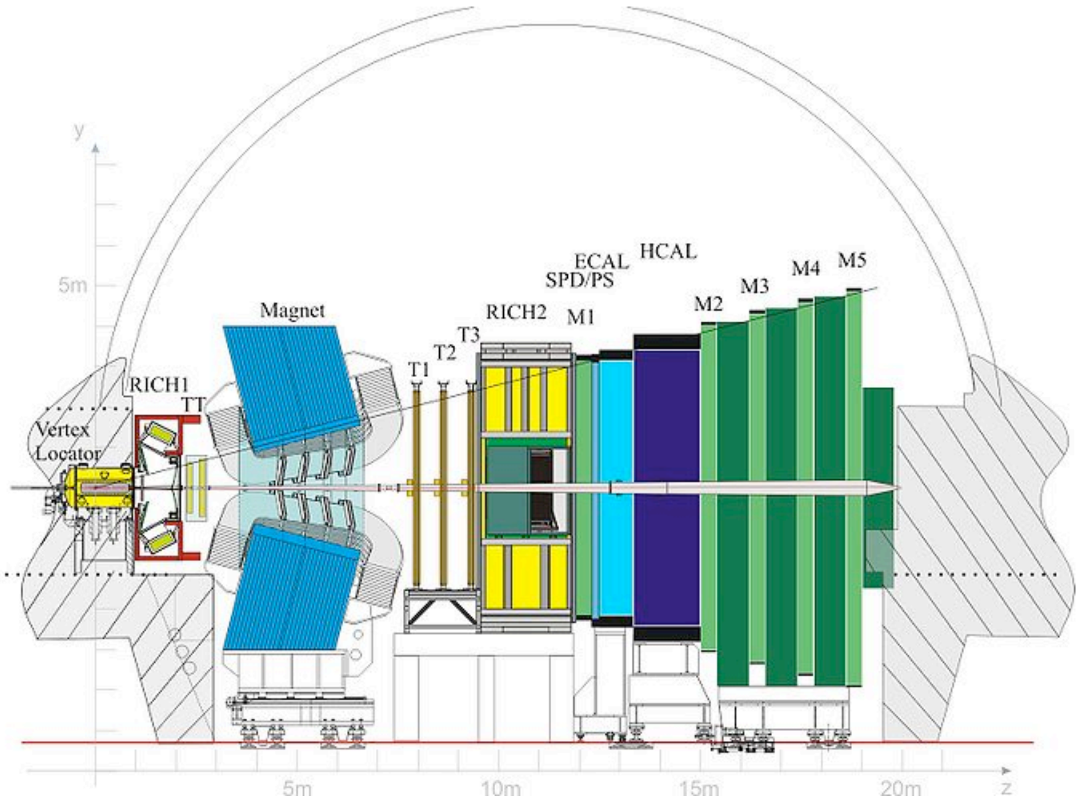
Everything* you wanted to know about LHCb but were afraid to ask



* Disclaimer: OK not EVERYTHING.

Sneha Malde
LHCb Collaboration

New physics

Historically many “New Physics” (of the time) discoveries have been made by flavour physics

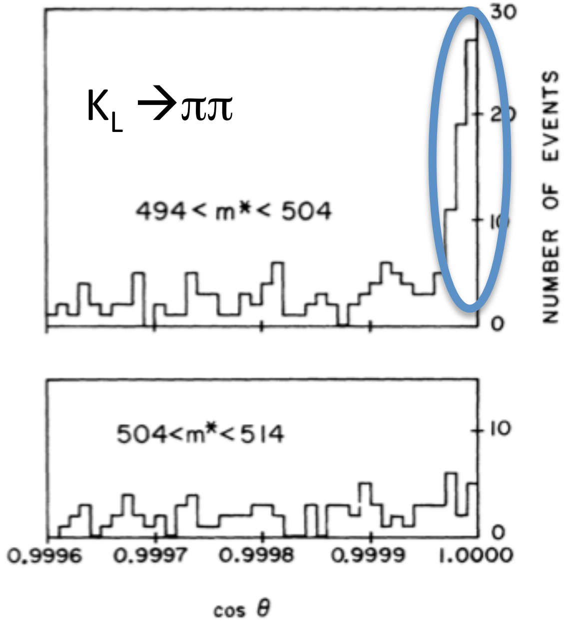
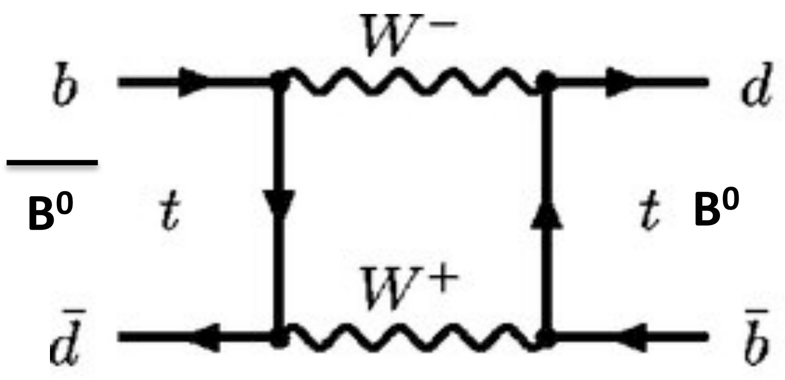


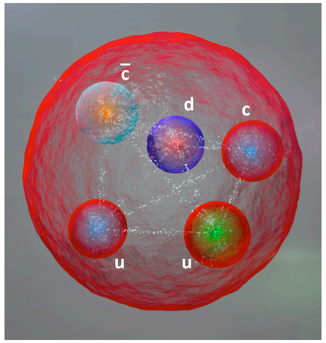
FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

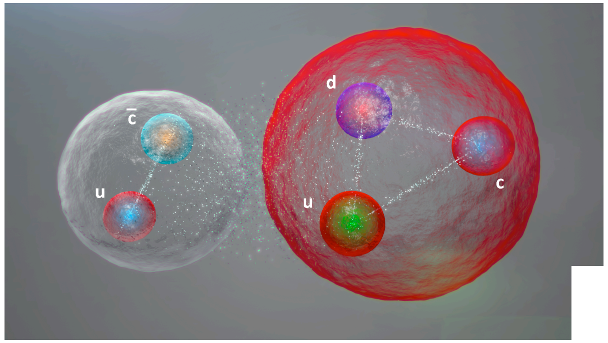
Entirely unexpected discoveries can lead to profound changes in understanding



- Observation of B^0 mixing in 1987
- Implied that m_t > 50 GeV
- Top eventually discovered in 1995 with mass ~175 GeV
- Low energy phenonmena is sensitive to heavy particles

Still plenty to learn about QCD

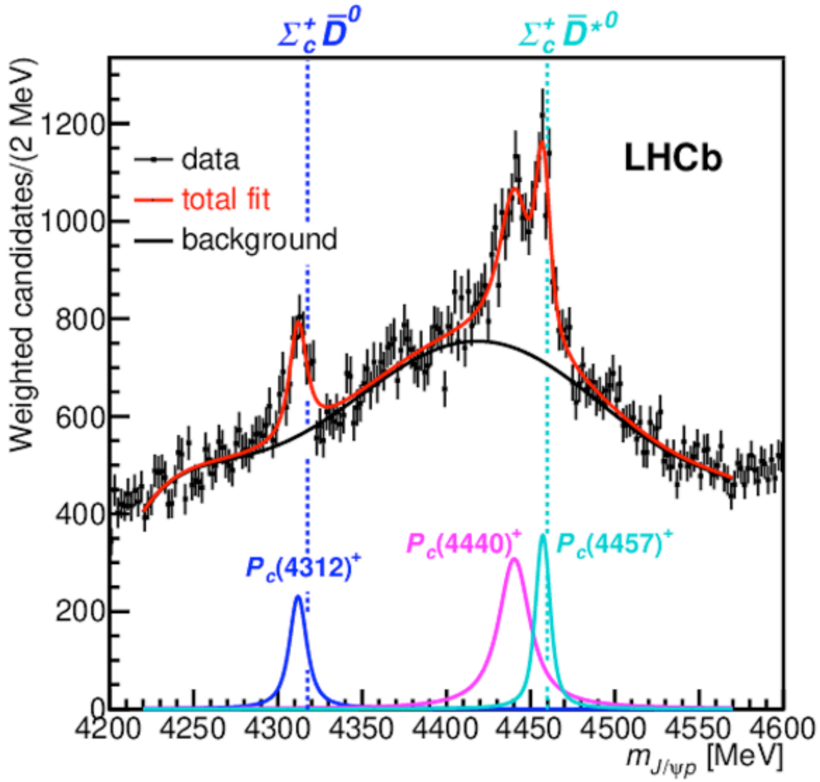




The Pentaquarks are found just below threshold by amounts that are plausible hadron-hadron binding energies.

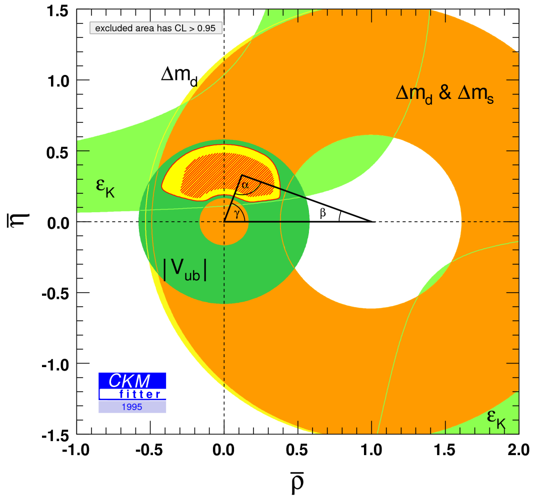
They are narrow.

While it points to the molecular interpretation further experimental and theoretical required to confirm this.

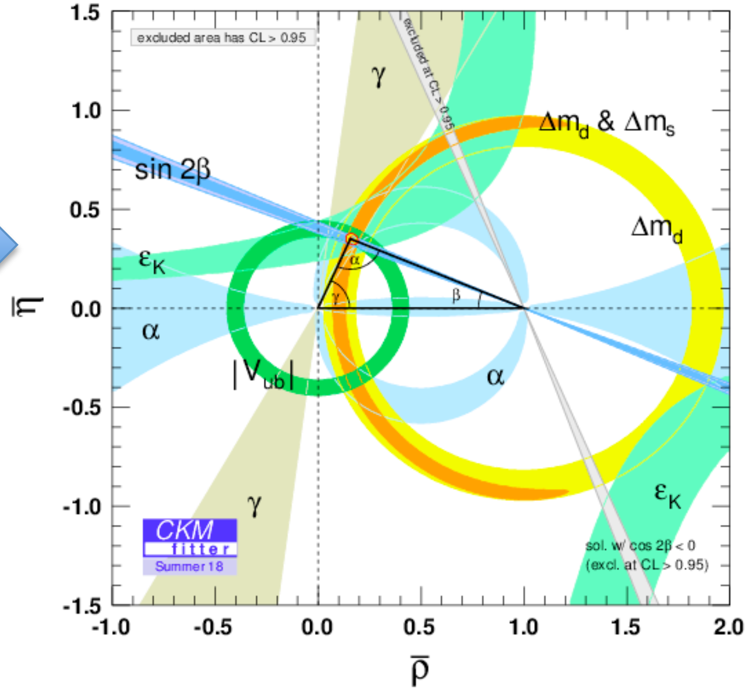


CP violation

1995



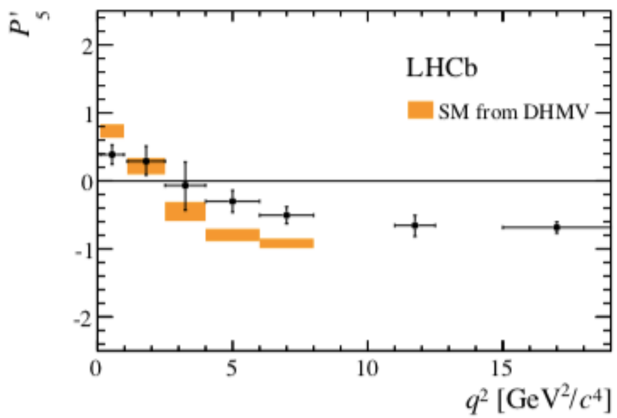
23 years work

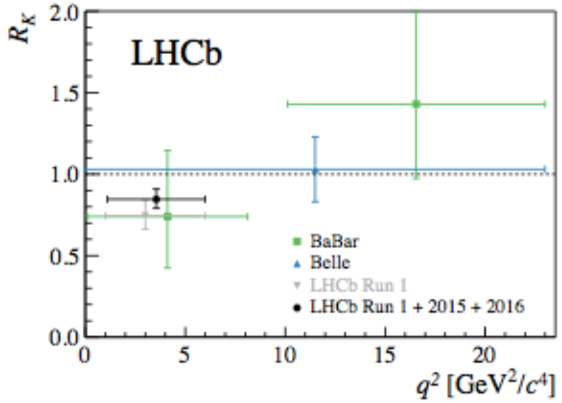


Every thing remain consistent with the SM picture
How does that relate to other information which tells us that NP must exist?

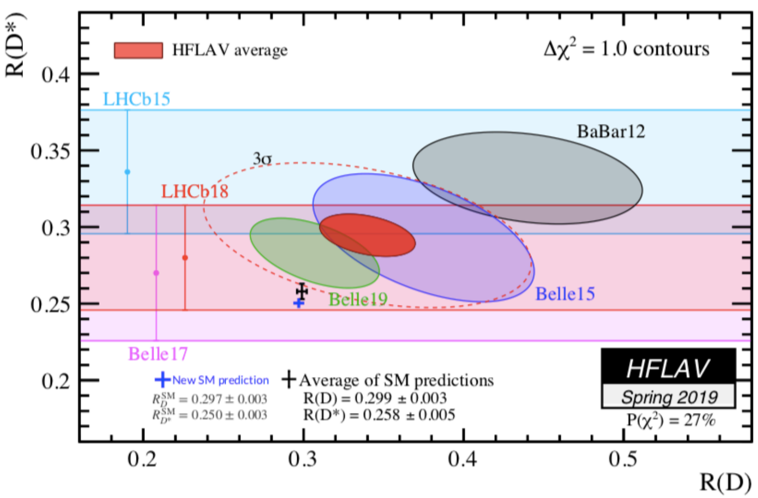
Flavour anomalies

Currently a few results are in tension with the Standard Model

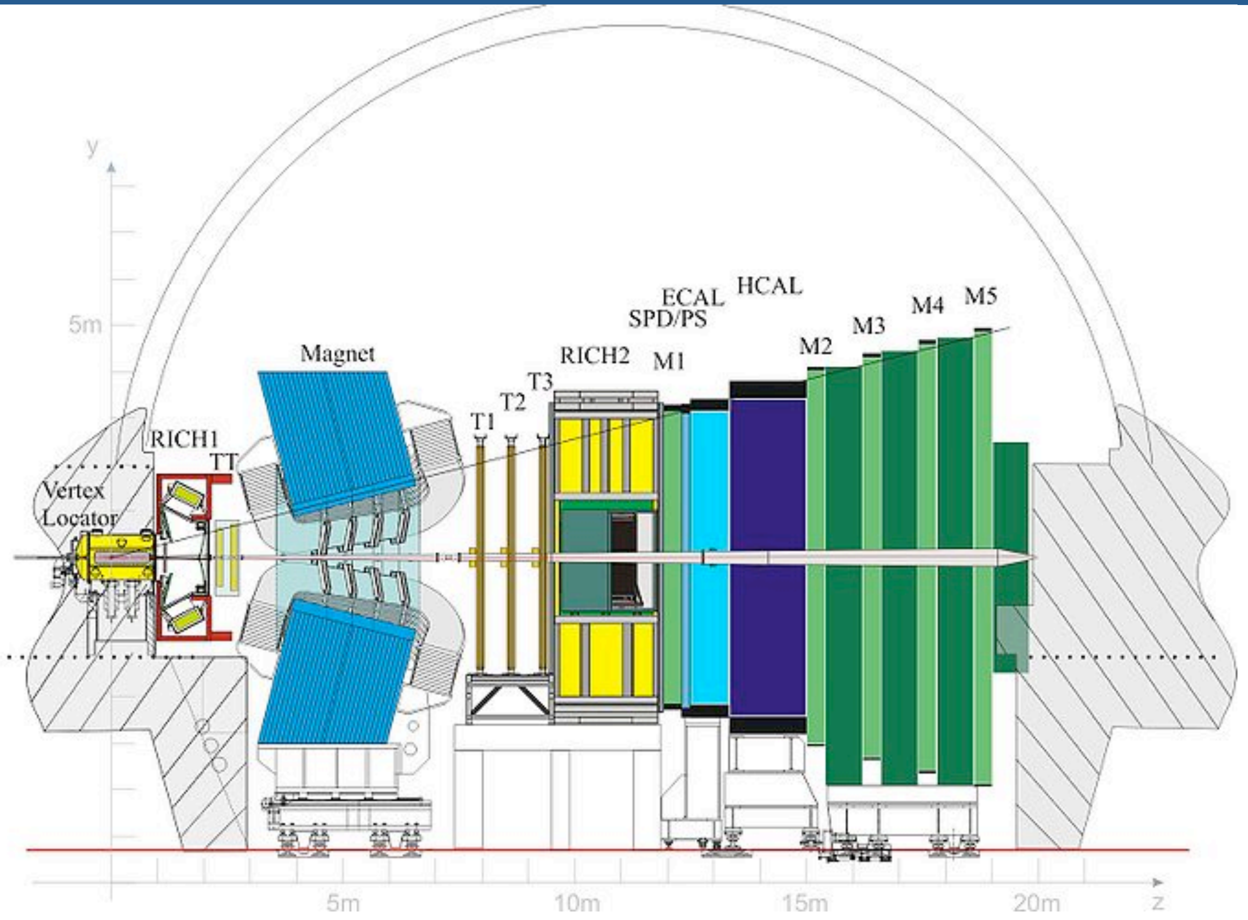




Are these anomalies here to stay?

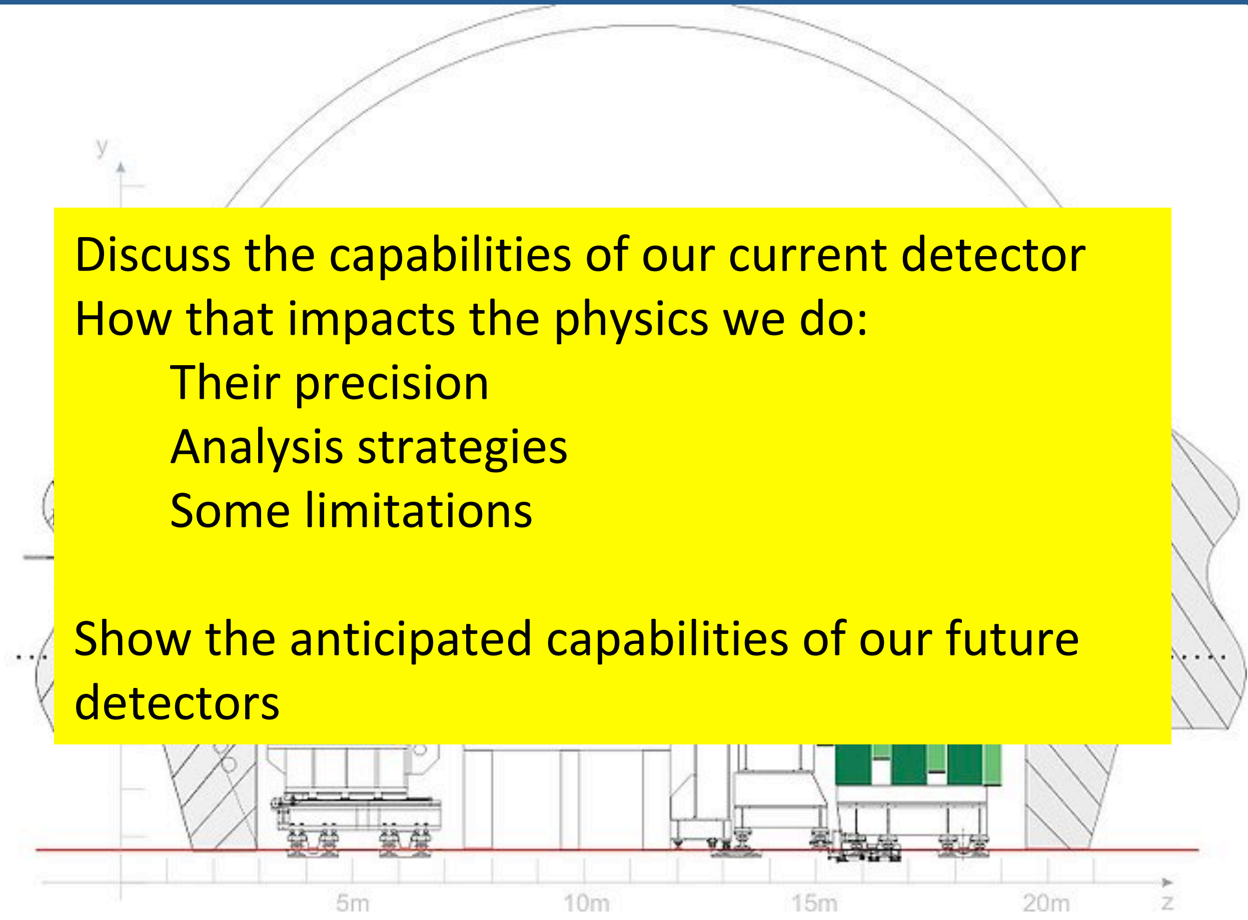


LHCb



"LHCb is a forward-arm spectrometer optimized for doing B-physics"

LHCb



Discuss the capabilities of our current detector

How that impacts the physics we do:

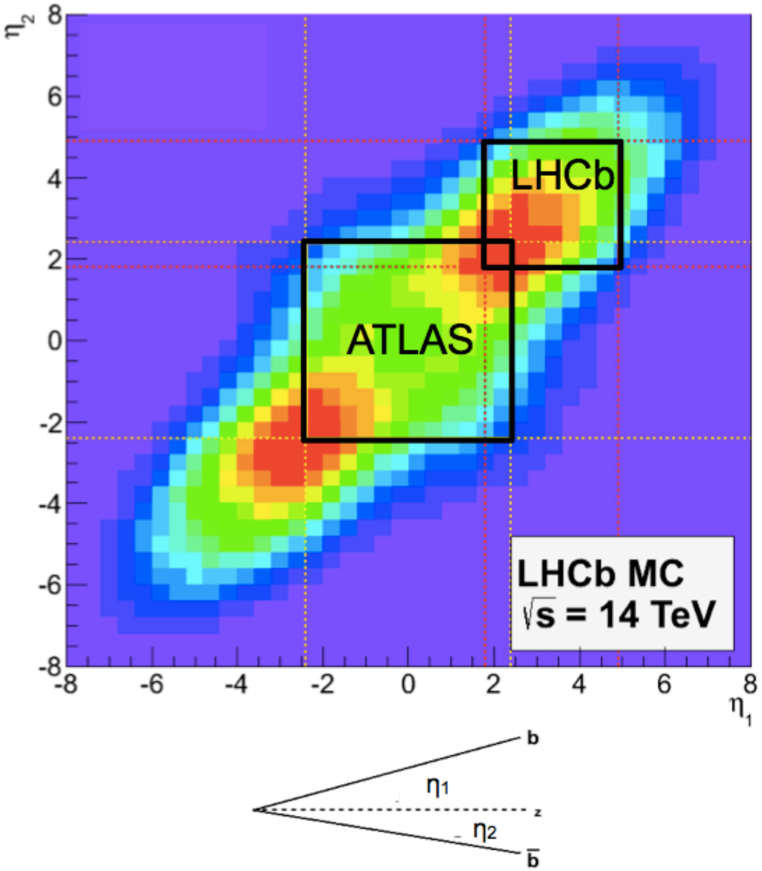
- Their precision
- Analysis strategies
- Some limitations

Show the anticipated capabilities of our future detectors

"LHCb is a forward-arm spectrometer optimized for doing B-physics"

Production

$b\bar{b}$ production



The majority of $b\bar{b}$ pairs are produced in the forward direction.

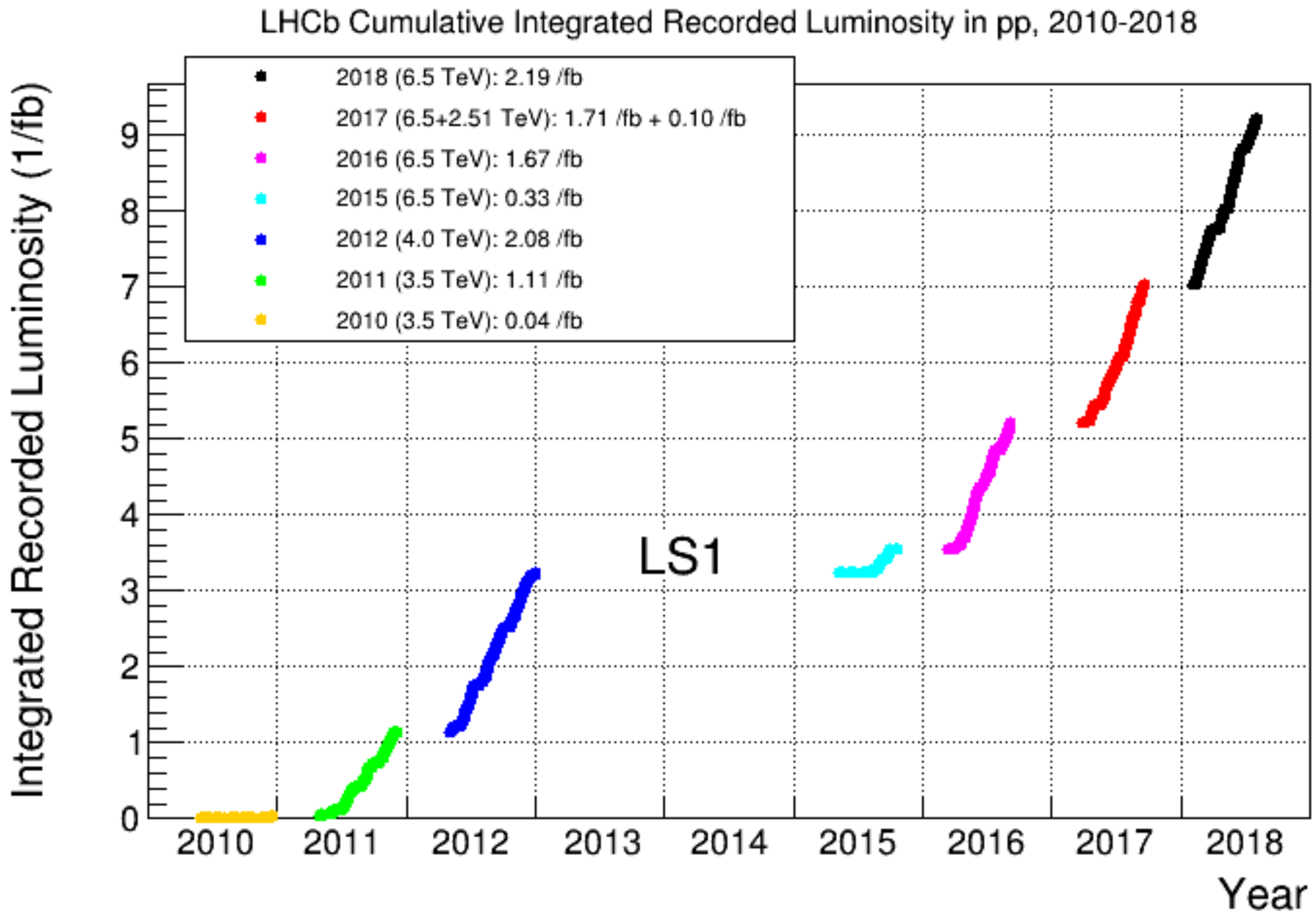
1.4 x 10^{11} $b\bar{b}$ pairs per fb^{-1} (Run2)

Our detector is instrumented in $2<\eta<5$

All species produced
B^+ B^0 B_s B_c Λ_b Σ_b ⋯
+ charm
+ strange

+ all the ones we are yet to observe

Data sets



Run 1 ~ 3fb @ 7, 8 TeV
Run 2 ~ 6fb @ 13 TeV

Data sets

Rules of thumb for scaling yields :

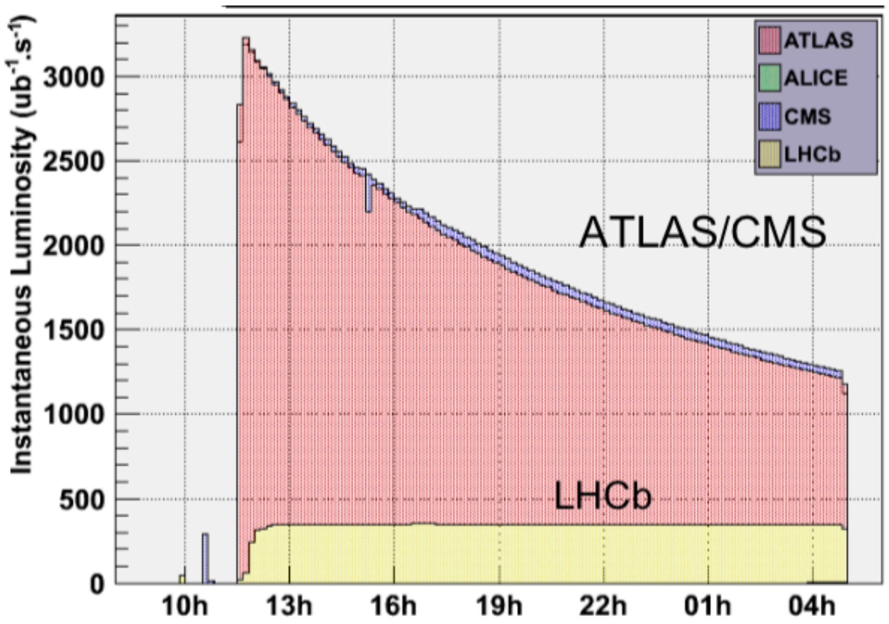
Due to cross section increase and trigger changes

N_{2011→2018} ~ 6x N_{2011 →2012}

N_{2011→2018} ~ 2x N_{2011→2016}

Data on tape: $9fb^{-1}$
Run 1 ~ 3fb @ 7,8 TeV
Run 2 ~ 6fb @ 13 TeV

Luminosity levelling



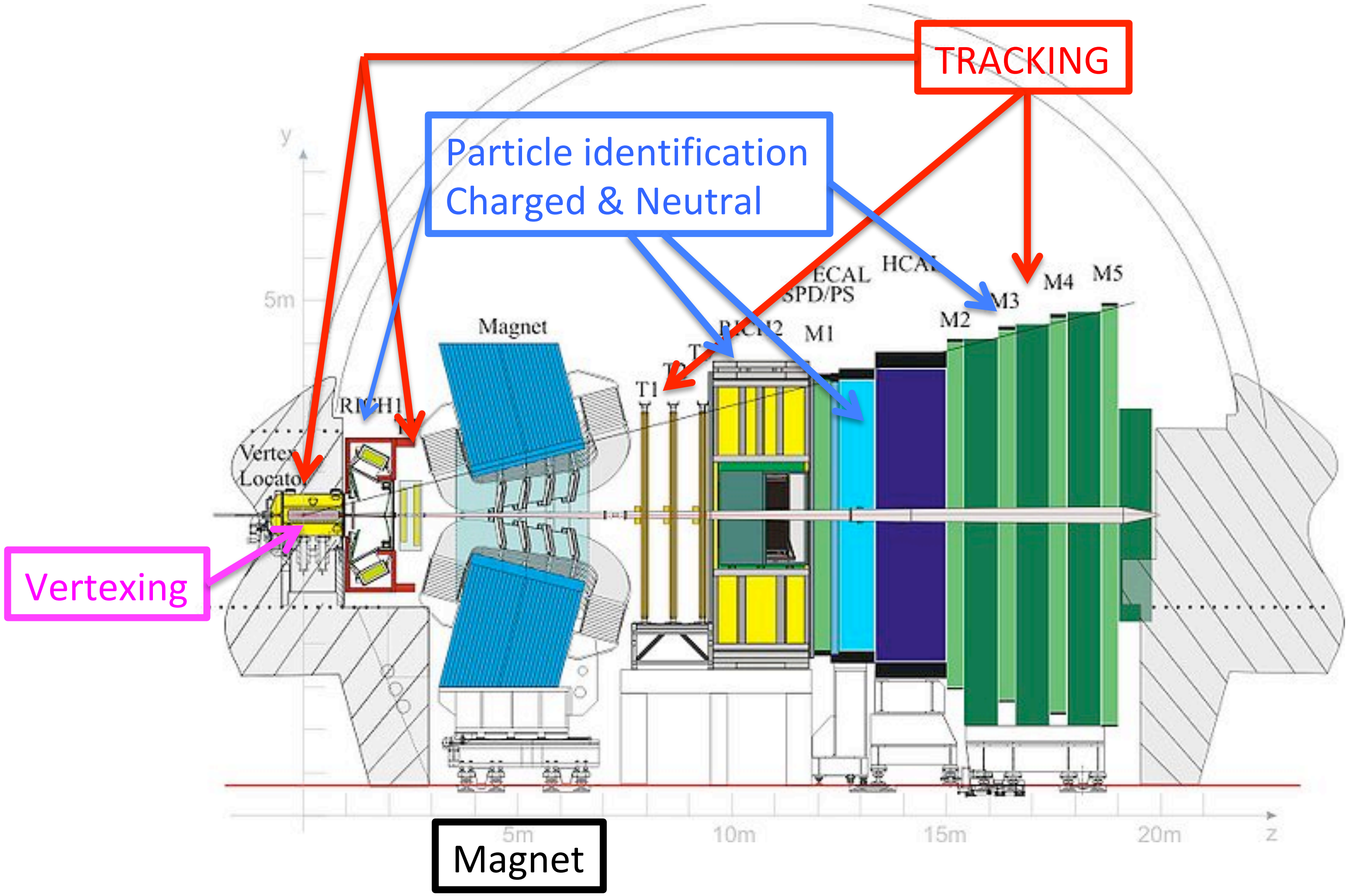
Operate at continuous luminosity

Beams are displaced and brought together as the proton concentration decreases.

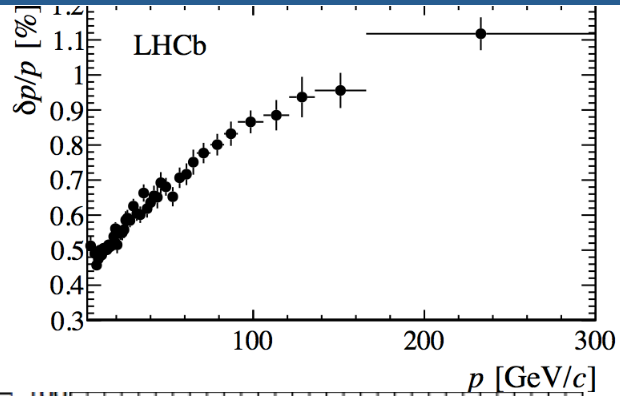
Rate chosen to give ~1 pp collision per bunch crossing.

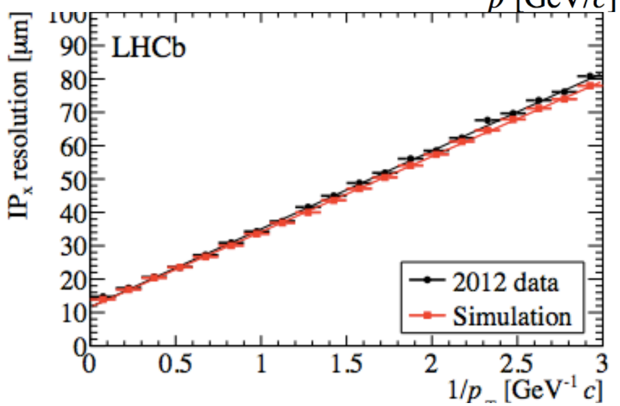
- Operational stability
- Constant trigger rates
- Constant multiplicity → constant detector performance
- Less integrated luminosity collected

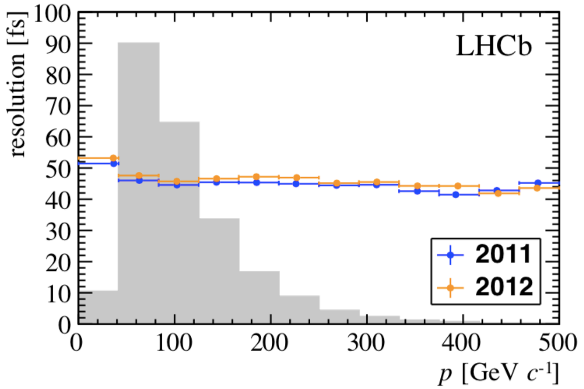
The detector



Tracking performance





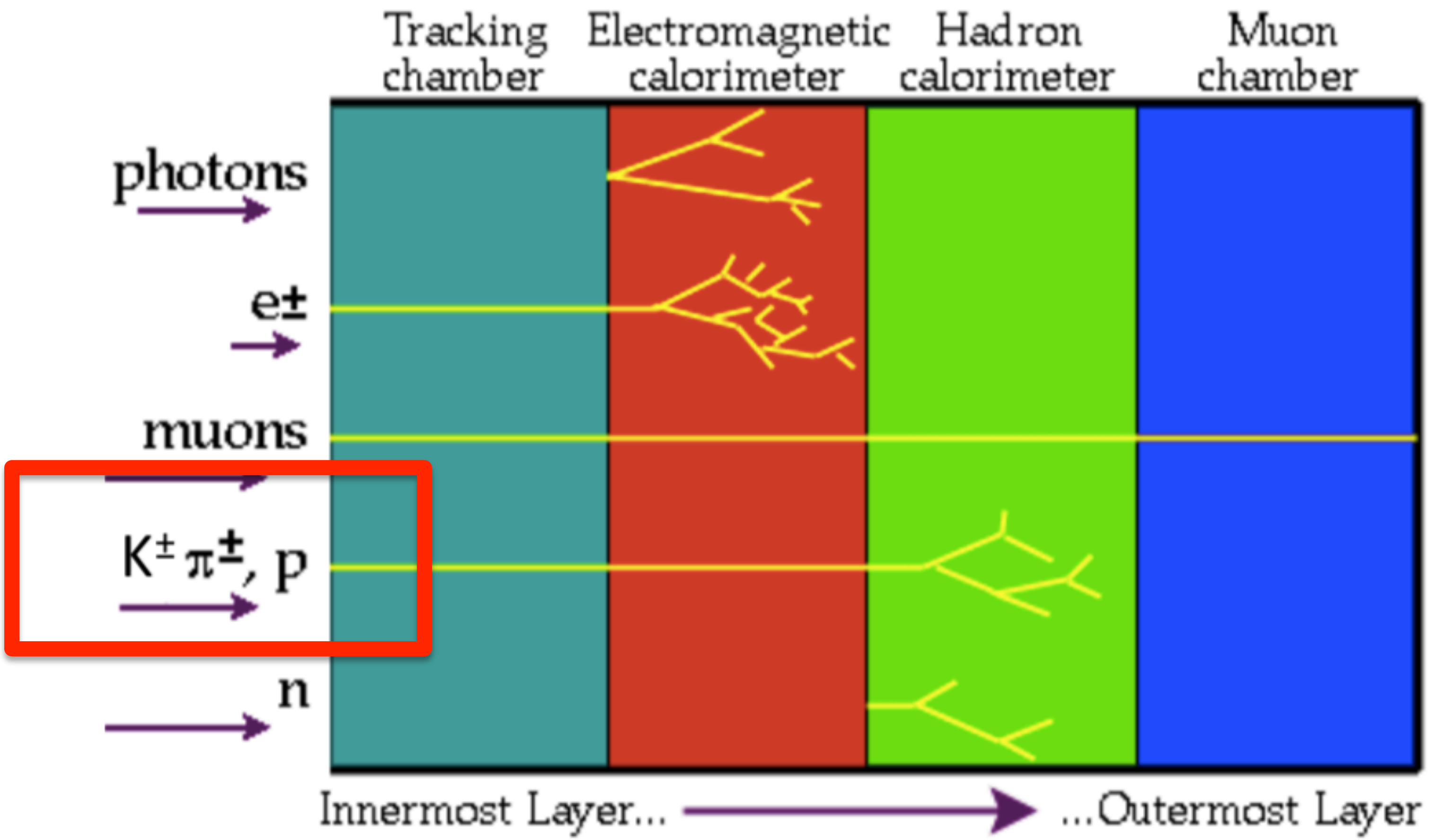


- Magnet bends the charged tracks allowing for momentum measurement
- Resolution is ~ 0.6%
- Find tracks that don't originate from the proton collision
- Typical resolutions IP ~ 40 microns
- Decay time resolution of a secondary vertex is ~ 50 fs

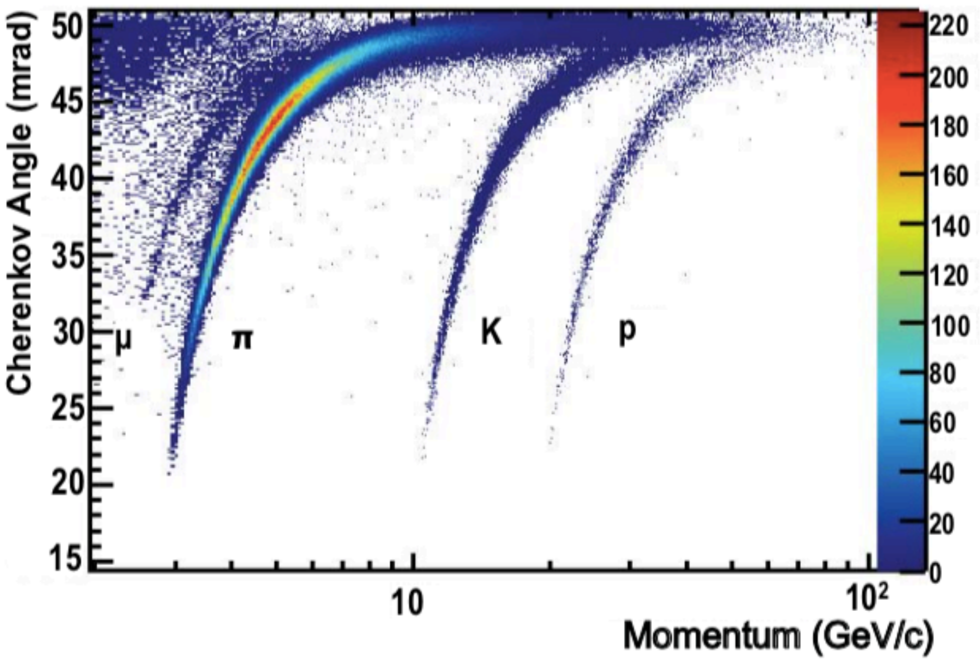
arXiv:1412.6352

Int. J. Mod. Phys. A 30, 1530022 (2015)

Charged hadron identification

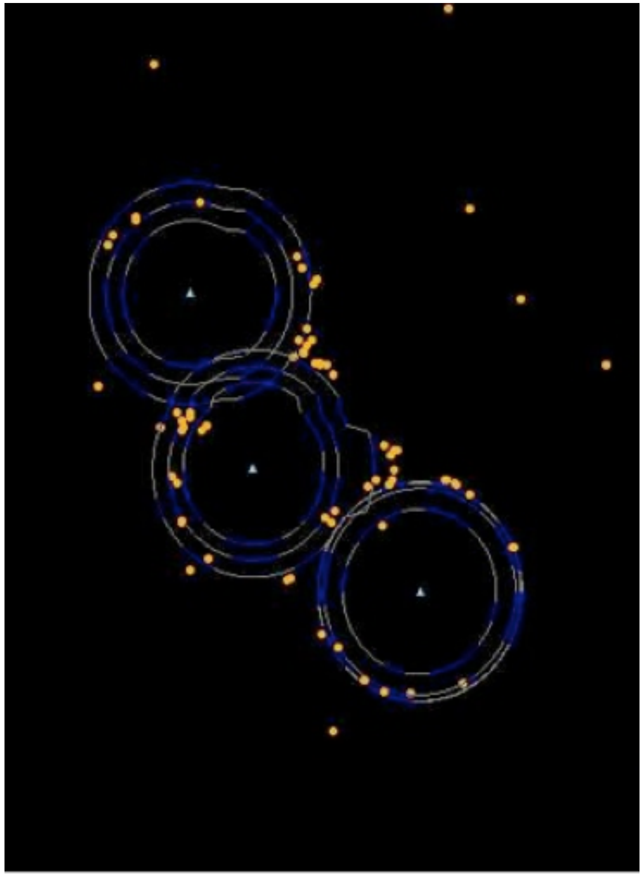


RICH detectors



The RICH detectors use the properties of Cherenkov radiation to separate the particles

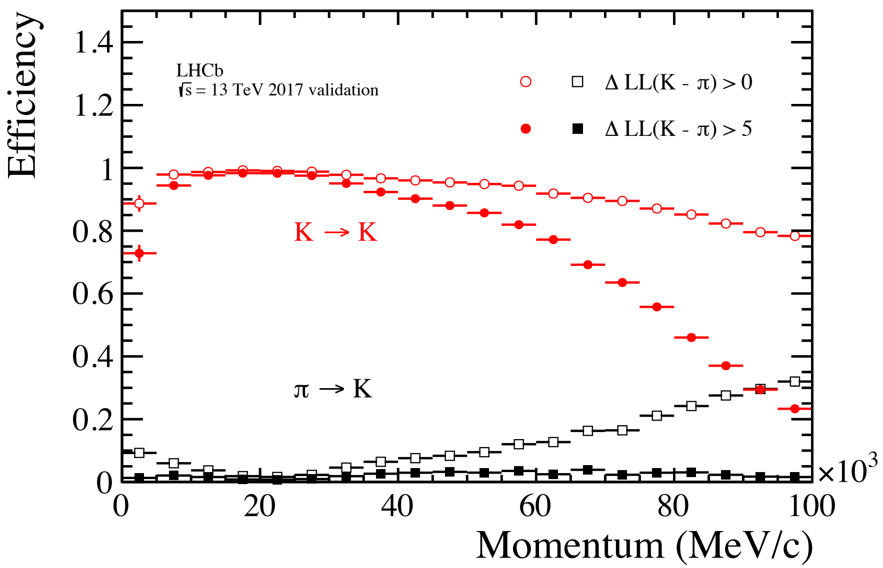
$$\cos\theta_C = \frac{1}{n\beta} = \frac{1}{n}\sqrt{1+\left(\frac{m}{p}\right)^2}$$

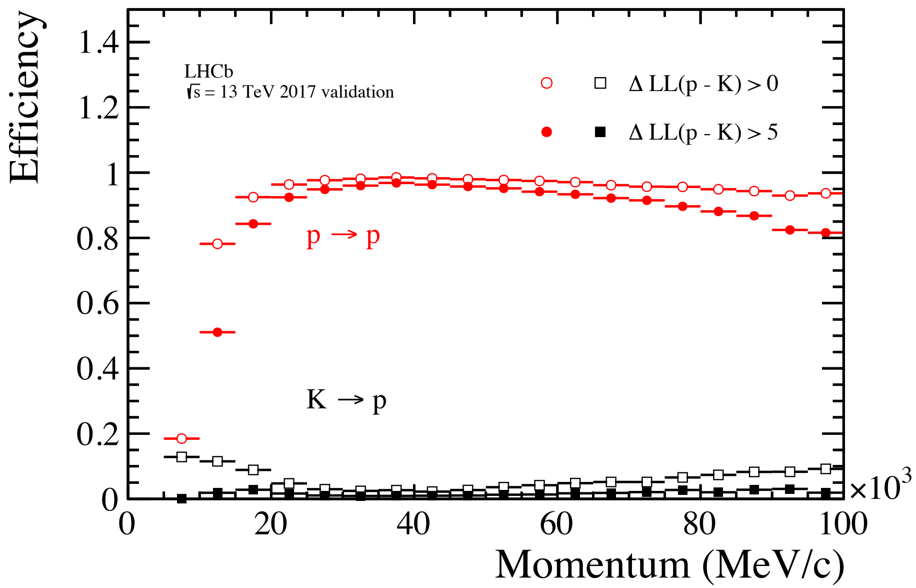


some of the first reconstructed RICH rings

Int. J. Mod. Phys. A 30, 1530022 (2015)

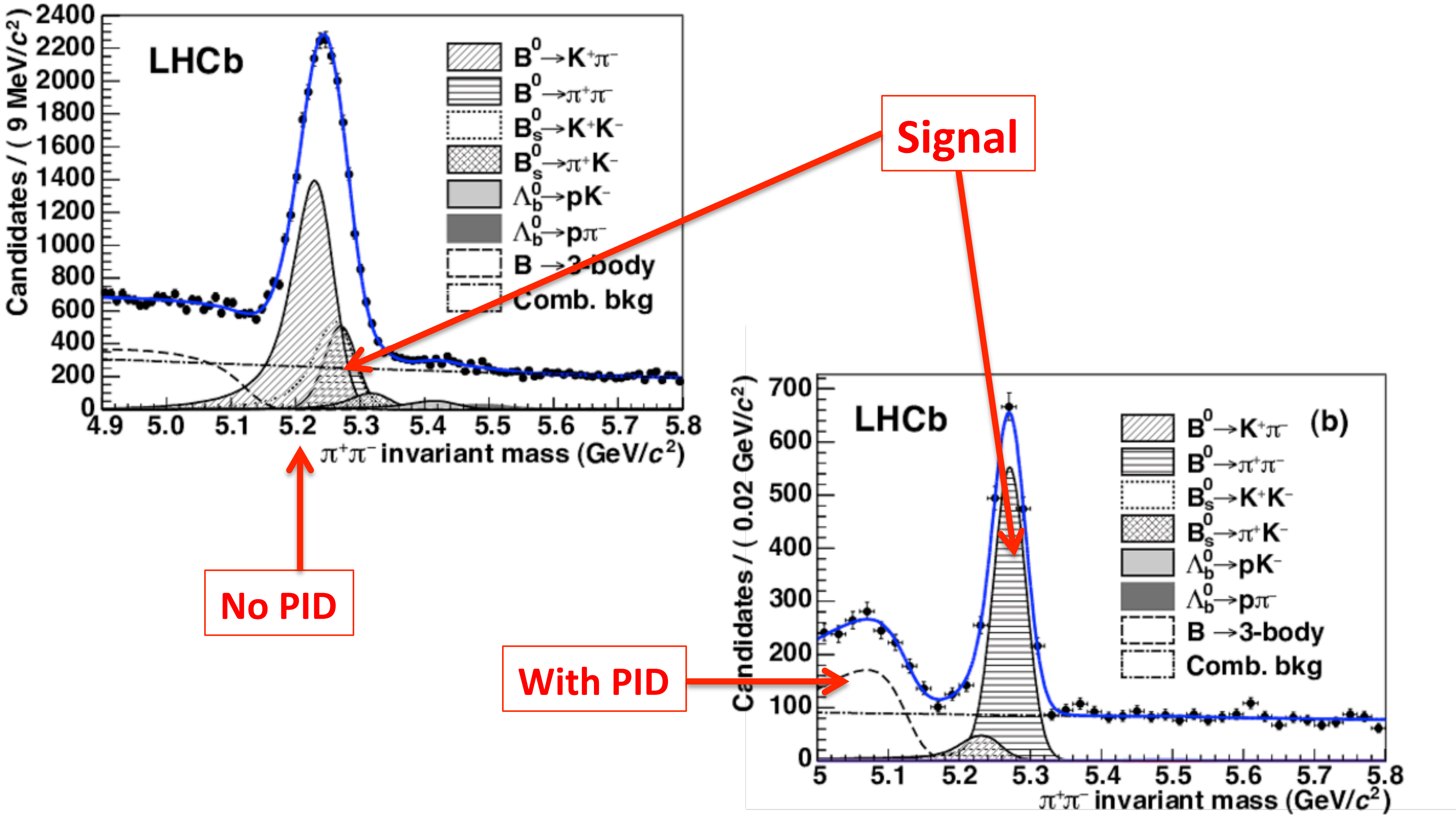
Hadron PID performance





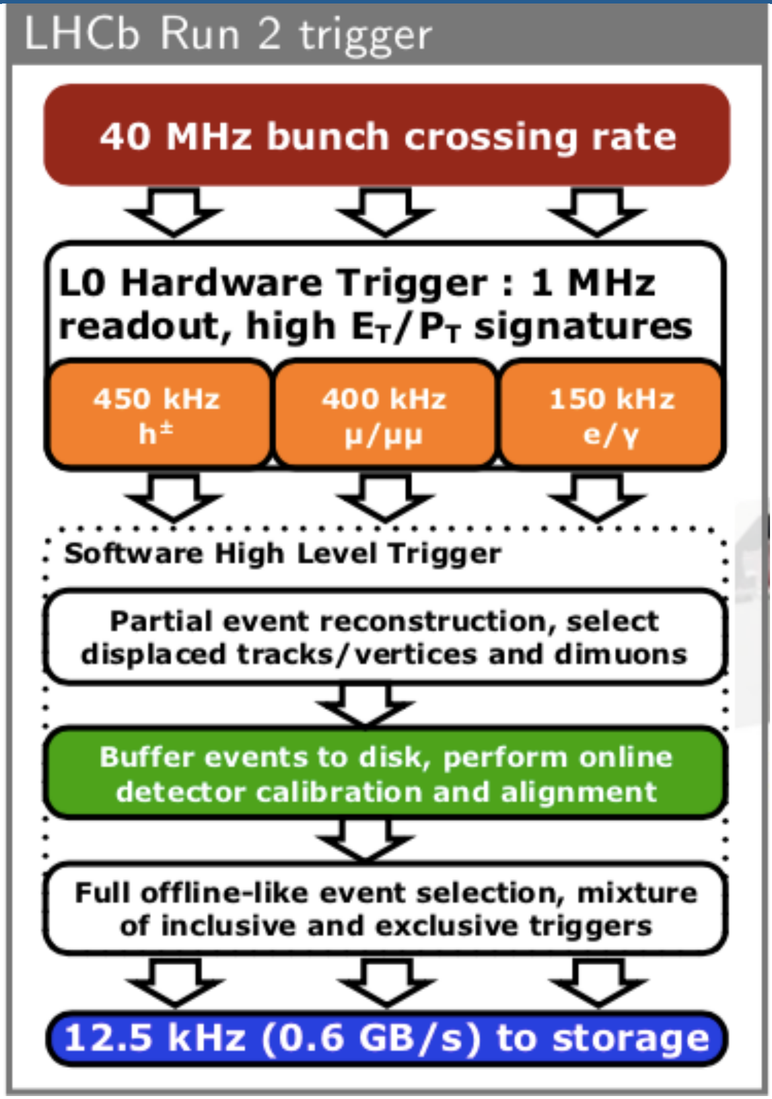
Can maintain high efficiency for low mis-ID rates

Impact of hadron PID



JHEP 1210 (2012) 037
arXiv:1206.2794

Trigger



Flexible trigger system

Low thresholds : e.g P_T (μ) > 1.8 GeV

Allows for hadronic decay triggering

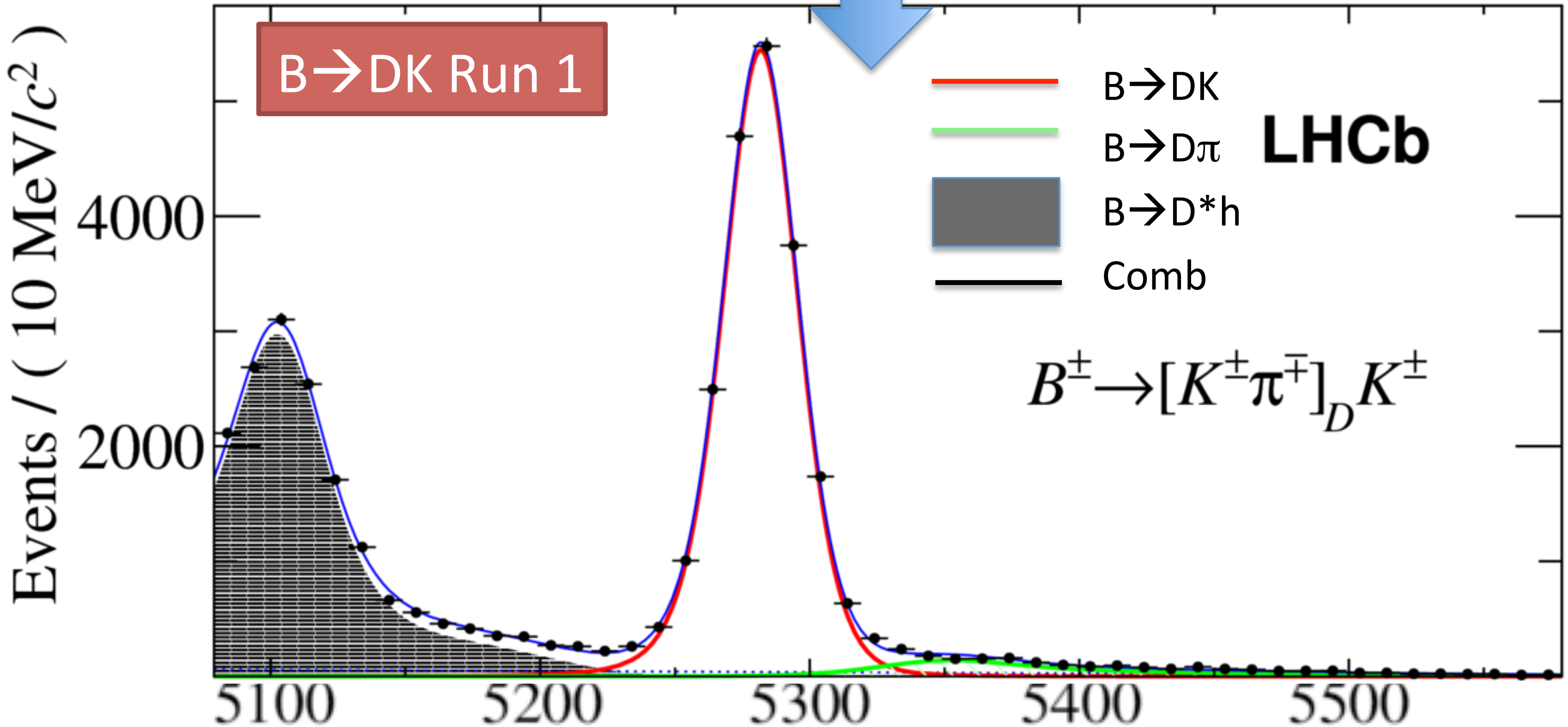
Calibrations and alignment run online

Many exclusive selections

An example of data

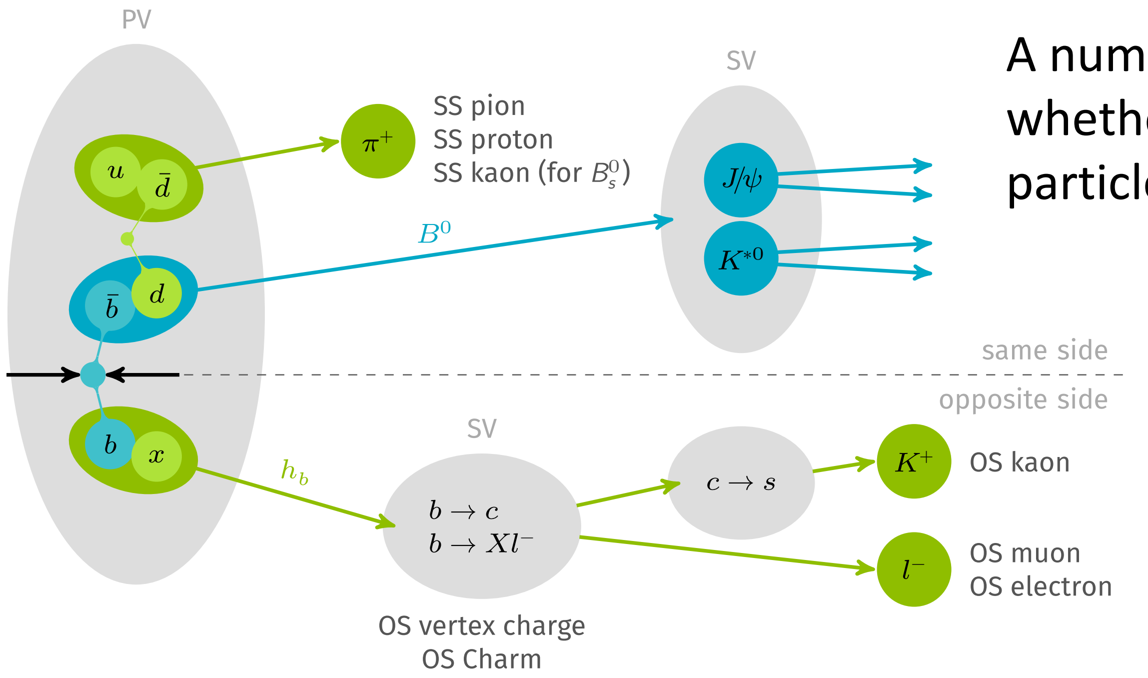
- IP, decay time resolution
- Momentum resolution
- Hadron PID
- Trigger

Mass Res: 15 MeV



Phys. Lett. B760 (2016) 117

Flavour Tagging



A number of algorithms to determine whether a neutral B meson is a particle or anti-particle at production.

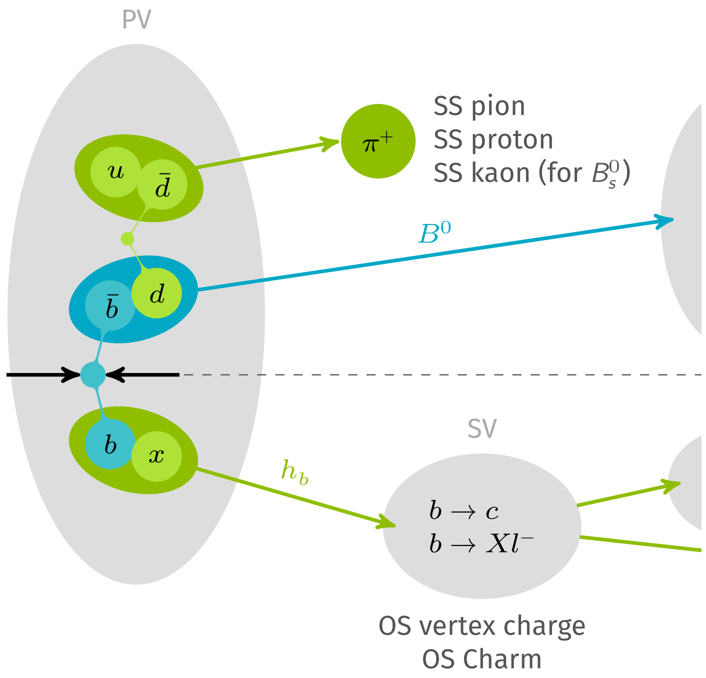
Effective tagging power, ε is determined

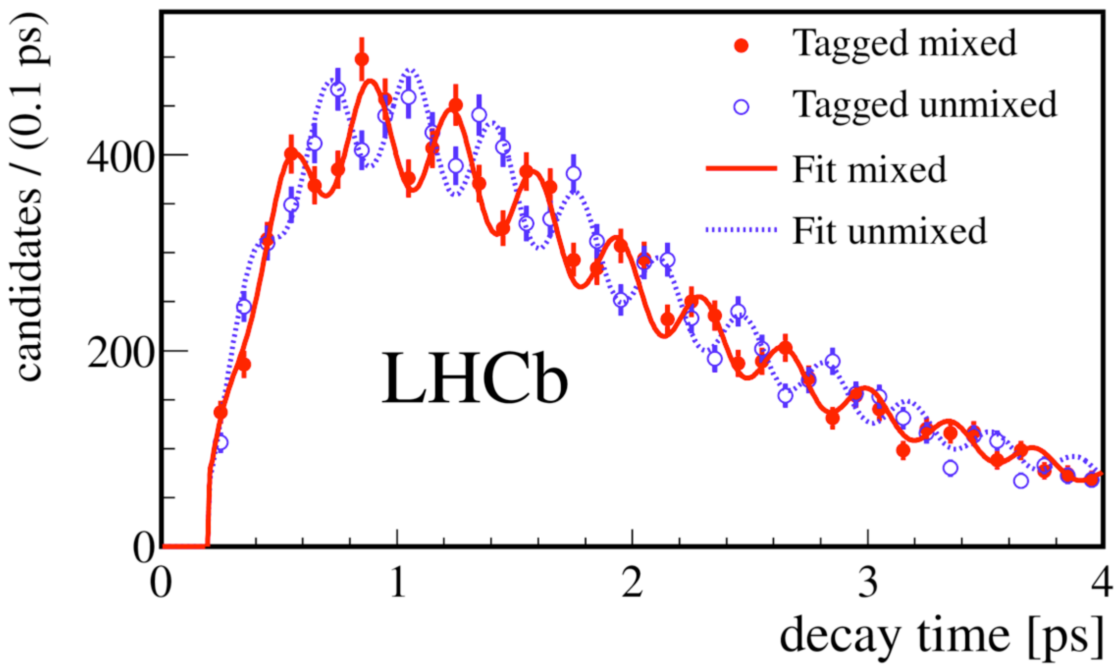
Uncertainty on time-dependent asymmetries

$\sigma \sim 1/\sqrt{(\varepsilon N)}$

Decay mode	ε	Reference
$B^0 \to D^+D^-$	8.1 ± 0.6 %	PRL 117 261801 (2016)
$B^0 \to D^* \mu\nu X$ (2012)	2.46 ± 0.04 %	EPJC 76 412 (2016)
$B_S \to J/\Psi KK$	4.73 ± 0.034 %	EPJC 79 (2019) 706

Flavour Tagging





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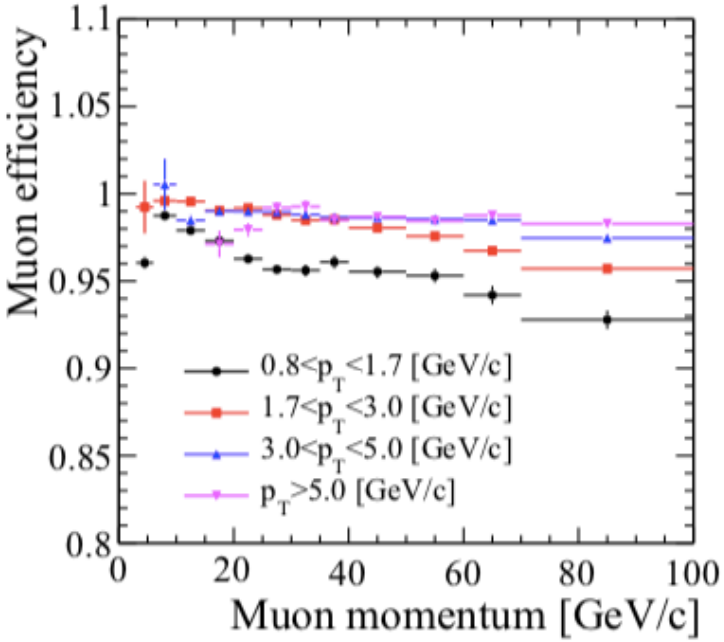
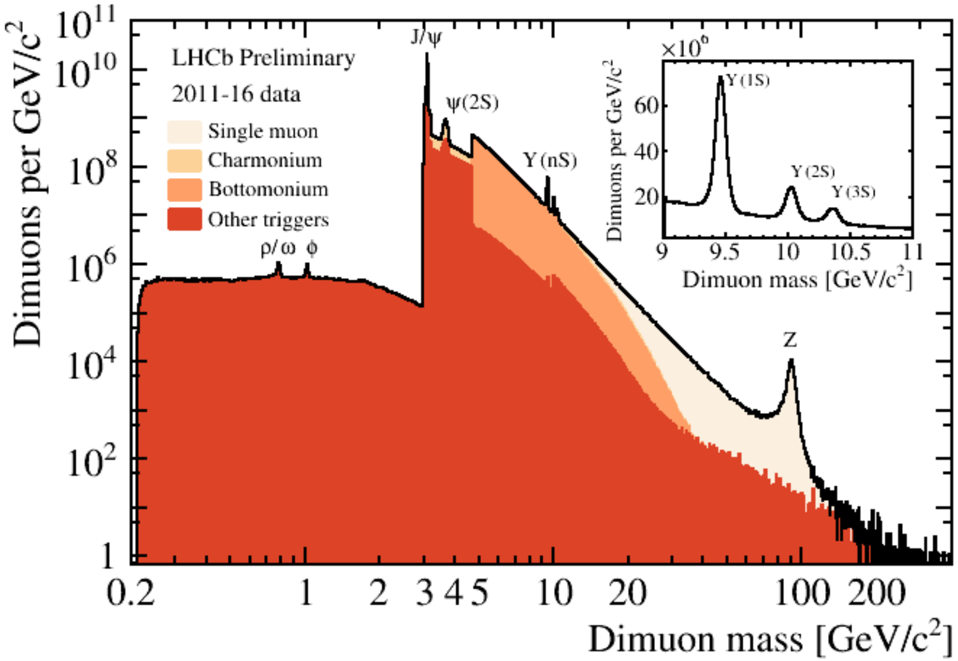
Charged lepton identification (μ)

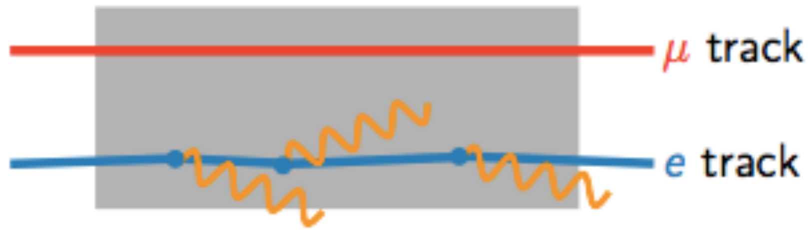
Muons traverse the full detector. High identification efficiency.

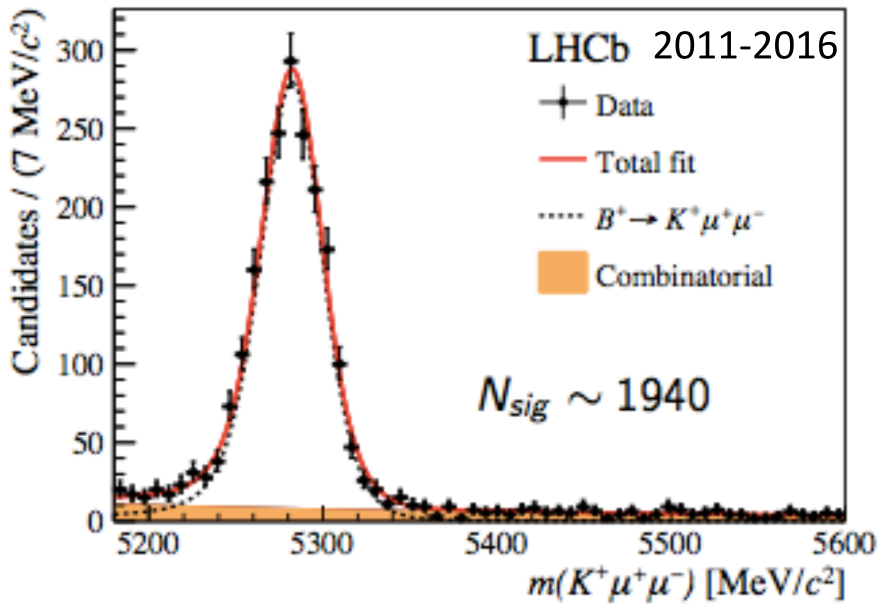


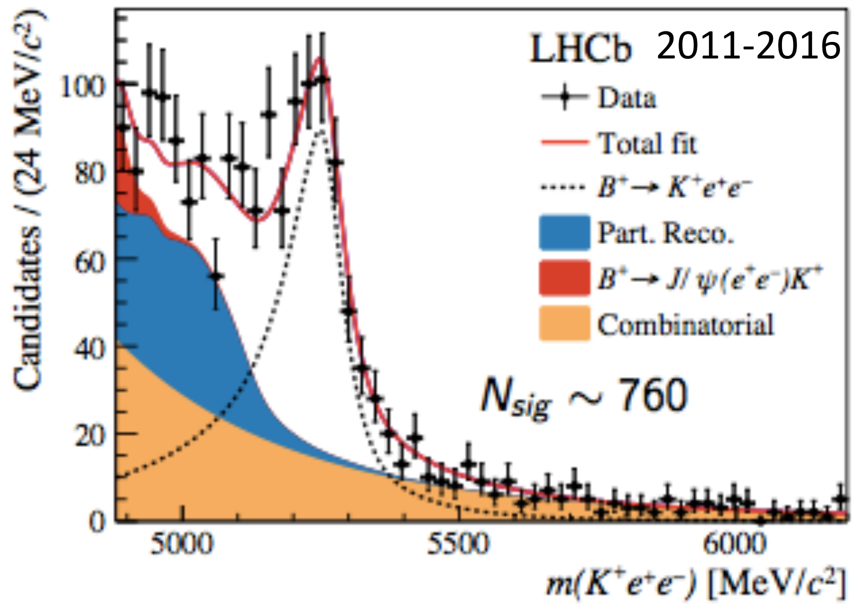


Charged lepton identification (e)

- Muon and Electron tracks are different in LHCb
- Interactions with material and bremsstrahlung emission.
- Muons have better PID and trigger perfomances

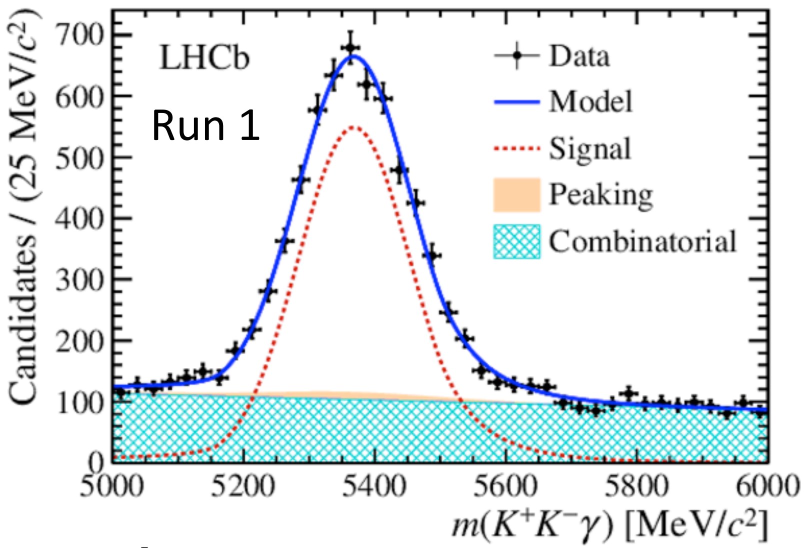




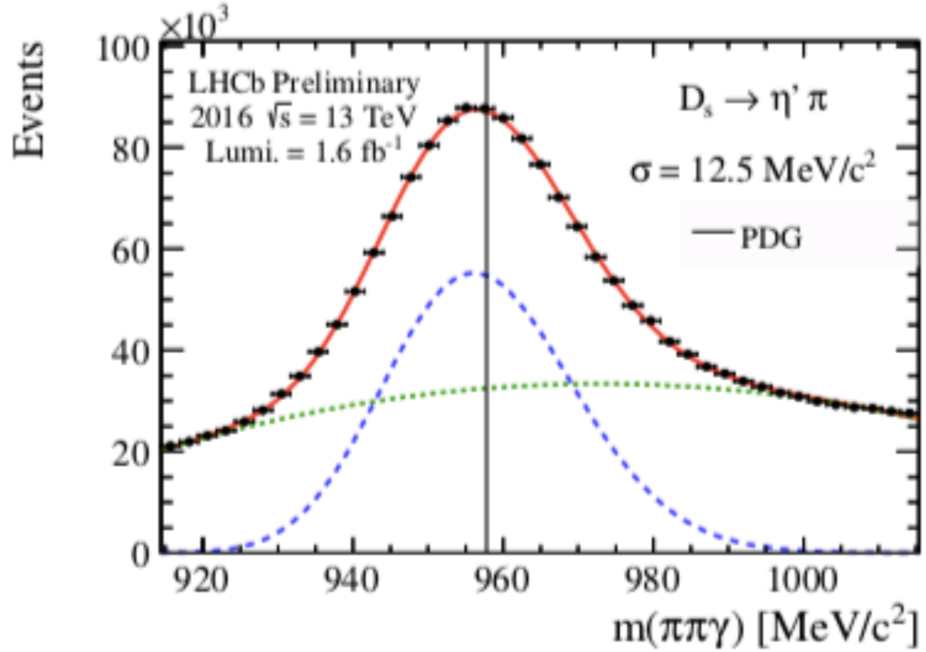


Neutral particle identification (γ)

- Efficiency of detection and energy resolution for neutrals not as good as charged tracks.
- Nonetheless we can reconstruct a variety of signal decays



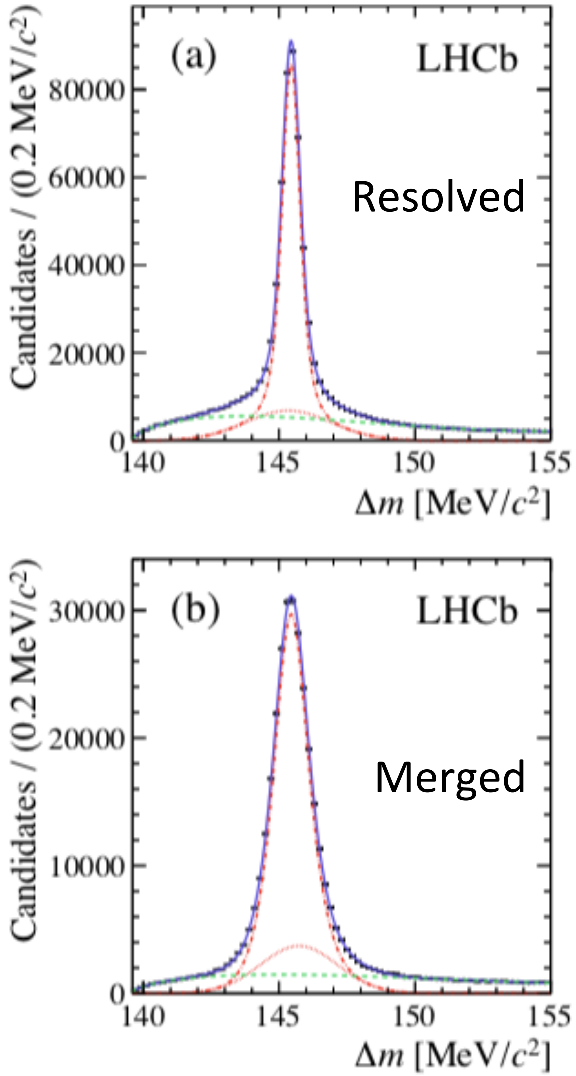
B → $\phi\gamma$. High momentum
Yield 5.1K
Mass res: 95 MeV



Calibration of the photons is good

 arXiv:1905.06284 PRL 123 (2019) 081802 Int. J. Mod. Phys. A 30, 1530022 (2015)

Neutral particle identification (π^0)



- Two categories dependent on the momentum of the π^0.
- Resolved – the two photons are identified separately.
- Merged – the two photons are a single cluster → wider resolution, but lower background as the π^0 has higher transverse energy and lower combinatorics
- Use of mass constraints where possible improves the overall resolution of the overall decay
- $\pi^\pm$ will always be ahead of π^0 performance

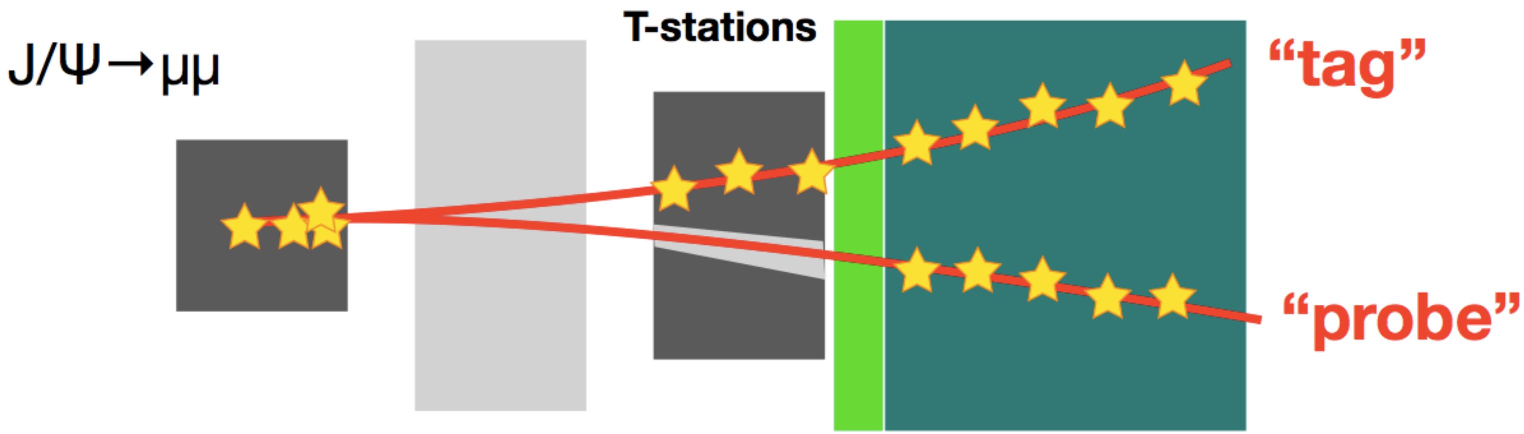
arXiv:1410.4170 Phys. Lett. B 740 (2015) 158

Controlling uncertainties

- Detector can easily be a source for a number of asymmetries/biases.
- Simulation is not perfect, and generating large amounts of becomes difficult
    - Active use of faster simulation techniques

- Regular magnet polarity reversal – averages the small differences between the halves of the detector

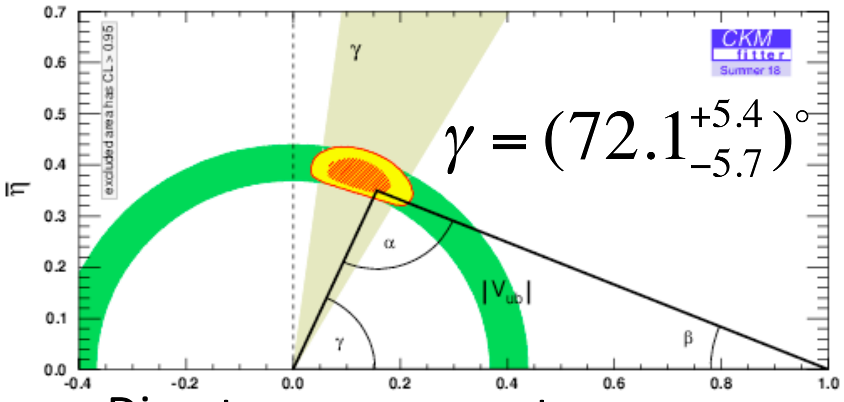
- Data-driven corrections and measurements for detection asymmetries, efficiencies is key

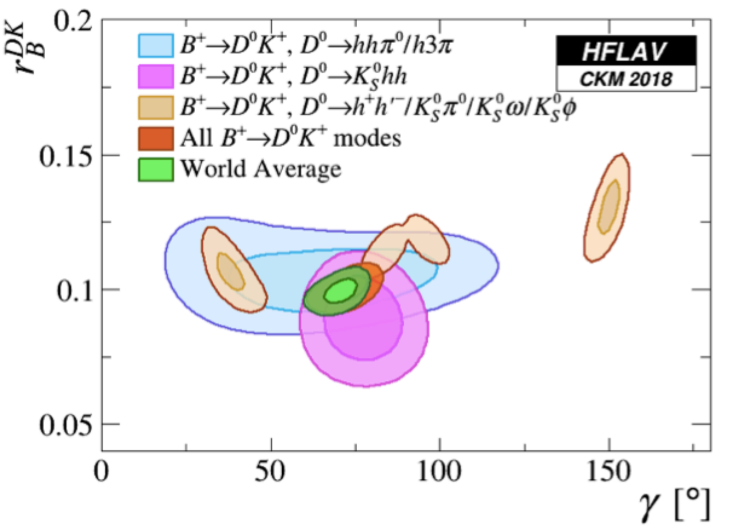


Let’s take a look at some current results*

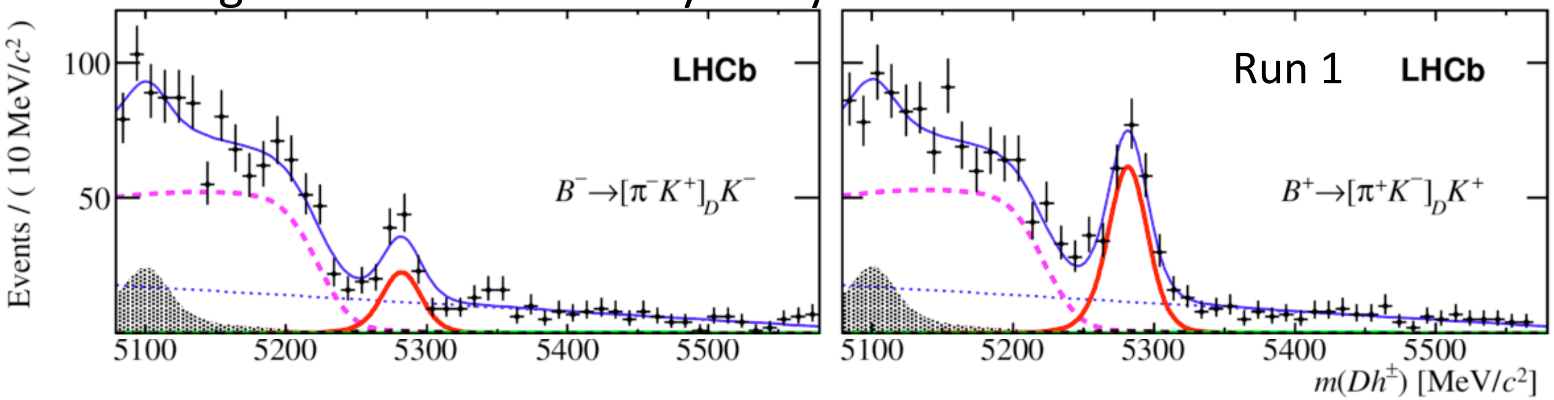
* New results will be shown in other talks

CP Violation : γ

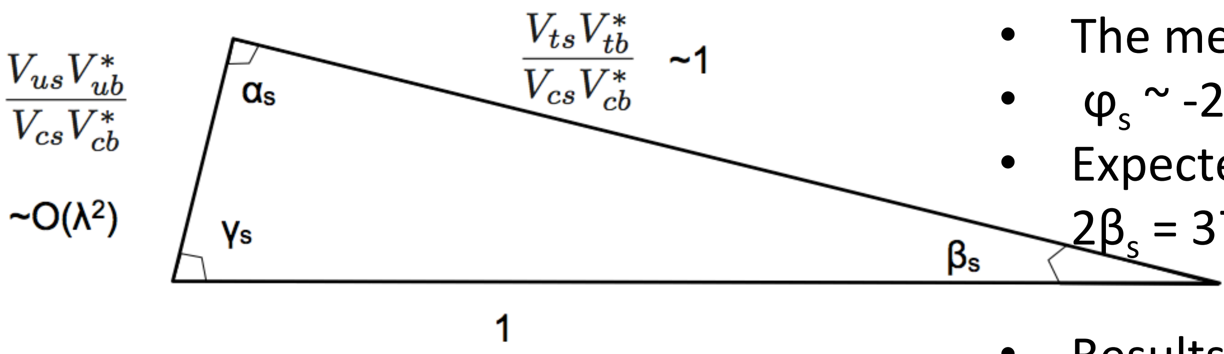




- Direct measurement:
- Large experimental uncertainties.
- ~ Factor 4 reduction in uncertainty in the last 10 years. Many analyses still Run1 only
- Prominent large visible CPV in many analyses.



CP Violation : ϕ_s

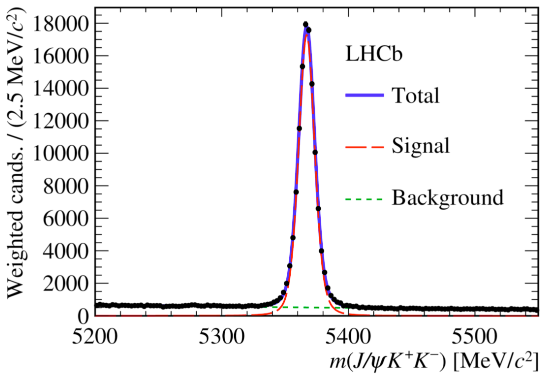


- The measured phase is φ_s.
- $\varphi_s \sim -2\beta_s$ (if no penguin)
- Expected to be very small in SM : $2\beta_s = 37.04 \pm 0.64$ mrad
- Results remain consistent with SM

Requires a time-dependent angular analysis

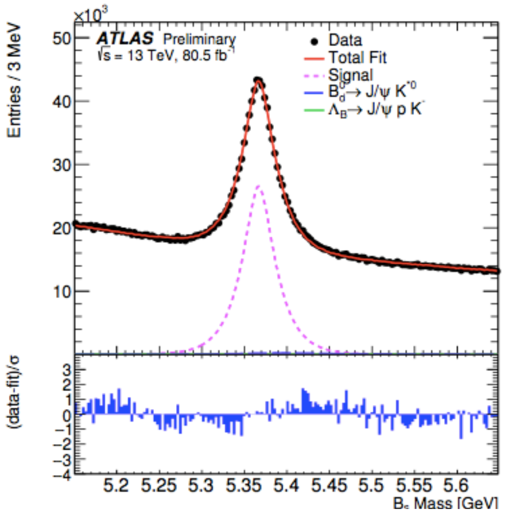
Yield ~ 117K

2015-2016



2017 – 2018 data under analysis

GPD's can trigger on di-muons
ATLAS yield 2015-2017: 447K



- Competitive precision (LHCb better)
- An event from LHCb is worth more
- LHCb can also explore a wider range of modes e.g Bs →J/ψ ππ

CP violation : Charm

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

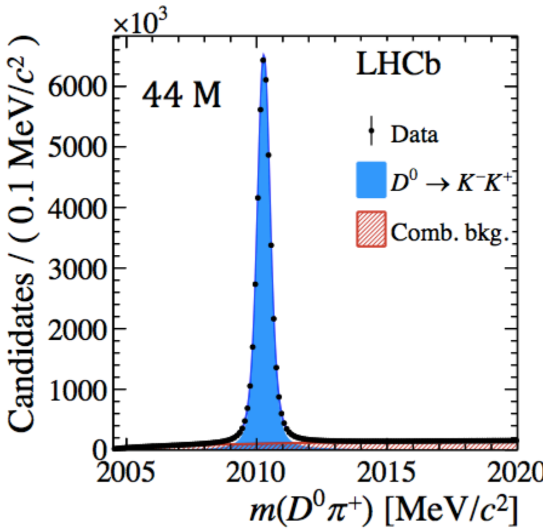
$$A_{raw}(f) \cong A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

Observable

Physical asymmetry

Detection asymmetry
→ 0 as the final states are symmetric

Soft π detection and production asymmetry. Independent of the subsequent decay (If the D* and π kinematics are reweighted to be the same)

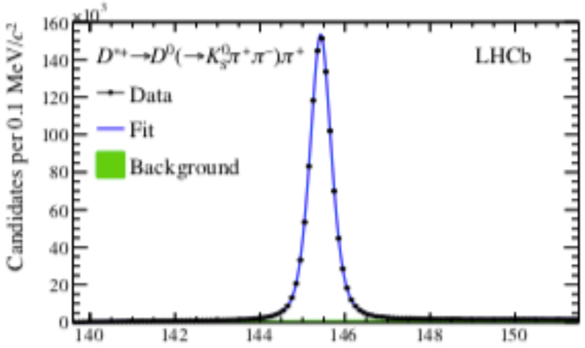


$$\Delta A_{CP} = (-15.4 \pm 2.9)\text{x}10^{-4}$$

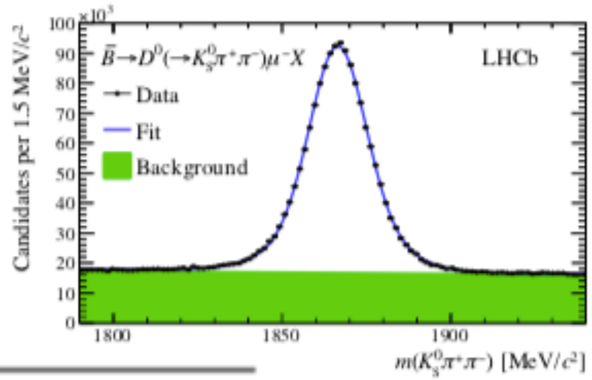
arXiv:1903.08726
Phys. Rev. Lett. 122, 211803 (2019)

Charm mixing and CPV

Prompt



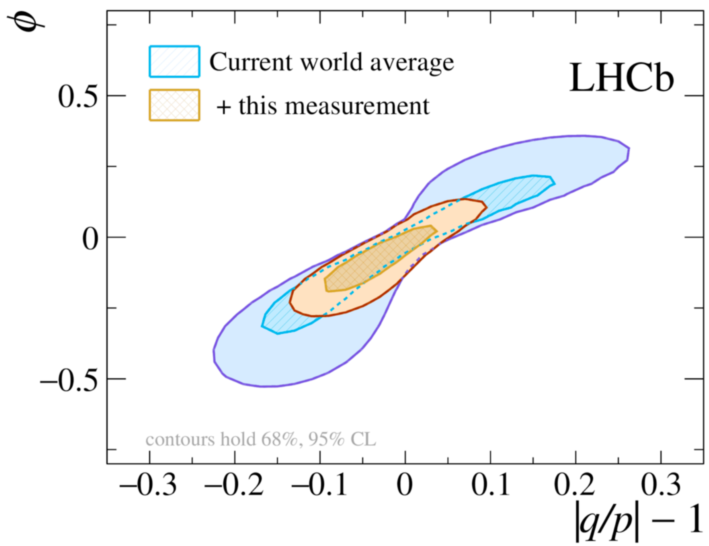
Semileptonic



Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05^{+0.22}_{-0.17}$	$[\ 0.55, 2.15]$
ϕ	$-0.09^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

Indirect CPV yet to be observed in charm

$D^0 \to K_S\pi\pi$



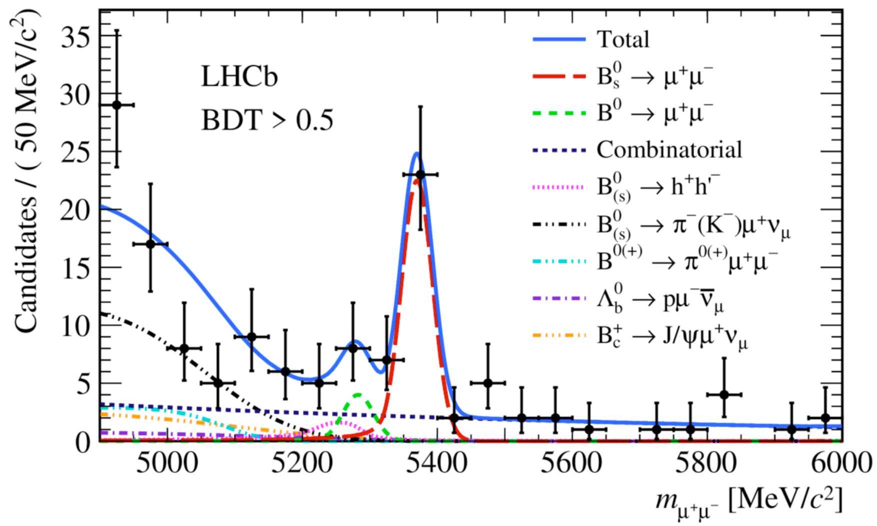
Run 1 analysis only
My rule of thumb doesn't apply here due to significant trigger improvements in Run2

New result on A_Γ will be shown on Friday

Rare Decays: $B_s \rightarrow \mu\mu$

- FCNC are forbidden in the SM
- $B \rightarrow \mu^+\mu^-$ decays are a powerful probe of the SM

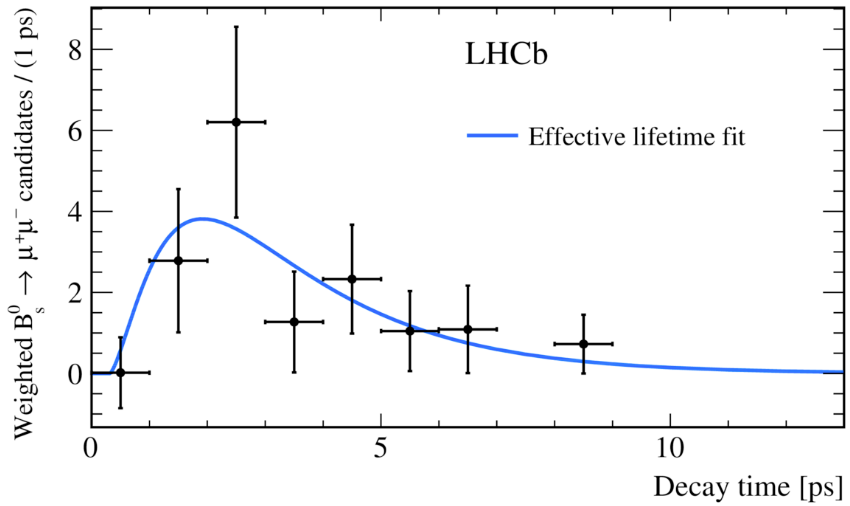
- 2011 – 2016 data



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$$

Effective lifetime

$$\tau^{\text{eff}}_{B_s^0 \to \mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

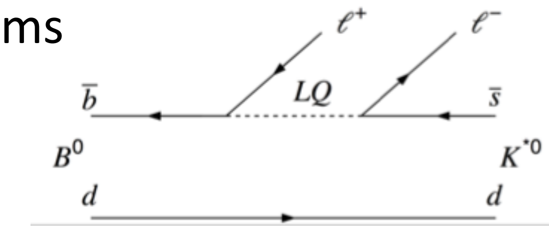


LFU : R_K

New particles at tree level can compete with SM loop diagrams and alter

$$R_h = \frac{\mathbf{B}(B \to h l_1 l_1)}{\mathbf{B}(B \to h l_2 l_2)}$$

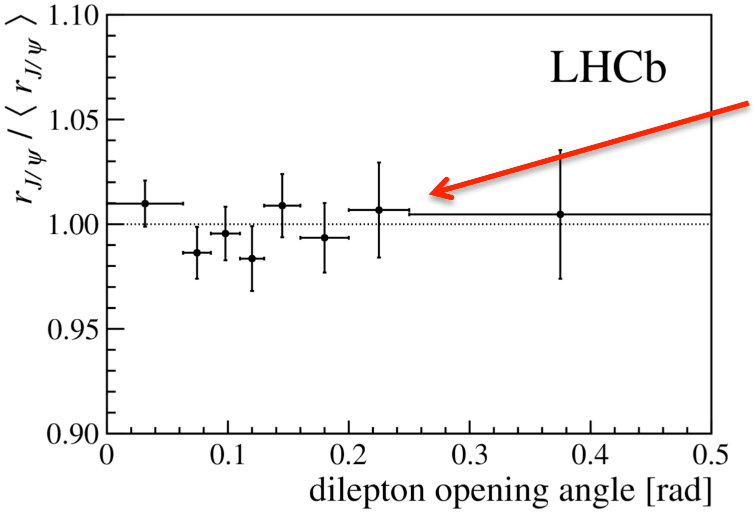
Precisely predicted in the SM (away from phasespace limits)



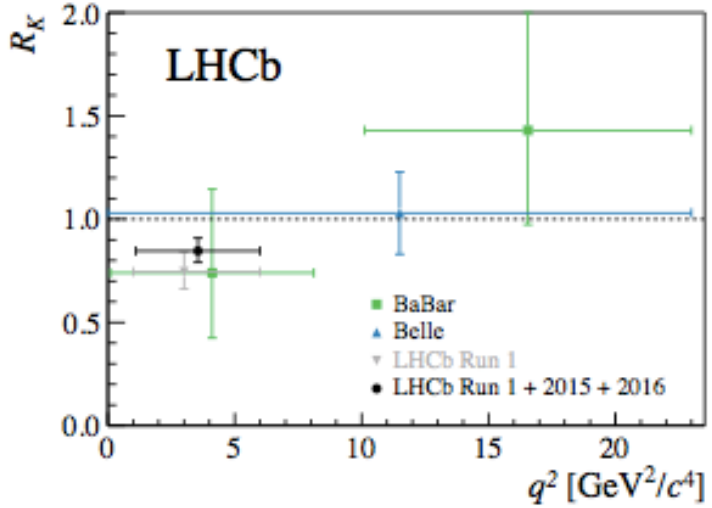
Double ratio strategy:

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

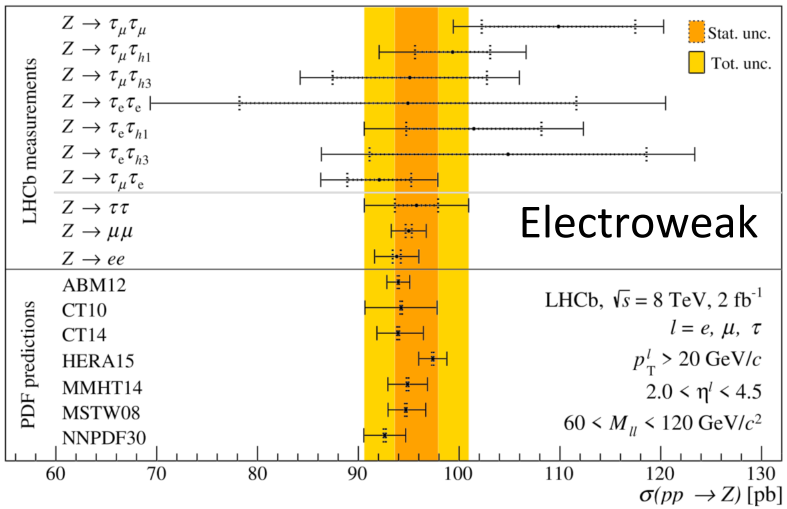
$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

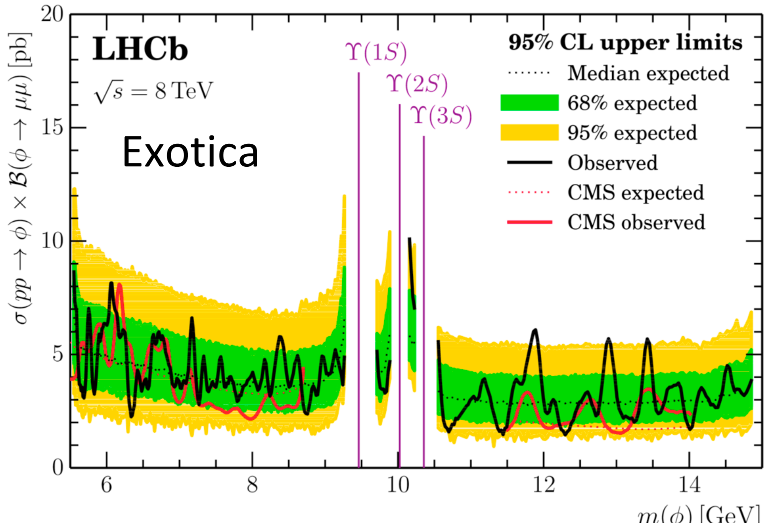


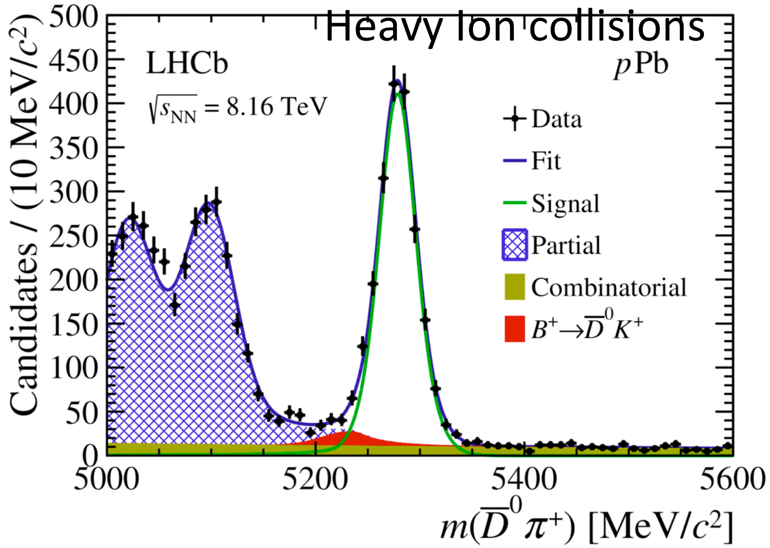
r(J/Ψ) =1 demonstrates that the efficiencies are under very good control

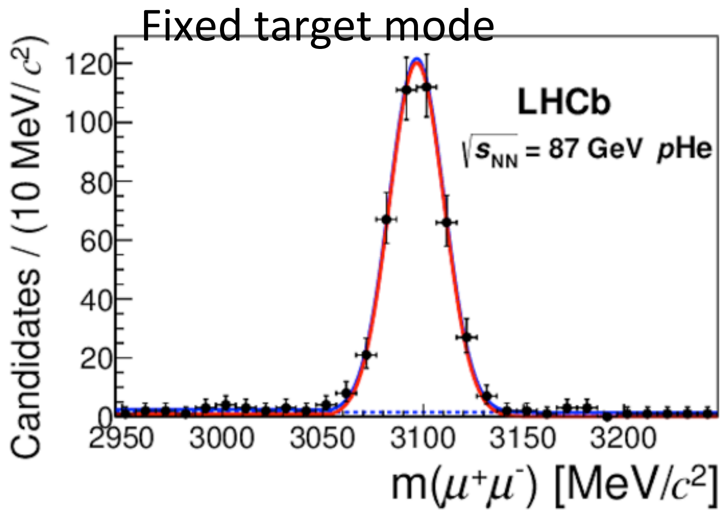


LHCb can do more





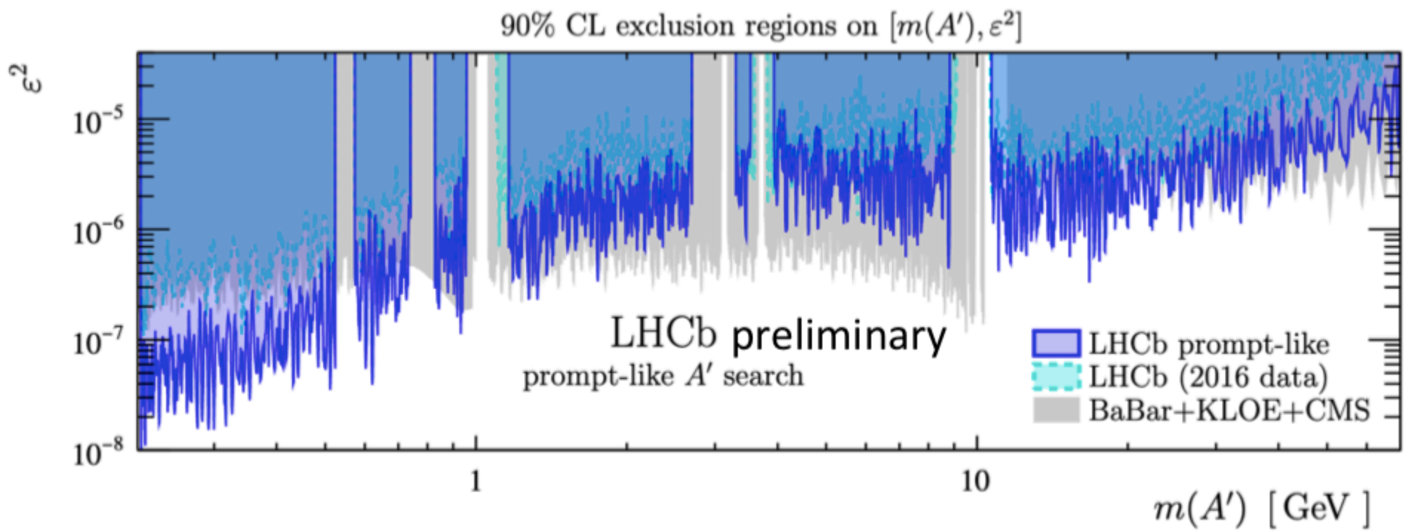




Low mass spin-1 boson searches

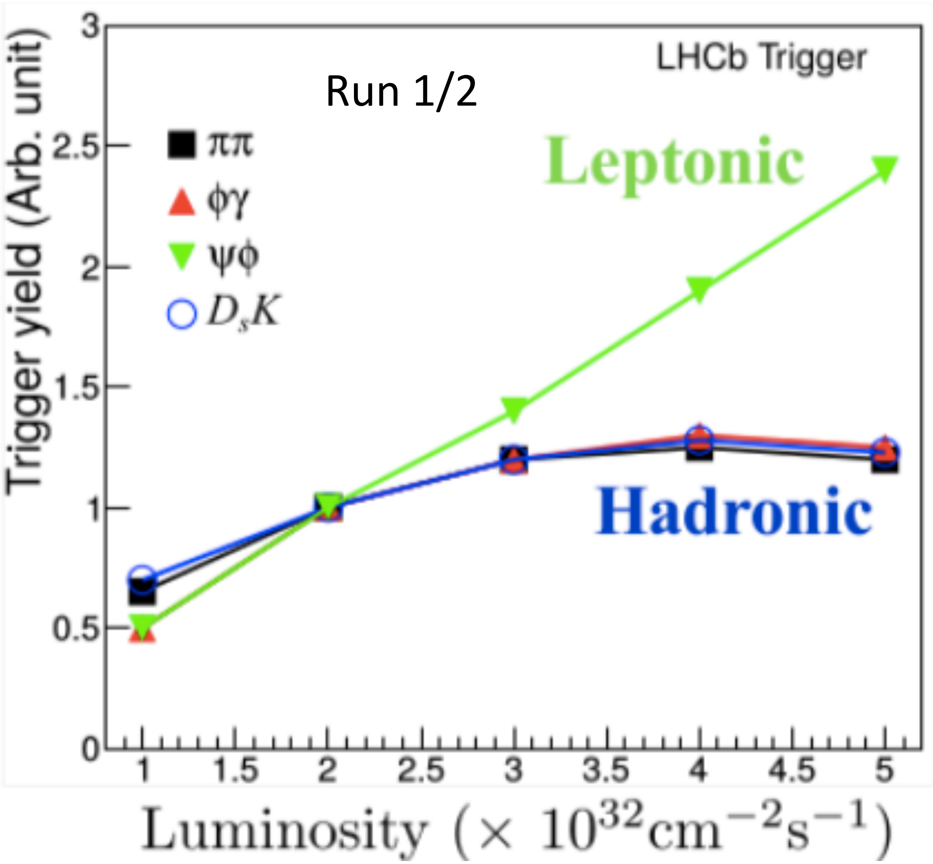
New Result

- Search for dark photon using full Run 2 dataset
- Limts set on kinematic mixing parameter between the photon and dark photon
- Prompt and displaced decays considered
- World Best limit set on prompt production in range 10.6<m< 30 GeV



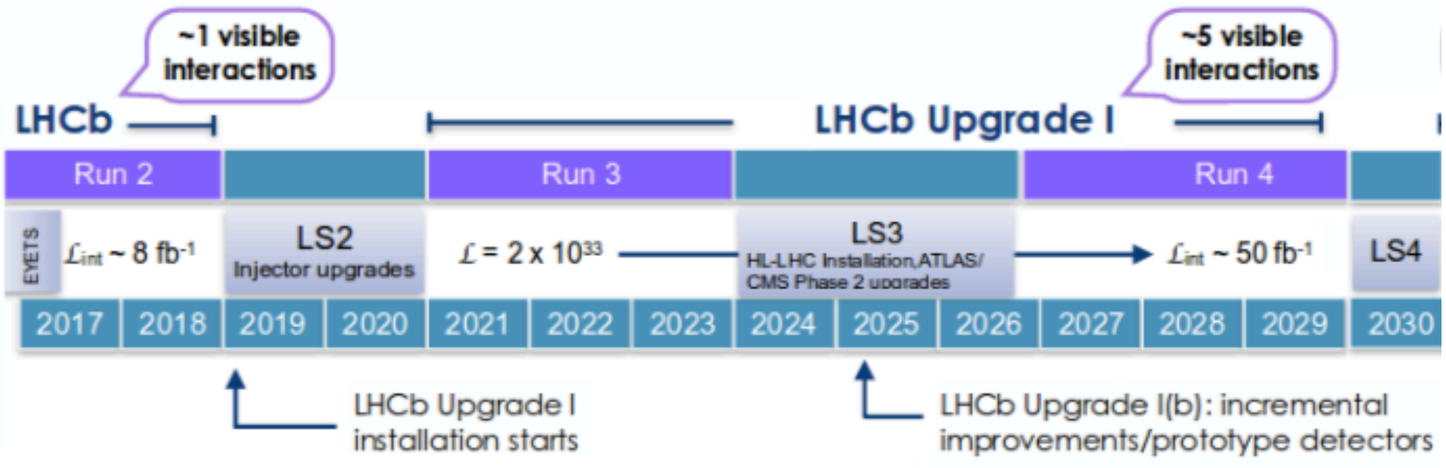
We look forward to the results using the full Run 1 and Run 2 dataset

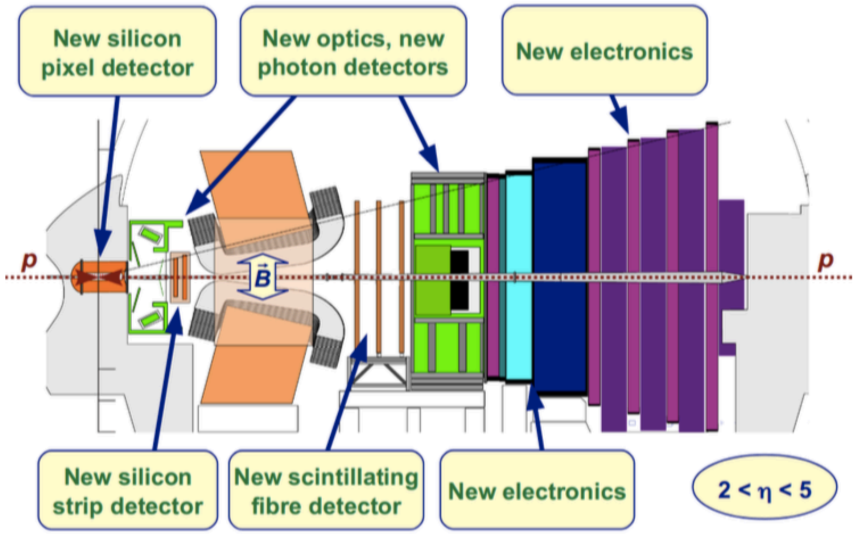
What comes next ?



- With our existing detector, time to double yields becomes too long.
- Running at higher instantaneous luminosity not a good idea:
- Moving to higher occupancy leads to degraded performance
- Limited radiation hardness of trackers
- Hadronic decays will not benefit much

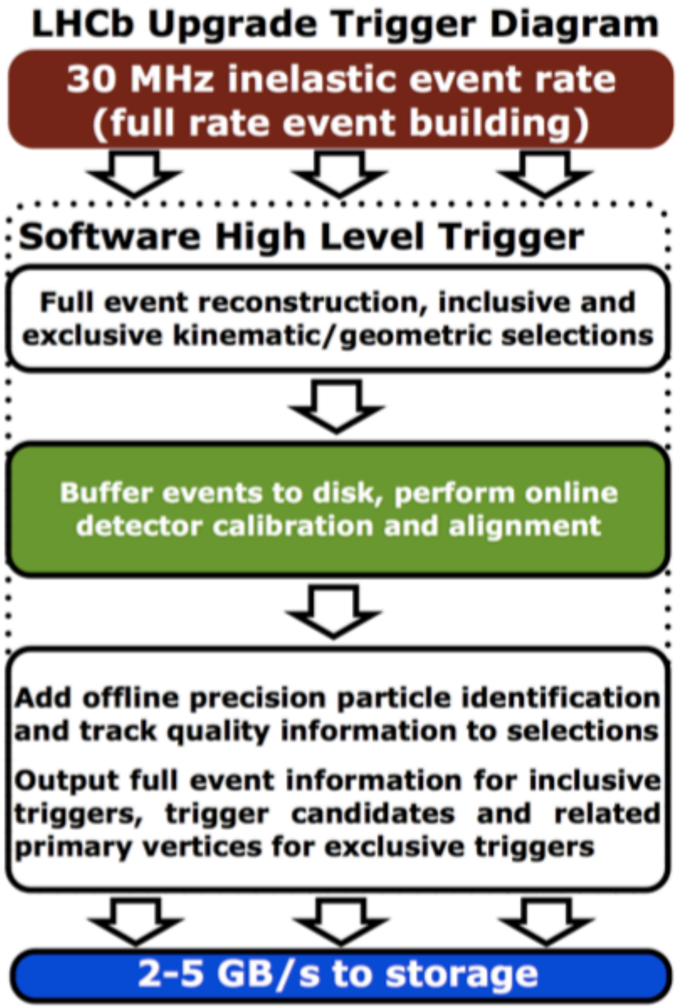
LHCb upgrade





- Essentially a brand new detector able to cope with the higher occupancies of running at higher luminosity
- Removal of the hardware trigger → hadronic decay modes selection will significantly increase in efficiency

Trigger in the upgrade



- Run I & II : Separate out signal from background
- Run 3: 24% of events will contain charm & 2% of events will contain beauty
- Separating the signal we want, from the signal we don't
- Volume of data also a challenge
- Output trigger candidates and related primary vertices for exclusive triggers

LHCb Upgrade vs Belle II

What LHCb shows

There will be competition between these two experiments

Fully charged modes: LHCb will have the advantage of higher signal and lower background

All B species are available to study at LHCb

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}	–
$\|V_{ub}\|/\|V_{cb}\|$	6% [201]	3%	1%
$B_s^0, B^0 \to \mu^+\mu^-$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–
$S_{\mu\mu}$	–	–	–
$b \to c\ell^-\bar{\nu}_l$ 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}

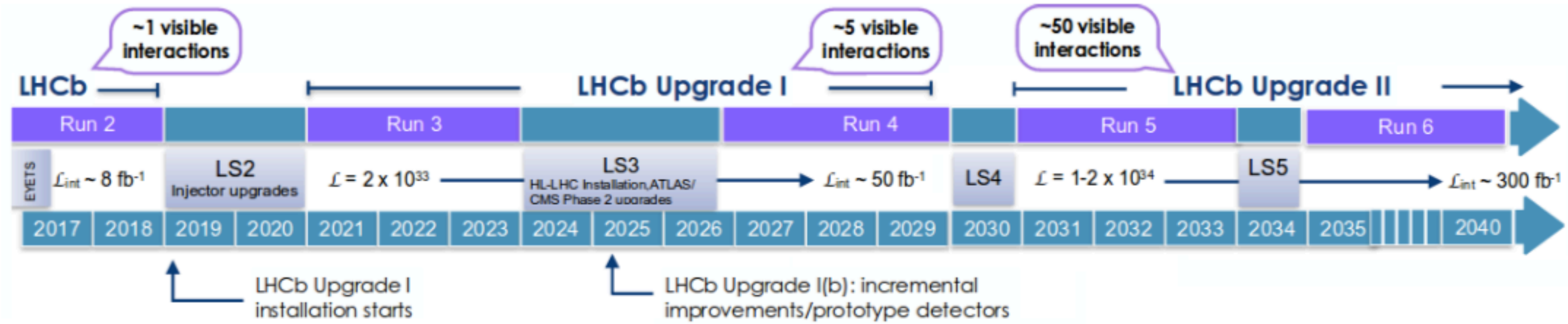
LHCb Upgrade vs Belle II

What Belle II shows

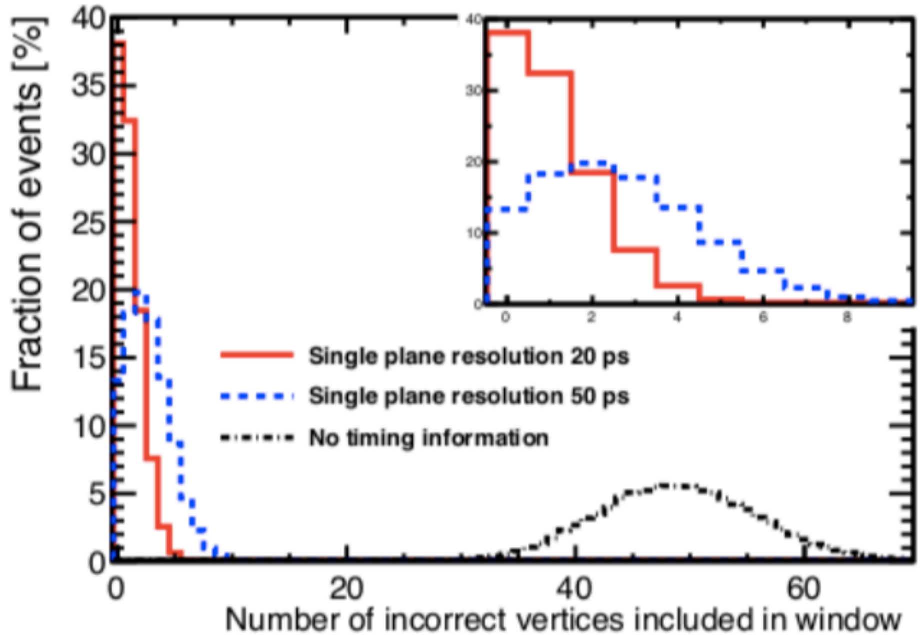
Choice of modes is dominated by final states including neutrals and missing particles, where Belle II has comparative strengths

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$A_{CP}(D^+ \to \pi^+\pi^0)$ $[10^{-2}]$	**	0.17	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

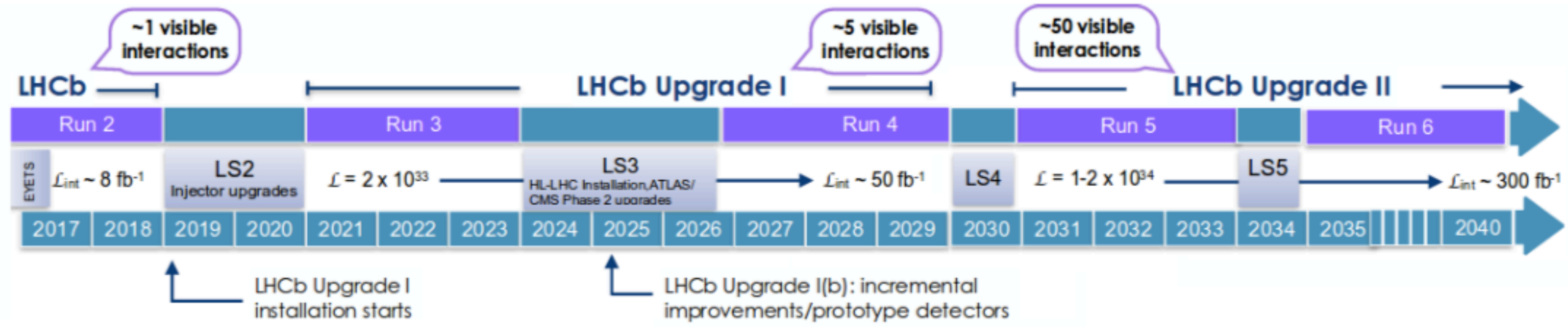
Upgrade II



- Beyond 2030 – HL-LHC
- Upgrade II will collect 300fb^{-1} to fully exploit HL-LHC
- All subsystems being further upgraded, use of new technology to keep high performance
- Use of timing information to mitigate pile-up – all collisions in a bunch crossing don't occur at the same time



Upgrade II



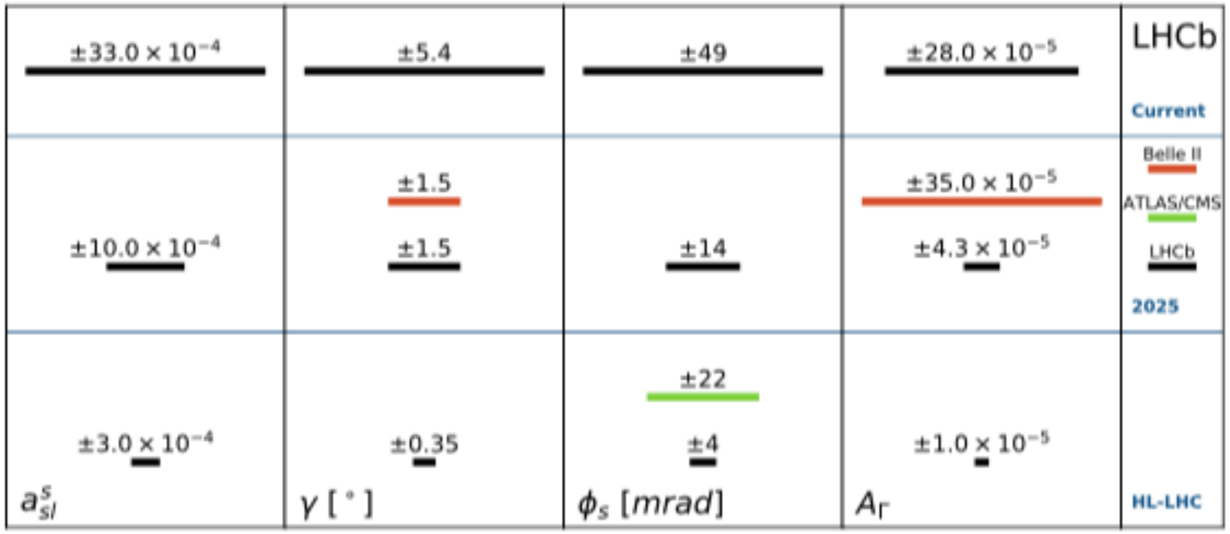
Response to this project has been very positive. EoI and physics case have been submitted

The LHCb Upgrade II was approved by the LHCC to proceed to a framework TDR

European Strategy Briefing Document: Strong support for project in the document (released last week)

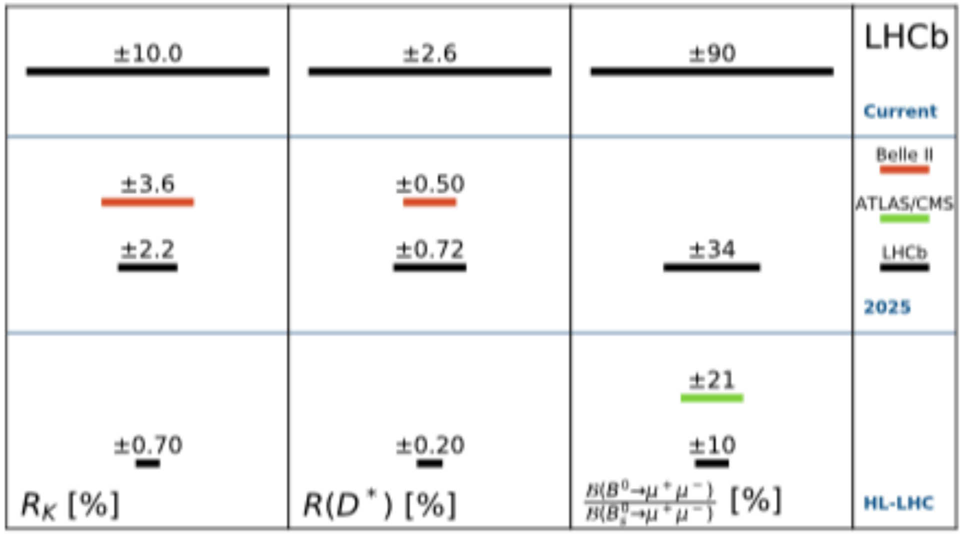
"The LHCb Upgrade II... will enable a wide range of flavour observables to be determined at HL-LHC with unprecedented precision"

Upgrade II physics reach



← Upgrade

← Upgrade II



← Upgrade

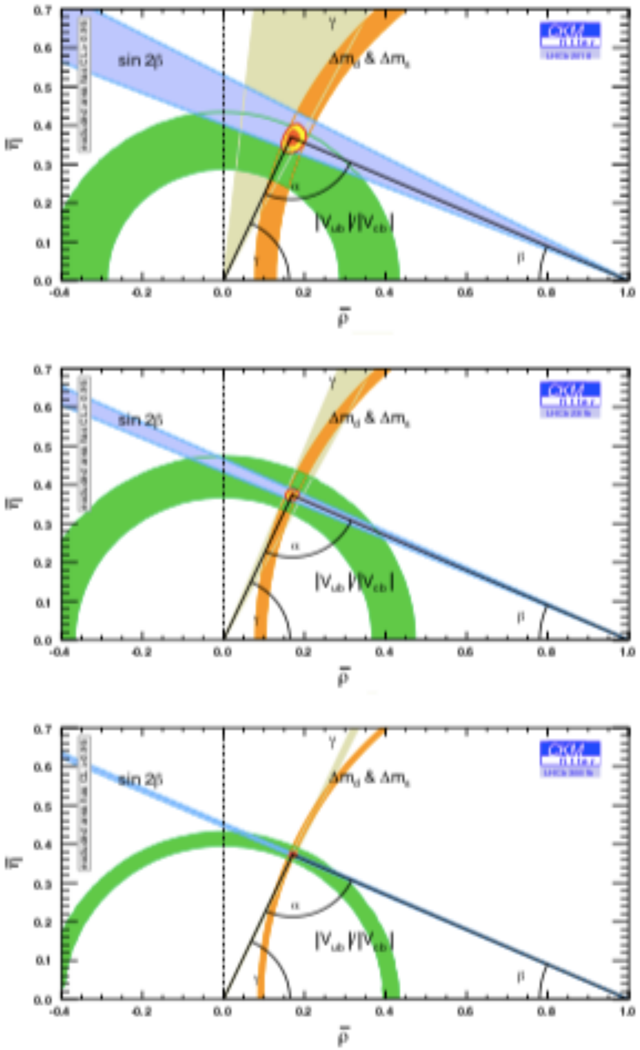
← Upgrade II

Conclusions

Now

Upgrade

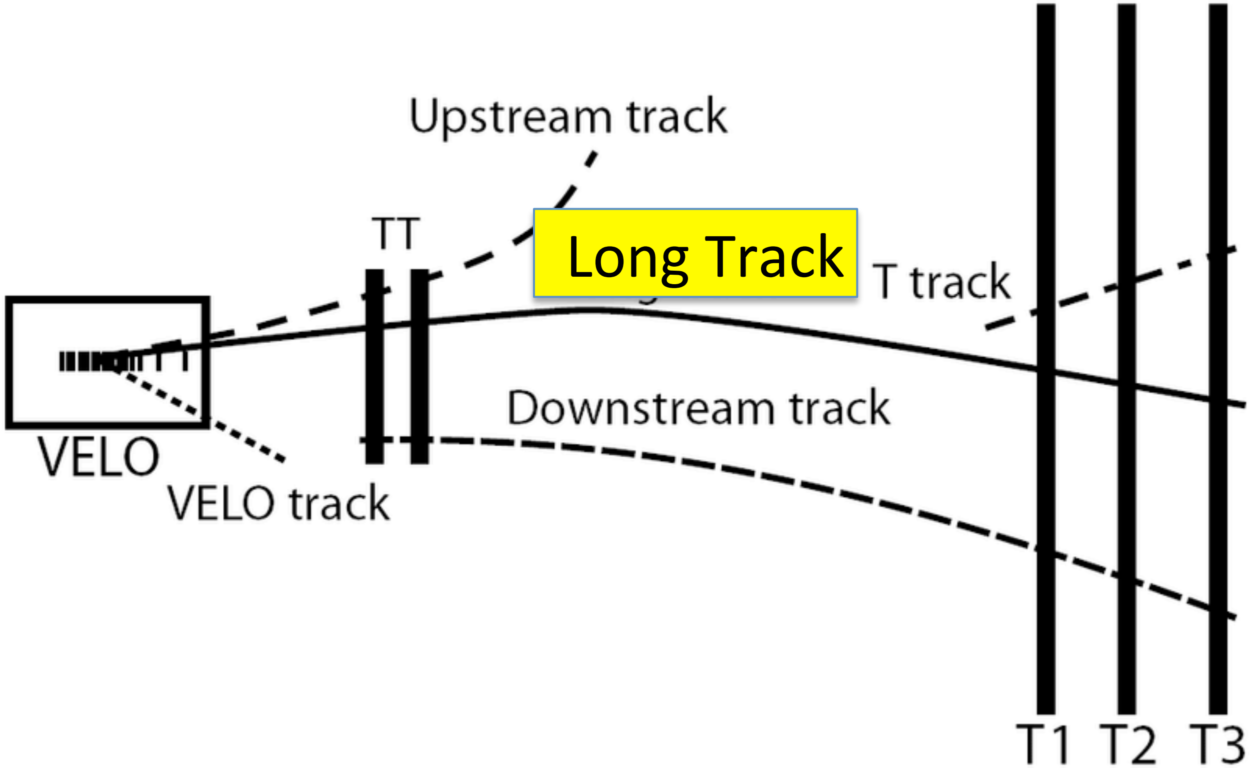
Upgrade II



- The precision that will be reached by LHCb in a number of measurements will continue to be more precise
- New channels will be accessed
- New Physics?

Backup

Tracking at LHCb



- Long Tracks traverse all tracking detectors before and just after magnet
- Highest quality for physics analysis - good IP resolution and momentum resolution
- Other track types are also employed for analysis specific reasons (e.g long lived particles like K_S and Λ also use downstream tracks