Future of charm, strangeness, $\tau^{\pm}$ at LHCb

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HL/HE LHC meeting

Fermilab, April 5, 2018

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

LHCb

erc European Research Council
Established by the European Commission

General aspects for a HL/HE LHCb

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
		Run III						Run IV					Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE Phase I		$L = 2 \times 10^{33}$			LHCb Consolidation			$L = 2 \times 10^{33}$ 50 fb^{-1}			LHCb Ph II UPGRADE *		$L = 2 \times 10^{34}$ 300 fb^{-1}	
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$			ATLAS Phase II UPGRADE			HL-LHC $L = 5 \times 10^{34}$			ATLAS		HL-LHC $L = 5 \times 10^{34}$	
CMS Phase I Upgr		300 fb^{-1}			CMS Phase II UPGRADE						CMS		3000 fb^{-1}	
Belle II		5 ab^{-1}	$L = 8 \times 10^{35}$		50 ab^{-1}									

$\times 10$ particle multiplicity
$\times 10$ vertex multiplicity
$\times 10$ radiation

Many challenges ahead

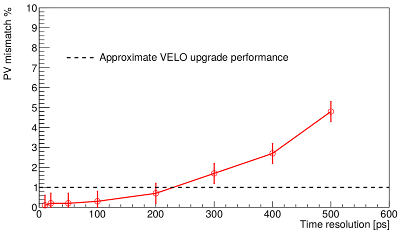
- Improve tracking system/trigger to fit in timing constraints
- Maintain or improve the current resolutions (mass, impact parameter, p_T, ...)
- Development of faster simulation methods

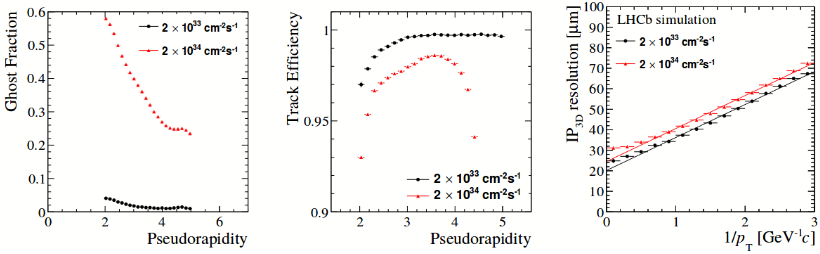
Tracking performance

$\mathcal{L} \times 10$ is challenging for tracking:

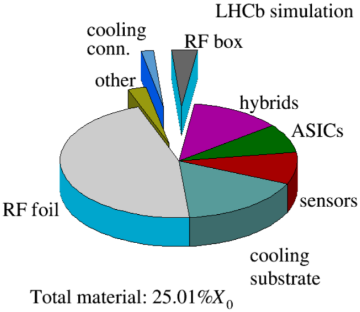
- Expected pile-up ~ 50
- Selection of b and c hadrons is based on the flight distance
- Requires correct association of production vertex and decay vertices
- 13% mismatching for b-hadron decays if we keep the Phase-I Upgrade configuration
- With a track hit time resolution of ~ 200 ps, we recover the current levels

[CERN-LHCC-2017-003]





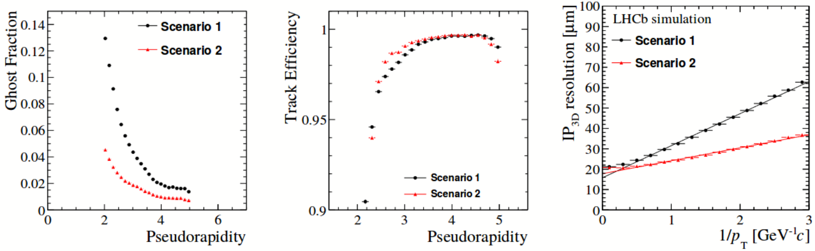
The VELO RF foil



- The RF foil separates VELO vacuum from primary LHC vacuum
- Isolates sensors from radio-frequency pickup
- Introduces a lot of material right in front of the interaction point
- Increases the resolution on the impact parameter due to multiple scattering

Removal of the VELO RF foil

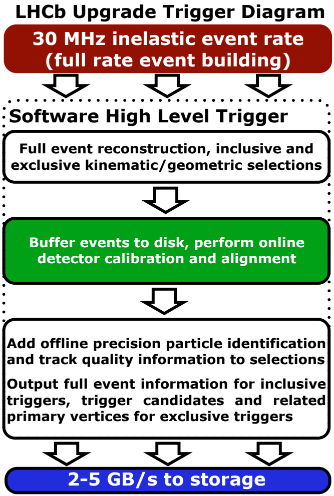
- A lot of effort has been put on reducing the amount of material
- For charm and τ decays (and partially reconstructed B decays), the impact parameter resolution is crucial
- RF foil removal is risky, but the improvement is very big!



[CERN-LHCC-2017-003]

Scenario 1: With RF foil **Scenario 2**: No RF foil

Improvements on the trigger



For the Phase-I Upgrade:

- Loose E_T and p_T cuts, increase the efficiencies to study soft processes (charm, strange and τ decays)
- Dynamic mix of inclusive and exclusive lines
- Only the requested information from the event is saved [arXiv:1604.05596]
- More efficient particle identification and reconstruction algorithms
- Efficiencies up to $\sim 90\%$ are possible

For Phase-II...

- Tighter throughput constraint
- Maybe need to restructure the trigger
- Usage of GPUs, FPGAs, etc... for simple processes

Interest on charm decays

- Charmed hadrons provide the only way to study CP violation (CPV) with up-type quarks
- After the Phase-II Upgrade, LHCb will have recorded the largest sample of charm hadrons ever
- This would constitute over 2 orders of magnitude of what is expected for Belle II in $D^0 \to h^+h^-$, $D^0 \to K^0_S h^+h^-$ $(h = \pi,\ K)$
- To study CPV, huge statistics needed for both real data and simulated samples

Direct CP violation

$$A_{\text{CP}} \equiv \frac{\Gamma_{D^0\to f} - \Gamma_{\bar{D}^0\to \bar{f}}}{\Gamma_{D^0\to f} + \Gamma_{\bar{D}^0\to \bar{f}}}$$

CP violation in $D^0 \leftrightarrow \bar{D}^0$ mixing

$$D_1 = p\,|D^0\rangle - q\,|\bar{D}^0\rangle$$

$$D_2 = p\,|D^0\rangle + q\,|\bar{D}^0\rangle$$

$m_i \Rightarrow$ mass of D_i

$$x \equiv \frac{m_1 - m_2}{\Gamma}$$

$\Gamma_i \Rightarrow$ decay width of D_i

$$y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

CP violation in the interference mixing-decay

$$\phi \equiv \arg\left(\frac{q}{p}\right)$$

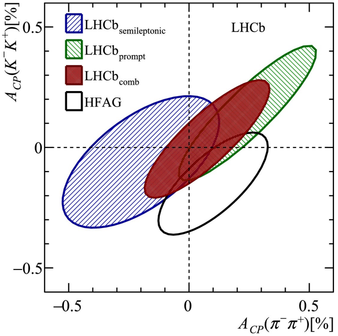
Direct CPV

- Direct CPV is not so cleanly predicted, smaller than $\sim 10^{-3}$ [arXiv:1608.06528], close to the current sensitivity.
- LHCb has the best measurements of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ asymmetries:

$$A_{\text{CP}}(D^0 \to K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{\text{CP}}(D^0 \to \pi^+\pi^-) = (0.07 \pm 0.14 \pm 0.11)\%$$

- The main systematic comes from the statistics of the control samples, like $D^+ \to K^0_S\pi^+$



[Phys.Lett. B 03 (2017) 62]

For Phase-II Upgrade

$$\sigma(A^{\pi\pi}_{\text{CP}} - A^{KK}_{\text{CP}}) \sim 10^{-5}$$

Opportunity to measure CP asymmetries with charmed baryons:

- Λ_c^+ sensitivity $\sigma(A_{\text{CP}}) \sim 10^{-4}$
- Ξ_{cc}^{++} sensitivity $\sigma(A_{\text{CP}}) \sim 10^{-3}$

Indirect CPV

- CPV in mixing-related phenomena are predicted to be $\sim 10^{-4}$ or less [arXiv:1510.05797]
- Direct access to CPV observables like x, y, $|q/p|$ and ϕ
- Current results are limited by statistics
- Improving the K_S^0 reconstruction would help to study $D^0 \to K_S^0 h^+ h^-$

For Phase-II, the expectation is to bring these parameters down to:

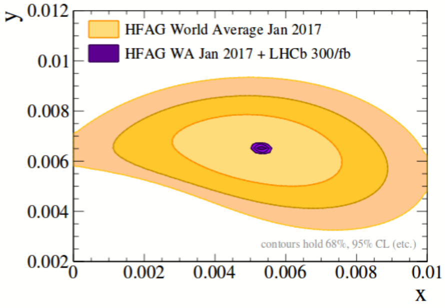
$$\sigma(x) \sim 10^{-5} \qquad \sigma(y) \sim 10^{-5}$$

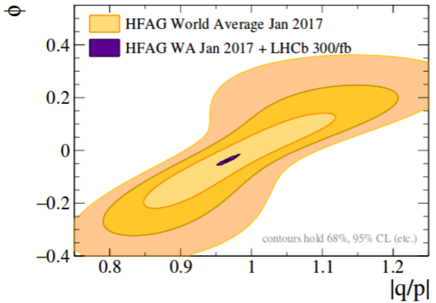
$$\sigma(|q/p|) \sim 10^{-3} \qquad \sigma(\phi) \sim 10^{-3}(^\circ)$$

No-mixing $\Rightarrow x = y = 0$

No CP violation $\Rightarrow \phi = 0^\circ$ and $|q/p| = 1$

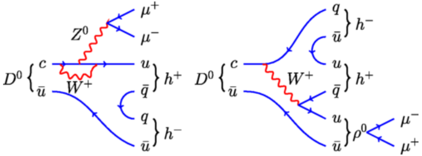
[CERN-LHCC-2017-003]

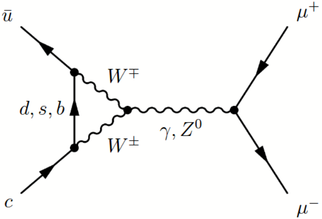


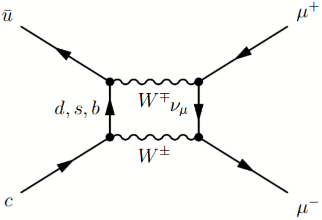


Rare decays

- Rare charm decays constitute a unique probe for New Physics in the up-quark sector
- Relatively unexplored
- Higher-order diagrams are very suppressed
- b-anomalies make progress on studying $c \to u$ more pressing







Rare decays

$D^0 \to h^+h^-\mu^+\mu^-$

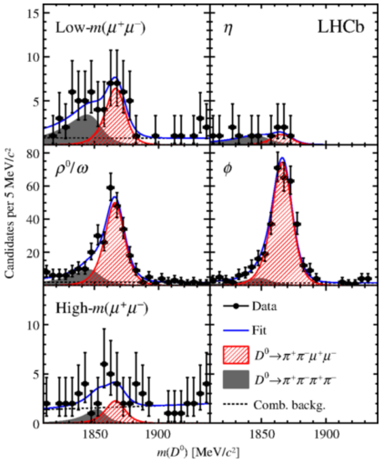
- Observed the first signal of leptonic decays of c mesons [Phys. Rev. Lett. 119, 181805]
- In Phase-II, high-statistics amplitude and angular analysis (disentangle between SD, LD)

$D^0 \to \mu^+\mu^-$

- Expectation for Phase-II:

  $\mathcal{B}\left(D^0 \to \mu^+\mu^-\right) \sim 10^{-10}$

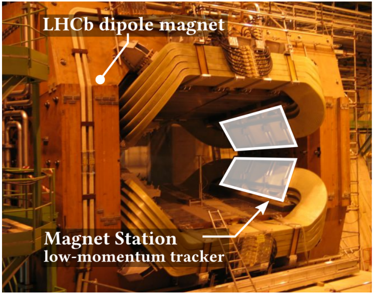
- Particle identification is crucial to reduce the background from $D^0 \to h^+h^-$

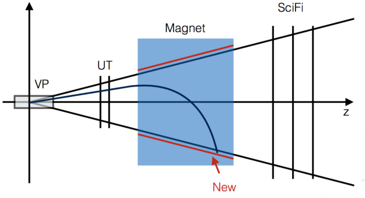


[Phys. Rev. Lett. 119, 181805]

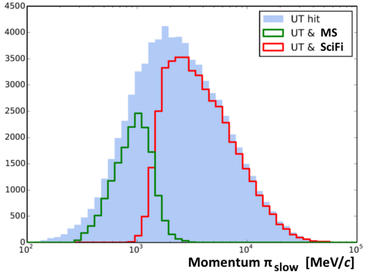
Searches also for $D \to hll$, $\Lambda_c^+ \to p\mu^+\mu^-$, ...
Possibility to explore the electron modes starting in Run-II
With an improved ECAL, search for radiative charm decays?

The magnet stations

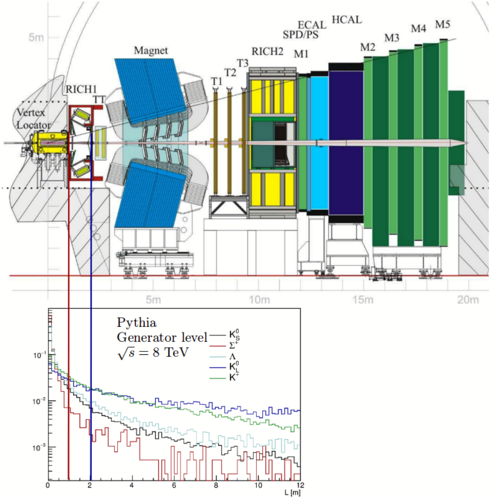




- D^0 mesons are usually tagged using $D^{*+} \to D^0\pi^+_{\text{soft}}$
- The track of the π^+_{soft} has a high chance of running outside the detector
- Aim to place tracking stations in the magnet region
- Gain of 21% for $D^{*+} \to D^0(K\pi)\pi^+_{\text{soft}}$
- Improvements also for $R(D^*)$, Heavy Ion, ...



Strange decays at LHCb



- Huge production of strange hadrons at LHCb
- Larger lifetimes
- $\mathcal{O}(10^{13})/\mathrm{fb}^{-1}$ K^0_S decay inside the VELO
- Efficiencies have been proved to be high enough already in 2011, using the $K^0_S \to \mu^+\mu^-$ analysis as a benchmark
- Many possibilities to study: K^0_S, Λ^0, Σ^+, Ξ^-, ...
- Currently developing tracking, particle identification and tagging algorithms

$K^0_S \to \mu^+\mu^-$

- Flavour-changing neutral current (FCNC) transition
- Dominated by long distance contributions through $K^0 \to \gamma\gamma$
- $\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right)$ helps to kill models with leptoquarks [arXiv:1712.01295], or supersymmetric contributions [arXiv:1711.11030], [arXiv:1712.04959]
- Study of the interference between $K^0_L \to \mu^+\mu^-$ and $K^0_S \to \mu^+\mu^-$ allows to determine sign$(A^{\mu}_{L\gamma\gamma})$

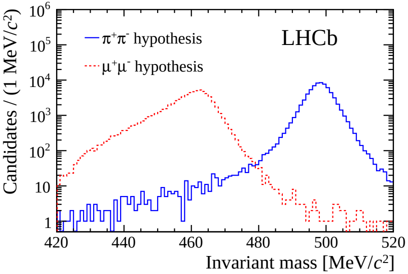
$$\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$$

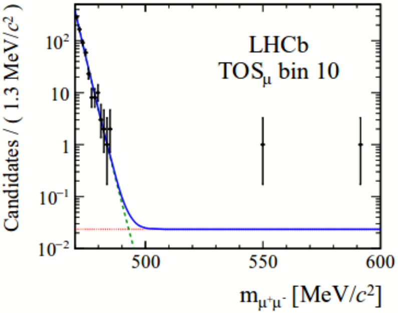
$$\mathcal{B}\left(K^0_L \to \mu^+\mu^-\right) = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} & \text{if } A^{\mu}_{L\gamma\gamma} > 0 \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9} & \text{if } A^{\mu}_{L\gamma\gamma} < 0 \end{cases} \quad A^{\mu}_{L\gamma\gamma} = \text{sign}\left(\frac{\mathcal{A}(K^0_L \to \gamma\gamma)}{\mathcal{A}(K^0_L \to (\pi^0)^* \to \gamma\gamma)}\right)$$

[Nucl. Phys. B366 (1991) 189] [JHEP 01 (2004) 009] [Phys. Rev. Lett. 119, 201802 (2017)]

$K_S^0 \to \mu^+\mu^-$ invariant mass

- Backgrounds are currently under control
- $K_S^0 \to \pi^+\pi^-$ with the two pions misidentified as muons dominates the spectrum
- Benefit from improvements on muon identification at low-p_T
- Currently we have a very good resolution around the K_S^0 mass (~ 4MeV/c^2). Mantaining it is completely necessary.





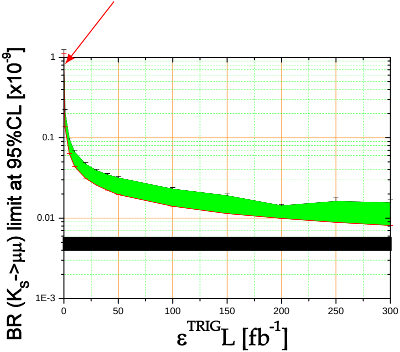
[Eur. Phys. J. C (2017) 77: 678]

At high luminosity, another enemy appears...

- $K^0_L \to \mu^+\mu^-$ is an irreducible background ($\mathcal{B} = (5.8 \pm 0.6 \pm 0.4) \times 10^{-9}$ [Phys. Rev. Lett. 63, 2185])
- For Run-I, $\mathcal{B}_{\text{eff}}\left(K^0_L \to \mu^+\mu^-\right)$ was out of the sensitivity $\sim 10^{-11}$
- With 300 fb^{-1}, both branching fractions will be of the same order of magnitude
- Need to define a strategy to differenciate $K^0_S \leftrightarrow K^0_L$
- Having a good proper time resolution is crucial!

Now we are here!

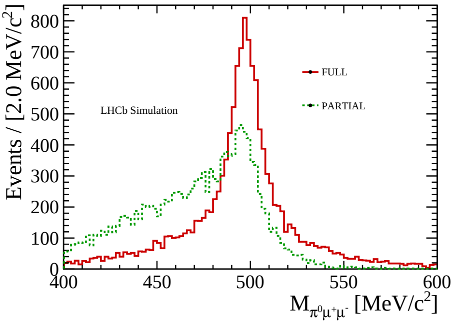
[Eur. Phys. J. C (2017) 77: 678]



$K_S^0 \to \pi^0\mu^+\mu^-$

- SM prediction of $K_L^0 \to \pi^0\mu^+\mu^-$ depends on the measurement of $\mathcal{B}\left(K_S^0 \to \pi^0\mu^+\mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ [Phys. Lett. B599 (2004) 197]
- Current kaon experiments do not expect to improve such measurement
- A sensitivity study was performed at LHCb
- Low π^0 reconstruction efficiency at LHCb
- The K_S^0 mass does not depend too much on the information from the π^0

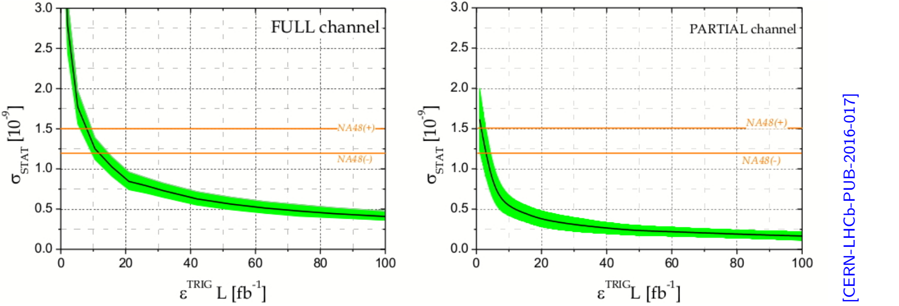
[CERN-LHCb-PUB-2016-017]



Two possible strategies → FULL: fully reconstruct the candidate

Two possible strategies → PARTIAL: omit the π^0 reconstruction

$K_S^0 \to \pi^0 \mu^+ \mu^-$ prospects



[CERN-LHCb-PUB-2016-017]

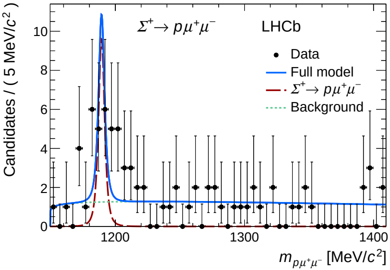
- Beating the NA48 measurement [Phys. Lett. B599 (2004) 197] is possible in the upgrade $\mathcal{L}_{\text{eff}} > 5$ fb^{-1}
- Best strategy omitting the π^0 reconstruction
- Maybe benefit from an upgraded ECAL

Other strange friends

There are many other interesting studies that can be done at LHCb:

- $K^0_S \to x^+x^-l^+l^-$: highly suppressed in the SM ($\sim 10^{-14}$ for muons)
- $K^+ \to \pi^+\mu^+\mu^-$: maybe competitive with NA62 (LFU)
- Semileptonic/rare Hyperon Decays ($\Lambda^0 \to p\mu^-\bar{\nu}$, $\Sigma^+ \to p\mu^+\mu^-$, ...)
- $K^0_S \to \pi^+\mu^-\bar{\nu}$: no measurement at present (V_{us}, CPT, LFU)

[LHCb-PAPER-2017-049]

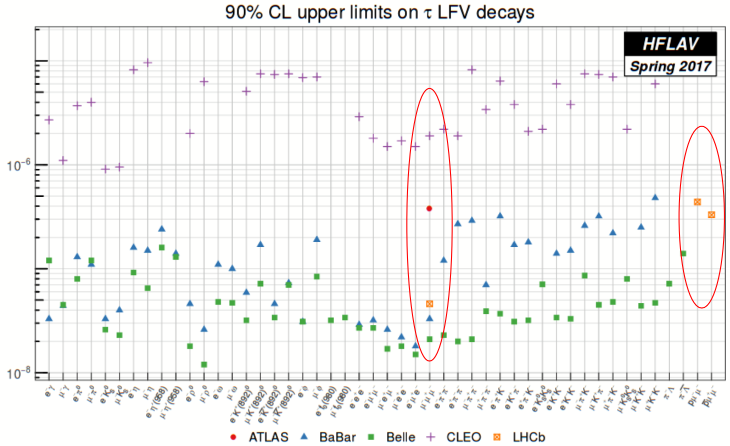


For the moment, everything very preliminar in most cases:

- No dedicated trigger lines for SHD or $K^0_S \to \pi^+\mu^-\bar{\nu}$ ($\mathcal{B} \sim 10^{-4}$)
- Apart from $\Sigma^+ \to p\mu^+\mu^-$, nothing published so far, set benchmarks for Run-II
- Tracking is challenging for K^+ studies (flight distance $\sim$ m)

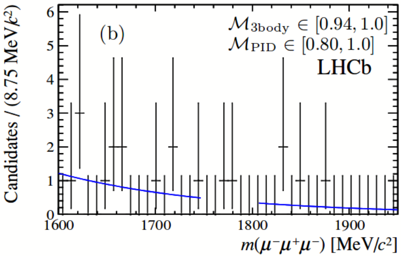
τ decays

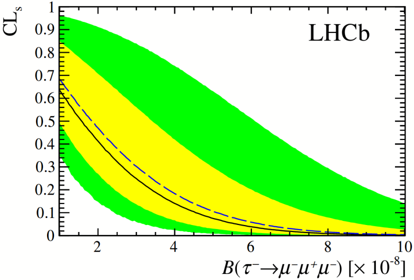
- LHCb was the first experiment to search for LFV τ decays on a hadron collider
- Inclusive production of τ leptons, mainly from *b* and *c* hadron decays
- Calibration and normalization channel $D_s^- \to \phi(\mu^+\mu^-)\pi^-$



$\tau^- \to \mu^+\mu^-\mu^-$

- Getting close to B-factories (ongoing studies with Run-II data samples)
- With ~ 300 fb^{-1}, we expect $\mathcal{B}\left(\tau^- \to \mu^+\mu^-\mu^-\right) < 3 \times 10^{-9}$, similar to what is expected for Belle 2 with 50 ab^{-1}
- Irreducible background of $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$, reduced with cuts in $m_{\mu^+\mu^-}$
- Benefit from any improvement on the ECAL

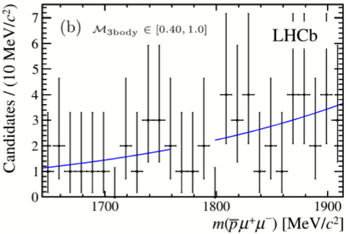




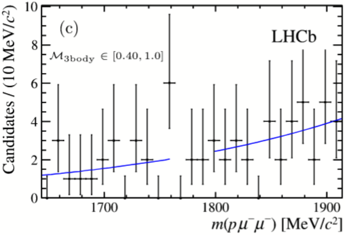
[JHEP 02 (2015) 121]

$\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$

- Test for models where $|\Delta(B-L)| = 0,\ 2$
- Analysis done using the data sample from 2011 (no update since then)
- Clean signature, no expected peaking backgrounds
- We might expect a factor of 20 of improvement using the full Run-(I - V) samples



$\mathcal{B}\left(\tau^- \to \bar{p}\mu^+\mu^-\right) < 3.3\times10^{-7}$



$\mathcal{B}\left(\tau^- \to p\mu^-\mu^-\right) < 4.4\times10^{-7}$

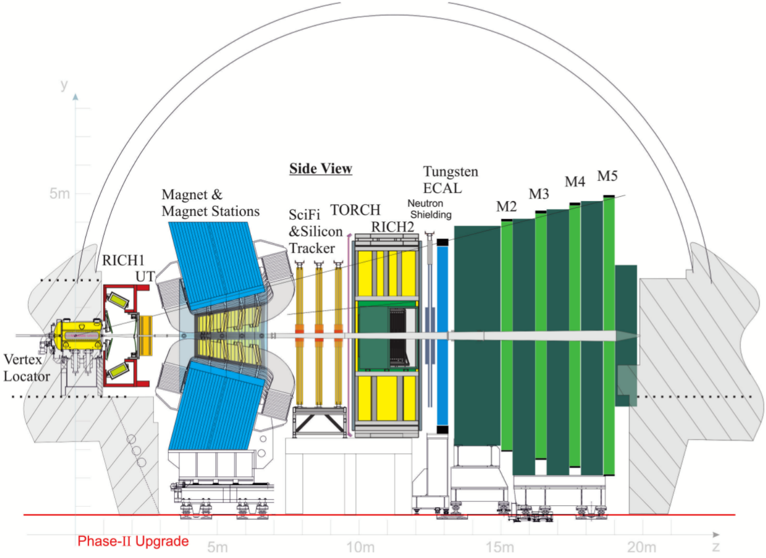
[Phys. Lett. B 724 (2013) 36-45]

Conclusions

- LHCb has a big power of adaptation to new fields
- Tracking and trigger improvements are crucial:
  - Tracking efficiency
  - Ghost removal
  - Low-p_T reconstruction
  - Full software trigger
- An upgraded ECAL allows to better control backgrounds and use other normalization channels
- Larger samples of both real and simulated data allows approaching SM predictions for CPV in charm decays
- New possibilities to study strange decays at LHCb, reach SM prediction for $K_S^0 \to \mu^+\mu^-$
- Expected a very big improvement on τ decays, competitive with B-factories

BACKUP

The LHCb detector in Phase-II Upgrade



[CERN-LHCC-2017-003]

LHCb schedule

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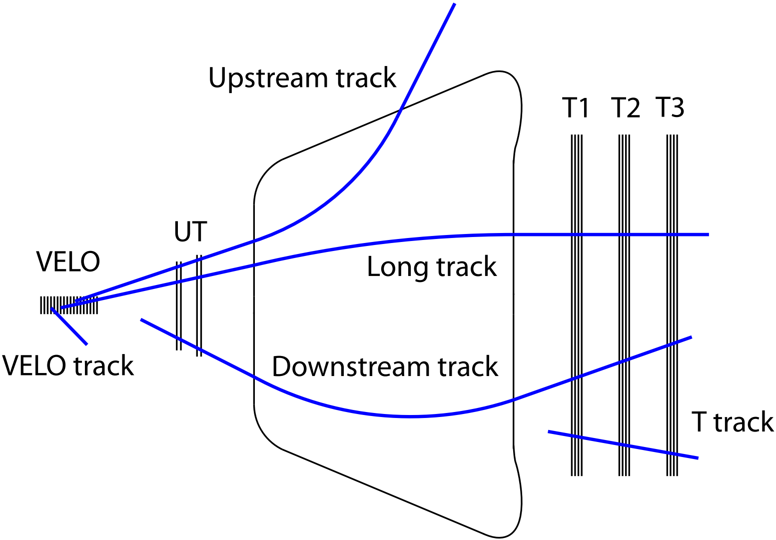
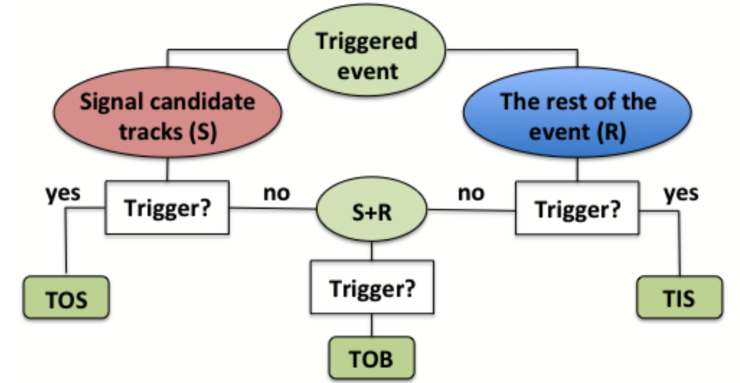
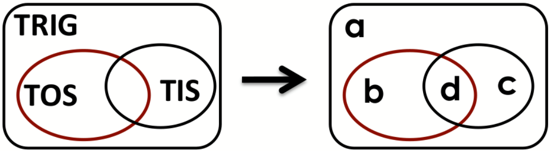
CMS Phase I Upgr		300 fb^{-1}			CMS Phase II UPGRADE						CMS		3000 fb^{-1}	
Belle II		5 ab^{-1}	$L = 8 \times 10^{35}$		50 ab^{-1}									

Track types at LHCb



Trigger definitions





Where:

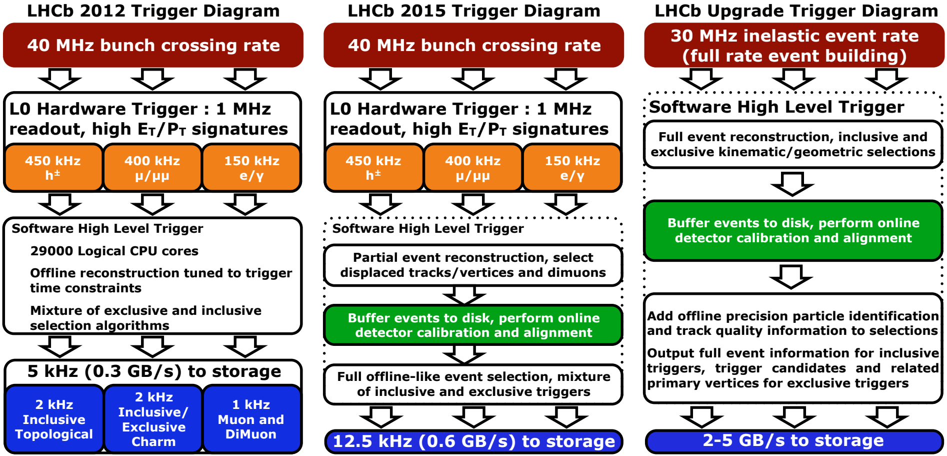
$a = N^{TRIG} - N^{TIS} - N^{TOS} + N^{TISTOS}$

$b = N^{TOS} - N^{TISTOS}$

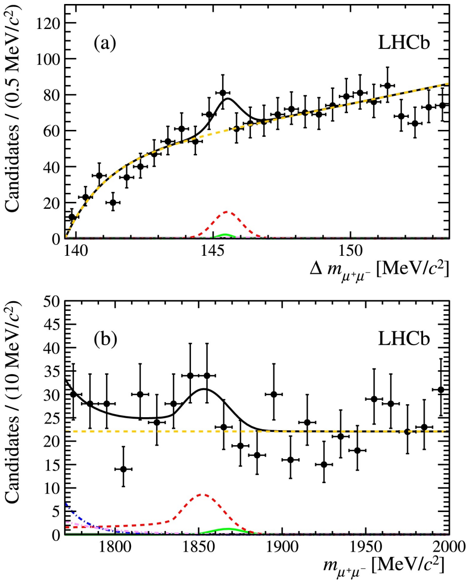
$c = N^{TIS} - N^{TISTOS}$

$d = N^{TISTOS}$

LHCb trigger diagrams

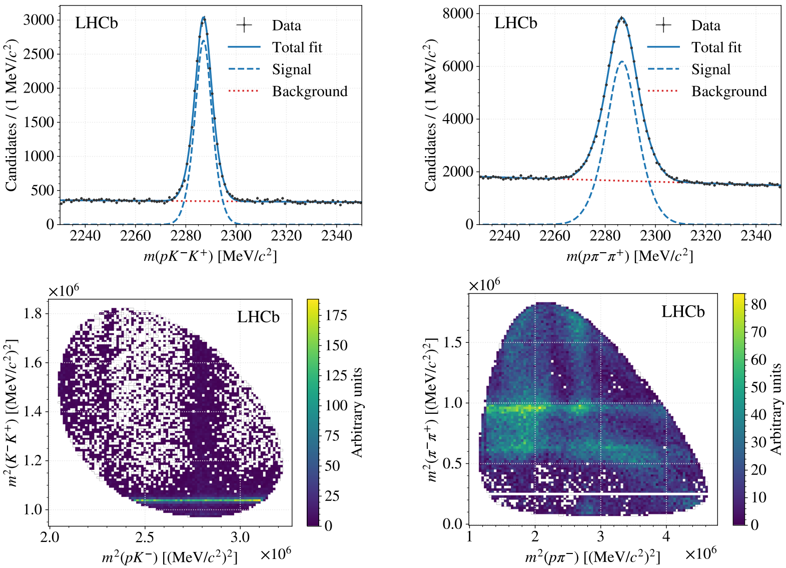


$D^0 \to \mu^+\mu^-$ mass distributions



[Phys. Lett. B 725 (2013) 15-24]

$\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$



[arXiv:1712.07051 Submitted to JHEP]

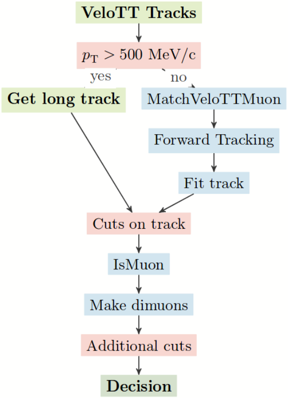
The di-muon triggers for Run-II

Efficiency	$K_S^0 \to \mu^+\mu^-$	$K_S^0 \to \pi^0\mu^+\mu^-$
L0	0.361 ± 0.004	0.344 ± 0.009
HLT1/L0	0.699 ± 0.007	0.705 ± 0.015
HLT1/L0 (old)	0.274 ± 0.006	0.299 ± 0.015
HLT2/HLT1	0.9898 ± 0.0017	0.983 ± 0.005
HLT2/HLT1 (old)	0.293 ± 0.013	0.26 ± 0.03
global	0.250 ± 0.004	0.238 ± 0.008
global (old)	0.0290 ± 0.0015	0.026 ± 0.003

green: trigger with new lines

red: trigger without new lines

- Big increase on the efficiencies: a factor ~ 2.4 for HLT1 and ~ 3.5 for HLT2
- Total efficiency increased by a factor ~ 10



[CERN-LHCb-PUB-2017-023]

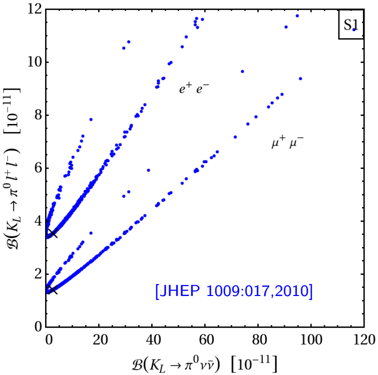
$K_S^0 \to \pi^0\mu^+\mu^-$

$\mathcal{B}\left(K_L^0 \to \pi^0\mu^+\mu^-\right)$ has a variation of ~ 1 order of magnitude in models with extra dimensions.

$$\mathcal{B}\left(K_L^0 \to \pi^0 l^+ l^-\right)_{\text{SM}} = \left(C^l_{\text{dir}} \pm C^l_{\text{int}}|a_S| + C^l_{\text{mix}}|a_S|^2 + C^l_{\gamma\gamma} + C^l_S\right) \times 10^{-12}$$

$|a_S| = 1.2 \pm 0.2$ dominates the theoretical uncertainty. Comes from the measurements of $\mathcal{B}\left(K_S^0 \to \pi^0 l^+ l^-\right)$.

Randall-Sundrum model



Large uncertainties on $\mathcal{B}\left(K_S^0 \to \pi^0\mu^+\mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ (NA48) [Phys. Lett. B599 (2004) 197]