New Tools for the Next Generation of Particle Physics and Cosmology

Hong Kong, 30 June – 4 July 2019

Prospects of Future Flavour Physics Program at LHC(b)

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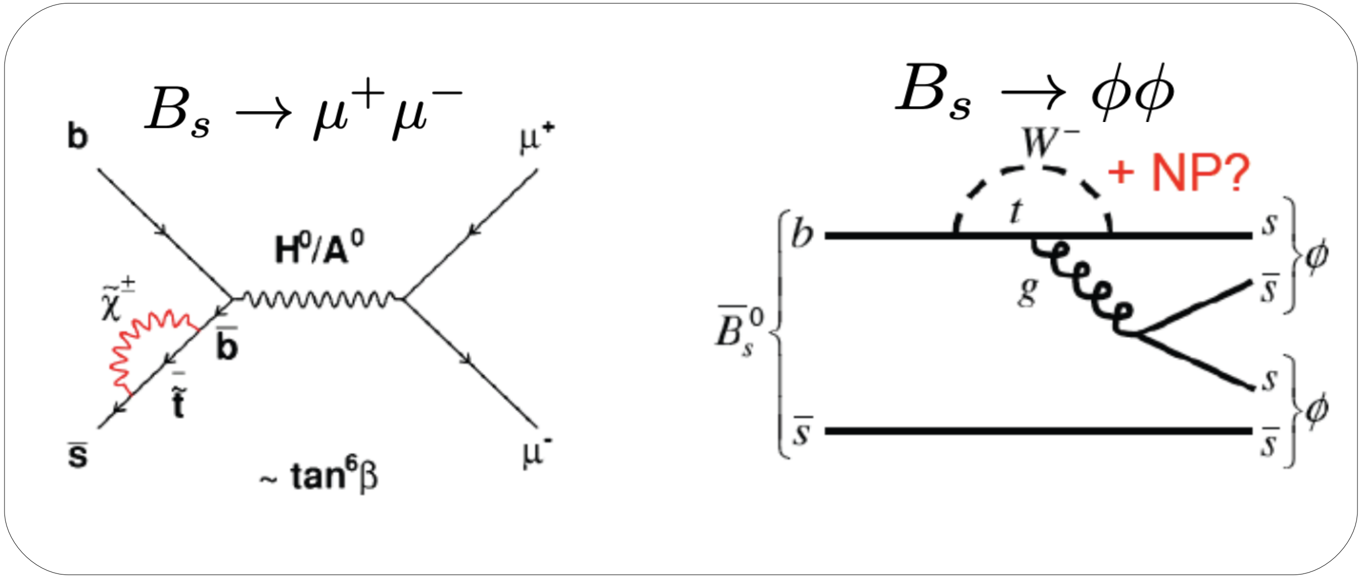
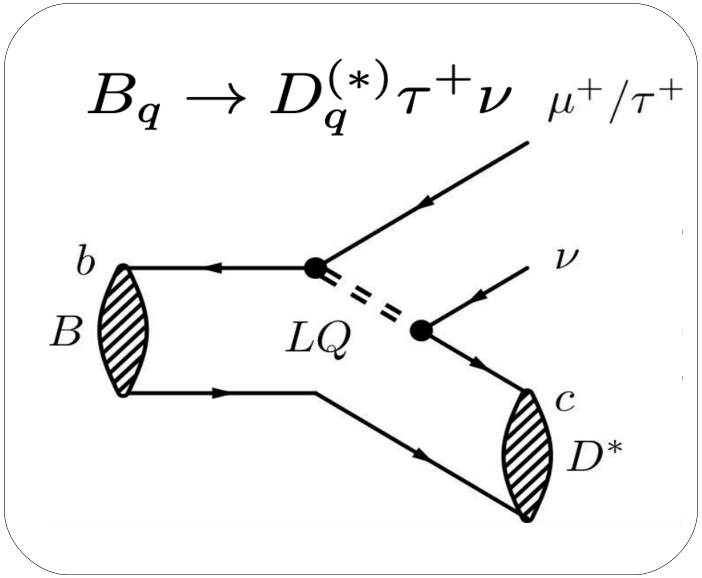
On behalf of LHCb Collaboration

The flavor physics program

- New Physics evidence may appear in measurement of CP violation, rare decays (or in tree level process with final states not fully explored in the past)





- "High intensity frontier" is sensitive to high mass scale
- Complementary to direct searches at ATLAS & CMS
  - When NP will be discovered, its structure need to be determined: flavor physics!

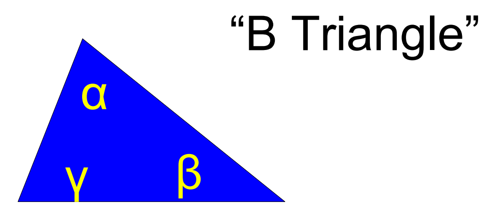
CKM and Unitarity Triangle

- Up to $O(\lambda^6)$ the CKM matrix is

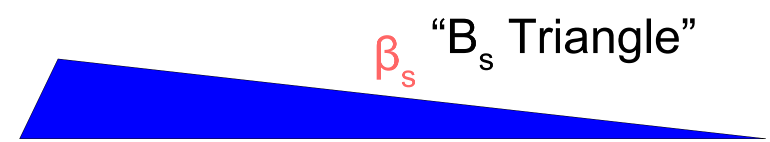
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\bar\rho+i\bar\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(\bar\rho+i\bar\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\bar\rho+i\bar\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

- Many relations from Unitarity

$$\overset{1\cdot\lambda^3}{V_{ud}V_{ub}^*} + \overset{\lambda\cdot\lambda^2}{V_{cd}V_{cb}^*} + \overset{\lambda^3\cdot 1}{V_{td}V_{tb}^*} = 0$$



$$\overset{\lambda\cdot\lambda^3}{V_{us}V_{ub}^*} + \overset{1\cdot\lambda^2}{V_{cs}V_{cb}^*} + \overset{\lambda^2\cdot 1}{V_{ts}V_{tb}^*} = 0$$



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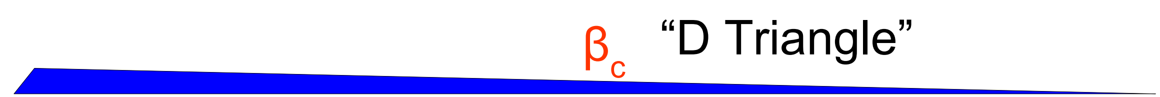


- Measure CKM quantities from loop and tree level processes → overconstrain the UT, check the SM

Heavy flavour production at LHC

- Huge $b\bar{b}$ cross section from pp collisions

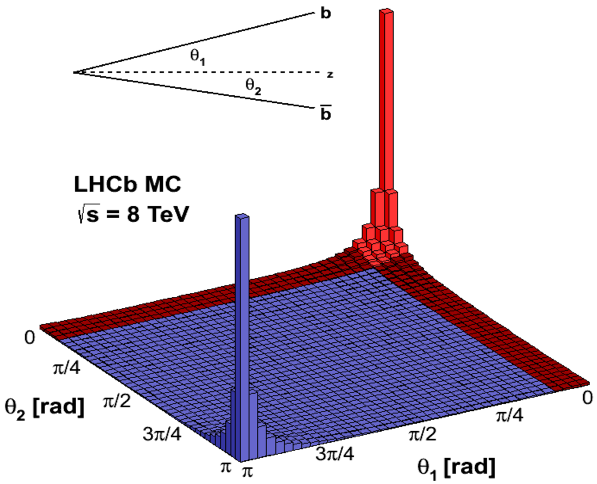
$$\sigma(b\bar{b})(7\ TeV) = 295\mu b$$
$$\sigma(b\bar{b})(13\ TeV) = 560\mu b$$

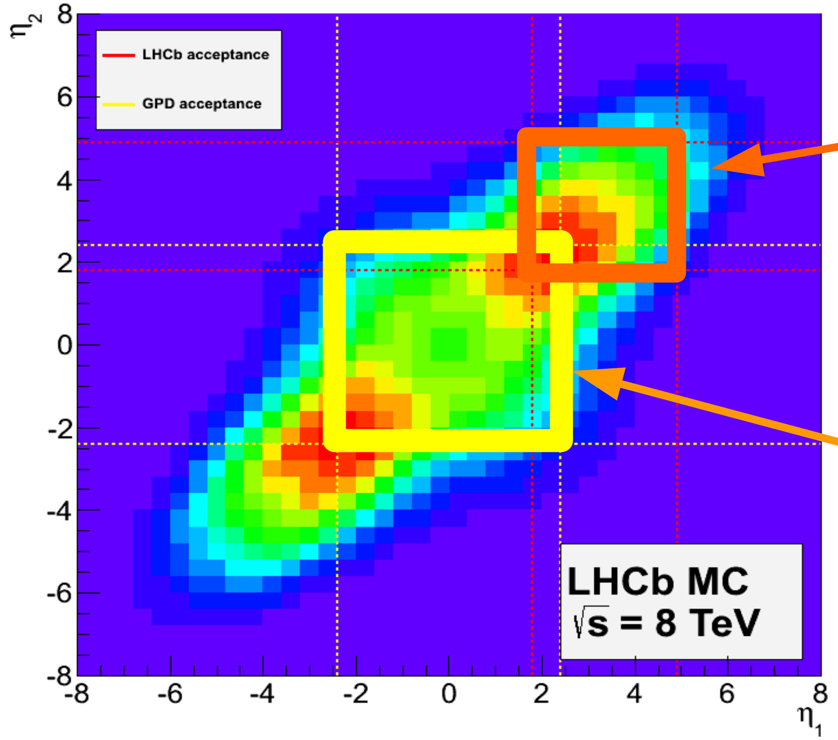
PLB 118, 052992(2017)

- Charm ~ 20 x beauty

JHEP 03(2016)159

gluon-gluon fusion





LHCb acceptance: 2 < η < 5

4% of solid angle

7 TeV 25% of $b\bar{b}$
14 TeV 24% of $b\bar{b}$

$N(b\bar{b}) = 70\cdot10^9/fb^{-1}$
$N(b\bar{b}) = 134\cdot10^9/fb^{-1}$

ATLAS/CMS acceptance: -2.4 < η < 2.4

7 TeV 44% of $b\bar{b}$
14 TeV 41% of $b\bar{b}$

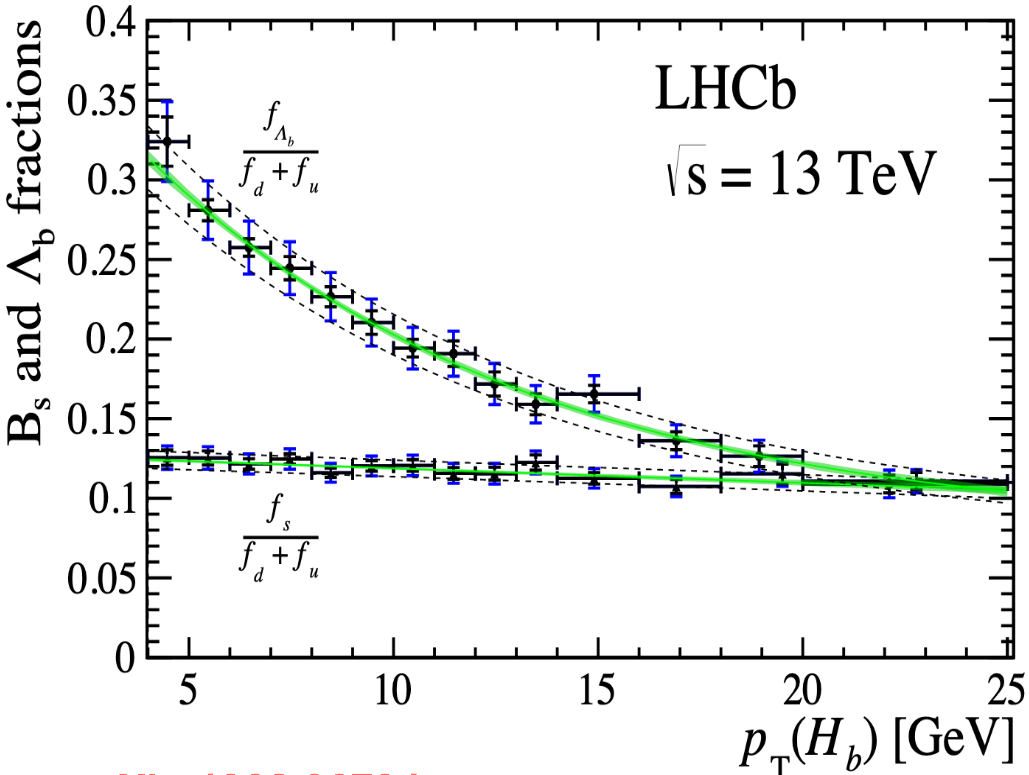
Beauty production at LHC

- All b-hadron species are produced at LHC

$$B^0, B^+, B_s, B_c, \Lambda_b, \Sigma_b, \ldots$$

Analogously: all kind of charmed hadrons

$$N(H_b) = 2 \cdot \sigma(b\bar{b}) \cdot \epsilon(\eta) \cdot f_{H_b} \cdot \mathcal{L}$$



arXiv:1902.06794

@13 TeV
$N(B^0) \approx 54 \cdot 10^9/fb^{-1}$
$N(B_s) \approx 13 \cdot 10^9/fb^{-1}$
$N(\Lambda_b) \approx 20 \cdot 10^9/fb^{-1}$

fraction at high energy

HFLAV

$f(B_s) = 0.101 \pm 0.004$

$f(b\text{-baryon}) = 0.089 \pm 0.012$

$f(B_d) = f(B_u) = 0.405 \pm 0.006$

$f(B_s)/f(B_d) = 0.250 \pm 0.012$

LHCb flavour physics program

CKM and CP violation

$\sin 2\beta$, γ, Φ_s, $|V_{ub}|/|V_{cb}|$, semileptonics, CPV in B^0, B_s, D^0, b-baryons...

Rare decays

$B_{d,s} \to \mu\mu$, $B_{d,s} \to \tau\tau$, $B_s \to \gamma\gamma$, $B_{d,s} \to \tau\mu$, $b \to s\mu^+\mu^-$, $b \to se^+e^-$, $K \to \mu\mu$, $D \to \mu\mu$

Spectroscopy

Tetraquarks, pentaquarks, double-heavy hadrons, excited states...

Electroweak, QCD, Exotica

Z, W, top, $H \to bb$, $H \to cc$, dark photons, Long-lived particles...

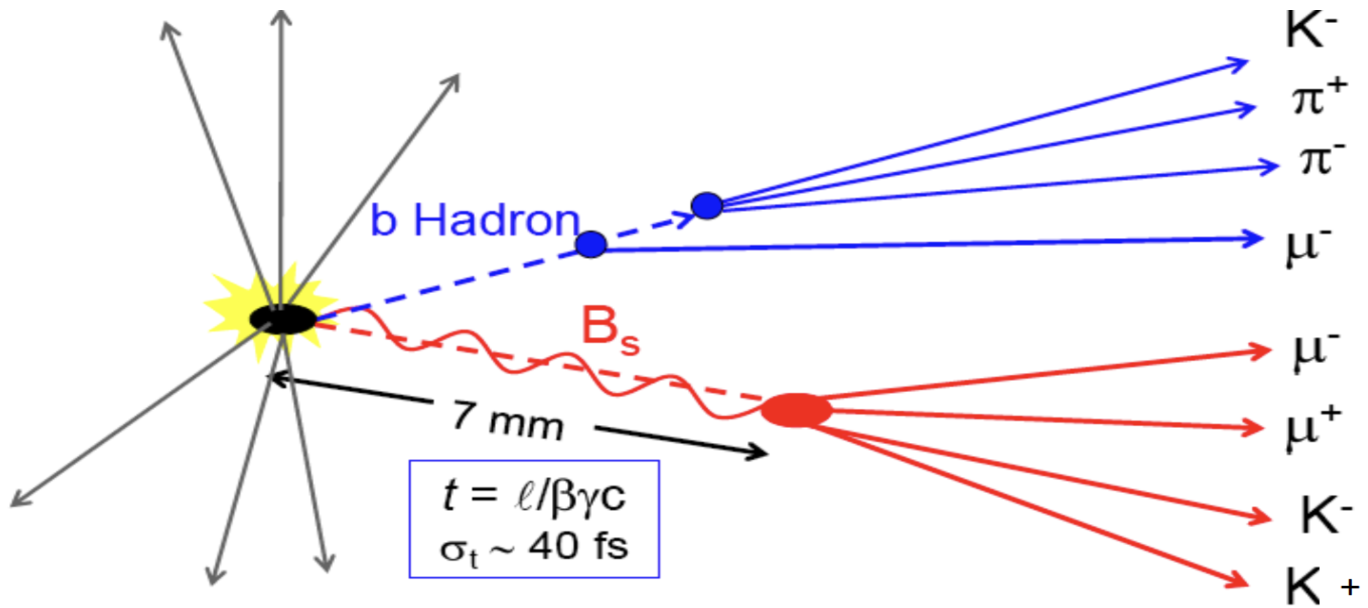
Ion physics, fixed target

Heavy ions, p-Pb, p-Gas (SMOG) ...

Inclusive channels, or channels with many neutrals are very difficult in LHCb - complementarity with Belle-II

Hadronic decay channels that require PID, or low trigger thresholds are only accessible at LHCb

Beauty physics requirements @ LHC



- High statistics: need efficient trigger to select hadronic and leptonic B meson decays $\sigma(b\bar{b})/\sigma(\text{inelastic}) \sim O(10^{-3})$
- Excellent vertex resolution: resolve a displaced secondary vertex
- Very good mass resolution: reduce the background
- Many channels require efficient particle identification (K/π)

The 2010-2018 LHCb Apparatus

JINST 3 (2008) S08005

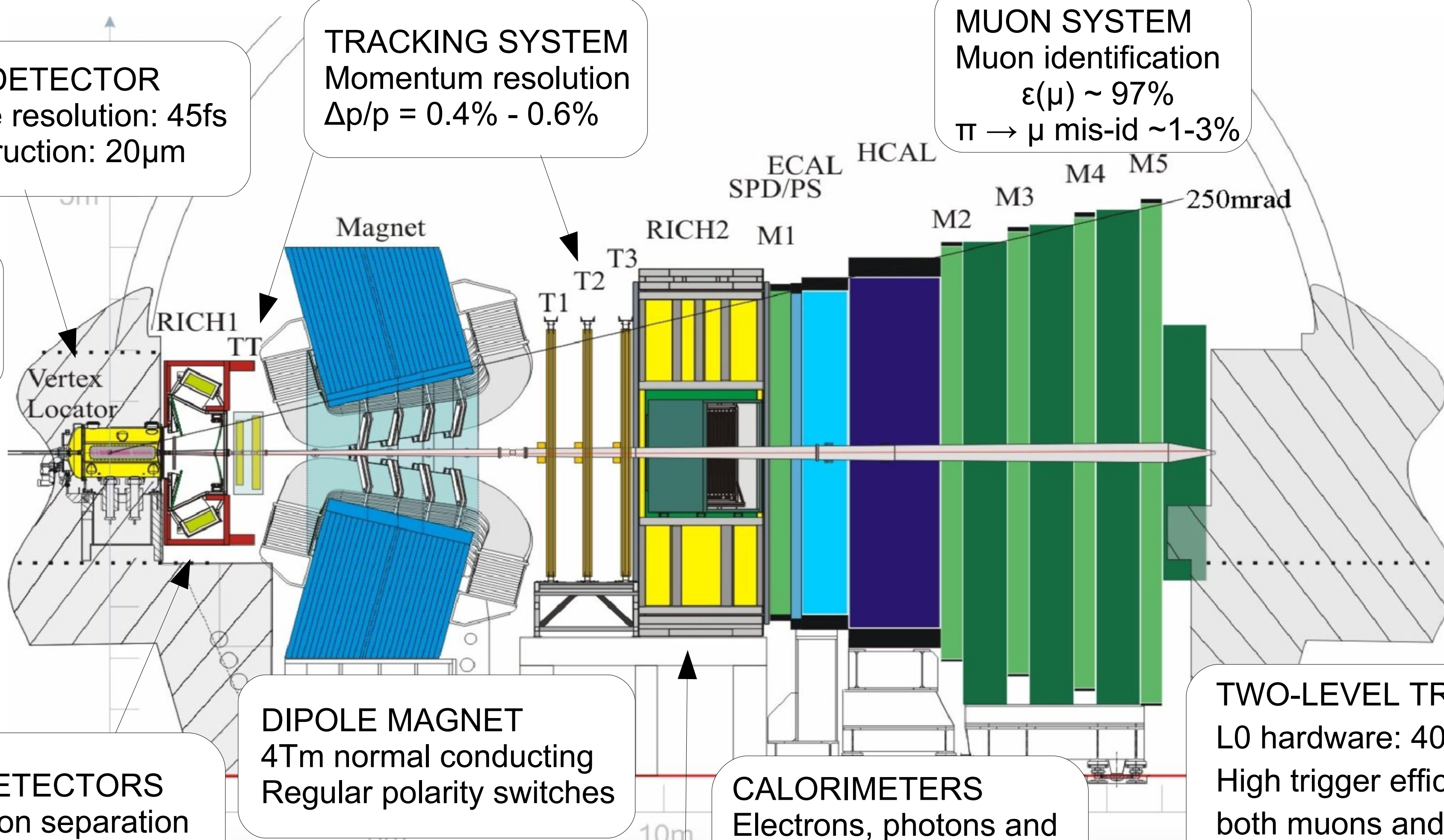
LHCb: a general purpose spectrometer in the forward direction optimized for high-precision heavy-flavor physics

VERTEX DETECTOR
decay time resolution: 45fs
IP reconstruction: 20μm

TRACKING SYSTEM
Momentum resolution
Δp/p = 0.4% - 0.6%

MUON SYSTEM
Muon identification
ε(μ) ~ 97%
π → μ mis-id ~1-3%

L_Z ~ 20m
L_Y ~ 10m
L_X ~ 13m



RICH DETECTORS
K/π/proton separation
ε(K) ~ 95%
π → K mis-id ~5%

DIPOLE MAGNET
4Tm normal conducting
Regular polarity switches

CALORIMETERS
Electrons, photons and hadrons identification
ε(electron) ~ 97%
e → π mis-id ~5%

TWO-LEVEL TRIGGER
L0 hardware: 40 →1 MHz
High trigger efficiencies for both muons and hadrons.
Low momentum thresholds.

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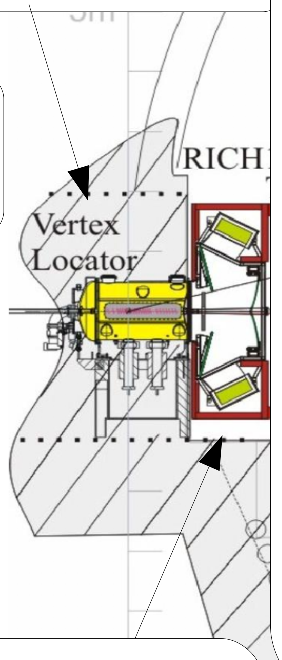

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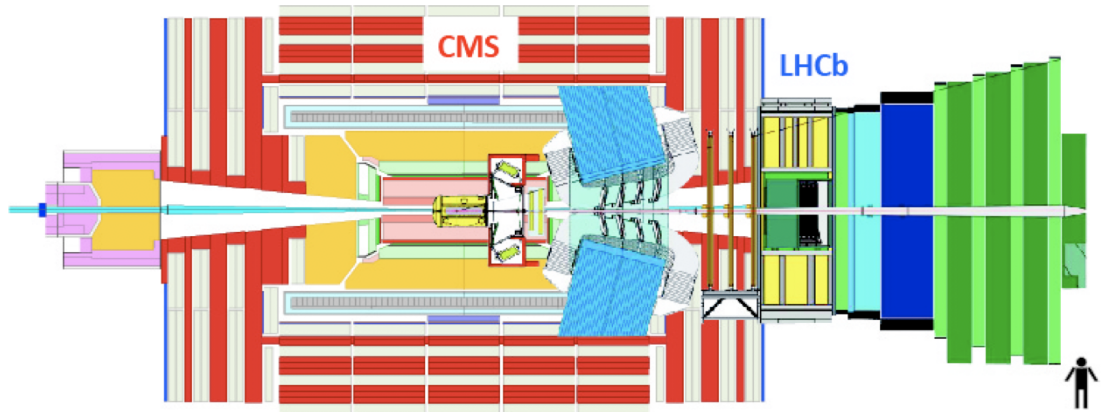


ATLAS and CMS are contributing on flavor physics program with important measurements

When possible I'll compare LHCb performances with GP experiments

RICH DETECTORS
K/π/proton separation
ε(K) ~ 95%
π → K mis-id ~5%

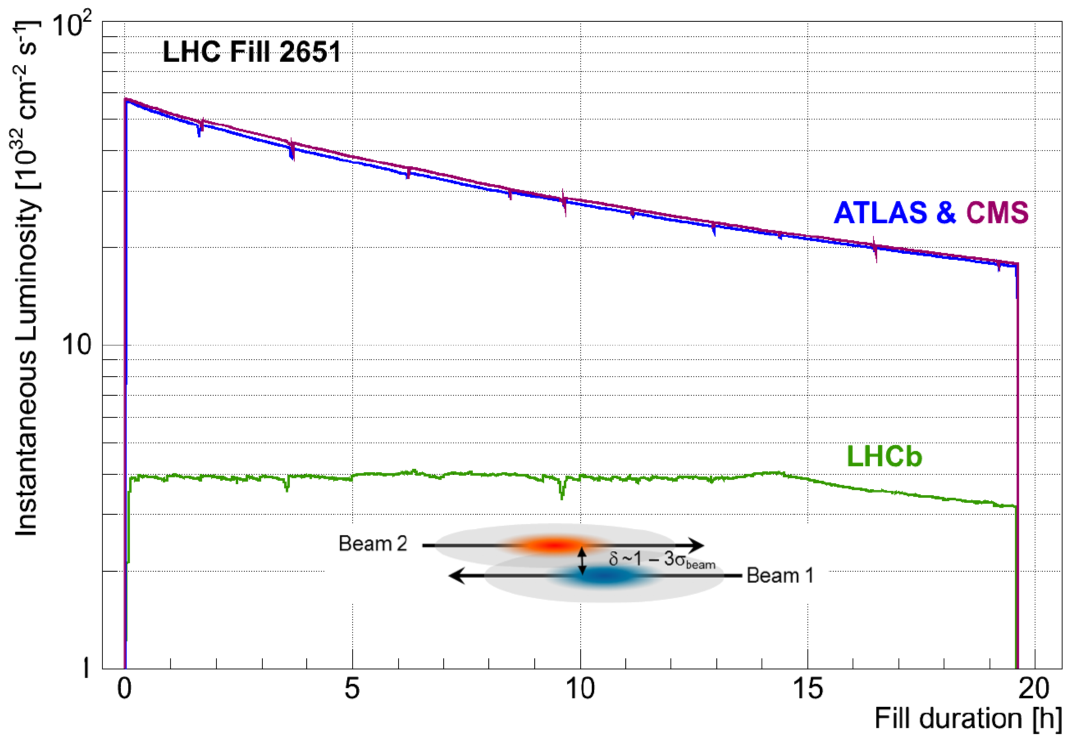
Electrons, photons and hadrons identification
ε(electron) ~ 97%
e → π mis-id ~5%

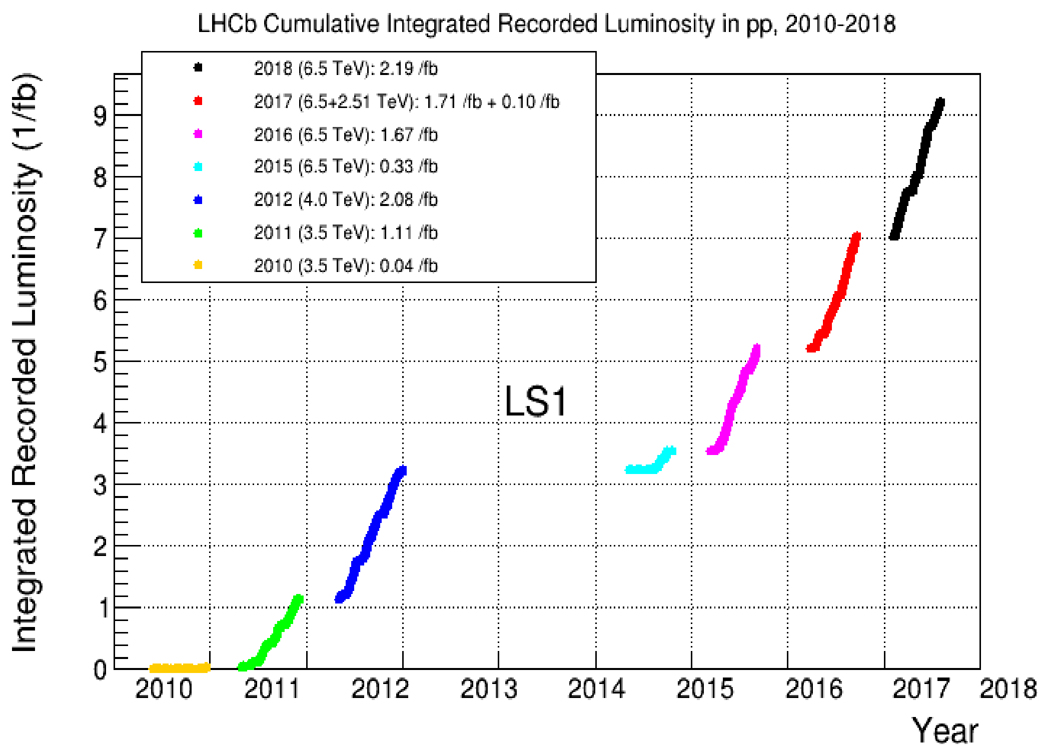
LEVEL TRIGGER
dware: 14→1 MHz
trigger efficiencies for both muons and hadrons.
Low momentum thresholds.

LHCb Detector Operation Run1 & Run2

- LHCb designed to run at lower instantaneous luminosity than ATLAS & CMS
  - pp beams displaced to reduce L
    - $4 \times 10^{32}\ cm^{-2}s^{-1}$
  - Mean number of interactions per bunch crossing ~1

IJMP A30 (2015) 1530022



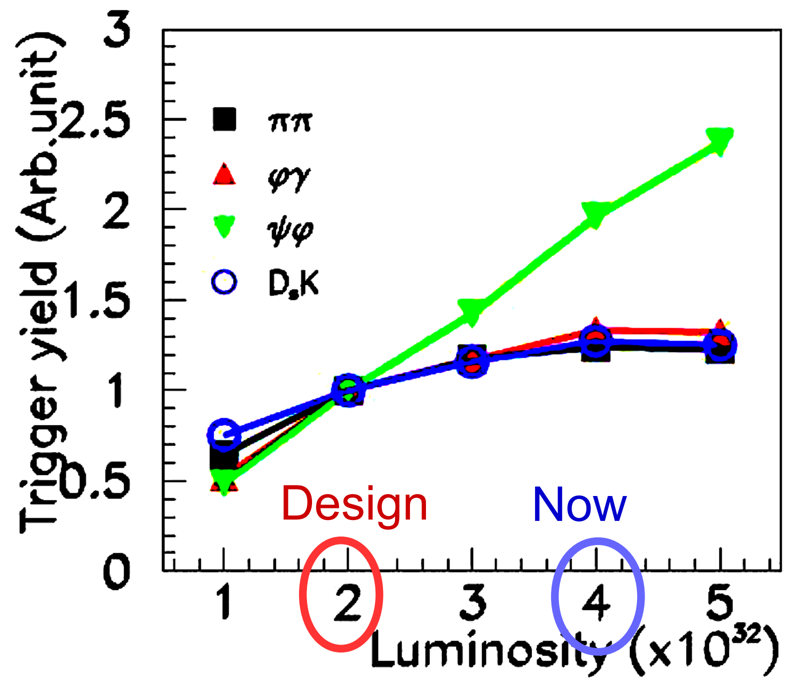


- 1 fb^{-1} pf pp collisions at 7 TeV
- 2 fb^{-1} of pp collisions at 8 TeV
- 6 fb^{-1} of pp collisions at 13 TeV
- Total at end of Run2: 9 fb^{-1}

Imminent LHCb upgrade

CERN-LHCC-2011-001

- Excellent results from Run-I and Run-II physics data analysis
- In most of the case the precision is limited by statistical uncertainties
  - Hardware trigger limited @1MHz rate
  - The high p_T and E_T cuts saturate hadronic channels



- At higher luminosity the current LHCb could not perform successfully track reconstruction and PID information
  - Larger number of primary vertexes: much higher track multiplicity
  - Higher occupancy in the detector
  - Processing time in the online farm too high

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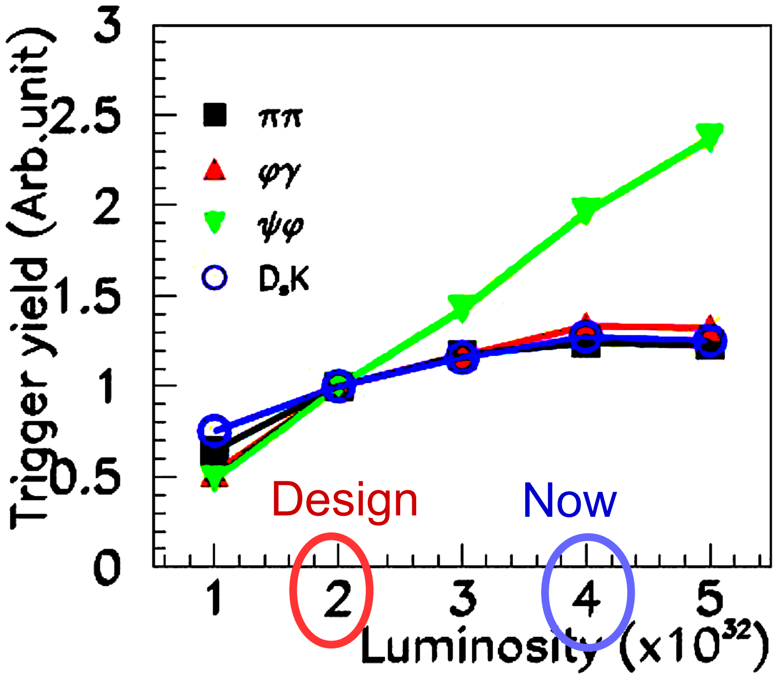


- At higher luminosity the current LHCb could not perform successfully track reconstruction and PID information
  - Larger number of primary vertexes: much higher track multiplicity
  - Higher occupancy in the detector
  - Processing time in the online farm too high

- $L = 20 \times 10^{32}\ cm^{-2}s^{-1}$

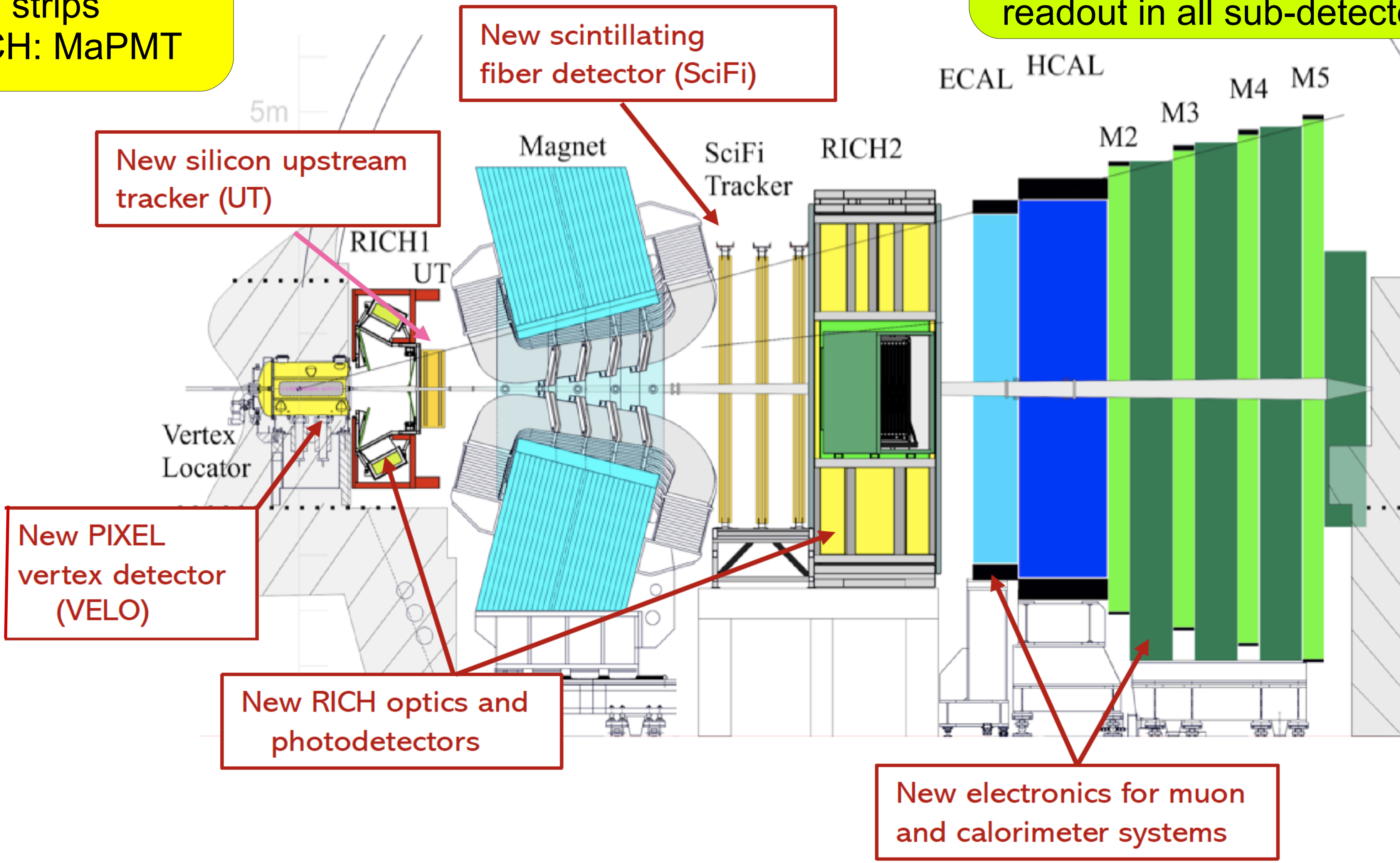
The LHCb Upgrade I

CERN-LHCC-2011-001

Finer sensors:
Velo: pixel
UT: strips
RICH: MaPMT

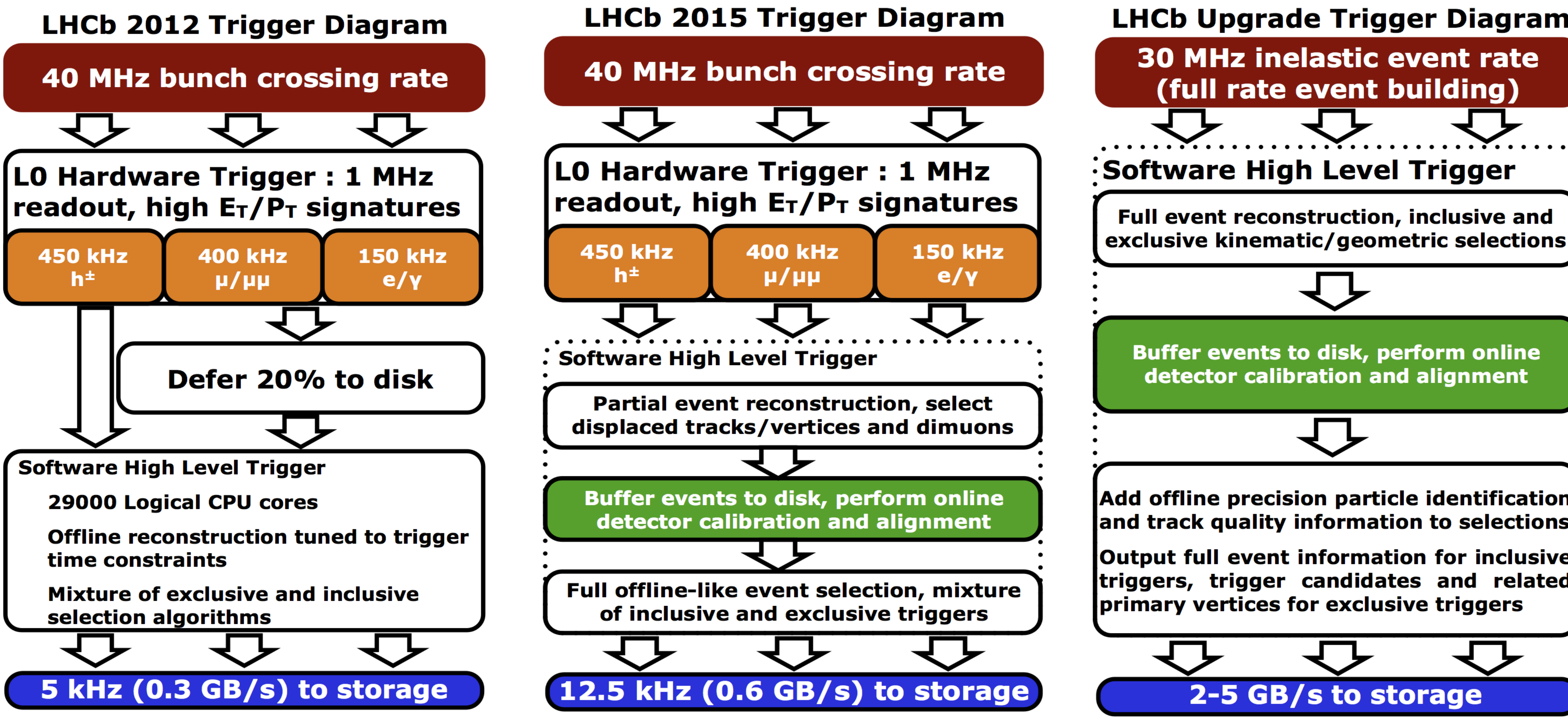
Allow for a factor 5 luminosity increase

Remove the first-level hardware trigger:
Trigger-less 40MHz readout in all sub-detectors



The LHCb Trigger Evolution

LHCB-TDR-016

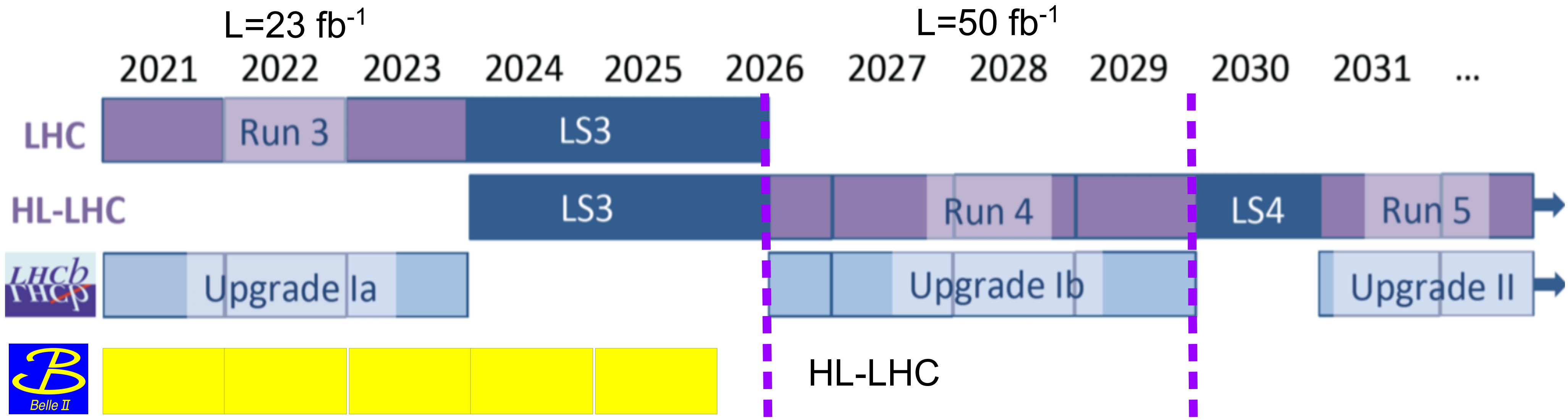


- First-level hardware trigger L0

- First-level hardware trigger L0
- HLT and real time calibration

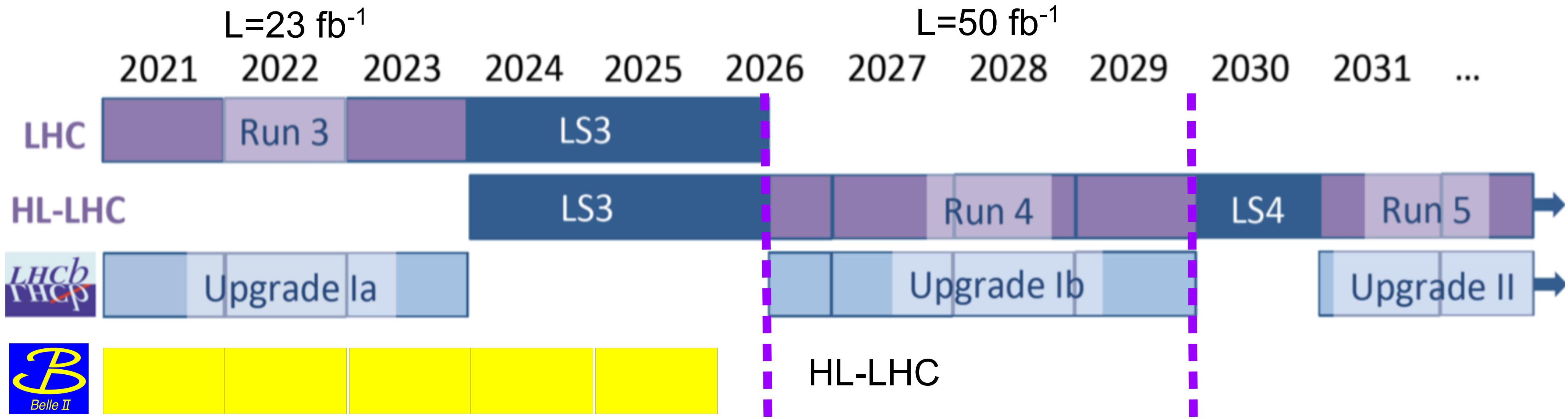
- First-level hardware trigger L0 removed
- Fully software flexible trigger

Post LS2 LHCb Calendar



LHCb luminosity limited
To a max of 2×10^{33} cm^{-2}s^{-1}
5 interactions/bunch crossing

Post LS2 LHCb Calendar



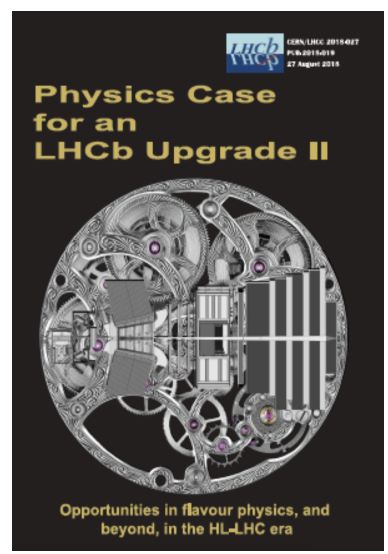
LHCb luminosity limited
To a max of 2x10^{33} cm^{-2}s^{-1}
5 interactions/bunch crossing

Luminosity 10 times higher than UpgradeI
25-50 inter./bunch crossing

Expression of Interest
CERN-LHCC-2017-003

- Fully exploit HL-LHC for flavor physics in LHCb
- Release limits on luminosity: L=10-20 x 10^{33} cm^{-2}s^{-1}
- Goal: collect > 300 fb^{-1}

Physics case for an Upgrade II
arXiv:1808.08865



Green light from LHCC
To proceed to detector TDR's
Expected by late 2020

LHCb Upgrade I: Physics Case

Observable	Current LHCb	LHCb 2025	Belle II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–
$S_{\mu\mu}$	–	–	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**			
$R(D^*)$	0.026 [215, 217]	0.0072	0.005
$R(J/\psi)$	0.24 [220]	0.071	–
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}

Belle-II:
1) Unique capability to perform inclusive measurements
2) precise studies with modes involving many neutrals

LHCb Upgrade II: Physics Case

arXiv:1808.08865

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B^0_s \to D^+_s K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B^0_s \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B^0_s \to D^+_s D^-_s$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B^0_s, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B^0_s\to\mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
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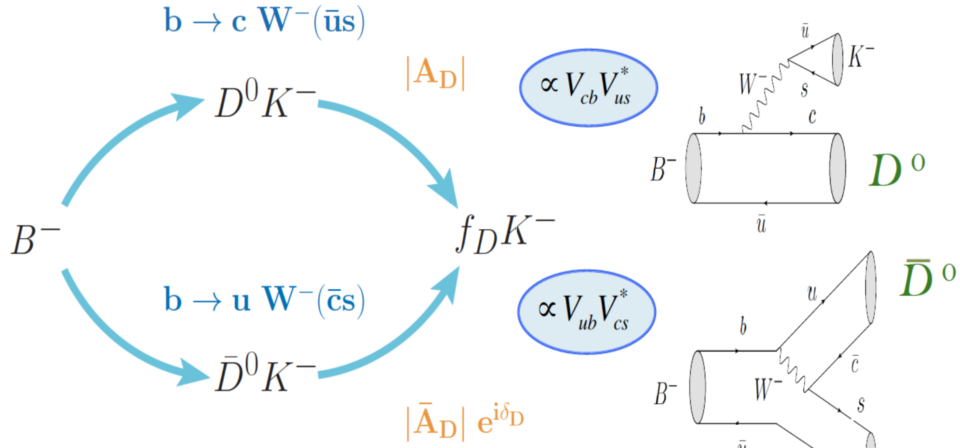
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Current status on γ

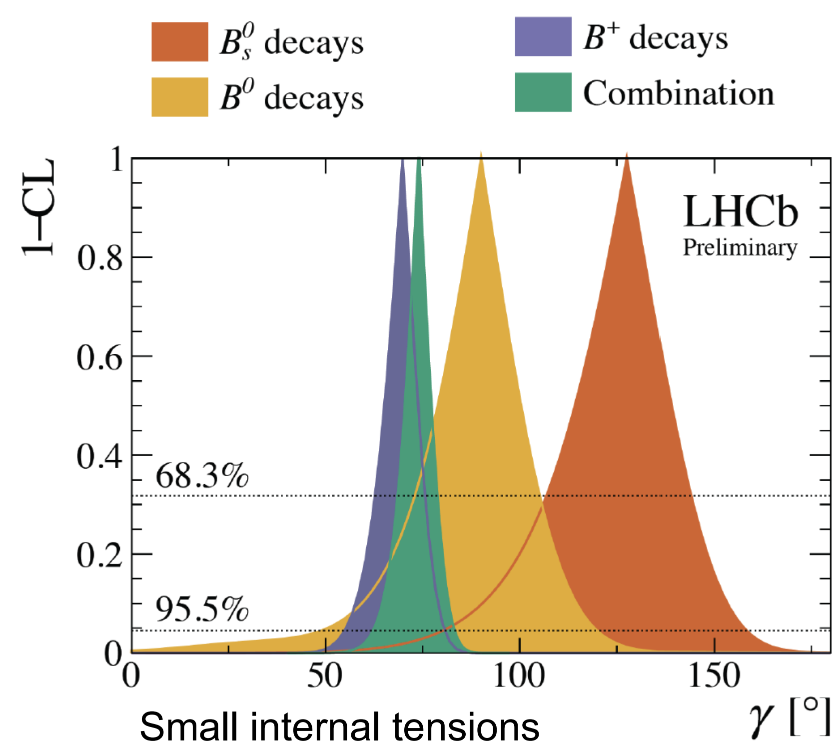
- Extracted from tree-level decays
- Exploit interference between amplitudes



$$\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^+ \to D^0 K^+)} \equiv r_B e^{i(\delta_B - \gamma)}$$

- Neutral B-mesons are also used
  - Time dependent analysis with $B_s \to D_s K$

$f_D = \pi^+\pi^-, K^+K^-$	GLW
$K^+\pi^-$	ADS
$K^0_S\pi^+\pi^-$	GGSZ



Small internal tensions between B+ and Bs.

LHCb combination: $\gamma = (74.0^{+5.0}_{-5.8})^\circ$

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

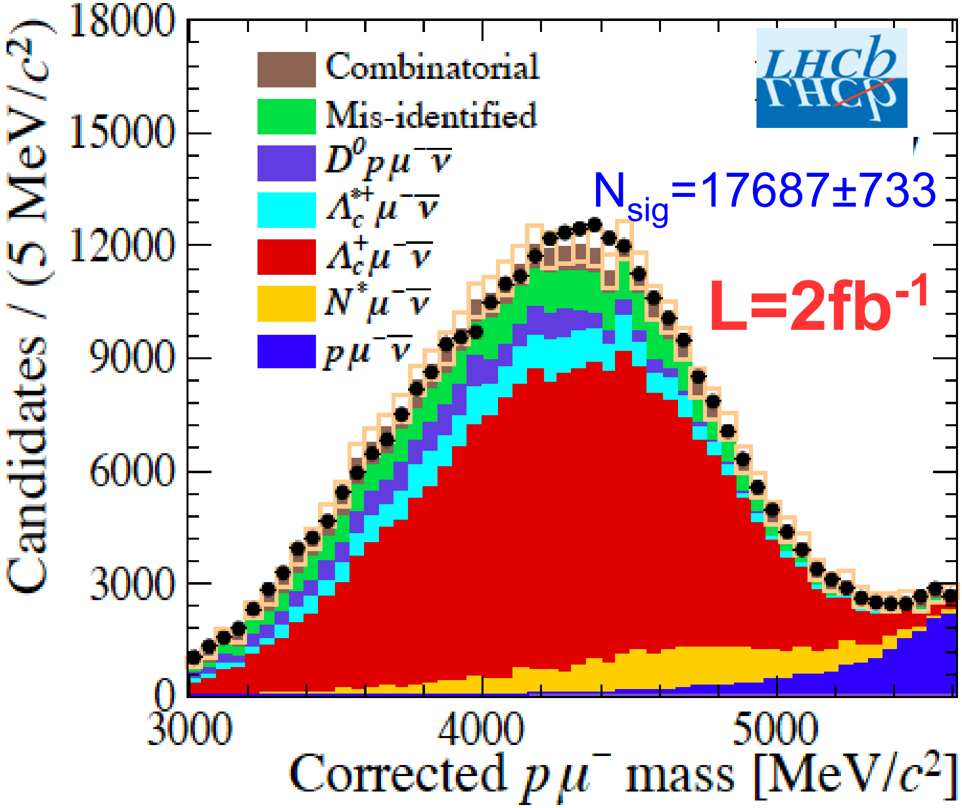
Utfit summer 2018 $\gamma = (65.8 \pm 2.2)^\circ$

LHCb-CONF-2018-002

The side of the UT: $\Lambda_b \to p\mu\nu$

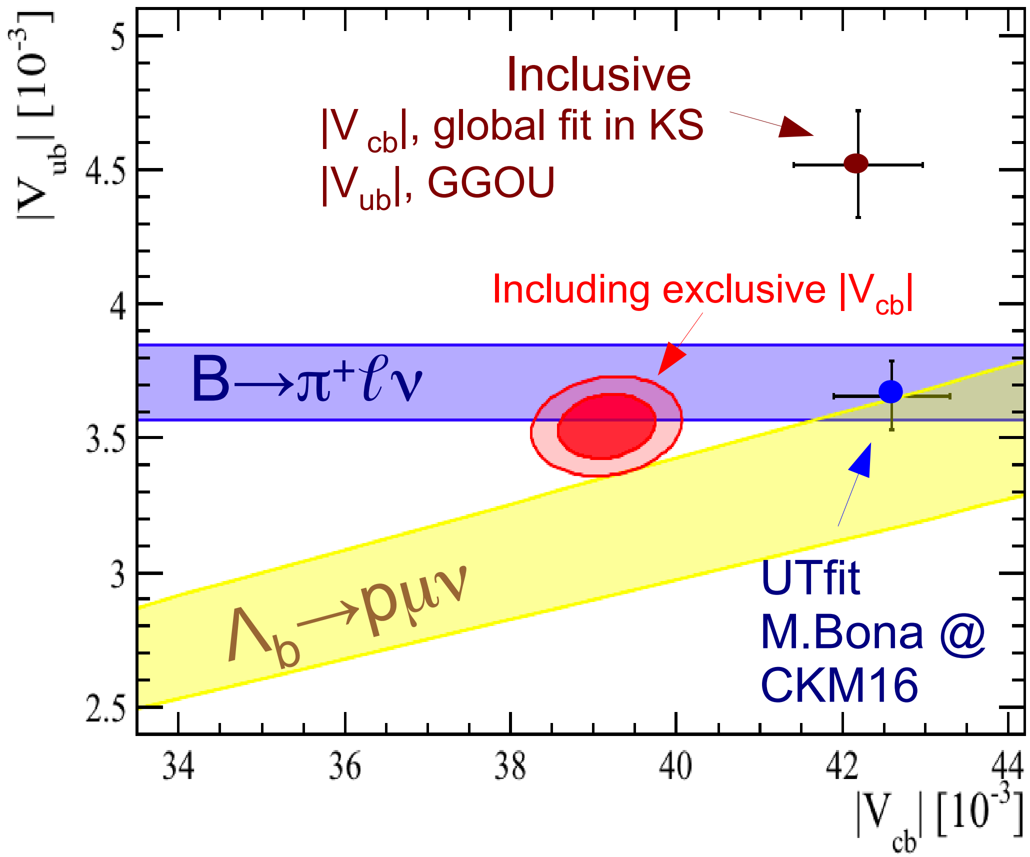
Nature Physics 10(2015) 1038

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



$$\frac{|V_{ub}|}{|V_{cb}|} = 0.080 \pm 0.004_{Exp.} \pm 0.004_{F.F.}$$

σ_{tot}=7%



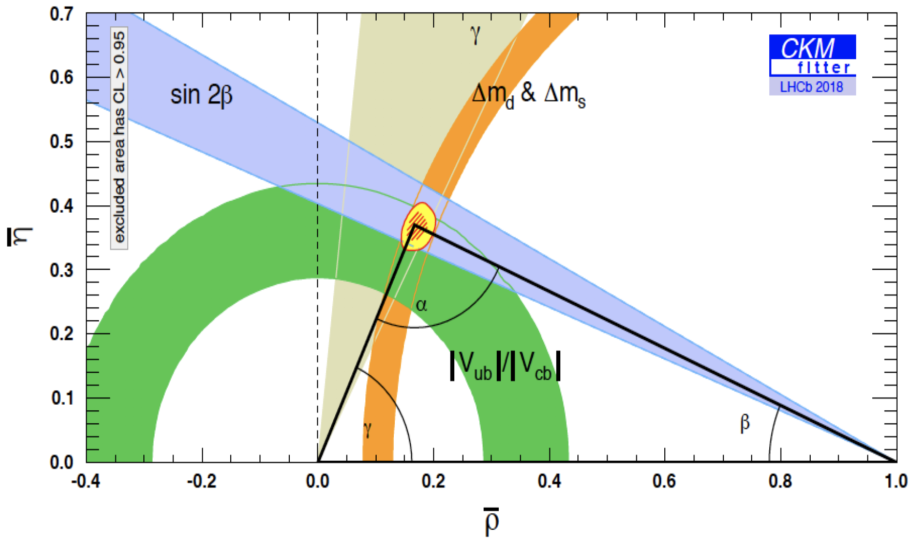
$$R = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)_{q^2>15\ GeV^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\ GeV^2}} = (0.95 \pm 0.04 \pm 0.07) \times 10^{-2}$$

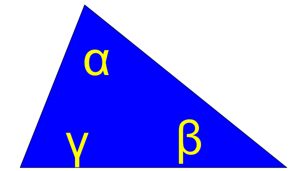
Systematics dominated by
BF($\Lambda_c \to pK\pi$)=(6.46 ± 0.24)%
HFLAV using BESIII-Belle
measurements

The B -Triangle: LHCb only inputs

arXiv:1808.08865

Current





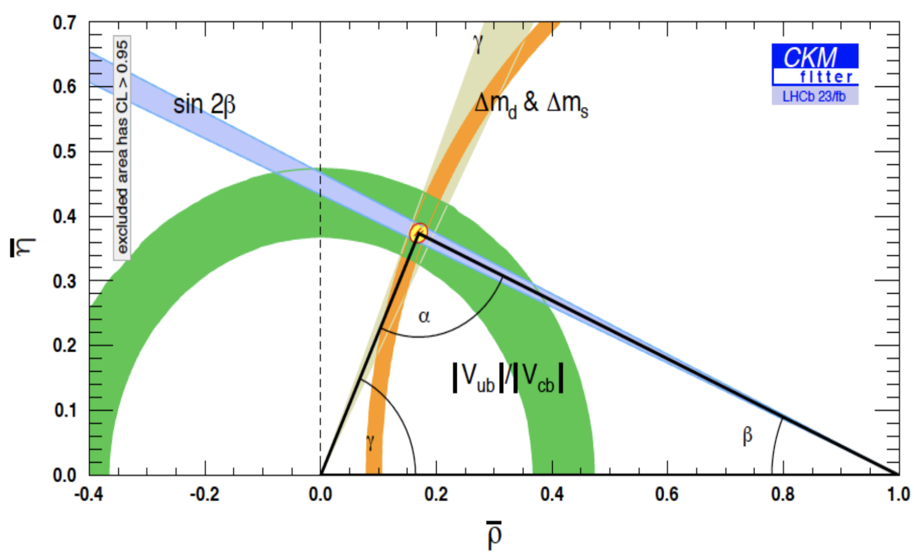
Crucial:

- improvements from Lattice QCD
- improvements on external inputs

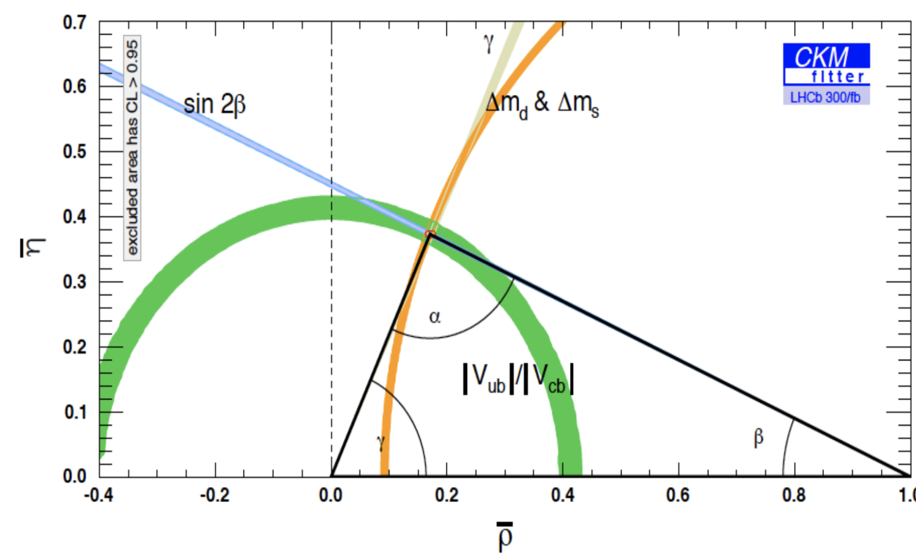
Branching ratios ($\Lambda_c \to pK\pi$): **BelleII, BESIII**

Strong phases over $D \to K_s\pi\pi$ Dalitz: **BESIII**

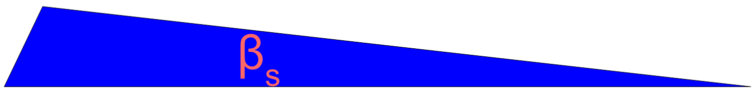
Pre-HL-LHC



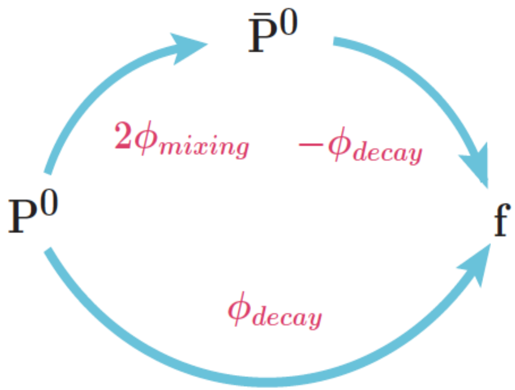
Post-HL-LHC



The B_s-Triangle: Φs



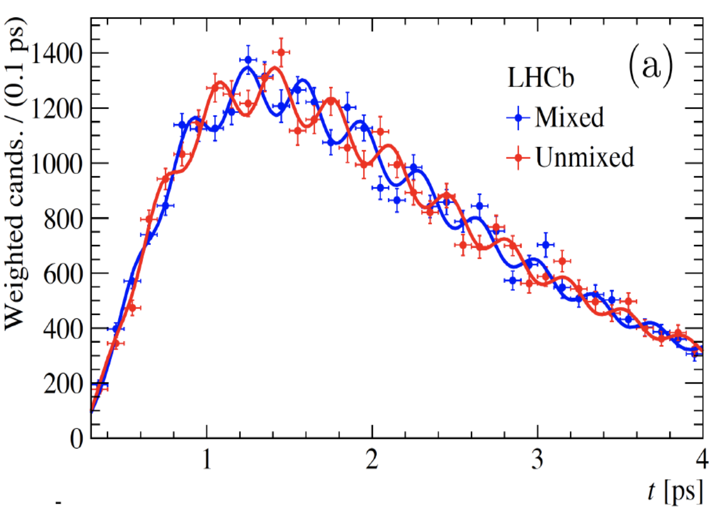
- The interference between the decay and the $B_s\bar{B}_s$ mixing amplitude is governed by the phase β_s
  - Ignoring subleading diagrams: $\Phi_s \sim -2\beta_s$
- Strongly constrained by the CKM unitarity



$$-2\beta_s^{SM} = -0.0368^{+0.00096}_{-0.00068} \text{ rad} \quad \text{CKMfitter group}$$

$$-2\beta_s^{SM} = -0.0370 \pm 0.0010 \text{ rad} \quad \text{UTfit collaboration}$$

arXiv:1906.08356



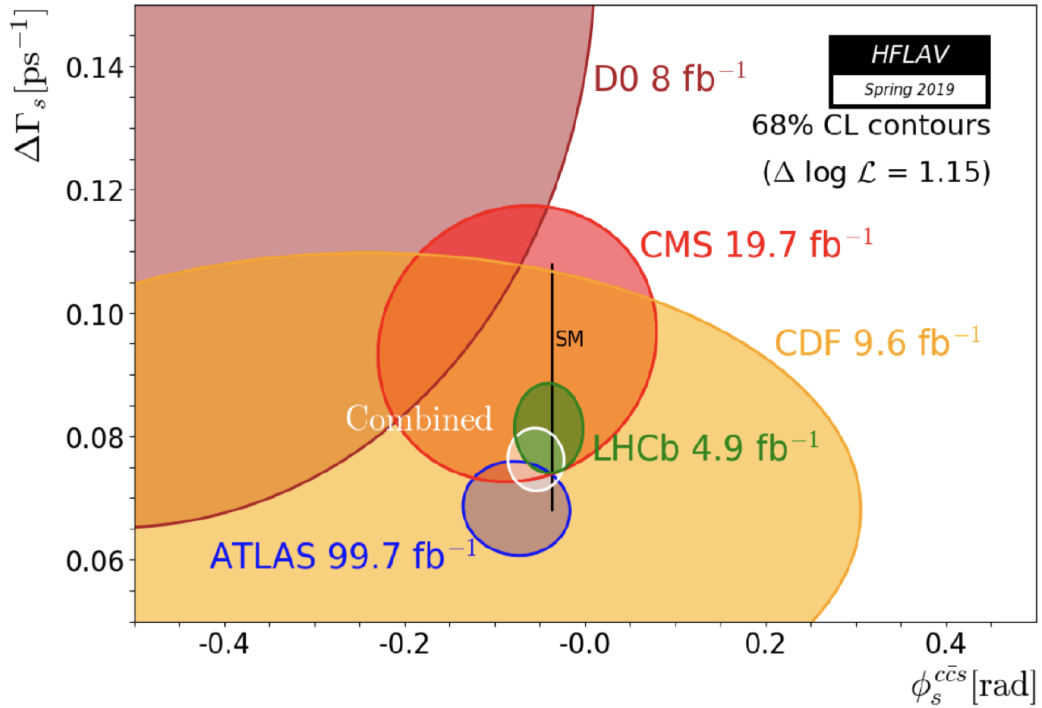
- Because of the very fast B_s oscillation frequency, two critical parameters need to be known with precision to reach the *mrad* precision
  - B_s flavor tagging at production t=0
  - Time resolution better than $\sigma_t < 2\pi/\Delta m_s \approx 350\ fs$

Current status: Φs with $B_s \to J/\psi\ K^+K^-$

- $B_s \to J/\psi\ K^+K^-$ requires a full angular analysis because of the presence of scalar K^+K^- contribution
- LHCb added also $J/\psi\ \pi^+\pi^-$, $\psi(2S)\ K^+K^-$, $D_s^+D_s^-$

$$\begin{aligned} \phi_s &= -0.041 \pm 0.025\,\text{rad}\,, \\ |\lambda| &= 0.993 \pm 0.010\,, \\ \Gamma_s &= 0.6562 \pm 0.0021\,\text{ps}^{-1} \\ \Delta\Gamma_s &= 0.0816 \pm 0.0048\,\text{ps}^{-1} \end{aligned}$$

- LHCb, ATLAS and CMS have not analyzed the full Run2 yet



LHCb: arXiv:1906.08356
ATLAS: ATLAS-CONF-2019-009
CMS: 1507.07527

Tagging performances

LHCb

Category	$\varepsilon_{\rm tag}(\%)$	$\mathcal{D}^2$	$\varepsilon_{\rm tag}\mathcal{D}^2(\%)$
OS-only	11.35	0.078	0.88 ± 0.04
SSK-only	42.57	0.032	1.38 ± 0.30
OS&SSK	23.84	0.104	2.47 ± 0.15
Total	77.76	0.061	4.73 ± 0.34

ATLAS

Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

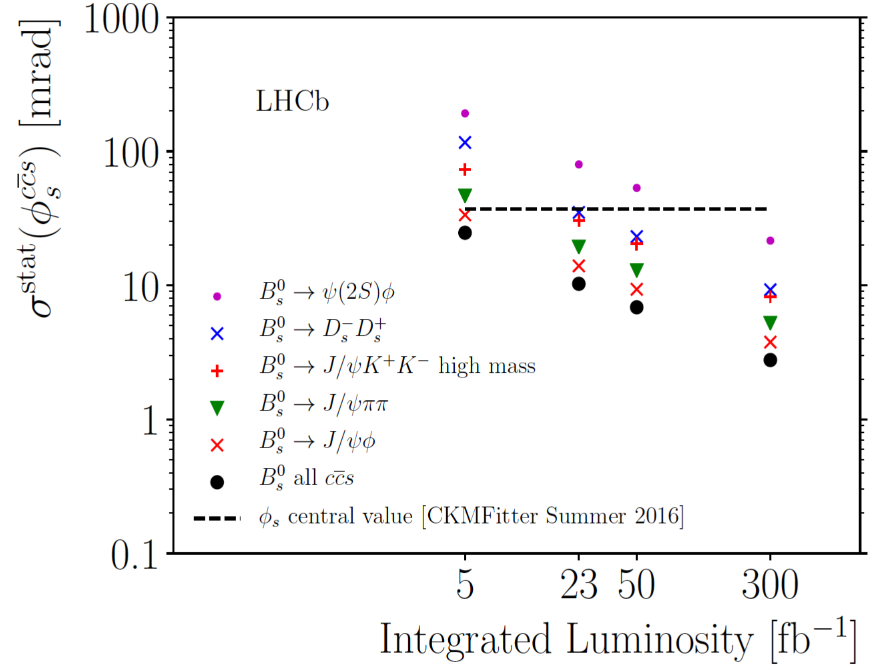
Projections to Post-HL-LHC

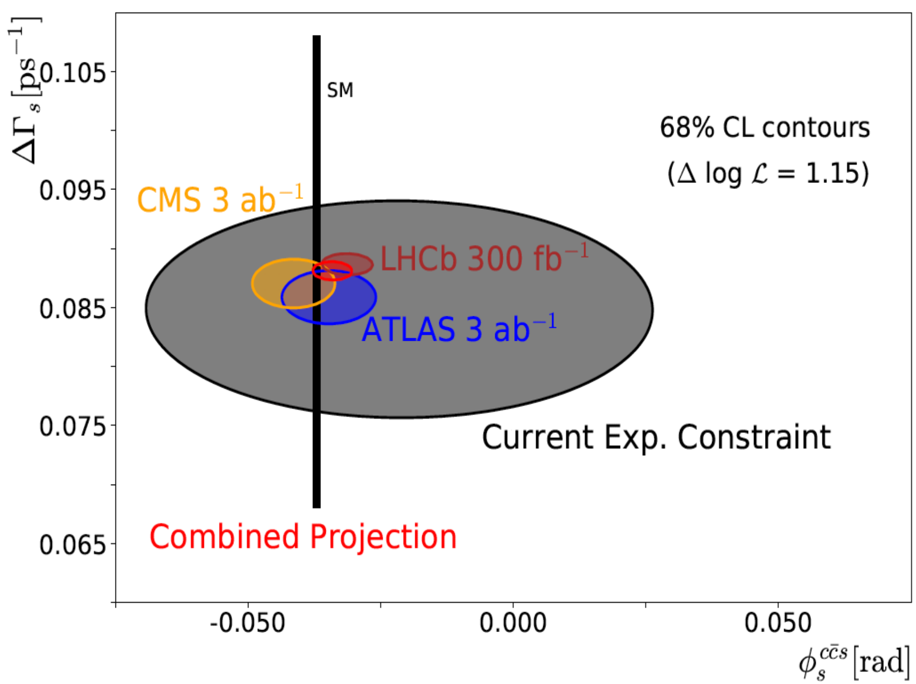
ATLAS, $B_s \to J/\psi\ K^+K^-$

Different assumptions on muon p_T thresholds

LHCb

Period	L_{int} [fb^{-1}]	N_{sig}	ϵD^2	$\sigma(t)$ [ps]	$\delta^{stat}_{\phi_s}$ [rad]	$\delta^{stat}_{\Delta\Gamma_s}$ [ps^{-1}]
2011	4.9	22700	1.45	0.1	0.25 (0.22)	0.021
2012	14.3	73700	1.5	0.09	0.082	0.013
HL-LHC $\mu6\mu6$	3000	$9.7 \cdot 10^6$	1.5	0.05	(0.004)	(0.0011)
HL-LHC $\mu10\mu6$	3000	$5.9 \cdot 10^6$	1.5	0.04	(0.005)	(0.0014)
HL-LHC $\mu10\mu10$	3000	$1.7 \cdot 10^6$	1.5	0.04	(0.009)	(0.003)





- LHCb: also with penguin dominated $B_s \to \Phi\Phi$, K*K*... processes
- Lack of PID limits the CMS and ATLAS measurements of fully hadronic final states
  - Usage of the tracking in the trigger selection is under study for $B_s \to \Phi\Phi$

Projections to Post-HL-LHC

ArXiv:1812.07638
CERN-LPCC-2018-06

ATLAS, $B_s \rightarrow J/\psi\ K^+K^-$

LHCb

Different assumptions on muon p_T thresholds

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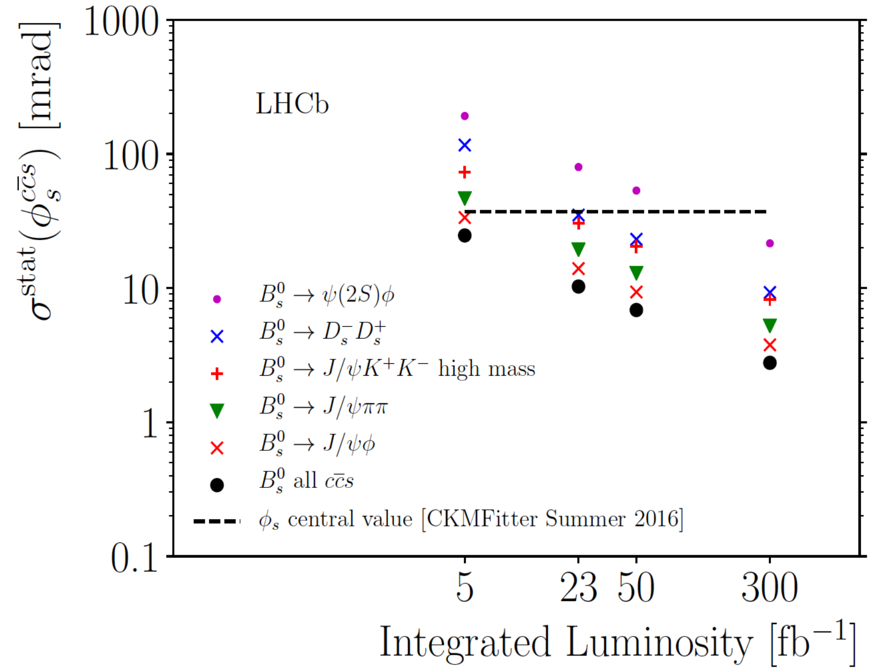
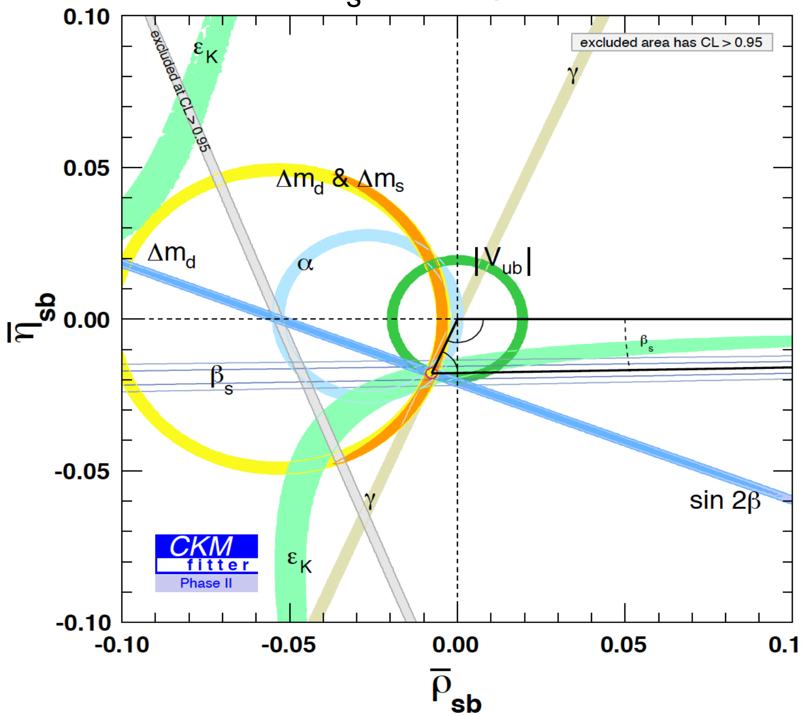


B_s Triangle



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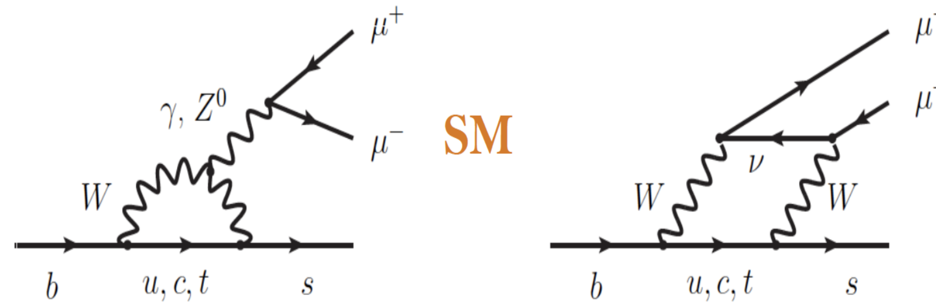
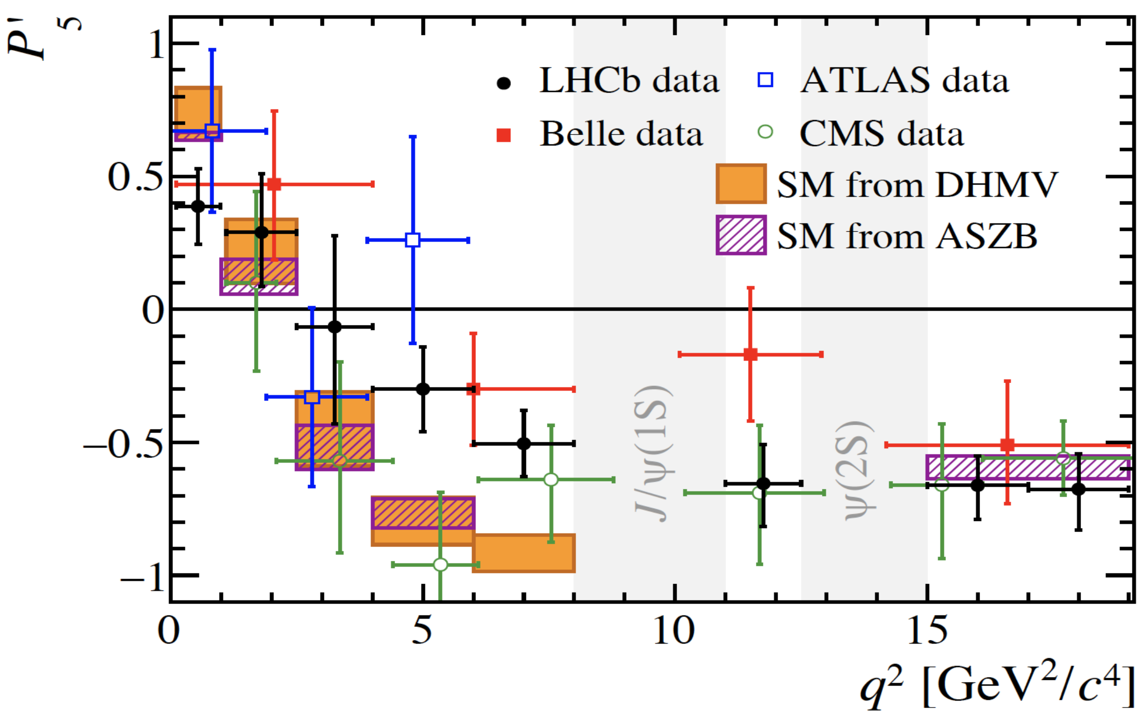
    - Usage of the tracking in the trigger selection is under study for $B_s \rightarrow\ \Phi\Phi$

Current status on B→K*μμ anomaly

- b→sμμ transitions are sensitive to new heavy particle contributions
- Many observables accessible from full angular analysis
  - **P5':** one of the observable free of form-factor contribution
  - possible pollution due to intrinsic-charm is under scrutiny



- Global significance of the difference with SM at 3.4sigma: Belle includes both electrons and muons

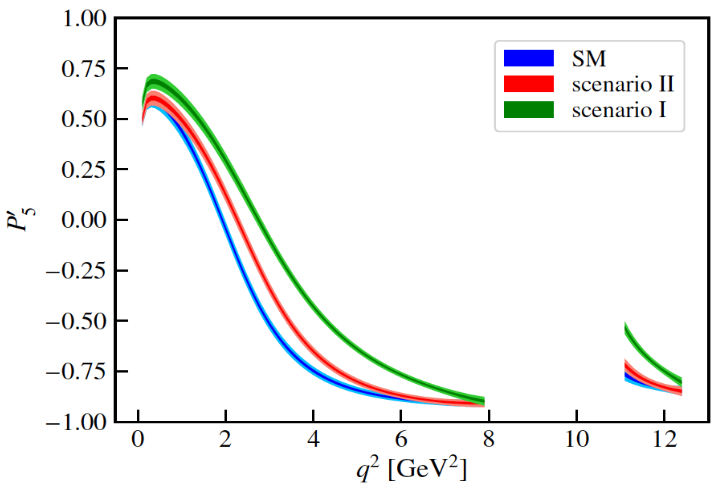


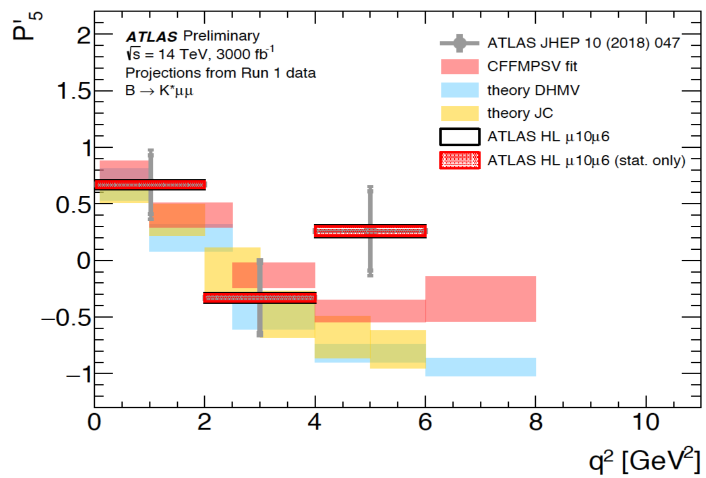
- Measurements statistically limited
  - With larger statistics, hadronic pollutions can be constrained on data
- At LHC b→sμμ in other b-hadron decays have been studied
  - Few anomalies in $\Delta BF/\Delta q^2$ a in similar q^2 window

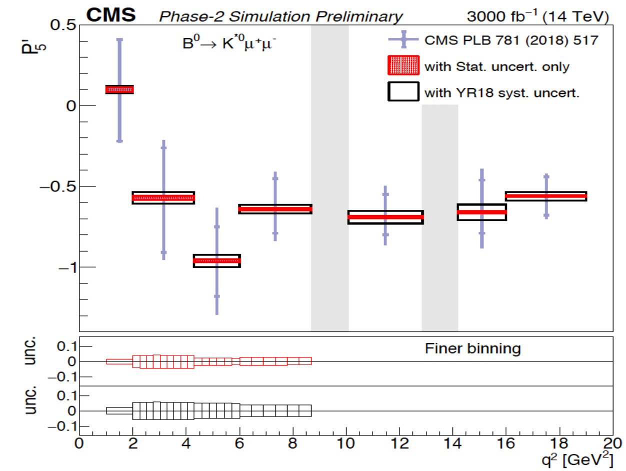
Prospects on B→K*μμ

ArXiv:1812.07638
CERN-LPCC-2018-06

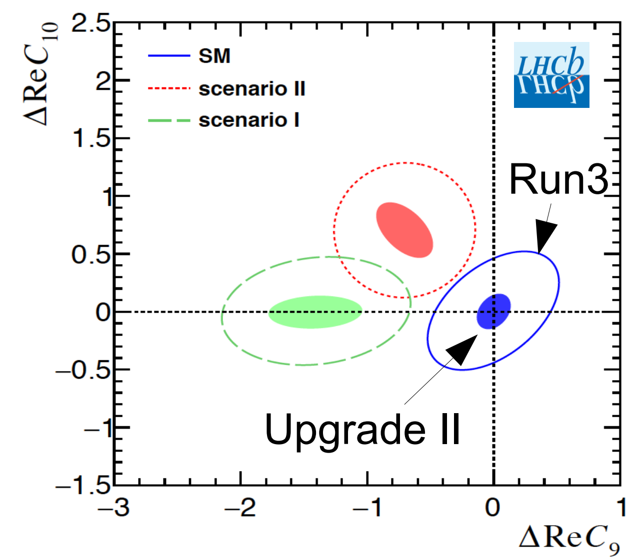
- With higher statistics: full angular analysis in finer binning
- Ongoing physics reach studies from LHCb, ALTAS and CMS for Phase-II







- Other channels of the b→sμμ family accessible
- Proof of angular analysis in B→K*ee in LHCb done
  - Competition/synergy with Belle-II on electron modes

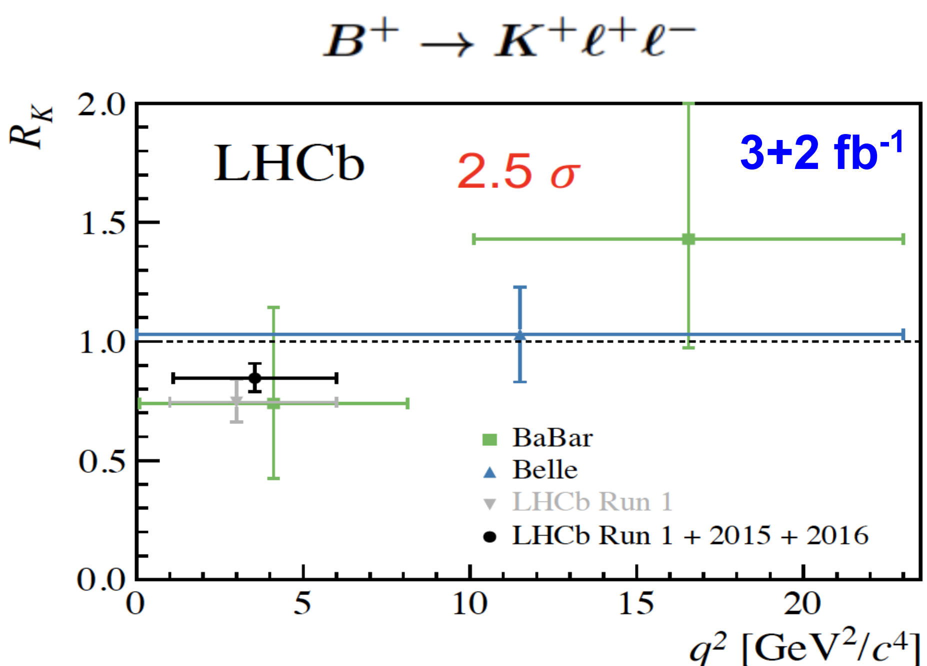


R observables for B→K(*)μμ and B→K(*)ee

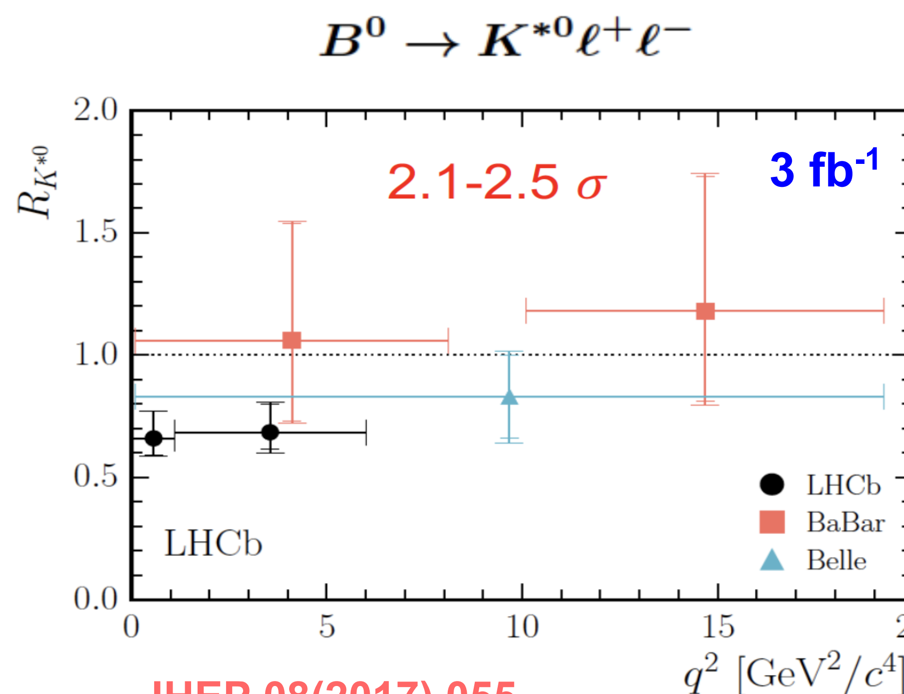
- Very clean probes of New Physics
  - New interaction may render the coupling to muons and electrons non-universal
  - Hadronic uncertainties cancel in the ratio
  - Residual QED corrections at % level

$$R_{K^{*0}} = \frac{BR(B^0 \to K^{*0}\mu^+\mu^-)}{BR(B^0 \to K^{*0}e^+e^-)}$$

Analogous with K, Phi, Lambda, pK...



PRL 122(2019) 191801



JHEP 08(2017) 055

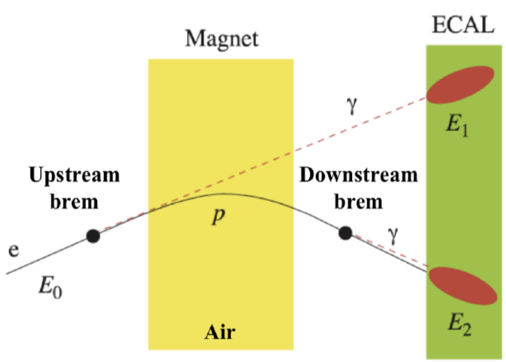
LHCb: full dataset not analyzed yet

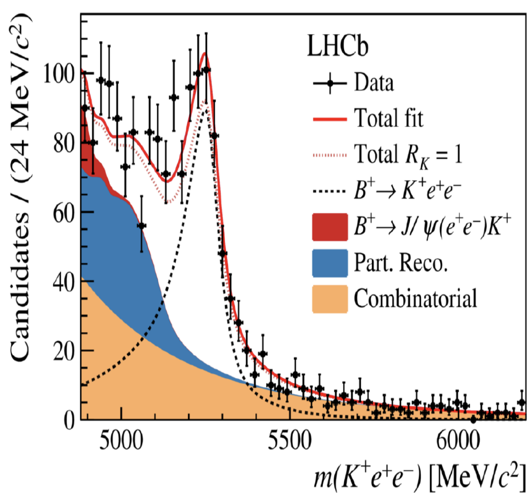
PRL 122(2019) 191801

- Measure a double-ratio to cancel experimental systematics

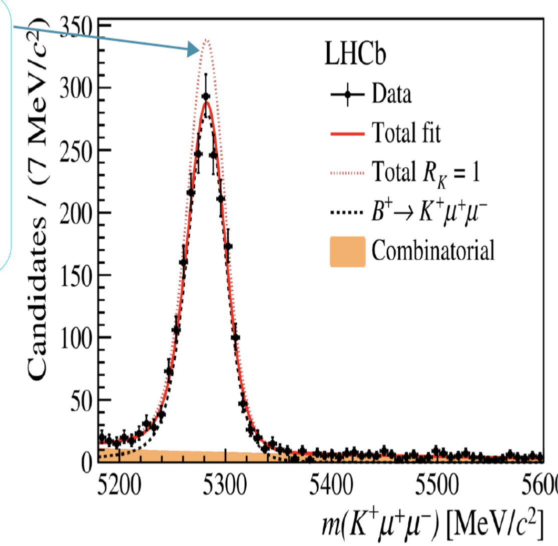
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+ e^-))}$$

- Photon bremsstrahlung is accounted for





Expectation for Assuming RK=1 and the fitted yields for the electrons



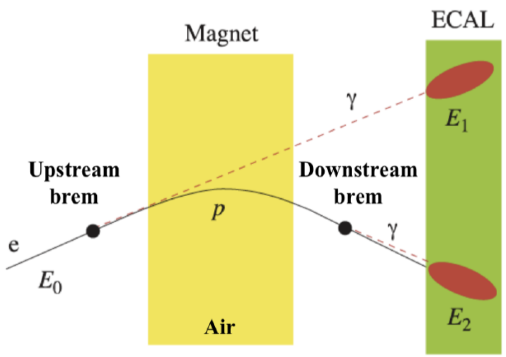
B→K(*)μμ/B→K(*)ee: prospects

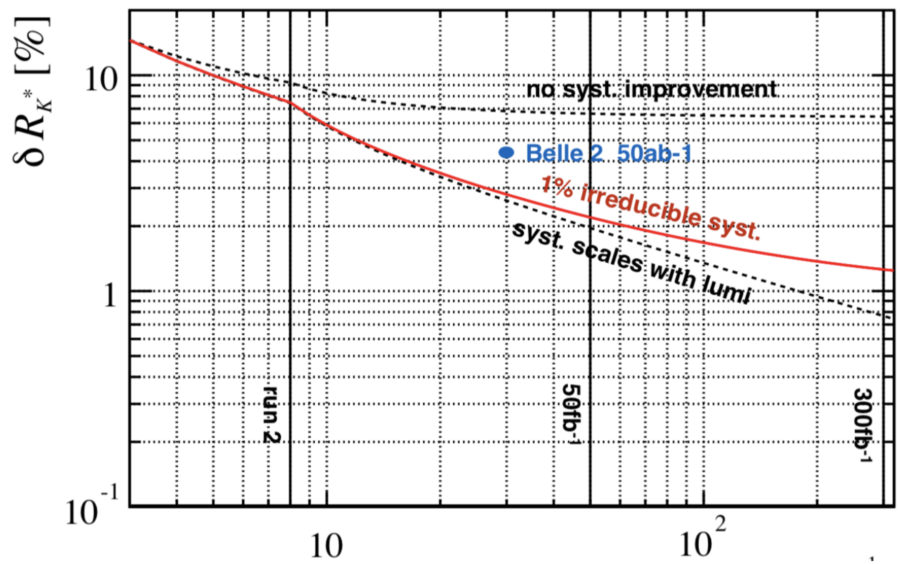
CERN-LHCC-2017-003

- Measure a double-ratio to cancel experimental systematics

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))}$$

- Photon bremsstrahlung is accounted for





- Assuming constant ECAL performance
- Systematics from limited modeling of bremsstrahlung
- Reduced material before the magnet would help (see next slides)

Expected B → Xe^+e^- yields and R(X) precision for q^2 between 1.1 – 6.0 GeV^2

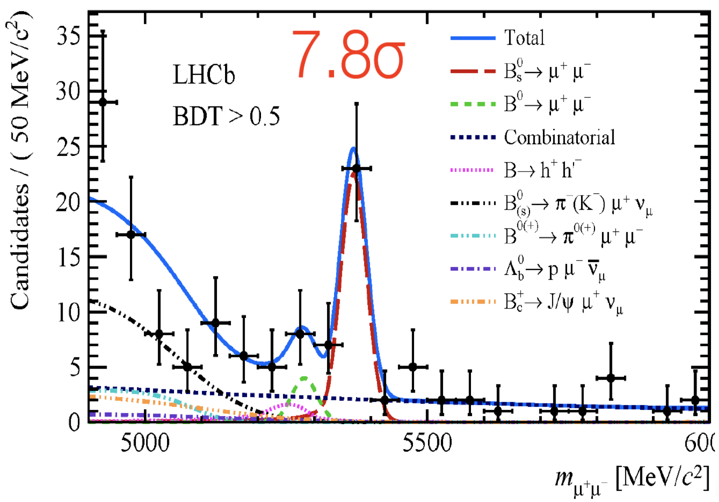
Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [5]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [6]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	0.745 ± 0.090 ± 0.036 [5]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.69 ± 0.11 ± 0.05 [6]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

$B_s \to \mu\mu$ and $B_d \to \mu\mu$

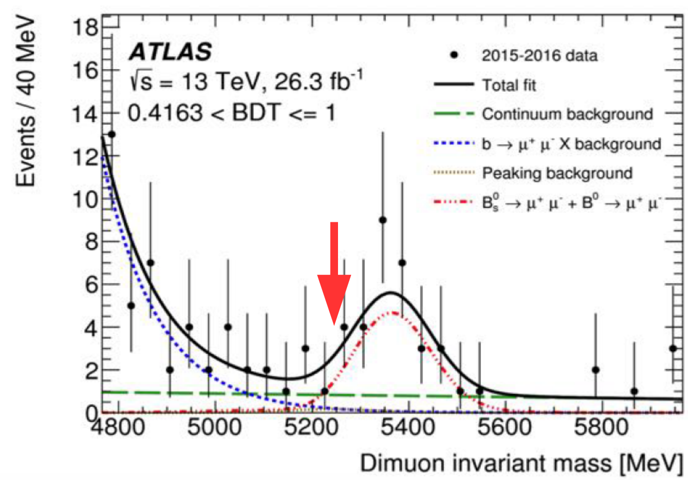
LHCb: PRL118(2019)191801
ATLAS:JHEP 04(2019)098
CMS: PRL111(2013)101804

- Bs → μμ is the cleanest exclusive b → sμμ process
- All QCD effects embedded in the decay constant f_{Bs} = 230.7(1.3) MeV

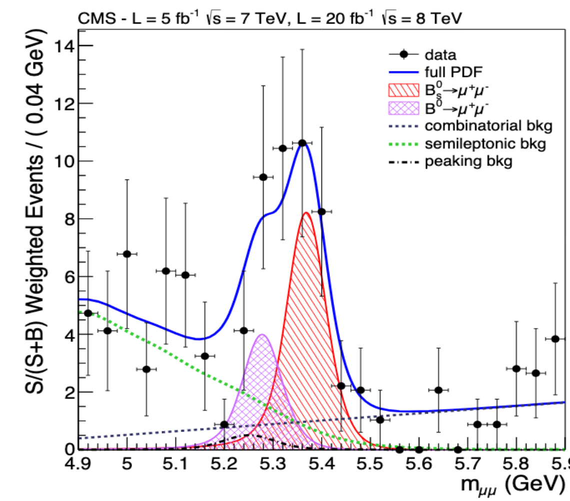
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$



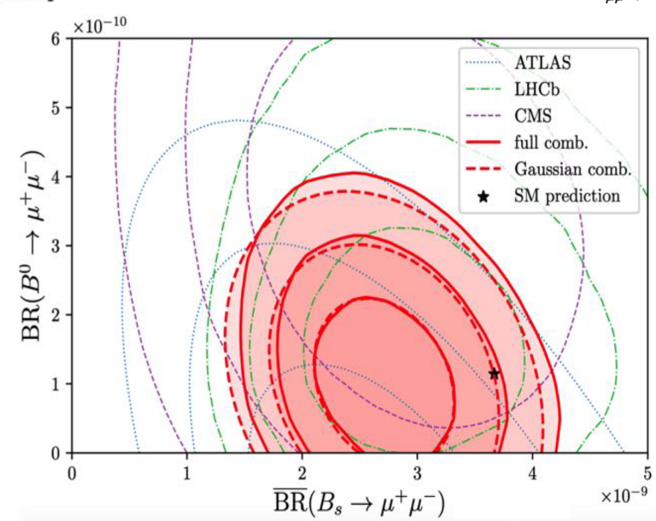
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0^{+1.0}_{-0.9}\right) \times 10^{-9}$$



- LHCb: first observation from a single experiment
- All LHC experiments have contributed to establish the signal
- Still need to fully exploit the full dataset available
- “Official” combination of the results not available yet

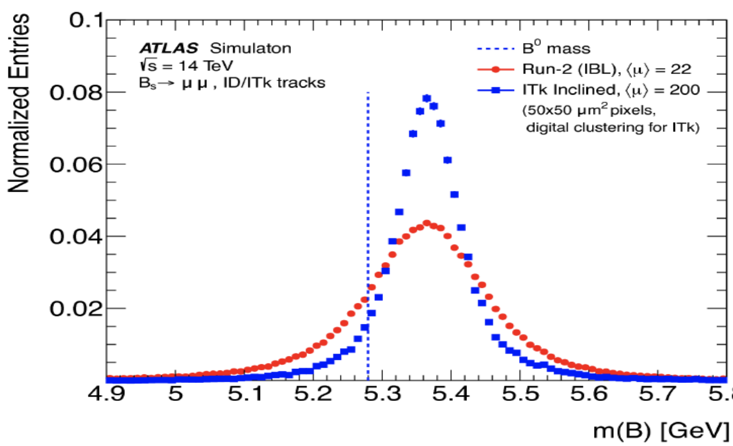


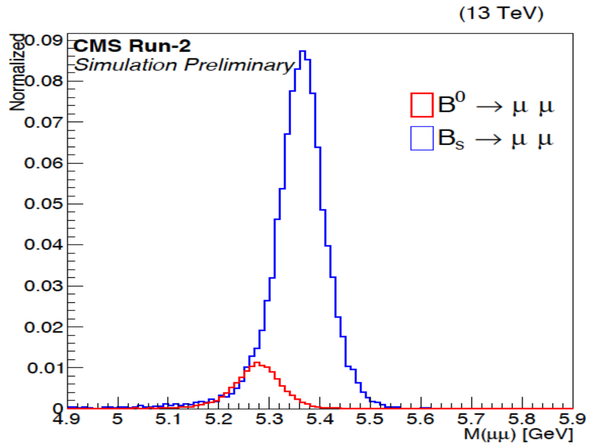
J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P Stangl and M. Straub, arXiv:1903.10434

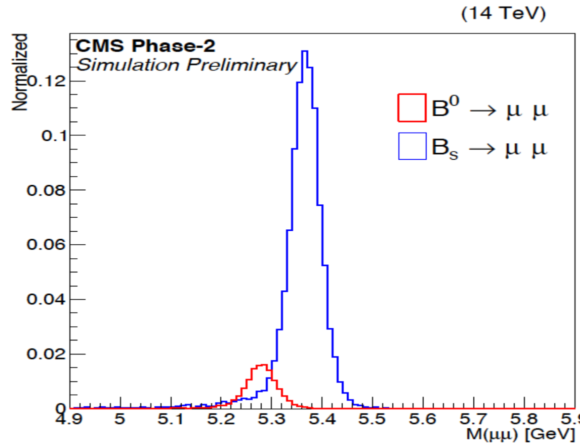
$B_s \to \mu\mu$ and $B_d \to \mu\mu$: prospects

ArXiv:1812.07638

- The performances for these channels at HL-LHC are determined by low-p_T di-muon triggers and the mass resolution







- Improved tracking detectors will result in improved B_d/B_s separation
- CMS studied possibility of lifetime measurement
- At LHCb, improved tracking and a muon shielding will ensure non degraded performances with increasing pileup

Experiment	Scenario	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ stat + syst %	$\mathcal{B}(B^0 \to \mu^+\mu^-)$ stat + syst %
LHCb	23 fb^{-1}	8.2	33
LHCb	300 fb^{-1}	4.4	9.4
CMS	300 fb^{-1}	12	46
CMS	3 ab^{-1}	7	16
ATLAS	Run 2	22.7	135
ATLAS	3 ab^{-1} Conservative	15.1	51
ATLAS	3 ab^{-1} Intermediate	12.9	29
ATLAS	3 ab^{-1} High-yield	12.6	26

Discovery of CP violation in charm

PRL122,21803(2019)

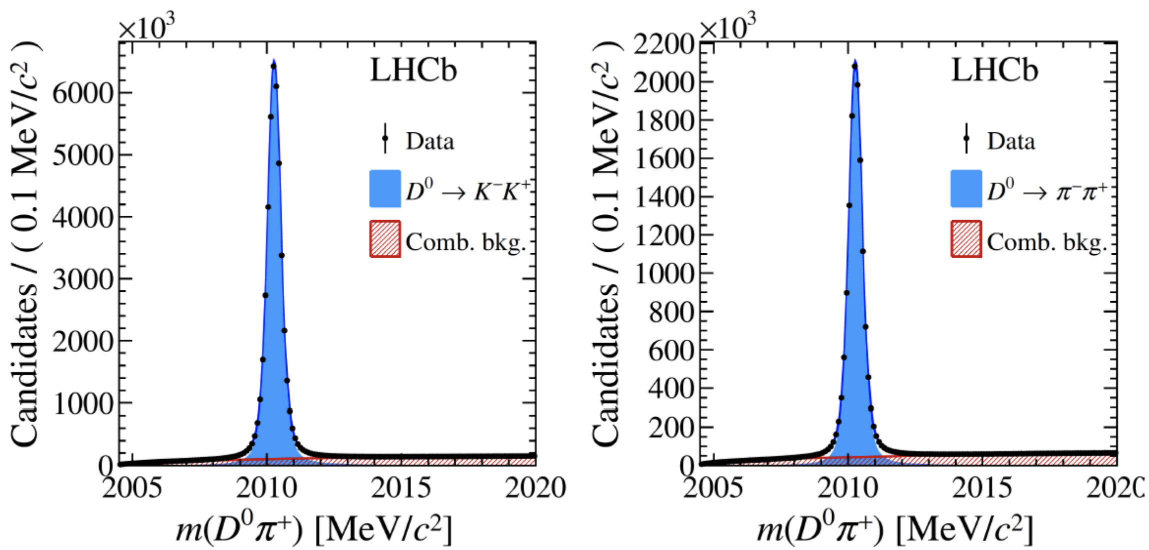
- Measured a non-zero time integrated CP-violation asymmetry In Charm

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}$$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi + \pi^-) = (15.4 \pm 2.9) \times 10^{-4}$$

A_{CP} primary sensitive to direct CPV

- Result is consistent with SM prediction (10^{-4}-10^{-3})
- Long range strong interaction prevents more precise predictions



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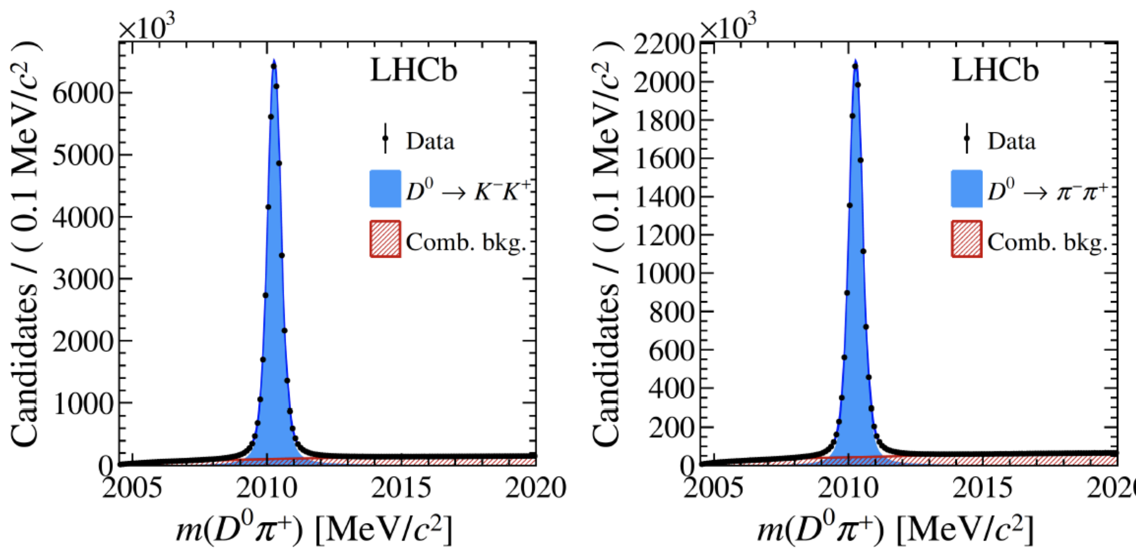


- Time dependent measurements allows measurement of indirect CPV which is predicted in SM with better precision $A_\Gamma \sim 3\times10^{-5}$
- This would offer a great opportunity for NP but would require very large statistics

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)_{K^+K^-}$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)_{\pi^+\pi^-}$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

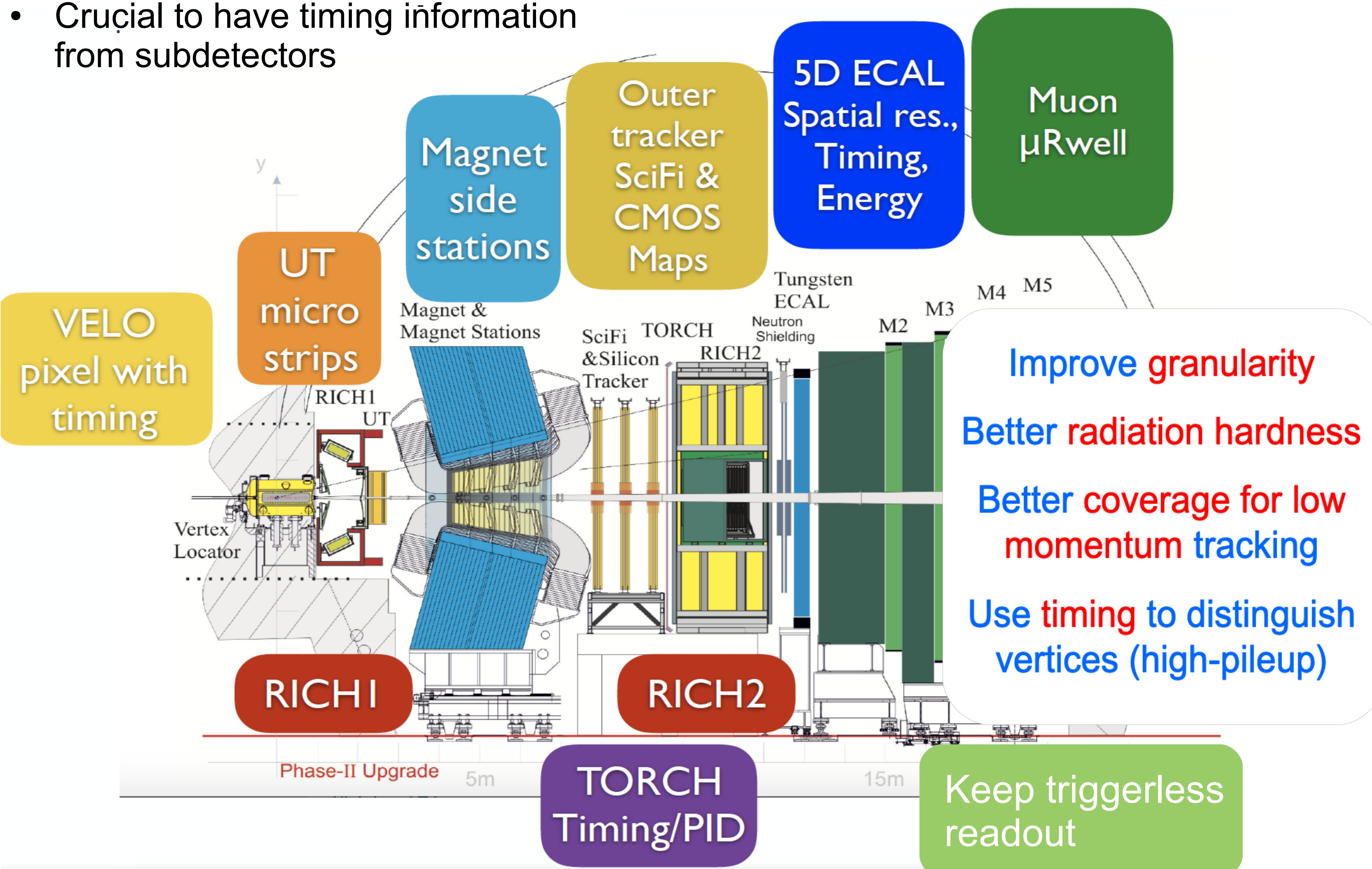
LHCb Upgrade II detector

- Aiming at $L=2x10^{34}$ $cm^{-2}s^{-1}$, about 50 visible interactions per bunch crossing
- Tracking: 1500-3500 charged particles/bunch crossing
- PID: need to cope with high occupancy, upgrade the coverage at low ~10 GeV
- ECAL: sustain very high radiation dose
  - Energy resolution at $10\%/\sqrt{E}+1\%$, reduce Moliere radius
- TDAQ: big data-processing challenge!

Detector must be faster, harder, finer, smarter

LHCb Upgrade II detector

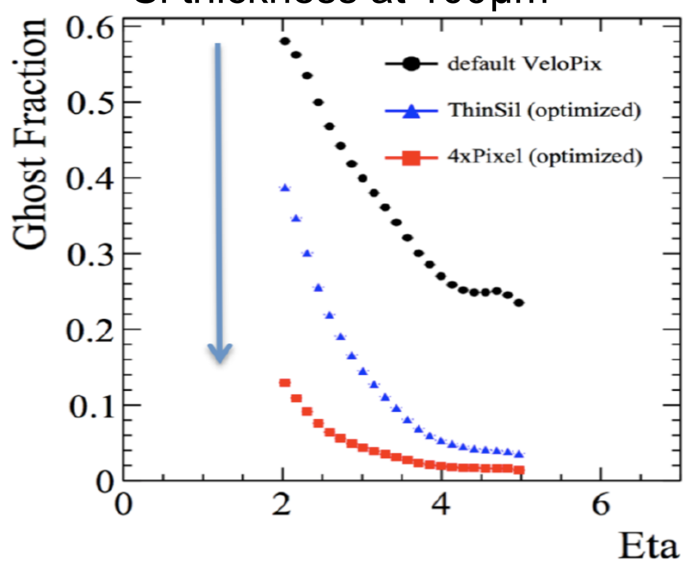
- Crucial to have timing information from subdetectors



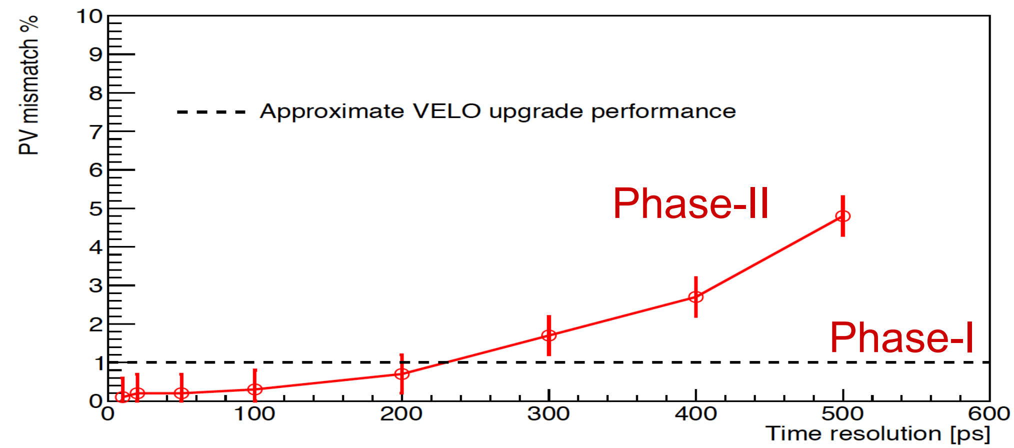
Tracking and vertexing

- Fast timing detectors for 4D track reconstruction
  - Suppress ghost tracks and improve PV: time resolution < 100ps
  - Increase granularity: pixel size < 55μm

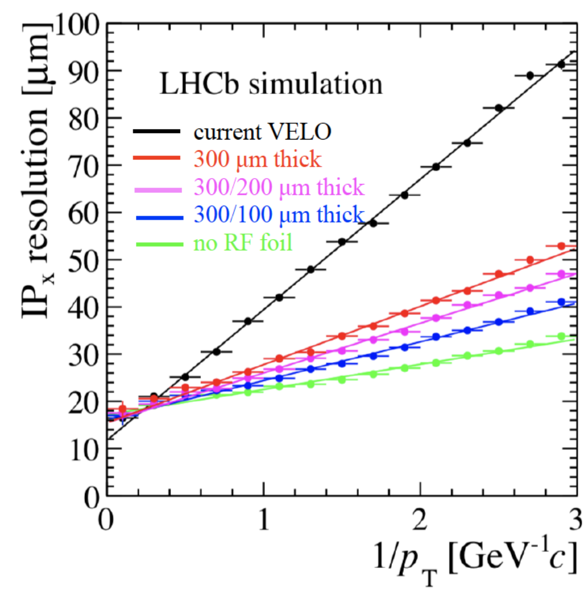
Reducing pixel size to 27.5μm
Si thickness at 100μm



B-hadron mismatched to the wrong PV

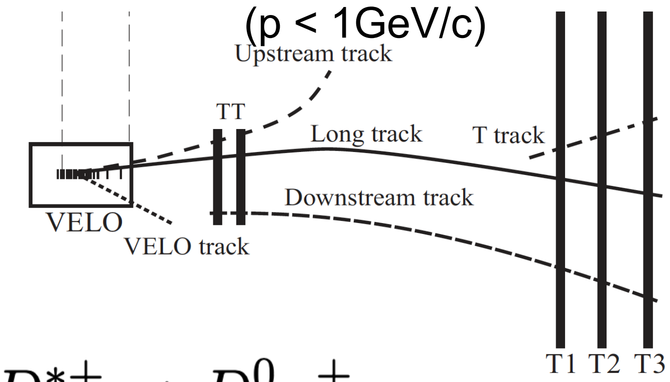


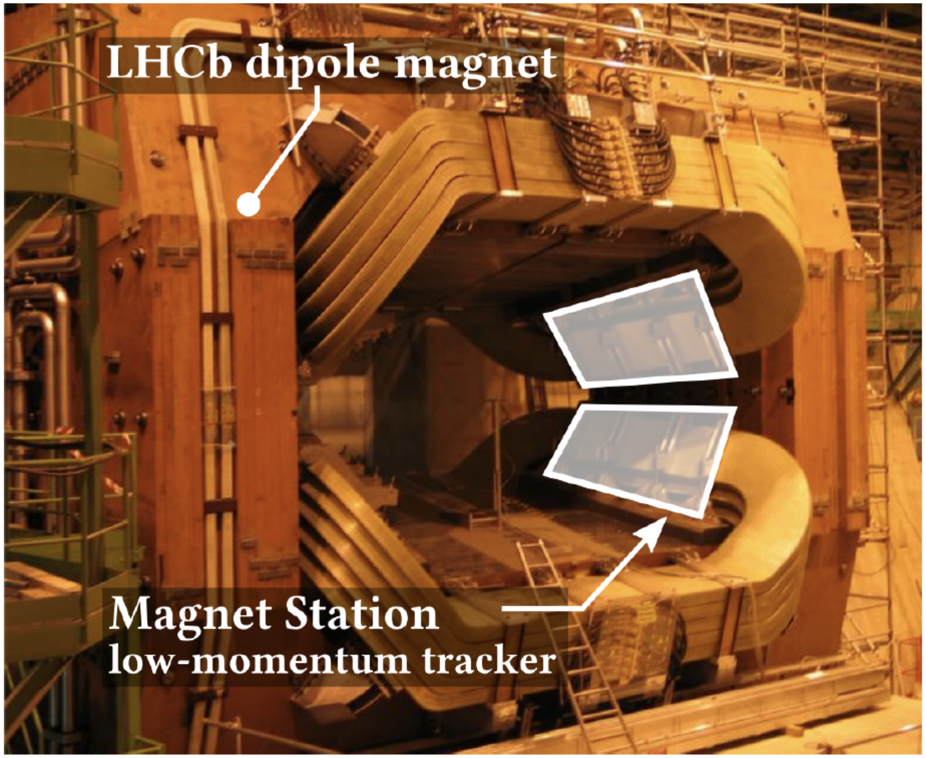
- Reduce material to improve resolution
  - Si thickness and VELO in vacuum
  - Important for electron bremsstrahlung



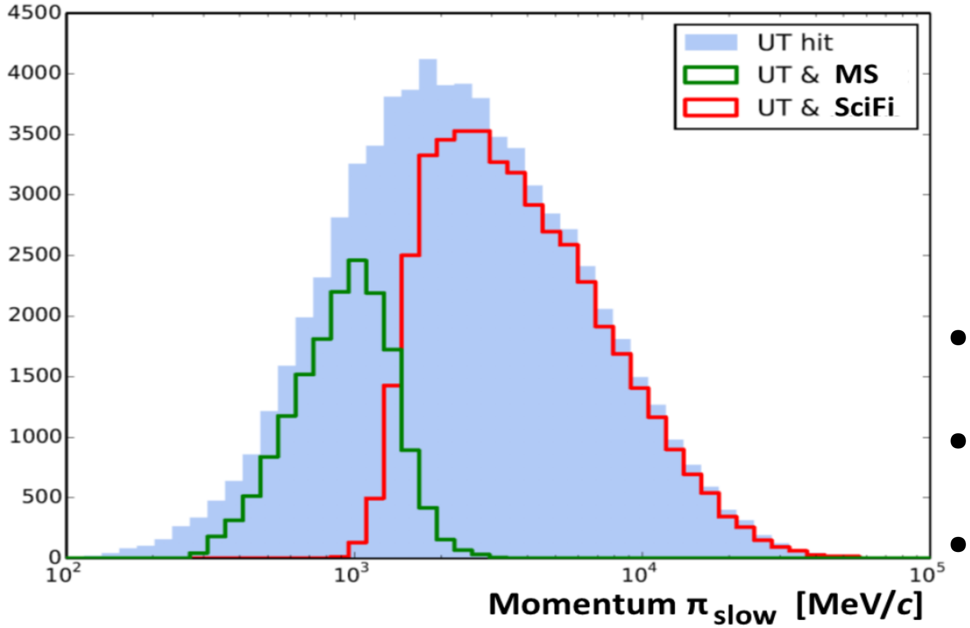
New detector for low momentum tracks

- Magnet side stations could be added to improve momentum resolution of tracks upstream of the magnet





$D^{*+} \to D^0 \pi^+_{slow}$



CERN-LHCC-2017-003

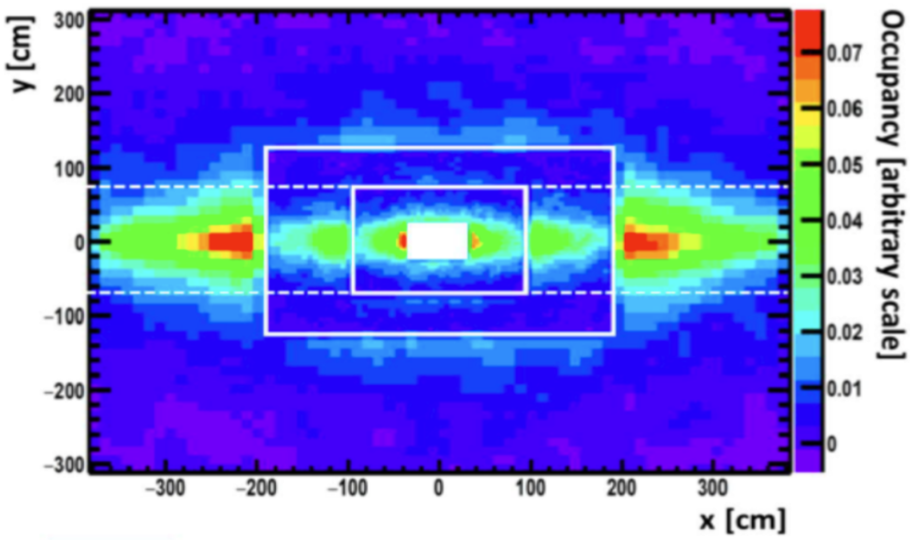
- Increase the charm-tagging by 40%
- Improvements of Same-side taggers
- General efficiency improvement for multi-body hadron decays and excited hadrons reconstruction

Calorimeter ECAL

CERN-LHCC-2017-003

- Inner region of the ECAL most affected by radiation
  - Degradation in performance would be seen in Run 4
- Inner modules need to be replaced during LS3 (Upgrade Ib)
  - Original plan was to replace with identical spare modules
- Alternatively: replace with newer technology and use as test for a new ECAL for Upgrade II
  - Reduce the cell size to 2x2cm^2 in the inner region
  - Different technology under study:
    - Timing will be important
    - Add timing in a separate detector or ECAL itself ?

Occupancies in different ECAL regions



Lot of interesting physics would benefit from an improved ECAL

$D^0 \to e\mu$
$D^+ \to \pi^+\pi^0(\to \gamma e^+e^-)$
$D^0 \to \Phi\gamma$, $K^*\gamma$, $\rho/\omega\gamma$

$B^+ \to D(hh\pi^0)K$
$B_s \to D_s{}^*K$
$B^+ \to D^*K$

$B \to D^{**}(\to D^0\pi^0X)\mu\nu$
$B \to De\nu$ vs. $B \to D\mu\nu$

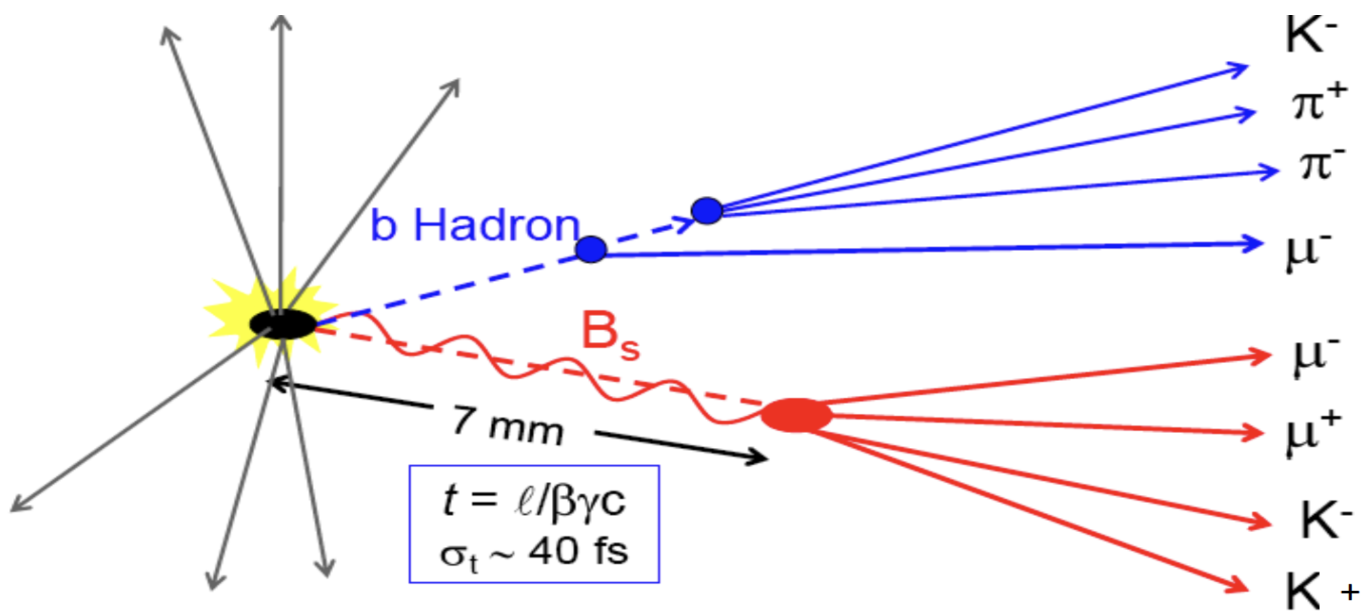
$B_{s,1} \to B_s\gamma$
$\Lambda_b{}^{**} \to \Lambda_b\gamma$
$B_c{}^* \to B_c\gamma/\pi^0$
χ_c, χ_b polarisation
Pentaquarks $\to \chi_{c,b}X$

Conclusion

- Successful Run1 and Run2: 3+6 $fb^{-1:}$ Many analysis ongoing
- Upgrade Phase I: installation ongoing
  - 10 times more data (20 times more hadronic events)
  - Complementarity with Belle
  - Synergy between LHCb, ATLAS and CMS on some important channels
- Upgrade Phase II: integrate overall sample larger than $300fb^{-1}$
  - Several theoretically-clean observables can be drastically improved
  - New Physics scale probed will be highly increased
  - Widen the set of observables under study to search and characterize new physics (semitauonic, $b\to sll$,...)
  - Many technological challenges, not all the answers yet:
    - You are welcome to join the enterprise!
- Strong program beyond flavour exploiting unique acceptance
  - Spectroscopy, electroweak, nuclear physics,

Backup

Beauty physics requirements @ LHC



- High statistics: need efficient trigger to select hadronic and leptonic B meson decays $\sigma(b\bar{b})/\sigma(\text{inelastic}) \sim O(10^{-3})$
- Excellent vertex resolution: resolve a displaced secondary vertex
- Very good mass resolution: reduce the background
- Many channels require efficient particle identification (K/π)

Conclusions II

- The LHCb detector after 2030, compared with the present detector, should have
  - Much higher radiation hardness
  - Higher granularity to cope with increased multiplicity
  - Timing capability to cope with pileup up to 50 collisions/bunch crossing