LHCb Upgrade and prospects of Charm Physics

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21st of May 2018, CHARM-2018 – Novosibirsk, Russia

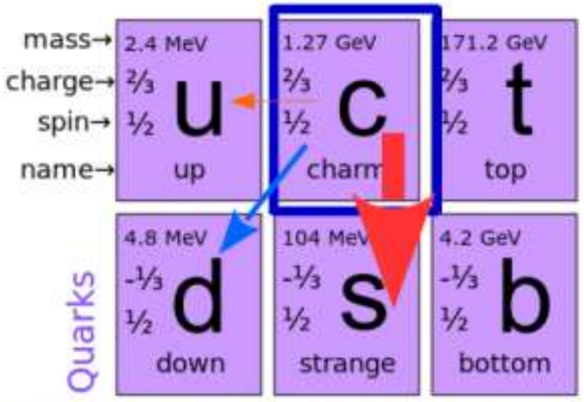
Scope of this talk

What are the main goals?

- CP violation at charm sector
- Indirect searches of New Physics in loops
- Further QCD development with heavy baryons and exotica.

- Which processes to explore with high luminosity *pp* collisions?
- Advantages of HEP hadronic machines as the tool for charm

- **From present to future:**
  - **achievements**
  - **challenges and key points**
  - **what's new?**
  - **expected performance**



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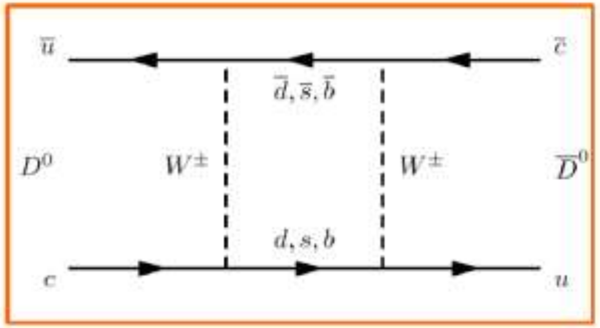
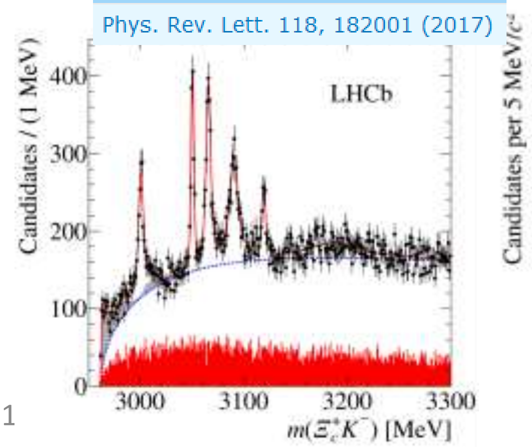
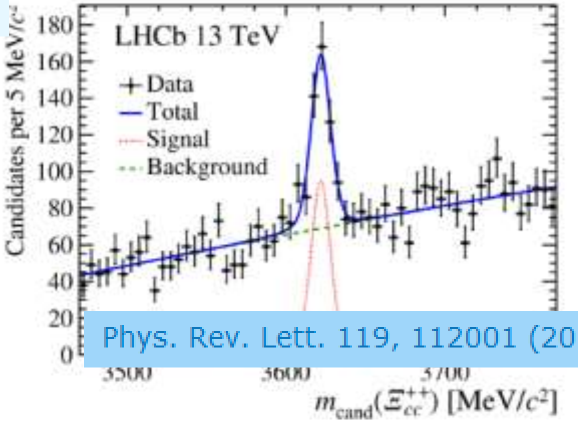


Mixing / FCNC

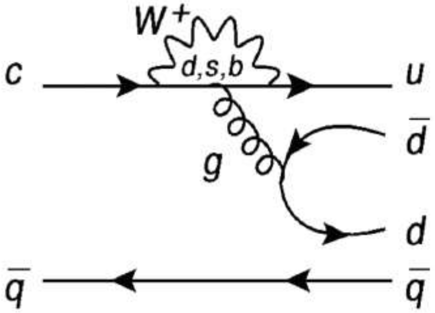

Phys. Rev. Lett. 118, 182001 (2017)

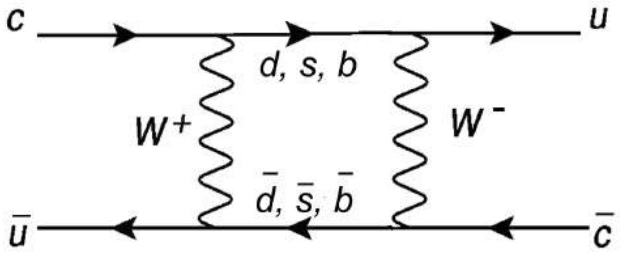

Phys. Rev. Lett. 119, 112001 (2017)

CPV at charm sector & New Physics in loops

$$
V_{\mathrm{Wolf}}^{(\mathrm{CK})} = \begin{array}{c|ccc|c}
 & d & s & b & \\
\hline
 & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} -\frac{\lambda^6}{16}[1+8A^2(\rho^2+\eta^2)]\,, & \lambda\,, & A\lambda^3(\rho-i\eta) & u \\
 & \underline{-\lambda+\frac{\lambda^5}{2}A^2(1-2\rho-2i\eta)}\,, & \underline{1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4A^2) -\frac{\lambda^6}{16}[1-4A^2(1-4\rho-4i\eta)]}\,, & A\lambda^2 & c \\
 & A\lambda^3(1-\rho-i\eta) +\frac{\lambda^5}{2}A(\rho+i\eta)\,, & -A\lambda^2+\frac{\lambda^4}{2}A(1-2\rho-2i\eta) +\frac{\lambda^6}{8}A\,, & 1-\frac{\lambda^4}{2}A^2 -\frac{\lambda^6}{2}A^2(\rho^2+\eta^2) & t
\end{array}
$$

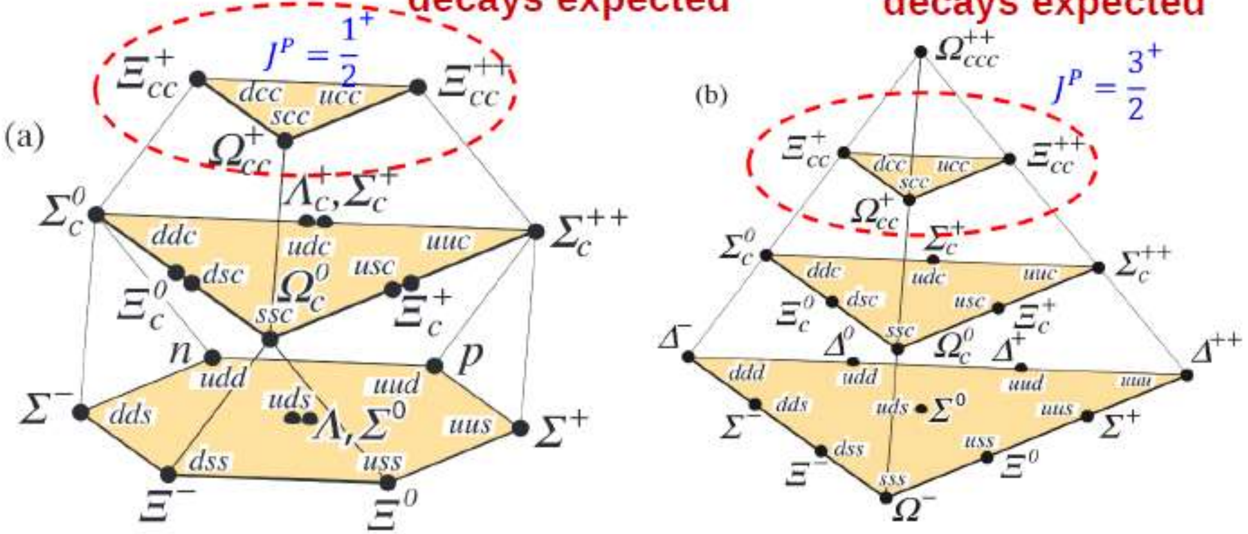
$$+\mathcal{O}(\lambda^7)$$





- CKM matrix provides clear prediction of very small CPV in charm sector (*D*-mesons are the only up-type quark system, where mixing and CPV can occur)
- New Physics in loop-diagrams driven processes, which are very suppressed in the SM (Keeping in mind: long-distance contributions, for which precise theoretical predictions are difficult, but can play important role)
- Need a lot of $c\bar{c}$ for discoveries

Better understanding of QCD



Weak force driven decays expected

EM / strong decays expected

- QCD is a natural part of the SM

- Chiral perturbation theory valid between 0.1 and 1 GeV
- Perturbative QCD calculations >> 1 GeV

- Although charm hadrons are in between of these two regimes, due to high ***c*** mass double and triple charm systems, as well as exotica are kind of natural bridges for QCD development

- Need intensive charm source to produce such bound systems

Machines for charm studies (Luminosity / $N_{c\bar{c}}$)

At threshold

Higher energies

e^+e^- colliders

CLEO-c (0.8 fb^{-1} / $5*10^6$) / **BESIII** (3fb^{-1} / $2*10^7$)

In future **Super-tau-charm Factories**

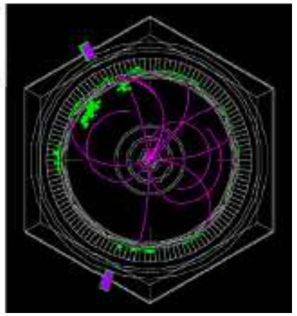
- at *ψ(3770)* resonance
- Quantum coherence, which allows to measure strong phase
- Almost no background

- No boost – no lifetime measurements
- Small sample size

Belle (1 ab^{-1} / $13*10^8$) / **BaBar** (550 fb^{-1} / $8*10^8$)

In future **Belle2** (50 ab^{-1})

- Neutrals / neutrino studies
- Clean environment
- Lifetime studies possible



hadron machines

In future **PANDA**

- Selective to hadron production thresholds
- Production cross sections measurements
- Polarization studies possible

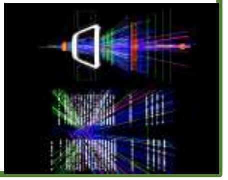
- no lifetime measurements / not large sample

CDF (10 fb^{-1} / $23*10^{10}$) / **LHCb** (5 fb^{-1} / $8*10^{12}$)

In future **LHCb Upgraded** (→ 50 fb^{-1} → 300 fb^{-1})

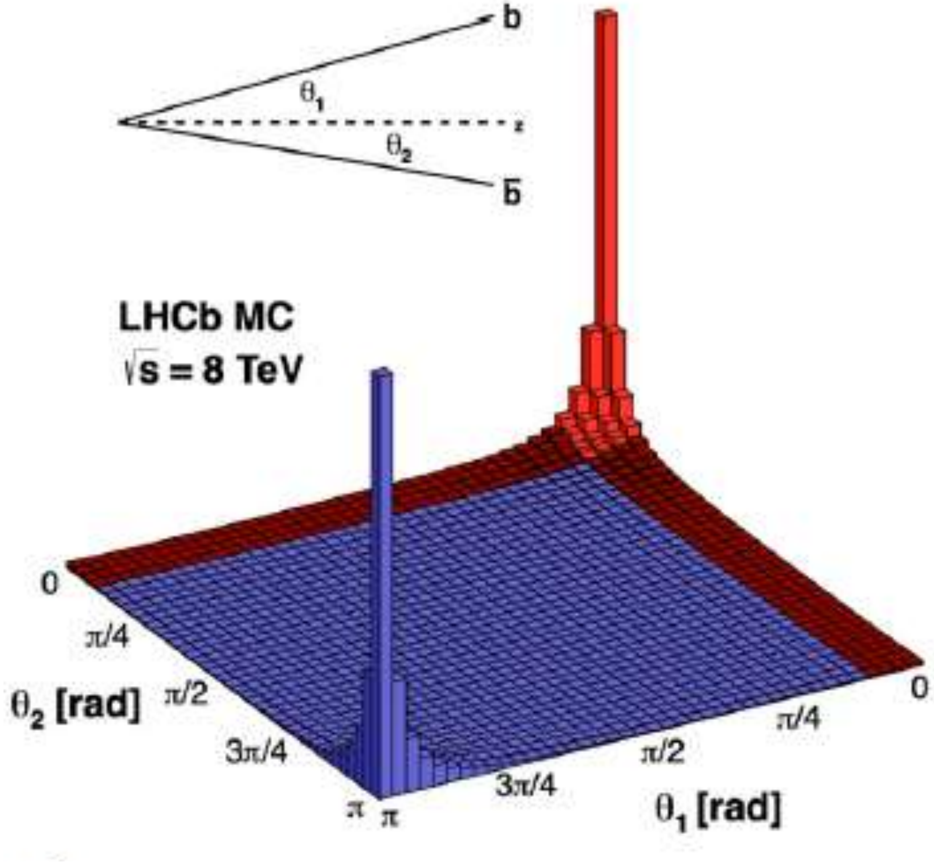
- **Huge rates**
- **Excellent lifetime resolution due to the boost**

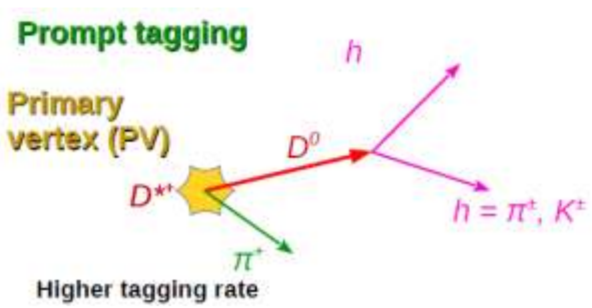
- **Large backgrounds**
- **Difficult to work with neutral**



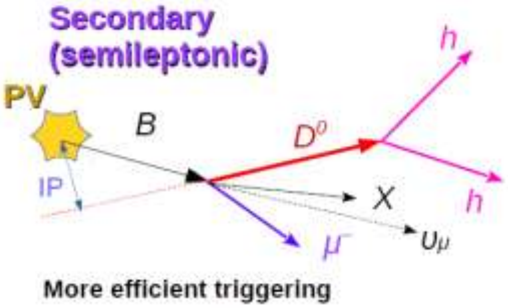
Charm and beauty production into forward region

- Gluon fusion is main production mechanism for pairs of heavy quark-antiquark pairs
- Produced charmed hadrons go together in forward direction (LHCb acceptance $2<\eta<5$)
- Lorentz boost provides signature for ***c***- & ***b***-hadrons selection
- Tagging for prompt-***c*** and ***c***-from-***b***




Prompt tagging

Higher tagging rate


Secondary (semileptonic)

More efficient triggering

LHCb: Find \ Identify \ Measure

Excellent vertexing allows efficient heavy quark hadrons selection / gives access to decay time distribution / prompt-secondary separation for charm

Protons collision point

Excellent PID allows to suppress background dramatically and explore many decay modes

Excellent tracking

Muon system – nice tagging & great potential to search for rare decays with di-muons

$\epsilon_{PID}(K) \approx 95\ \%$

MisID $(K \to \pi) \approx 5\ \%$

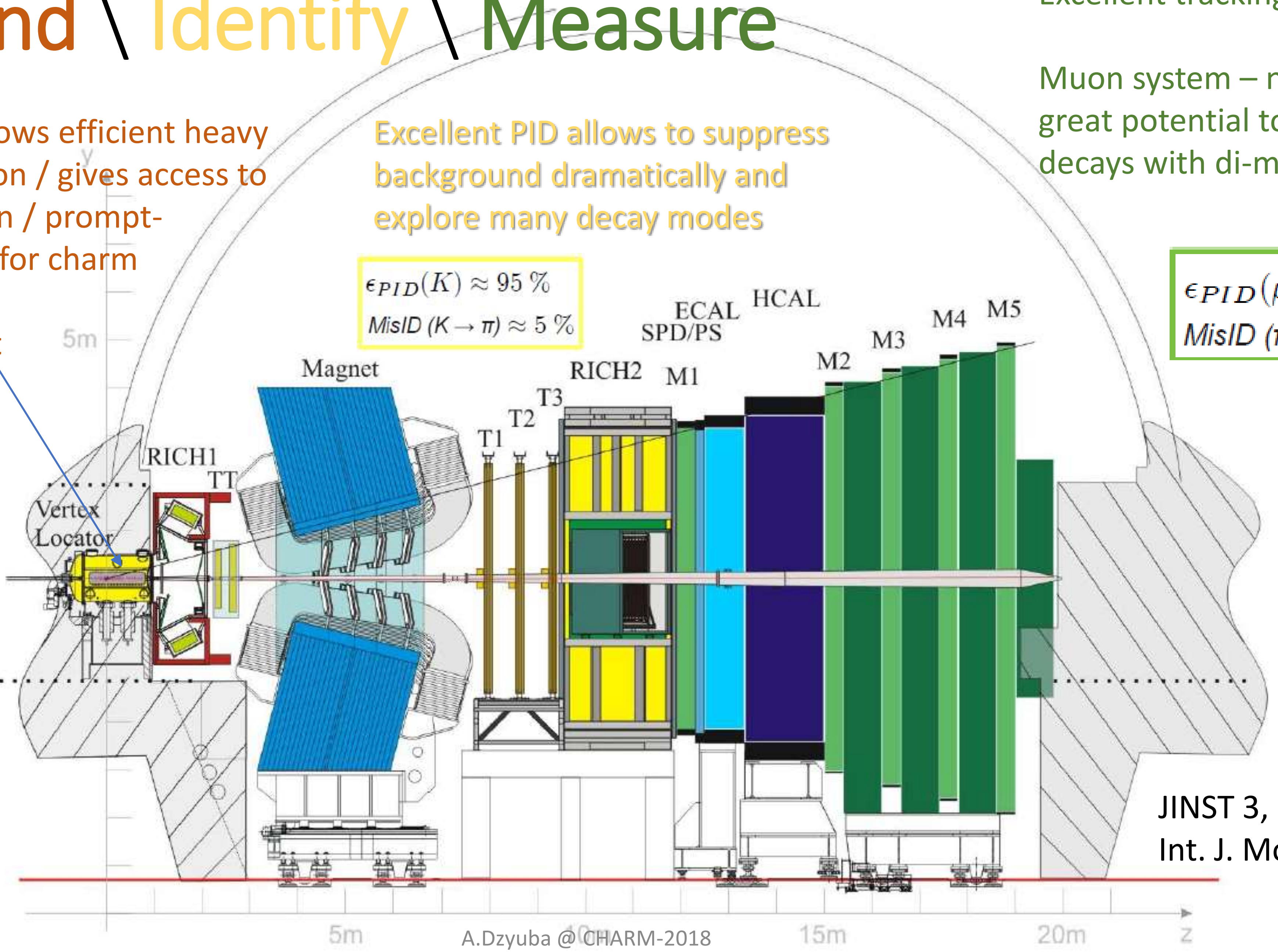
$\epsilon_{PID}(\mu) \approx 97\ \%$

MisID $(\pi \to \mu) \approx 3\ \%$

$\sigma(IP) \approx 20 \mu m$

$\delta p/p = 0.4 - 0.6\ \%$

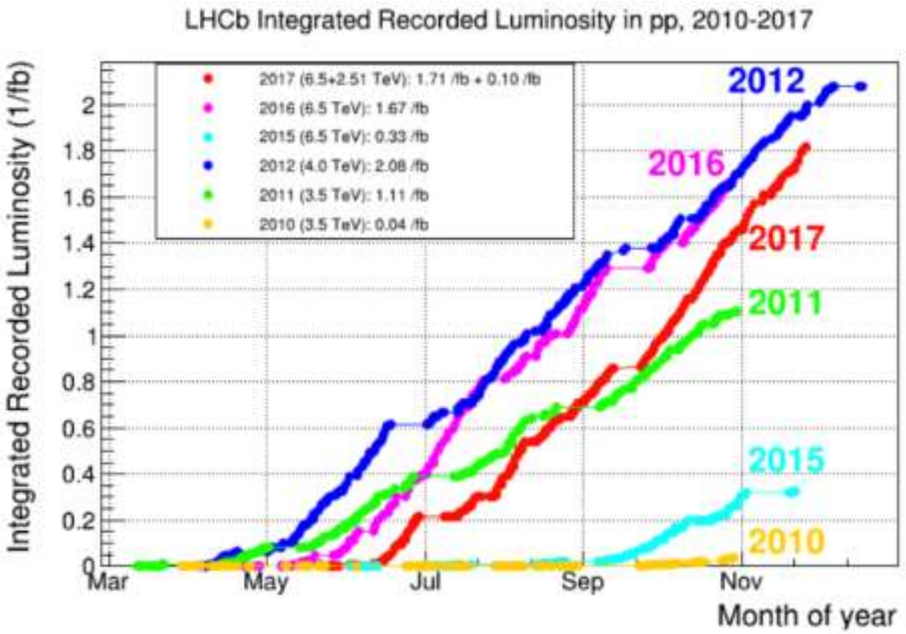
$\epsilon_{track} > 96\ \%$

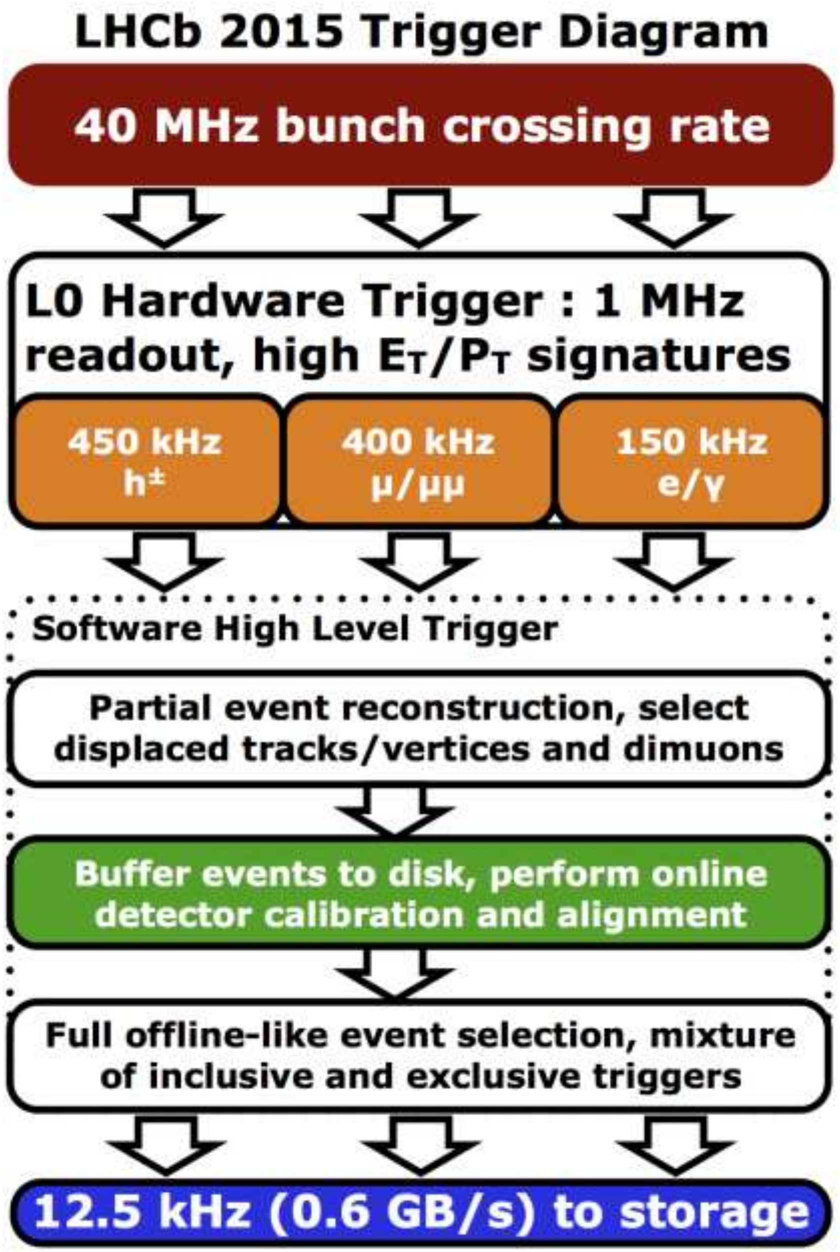


JINST 3, (2008) S08005;
Int. J. Mod. Phys. A 30, (2015) 153022

Luminosity and trigger

- LHCb operated in constant instantaneous luminosity mode (1.1 visible interactions per bunch crossing)
- Two stage trigger, which is efficient for hadrons and muons
- **Turbo stream for Run-2** – candidates reconstructed at the trigger level saved directly for offline analysis + (online alignment and calibration):
  - huge accepted rates (more data, as event sizes are smaller)
  - widely used for charm analyses (see example on next slide)
  - a kind of revolution in experiments HEP





LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$ | **400 kHz $\mu/\mu\mu$** | **150 kHz e/γ**

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

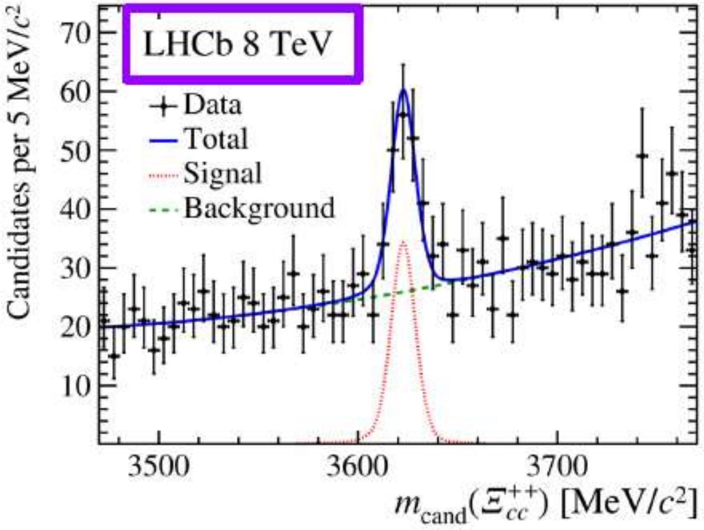
Full offline-like event selection, mixture of inclusive and exclusive triggers

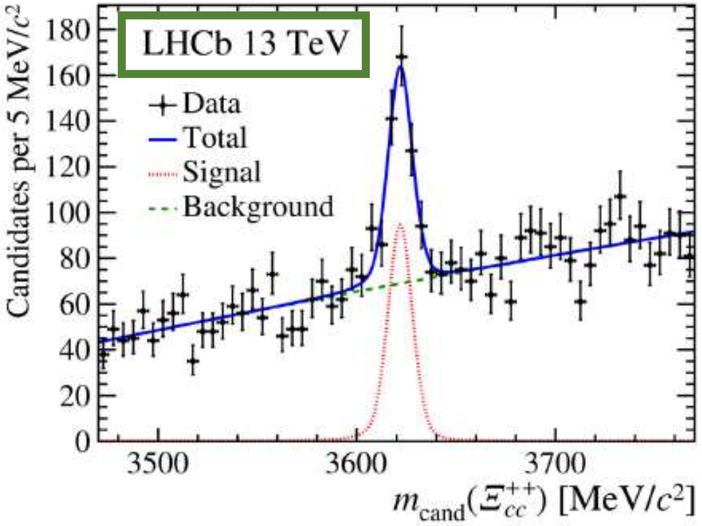
12.5 kHz (0.6 GB/s) to storage

Comput. Phys. Commun. 208 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)

Impact of Turbo (doubly-charmed baryons)

Phys. Rev. Lett. 119, 112001 (2017)





In 2017 LHCb announced discovery of doubly-charmed baryon

Statistics in **Run-1** and **Run-2** were:

8 TeV 113 ± 21 candidates for 2.0 fb^{-1},
13 TeV 313 ± 33 candidates for 1.7 fb^{-1}.

The gain in yields are partially due to cross section and **approximately factor 2** is due to used Turbo

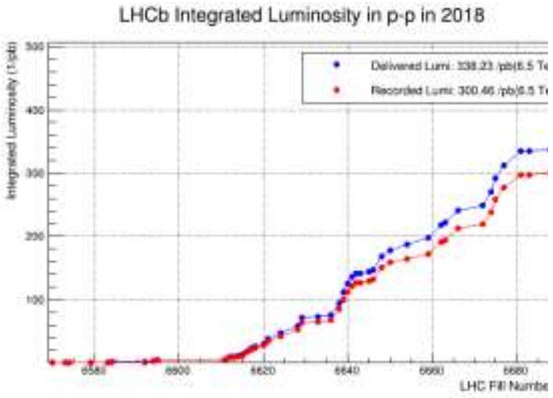
Will become standard for many physics analyses after Upgrade

More about Ξ_{cc}^{++} in the contribution of Daniel Vieira

Timeline

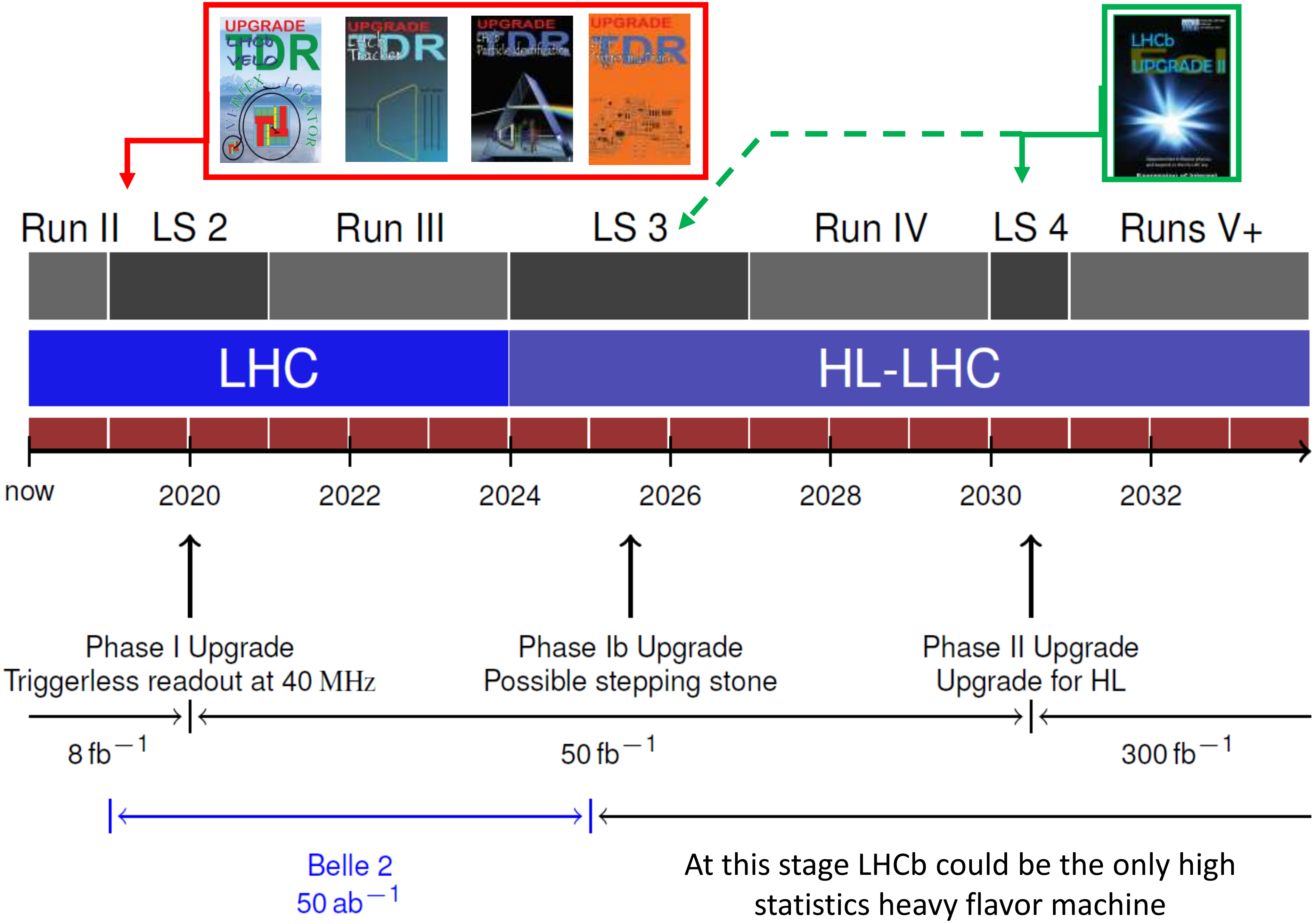
LHCb is currently in last year of operation (Run-II)

Performing well


LHCb Integrated Luminosity in p-p in 2018

Upgrade I is under construction for installation from 2019

Expression of Intent for the second phase



Run II LS 2 Run III LS 3 Run IV LS 4 Runs V+

LHC HL-LHC

now 2020 2022 2024 2026 2028 2030 2032

Phase I Upgrade
Triggerless readout at 40 MHz

Phase Ib Upgrade
Possible stepping stone

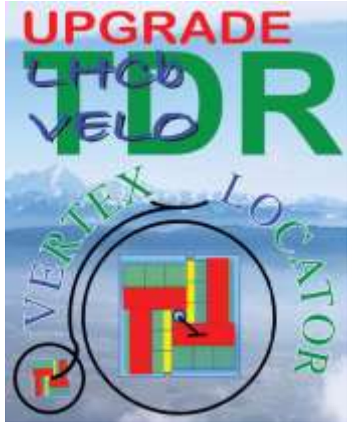
Phase II Upgrade
Upgrade for HL

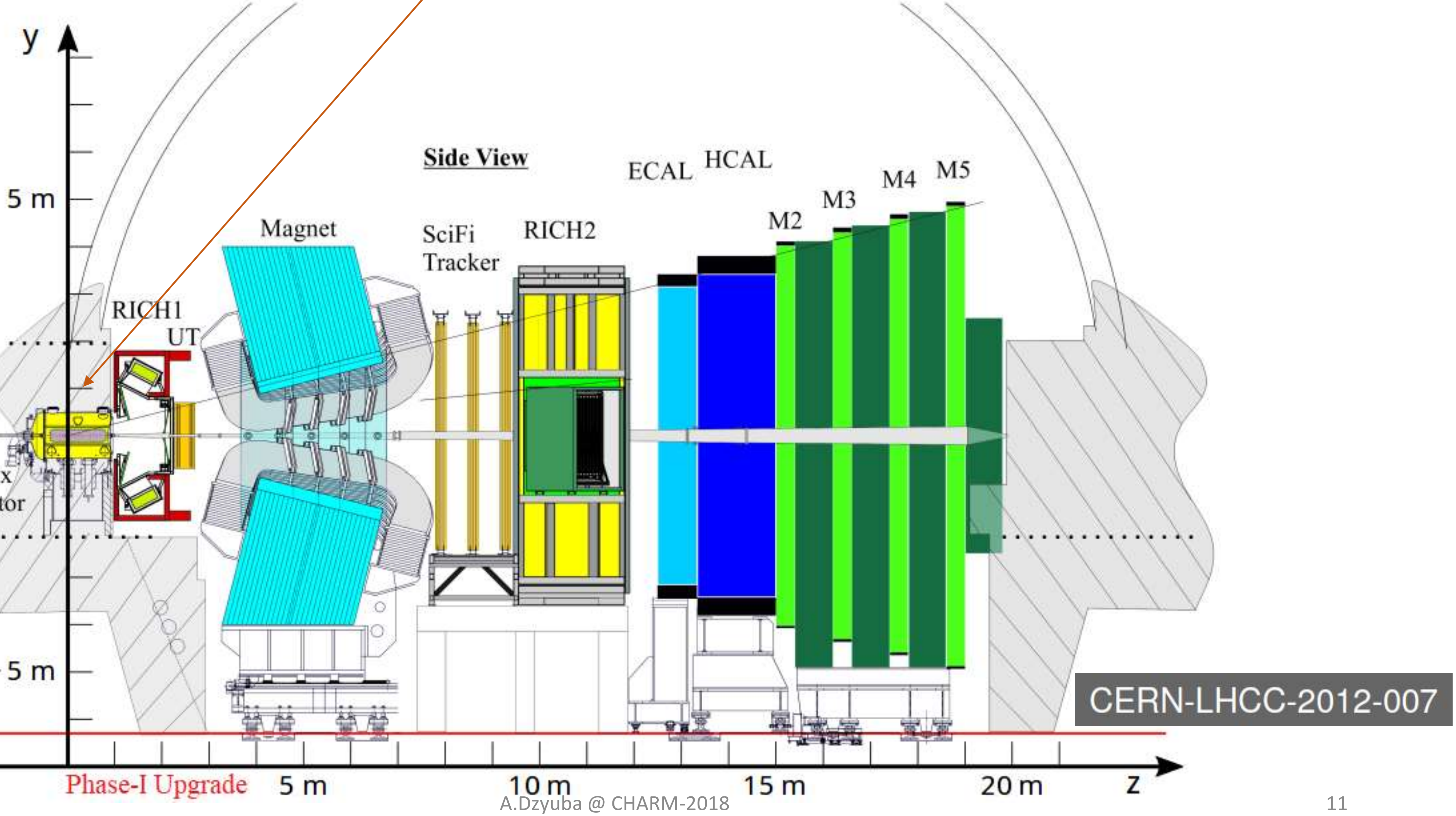
$8\ \mathrm{fb}^{-1}$ $50\ \mathrm{fb}^{-1}$ $300\ \mathrm{fb}^{-1}$

Belle 2
$50\ \mathrm{ab}^{-1}$

At this stage LHCb could be the only high statistics heavy flavor machine

New after Upgrade: VELO, Tracking, PID, Trigger



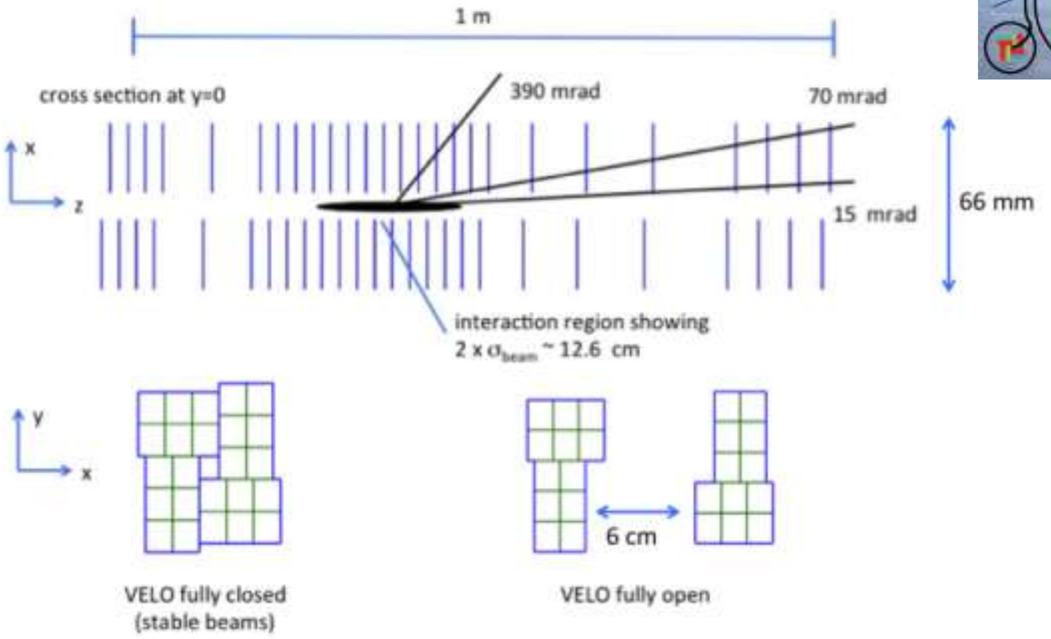


Will be replaced with new hybrid pixel detector

Old and New VErtex LOcator

Current VELO

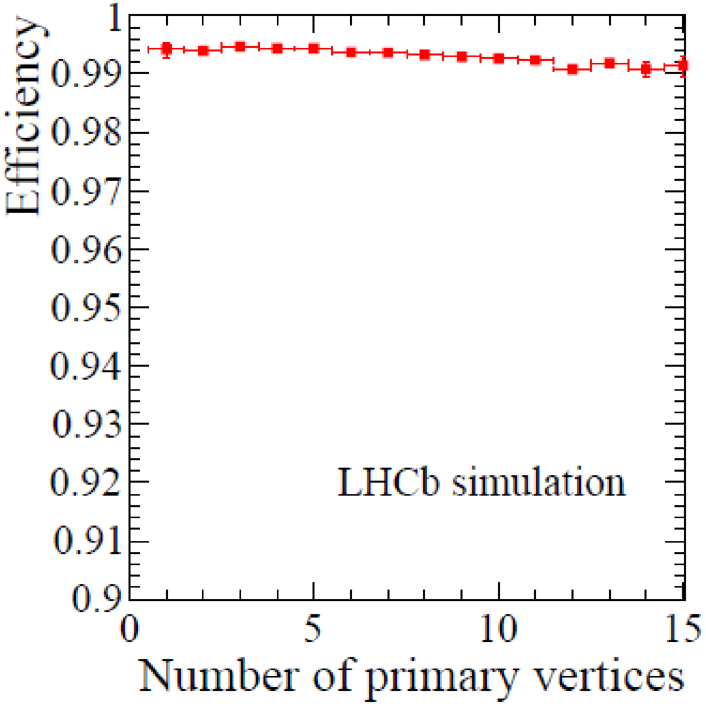
42 modules with 300μm sensors (R and φ) placed less than in 1 cm from collision point (moved every fill)

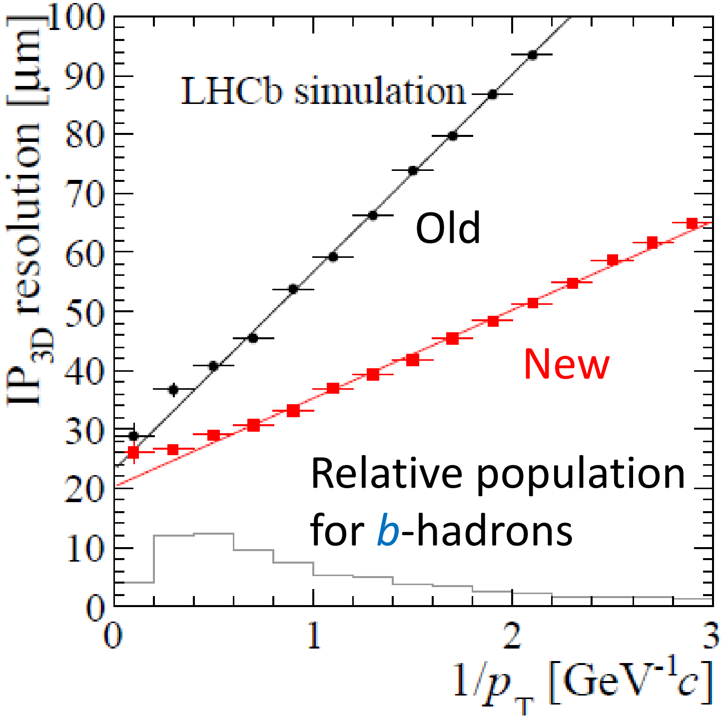


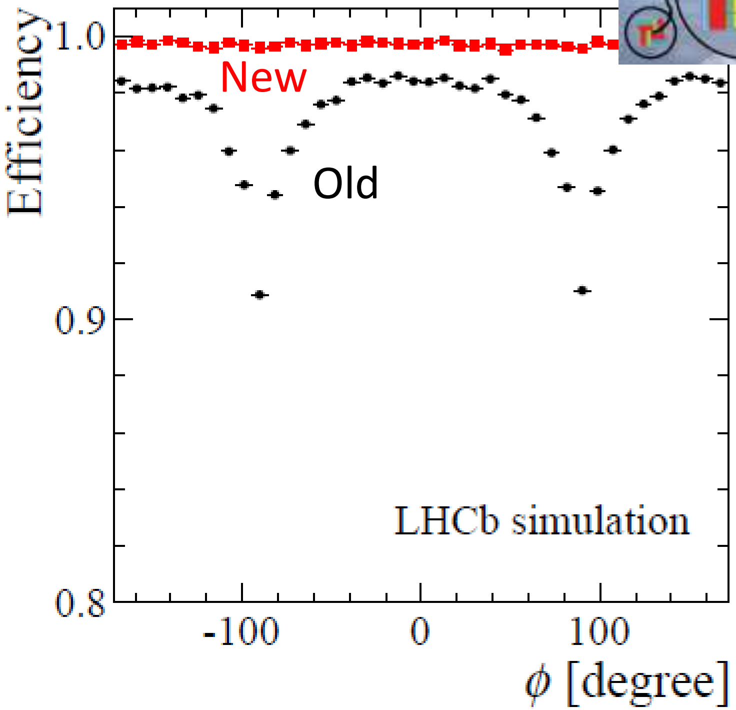
More PVs suggest to move from (R and φ)-sensors to pixels

	VELO	VELO Upgrade
Readout	1 MHz	40 MHz
Channels/Module (Tot)	4096 (172k)	790k (40.9M)
Max Radiation Dose	5.2×10^{14} n_{eq}/cm^2 (9.6 fb^{-1})	8×10^{15} n_{eq}/cm^2 (50 fb^{-1})
Visible Interactions (μ)	≈ 1.1	5.2
Operating Temperature	$-10°C$	$-20°C$
Max High Voltage	500V	1000V

Efficiency and resolution for new VELO







Lifetime resolution from simulations:

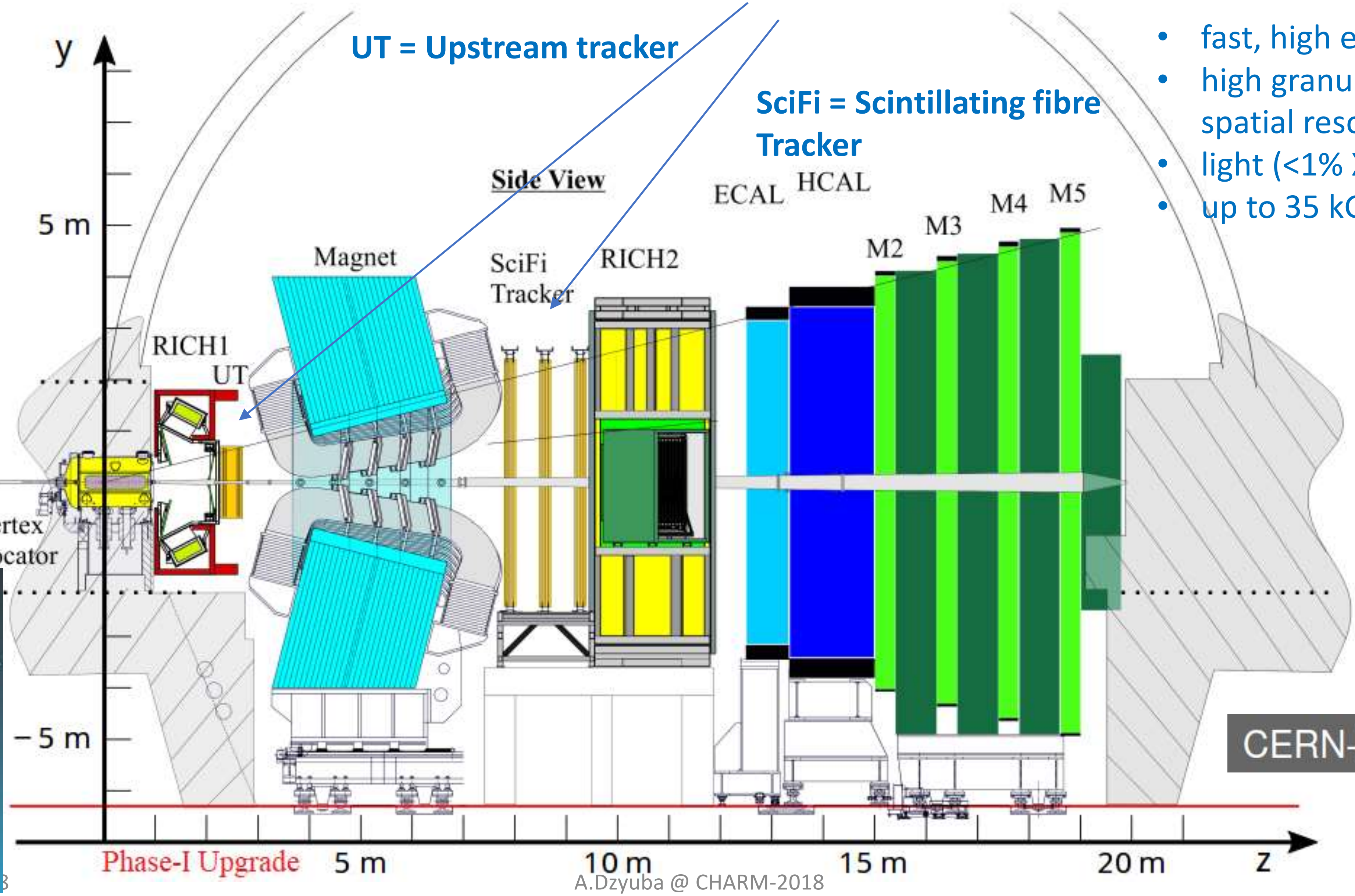
	$B_s^0 \to \phi\phi$	$B^0 \to K^{*0}\mu^+\mu^-$
Current VELO	48.3 ± 0.5	41.2 ± 0.5
Upgraded VELO	43.4 ± 1.6	35.3 ± 0.3

- Simulations are done for 14 TeV with 7.6 int./bunch.cr.

  (5.2 visible interaction per bunch crossing)

- Better performance expected for the much higher rates

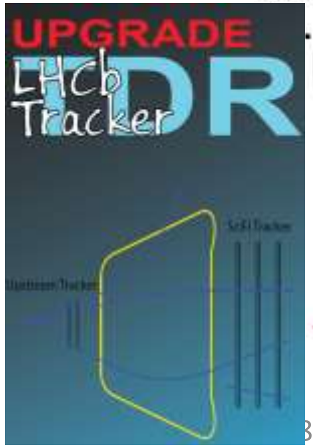
New after Upgrade: VELO, Tracking, PID, Trigger



UT = Upstream tracker

SciFi = Scintillating fibre Tracker

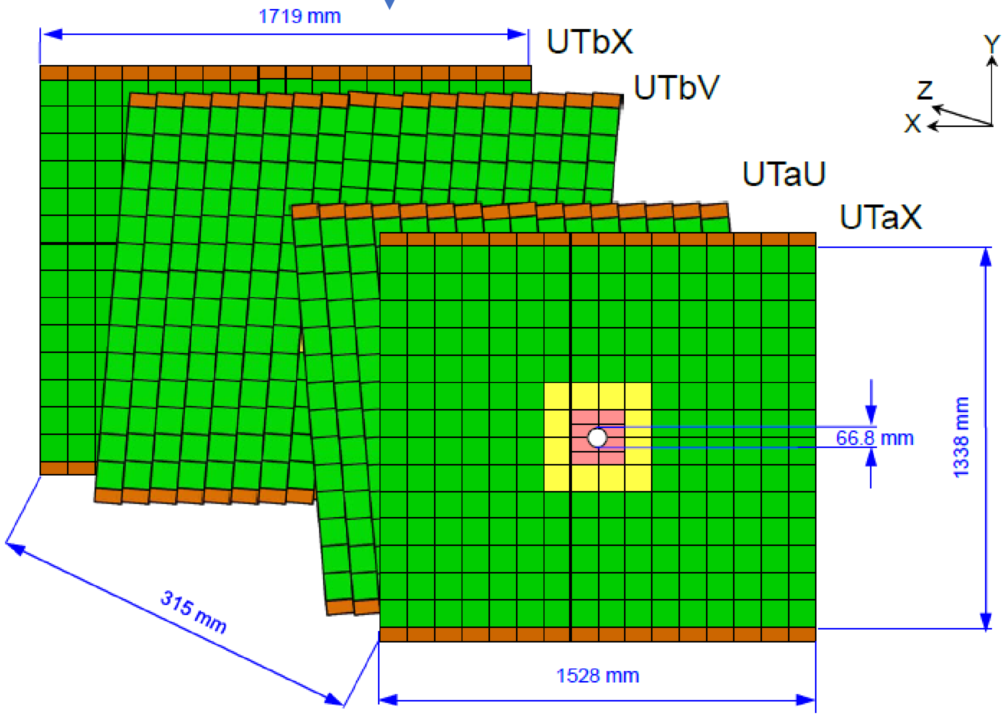
- fast, high efficient (~99%),
- high granularity → for high spatial resolution (<100 μm)
- light (<1% X_0/layer)
- up to 35 kGy dose

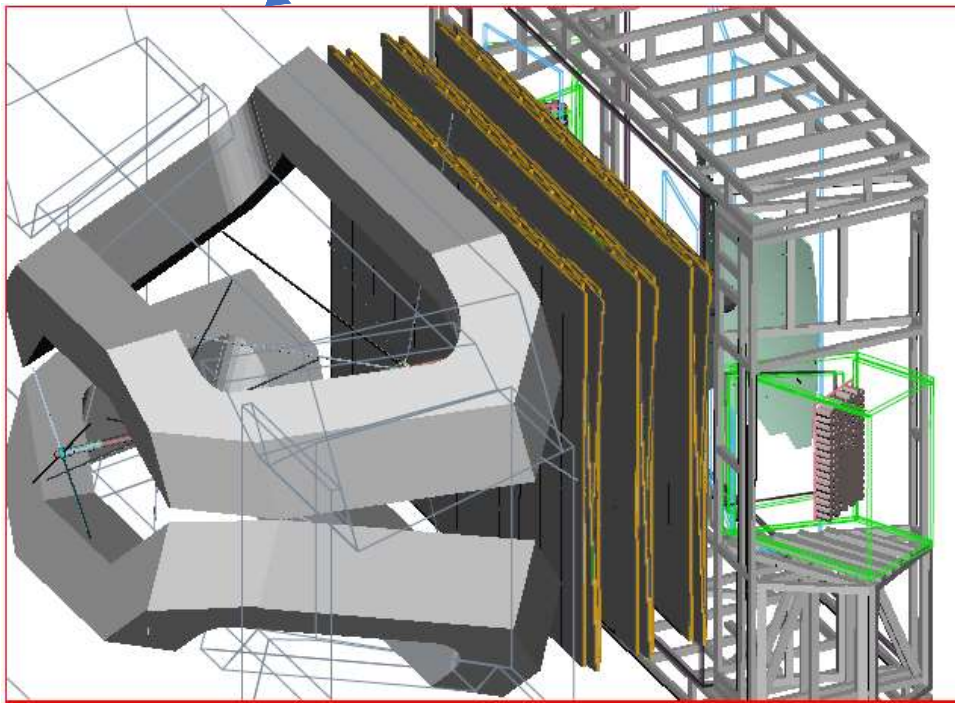


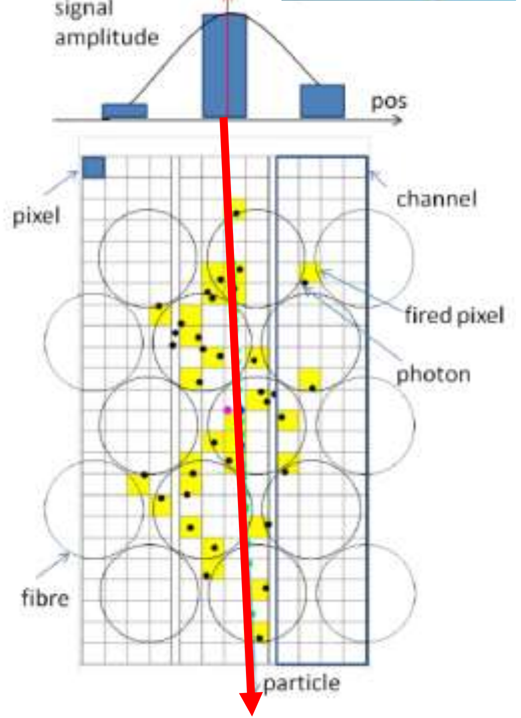
UPGRADE
LHCb Tracker TDR

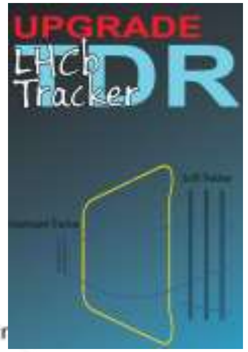
CERN-LHCC-2012-007

Upstream and SciFi Trackers







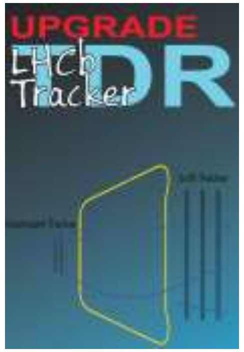


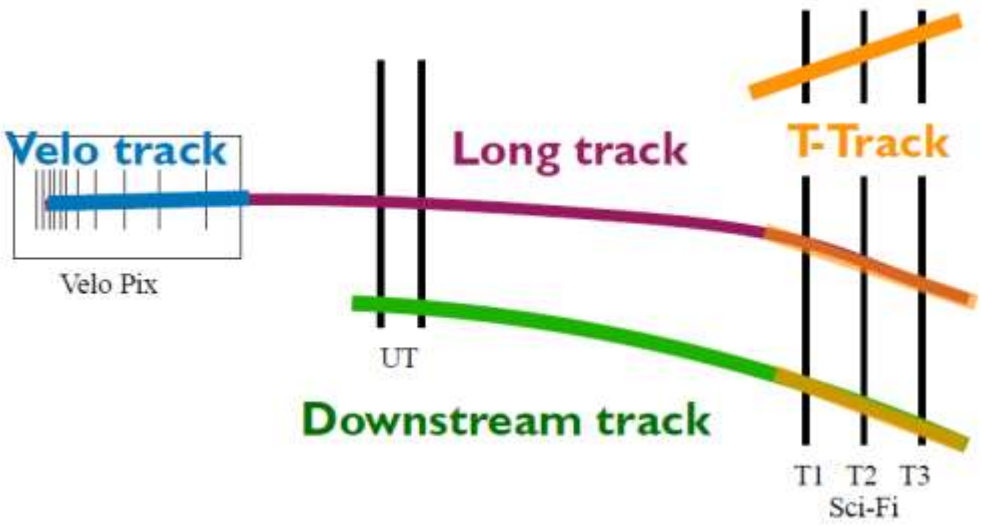
- Four planes of silicon strips with thinner sensors, thinner segmentation and larger coverage
- ~1000 sensors with lower noise expected wrt. TT

- Fast & high efficient (~99%) **Scintilating Fibre Tracker** will cover full acceptance after magnet.
- 2*2.5 meters long, 250 μm diameter with Silicon Photomultipliers readout (~524k channels).

Goal: <100 μm resolution over a total active surface of ~ 340 m^2

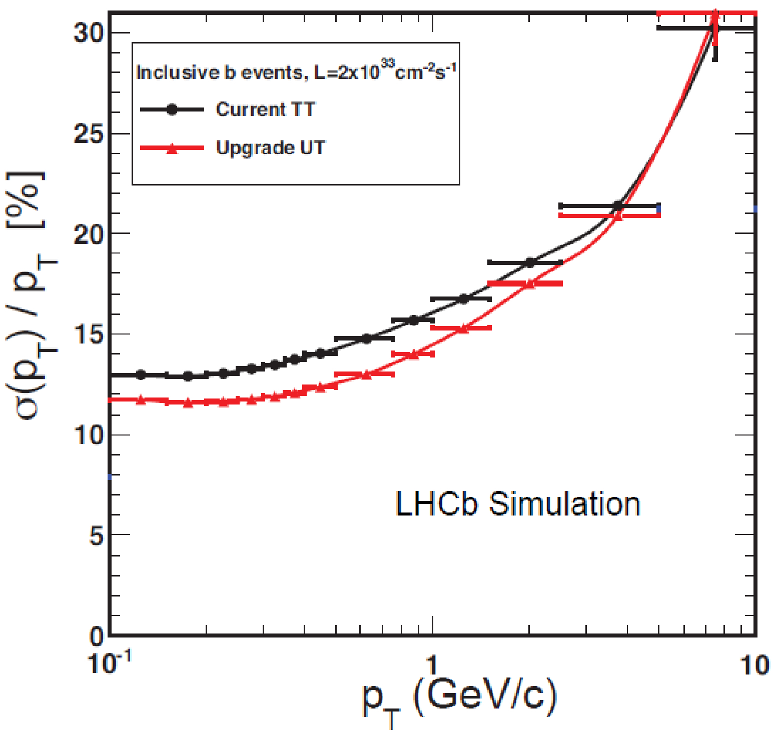
Tracking for full event reconstruction

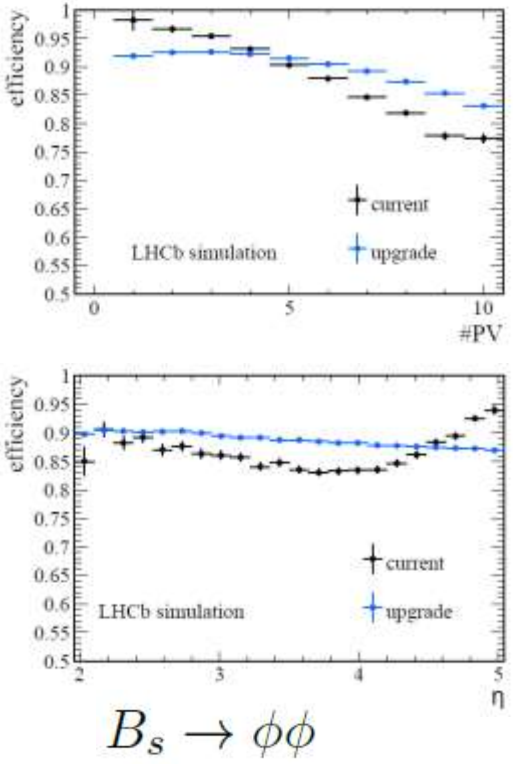




T-Track seed reconstruction of:

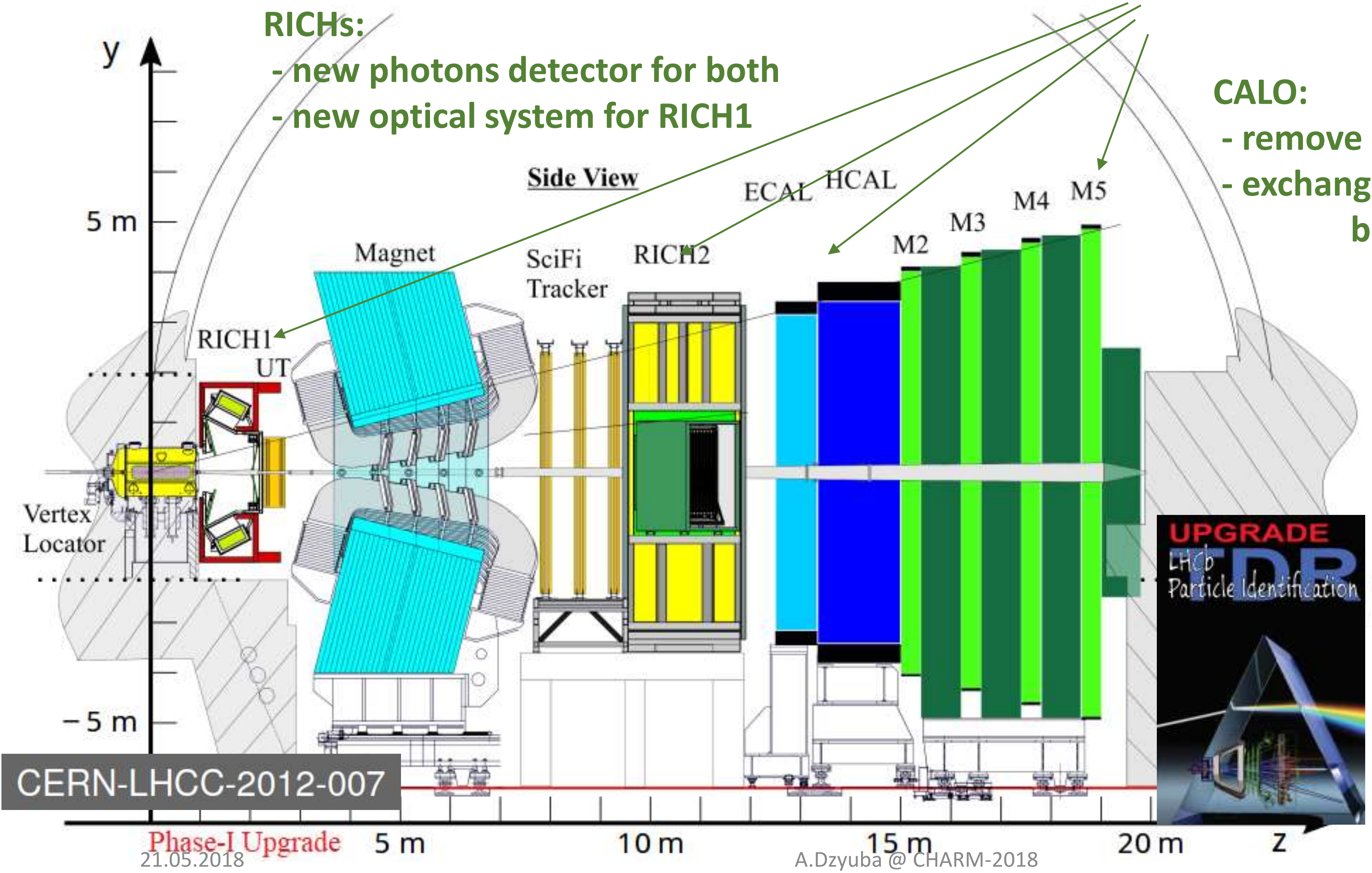
- **Long tracks** – daughter of ***c***- and ***b***-hadrons
- **Downstream tracks** – from long lived particles (Λ and K_S^0)





Simulations suggest resolution and efficiencies to be even better than in Run-I,II despite the higher event rates

New after Upgrade: VELO, Tracking, PID, Trigger



RICHs:

- new photons detector for both
- new optical system for RICH1

CALO:

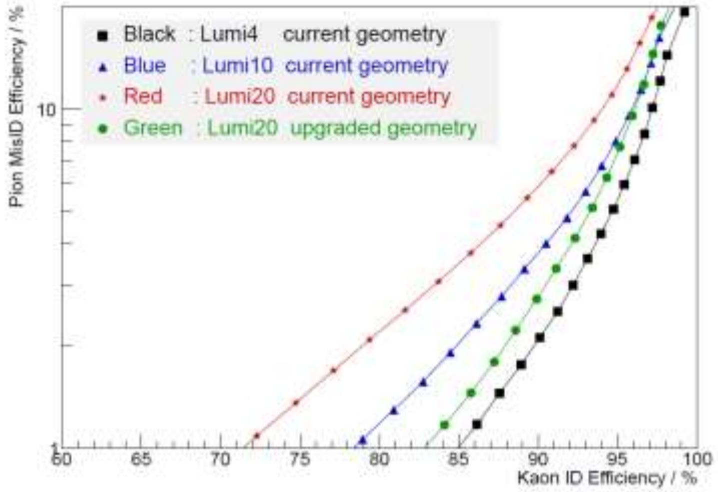
- remove SPD and PS
- exchange electronics (front- & back-end)

Muon:

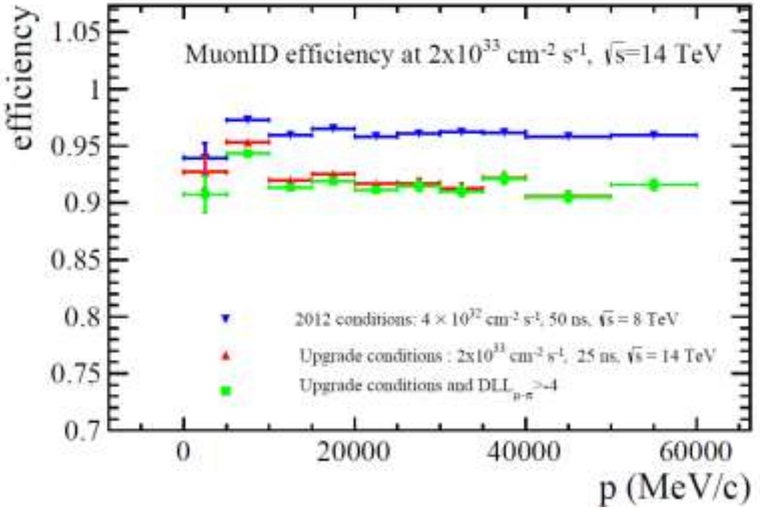
- Remove M1
- New readout
- Additional shielding in front of M2

Expected ID efficiencies (hadrons / photons / muons)

- Hadron PID – key feature to explore a lot of channels
- Expect PID performance at the same level as in Run-I,II



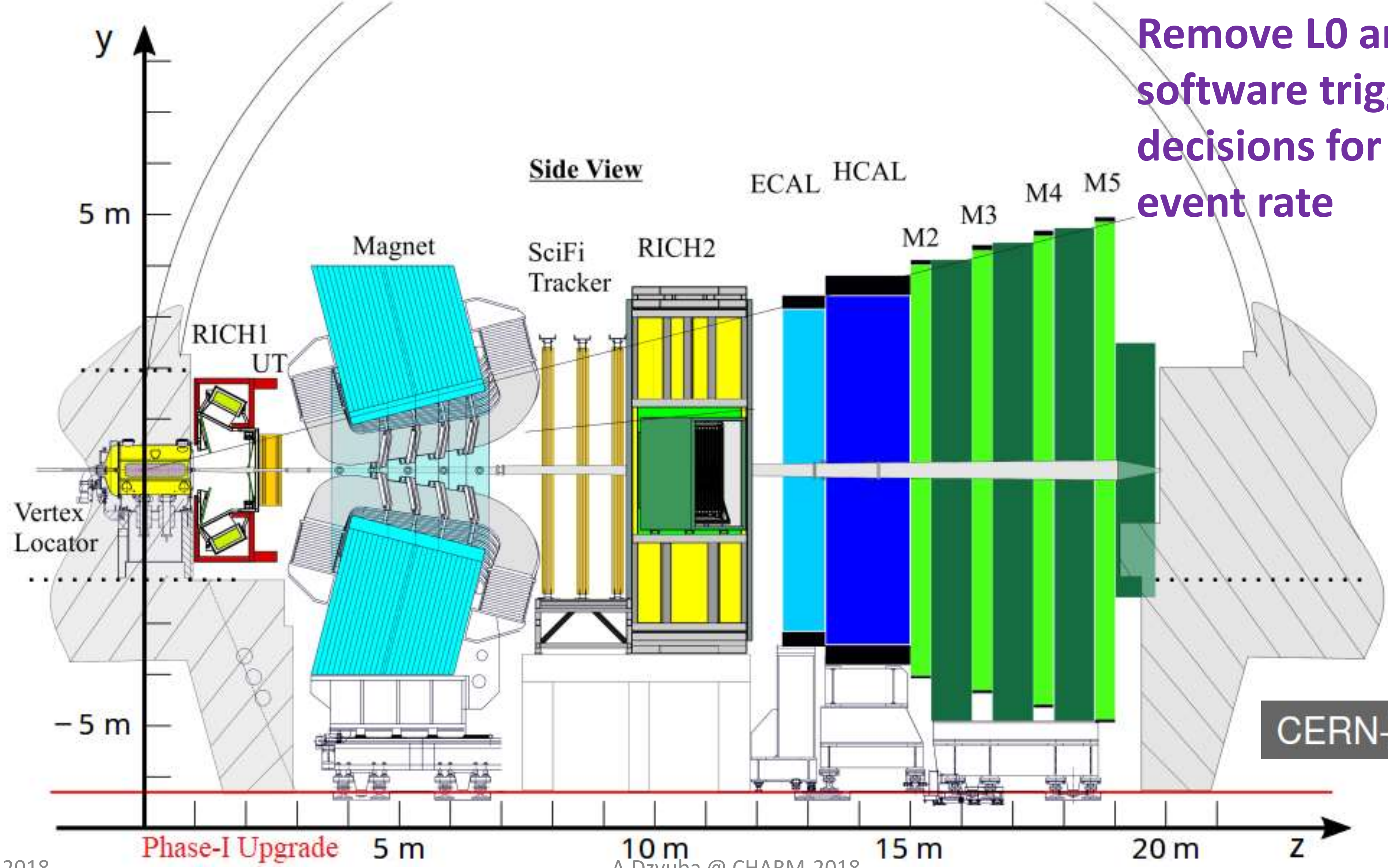
- Photon and electron detection efficiencies and mis-ID rate make possible to continue charm radiative decays program and LFU studies



- Muons efficiencies expected to be comparable with Run-I,II

  (Will allow to push down limits for rare decays with muons)

New after Upgrade: VELO, Tracking, PID, Trigger



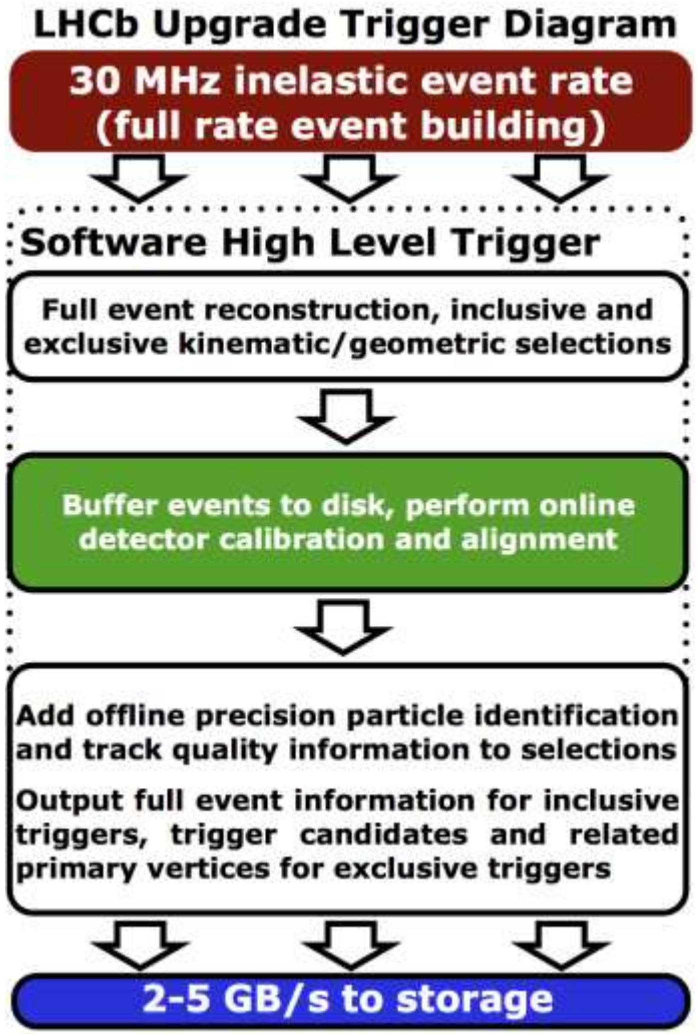
Remove L0 and make software trigger (HLT) decisions for 30-40 MHz event rate


UPGRADE
LHCb TDR
Trigger and Online

CERN-LHCC-2012-007

LHCb trigger in Run-3 (original & revised)

Original



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate
(full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

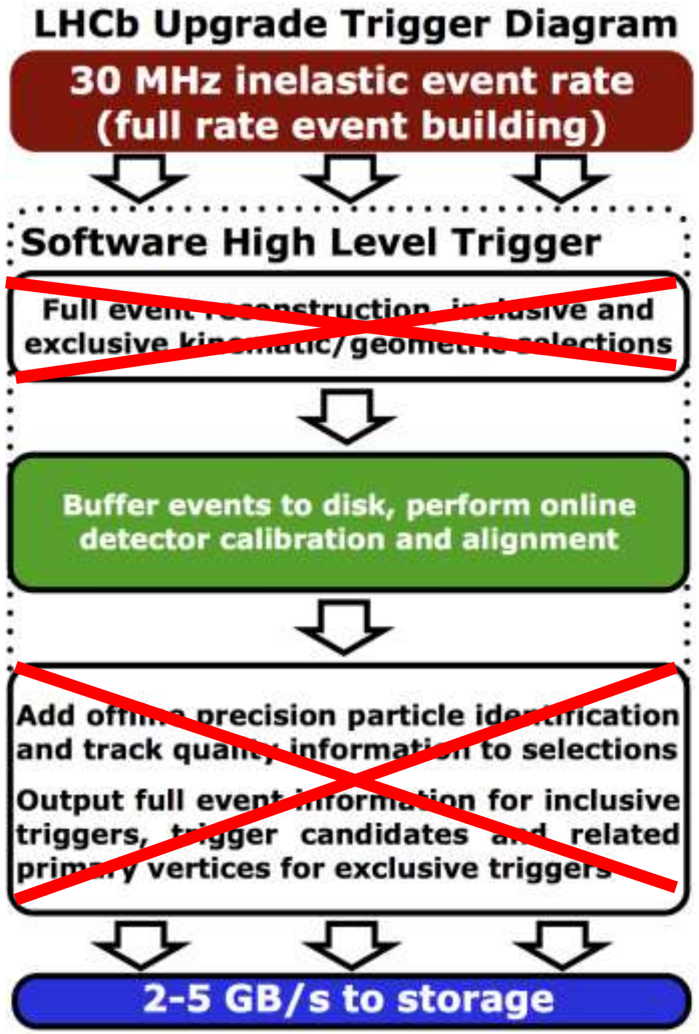
Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

LHCb trigger in Run-3 (original & revised)

Original



After review [LHCb-PUB-2017-005]

Strong constraints due to CPU resources and not-infinite budget

Partial event reconstruction (HLT-1)
Data for tracking / Track reconstruction
Efficient event selection to reduce rate <1MHz

Re-use Run-2 framework

Full event reconstruction (HLT-2)
Best tracking performance, add PID info. & offline quality selection

Perform analysis directly on trigger output

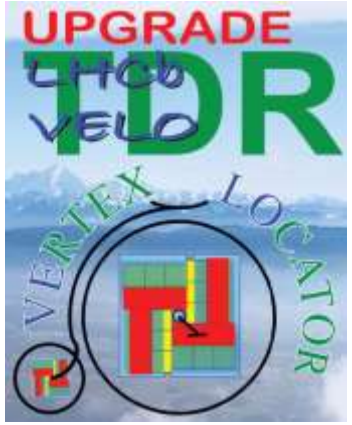
Work still in progress…

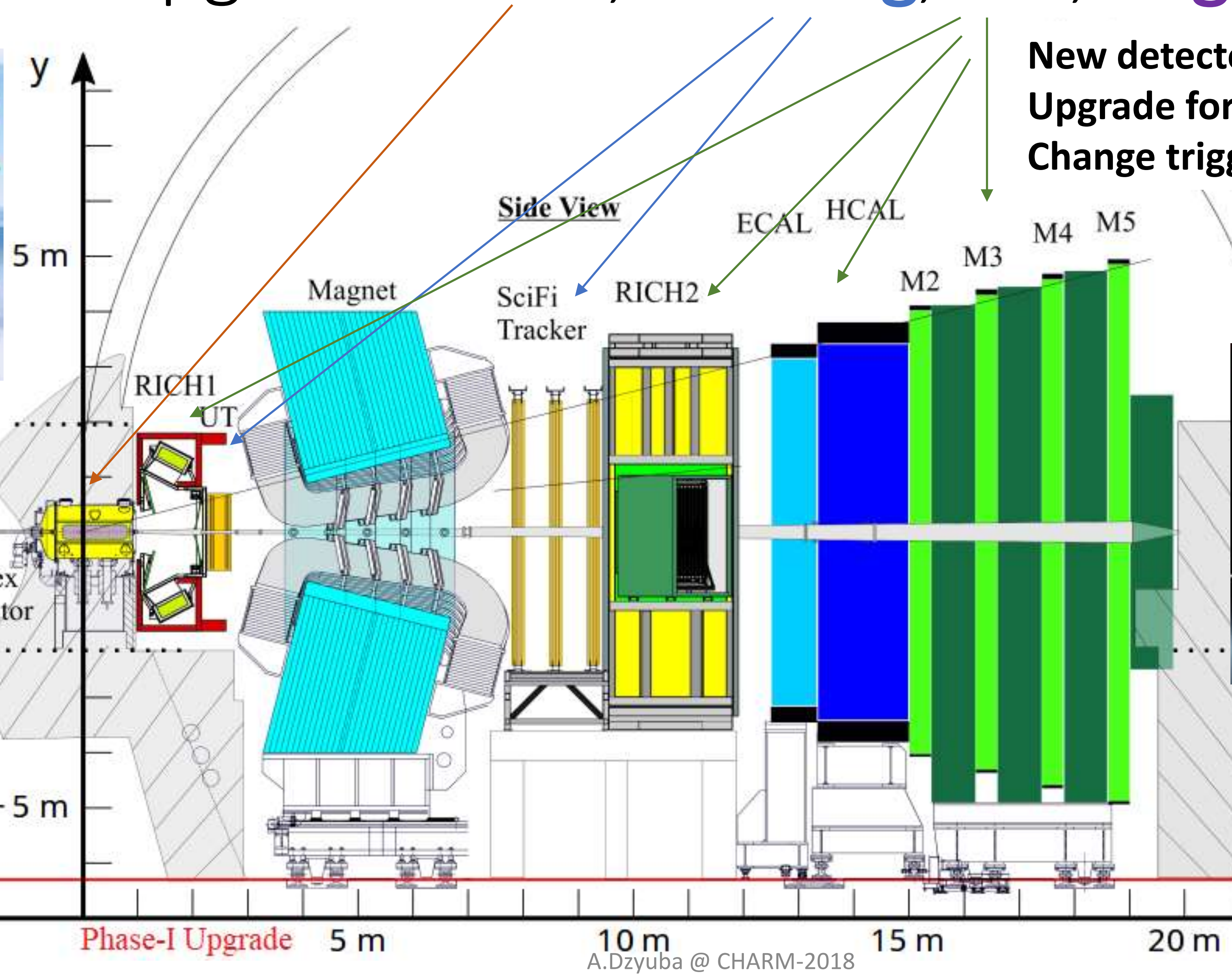
New after Upgrade: VELO, Tracking, PID, Trigger

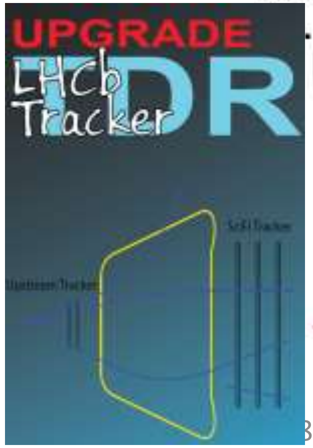
New detectors: VELO, UT & SciFi

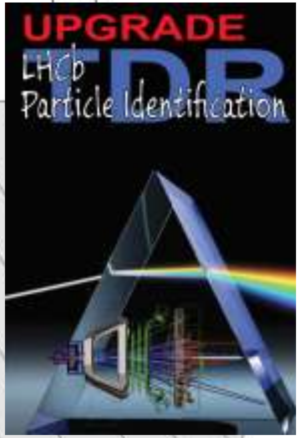
Upgrade for RICHs, CALO and MUON

Change trigger strategy wrt. Run-I & II









CERN-LHCC-2012-007

Projections for CPV observables: ΔA_{CP}

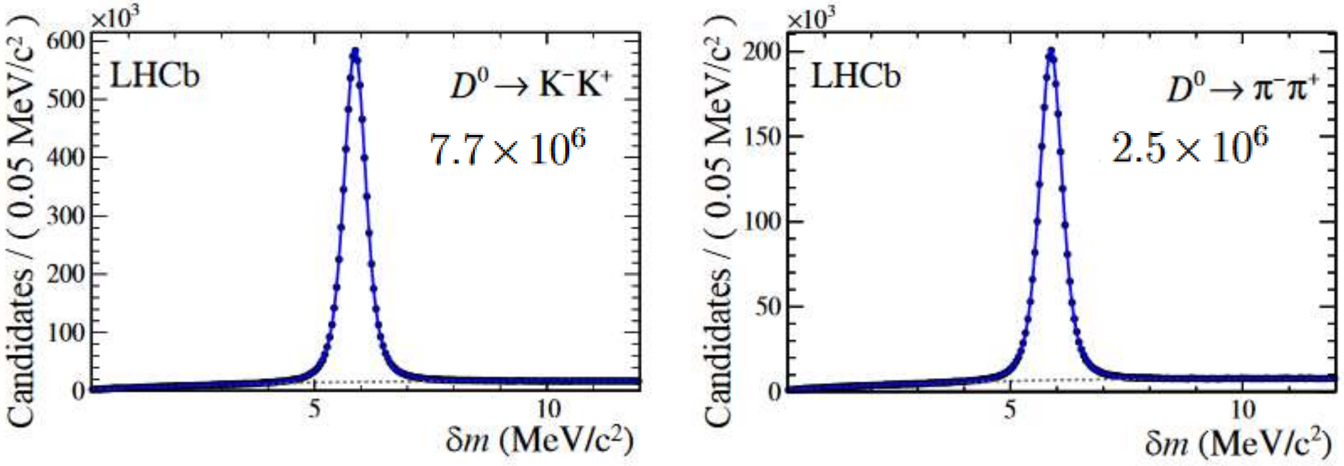
$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+).$$

$$A_{\rm raw}(f) \approx A_{CP}(f) + \underline{A_{\rm D}(f)} + \underline{A_{\rm D}(\pi_s^+) + A_{\rm P}(D^{*+})},$$

Cancel

Almost cancel

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a_{CP}^{\rm dir}\left(1 + \frac{\langle t \rangle}{\tau} y_{CP}\right) + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\rm ind},\end{aligned}$$



Run-I dataset:

$$\boxed{\Delta A_{CP} = (-0.10 \pm 0.08\ ({\rm stat}) \pm 0.03\ ({\rm syst}))\,\%,}$$

Phys. Rev. Lett. 116, 191601 (2016)

- The statistics in Run-II can be increased roughly factor of ten
- **Another factor of 10 for Runs III & IV (50 fb^{-1})**

Projected statistical uncertainty (LHCb-PUB-2014-040):

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade *
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	0.1

*** we expect that systematical uncertainly also will scale down, as data driven methods are used**

A_Γ projections

Time integrated CP asymmetries as well as mixing parameters are small:

$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \simeq a^f_{\mathrm{dir}} - A_\Gamma \frac{t}{\tau_D}$$

CPV in decay close-to-zero

CPV in mixing / interference

Expected to be less 0.005

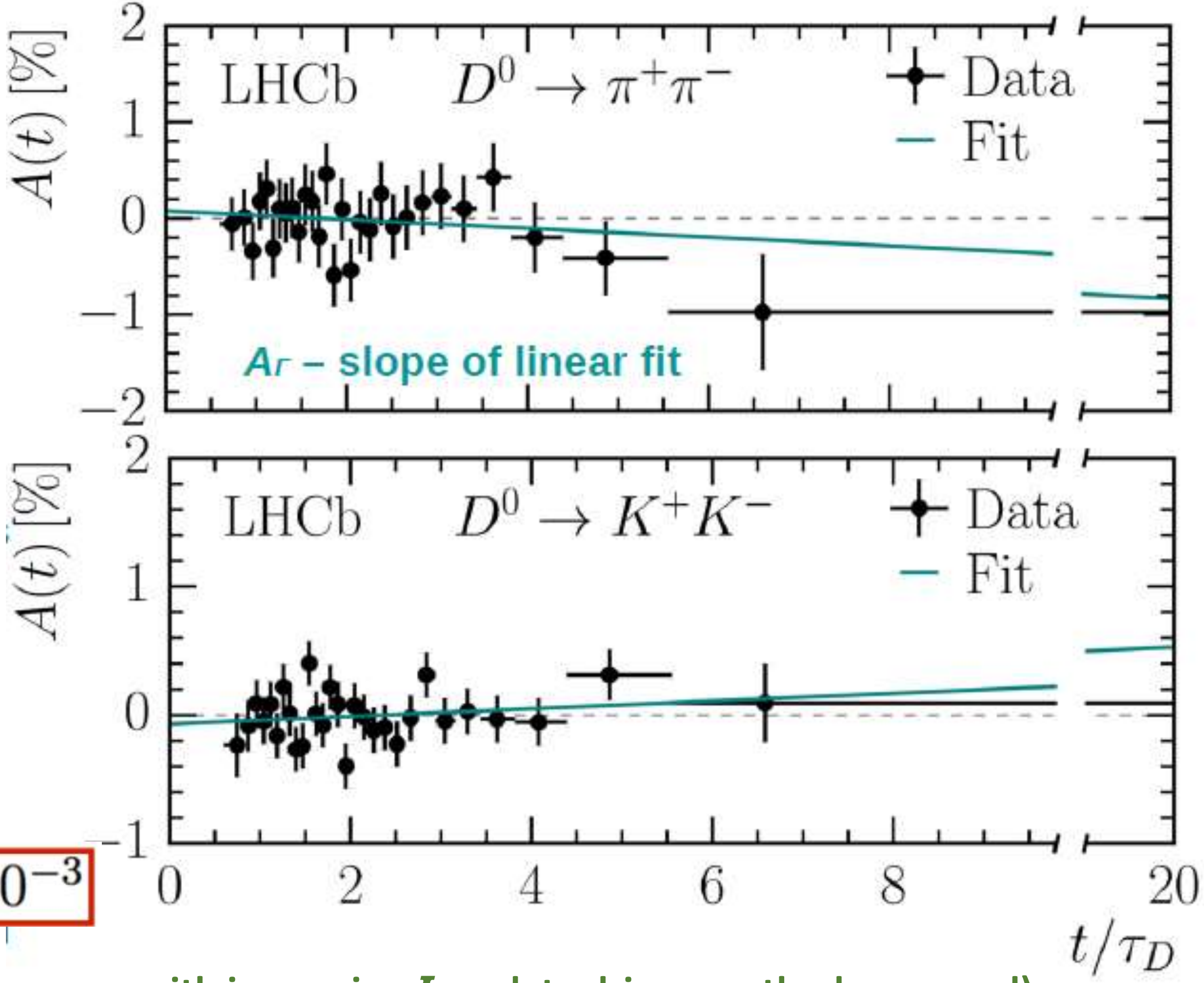
$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\overline{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\overline{D}^0 \to f}}$$

Inverse of effective lifetime

Combination of prompt and semileptonic tagging gives most precise CPV measurement:

$$\boxed{A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}}$$

PRL 118 (2017) 261803



A_Γ – slope of linear fit

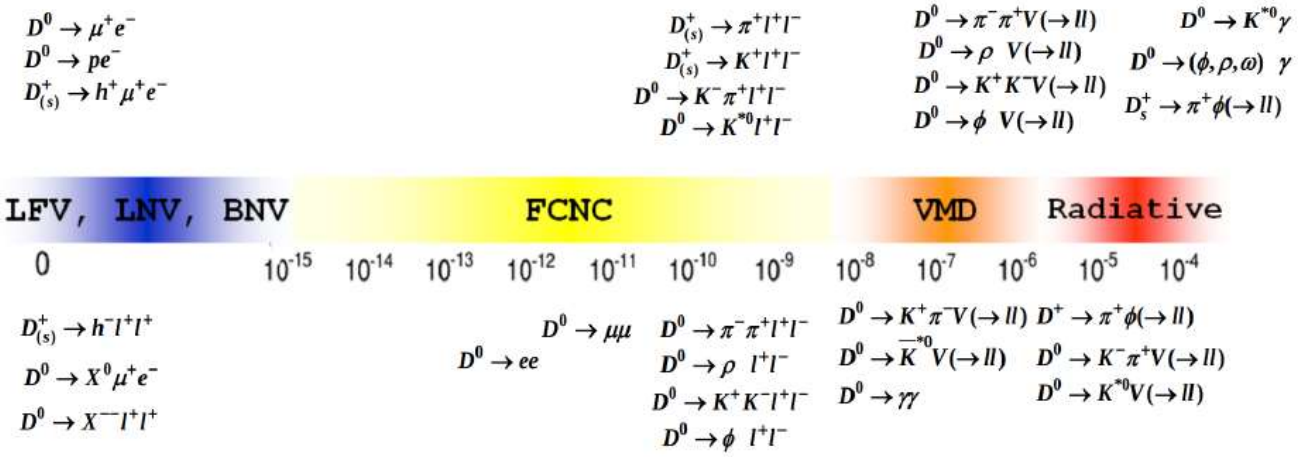
More improvement after Upgrade (we expect that systematics will improve with increasing L as data driven methods are used):

Observable	LHC Run 1	LHCb 2018	LHCb upgrade
$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**

LHCb-PUB-2014-040

For more details about LHCb CPV studies see talks of Maxime Schubiger and Angelo Carbone

Impact for rare decays (what can be done?)



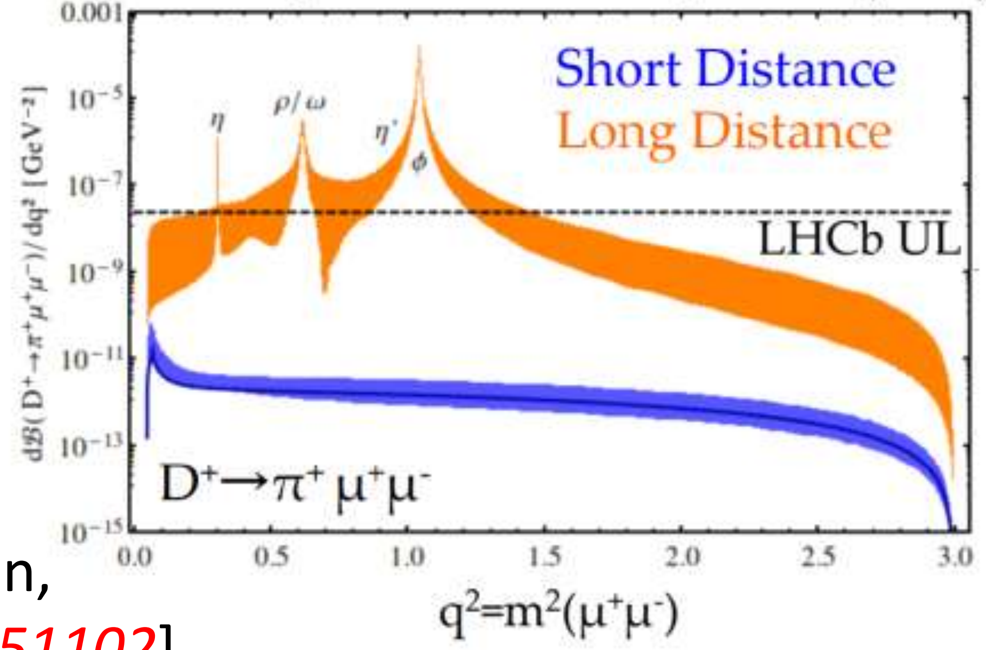
[PRD 66 (2002) 014009]

Intermediate vector resonances in the dimuon spectrum can hide short distance (SM) contribution

LHCb will keep pushing down the limits as there is still some room for New Physics:

- BR(***$D^0 \to \mu^+ \mu^-$***) < 7.6 x 10^{-9} (90% CL) with 1 fb^{-1} *PLB 725 (2013) 15 (working on update)*
- SM predictions ~ 10^{-12} [long distance ***$\gamma\gamma$*** recombination, based on Belle limits on BR(***$D^0 \to \gamma\gamma$***), *PRD 93 (2016) 051102*]

S.de Boer, G.Hiller PRD 93, 074001(2016)



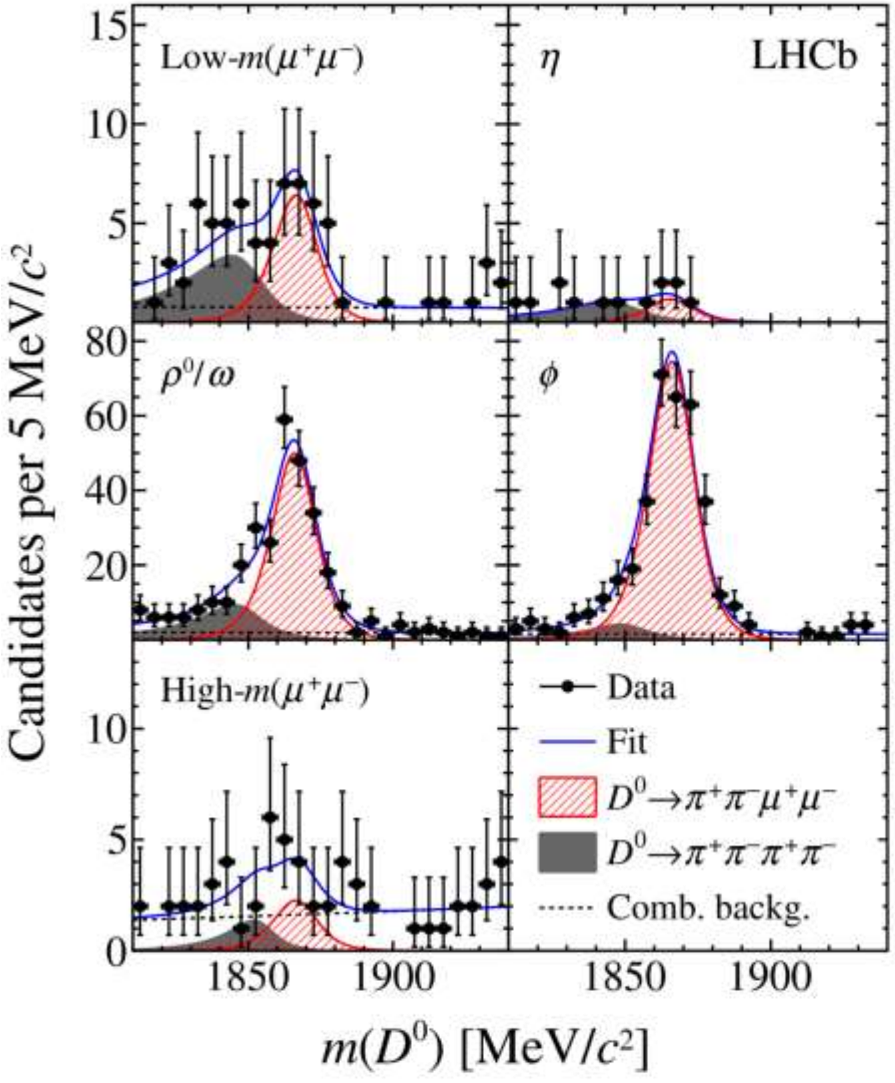
Impact for rare decays (what can be done?)

Phys. Rev. Lett. 119, 181805 (2017)

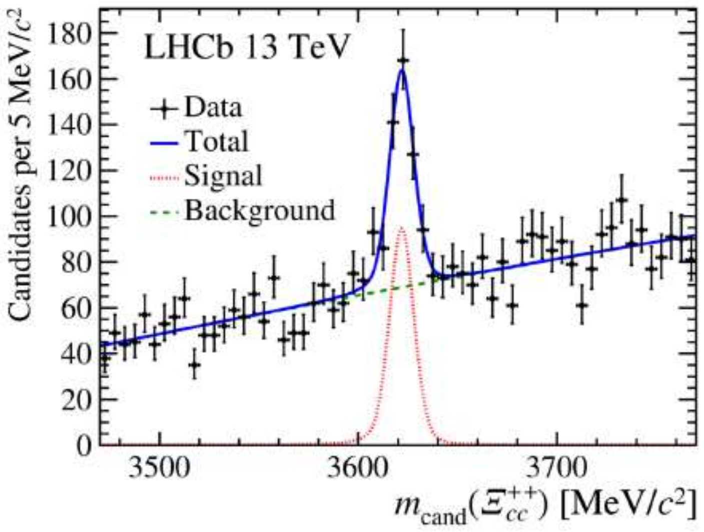
- *CP*- and *T*-asymmetries for rare decays
- Lepton Flavor Violation (LFV) to be examined
- Lepton Universality (LU) in charm sector
- Angular and amplitude analyses

Much more about charm rare decays

in Dominik Mitzel's talk



Spectroscopy with high luminosity



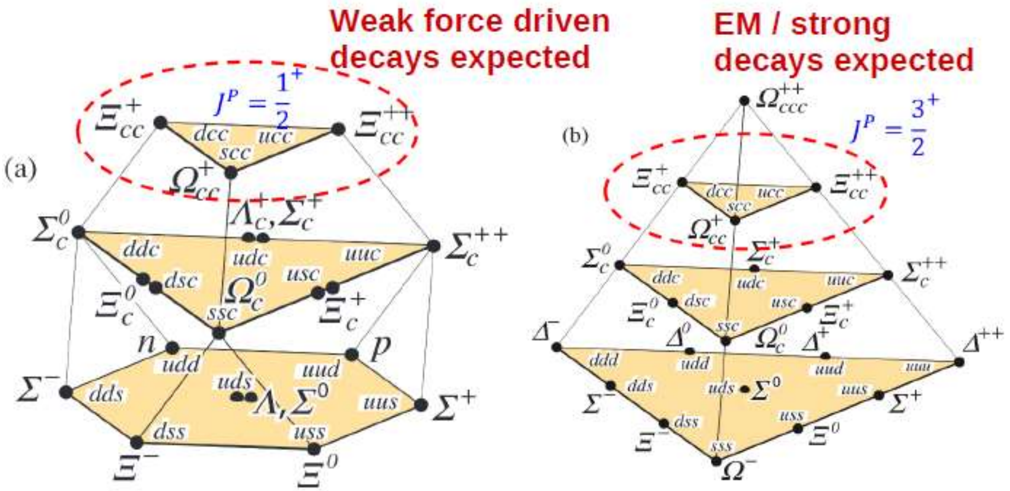
LHCb will continue to study charmed heavy baryons

Possible to have ~9k sample of Ξ_{cc}^{++} at 50 fb^{-1}

(under assumption that data scales with luminosity

~300 candidates \ √s = 13 TeV \ 1.7 fb^{-1})

Search for other decays channels


Weak force driven decays expected

EM / strong decays expected

Precise investigations of decay properties

Search for partners: Ξ_{cc}^{+}, Ω_{cc}^{+}

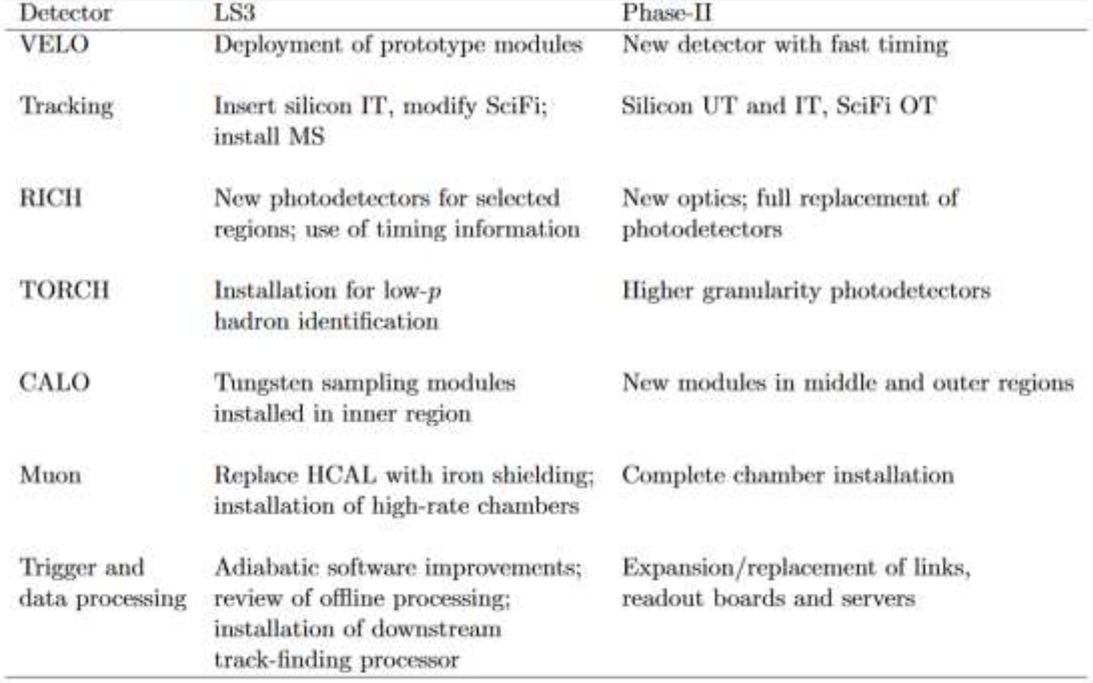
Wide program for exotica (**will be discussed by Tomasz Skwarnicki and Anton Poluektov**)

Long term future

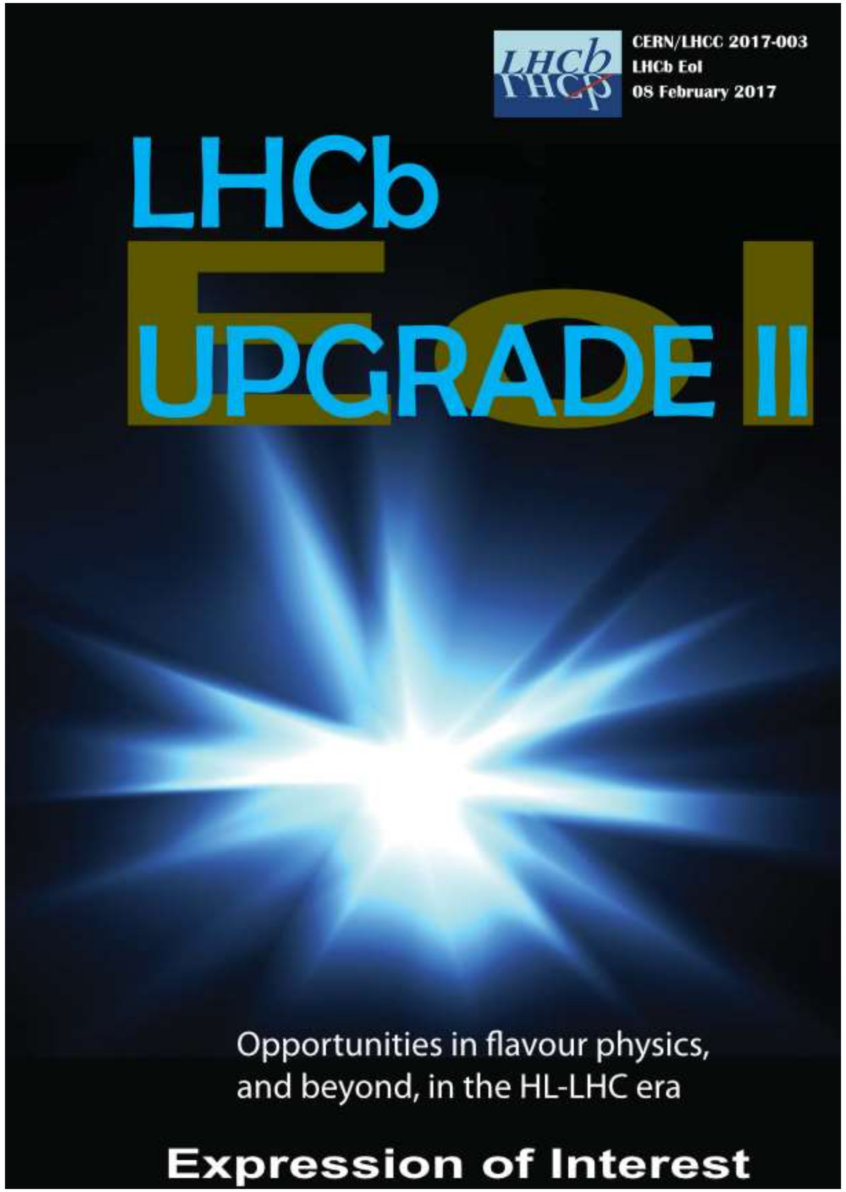
The Phase-II Upgrade is proposed for the LHCb to take full advantage of the flavour-physics opportunities at the HL-LHC

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}	9 fb^{-1}	30 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2x10^{34} cm^{-2}s^{-1}



Detector	LS3	Phase-II
VELO	Deployment of prototype modules	New detector with fast timing
Tracking	Insert silicon IT, modify SciFi; install MS	Silicon UT and IT, SciFi OT
RICH	New photodetectors for selected regions; use of timing information	New optics; full replacement of photodetectors
TORCH	Installation for low-p hadron identification	Higher granularity photodetectors
CALO	Tungsten sampling modules installed in inner region	New modules in middle and outer regions
Muon	Replace HCAL with iron shielding; installation of high-rate chambers	Complete chamber installation
Trigger and data processing	Adiabatic software improvements; review of offline processing; installation of downstream track-finding processor	Expansion/replacement of links, readout boards and servers



CERN/LHCC 2017-003
LHCb EoI
08 February 2017

LHCb
UPGRADE II

Opportunities in flavour physics, and beyond, in the HL-LHC era

Expression of Interest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LHCb
EoI
UPGRADE II

Opportunities in flavour physics,
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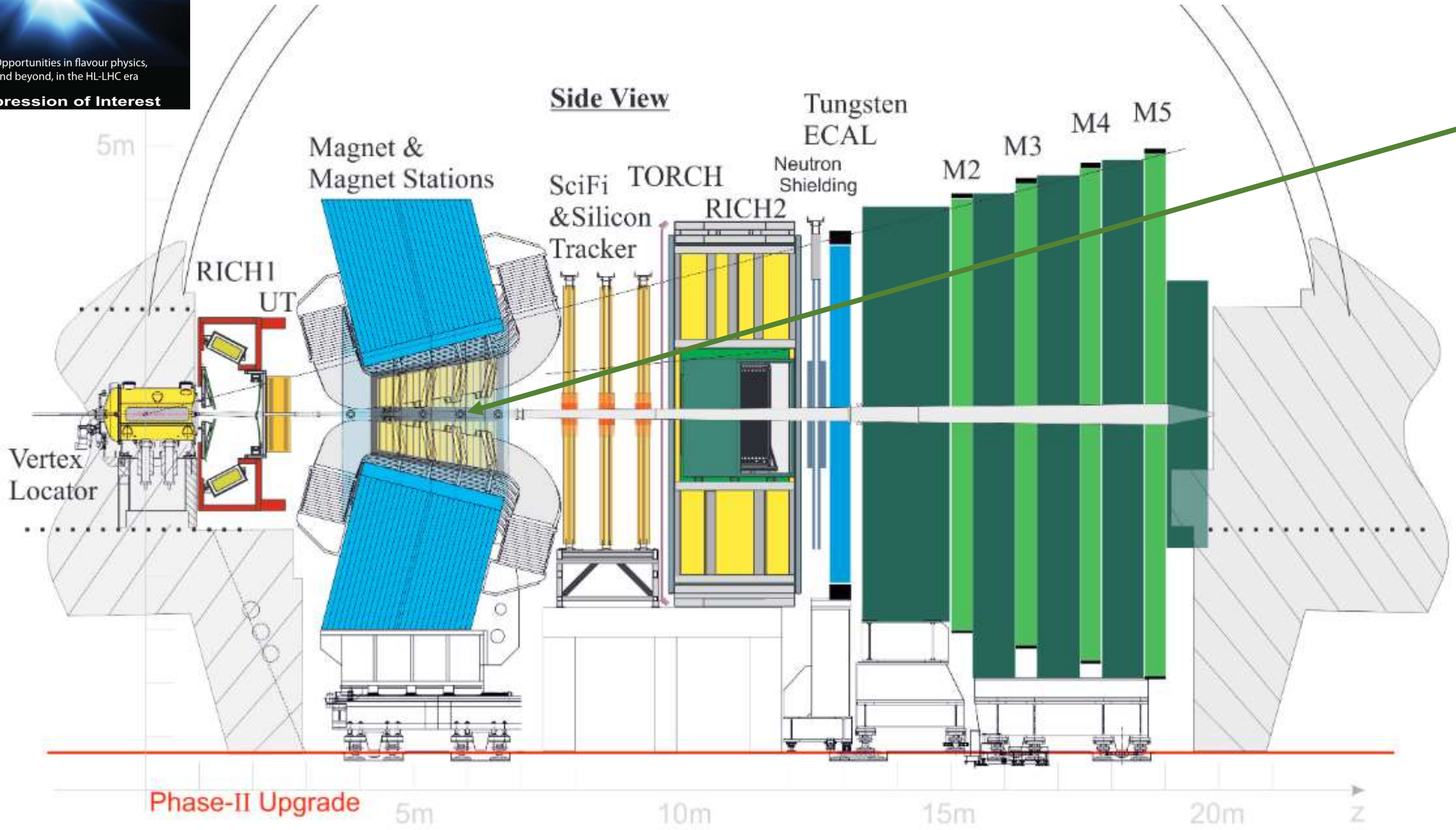
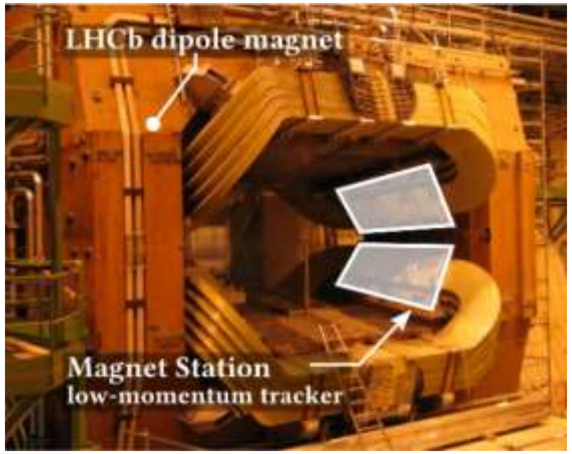
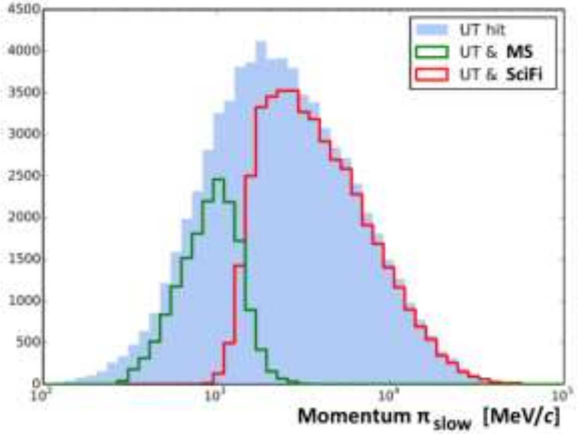
Expression of Interest

Example: magnet stations

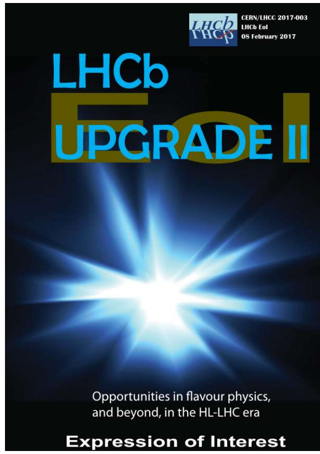






Very important for prompt tagging for charm CPV studies

Very high precision can be achieved with 300 fb^{-1}



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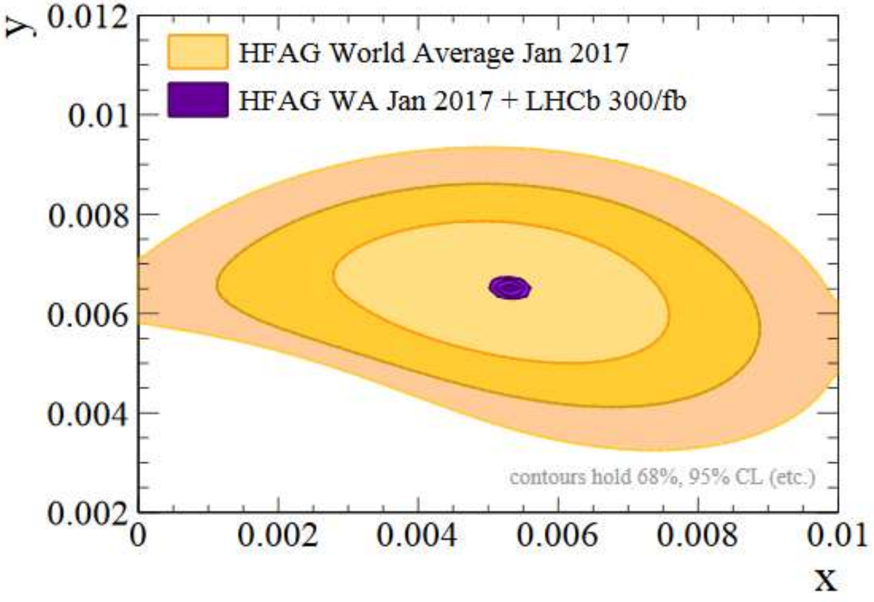
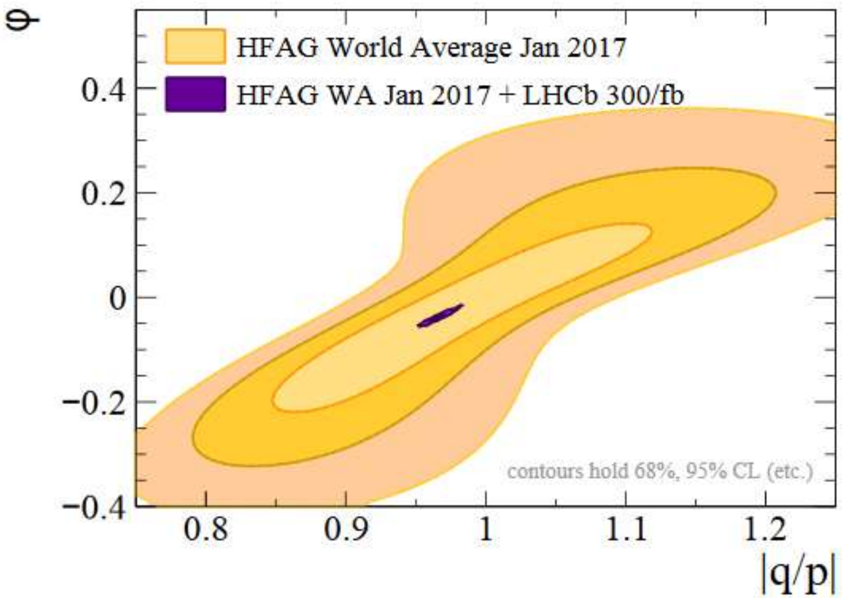
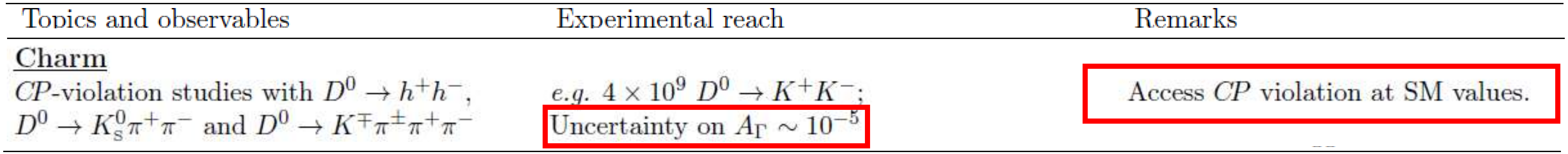
Mixing parameters



Indirect CPV parameters in charm



- We expect that systematical uncertainty will scale down together with statistical one.
- All chances to find CPV in charm sector



Topics and observables	Experimental reach	Remarks
<u>Charm</u>		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; Uncertainty on $A_\Gamma \sim 10^{-5}$	Access *CP* violation at SM values.

Summary & Conclusions

- **Excellent LHCb performance during Run-I & II.**
- A lot of important results in charm sector exploiting huge charm rate
- Some novel techniques (like Turbo) will be default in next Run-III and IV
- **Upgrade program is already going**
- VELO / Tracking / PID / Trigger innovations will allow to work with quite

  high (for forward spectrometer) number of PVs
- **Second phase of Upgrade approaching $L_{int} = 300\ fb^{-1}$**
- Expect to have a lot of new and important results for Charm Physics