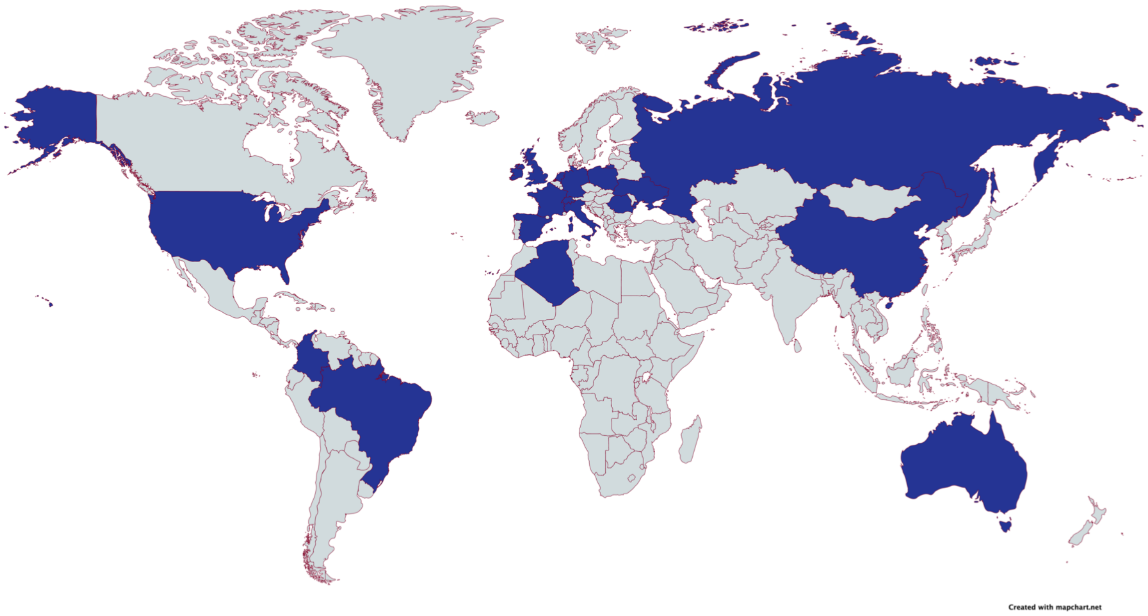
LHCb Upgrade Phase 2 and Heavy Ions

Patrick Robbe, IJCLab Orsay, 26 Jan 2021

LHCb Collaboration

Almost 1000 authors (1400 members) from 88 institutes and 18 coutries



<u>In France:</u>

IJCLab Orsay

LAPP Annecy

LPC Clermont-Ferrand

CPPM Marseille

LPNHE Paris

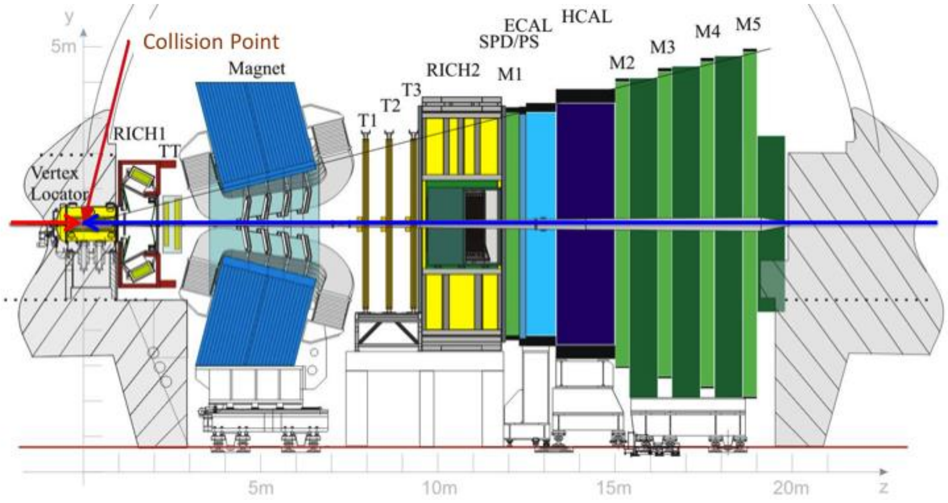
LLR Palaiseau

Interests from CEA Saclay and Subatech Nantes to join LHCb for Heavy Ion physics programme

LHCb up to 2018

- Physics core program: search for New Physics through heavy flavor decays
  - Study *CP* violation
  - Rare *B* decays
- Optimized acceptance: $1.6 < \eta < 4.9$
- Good particle ID: e, μ, p, K, π, γ identification up to p=100 GeV
- Good vertex and proper-time resolution: Interaction point resolution better than 80 μm
- Good mass and low momentum resolution
- Efficient trigger for lepton and hadron channels: 1 MHz readout rate up to 2018 – main improvement point for first upgrade.
- LHCb became a more general detector in the forward region

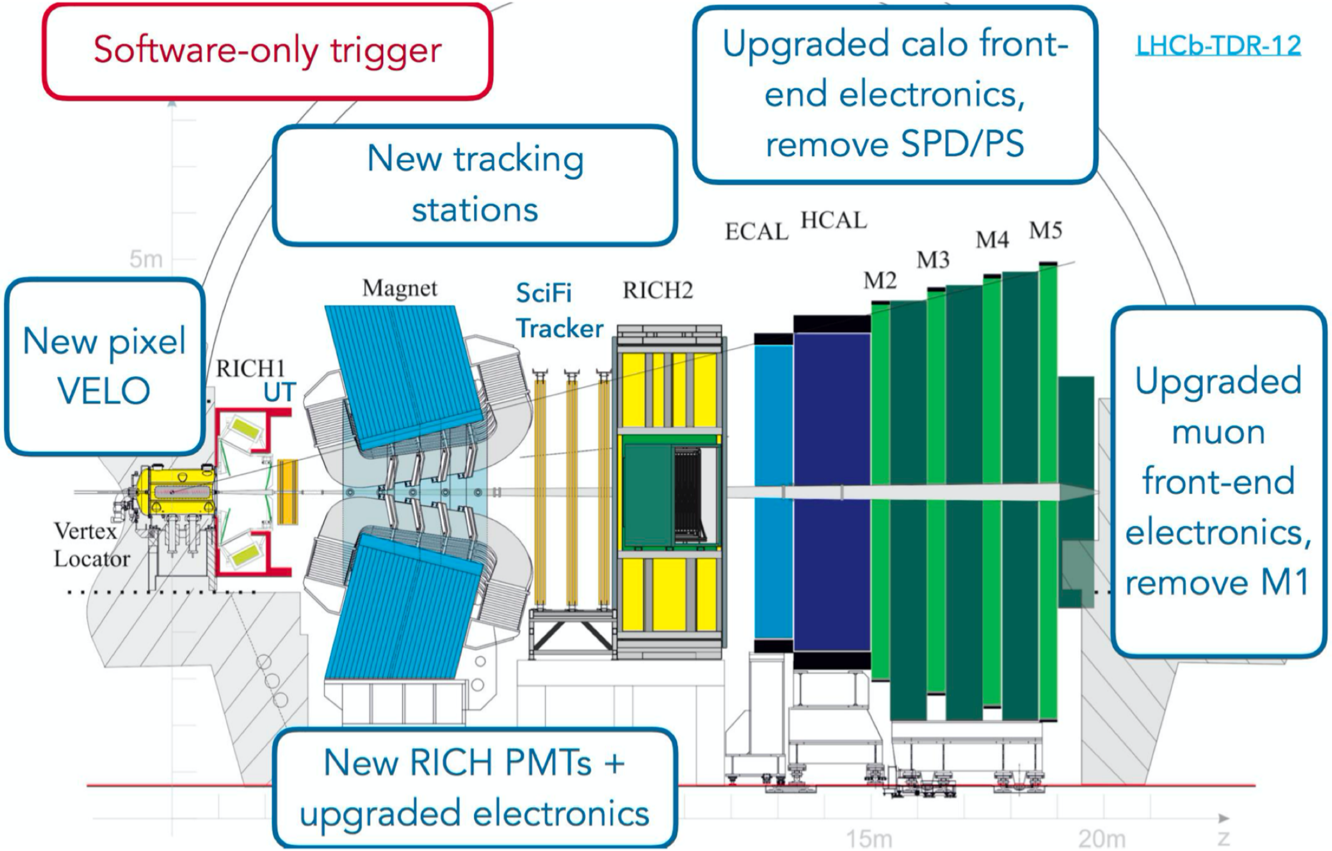
[*JINST* 3 (2008) S08005]



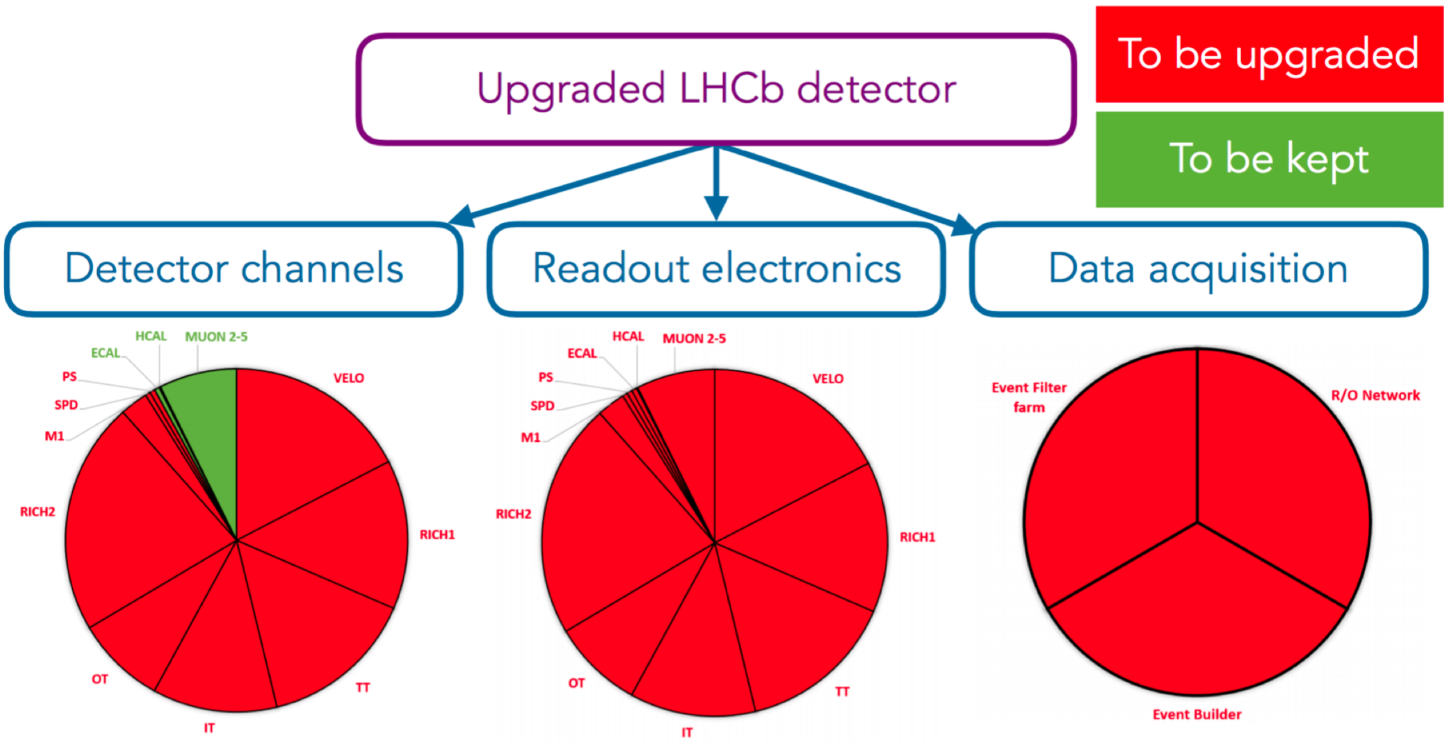
LHCb upgrades

NB: Run 3 and following steps shifted by 1 year due to COVID19

LHCb Upgrade Phase I

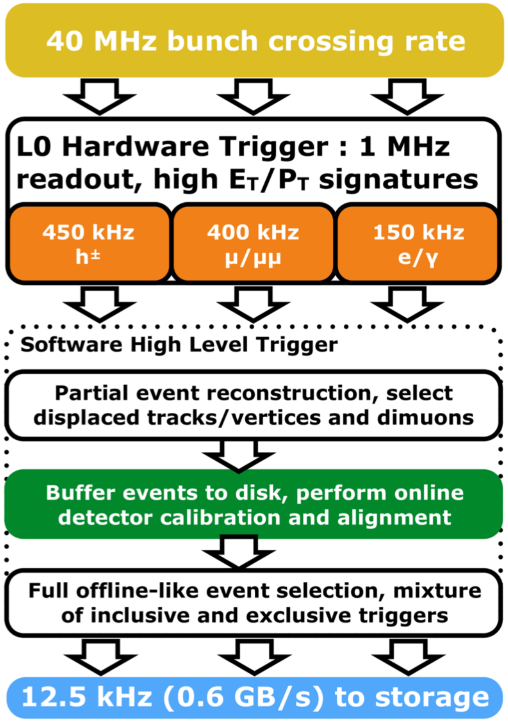


LHCb Upgrade Phase I

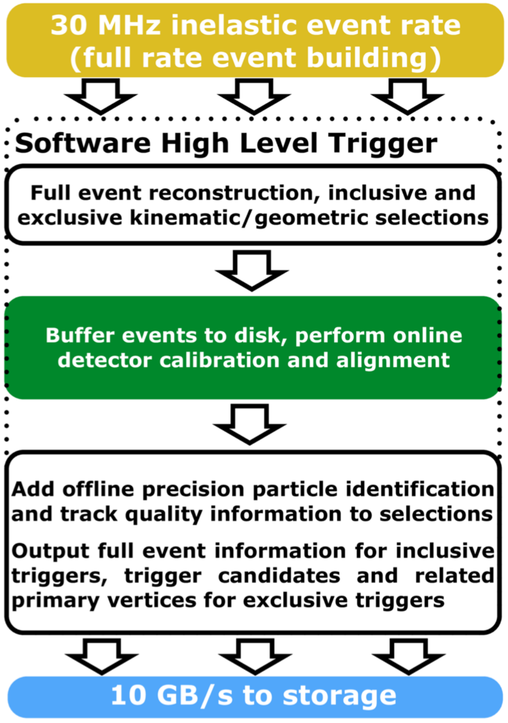


Full Software Trigger

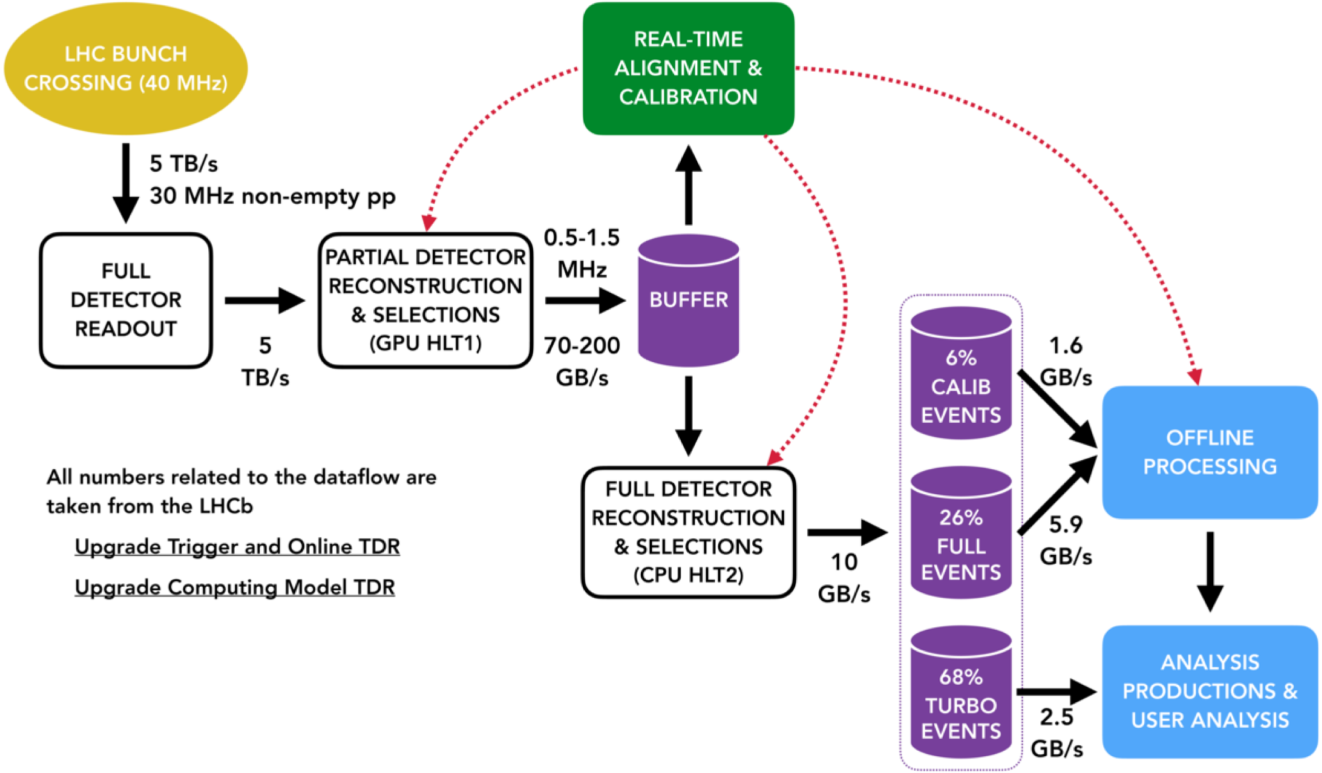
LHCb Run 2 Trigger Diagram



LHCb Run 3 Trigger Diagram

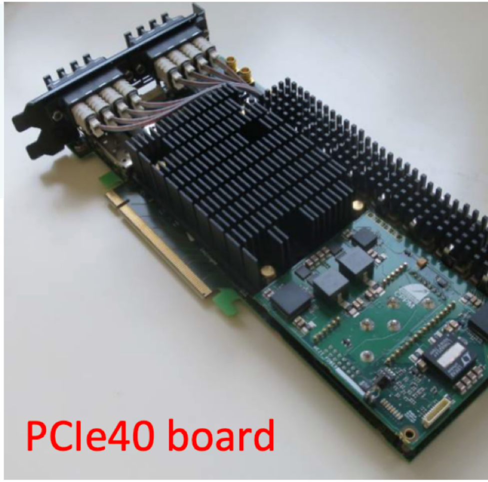


Run 3 Dataflow



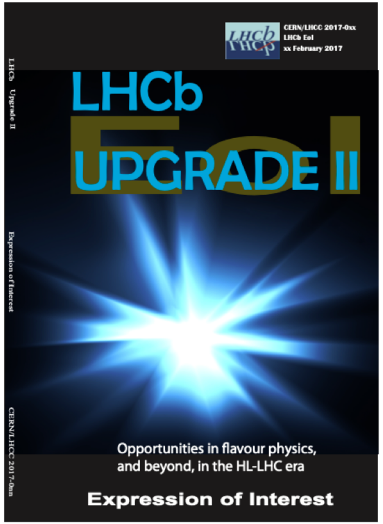
All numbers related to the dataflow are taken from the LHCb

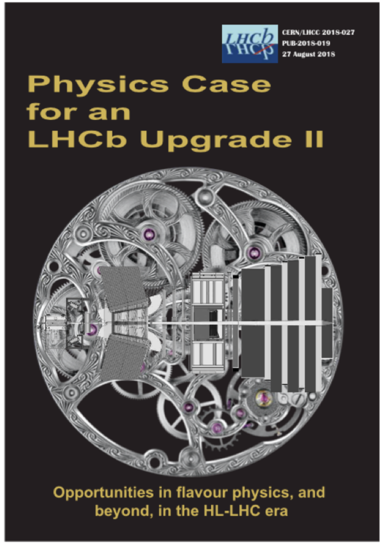
- Upgrade Trigger and Online TDR
- Upgrade Computing Model TDR



Future Upgrades: Upgrade Ib and II

- Approved to proceed to design by LHCC and CERN Research Board
- Framework TDR: September 2021
- Upgrade Ib data-taking: 2026/2027 (consolidation and enhancement)
- Upgrade II data-taking: 2031-2038



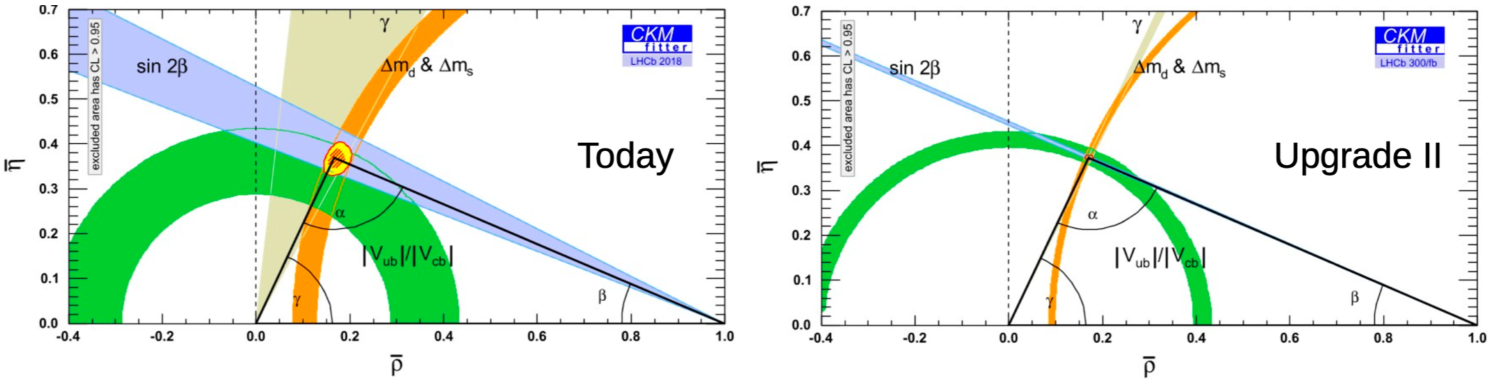


European Strategy Briefing Document

- Strong support for project (http://cds.cern.ch/record/2691414)
- "The LHCb Upgrade II... will enable a wide range of flavour observables to be determined at HL-LHC with unprecedented precision”

Constraining Unitarity Triangle

- Measurement of the Unitary Triangle (i.e. description of CP violation in the Standard Model) will impose strong constraints on New Physics.

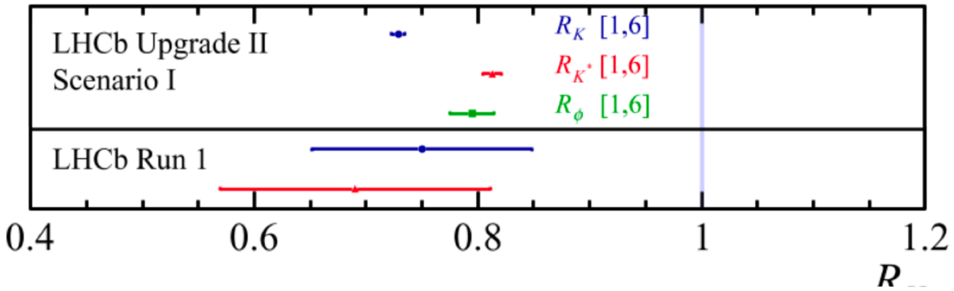


- Two independent measurements of the triangle apex:
  - ($\Delta m_d/\Delta m_s$, sin 2β) and (V_{ub}, γ)
  - Both pairs require upgrade II for statistics (sin 2β and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})

Lepton Flavour Universality

- Looking for New Physics by comparing decays with muons and electrons: huge challenge
- Calorimeter has to keep current performance but with much higher occupancy:
  - Upgrade of calorimeter is mandatory, not done in Upgrade Phase I
- These measurements have almost no theoretical uncertainties

arXiv:1808.08865



$R_K = Br(B^+ \to K^+ e^+ e^-)/Br(B^+ \to K^+ \mu^+ \mu^-)$

$R_{K^*} = Br(B^0 \to K^{*0} e^+ e^-)/Br(B^0 \to K^{*0} \mu^+ \mu^-)$

$R_\phi = Br(B_s^0 \to \phi e^+ e^-)/Br(B_s^0 \to \phi \mu^+ \mu^-)$

Performance Table

arXiv:1808.08865

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

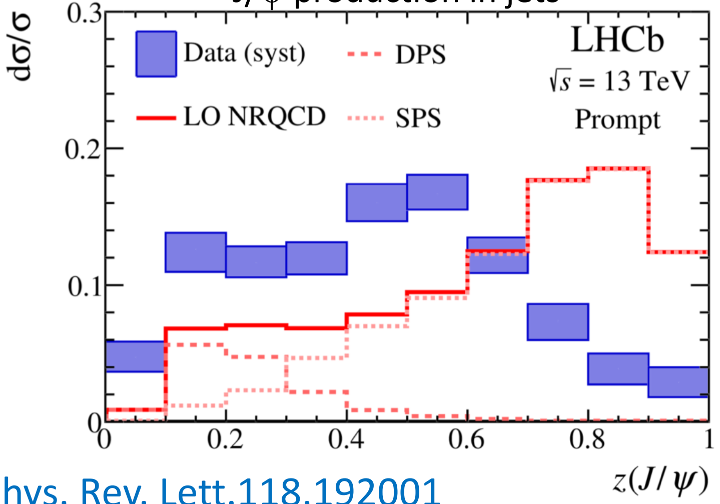
European Strategy Briefing Document

- Strong support for project (http://cds.cern.ch/record/2691414)
- "The LHCb Upgrade II… will enable a wide range of flavour observables to be determined at HL-LHC with unprecedented precision”
- Including ion and fixed target program at LHCb
- “For heavy-ion studies, the proposed fixed-target experiments with LHCb and ALICE enable the exploration of new energy regimes…and the use of new physics probes…to test the factorisation of nuclear effects.”

LHCb as general detector

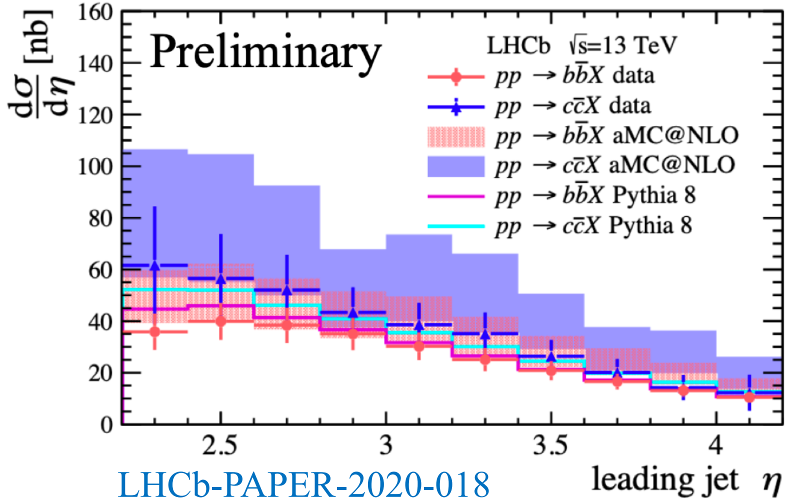
- Many results obtained beyond initial physics program:
  - Observation of CP violation in charm decays,
  - Discovery of pentaquarks or double-charm baryons
  - Physics with jets

J/ψ production in jets



Phys. Rev. Lett.118.192001

$b\bar{b}$ or $c\bar{c}$ production in jets

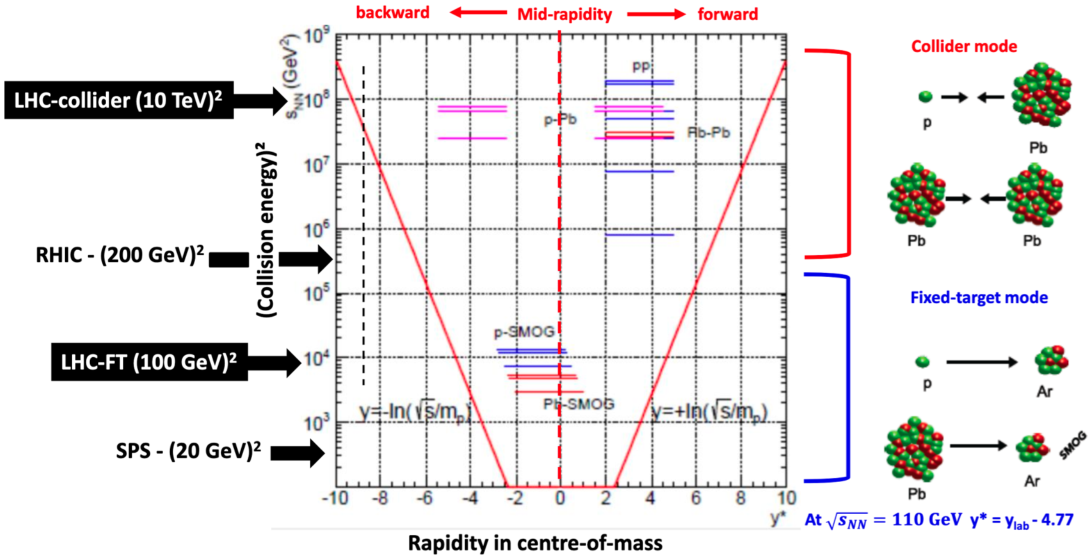


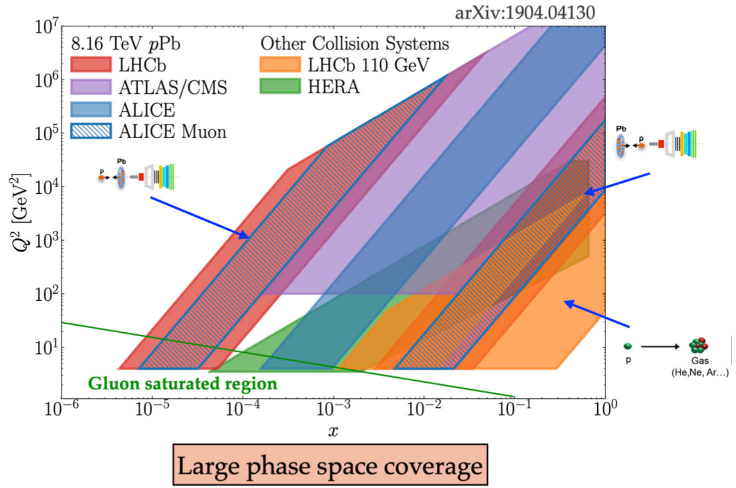
LHCb-PAPER-2020-018

LHCb Heavy Ion Physics Program

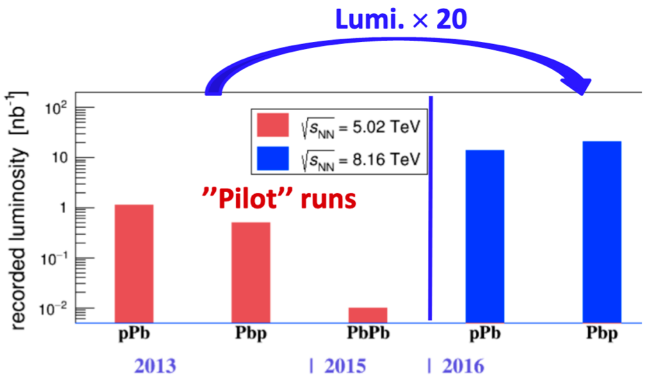
- And Heavy Ion – Fixed Target ….
- So far mostly concentrated on study of heavy-flavor production in *p*Pb collisions: well established performances and large statistics
- New areas emerging, that will be consolidated with the future upgrades of the detector:
  - Fixed target program (SMOG)
    - Limited for the moment by the small statistics available: fixed target data taking required dedicated time limited slots
  - PbPb collisions
    - Limited by the reach in centrality of the detector
- More generally, already existing datasets are under-exploited because only a small group of persons are active in this area in LHCb

LHCb Heavy Ion Physics Program





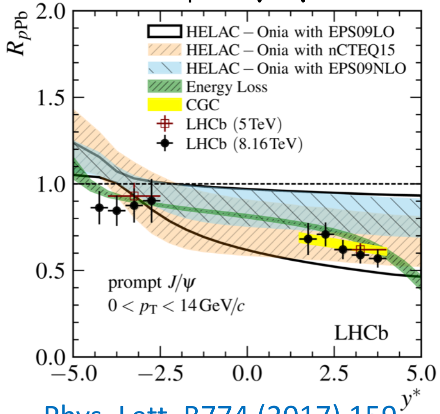
Flavour Production in *p*Pb collisions



$$R_{pPb} = \frac{\sigma_{pPb}}{A_{Pb}\sigma_{pp}} = \frac{\sigma_{pPb}}{208\ \sigma_{pp}}$$

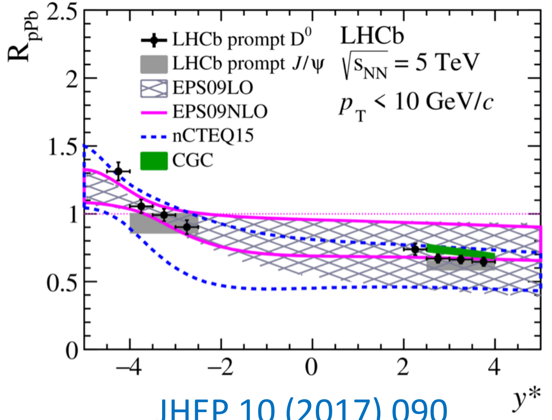
- Nuclear modification factors of several final states, decaying to muons or to hadrons

$J/\psi \rightarrow \mu^+\mu^-$



Phys. Lett. B774 (2017) 159

$D^0 \rightarrow \pi^+ K^-$

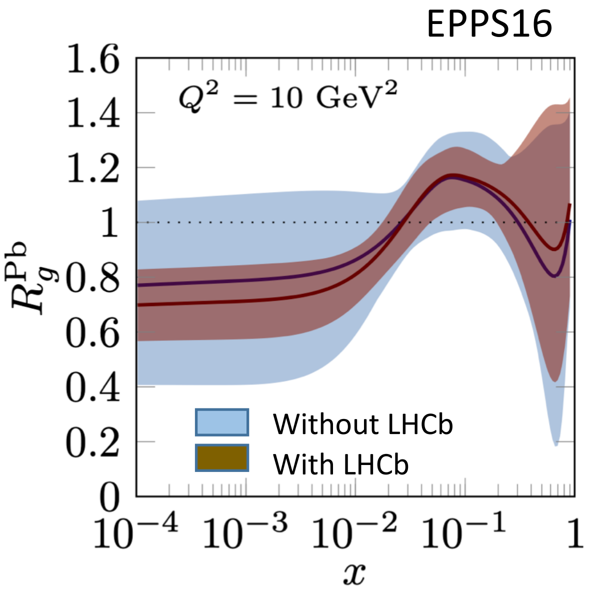


JHEP 10 (2017) 090

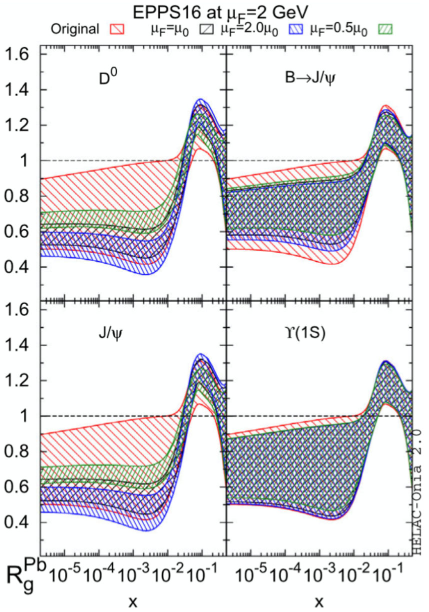
- Several new results under preparation: Λ_c, $\psi(2S)$, χ_c

Flavour Production in *p*Pb collisions

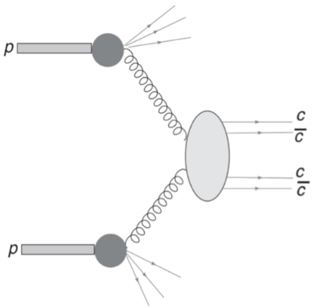
- **A QCD analysis of LHCb *D*-meson data in pPb collisions** (K.J. Eskola *et al.*, JHEP 20 (2020) 37)
- LHCb D^0 measurement in *p*Pb included in a global nPDF analysis. Large impact on gluon modification factors at small *x*.



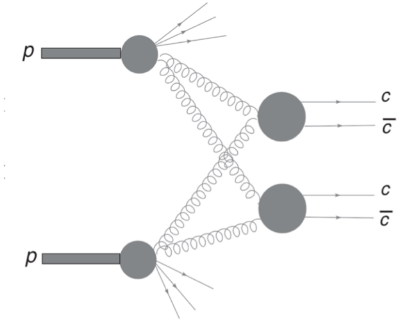
- **Gluon shadowing in heavy-flavour production at the LHC** (A. Kusina *et al.*, PRL 121 (2018) 052004)
- LHCb D^0, J/ψ, *B*, Υ(1S) measurement in pPb



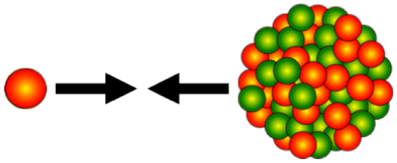
Double Charm Production in *p*Pb collisions



Single Parton Scattering (SPS)



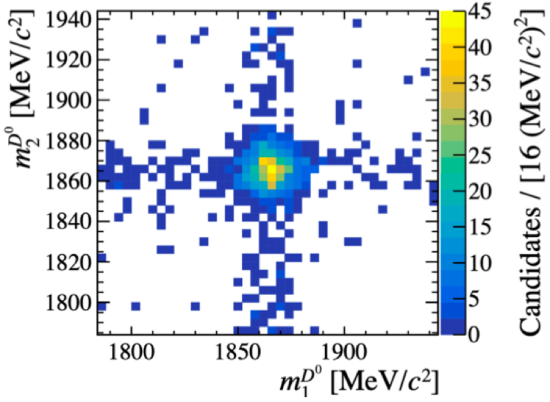
Double Parton Scattering (DPS)

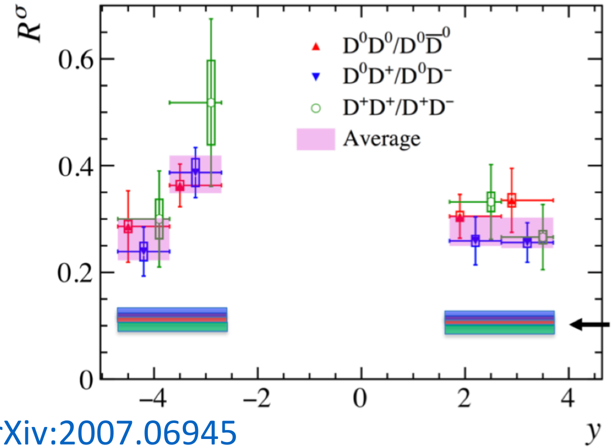


Enhancement of DPS is expected in *p*Pb compared to *pp*

- Measure pairs of D^0, D^+, D_s^+, J/ψ mesons: they are correlated in SPS and not in DPS. From *pp* measurements, it is still impossible to know if SPS or DPS dominates pair production in hadronic collisions. It is important because DPS cross-section value is important to describe *pp* collisions in general in generators.
- Naively, SPS mechanism is expected to be linear with the number of colliding partons, while DPS should increase much more.
- This assumption is however impacted by nuclear effects.

Double Charm Production in *p*Pb collisions





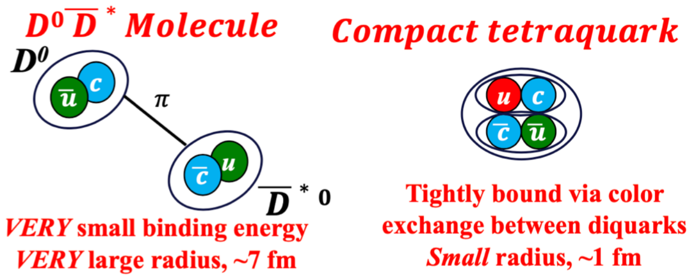
Results from pp collisions
JHEP 06 (2012) 141

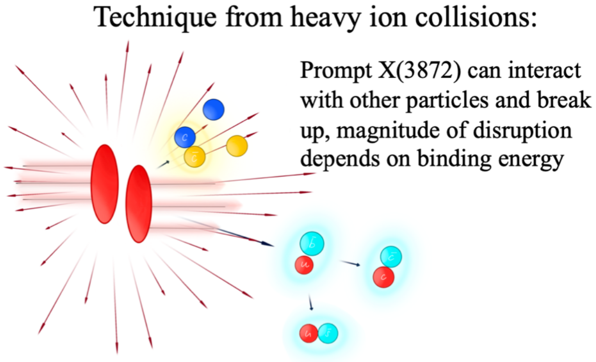
- R_σ is the ratio of *DD* production over $D\overline{D}$
- $D\overline{D}$ production comes mainly from the "simple" $c\overline{c}$ production, which scales (if no nuclear effects) with the number of nucleons
- Significant increase of *DD* production in *p*Pb collisions
- Consistent with expectations for DPS
- Sign that *DD* production is dominated by DPS production

arXiv:2007.06945

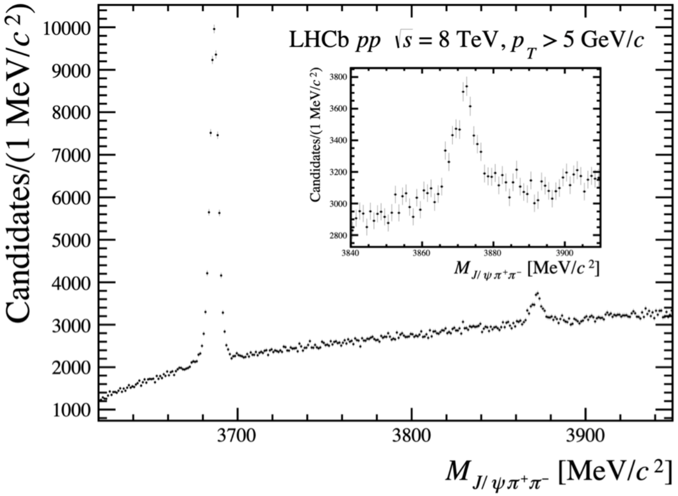
X(3872) suppression in *pp* collisions

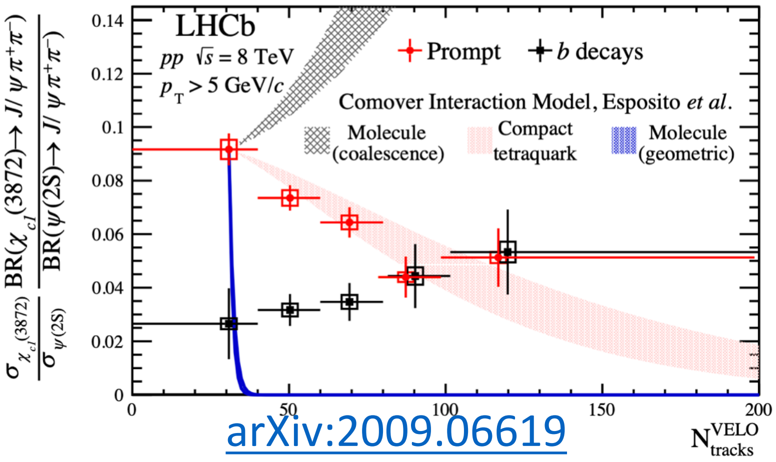
- Ongoing efforts to measure nuclear effects in high multiplicity *pp* collisions, mostly by ALICE and CMS (i.e. ψ(2S) production in high multiplicity *pp* collisions)
- X(3872) = χ_{c1}(3872) is an exotic $c\bar{c}$ meson first observed by BELLE (PRL 21 (2003) 262001) in *B* decays
- Structure unknown but ultimately could be understood by studying its production in heavy ion collisions. This is still out of reach, but high multiplicity *pp* collisions can also be used.





X(3872) suppression in *pp* collisions





arXiv:2009.06619

Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

Coalescence of D mesons into molecular X(3872) increases ratio

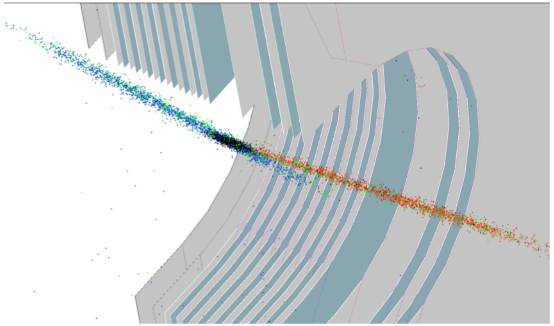
Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases

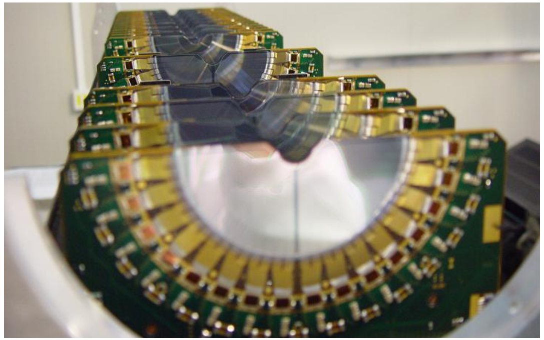
arXiv:2006.15044 (A. Esposito *et al.)*

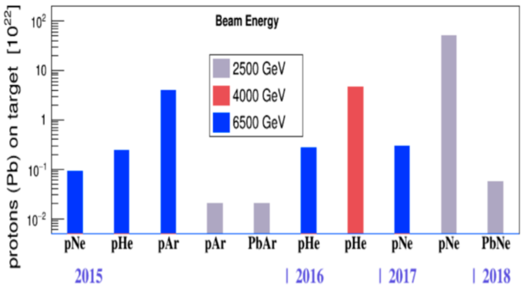
- Suppression of X(3872) prompt production relative to ψ(2S) at high multiplicity,
- While production from *b* decays is compatible with being flat as expected (*B* decay is not affected by what happens at the time of production, since it has a large decay time)

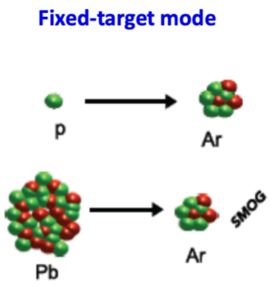
Fixed target physics with LHCb

- Gas can be injected inside the LHC vacuum, in the VELO.
- Designed and used to determine the luminosity but since 2015 is used to collect physics data. [JINST 7 (2012) P01010]
- Originally use Neon gas
- Other non-getterable noble gases can be used: we used also **Ar** and **He**
- The pressure in the LHC when the gas is injected is ~2x10^{-7} mbar (instead of 10^{-9} mbar with no injection), between 1 day to 2 weeks of dedicated run. During Heavy Ion runs, we also took data in parallel collisions/beam-gas.



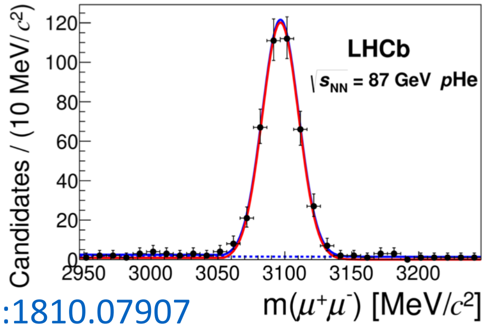


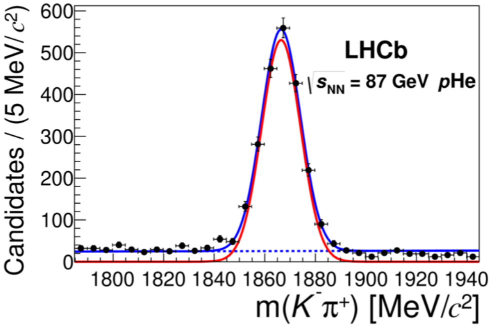


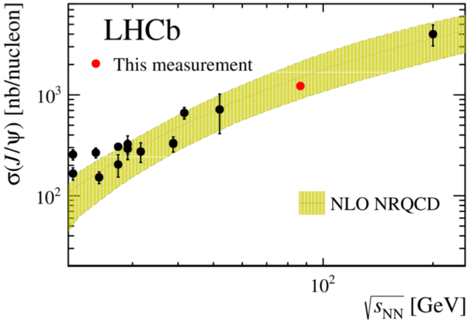


Production of heavy flavor in fixed target

- $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^-\pi^+$ in *p*He collisions at 86.6 GeV

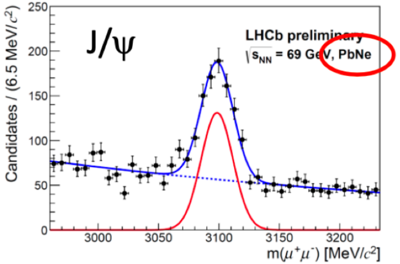


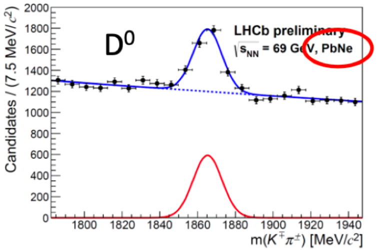




arXiv:1810.07907

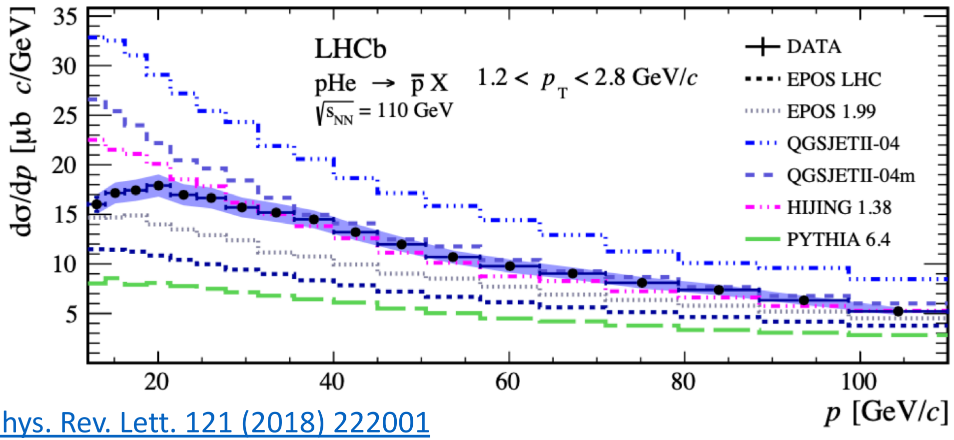
- $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^-\pi^+$ in PbNe collisions at 69 GeV, no centrality limitation



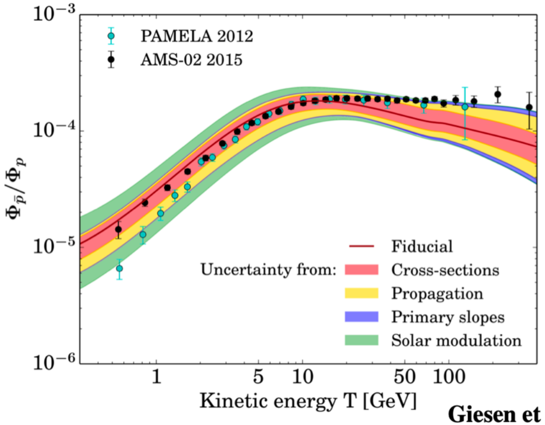


SMOG: anti-protons in *p*He collisions at 110 GeV

- Interesting to reduce uncertainties on anti-proton production in inter-stellar medium: $p\mathrm{He} \rightarrow \bar{p}X$ is ~40% of secondary cosmic anti-proton



Phys. Rev. Lett. 121 (2018) 222001

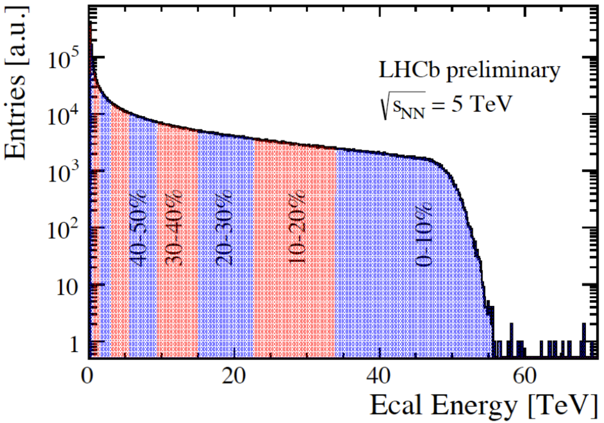


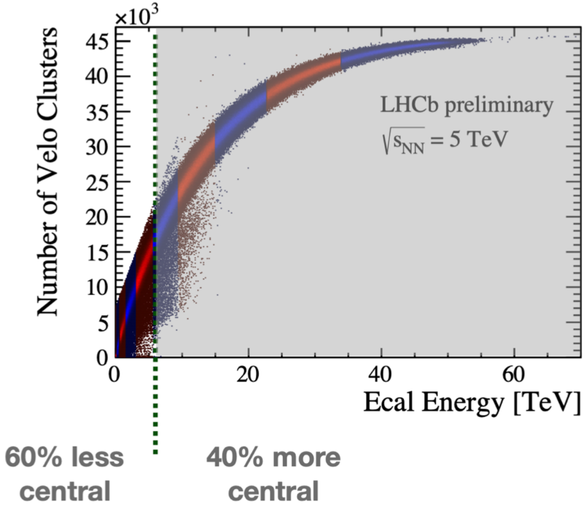
Giesen et al., JCAP 1509, 023

EPOS LHC PRC92 (2015) 034906
EPOS 1.99 Nucl.Phys.Proc.Suppl. 196 (2009) 102
QGSJETII-04 PRD83 (2011) 014018
QGSJETII-04m Astr. J. 803 (2015) 54
HIJING 1.38 Comp. Phys. Comm. 83 307
PYTHIA 6.4 (2pp + 2pn) JHEP 05 (2005) 026

PbPb collisions

- Since LHCb is designed for low multiplicity events, the first question is to know up to which centrality events can be reconstructed.
- Observables to measure event activity: energy deposited in the ECAL and HCAL, which are not saturated even at large multiplicities

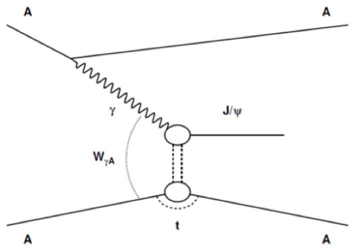


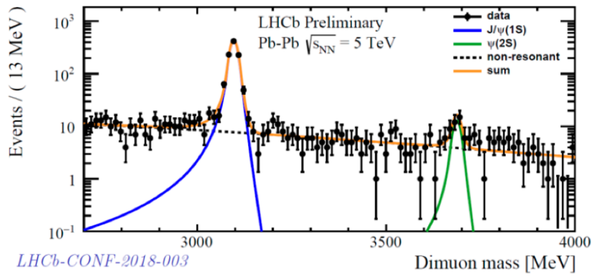


- VELO (tracking) saturates at large multiplicities, and reconstruction is performed only up to 15000 clusters (using standard *pp* reconstruction algorithms)
- This corresponds to the 50-100% event activity region (based on ECAL energy)

PbPb ultra-peripheral collisions

- **J/ψ→μ⁺μ⁻ in Ultra-Peripheral Collisions (UPC)**



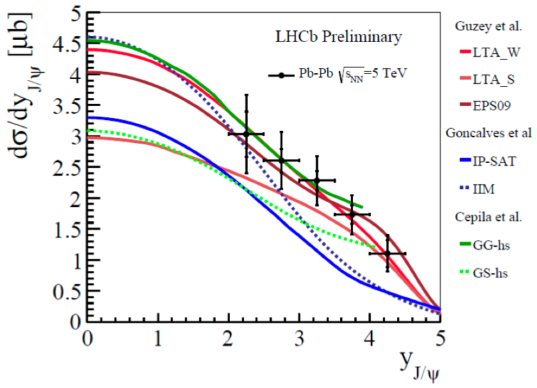


One ion interacts with the electromagnetic field of the other : coherent J/ψ photo-production
Sensitive to nPDF, saturation, …

Nothing in the detector but two tracks

$$\sigma^{\text{coherent}}_{J/\psi} = 5.27 \pm 0.21 \pm 0.49 \pm 0.68\ \text{mb}$$

(stat.) (syst.) (lumi.)



LHCb-CONF-2018-003, paper in preparation

Analysis of J/ψ and ψ(2S) production in PbPb 2018 UPC data ongoing (stat. ×20)
Analysis of J/ψ and D^0 production in peripheral PbPb 2018 ongoing (can also do χ_c)

LHC Heavy Ion Schedule

LHC: LS2 - LHCb upgrade Ia → Run3 → LS3 - LHCb upgrade Ib

HL-LHC: Run4 → LS4 - LHCb upgrade 2 → Run5

arXiv:1812.06772 - CERN-LPCC-2018-07

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

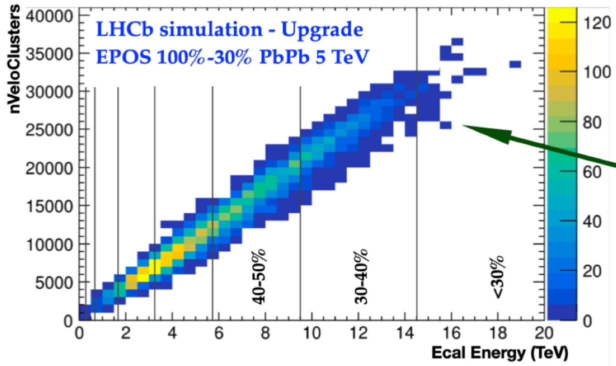
LHCb is very well placed to have a **decisive contribution** to Heavy Ion Physics **in LHC run 3 and HL-LHC**

- **Best placed in pp and pPb** at forward rapidity
  - In pPb/Pbp: $\mathcal{L}$ ~ 30 nb^{-1} in run 2 (~1M J/ψ, ~8M D^0) ➔ $\mathcal{L}$ ~ 300 nb^{-1} in run 3 + 300 nb^{-1} in run 4
- **Well placed** (less limited) **in PbPb** at forward rapidity
  - Will benefit from **detector upgrade**
- Start **full physics** program in **fixed-target** mode
  - Will benefit from target and detector upgrade

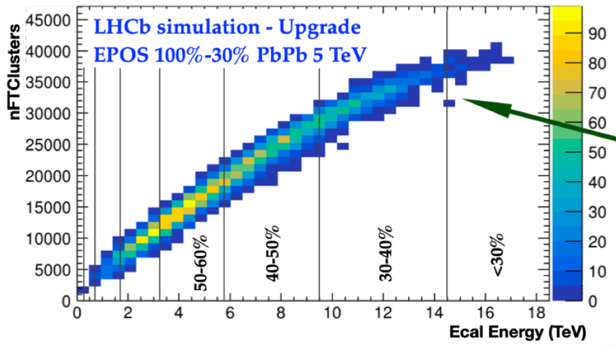
PbPb collisions Upgrade I

- Limit increased to 30% centrality
- SciFi is the expected limitation: it will be upgraded in Run 4 with a inner tracker and then in Run 5 with a middle track. One can assume that the centrality reach will also increase towards most central collisions in Run 5.

Run 3



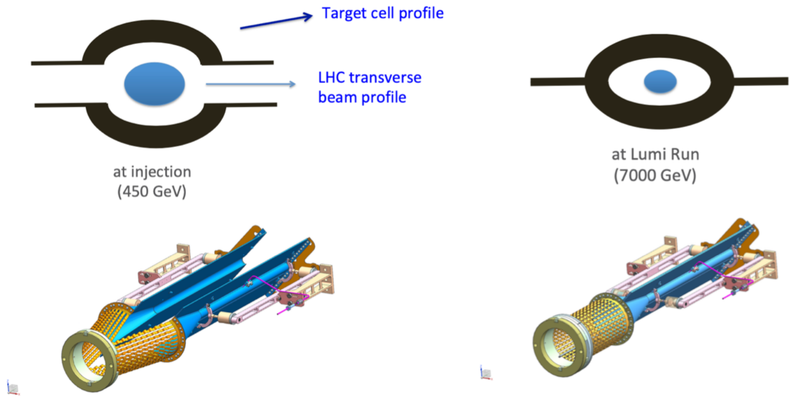
New Vertex Locator does not saturate



Expect SciFi to saturate in most central collisions

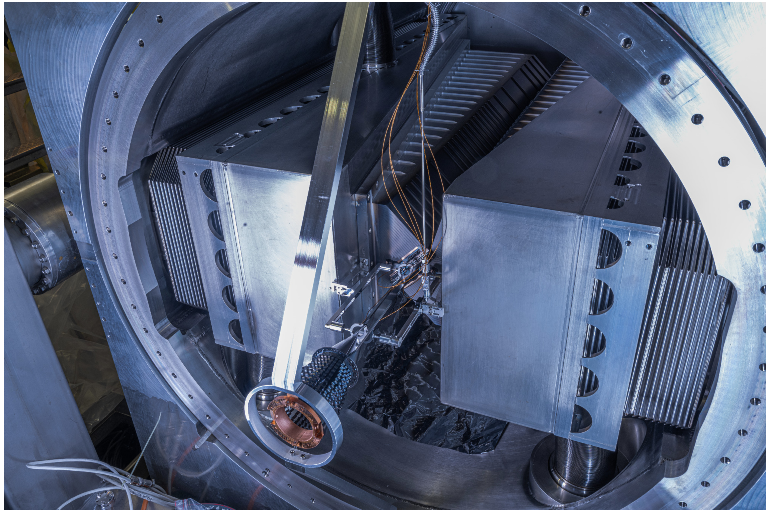
SMOG2

- SMOG mostly proved the feasibility of a fixed target experiment at the LHC, but was not designed for this goal.
- Improve system by increasing the gas pressure and keeping the gas contained in a better defined region: gas cell in the LHC vaccuum.
- The LHC beam transverse size changes between the injection at 450 GeV (large) and the beam at 7000 GeV (small): cell has to open (like the VELO)



Solution adopted for SMOG2: L = 20 cm, R = 0.5 cm
for LHCspin: L = 30 cm, R = 0.5 cm

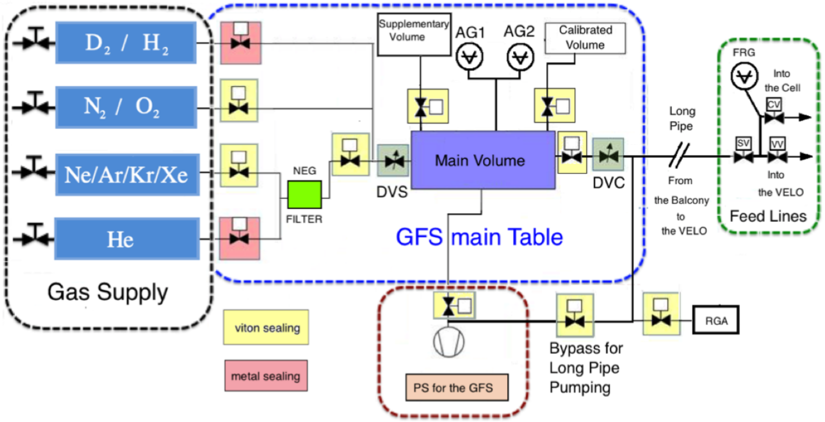
SMOG2 was installed in August 2020



SMOG2

- Other improvements include:
  - Gas Feed system, to select dynamically the type of gas to use

Gas Feed System



  - Improvements in software trigger (GPU based): potentially we can run in parallel *pp* data taking and fixed target mode continuously.

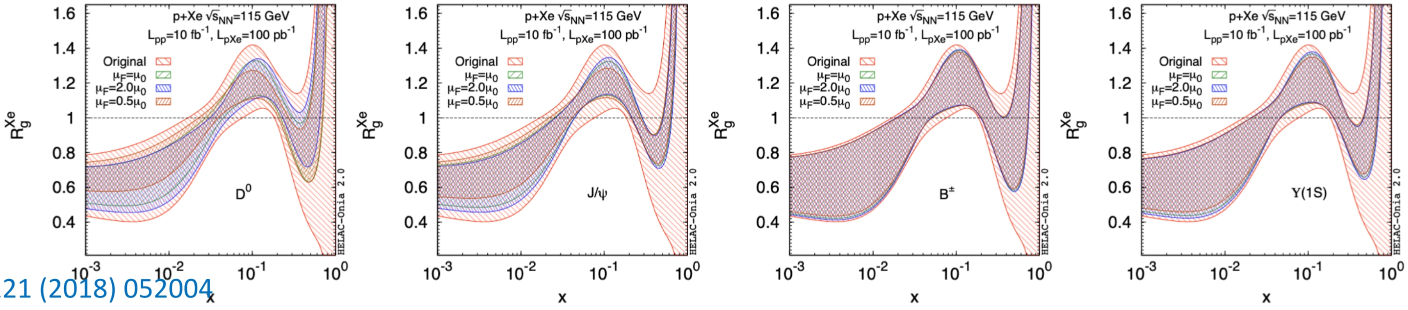
SMOG2 Luminosity Projections per year

LHCb-PUB-2018-015

Storage cell assumptions	gas type	gas flow (s^{-1})	peak density (cm^{-3})	areal density (cm^{-2})	time per year (s)	int. lum. (pb^{-1})
SMOG2 SC	He	1.1×10^{16}	10^{12}	10^{13}	3×10^{3}	0.1
	Ne	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	Ar	2.4×10^{15}	10^{12}	10^{13}	2.5×10^{6}	80
	Kr	8.5×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	Xe	6.8×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	H_2	1.1×10^{16}	10^{12}	10^{13}	5×10^{6}	150
	D_2	7.8×10^{15}	10^{12}	10^{13}	3×10^{5}	10
	O_2	2.7×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	N_2	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1

Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

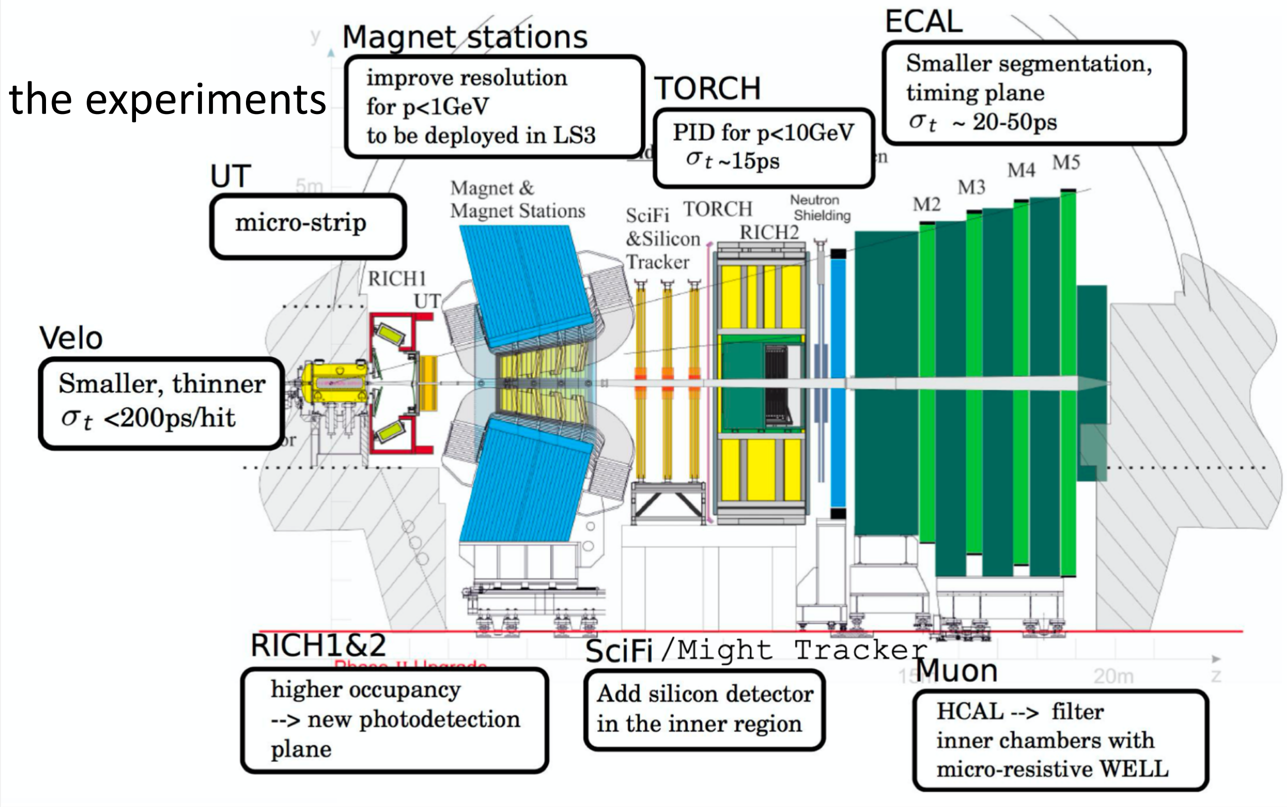
- Assuming parallel data taking is feasible, factor ~10000 increase in signal statistics in one year
- Constraints on gluon nPDF, at high x, expected at the end of Run 3



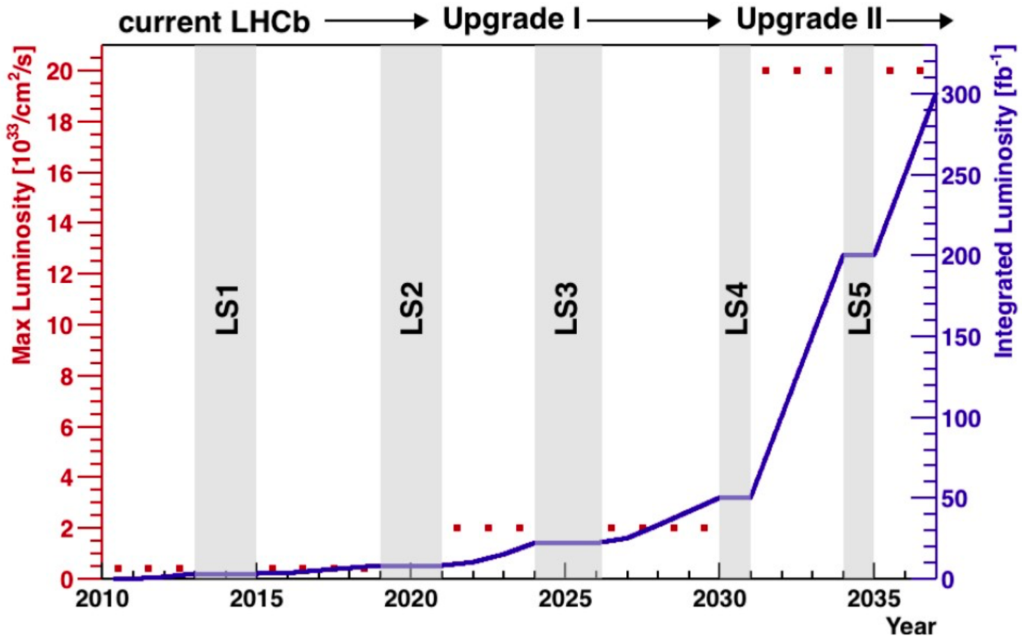
A. Kusina *et al.*, PRL 121 (2018) 052004

Upgrade Ib and II

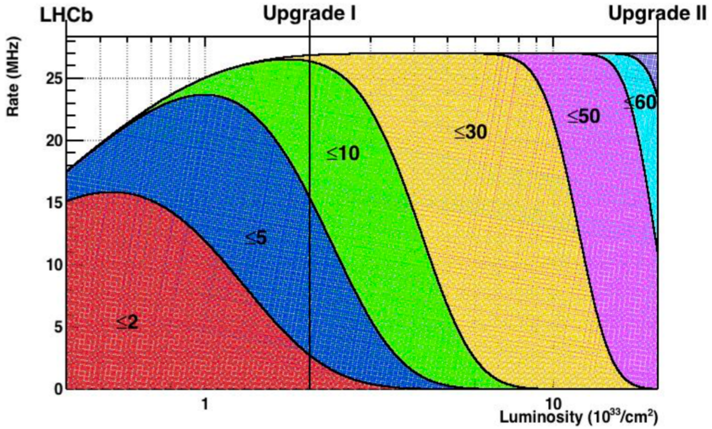
Changes to all parts of the experiments



Upgrade II



current LHCb
Upgrade I
Upgrade II
Max Luminosity [10^{33}/cm^2/s]
Integrated Luminosity [fb^{-1}]
LS1
LS2
LS3
LS4
LS5
Year



LHCb
Upgrade I
Upgrade II
Rate (MHz)
Luminosity (10^{33}/cm^2)
≤2
≤5
≤10
≤30
≤50
≤60

Upgrade II conditions

	LHCb	LHCb Upgrade I	LHCb Upgrade II
$\mathcal{L}_{instantaneous}$ $(cm^{-2}s^{-1})$	4×10^{32}	2×10^{33}	$\mathbf{2 \times 10^{34}}$
Pile-up	1	6	**60**
b-hadron per evt.	0.003	0.02	**0.2**
c-hadron per evt.	0.04	0.22	**2**
light,long-lived per evt.	0.51	2.08	**21**

[LHCb-PUB-2014-027]

σ_t = 185 ps

σ_z = 45 mm

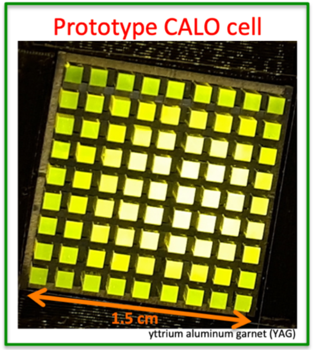
- Radiation hardness:
  - Replaceable active areas
  - New materials
- Occupancies:
  - Timing information with <50 ps resolution for 4D tracking or clustering (does not help for heavy ion collisions)
  - Higher granularity
- Data streaming:
  - Huge data rates (30 TB/s)
  - FPGA-based cluster or tracking near Front-End electronics to reduce huge flow of data (In France: CPPM, IJCLab, LPNHE, LAPP)

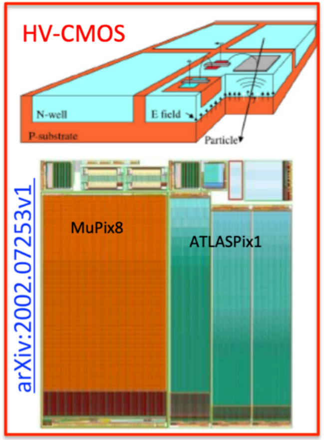
Upgrade II Detector Technologies

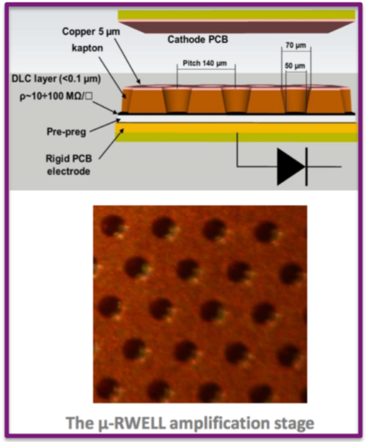
R&D phase for the moment, no detector design is already frozen

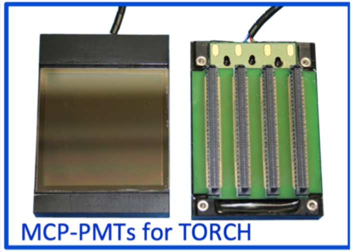
Lots of R&D across collaboration.

- SPACAL with crystal fibres.
- CMOS tracker chip in design.
- Silicon with timing capabilities.
- Photon sensors with timing .
- New MPGDs for high-rate muon detection.







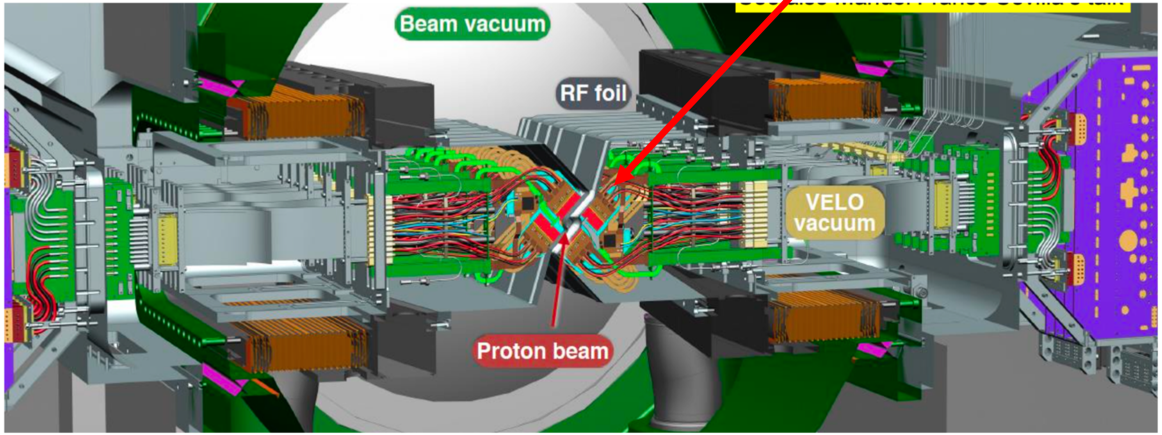


21

VELO

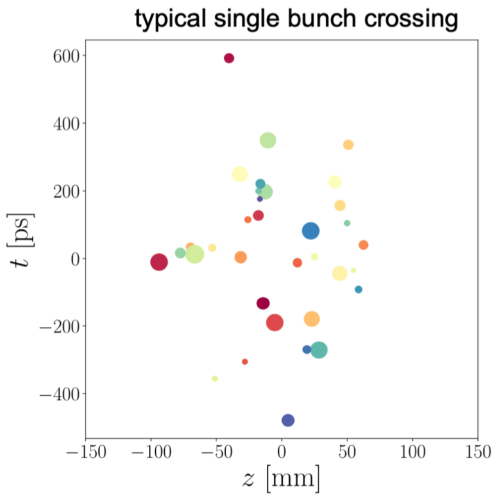
- Very early stage of design, considerations based on Upgrade I
- Moveable detector (for beam injection and ramping)
- In vacuum to minimize material (*ie* no beam pipe between first vertex and first sensor)

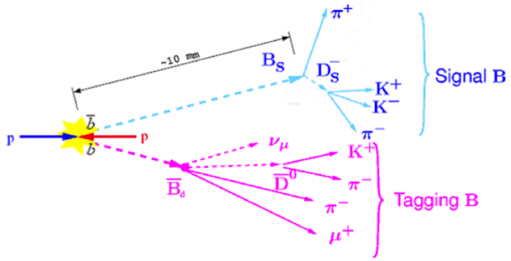
Sensor + ASIC

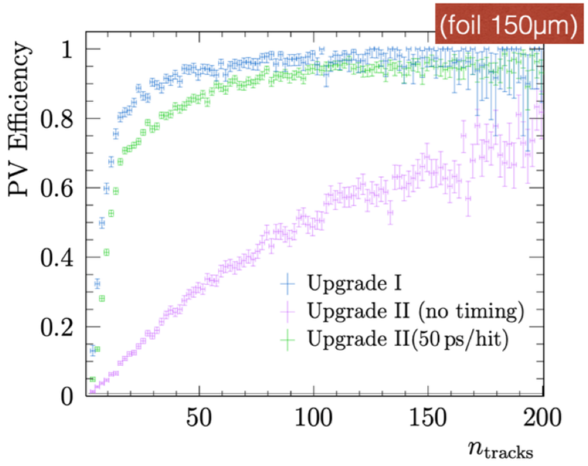


VELO: Timing for high luminosity

- Disentangle multiple primary vertices
- Assign secondary vertices to the correct primary vertices
- Physics background reduction
- Reach similar performance than current one when time resolution is better than 50 ps

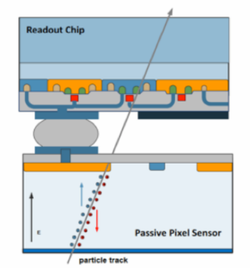


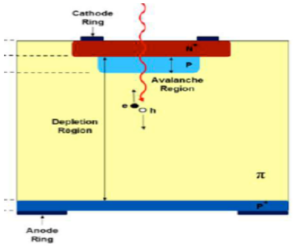


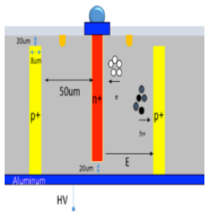


VELO

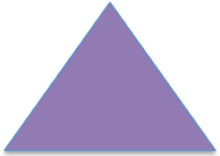
- Active R&D on several alternative sensors
  - Hybrid Planar, Low Gain Avalanche Detector, 3D







Radiation Hardness $5\mathrm{x}10^{16}\ n_{eq}/cm^{-2}$

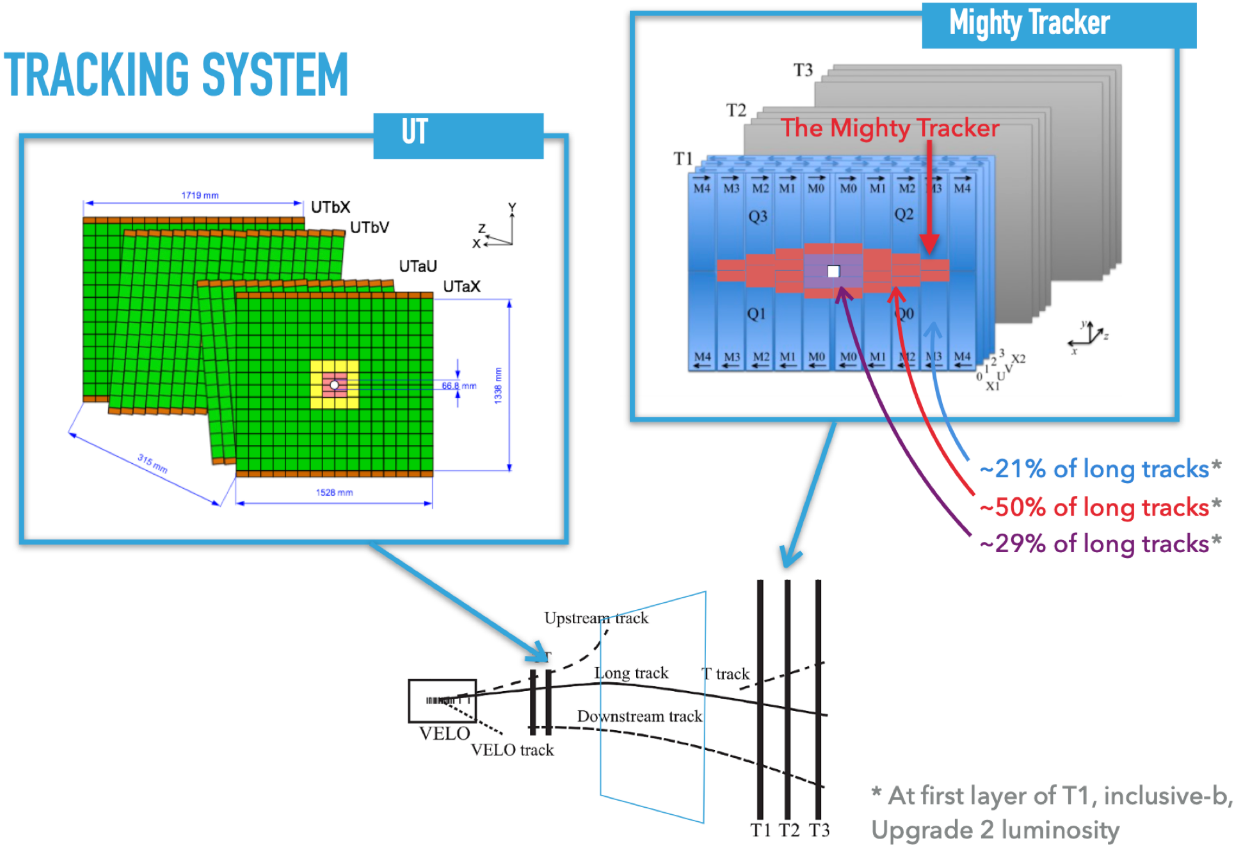


Pixel Size 25-50µm

Timing Resolution 25-50ps

- Two chip designs:
  - Timepix4 (Medipix) 65nm
  - Timespot (INFN) 28nm
- Mechanics & Cooling challenges

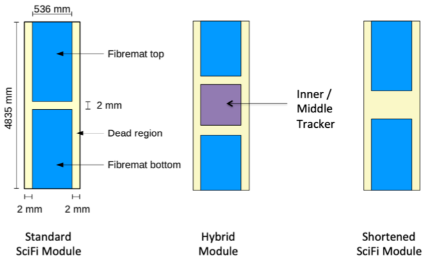
Tracking



* At first layer of T1, inclusive-b, Upgrade 2 luminosity

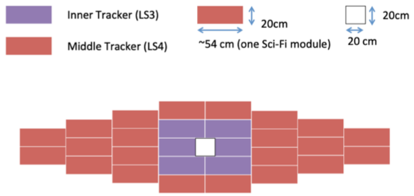
Mighty Tracker

- Replace inner and middle areas with CMOS detectors in steps: inner part in 2025 (radiation) and middle part (occupancy) in 2030
- Keep current SciFi detector for the rest
- In France, LPNHE and LPC involved in the SciFi project



Hybrid Technology Tracker

- Scintillating fibres
- CMOS

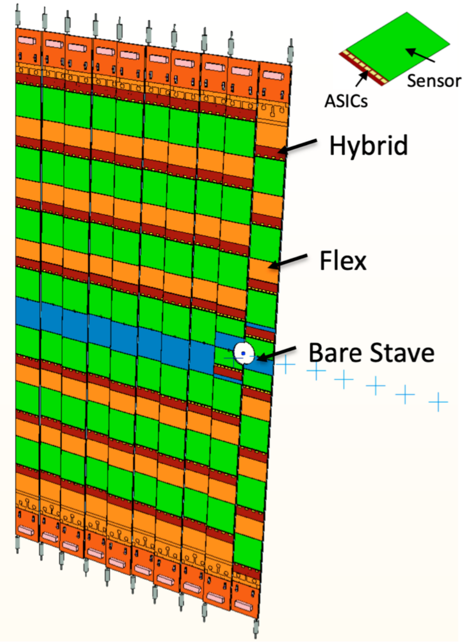


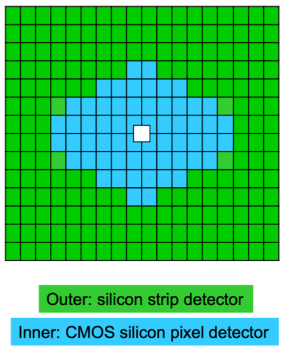
Radiation: $3x10^{14}$ 1 MeV n_{eq}/cm^2

- LS3 (~2025) $4m^2$
- LS4 (~2030) $20m^2$

UT

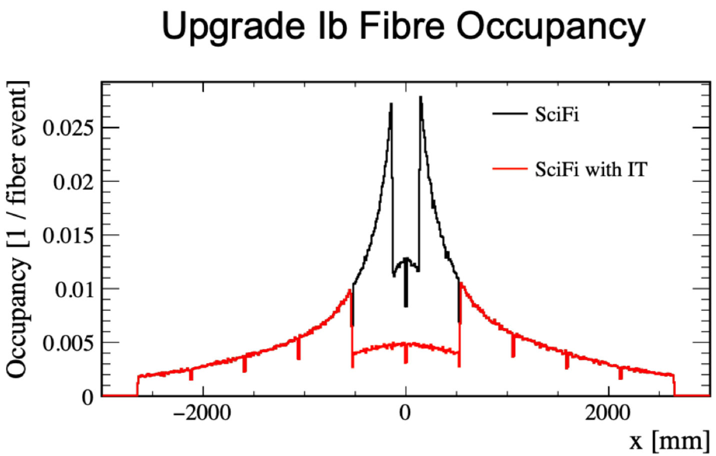
- UT now in Upgrade I is composed of silicon strip sensors, readout by on detector electronics (SALT ASIC).
- Studies for Upgrade II only starting:
  - ASIC have a limited bandwidth, strips have limited radiation tolerance: they can be kept only in the regions of smaller occupancies (outer area)
  - For the Inner part, use CMOS pixel detector
  - Only the beginning of the detector design, several possibilities under study (larger strip areas, or on the contrary full pixel detector)
- In France, CEA Saclay and Subatech Nantes interested to contribute





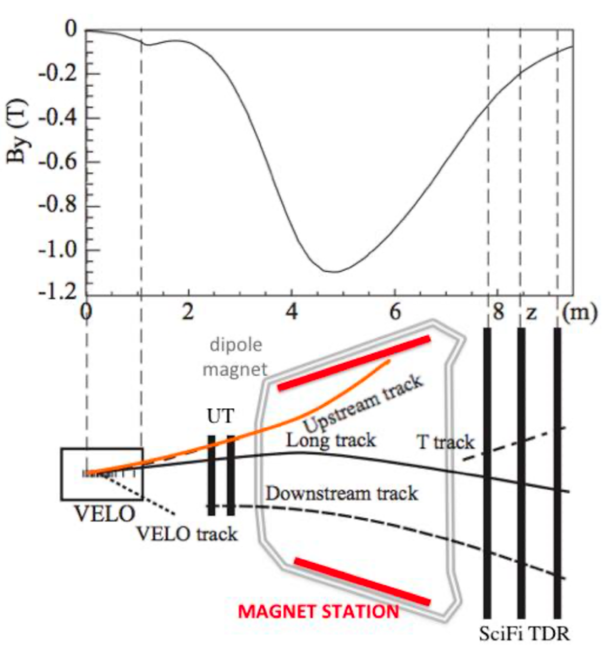
Tracking Performances

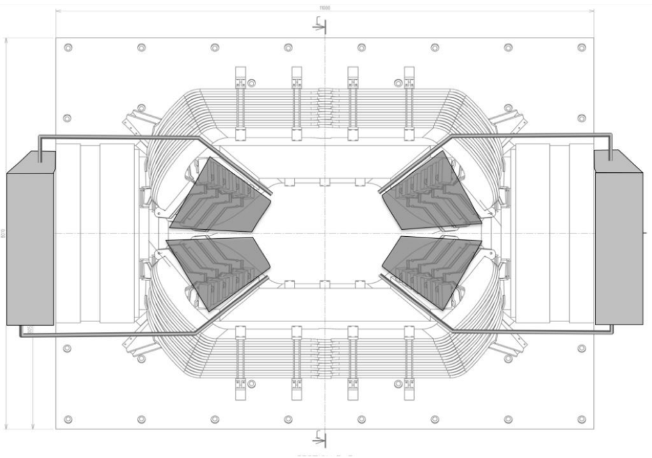
- Size of central detector in Might Tracker is driven by
  - Occupancy in fiber parts
  - Radiation damages of fibers
- For Upgrade Ib:
  - Necessity to replace most inner part because of radiation damage: decreases ghost rate (fake tracks)
  - According to simulations in Heavy Ion, this change will also increase acceptance in centrality



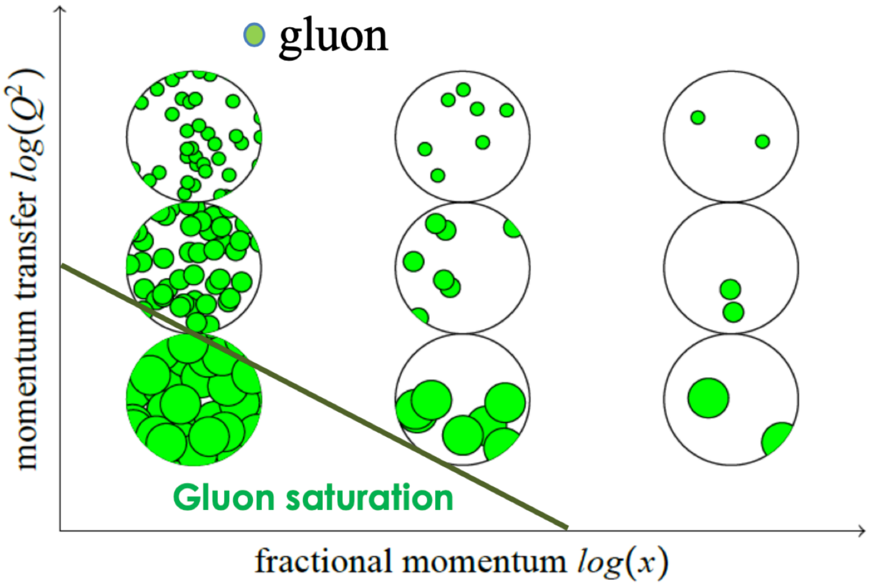
Magnet Station: Soft Particle Tracker

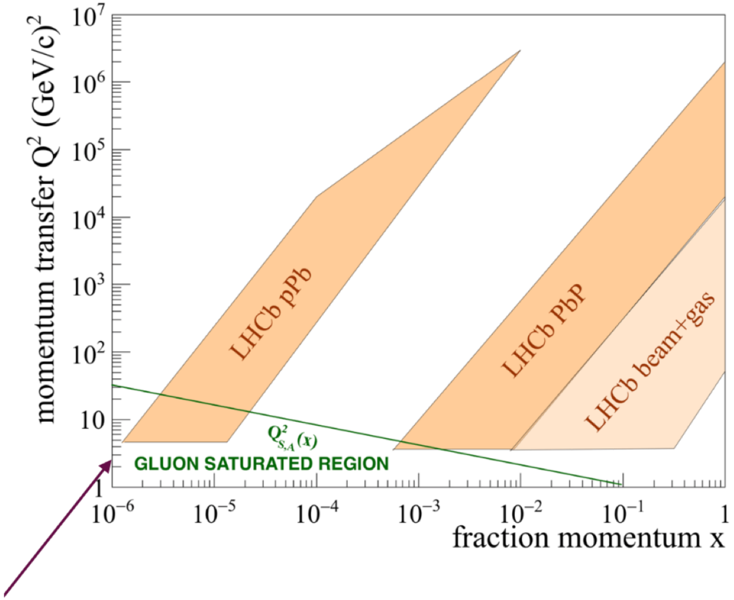
- New detector, to be installed during LS3, to track low momentum particles in combination with UT
- Project lead by Los Alamos group, which joined LHCb for the Heavy Ion program





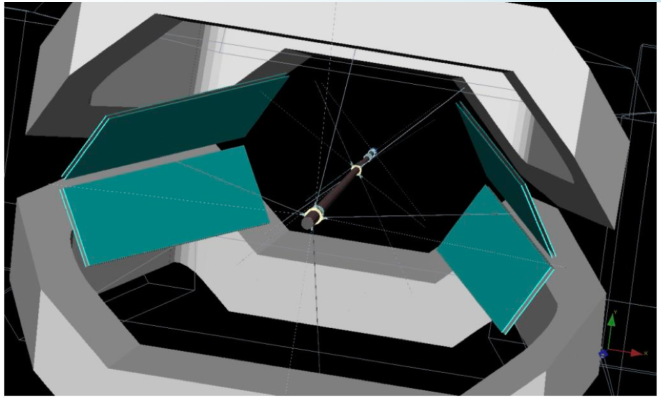
Magnet Station: small-x, small-Q^2 physics

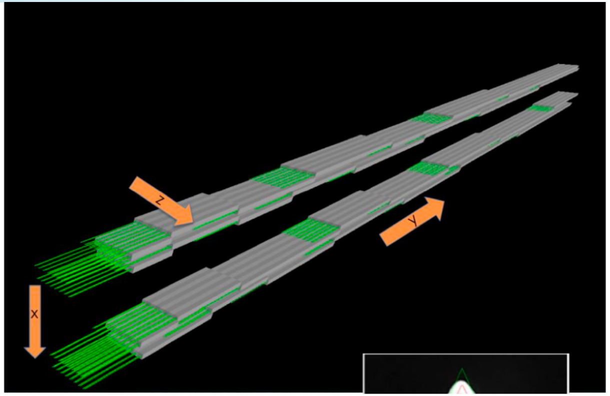




- LHCb has unique coverage of Bjorken-x>10^{-6} in the expected gluon saturated region with full detector instrumentation
- Poorly constrained PDF and nPDFs in the small-Q^2 region requiring soft particle tracking like the one provided by the Magnet Station.

Magnet Station: Implementation

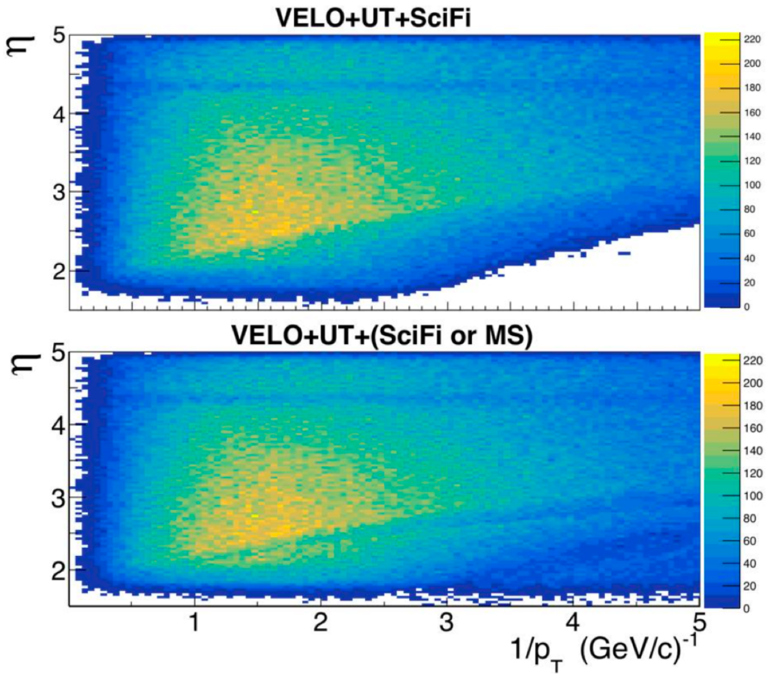




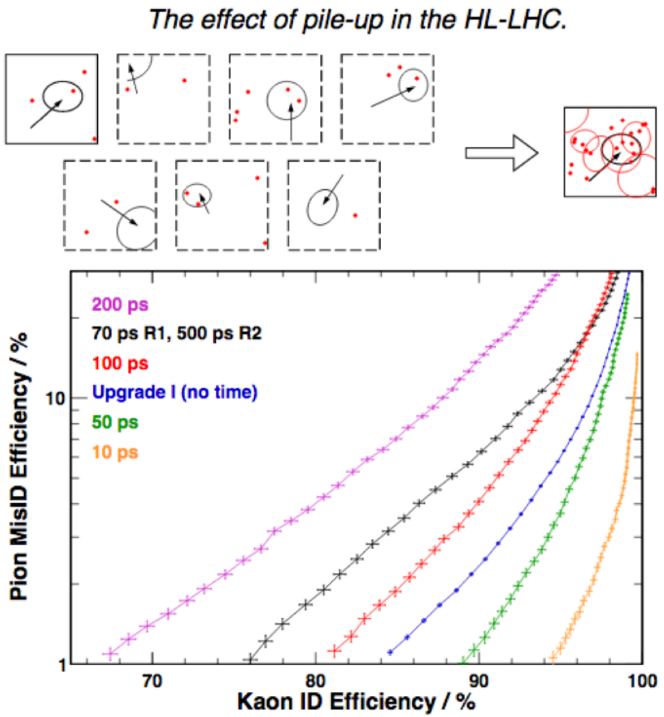
- 4 panels outside LHCb acceptance
- Each 1m tall, 3m long panel consist of 4 planes of extruded scintillating bars (concept implemented in DØ)
- 5mm width bars with horizontal segmentation following the expected occupancy in 60 piled up events per crossing
- Scintillating light guided to SiPMs outside the magnet to minimize radiation exposure

Magnet Stations: performances

- Magnet Stations open up a new phase-space for soft particle detection with high momentum resolution.
- **Momentum resolution:**
  - VELO+UT : $\sigma(p)/p$ =12%
  - VELO+UT+MS : $\sigma(p)/p$ = 0.5%

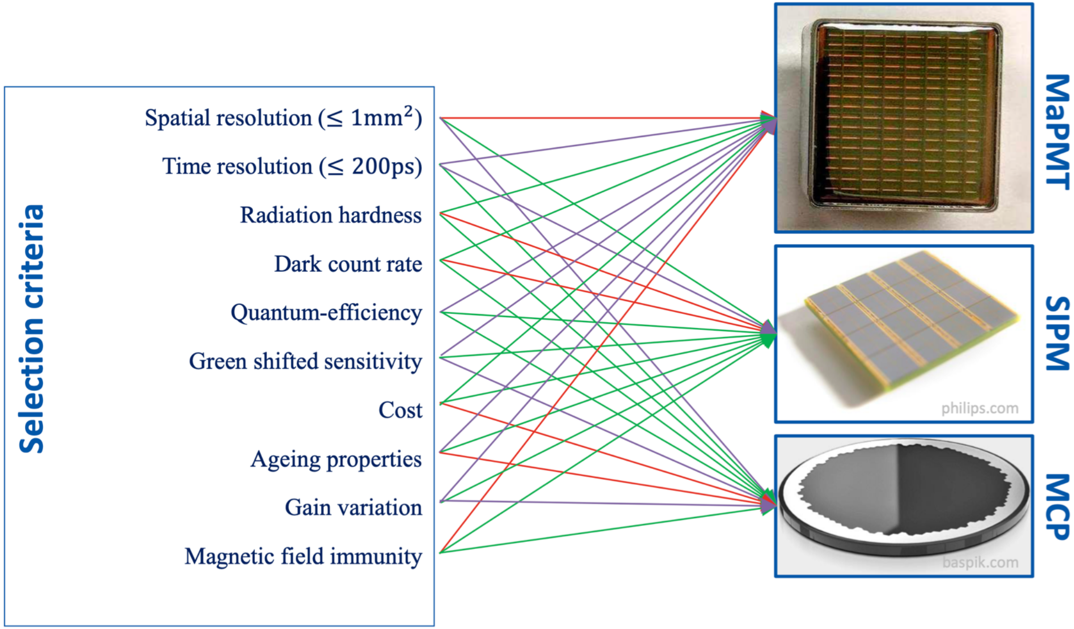


Hadron Identification: RICH

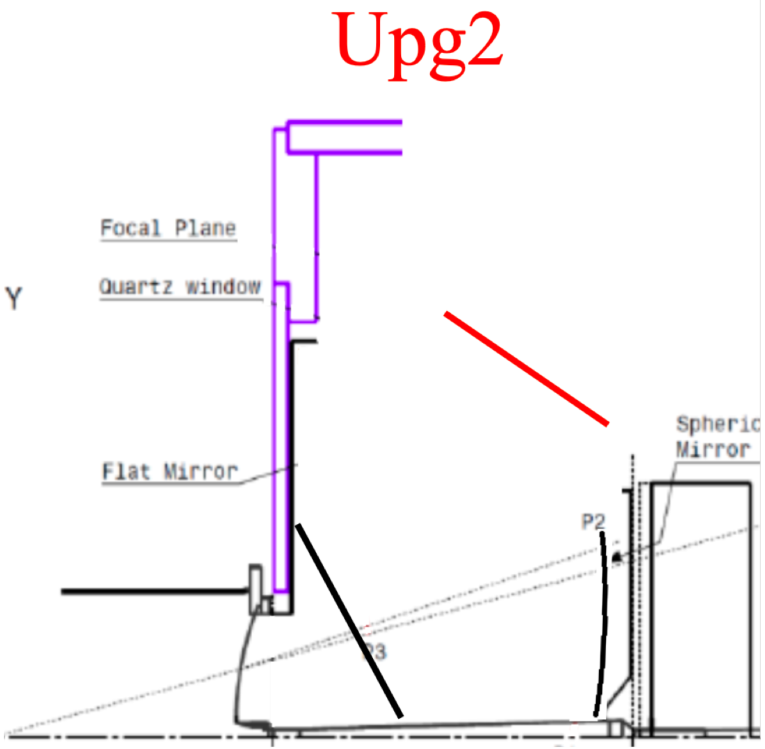


- Again timing is mandatory to recover loss of efficiency due to pile-up
- Study of various technologies (MaPMT, SiPMs, MCP):
  - improve the Cherenkov angle resolution from 0.9 mrad now to 0.5 mrad
  - Keep occupancy in Cherenkov photon readout below 30%, meaning reducing the pixel size of the photodetectors to 1 mm

RICH



Selection criteria
Spatial resolution (≤ 1mm²)
Time resolution (≤ 200ps)
Radiation hardness
Dark count rate
Quantum-efficiency
Green shifted sensitivity
Cost
Ageing properties
Gain variation
Magnetic field immunity
MaPMT
SIPM
MCP
philips.com
baspik.com

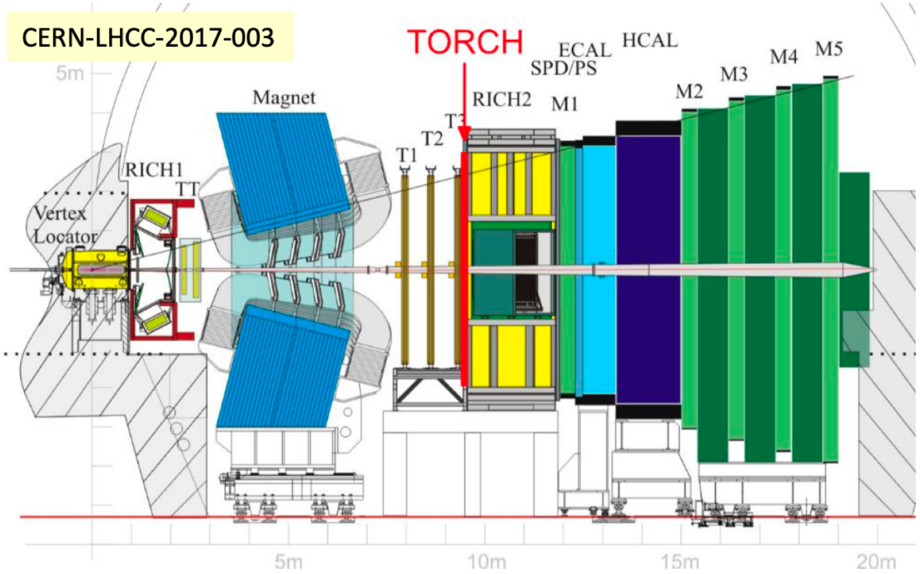


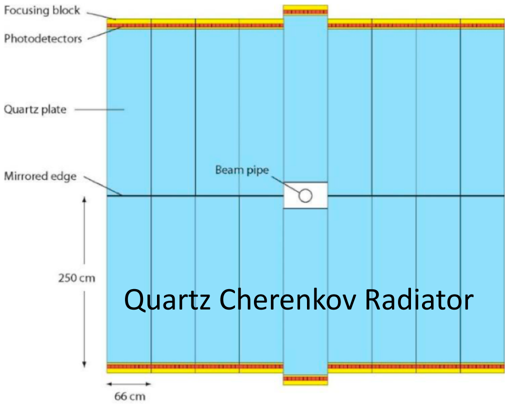
Upg2
Focal Plane
Quartz window
Y
Flat Mirror
Spheric
Mirror
P2
P3

TORCH

MCP = Micro Channel Plate PMT

- TORCH area 5 x 6 m^2
- 18 module system
- 11 MCPs per module





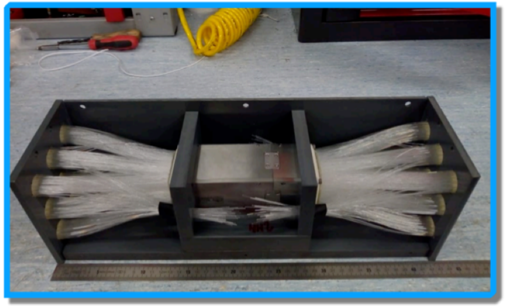
TORCH will add particle identification (for K and p notably) capabilities to LHCb for low momentum particles (<10 GeV), by measuring Time-of-flight

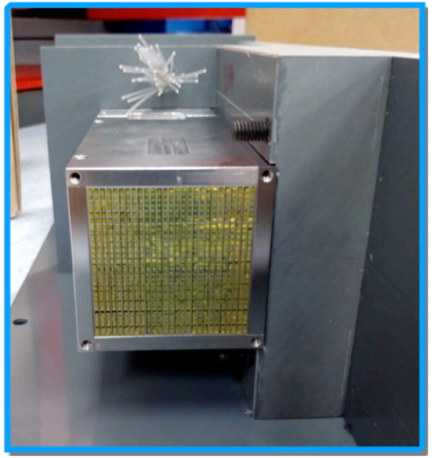
Calorimeter

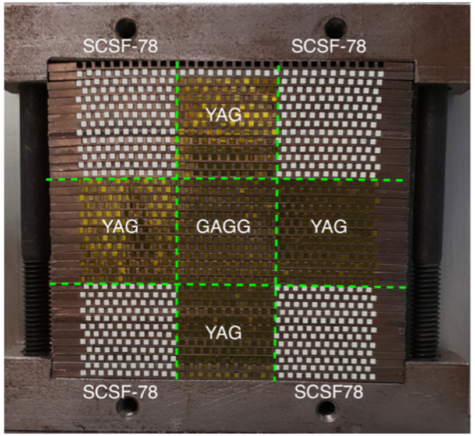
- Electromagnetic Calorimeter essential for physics program
- Current ECAL modules will have to be replaced in the most inner part for Upgrade Ib because of radiation damages
- Addition of timing information is mandatory to work at high luminosity
- Cell technology choice driven by:
  - Increase granularity reducing simultaneously the Moliere Radius
  - Keep X0 small
  - Do not increase too much cost and complexity
  - Radiation resistance
  - Good resolution of 10%/sqrt(E)

Calorimeter

- Current best candidate is SPACAL module (scintillating square fibers in W or Pb absorber, segmented longitudinally in 2 parts)







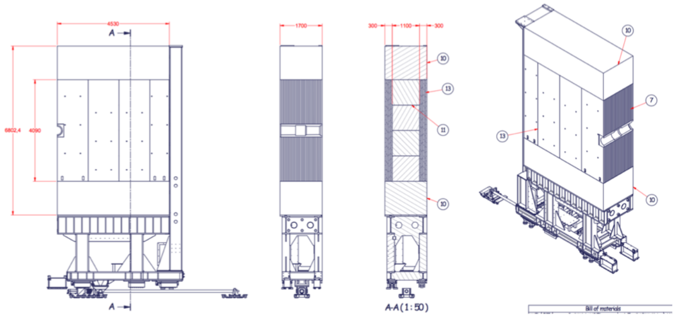
- Addition of a timing layer with silicon detectors is likely to be required to reach the timing performances
- IJCLab group in France taking part to ECAL design

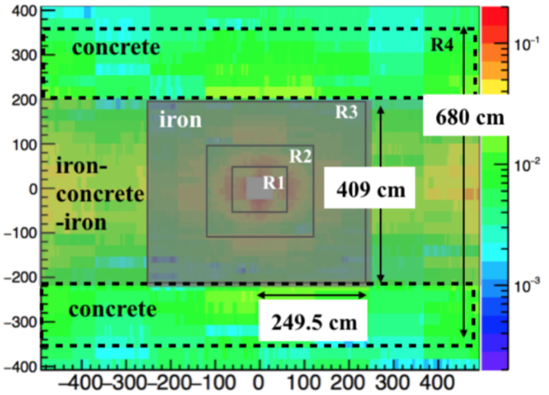
Muon

this is fixed *to be discussed*

With almost 400 m² of sensitive area and ~1650 m² of chambers the LHCb Muon Detector is one of the largest and most irradiated detectors in the world

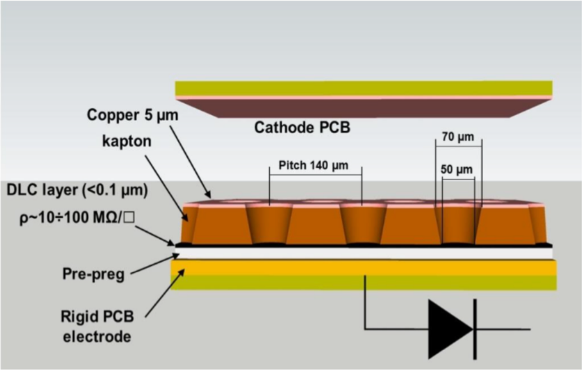
- Shielding: reduce fake muon rate to be able to sustain the rate with technologies based on existing detectors



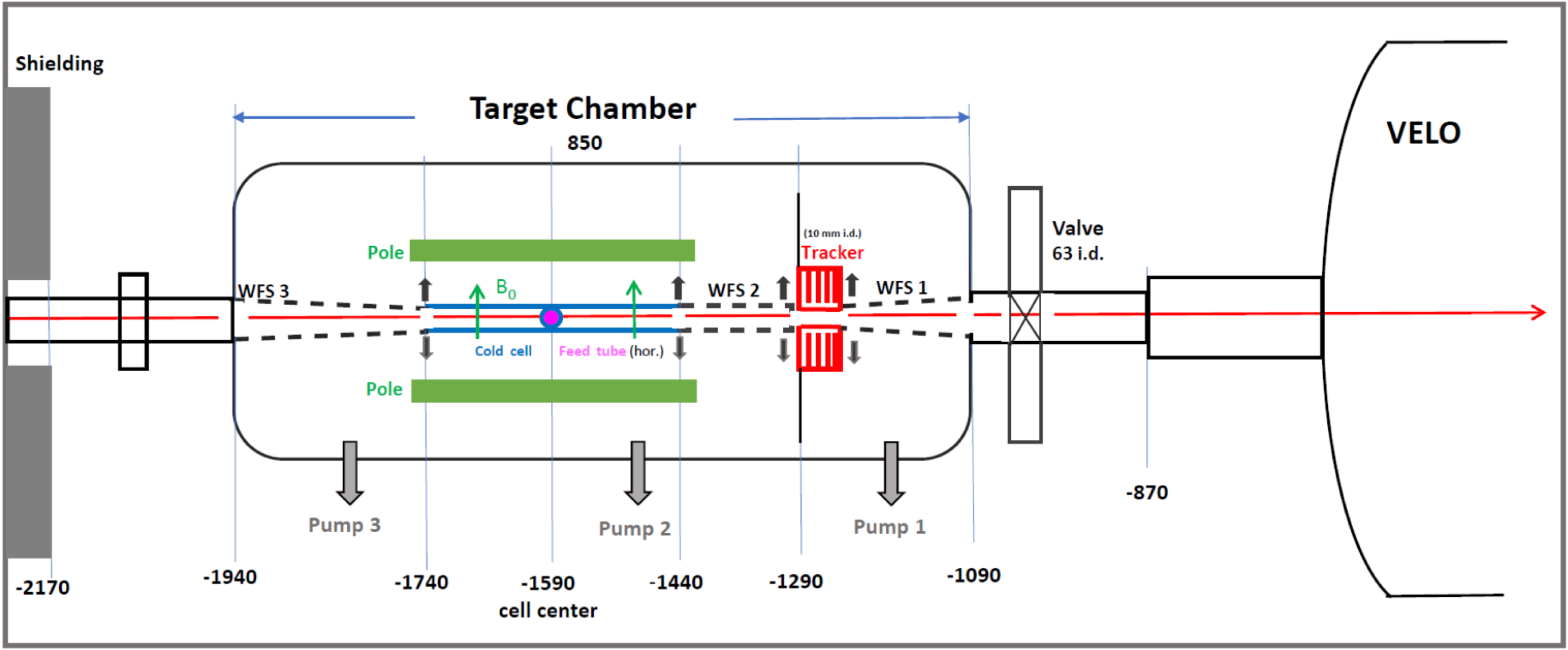


Muon

- Strategy for upgrade
  - R1+R2 (Inner parts, rates of ~ 1 MHz): MPGD gas detector of new generation R&D ongoing
  - R3+R4 (Outer parts, rates of ~10 kHz):
    - MWPC (multi-wire proportional chamber) like current detector, reusing current detector chambers since they do not show visible effect of ageing, and projections from Run 1 and 2 give an expected lifetime of 500 fb^{-1}
    - RPC (Resistive Plate Chambers) developed for ATLAS upgrade project
    - Scintillating tiles

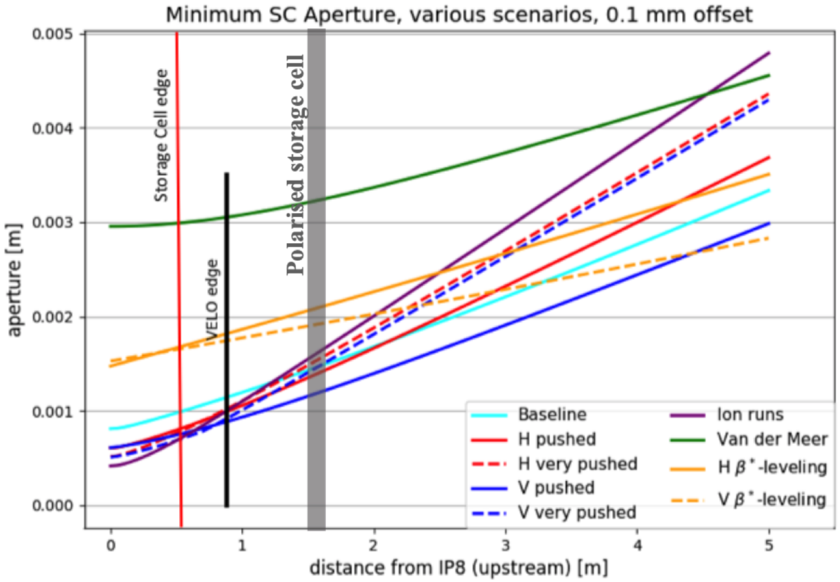


Polarized Gas Target Topology



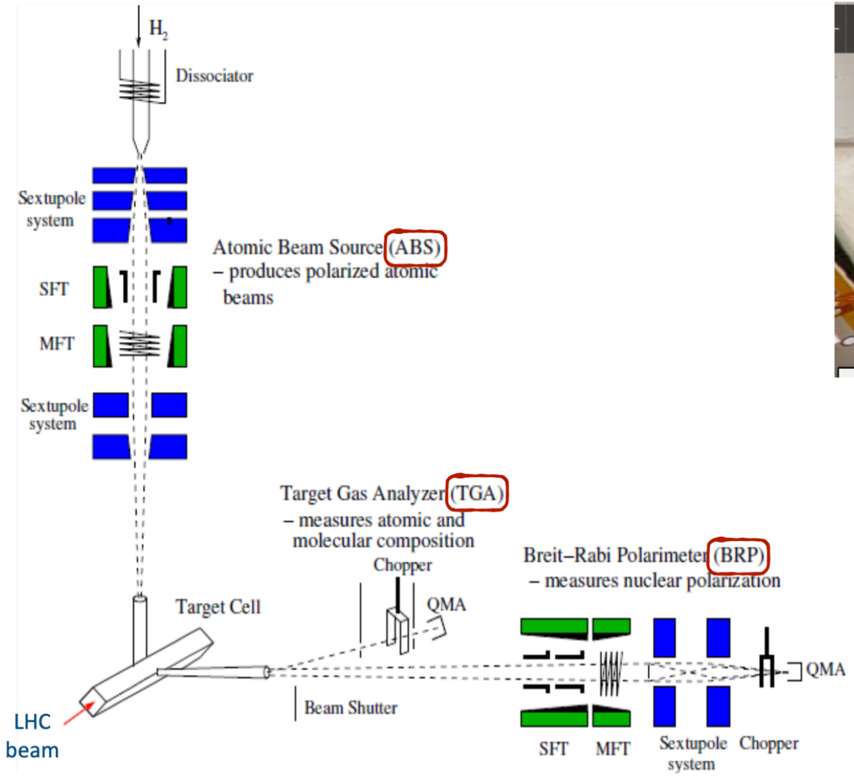
Polarized Gas Target: Luminosity

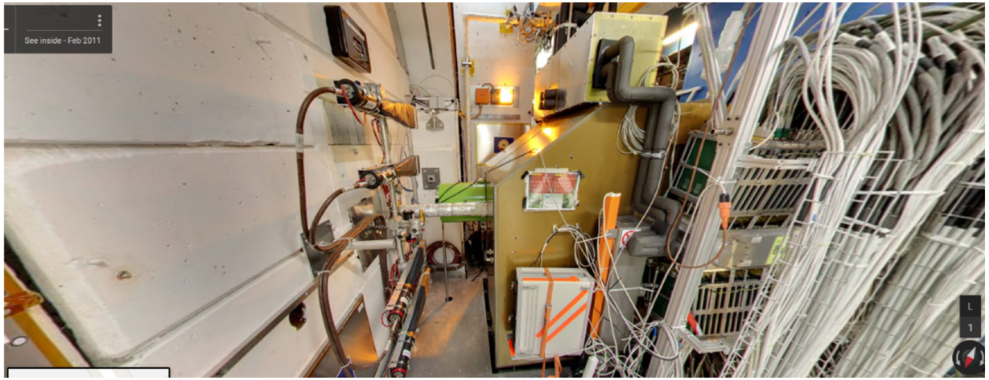
- Driven by aperture of the beam which limits the size of the target



- R = 0.5 cm, L = 30 cm means target density 1.2×10^{14} cm^{-2}
- At High Luminosity LHC, fixed target luminosity can reach L=8.3×10^{32} cm^{-2}.s^{-1}
- Impact on the LHC beam lifetime less than 1%

Polarized Gas Target

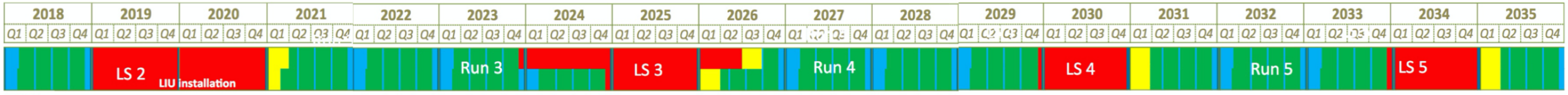




Space in front of LHCb ~1.5 m

Polarized Gas Target

- R&D already started at INFN Frascati, Ferrara, Erlangen, Julich, PNPI
- Groups interested in Italy, France (IJCLab, LLR, Saclay), Michigan, Los Alamos, MIT, PSI
- Budget: 2 – 4 MEuros



SMOG2

Polarized Gas Target

or

Vacuum chamber + ABS and diagnostic during YETS

Conclusions

- LHCb will start its upgrade Phase I in 2022 but it also starting to design following Upgrade to continue running at the High Luminosity LHC
- Core physics program on flavor physics but heavy ion part now recognized and encouraged to go further
  - Heavy Ion physics program fits well in main LHCb physics: puzzles seen in *pp* collisions can be studied with heavy ion methods perspective
  - It will benefit a lot from the improvements foreseen on the LHCb detector (aiming at recording events with more and more tracks)
- Phase II upgrade is a good opportunity for new groups to join the collaboration