Alessandro Cardini

on behalf of the Cagliari LHCb Group

Outline

- LHCb: the history
- The Cagliari Group along the years
- Our contributions: hardware & analyses
- The current upgrade
- The future: toward the next upgrade

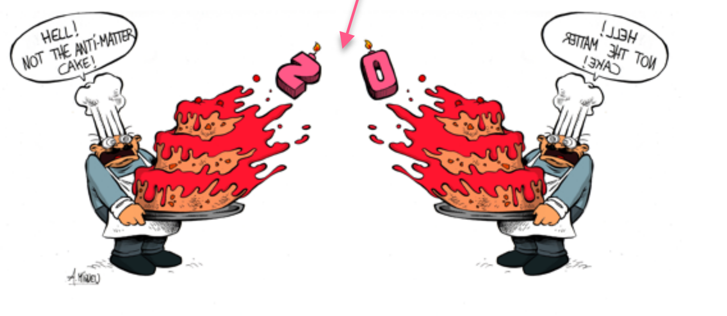
LHCb Cagliari: 20 years!

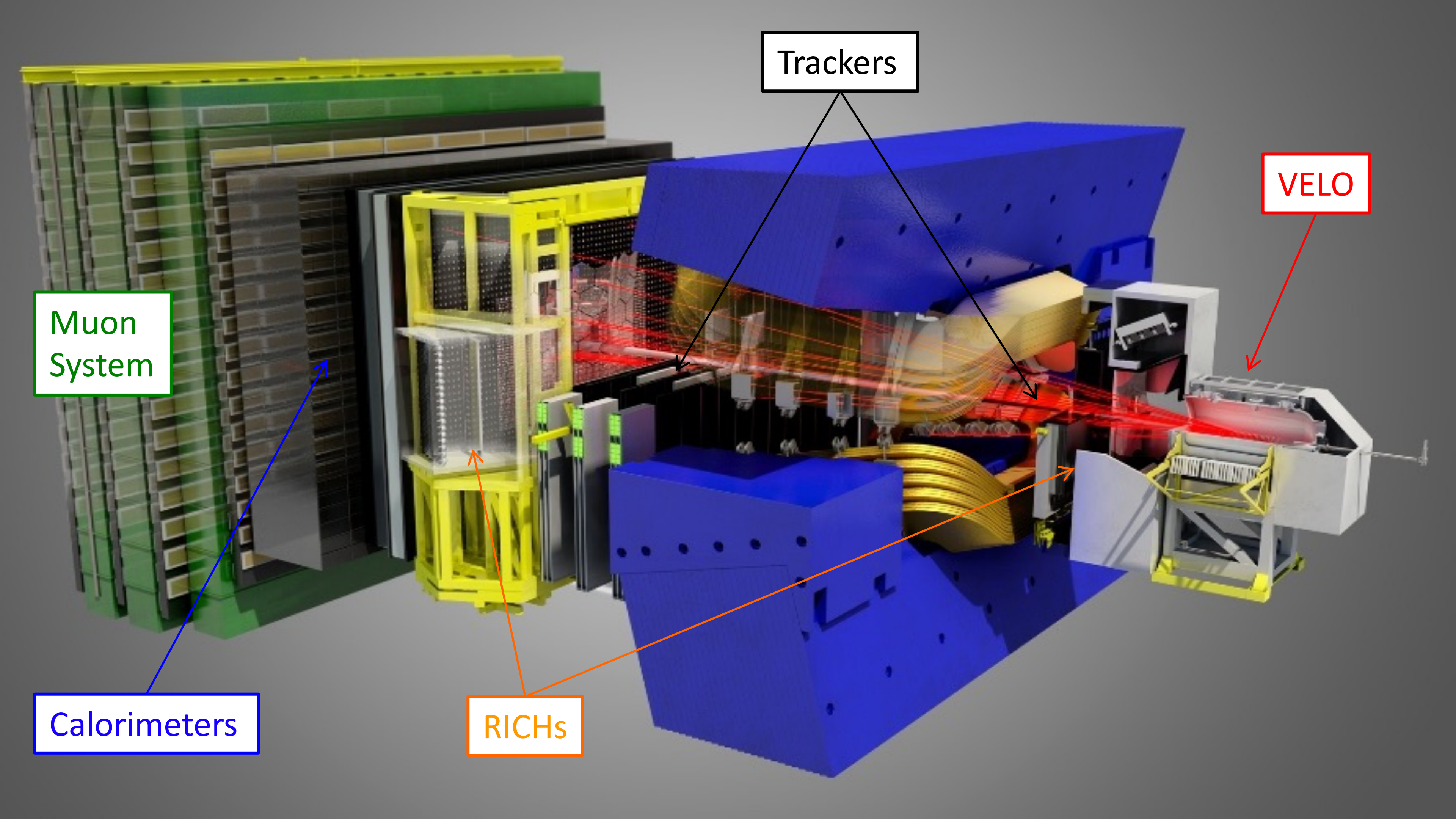
- It was well known that the B production cross section at LHC would have been quite large. At the 1992 Evian Workshop three proposals are submitted: 2 fixed-target experiments (LHB and GAJET) and one proposing a forward spectrometer operating in collider-mode (COBEX)

- LHCC suggests the three groups to converge to a common experiment operating in **collider-mode** to exploit the large B-production cross section and using a **convincing trigger strategy**

- The LoI is submitted to LHCC in 1995, "*to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles*"

- The experiment is approved in 1998. **The Cagliari Group joined the Collaboration in 1999.** The experiment design is finalized by 2003, and data-taking starts on November 23, 2009

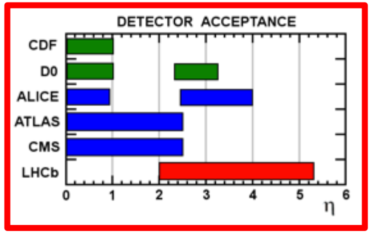


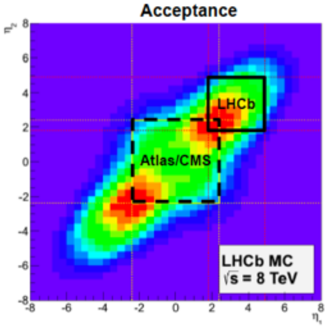


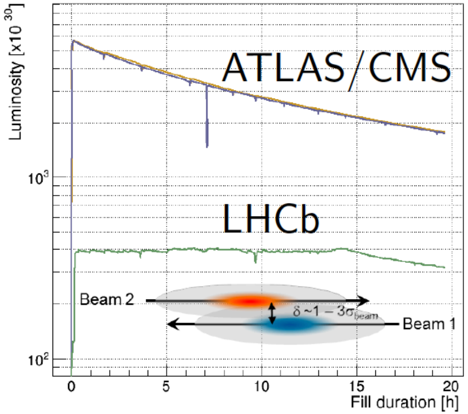
Trackers
VELO
Muon System
Calorimeters
RICHs

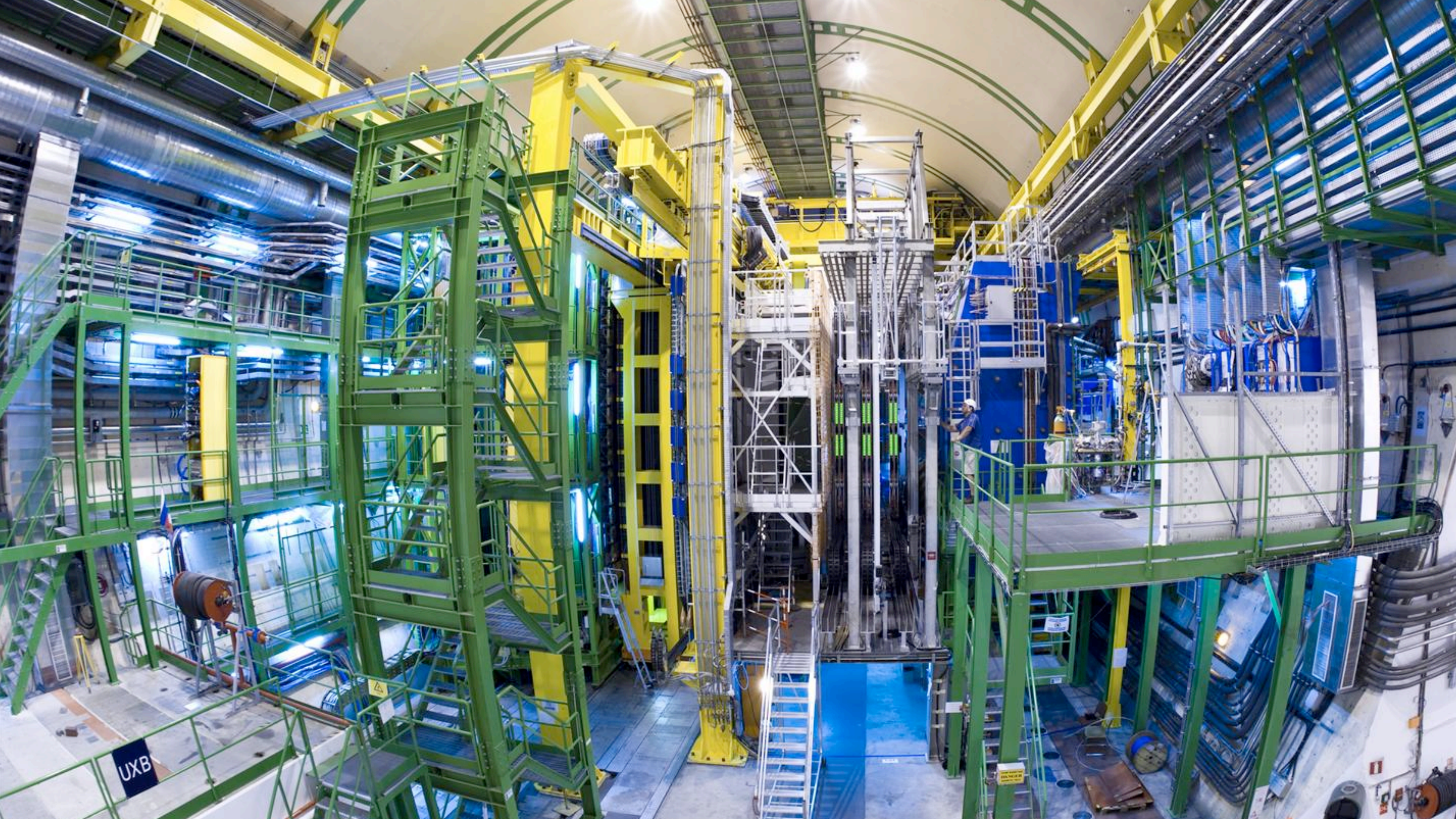
LHCb: specifications

- LHCb is a F-GPD (Forward General-Purpose Detector)
- **Forward spectrometer**, acceptance $2<\eta<5$, 4% of the solid angle
- Can exploit ~40% of the heavy quark production cross section
- To perform precision measurements in the Beauty and Charm sector:
  - $\Delta p/p$ = 0.35% @ 5 GeV/c ÷ 0.55% @ 100 GeV/c
  - High p_t tracks impact parameter resolution of 20 µm
  - Decay time resolution of 45 fs ($B_s \rightarrow D_s \pi$)
  - Operates at a constant instantaneous luminosity of 4E+32 $cm^{-2}s^{-1}$
  - High efficiency multi-level trigger, optimized for leptonic and hadronic final states

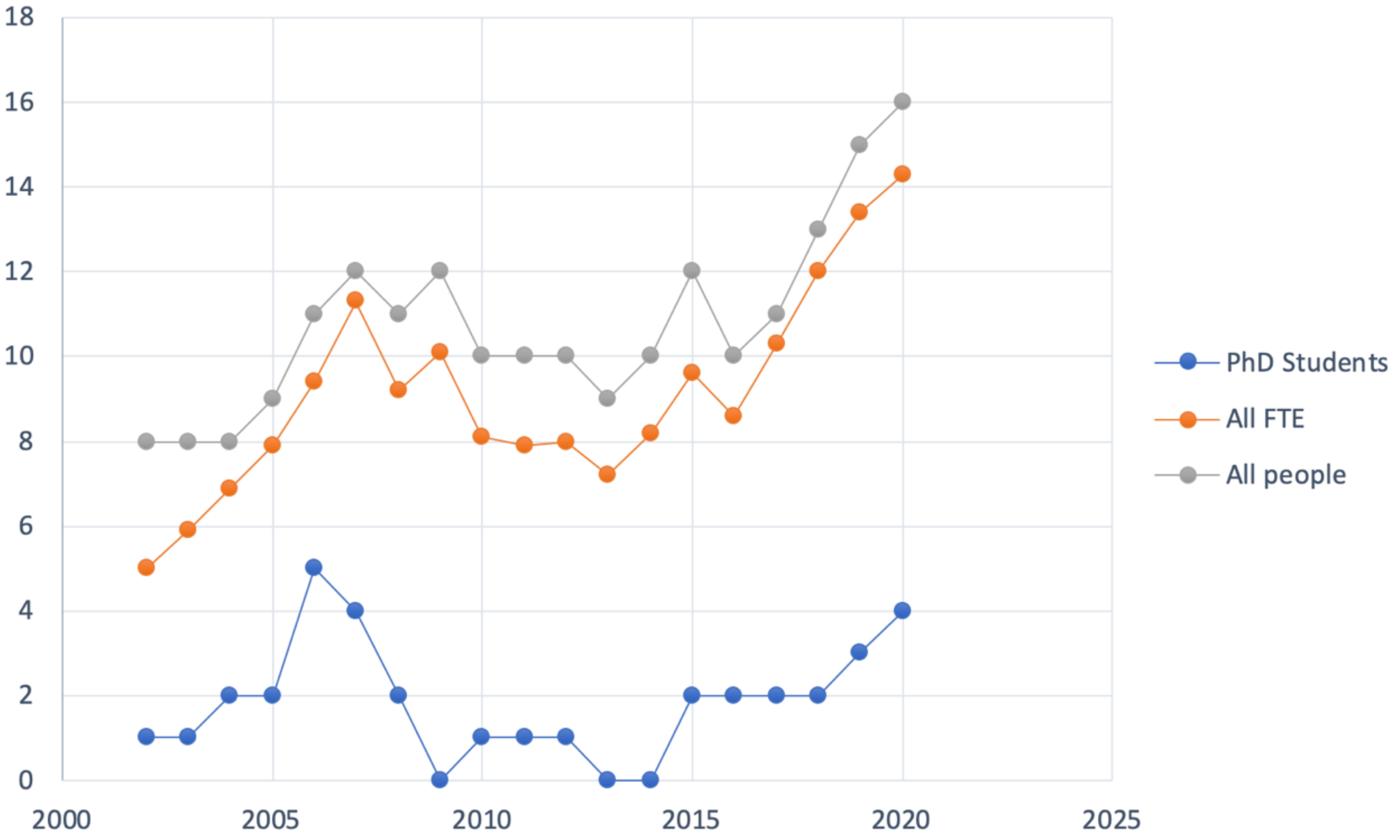







UXB

LHCb Cagliari People



A Strong Commitment in time

- Muon system readout Coordinator
- M2-M5 Commissioning Responsible (2006-2008)
- M1 installation and commissioning Coordinator (2008-2009)
- Muon system operation Coordination (2009, 2010, 2012)
- Muon Piquets all along Run1 and Run2
- Triple-GEM operation Responsible (2009-2018)
- Muon deputy PL (2009-2012), Muon PL (2012-2015)
- LHCb National Coordinator (2015-2018)
- Editorial Board Chair (2013-2015), EB component (2019-2021)
- Charm Physics Group convenors
- B to charmonia convenor
- Luminosity and Ion runs co-convenor
- IFT and CEP Convenor
- ERC on Heavy Ions Physics
- ECGD Chair (2019-2021)
- LHC HFVG (now)
- LHCC CMS P2UG (2018-)
- …

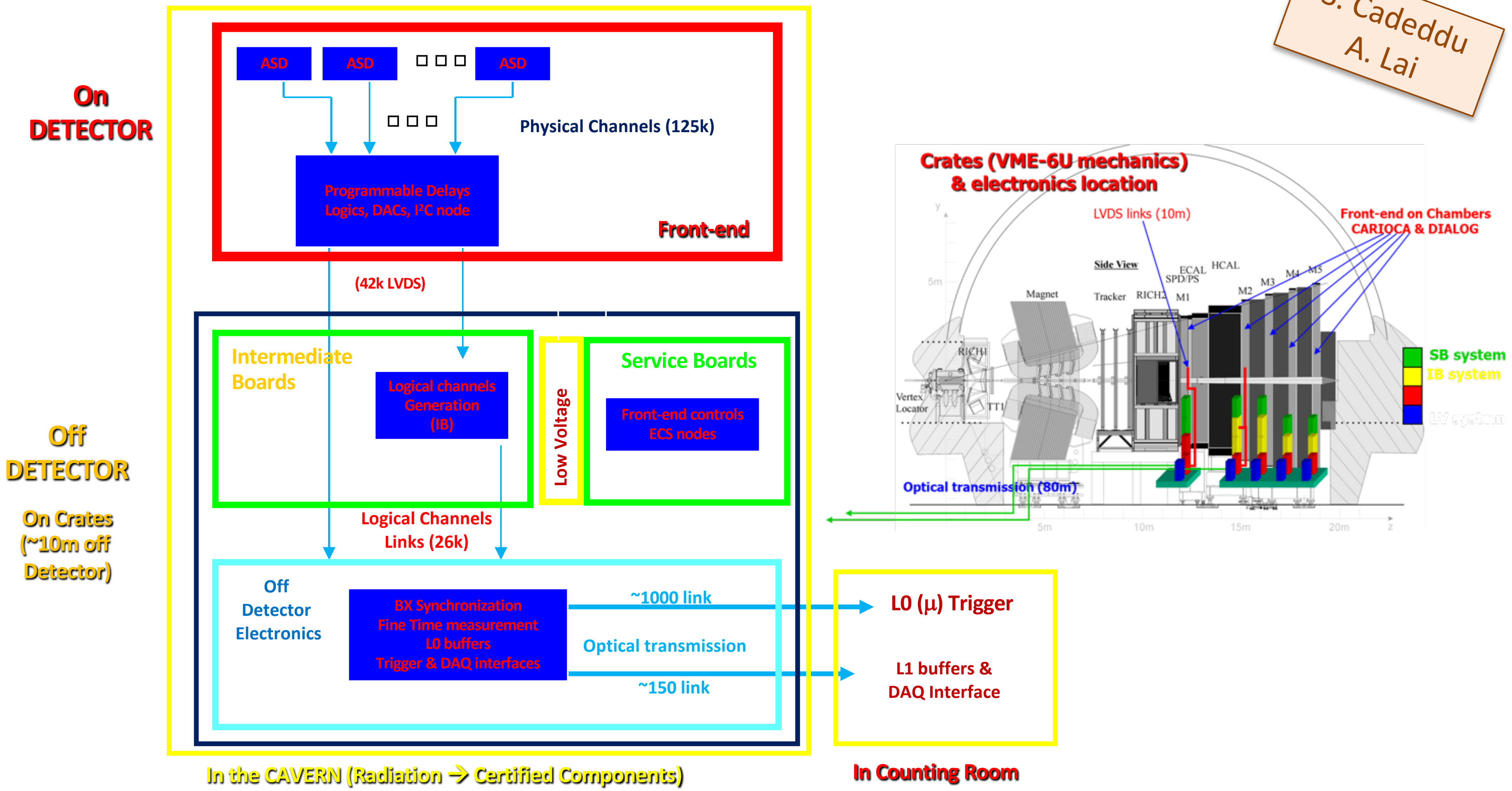
Official responsibilities of the members of the Cagliari LHCb Group

THE BEGINNING, THEN RUN1 & RUN2

Muon System Readout

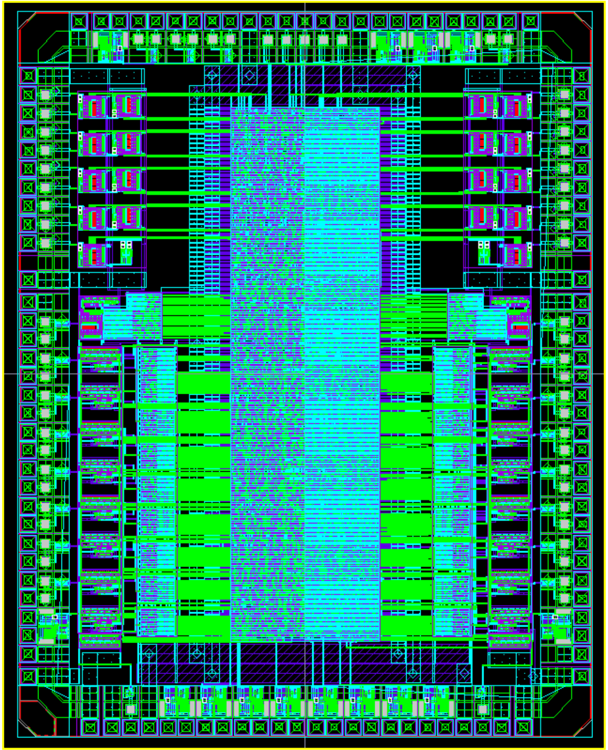
- Design a R/O system of a complex projective detector feeding info to level-0 muon trigger at 40 MHz
- Design an ASIC to perform the on-chamber logic operations and time alignment → **DIALOG**
- Design an ASIC with on-board pipelines to perform the front-end readout at 1 MHz → **SYNC**
- Design the FEE board for all the chambers → **CARDIAC**

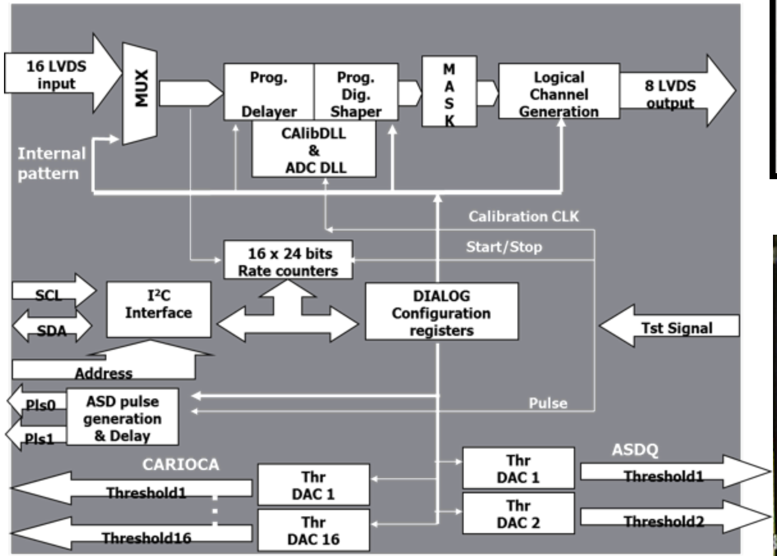
The Muon detector readout Architecture

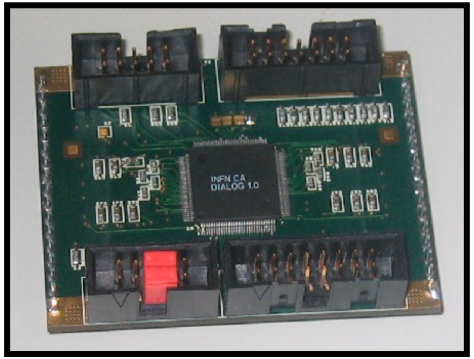


The DIALOG ASIC

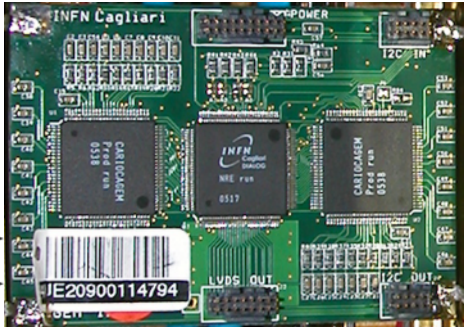
S. Cadeddu
A. Lai
D. Marras
W. Bonivento
A. Cardini





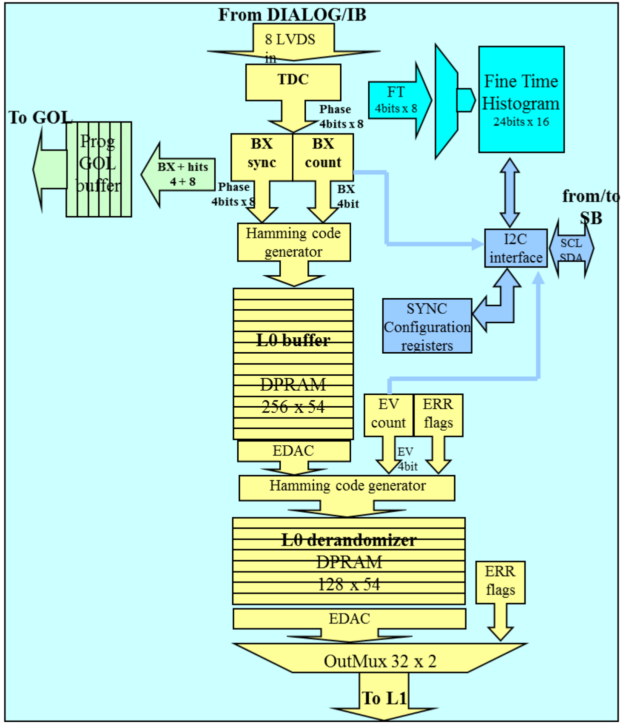


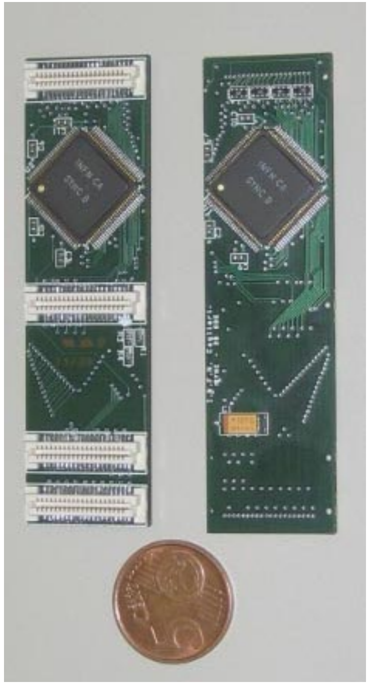
CARDIAC FRONT-END BOARD

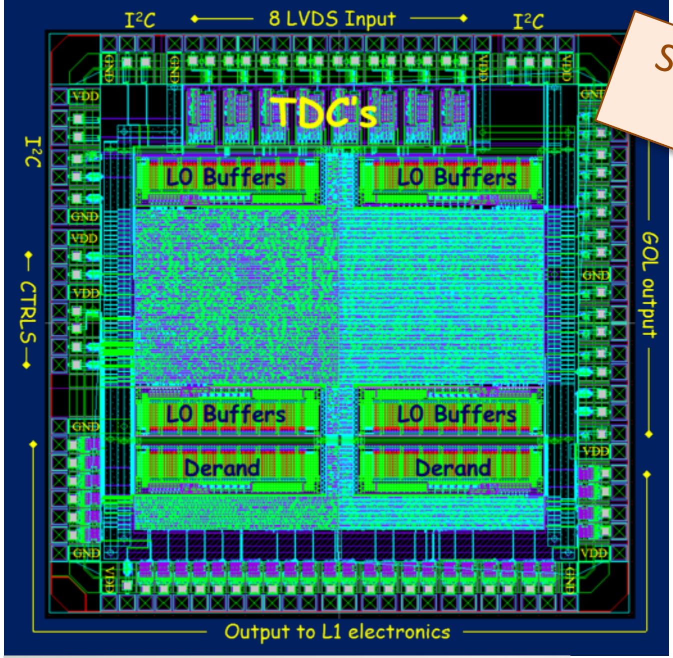


CARDIAC-GEM FRONT-END BOARD

The SYNC ASIC





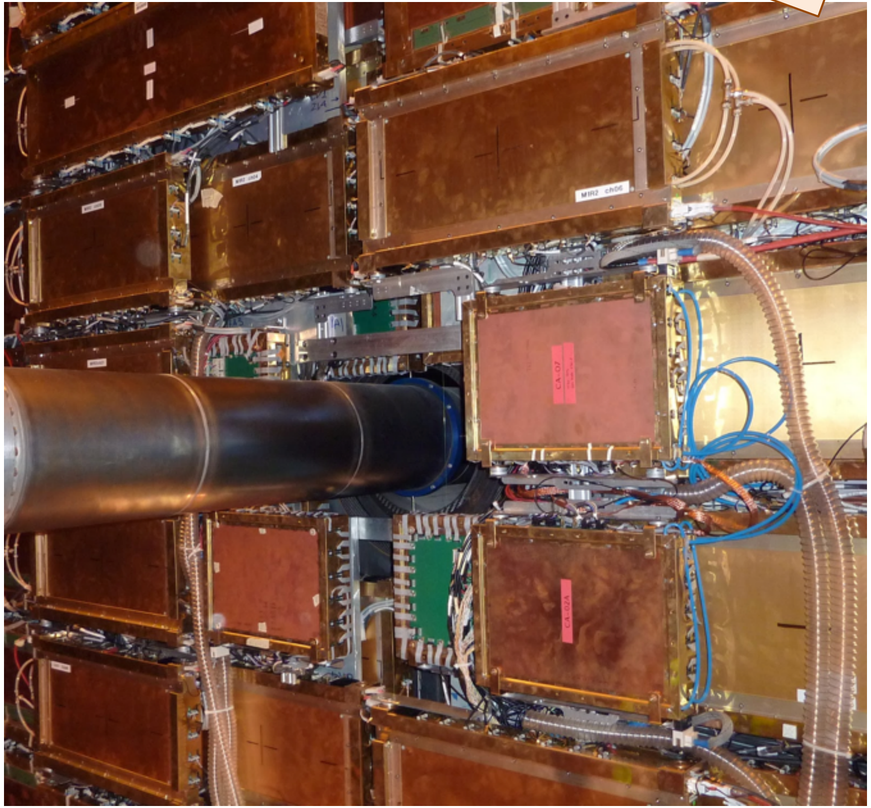


S. Cadeddu
A. Lai

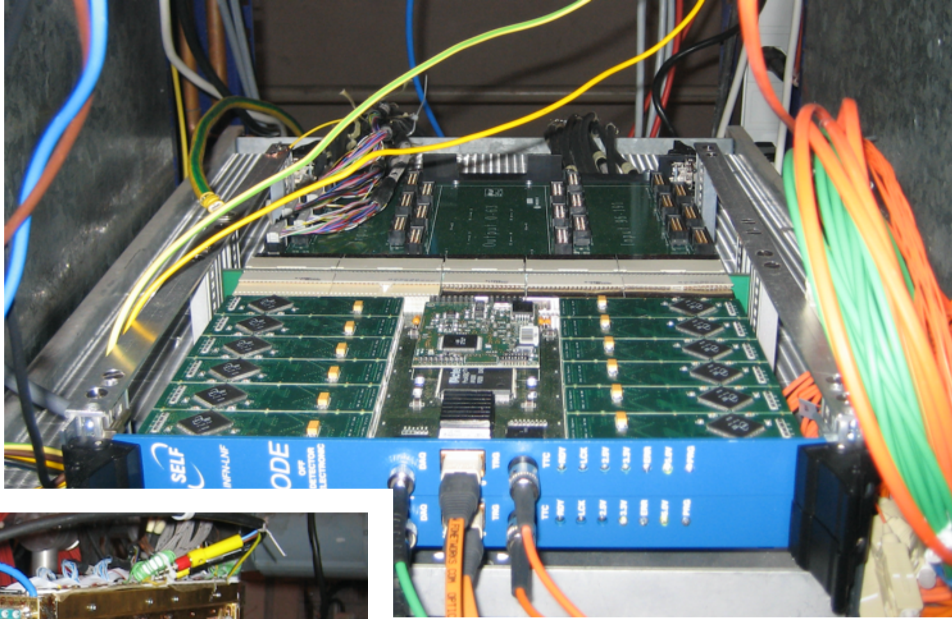
Triple-GEM for the first muon station

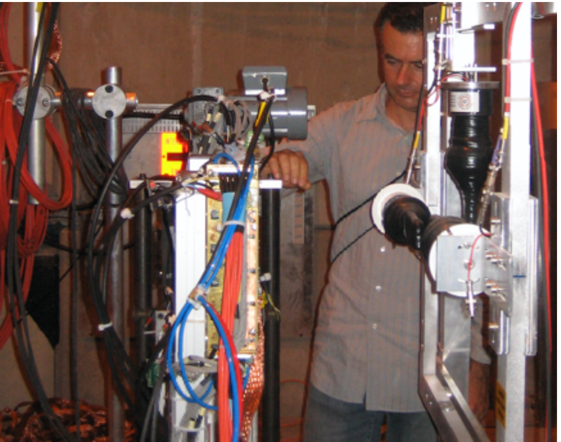
A. Cardini
D. Pinci
D. Raspino
B. Saitta

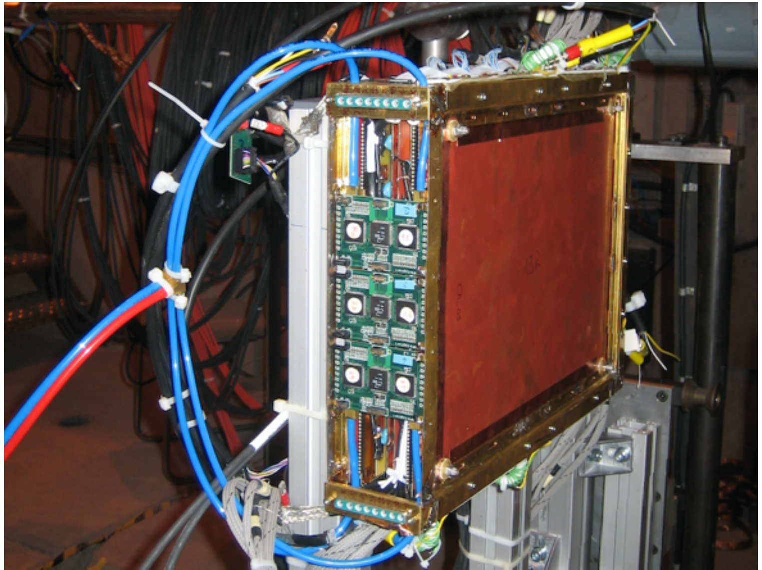
- In 2000 we started an R&D to develop a fast triple-GEM based detector for M1
  - 96% efficiency in 20ns window – fast gas!
  - Could operate up to 1 MHz/cm
  - Could withstand Run1+2
- 50% built in Cagliari
- First detector of this kind approved for an LHC experiment
- It has become **the reference** for CMS triple-GEM detector development for phase-1 upgrade (GE1, GE2, ME0)
- Operated successfully all along Run1 and Run2
- Dismounted in early 2019




H8 Beam Test October 2006







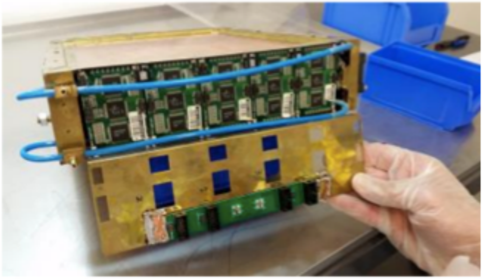
Commissioning Time 2006-2008

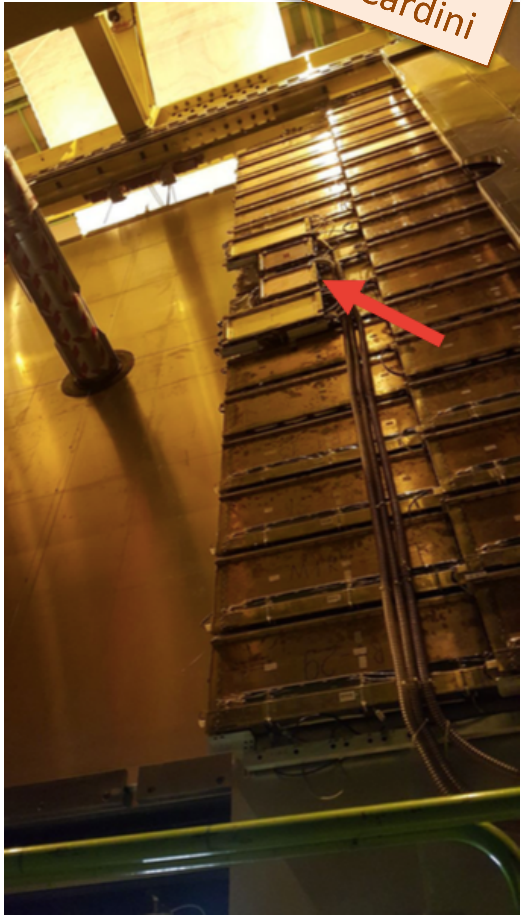
M1 ready, Summer 2009

GEM detectors: Mantainance / Dismantling

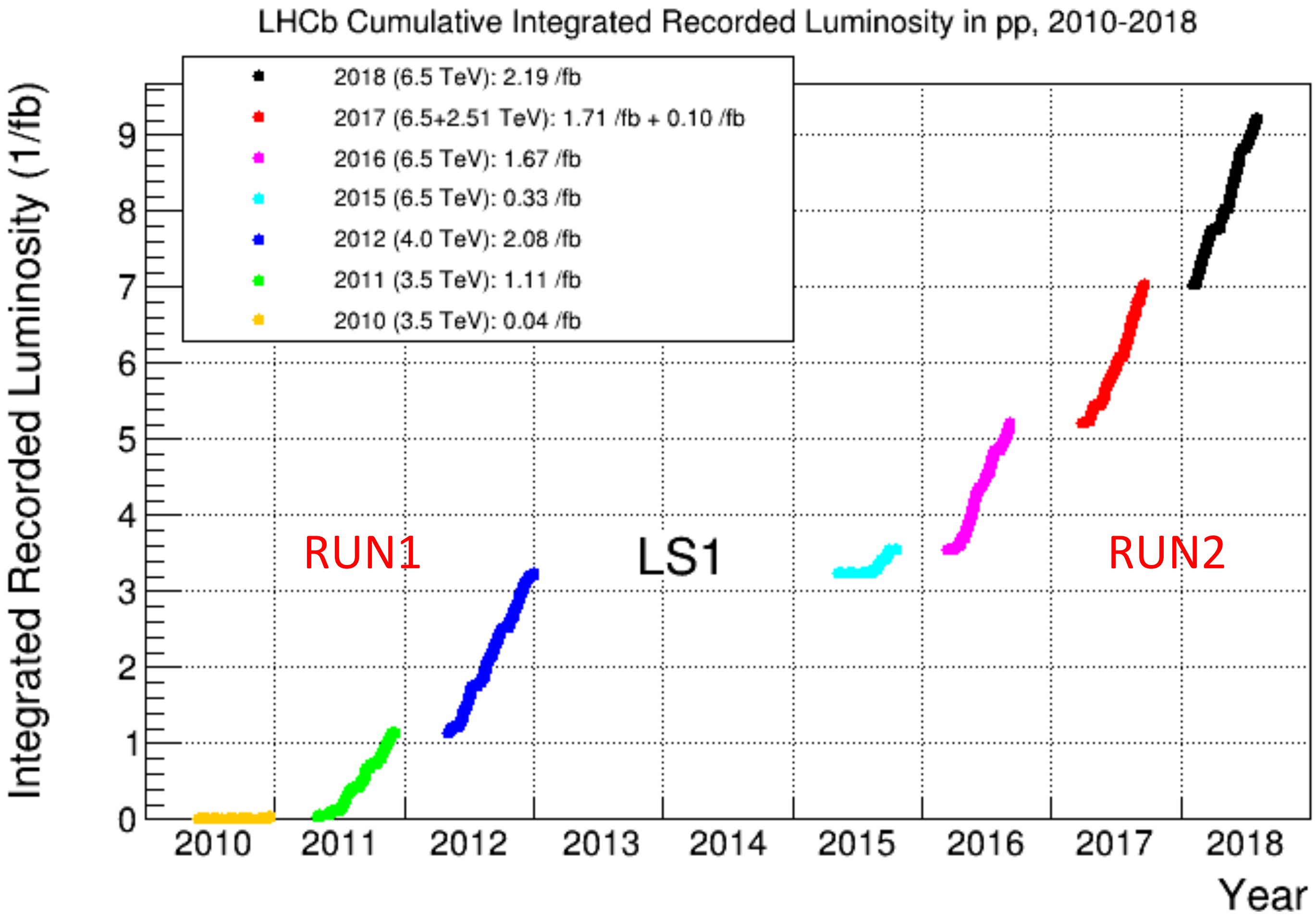
D. Brundu
A. Cardini

- Periodic maintenance or replacement of the GEM detectors
- Starting from March 2019 the M1 station has been fully dismounted as foreseen for the upgrade of LHCb
- Further study of triple-GEM detector aging at the CERN improved Gamma Irradiation Facility (GIF++)





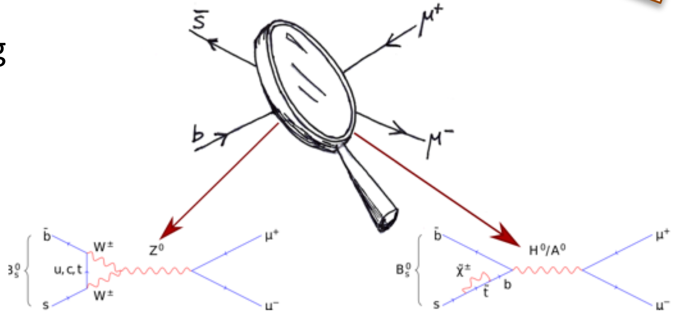
ONGOING ANALYSIS ACTIVITIES


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
RUN1
LS1
RUN2
Integrated Recorded Luminosity (1/fb)
0
1
2
3
4
5
6
7
8
9
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

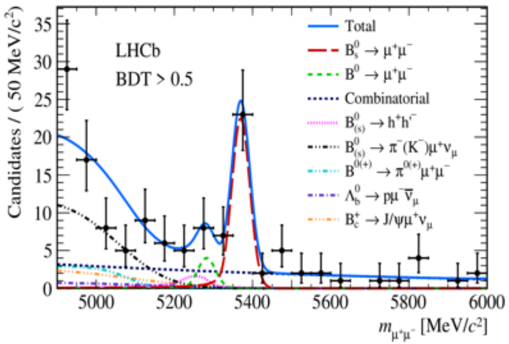
Search for new (pseudo) scalar interactions: $B_s \to \mu^+\mu^-$ and $D \to \mu^+\mu^-$

F. Dettori
A. Contu
(W. Bonivento)
(M. Fontana)

- Very rare decays of a pseudo scalar mesons to two leptons branching fractions
- Probe new possible scalar or pseudo scalar interactions
- Model independent searches for New Physics
- $B_s \to \mu^+\mu^-$ observed by LHCb and CMS combination and by LHCb alone
- Full Run 2 analysis ongoing: world best BR measurement
- Three experiments combination (Atlas CMS LHCb) in the plans for better sensitivity



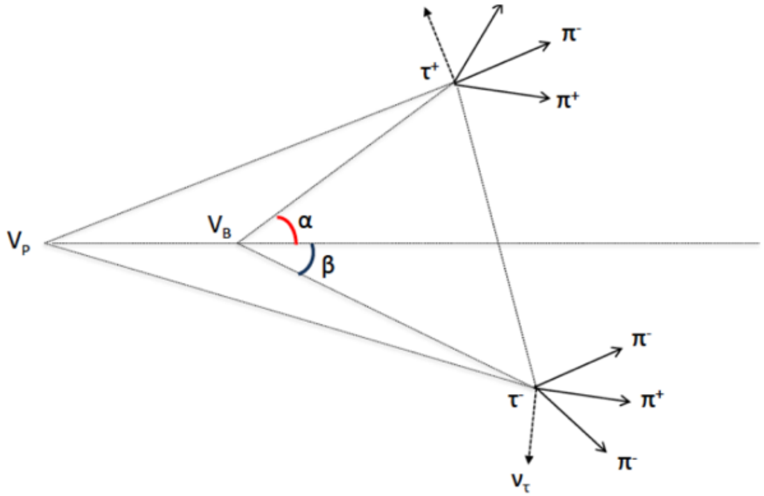
- $D^0 \to \mu^+\mu^-$ probes the up sector currents and complementary New Physics (e.g. leptoquarks)
- Run1-2 analysis at full speed led by Cagliari together with CERN
- Will reach values close to SM branching fraction 10^{-11}!



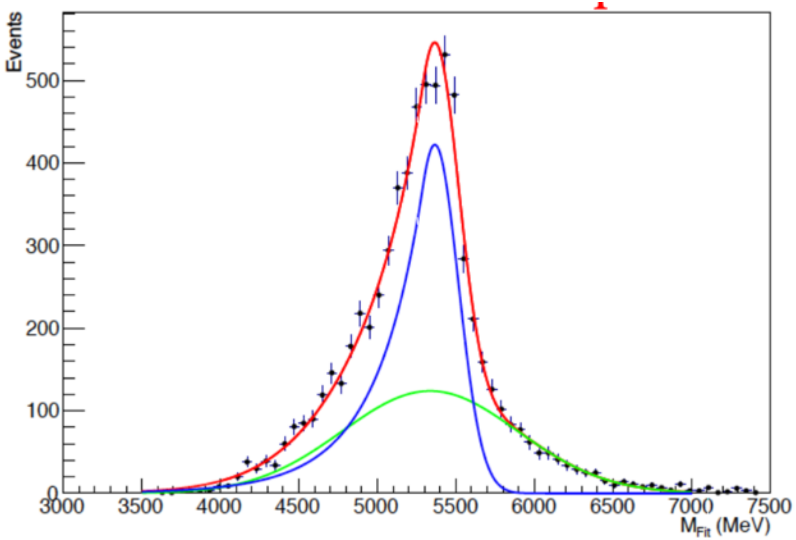
$B_s \rightarrow \tau\,\tau$

B. Saitta

Decay Scheme



(Novel) method of Bs reconstruction

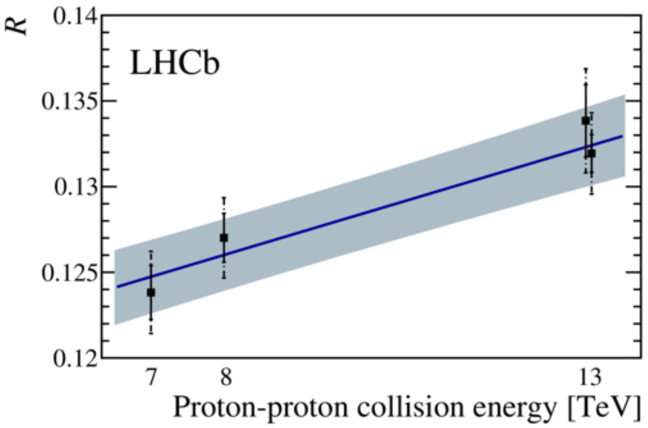


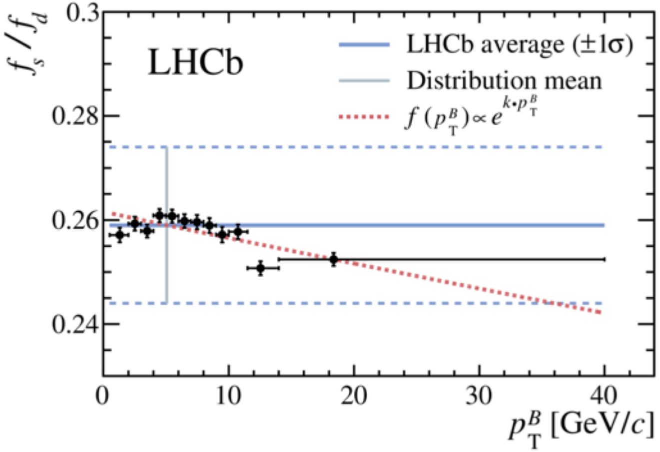
B_s mass plot from this new reconstruction method

b-quark hadronization variation with energy and kinematics

F. Dettori

- Fraction of b quarks forming a B_s is fundamental to measure branching fractions sensitive to New Physics and also probes interesting non-perturbative QCD
- Its variation with collision energy and B kinematics measured with Bs→ J/ψ φ vs B^+→J/ψ K^+ decays at LHCb
- First observation of a dependence with p_T and strong evidence for the dependence with energy
- Submitted to PRL (arXiv:1910.09934)

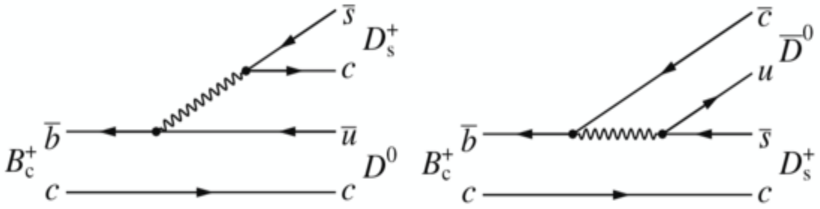




B decays to double charm

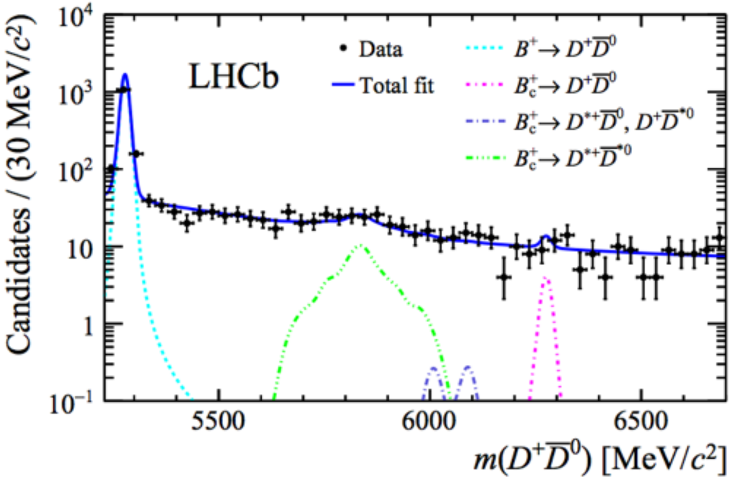
R. Oldeman

- Interference at tree level in $B_c^+ \to D_s^+ \overline{D}^0 (D^0)$ to measure CKM angle γ, *the weak phase of V_{ub}*



- Completed measurement of Run I data: No signal, first limits on 12 B_c^+ decay modes
  consistent with expectations
  [ARXIV:1712.04702](), [NUCL. PHYS. B 930(2018)563]()

- Spin-off: measurement of direct CPV in normalisation channels
  $A^{CP}(B^- \to D_s^- D^0) = (-0.4 \pm 0.5 \pm 0.5)\%$ ***first measurement***
  $A^{CP}(B^- \to D^- D^0) = (2.3 \pm 2.7 \pm 0.4)\%$ ***world best measurement***
  [ARXIV:1803.10990](), [J. HIGH ENERG. PHYS. 05 (2018) 160]()



- Run II analysis in advanced state
  - *All Run 2 data, higher $\sigma_{b\overline{b}}$*
  - *Include $B_c^+ \to D^{*+}\overline{D}^0(D^0)$ channels*
  - *Revisiting BDT, background model, fit method*

B meson decays with charmonia ($c\bar{c}$) in final state

F. Dordei

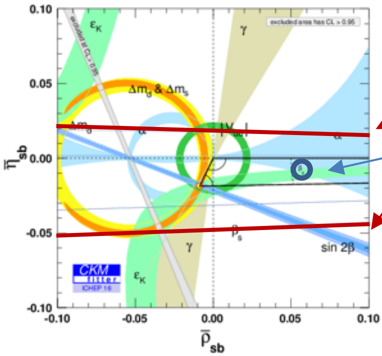
Analyses done within the B2CC physics working group, that comprises analyses of CP violation and precise determination of particle properties exploiting decays with charmonia resonances (J/ψ, $\psi(2S)$, …) in the SM (served as convener in 2017-2018).

- **Contact author for Measurement of CP violation using $B_s^0 \to J/\psi\phi$ in LHCb Run II data (2015-2016 data taking)** **Eur. Phys. J. C 79 (2019) 706**, done in collaboration with Edinburgh, Heidelberg, Santiago, Nikhef and China

CKM matrix: 3x3 matrix describing quark mixing (**3 angles**, **1 phase**). Parameters need to be measured!

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Imposing unitarity

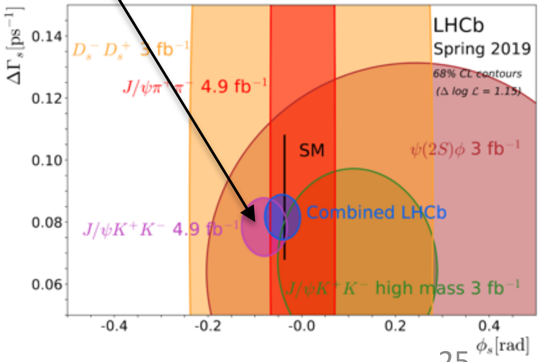


Aim: Measure the phase (angle) β_s

Experimental limits

Theory prediction

Core program of LHCb
Most precise world result



- **Now: Measurement of CP violation using $B_s^0 \to J/\psi\pi\pi$ using full LHCb Run II data**

  Performed with Piera Muzzetto in collaboration with Tsinghua University

- **Planned: Measurement of the decay width difference in the B^0 system using LHCb Run II data**

  Preliminary work performed in the master student work of Danilo Deiana

Study of the rare decay $\Sigma^+ \to p\mu^+\mu^-$

F. Dettori
F. Dordei

- Analysis performed using 2011 and 2012 data, excess observed at 4.1σ significance, preliminary Branching Fraction measured $(2.2^{+1.8}_{-1.3})\text{x}10^{-8}$, wrt SM~ $5\text{x}10^{-8}$
- Now: Improved analysis using Full Run 2 dataset (2016-2018)

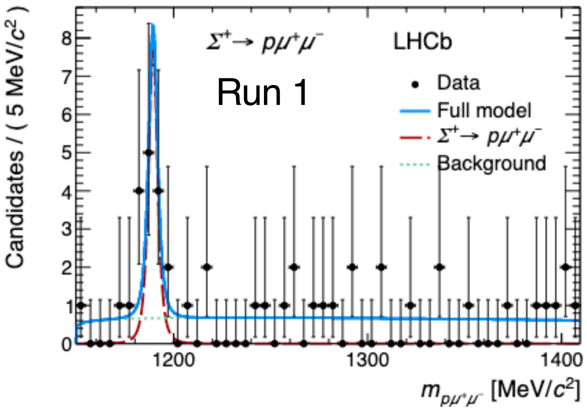
- Revisit the measurement of the BF
  - Better control of the background, in particular that coming from $\Lambda \to p\pi^-$
  - Exploiting a dedicated trigger selection, 10 times more luminosity
  - Revisiting the efficiency determination

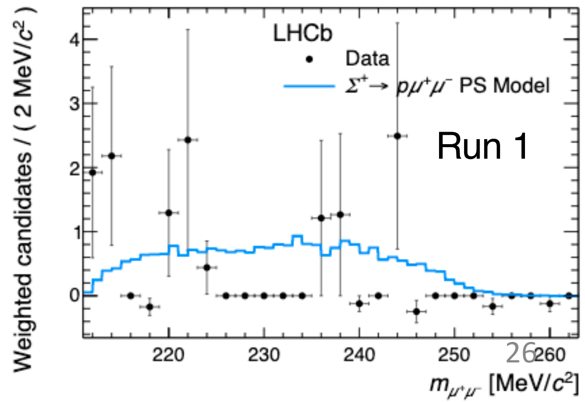
- Study of the di-muon mass
  - «**HyperCP anomaly**» 3 candidates observed, remarkably with the same di-muon mass 214 ± 0.5 MeV/c^2
  - This would point towards an intermediate particle X^0
  - For LHCb di-muon invariant mass is phase-space like: no resonance seen

- Study of direct CP violation

Currently one bachelor student and soon one master student on it!

Very rare flavour changing neutral current

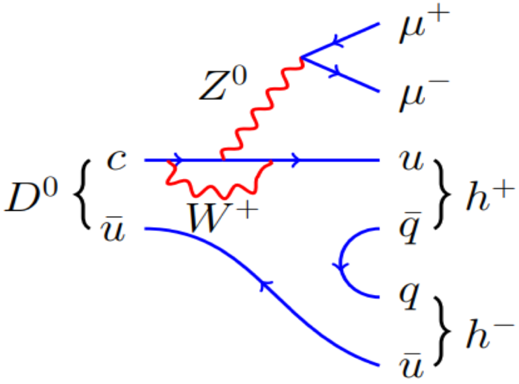


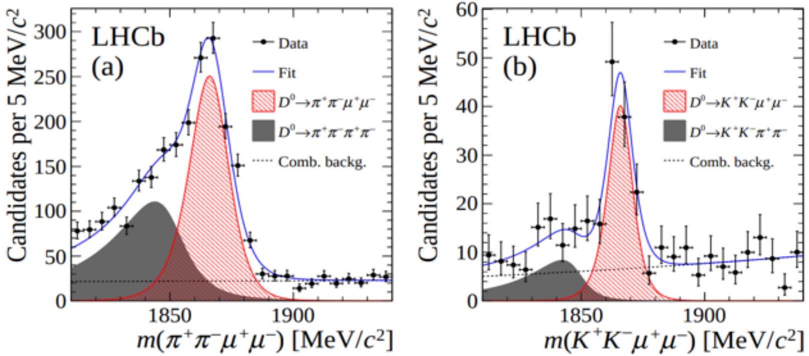


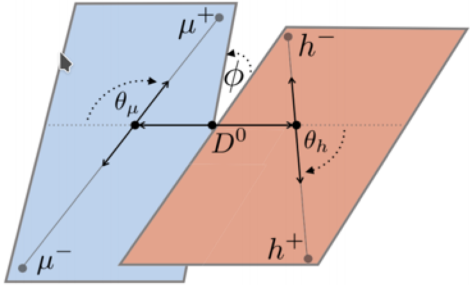
[PRL 120, 221803 (2018)]

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

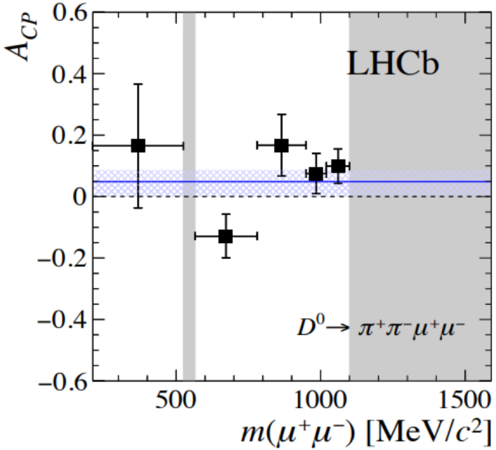
D. Brundu
A. Contu







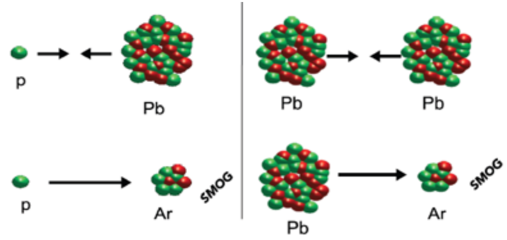
Cabibbo-Maksimowicz
5-dim. parametrisation:
$\cos(\theta_h), \cos(\theta_\mu), \phi$
$m^2(hh)\ m^2(\mu\mu)$



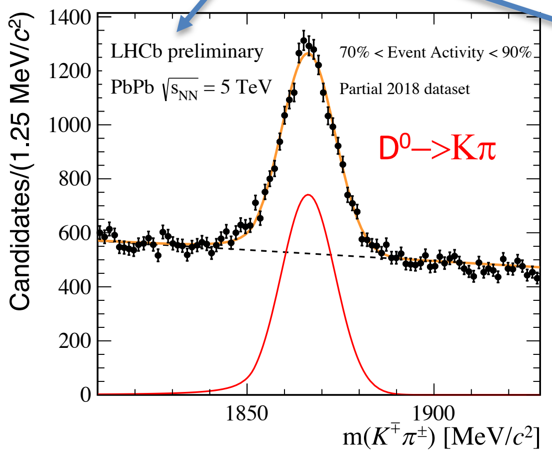
Heavy Ion Activities

- LHCb started Heavy Ion activities in 2015; three setups on top of pp collisions:
  - p/Pb-GAS (SMOG) [NEW], p-Pb [new √s], Pb-Pb [NEW]
  - Cagliari deeply involved in running, trigger, reconstruction,

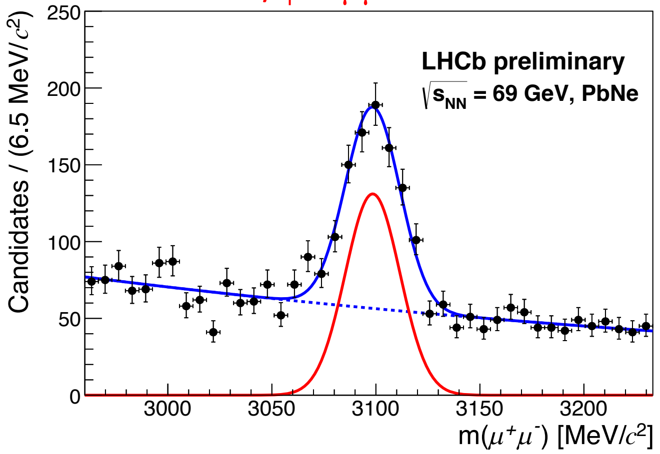
  data quality and selection studies together with LAL group



- Huge potential to study uniquely
  - Quark Gluon Plasma (QGP) in PbPb (χ_c,J/ψ from B) and SMOG (unique √s)
  - Cold Nuclear Matter Effects in pPb
- Results from PbPb/PbNe 2018 run



J/ψ–>μμ

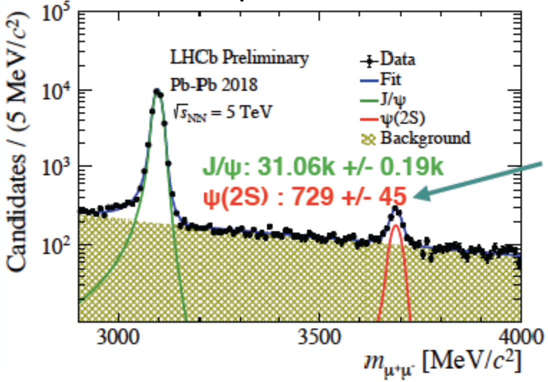


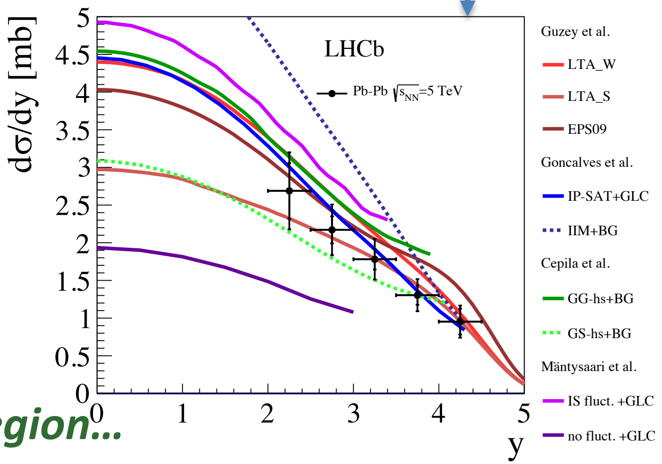
B.Audurier,
S.Belin,
A.Bursche,
S.Chen,
G.Manca

Selected Results: PbPb

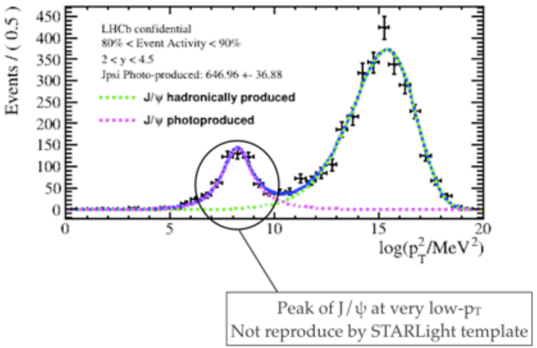
- **Peripheral and ultra peripheral J/ψ in PbPb** (LHCb-CONF-2018-003, going to paper)

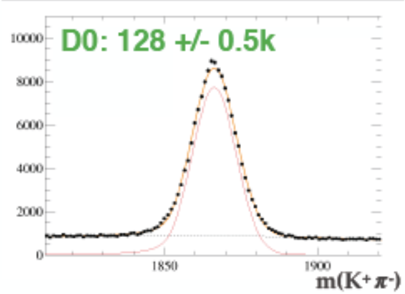
2018 sample 20x more data

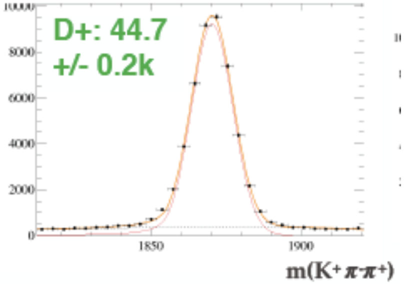




2018 data: ***Zoom in the low pT region…***

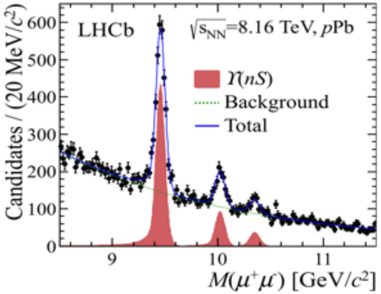


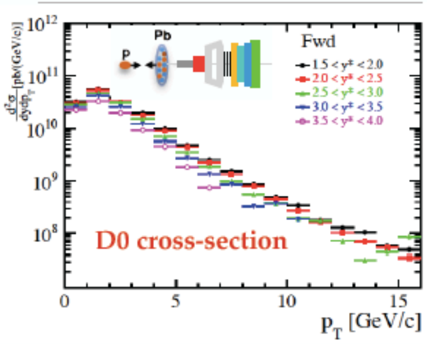


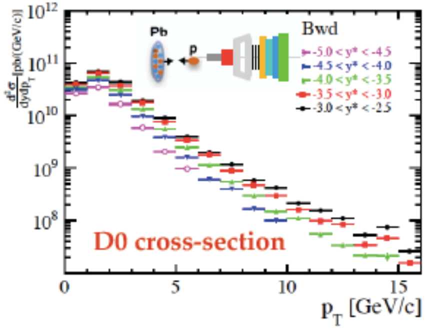


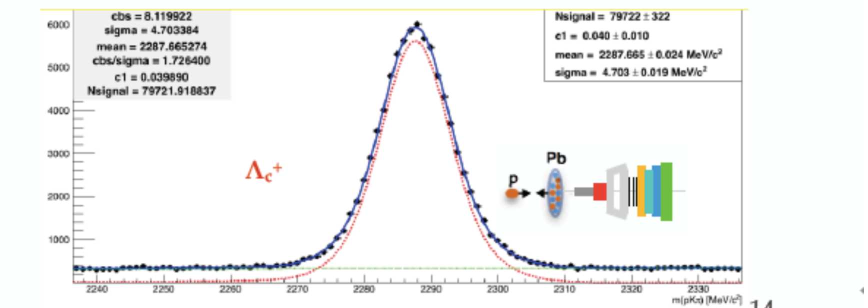
Proton lead

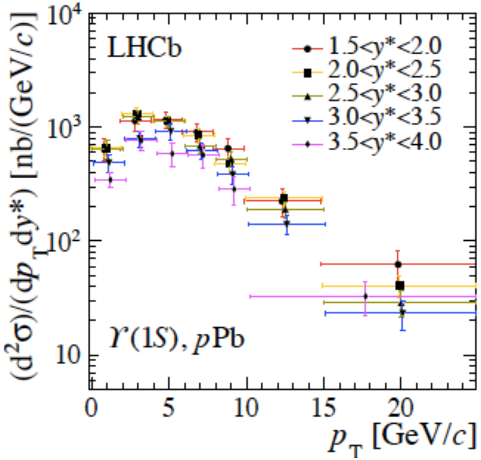
$\sqrt{s}$=8.16 TeV, pPb/Pbp, L~34 nb^{-1}



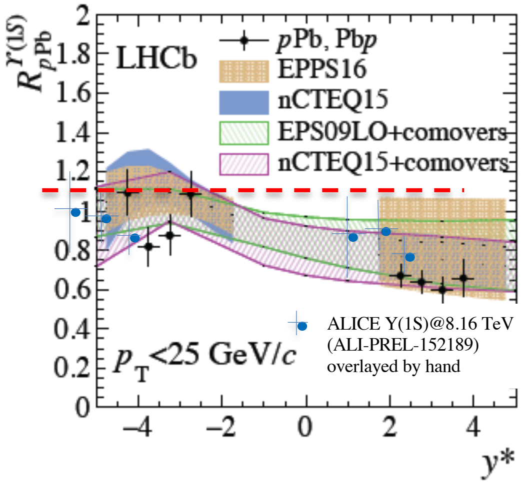








Upsilon cross section [JHEP11(2018)194]



Upsilon nuclear modification factor

THE PRESENT: UPGRADE 1

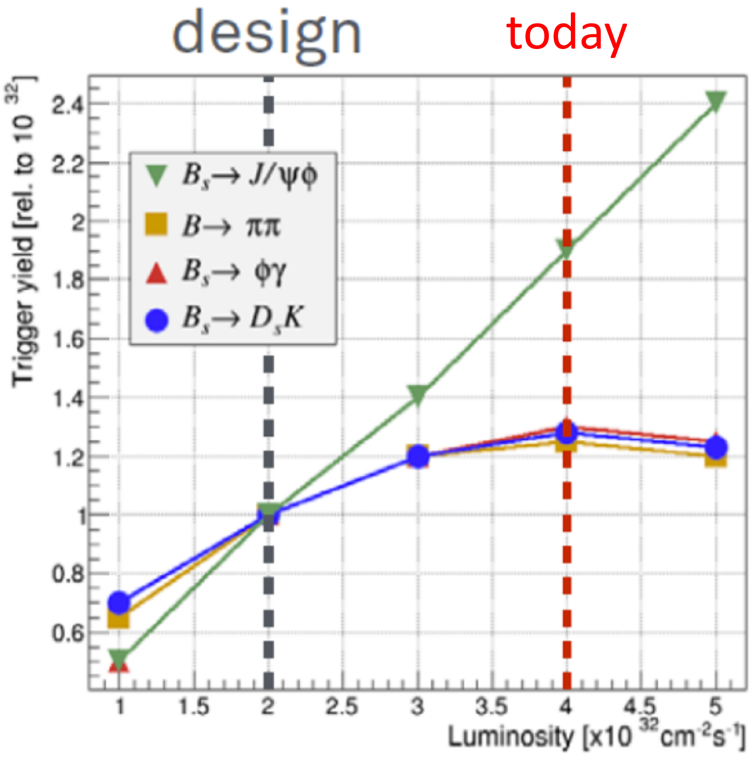
Motivations

- No (yet) evidence for New Physics
- Look for tiny deviation from SM predictions
- More (x10) data required

- The current 1 MHz level-0 trigger output is a severe limitation!

- If luminosity increases:
  - trigger yield of hadronic events saturates
  - need harder cuts on Pt and Et due to the 1 MHz bandwidth limit
    - → no gain in statistics
    - → limited to ~5 fb-1 in Run2

- Note that our upgrade luminosity does not depend LHC upgrade, we only use a fraction of the available luminosity (i.e. what is used by ATLAS and CMS)



CERN-LHCC-2011-001
CERN-LHCC-2012-007

Upgrade HOWTO

CERN-LHCC-2011-001
CERN-LHCC-2012-007

- Remove the level-0 hardware trigger
- Readout an event at every bunch crossing (40 MHz)
- New front-end electronics (with on-chip zero suppression)
- New DAQ system
- Use an efficient fully software trigger accessing complete event information, running at the bunch crossing rate, performing a full online event reconstruction
- Redesign several detectors to cope with increased occupancies

LHC era → HL-LHC era

Run (years)	Run 1 (2010-2012)	Run 2 (2015-2018)	Run 3 (2021-2023)	Run 4 (2027-2029)
Integrated luminosity	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}
Instantaneous luminosity	4×10^{32} $cm^{-2}s^{-1}$		2×10^{33} $cm^{-2}s^{-1}$	

Current LHCb → Upgraded LHCb

LS2
LHCb Upgrade

- **Data taking conditions**
  - Leveled L = $2 \cdot 10^{33}/cm^2/s$
  - 30 MHz collisions
  - 20-100 kHz to disk
  - ~5 fb^{-1} per year
- **Challenges**
  - High pile-up
  - Large occupancies - difficult event reconstruction and PID
  - Huge Data Rate
  - Radiation damage

nSYNC project

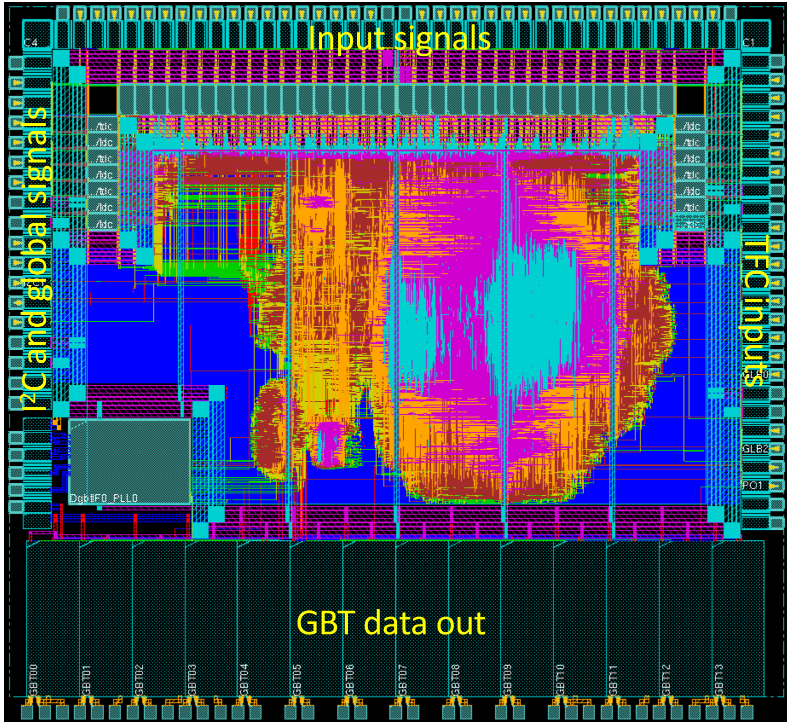
S. Cadeddu
A. Loi
L. Casu

Version 2:
Submitted: November 2016
Received: March 2017
PRR: October 2017

Start Tender: November 2017
Contract Signed: July 2018

Delivered: January 2019
- 2800 chip packaged
- 4 wafer ready in our hands
- 6 more wafer on hold at UMC

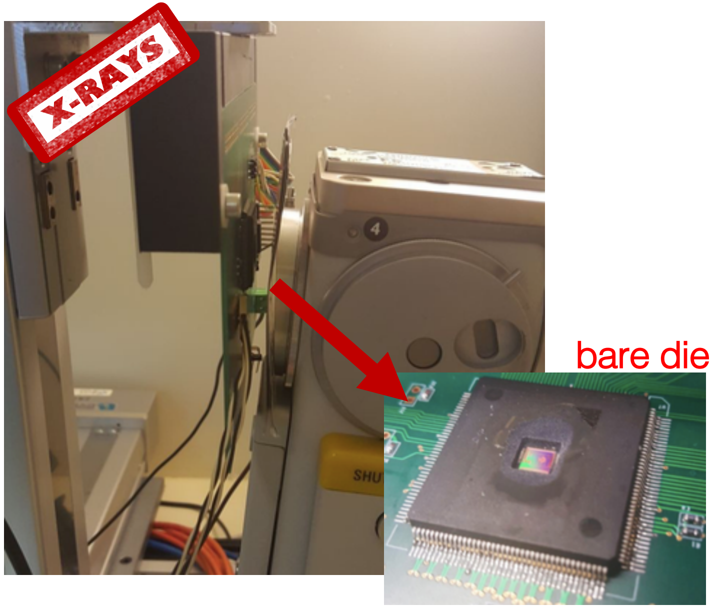
Prod. Test End: July 2019
- Needs for the installation
    - About 800 nSYNC including spares
    - 840 good nSYNC already selected
    - Others 200 nSYNC selected as spares.

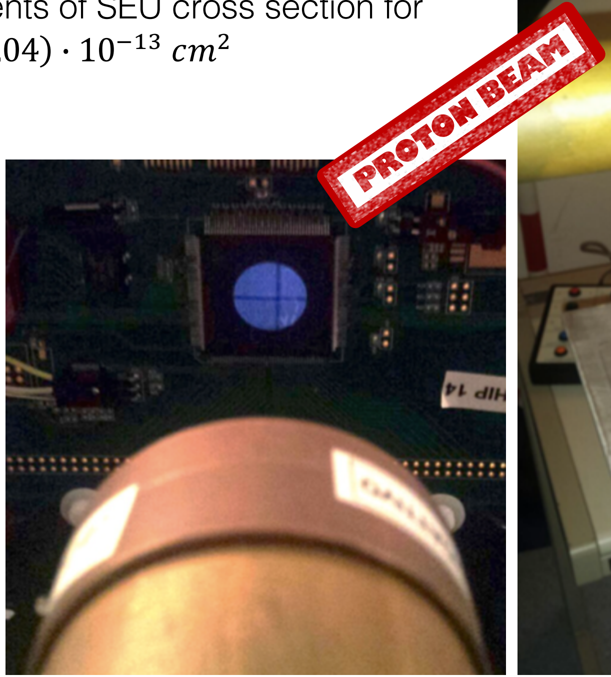


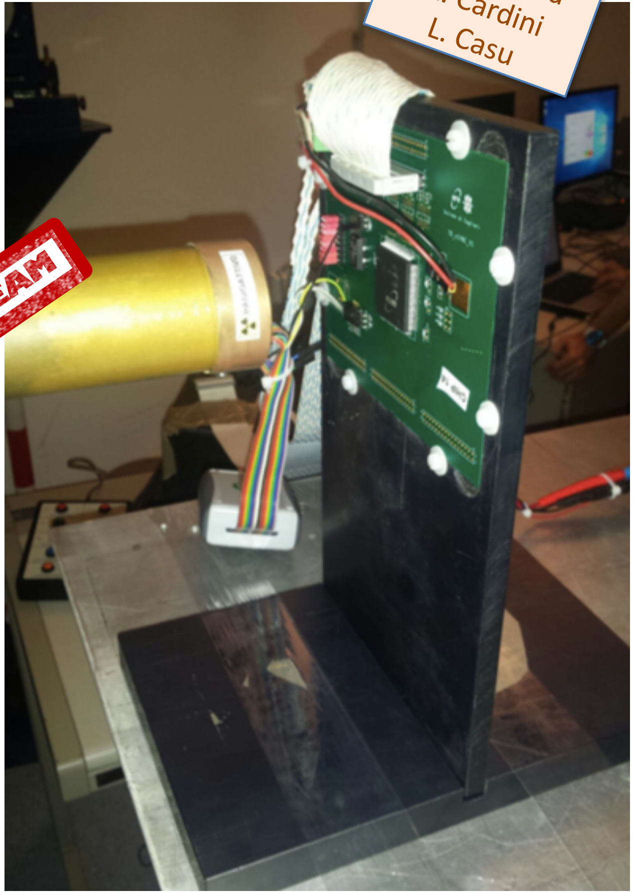
Irradiation test of nSYNC

D. Brundu
S. Cadeddu
A. Cardini
L. Casu

- The nSYNC chip has been tested under radiation using both 60 MeV proton beam (at Catana facility, LNS) and X-Ray (Cagliari), up to 1.2 kGy and 3 kGy respectively.
- Excellent performance in terms of Single Event Upset (SEU), power consumption, TDC functionalities.
- Interesting for the community: first measurments of SEU cross section for UMC 130 nm technology, $\sigma/bit = (0.53 \pm 0.04) \cdot 10^{-13}\ cm^2$



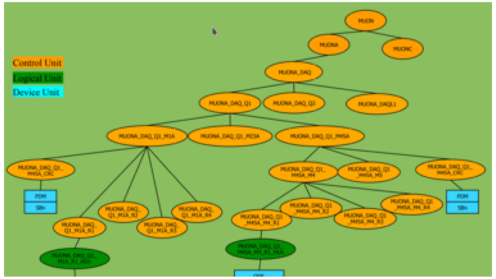




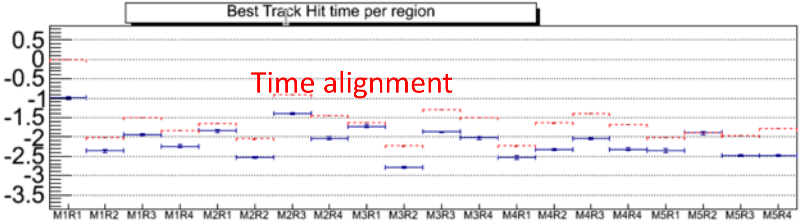
D. Brundu
S. Cadeddu
A. Contu

Upgrade muon detector commissioning

Detector control system

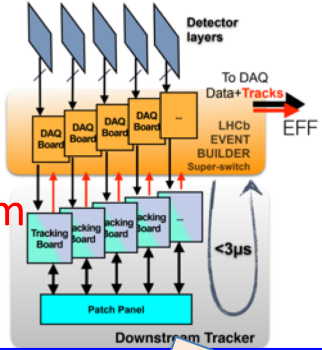


Time alignment



Tracking with FPGAs

Integration in the online farm



A. Contu

F. Dordei
P. Muzzetto

Istituti	Allineamento	Tracking e Acceleratori	PID	Monitoring	HLT
Ferrara	+		+ (?)		
Cagliari	+	+	++		
Frascati			++	++	+ (smog)
Pisa		+++			
Milano		+ (dal 2020)			+(smog?)
Firenze		+	+		+ (smog)
Bologna		+		+	

THE FUTURE: UPGRADE 2

Towards Upgrade 2

LHCb has started to study the possibility of operating up to an instantenaous luminosity of 2E+34 $cm^{-2}s^{-1}$

LS2: Major changes, Upgrade I Installation

- Run 3 (2021-2023)
  - LHCb Upgrade I
  - $L = 2 \times 10^{33}$ cm^{-2} s^{-1}, ~5 fb^{-1}/yr

Upgrade I, ongoing

LS3: "Consolidation", Upgrade 1b Installation

- Run 4 (2026-2029)
  - LHCb Upgrade Ib
  - $L = 2 \times 10^{33}$ cm^{-2} s^{-1}, ~5 fb^{-1}/yr Total Int. L ~ 50fb^{-1}

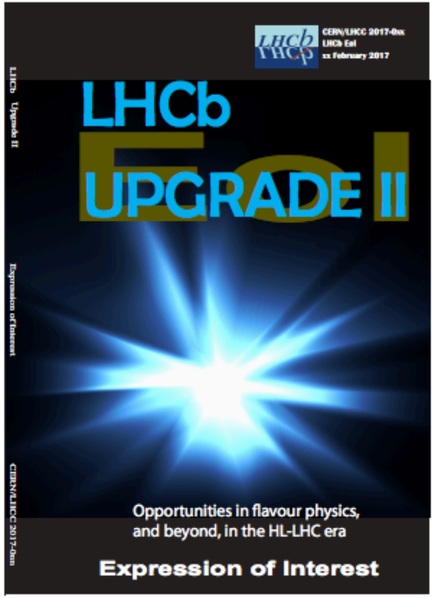
Consolidation

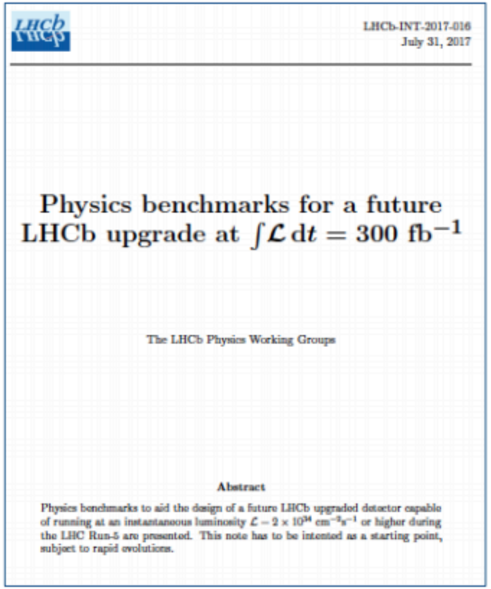
LS4: Major Changes, Upgrade II Installation

- Run 5/6 (2031-)
  - LHCb Upgrade II
  - $L = 1\text{-}2 \times 10^{34}$ cm^{-2} s^{-1}, ~50 fb^{-1}/yr

Upgrade II

Total Int L ~ 300fb^{-1}




LHCb-INT-2017-016
July 31, 2017

Physics benchmarks for a future LHCb upgrade at $\int \mathcal{L}\,dt = 300$ fb^{-1}

The LHCb Physics Working Groups

Abstract

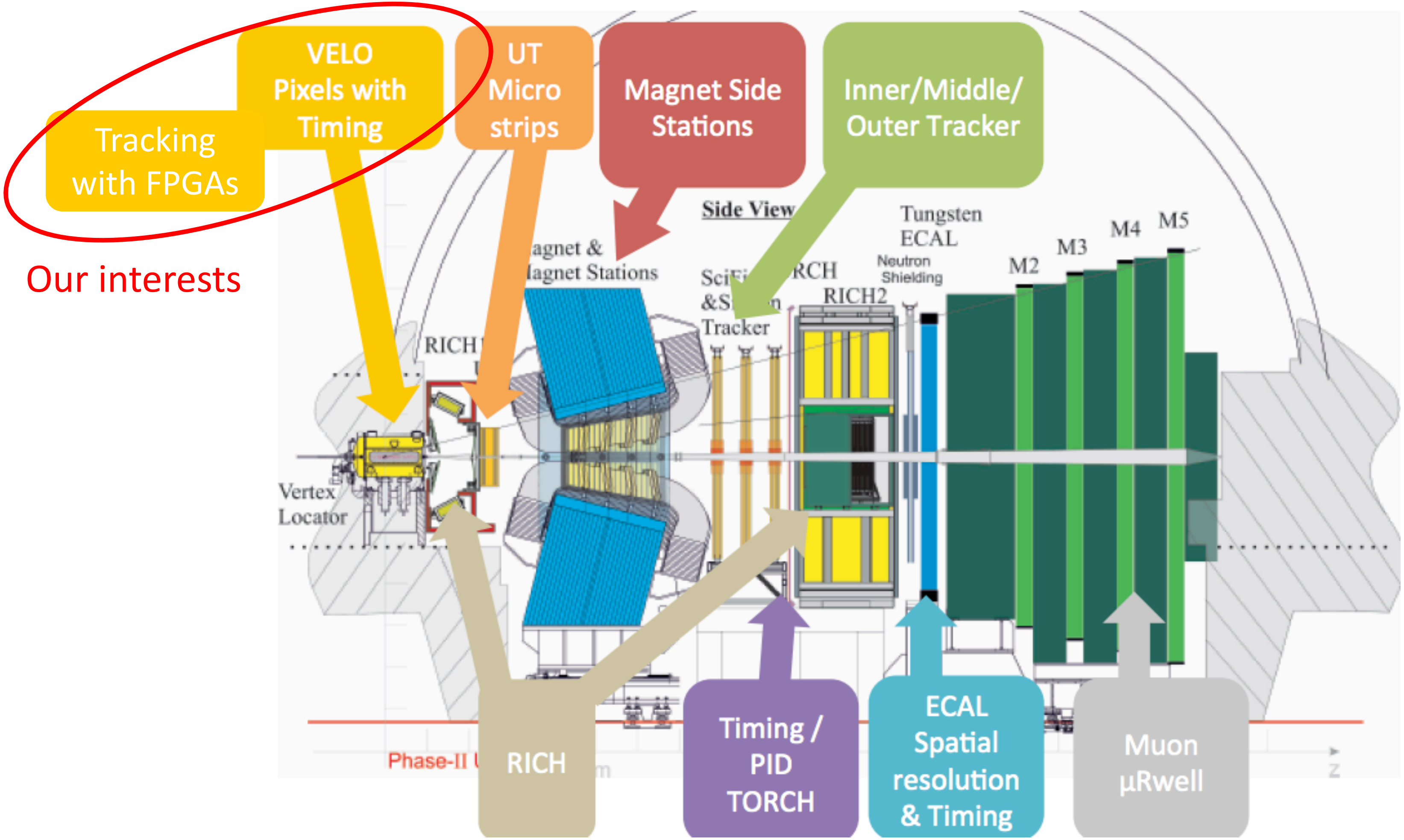
Physics benchmarks to aid the design of a future LHCb upgraded detector capable of running at an instantaneous luminosity $\mathcal{L} = 2 \times 10^{34}$ $cm^{-2}s^{-1}$ or higher during the LHC Run-5 are presented. This note has to be intended as a starting point, subject to rapid evolutions.

Physics Motivations for an Upgrade 2

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}	–

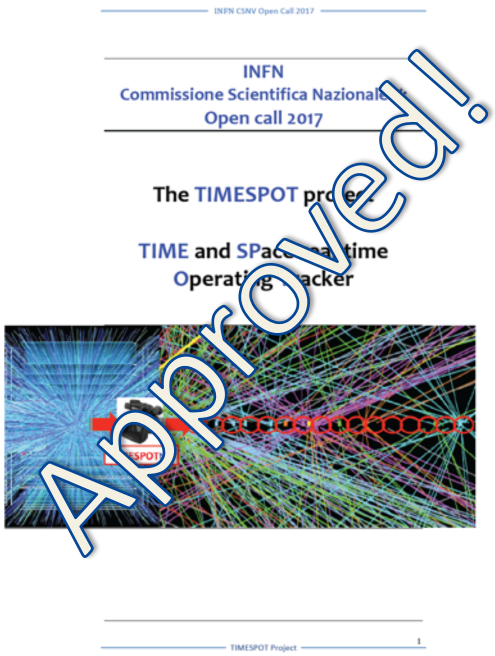
CERN-LHCC-2018-027
LHCB-PUB-2018-009



Tracking with FPGAs
Our interests
VELO Pixels with Timing
UT Micro strips
Magnet Side Stations
Inner/Middle/ Outer Tracker
Side View
Tungsten ECAL
Neutron Shielding
M2
M3
M4
M5
RICH2
Tracker
RICH
Vertex Locator
RICH
Timing / PID TORCH
ECAL Spatial resolution & Timing
Muon µRwell

Pixel with ps timing → TIMESPOT

- At the end of 2015 we started to think of the possibility of developing ultra-fast silicon sensors. The first step was a PRIN proposal prepared by some of the LHCb Italian groups
- In 2017 we decided to write a proposal for a CSN5 CALL, aiming at the development of a prototype of a solid-state 4D tracker with real-time tracking capabilities
- This proposal attracts many persons and not only within LHCb → 20 FTE, 1/3 from LHCb
- Approved in September 2017, activity takes off in 2018
- Excellent opportunity in a very competitive international scenario, extremely interesting for future experiments operating at very high instantaneous luminosity



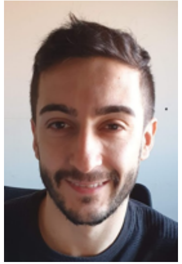
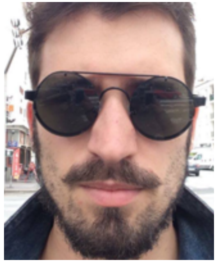
Many more details on Adriano's presentation

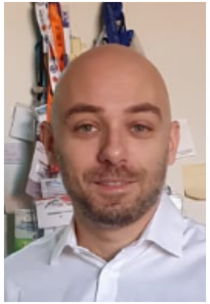
Conclusions

- LHCb continues to produce lot of excellent physics results
- Upgrade work is proceeding as expected, data taking will start in 2021
- Cagliari Group members continue to play important roles inside INFN and within the Collaboration
- Personnel continue to increase, both in Cagliari, in Italy and overall in the Collaboration
  → The Cagliari Group is today among the largest LHCb groups in Italy
- We have started to look at the future upgrade to exploit even better what LHC can provide, and we have started new exciting activities
- The future of flavor physics at very high statistics is extremely challenging: with the experience accumulated so far and the new R&D opportunities that have already started LHCb will continue to play a leading role in this field







Thank you!