LHCb Calorimetry Impact

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On behalf of the LHCb Collaboration

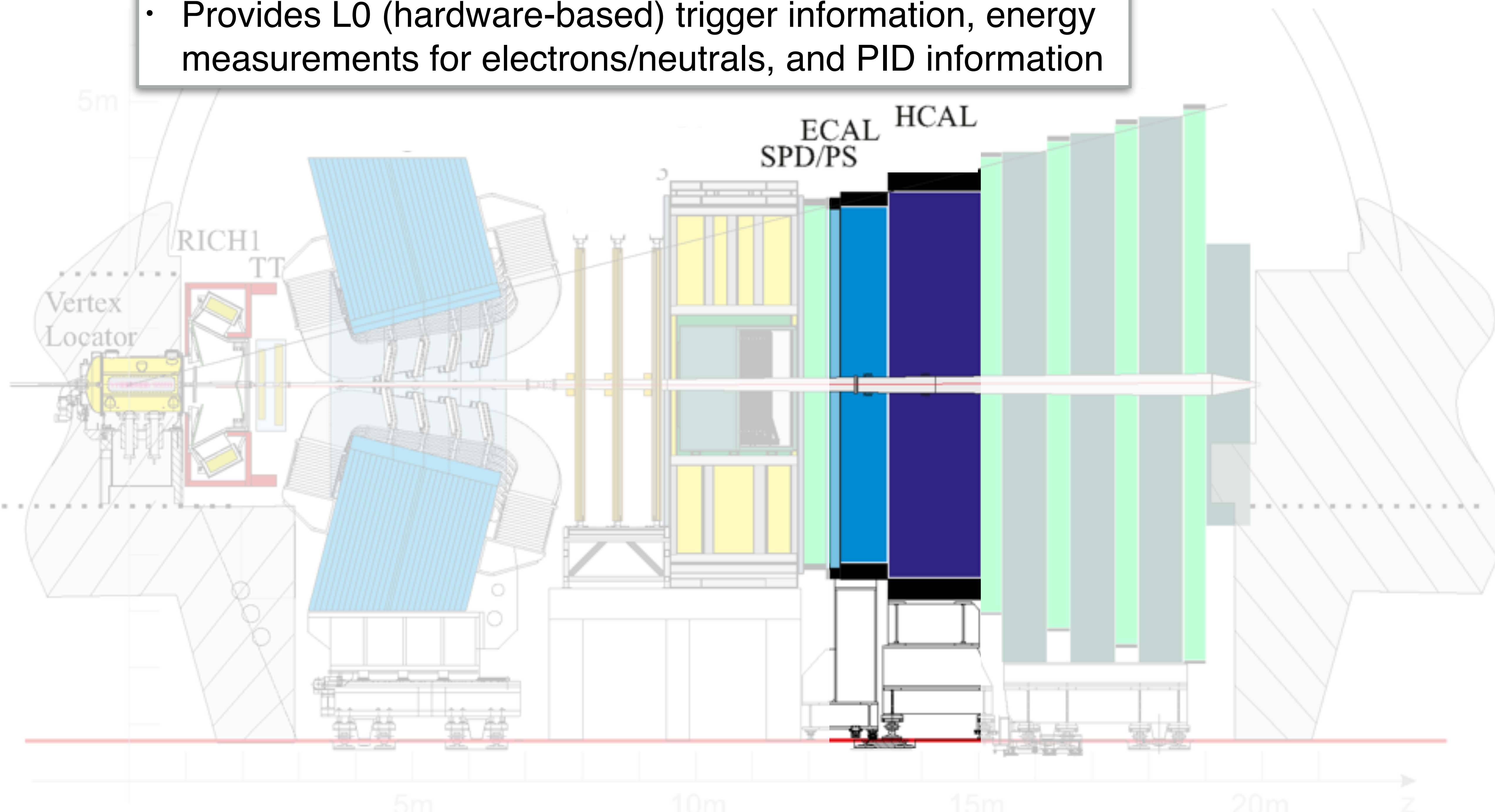
Workshop on the physics of HL-LHC, and perspectives at HE-LHC

November 1, 2017

The LHCb Detector

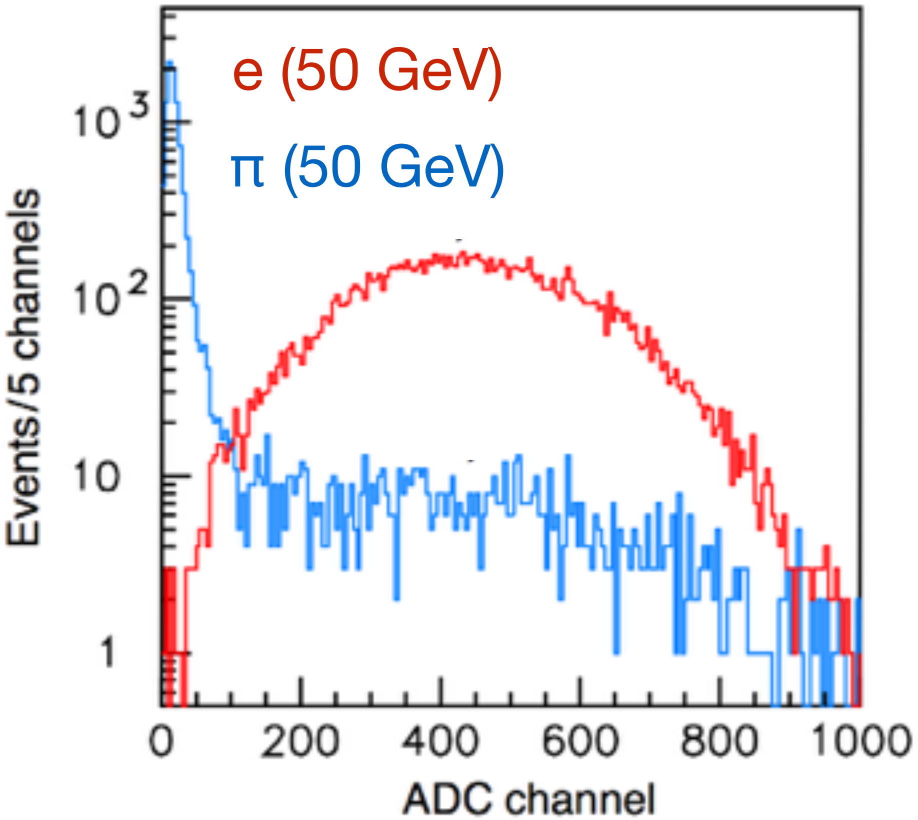
Calorimetry

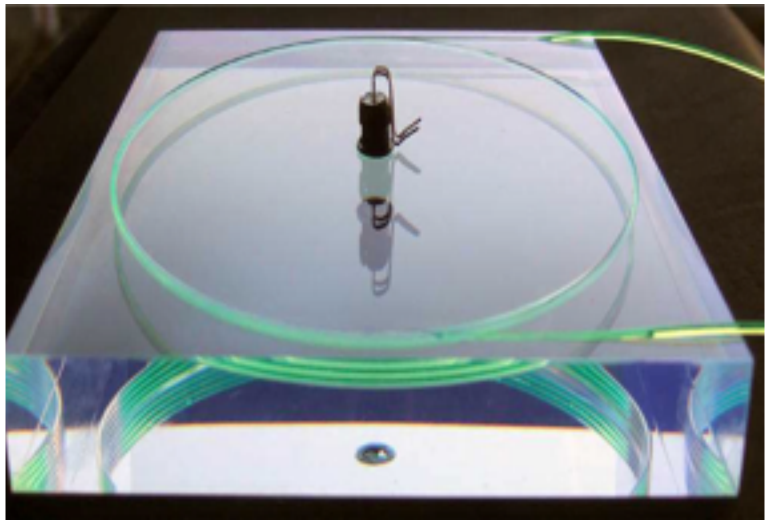
- Located ~12.5 m from the interaction point
- Four sub-detectors: SPD, PS, ECAL, HCAL
- Provides L0 (hardware-based) trigger information, energy measurements for electrons/neutrals, and PID information

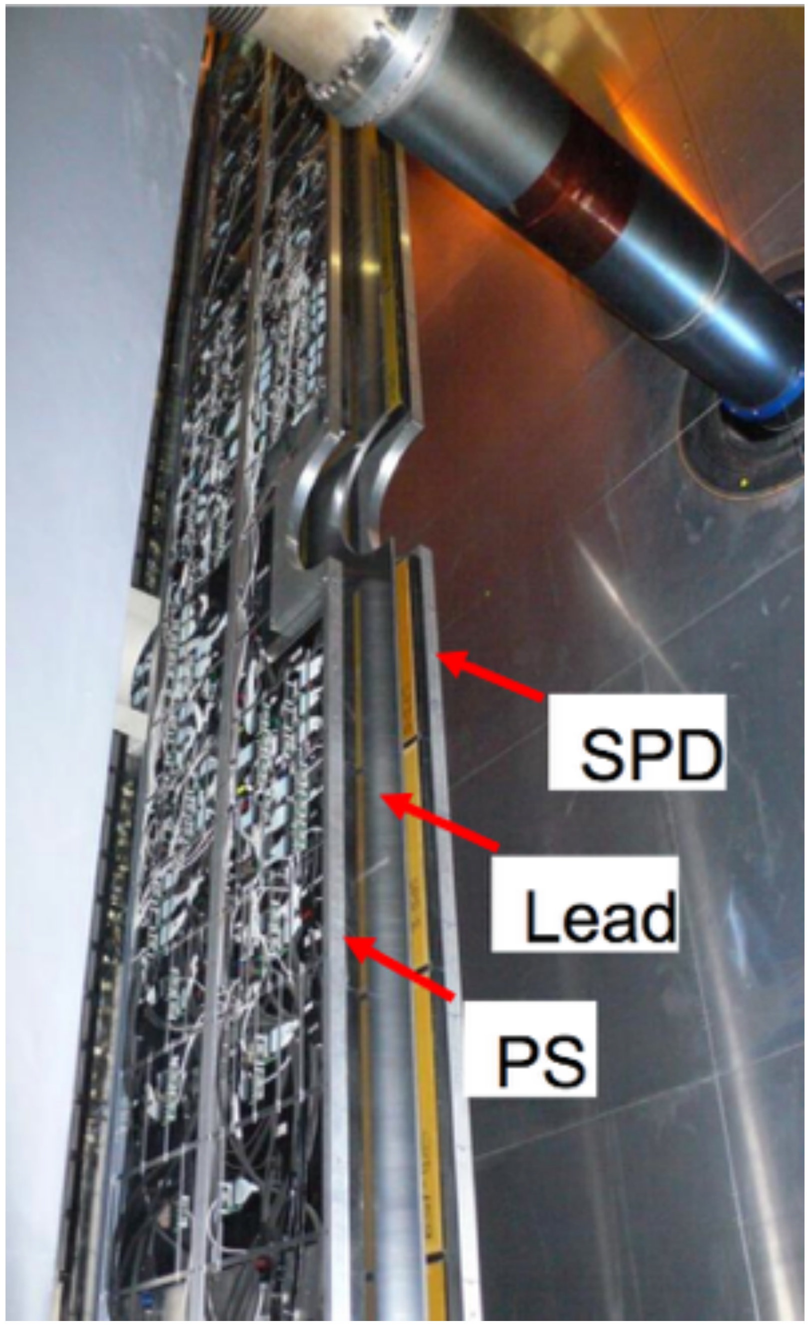


SPD & PS

- 2 scintillating pads (15mm thickness) separated by 14 mm thick (2.5 X_0) lead absorber
- SPD: distinguish between charged and neutral particles
- PS: π^0-γ discrimination (longitudinal segmentation)
- Readout by WLS fibres (3.5 loops, embedded in a groove in the tile) that guide light to multi-anode PMT

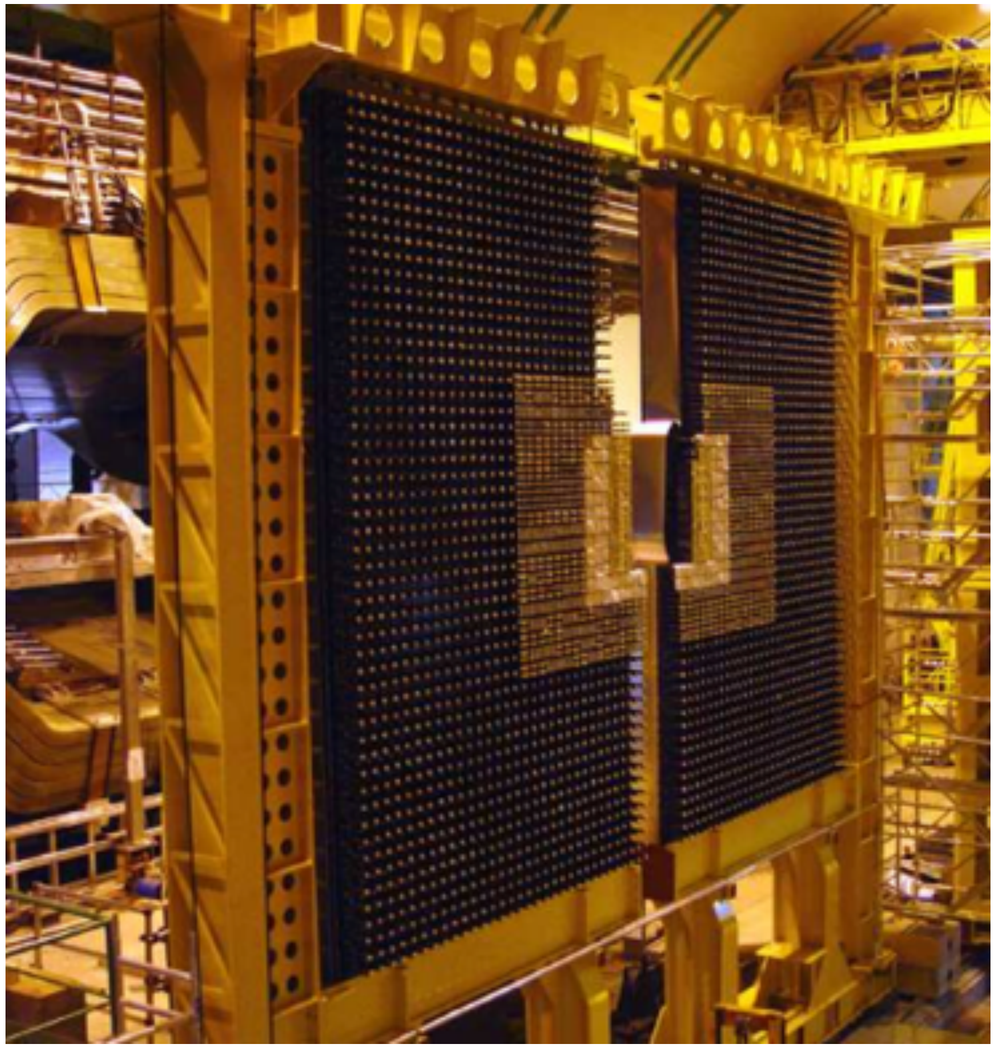


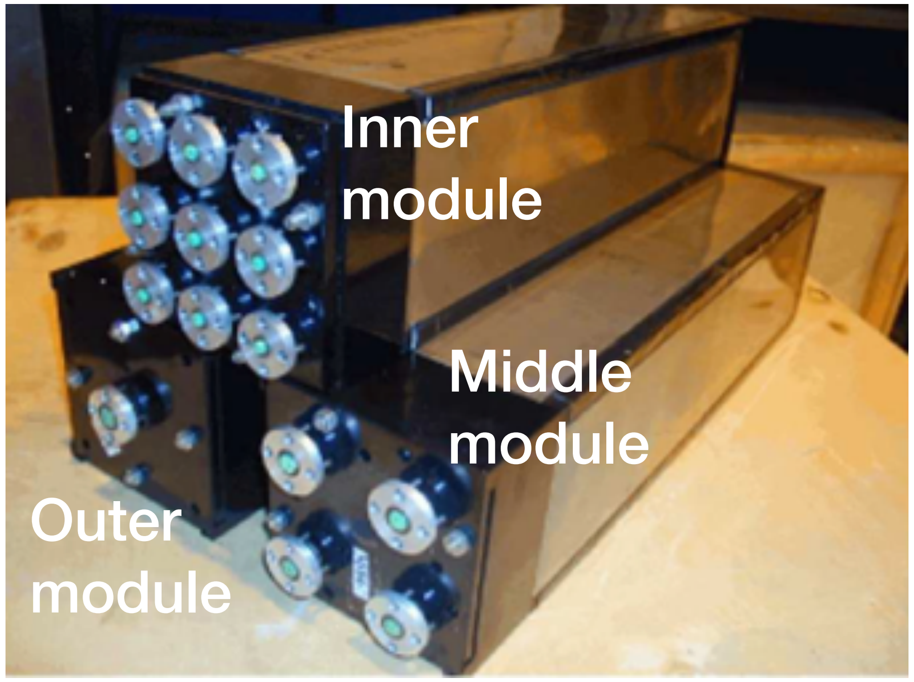


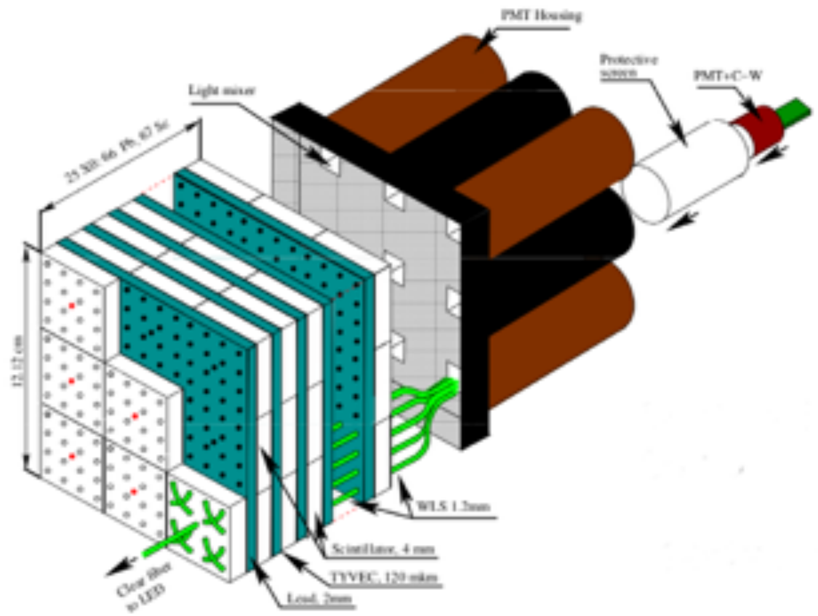


Electromagnetic Calorimeter

- Shashlik calorimeter with alternating lead absorber (2mm), scintillating tiles (4mm)
- Total length of $25X_0$
- Module size ~12 x 12 cm^2 , three different segmentation types
- Readout by PMTs
- Resolution
  - $\sigma_E/E = 10\%/\sqrt{E(GeV)} \oplus 0.9\%$

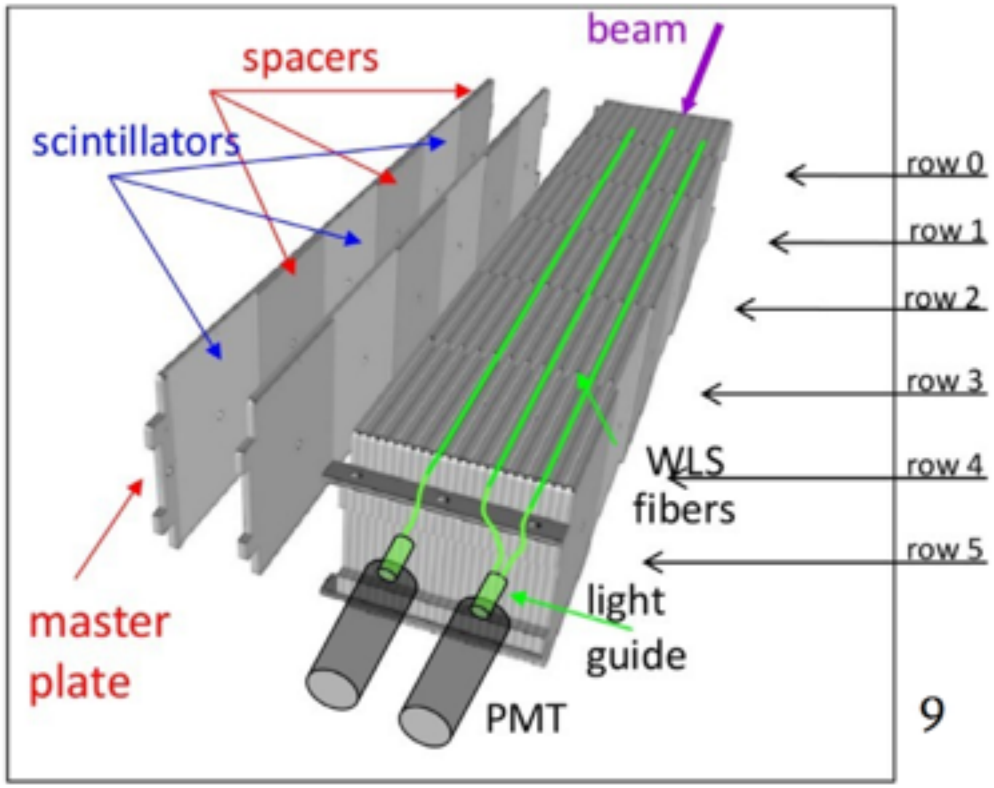






HADRONIC CALORIMETER

- Fe+scintillator Tile calorimeter
- 52 modules, 6 tile rows (~5.6λ)
- Inner modules - 13 x 13 cm^2; outer modules - 26 x 26 cm^2
- Readout system similar to ECAL (fibres + PMTs)
- $\sigma_E/E = (69\pm5)\%/\sqrt{E(GeV)} \oplus (9\pm2)\%$



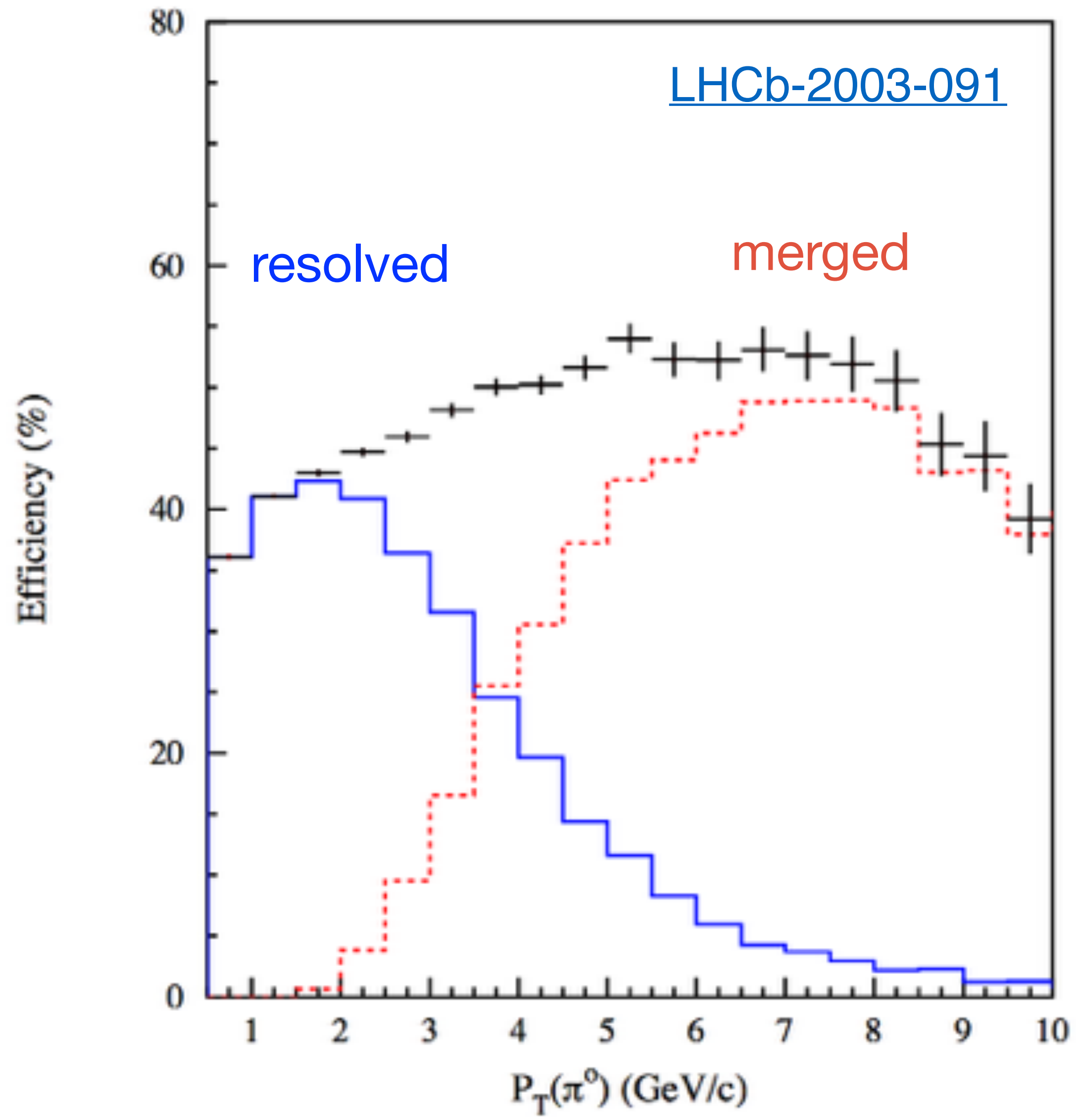
EXPERIMENTAL CHALLENGES

✦ Neutral pion reconstruction:

- Above transverse energies of 4 GeV, $\pi^0 \rightarrow \gamma\gamma$ reconstructed as a single cluster in the calorimeter ('merged' π^0)

Significant source of background:

- Studies of lepton flavor universality in $B \rightarrow Dl\nu$
  - Affected by feed-down from $B \rightarrow D^*l\nu$, where $D^* \rightarrow D\,\pi^0$
  - Use neutral calo isolation; require that no photon be reconstructed in a large cone around the D meson
  - Efficient if a photon from the π^0 is reconstructed; this happens only 15% of the time



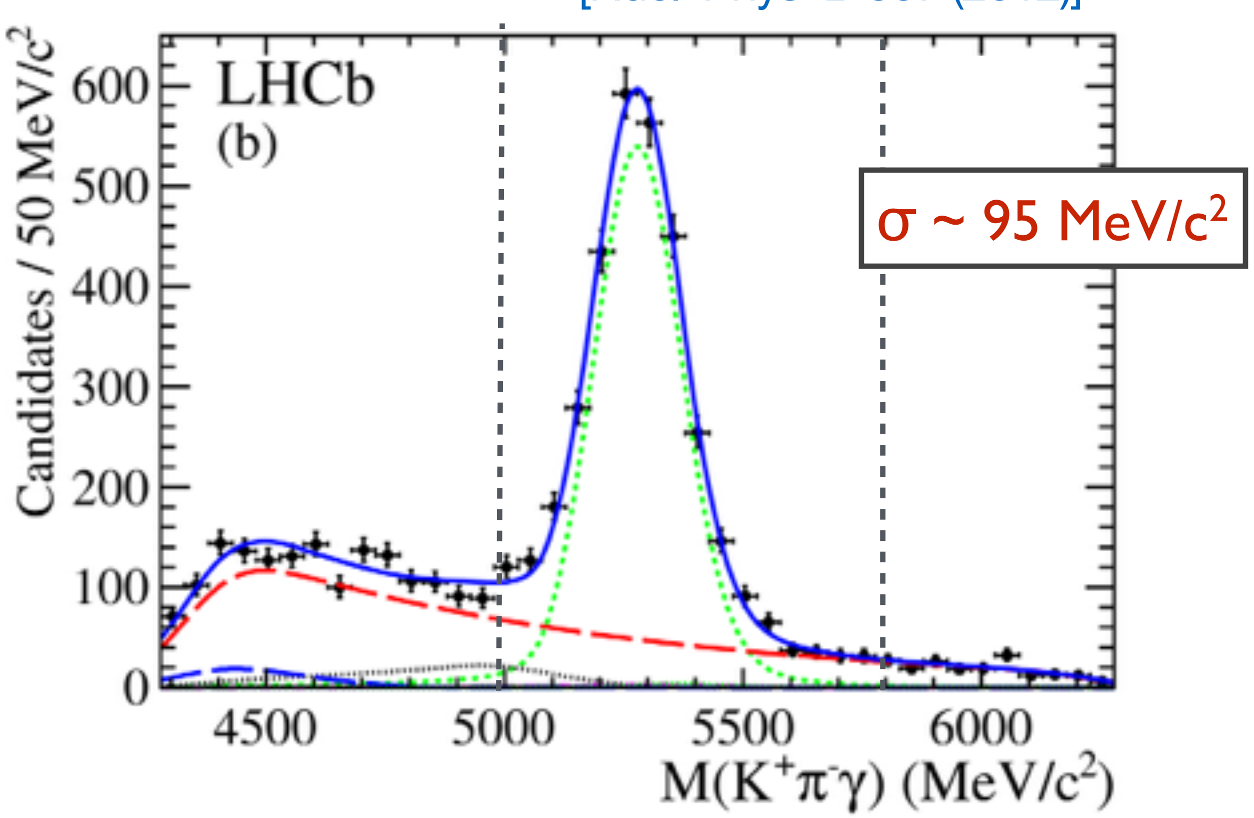
- Studies of CP violation in $D \rightarrow \phi\gamma, \rho\gamma$ decays (Francesca's talk)
  - Extremely challenging due to contamination from $D \rightarrow \phi\pi^0$ decays

EXPERIMENTAL CHALLENGES

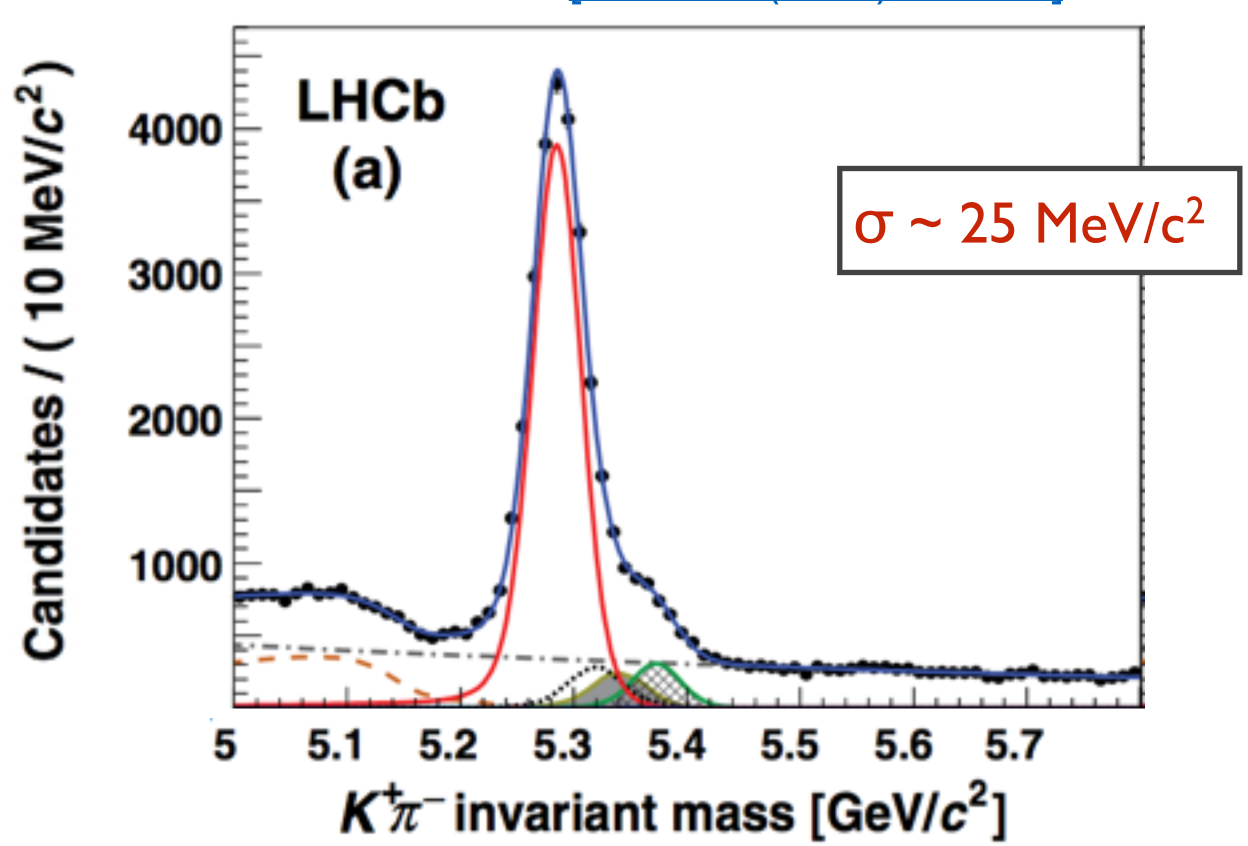
- Invariant mass resolution dominated by photon reconstruction in radiative decays (Paula's talk)
  - **σ~95 MeV/c^2** for $B \rightarrow K^*\gamma$ decays, compared to ~25 MeV/c^2 for $B \rightarrow K\pi$ decays

- Significant combinatorial background: $O(10)$ reconstructed photons per event
- Current hardware-based (L0) trigger requires $E_T(\gamma) > 3$ GeV
  - Limits analyses with low p_T photons, neutral pions (studies of the X(3872) meson, Marco's talk)

[Nucl. Phys. B 867 (2012)]

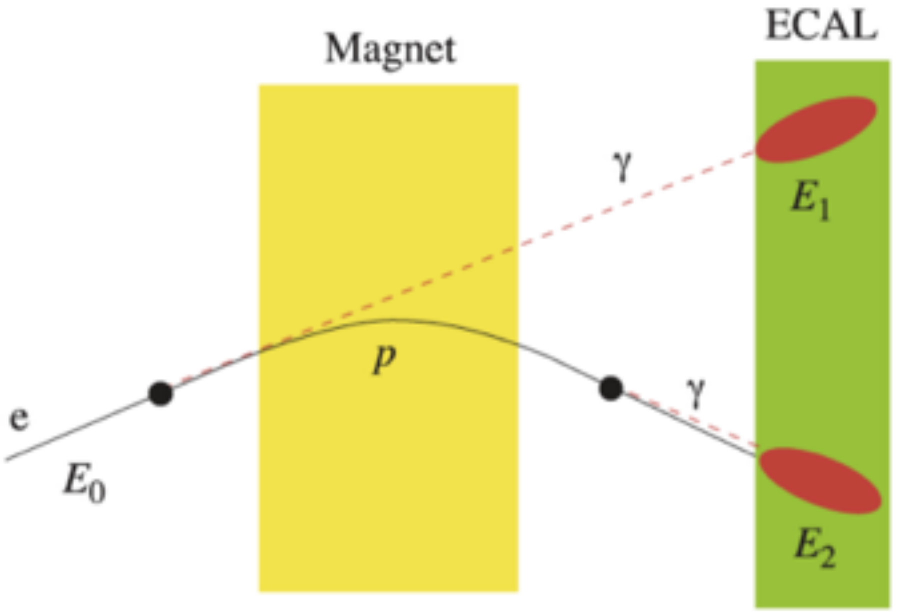


[PRL 110 (2013) 221601]



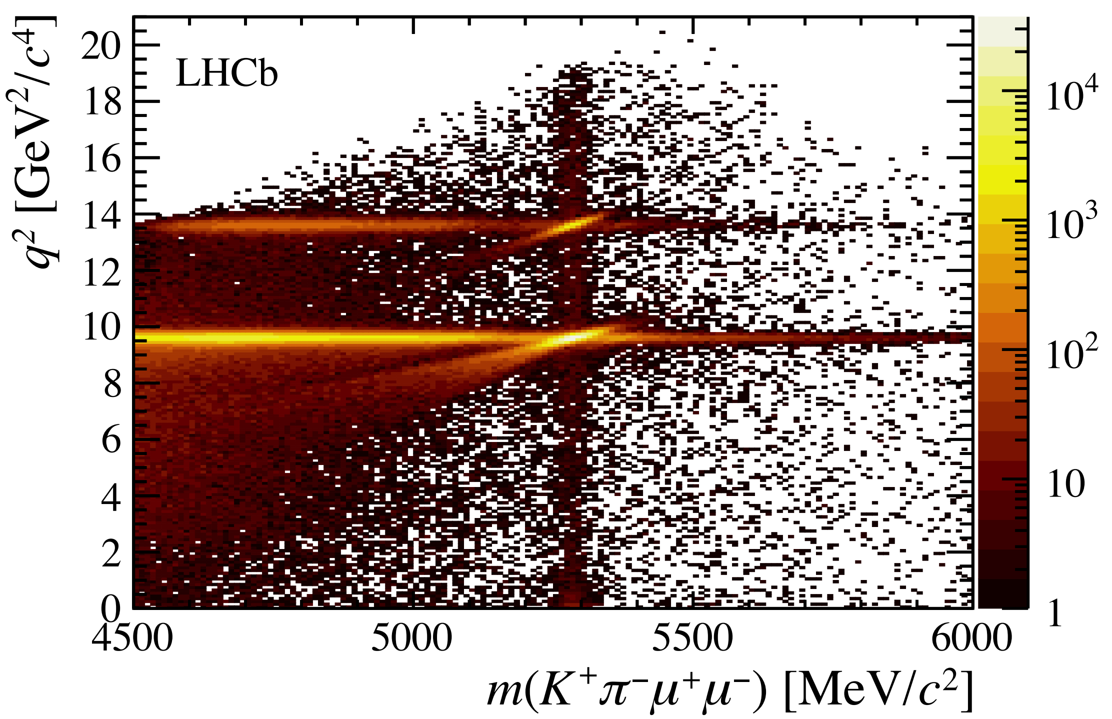
EXPERIMENTAL CHALLENGES

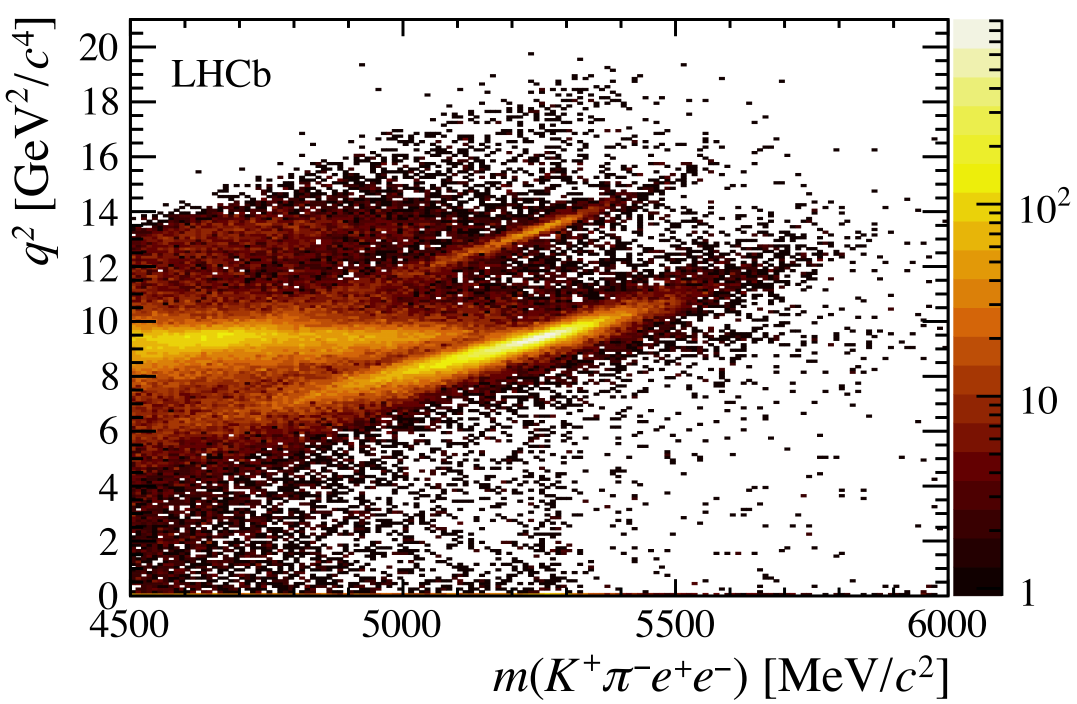
- ✦ Electron reconstruction:
  - Challenging due to bremsstrahlung; momentum and mass resolution degraded
  - Recover by adding ECAL clusters to extrapolated upstream electron track
    - Limited by calorimeter acceptance, energy threshold (E_T > 75 MeV)



- As an example, look at a study of lepton flavor universality in b→sll transitions (Paula's talk)
  - Compute ratio of branching fractions of $B^0 \to K^{*0}\mu\mu$ and $B^0 \to K^{*0}ee$ in regions of dilepton mass squared (q^2)

JHEP 08 (2017) 055





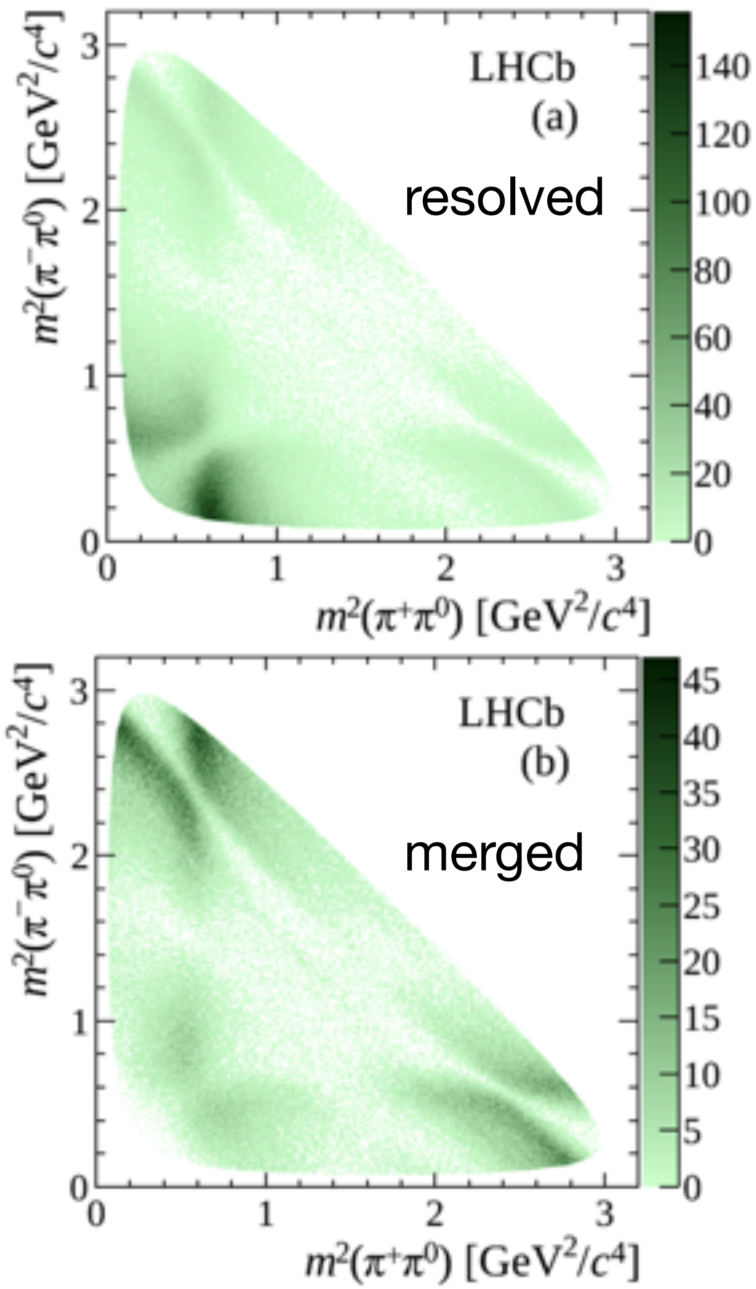
Physics with an Improved Calorimeter

- Increased spatial resolution would improve resolved π^0 reconstruction
  - Potential to improve sensitivity in existing analyses (CP violation in $D \rightarrow \pi^+\pi^-\pi^0$ decays)
  - Enable new analyses with final states containing π^0 (γ measurements using $hh\pi^0$ decay modes, Francesca's talk)

- Fast-timing calorimeter information
  - Would enable significant pile-up mitigation (required in the HL-LHC environment)

- Analyses will also benefit from improvements to trigger system
  - L0 trigger is currently the main limiting factor for analyses with photons
  - Must reduce timing in order to run reconstruction at lower energies

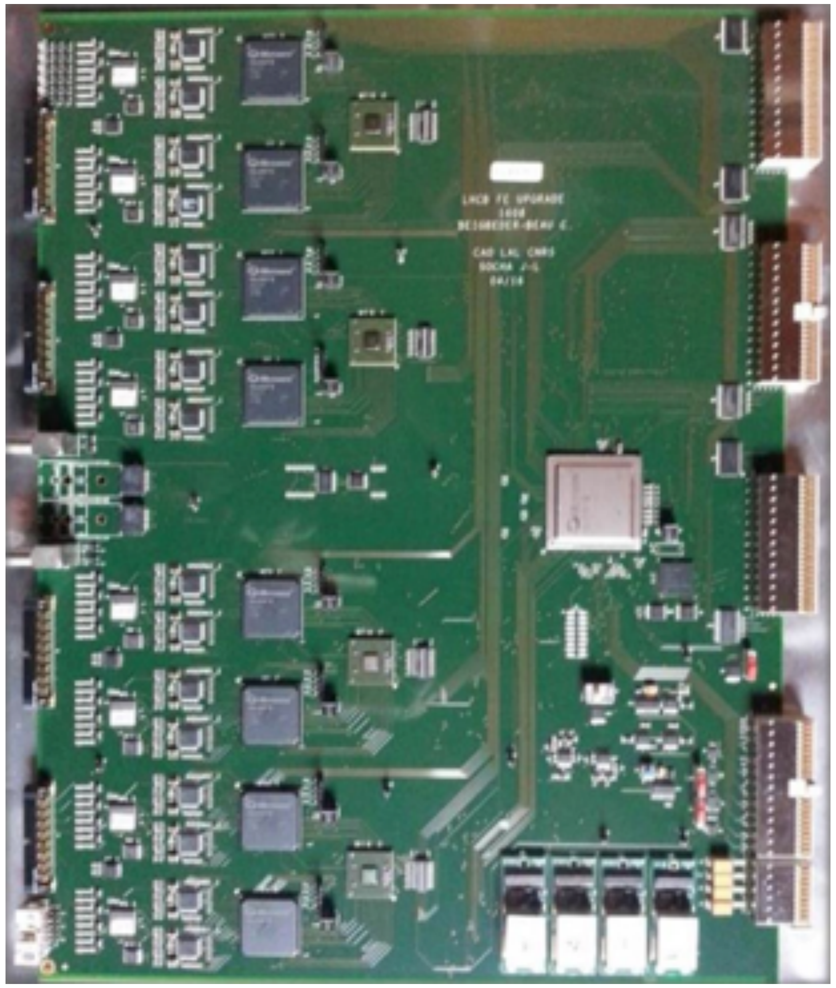
PLB 740 (2015) 158055



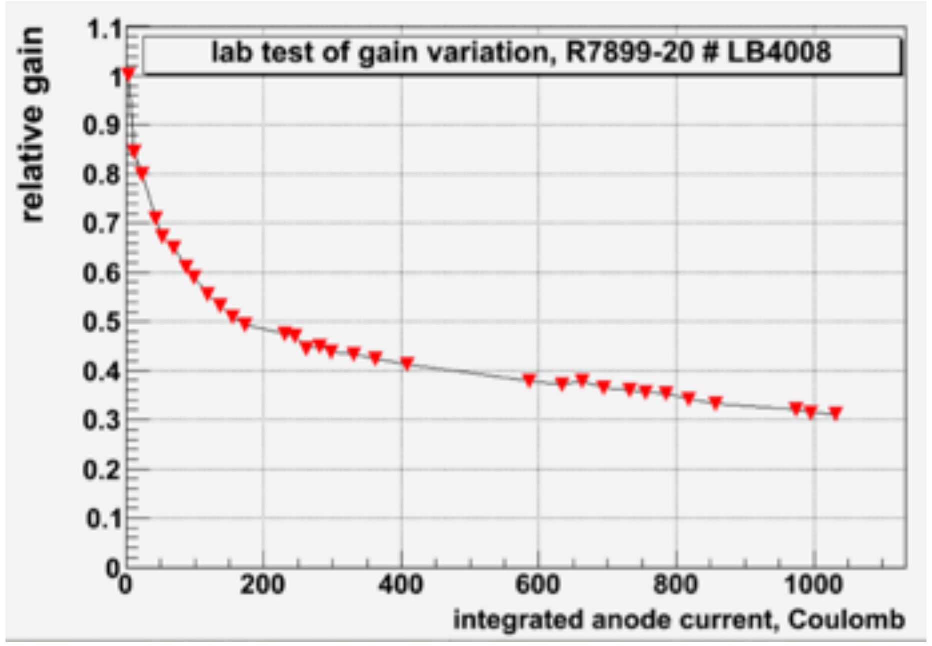
- Increased energy resolution would improve invariant mass resolution
  - Since a number of radiative decays analyses will not be statistically limited after Run 3, important to reduce systematic uncertainties

LHCb Upgrade I (LS2)

- ECAL/HCAL detectors unchanged during LS2
  - SPD/PS will be dismantled
- Move to software-based trigger → front-end electronics must be rebuilt
  - New FE boards and control boards
- Reconstruction improved for higher occupancy environment

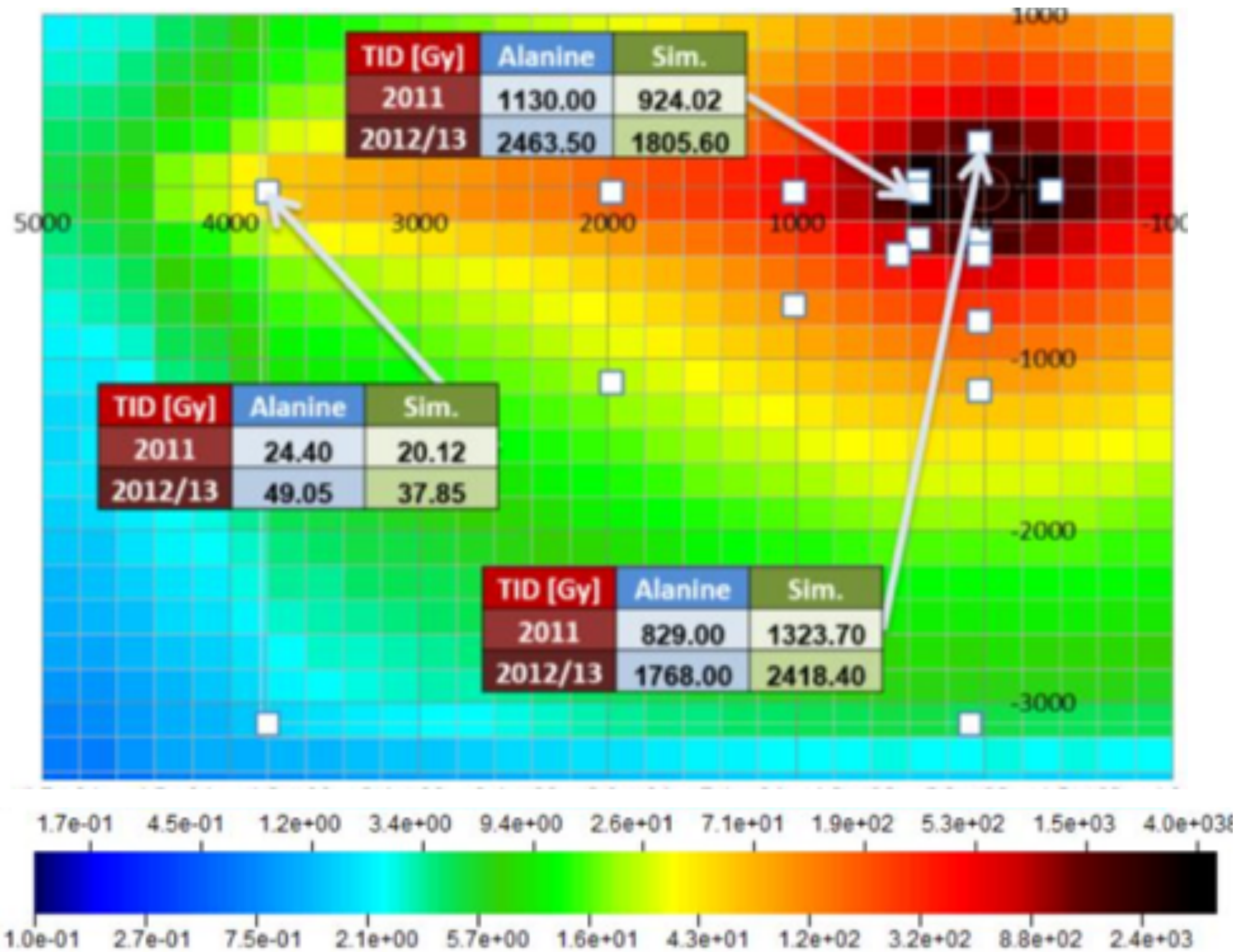


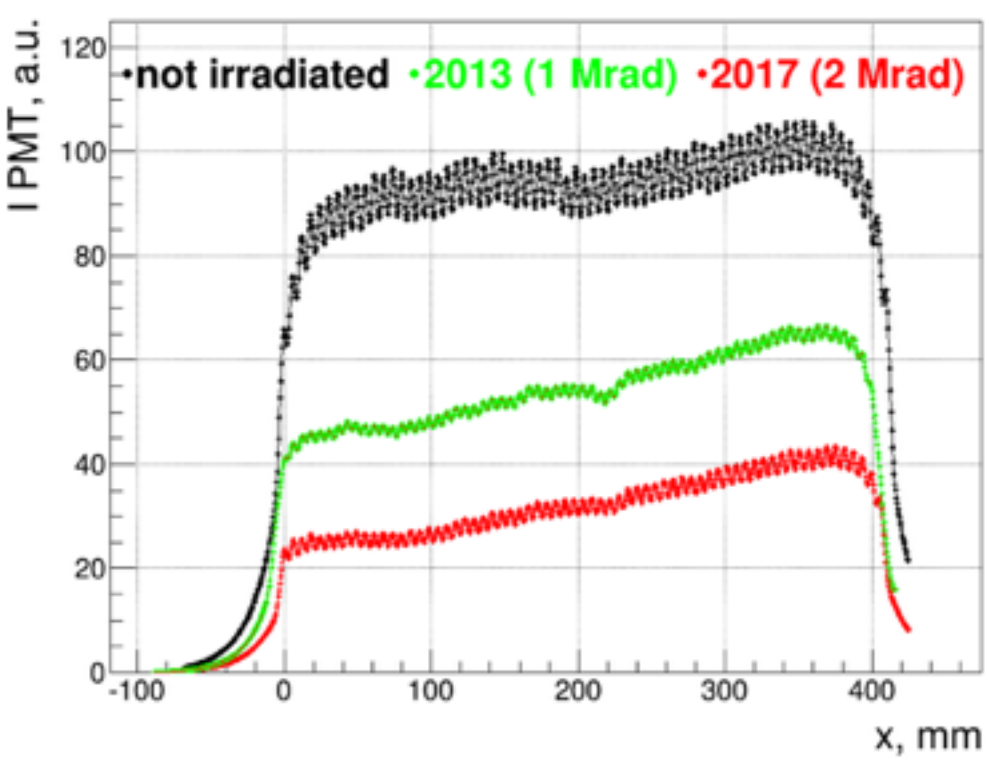
- Degradation of PMT photo-cathodes from integrated DC current
  - Use HV to compensate
  - PMT gain will be reduced by a factor of 5 for Run 3
- To compensate, the front-end gain is increased by the same factor
  - Low-noise FE ASIC developed



Detector Aging

- WLS and scintillators suffer from radiation damage
  - LED flashes used for monitoring, HV used to compensate (fill-by-fill); corrections in periodic absolute calibration (ECAL+HCAL)
- Radiation effects are highly non-uniform:
  - ECAL (front) dose map - 2012 FLUKA simulation (E_{CM} = 8 TeV, 2.21 fb^{-1})
  - Factor ~1.7 from 8 TeV ⟶14 TeV

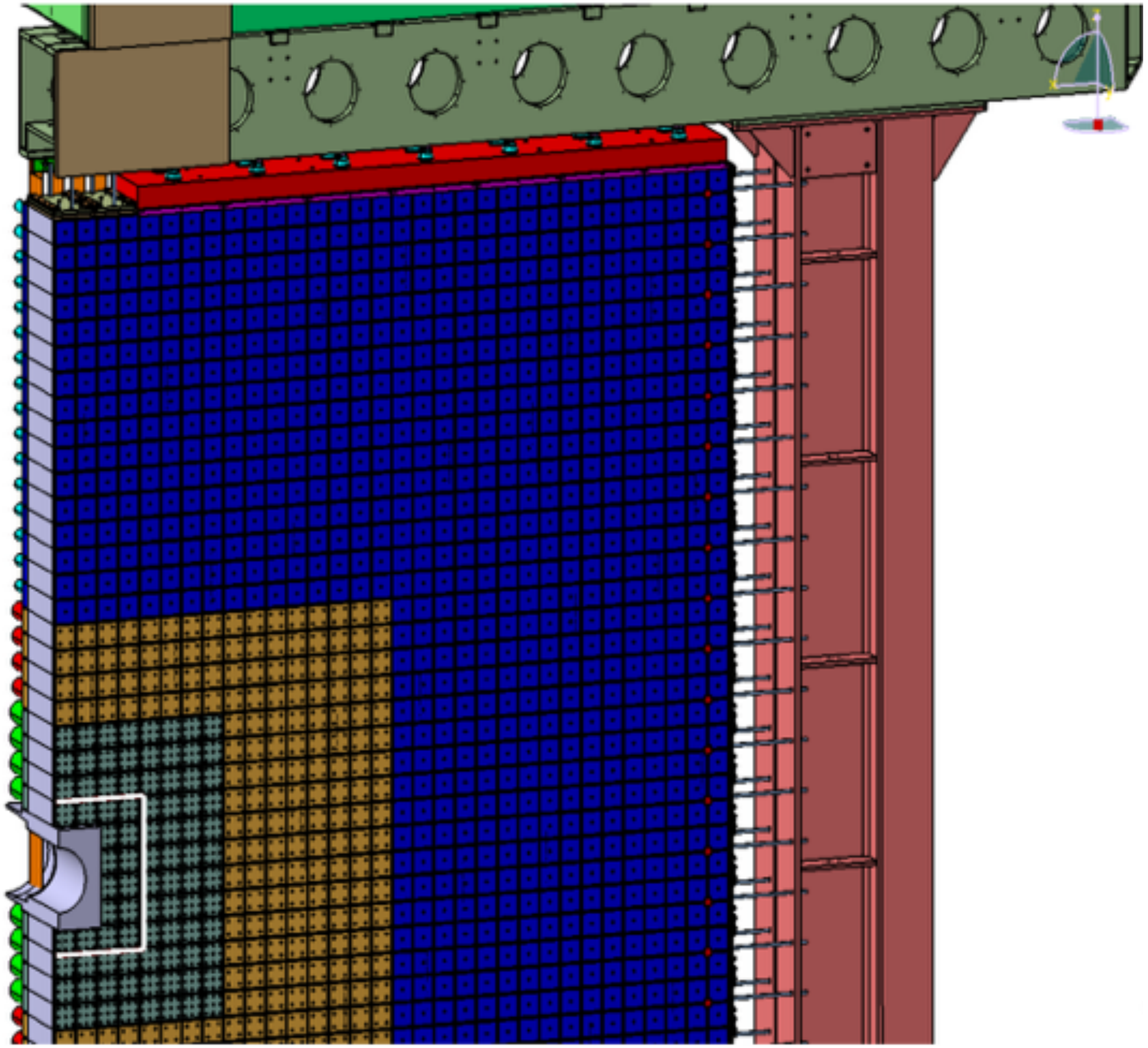




- ECAL irradiation: two modules installed (in 2009) near beam pipe; dose measured at module surface
- Modules operational until ~3-4 Mrad at shower max.
  - 10 -13 fb^{-1} @ 14 TeV at 32 cm from BP (innermost modules)
  - 25 -30 fb^{-1} @ 14 TeV at 48 cm from BP

LHCb UPGRADE Ib (LS3)

- Inner region of the ECAL most affected by radiation, pile-up
  - Innermost modules need to be replaced during LS3
- Original plan was to replace with (identical) spare modules
  - 32 modules already available
- However, degradation in performance would be seen in Run 4 (2 x 10^{33} $cm^{-2}s^{-1}$)

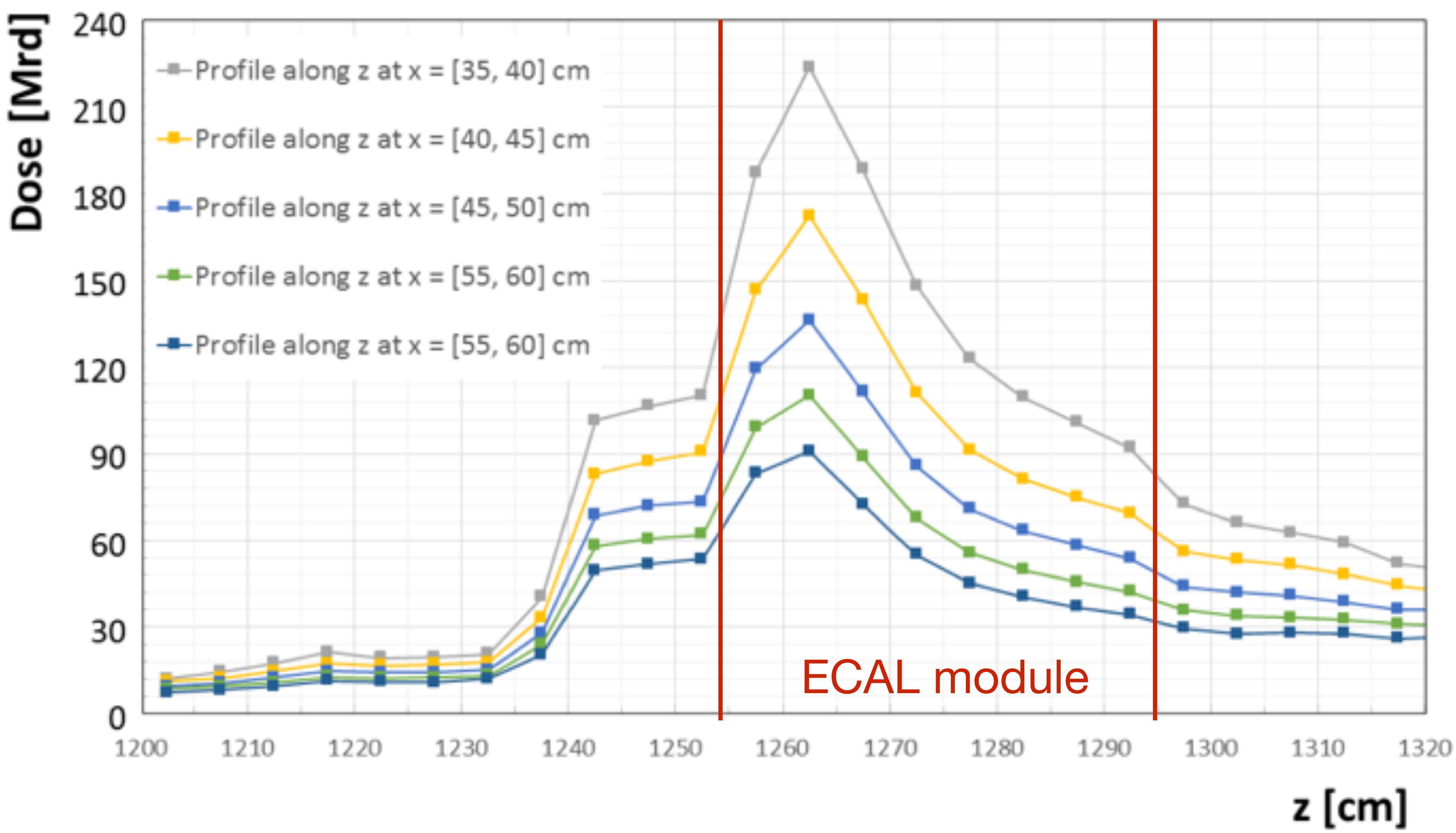


LS3 is an ideal opportunity to begin the staged ECAL upgrade, starting from the inner cells

Challenges in the HL-LHC Environment

Radiation Damage

- Effects are highly non-uniform:
  - Simulated fluence (FLUKA) seen for modules closest to the beam pipe
    - Includes safety factors (simulation, removal of PS/SPD)
  - Innermost regions see significant radiation at 300 fb^{-1}
  - Modules may require replacing if a sufficiently radiation-tolerant solution is not found

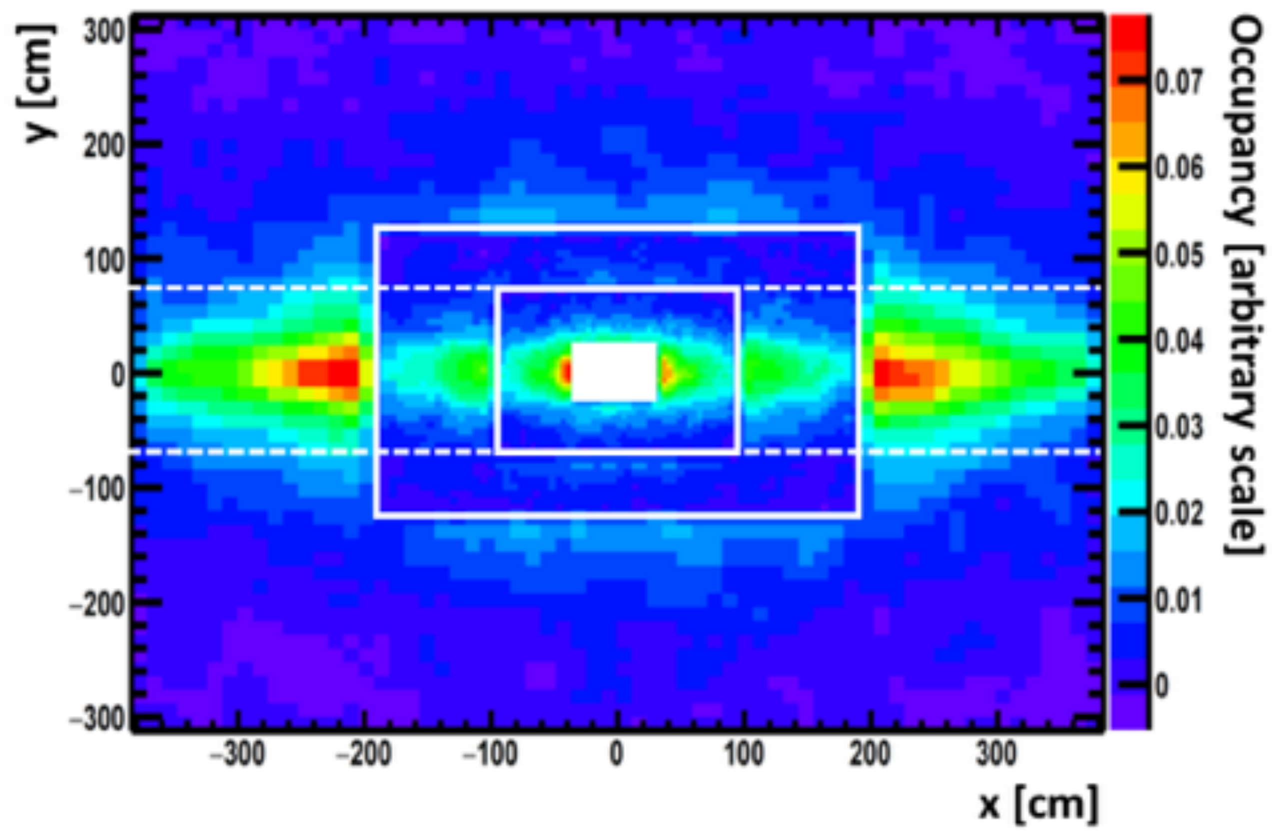


Challenges in the HL-LHC Environment

High occupancy

- Regions of high occupancy would benefit from modules with higher granularity
  - Innermost modules would be highest priority, followed by horizontal band
  - 'Natural' module size - 2x2 cm^2
  - Smaller Moliere radius
- More precise spatial information?
  - Smear photon energy resolution, study effect on reconstructed π^0 mass resolution in simulation
  - Using perfect spatial information improves resolution from 9 MeV to 6 MeV (for σ_S~10%)

$$\sigma_E/E = \sigma_S/\sqrt{E(\mathrm{GeV})} \oplus \sigma_C$$

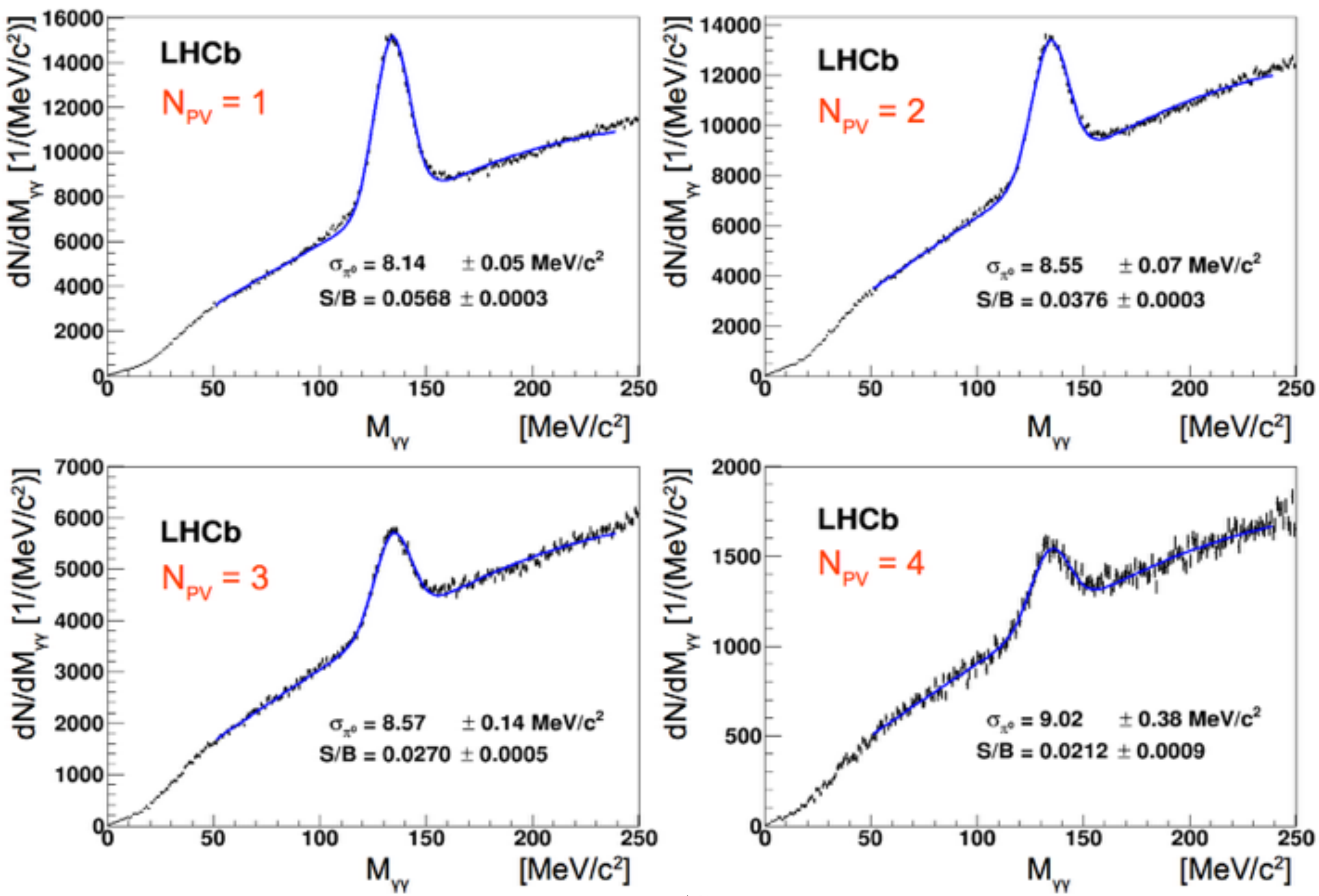


	Spatial information from clusters σ_C		Perfect spatial knowledge σ_C	
σ_S	1%	2%	1%	2%
7%	7.5	8.2	4.2	5.2
10%	8.5	9.3	5.5	6.5
15%	10.5	11.3	8.0	8.9

Challenges in the HL-LHC Environment

High pile-up

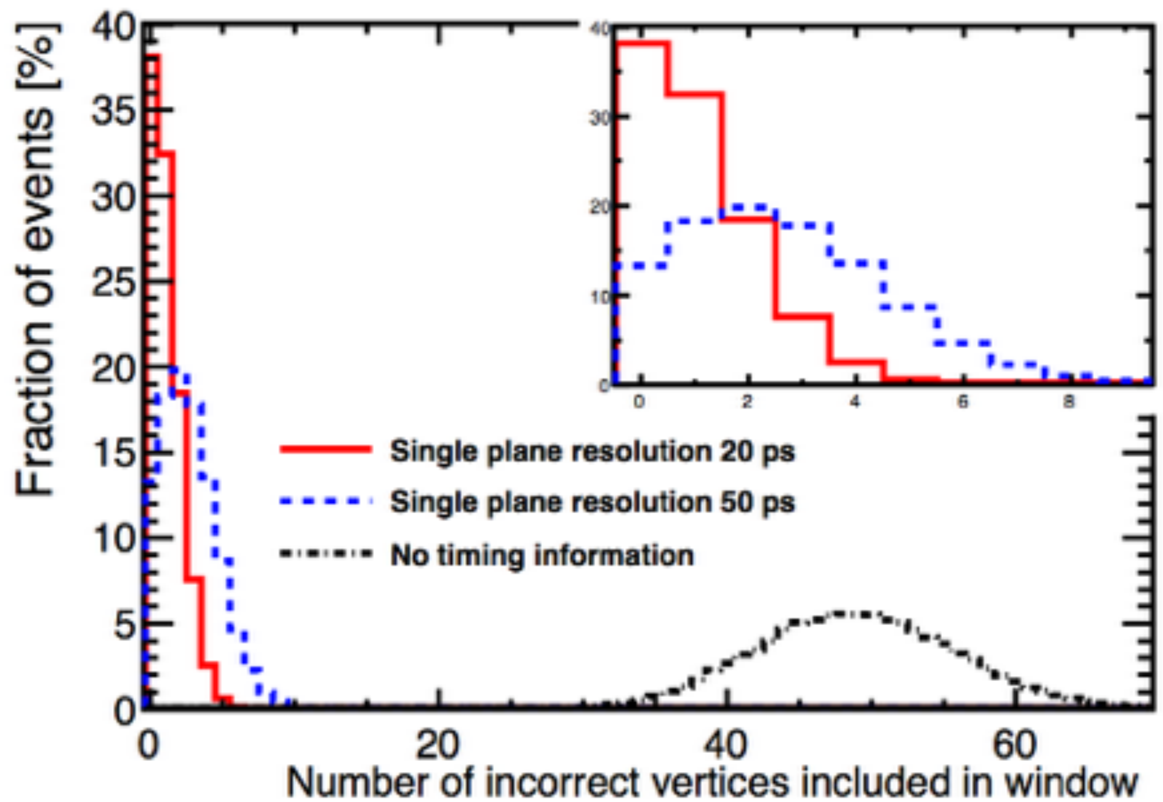
- Effect on π^0 reconstruction seen in Run 2 minBias data
  - Split reconstructed resolved π^0 by number of primary vertices
  - Increased background (and some loss in invariant mass resolution) as N_{PV} increases

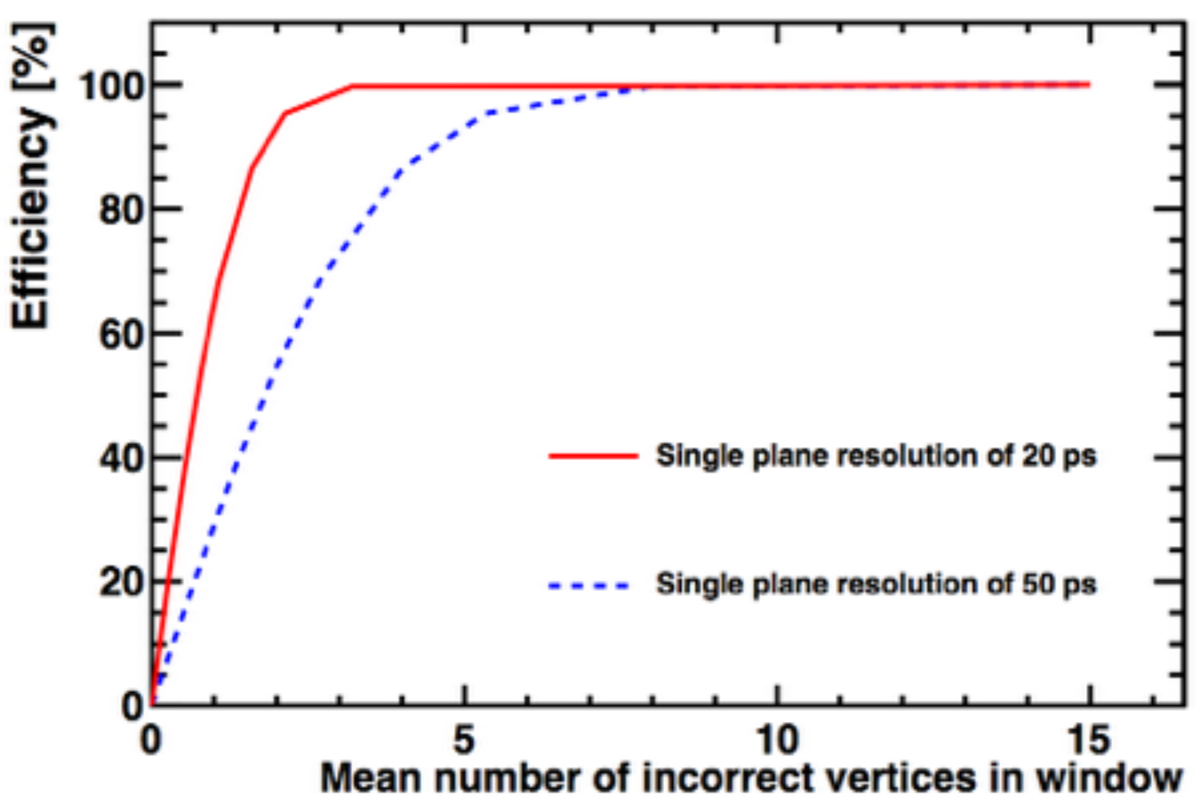


CHALLENGES IN THE HL-LHC ENVIRONMENT

High pile-up

- Use of silicon pads/strip would also provide fast-timing information
  - Impact of addition of timing information seen in a simulated environment with 50 interactions per bunch crossing
  - Introduce three layers of Si planes with spatial resolutions of 20ps or 50ps
  - Number of incorrect PVs with background hits in a one sigma window around signal arrival time: ~2.7 (50ps resolution), ~1.1 (20ps resolution)





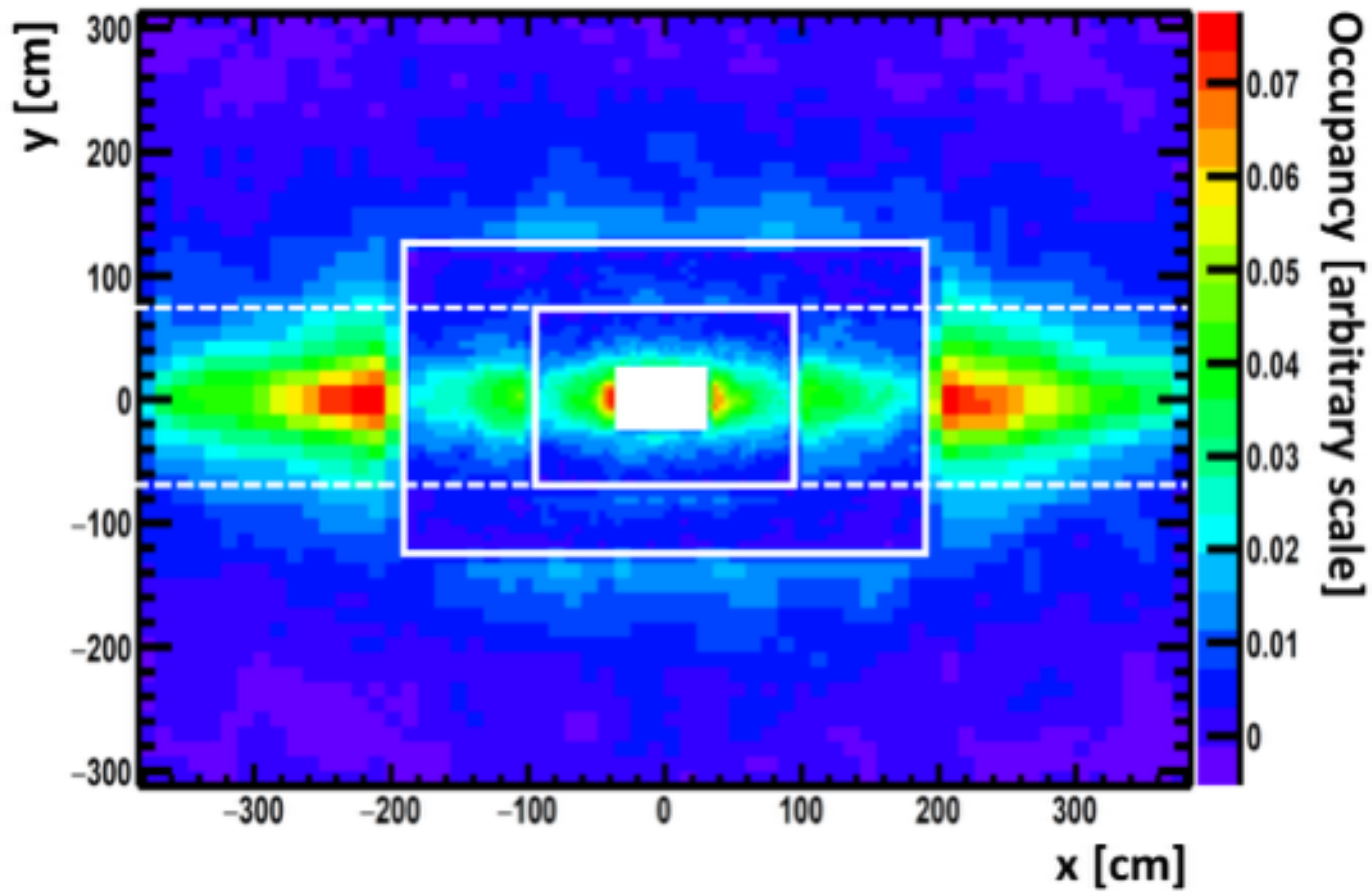
TOWARDS UPGRADE II (LS4)

Need calorimetry that can perform at luminosity expected in Runs 4 and 5 (2×10^{34} $cm^{-2}s^{-1}$)

- Must be extremely radiation hard, higher granularity than current design
- Other considerations? Position and energy resolution, mitigation of pile-up effects

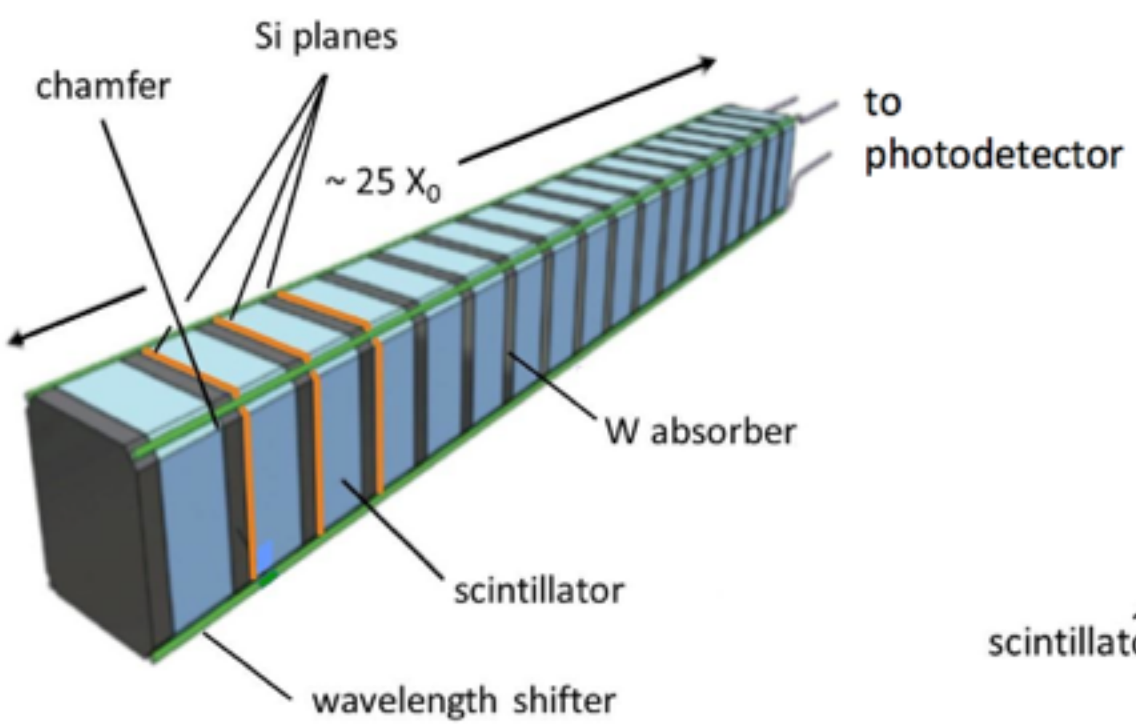
Overall detector geometry:

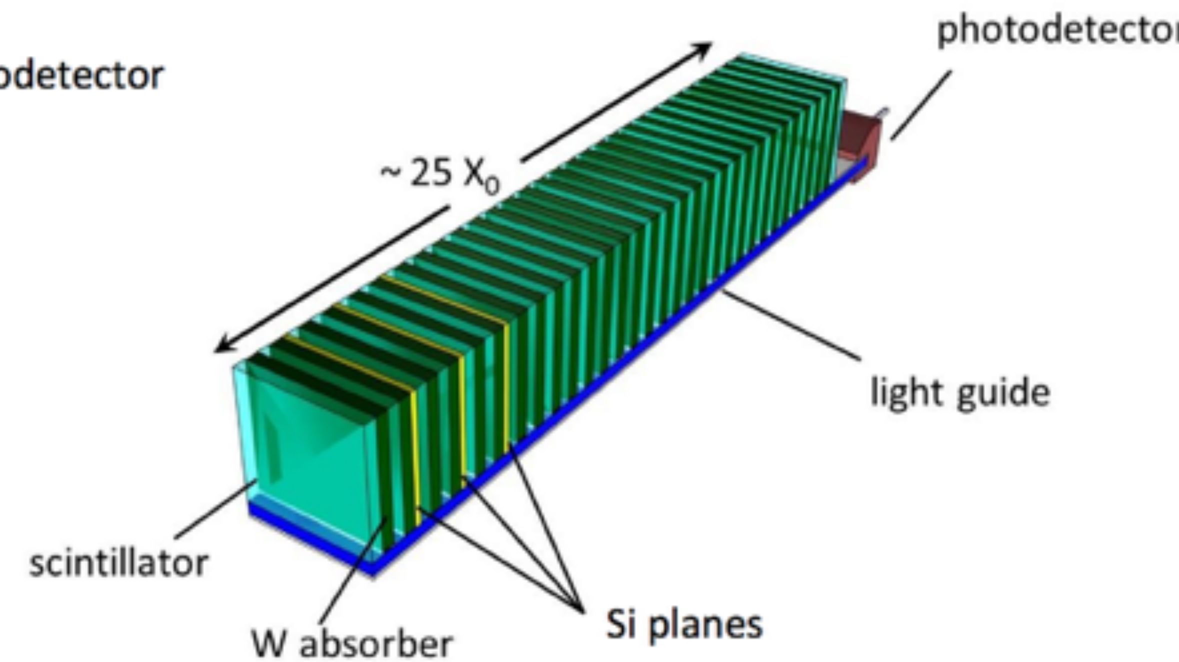
- Could upgrade the innermost modules to have high granularity, timing information
- Removed inner modules could be placed in middle regions, middle modules moved to outer regions
- Particularly useful for horizontal band (higher occupancy)



POTENTIAL TECHNOLOGIES

- Sampling calorimeters:
  - Tungsten-based absorber
  - CMS-inspired designs:
    - WLS in chamfers along side of module (tested with CeF_3 as a scintillator)
    - Cerium-doped LYSO, quartz - radiation-hard alternatives to WLS fibres
    - Could also have compact LYSO/W shashlik
  - As an alternative, could use clear light-guides
    - Potentially better light yield and radiation hardness



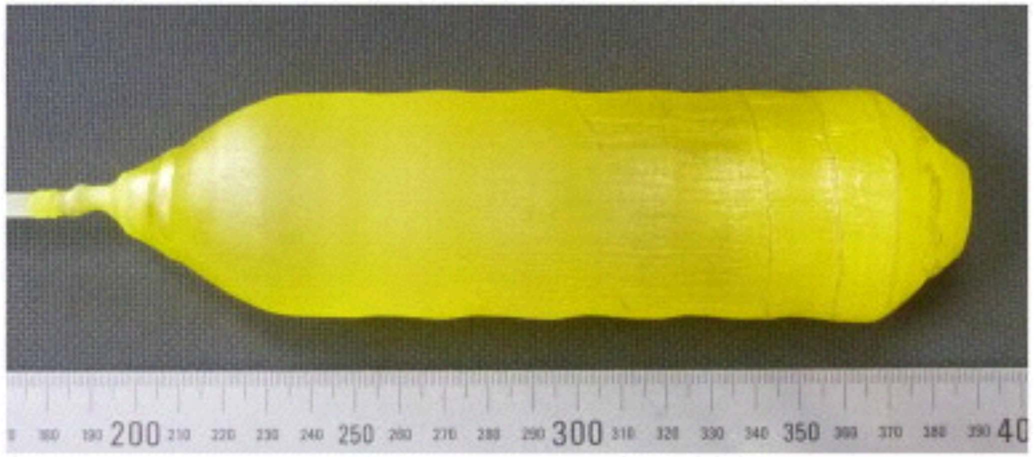


Inspired by CMS calo R&D

POTENTIAL TECHNOLOGIES

Other options?

- GAGG:Ce crystals
  - At least as radiation hard as LYSO, less expensive
  - Work needed to identify compatible photodetectors
- Air gap + mirrors instead of WLS?



https://doi.org/10.1016/j.jcrysgro.2011.11.085

Homogenous calorimeters

- Cherenkov crystals?
  - Fast readout, but relatively low light yield
- GAGG crystals + embedded Si-based photodiodes
  - Longitudinal segmentation
  - New rad-hard SiPMs developed

- Work needed to improve reconstruction (novel algorithms, using machine learning?)

Many options, R&D with potential upgrade technology is in early stages

SUMMARY

- LHCb has a diverse physics program, with many analyses that use calorimeter information
- Upgrades to the front-end electronics (and removal of the L0 trigger) will be made during LS2
- Radiation, high occupancy expected during HL-LHC data-taking challenging for calorimetry
- Innermost ECAL modules must be replaced during LS3
    - Excellent opportunity to test upgraded module designs before Upgrade II (LS4)
    - Increased granularity, spatial resolution, addition of timing info?
- R&D with potential upgrade calorimeter technology is just beginning
    - Early irradiation tests with GAGG:Ce crystals, Si photodiodes

Backup