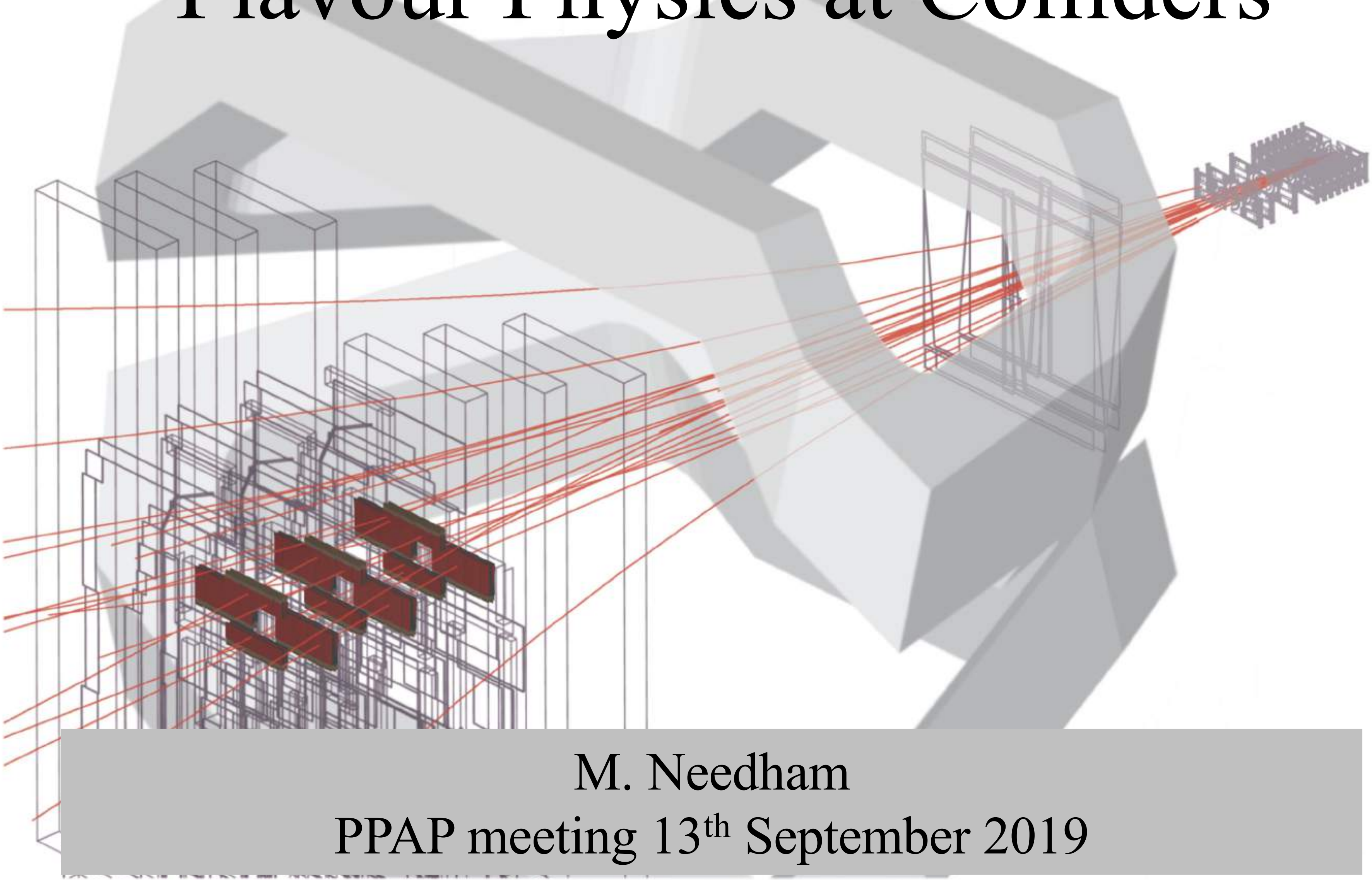
Flavour Physics at Colliders



M. Needham
PPAP meeting 13th September 2019

Outline

- Introduction
- Selected (recent) physics highlights from LHCb
- BESIII
- Belle2
- LHCb upgrade preparation
- Future LHCb upgrades (U1b, U2)

Focus on LHCb and upgrades

Tried to focus on areas
with strong UK participation

Many things not covered

Physics Goals

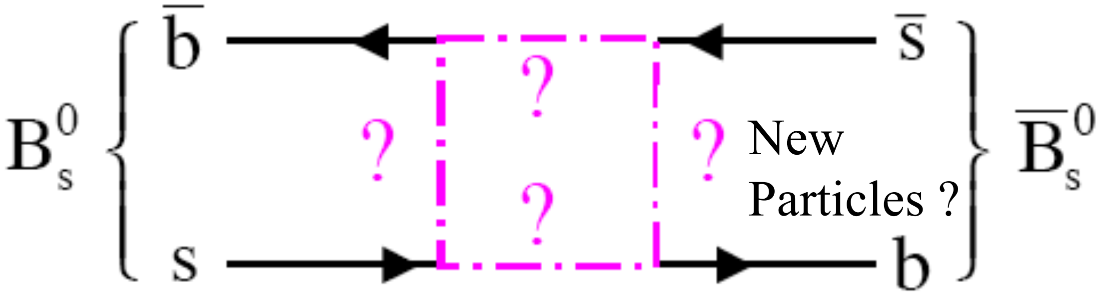
Standard Model completed by discovery of Higgs Boson

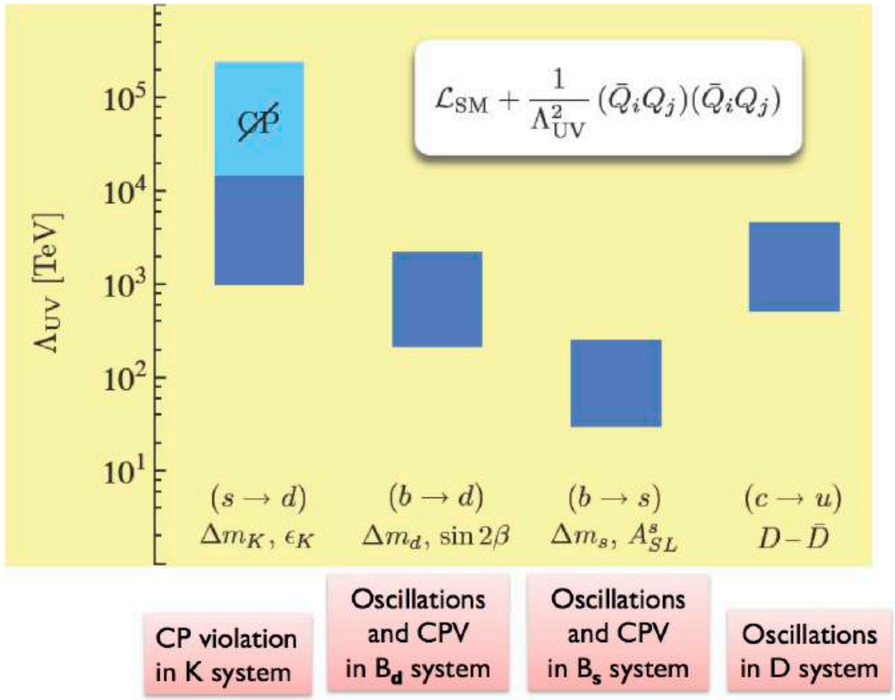
But many reasons to believe SM is not final word

e.g. CP violation in SM not enough to explain absence of anti-matter in visible universe

Precision indirect searches provide telescope to scales of O(100) TeV

Complement direct searches

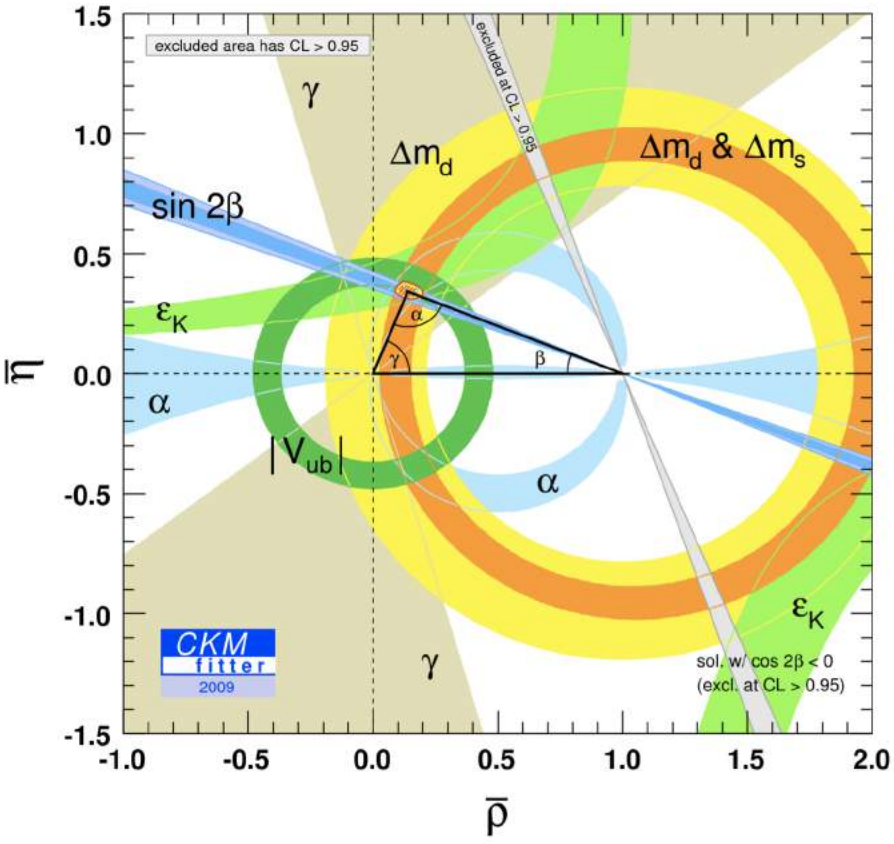




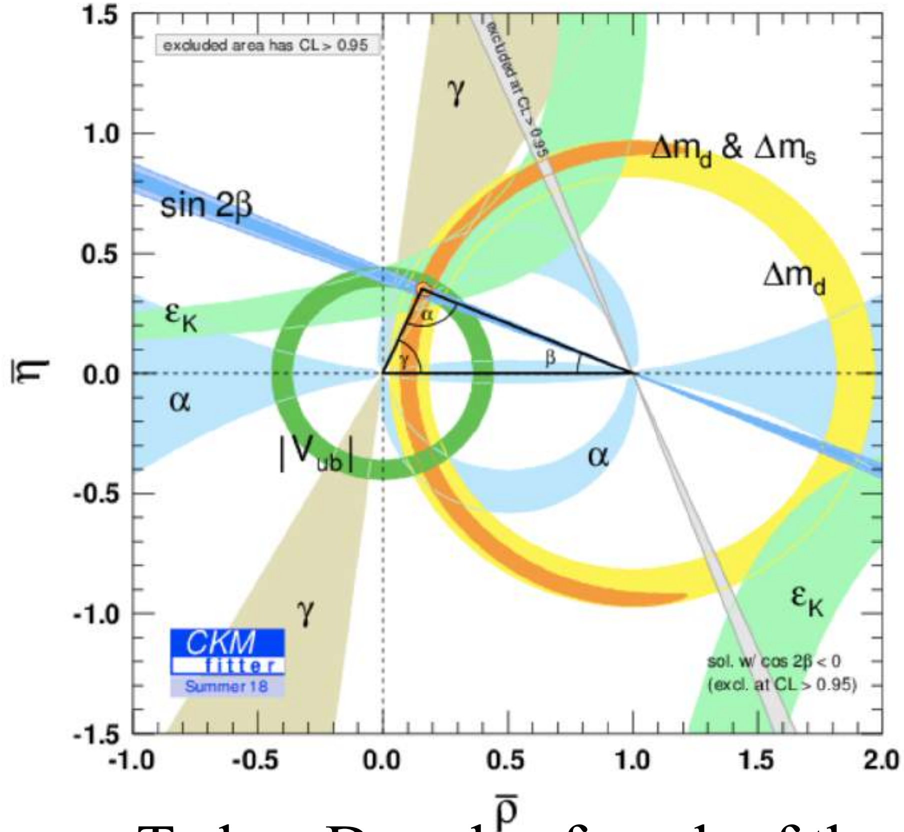
(Fig. Neubert, EPS-HEP'11)

Physics Goals

Search for New Physics and CP violation in rare processes using b and c quark decays



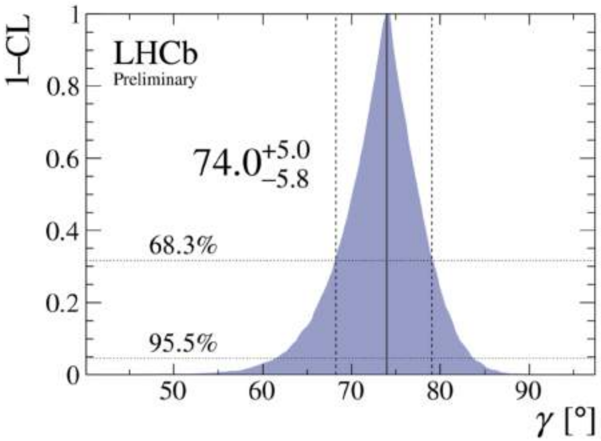
2009: Pre LHCb

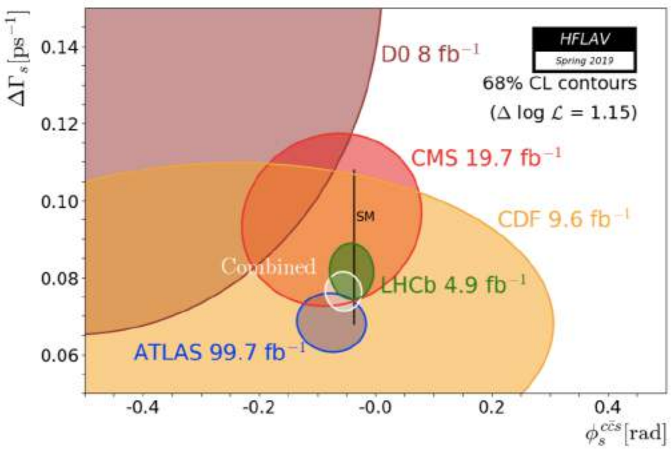


Today: Decade of work of the experimental + theory flavour community

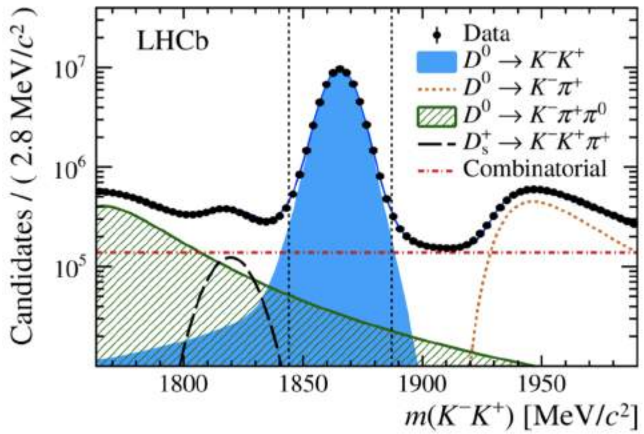
And achievements

CKM parameters

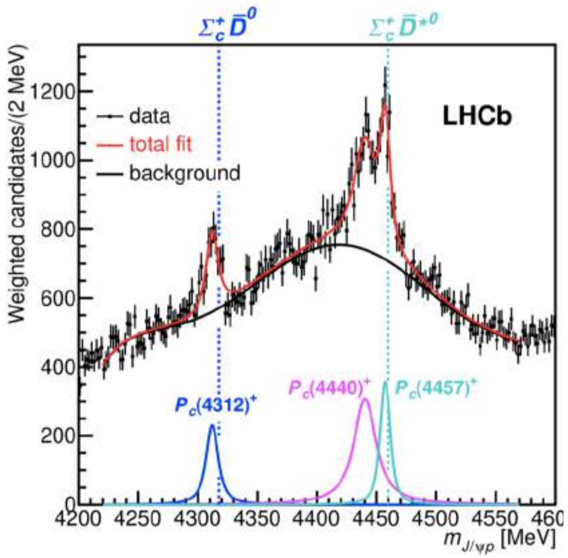




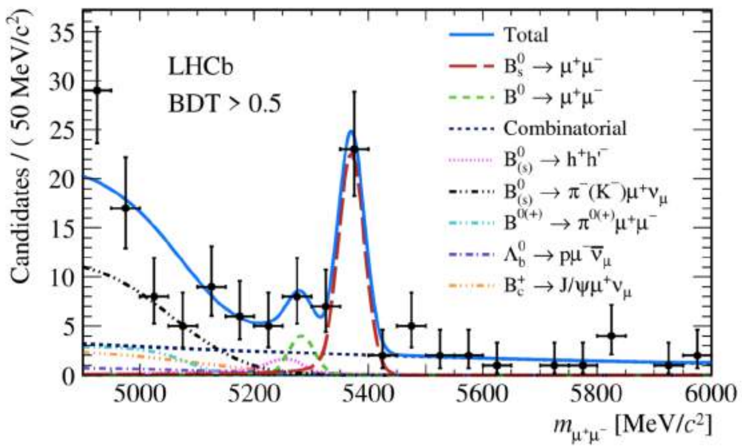
CP violation in charm



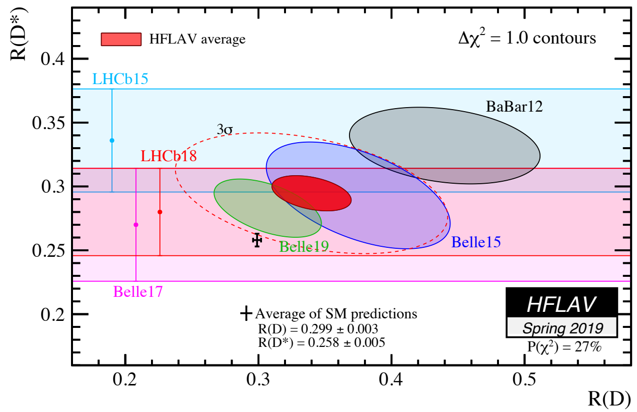
Pentaquarks



Rare decays

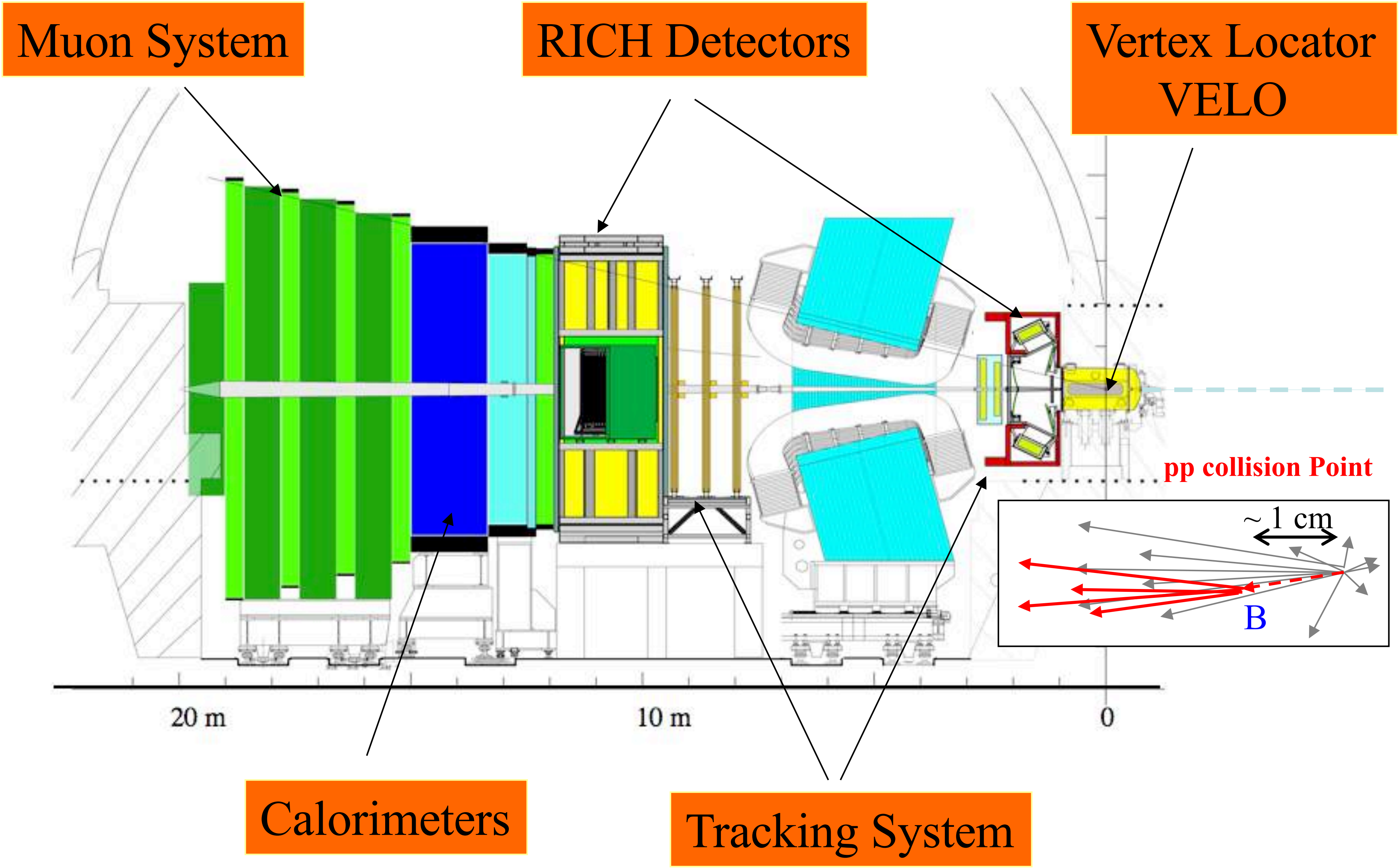


Semileptonics



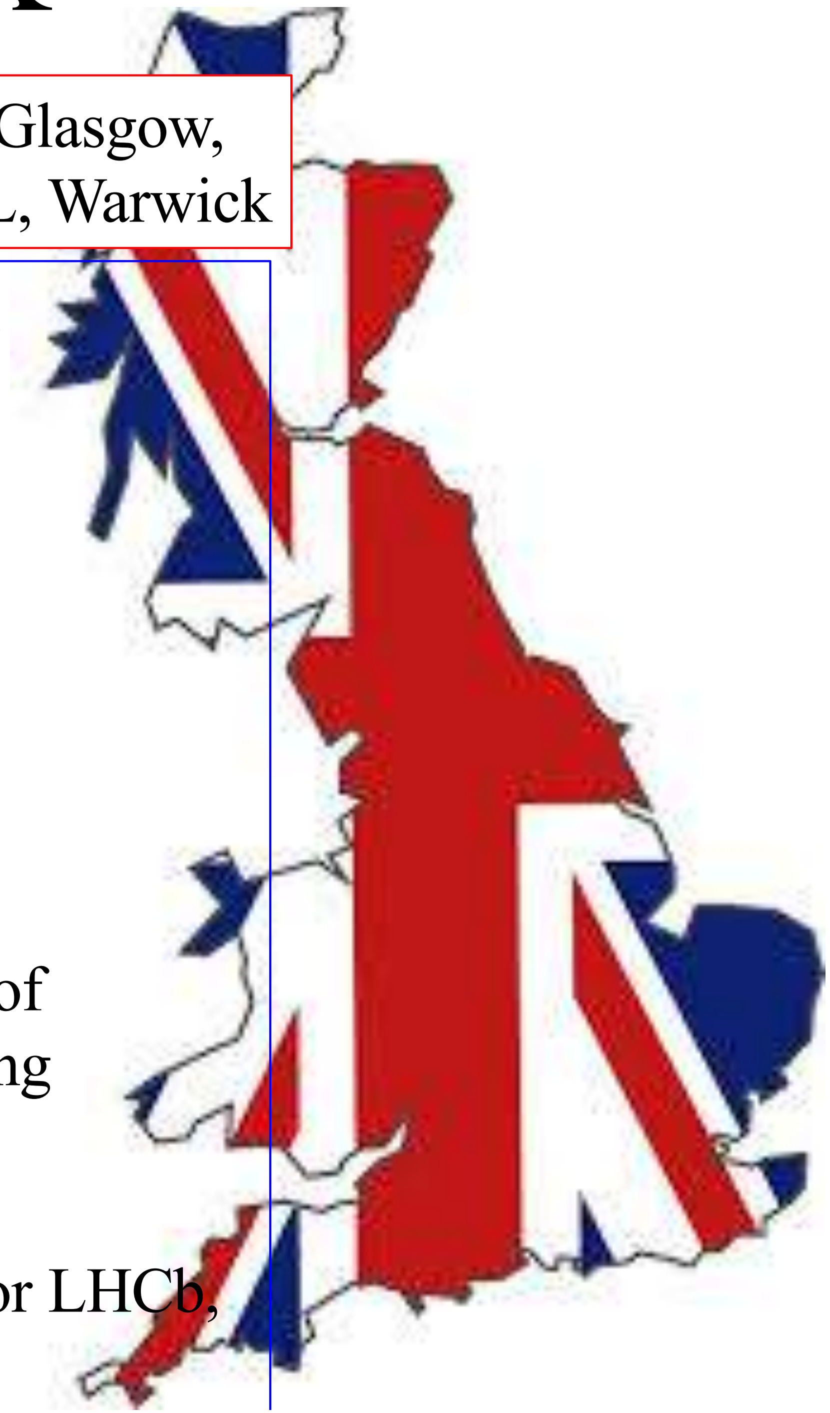
Demonstrated LHC ideal place to do flavour physics

The LHCb Detector



LHCb-UK

Birmingham, Bristol, Cambridge, Edinburgh, Glasgow, Imperial, Liverpool, Manchester, Oxford, RAL, Warwick



Collaboration 850 authors, 19 % UK affiliated

Current Deputy spokeperson (C. Parkes) and
CB chair (V. Gibson)
NCB chair
Operations coordinator (+Deputy)

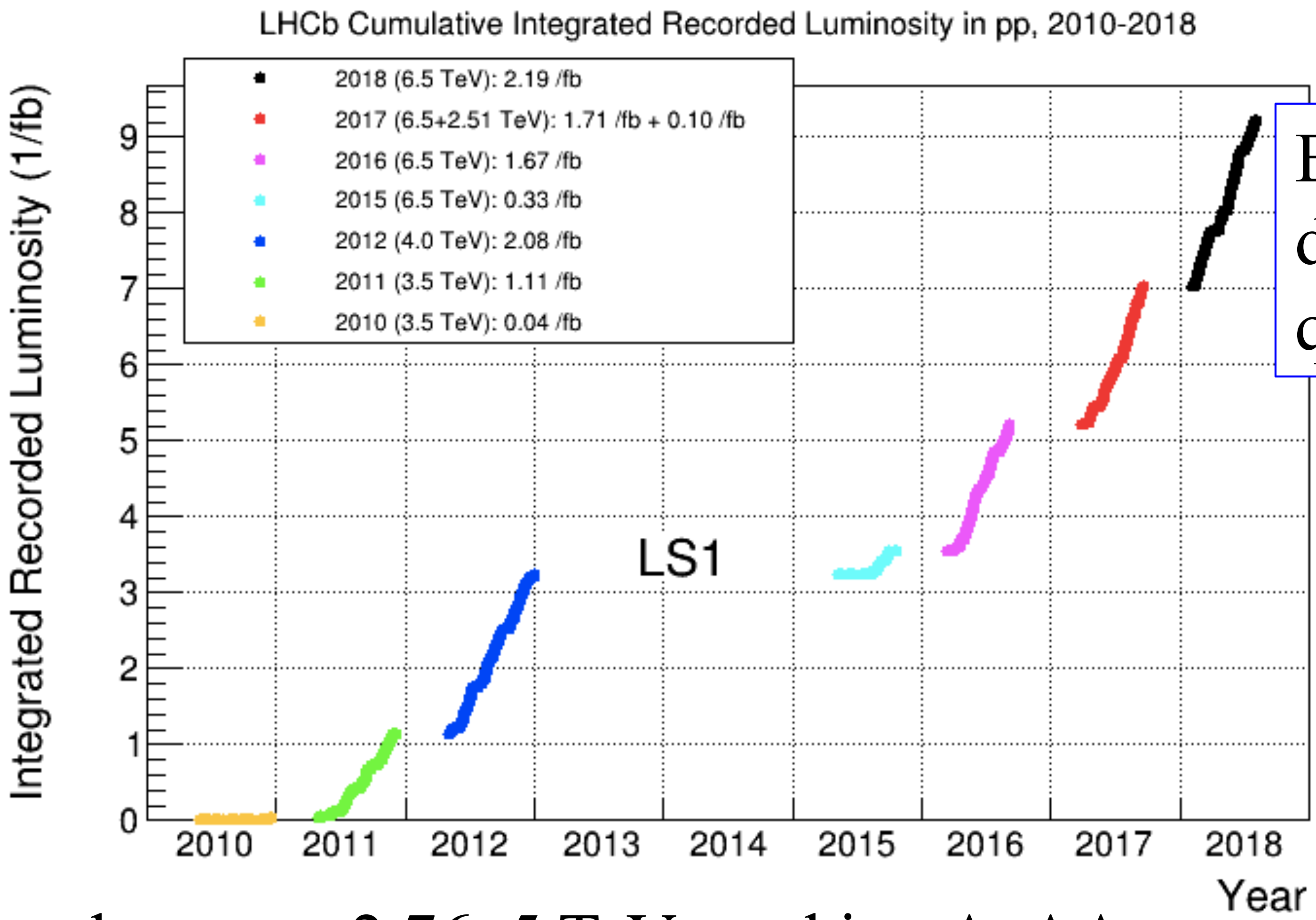
25 % of physics groups convenors from UK

UK led construction and successful operation of Vertex detector + RICH for LHCb. Now playing same role for UI upgrade

UK provides appropriate Tier-1 data storage for LHCb, GRID sites, core software development

LHCb: Run 1+2 Overview

~ 9.2 fb^{-1} of data collected

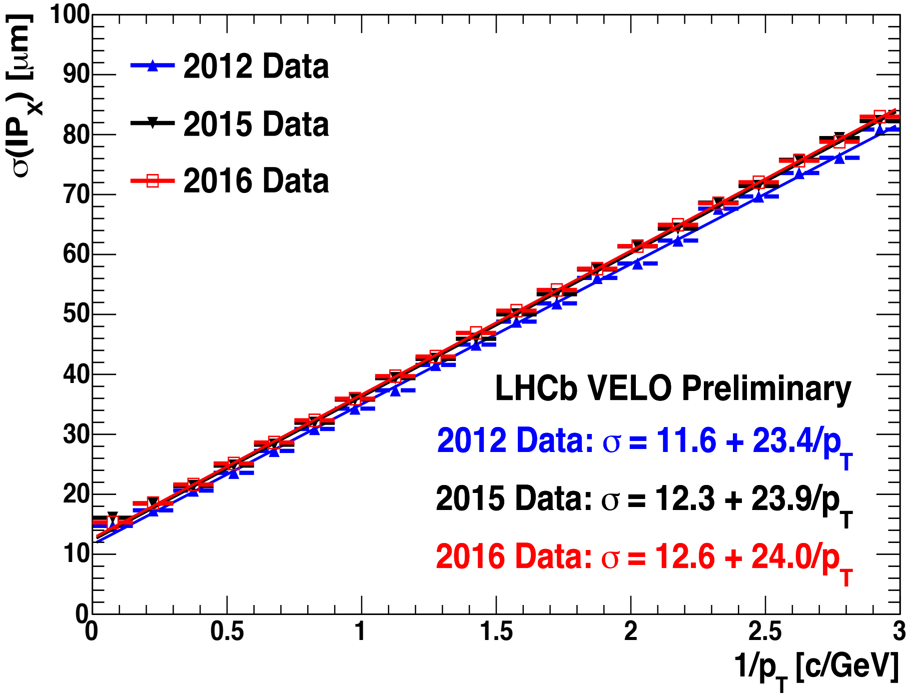


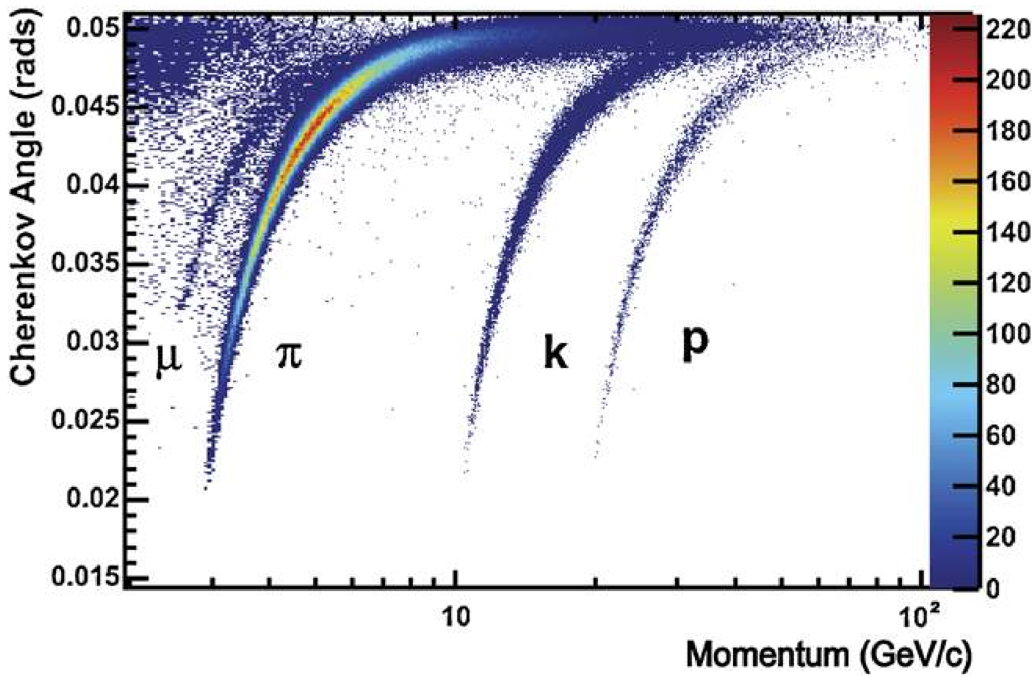
Essentially all data physics quality

Plus dataset at 2.76, 5 TeV, and in pA, AA,
Unique fixed target mode (SMOG)

Detector Performance

Detector performed as designed. Superb foundation to do good physics





Impact parameter resolution in vertex detector

Cherenkov angle for isolated tracks

Run 2 Data Taking

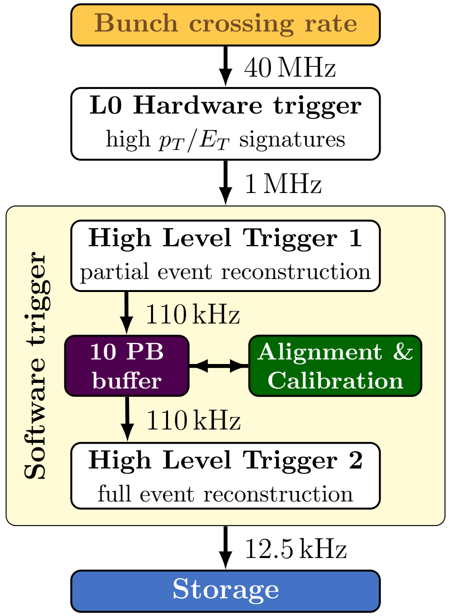
[JINST 14 (2019) P04013]

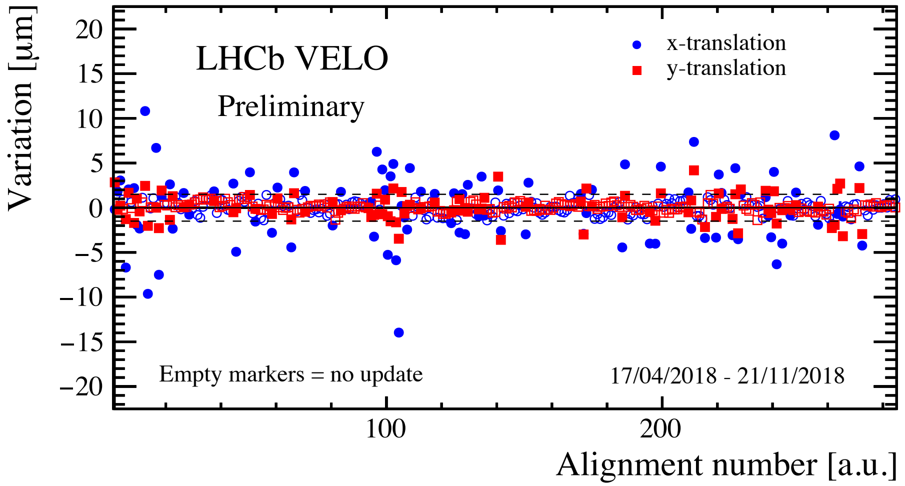
Physics output maximized by doing more analysis and selection online

Data buffering in farm: time to make 'offline' quality decision at HLT2

Real-time calibration + alignment

Selective persistency ('TURBO')

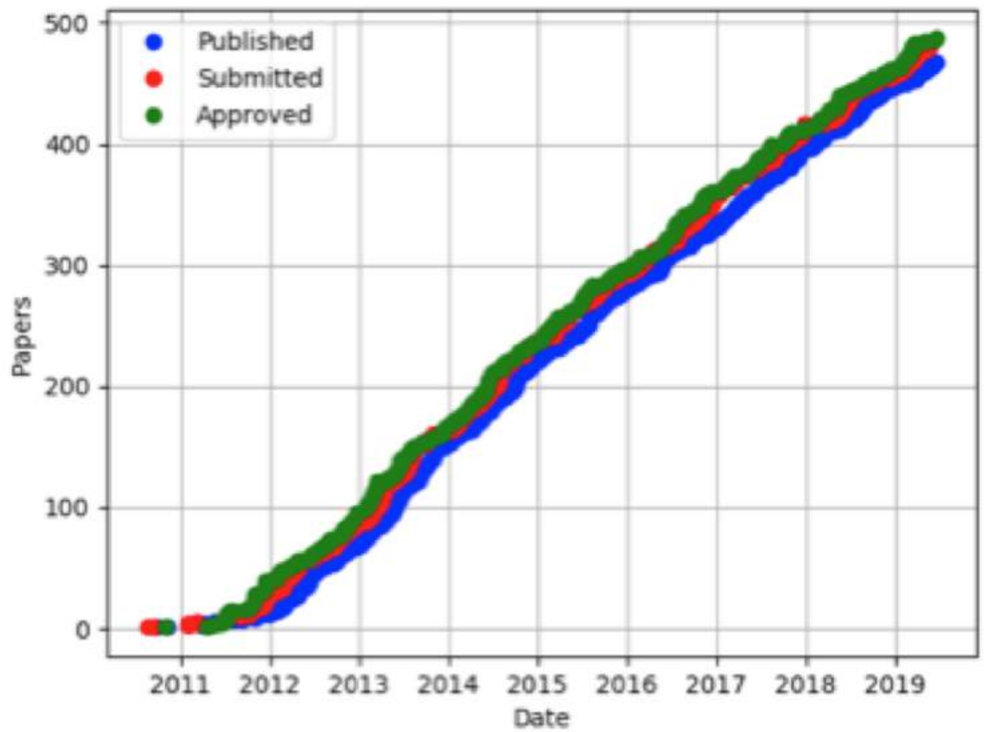




Many of these techniques will be default way of working for Run 3

Scientific Output

- 492 papers submitted or published papers
- Harvest of Run 1+2 data will continue for some time
- Focus on a few recent results



Spectroscopy

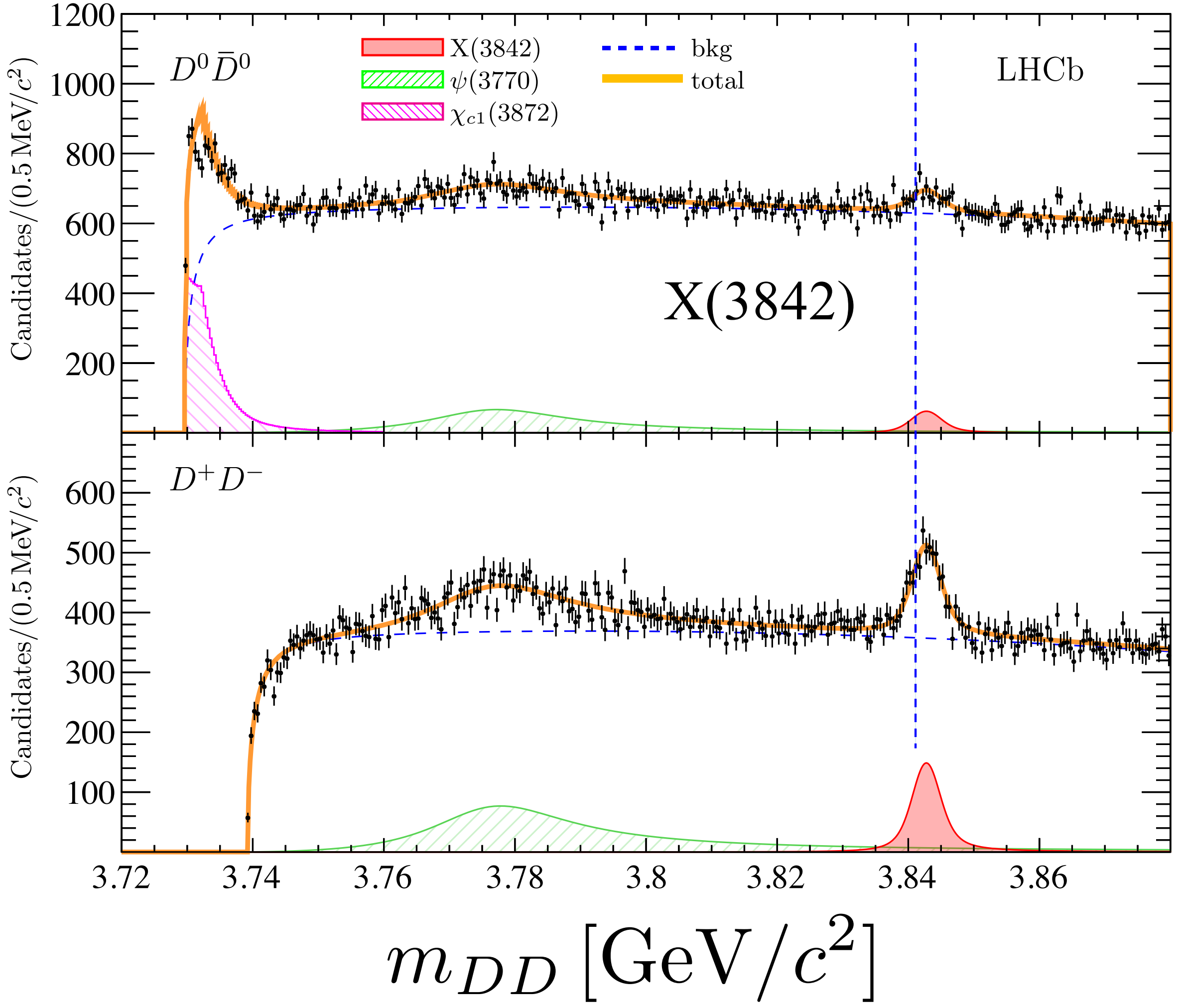
Large collected dataset has created new golden age for spectroscopy

Many new conventional and exotic states founs

Conventional states
e.g. Observation of narrow X(3842) state likely $^3D_3$ state of charmonium system

Measurement using the full dataset reported at spring conferences

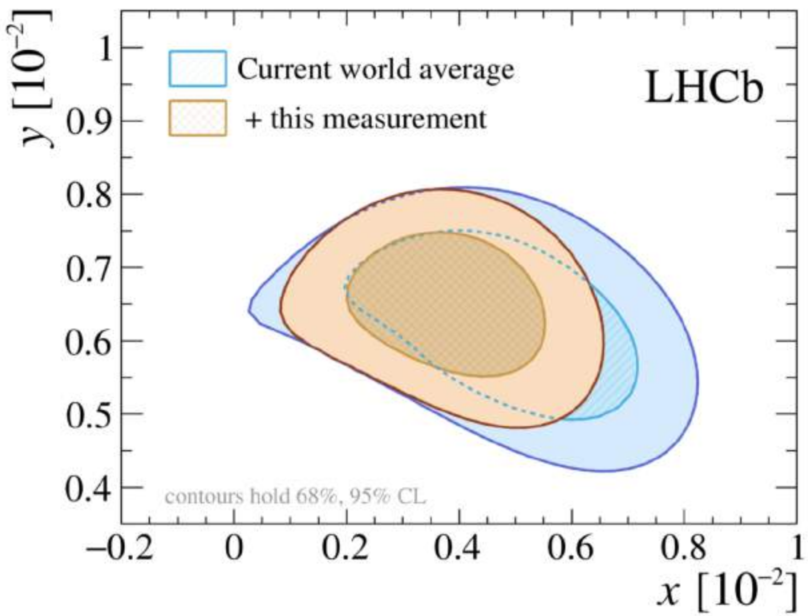
JHEP 07 (2019) 035



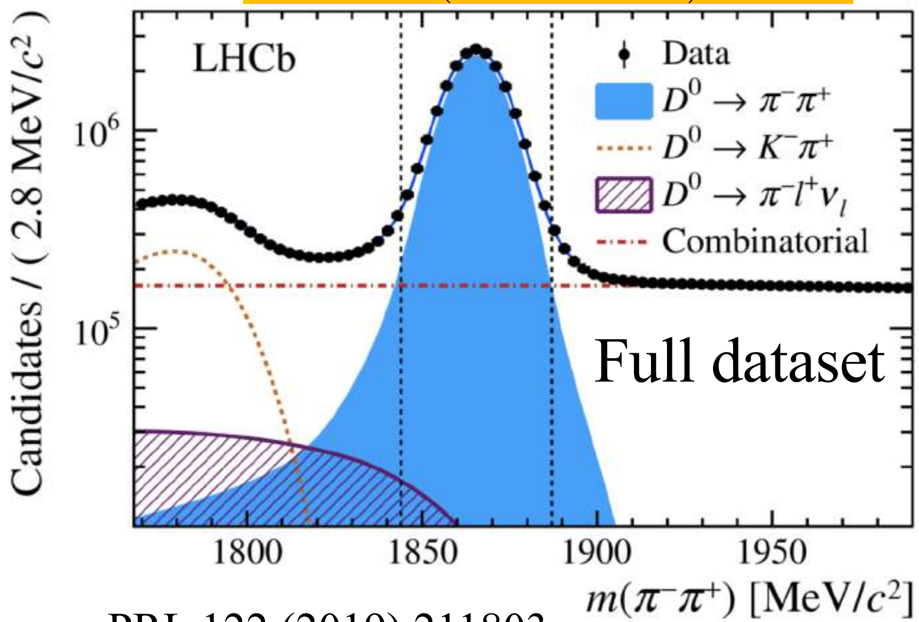
Charm

- Wide program in charm rare decays and CP violation searches
- Huge statistics: Run 2 profits from improved trigger + extensive use of TURBO:
  - Combined gives factor 4 improvement compared to Run 1
- UK has strong leadership of the program
- Many important results in recent months: first measurement of mass difference between neutral charm eigenstates, **first observation of CP violation in charm**

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

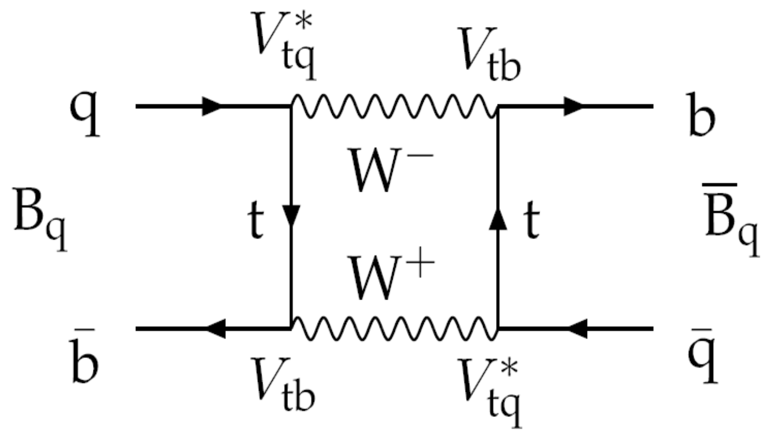


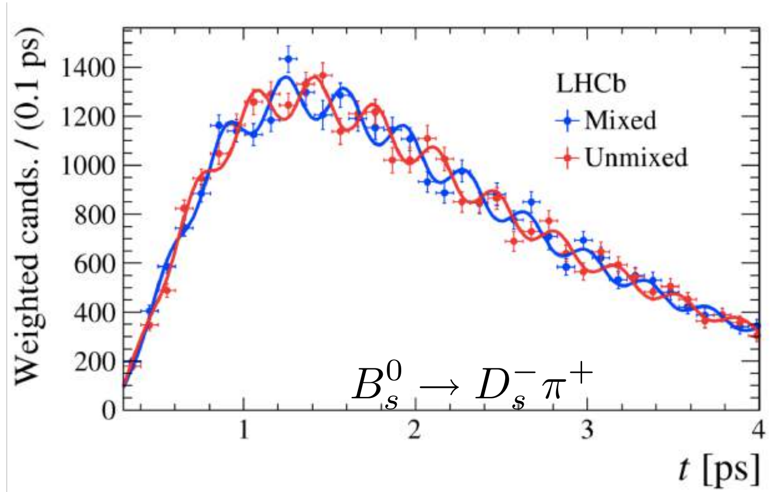
PRL. 122 (2019) 231802



PRL 122 (2019) 211803

CP violation in B_s mixing





Observable CP violating phase ϕ_s (analogous to sin2β in B^0 case): SM expectation ϕ_s ~ -0.037 rad. Can be enhanced in New Physics models

LHCb measure ϕ_s in J/ψϕ, J/ψππ modes, ATLAS/CMS in J/ψϕ

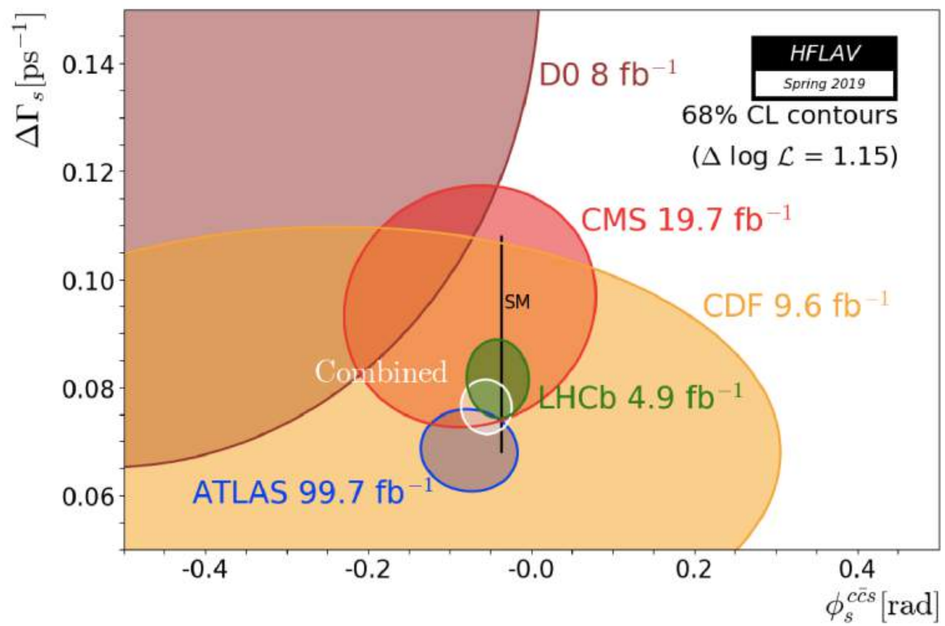
LHCb combination

$$\phi_s = -41 \pm 25\,\mathrm{mrad}$$

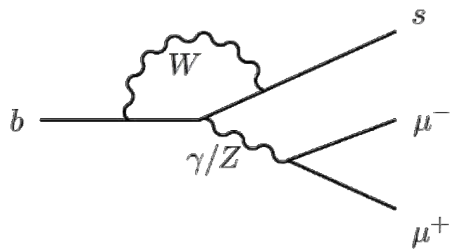
EPJC 79 (2019) 706

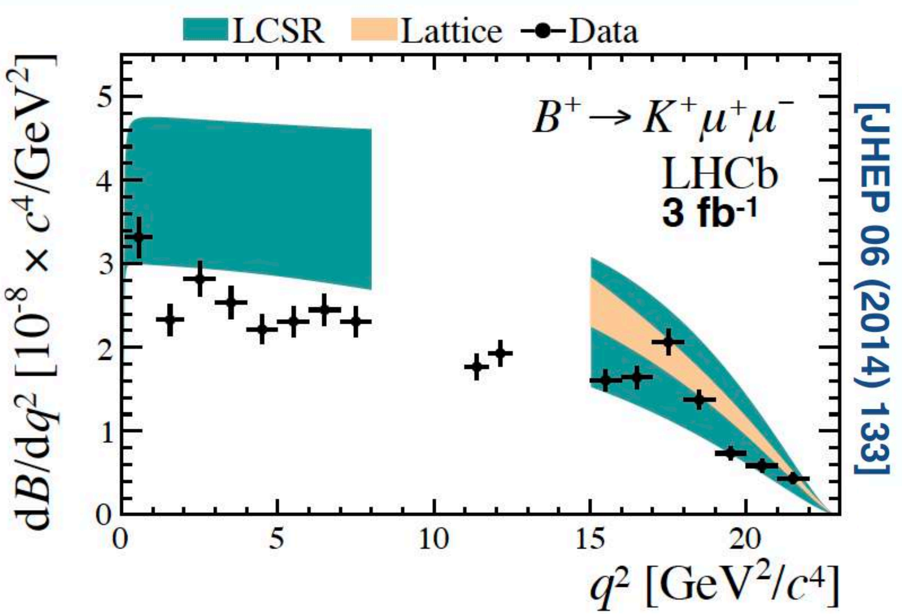
HFLAV Average

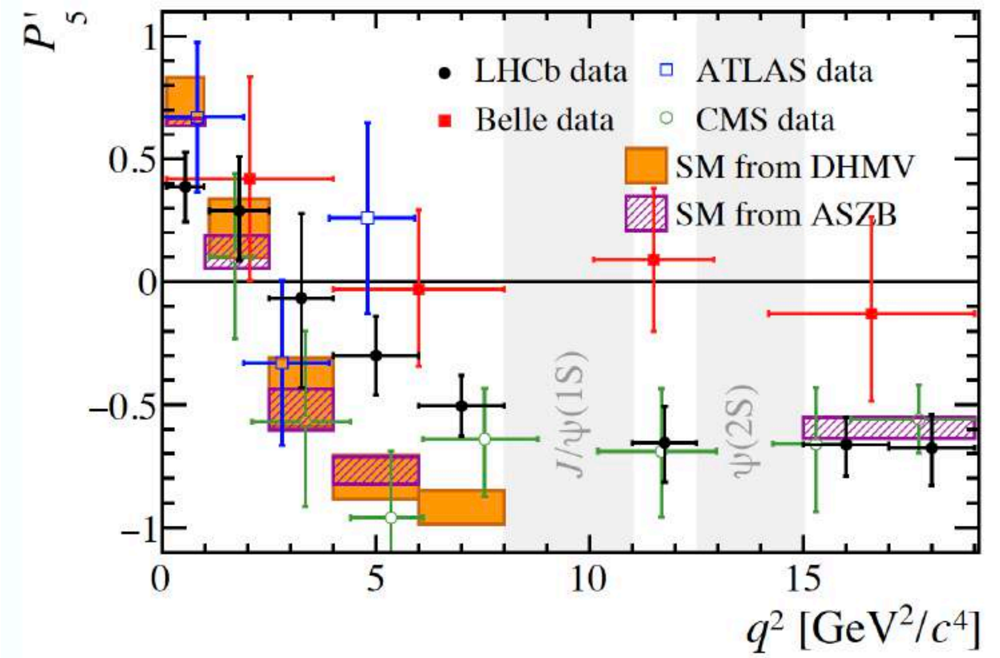
$$\phi_s = -55 \pm 21\,\mathrm{mrad}$$



Electroweak penguin







Long-standing anomalies from Run 1 in electroweak penguin decays

Muon BF for many modes low compared to SM predictions

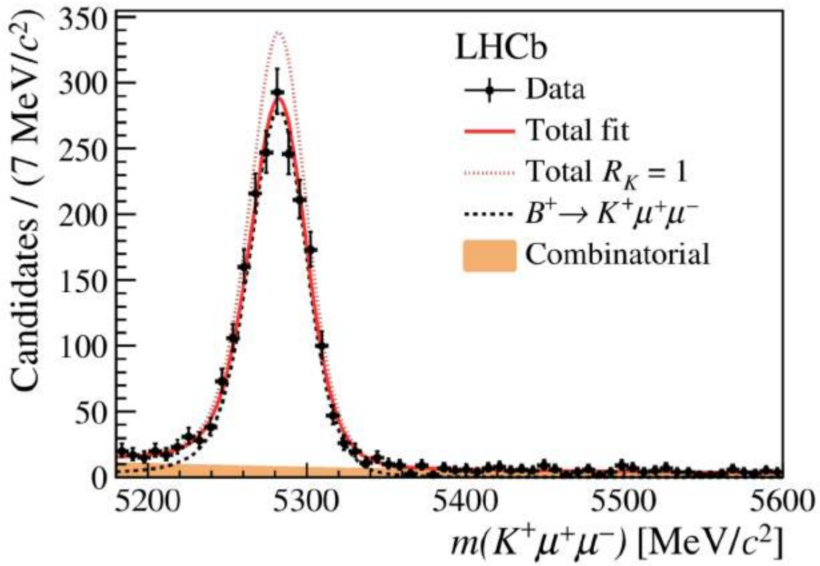
LHCb Angular analysis of $B \to K^*\mu\mu$ shows tension in P_5' variable

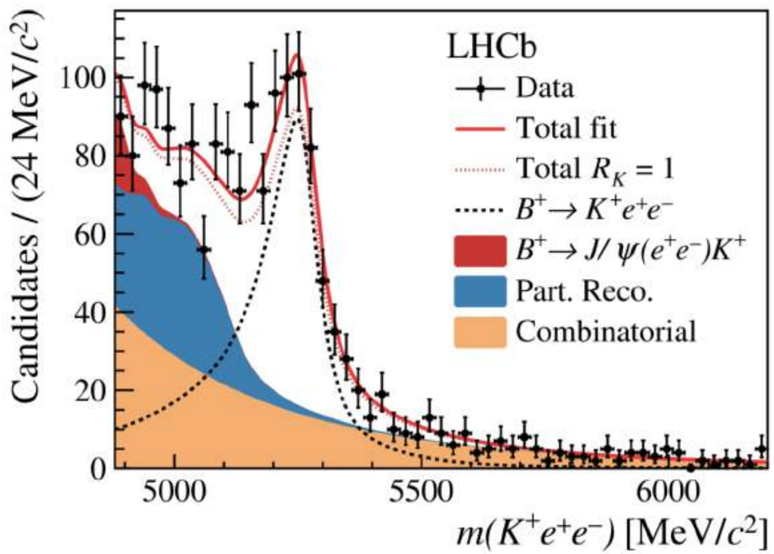
More data needed but data points to new physics in Wilson coefficients C_9 (vector coupling) or C_9+C_{10} (axial Vector)

Parallel hints of LFU violation (R_K, R_{K*})

R_K

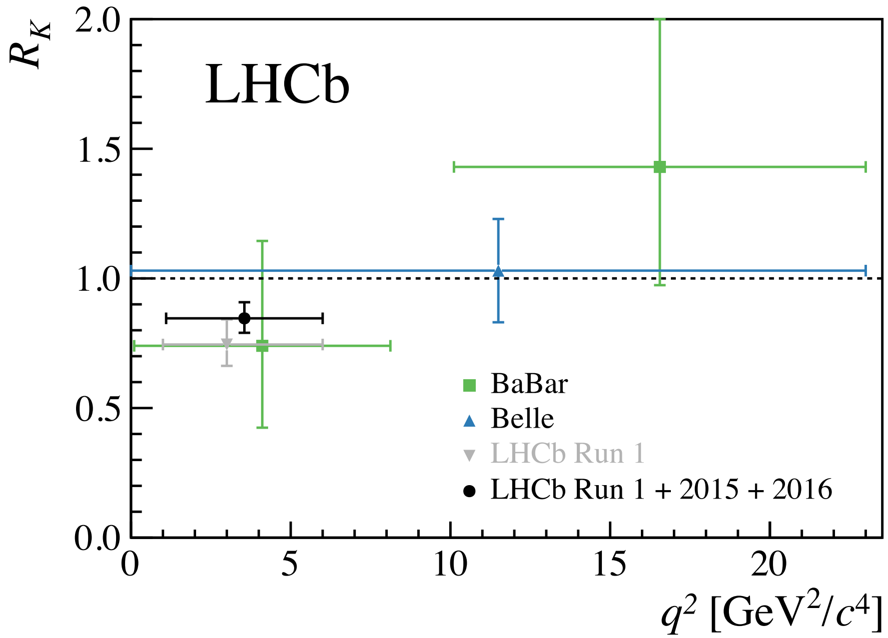
PRL 122 (2019) 191801





Recent update from LHCb using data up to 2016 on

$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$



$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$$

Consistent with SM at 2.5σ level

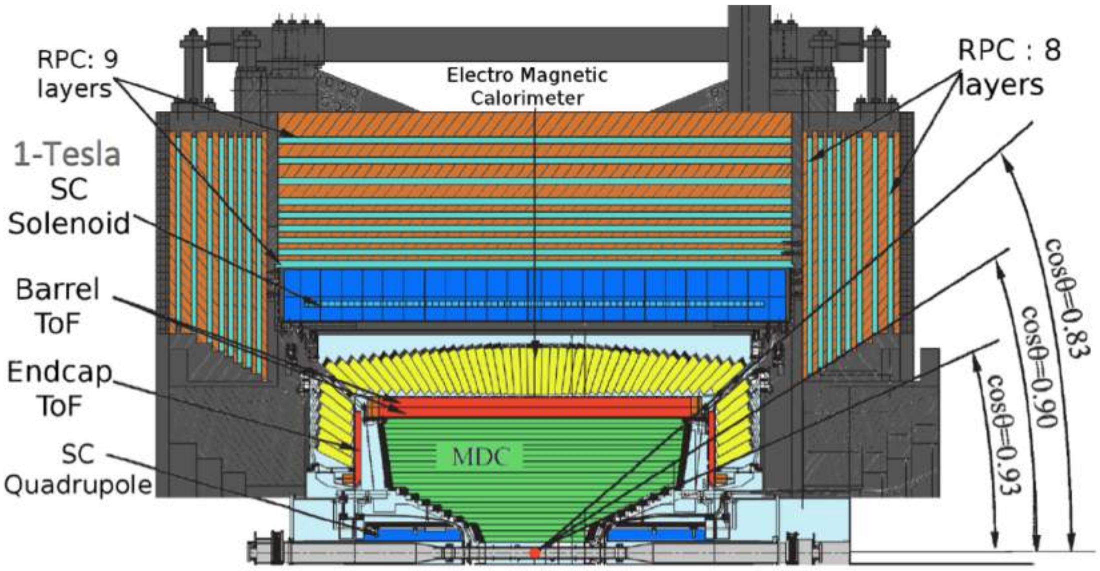
Still to come…

Full Run 1+2 results

- R_K, R_{K*} , R_D* and others
- Angular analysis of K*$\mu\mu$
- $B_s \rightarrow \mu\mu$ with full dataset
- Charm mixing and CP observables
- CKM parameters: sin2β , γ, ϕ_s, …
- Further exploration of heavy flavor spectroscopy

The BESIII experiment and Collaboration

Cornerstone of the Chinese experimental particle physics programme



Located in Beijing @ BEPCII accelerator

e^+e^- collider $\sqrt{s}$ = 2-4.6 GeV
Hermetic detector

Third generation of BES experiments

Data collected at $\sqrt{s}$ = 3.770 gives access to quantum correlated D decays

Allows for **unique work** in charm strong phase measurements

Oxford and Manchester joined in December 2017, specifically due to expertise in charm strong phase measurements

Specific UK interests

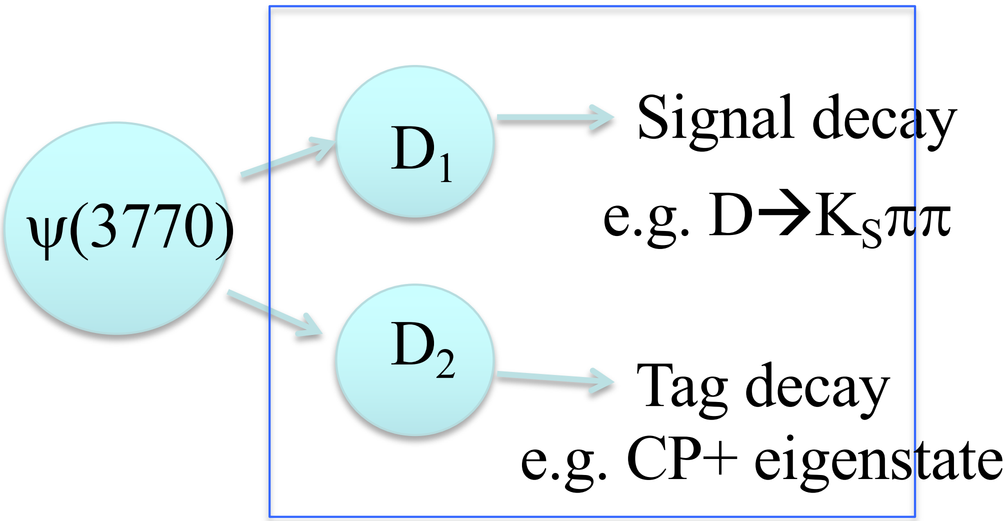
- UK interests in BESIII are primarily tied to the interests of some flagship LHCb Upgrade (and BELLE II) measurements.

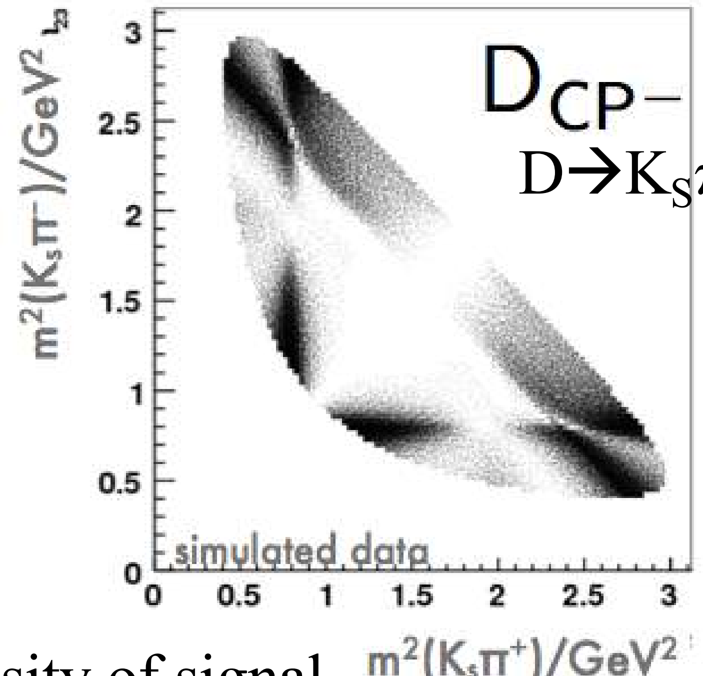
- Production mechanisms at BESIII allow for unique, precise, and vital, charm measurements which essentially cannot be performed elsewhere.

- Joint LHCb-BESIII workshops in Feb 2019 and May 2019 to explore mutual benefit (LHCB-PUB-2016-025)
- Perfect fit with the European strategy
- Replicate the success of the UK CLEO-c contribution
- Funded through Royal Society (multiple grants) & ERC starter grant, MSCA IF
- Oxford and Manchester active in the collaboration (Publication Committee and Speakers Bureau)
- Manchester provides UK grid resources for BESIII jobs (Blackett facility)

Strong phase parameters from ψ(3770)

- Phase measurement requires system with interference
- $e^+ e^- \rightarrow \psi(3770) \rightarrow DD$
- Two D mesons are quantum correlated.





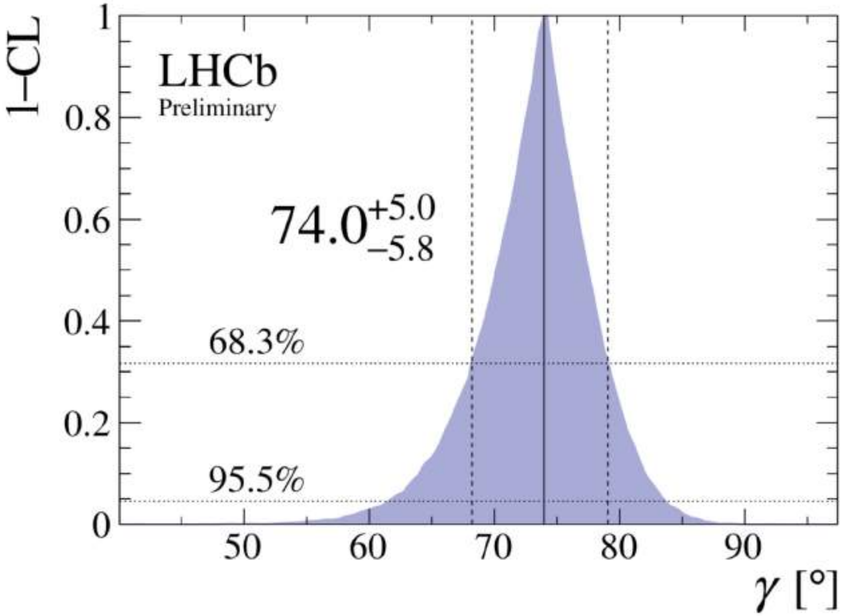
Density of signal
$$\propto |A|^2 + |\bar{A}|^2 - 2|A||\bar{A}|\boxed{\cos(\delta)}$$

$D \rightarrow K_S\pi\pi$ is one decay mode, of interest. There are many more of interest to LHCb and BELLEII

Between Oxford and Manchester the following modes are under study:
$D \rightarrow K_S\pi\pi$, $D \rightarrow K3\pi$ $D \rightarrow 4\pi$,

First multibody strong phase results from BESIII anticipated by end of year.

Strong phase parameter uses

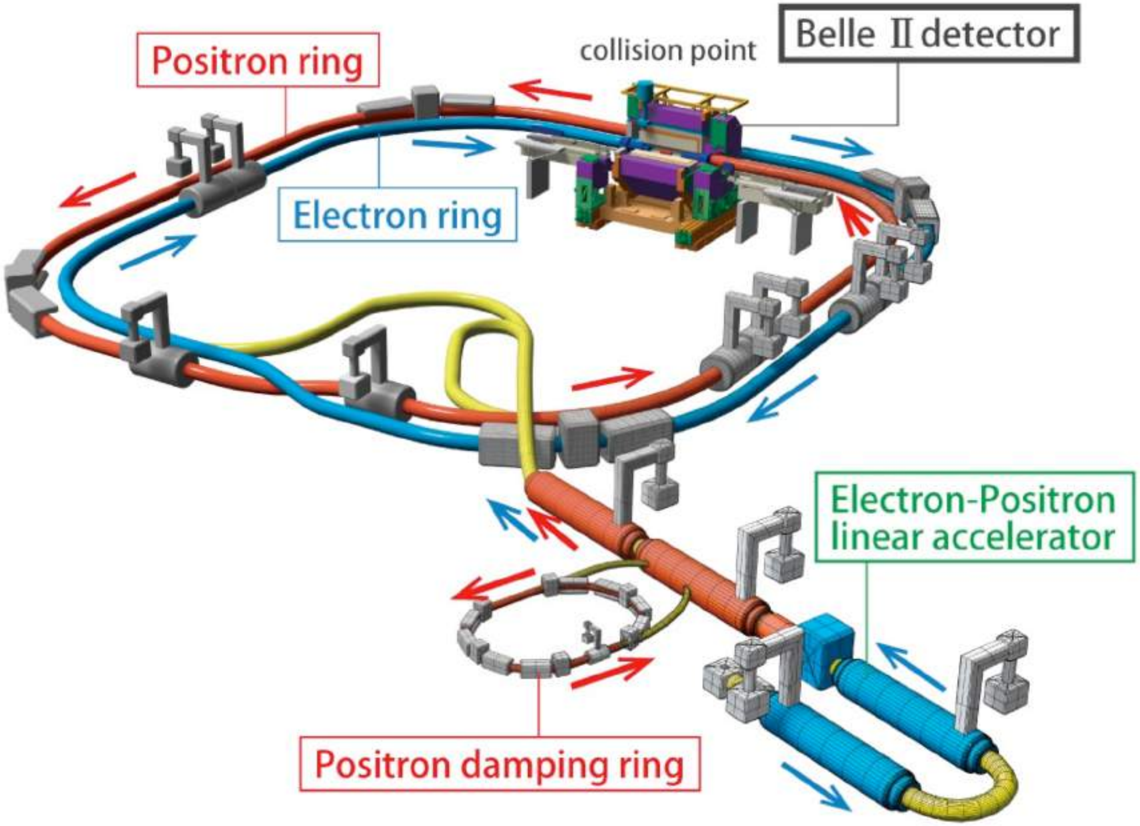


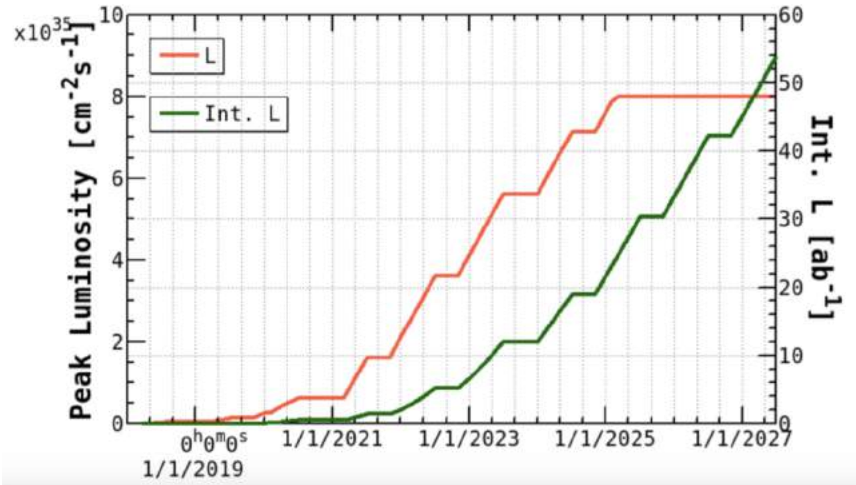
- CKM angle γ is measured in a variety of B decays
- Most of these measurements include a decay of a neutral D
- Strong phase parameters provide input on this part of the decay in a model-independent way → crucial for precision measurement.
- Analyses of BESIII data would open new channels and methods for γ measurement.
- A number of current inputs only possible due to the UK involvement in CLEO-c

BESIII precision required for LHCb run2 onwards and Belle II

Dataset	Contribution to $\sigma(\gamma)$	Comment
CLEO-c 0.8 fb^{-1}	2°	Not precise enough + limited observables
BESIII 3 fb^{-1} (2010 + 2011)	Projected : 1°	Data analysis now underway
BESIII 10-20 fb^{-1} (planned)	Projected : 0.5°	Essential for LHCb upgrade and BELLE II

Belle 2





See talk of T. Browder at EPS19

- Belle 2 is starting to take data (No UK involvement)
- Aim to collect 50 ab^{-1} by 2027 (50 times more than b-factories)

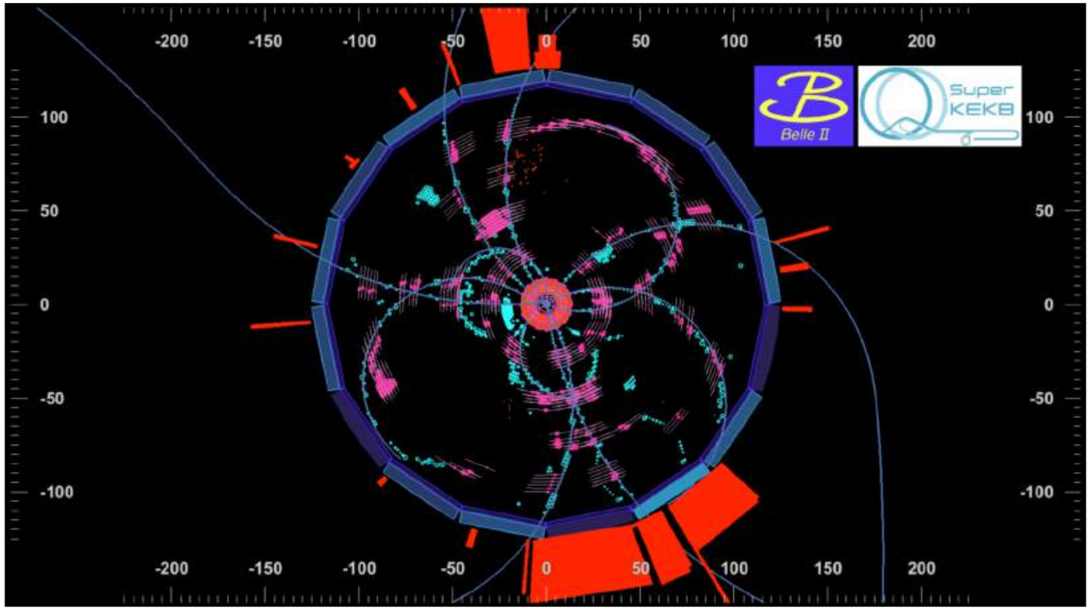
Belle 2

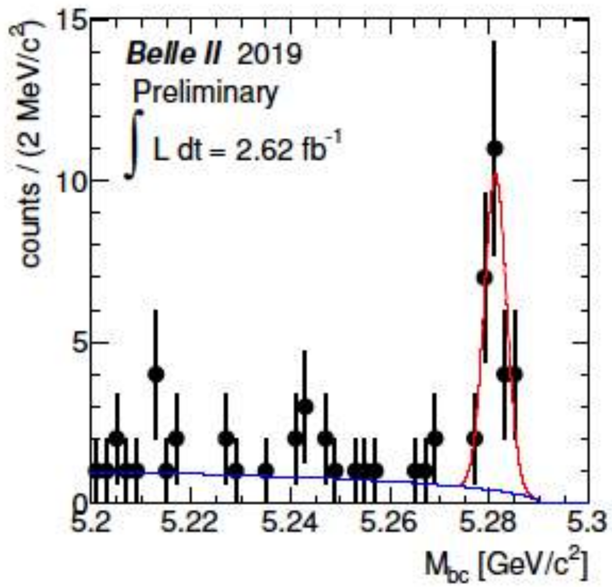
First physics Run in Spring 2019

6.2 fb^{-1} of data collected

Good detectors performance demonstrated

First b-meson signals





$$N(B \rightarrow J/\psi K_S) = 26.9 \pm 5.2$$

From talk of T. Browder EPS2019

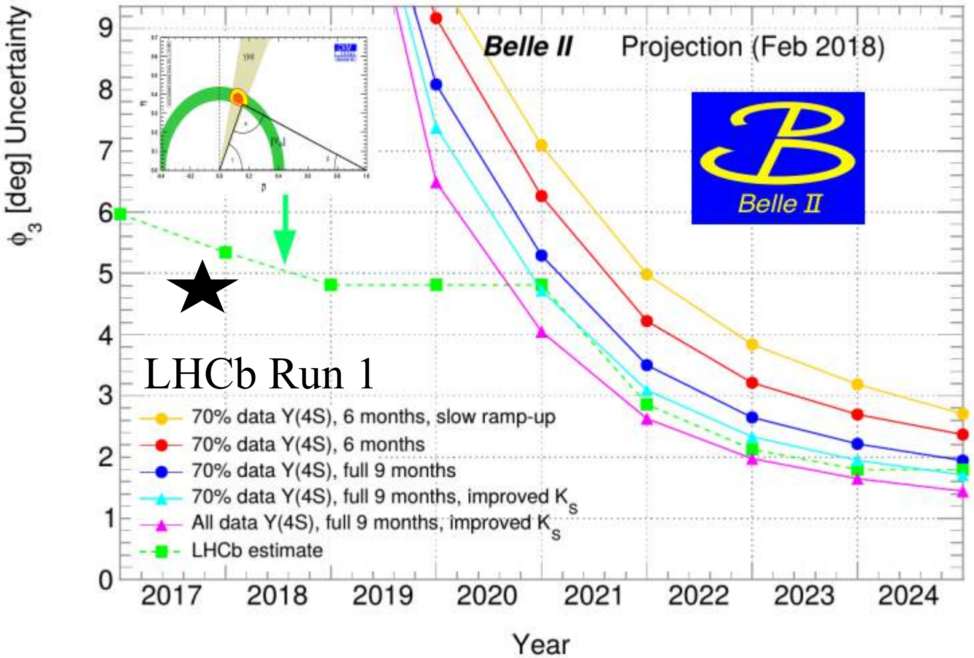
Belle 2

Belle 2 has exciting physics program

Complements LHCb by

- Modes with neutrals
- Modes with missing energy

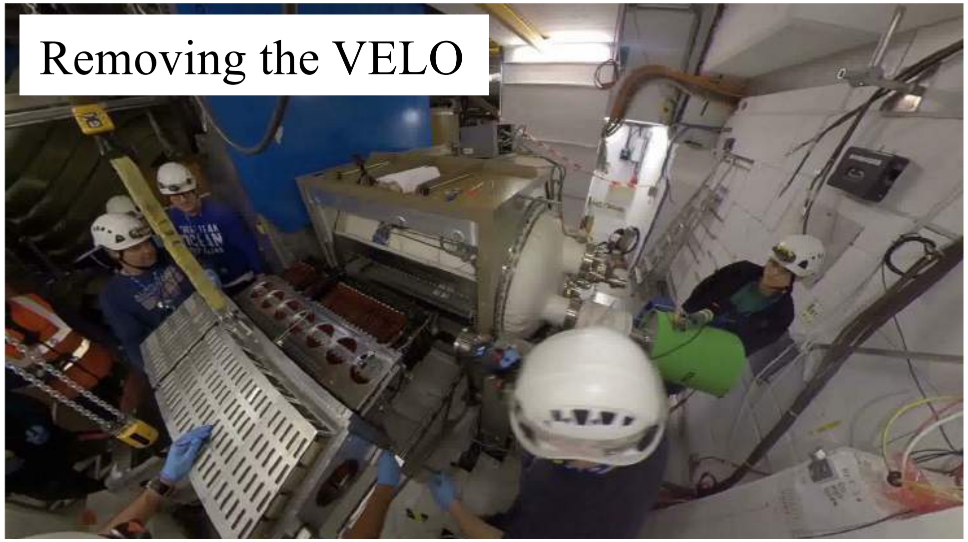
Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–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



arXiv: 1808.10567

https://tinyurl.com/y2l4xz8g

Wish me luck as you wave LHCb goodbye


Removing the VELO


Rich mirror removal


Dismantling the RICH

Decommissioning of first phase of LHCb complete

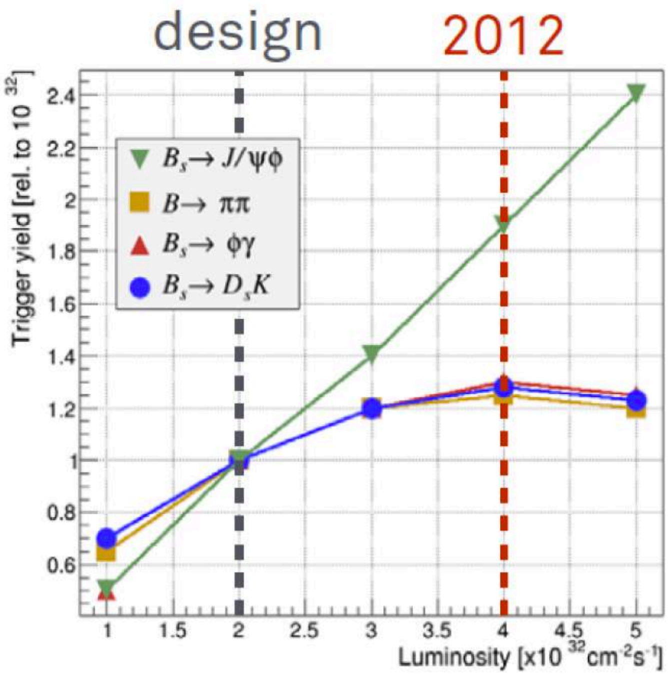
The Upgrade

Why dismantle a beautiful machine ?

- Detector reaching end of design life (10 fb^{-1})
- Dataset doubling time becomes too long
  - To gain statistics run at higher luminosity (10^{33} cm^2 s^{-1})

Limited by L0 hadron trigger

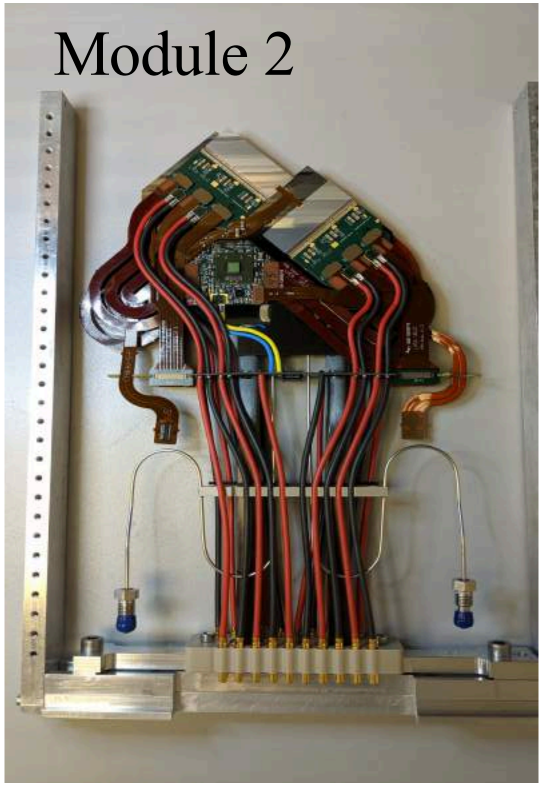
- Replace front-end electronics to allow full detector readout at 40 MHz crossing rate
- Full software trigger
- Aim to collect 50 fb^{-1}



Muon trigger

Hadronic trigger

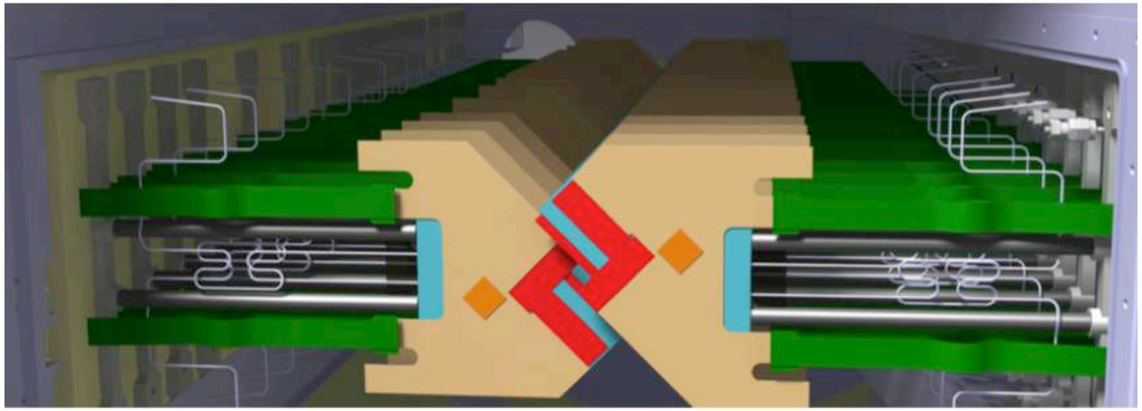
Pixel Detector

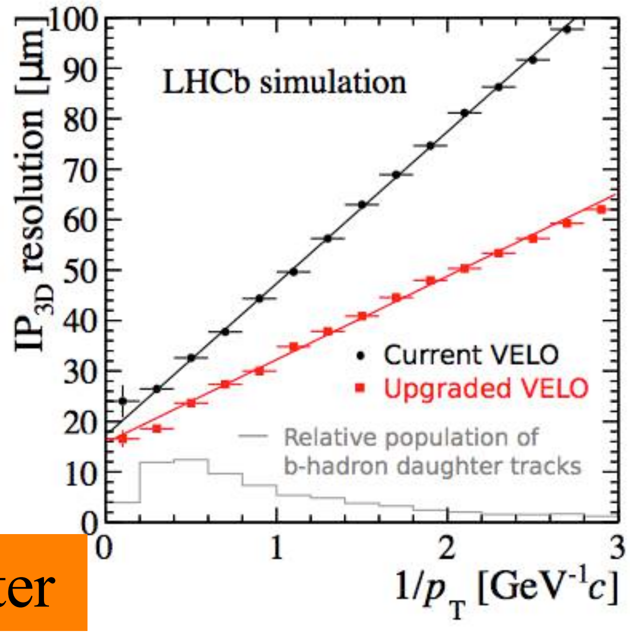


Replace Silicon strips with 55 × 55 μm pixels
41 Million Pixels with 40 MHz readout

Improve IP resolution by moving closer to beam
8.1 mm to 5.1 mm
Rad hard to 8 $\times 10^{16}$ MeV/n_{eq}cm^{-2}

Bi-phase CO2 cooling with micro channels etched on the Silicon substrate





First two modules now produced at Manchester

RICH

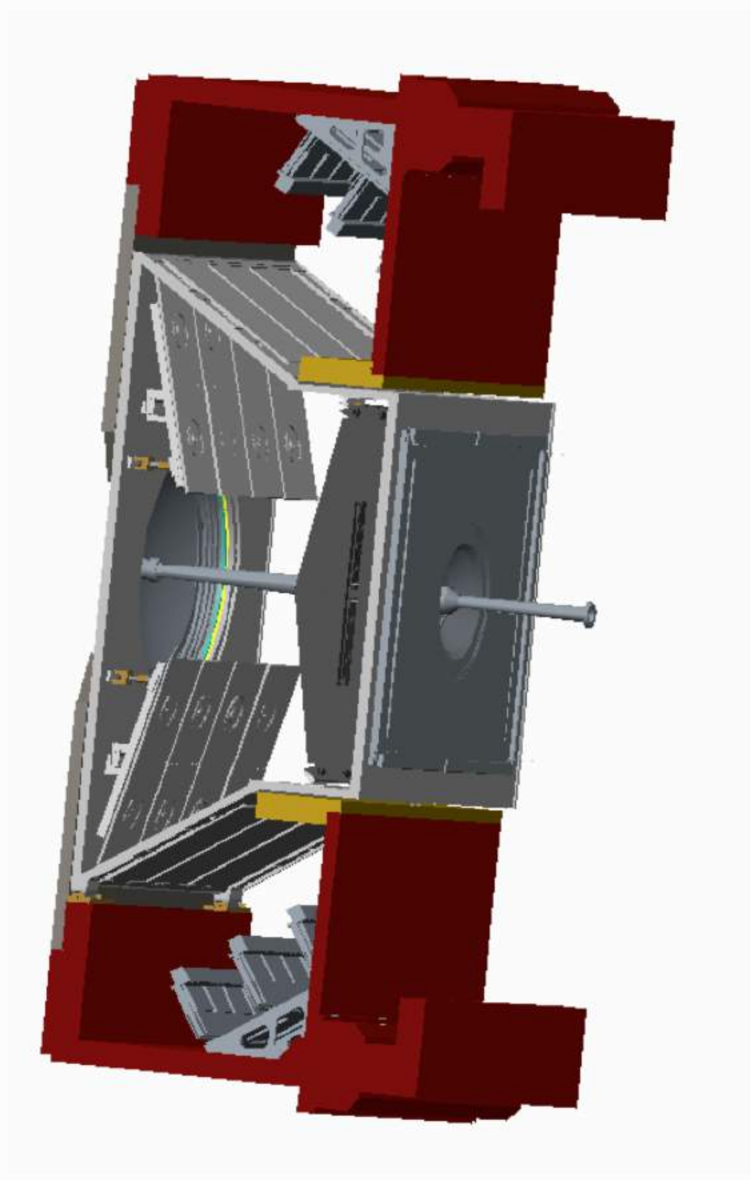
RICH 1

- New photon detectors
- New optics

RICH 2

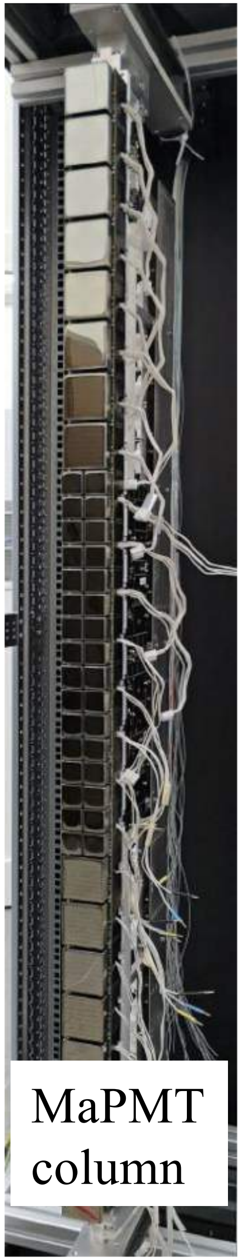
- New photon detectors
- Associated support mechanics

Manufacture and installation progressing well

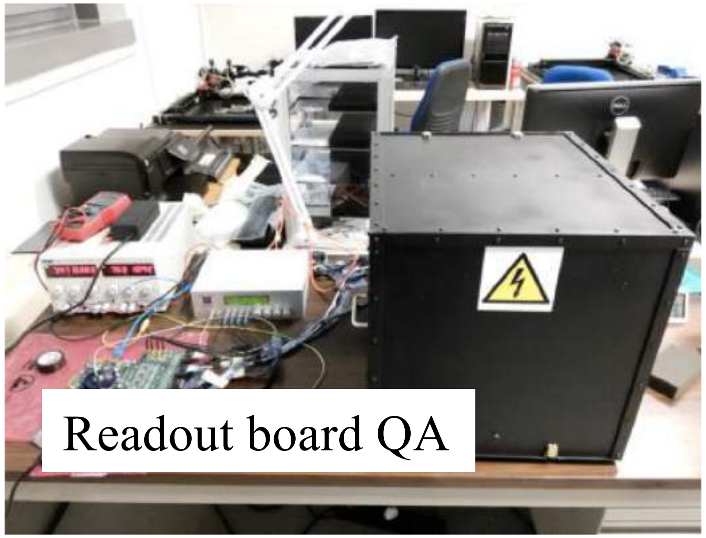


RICH

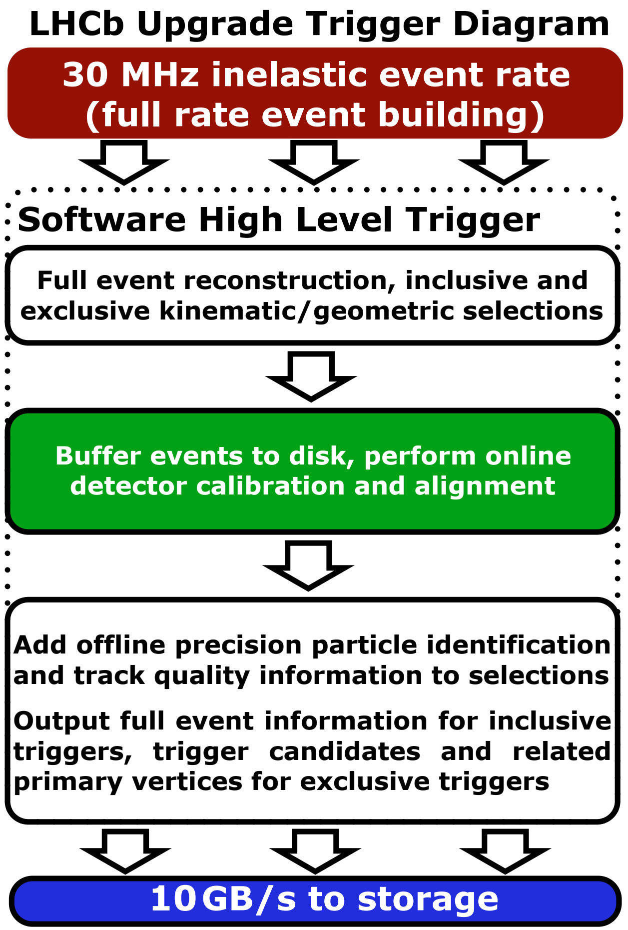

RICH 1 Chassis assembly


MaPMT column


RICH1Quartz window assembly


Readout board QA

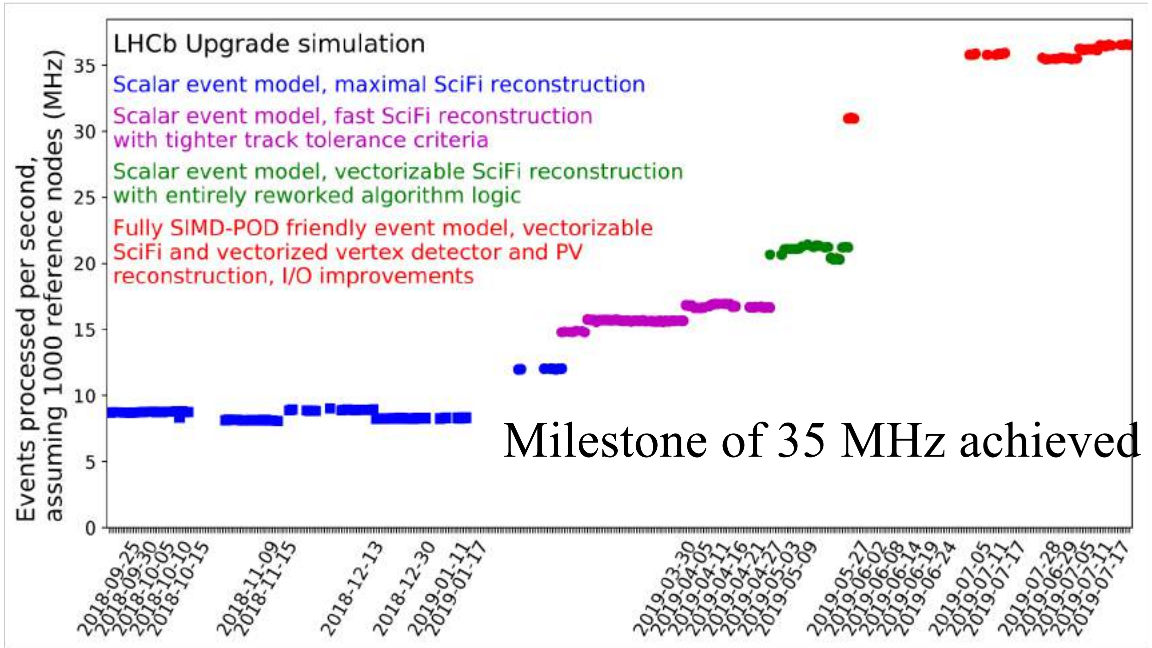
Run 3 Trigger



Full software trigger to reduce rate from 30 MHz to 30 kHz

Remove L0: factor of two better for hadronic modes

A lot of ongoing work to achive this goal exploiting latest programming techniques (vectorization, SIMD)



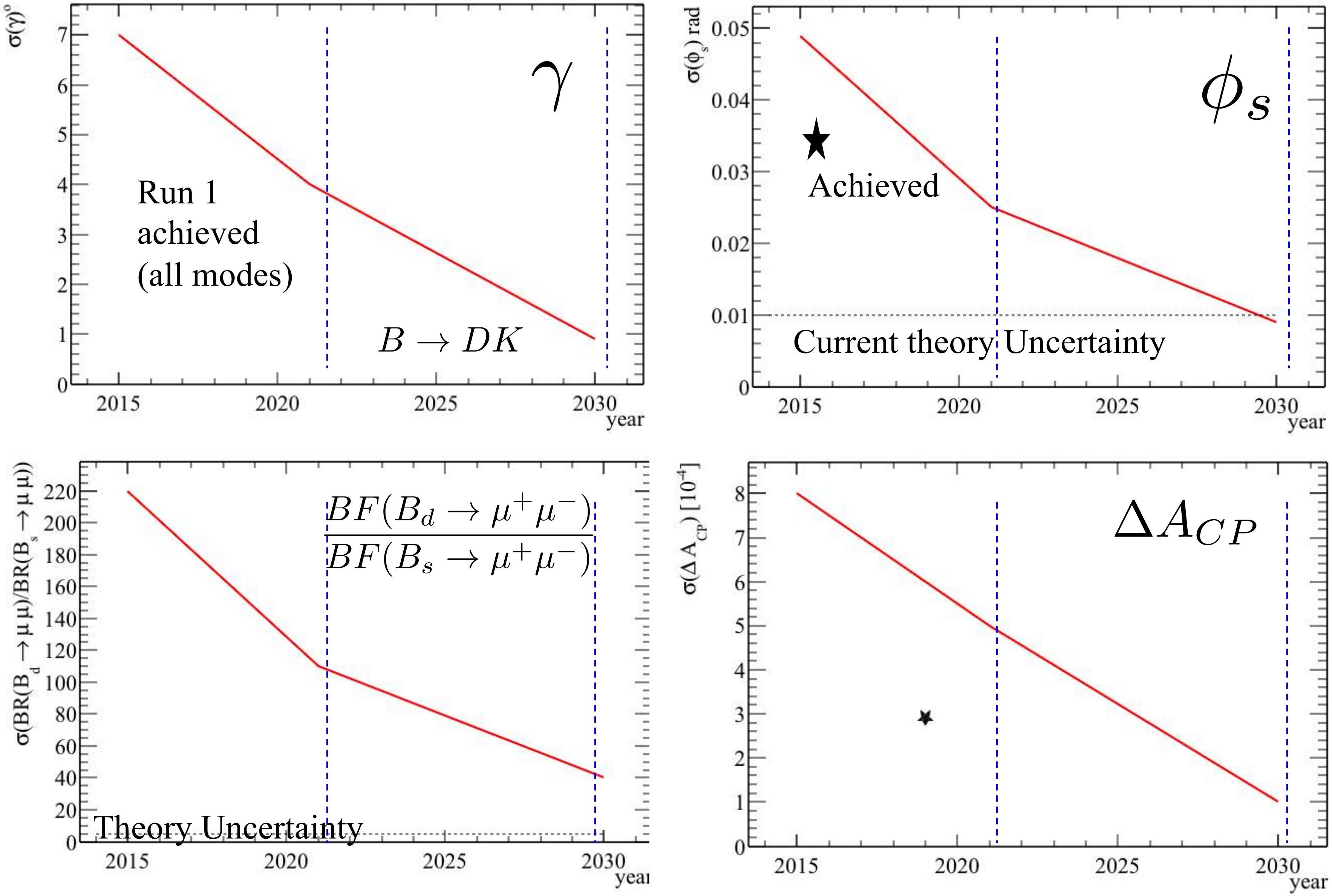
CERN-LHCC-2018-007
CERN-LHCC-2018-014
CERN-LHCC-2014-016

Upgrade Reach

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_{\rm S}^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\ K_{\rm S}^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

LHCB-PUB-2014-040

LHCb: Upgrade Reach

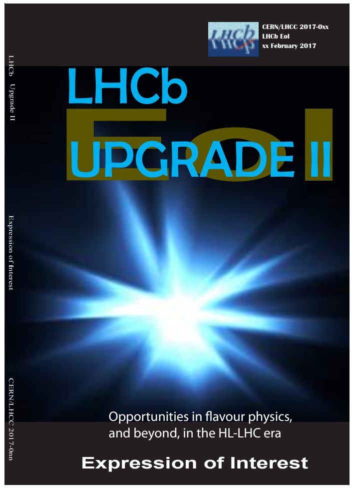


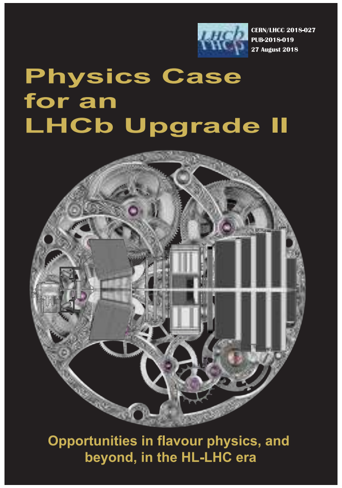
LHCB-PUB-2014-040

LHCb exceeded expectations

Even with 50 fb-1 many measurements still not limited by theory

UII Upgrades



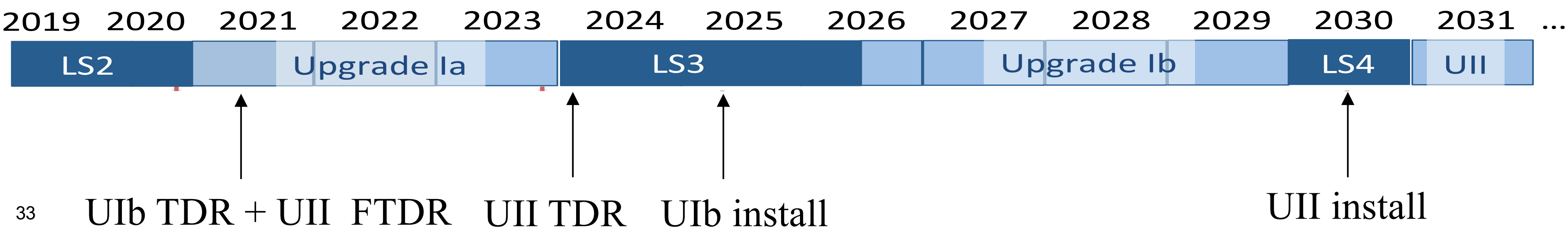


Run LHCb beyond LS4 at luminosity of $\sim 1.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (UII upgrade), 56 interactions/crossing

Collect >300 $\mathrm{fb^{-1}}$ data: realistic from machine side

UIb upgrade: Planned consolidation work after LS3

- Letter of Intent and Physics case submitted to LHCC
- First studies of operating conditions made by the machine
- Positive feedback: Collaboration approved to move to TDR in early 2021 by LHCC/RB
- Statement of Interest to be submitted to STFC this Autumn



Future Upgrades: VELO

Correct and fast assignment of tracks to primary vertices critical for LHCb

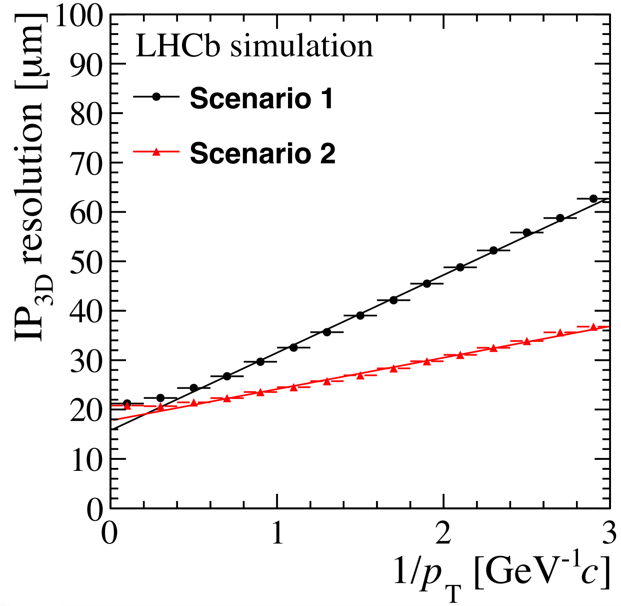
RF foil material be reduced or removed: improves resolution, reduces material interactions

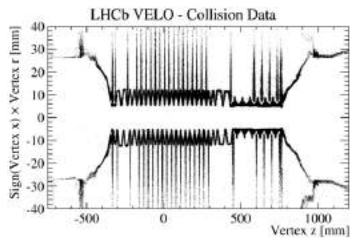
Reduce pixel size < 55 μm in inner Part

4d detector:
Timing with precision < 50 ps

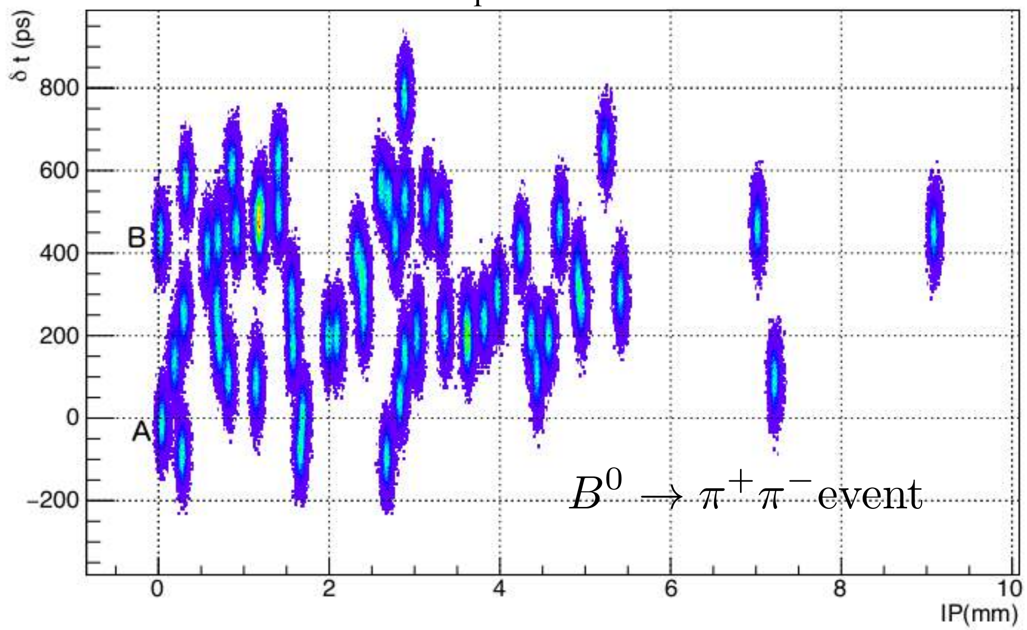
Extra dimension of timing reduces wrong PV assignment from 20 % to 5 % (similar to now)

Also speeds up pattern recognition

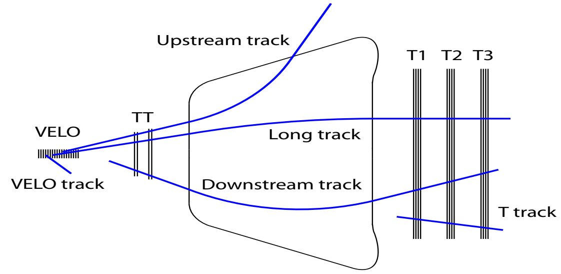




Remove RF foil



Mighty Tracker



Replace inner part of T-stations with HV CMOS

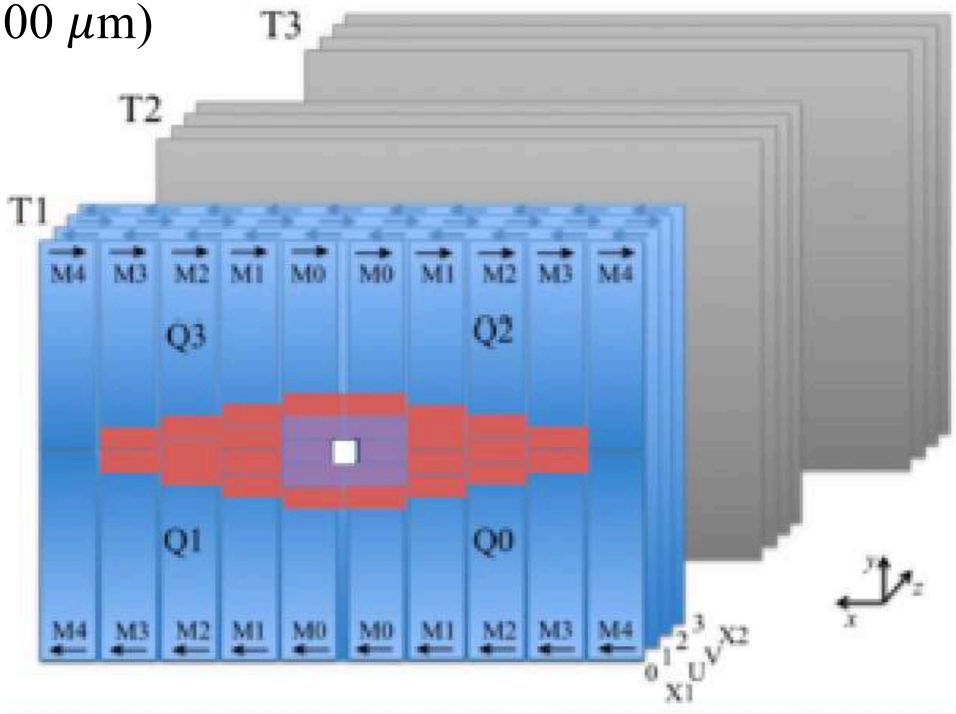
Two step process fitting into plan to already replace inner modules of Fibre Tracker in UIb

Inner Tracker: U1b

- Minimal modification of SciFi
- 6 layers of pixels (HV/CMOS)
- Relatively large pixels ok, (baseline 100 × 500 μm)
- Modified MuPix chip seems suitable
  - Engineering run Q4 2019
- Each layer 0.7 m^2 ~4 m^2 total
- Challenge: combined SciFi/Silicon modules to minimize material

Middle Tracker UII

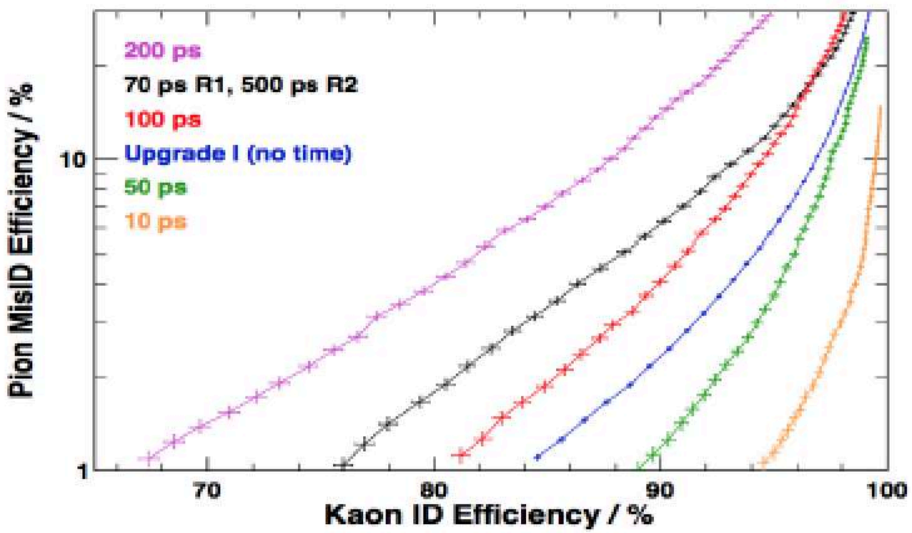
- Expand coverage of IT
- Each layer covers 3 m^2, 18 m^2 total



RICH

Evolution in U2:

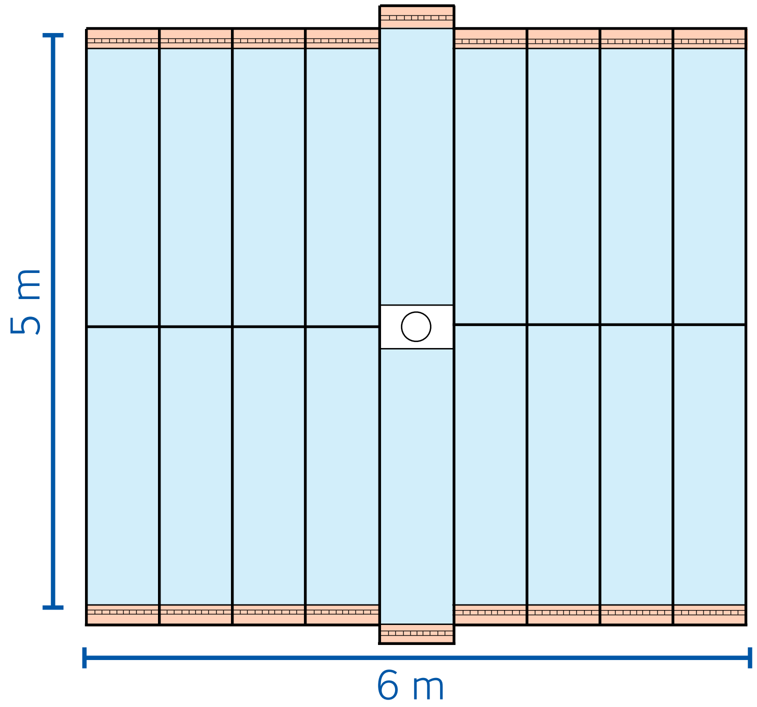
- Improved photodetectors:
- Reduced Pixel size
- Green peaked photocathode

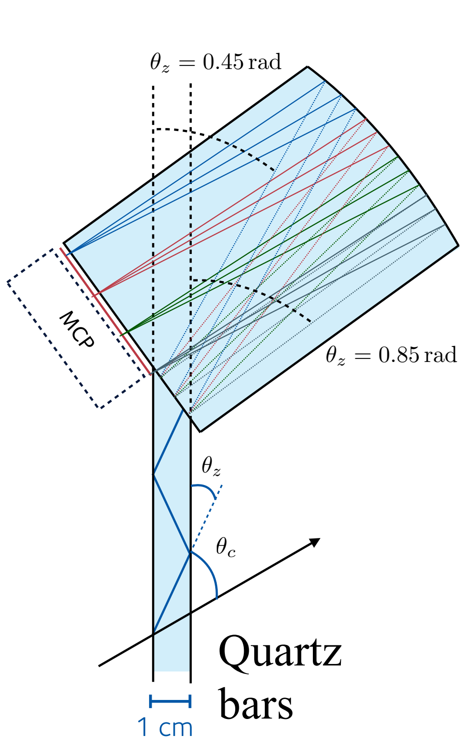


PID performance of the Upgrade I RICH detector with hit time information in the HL-LHC environment.

- Possible photo-detectors: MaPMTs, SiPMs, MCPs
  - e.g. SiPMs have 200 ps time resolution and good QE in green
- Performance improved with fast timing detectors (e.g. MCPs)

Future Upgrades: TORCH





Particle identification in 2- 10 GeV range (below Cherenkov threshold) using time of flight detector

Aim to achieve 15 ps resolution per track (70 ps per photon)

Fast timing using MCPs developed by UK company (Photek)

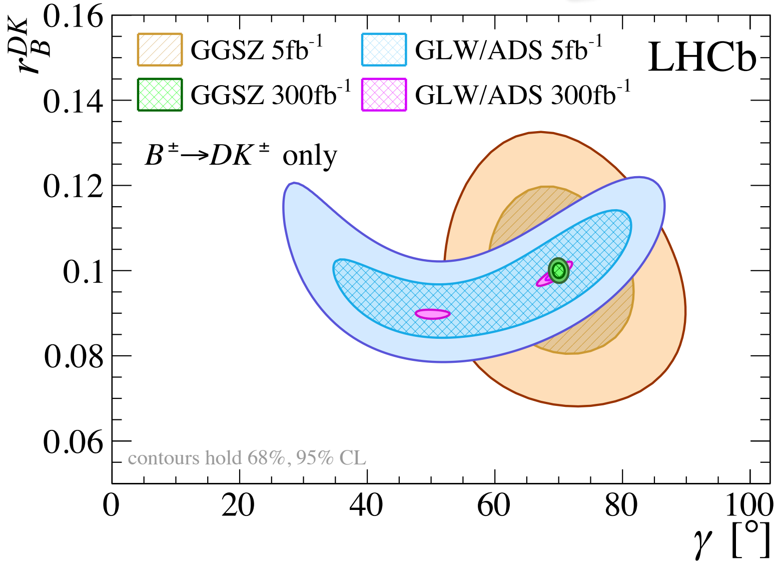
Computing

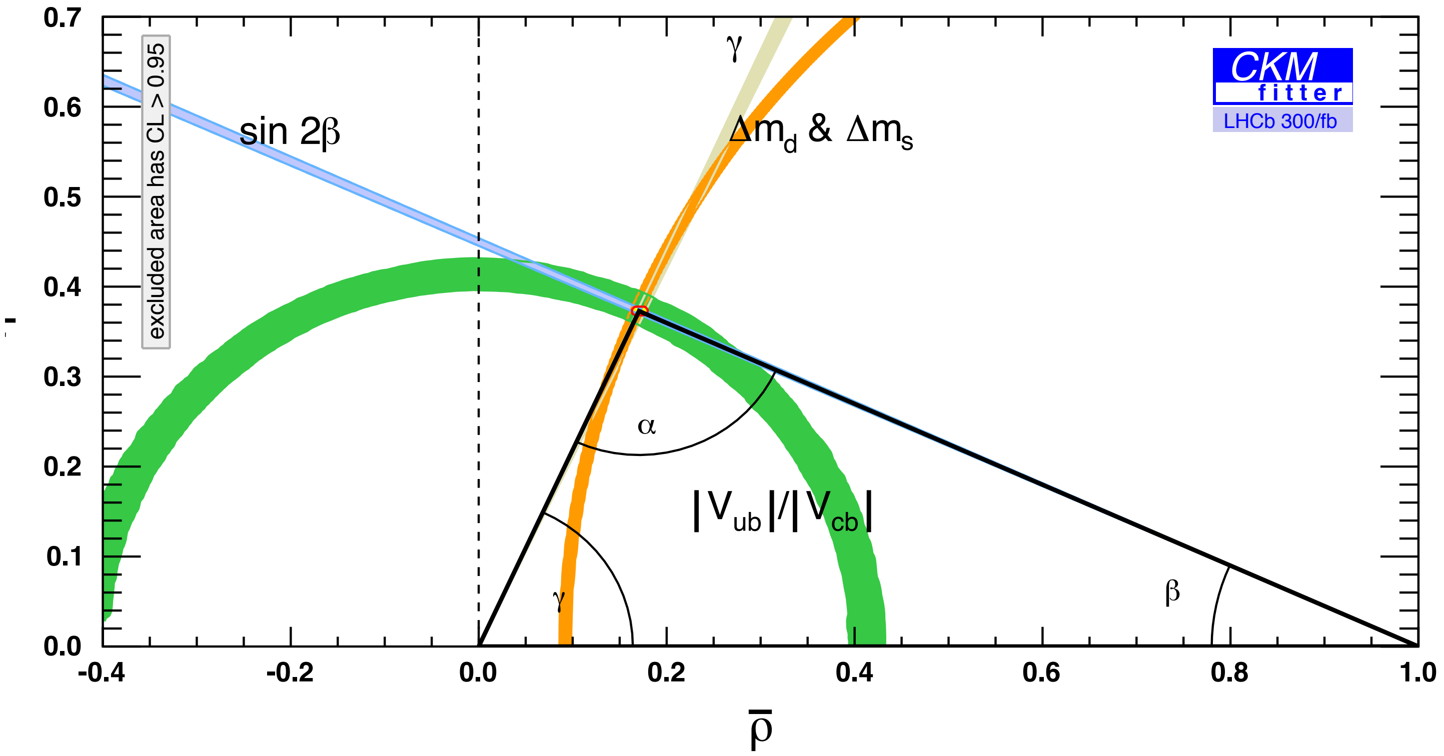
- Many interesting and challenging problems
- Triggering and reconstruction at 30 MHz
- 2500 tracks in the detector acceptance
- Data compression: picking the interesting features from events
- ….

UII Upgrade

What precision could be achieved on CKM matrix parameters with 300 fb^{-1} ?

e.g. $\sigma(\gamma) \sim 0.35^{o}$



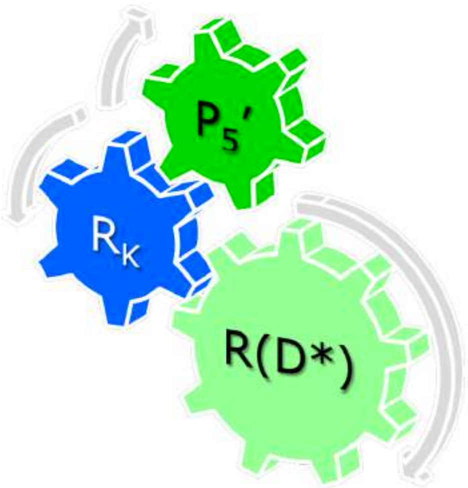


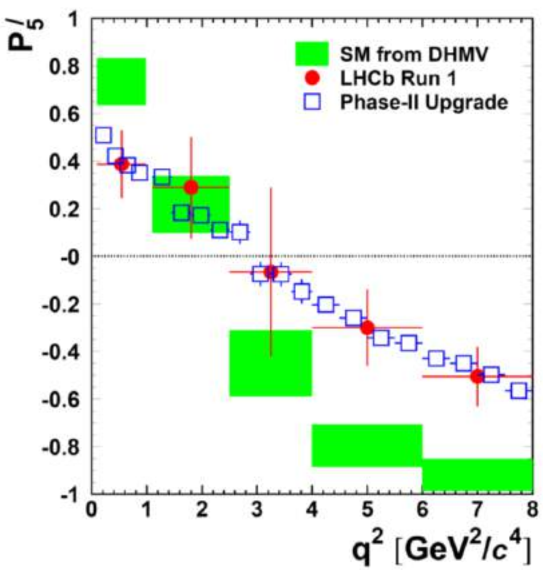
UII Upgrade

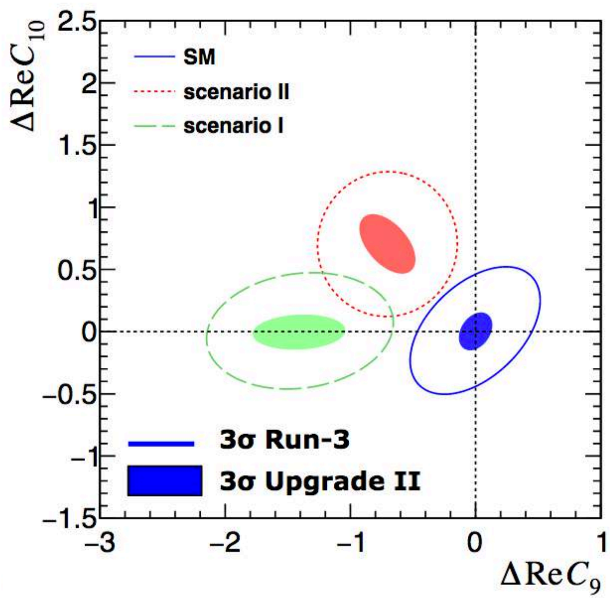
Situation with flavor anomalies will evolve rapidly in the next years

- New $R_{K,}$ $R_{K*,}$ R_{D*} and friends from LHCb
- Belle 2: $R_{K,}$ $R_{K*,}$ R_D, R_{D*}
- ATLAS/CMS LFU results to come ?

What would things look like with 300 fb^{-1}, which could be achieve in a LHCb UII upgrade







UII Upgrade

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	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 $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	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%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **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					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

9 fb^{-1} — Goal: 50 fb^{-1} — Goal: 300 fb^{-1}

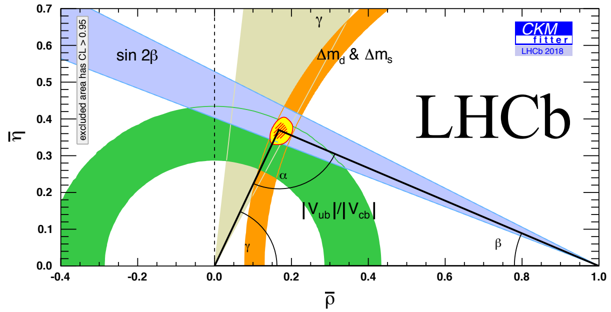
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025	2026 2027 2028 2029	2030	2031 2032 2033	2034	2035 2036 2037

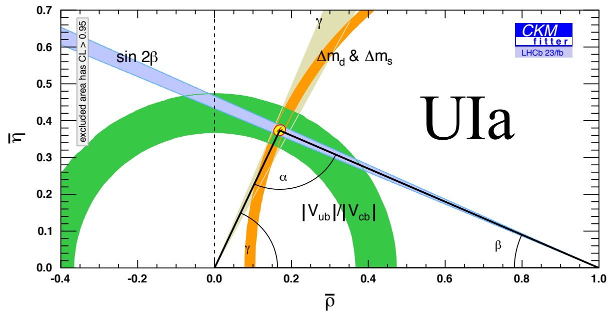
Upgrade I — Upgrade Ib — Upgrade II

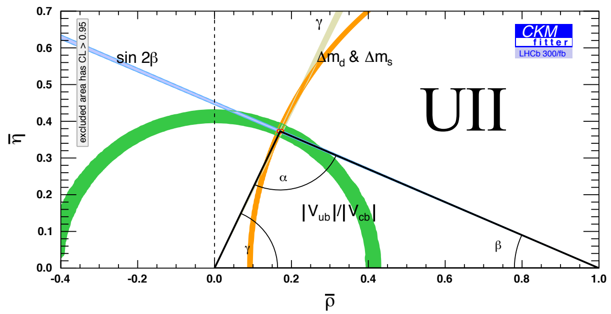
Belle II

Much to look forward to !

- Full exploitation of Run 1+2 dataset of LHCb, ATLAS and CMS
- Belle 2 has started to take data
- Installation of LHCb upgrade progressing well for running after LS2
- LHCb UII upgrade will take flavor physics program into the 2030s with unprecedented precision



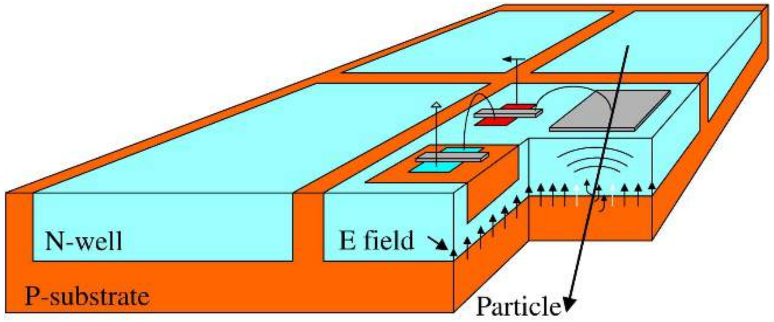


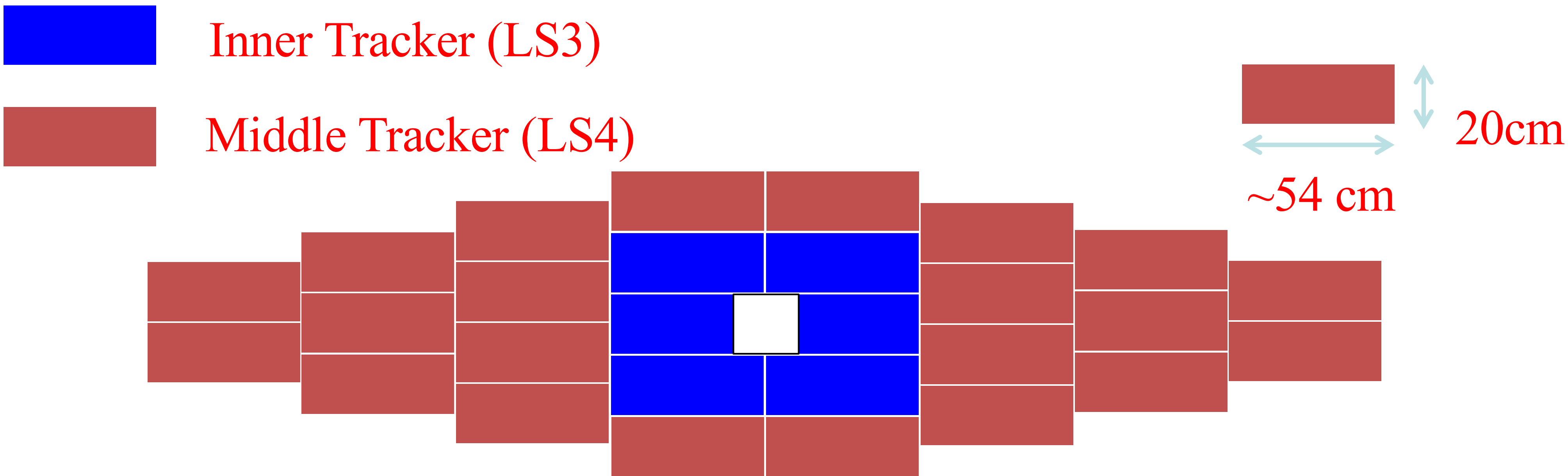


Backup

Mighty Tracker

- Emerging (HV) CMOS technology suitable for this detector
- Relatively large pixels ok, (baseline $100 \times 500\ \mu m$)
- Modified MuPix chip seems suitable
  - Engineering run Q4 2019

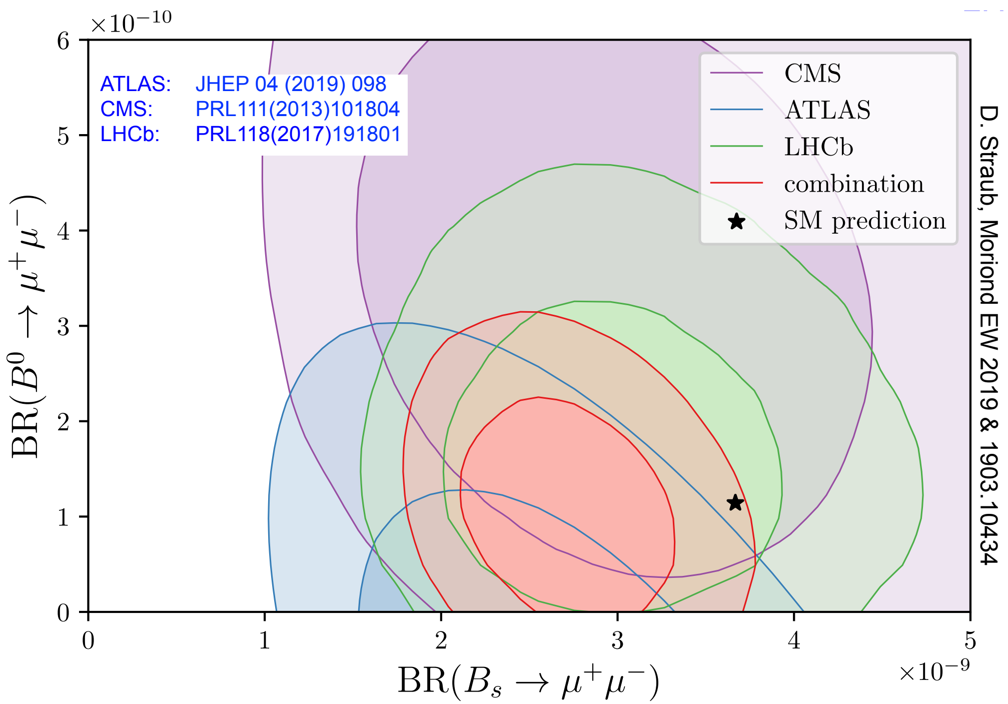




ATLAS + CMS

ATLAS and CMS still to publish results with full Run 1+2 datasets
$K^*\mu\mu$, $B_s \to \mu\mu$, ϕ_s

CMS collected sample of 10 billion events tagged as containing b-hadron
In 2018 and aim to target flavour anomalies



$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.7 \pm 0.4) \times 10^{-9}$$

~ 2 σ below SM

Recent CMS update (data till 2016)

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9^{+0.7}_{-0.6} \pm 0.2) \times 10^{-9}$$

Interesting to follow, with full LHC dataset