Future Facilities: LHC Plans

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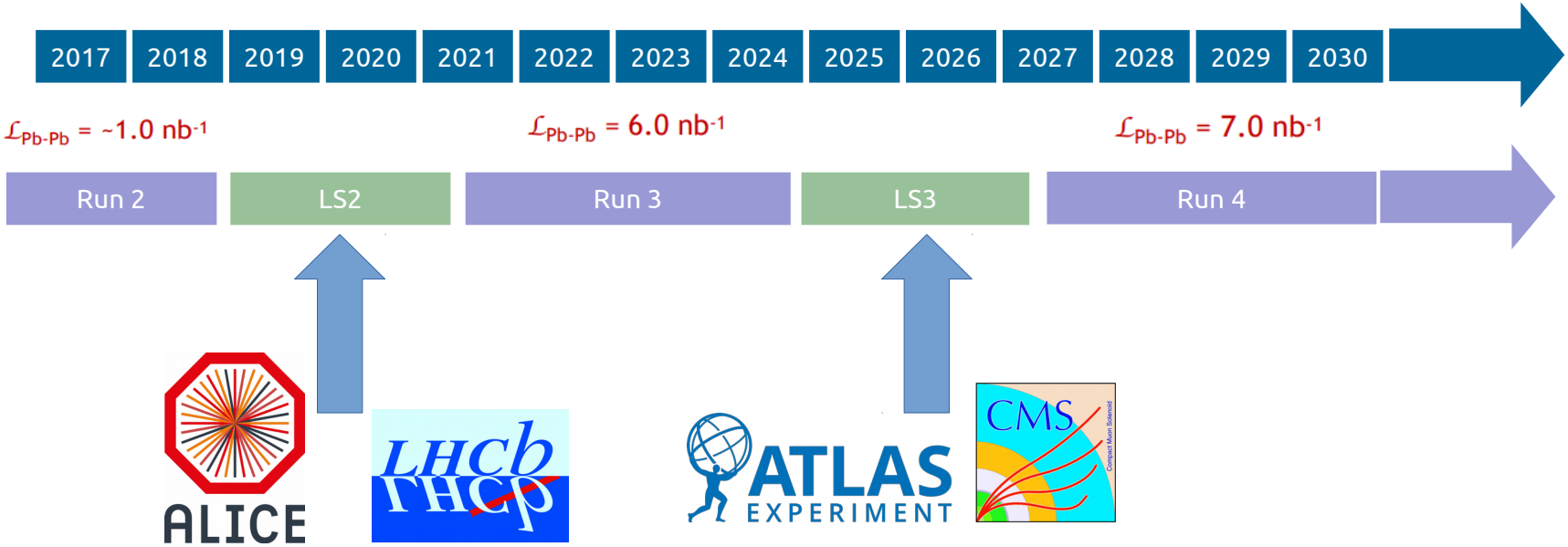
for the ALICE, ATLAS, CMS and LHCb collaborations

Hard Probes 2020 (Online)
June 5th

LHC timeline



- **LHC** injector upgrades:

  → interaction rate up to 50 kHz for PbPb
  Run2 <10 kHz for ALICE and up to 35 kHz CMS/ATLAS

- **ALICE** and **LHCb** major upgrades

- **CMS** and **ATLAS** upgrades
- ALICE and LHCb additional upgrades

[CERN-LPCC-2018-07]

Run 3+4 main priority = large PbPb sample (13 nb^{-1}) :

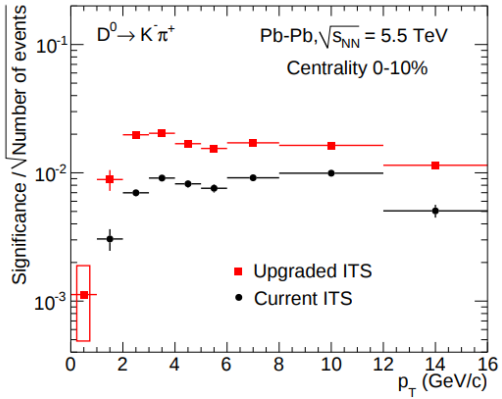
- **x100** more statistics for MB for ALICE wrt Run2
- **x10** more statistics ATLAS/CMS wrt Run2

Physics program highlights for Run3 and Run4

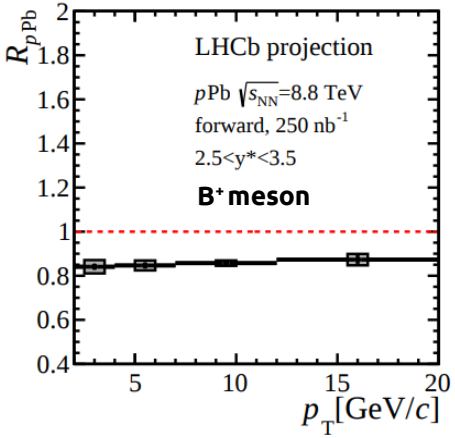
ALICE : rare probes at low p_T

- Heavy-flavour (charm and beauty)
- Charmonium
- Di-leptons from QGP radiation
- Light and hyper-nuclei

[ALICE-TDR-017]

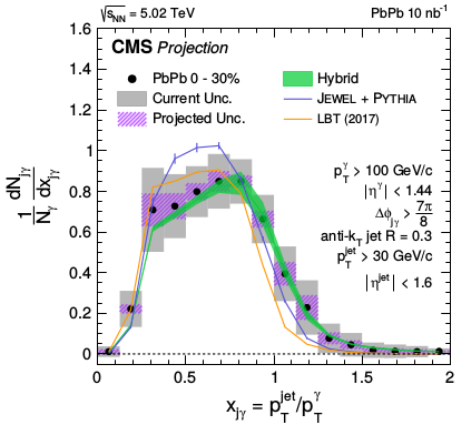


[CERN-LPCC-2018-07]

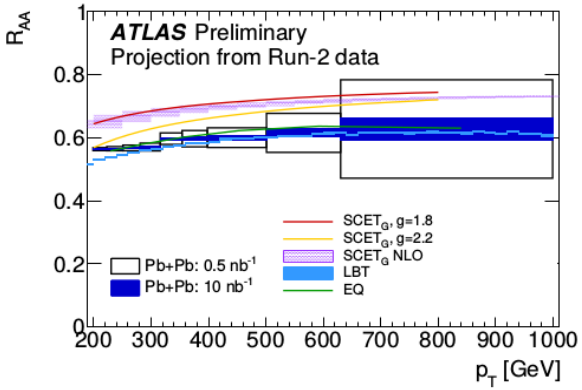


LHCb :

- Fixed target : nPDFs, phase transition scan, Generalised Parton Distributions
- PbPb : going to more central events
- Heavy flavors, quarkonia and exotic states in pPb and more central PbPb



[CERN-LPCC-2018-07]



CMS and ATLAS:

- Hard probes precise measurements at high p_T
- Heavy flavor at low p_T
- Rare exotic probes with UPC events for BSM

ALICE Upgrades for Run3

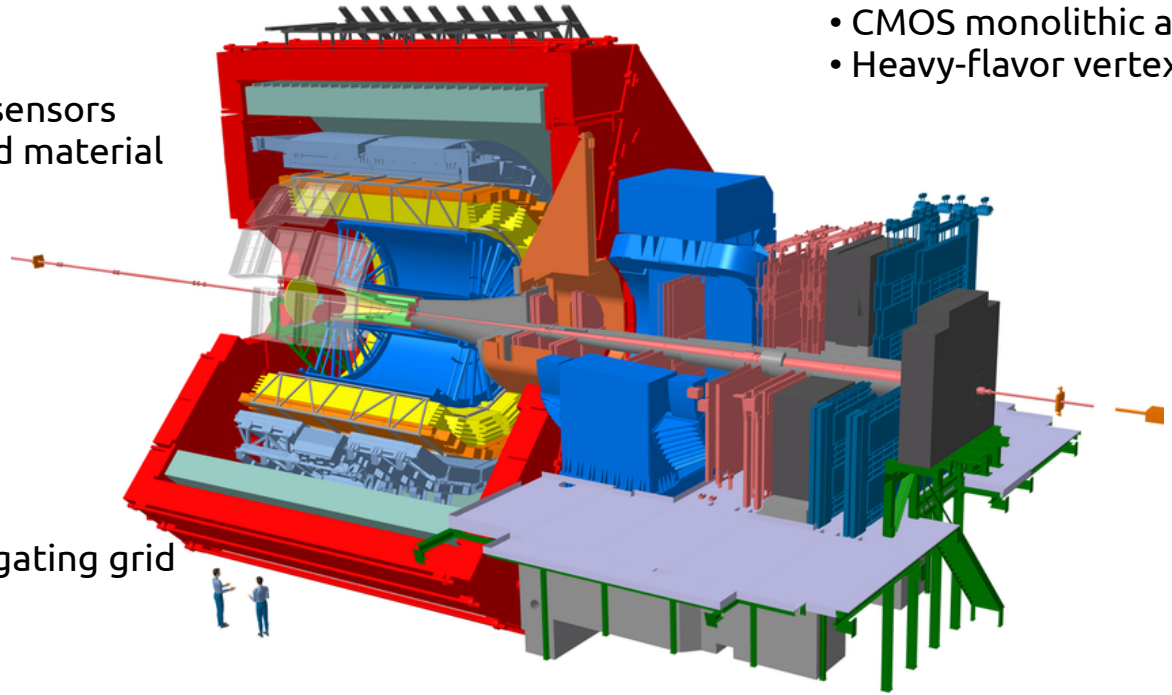
Rare probes at low pT

Muon forward tracker

- CMOS monolithic active pixel sensors
- Heavy-flavor vertex reconstruction

Inner tracker system upgrade

- CMOS monolithic active pixel sensors
- Higher granularity and reduced material budget



TPC readout

- GEM based read-out → operate TPC at 50 kHz without gating grid

O2 (online-offline) system

FOCAL (Run4) – TDR in preparation

- Si sensors covering $3.4 < \eta < 5.8$
- Direct photons measurements

LHCb Upgrades for Run3

Towards more central events (30-100%)

Tracker

- UT Si-strip, granularity & coverage
- T Scintillating Fiber + SiPMs

PID

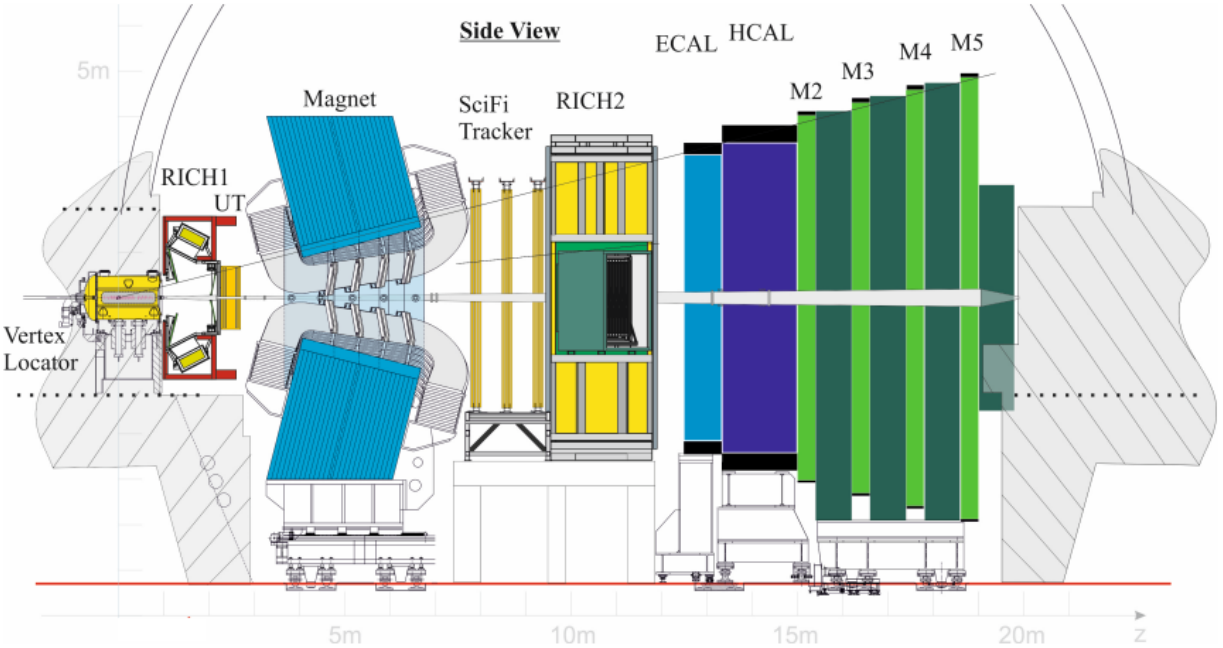
- New photosensors in both RICH
- Modified optics in RICH1

SMOG2

- Fixed gas target
- Running in parallel with collider mode

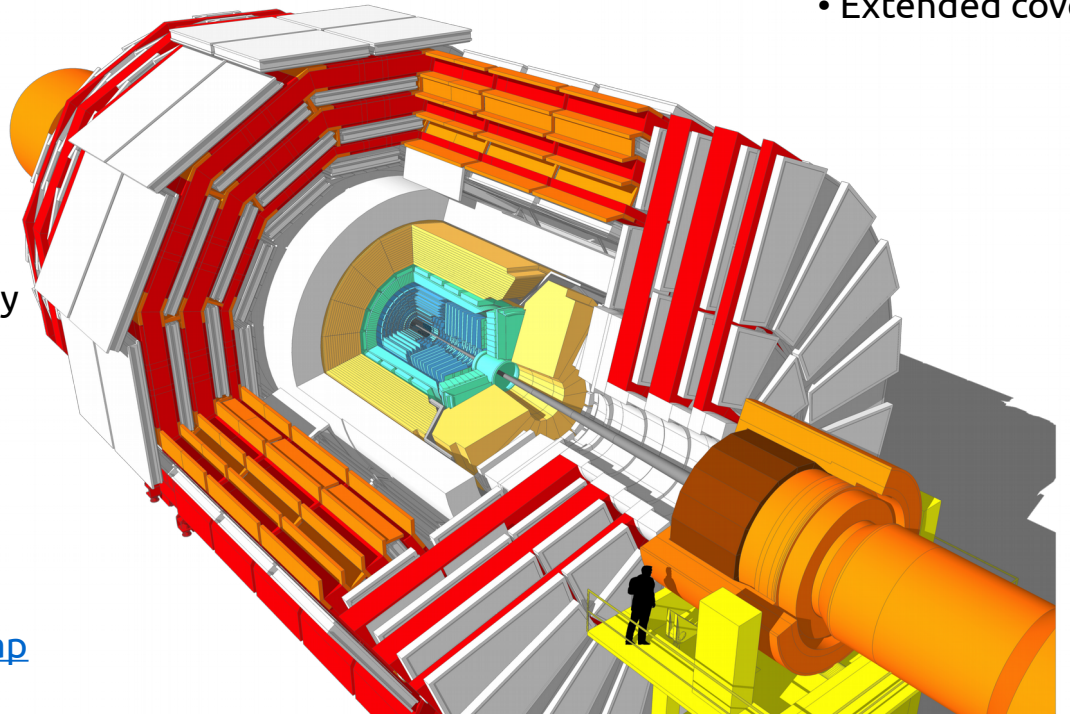
Vertex

- New Si-pixel system



CMS Upgrades for Run4

Coverage extension



New tracker

- Si-Strip & Pixels increased granularity
- Extended coverage to $\eta \simeq 3.8$

High Granularity Calorimeter Endcap

- 5D imaging : energy, time, x, y, z
- Si sensors/plastic scintillator tiles+SiPMs
- 6 millions Si channels

Muon systems

- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

MIP timing detector

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

ATLAS Upgrades for Run4

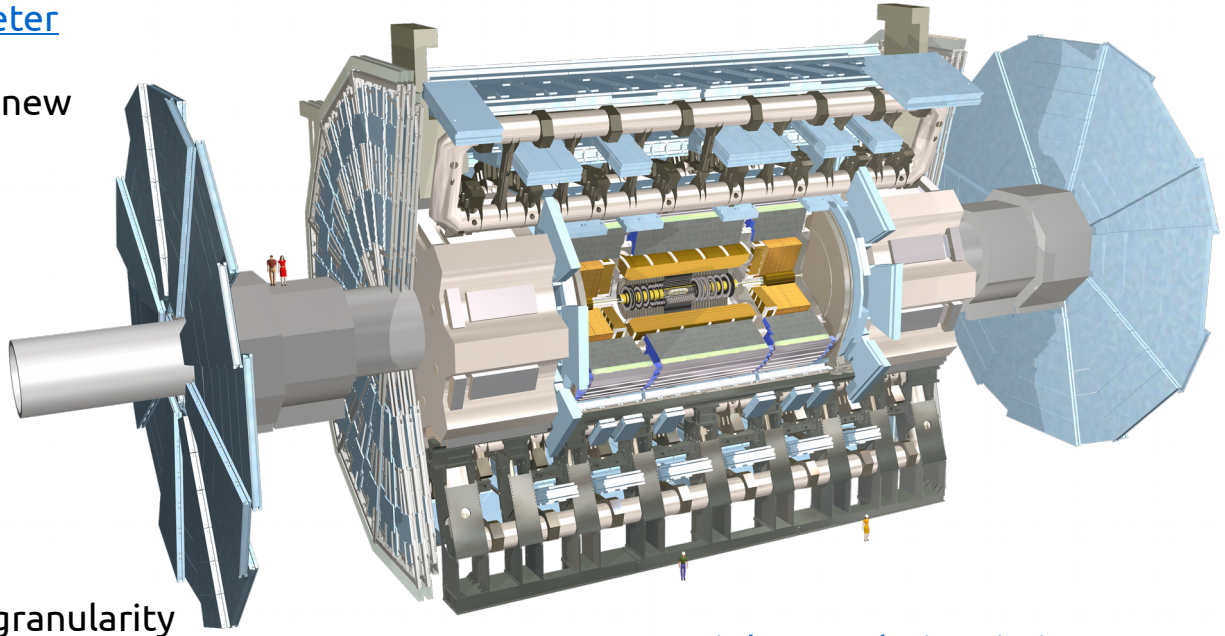
Coverage extension

Muon systems

- New electronics
- New inner barrel chambers

Liquid Argon and Tile calorimeter

- Increased granularity due to new electronics



New tracker

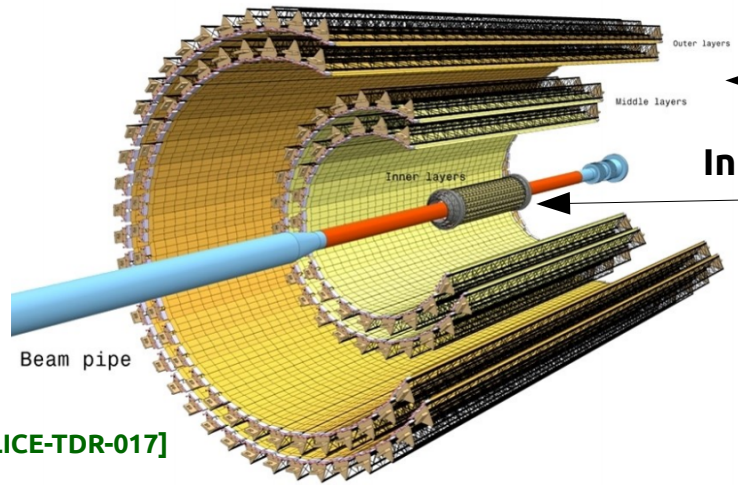
- Si-Strip & Pixels increased granularity
- Extended coverage to $\eta \simeq 4$

High Granularity Timing Detector
(TDR in preparation)

- Low Gain Avalanche Diodes $2.4 \lesssim \eta \lesssim 4$

ALICE Upgrades : Inner Tracking System

Run3



[ALICE-TDR-017]

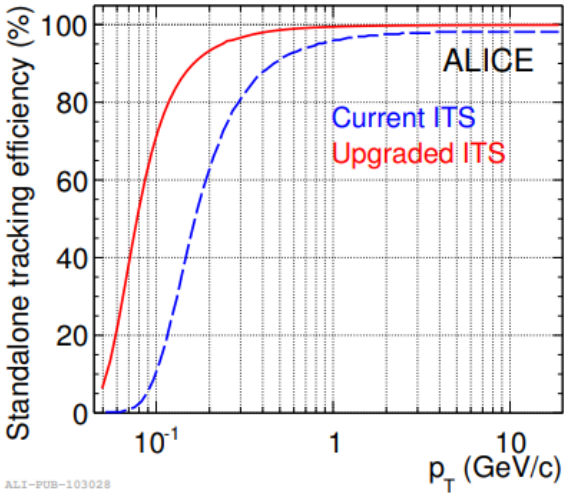
Outer Barrel

Inner Barrel

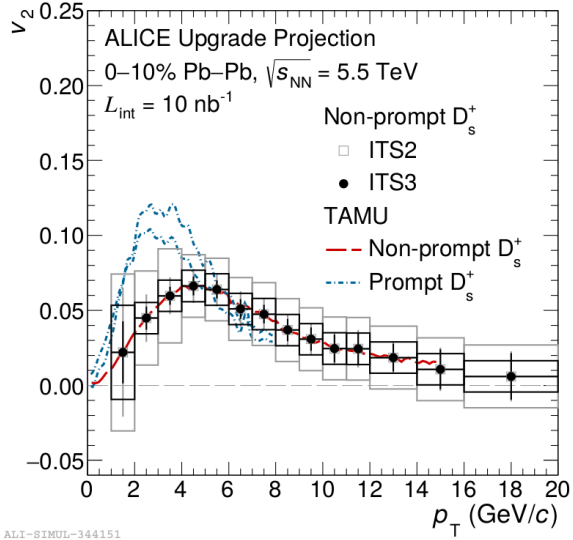
10m² active silicon area, 12.5x10⁹ pixels

ALPIDE Monolithic Active Pixel Sensor:
→ Detection efficiency > 99%
→ Low fake-hit rate < 10^{-9} /pixel/event

Excellent tracking down to very low p_T



Tracking efficiency >95% at p_T = 500 MeV/c



Commissioning :

- Fake-rate is stable over time
- Very good uniformity

Run4

Marco Van Leeuwen's talk
(4 Jun 2020, 11:15)

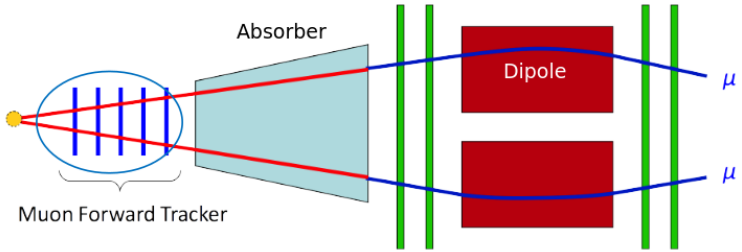
Inner barrel replacement :
Truly cylindrical detector using thinned, wafer-sized sensors

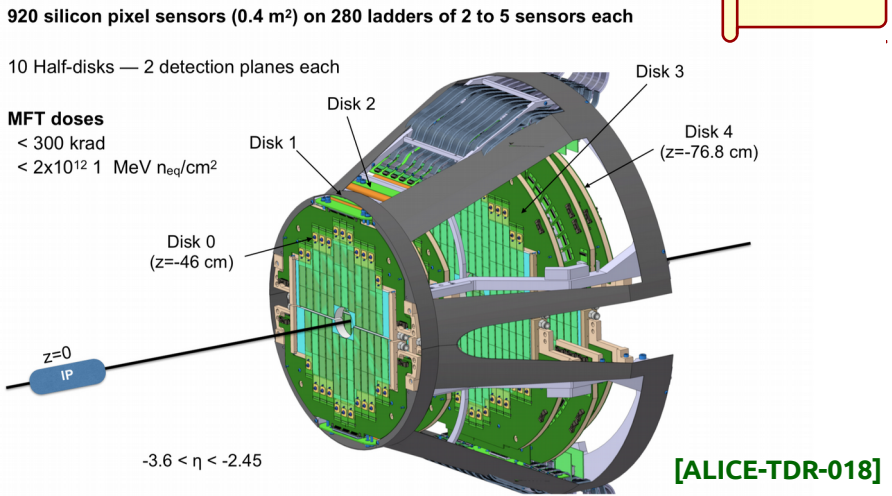
ALICE : Muon Forward Tracker

Run3

Precise determination of production vertex and tracking :

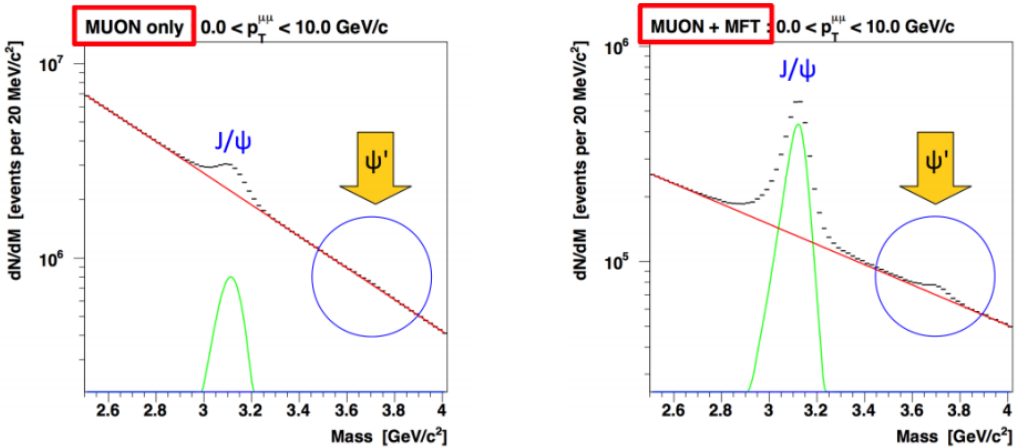
- single μ offset at primary vertex
- secondary vertices : prompt vs non-prompt J/ψ



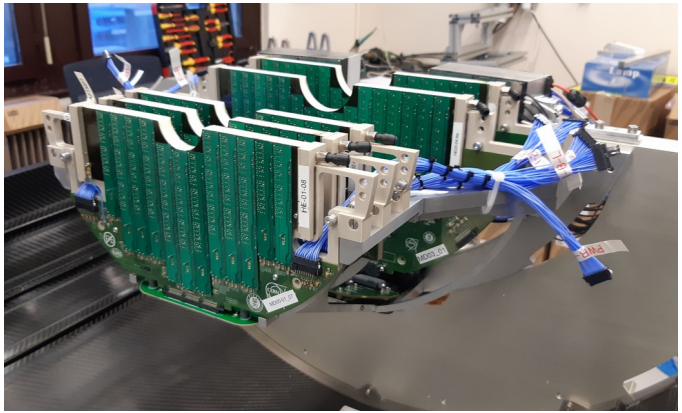


[ALICE-TDR-018]

Identification of forward prompt J/ψ



Bottom half MFT already assembled and installed on surface at CERN

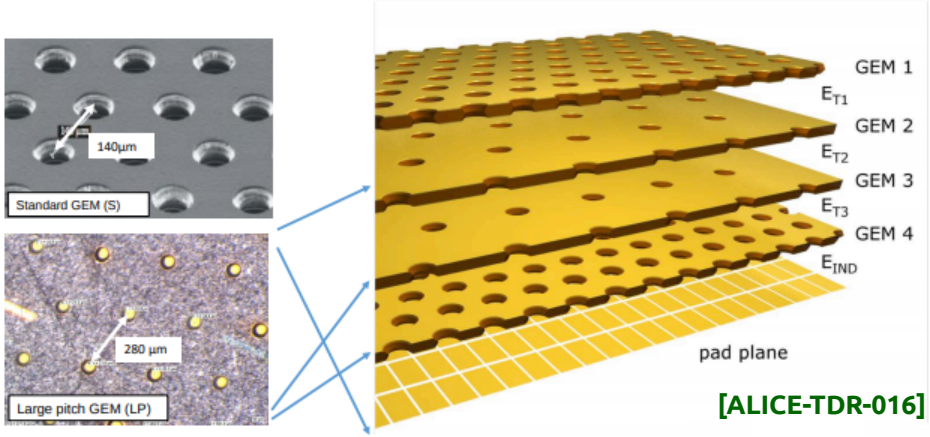


ALICE : TPC readout

Run3

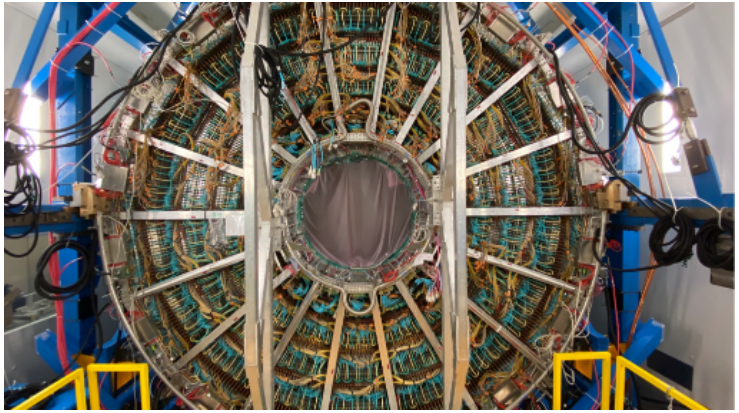
50 kHz PbPb → continuous readout → Gas Electron Multiplier readout instead of Wire gating grid

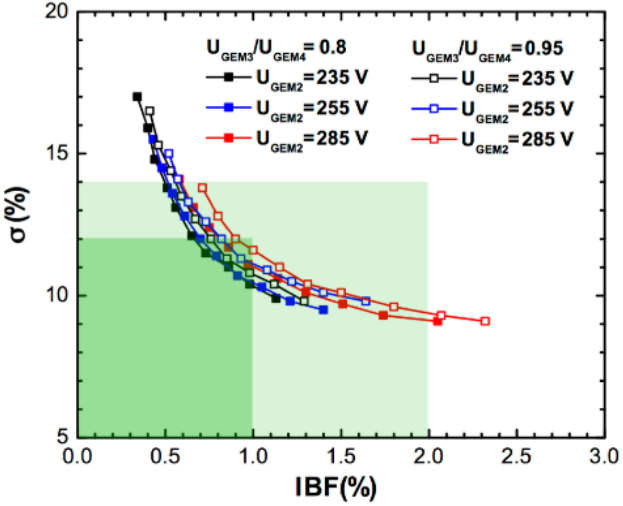
Combination of standard and large pitch GEM foils :



[ALICE-TDR-016]

Upgraded TPC





New GEM readout :

- Result of intensive R&D
- Highly optimized HV configuration to keep **Ion Back-Flow (IBF) < 1%**
- Preserves momentum resolution for TPC+ITS combined tracks
- Preserves particle identification via dE/dx

[Nucl.Instrum.Meth.A 903 (2018) 215]

LHCb : Tracking system

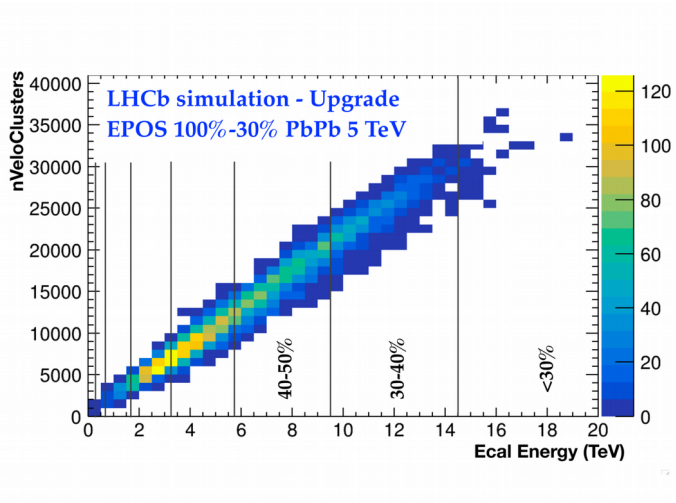
Run3

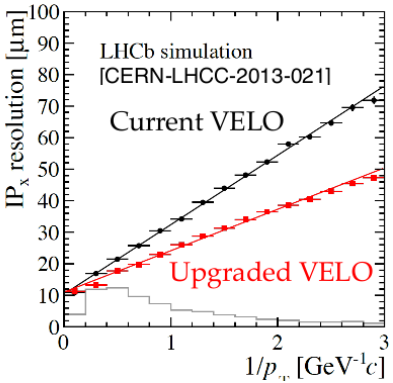
VELO : in Run3 will not be saturated in central PbPb

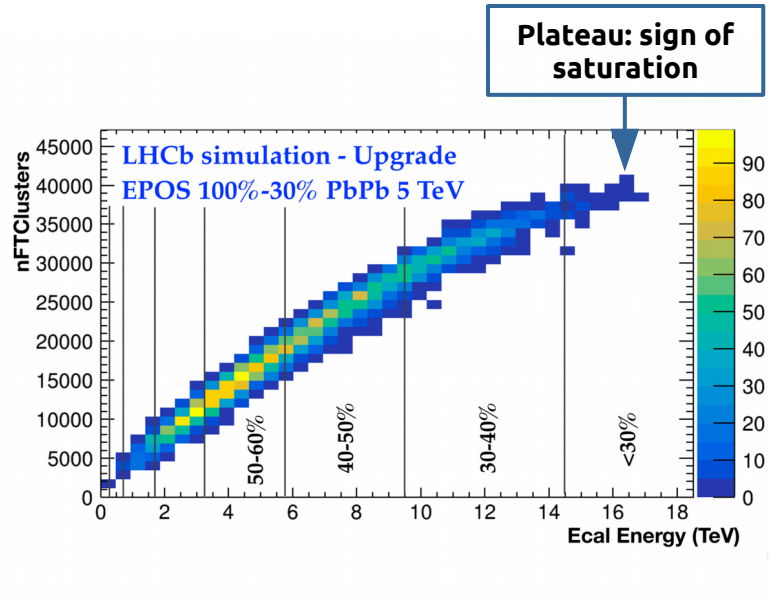
Upgrade :

- Silicon pixel detector, 55x55 μm² pixels
- Closest pixels at 5.1 mm from the beam line

[LHCB-TDR-013]







SciFi : saturate in the most central PbPb (0-30%)

Upgrade :

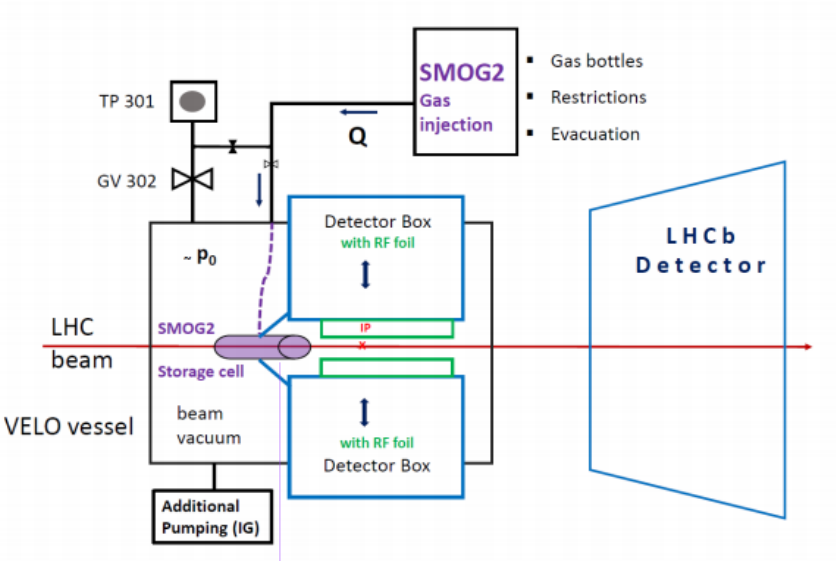
- 11000 km of ∅250 mm scintillating fibers with SiPM
- SiPM cooled down to -40° to reduce the dark current

[LHCB-TDR-015]

Run 5 : no saturation expected after the MIGHTY tracking detector installation

LHCb : SMOG2

Run3



[LHCB-TDR-020]

20 cm long, with 5 mm radius around the beam,
30 cm away from IP
made of two rectractable halves

Samuel Belin's talk
(4 Jun 2020, 10:55)

Upgrade of the SMOG target by adding the **storage cell** :

- Increase the gaz density by factor 100, keeping the same gas flow
- Possibility to run in parallel with pp collisions and inject non noble gaz

Running in parallel with collider mode

	SMOG released result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass ($5-9$ GeV) Drell-Yan	negl.	5	9k

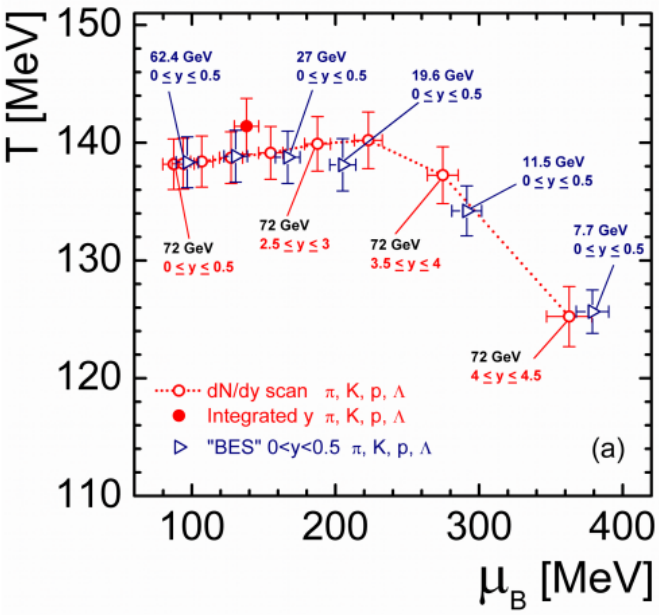
Cold nuclear matter effects with higher precision

LHCb : new physics opportunities with SMOG2

Run3

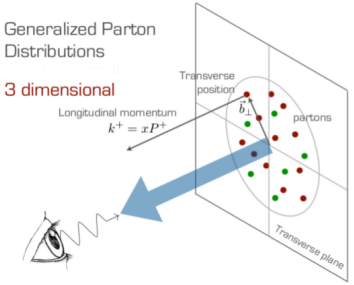
QGP and phase transition

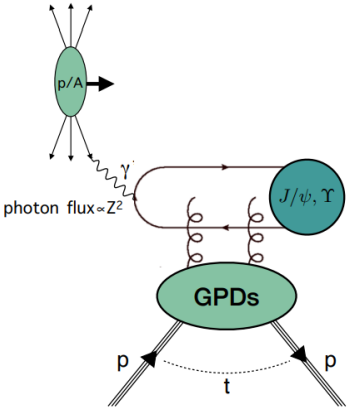
[Phys.Rev.C98 (2018) 034905]



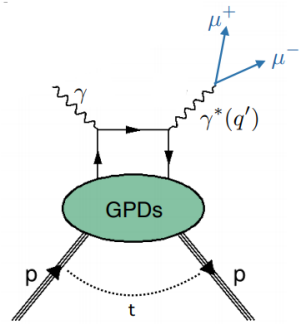
Rapidity scan at 72 GeV can complement the RHIC beam energy scan

Hadronic physics :
Generalised Parton Distributions





Exclusive meson production



Timelike Compton scattering

nuclear PDFs and Generalized Parton Distibutions at large Bjorken-x

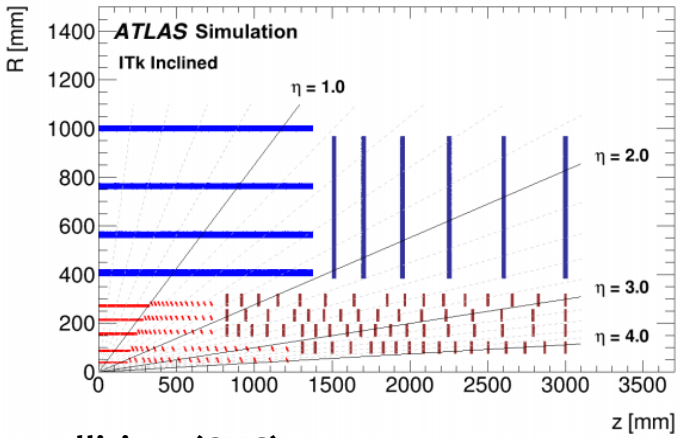
CMS and ATLAS : tracking systems

Run4

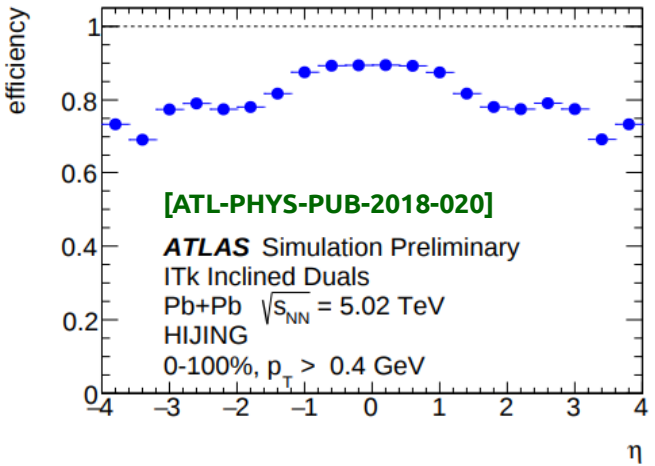
ATLAS and CMS :

- Si-sensors: 3D inner pixel layer, thinner, granularity x4 to 6
- Pixel coverage extension to η ≃ 4

[ATLAS-TDR-025]

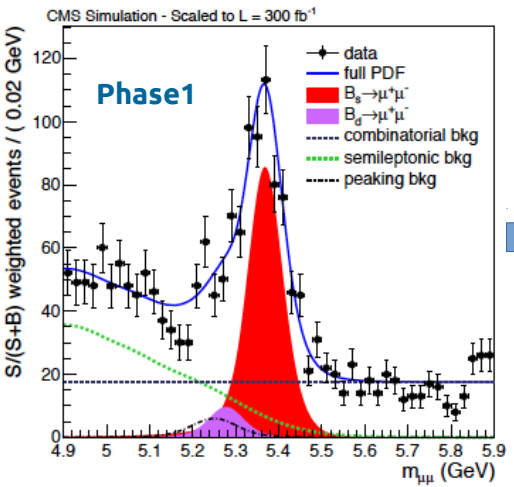


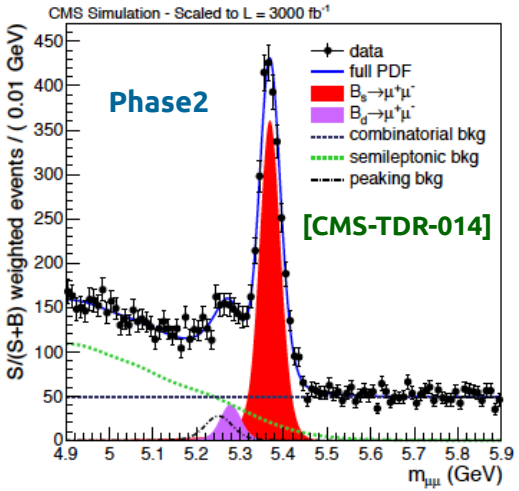
Tracking reconstruction efficiency (ATLAS)



~20% for |η|<1 and ~30% for |η|~2 improvement

B_0/B_s separation in pp collisions (CMS)





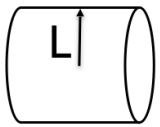
50% improvement in mass resolution, same improvement is expected in PbPb → Υ(3S) observation?

CMS and ATLAS : precise ToF MIP

Run4

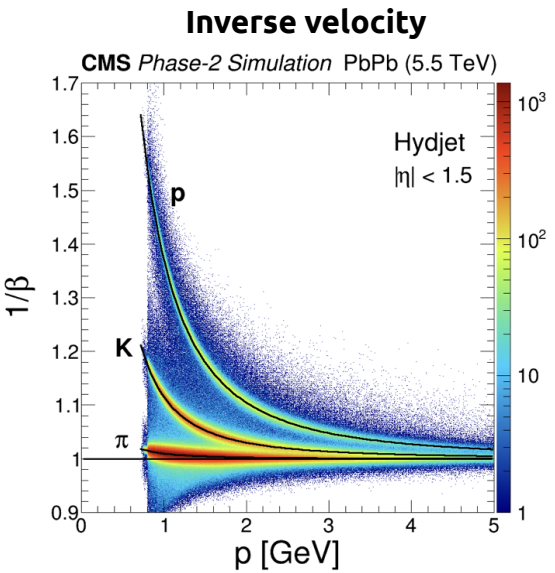
- Designed for pile-up mitigation

ATLAS HGTD : 2.4 < η < 4.0 , TDR in preparation
CMS MTD : hermetic up to η = 3 → PID of protons up to $p_T \approx 5$ GeV;
pions and kaons up to $p_T \approx 2.5$ GeV



Experiment	η coverage	L at $\eta = 0$ (m)	σ_T (ps)	L/σ_T ($\times 100$)
CMS	$\lvert\eta\rvert < 3.0$	1.16	30	3.9
ALICE	$\lvert\eta\rvert < 0.9$	3.7	56	6.6
STAR	$\lvert\eta\rvert < 0.9$	2.2	80	2.2

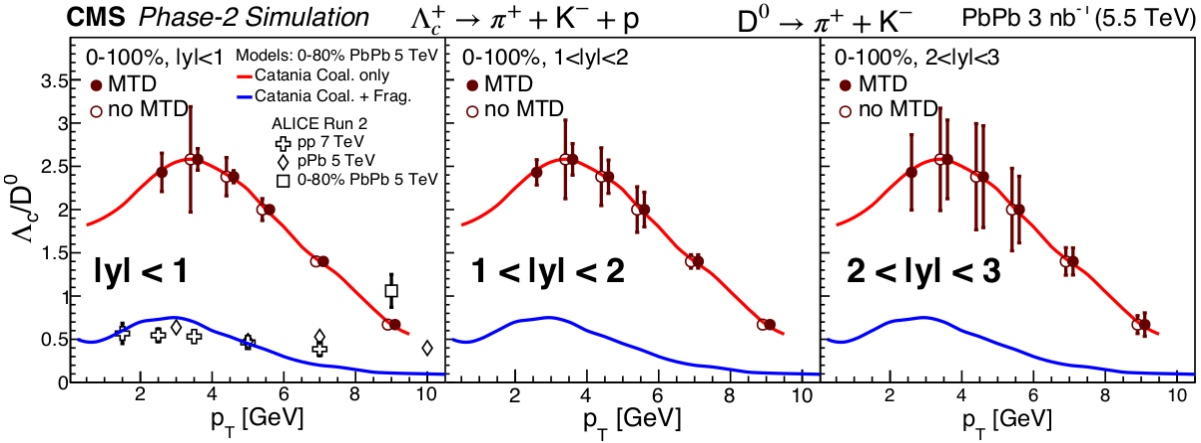
CERN-LHCC-2017-027



CMS MTD to probe charm hadronization effects :

- Precision in mid-rapidity is significantly improved → competitive to ALICE (including Phase2 upgrades)
- Gives insights into the forward region → complimentary to ALICE

[CMS-TDR-020]



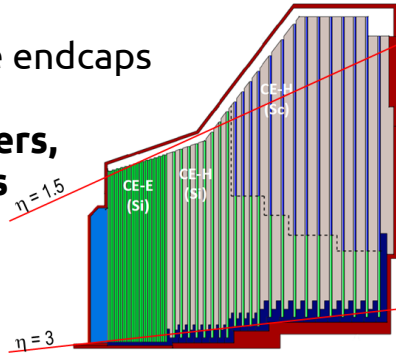
Geonhee Oh's talk
(4 Jun 2020, 11:35)

CMS and ALICE: High Granularity Calorimeter

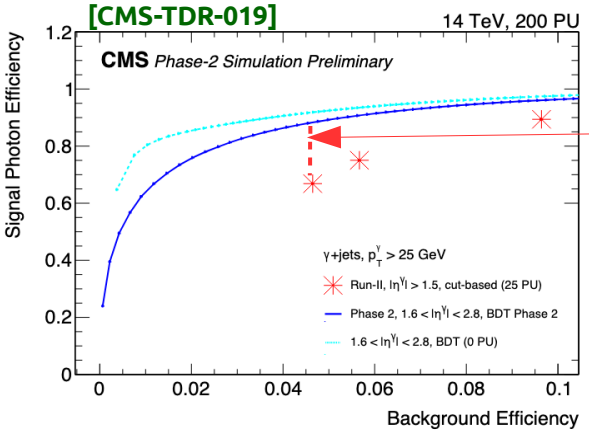
Run4

CMS HGCAl = ECAL and HCAL in the endcaps

Completely new type of calorimeters, based on Si-sensors with 6 millions channels



[CMS-TDR-019]

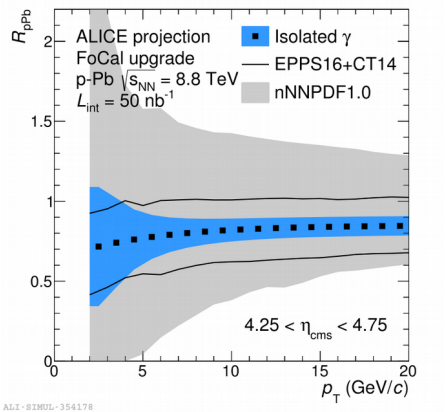


Improvement in pp : up to 25%

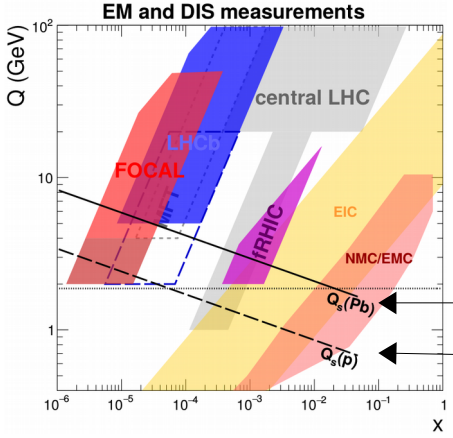
|η| < 1.44 → 2.8 : for isolated photons, photon-jet and jet substructure measurements

ALICE FOCAL design : similar to CMS HGCAL one (rapidity range 3.4-5.8) → **direct photon measurement at low p_T**

5% accuracy (p_T > 5 GeV) on the direct photon measurement



[ALICE-PUBLIC-2019-005]



Gluon density in protons and Pb nuclei at x ~ 10^{-5} :

gluon saturation and non-linear effects in the gluon density may become apparent

Estimated saturation scale for Pb

Estimated saturation scale for proton

LHC experiments: Trigger, DAQ and Computing

	Run3+4 statistics goals	Upgrades
ALICE	100B MB events	**New Online-Offline system :** • data readout, compression, processing, data volume reduction > an order magnitude **New Fast Interaction Trigger Detector (instead of T0 and V0)** **Continuous readout**
LHCb	pPb/Pbp : x20 more statistics	Readout the full detector at 40 MHz (pp collisions) Real time reconstruction and selection on bunch crossings at ~30 MHz with 5 visible pp collisions **SMOG2 : simultaneous runs with collision mode**
CMS and ATLAS	• x10 more statistics for triggerable probes • Large MB sample	**In Run4 : L1 and HLT read-out rates x10 wrt Run2**

Summary

- **ALICE and LHCb upgrades** for **Run3** are already in the comissioning phase
- **CMS and ATLAS upgrades** are in the R&D and production phase, to be installed for **Run4**
- Higher LHC luminosity and enhanced readout capabilities of all detectors → **very high statistics**

High precision measurements of the QGP properties with standard candles and new rare probes

And many more topics to explore :

- Extension of “small systems” program : pPb, OO (and pO) run, pp 14 TeV low-PU run …
- Hadronic physics with SMOG2
- BSM searches in PbPb UPC collisions
- …

Thanks to: M. van Leeuwen, J. Klein, S. Panebianco and M. Winn (ALICE), I. Cali and M. Nguyen (CMS), B. Audurier (LHCb)

Additional slides ahead …

Proposal for future luminosity at LHC from WG5

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	

CERN-LPCC-2018-07

ALICE : ALPIDE (ALICE Pixel Detector)

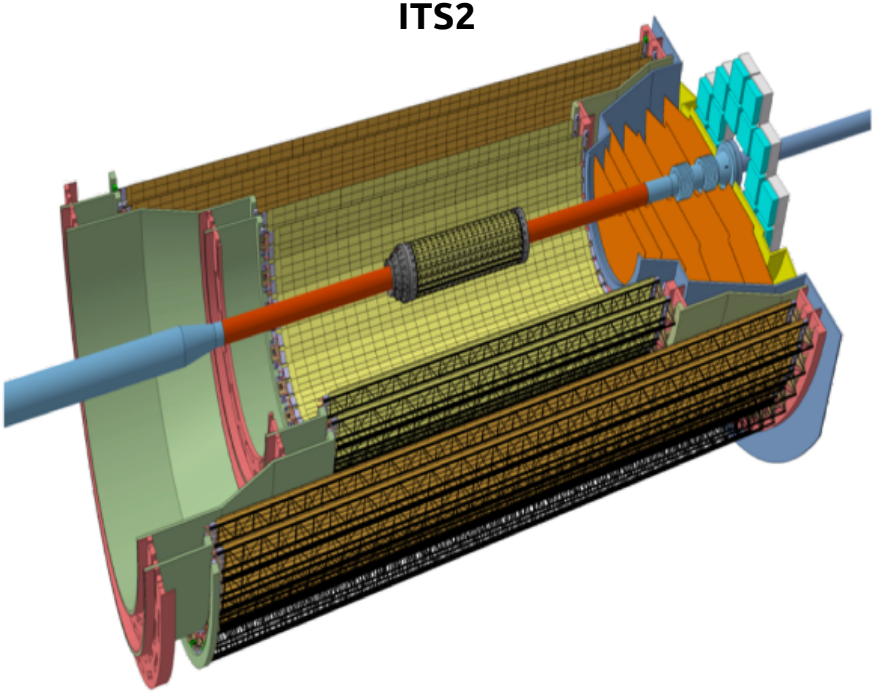
- Developed for the ALICE upgrade (ITS and MFT)
- 130 000 pixels/cm^2
- Max. particle rate: ~ 100 MHz/cm^2
- Spatial resolution: ~ 5 μm
- Thickness: 50 μm for the inner layers
- Fake-hit rate: < 10^{-9} /pixel/event

10 m^2 active silicon area, 12.5×10^9 pixels

Improves vertex and tracking precision, faster readout:

- Closer to IP: 39 mm → 22 mm
- Pseudorapidity coverage: $-1.0 \leq \eta \leq 1.0 \rightarrow -1.4 \leq \eta \leq 1.4$
- Thinner: for innermost layers ~ 1.14% X_0 → ~0.35% X_0
- Smaller pixels: 50 × 425 μm^2 → 27 × 29 μm^2
- Granularity: 20 ch/cm^3 → 2000 pixels/cm^3
- Readout rate: 1 kHz → 100 kHz

ITS2



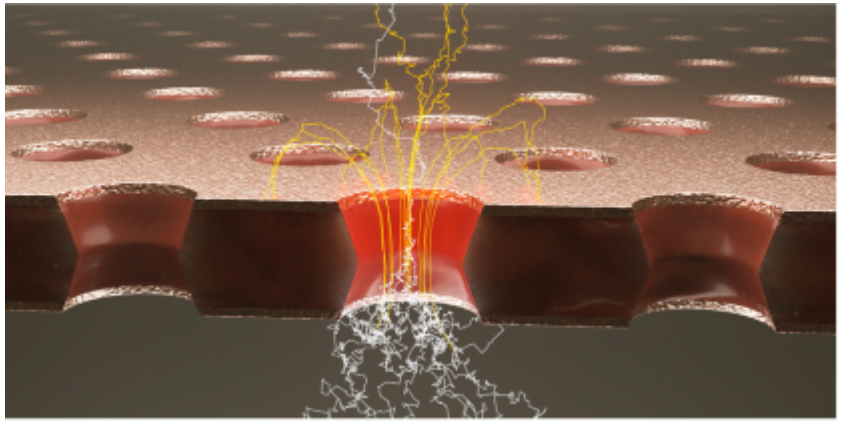
ALICE : Gas Electron Multiplier for TPC readout

Today's readout-electronics for gaseous detectors aren't sensitive to ~single electrons

→ Primary ionisations need to be amplified
→ Increase the kinetic energy of primary electrons until they further ionise the gas
→ Transport the electrons into a region with high electric field to provide the electrons with enough kinetic energy to create **electron multiplication**

Requirements for TPC readout :

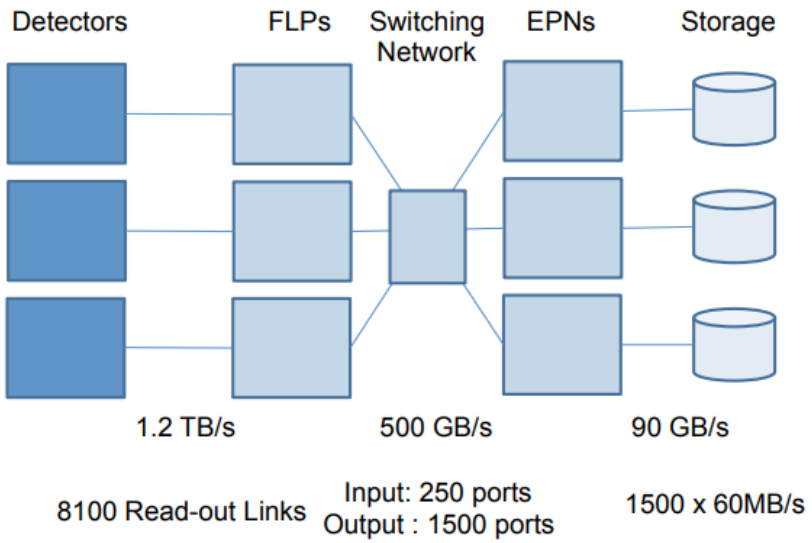
- Nominal gain = 2000
- Ion backflow < 1%
- Energy resolution : σ_E/E < 12% for ^{55}Fe
- Stable operations



ALICE : data flow

Reading out PbPb collisions at rates of 50kHz, sampling the pp and pPb at up to 200kHz.
The resulting data throughput from the detector : > 1TB/s for PbPb events.

- **Detector** Front-end electronics send data according to time intervals and/or trigger over ~ 8100 read-out links
- Local aggregation of data from up to 48 optical links per **First Level Processor** in Timeframes; Local reconstruction and calibration.
- **Switching Network:** Physical transportation of timeframe data
- **Event processing node:** Aggregation of all sub-timeframes and global reconstruction of the full Timeframe data sample
- Intermediate/permanent **storage** of pre-processed and compressed data



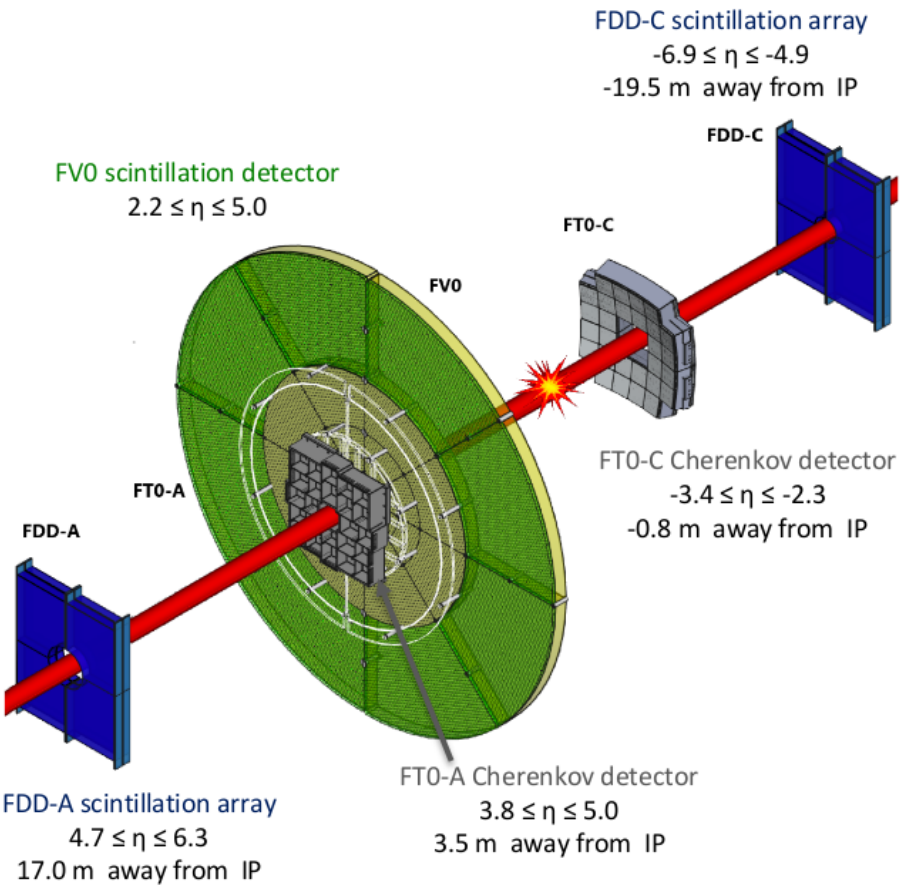
ALICE : Fast Integration Trigger (FV0, FT0, FDD)

Upgrade of the existing T0 and V0 and AD detectors :

- Luminosity leveling
- Identification of diffractive processes
- Fast Interaction Trigger with latency < 425 ns :

  → Online vertex determination
  → Minimum bias and centrality selection
  → Rejection of beam/gas events
  → Veto for ultra peripheral collisions

- Multiplicity → Centrality and Event Plane
- Collision time for Time-Of-Flight particle ID

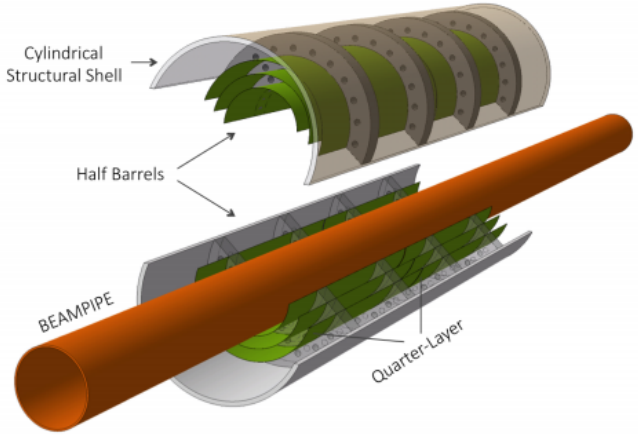


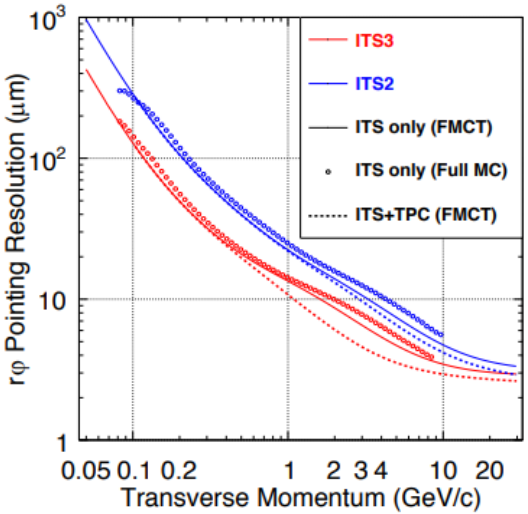
ALICE : ITS3

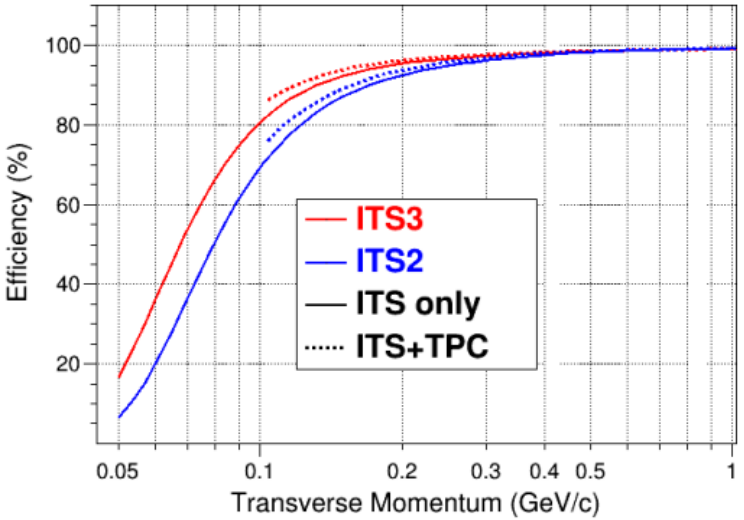
- Smaller beam pipe diameter
- Sensor thickness 20 - 40 μm (0.02 - 0.04% X_0)
- Total material up to r~4 cm reduced by a factor of 3
- Material homogeneously distributed

→ essentially zero systematic error from material distribution

- Plug-in replacement of the current Inner Barrel



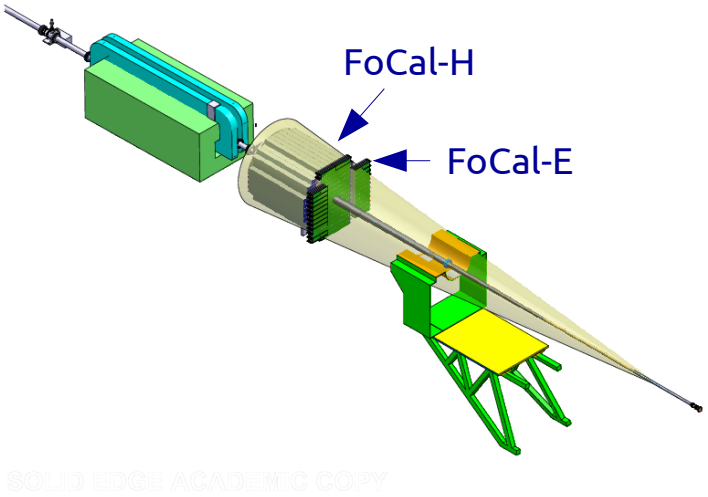




- Pointing resolution x2 better
- Improved tracking efficiency for low momenta

→ **Improved physics performance for heavy-flavour baryons and low-mass dielectrons**

ALICE : FOCAL



FoCal: forward electromagnetic and hadronic calorimeters

→ **FoCal-E:** high-granularity Si-W sampling calorimeter for the measurement of direct γ and π^0

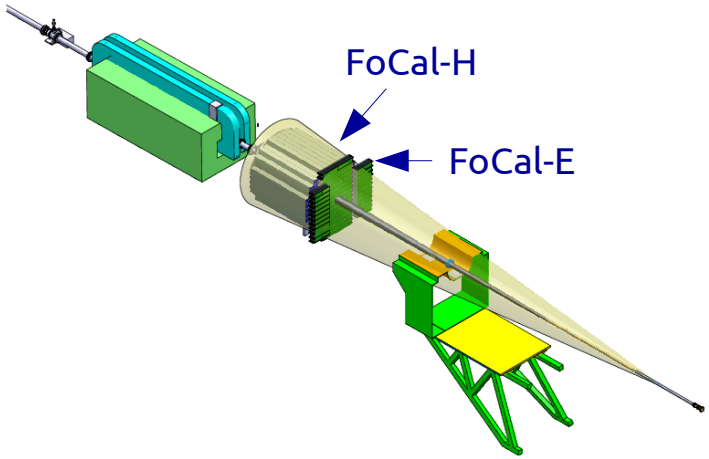
→ **FoCal-H:** Pb-Sc sampling calorimeter for photon isolation and jets

Main challenge: separate γ and π^0 at high energy

- two photon separation from π^0 decay ~2 mm
- needs small Molière radius and high granularity readout
- Si-W calorimeter with effective granularity ~1 mm^2

Timeline : TDR end of 2021

ALICE : FOCAL



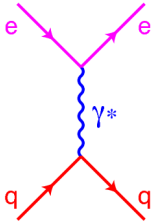
FoCal: forward electromagnetic and hadronic calorimeters

→ **FoCal-E:** high-granularity Si-W sampling calorimeter for the measurement of direct γ and π^0

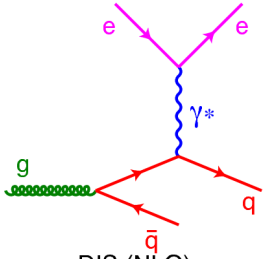
→ **FoCal-H:** Pb-Sc sampling calorimeter for photon isolation and jets

Deep-Inelastic Scattering (DIS) :

- Classical PDF method
- Not sensitive to gluons at LO
- Gluons from NLO



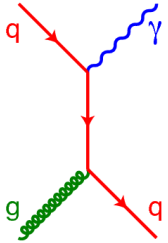
DIS (LO)



DIS (NLO)

Photon production in hadronic collisions :

- **Sensitive to gluons at LO**

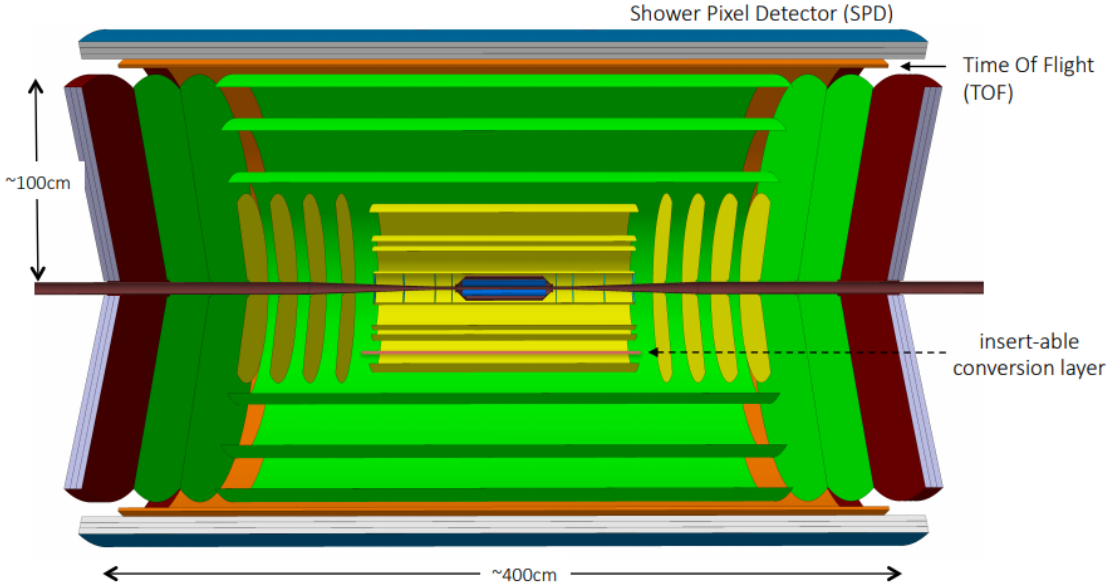


direct-γ, Compton (LO)

Next generation HI detector

https://arxiv.org/abs/1902.01211

- EoI for a “all silicon” detector to be installed during LS4, input to the European Strategy Update
- Increase rate capabilities : factor 50 wrt to ALICE Run 4
- Tracker: ~10 tracking barrel layers based on MAPS
- TOF PID – few barrel layers instrumented with silicon sensors : σ_t < 30 ps
- High-granularity shower pixel detector for e/γ identification

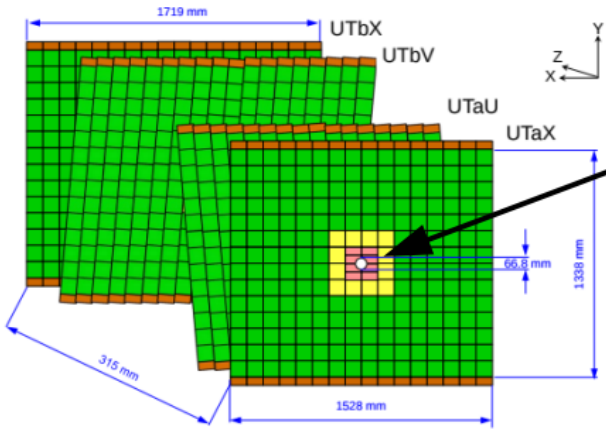


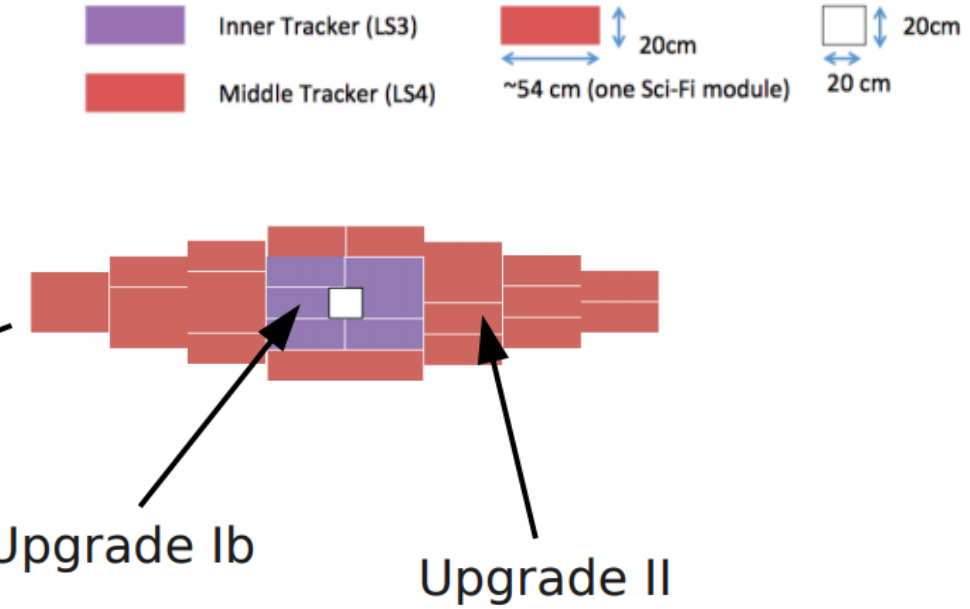
Physics: from EM probes at ultra-low p_T to precision physics in charm and beauty sector

LHCb : MIGHTY silicon tracker starting from Run4

Composed of a silicon central region (Inner Tracker and Middle Tracker) and an outside part with SciFi

New Upstream Tracker for Run3
(based on Si strip sensors)





Upgrade Ib : Inner Tracker + Scifi

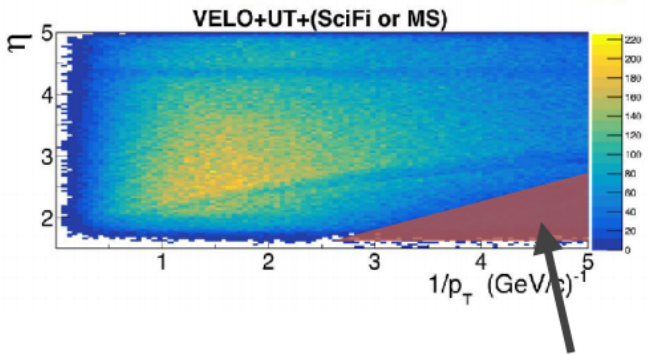
Upgrade II: New mighty silicon tracker covering larger area.

LHCb : Magnet Tracking Station for Run4

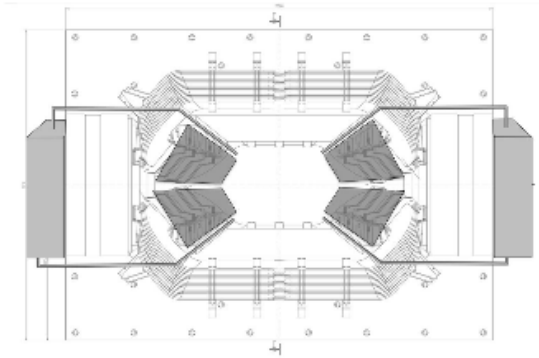
Proposal for tracking station inside the magnet :

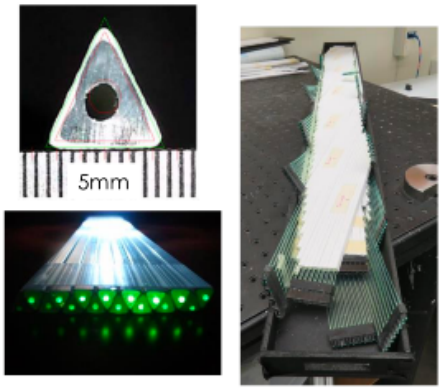
- Triangular Extruded Scintillating Bars
- Increase coverage of low-p_T tracks.
- Physics motivations : access to converted photons.

Proposing the installation of a small prototype inside the magnet during LS3.

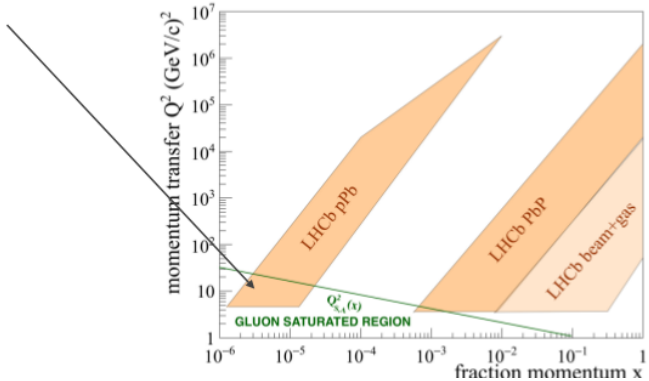


Extended acceptance





Extended coverage



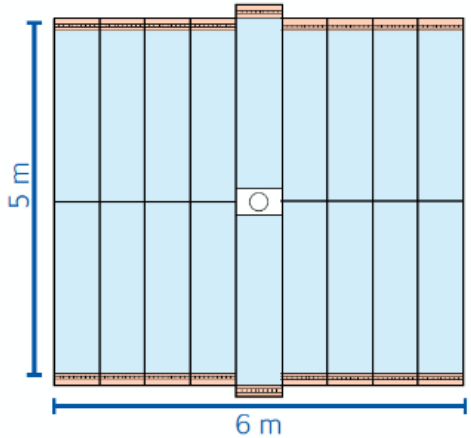
LHCb : Time of Reflected Cerenkov Light Rich (TORCH)

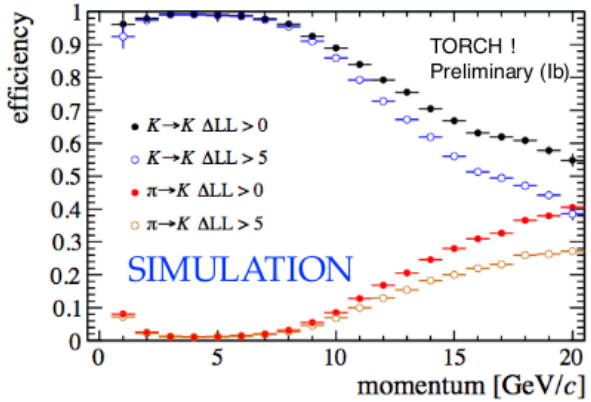
Wall of 18 elements in front of RICH2 :

- Exploit prompt production of Cherenkov light in a quartz radiator plate to provide a fast timing signal.

- **Aim for a resolution of 10-15 ps per track**
- A large-scale prototype has been developed

Good separation between pion/K/p is possible in 2-10 GeV/c range





Half-scale demonstrator

[LHCb-INT-2019-006]

CMS : tracker upgrade

Material budget :

- Fewer layers
- Lighter materials
- Optimized service routing
- New geometry

Radiation level :

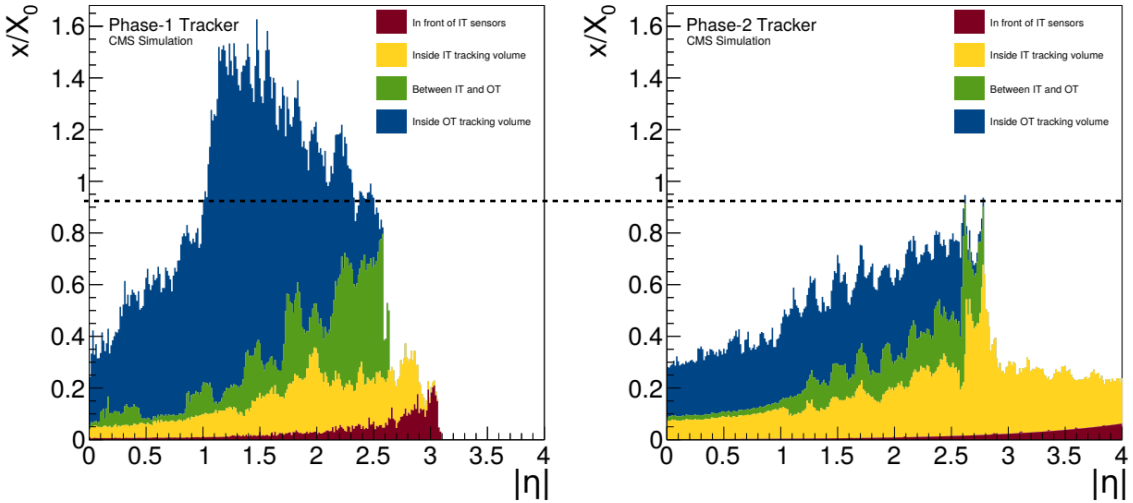
- 1000 fb^{-1} limit → 3000 fb^{-1} limit

Number of channels :

- 10 million → 200 million

Forward coverage :

- $|\eta| < 2.5$ → $|\eta| < 4$

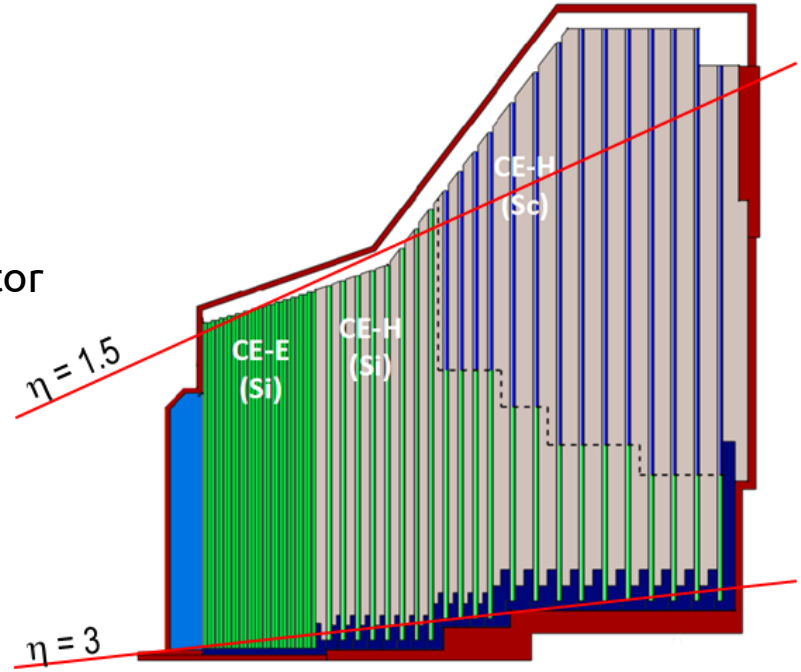


CMS : HGCAL

Sampling calorimeter consists of:

- 28 layers Si-based EM compartment (**CE-E**), ~25X_0 and ~1.3λ
- 22 layers hadronic compartment (**CE-H**): Si-based + Scintillator tiles, ~8.5λ

- ~620 m^2 Si sensors in ~30k channels
- **6M Si channels of 0.5/1 cm^2 cell size**
- ~400 m^2 of scintillators in 4k boards
- ~240k scintillators channels, 4-30 cm^2 cell size
- Operating temperature: -35 C



CMS : Trigger and DAQ upgrade

CMS detector	LHC Run-2	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size	2.0 MB [a]	5.7 MB [b]	7.4 MB
Event Network throughput	1.6 Tb/s	23 Tb/s	44 Tb/s
Event Network buffer (60 seconds)	12 TB	171 TB	333 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [c]	0.5 MHS06	4.5 MHS06	9.2 MHS06
Storage throughput	2.5 GB/s	31 GB/s	61 GB/s
Storage capacity needed (1 day)	0.2 PB	2.7 PB	5.3 PB

[a] Design value.

[b] Obtained by scaling the Event Size at ⟨PU⟩ = 200 with pile-up (140/200), except for sub-detectors with fixed size readout.

[c] Does not include Data Quality Monitoring.

[CMS-TDR-018]