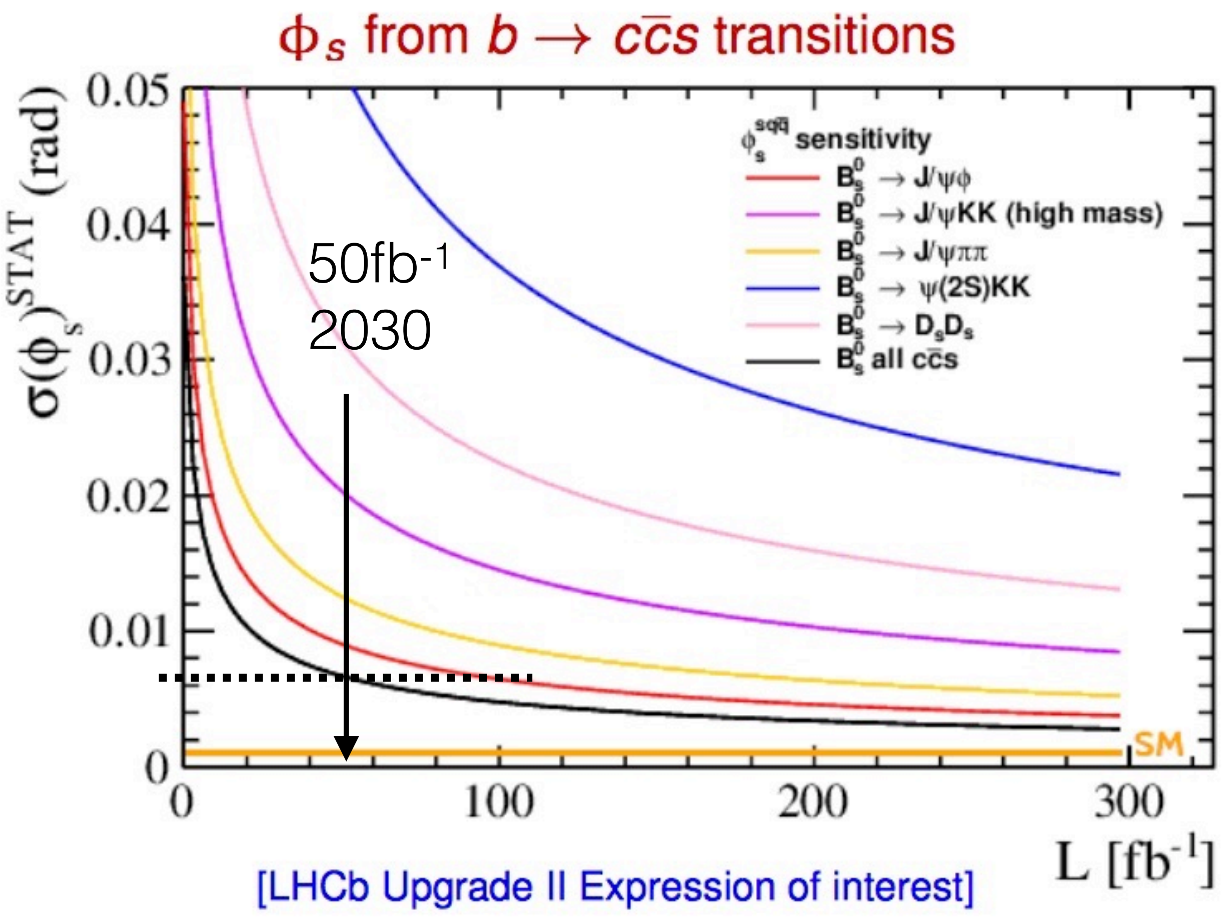
With 1fb^{-1} of data in Run 1 LHCb measures:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = -0.044 \pm 0.025 \pm 0.011$$

JHEP04(2014)114

Prospect for ϕ_s

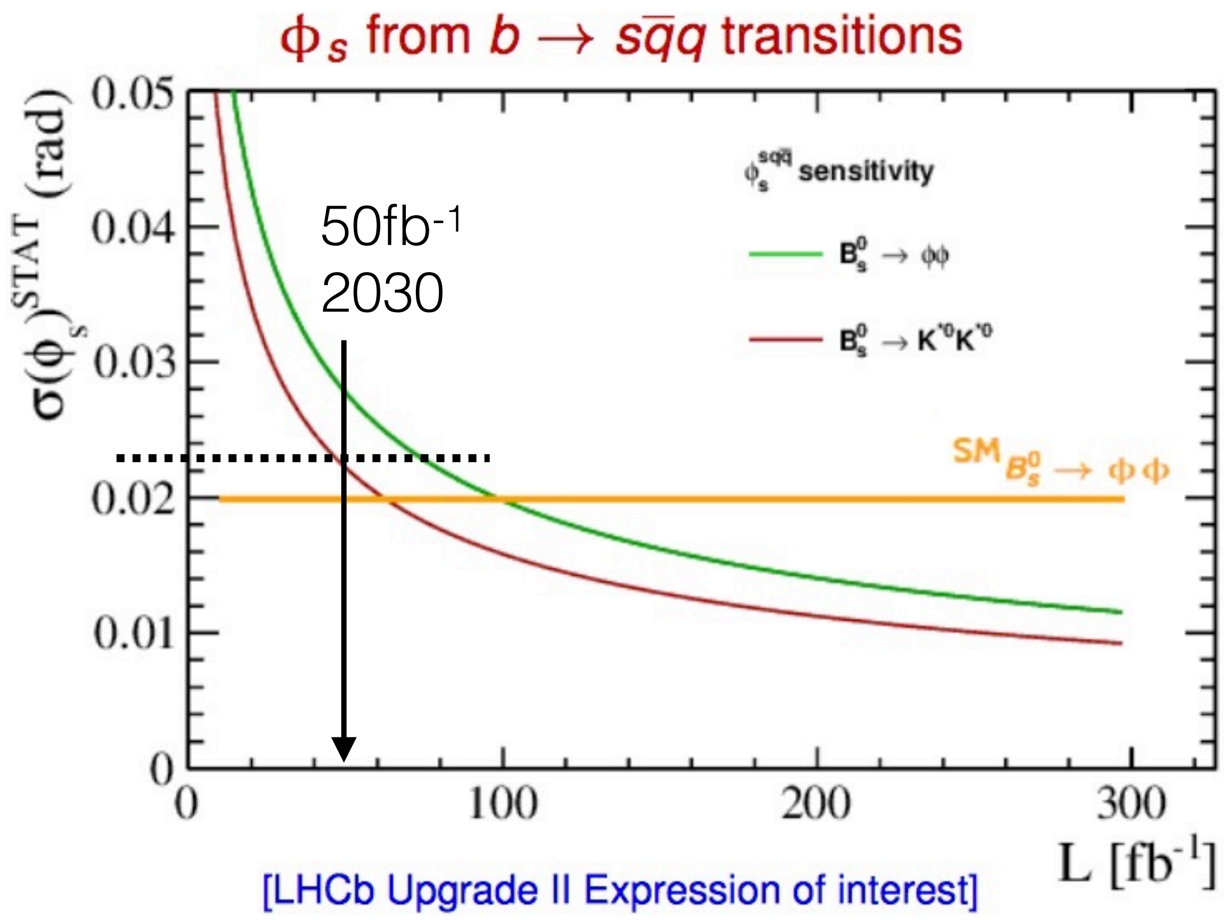
Statistical uncertainty as a function of integrate luminosity assuming current detector performances.



ϕ_s from $b \to c\bar{c}s$ transitions

50fb^{-1}
2030

[LHCb Upgrade II Expression of interest]



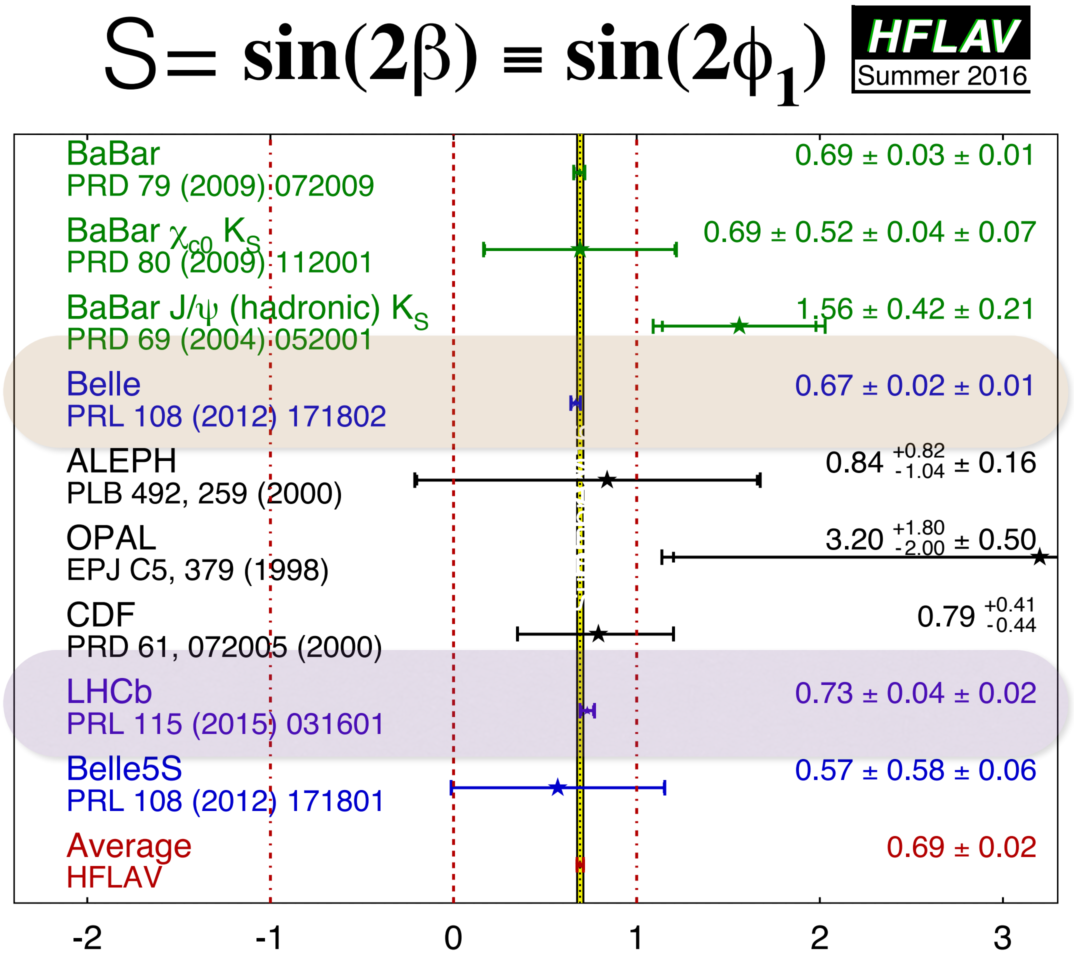
ϕ_s from $b \to s\bar{q}q$ transitions

50fb^{-1}
2030

[LHCb Upgrade II Expression of interest]

Complementary channels like b→s$\bar{s}$s would in principle greatly benefit of the new trigger approach, that should be more efficient of the current hadronic trigger (Calorimeter+HLT). This assumes LHCb will be able to reconstruct at offline quality all tracks in real-time including also PID.

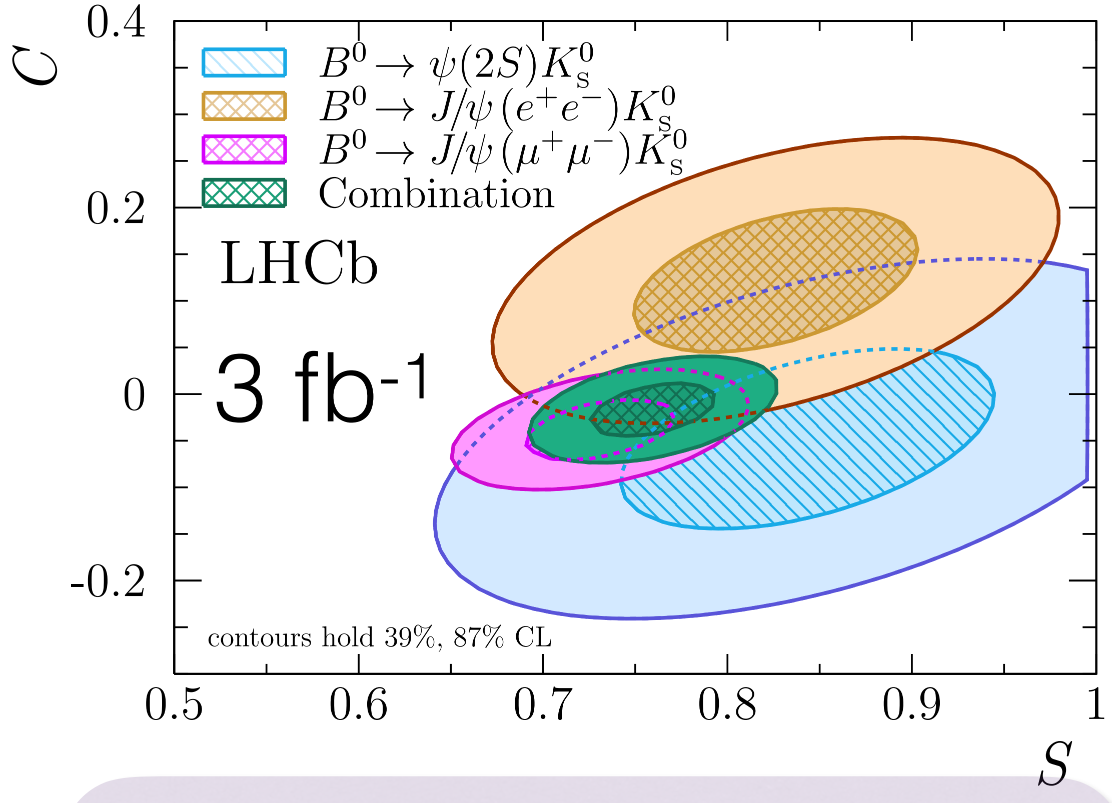
State of the art - sin(2β)



$$\boxed{S^{SM} \equiv \sin 2\beta^{SM} = 0.740^{+0.020}_{-0.025}}$$

[CKM Fitter]

arXiv:1709.03944 [hep-ex] (2017)



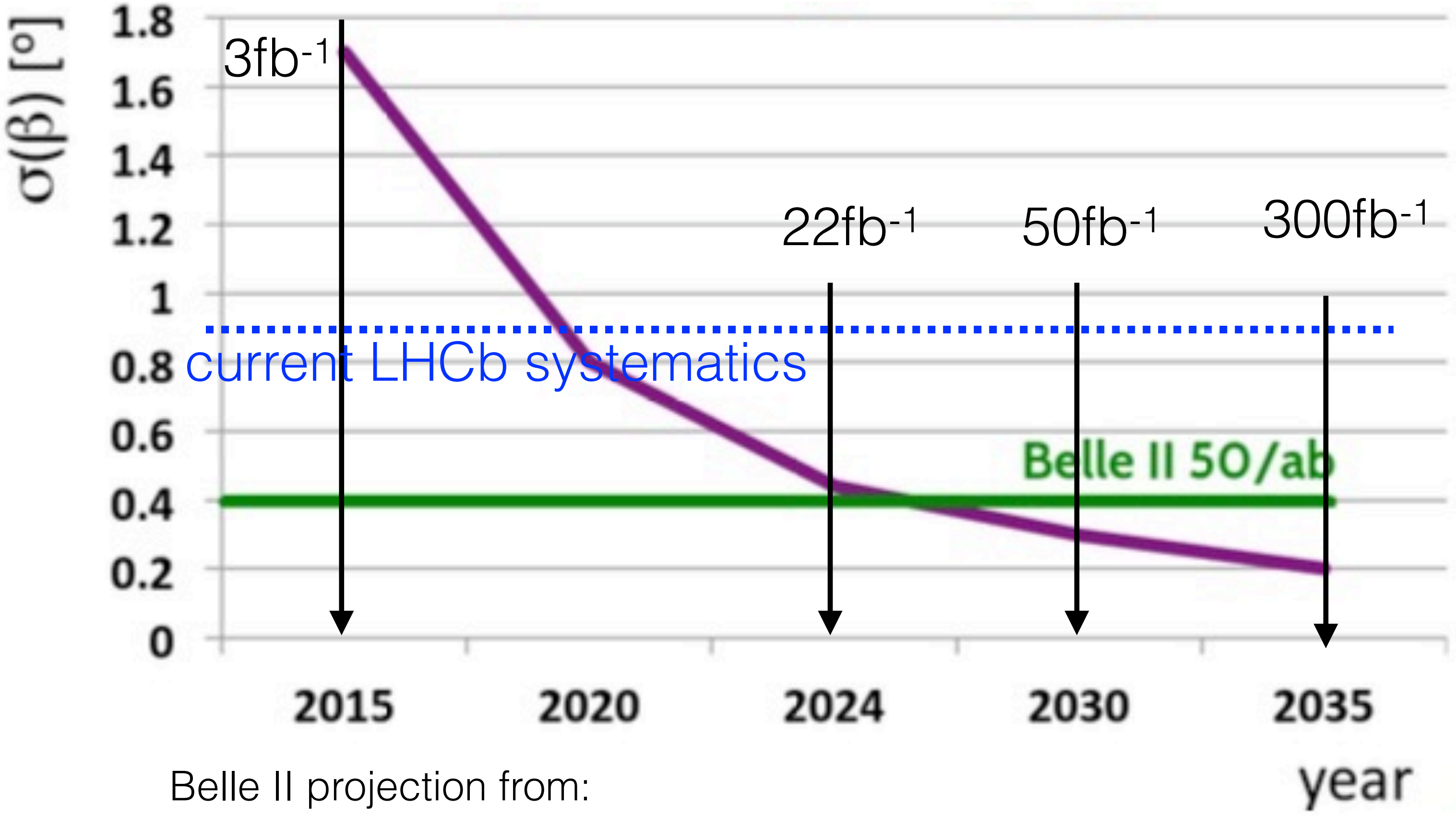
Final LHCb results on Run 1

$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = \quad 0.760 \pm 0.034$$

LHCb Run 1 precision very close to that of B-Factories.
Run 1 + Run 2 measurement is coming.

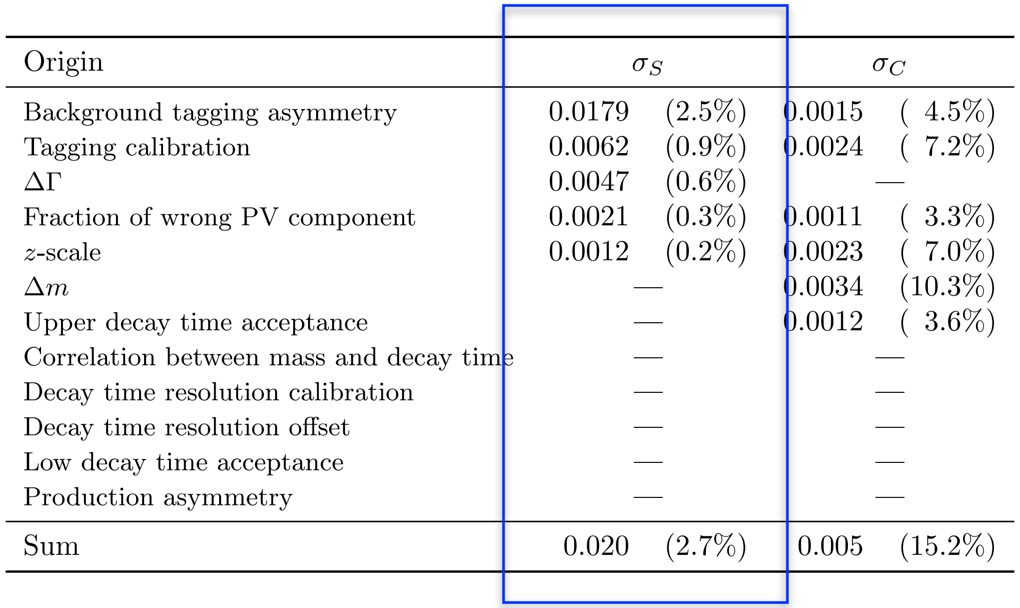
Prospect for sin(2β)

β from $B^0 \rightarrow J/\psi K_S \rightarrow [\mu^+\mu^-]K_S$



Belle II projection from:
https://confluence.desy.de/display/BI/B2TiP+B2TIPGoldenModes

Dominant Run 1 systematic uncertainty (Backg. tagging asymmetry) should easily reduce with the increasing of the statistics at the level or lesser than others.



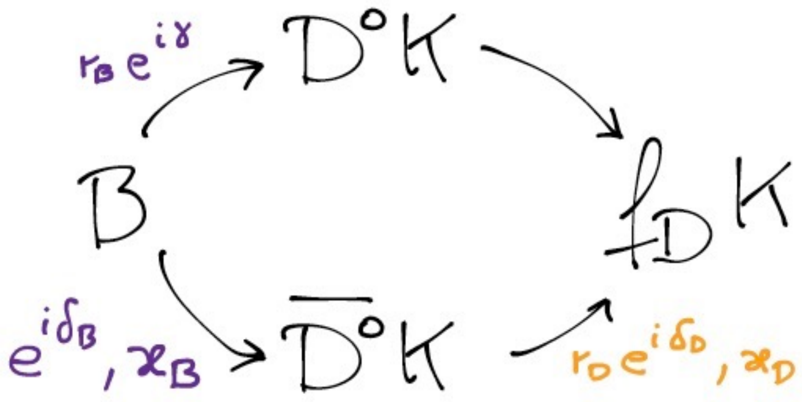
Origin	σ_S		σ_C	
Background tagging asymmetry	0.0179	(2.5%)	0.0015	(4.5%)
Tagging calibration	0.0062	(0.9%)	0.0024	(7.2%)
$\Delta\Gamma$	0.0047	(0.6%)	—	
Fraction of wrong PV component	0.0021	(0.3%)	0.0011	(3.3%)
z-scale	0.0012	(0.2%)	0.0023	(7.0%)
Δm	—		0.0034	(10.3%)
Upper decay time acceptance	—		0.0012	(3.6%)
Correlation between mass and decay time	—		—	
Decay time resolution calibration	—		—	
Decay time resolution offset	—		—	
Low decay time acceptance	—		—	
Production asymmetry	—		—	
Sum	0.020	(2.7%)	0.005	(15.2%)

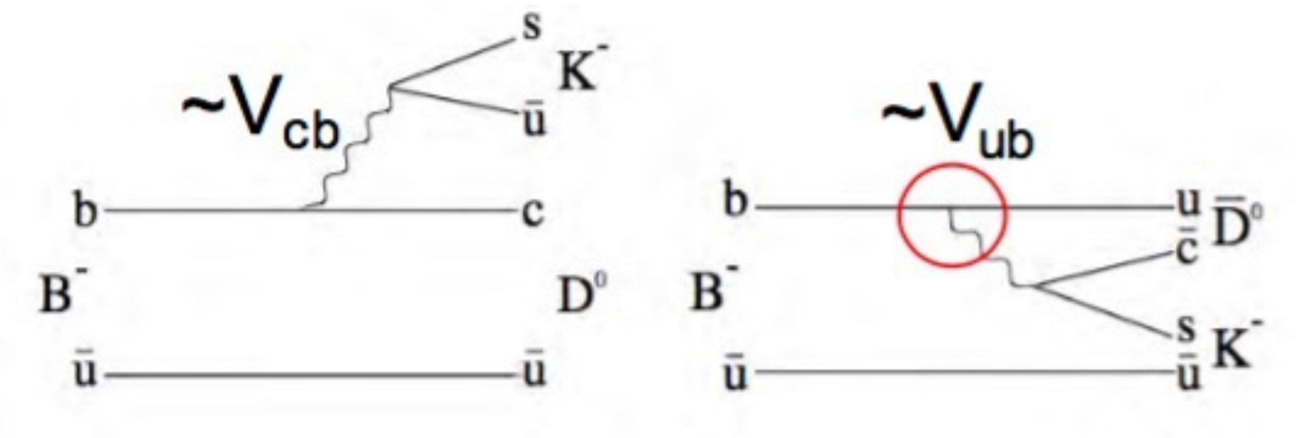
Phys. Rev. Lett. 115, 031601 (2015)

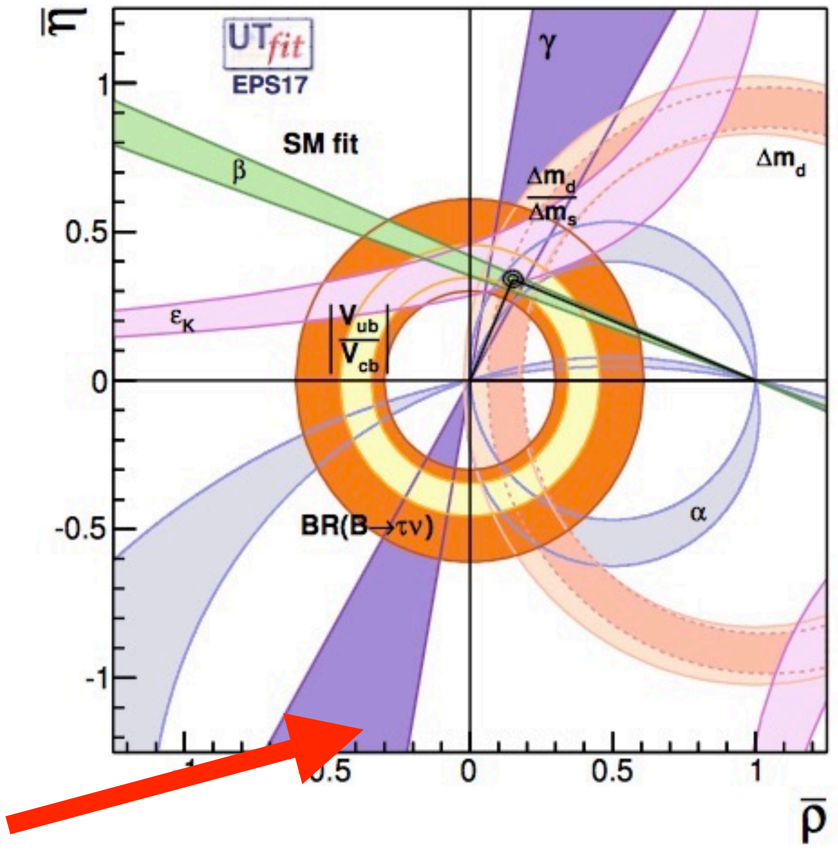
Really nice competition here.
In 2025 both experiments will reach a precision of about 0.4 degree.

Measurement of γ

- γ is the least known angle of the UT, although not for too long yet, measured via the interference between b → u and b → c tree-level transitions







- Simple and clean theoretical interpretation, but statistically very challenging (even if many cases flavour tagging not necessary).

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$$

LHCb combination of γ

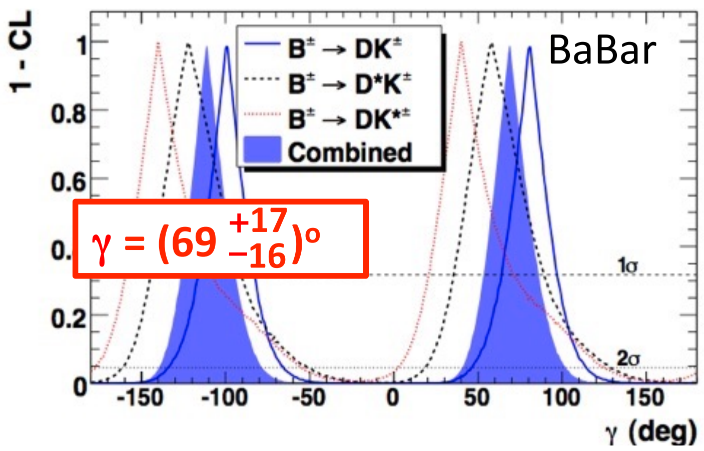
- A plethora of independent measurements exploiting different methods and decays.
- Recent additions to the LHCb combination.

- $B^\pm \to D^0 K^{*\pm}$ ADS/GLW [LHCb-CONF-2016-014] NEW
- $B^\pm \to D^{*0} K^{*\pm}$ GLW [LHCb-PAPER-2017-021] NEW
- $B_s^0 \to D_s^\mp K^\pm$ TD [LHCb-CONF-2016-015] $1\ \text{fb}^{-1} \to 3\ \text{fb}^{-1}$
- $B^\pm \to D^0 K^\pm$ GLW [LHCb-PAPER-2017-021] $3\ \text{fb}^{-1} \to 5\ \text{fb}^{-1}$

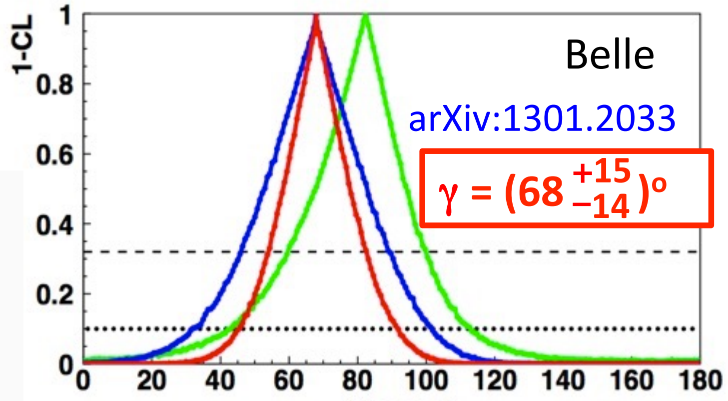
- Significantly more precise than previous results from the B- factories and undergoing continuous improvements.

[For more details see talk of F. Dordei LHCb Implication Workshop]

Phys. Rev. **D87** (2013) 052015

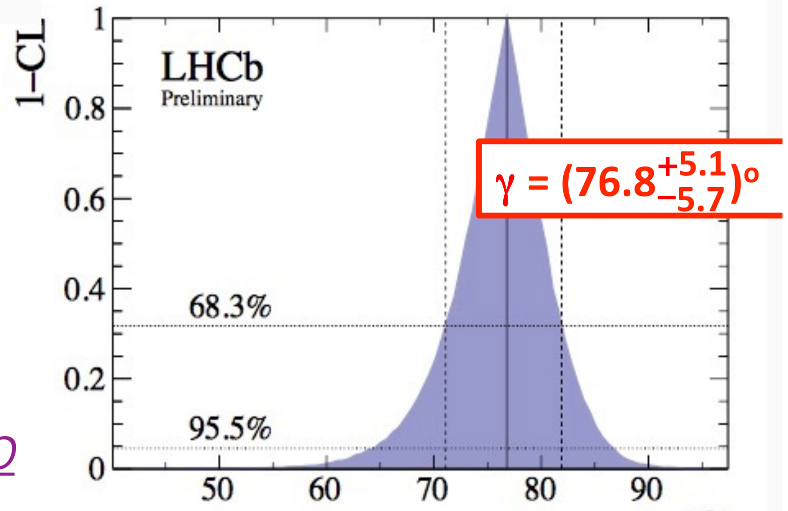


$\gamma = (69^{+17}_{-16})^\circ$



arXiv:1301.2033

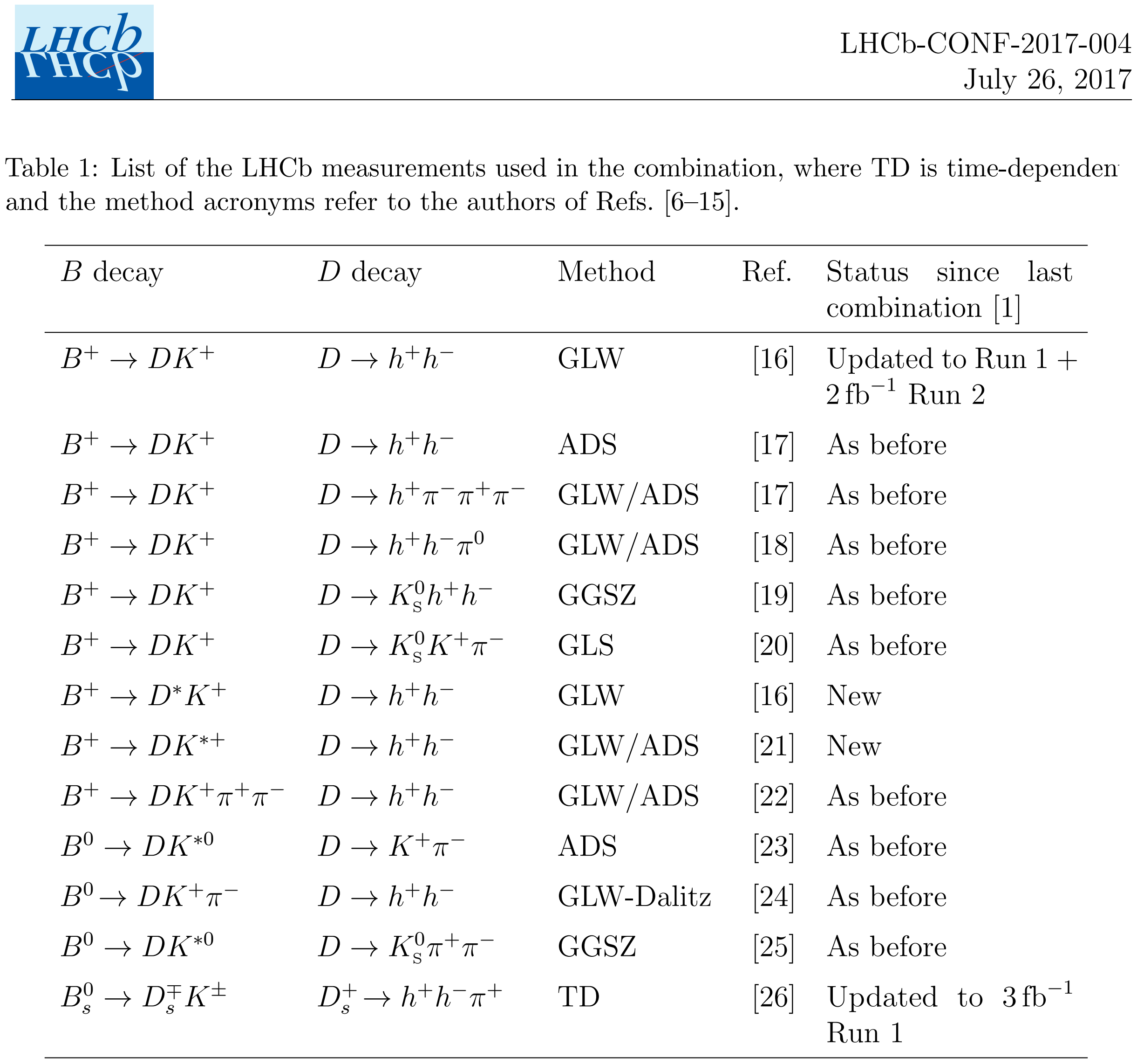
$\gamma = (68^{+15}_{-14})^\circ$



$\gamma = (76.8^{+5.1}_{-5.7})^\circ$

LHCb-CONF-2017-004

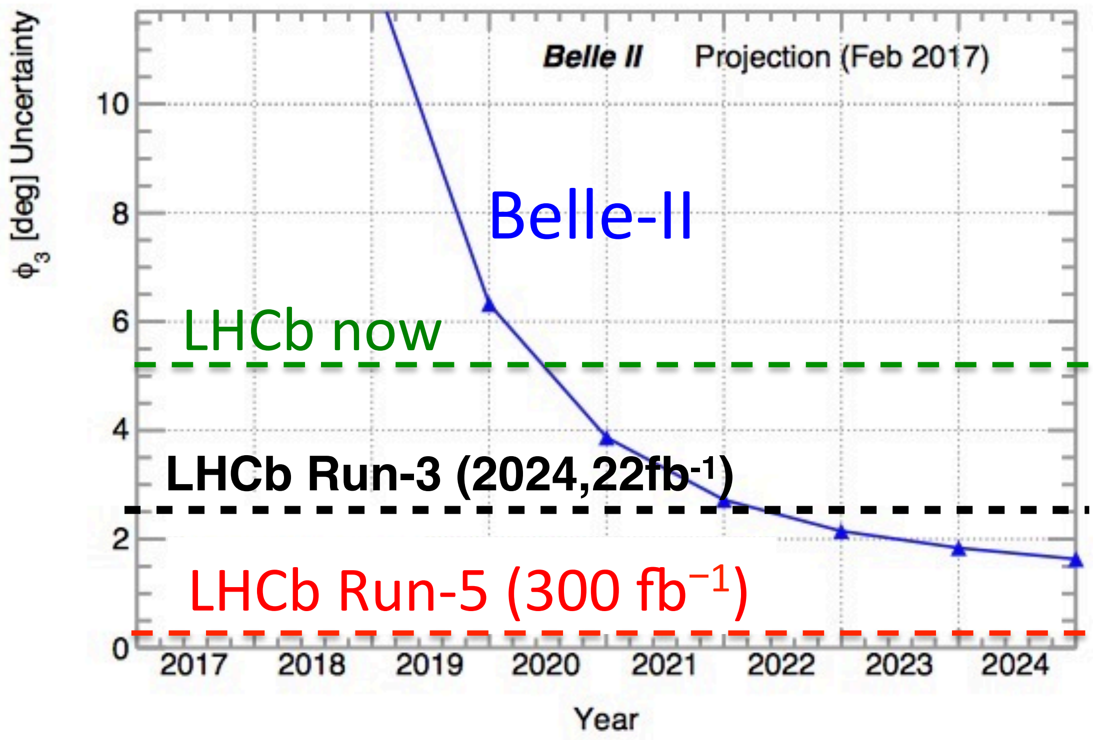
Prospect for γ



LHCb-CONF-2017-004
July 26, 2017

Table 1: List of the LHCb measurements used in the combination, where TD is time-dependen
and the method acronyms refer to the authors of Refs. [6–15].

B decay	D decay	Method	Ref.	Status since last combination [1]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[16]	Updated to Run 1 + 2 fb^{-1} Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[18]	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[19]	As before
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[20]	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[16]	New
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[21]	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[22]	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[23]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[24]	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[25]	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[26]	Updated to 3 fb^{-1} Run 1



Belle-II

LHCb now

LHCb Run-3 (2024,22fb^{-1})

LHCb Run-5 (300 fb^{-1})

a^d_{SL} and a^s_{SL}

$$A_{sl} = \frac{\Gamma(\overline{B}^0 \to B^0 \to f) - \Gamma(B^0 \to \overline{B}^0 \to \overline{f})}{\Gamma(\overline{B}^0 \to B^0 \to f) + \Gamma(B^0 \to \overline{B}^0 \to \overline{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_M$$

Sensitive to CPV in mixing.
SM predictions very small

- In order to improve precision must control detection asymmetries at very high precision, up to O(10^{-4})
- Large $D^+ \to K_S\pi^0$ control samples used to measure detector-induced charge asymmetries.
- Today estimate of residual backgrounds from simulation. It may be the challenge for future measurements.
- Future stat. uncertainty may approach the level of 0.2 x 10^{-3} with 300 fb^{-1} for both measurements.

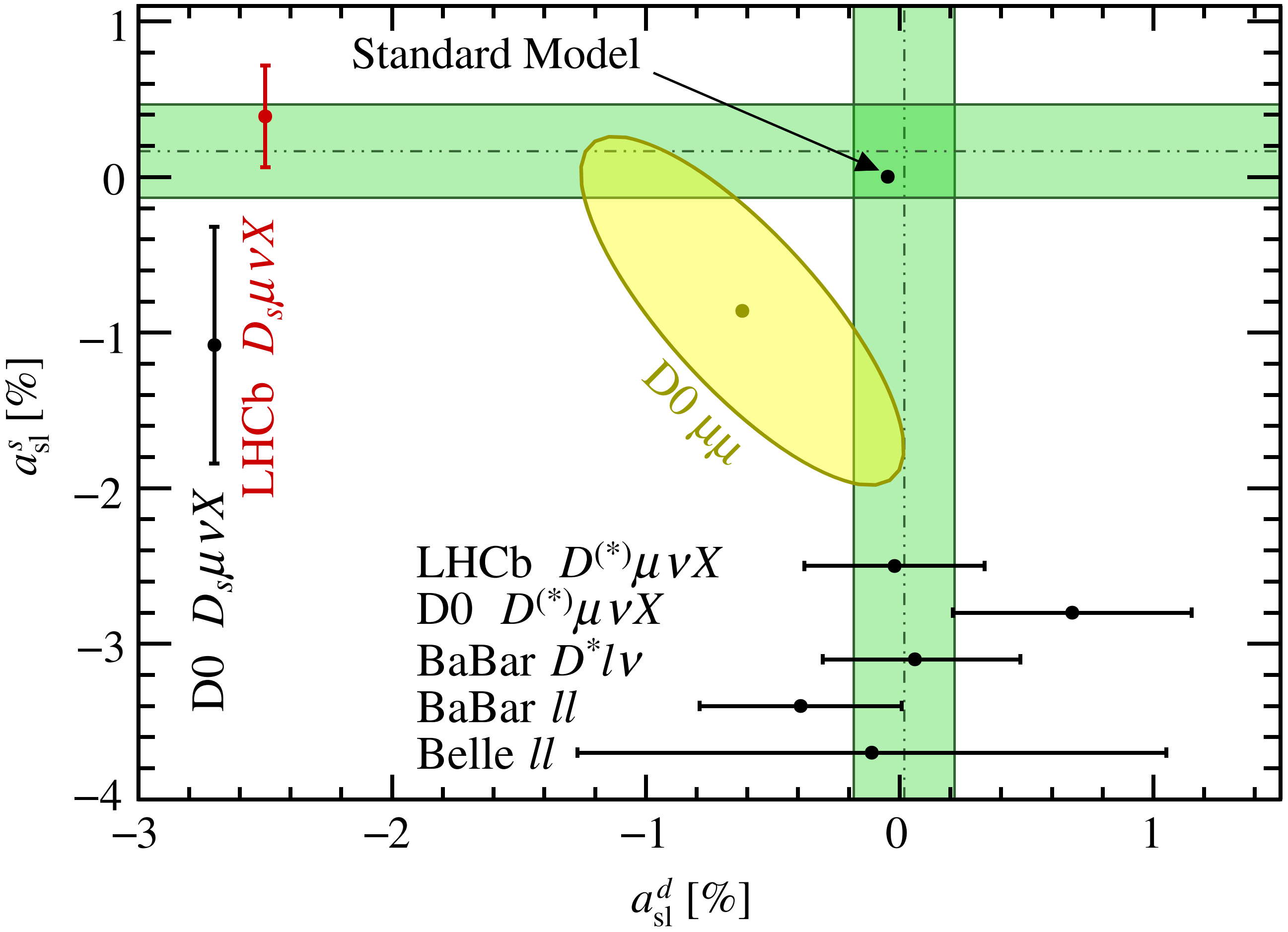
Run 1 - $3fb^{-1}$

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

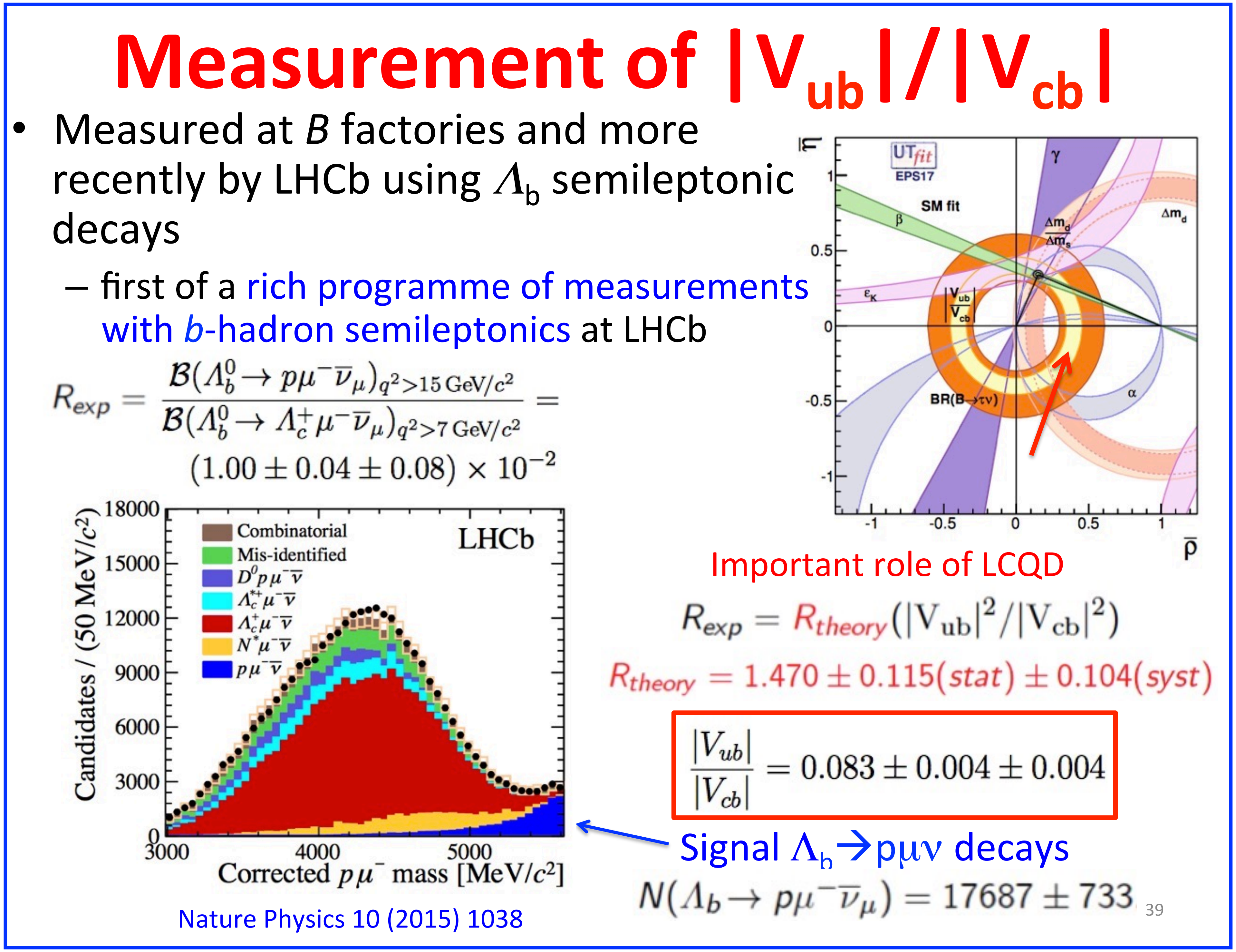
PRL 117, 061803 (2016)

$$a^d_{sl} = (-0.02 \pm 0.19 \pm 0.30)\%$$

PLB 713, 186 (2012)



V. Vagnoni, HL-LHC workshop 1 Nov 2017, https://indico.cern.ch/event/647676/



Measurement of $|V_{ub}|/|V_{cb}|$

- Measured at *B* factories and more recently by LHCb using Λ_b semileptonic decays
  - first of a rich programme of measurements with *b*-hadron semileptonics at LHCb

$$R_{exp} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08)\times 10^{-2}$$

Important role of LCQD

$$R_{exp} = R_{theory}(|V_{ub}|^2/|V_{cb}|^2)$$

$$R_{theory} = 1.470 \pm 0.115(stat) \pm 0.104(syst)$$

$$\boxed{\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004}$$

Signal $\Lambda_b \to p\mu\nu$ decays

$$N(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = 17687 \pm 733$$

Nature Physics 10 (2015) 1038

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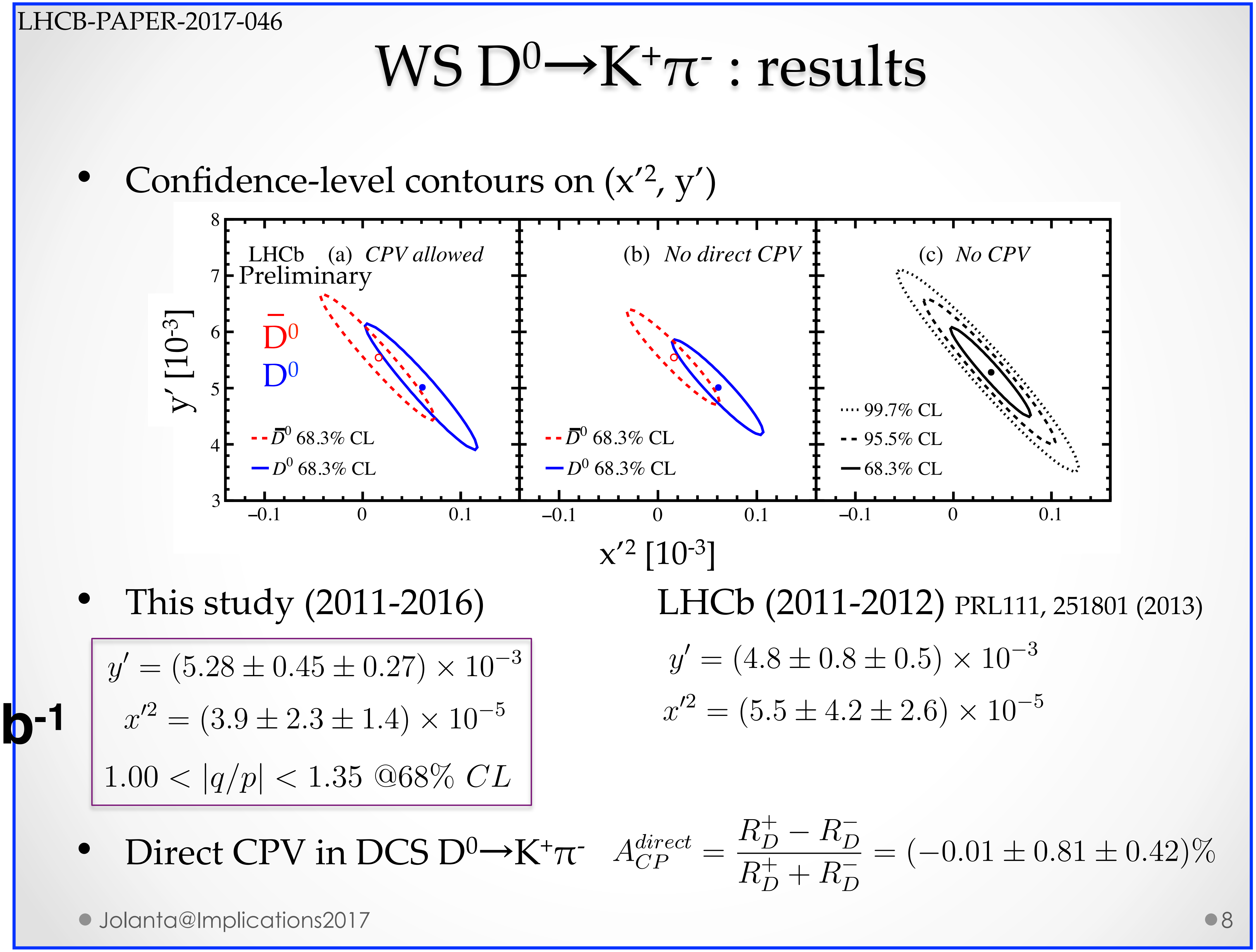
Mixing and CPV in charm

- D^0 mixing established by LHCb with overwhelming sensitivity measuring mainly time-dependent ratio of WS to RS $D^0 \rightarrow K\pi$ decays.
- "Large" mixing encourages searches for CP violation.
- Both direct and indirect CP violation searches have been performed with unprecedented precision with Run 1 data.
- No sign of CP violation yet, but now entering the interesting range.
- Formidable experimental challenge in preparation of very high precision measurements in the beauty sector in the Upgrade era. Charm is our crystal ball to see the future.

Jolanta Brodzicka , Implication workshop Nov 9th,2017
https://indico.cern.ch/event/646856/

NEW



LHCB-PAPER-2017-046

WS $D^0 \to K^+\pi^-$: results

- Confidence-level contours on (x'^2, y')

- This study (2011-2016)

$$y' = (5.28 \pm 0.45 \pm 0.27) \times 10^{-3}$$
$$x'^2 = (3.9 \pm 2.3 \pm 1.4) \times 10^{-5}$$
$$1.00 < |q/p| < 1.35 \ @68\% \ CL$$

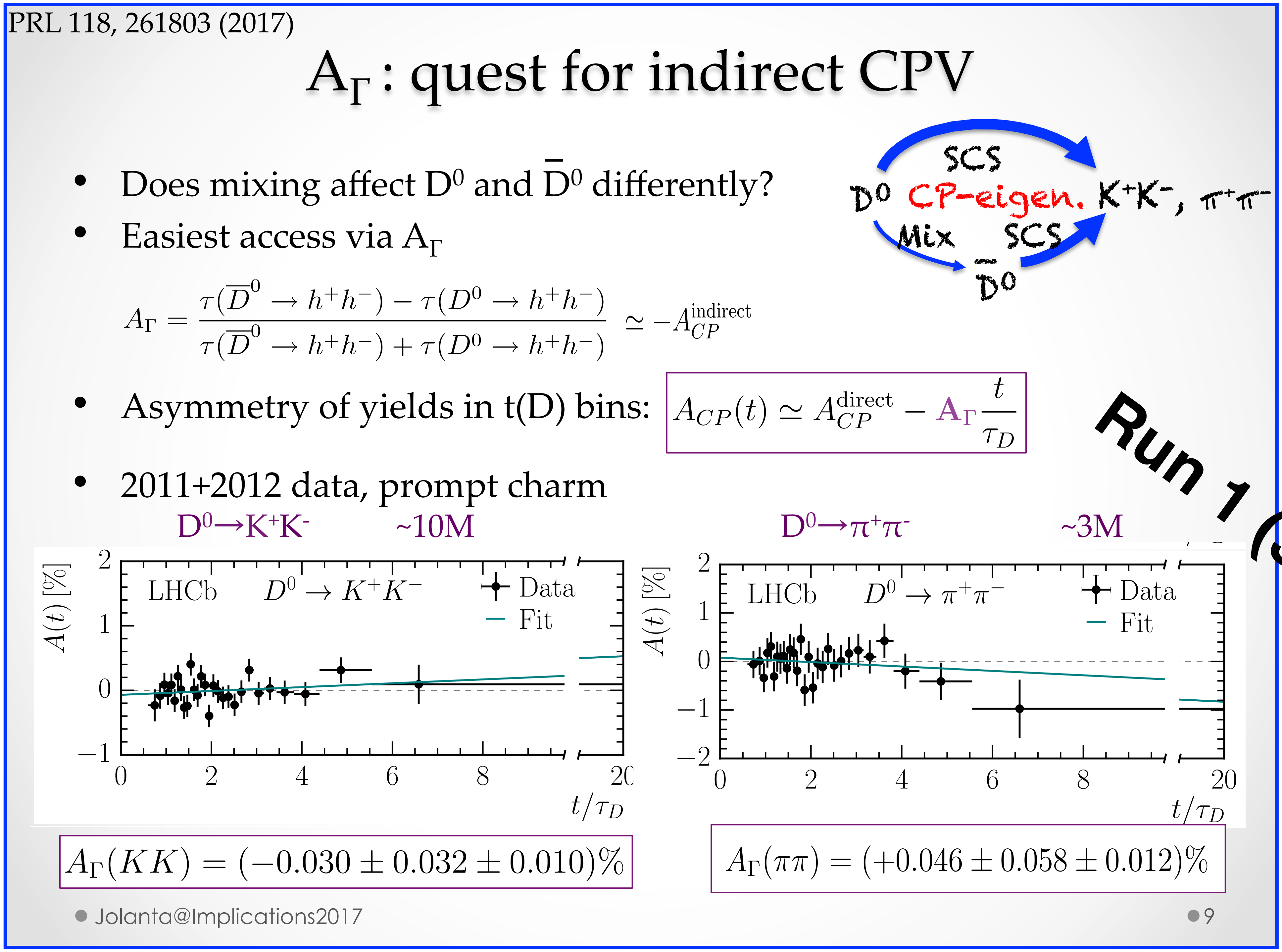
~5fb^{-1}

LHCb (2011-2012) PRL111, 251801 (2013)

$$y' = (4.8 \pm 0.8 \pm 0.5) \times 10^{-3}$$
$$x'^2 = (5.5 \pm 4.2 \pm 2.6) \times 10^{-5}$$

- Direct CPV in DCS $D^0 \to K^+\pi^-$ $A_{CP}^{direct} = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.01 \pm 0.81 \pm 0.42)\%$

Jolanta Brodzicka , Implication workshop Nov 9th,2017
https://indico.cern.ch/event/646856/



PRL 118, 261803 (2017)

A_Γ : quest for indirect CPV

- Does mixing affect D^0 and $\bar{D}^0$ differently?
- Easiest access via A_Γ

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \simeq -A_{CP}^{\text{indirect}}$$

- Asymmetry of yields in t(D) bins: $\boxed{A_{CP}(t) \simeq A_{CP}^{\text{direct}} - A_\Gamma \frac{t}{\tau_D}}$
- 2011+2012 data, prompt charm

$D^0 \to K^+K^-$ ~10M

$D^0 \to \pi^+\pi^-$ ~3M

$$\boxed{A_\Gamma(KK) = (-0.030 \pm 0.032 \pm 0.010)\%}$$

$$\boxed{A_\Gamma(\pi\pi) = (+0.046 \pm 0.058 \pm 0.012)\%}$$

Jolanta@Implications2017

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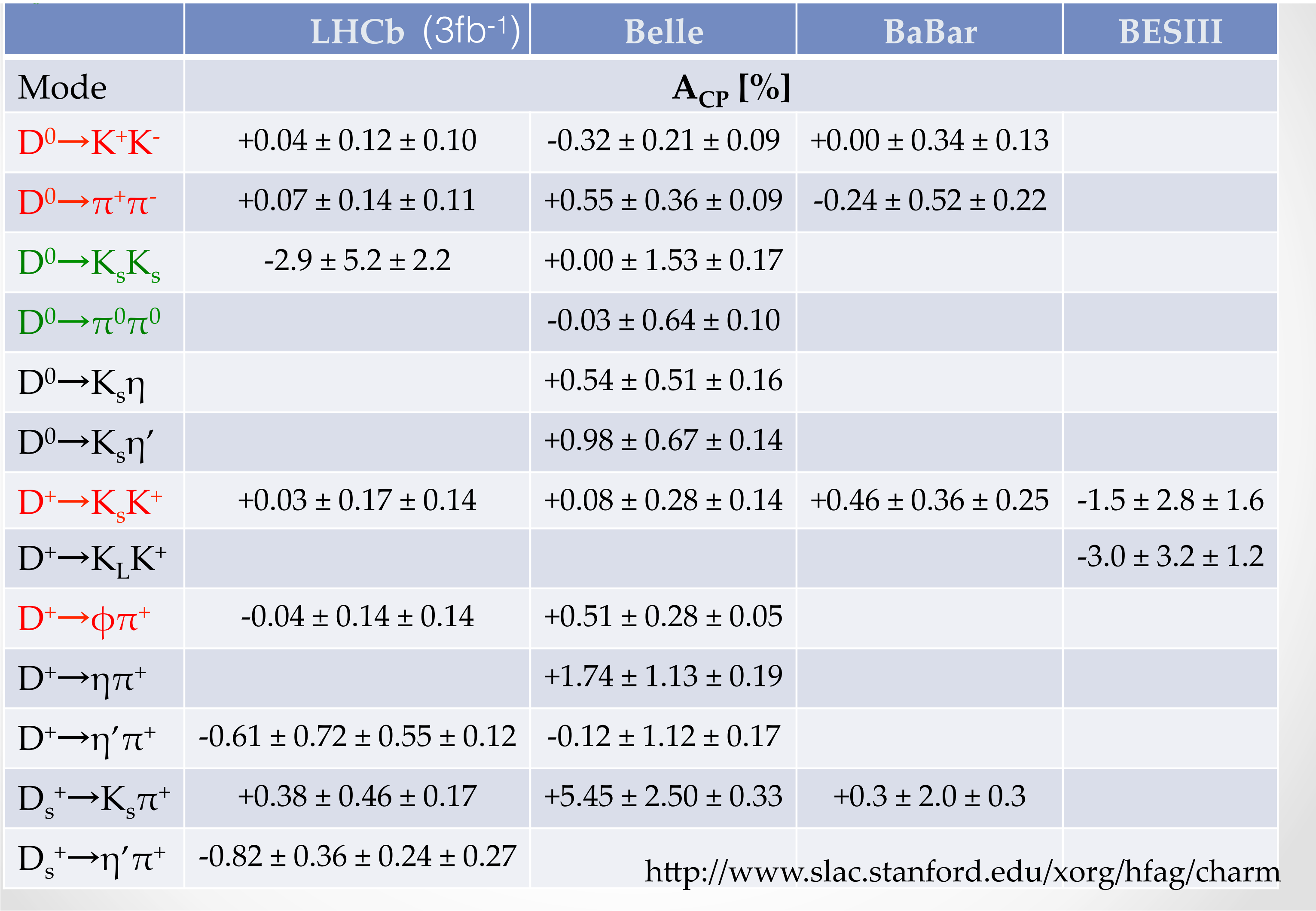
Run 1 (3fb^{-1})

Adding 2015-2016 data (~2fb^{-1}) ⇒ 30M $D^0 \to KK$ and 9M $D^0 \to \pi\pi$

Today (~5fb^{-1}): stat. uncertainty~ 2 x10^{-4} (expected syst. ~0.5 x10^{-4})
LHCb-Upgrade (50fb^{-1}): stat. uncertainty ~ 5 x10^{-5}

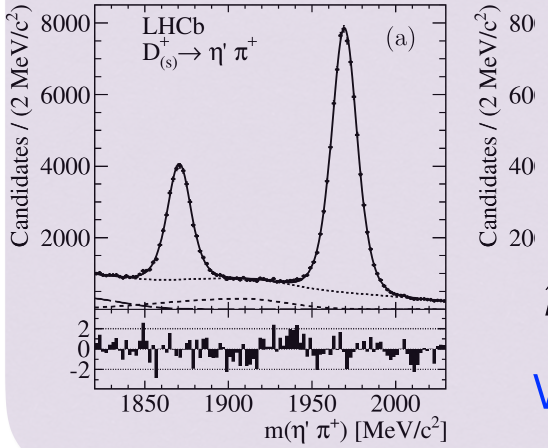
Time-integrated ACP in two-body decays



	LHCb (3fb^{-1})	Belle	BaBar	BESIII
Mode	A_{CP} [%]			
$D^0 \to K^+K^-$	+0.04 ± 0.12 ± 0.10	-0.32 ± 0.21 ± 0.09	+0.00 ± 0.34 ± 0.13	
$D^0 \to \pi^+\pi^-$	+0.07 ± 0.14 ± 0.11	+0.55 ± 0.36 ± 0.09	-0.24 ± 0.52 ± 0.22	
$D^0 \to K_sK_s$	-2.9 ± 5.2 ± 2.2	+0.00 ± 1.53 ± 0.17		
$D^0 \to \pi^0\pi^0$		-0.03 ± 0.64 ± 0.10		
$D^0 \to K_s\eta$		+0.54 ± 0.51 ± 0.16		
$D^0 \to K_s\eta'$		+0.98 ± 0.67 ± 0.14		
$D^+ \to K_sK^+$	+0.03 ± 0.17 ± 0.14	+0.08 ± 0.28 ± 0.14	+0.46 ± 0.36 ± 0.25	-1.5 ± 2.8 ± 1.6
$D^+ \to K_LK^+$				-3.0 ± 3.2 ± 1.2
$D^+ \to \phi\pi^+$	-0.04 ± 0.14 ± 0.14	+0.51 ± 0.28 ± 0.05		
$D^+ \to \eta\pi^+$		+1.74 ± 1.13 ± 0.19		
$D^+ \to \eta'\pi^+$	-0.61 ± 0.72 ± 0.55 ± 0.12	-0.12 ± 1.12 ± 0.17		
$D_s^+ \to K_s\pi^+$	+0.38 ± 0.46 ± 0.17	+5.45 ± 2.50 ± 0.33	+0.3 ± 2.0 ± 0.3	
$D_s^+ \to \eta'\pi^+$	-0.82 ± 0.36 ± 0.24 ± 0.27			

http://www.slac.stanford.edu/xorg/hfag/charm

PLB 771 (2017) 21-30



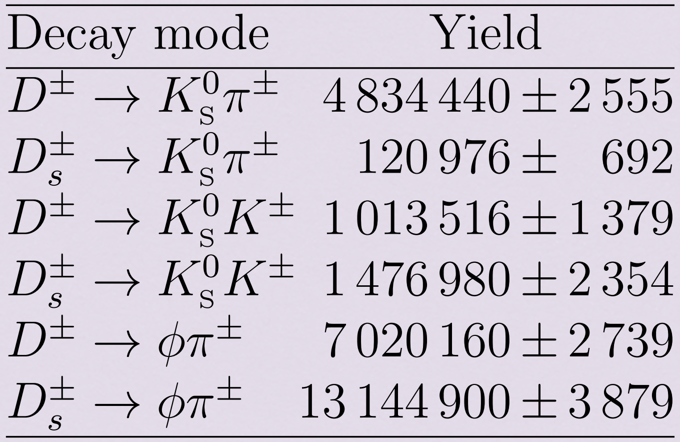
N($D^\pm$)=63k

N($D_s^\pm$)=152k

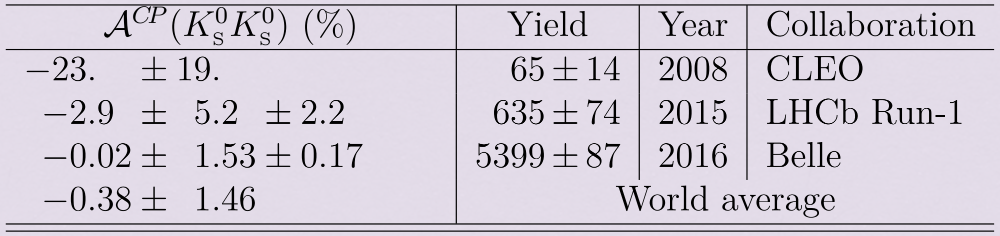
$\eta' \to \pi^+\pi^-\gamma$

with neutral

JHEP 10 (2014) 025 - 3fb^{-1}



Decay mode	Yield
$D^\pm \to K^0_S\pi^\pm$	$4\,834\,440 \pm 2\,555$
$D^\pm_s \to K^0_S\pi^\pm$	$120\,976 \pm 692$
$D^\pm \to K^0_S K^\pm$	$1\,013\,516 \pm 1\,379$
$D^\pm_s \to K^0_S K^\pm$	$1\,476\,980 \pm 2\,354$
$D^\pm \to \phi\pi^\pm$	$7\,020\,160 \pm 2\,739$
$D^\pm_s \to \phi\pi^\pm$	$13\,144\,900 \pm 3\,879$



$\mathcal{A}^{CP}(K^0_S K^0_S)$ (%)	Yield	Year	Collaboration
$-23. \pm 19.$	65 ± 14	2008	CLEO
$-2.9 \pm 5.2 \pm 2.2$	635 ± 74	2015	LHCb Run-1
$-0.02 \pm 1.53 \pm 0.17$	5399 ± 87	2016	Belle
-0.38 ± 1.46	World average		

JHEP 10 (2015) 055

$D^0 \to K_SK_S$ - No trigger in Run 1 for this mode.
Run 1+Run 2 (2018 - 8fb^{-1}) expected uncertainty ~ 1-2%.
Very hard to make reliable projections for Run 3. Proposed a dedicated “realtime” downstream tracker to be installed during LS3 (Run 4) to recover acceptance.

More charm

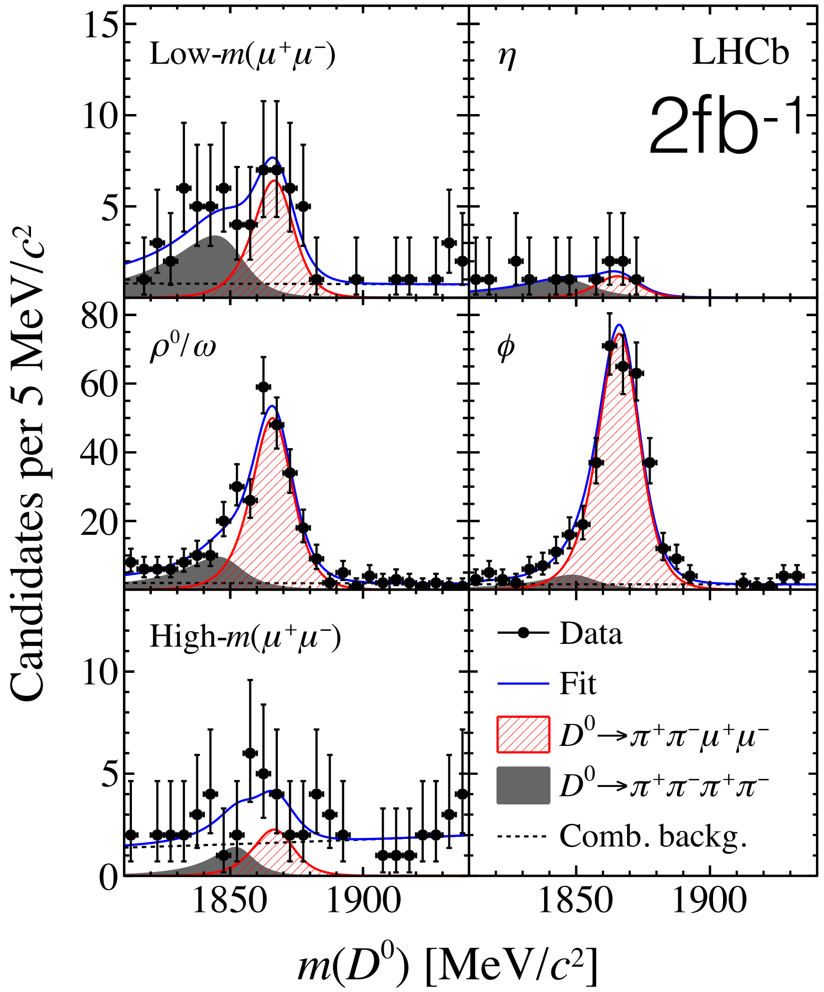
- LHCb collected huge sample of multi-body charm decays where CPV can be studied through the phase space (local asymmetries larger than integrated ones). Also measure how phase space evolves with time [t dep. Dalitz].
    - $D^0 \rightarrow K_s\pi\pi$ (2M), $D^0 \rightarrow$ KsKpi (200K), $D^0 \rightarrow$ K3pi (11M RS and 43k WS), $D^0 \rightarrow$ 4pi (1M), etc… yield in parentheses from Run 1 data.

- Limits improved by orders of magnitude with only Run 1 data on the search of rare decays ($D^0 \rightarrow \mu+\mu-$, $D^0 \rightarrow e\mu$, $D^0 \rightarrow \pi^-\pi^+\mu^-\mu^+$, $D^+_{(s)} \rightarrow \pi^+\mu^+\mu^-$, etc..).

- Pioneering the exploration of charm baryons (i.e Λ_c).

- Spectroscopy $B_c(2S)$, Ω_c excitations, first observation of a doubly-charmed baryon, the Ξ_{cc}^{++}

Phys. Rev. Lett. 119, 181805 (2017)



The rarest charm-hadron decays ever observed

$$\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \rightarrow K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

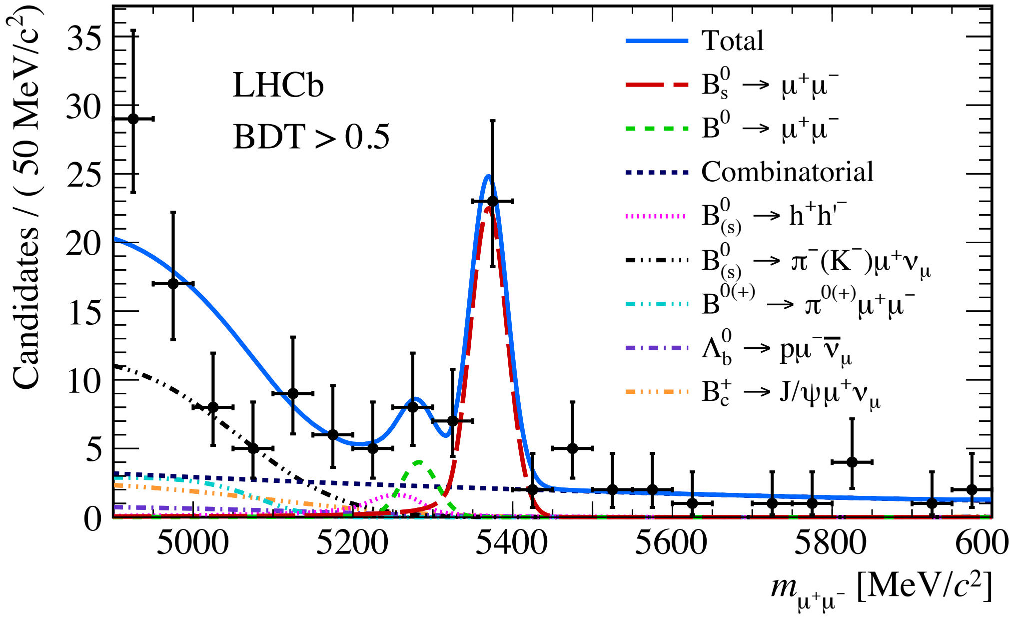
Update on B→μμ by LHCb with Run-2 data

PRL 118, 191801 (2017)

- New measurement from LHCb using Run-2 data has led this year to the first observation of the B_s→μμ decay from a single experiment:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9}$$

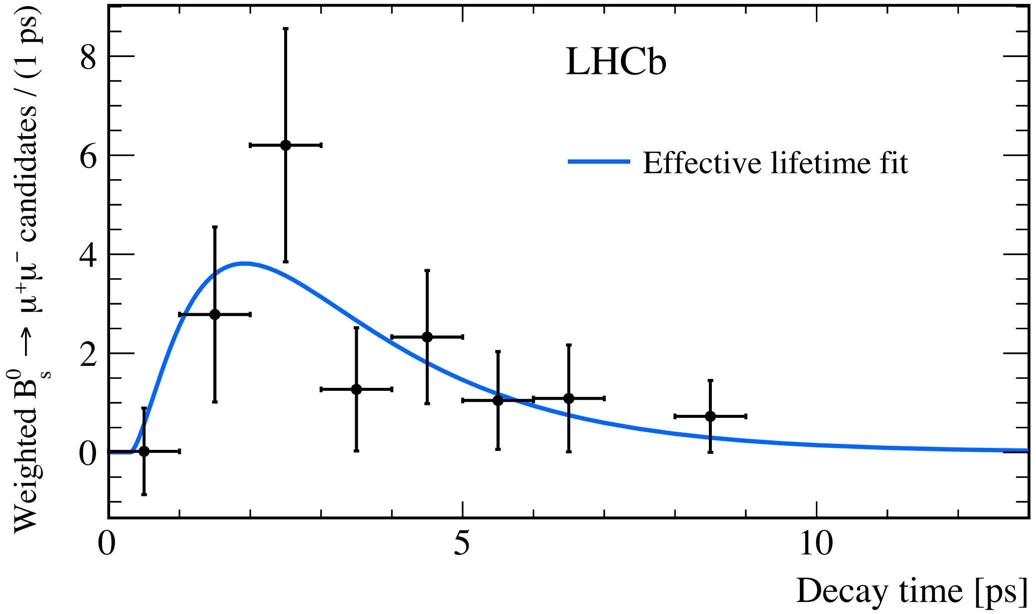
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$



- Moreover, it starts to be possible to measure other properties, such as the effective lifetime, that will be useful for discriminating between NP models.

- Experimental precision not yet in the interesting range, but important proof of concept.

- With 300 fb^{-1} in Run 5, LHCb has the potential to reach a relative uncertainty on the the ratio of B^0 to B_s branching fractions at better than 10%.
SM prediction BR(B^0) =$(1.0\pm0.1)\times10^{-10}$.



Some prospects

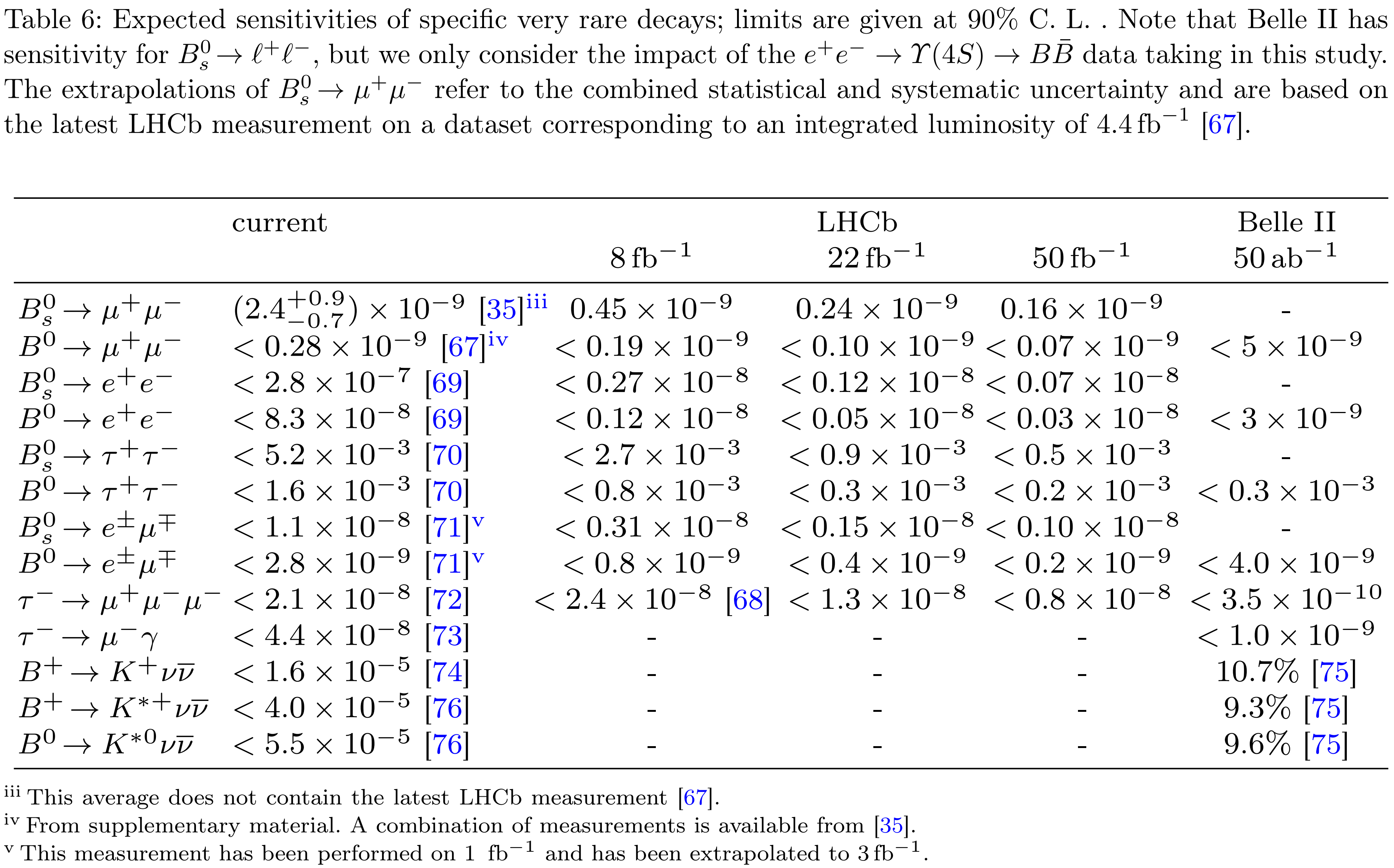


Table 6: Expected sensitivities of specific very rare decays; limits are given at 90% C. L. . Note that Belle II has sensitivity for $B^0_s \to \ell^+\ell^-$, but we only consider the impact of the $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ data taking in this study. The extrapolations of $B^0_s \to \mu^+\mu^-$ refer to the combined statistical and systematic uncertainty and are based on the latest LHCb measurement on a dataset corresponding to an integrated luminosity of $4.4\,\mathrm{fb}^{-1}$ [67].

	current	LHCb			Belle II
		$8\,\mathrm{fb}^{-1}$	$22\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^0_s \to \mu^+\mu^-$	$(2.4^{+0.9}_{-0.7}) \times 10^{-9}$ [35][iii]	0.45×10^{-9}	0.24×10^{-9}	0.16×10^{-9}	-
$B^0 \to \mu^+\mu^-$	$< 0.28 \times 10^{-9}$ [67][iv]	$< 0.19 \times 10^{-9}$	$< 0.10 \times 10^{-9}$	$< 0.07 \times 10^{-9}$	$< 5 \times 10^{-9}$
$B^0_s \to e^+e^-$	$< 2.8 \times 10^{-7}$ [69]	$< 0.27 \times 10^{-8}$	$< 0.12 \times 10^{-8}$	$< 0.07 \times 10^{-8}$	-
$B^0 \to e^+e^-$	$< 8.3 \times 10^{-8}$ [69]	$< 0.12 \times 10^{-8}$	$< 0.05 \times 10^{-8}$	$< 0.03 \times 10^{-8}$	$< 3 \times 10^{-9}$
$B^0_s \to \tau^+\tau^-$	$< 5.2 \times 10^{-3}$ [70]	$< 2.7 \times 10^{-3}$	$< 0.9 \times 10^{-3}$	$< 0.5 \times 10^{-3}$	-
$B^0 \to \tau^+\tau^-$	$< 1.6 \times 10^{-3}$ [70]	$< 0.8 \times 10^{-3}$	$< 0.3 \times 10^{-3}$	$< 0.2 \times 10^{-3}$	$< 0.3 \times 10^{-3}$
$B^0_s \to e^\pm\mu^\mp$	$< 1.1 \times 10^{-8}$ [71][v]	$< 0.31 \times 10^{-8}$	$< 0.15 \times 10^{-8}$	$< 0.10 \times 10^{-8}$	-
$B^0 \to e^\pm\mu^\mp$	$< 2.8 \times 10^{-9}$ [71][v]	$< 0.8 \times 10^{-9}$	$< 0.4 \times 10^{-9}$	$< 0.2 \times 10^{-9}$	$< 4.0 \times 10^{-9}$
$\tau^- \to \mu^+\mu^-\mu^-$	$< 2.1 \times 10^{-8}$ [72]	$< 2.4 \times 10^{-8}$ [68]	$< 1.3 \times 10^{-8}$	$< 0.8 \times 10^{-8}$	$< 3.5 \times 10^{-10}$
$\tau^- \to \mu^-\gamma$	$< 4.4 \times 10^{-8}$ [73]	-	-	-	$< 1.0 \times 10^{-9}$
$B^+ \to K^+\nu\bar{\nu}$	$< 1.6 \times 10^{-5}$ [74]	-	-	-	10.7% [75]
$B^+ \to K^{*+}\nu\bar{\nu}$	$< 4.0 \times 10^{-5}$ [76]	-	-	-	9.3% [75]
$B^0 \to K^{*0}\nu\bar{\nu}$	$< 5.5 \times 10^{-5}$ [76]	-	-	-	9.6% [75]

[iii] This average does not contain the latest LHCb measurement [67].
[iv] From supplementary material. A combination of measurements is available from [35].
[v] This measurement has been performed on $1\ \mathrm{fb}^{-1}$ and has been extrapolated to $3\,\mathrm{fb}^{-1}$.

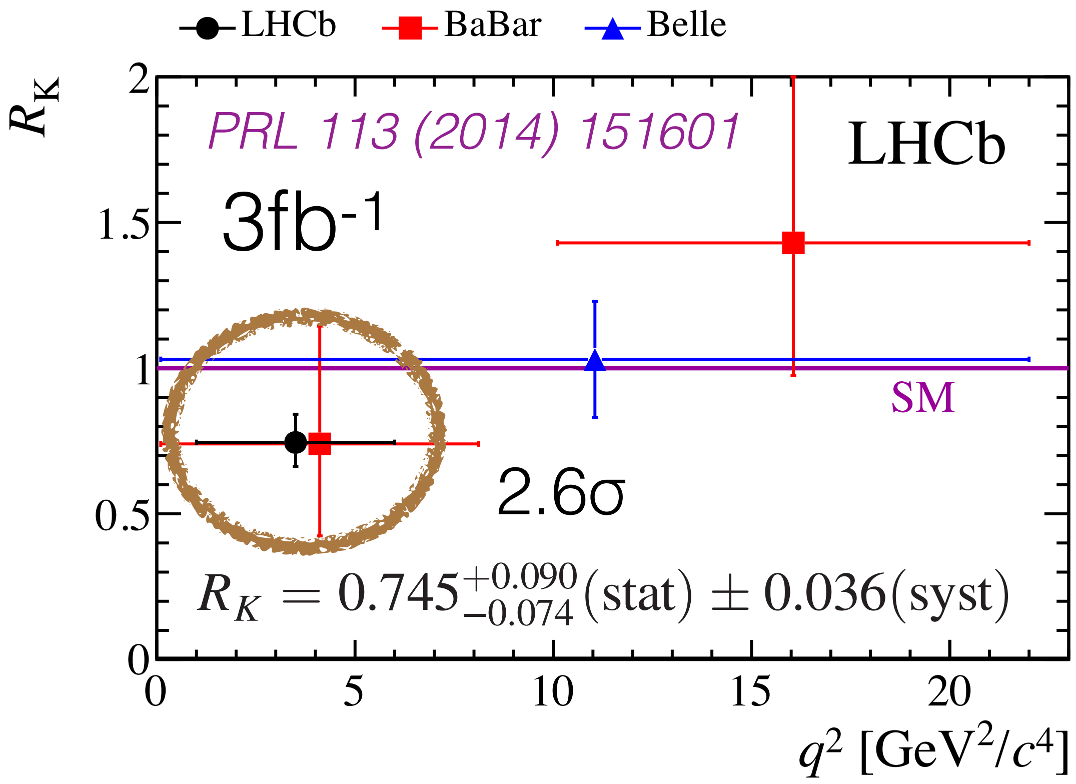
arXiv:1709.10308 [hep-ph]

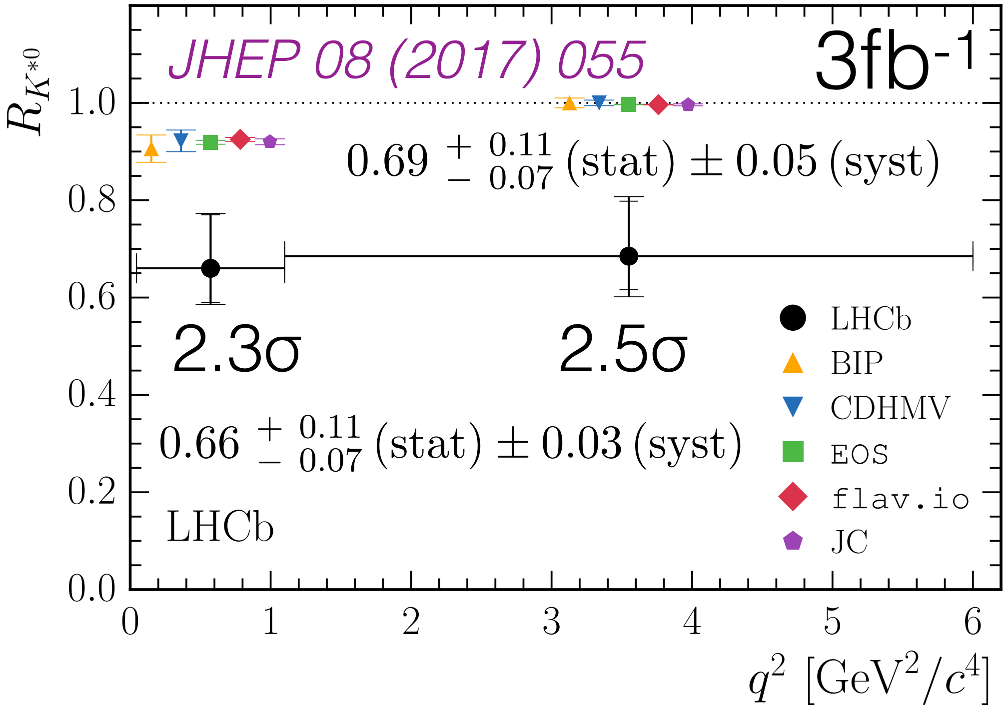
Flavour anomalies

LFU tests in b→sl$^+$l$^-$ transitions

R_K = BF($B^+ \rightarrow K^+\mu^+\mu^-$) / BF($B^+ \rightarrow K^+e^+e^-$)
R_{K*} = BF($B^0 \rightarrow K^{*0}\mu^+\mu^-$) / BF($B^0 \rightarrow K^{*0}e^+e^-$)

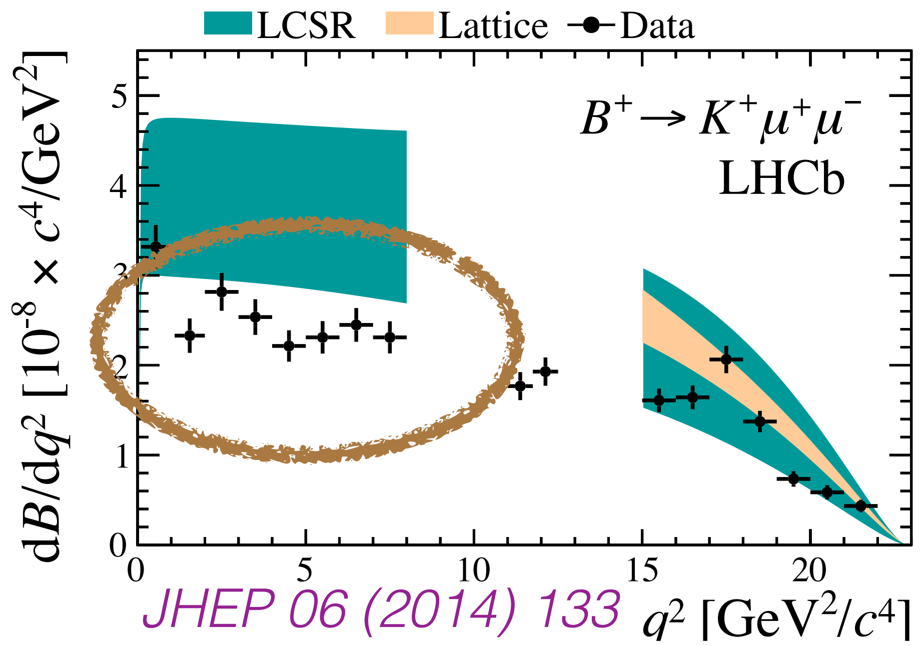
- Theoretically very clean
- Observation of non-LFU would be a clear sign of new physics.
- For the moment at the 3σ-ish level from the SM
- Updates with Run-2 as well as other new measurements with different decay modes expected for next year.



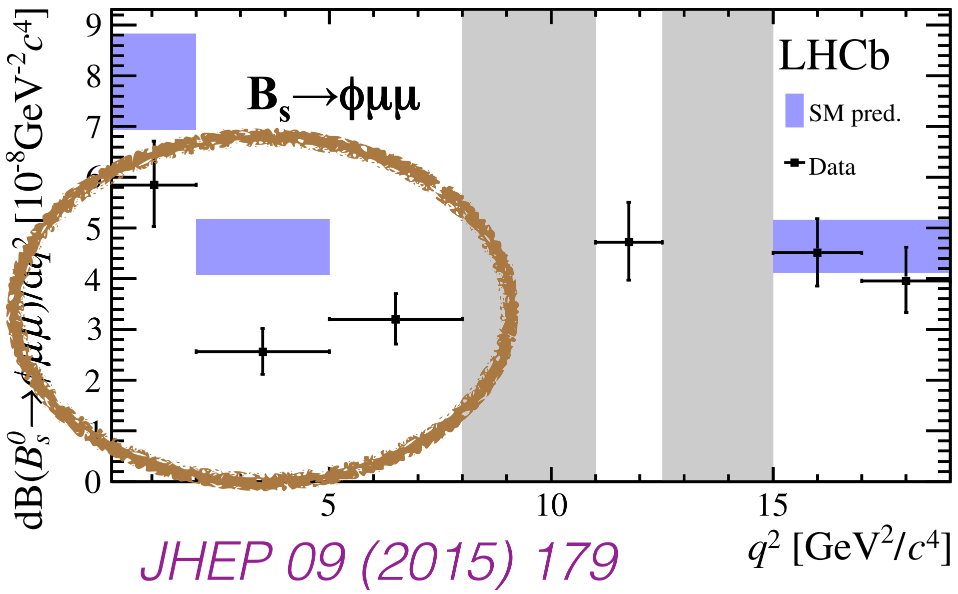


Other anomalies in the b→sl⁺l⁻ sector

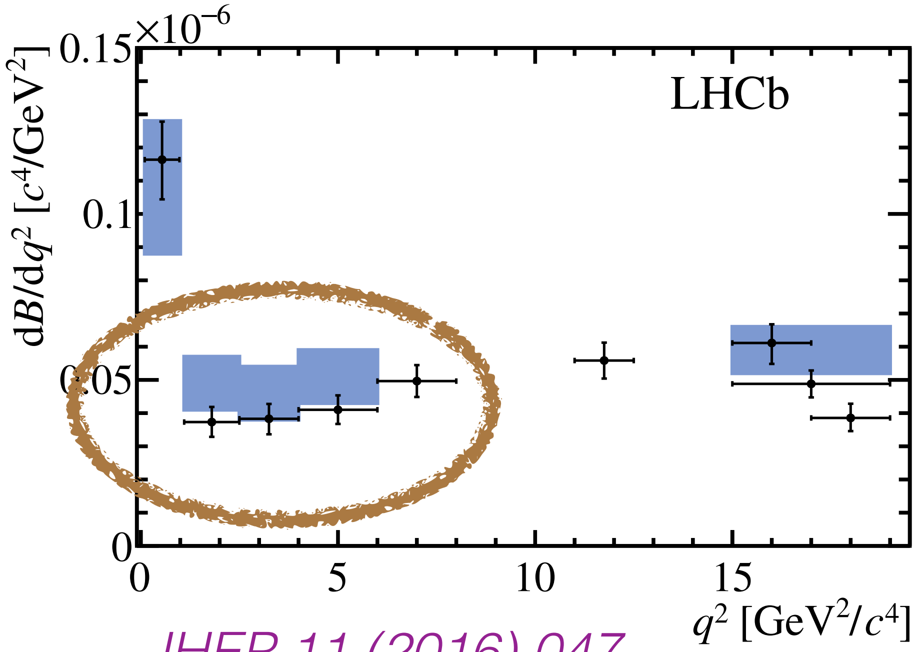
Differential branching fractions consistently lower than SM expectations, although predictions are still matter of discussion



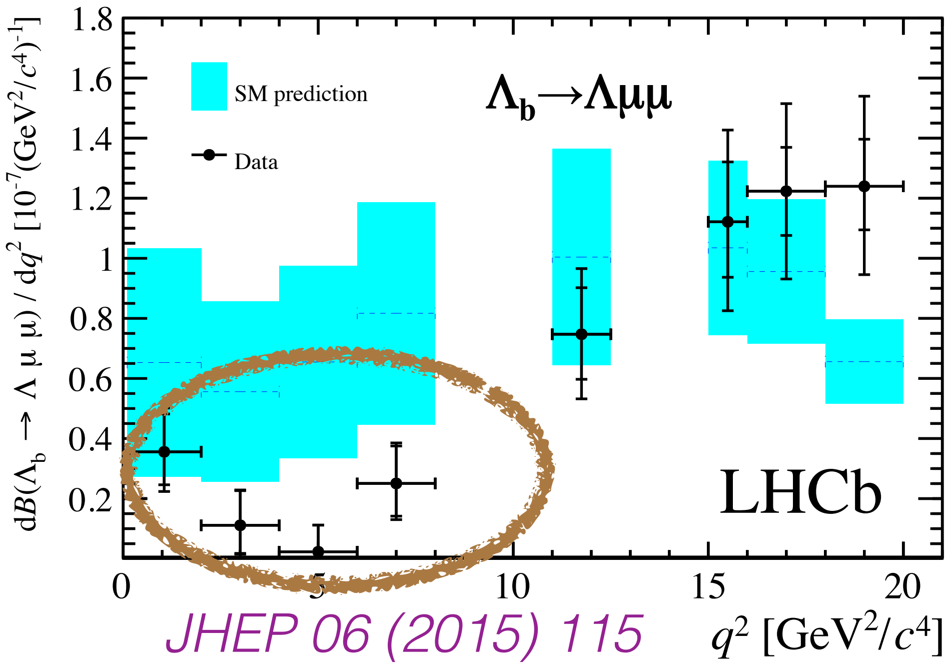
JHEP 06 (2014) 133



JHEP 09 (2015) 179



JHEP 11 (2016) 047
JHEP 04 (2017) 142



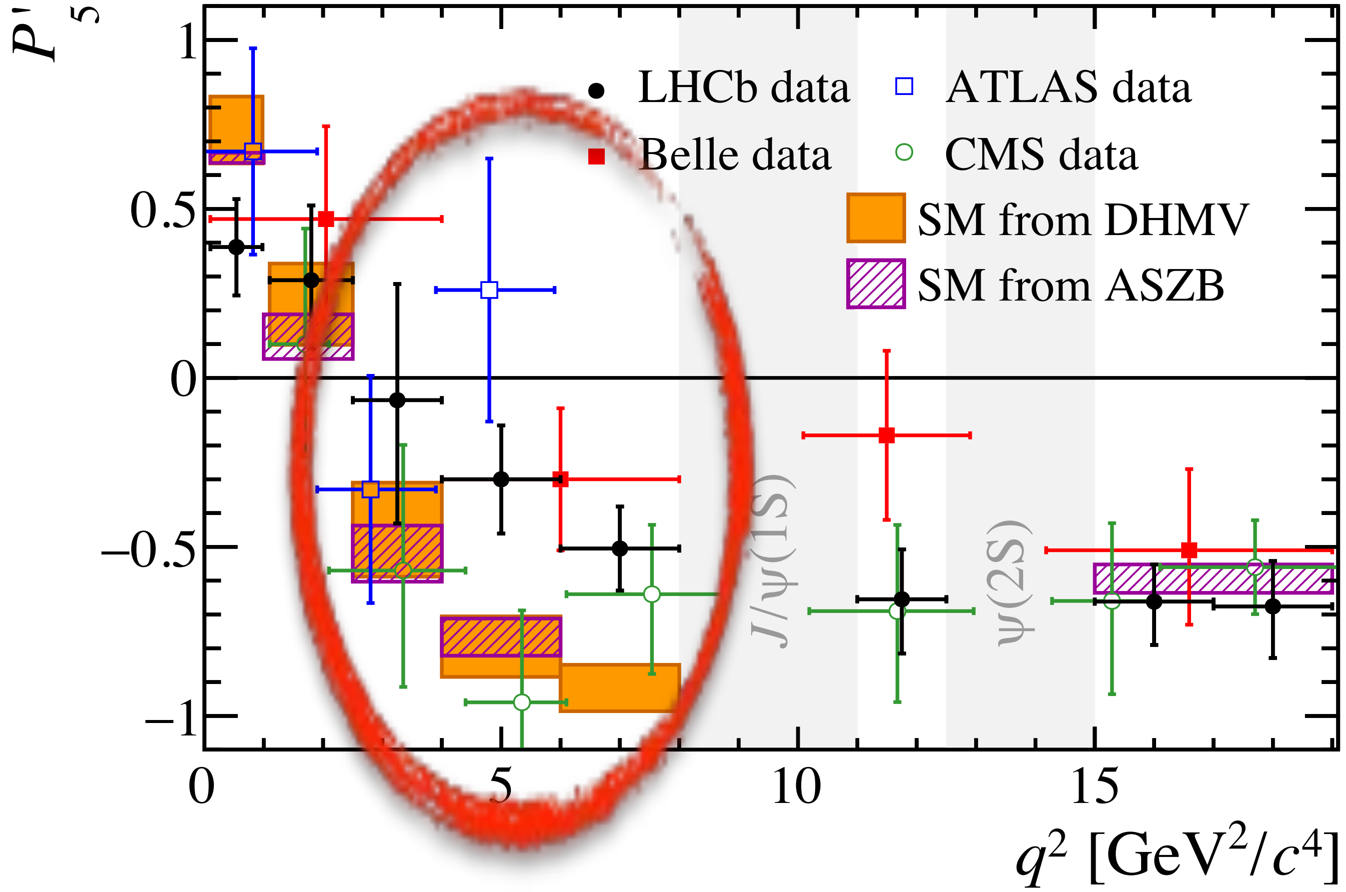
JHEP 06 (2015) 115

Other anomalies in the b→sl$^+$l$^-$ sector

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

- Can construct less form-factor dependent ratios of observables, like P5'.

- It is important to remark that global fits by several theory groups take into account up to 90 observables from various experiments, notably including $B \to \mu\mu$ and $b \to sl^+l^-$ transitions, and nicely get a consistent overall picture.

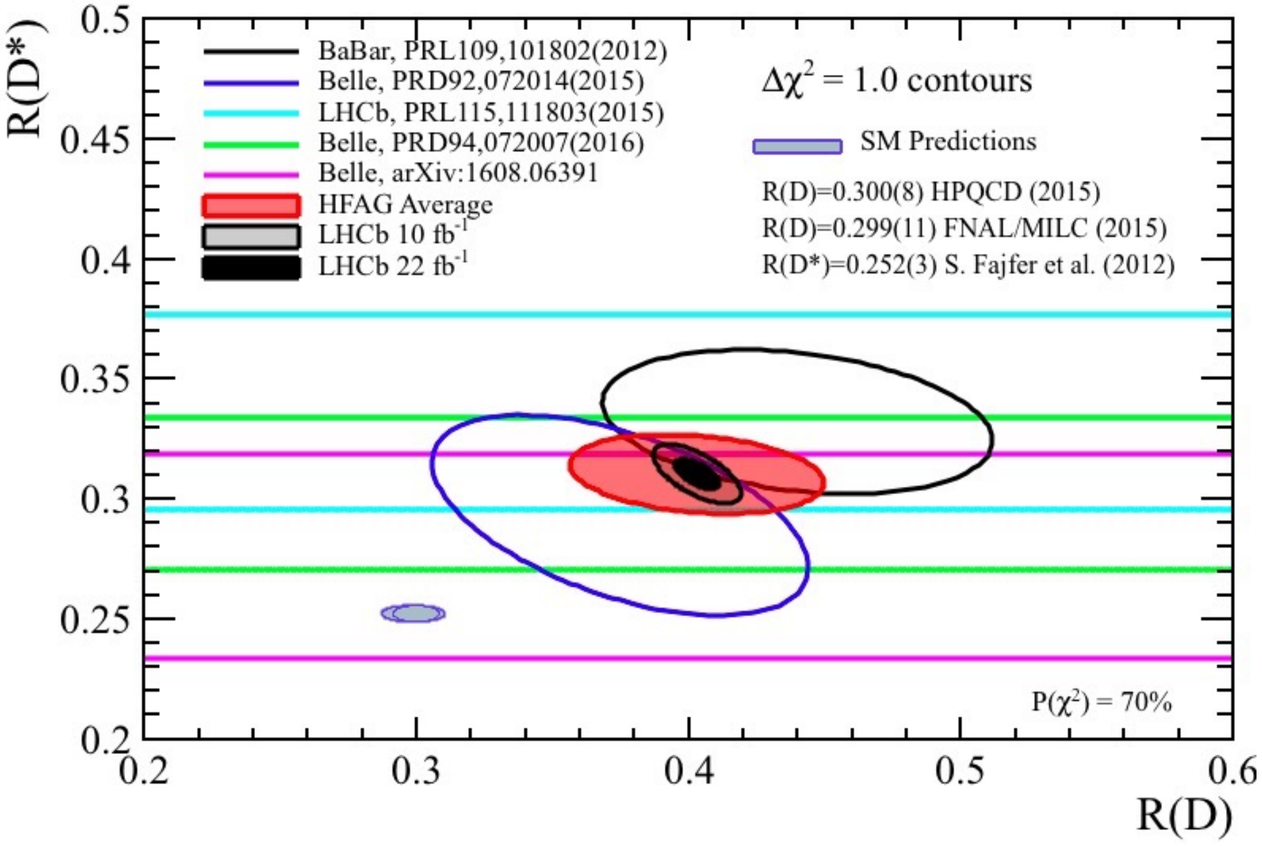


- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

More details on S. Descotes-Genon, Implication Workshop
https://indico.cern.ch/event/646856/

LFU tests in semileptonic b-hadron decays

- Measure ratio $R_{D(*)}$ = BF(B→$D^{(*)}\tau\nu$) / BF(B→$D^{(*)}\mu\nu$).
- Measurements of R(D) and R(D*) by BaBar, Belle and LHCb.
  - Overall average shows a 4σ discrepancy from the SM
  - LHCb has recently demonstrated to be able to make the measurement also with 3-prong τ decays [*arXiv:1708.08856*]



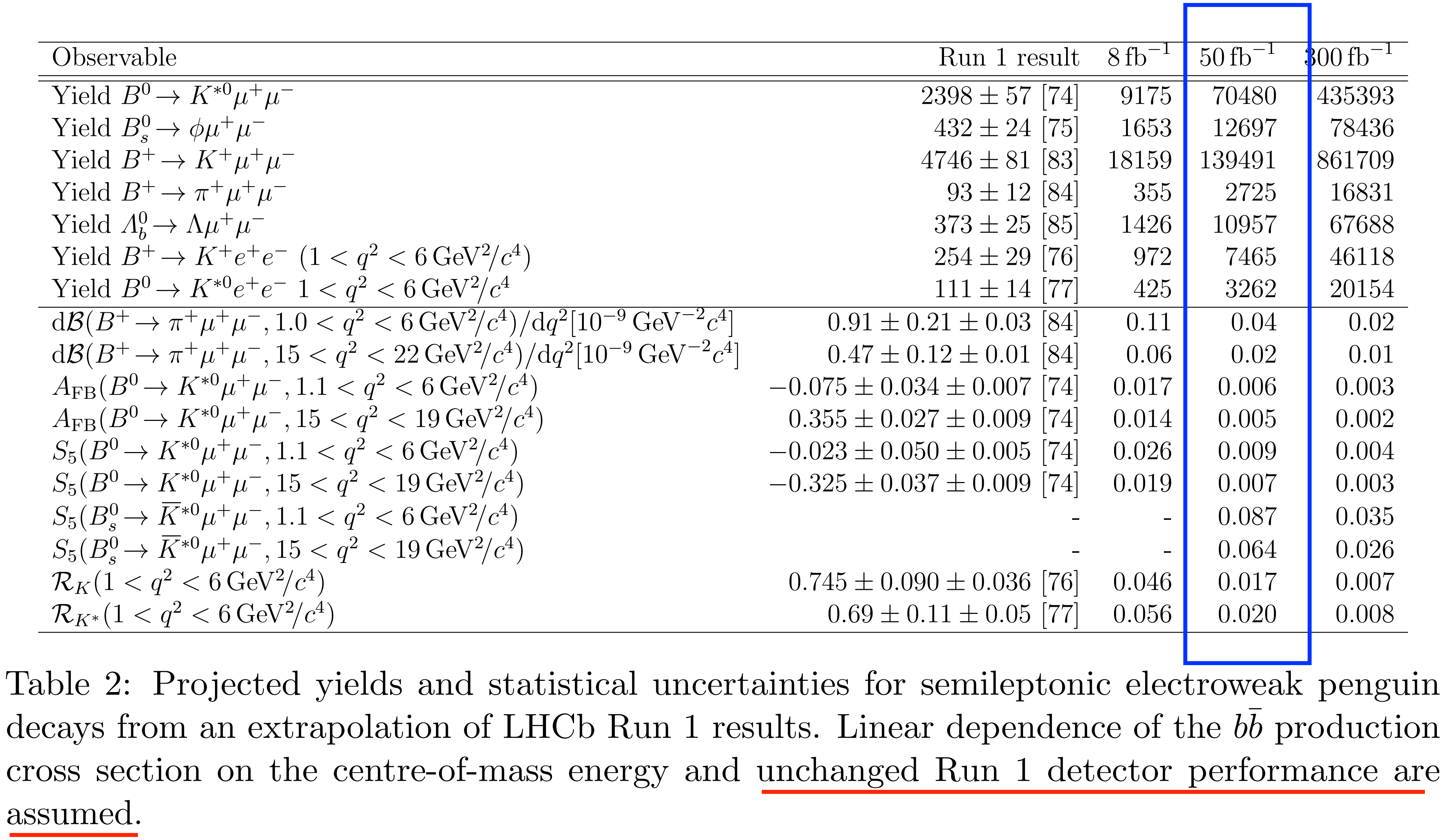
- LHCb can also perform measurements with other b hadrons:
  - Recent determination of R(J/ψ) = BF(B_c→J/ψτν) / BF(B_c→J/ψμν)[*arXiv:1711.05623*]

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

R(J/ψ)-SM in [0.25-0.28]

  - Other modes with B_s and Λ_b decays will also come .

Flavour anomalies prospects



Observable	Run 1 result	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
Yield $B^0 \to K^{*0}\mu^+\mu^-$	2398 ± 57 [74]	9175	70480	435393
Yield $B_s^0 \to \phi\mu^+\mu^-$	432 ± 24 [75]	1653	12697	78436
Yield $B^+ \to K^+\mu^+\mu^-$	4746 ± 81 [83]	18159	139491	861709
Yield $B^+ \to \pi^+\mu^+\mu^-$	93 ± 12 [84]	355	2725	16831
Yield $\Lambda_b^0 \to \Lambda\mu^+\mu^-$	373 ± 25 [85]	1426	10957	67688
Yield $B^+ \to K^+e^+e^-$ $(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	254 ± 29 [76]	972	7465	46118
Yield $B^0 \to K^{*0}e^+e^-$ $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$	111 ± 14 [77]	425	3262	20154
$\mathrm{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 1.0 < q^2 < 6\,\mathrm{GeV}^2/c^4)/\mathrm{d}q^2[10^{-9}\,\mathrm{GeV}^{-2}c^4]$	$0.91 \pm 0.21 \pm 0.03$ [84]	0.11	0.04	0.02
$\mathrm{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 15 < q^2 < 22\,\mathrm{GeV}^2/c^4)/\mathrm{d}q^2[10^{-9}\,\mathrm{GeV}^{-2}c^4]$	$0.47 \pm 0.12 \pm 0.01$ [84]	0.06	0.02	0.01
$A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$-0.075 \pm 0.034 \pm 0.007$ [74]	0.017	0.006	0.003
$A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\mathrm{GeV}^2/c^4)$	$0.355 \pm 0.027 \pm 0.009$ [74]	0.014	0.005	0.002
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$-0.023 \pm 0.050 \pm 0.005$ [74]	0.026	0.009	0.004
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\mathrm{GeV}^2/c^4)$	$-0.325 \pm 0.037 \pm 0.009$ [74]	0.019	0.007	0.003
$S_5(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	-	-	0.087	0.035
$S_5(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\mathrm{GeV}^2/c^4)$	-	-	0.064	0.026
$\mathcal{R}_K(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$0.745 \pm 0.090 \pm 0.036$ [76]	0.046	0.017	0.007
$\mathcal{R}_{K^*}(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$0.69 \pm 0.11 \pm 0.05$ [77]	0.056	0.020	0.008

Table 2: Projected yields and statistical uncertainties for semileptonic electroweak penguin decays from an extrapolation of LHCb Run 1 results. Linear dependence of the $b\bar{b}$ production cross section on the centre-of-mass energy and unchanged Run 1 detector performance are assumed.

Observed anomalies will be either confirmed or ruled out by LHCb-Upgrade and Belle II experiments independently with very high significance by the end of their data-taking.

Conclusions

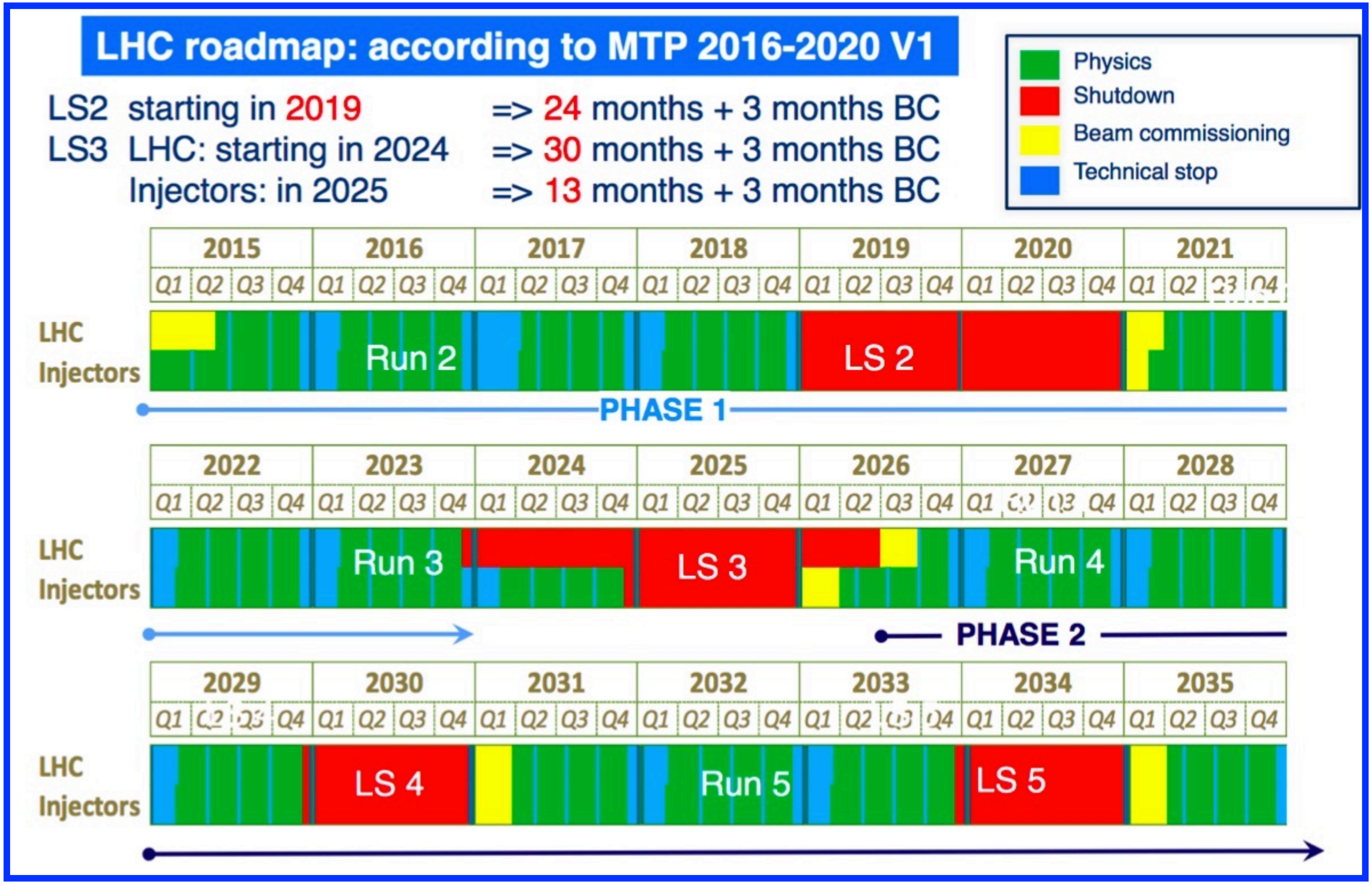
- Performing very high precision measurements in all areas of Flavor Physics is fundamental w/ or w/o a direct evidence of new particles at LHC:
    - w/o — flavour physics will indicate the way for future developments of the entire field.
    - w/ — flavour physics as a fundamental ingredient in understanding NP dynamics
- Run 1 has demonstrated the huge potentialities of LHCb in producing a wide variety of extreme precise results.
- Run 2 and Run 3 (LHCb-Upgrade 1a) will push many relevant measurements to an unprecedented level of precision, however it is extremely necessary to have a programme as diversified as possible.
- Belle II will be a major player in the game to confirm and to complement LHCb measurements (like $B \rightarrow \tau\nu$, decays with neutrinos and neutral particles in the final states, some decays of long-lived particle, etc.).

Long term future (after 2031)

- LHCb will continue taking data in Run 4 (Phase 1b, 2027-2030) and eventually in Run 5 (Phase II, 2031-???) at higher luminosity ($L > 10^{34}$), the so-called “Extreme Flavor Experiment” in INFN What’s Next document.
- At the moment LHCb collaboration submitted a EoI document (CERN-LHCC-2017-003) to the LHCC for a new experiment to be installed in LS4 (Phase II Upgrade).
- This will certainly be a world-wide effort and it will require the support of all flavor experimentalists and theoreticians.

Backup

LHC timeline in the next decades



LHC roadmap: according to MTP 2016-2020 V1

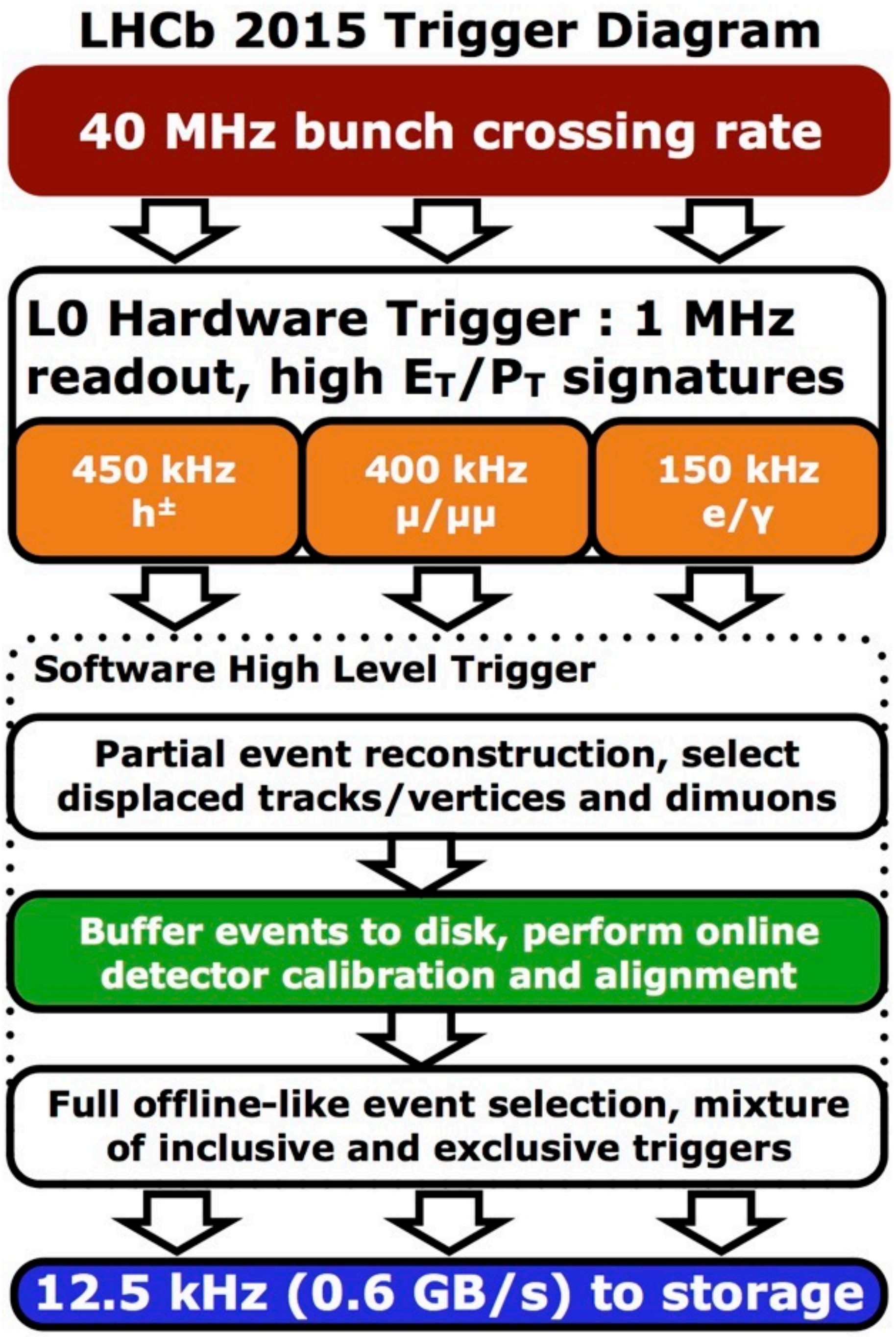
LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
🟦 Technical stop

Current Trigger (Run 2)

- Hardware trigger (L0):
  - Based on calorimeter and muon chambers infos
  - Detector readout limited to 1MHz
  - Tight cuts, e.g. $p_T(\mu) > 1.4$ GeV, $E(e)>2.5$ GeV

- Software trigger (HLT):
  - HLT1:
    - Partial event reconstruction (tracking and PV)
    - Track reconstruction for $p_T > 0.5$GeV
    - Multivariate inclusive selection (based on IP, kinematic and muonID)
  - HLT2:
    - Full event reconstruction
    - Inclusive lines (selection of displaced vertices and hight p_T tracks)
    - Exclusive lines with reduced events informations for all the rest (>300 lines)



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 (0.6 GB/s) to storage

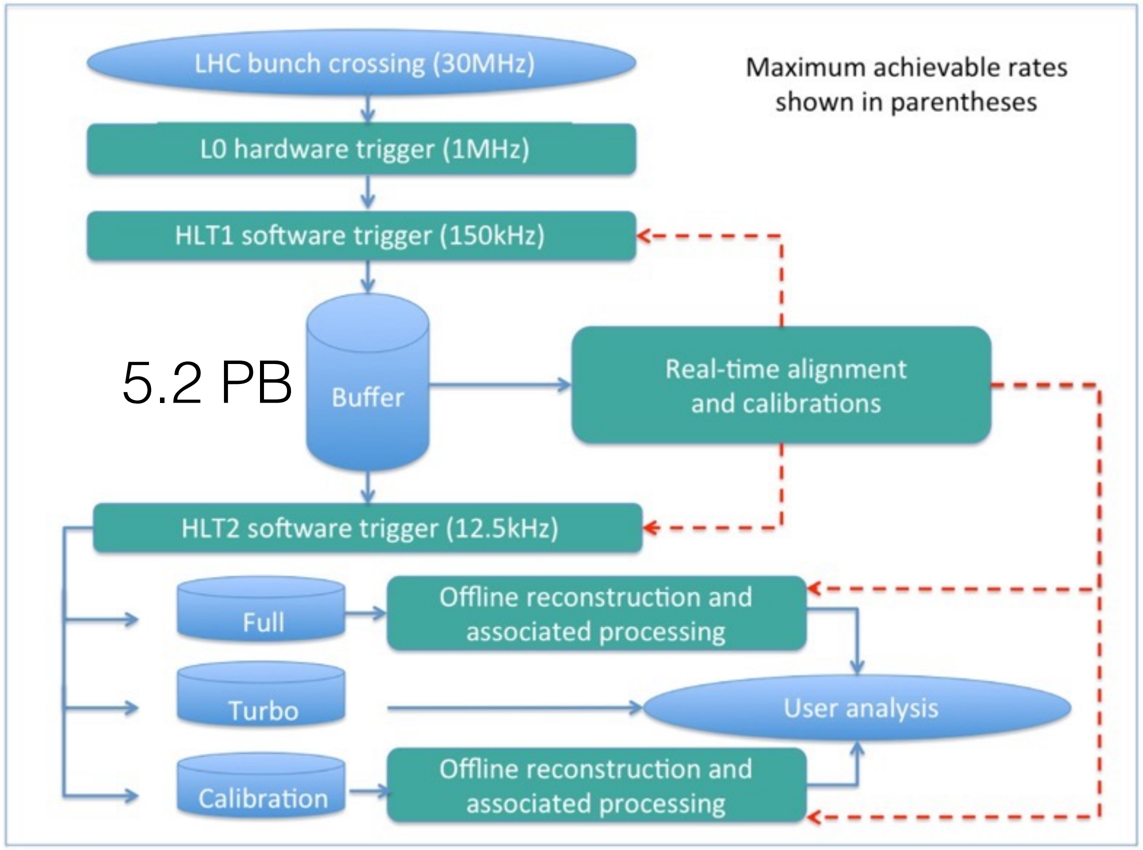
Event Filer Farm (Run 2)

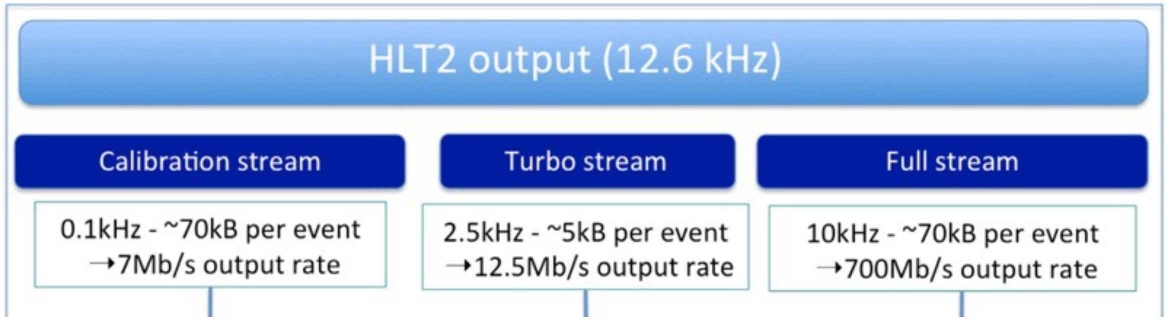
- Input rate: 1MHz
- Output rate: 10KHz
- Average event size (full) ~70kB
- The EFF now consists of approximately 1800 nodes, with 1000 containing 2 TB of hard disk space each and 800 nodes containing 4 TB each, giving a total of 5.2 PB.
- Each server node in the EFF contains 12/16 physical processor cores and 24–32 logical cores.

Turbo Stream (Run 2)

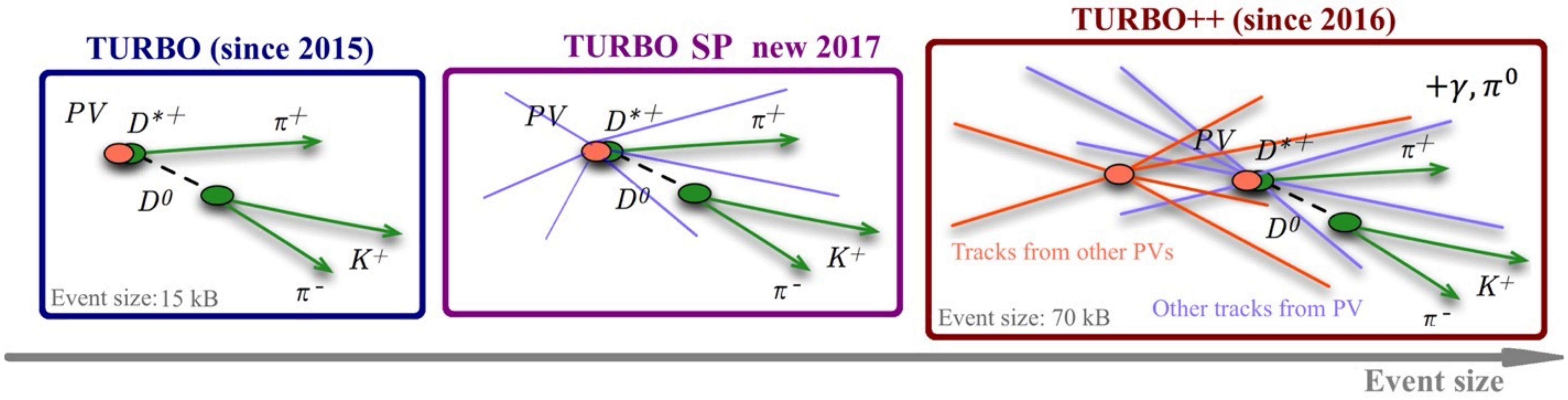
- Calibration and detector alignment performed in realtime between HLT1 (track momentum and impact parameter) and HLT2 (full reconstruction) stages.
- PID and its calibration performed at the trigger level too. Requirement applied at HLT2 stage.
- Current scheme exploits LHC duty cycle (~50%), thanks to the 5.2 PB buffer, where events are stored before the HLT2 processing.
- Close to the paradigma online = offline at current conditions (L= 4x10^{32} cm^{-2}s^{-1} and HLT input =1MHz).
- Candidates are directly saved on permanent storage after the trigger reconstruction, ready to be analyzed.
- Only reconstructed objects can be saved, discarding the rest. Smaller events ⇒ larger output rate.

R.Aaij, CPC 208 (2016) 35–42 [arXiv:1604.05596]

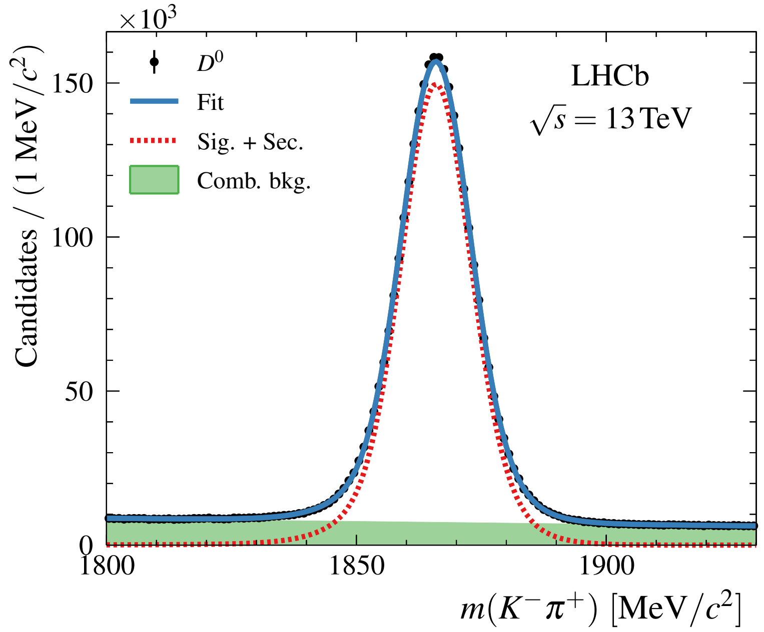




Trubo Stream (Run 2)



- Turbo:
  - only exclusive decays (and nothing else) saved
- Turbo++ :
  - Full event reconstruction can be persisted
  - Variables such as isolation, objects for jets reconstruction, can be saved
- Turbo SP:
  - New intermediate solution between Turbo and Turbo++
  - Trigger candidate + subset of reconstruction saved



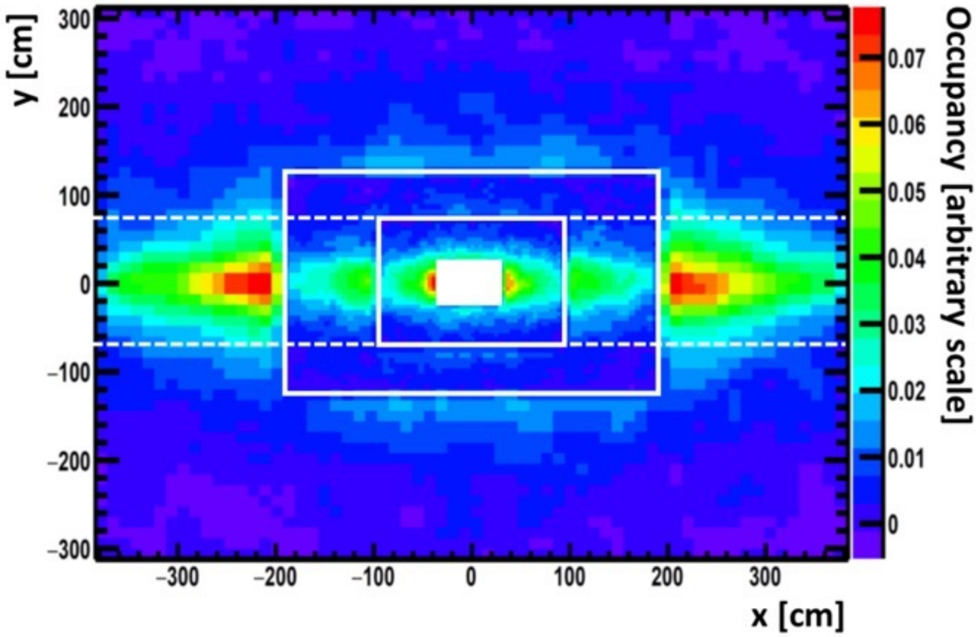
[JHEP03(2016)159]

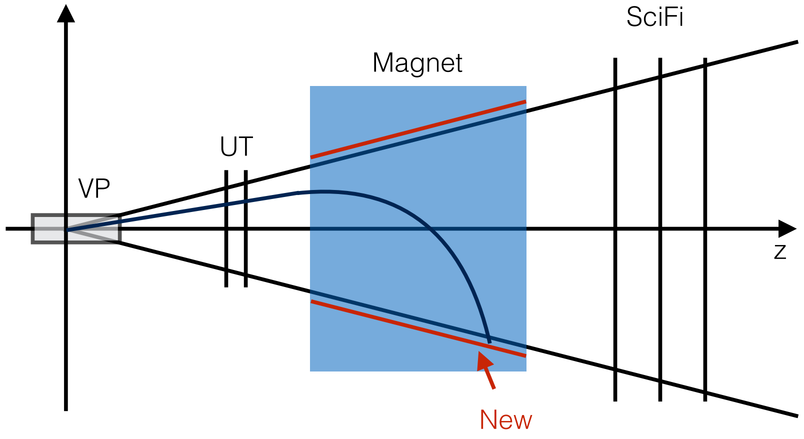
LS3 consolidation

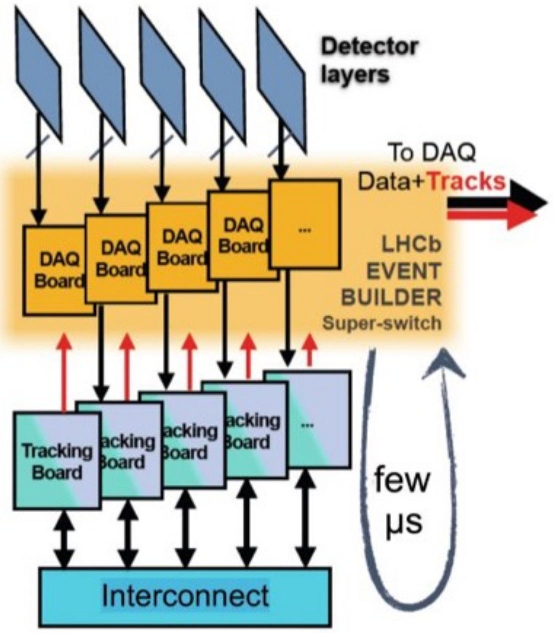
- Profit from LS3 to implement some consolidations of the upgraded LHCb in Run 4 (2027-2030).

- Some already planned and mandatory e.g. replace innermost part of ECAL due to radiation damage (strong physics interest: π^0, γ, e^-)

- Other proposed to improve LHCb performance and physics acceptance:
  - tracking stations inside the magnet to improve tracking acceptance for low momentum particles.
  - Build a downstream tracker unit (RETINA like) that can be integrated in the DAQ architecture and act as an embedded track-detector to reconstruct downstream tracks in realtime (long-lived particles K_S, Λ).



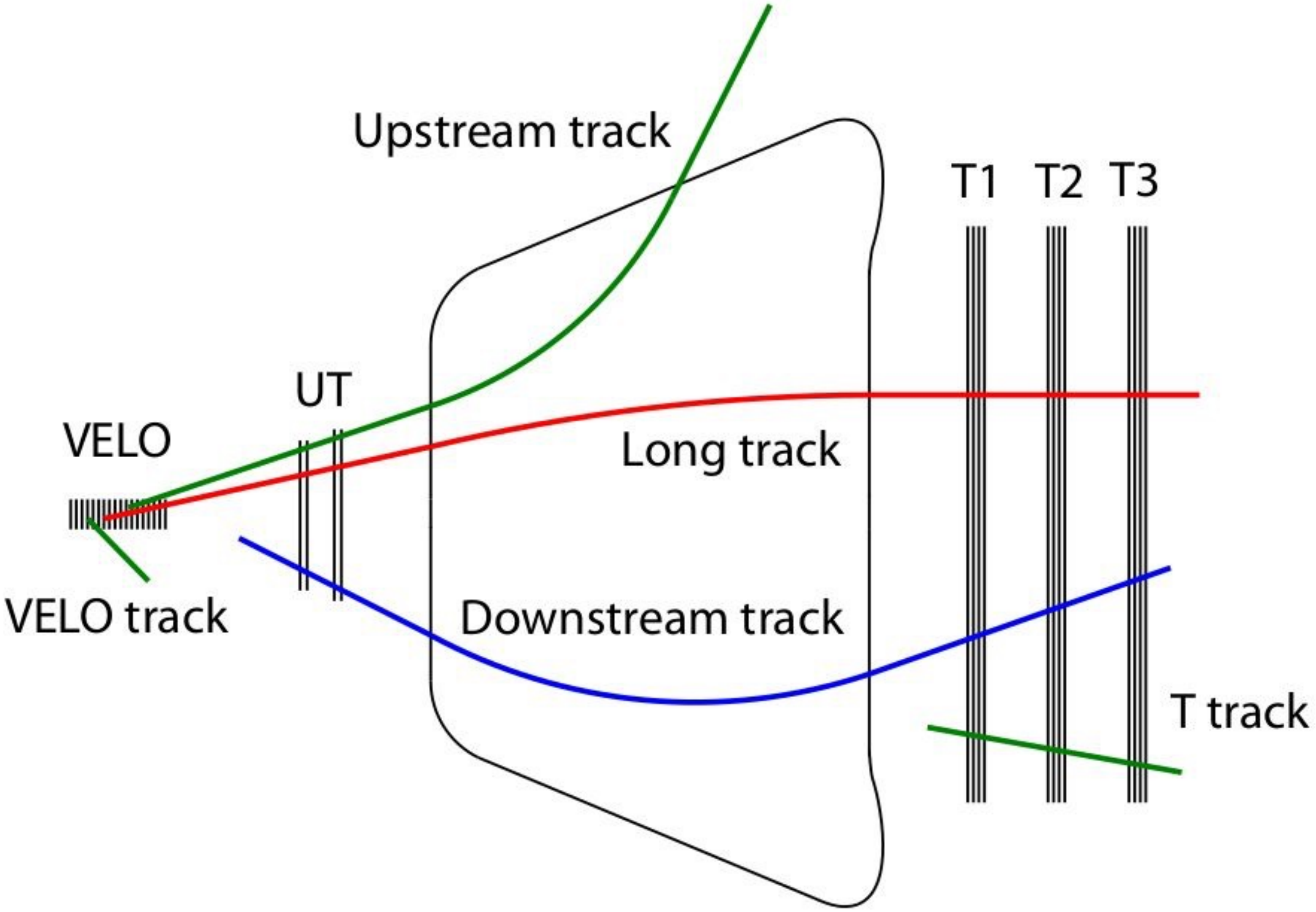




More info: Beyond the LHCb Phase-1 Upgrade workshop
http://agenda.infn.it/event/LHCb-FU

Tracks in LHCb

Without T- and downstream tracks, LHCb is only 50 cm long



CKM physics and rare decays

- Look for inconsistencies in the global CKM fits
  - Measure CP violation in the interference between B^0 and B_s mixing and decay
    - Phases ϕ_s and sin2β and related measurements.
  - Measure the CP-violating angles γ and α of the UT.
  - Measure UT sides Δm_d and Δm_s, $|V_{ub}|/|V_{cb}|$.
  - Measure precisely D^0-meson mixing parameters, and search for CP violation in mixing and decay in the charm sector.
- Search for (or precisely measure) rare and lepton-flavour violationg decays
  - $K_s \to \mu\mu$, $B0 \to \mu\mu$, $B_s \to \mu\mu$, …
  - $\tau \to 3\mu$, $D \to e\mu$, $B \to e\mu$, ...

Δm_d and Δm_s

- Experimental precision has reached a remarkable level at the per mille level, dominated by LHCb

$\Delta m_d = 0.5065 \pm 0.0019\ \text{ps}^{-1}$

$\Delta m_s = 17.757 \pm 0.021\ \text{ps}^{-1}$

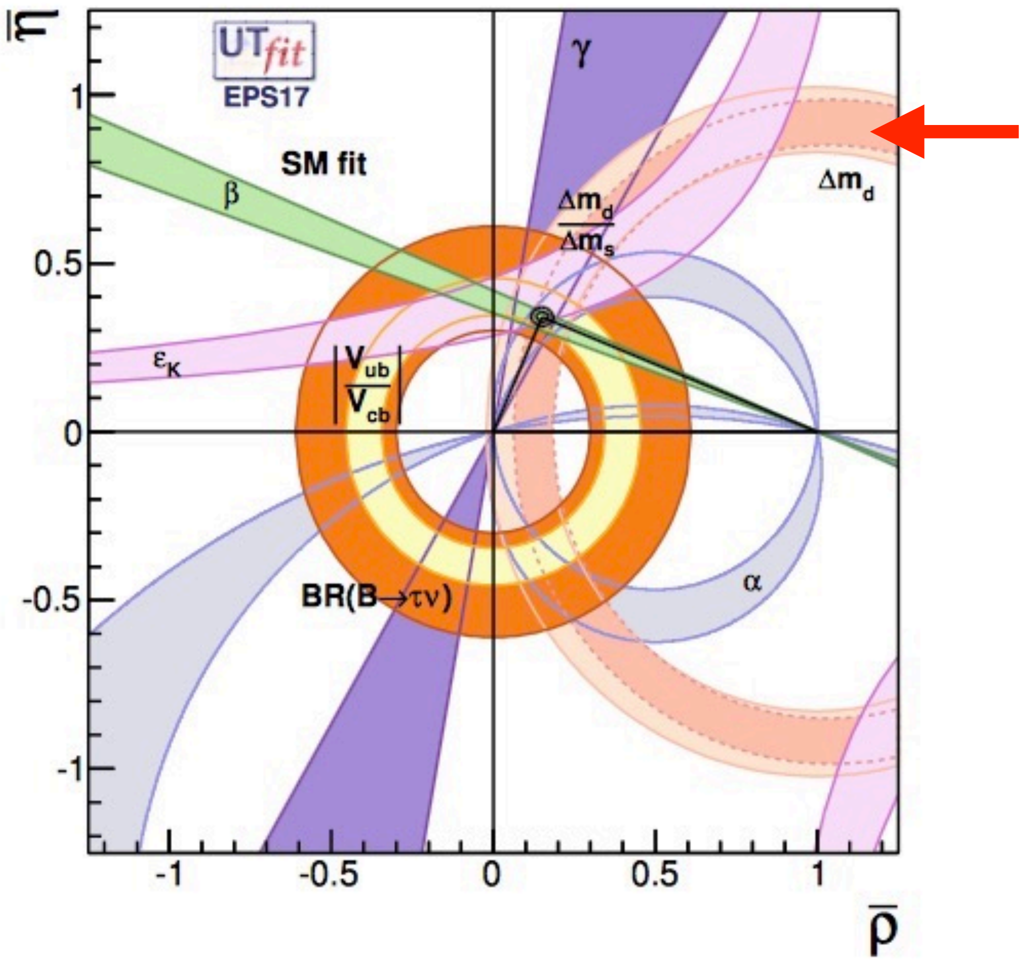
- Still far from systematic walls.

- However, the interpretation requires LQCD inputs

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar\rho)^2+\bar\eta^2]\ m_{B_d} \underbrace{\boxed{f^2_{B_d}\hat B_{B_d}}}_{\sim 7\%}$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \underbrace{\boxed{\frac{f^2_{B_d}\hat B_{B_d}}{f^2_{B_s}\hat B_{B_s}}}}_{\sim 4\%} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar\rho)^2+\bar\eta^2]$$

- The quest for precision with these constraints is now on LQCD. Need to sustain efforts from the LQCD community to reduce the theoretical uncertainties by x10



$\Delta m_d \propto |V_{tb}V^*_{td}|^2$

$\Delta m_s \propto |V_{tb}V^*_{ts}|^2$

LHCb-CONF-2017-004
July 26, 2017

Update of the LHCb combination of the CKM angle γ using $B \to DK$ decays

The LHCb collaboration †

Abstract

A combination of tree-level measurements of the CKM angle γ from $B \to DK$ decays at LHCb is performed. The results are obtained from time-integrated measurements of $B^+ \to DK^+$, $B^+ \to D^*K^+$, $B^+ \to DK^{*+}$, $B^0 \to DK^{*0}$, $B^0 \to DK^+\pi^-$ and $B^+ \to DK^+\pi^+\pi^-$ decays. In addition, inputs from a time-dependent analysis of $B_s^0 \to D_s^{\mp}K^{\pm}$ decays are included. This combination uses both new and updated results compared to an earlier LHCb combination, and gives a best fit value of $\gamma = 76.8°$ with confidence intervals, set using a frequentist procedure, of $\gamma \in [71.1, 81.9]°$ at 68.3% confidence level (CL) and $\gamma \in [64.3, 86.6]°$ at 95.5% CL, where all values are modulo 180°. Using the best fit value and the 68.3% CL interval, γ is measured to be

$$\gamma = (76.8\,^{+5.1}_{-5.7})^{\circ}\,,$$

where the uncertainty includes statistical and systematic contributions. This is the most precise measurement of the CKM angle γ to date.

Table 1: List of the LHCb measurements used in the combination, where TD is time-dependen and the method acronyms refer to the authors of Refs. [6–15].

B decay	D decay	Method	Ref.	Status since last combination [1]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[16]	Updated to Run 1 + $2\,\text{fb}^{-1}$ Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[18]	As before
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ	[19]	As before
$B^+ \to DK^+$	$D \to K_S^0K^+\pi^-$	GLS	[20]	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[16]	New
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[21]	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[22]	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[23]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[24]	As before
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ	[25]	As before
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[26]	Updated to $3\,\text{fb}^{-1}$ Run 1

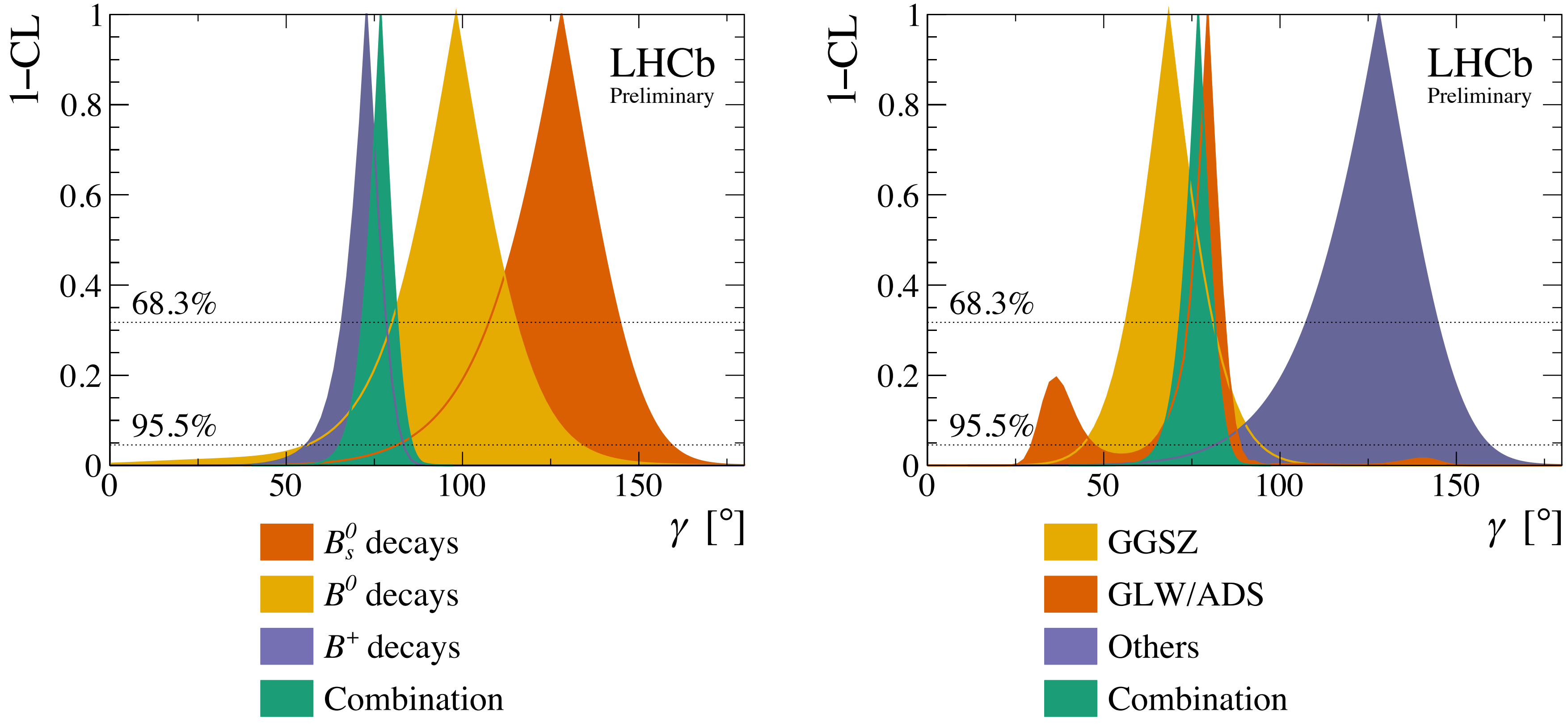


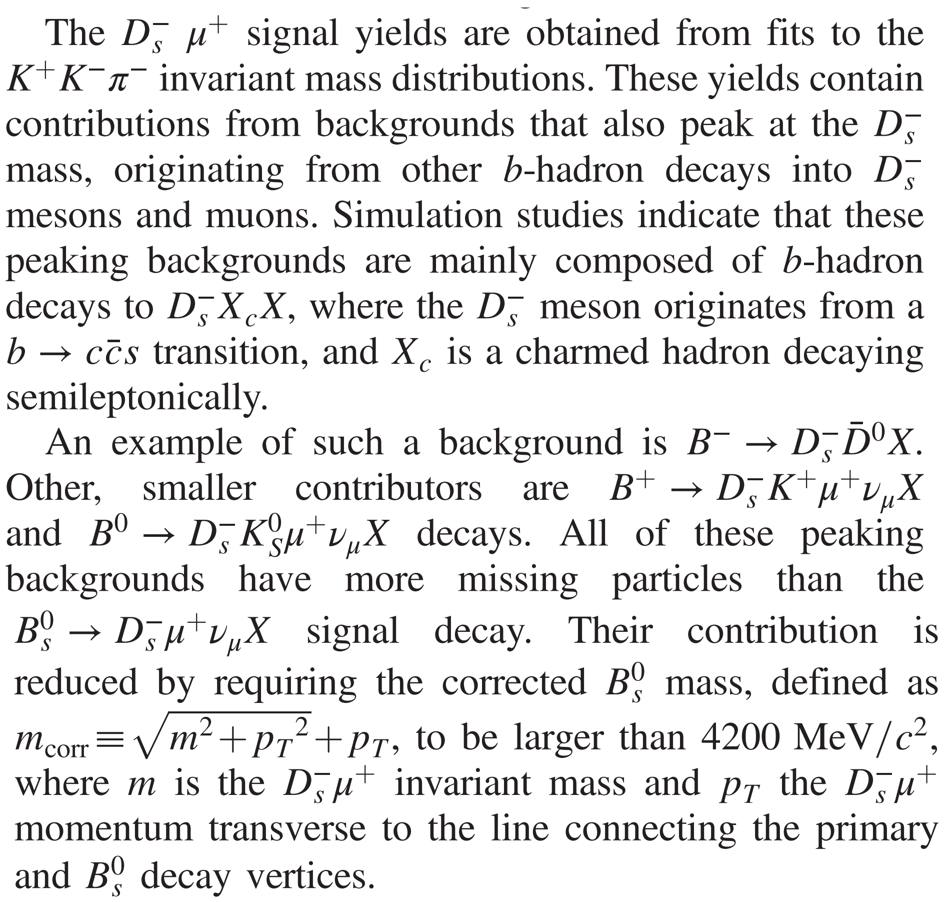
Figure 4: $1-\mathrm{CL}$ plots, using the profile likelihood method, for combinations split by the initial B meson flavour (left) and split by analysis method (right). Left: (orange) B_s^0 initial state, (yellow) B^0 initial states, (blue) B^+ initial states and (green) the full combination. Right: (yellow) GGSZ methods, (orange) GLW/ADS methods, (blue) other methods and (green) the full combination.

a^s_{SL} - $D_s^{\mp}\mu^{\pm}\overset{(-)}{\nu}_{\mu}X$

$$a^s_{\rm sl} = \frac{2}{1-f_{\rm bkg}}(A_{\rm raw} - A_{\rm det} - f_{\rm bkg}A_{\rm bkg})$$

PRL 117, 061803 (2016)

$$A_{\rm det} = A_{\rm track} + A_{\rm PID} + A_{\rm trig}$$



The $D_s^- \mu^+$ signal yields are obtained from fits to the $K^+K^-\pi^-$ invariant mass distributions. These yields contain contributions from backgrounds that also peak at the D_s^- mass, originating from other b-hadron decays into D_s^- mesons and muons. Simulation studies indicate that these peaking backgrounds are mainly composed of b-hadron decays to $D_s^- X_c X$, where the D_s^- meson originates from a $b \to c\bar{c}s$ transition, and X_c is a charmed hadron decaying semileptonically.

An example of such a background is $B^- \to D_s^- \bar{D}^0 X$. Other, smaller contributors are $B^+ \to D_s^- K^+ \mu^+ \nu_\mu X$ and $B^0 \to D_s^- K_S^0 \mu^+ \nu_\mu X$ decays. All of these peaking backgrounds have more missing particles than the $B_s^0 \to D_s^- \mu^+ \nu_\mu X$ signal decay. Their contribution is reduced by requiring the corrected B_s^0 mass, defined as $m_{\rm corr} \equiv \sqrt{m^2 + {p_T}^2} + p_T$, to be larger than 4200 MeV$/c^2$, where m is the $D_s^- \mu^+$ invariant mass and p_T the $D_s^- \mu^+$ momentum transverse to the line connecting the primary and B_s^0 decay vertices.

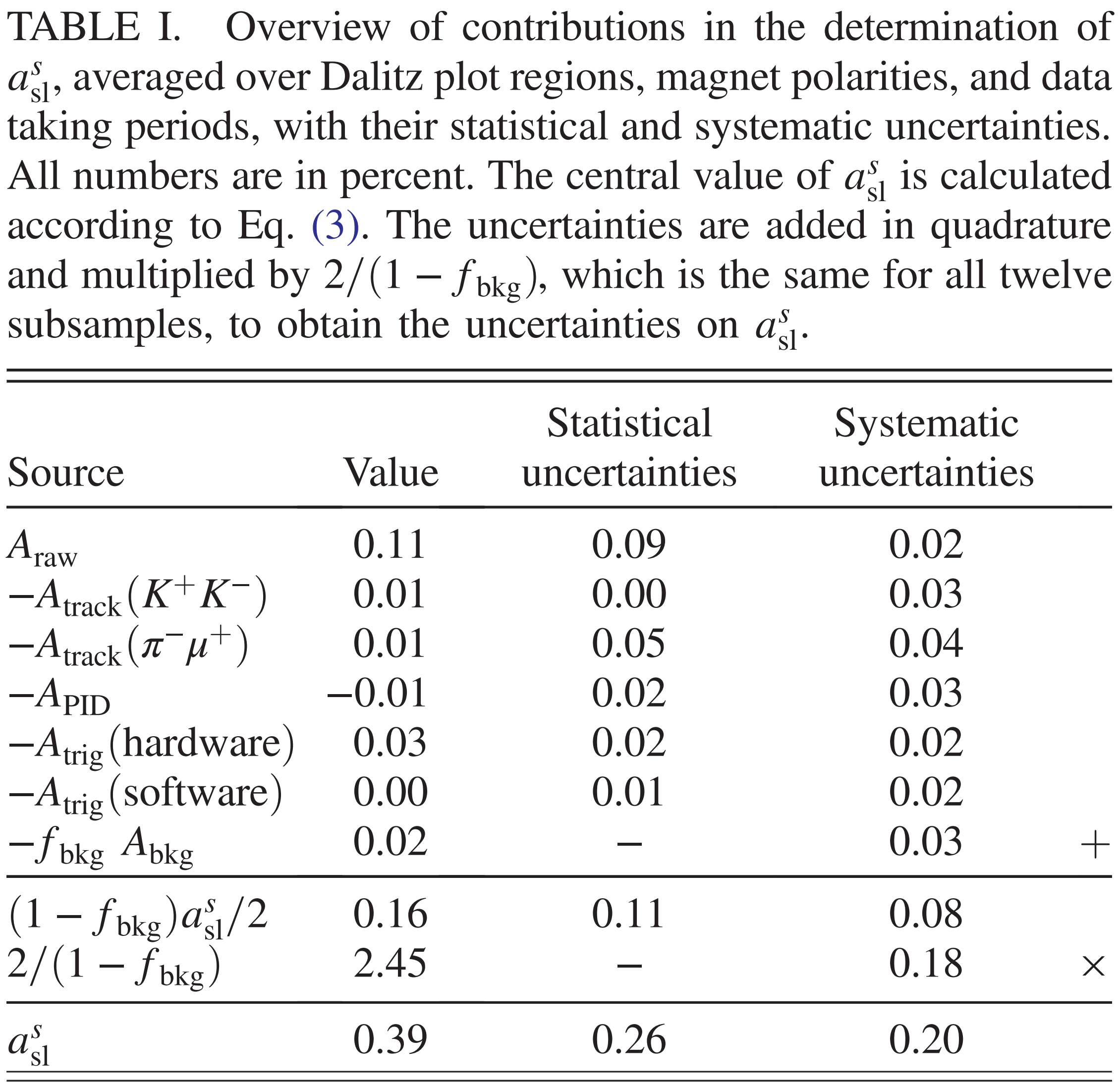


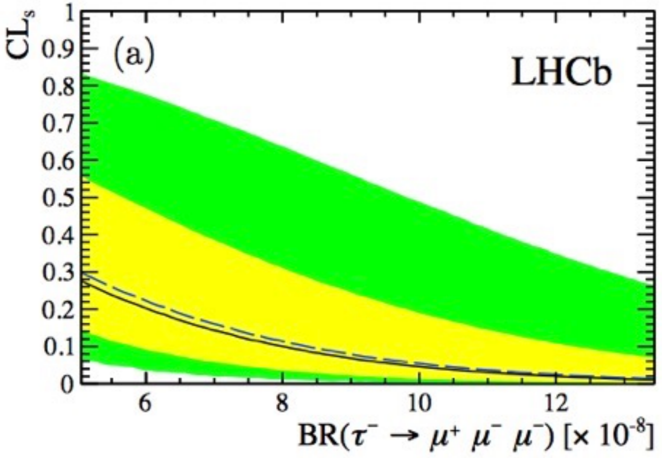
TABLE I. Overview of contributions in the determination of $a^s_{\rm sl}$, averaged over Dalitz plot regions, magnet polarities, and data taking periods, with their statistical and systematic uncertainties. All numbers are in percent. The central value of $a^s_{\rm sl}$ is calculated according to Eq. (3). The uncertainties are added in quadrature and multiplied by $2/(1-f_{\rm bkg})$, which is the same for all twelve subsamples, to obtain the uncertainties on $a^s_{\rm sl}$.

Source	Value	Statistical uncertainties	Systematic uncertainties	
$A_{\rm raw}$	0.11	0.09	0.02	
$-A_{\rm track}(K^+K^-)$	0.01	0.00	0.03	
$-A_{\rm track}(\pi^-\mu^+)$	0.01	0.05	0.04	
$-A_{\rm PID}$	−0.01	0.02	0.03	
$-A_{\rm trig}$(hardware)	0.03	0.02	0.02	
$-A_{\rm trig}$(software)	0.00	0.01	0.02	
$-f_{\rm bkg}\ A_{\rm bkg}$	0.02	–	0.03	+
$(1-f_{\rm bkg})a^s_{\rm sl}/2$	0.16	0.11	0.08	
$2/(1-f_{\rm bkg})$	2.45	–	0.18	×
$a^s_{\rm sl}$	0.39	0.26	0.20	

Searches for
$\tau \rightarrow 3\mu$, $K_S \rightarrow \mu\mu$, $D \rightarrow e\mu$, $B \rightarrow e\mu$

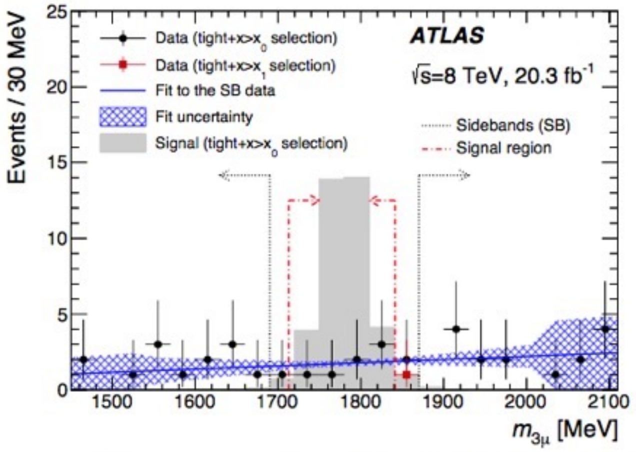
Table 1: Signal y
invariant mass fits

JHEP 02 (2015) 121



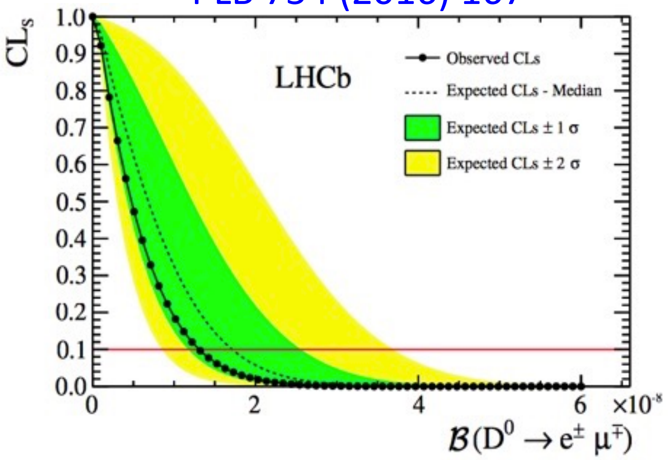
$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6\ (5.6) \times 10^{-8}$

EPJC 76 (2016) 232



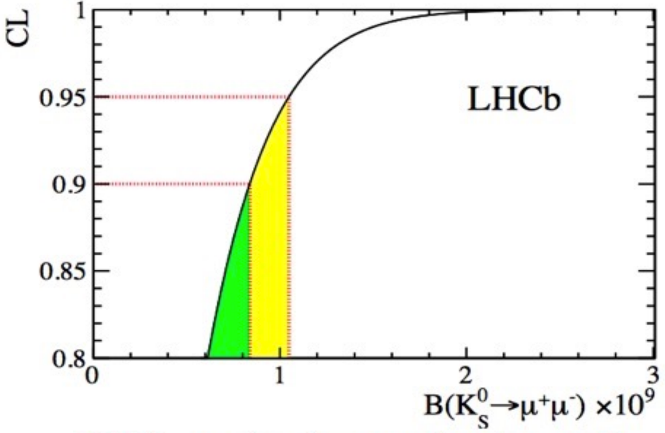
$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.76\times10^{-7}$

PLB 754 (2016) 167



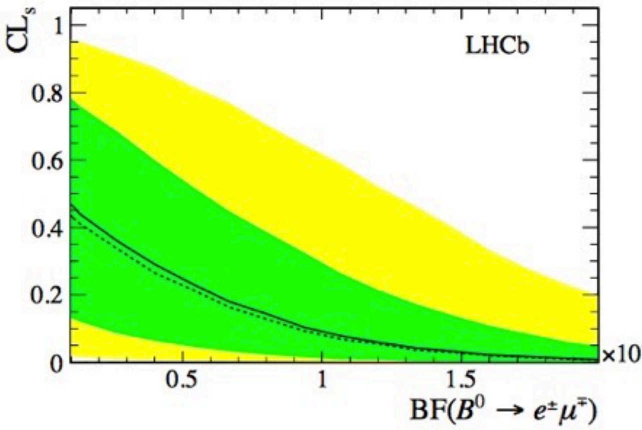
$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3(1.6)\times 10^{-8}$

EPJC 77 (2017) 678



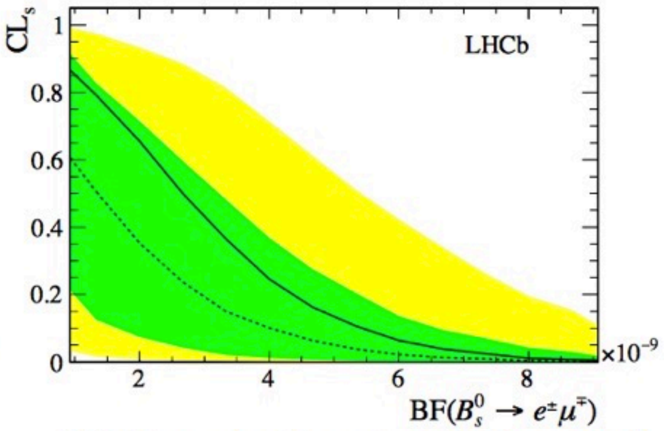
$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 0.8\ (1.0) \times 10^{-9}$

arXiv:1710.04111



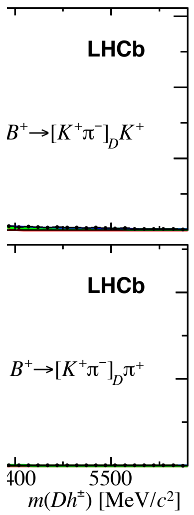
$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.0\ (1.3) \times 10^{-9}$

arXiv:1710.04111



$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 5.4\ (6.3) \times 10^{-9}$

Physic



idates, separated by
in the $B^\pm \to DK^\pm$
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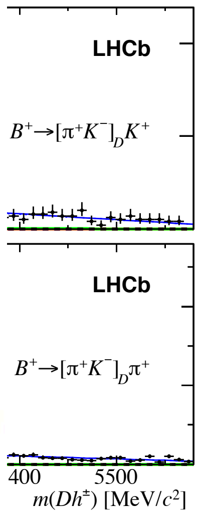


$^\pm$ decays, separated
tially reconstructed
avoured mode cross-

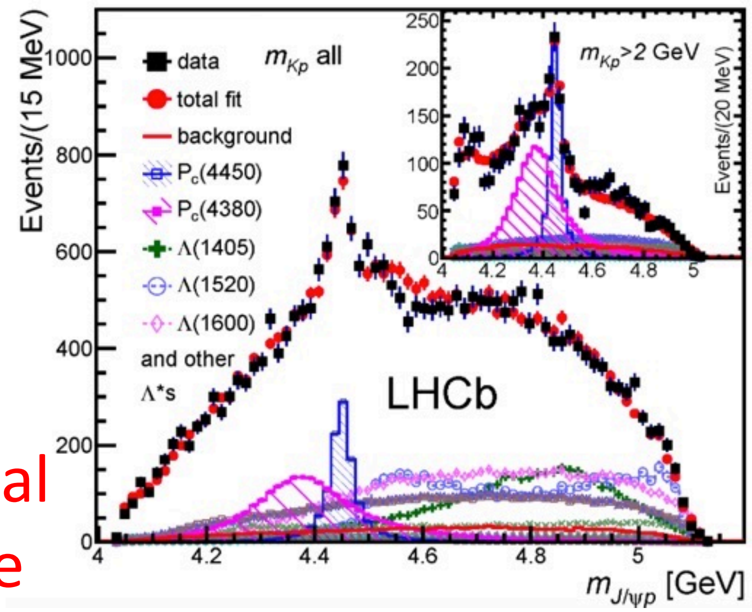
feed is also included in the fit, but is too small to be seen. See the caption of Fig. 1 for other definitions.

Tetraquarks and pentaquarks

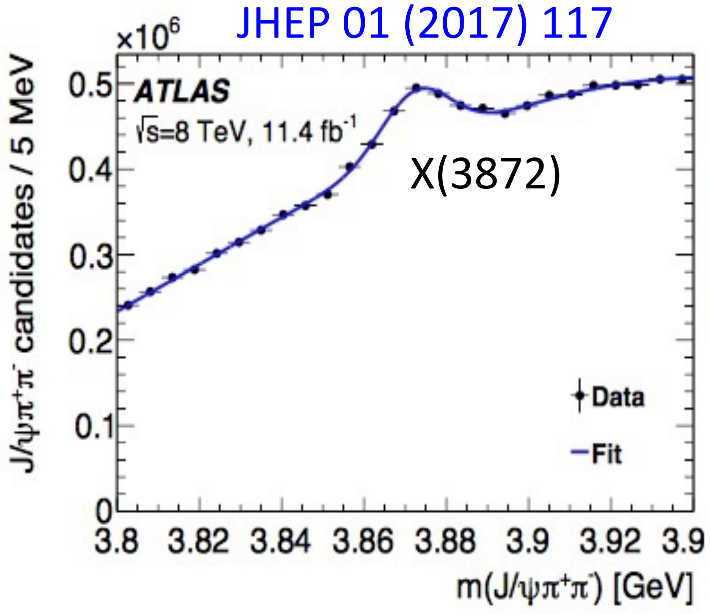
Parallel WG4 talks by
Marco Pappagallo, Pavel, Subir

- Sector in great expansion in the last decade
  - A renaissance of QCD in the non-perturbative regime
- Several “exotic” candidates have been identified and are now under the magnifying glass of experiments
  - Lots of work still needed to clarify the global picture and understand the nature of these states

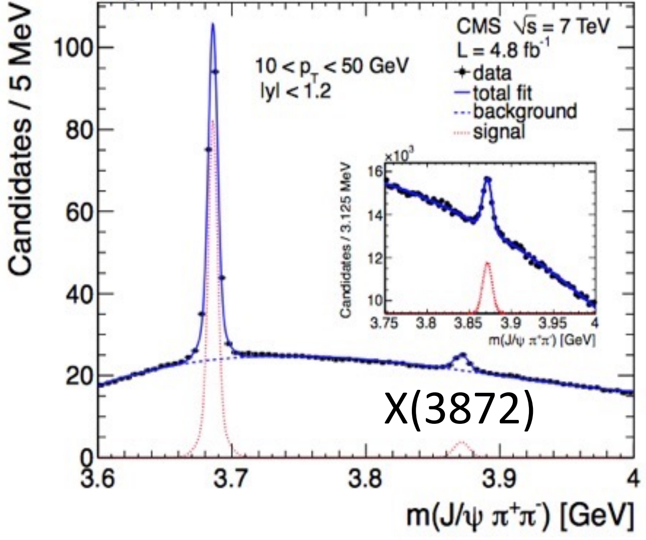
PRL 115 (2015) 072001



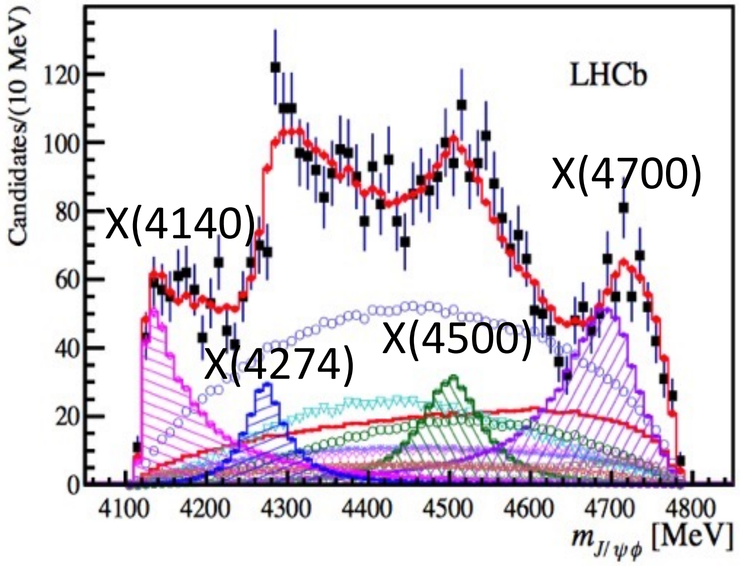
JHEP 01 (2017) 117



JHEP 04 (2013) 154



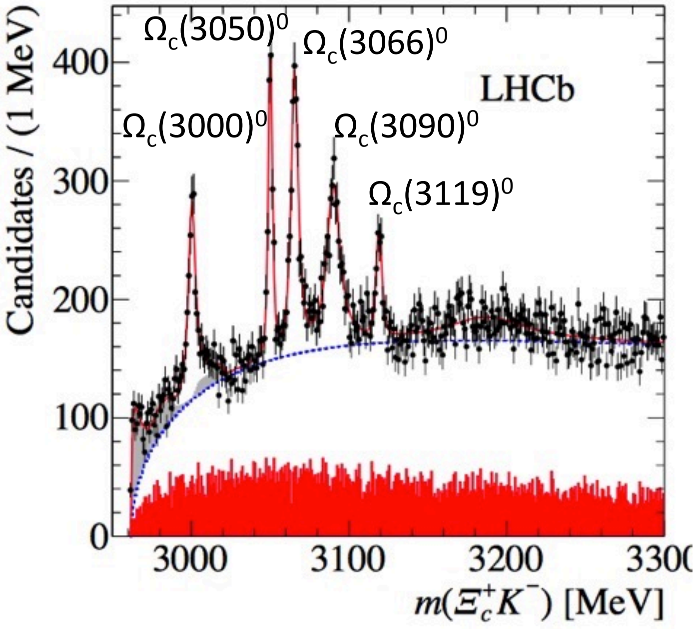
PRL 118 (2017) 022003



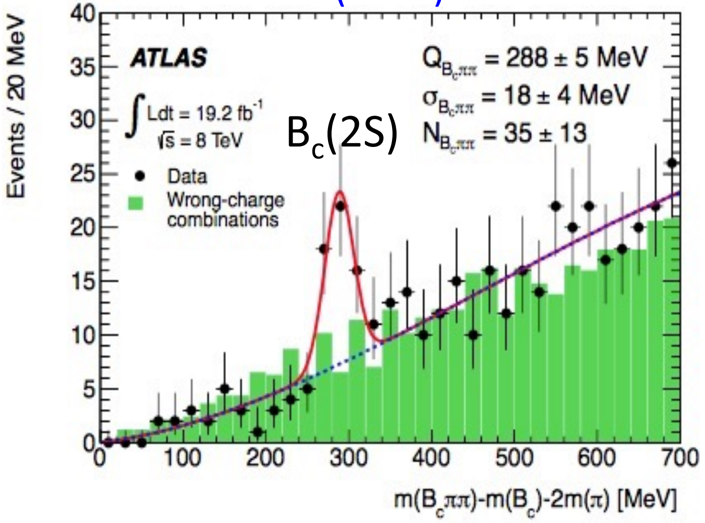
Other observations and measurements

- "Unexpected" observations of new excited states, $B_c(2S)$, Ω_c excitations
- First observation of a doubly-charmed baryon, the Ξ_{cc}^{++}
- Precision measurements of masses and widths of χ_{c1} and χ_{c2} mesons via a newly observed decay mode $(\chi_{c2} \rightarrow J/\psi\mu\mu)$

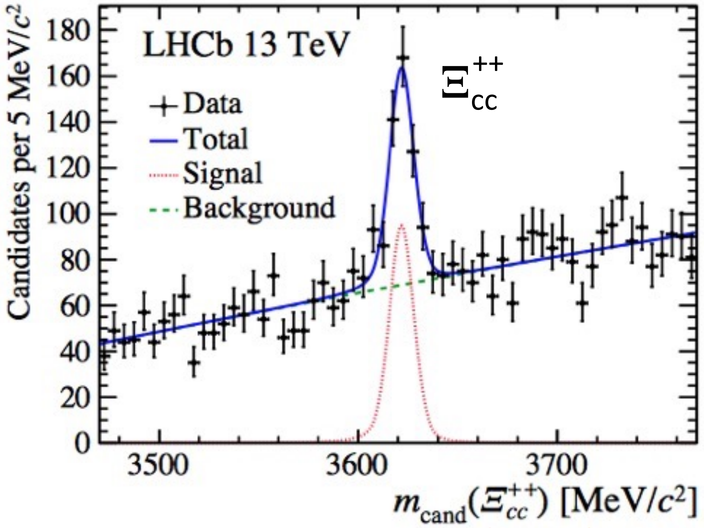
PRL 118 (2017) 182001

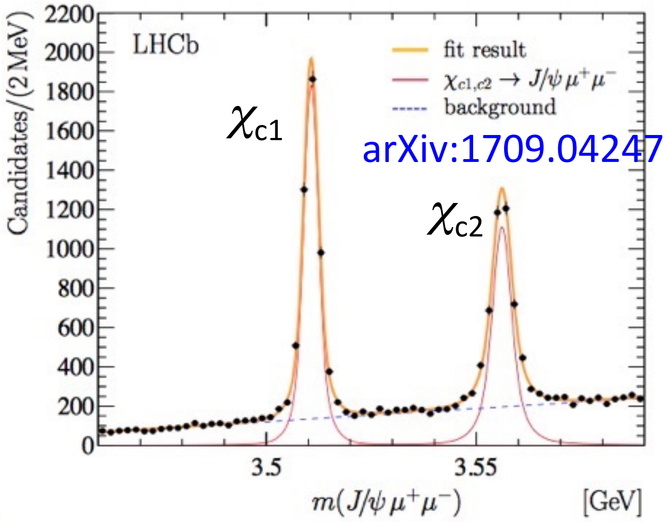


PRL 113 (2014) 212004



PRL 119 (2017) 112001



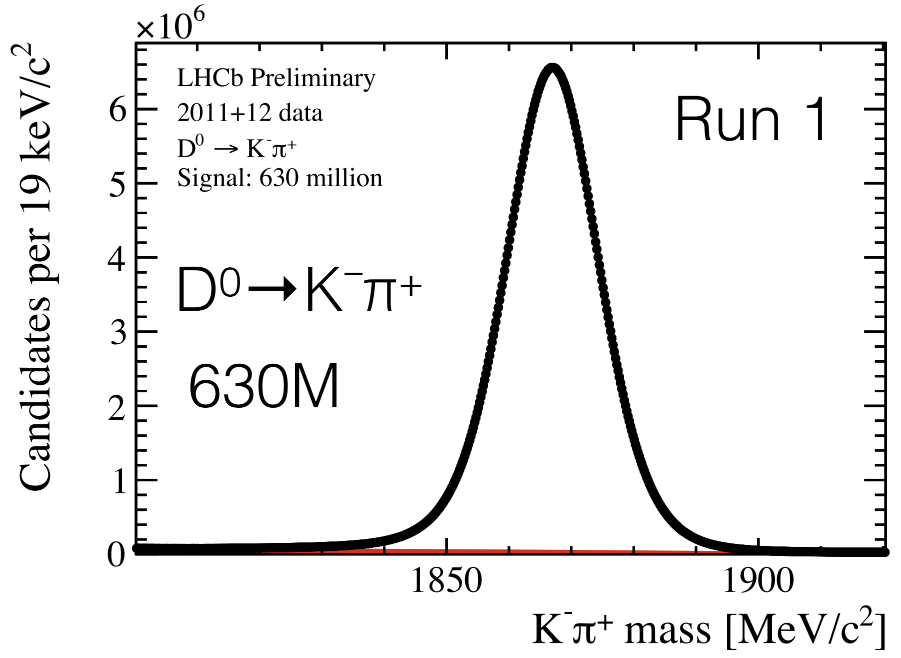


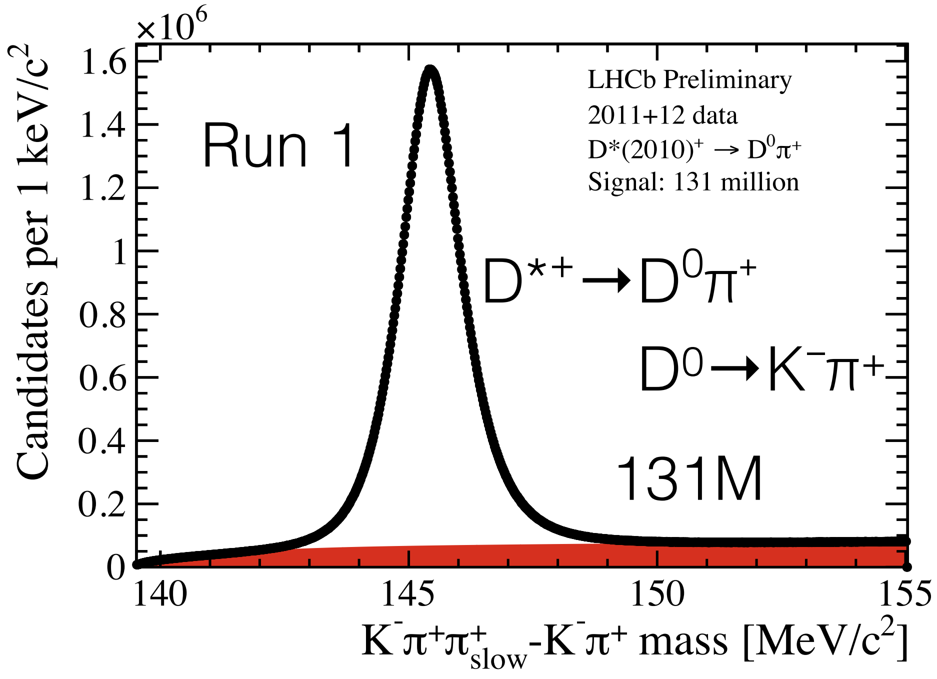
arXiv:1709.04247

- We need to keep pursuing strongly the spectroscopy programme in the present and future LHC phases

Charm Physics with LHCb

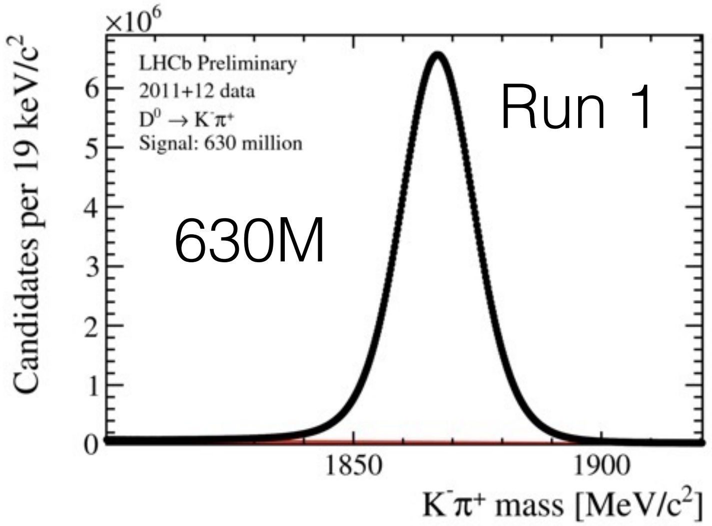
- All *c* species produced in *pp* collisions.
- Huge production cross-section $\sigma(pp \to DX) \sim 1000$ μbarn at 13 TeV.
- Produced ~5×10^{12} D^0 and ~2×10^{12} D^{*+} mesons in only 3fb^{-1} (Run 1) of data at $L_{inst} = 4 \times 10^{32}$ $cm^{-2}s^{-1}$.
- Final Run 1 sample about factor of 30 larger than samples collected by past experiments.

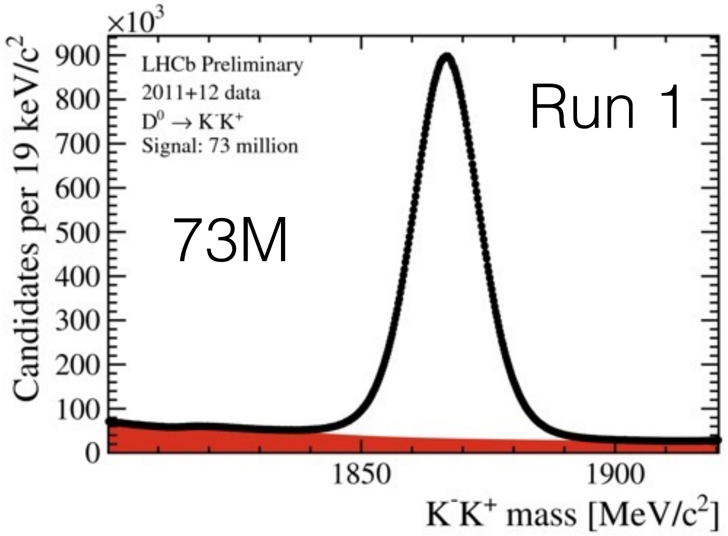


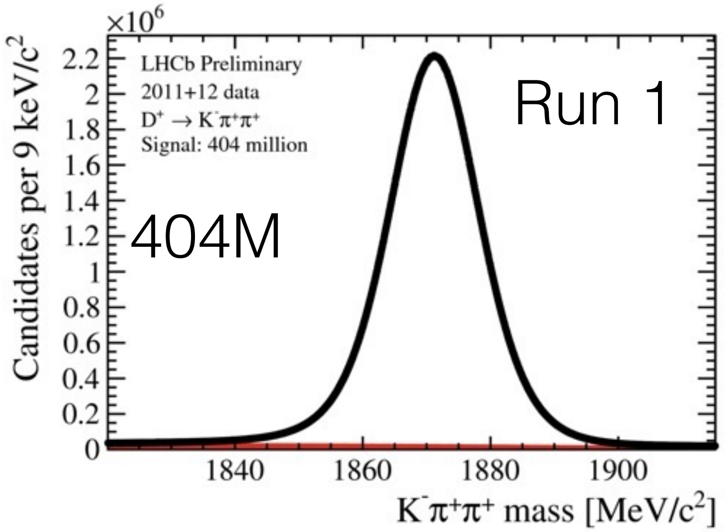


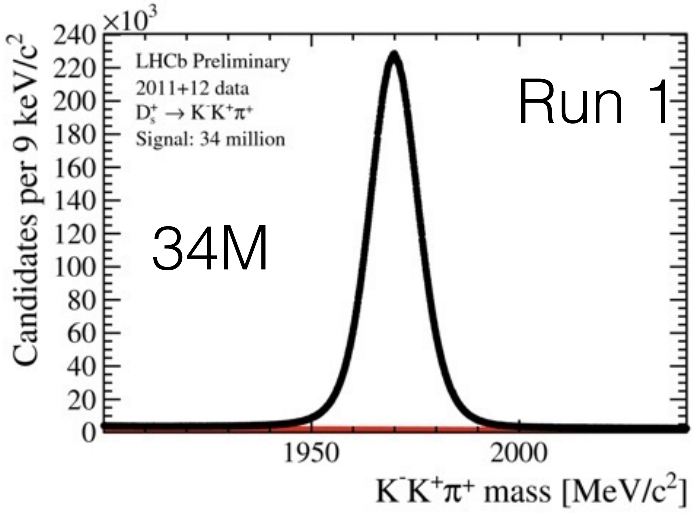
LHCb-CONF-2016-005

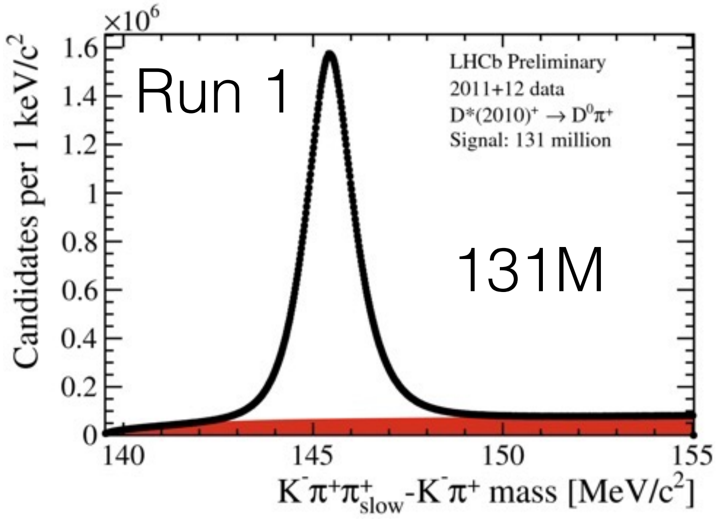
A plenty of charm

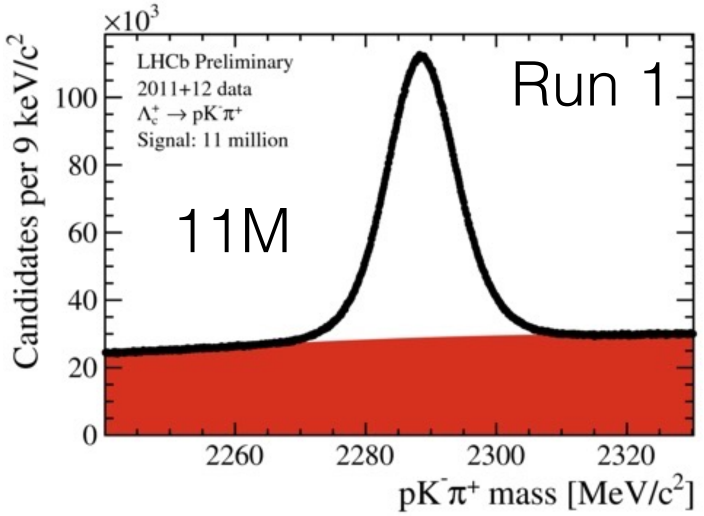










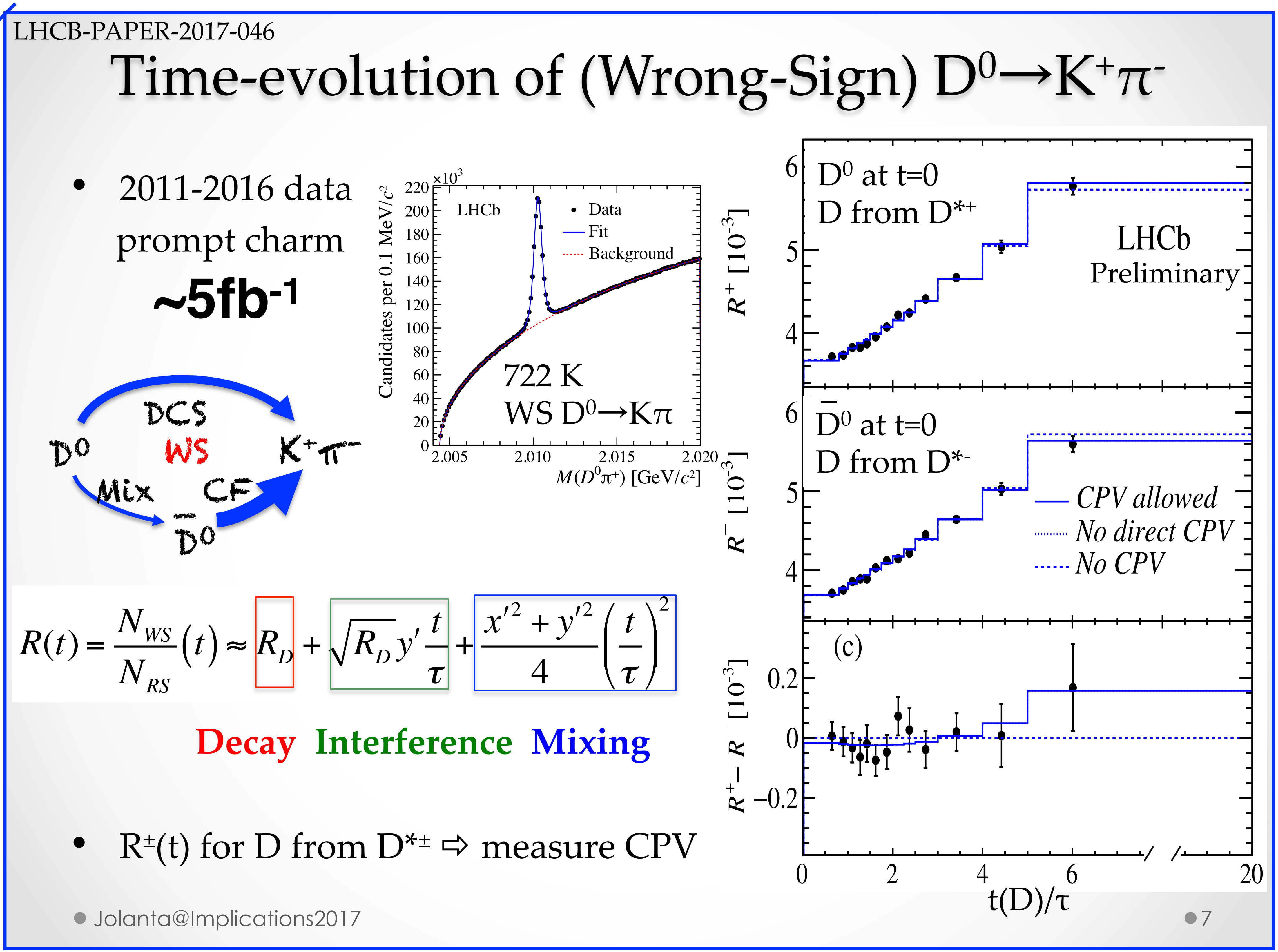


LHCb-CONF-2016-005

Today N$_{\text{sig}}$(Run 1 + Run 2) ~ 3.2 x N$_{\text{sig}}$(Run 1), and LHCb is taking data until the end of 2018, collecting about a total of 8fb^{-1} of data with the same efficiency and purity (yield per luminosity in 2015-16 increased by a factor of ~4 wrt Run 1).

Jolanta Brodzicka , Implication workshop Nov 9th,2017
https://indico.cern.ch/event/646856/

NEW



LHCB-PAPER-2017-046

Time-evolution of (Wrong-Sign) $D^0 \to K^+\pi^-$

- 2011-2016 data prompt charm

~5fb⁻¹

$$R(t)=\frac{N_{WS}}{N_{RS}}(t)\approx \boxed{R_D} + \boxed{\sqrt{R_D}\,y'\frac{t}{\tau}} + \boxed{\frac{x'^2+y'^2}{4}\left(\frac{t}{\tau}\right)^2}$$

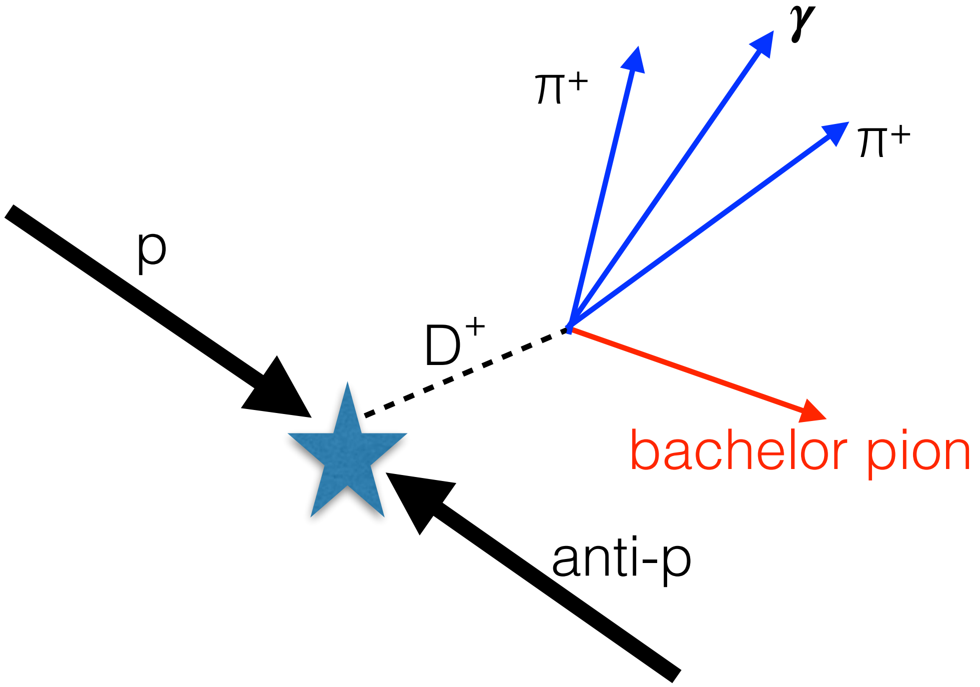
Decay **Interference** **Mixing**

- $R^\pm(t)$ for D from $D^{*\pm}$ ⇨ measure CPV

Jolanta@Implications2017

A_{CP} with neutrals: $D^+_{(s)} \to \eta'\pi^+$

First time measurement of CPV in charm with neutrals at LHCb.



Full Run 1 data sample, $N(D^{\pm})$=63k and $N(D_s^{\pm})$=152k. Measurement with respect to reference channels in order to cancel production and detection asymmetries.

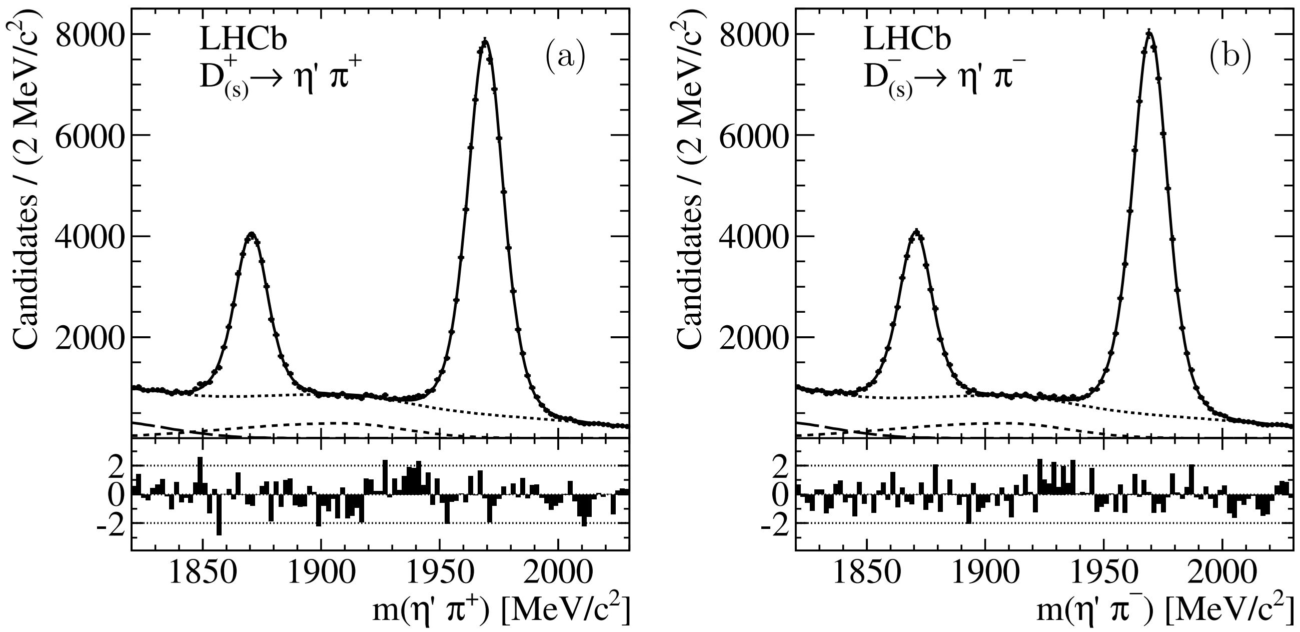
$$\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) \approx \Delta\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) + \mathcal{A}_{CP}(D^{\pm} \to K^0_S\pi^{\pm}).$$

$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) \approx \Delta\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) + \mathcal{A}_{CP}(D_s^{\pm} \to \phi\pi^{\pm}).$$

$$\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\%,$$
$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\%,$$

Most precise measurement of CP asymmetries in $D^+_{(s)} \to \eta'\pi^+$ decays to date. Previous measurements at e^+e^- machines error>1%.

PLB 771 (2017) 21-30



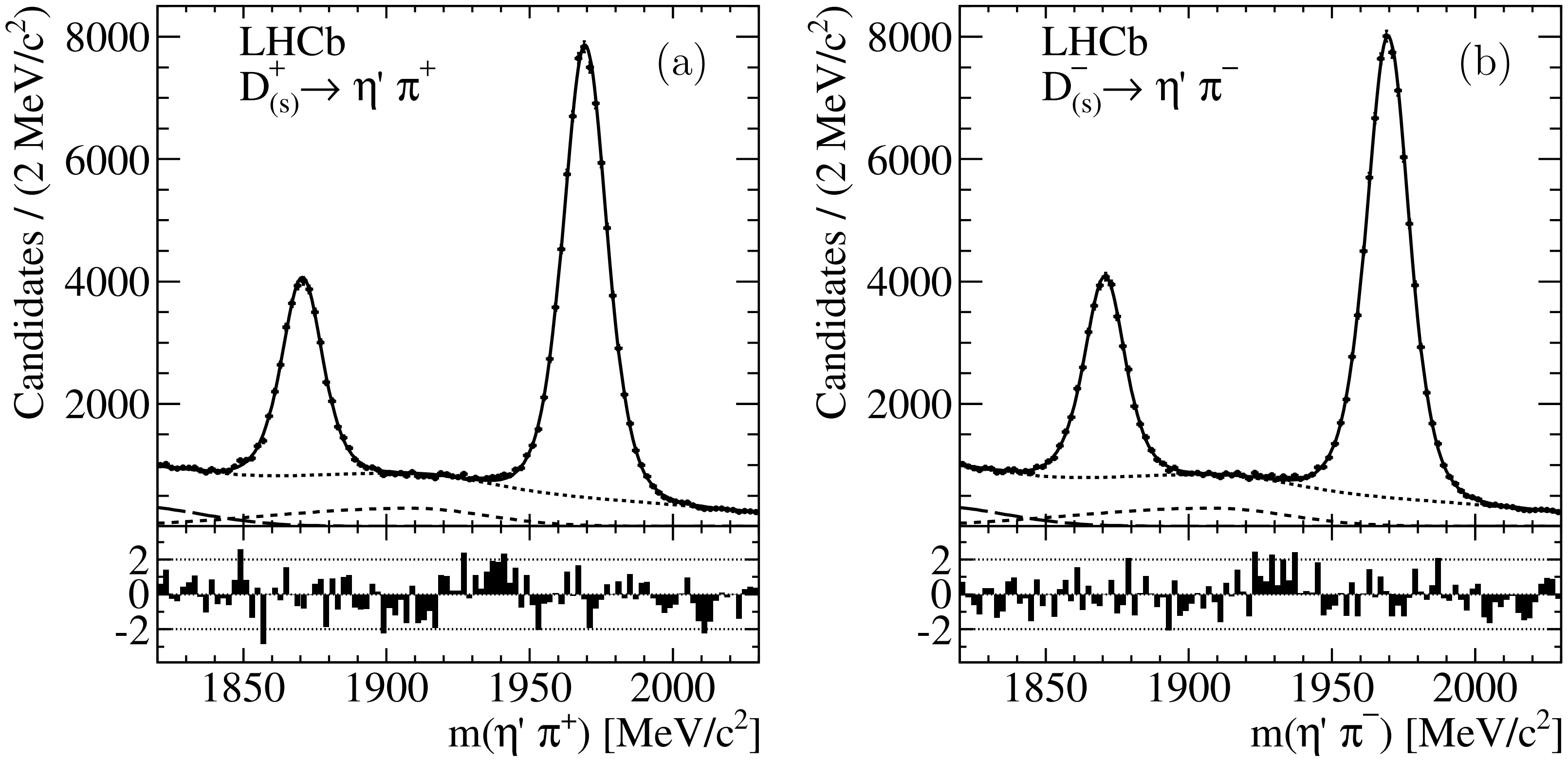
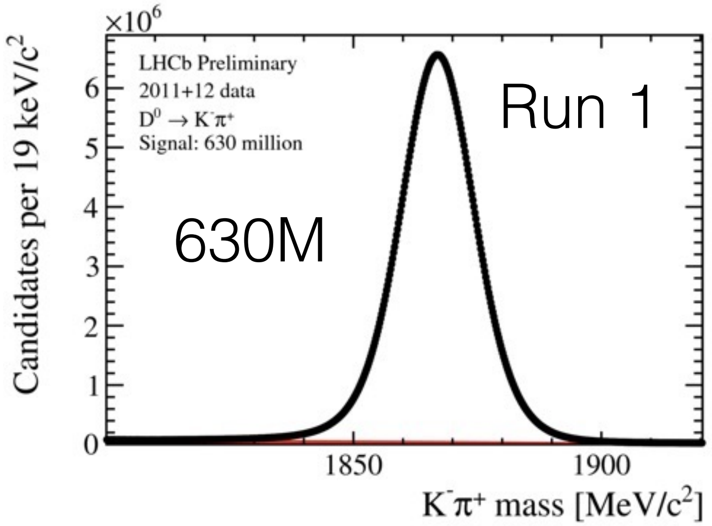
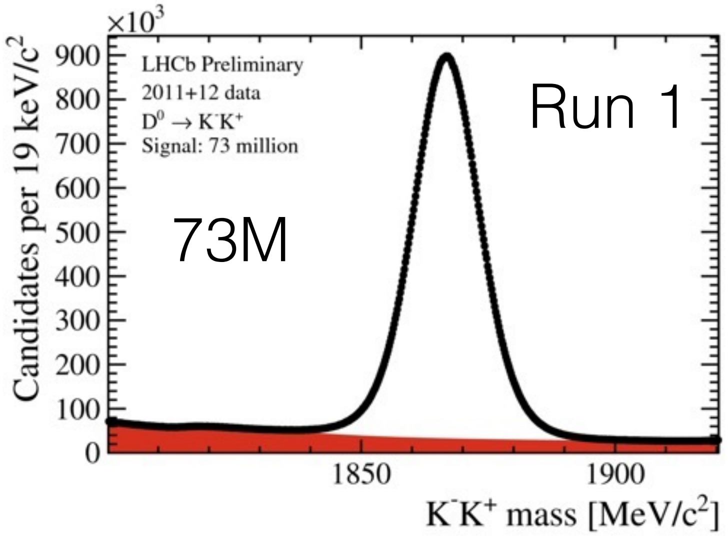
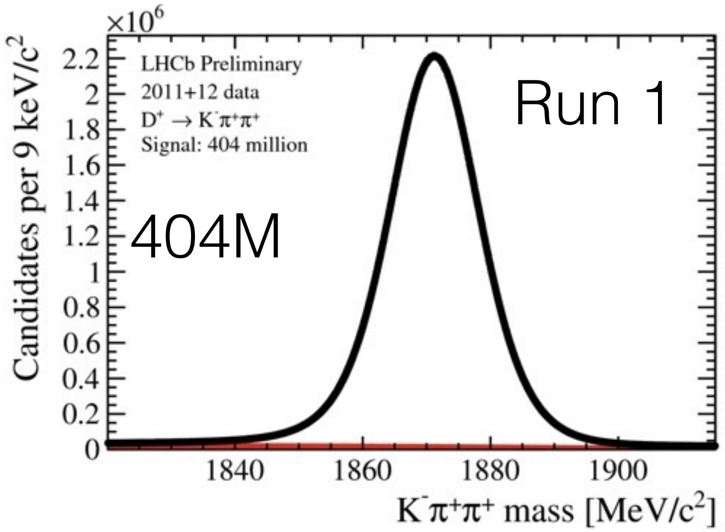


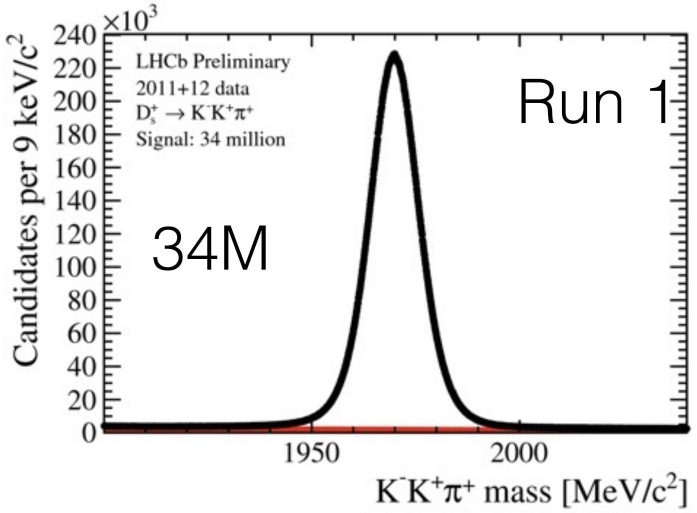
Figure 2: Mass distribution of $\eta'\pi^{\pm}$ candidates, combined over all kinematic bins, pp centre-of-mass energies, and hardware trigger selections, for (a) positively and (b) negatively charged $D^{\pm}_{(s)}$ candidates. Points with errors represent data, while the curves represent the fitted model (solid), the $D_s^{\pm} \to \phi_{3\pi}\pi^{\pm}$ (dashed) and $D^{\pm} \to \phi_{3\pi}\pi^{\pm}$ (long-dashed) components, and the sum of all background contributions (dotted), including combinatorial background. Residuals divided by the corresponding uncertainty are shown under each plot.

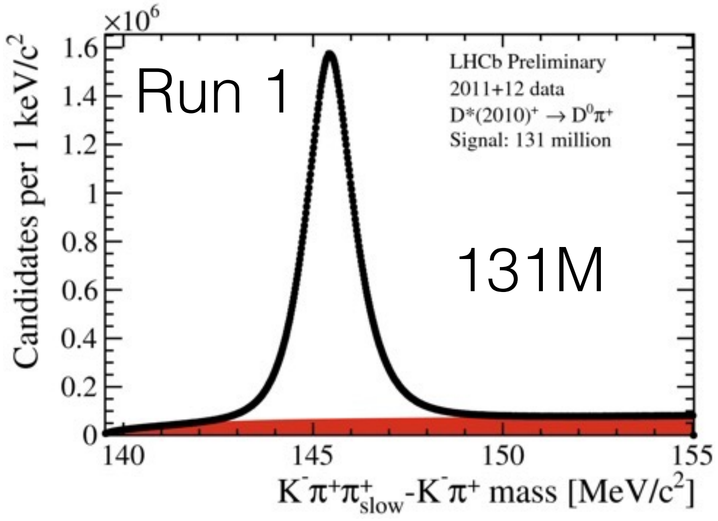
A plenty of charm

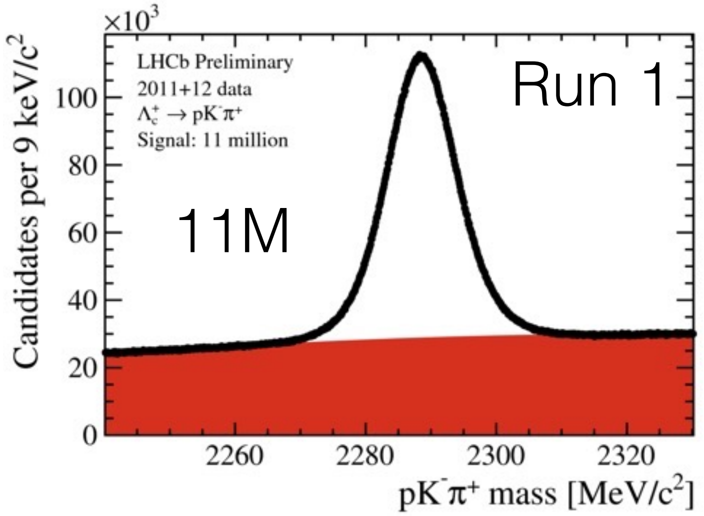












LHCb-CONF-2016-005

Today N_{sig}(Run 1 + 2015-2016) ~ 2-3 x N_{sig}(Run 1), yield per luminosity in 2015-16 increased up to a factor of ~4 wrt Run 1. Charm is already taking fully advantage from the Turbo Stream approach, the same as the LHCb-Upgrade.

Direct CPV: $\Delta A_{CP}(D^0 \rightarrow h^+h^-)$

- Effects of "direct" CP violation can be isolated by taking the difference between the time-integrated CP asymmetries in the K^+K^- and $\pi^+\pi^-$ modes:

$$\begin{aligned}\Delta A_{\rm CP} &\equiv A_{\rm CP}(D^0 \to K^+K^-) - A_{\rm CP}(D^0 \to \pi^+\pi^-)\\ &\approx \Delta A_{\rm CP}^{\rm dir}\left(1 + y_{\rm CP}\frac{\overline{\langle t \rangle}}{\tau}\right) + A_{\rm CP}^{\rm ind}\frac{\Delta\langle t \rangle}{\tau}\end{aligned}$$

- where a residual experiment-dependent contribution from indirect CP violation can be present, due to the fact that there may be a decay time dependent acceptance function that can be different for the K^+K^- and $\pi^+\pi^-$ channels.

- Well suited for LHCb because of cancellation of instrumental and production asymmetries. Measurement performed using both D*-tag *[PRL 116, 191601 (2016)]* and semi-leptonic $B \rightarrow D^0\mu X$ *[JHEP 07 (2014) 041]* decays.

D*-tag: $\Delta A_{CP} = (-0.10 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}))\ \%$

μ-tag: $\Delta A_{CP} = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$

LHCb dominates the world average with systematics well below statistical uncertainty.

Time-integrated $A_{CP}(D^0 \rightarrow K^+K^-)$

Full Run 1 data sample (3fb-1).
D^0 flavor inferred with strong $D^{*+} \rightarrow D^0\pi^+$ decay chain.
CPV in calibration channels assumed negligible

$$\begin{aligned}
&A_{CP}(D^0 \to K^-K^+) \\
&\quad = A_{\text{raw}}(D^0 \to K^-K^+) - A_{\text{raw}}(D^0 \to K^-\pi^+) \\
&\qquad + A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) - A_{\text{raw}}(D^+ \to \overline{K}^0\pi^+) \\
&\qquad + A_D(\overline{K}^0).
\end{aligned}$$

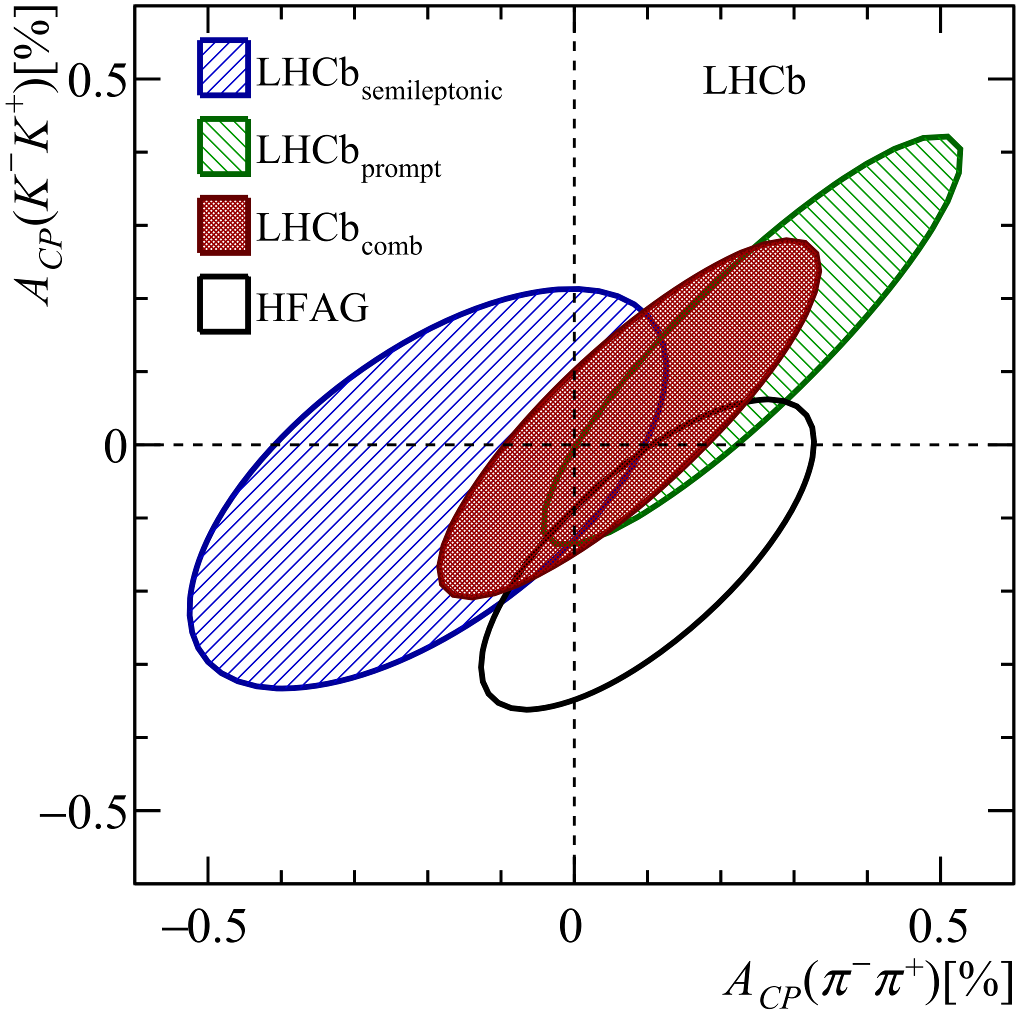
$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

A combination with other LHCb measurements yields

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\text{stat}) \pm 0.11\,(\text{syst}))\%$$

Phys.Lett. B767 (2017) 177-187



Most precise measurements from a single experiment. No evidence of CP asymmetry.

Time-dependent CPV in $D^0 \rightarrow h^+h^-$

Because of the slow mixing rate of charm mesons ($x, y \sim 10^{-2}$) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{t}{\tau}A_{CP}^{\mathrm{ind}}(h^+h^-)$$

$$A_{\Gamma} \approx -A_{\mathrm{CP}}^{\mathrm{ind}}$$

defined as the asymmetry between effective lifetimes

$$A_{CP}^{\mathrm{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\left[\underbrace{y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi}_{\text{CPV in the mixing } |q/p| \neq 1} - \underbrace{x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi}_{\text{CPV in the interference } \varphi_f \neq 0,\pi}\right],$$

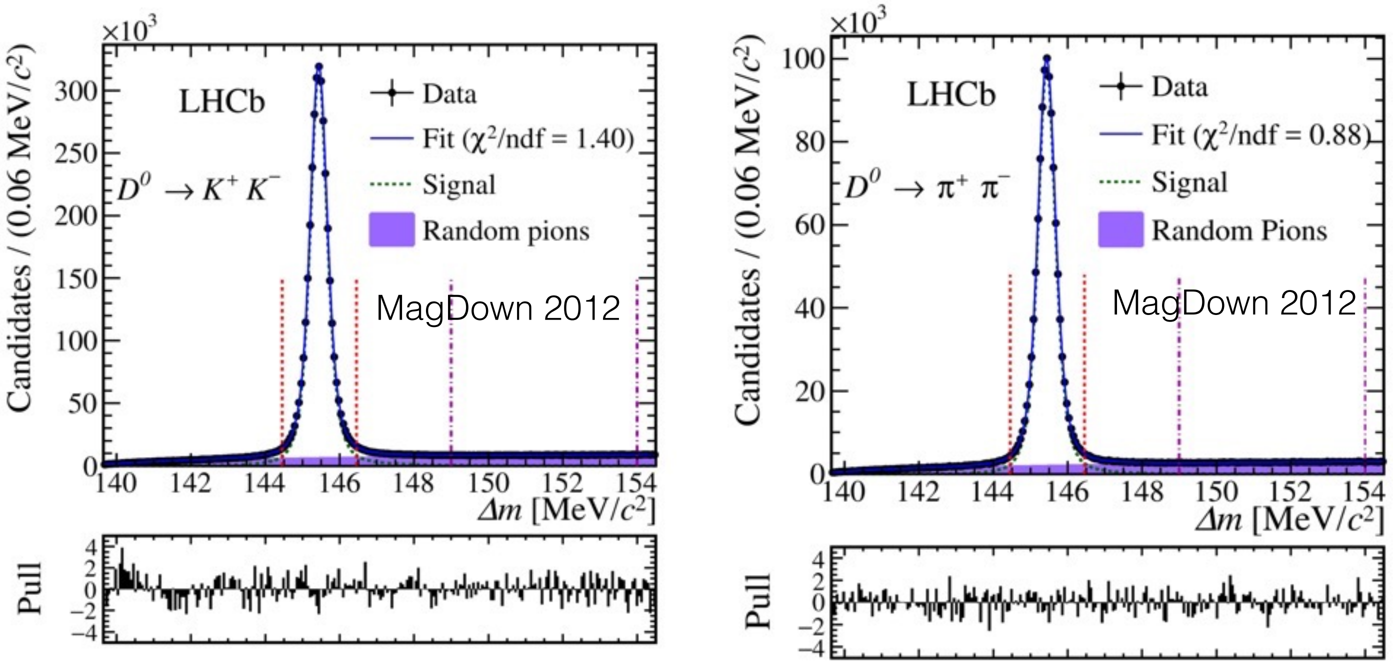
Neglecting subleading amplitudes A_Γ is independent of the final state f. Furthermore, in the absence of CP violation in mixing, it can be found that $A_\Gamma = -x \sin\varphi$ —> $|A_\Gamma| \leq |x| < 5\times10^{-3}$.

Full Run 1 data sample (3fb-1).

D^0 flavor inferred with strong $D^{*+} \rightarrow D^0\pi^+$ decay.

Subsample $[10^6]$	$D^0 \rightarrow K^-\pi^+$	$D^0 \rightarrow K^+K^-$	$D^0 \rightarrow \pi^+\pi^-$
2011 *MagUp*	10.7	1.2	0.4
2011 *MagDown*	15.5	1.7	0.5
2012 *MagUp*	30.0	3.3	1.0
2012 *MagDown*	31.3	3.4	1.1
Total	87.5	9.6	3.0

arXiv:1702.06490 [hep-ex]. Submitted to PRL.



Time-dependent CPV in $D^0 \to h^+h^-$

$$A_\Gamma(K^+K^-) \;=\; (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

arXiv:1702.06490 [hep-ex]. Submitted to PRL.

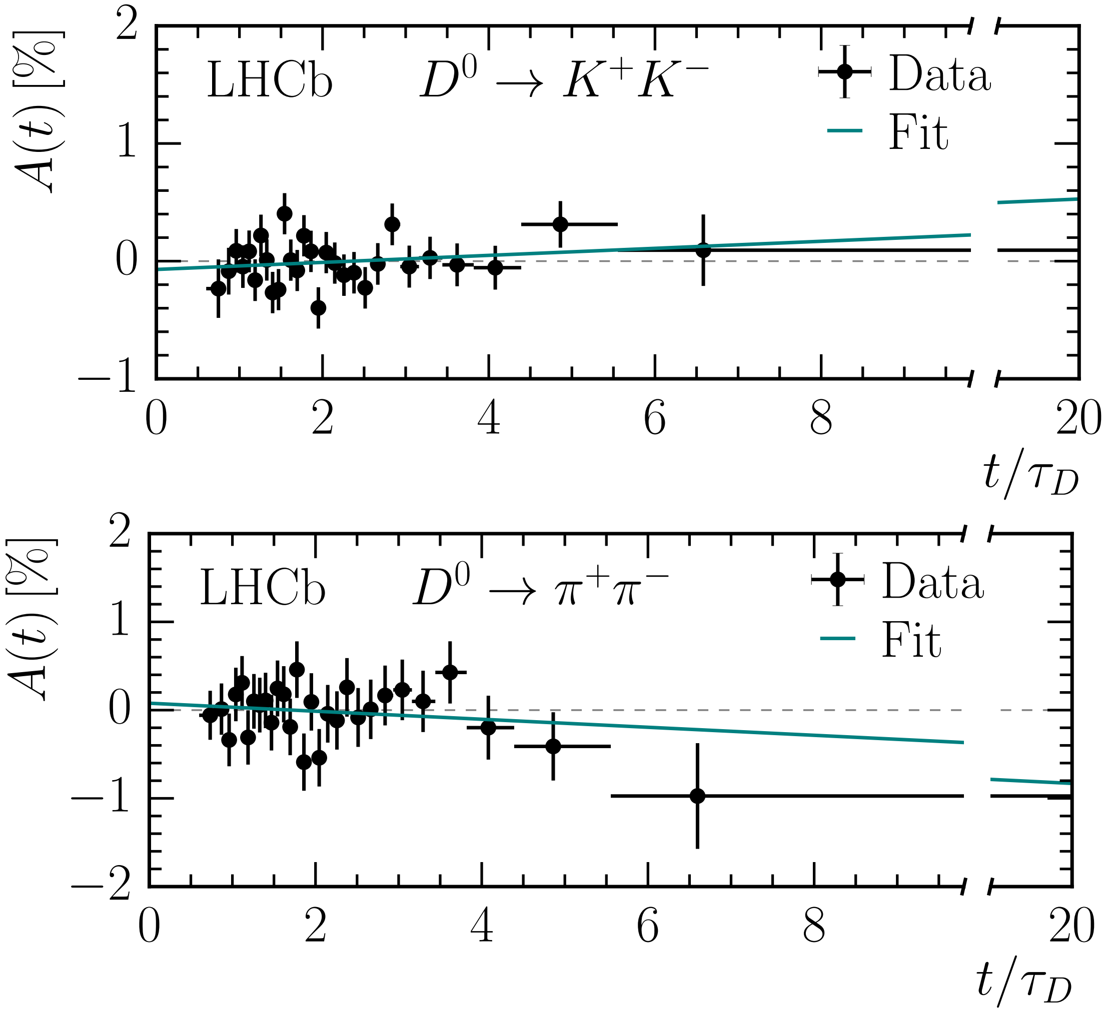
Precision approaches the level of 10^{-4}. No evidence for CP violation and improve on the precision of the previous best measurements by nearly a factor of 2.

Assuming that only indirect CP violation contributes to A_Γ, the two values, can be averaged to yield a single value:

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$

Consistent with the result obtained by LHCb in a muon-tagged sample [*JHEP 1504 (2015) 043*], which is statistically independent. The two results are therefore combined to yield an overall LHCb Run 1 value:

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



Most precise measurement of CPV in the charm sector.

The impact on LHCb on CP Violation of $D^0 \rightarrow h^+h^-$ decays in Run 1

From HFAG 2016 the world average values are:

$$\begin{aligned} A_{\mathrm{CP}}^{\mathrm{ind}} &= (\ \ 0.30 \pm 0.26) \times 10^{-3} \\ \Delta A_{\mathrm{CP}}^{\mathrm{dir}} &= (-1.34 \pm 0.70) \times 10^{-3} \end{aligned}$$

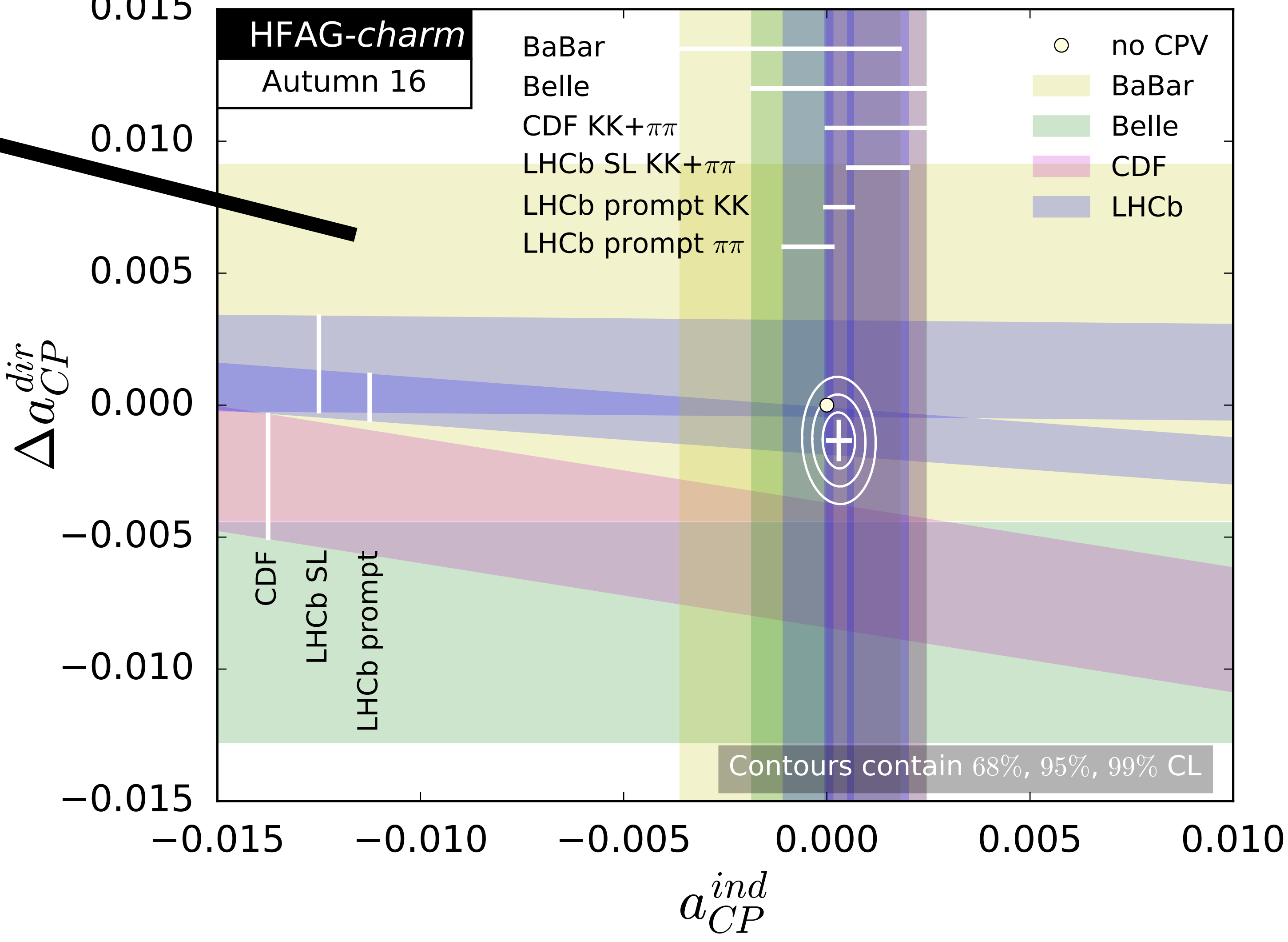
Consistent with the hypothesis of CP symmetry with a p-value of 9.3% (1.7$\boldsymbol{\sigma}$)

My “unofficial” LHCb-only average:

$$\begin{aligned} A_{\mathrm{CP}}^{\mathrm{ind}} &= (\ \ 0.29 \pm 0.28) \times 10^{-3} \\ \Delta A_{\mathrm{CP}}^{\mathrm{dir}} &= (-0.56 \pm 0.76) \times 10^{-3} \end{aligned}$$

Consistent with the hypothesis of CP symmetry with a p-value of 79%.

HFAG 2016 arXiv:1612.07233 [hep-ex]



LHCb dominates the world average and much more data are coming.

Observation of new narrow states

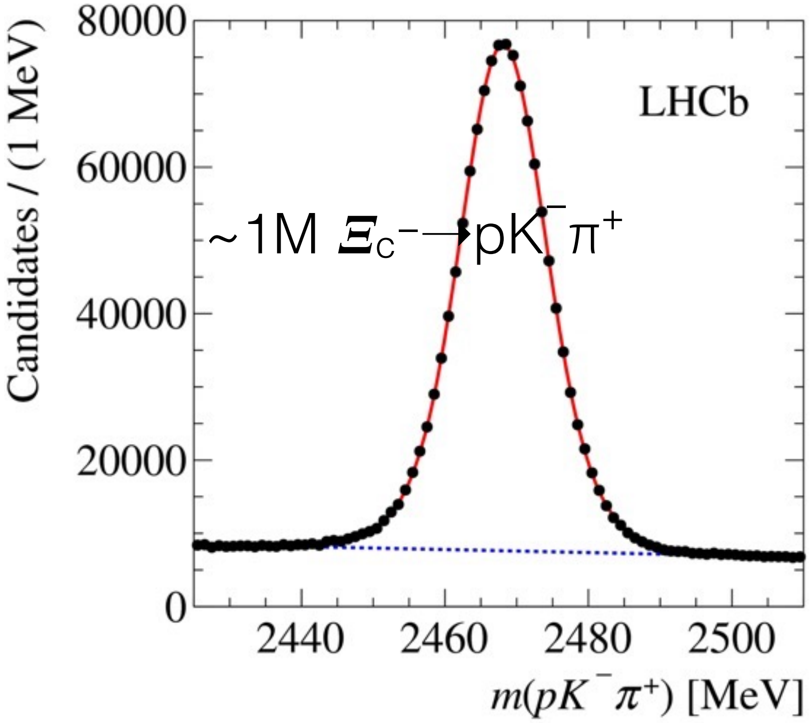
$\Omega^0_c \rightarrow \Xi_c^- K^+$

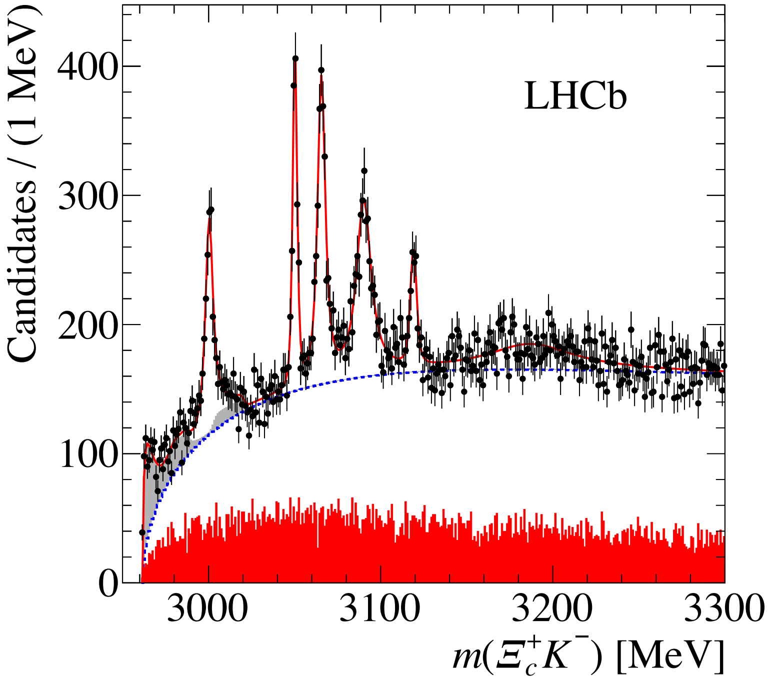
Spectroscopy of singly charmed baryons cqq' is intricate (many states are expected), but it provides a natural way both to understand the spectrum and improve accuracy of theory (i.e HQET).

arXiv:1703.04639 [hep-ex]. Submitted to PRL.

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ $< 1.2\,\mathrm{MeV}, 95\%$ CL	$970 \pm 60 \pm 20$	20.4
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ $< 2.6\,\mathrm{MeV}, 95\%$ CL	$480 \pm 70 \pm 30$	10.4

Run 1 + 2015 data ~ $3.3 fb^{-1}$





Charm Mixing and CPV

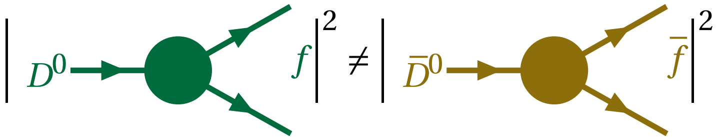
D^0 mixing experimentally well established.
Very slow rate x,y < 10^{-2}

$$|D_{1,2}\rangle = q\,|D^0\rangle \pm p\,|\bar{D}^0\rangle \qquad (|q|^2 + |p|^2) = 1, \phi = \arg\,(q/p)$$

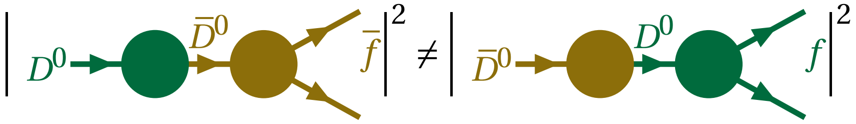
$$\begin{aligned} x &\equiv 2(m_2 - m_2)/(\Gamma_1 + \Gamma_2) \\ y &\equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2) \end{aligned}$$

CPV not yet observed in the charm sector.
SM expectations are of the order of 10^{-3} or less.

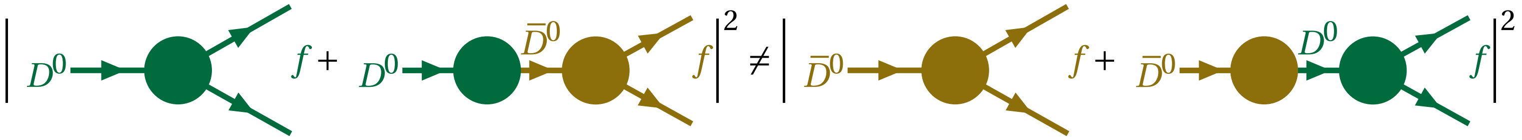
CPV in the decay $(|\bar{A}_f/A_f| \neq 1)$

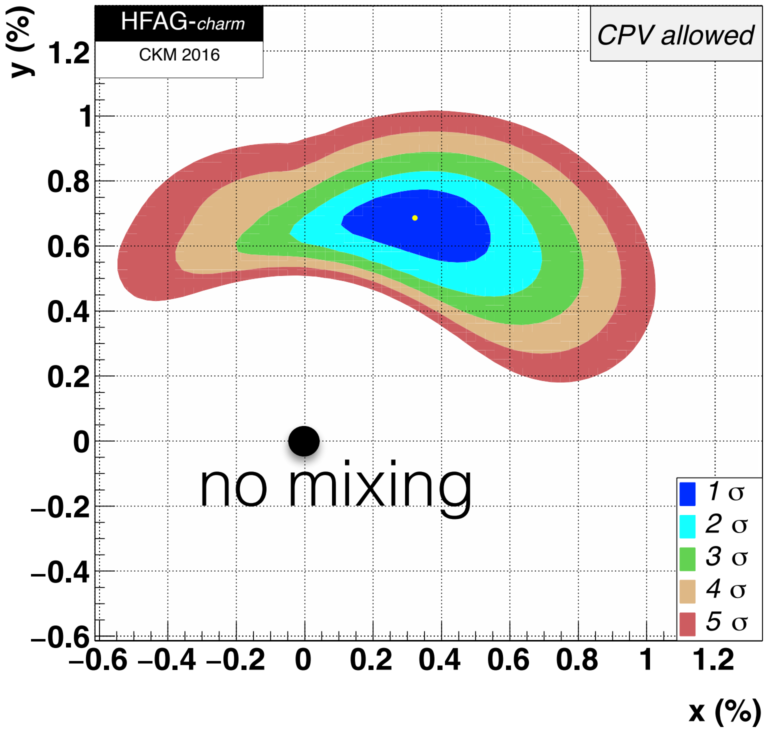


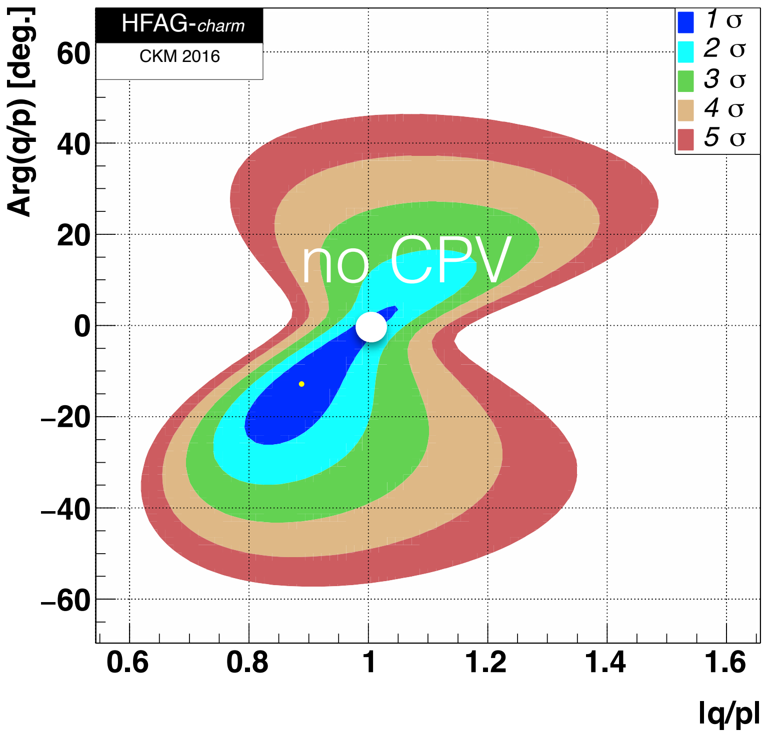
CPV in the mixing $(|q/p| \neq 1)$



CPV in the interference $(\phi_f = \arg(q\bar{A}_f/(pA_f)) \neq 0, \pi)$

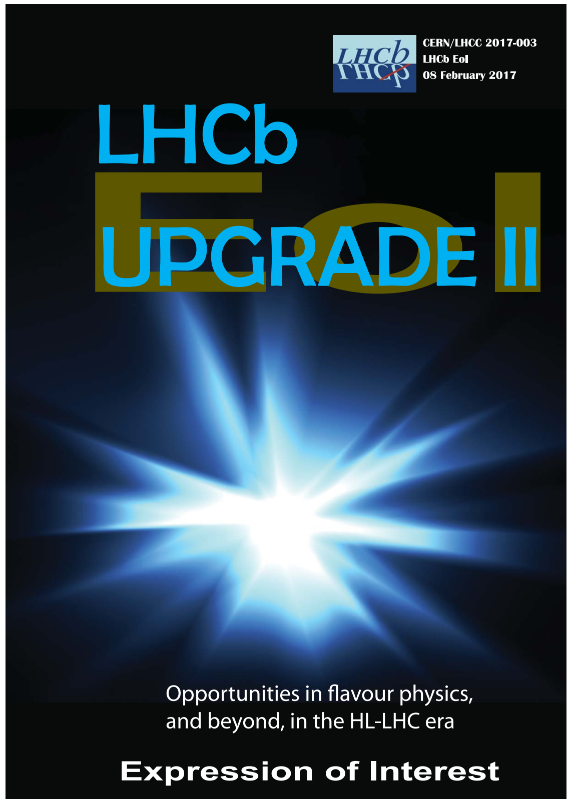






Future perspectives

- The Run 2 (2015-2018, ~8fb^{-1}) is currently ongoing and the size of LHCb samples already increased more than proportionally to the integrated luminosity.
- Phase1 LHCb-Upgrade at L = 2x10^{33} cm^{-2}s^{-1}. (2020-29, ~50fb^{-1}) is behind the corner.
- A proposal of a Phase 2 LHCb-Upgrade at L >10^{34} cm^{-2}s^{-1} (2031-??, >300fb^{-1}) is currently under discussion.


CERN/LHCC 2017-003
LHCb EoI
08 February 2017

LHCb
UPGRADE II
EoI

Opportunities in flavour physics,
and beyond, in the HL-LHC era

Expression of Interest

CERN-LHCC-2017-003

http://agenda.infn.it/event/LHCb-FU


BEYOND THE LHCB PHASE-1 UPGRADE
OPPORTUNITIES IN FLAVOUR PHYSICS IN THE HL-LHC ERA

La Biodola
Isola d'Elba (Italy)
May 28 - 31, 2017

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Guy Wilkinson, University of Oxford (UK)

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Scientific Secretariat
Lucia Lilli and Claudia Tofani

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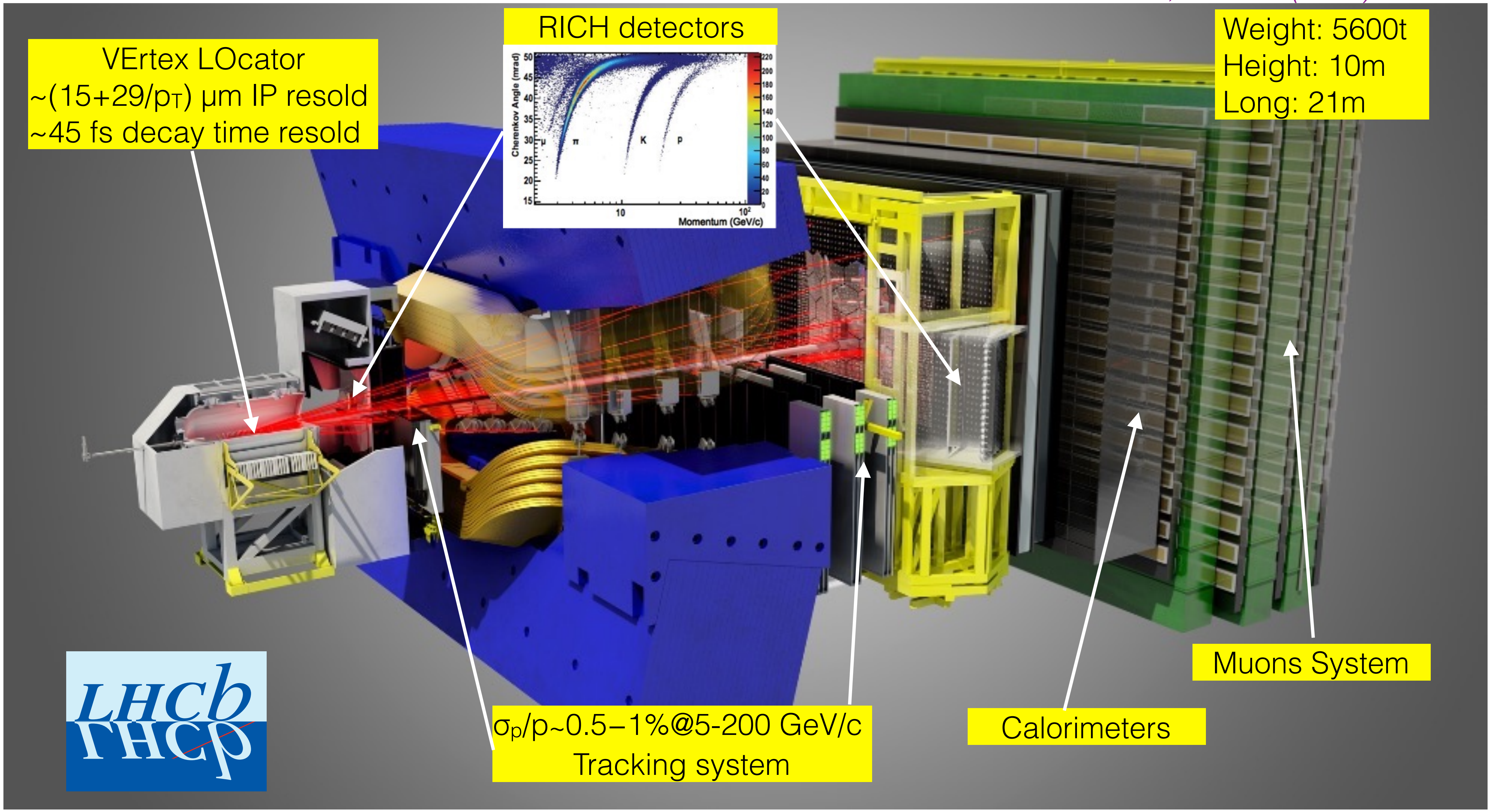
http://agenda.infn.it/event/LHCb-FU

The ‘charming’ beauty experiment

The LHC detector at LHC, JINST 3 (2008) S08005



VErtex LOcator
~$(15+29/p_T)$ μm IP resold
~45 fs decay time resold

RICH detectors

Weight: 5600t
Height: 10m
Long: 21m

σ_p/p~0.5–1%@5-200 GeV/c
Tracking system

Calorimeters

Muons System

Excellent trigger capabilities (Level-0 of custom electronics + HLT of commercial CPUs) to handle 11MHz of visible physics collisions. Events written on tape extremely fast at 5KHz, where typical event size is 60KBytes in Run 1 (2011-2012). In Run 2 (2015-2016) performances are even better. [LHCb-PROC-2015-011].