LHCb prospects

Jibo HE (UCAS), for the LHCb collaboration

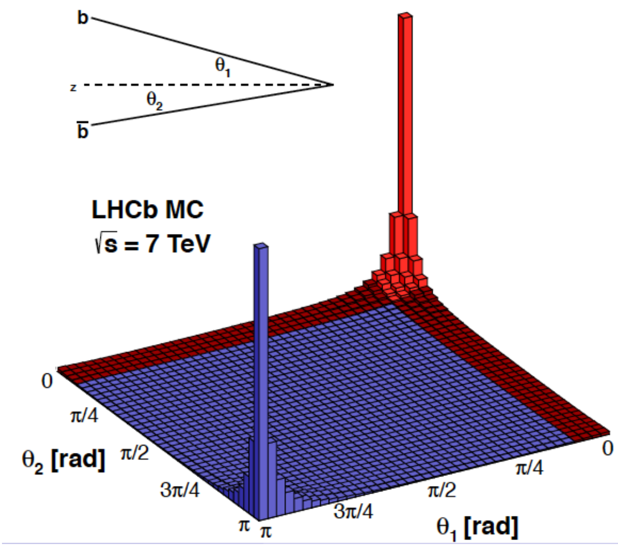
Presented at HCPFV 2016 @ SJTU

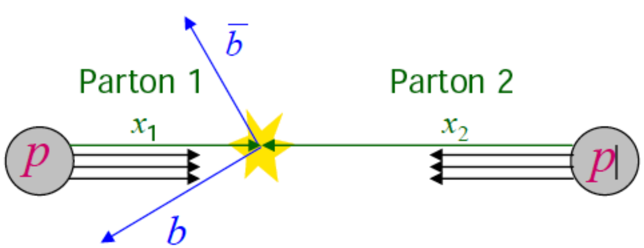
Outline

- Introduction
- The LHCb run-II
- The LHCb upgrade
- The LHCb future upgrade
- Summary

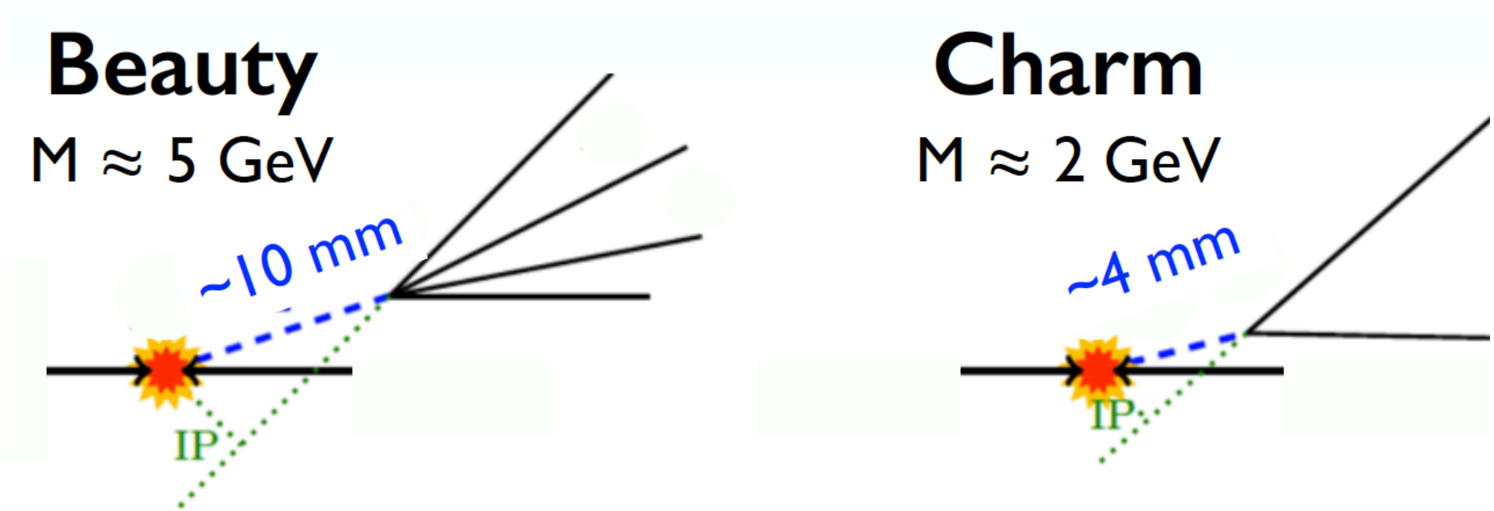
Beauty/charm production at LHC

- Large production cross-sections @ $\sqrt{s} = 7$ TeV
  $\sigma_{pp}^{\mathrm{inel}} \sim 60$ mb [JINST 7 (2012) P01010]
  $\sigma(pp \to c\bar{c}X) \sim 6$ mb [LHCb-CONF-2010-013]
  $\sigma(pp \to b\bar{b}X) \sim 0.3$ mb [PLB 694 (2010) 209], c.f. $\sigma(e^+e^- \to b\bar{b}) \sim 1$ nb @ $\Upsilon(4S)$
  $\Rightarrow$ LHC is a Flavour Factory!
- In high energy collisions, $b\bar{b}/c\bar{c}$ pairs are produced predominantly in forward or backward directions





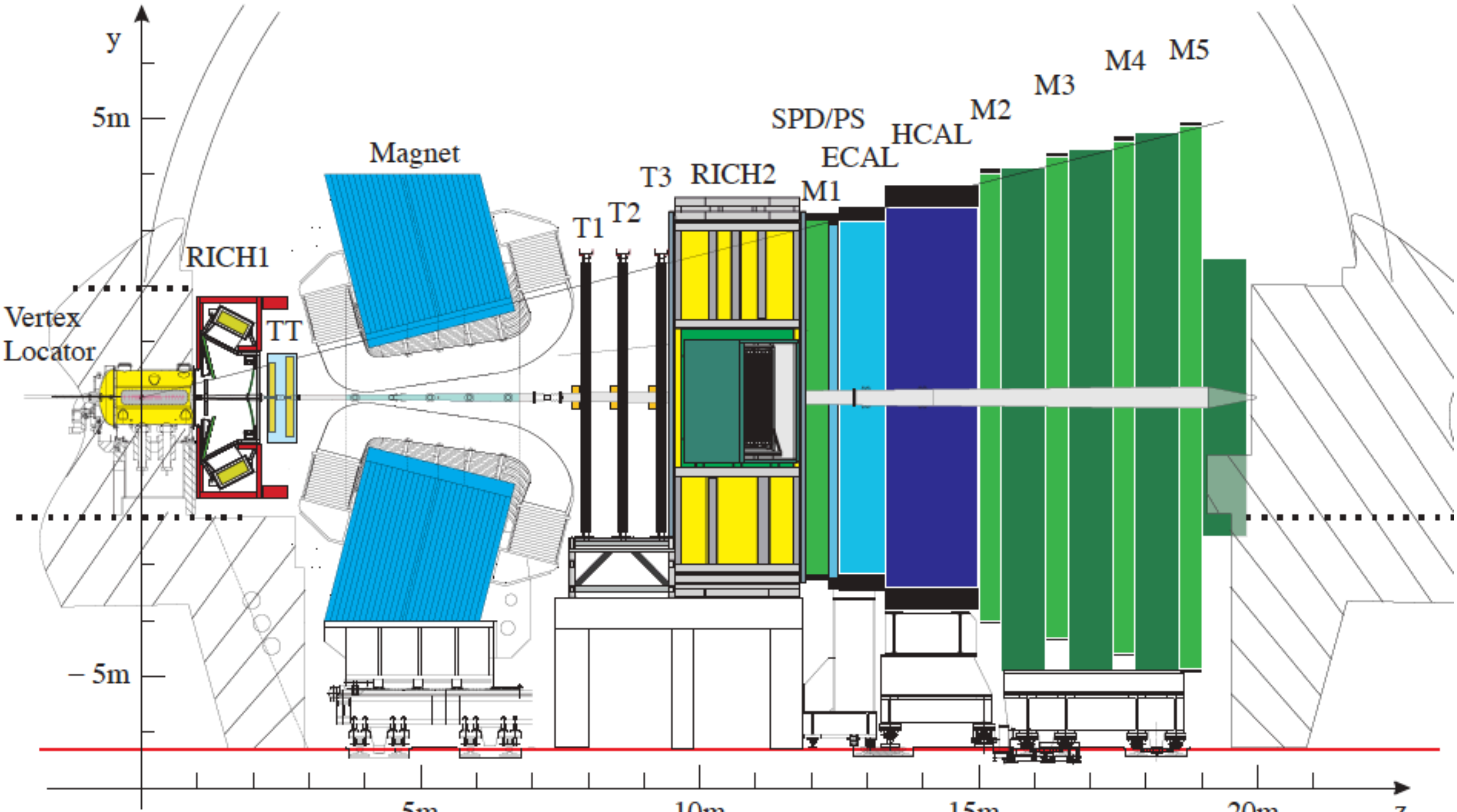
Beauty/charm signatures



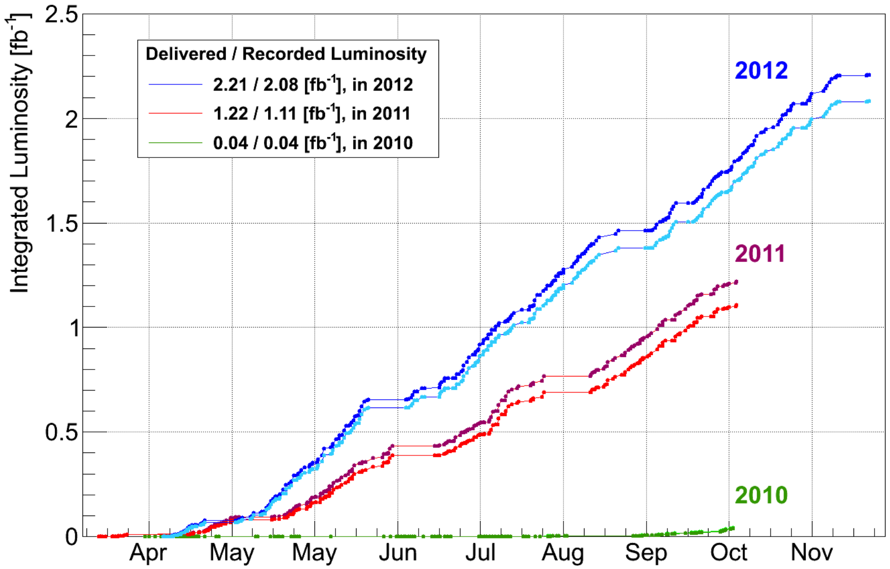
- Compared to minibias (background)
  - Relatively high mass → high p_T
  - Relatively long lifetime → large IP
- Requires excellent vertexing, tracking, PID

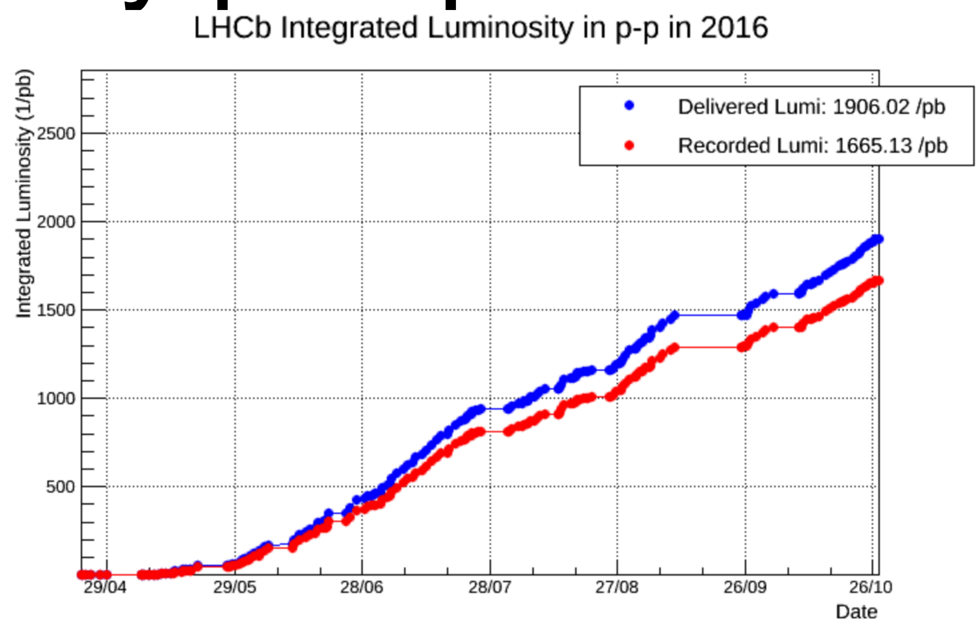
The LHCb experiment

- Dedicated to precision study of *b/c*-hadrons



LHCb luminosity prospects

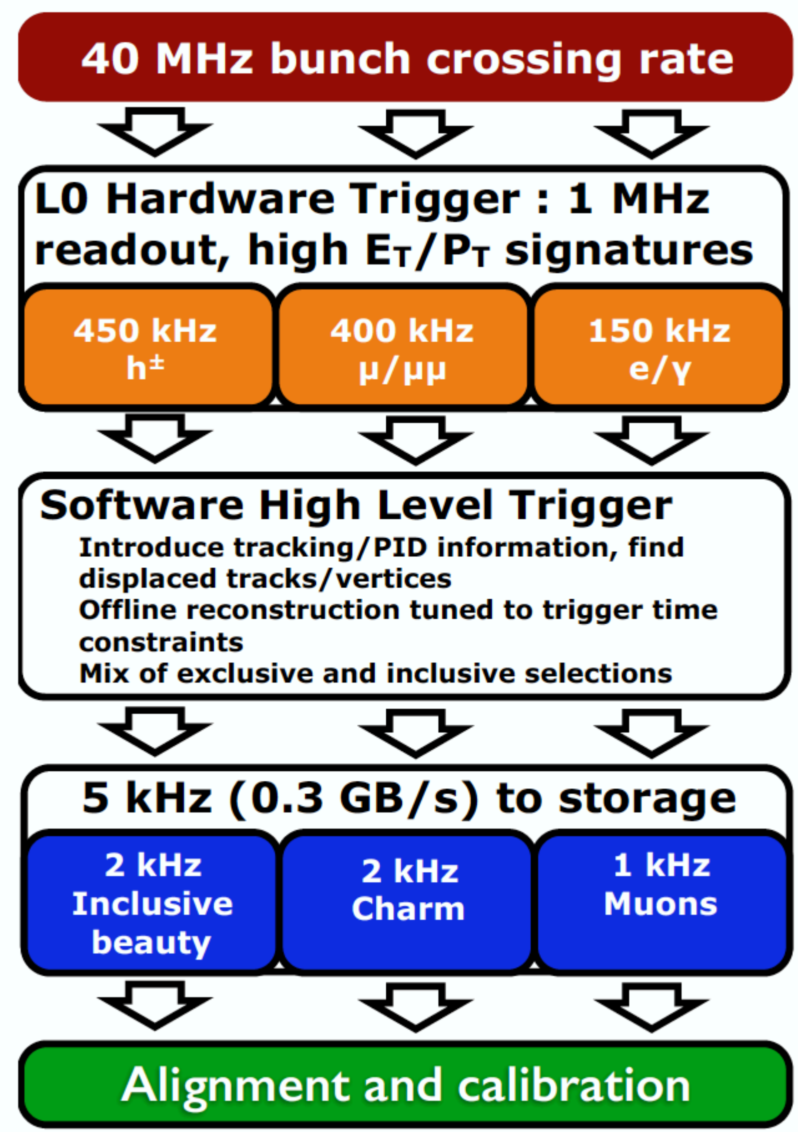




LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

The LHCb data flow: Run-I



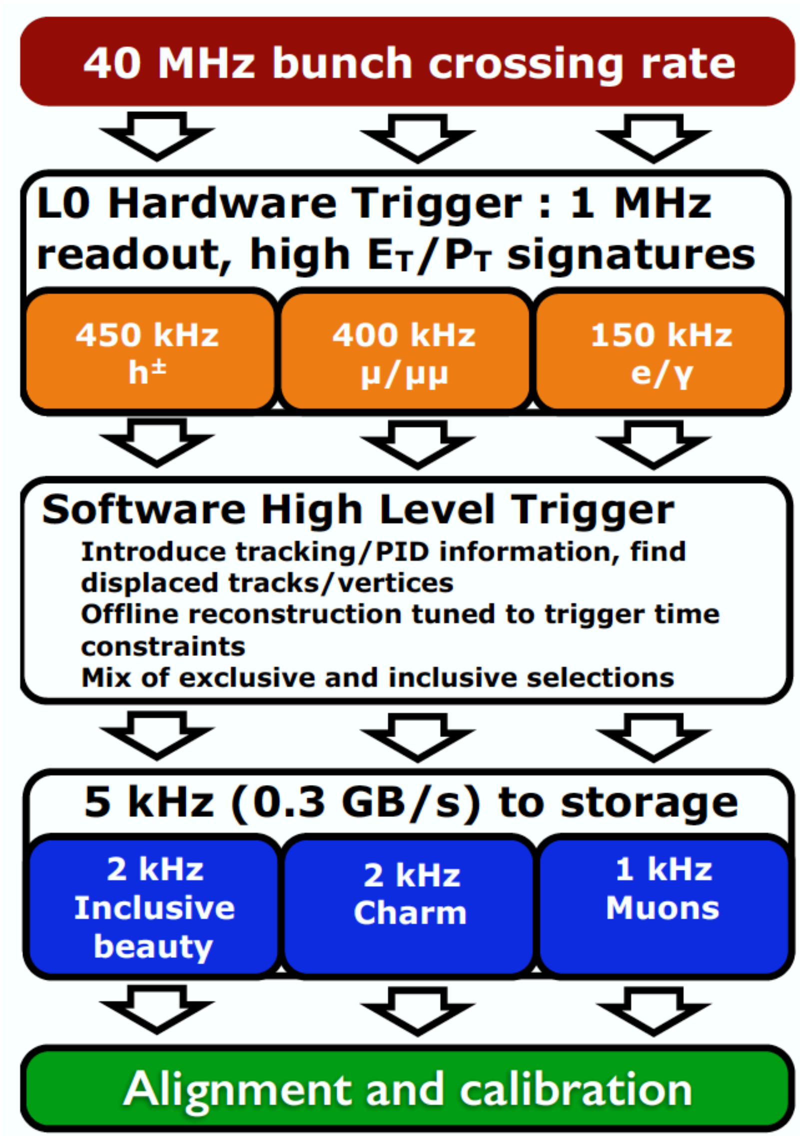
- Level-0, Hardware
  - Fully synchronous at 40 MHz
  - Selection of high p_T particles
    - ★ $p_T(\mu) >\sim 1.5$ GeV/c, $p_T(\mu_1) \times p_T(\mu_2) >\sim (1.5\,\mathrm{GeV}/c)^2$
    - ★ $E_T(h, e, \gamma) > 2.5 - 4$ GeV
- High Level Trigger (HLT), Software
  - Stage 1, tracking info, IP cuts
  - Stage 2, full reconstruction + selections

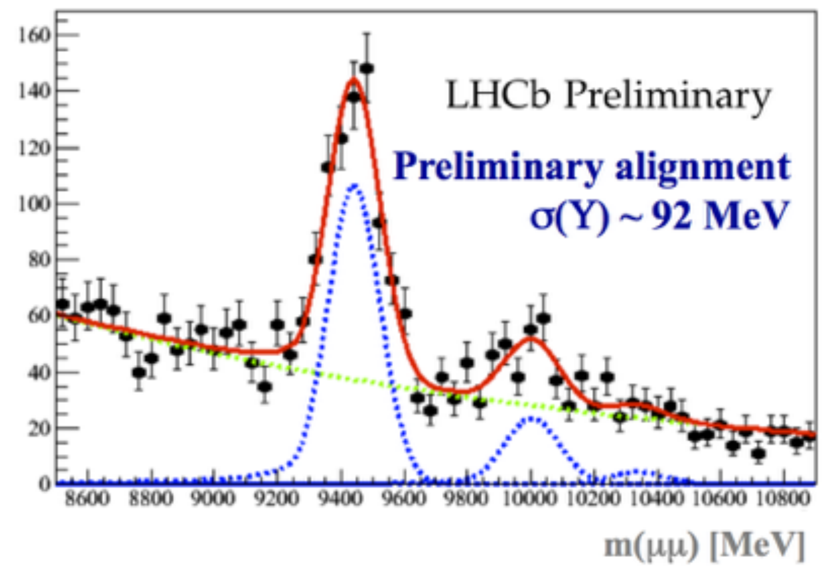
  $\sim$50 kB/event $\Rightarrow$ 0.25GB/s, $\sim$ 2 PB/year
- Offline data flow

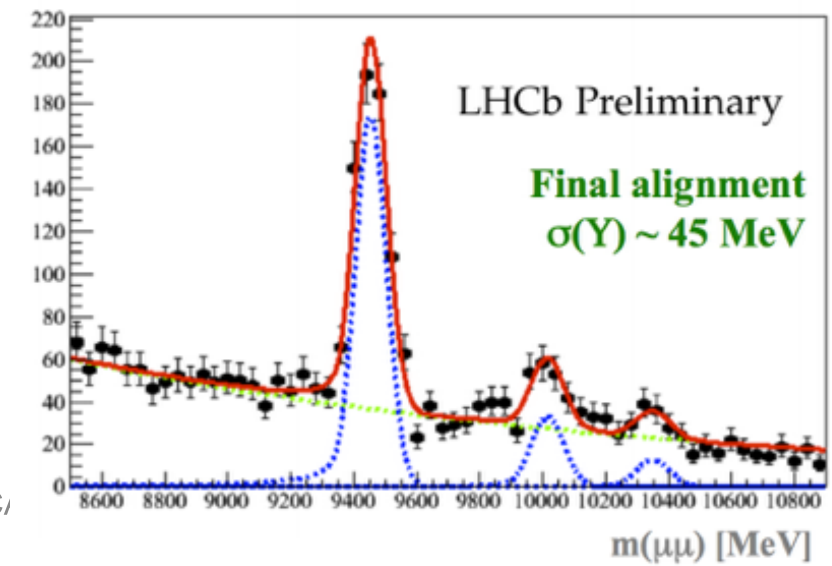
  Raw data $\xrightarrow{\text{Rec}}$ Stripping $\xrightarrow{10\%}$ (μ)DST

  Stripping, also as HLT3, Pre-selections of all decay channels under study

The LHCb data flow: Run-I

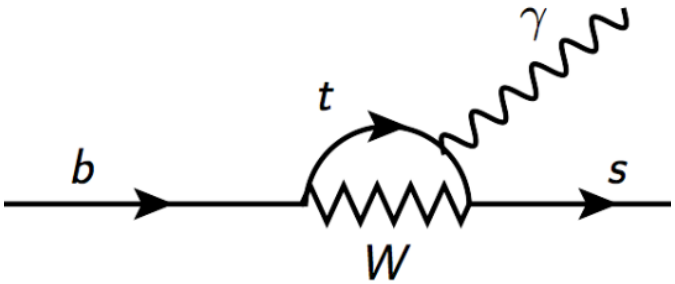






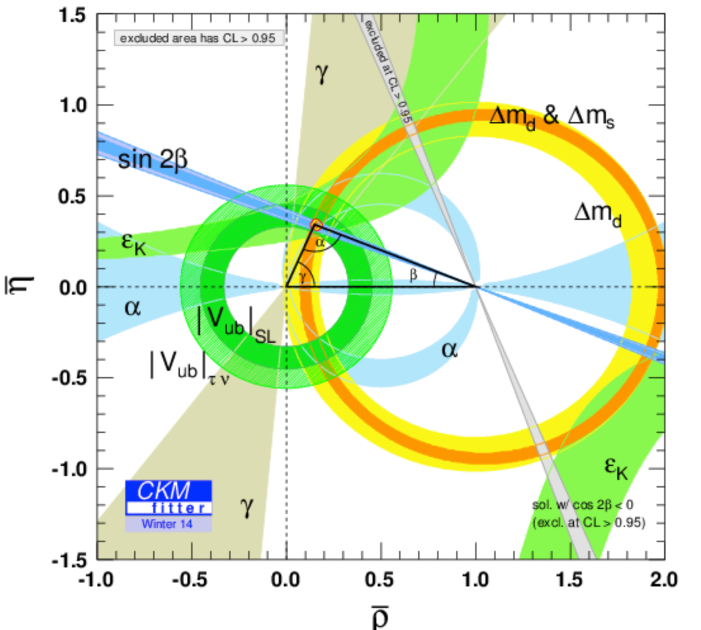
Indirect searches for New Physics

- FCNC



$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_{i=1\ldots10,S,P} (C_i O_i + C_i' O_i') + \text{h.c.}$$

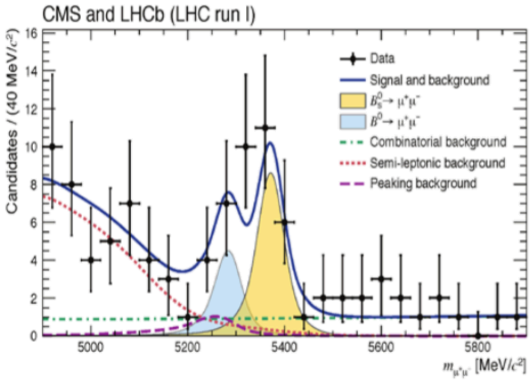
  - NP modify C_i,
  - NP introduce new O_i
- CKM
  - Over constrain CKM triangle



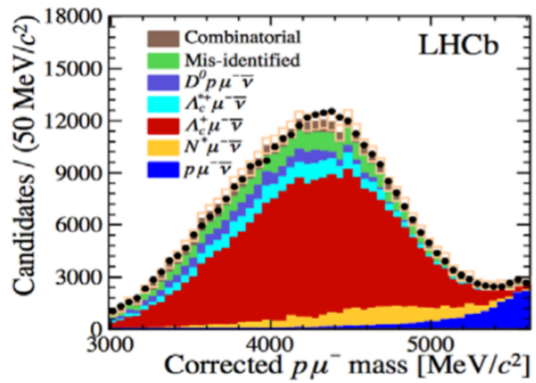
Highlights of Run-I results

See Prof. Zhang's talk, Dr. Yu's talk

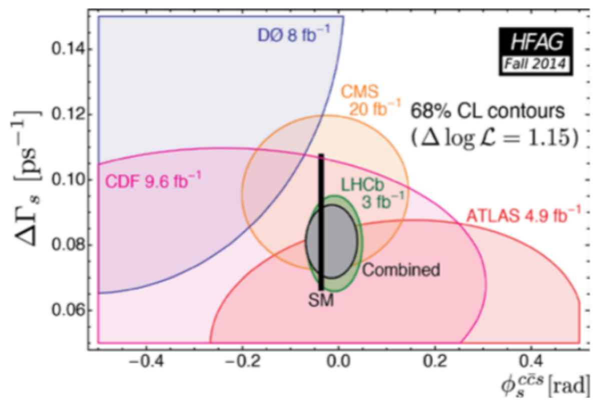
Observation of $B_s \to \mu\mu$



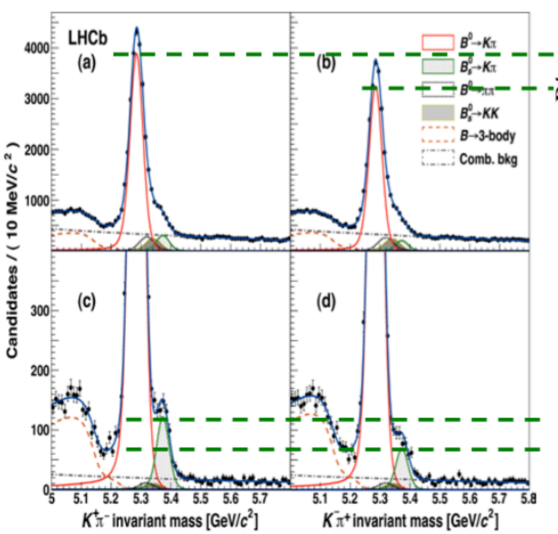
Measurement of V_{ub} in $\Lambda_b \to p\mu\nu$



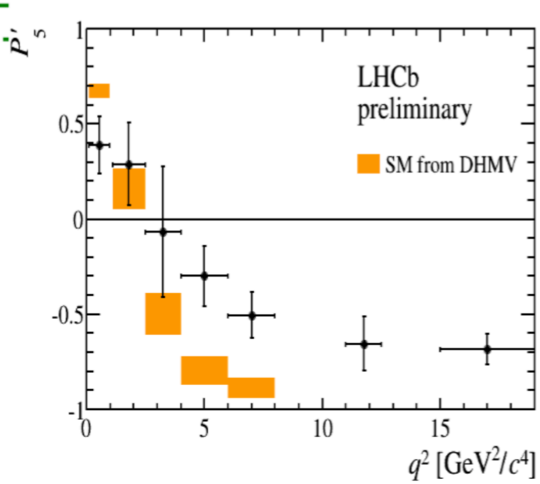
Best measurement of ϕ_s in $B_s \to J/\psi\phi$



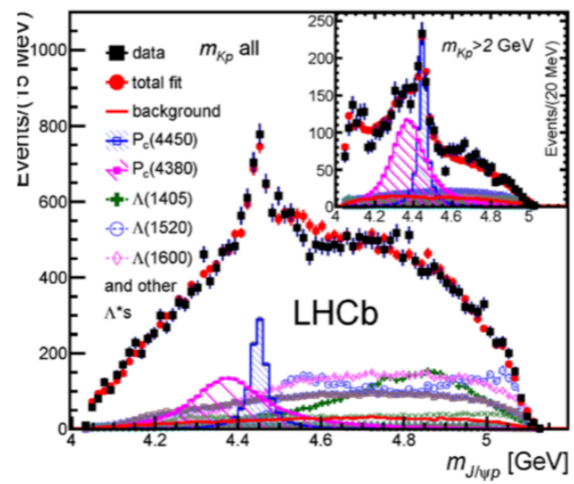
Observation of direct CP violation



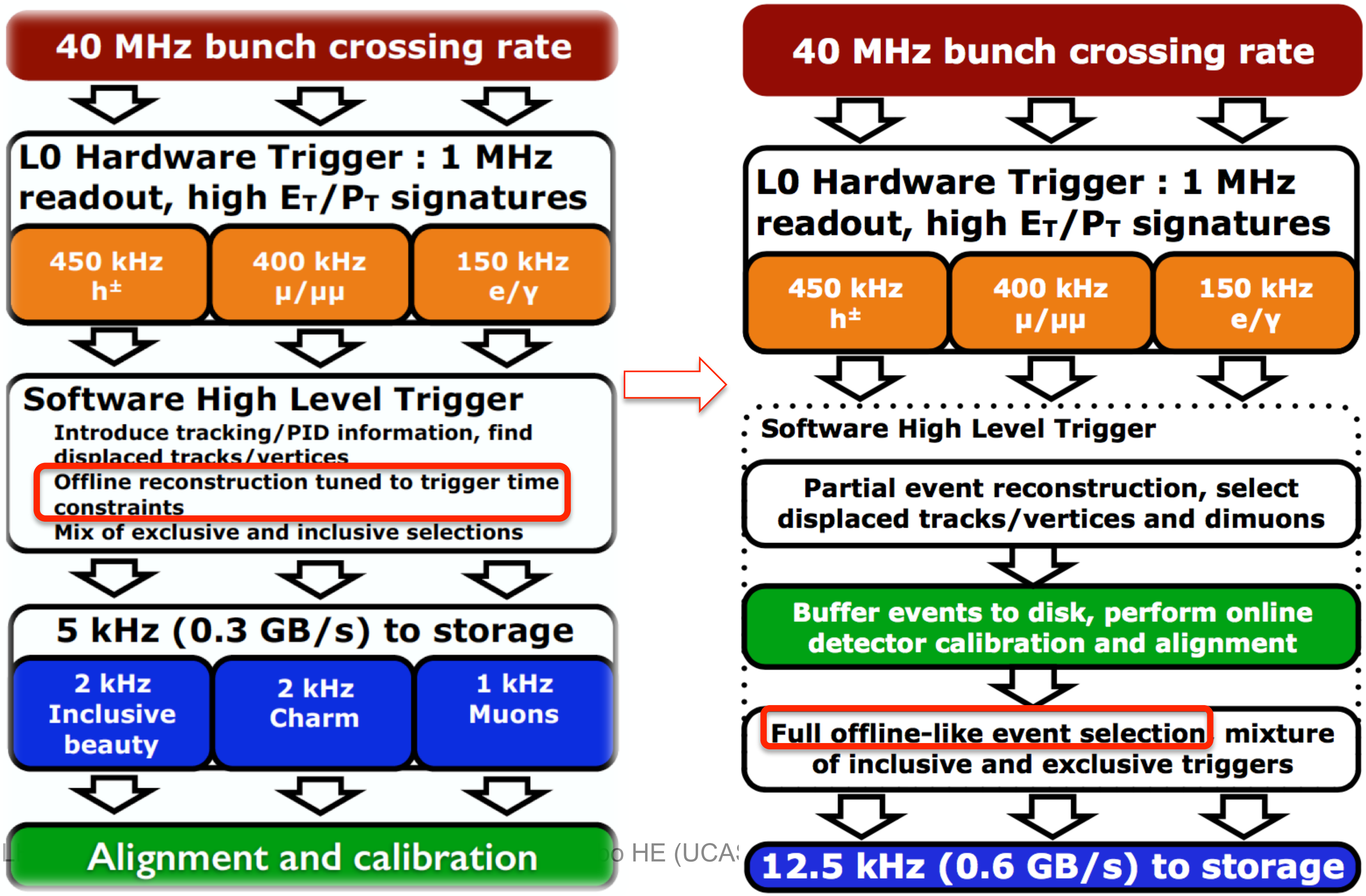
Angular analysis in $B^0 \to K^{*0}\mu\mu$



Observation of pentaquarks

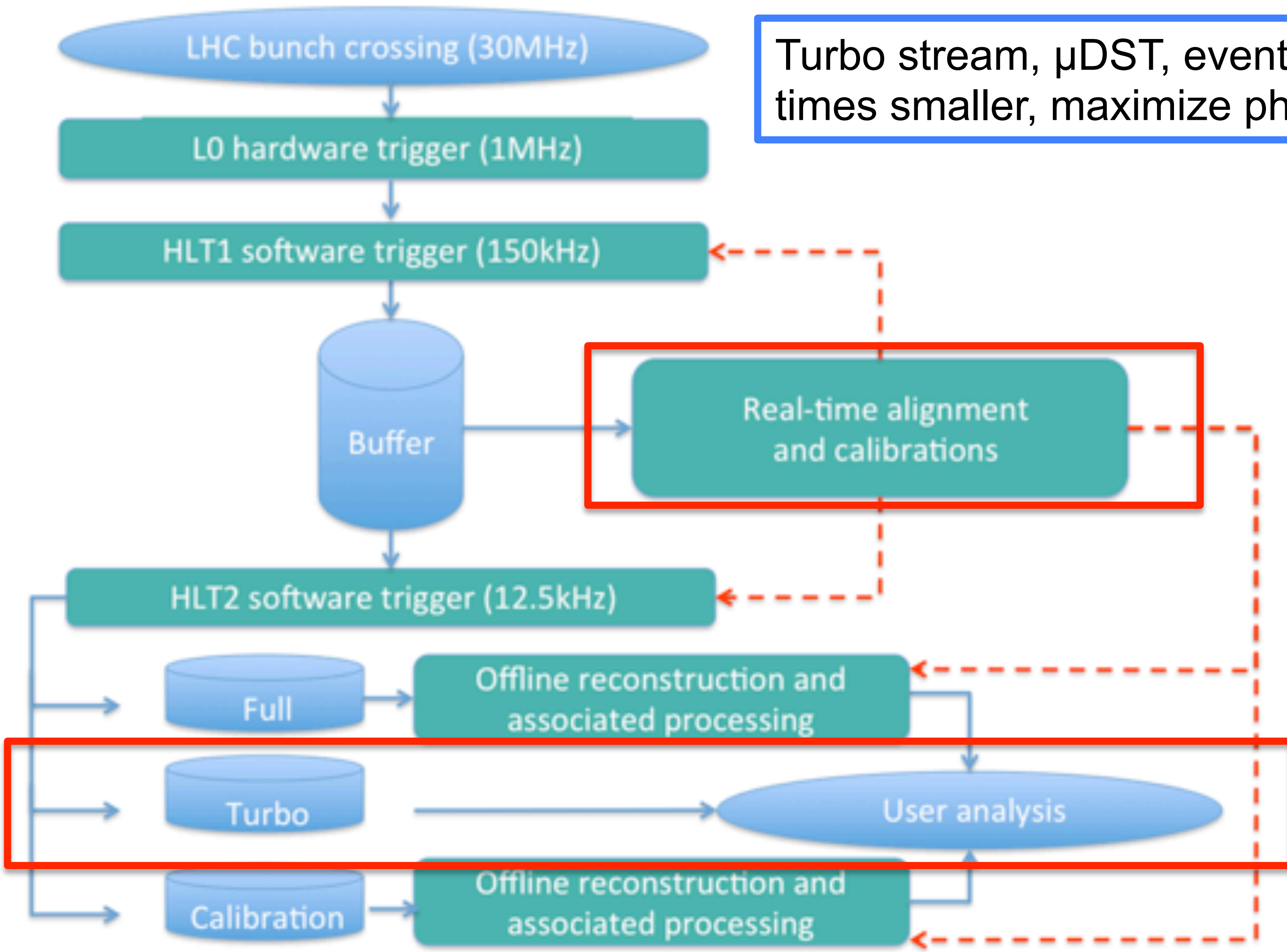


Run-I to Run-II



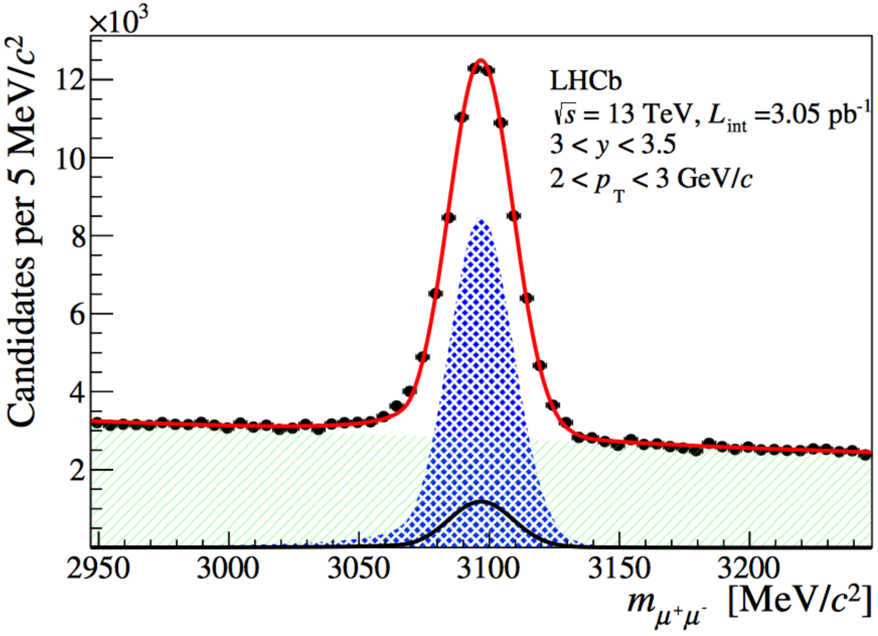
The turbo stream

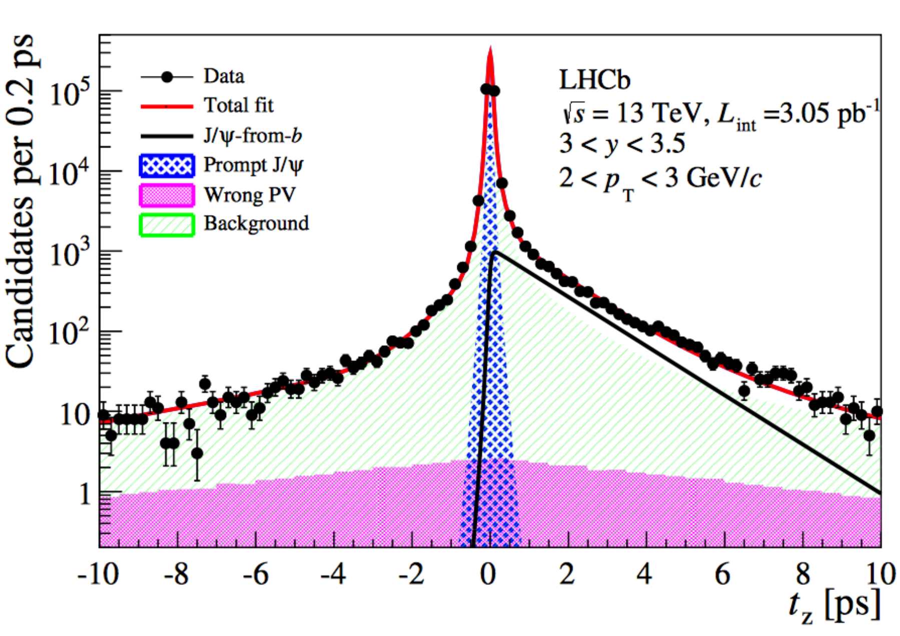
Turbo stream, μDST, event size 10 times smaller, maximize physics output!



Real-time analysis

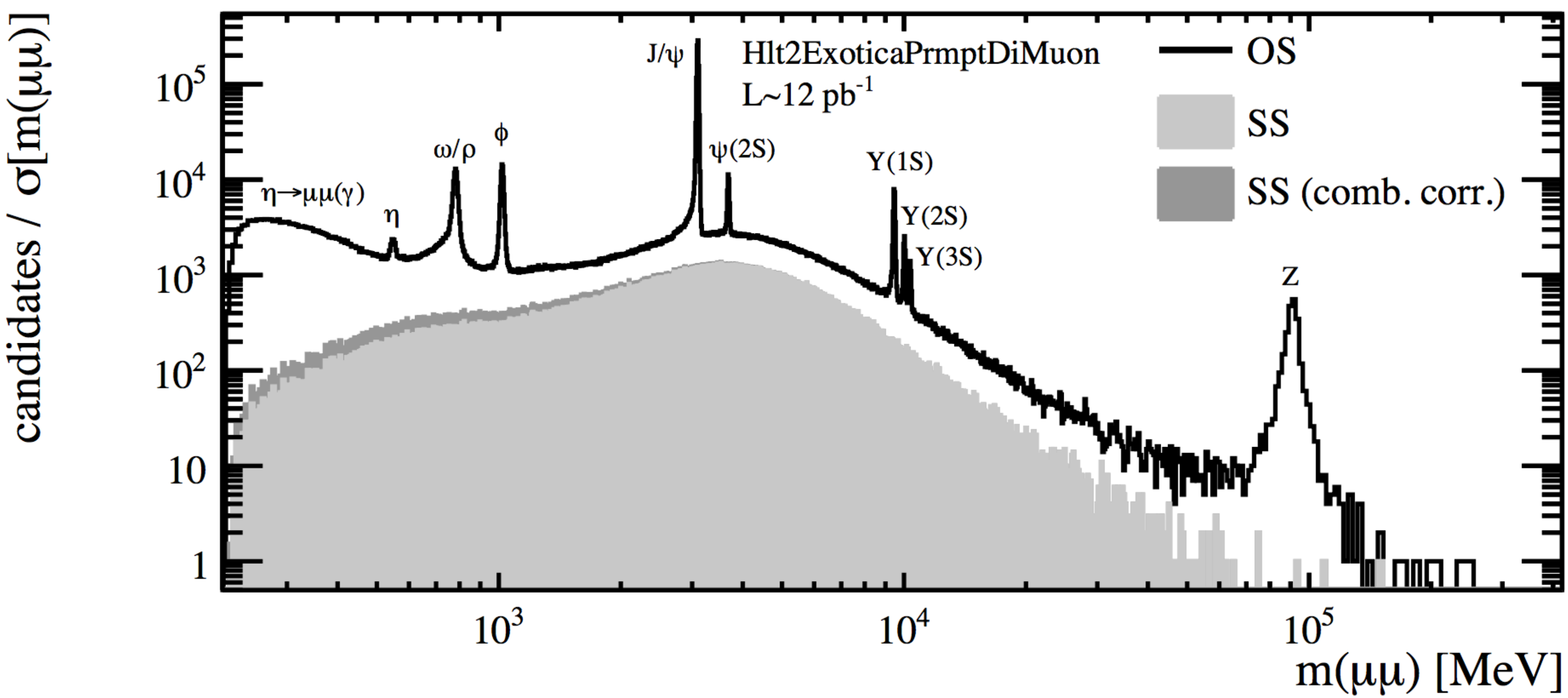
- *J/ψ* production @13 TeV presented within one week of recording the data





Bonus: full dimuon spectrum

- Useful for studies of, e.g., dark photon



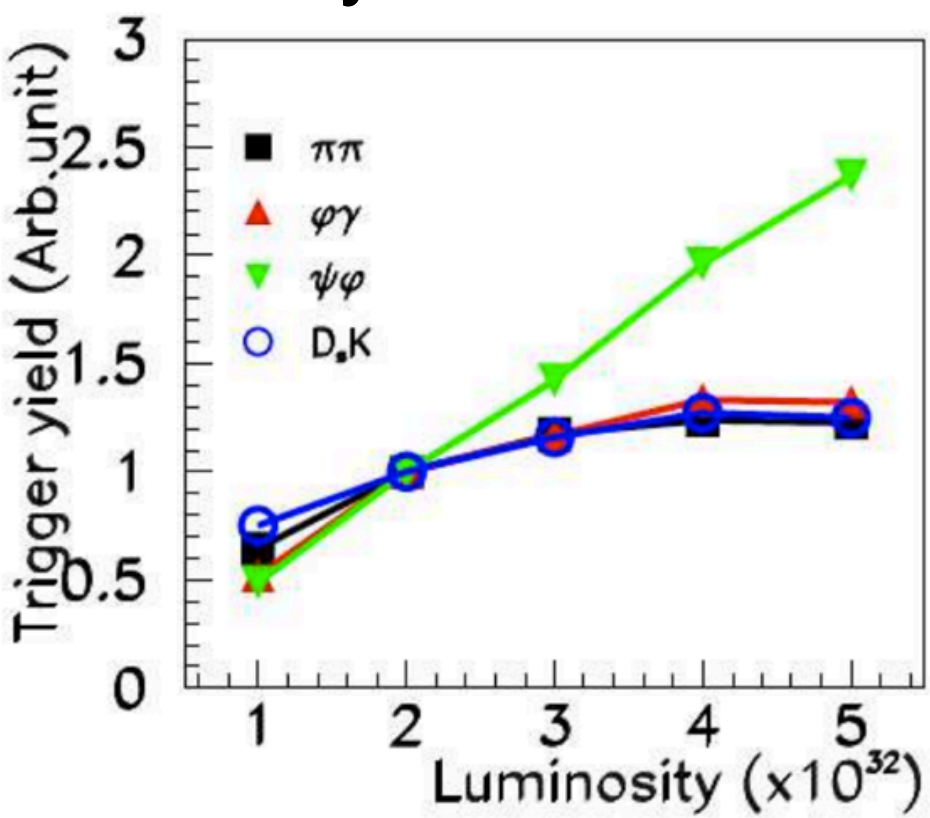
Projections after Run-II

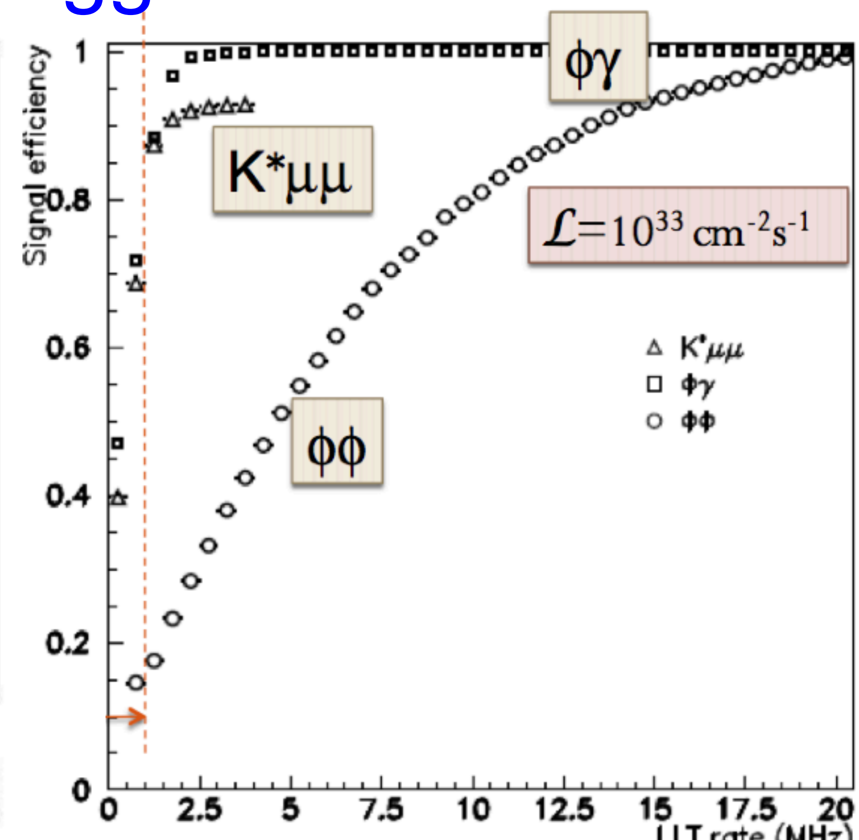
[LHCb, EPJC 73 (2013) 2373]

Type	Observable	Current precision	LHCb 2018	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	∼0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17 [219]	0.045	∼0.01
	a_{sl}^s	6.4×10^{-3} [44]	0.6×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{eff}(B_s^0 \to \phi\phi)$	–	0.17	0.02
	$2\beta_s^{eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$	0.17 [44]	0.30	0.02
Right-handed currents	$2\beta_s^{eff}(B_s^0 \to \phi\gamma)$	–	0.09	<0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\ \text{GeV}^2/c^4)$	0.08 [68]	0.025	0.02
	$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	7 %
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\ \text{GeV}^2/c^4)$	0.25 [77]	0.08	∼0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	∼10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	∼100 %	∼5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	∼10–12° [252, 266]	4°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	–

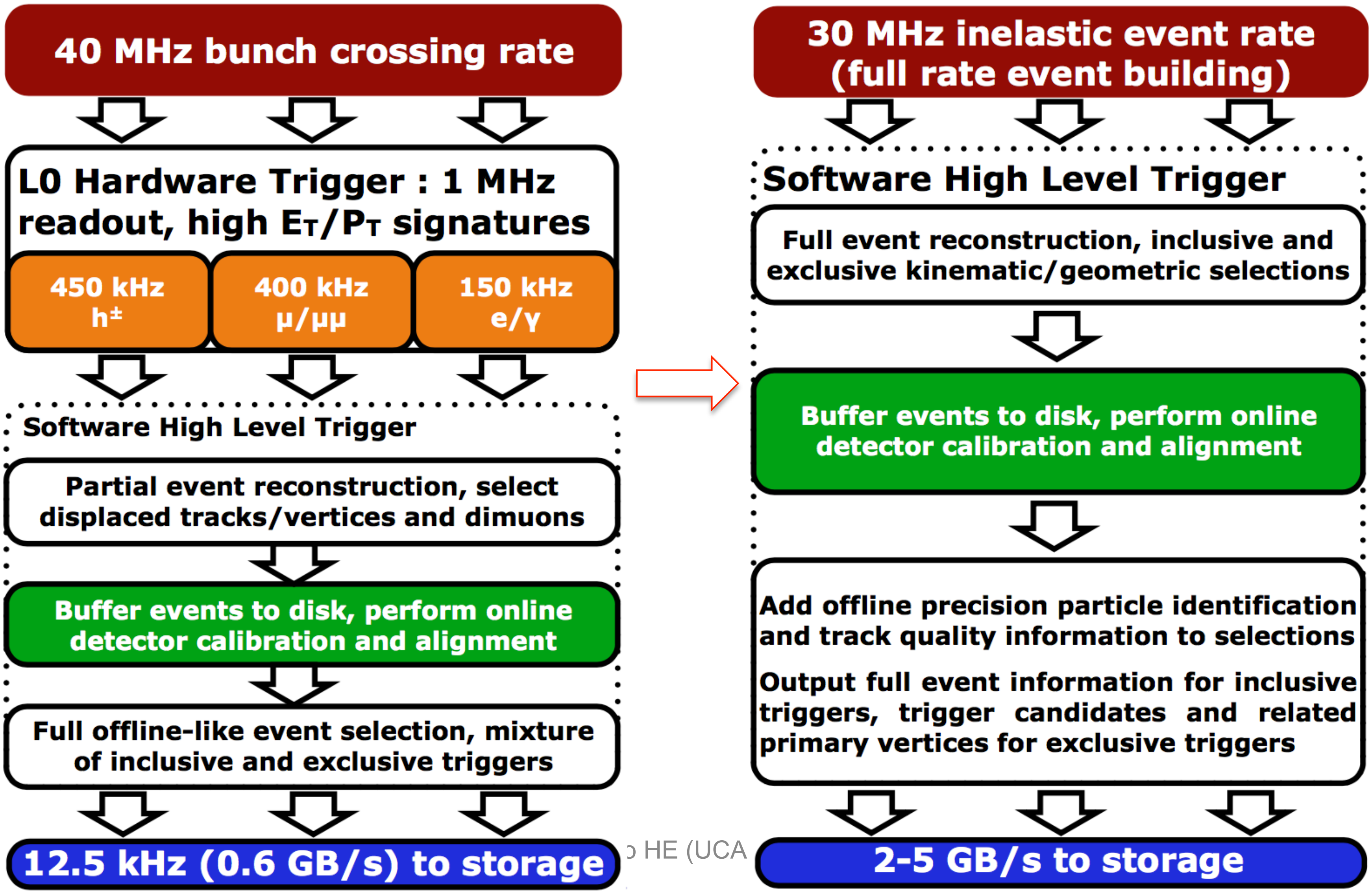
The LHCb upgrade

- Lumi, from $4x10^{32}cm^{-2}s^{-1}$ to $20x10^{32}cm^{-2}s^{-1}$
- Increase trigger efficiency of hadronic decays ➔ hardware trigger removed



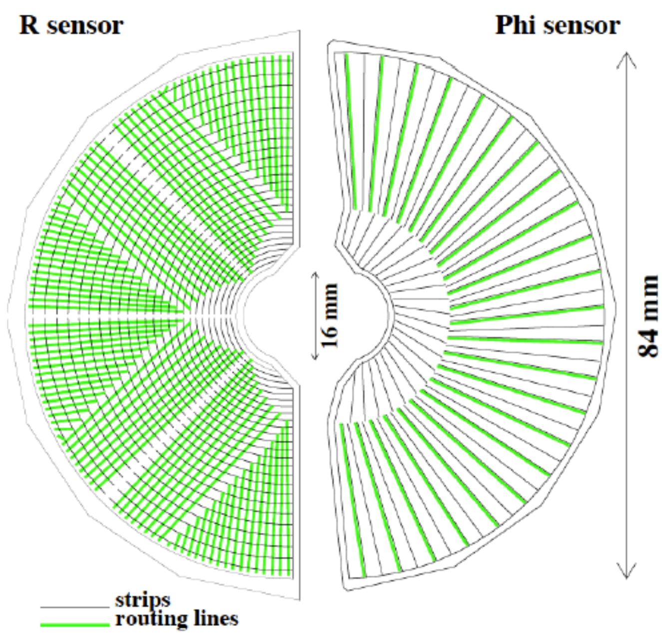


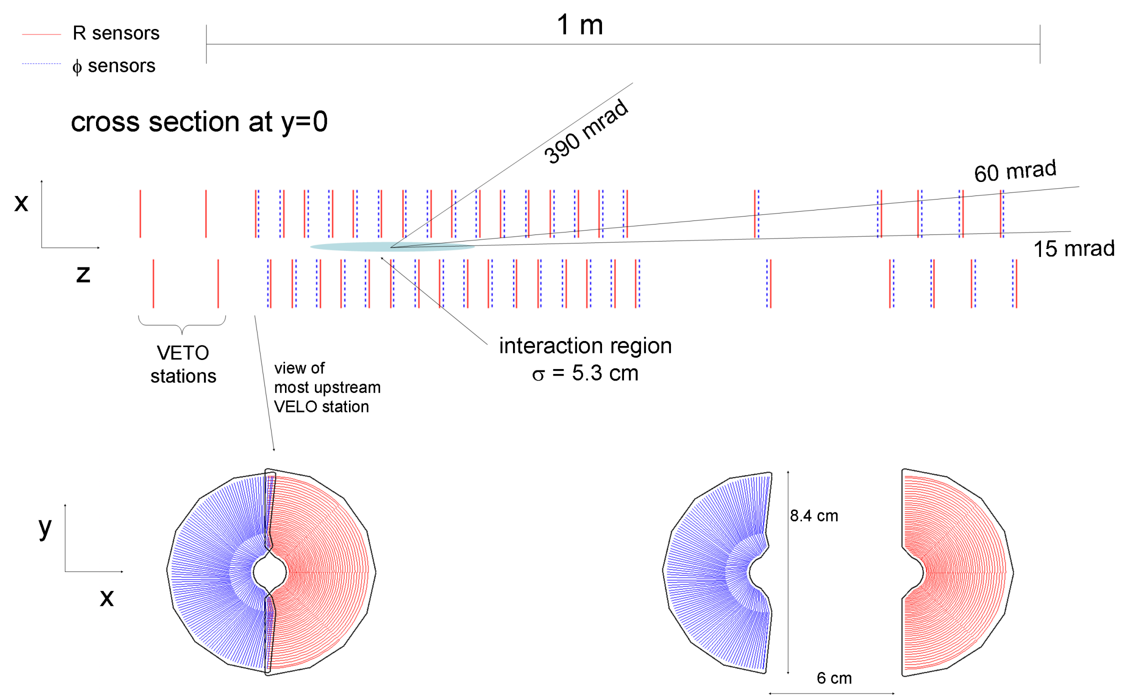
Trigger: run-II to the upgrade



The present VELO

- Present VELO (Vertex Locator) uses microstrip sensors along z
  - Left and right halves can move into/out of the beam, $\langle r_{sens} \rangle \sim 8$ mm
  - Primary (beam) and secondary (VELO) vacuum separated by thin Al box ("RF foil"), inner radius ~ 5.5 mm



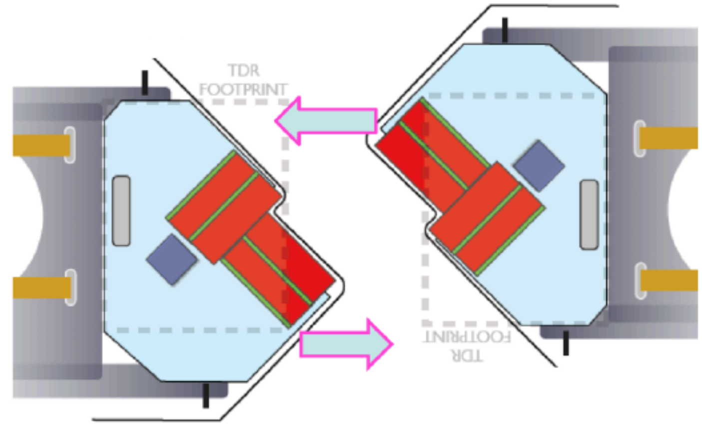


VELO fully closed (stable beam)

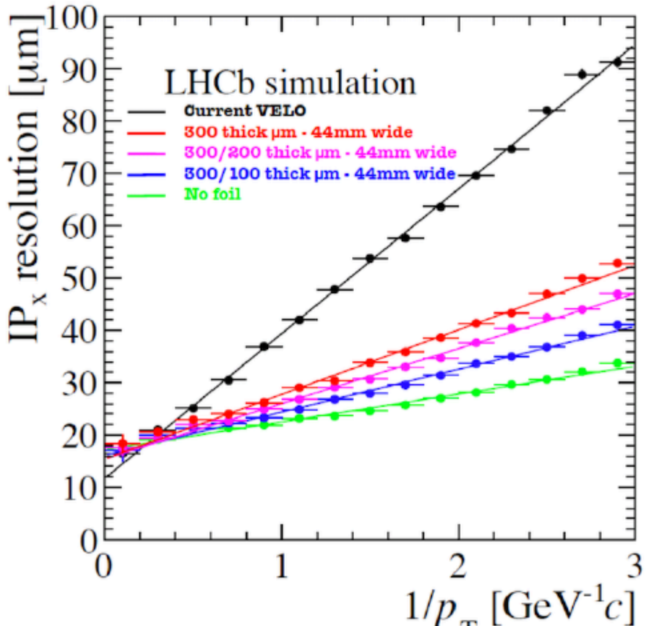
VELO fully open

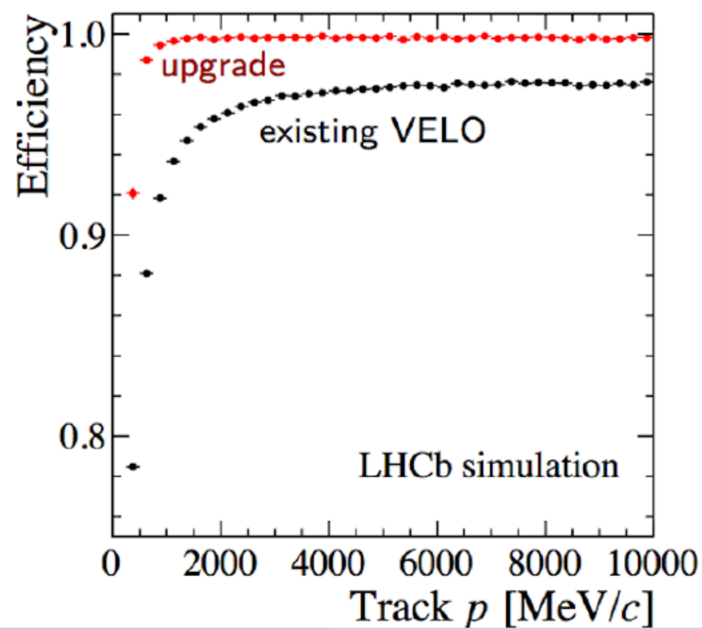
The upgraded VELO

- Upgraded VELO will use hybrid silicon pixel detectors ($55 \times 55\ \mu m^2$), 41 M pixels
  - Thinner RF foil, 150 μm
  - Inner aperture reduced from 5.5 mm $\rightarrow$ 3.5 mm
  - $\langle r_{sens} \rangle \sim 5$ mm



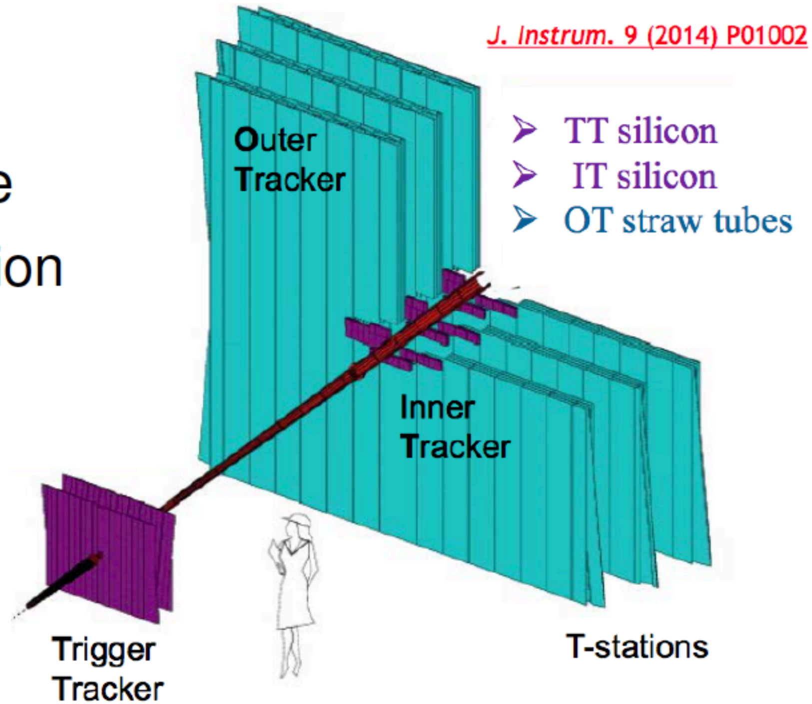
- Improved σ_{IP} and efficiency

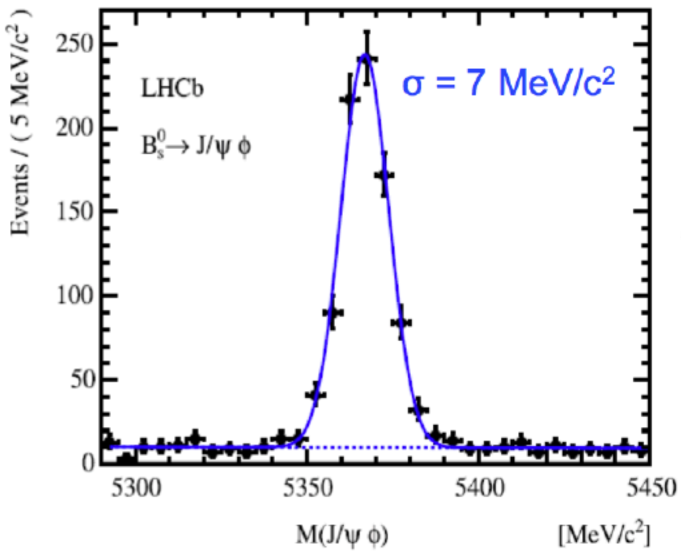


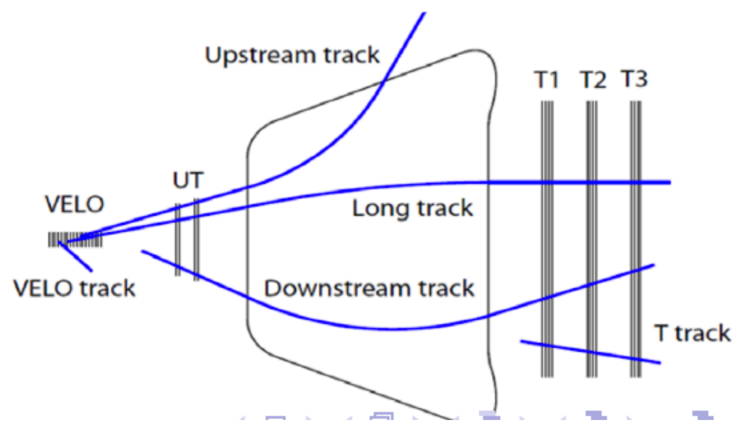


The present tracking system

- TT&IT, silicon; OT: straw tube
- Excellent momentum resolution

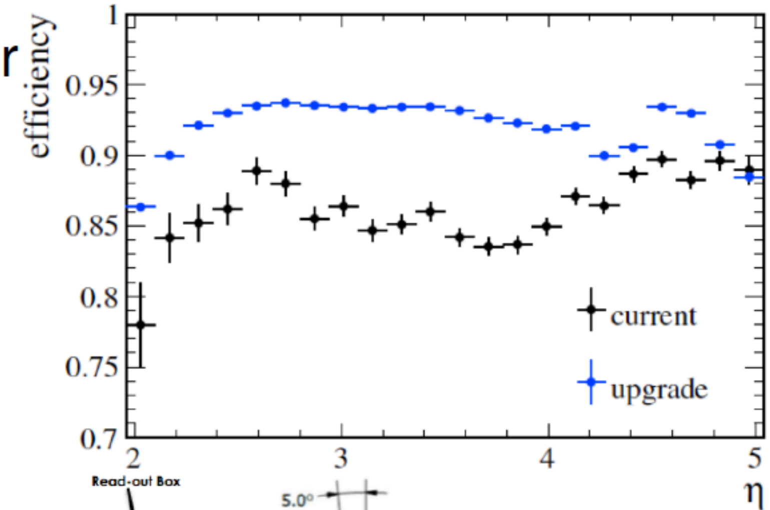


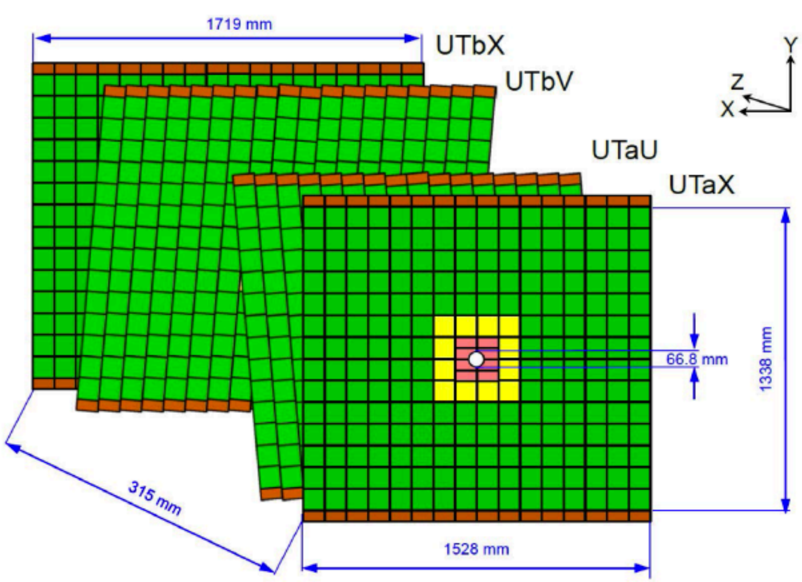


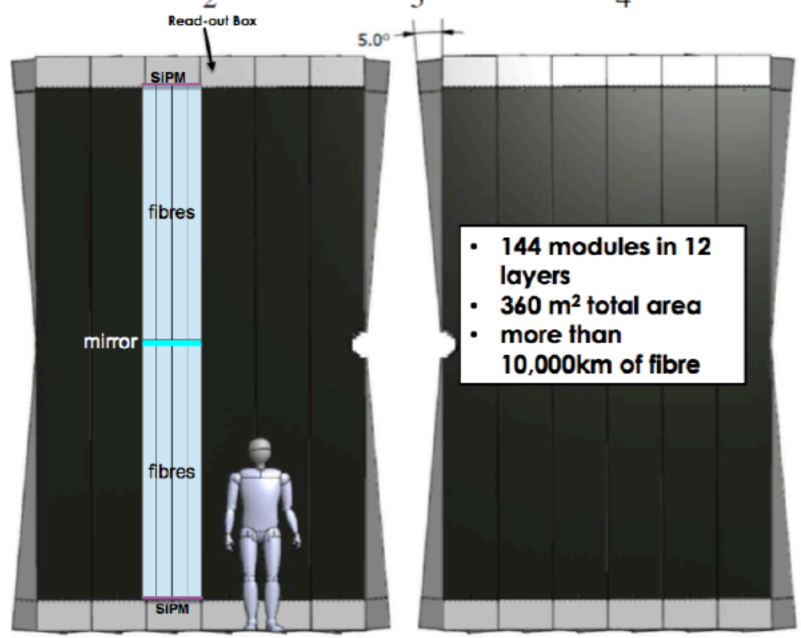


The upgraded tracking system

- TT replaced with Upstream Tracker
- IT+OT replaced with Fibre Tracker
- Improved tracking performance

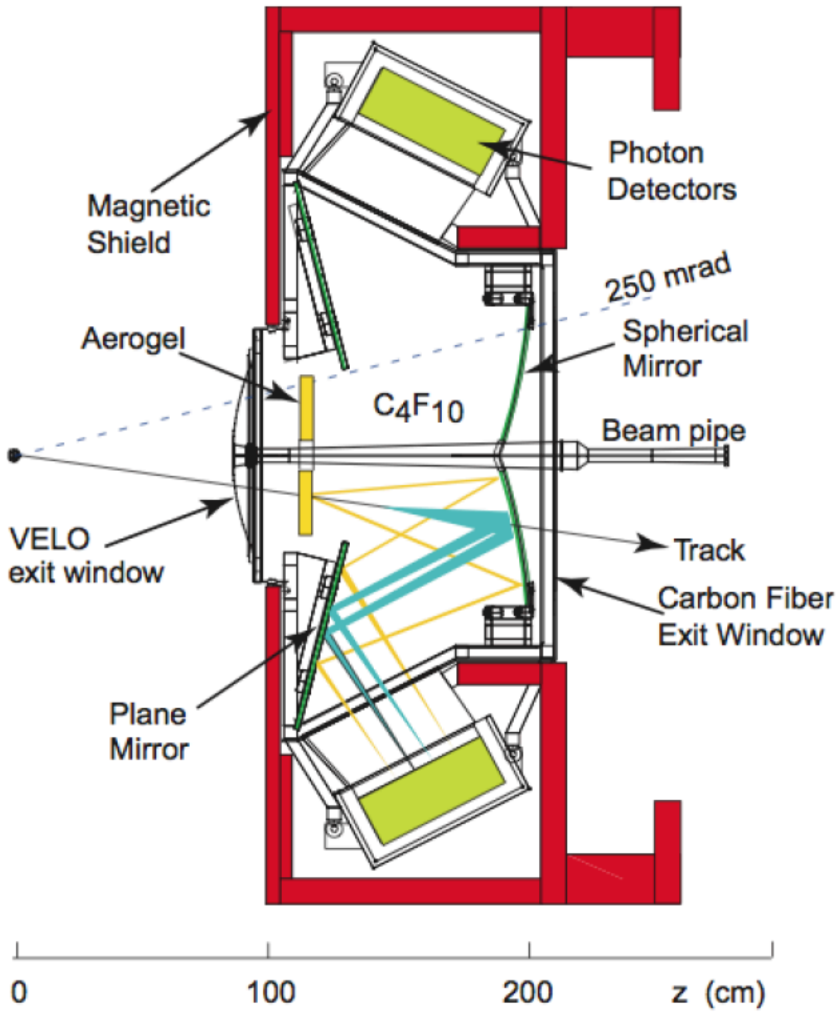


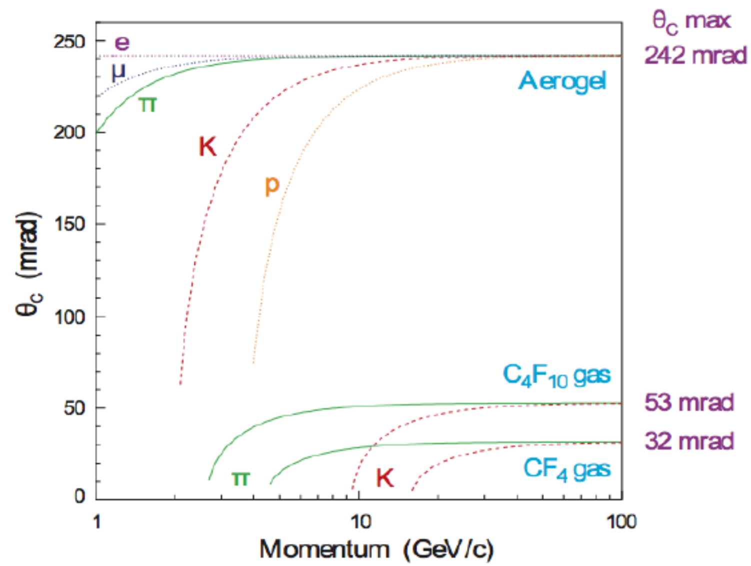


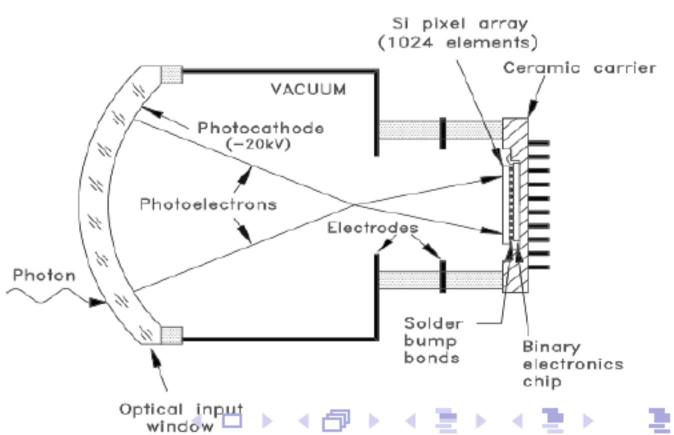


The current RICH

- RICH-1, 30-300 mrad, 2-60 GeV, Aerogel (1.03) + C_4F_{10}(1.0014)
- RICH-2, 10-120 mrad, 16-100 GeV, CF_4(1.0005)



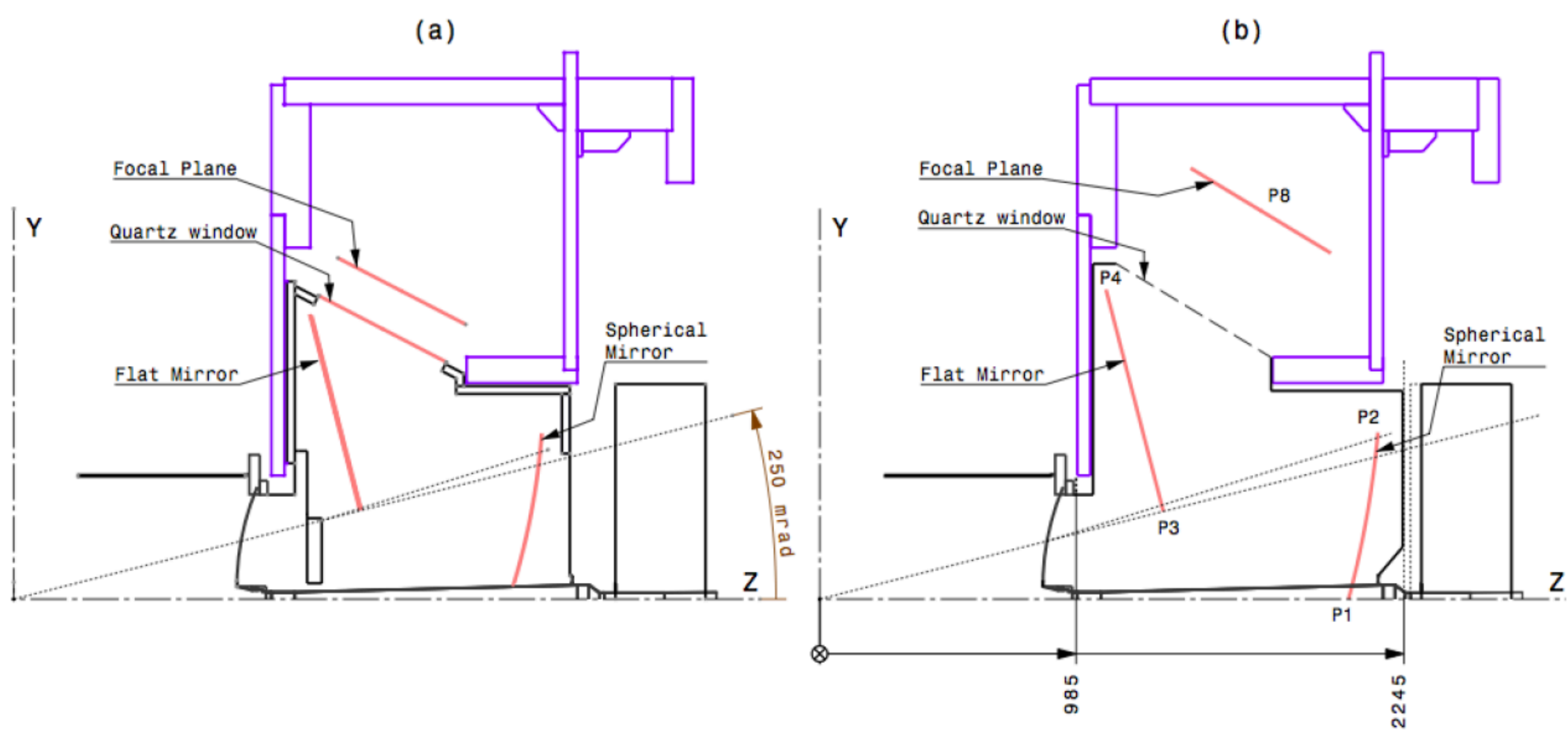




The upgraded RICH

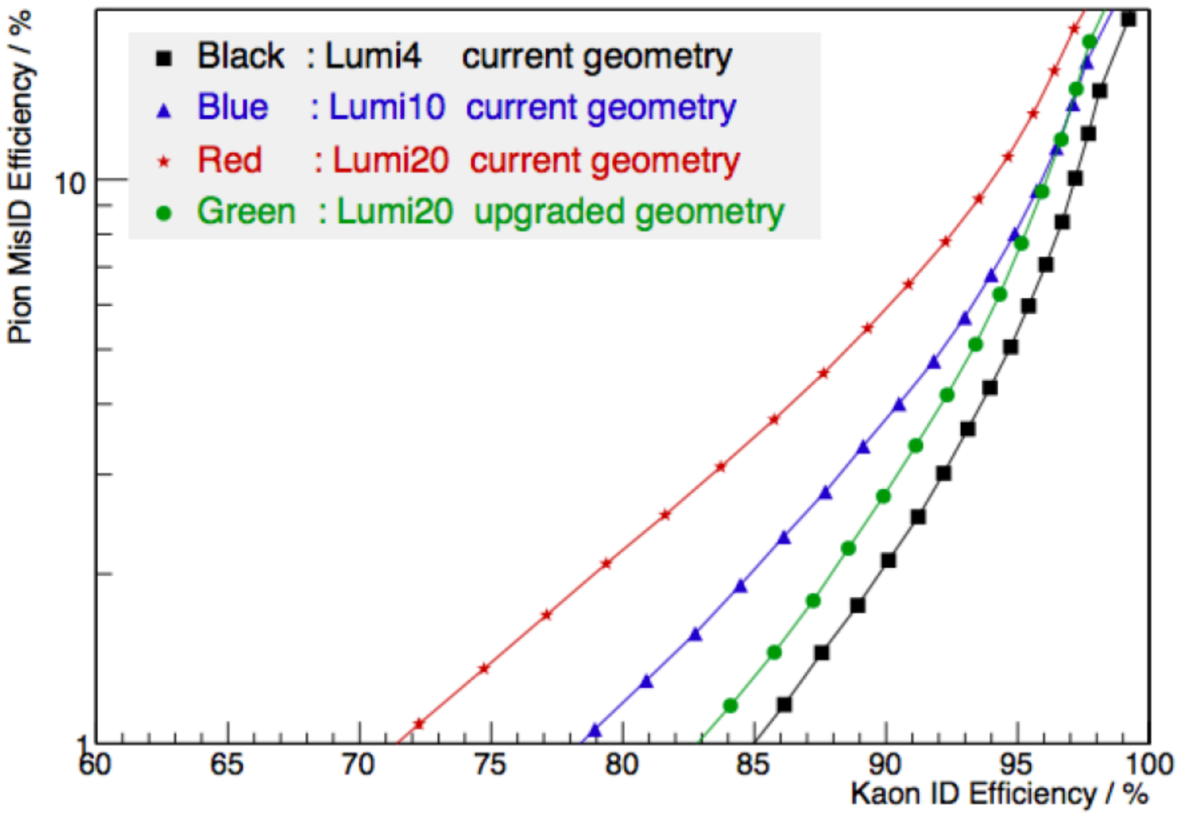
[C. D'Ambrosio *et al.*, LHCb-PUB-2013-011]

- RICH-1, Aerogel removed; RoC of Spherical mirror increased
  - Cherenkov angle resolution improved
  - Radiator length increased ⇒ increased photon yields



The upgraded RICH, PID

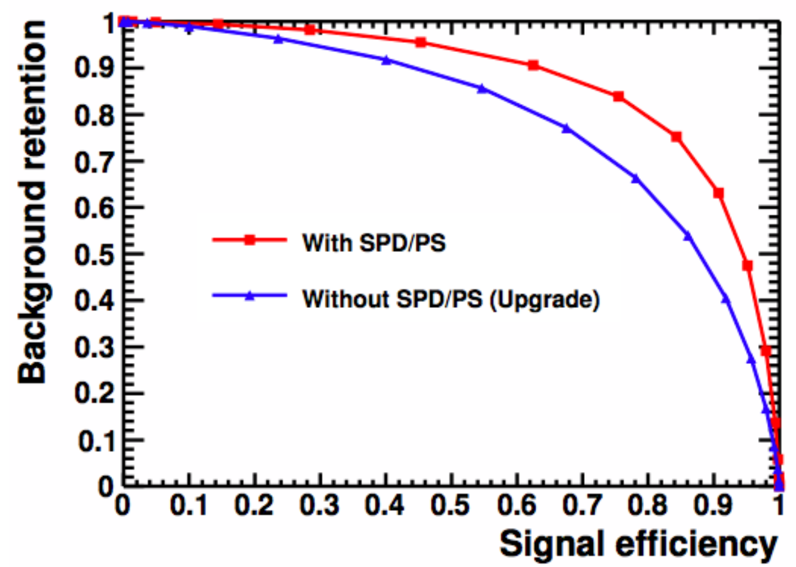
- With improved σ_{ckv} and increased N_{pe}, PID performance improved
  $\Rightarrow$ After upgrade, PID performance at $20 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  similar to the current RICH at $4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$



The upgrade of calorimeters

- Scintillating Pad Detector (SPD) and Pre-Shower (PS) removed
- Degraded γ & lower momentum electron PID
  - Mis-ID rate:

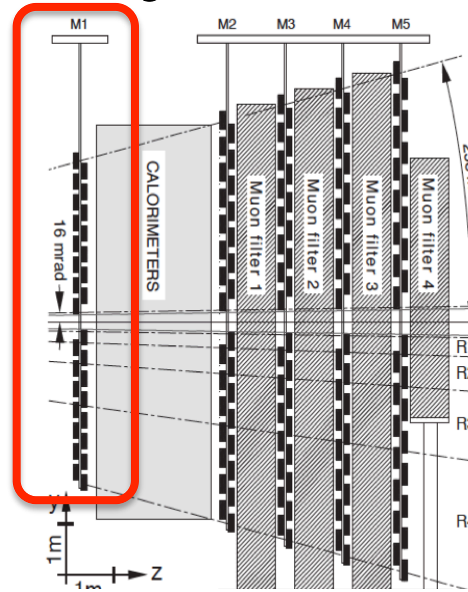
Photon PID

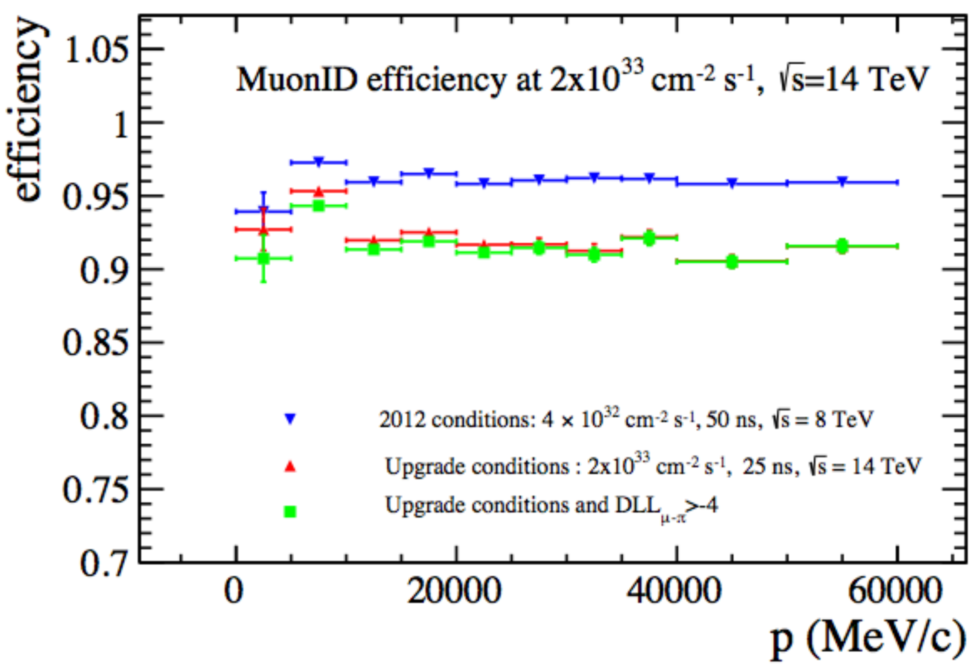


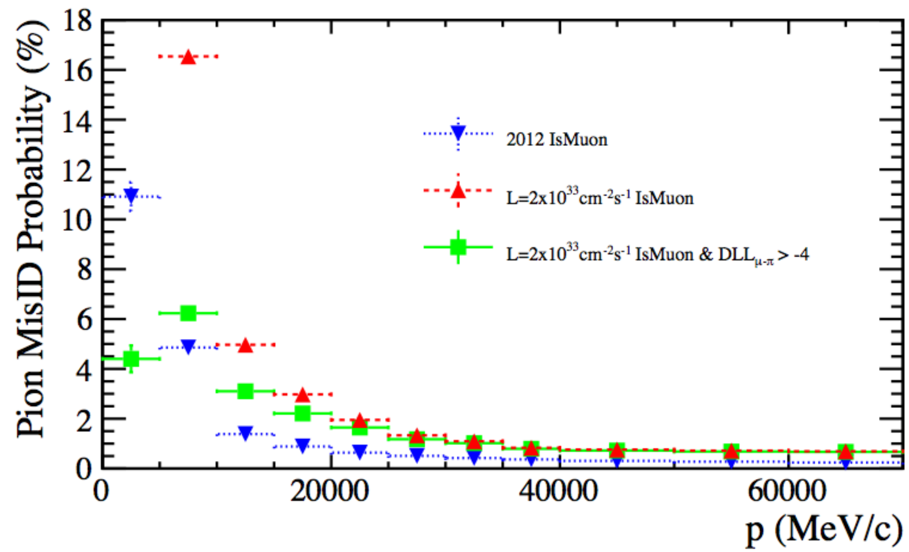
Momentum (GeV/c)	SPD/PS $\nu = 2.0$	SPD/PS $\nu = 3.8$	no SPD/PS $\nu = 3.8$	SPD/PS $\nu = 7.6$	no SPD/PS $\nu = 7.6$
selection efficiency $\varepsilon = 80\%$					
$0 < p < 10$	0.62	0.57	4.6	3.2	9.0
$p > 10$	0.16	0.12	0.16	0.29	0.32
selection efficiency $\varepsilon = 90\%$					
$0 < p < 10$	2.1	2.5	11	12	18
$p > 10$	1.1	0.73	0.72	1.3	1.4

The upgrade of the muon system

- M1 will be removed
- Slightly degraded PID







Projections after the upgrade

[LHCb, EPJC 73 (2013) 2373]

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
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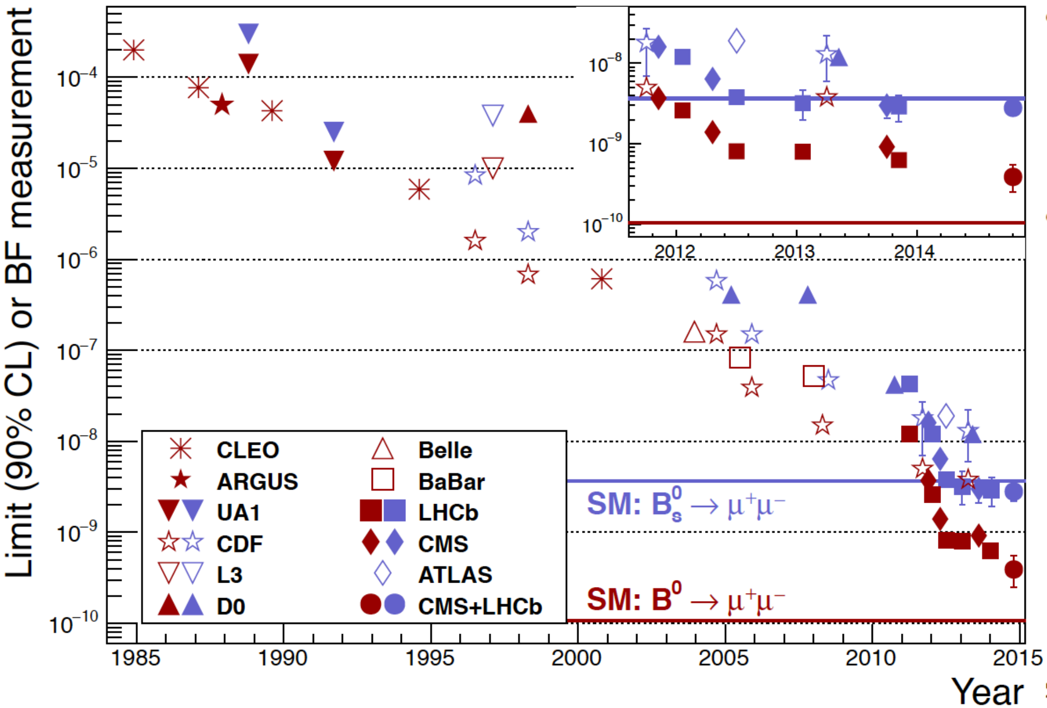
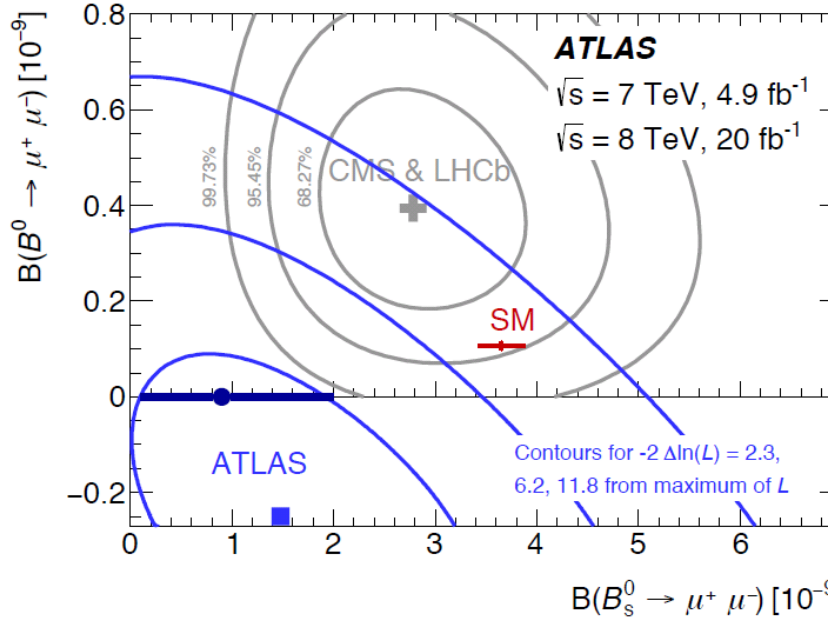
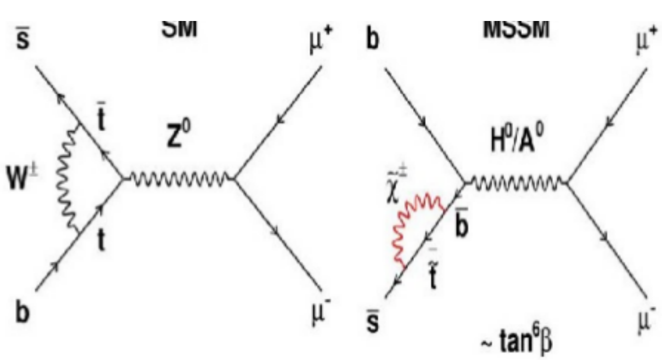
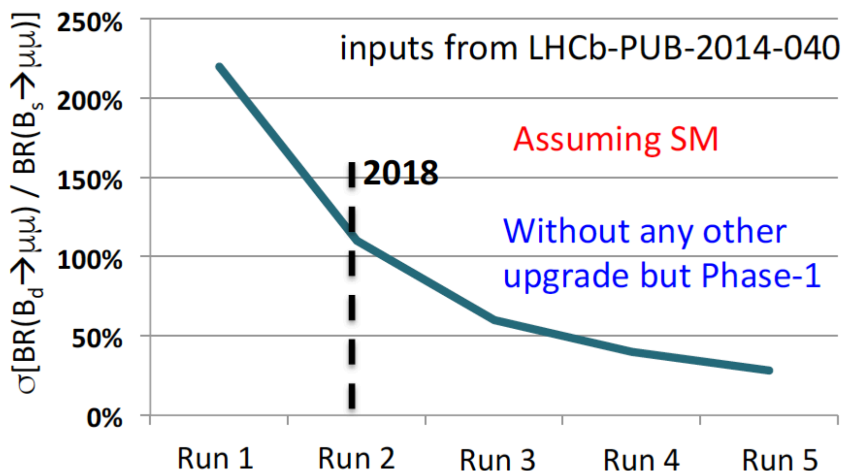
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [77]	0.08	0.025	~0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	~10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~100 %	~35 %	~5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	~10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

$B_{(s)} \rightarrow \mu^+\mu^-$

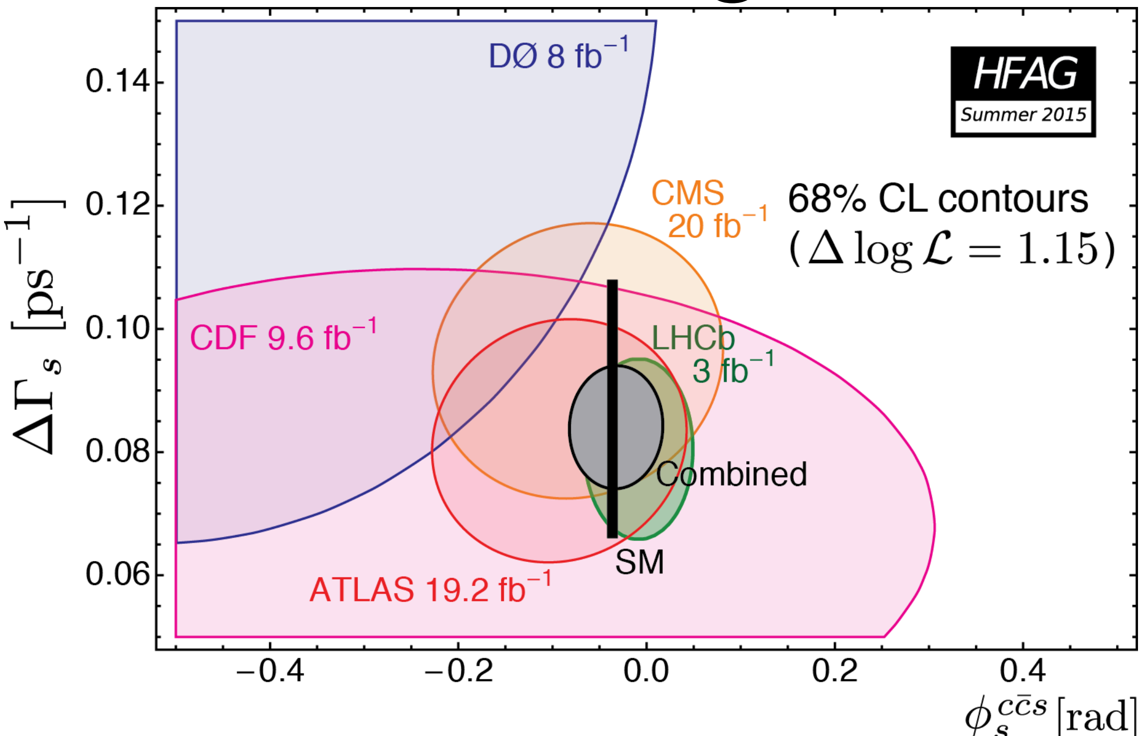


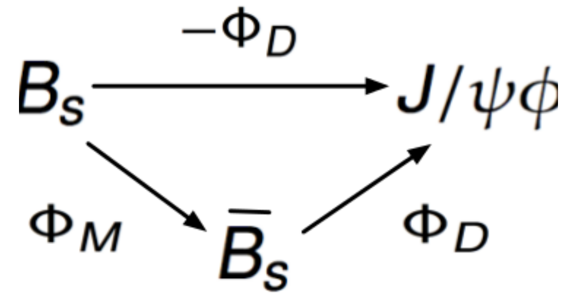






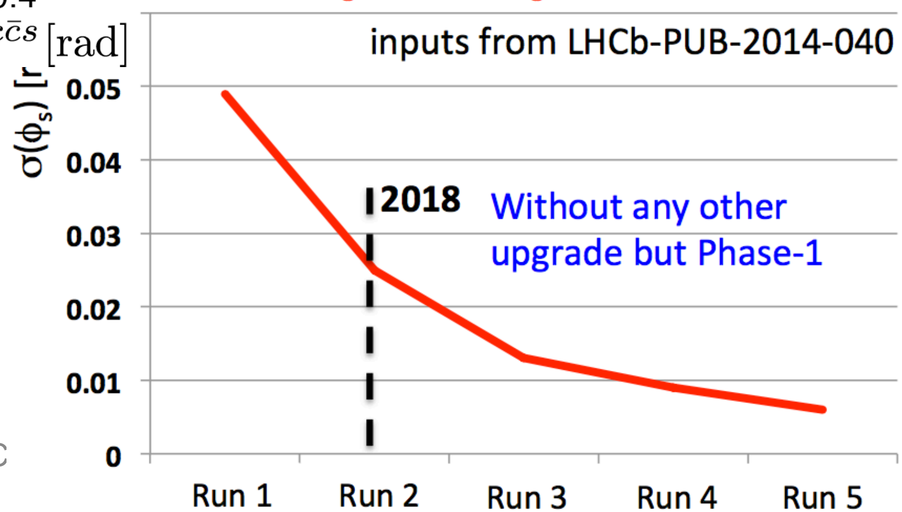
Mixing induced CPV



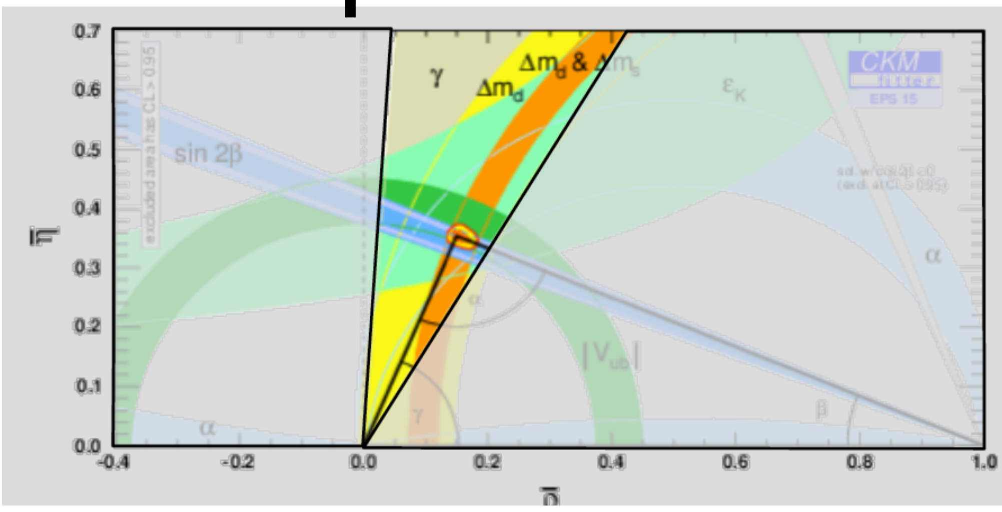


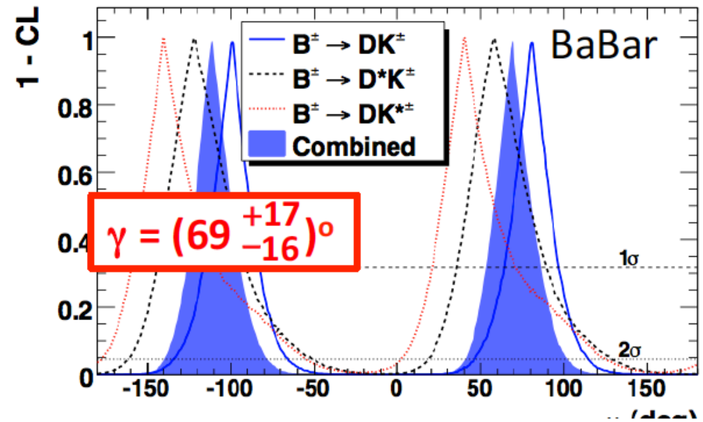
Important to control penguin pollution using SU(3) partner, e.g. $B_s \to J/\psi K^{*0}$

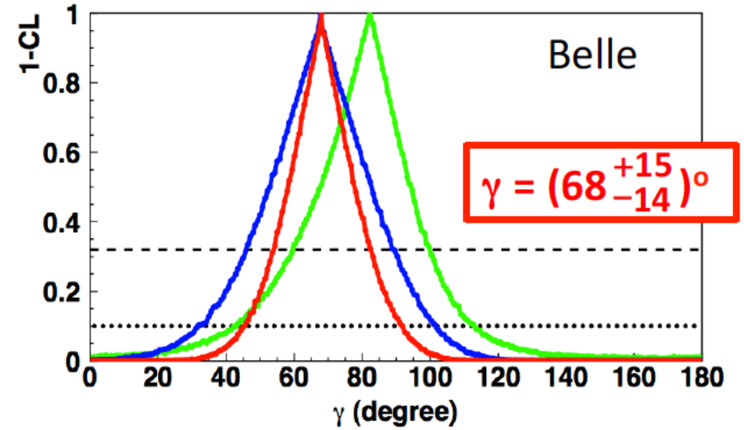
ϕ_s from $B_s \to J/\psi\phi$



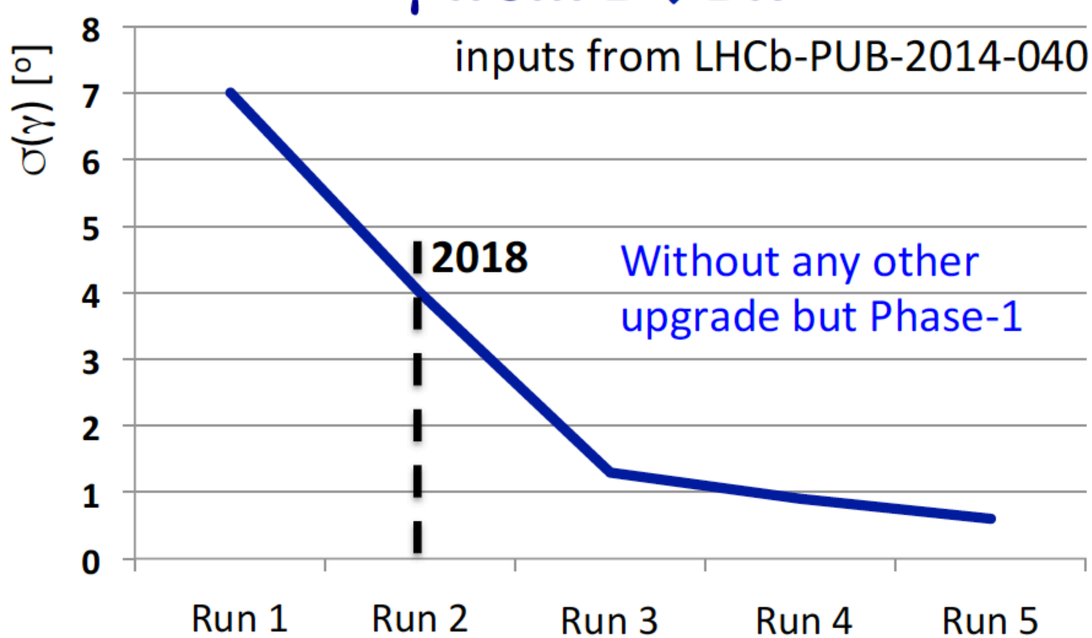
CKM-γ

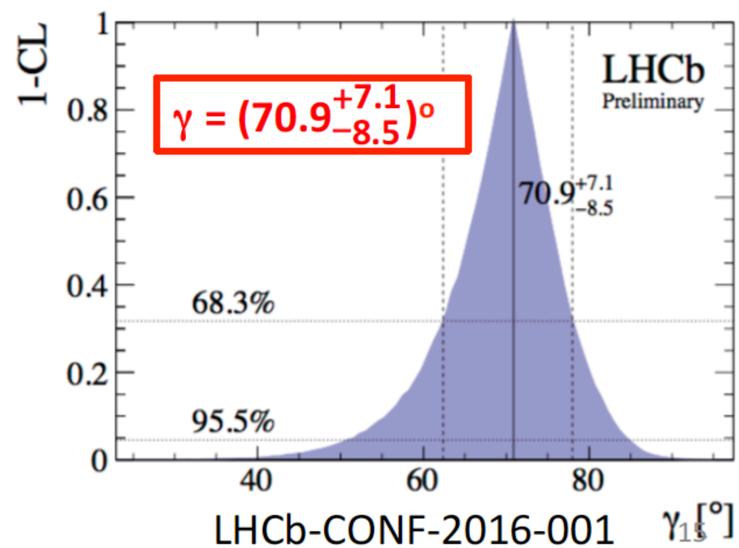






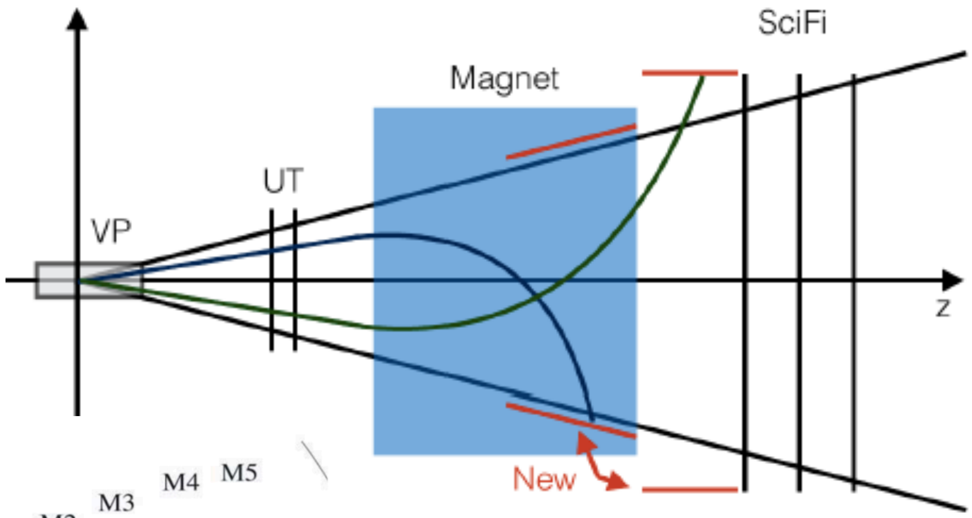
γ from B→DK

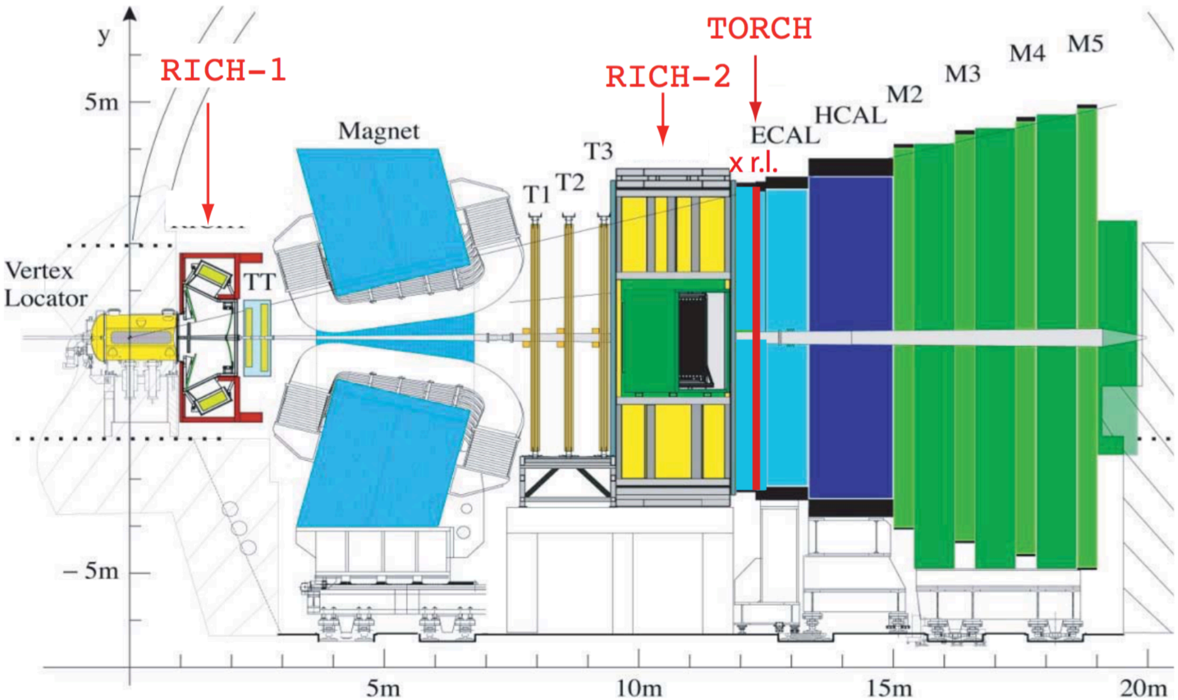




Phase-1b upgrade

- Run at same lumi
- New trackers

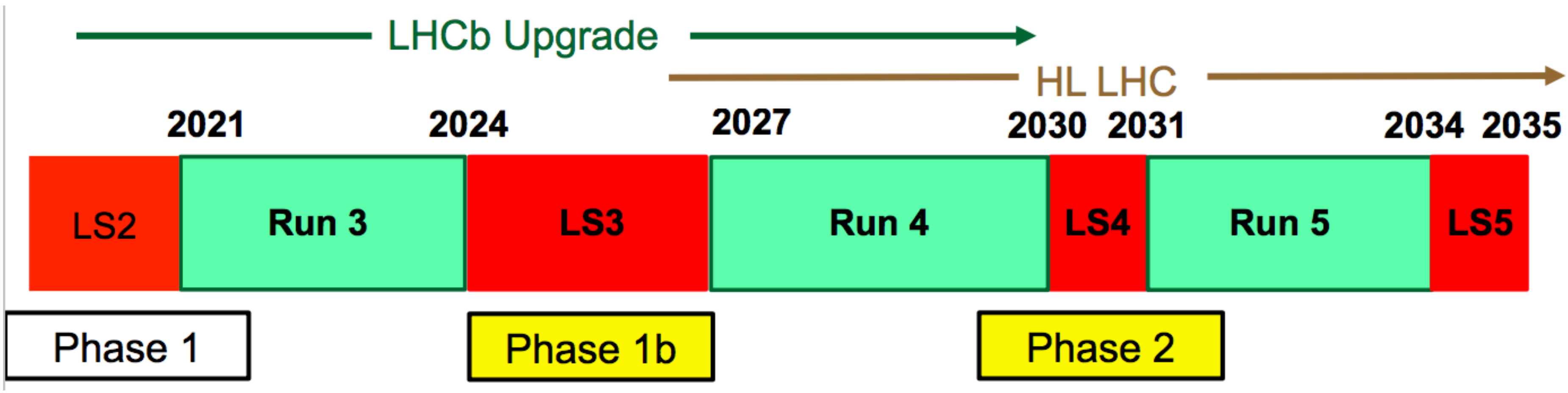




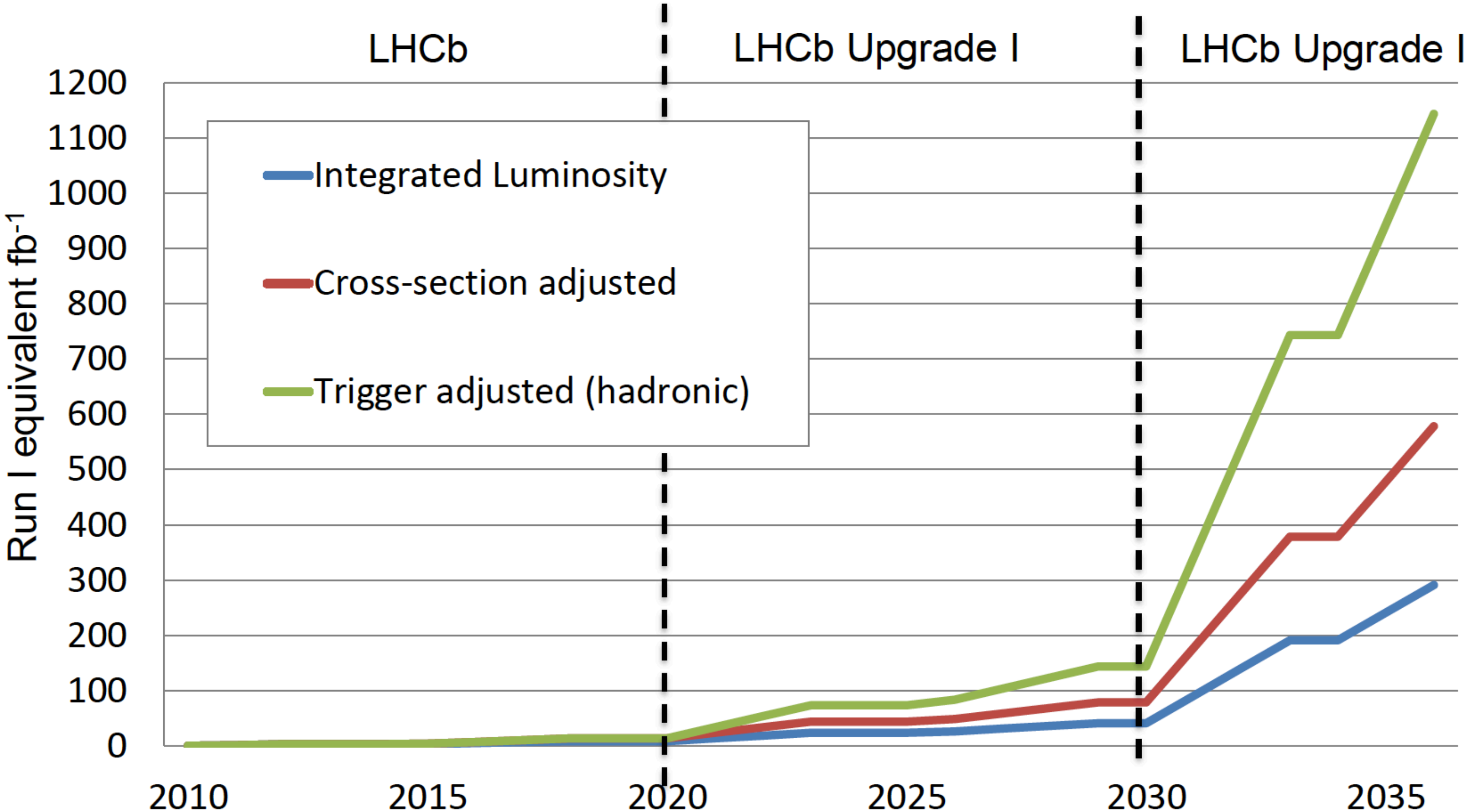
- TORCH for low momentum PID

Phase-II upgrade

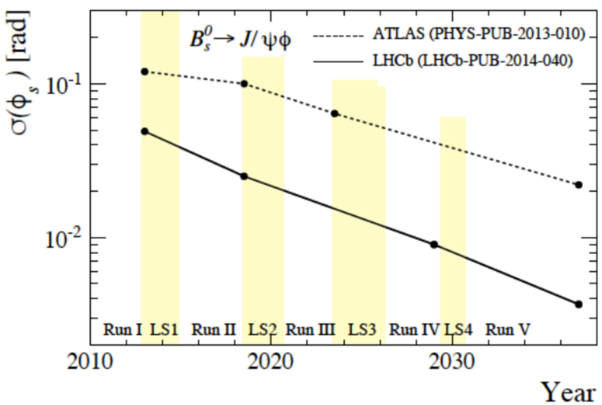
- Under discussions: physics, feasibility
- Lumi: from $2 \times 10^{33} cm^{-2} s^{-1}$ to $2 \times 10^{34} cm^{-2} s^{-1}$
- 4D (timing) detector to mitigate pile-up
- Aim to take 300 fb^{-1}

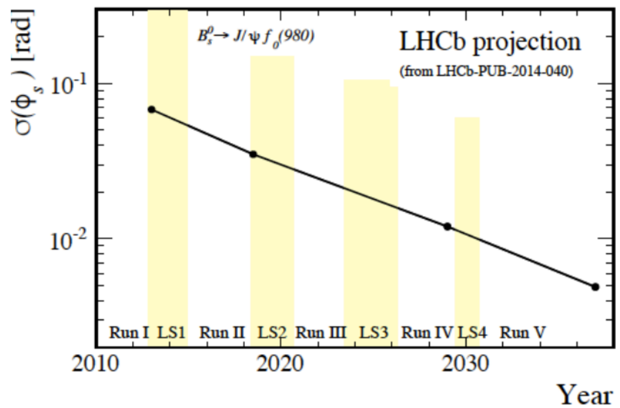


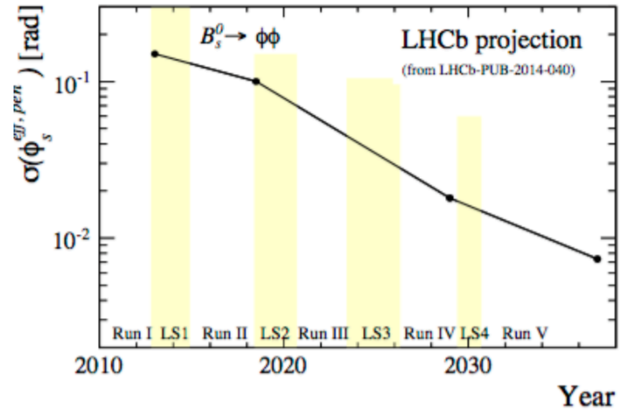
LHCb statistics-timeline

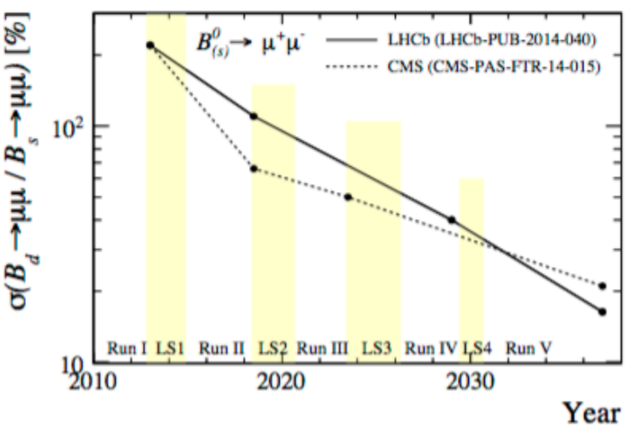


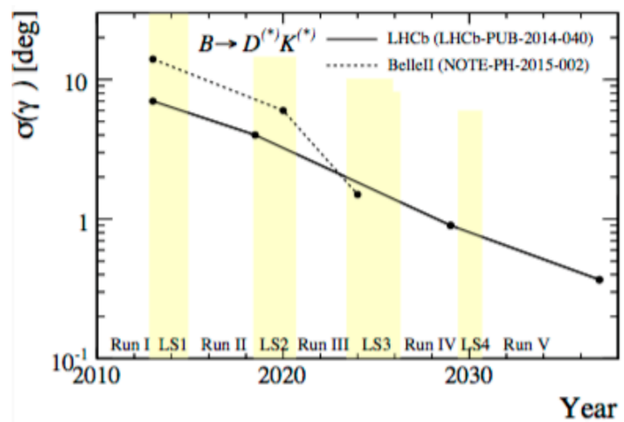
Projections on some key variables

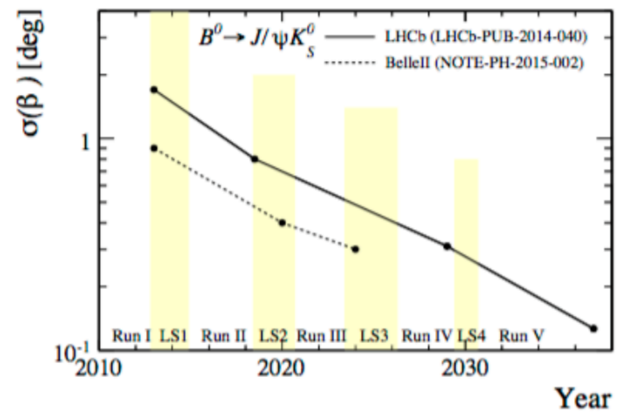








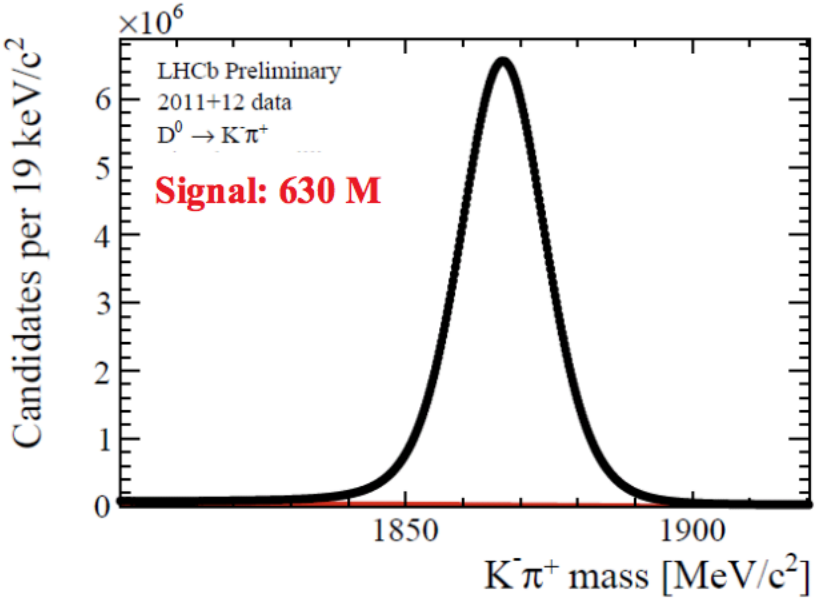




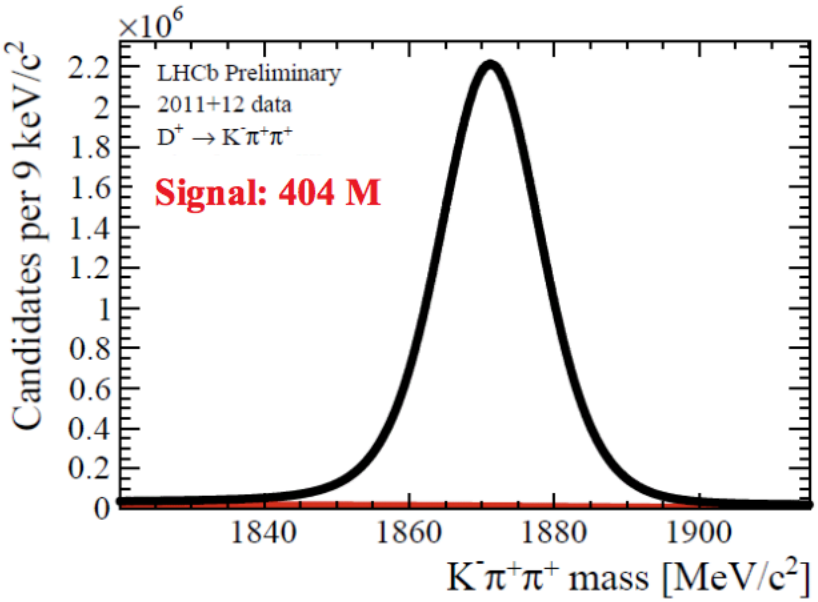
Charm

- Probing the up-sector
- Enormous data-set
- Prospects
  - CPV in mixing (y_{CP},q/p)
  - A_{cp} in $D^0 \rightarrow KK/\pi\pi$, $K_S hh$

Run	σ(x) (10^{-3})	σ(y) (10^{-3})	σ(|q/p|) (10^{-3})	σ(Φ) (mrad)
I	1.22	0.53	59	89
II	0.92	0.37	44	70
III	0.42	0.15	20	33
IV	0.25	0.09	12	20



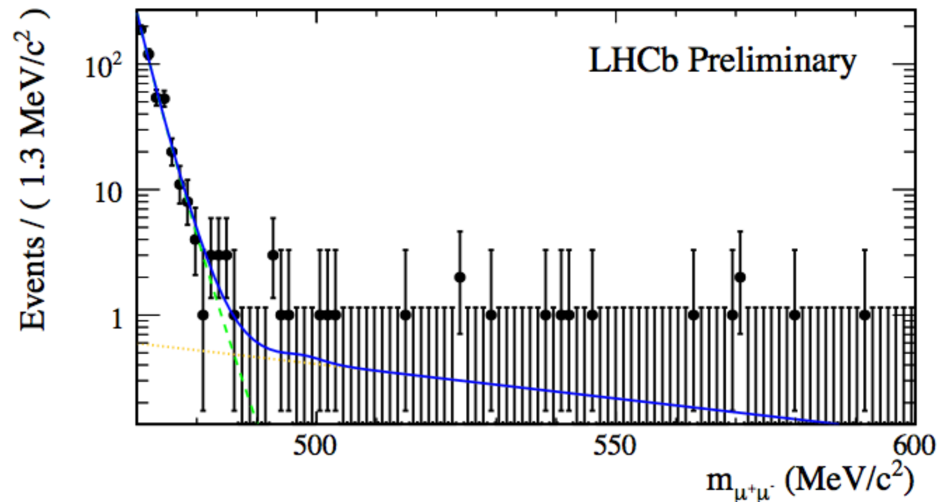
(a) $D^0 \rightarrow K^-\pi^+$

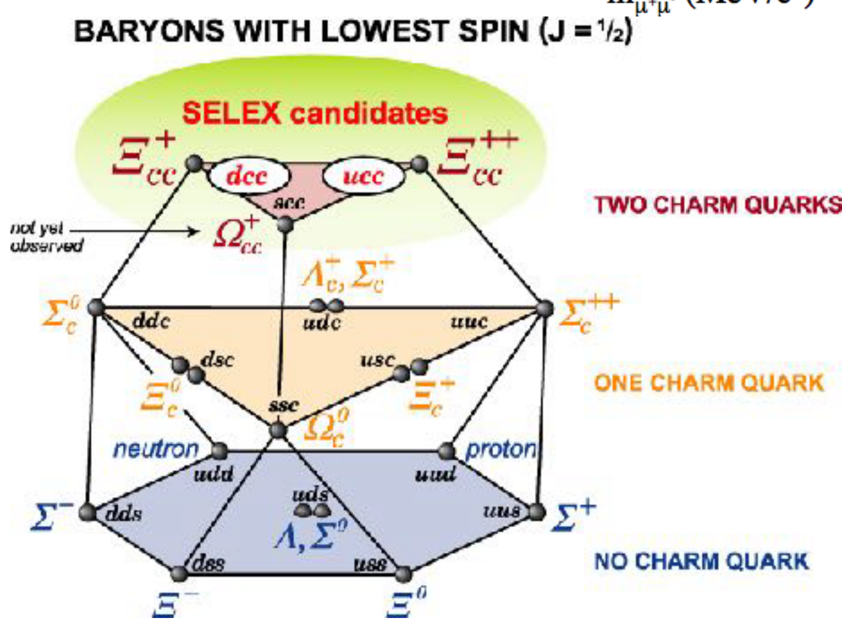


(c) $D^+ \rightarrow K^-\pi^+\pi^+$

Prospects for other measurements

- Strangeness
  - $K_S \rightarrow \mu^+\mu^-$
- *b*-hadrons
  - Excited B_c
- Exotics
  - P_c^+ strange partner $J/\psi\Lambda$





Summary

- LHCb: one of main players on flavor physics
- New trigger strategy in Run-II increases the LHCb physics potentials, e.g., dark photon
- With the ongoing upgrade
  - Indirect search for NP: much improved precision
  - Experimental QCD studies
- Further upgrade (300 fb^{-1}) under discussion
- Inputs from you are always welcome