BEAUTY 2018

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LHCb Upgrade I

Paula Collins
On behalf of the LHCb collaboration

CERN

LHCb

Contents

- The LHCb Upgrade
- Tracking: Pixels, Strips, SciFi
- PID: CALO, Muon, RICH
- Computing, DAQ, Trigger
- Physics Prospects

The LHCb Upgrade I

Indirect search strategies for New Physics e.g. precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive; current LHC experience is that direct signals are elusive.

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes

The LHCb Upgrade

1) Full Software trigger
   - Removal of current 1 MHz bottleneck
   - Allows effective operation at higher luminosity
   - Improved efficiency in hadronic modes
2) Raise operational luminosity to $2 \times 10^{33}\ cm^{-2}\ s^{-1}$
   - Necessitates redesign of several sub-detectors and overhaul of readout

➡ Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector

Flexible trigger and unique acceptance opens up opportunities in topics apart from flavour → a general purpose detector in the forward region

Upgrade I detector challenges

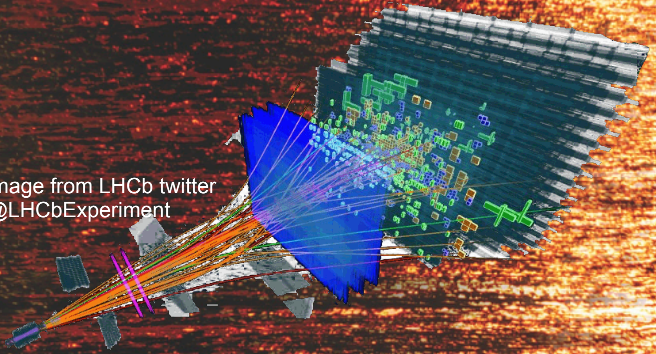


image from LHCb twitter @LHCbExperiment

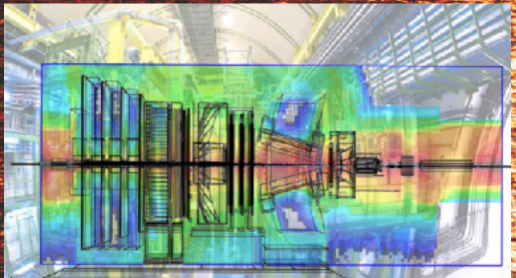


image courtesy
Matthias Karacson
indico 695271

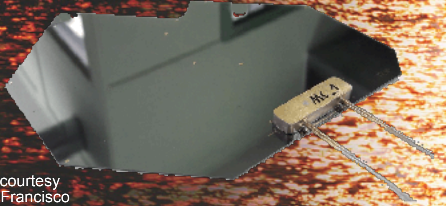


Photo courtesy
Oscar Francisco
Wiktor Byczynski

Maintain Physics Performance in very high occupancy and pile up conditions

- combinatorial complexity and fake tracks
- Pile-up energy
- mitigated by **granularity, high readout speed** and **trigger** innovations (**timing** will be for Upgrade II)

Operate with detector elements exposed to very high radiation doses

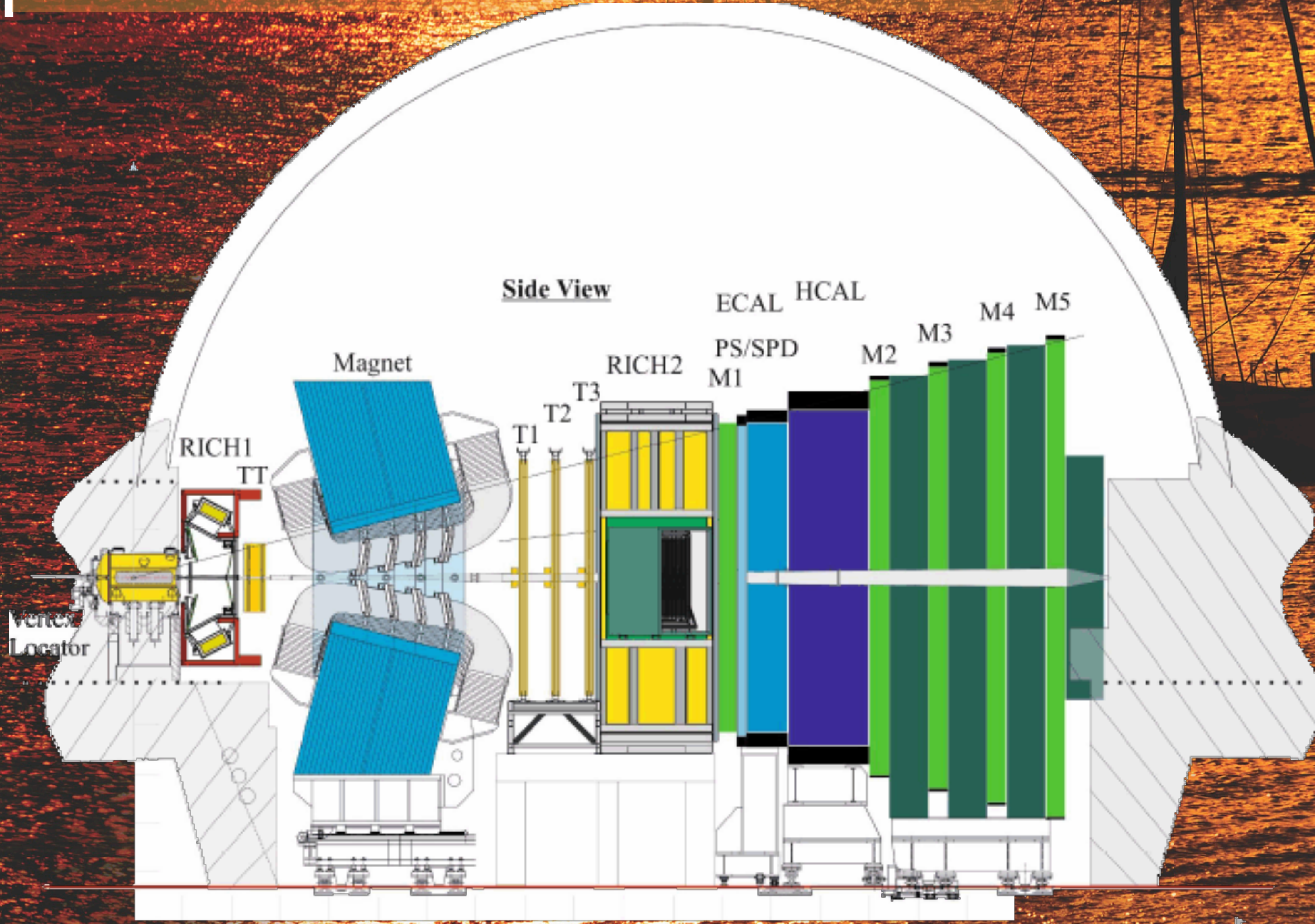
- **Radiation hardness** needed for all subdetectors

Control Systematics to match statistics

- **low material budget** hence creative solutions needed at mechanics level; support structures, cooling, power delivery, and **thin detectors** for innermost regions

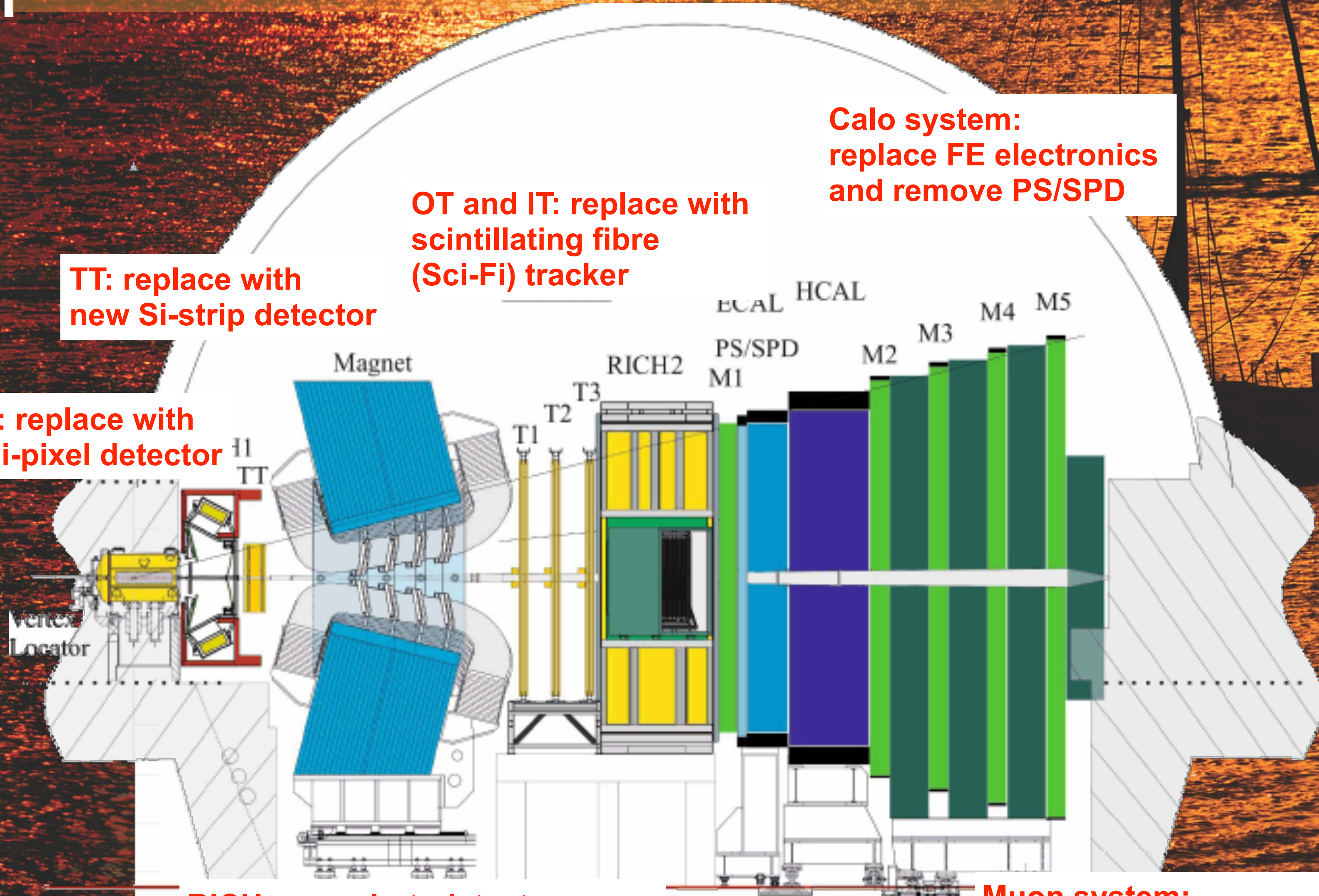
- **Cope with tremendous DAQ and data processing challenges**

Current Detector



Required Modifications

Full s/w trigger → Replace read-out boards and DAQ



Calo system: replace FE electronics and remove PS/SPD

OT and IT: replace with scintillating fibre (Sci-Fi) tracker

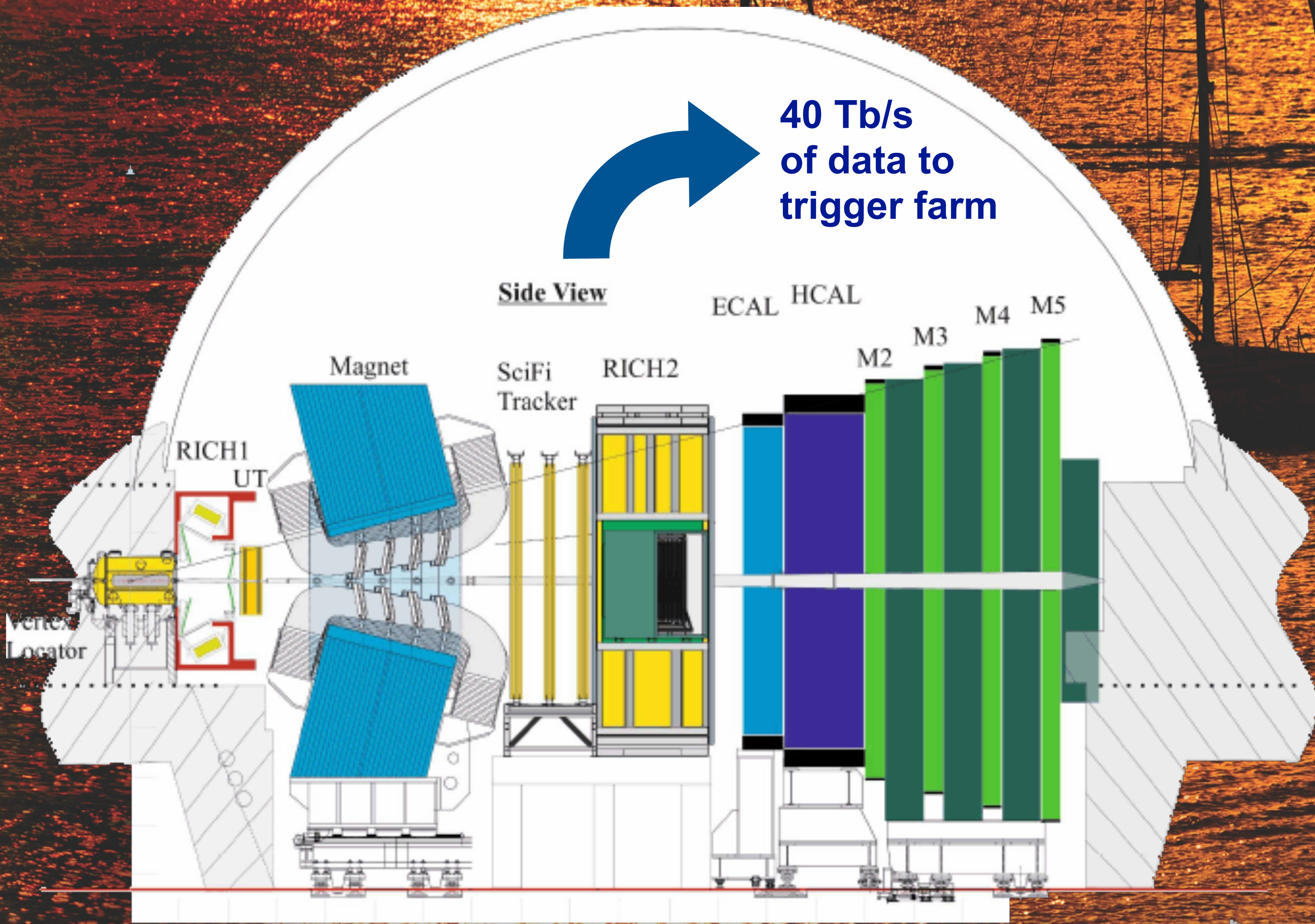
TT: replace with new Si-strip detector

VELO: replace with new Si-pixel detector

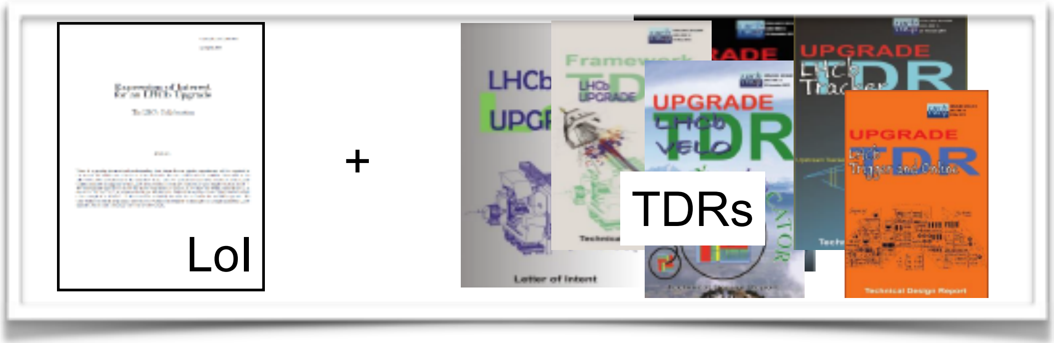
RICH: new photodetectors and FE electronics, and modify RICH1 optics and mechanics

Muon system: replace FE electronics and remove M1

Upgraded Detector



Timeline



LHCb currently in last year of operation
LHCb Upgrade I is under construction, for installation from 2019

We are here

2017	2019	2021	2023	2025	2027	2029	2031	2033	2035

Run 2 — $L = 4 \times 10^{32}$, $L_{int} \sim 8\ fb^{-1}$

LS2

Run 3 — Lumi 2×10^{33}

LS3

Run 4 — Lumi 2×10^{33}, $L_{int} \sim 50\ fb^{-1}$

LS4

Run 5 — Lumi 2×10^{34}

LS5

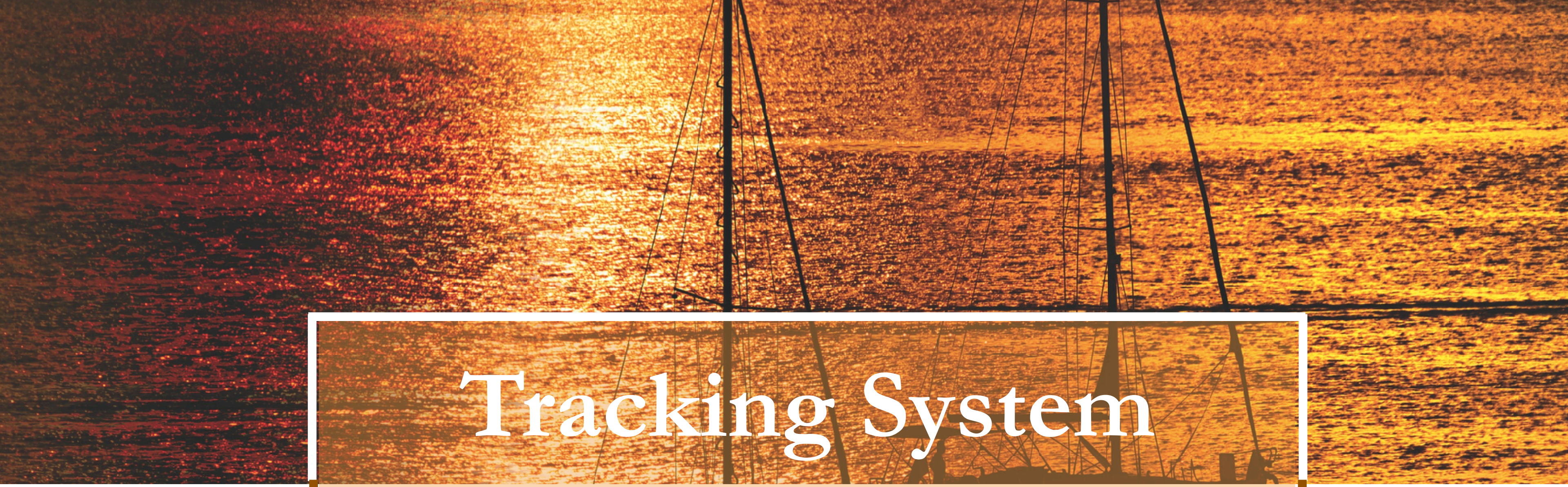
Run 6 — $L_{int} \sim 300\ fb^{-1}$

LHCb Upgrade I
40 Mhz Readout
New detectors/electronics

Consolidation &
Maintenance

LHCb Upgrade II

See talk from Nicola Neri



Tracking System

- **Vertex Loca**tor Si strips
  → new hybrid **pixel detector**
- TT Si strips
  → new **Si strip detector**
- Inner (Si) and Outer (straws) Tracker
  → **Scintillating Fibre Tracker**

Sci-Fi

New tracking system:

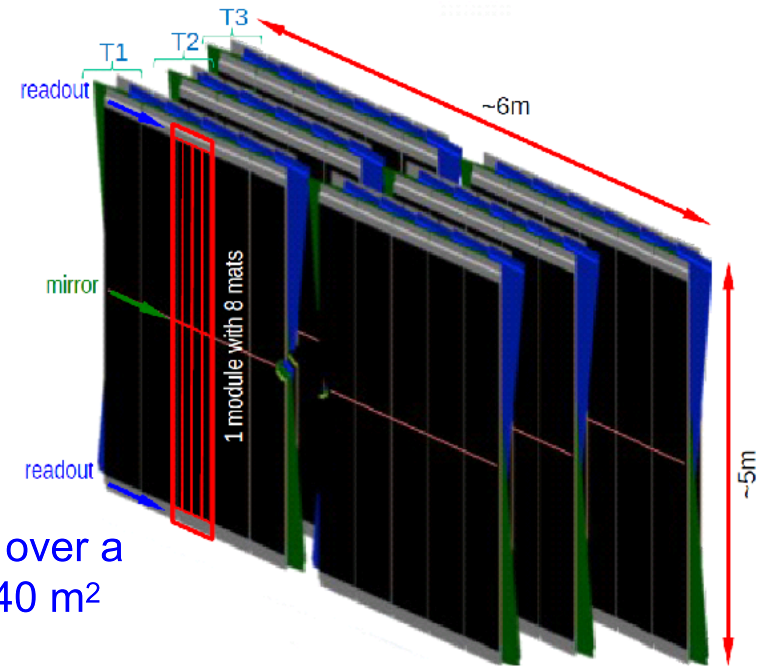
- **Vertex detector** Si strips → pixels
- TT Si strips → new **Si strip detector**
- Inner (Si) and Outer (straws) Tracker
  → Novel **Scintillating Fibre Tracker**

fast, high efficiency (~99%)
high granularity (250μm),
high spatial resolution (<100μm),
light (<1% X_0 /layer), up to 35 kGy

128 modules (0.5 x 5 m^2) arranged in 3 stations × 4 layers (XUVX)

11,000 km of fibres,
524k channels

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



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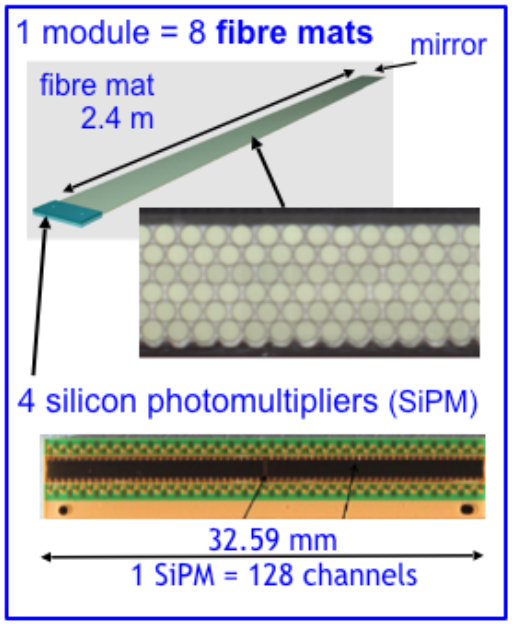

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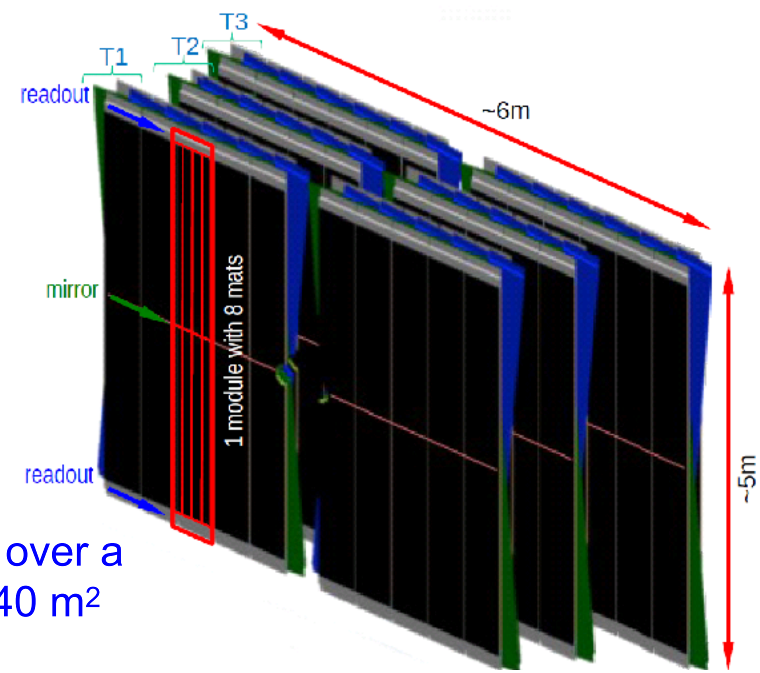

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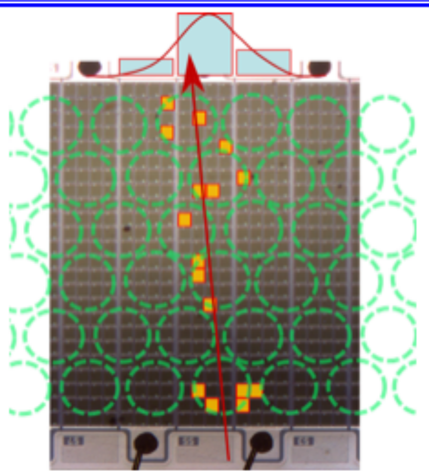
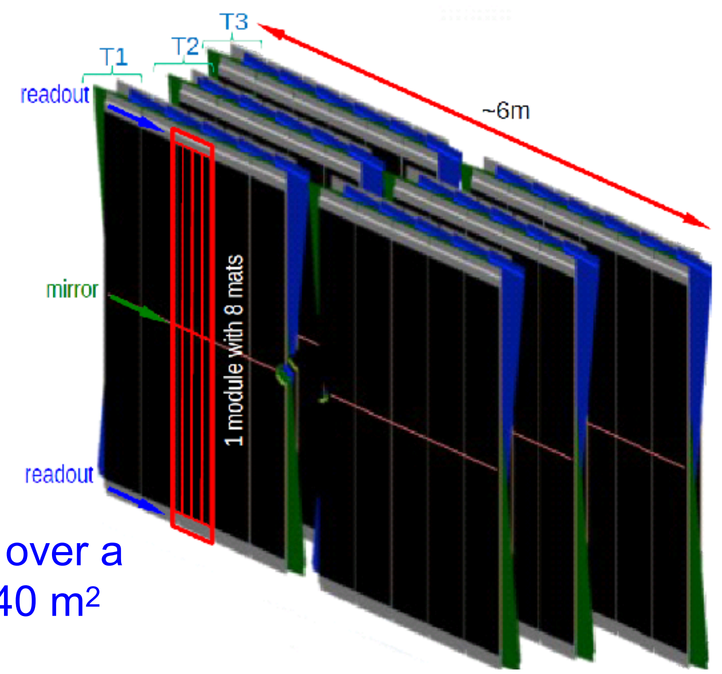


Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)

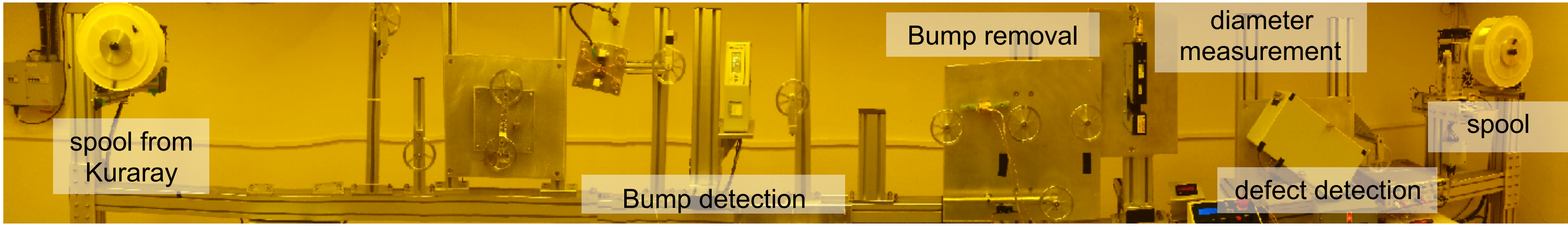
128 modules (0.5 x 5 m²)
arranged in 3 stations × 4 layers
(XUVX)

11,000 km of fibres,
524k channels

Goal: <100 μm resolution over a total active surface of ~ 340 m²

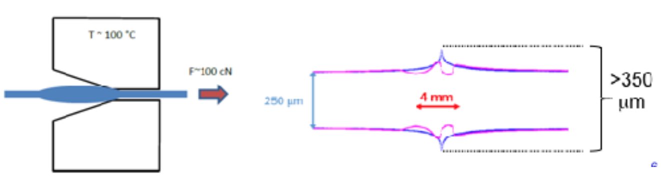


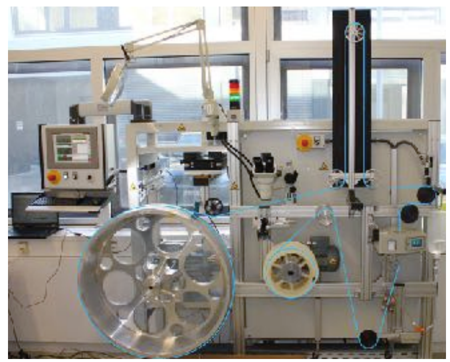
Sci-Fi: Modules



All fibre spools scanned for mechanical defects and irregularities (so far ~6000 km scanned).

Any detected bumps >350 μm (typ. ~8 per 12500 m) are removed by a "hot drawing" tool. Applied routinely.





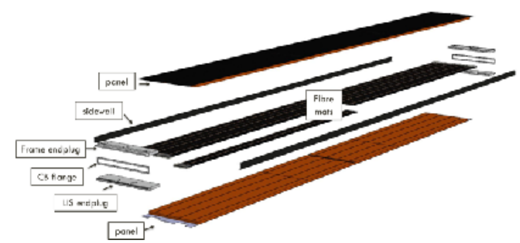
Custom winding machine using a threaded wheel
Mat production at 4 sites (1 mat/6 hours)
>83% of mats already produced

8 fibre mats assembled into a module

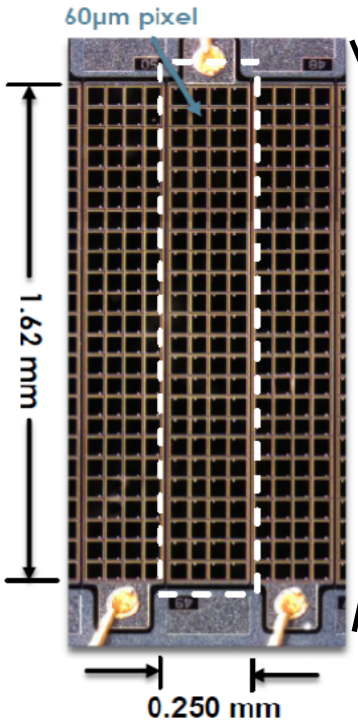
Material budget: 1.1 % X_0 / module

Alignment of mats w/r to straight line better than 50 μm over length of 5 m - **alignment pins** in precision template

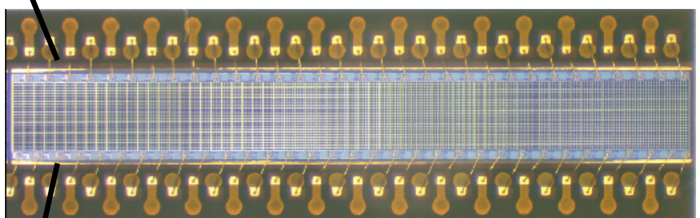
module production > 50% complete



Sci-Fi: Silicon Photomultiplier

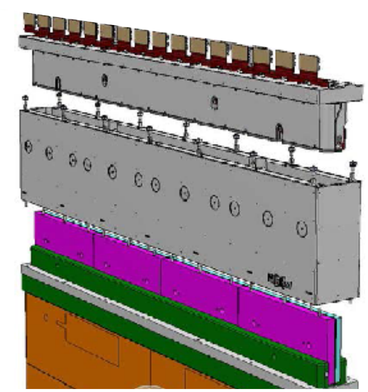


1 die = 64 channels



SiPM = 2 dies = 32 mm

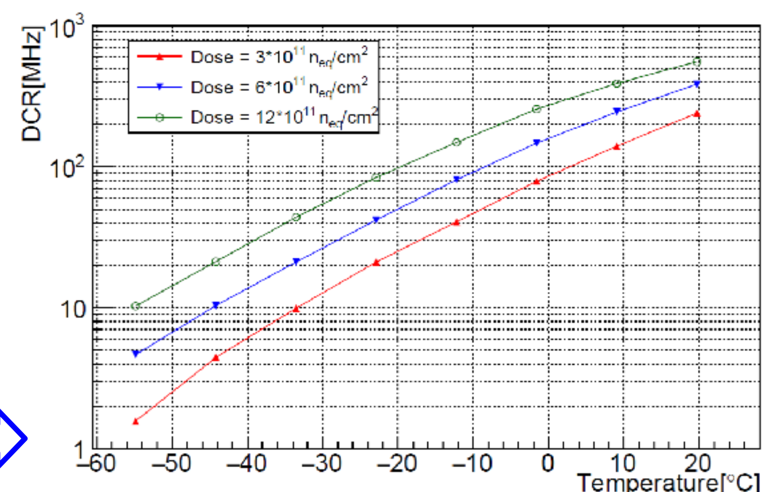
3d printed nylon cold box housing to maintain SiPMs at -40°C



Performance:

- peak PDE = 48% (at 3.5 V)
- direct cross-talk = 3 %,
- delayed cross-talk = 2.5%
- afterpulses < 0.1%.

Dark count rate per channel after neutron irradiation:

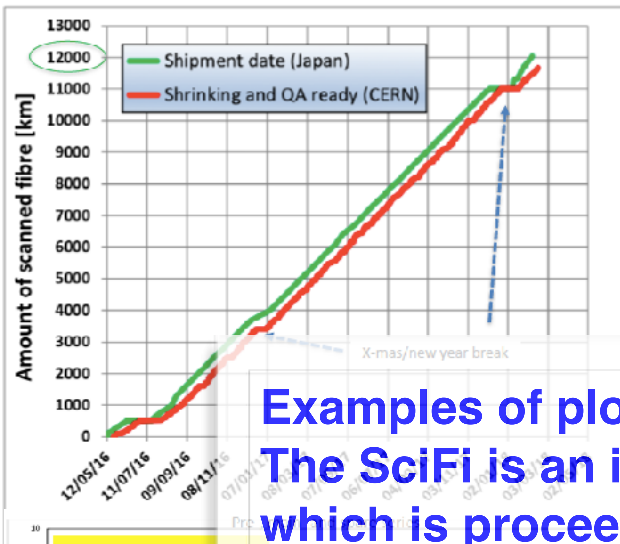


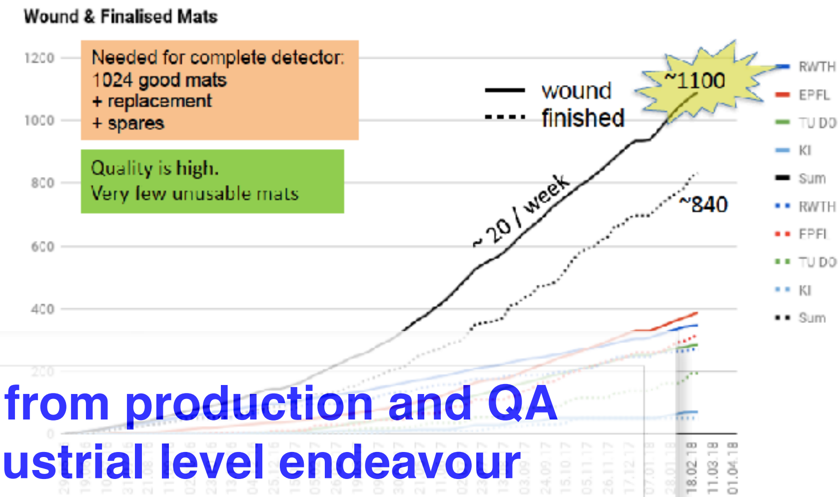
DCR halved every -10 K:

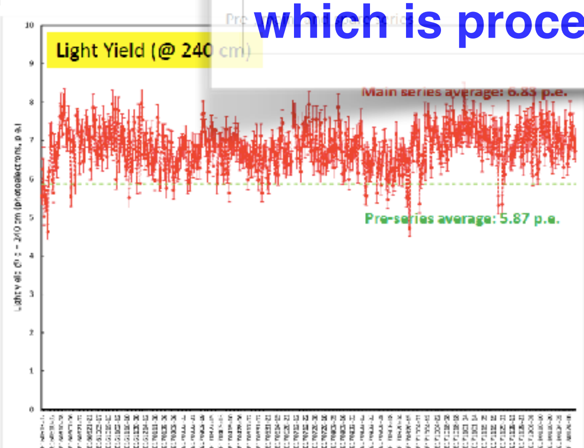
$\Phi = 6 \cdot 10^{11}$ $n_{eq}/cm^2 \rightarrow$ 14 MHz at -40C

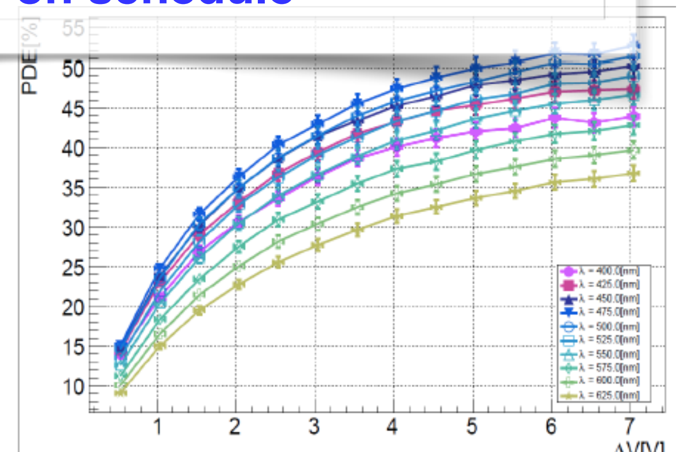
Readout: custom PACIFIC chip

SciFi - Production









Examples of plots from production and QA
The SciFi is an industrial level endeavour which is proceeding on schedule

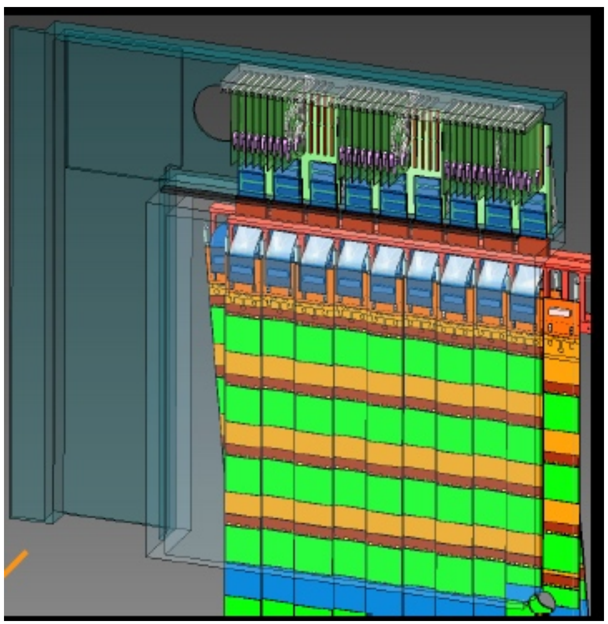
UT

- ○ **Vertex LOcat**or **Si strips → pixels**
- ○ TT Si strips → new **Si strip detector**
- ○ Inner (Si) and Outer (straws) Tracker
  → Novel Scintillating Fibre Tracker

4 planes x-u-v-x of Si microstrip detectors: ~1000 sensors, 4 designs

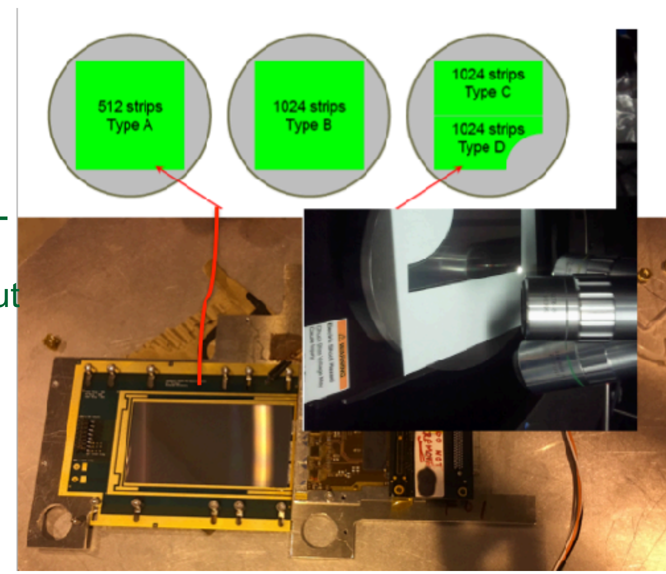
Hybrid sensor modules mounted on both sides to achieve full coverage

Low mass flex circuits provide electrical connections between dedicated front end ASICs (SALT) hybrid/sensor modules and near detector electronics

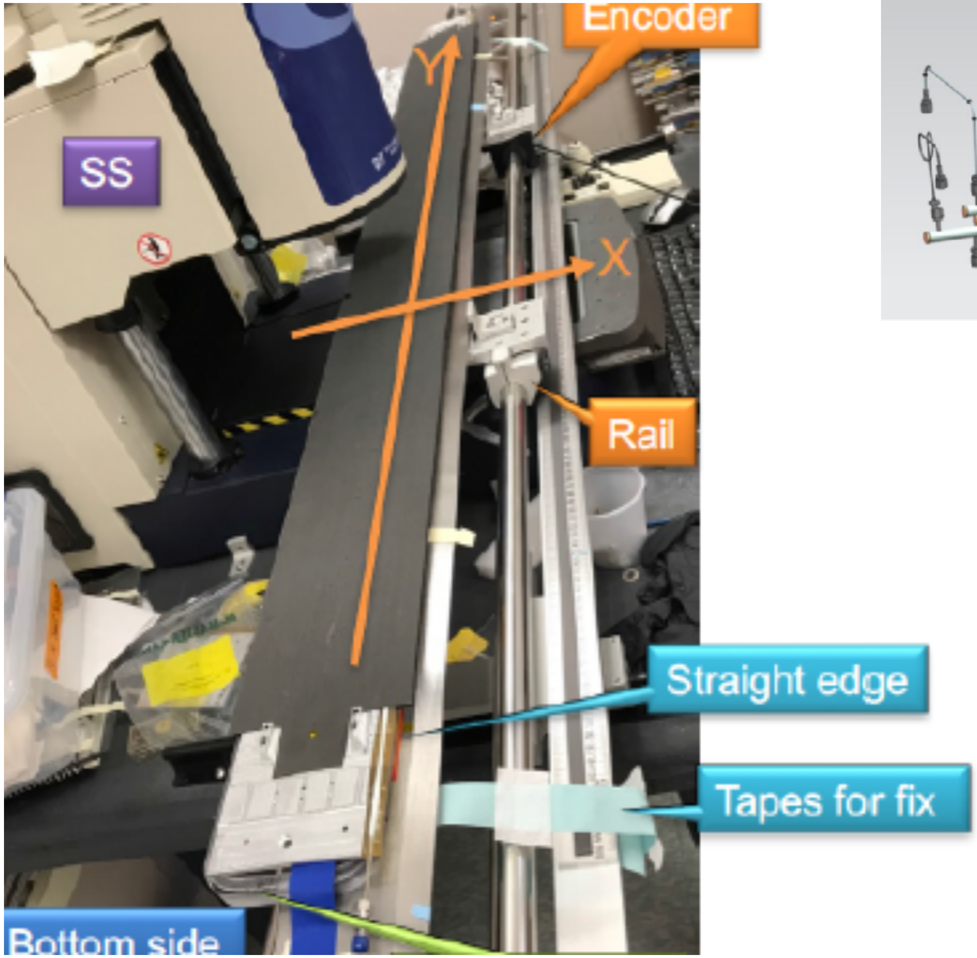


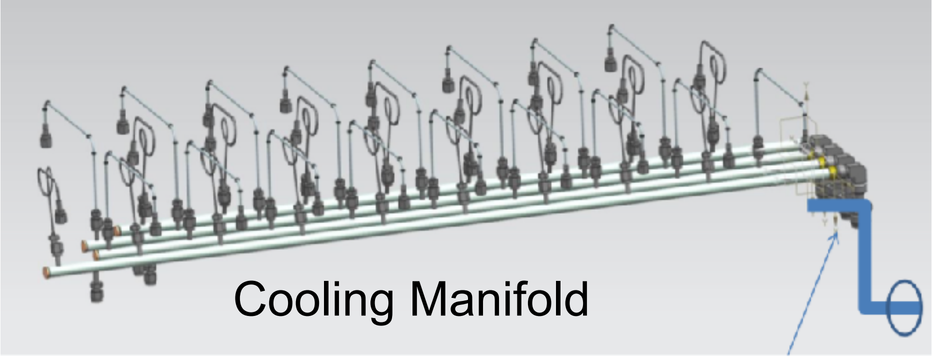
Key technical aspects:

- n-in-p used for most irradiated internal region, p-in-n for remaining
- Sensors with circular cut-out to maximise acceptance near beam pipe
- Built-in pitch adapters
- Top-side biasing
- Evaporative CO_2 cooling



UT Production

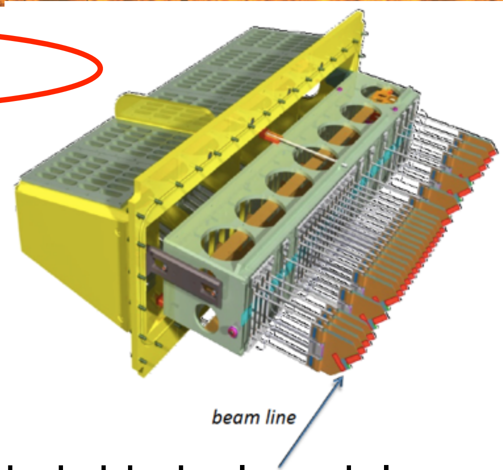




Stave Production in full swing

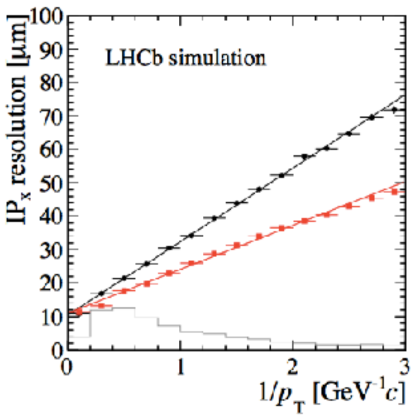
VELO

- **Vertex LOcator Si strips → pixels**
- TT Si strips → new **Si strip detector**
- Inner (Si) and Outer (straws) Tracker
- → Novel Scintillating Fibre Tracker

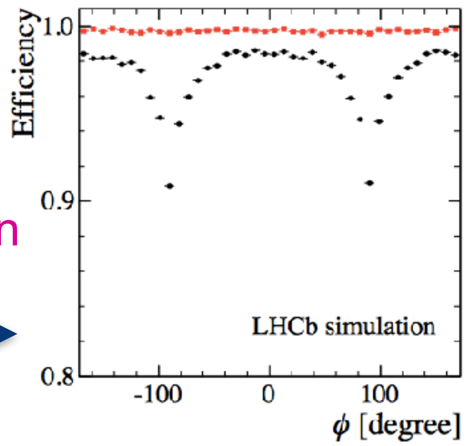


rows of silicon microstrip modules

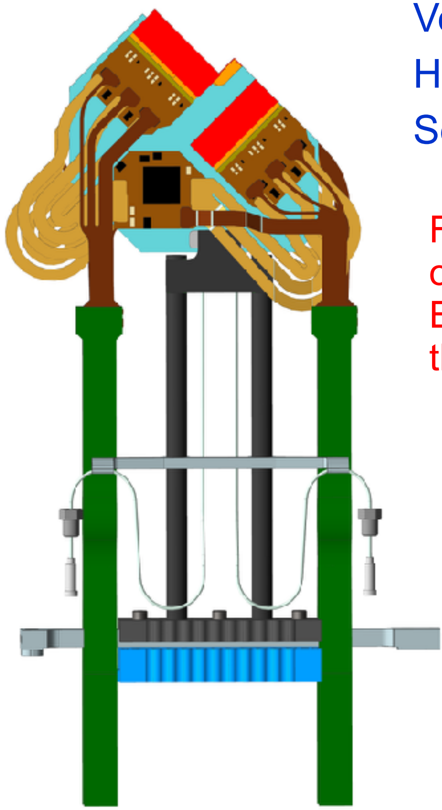
rows of silicon hybrid pixel modules



Pixel design with uchannel cooling superior to strips for impact parameter resolution and efficiency



VELO Sensors and ASICs



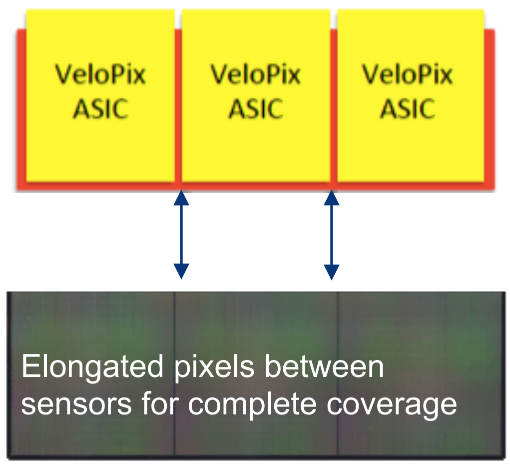
Challenges:

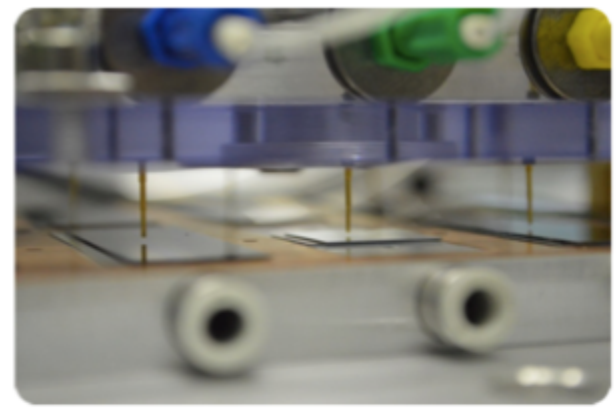
Very high (8×10^{15} n_{eq}/cm^2 for 50 fb^{-1}) & non-uniform irradiation ($\sim r^{-2.1}$)

Huge data bandwidth: up to 20 Gbit/s for central ASICs and ~ 3 Tbit/s in total

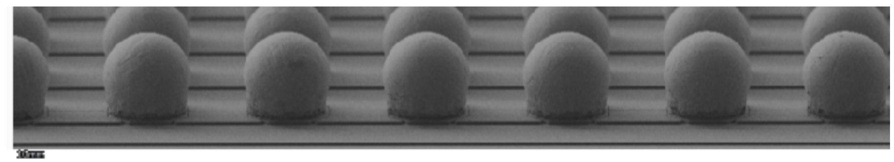
Sensor temperature must be maintained < -20°C with minimal cooling

Four sensors per module (sensors on other side shown with dotted lines)
Each sensor (43 x 15 mm) bonded to three VeloPix ASICs





Sensors are bump bonded and automatically probed before vacuum testing to 1000V with spring loaded needle contacts to ASIC backplane



SEM image of 55 µm pitch SgAn bumps courtesy Sami Vähänen, ADVACAM Oy

VELO Cooling

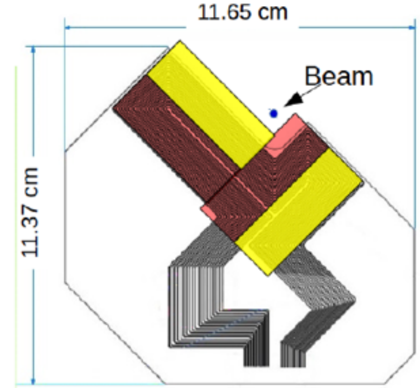
Due to the harsh radiation environment an efficient cooling solution is required to maintain the sensors at < -20°C

This is provided by the novel technique of evaporative CO_2 circulating in 120 μm x 200 μm channels within a silicon substrate.

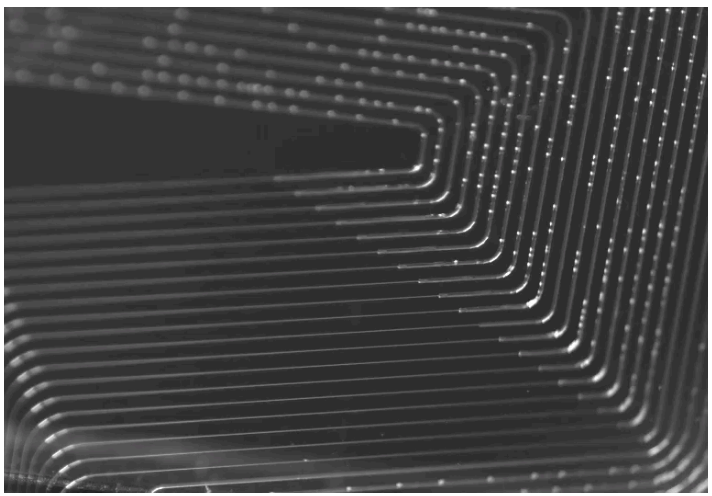
Total thickness: 500 μm

⇨

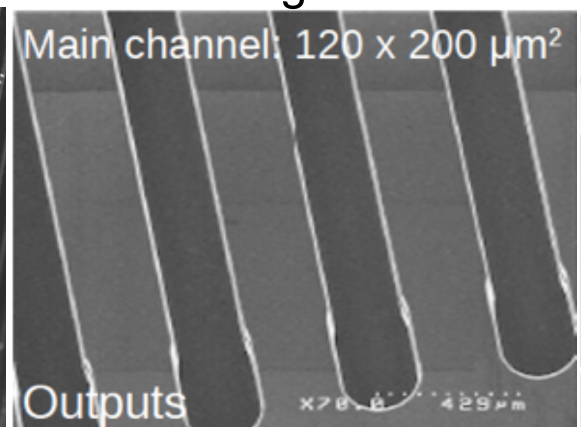
- High thermal efficiency
- CTE match to silicon components
- Minimum and uniform material
- radiation hard



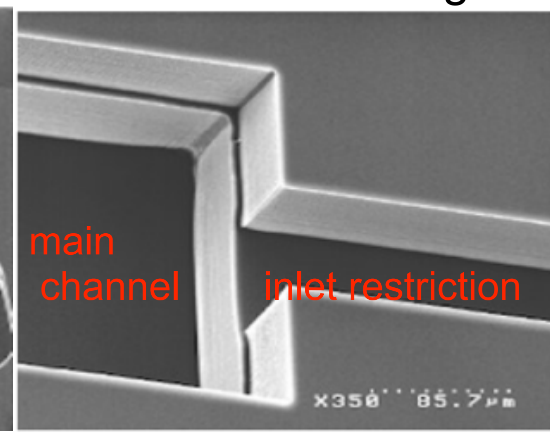
SEM images of etched wafer before bonding



(click for movie)

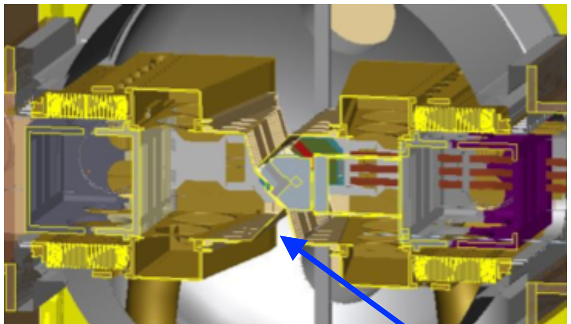


channels output directly to connector



Two step channel etching

VELO RF Foil

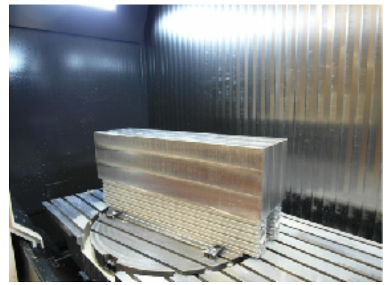


The VELO is separated from the primary vacuum by the 1.1 m long thin walled "RF foil" which also shields the detector and guides the beam wakefields

At just 3.5 mm clearance from the beam and 900 μm clearance from the sensors, production represents a huge technical achievement

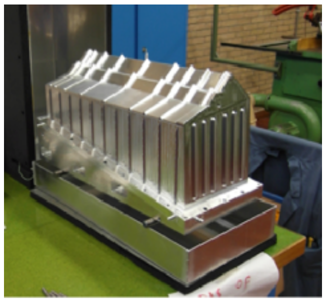
The final foil withstands 10 mbar pressure variations, is leak tight, and has a final thickness of 250 μm, with an option to go to 150 μm maintained

RF foil: some production steps

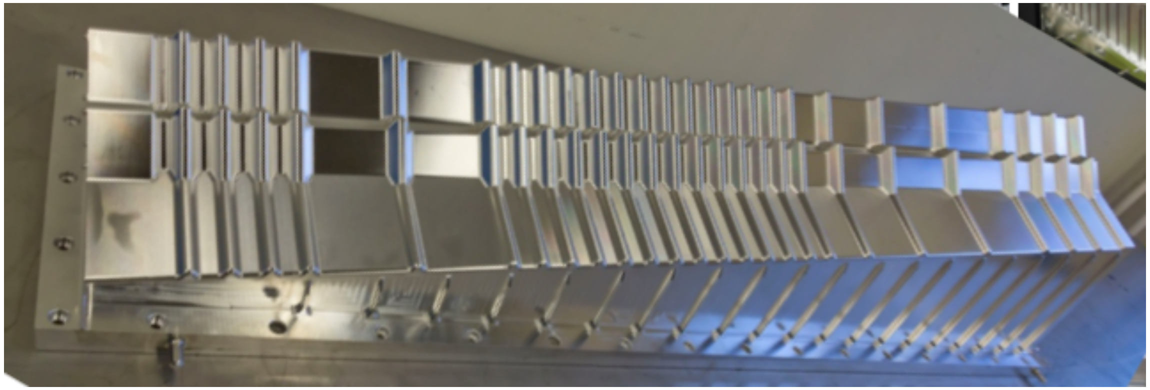


Initial solid forged Al alloy block

>98% of material removed



Internal mould support during machining steps



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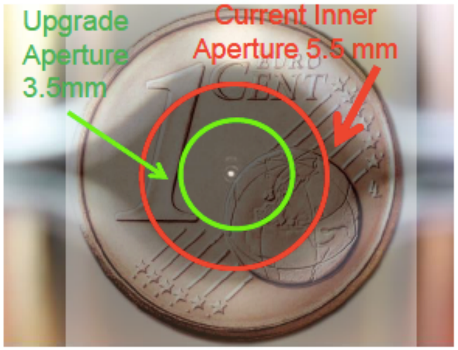

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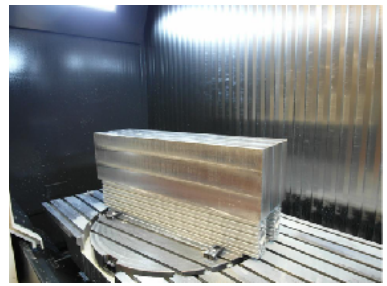

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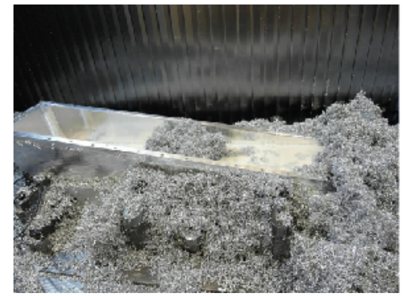

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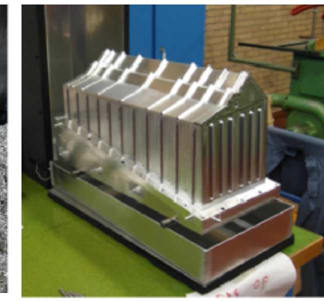

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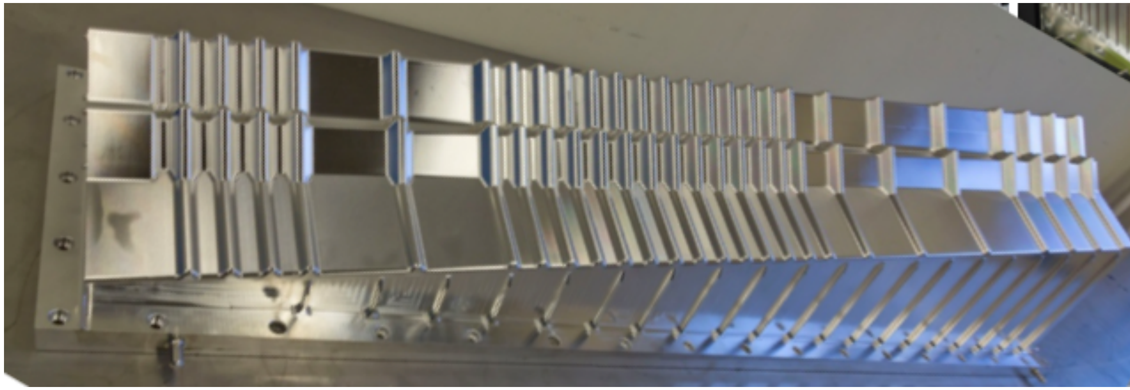

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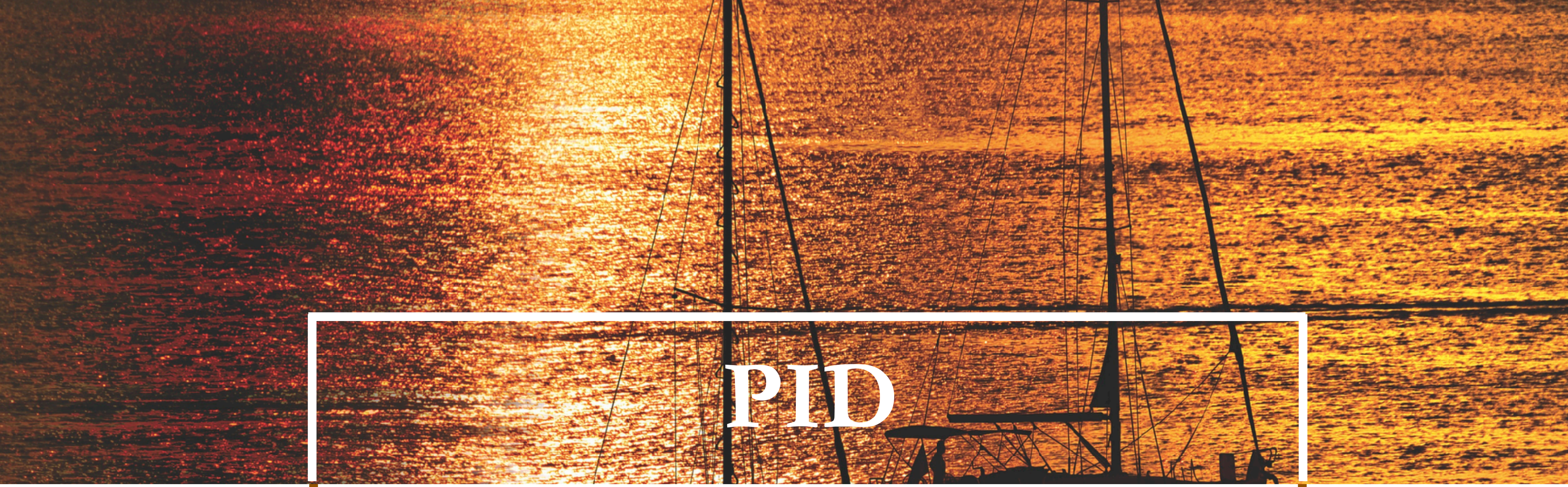
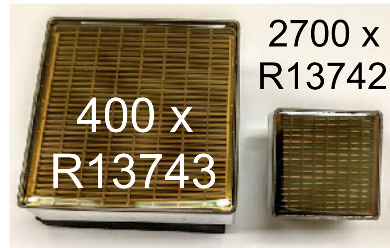


PID

- RICH - photodetector + mechanics upgrade
- CALO - electronics + replacement
- Muons - electronics + inner region PADs

RICH system

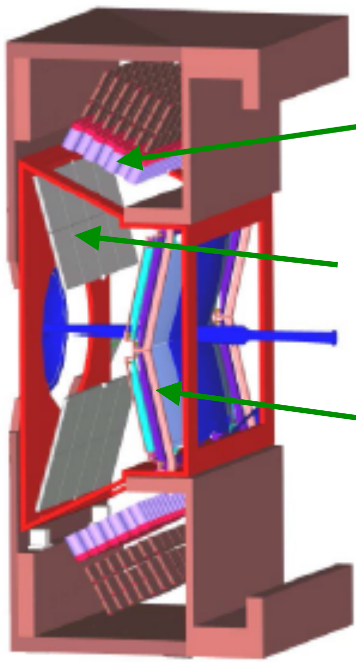
Challenge: Provide optimal PID performance at the increased luminosity with new photodetectors and completely revamped mechanics



Two types of MaPMTs:

pixel size ~ 6x6 and 2.9x2.9 mm
active area > 80%
cross talk < 5%
gain 1x10^{6} with variation less than 1:4
QE peaked at higher wavelength to help for chromatic error

New ASIC CLARO & R/O chain

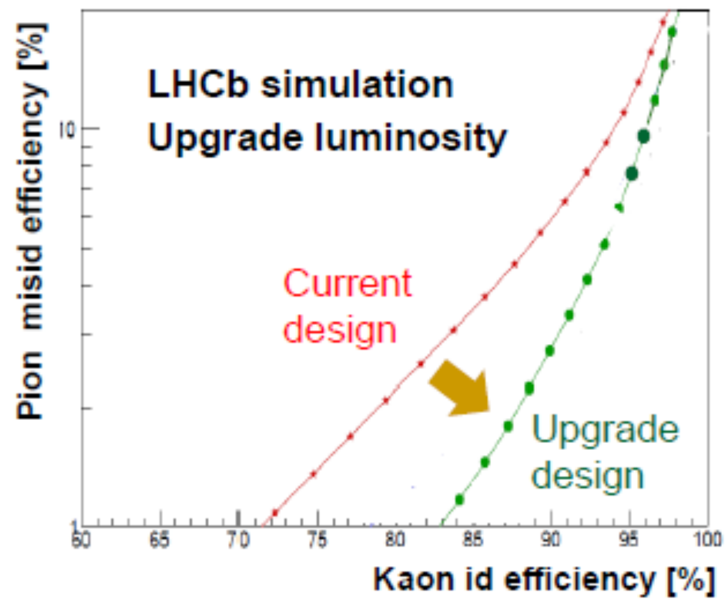


Arrays of MaPMTs equipped with 40 MHz FE electronics + r/o boards

New glass flat mirrors and mechanics, with longer radiator length and photon yield

Carbon fibre spherical mirrors with ROC increased from 2710 to 3650 mm to reduce occupancy

RICH 1 Mechanics



CALO and MUON

Present Calorimeter Detectors will be kept

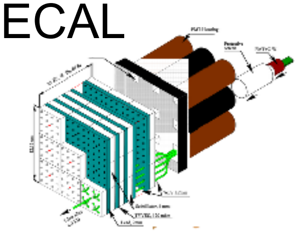
- ECAL (Shashlik 25 X_0 Pb + scintillator)
- HCAL (TileCal Fe + scintillator)

→ PreShower / ScintillatingPadDetector (PS/SPD) will be removed and functionality taken over in HLT

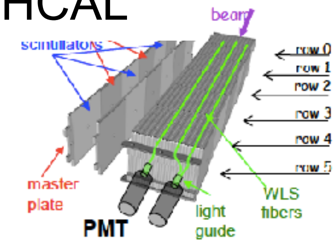
PMT gain reduced by a factor 5 to limit PMT degradation
Frontend electronics rebuilt to compensate the gain and to match the 40 MHz readout

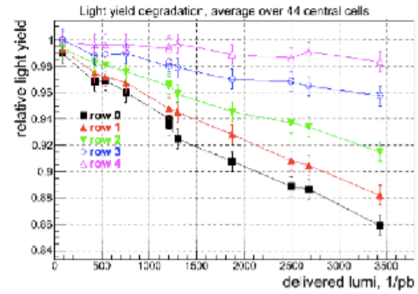
ECAL Inner modules to be replaced in Run 3

ECAL



HCAL

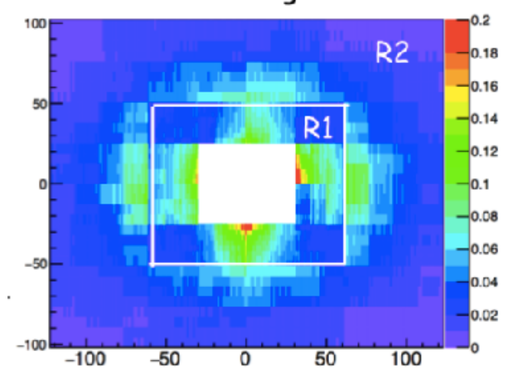




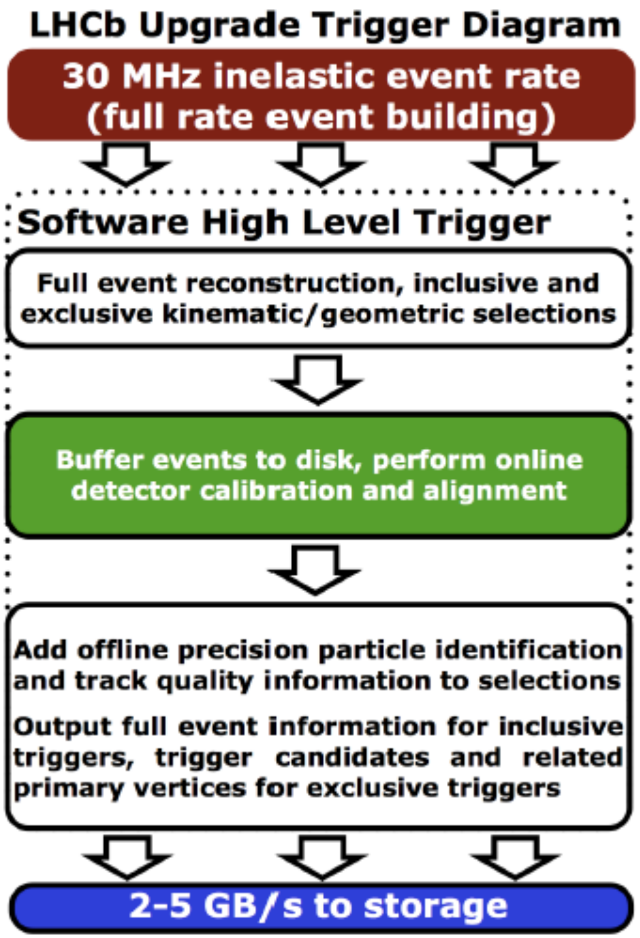
Present Muon Detectors will be kept

- 4 layers of MWPC; first layer of GEMS removed
- Front end electronics to be rebuilt and granularity improved
- Dead-time induced local efficiency losses in the innermost region will be eliminated by installing 36 new PAD chambers in the innermost region

M2 inner regions

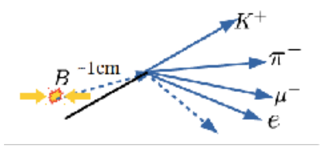


Trigger and DAQ



Data from detector zero suppressed and asynchronous
Upgrade software trigger has to process events at 30 MHz real time from the very first stage

Heavy flavour signatures available will include



- High transverse momentum
- High impact parameters
- Muon ID

Buffer to store events for alignment and calibration and continuously use computing farm

Precision particle identification, reduce event size, and write 2/25 Gb/s of beauty/charm to disk

Multiple innovations still being incorporated to be able to deal with data flow

For more details see R.Quagliani, *Connecting the Dots 2018*

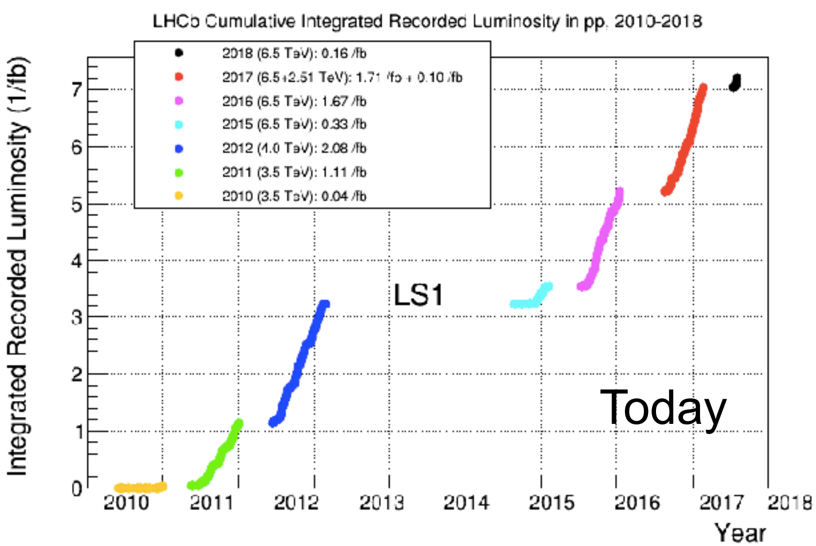
Upgrade I Prospects

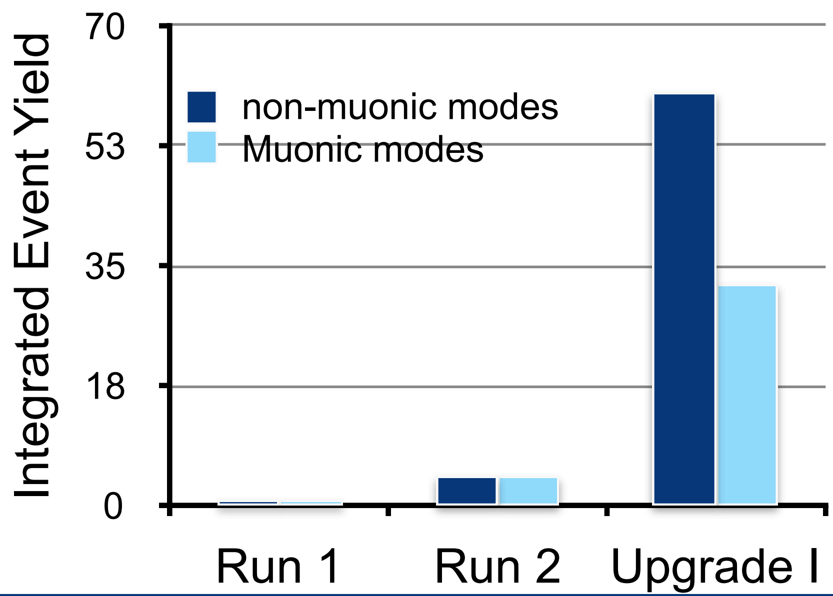
Many results presented at this conference come from Run I (~3 fb^{-1})

The bulk of the Run II statistics are still to come (~6 fb^{-1} at raised energy)

Upgrade I will push $\mathcal{L}_{int}$ to 50 fb-1, and this will be magnified by the full software trigger, resulting in a big step up in yields

All of this without considering enhancements in detector/analysis performance





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Prediction as of 2013

Type	Observable	Current precision	LHCb 2018 *	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

* Outdated estimations, already doing better (γ at 5º already)

B→μμ

LHCb first single experiment observation of BF(B_s→μμ)

First measurement of B_s→μμ effective lifetime

Updated (best) limits on B→eμ, search for B→ττ

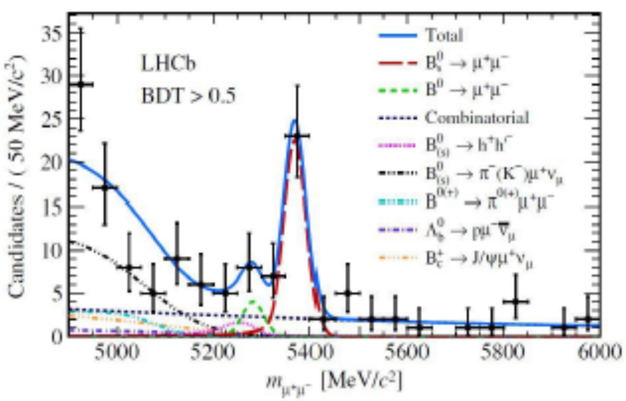
see talk from Matteo Rama

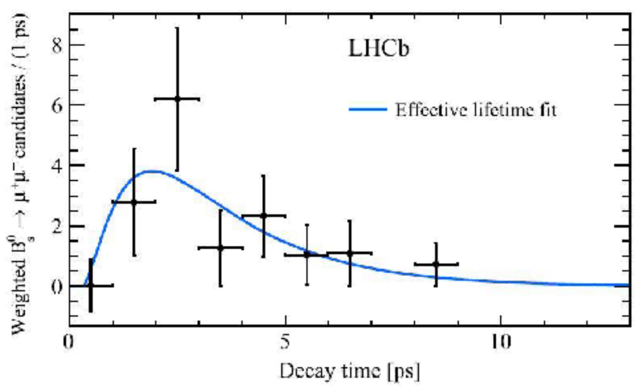
Analysis uses 4.4 fb^{-1} of Run I and Run II data

$BF(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$

$BF(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95% CL

$\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05$ ps





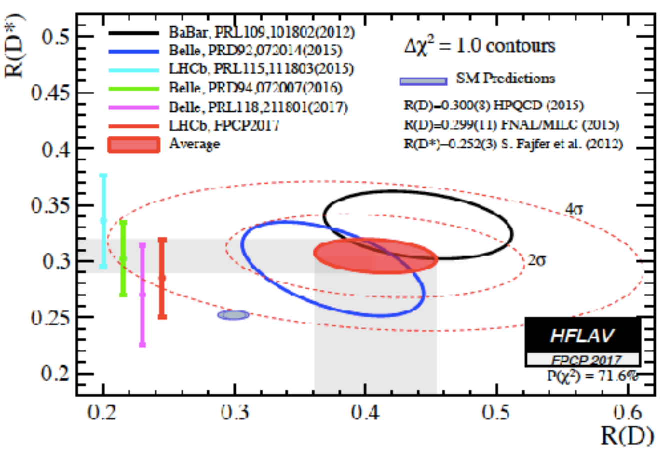
Expect additional 4-5 fb^{-1} from Run II then up to 50 fb^{-1} at Upgrade I

Projected Upgrade I errors σ(R)~22%, σ($\tau_{(Bs\to\mu\mu)}$)~ 0.08 ps, driven by $\mathcal{L}_{int}$

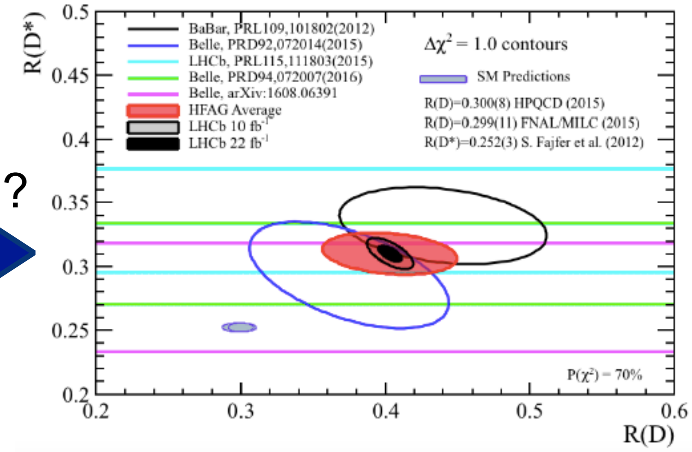
LFU in b→clν

$$R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$$

All experiments see excess of signal w.r.t. SM prediction up to 4σ HFLAV



End Run 3?



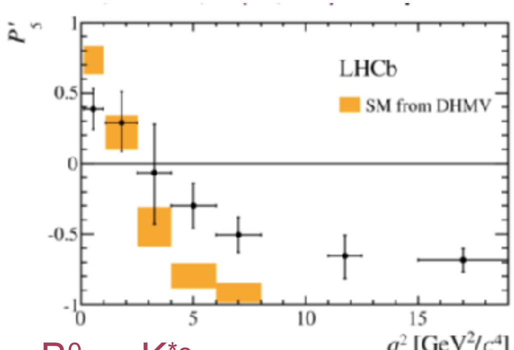
CKM2016, Concezio Bozzi
courtesy Patrick Owen

- B_c meson gives access to R(J/ψ) equivalent ratio, already looked at by LHCb and confirms trend
- Need to improve the precision of R_{D^*} ratios; explore other b hadron systems (R_{Ds}, $R_{\Lambda c}$)
- All modes benefit from upgraded trigger to access τ→πππν
- Angular observables can constrain new models (see talk of Olcyr Sumensari)
- Upgrade I very well suited for all these studies

b→sll

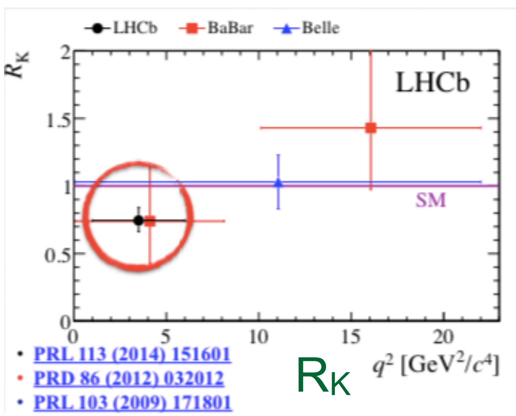
Interesting anomalies are being suggested in b → sll decays

- Angular observables in $B^0 \to K^{*o}$ μμ
- Branching fractions in several b → sll processes
- Lepton-flavour universality ratios in b → sll decays

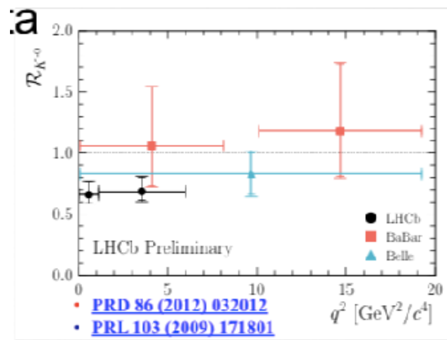


$B^0 \to K^{*o}$ μμ

angular observables



R_K



R_{K^*}

These are all statistically limited and will benefit tremendously at Upgrade

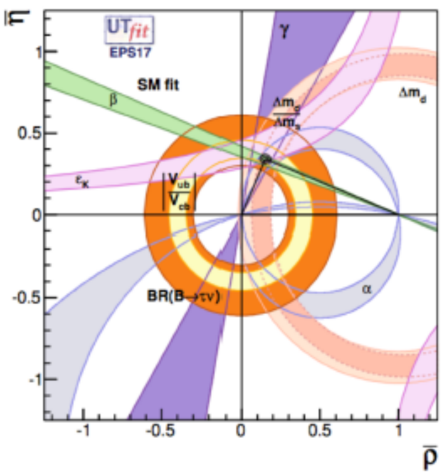
With more statistics full angular analysis will also possible in electron modes

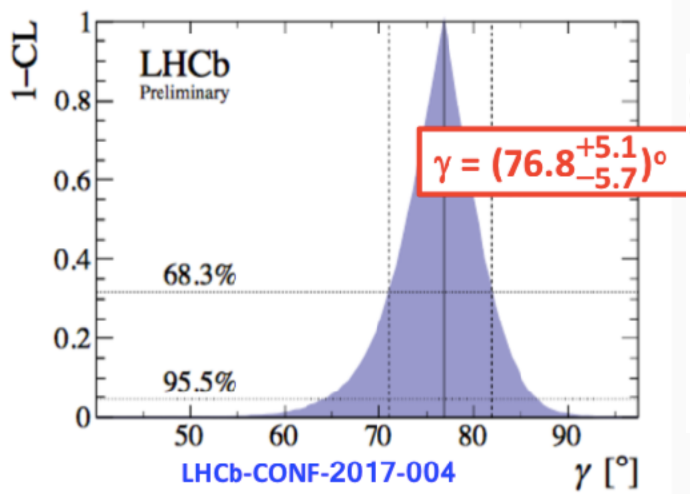
Upgrade statistics open up many additional final states and possibility of b → dll modes

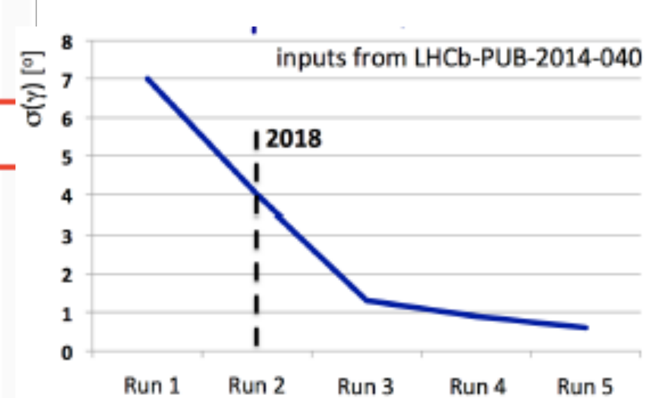
At the Upgrade the software trigger will improve efficiency for e+e- final states

γ

LHCb combination for γ: a plethora of independent measurements exploiting different methods and decays







Analysis depends on hadronic final states and well placed to benefit from improvements in trigger

Upgrade will aim for <1°

see talk from Matt Kenzie

Conclusions I

"The tower that hangs, that hangs, and never will come down..."

Pisan jingle

LHCb Upgrade I is entering the construction and installation phase

The upgraded detector should deliver the same or better quality reconstruction at higher luminosity and efficiency and accumulate up to 50 fb^{-1} of data for Run 1+2+3+4

The upgraded LHCb detector will confront open issues in flavour physics as well as being a general purpose forward physics detector. A consolidation phase between Run 3&4 will allow some detector improvements and possible preparations for Upgrade II

Conclusions II

"The tower that hangs, that hangs, and never will come down..."

Pisan jingle

Will LHCb go from propping up the standard model…

to pushing it down?