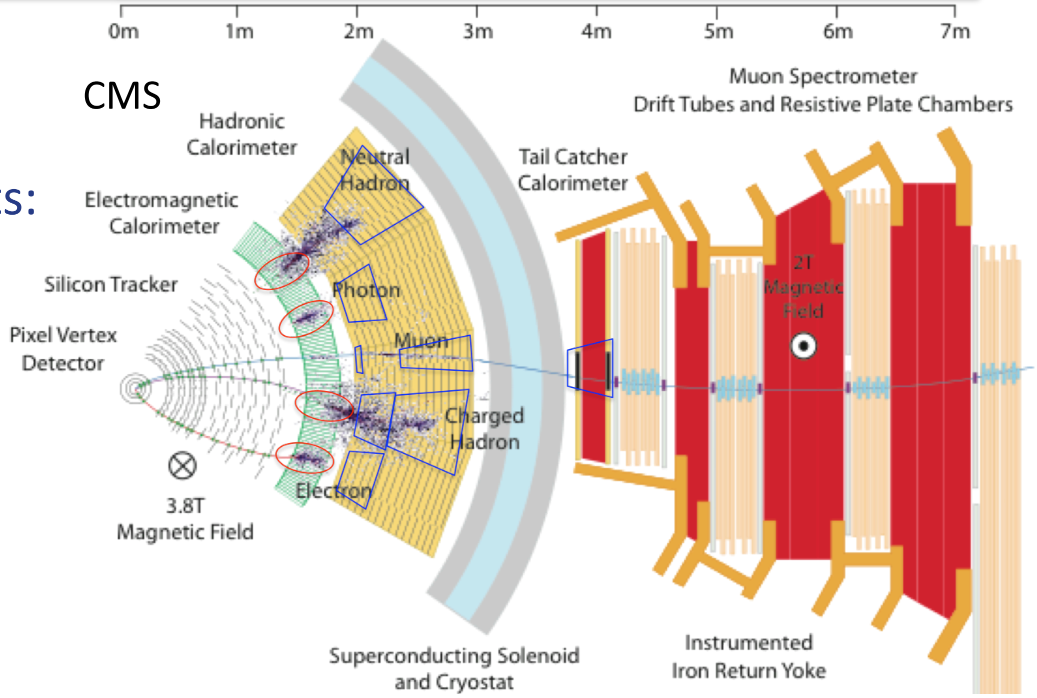
ATLAS and CMS Upgrade programs and performance goals

RLIUP LHC workshop
Archamps, Oct. 29
D. Contardo

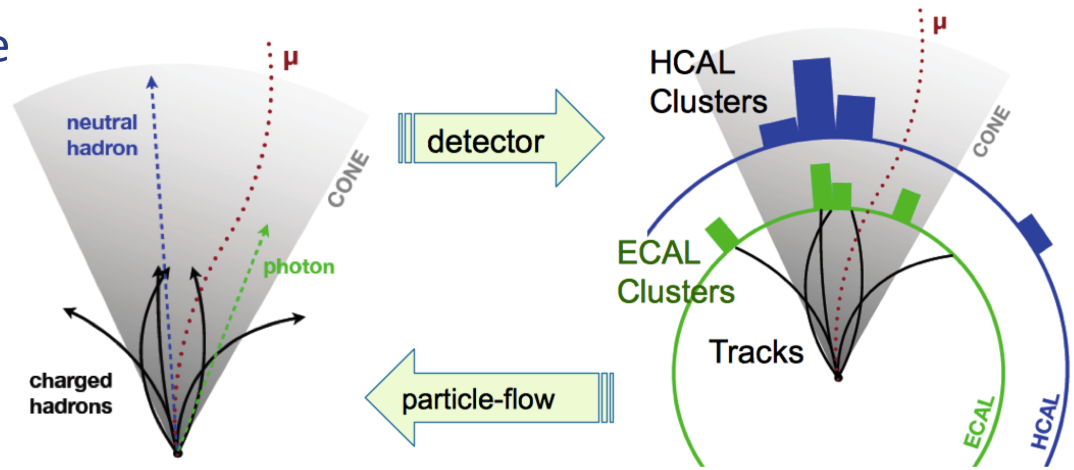
- Physics goals and detector longevity in presentations of Fabiola & Beniamino
- In this talk
  - ATLAS and CMS upgrades through LHC luminosity rise
  - Focus on performance at high rate and pile-up

The challenge of high luminosity



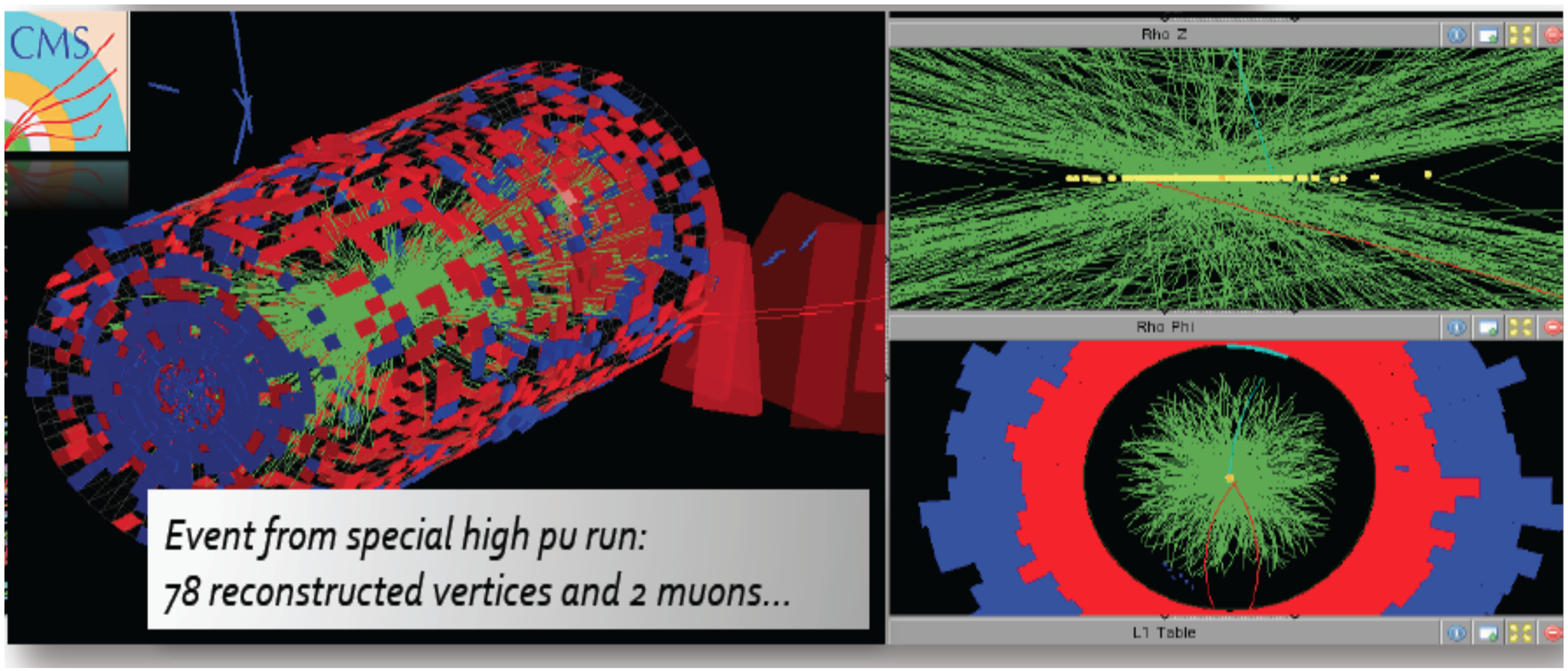
- Detector measures charge deposits:
  - Charged particles (tracker)
  - e/γ (electromagnetic calorimeter)
  - Hadrons (hadronic calorimeter)
  - μ (gas chambers)

- Sophisticated algorithms combine all information to reconstruct:
  - Physics objects
    - Identified and isolated particles
      - Jets - total and missing energy
  - Decay of fundamental particles
    - W, Z, H, t …



The challenge of high luminosity

- With multiple collisions per bunch crossing (Pile-Up) we mainly rely on the measurement of the charged track origin in the tracker to properly associate physics objects to the primary interaction of interest
  - The increasing PU affects
    - Mostly the Tracker and Calorimeters and the online Trigger event selection
    - And the data flow and the event complexity increase also requires higher readout bandwidth for all detectors and more computing capabilities

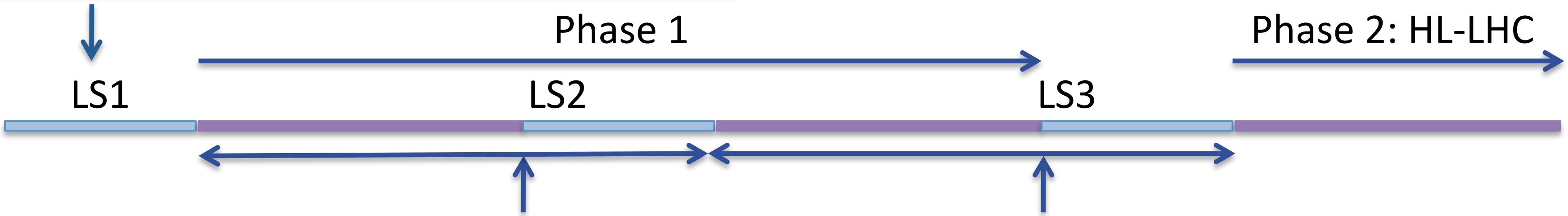


Experiments can reconstruct high piled-up event but are not designed to sustain it as a mean

ATLAS and CMS upgrade stages

LS1:

- Complete original detectors and consolidate operation for nominal LHC beam conditions 13-14 TeV, 1×10^{34} Hz/cm^2 , Ave. Pileup (<PU>) ~ 25
- Prepare or start upgrades for higher <PU>



LS1 through LS2:

- Prepare detector to maintain physics performance for
  - 1.6×10^{34} Hz/cm^2 , <PU> ~ 40, ≤ 200 fb^{-1} by LS2
  - 2.5×10^{34} Hz/cm^2, <PU> ~ 70, ≤ 500 fb^{-1} by LS3

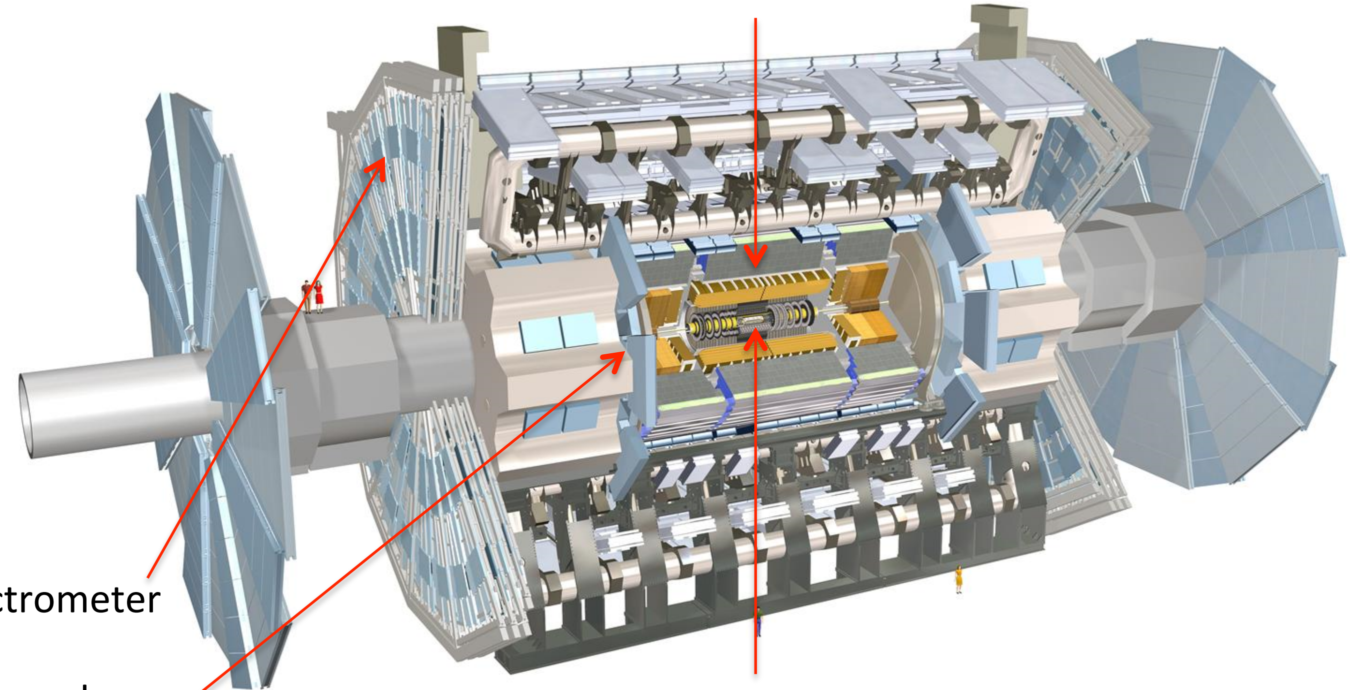
LS2 through LS3:

- Prepare for ≥ 5×10^{34} Hz/cm^2 (with leveling), <PU> 140 total of ~ 3000 fb^{-1} in ~10 years operation - consider higher PU operation
  - Replace subsystems that no longer function due to radiation damage or aging
  - Maintain physics performance at very high PU

ATLAS upgrades for Phase 1

Trigger/DAQ
→ New backend electronic systems
→ Fast Track Trigger (FTK) input at High Level Trigger
- before LS2

Liquid Argon calorimeter (barrel - endcap)
→ Front-end for finer granularity in Trigger
- during LS2



Forward proton spectrometer (AFP)

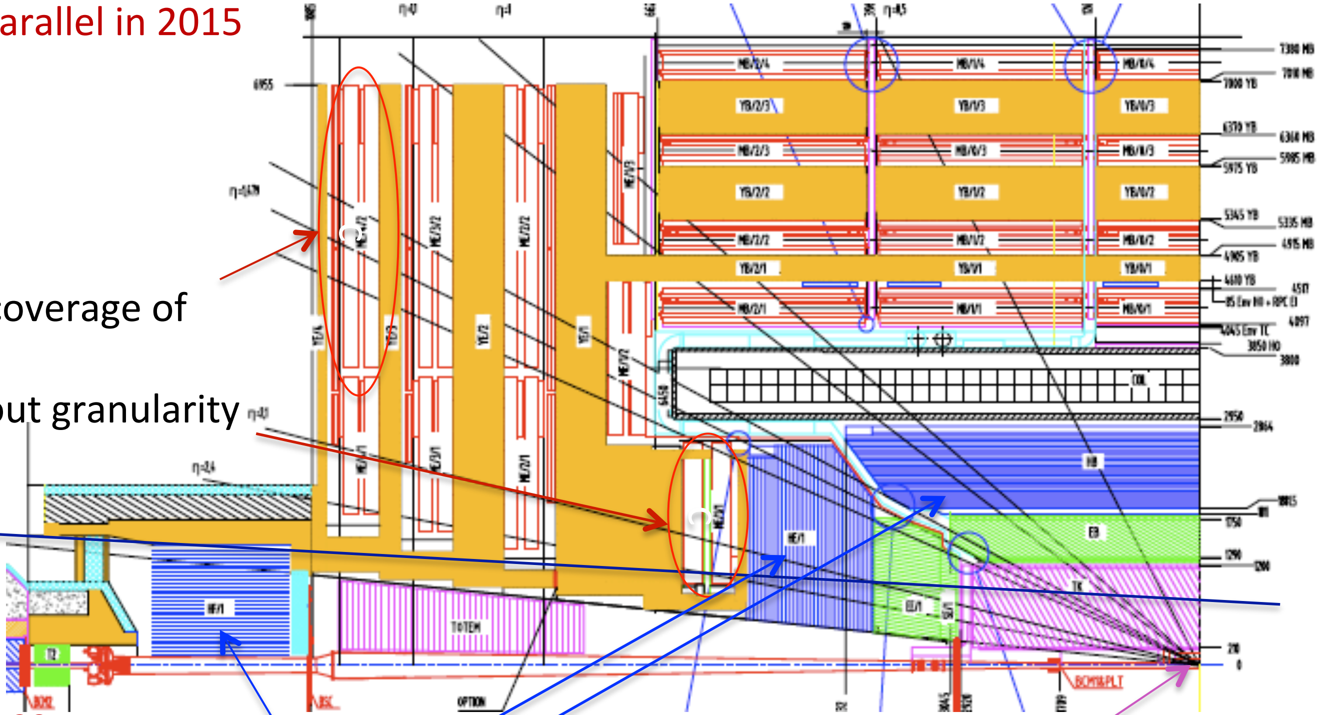
Muon systems
→ Complete muon spectrometer
- during LS1

→ New Small Wheel forward muon chambers (micromegas)
- during LS2

Pixel detector
→ Insertable Barrel Layer
- during LS1

LoI 2013 https://twiki.cern.ch/twiki/pub/Atlas/UpgradeLOI/LoI_v50_with_covers.pdf - TDRs last LHCC

CMS upgrades for Phase 1



Trigger/DAQ
→ New backend electronic systems
- Commission in parallel in 2015

Muon systems
→ Complete muon coverage of CSCs and RPCs
→ CSC higher read-out granularity
- during LS1

Forward proton spectrometer (PPS)
- staged from LS1 to LS2

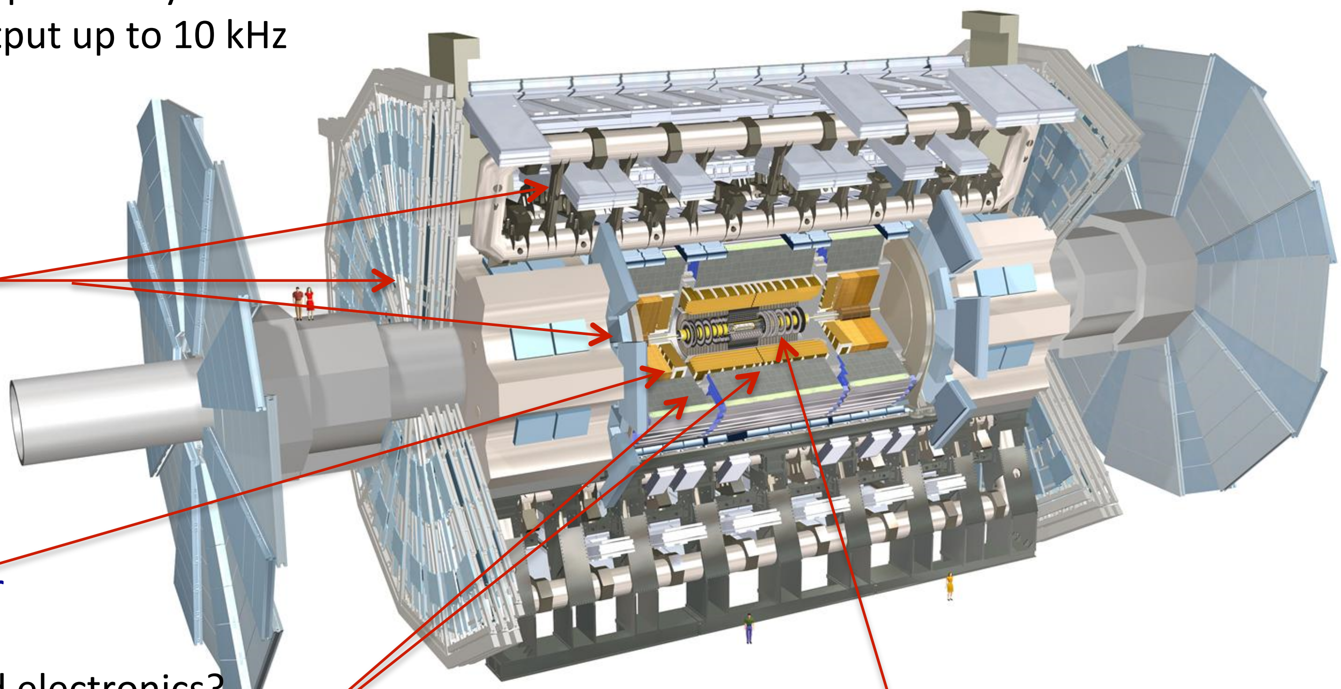
Hadron calorimeters HF/HE/HB
→ Replace photo-detectors and read-out
- staged from LS1 to LS2

Pixel detector
→ Full replacement
- extended YETS in 2016

TDRs: Pixel http://cds.cern.ch/record/1481838?ln=en - HCAL http://cds.cern.ch/record/1481837?ln=en
- L1-Trigger http://cds.cern.ch/record/1556311?ln=en

ATLAS upgrades for Phase 2

Trigger/DAQ
→ L1 rate at least 500 kHz
→ Tracks at L2 - 20 μs latency at least 200 kHz
→ Possible HLT output up to 10 kHz



Muon systems
→ New Front-End Electronics

Forward calorimeter
→ Replace FCAL ?
→ Replace HEC cold electronics?

Calorimeters: Liquid Argon - Tile calorimeter
→ New front-end and back-end electronics (full digital information at L1 trigger)

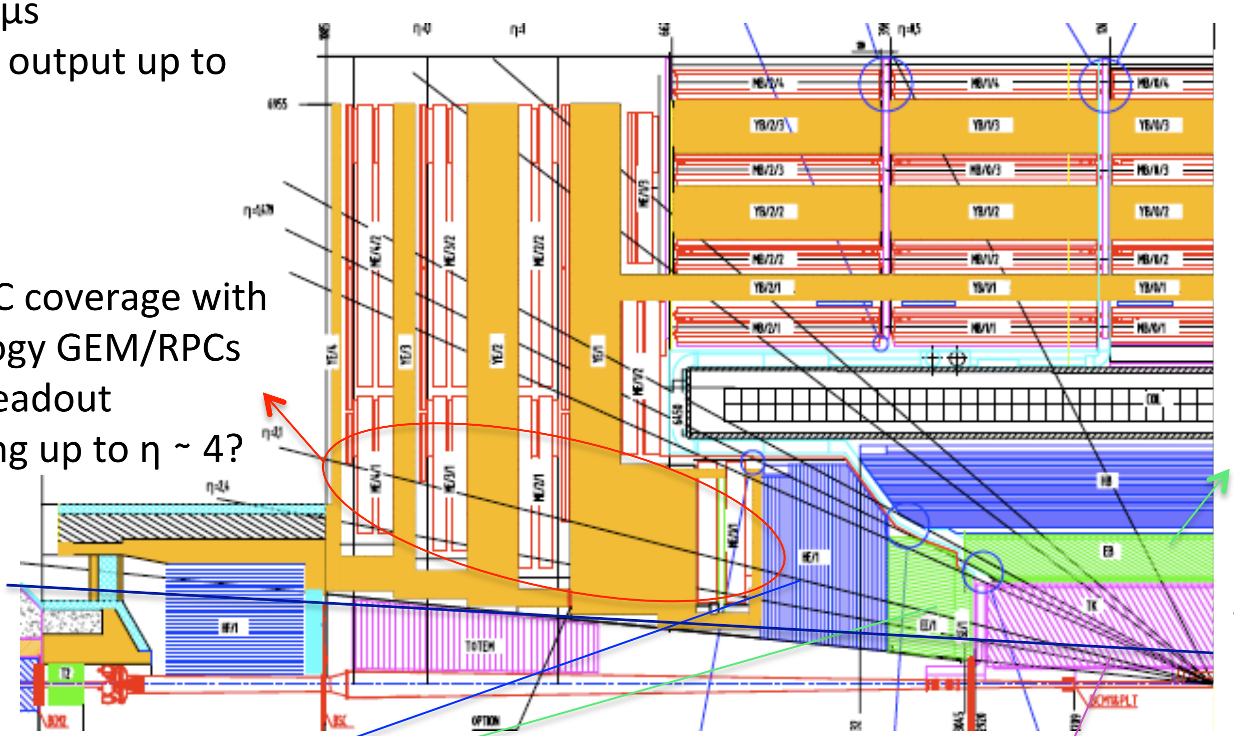
New Tracker
→ Longevity - occupancy - readout bandwidth
→ Implement Track Trigger in L2
→ Extend η coverage?

LoI in 2013 https://cds.cern.ch/record/1502664/

CMS upgrades for Phase 2

Trigger/DAQ
→ L1 rate up to 1 MHz with tracks
→ Latency ≥ 10μs
→ Possible HLT output up to 10 kHz

Muon systems
→ Complete CSC coverage with new technology GEM/RPCs
→ Replace DT readout
→ Muons tagging up to η ~ 4?



ECAL Barrel
→ New front-end electronics (crystal granularity)

Upgrade/Replace HE/EE
→ longevity
→ Extend coverage up to η ~ 4?
→ Precise timing measurement (also in barrel)?

Replace Tracking
→ Longevity - occupancy - readout bandwidth
→ Implement Track Trigger in L1
→ Extend coverage up to η ~ 4?

Technical Proposal in 2014

ATLAS and CMS Tracker upgrades

From Phase 1 to Phase2

Upgrade of ATLAS and CMS pixel detectors in Phase 1

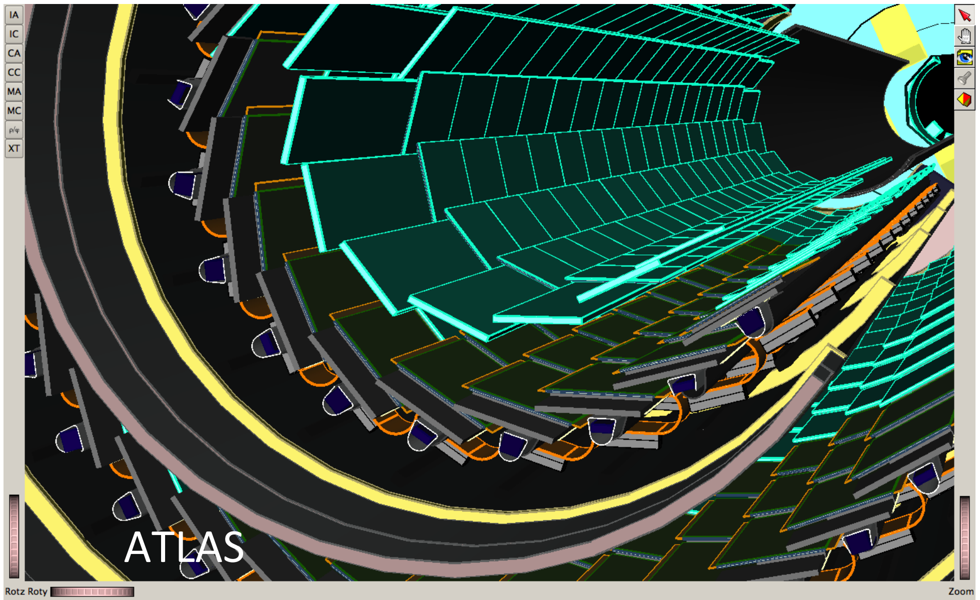
- Common features
  - 4 space points and smaller inner radius (3 cm)
  - Acceptance up to η = 2.5
  - Lighter detector

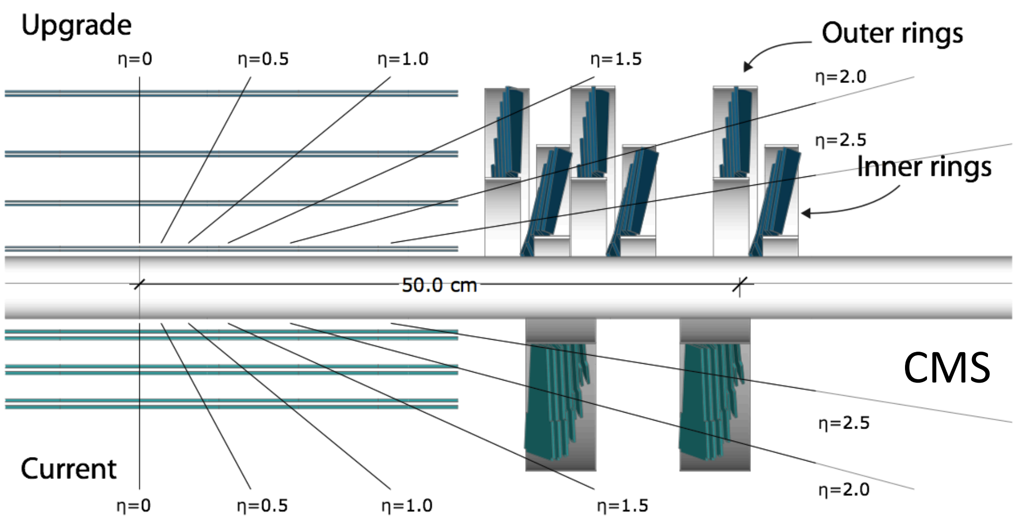
- ATLAS Insertable Barrel Layer
  - Use planar (75% at smaller eta) and 3D (25% at higher eta) technologies

→ Installation during LS1

- CMS new detector
  - Similar technology as present
  - New readout chip for high rate

→ Installation in Year End Technical Stop 2016-17

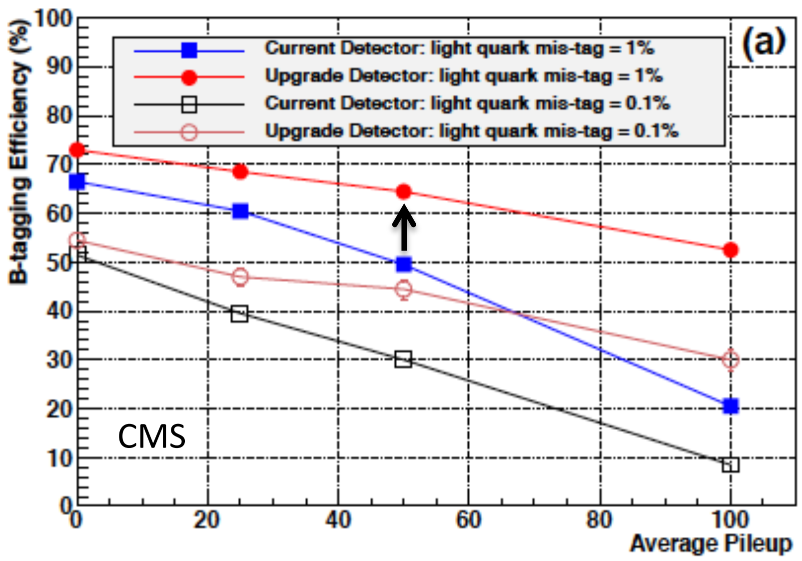


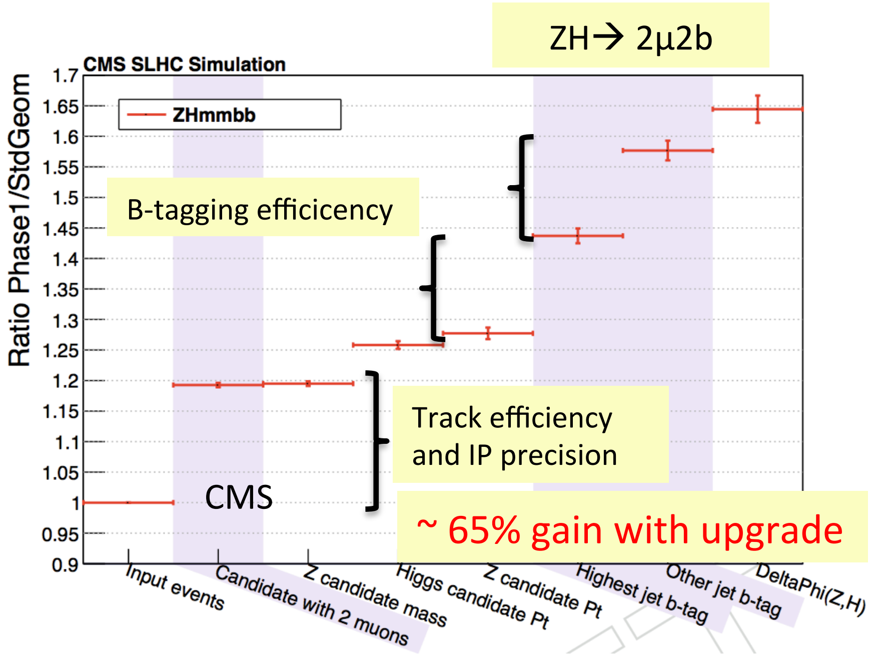


Performance of pixel detectors in Phase 1

- Improved track reconstruction efficiency and resolution
- Improved association of tracks at primary vertex and improved b-tagging (close secondary vertex)

  → Illustration below, gain in efficiency squares for multiple objects

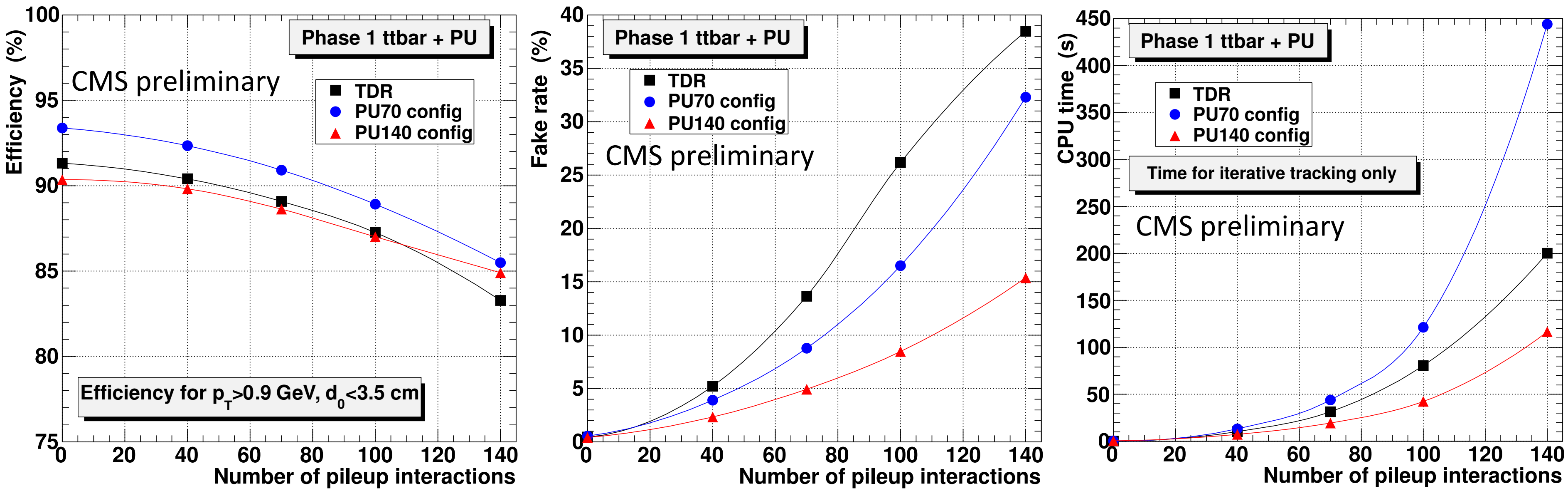




- Pixel detector upgrade is needed for Phase 1
- Can handle up to ~ 70 PU with present detector performance

Trackers for Phase 2

- At 140 PU Phase 1 track reconstruction performance degrades significantly
  - Despite significant improvements in offline algorithms and tuning (efficiency versus rate of fake tracks)

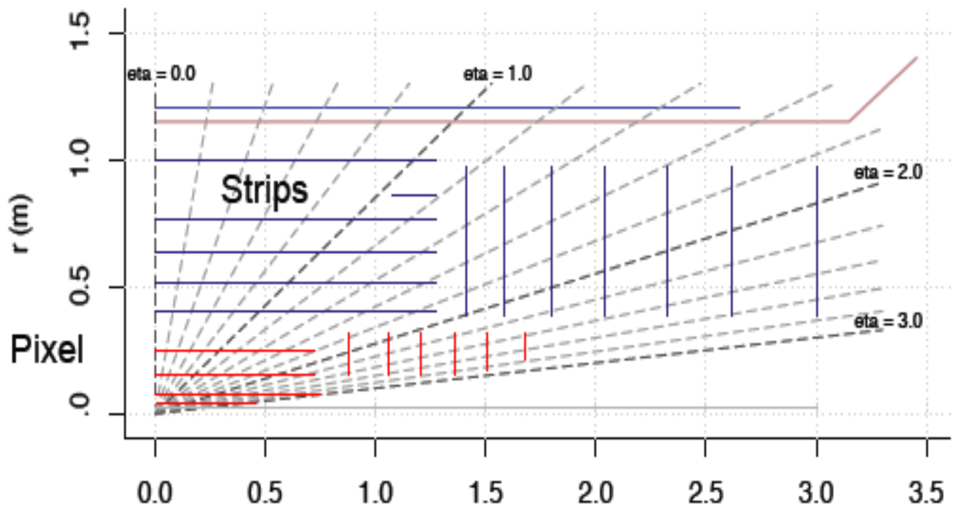


- Tracker requisites for Phase 2:
  - Higher granularity for efficient track reconstruction at 140 to 200 PU
    - And also increased readout bandwidth and improved computing and algorithms capabilities
  - Low beam pipe radius (as now) for precision
  - Integration in hardware Trigger level

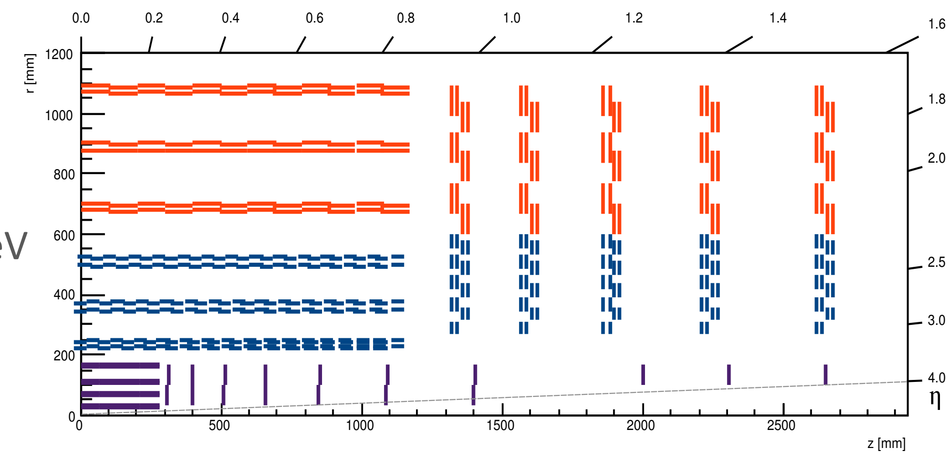
ATLAS and CMS Phase 2 Tracker designs

- Common features
  - Granularity
    - Strip pitch ~ 80-90 μm & length ~ 2.5/5 cm in inner/outer layers (& macro-pixel sensors in CMS 1.5 mm long)
    - Pixel pitch ~ 25-30 μm and ~ 100 μm length
  - Sensor Technology
    - n-in-p planar technology for increased radiation hardness
    - n-in-n, 3D, diamond or other technologies for innermost layers
  - Trigger implementation
    - Custom ASIC Associative Memory chips (as developed for FTK) for pattern recognition followed by a track fit in FPGA
- Specific configurations
  - CMS trigger read-out at 40 MHz - Pt-module concept select "stubs" for tracks with Pt ≥ 2 GeV
  - ATLAS read-out region of interest at ≥ 500 kHz
- Proposal to extend coverage of Pixel detectors up to |η| ~ 4
  - Associate jets to primary vertex through track matching

ATLAS design

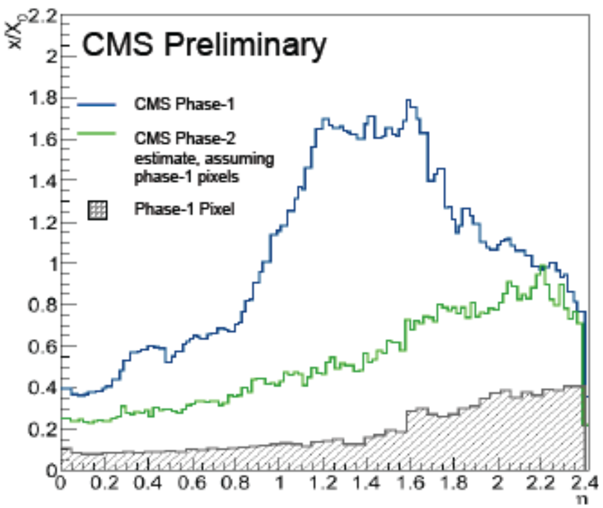


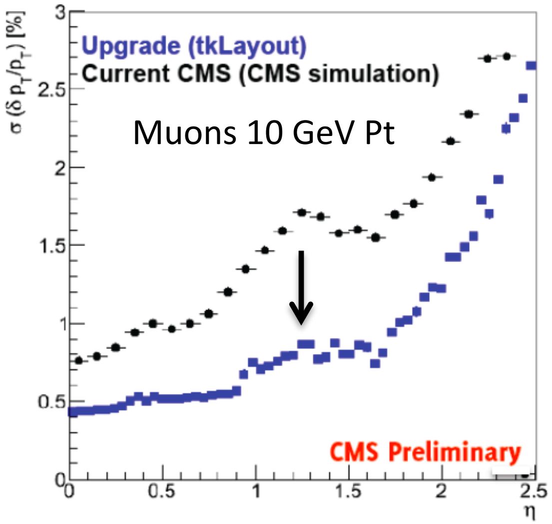
CMS design



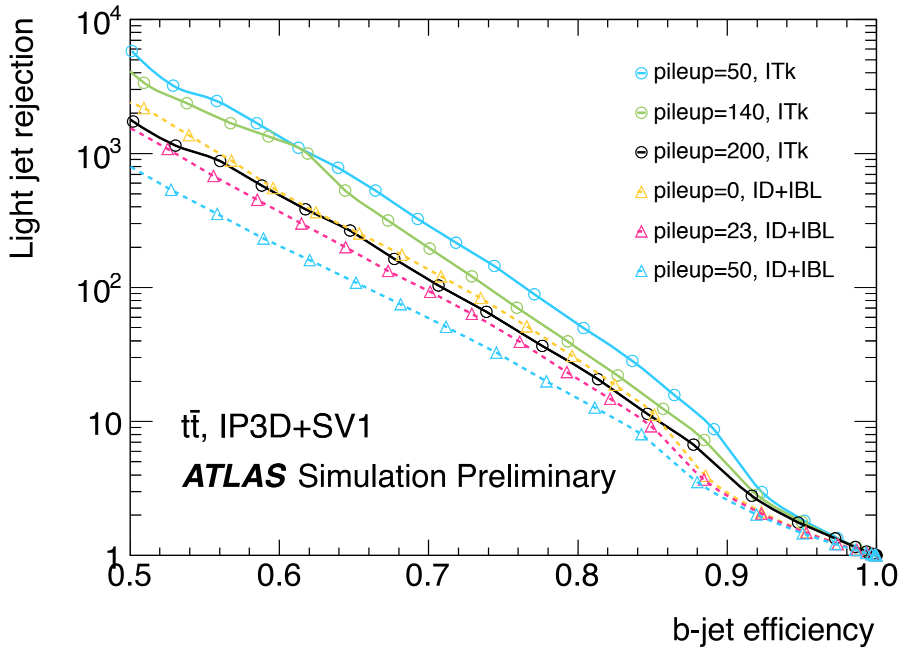
Performance of Phase 2 Trackers

- **Light weight** → improved momentum precision and lower rate of photon conversion
- **Lower pixel size** → improved tagging efficiency - good performance up to 200 PU
- **η extension** → lower rate of fake jets in region of VBF processes

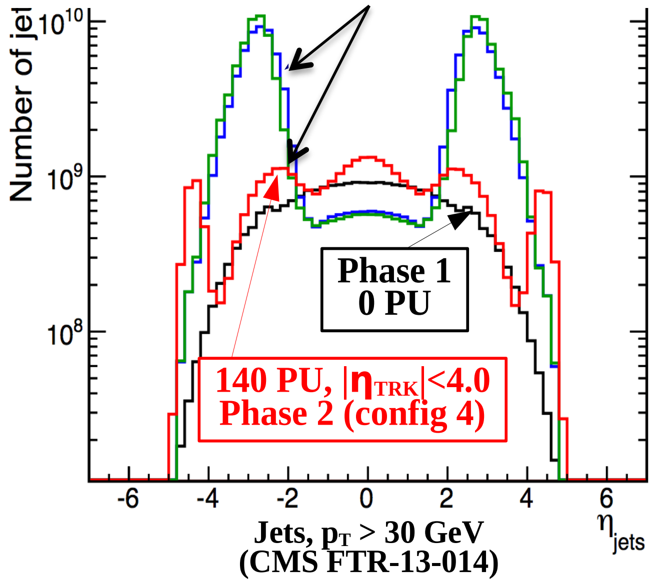




This will have major benefit for key physics channels at HL-LHC



Jet rate with & without pixel coverage extension at 140 PU



ATLAS and CMS Trigger upgrades

From Phase 1 to Phase2

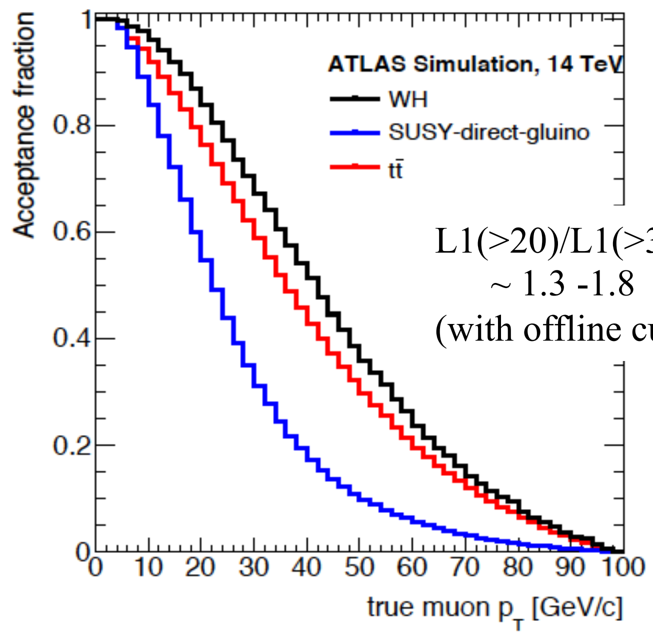
(includes upgrades of calorimeter and muon detectors)

Upgrade of ATLAS and CMS L1-Trigger systems in Phase 1

- In Phase 1 ATLAS and CMS L1-Trigger bandwidth is limited to 100 kHz
- Hardware event selection is based on calorimeter and muon information

CMS simplified menu	8 TeV 7E33 ~25 PU		14 TeV 2E34 50 PU	
	Thresh (GeV)	Rate (kHz)	Thresh (GeV)	Rate (kHz)
Single EG	22	10	46	10
Single IsoEG	18	9	31	9
DoubleEG	13, 7	9	22, 12	9
Single Muon	16	9	50	9
Dble Muon	10, open	5	35, open	5
EG+Mu	12, 3.5	3	21, 6	3
Mu+EG	12, 7	2	25, 15	2
SingleJet	128	2	188	2
DoubleJet	56	10	132	10
QuadJet	36	2	96	10
Double Tau	44	2	56	2
MET	36	7	84	7
HTT	150	2	511	2

- Aside, threshold raise to remain within 100 kHz at 2 x 10^{34} Hz/cm^2 without upgrades
- Multi-object trigger rates are highly non linear with increasing PU
- Physics acceptance will be significantly affected (example in plot below)

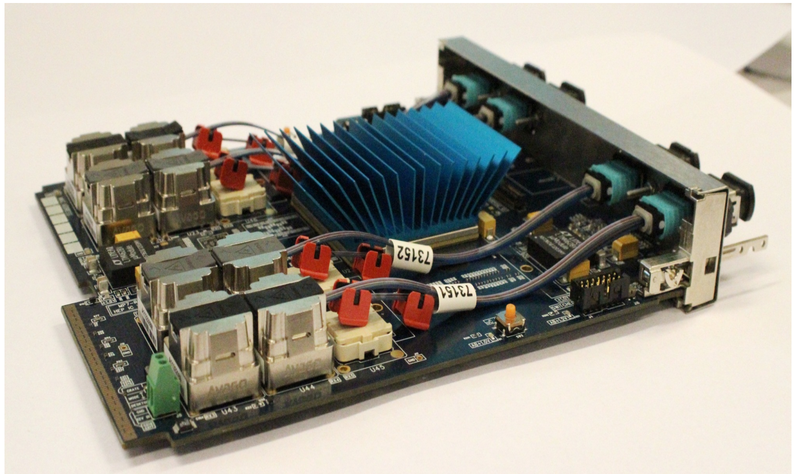


L1(>20)/L1(>30) ~ 1.3 -1.8 (with offline cuts)

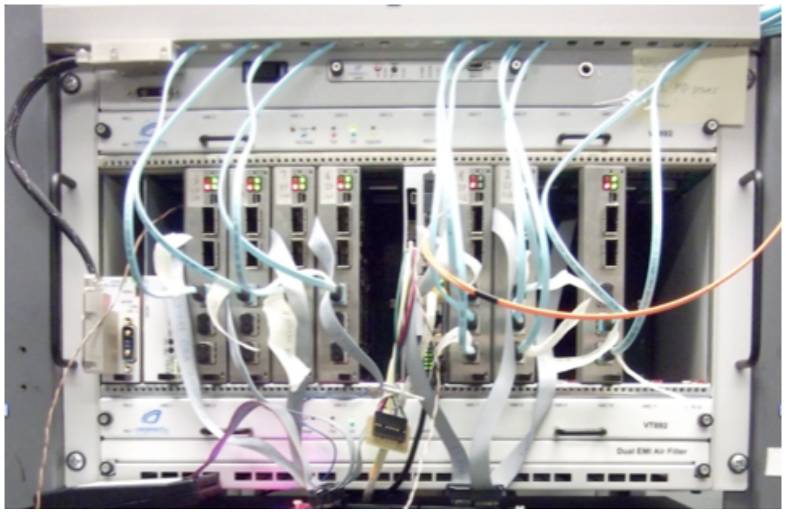
L1-Trigger upgrades are needed to operate at 50 pile-up

Upgrade of ATLAS and CMS L1-Trigger systems in Phase 1

- Common features
  - Higher bandwidth and processing power with modern FPGAs and xTCA back-plan
    - Improved calorimeter granularity
    - Improved muon trigger with new chambers and readout
    - More objects and topological triggers



CMS MP7 calorimeter trigger board & µTCA crate



- ATLAS
  - Fats Track Trigger input at HLT

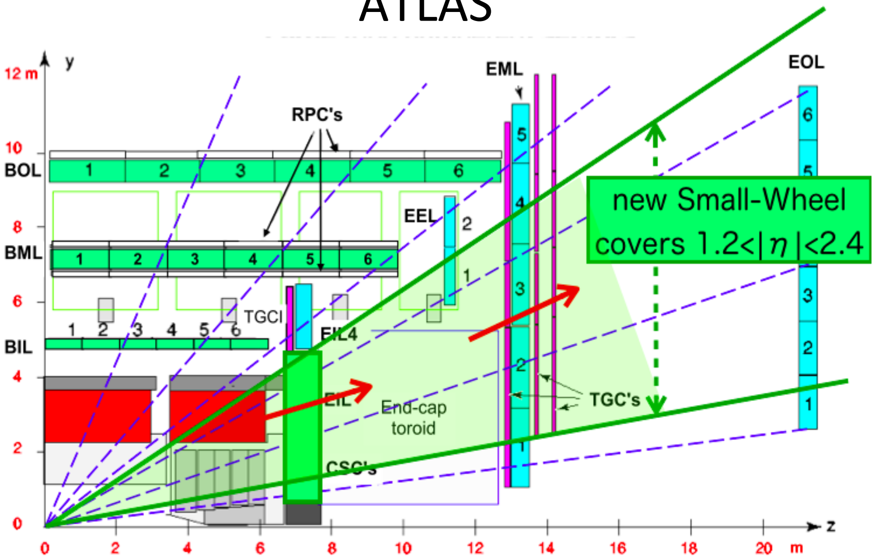
  → Installation through LS1 to LS2

- CMS
  - New architecture (Time Multiplexed Trigger) with full event in 1 Processor

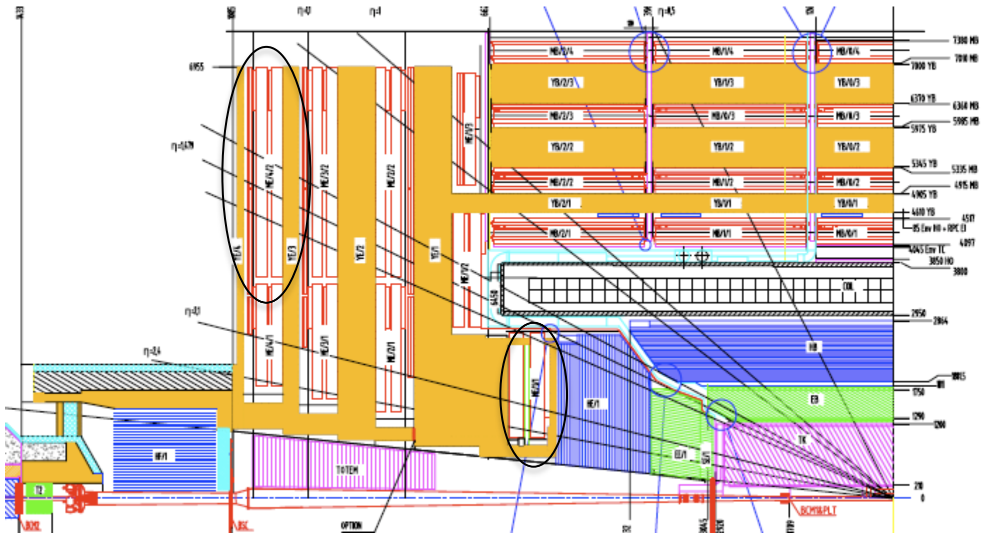
  → Slice after LS1 to grow to commissioning of new trigger in parallel for 2016 run

Upgrade of ATLAS and CMS Muon chambers in Phase 1

ATLAS

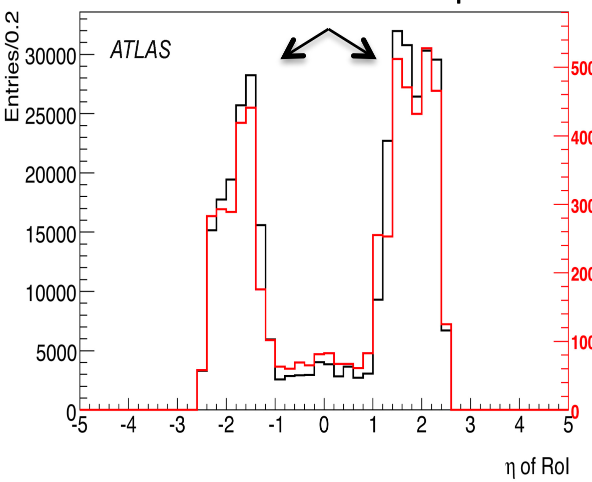


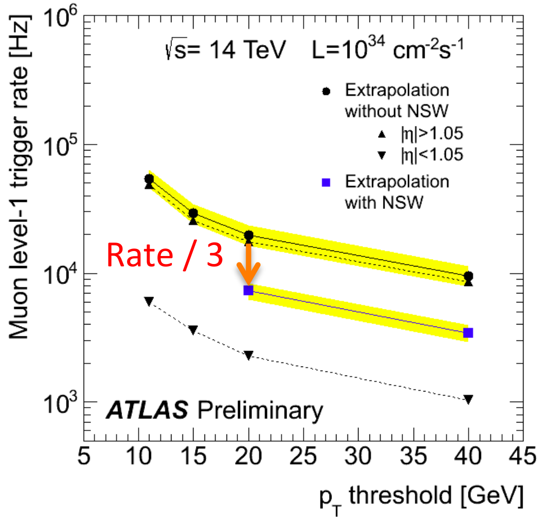
CMS

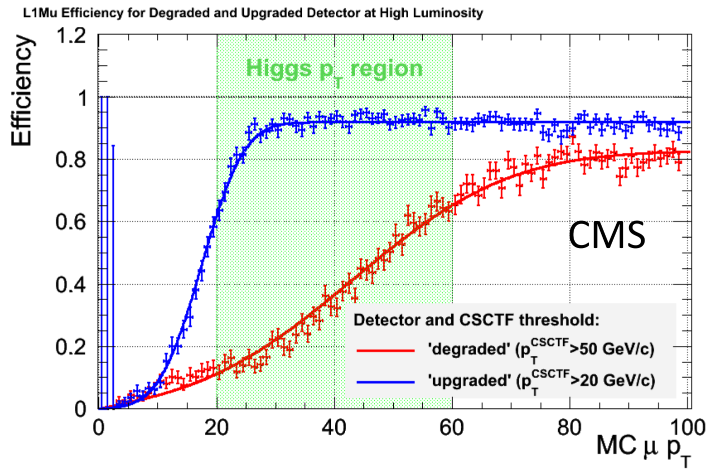


Similar issues and benefit in trigger for upgrades in ATLAS and CMS

Rates in endcaps



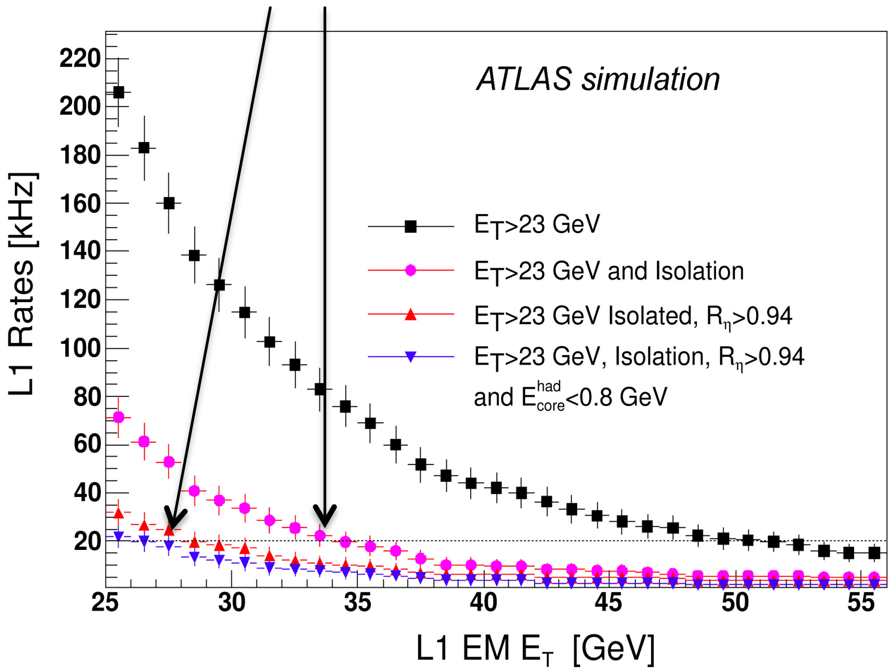


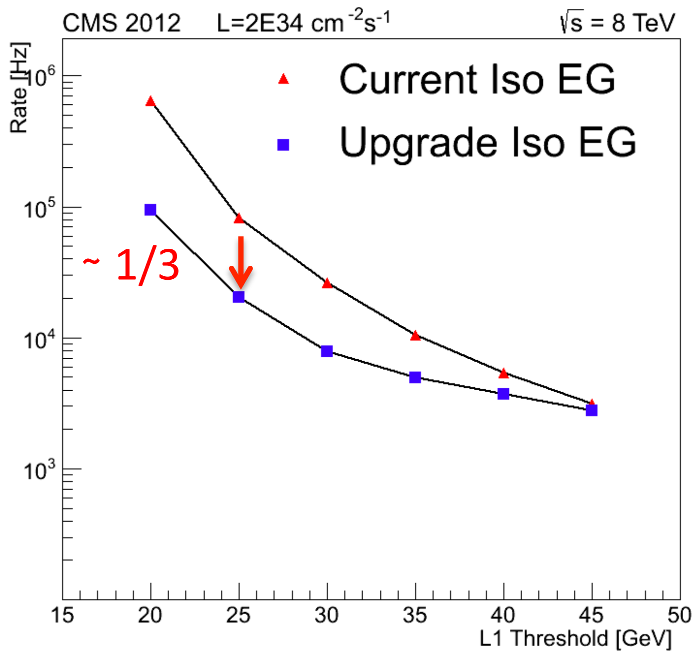


Upgrade of ATLAS and CMS Calorimeter Trigger systems in Phase 1

- Different implementations in ATLAS and CMS but similar benefits
  - e and γ isolation with PU subtraction
  - Jet finding and Et missing with PU subtraction
  - Improved τ identification
  - μ isolation
- Global trigger with topological capabilities
  - Mass selection, angular correlations…

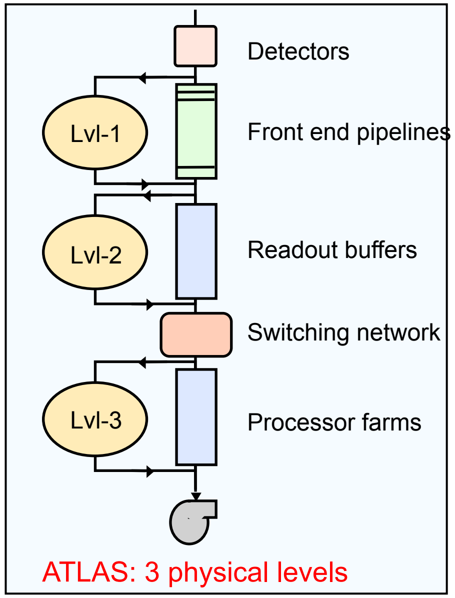
e/γ isolation W/O upgrades 1 x 10^{34} Hz/cm² $cm^{-2}s^{-1}$



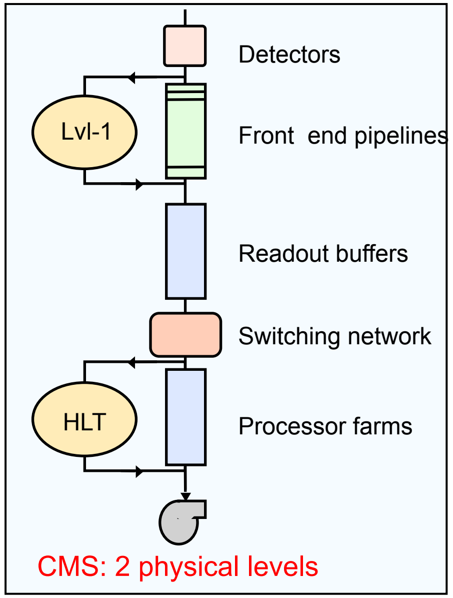


Trigger/DAQ systems for Phase 2

- ATLAS
  - Increase Level 1 bandwidth to 500 kHz in 5 μs latency
    - Readout of tracker information in Region of Interest
  - Level 2 in 20 μs latency with tracks and 200 kHz HLT input
  - Possible HLT output up to 10 kHz
  - → Requires
    - Upgrade of front-end and back-end electronics of Calorimeter and Muon detectors



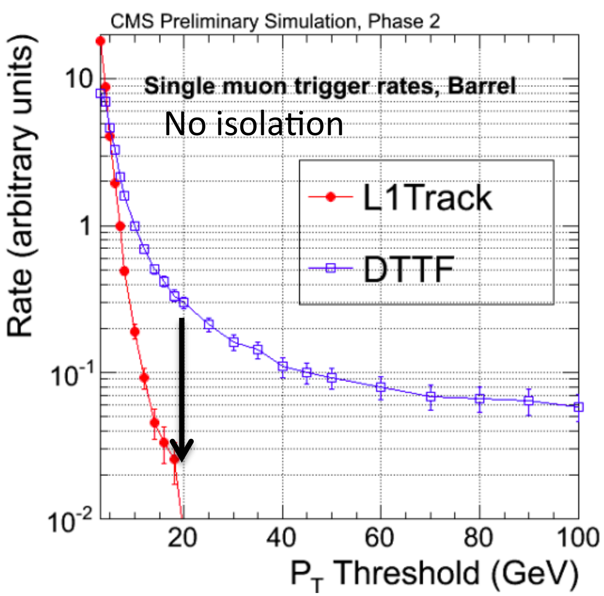
- CMS
  - Readout Tracker “stubs” at 40 MHz
  - Readout crystal granularity in ECAL
  - Increase latency to 10 μs and level 1 rate up to 1 MHz
  - Possible HLT output up to 10 kHZ (present HLT rejection)
  - → Requires
    - New ECAL Barrel front-end electronics
    - Upgrade of back-end electronics
    - Increased computing power - HLT can benefit from L1-track reconstruction (as for ATLAS phase 1 FTK)

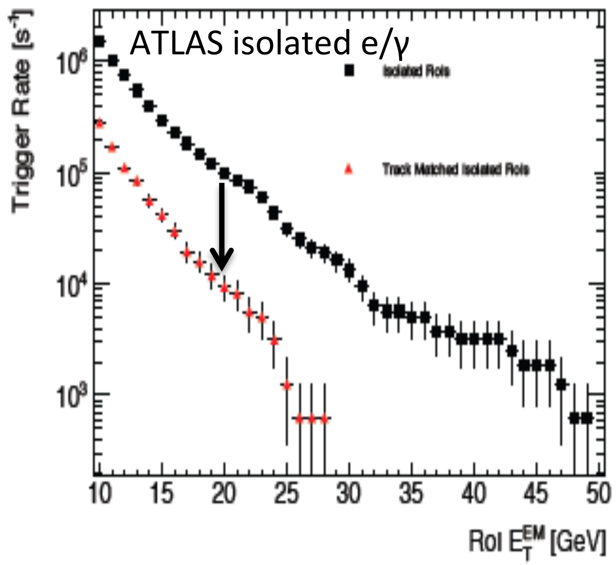


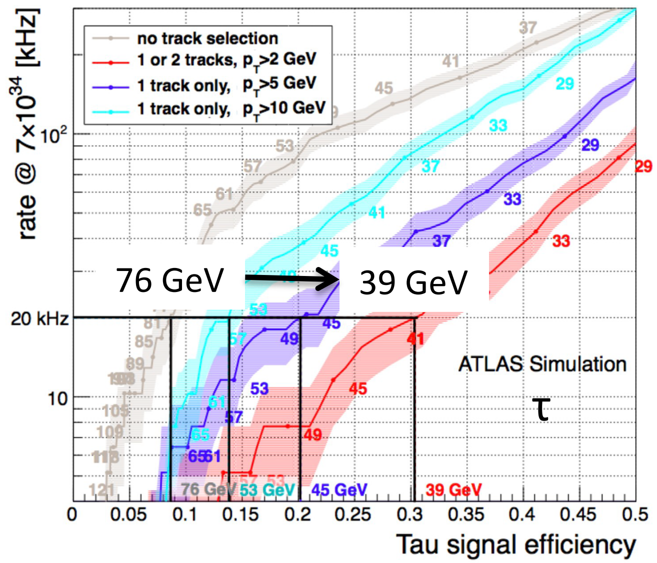
Performance of Trigger/DAQ systems for Phase 2

- Track trigger provides
  - High momentum resolution for improved momentum selection of leptons
  - Surrounding tracks for isolation of e/γ/μ/τ
  - Association of trigger objects to a primary or secondary vertex to reduce combinatorial effect of PU in multiple object triggers (especially Jet triggers)
- Increase of L1 bandwidth provides
  - Flexibility to allocate higher trigger bandwidth (lower trigger thresholds) for objects where track-trigger is less efficient
  - Further margin to operate at PU beyond 140

Studies confirm significant rate reductions as expected - with factor ~ 10 for lepton triggers, with good efficiency - this allows to maintain low trigger thresholds

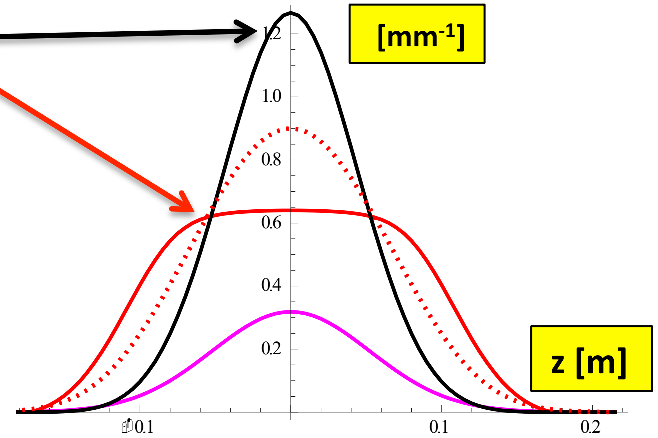




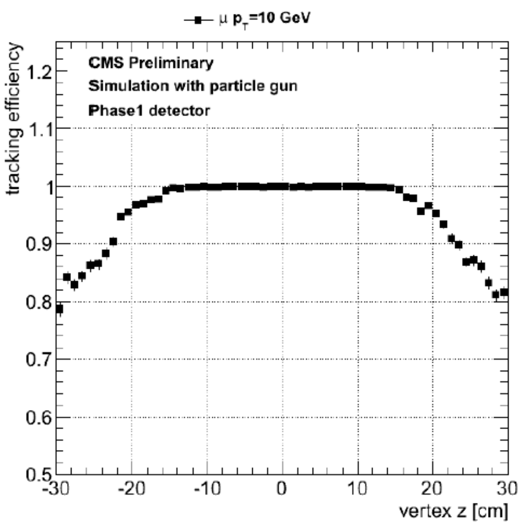


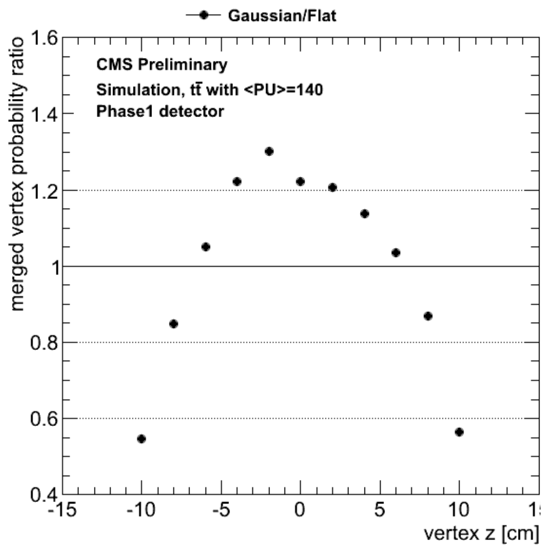
Another means of pile-up mitigation: collision density

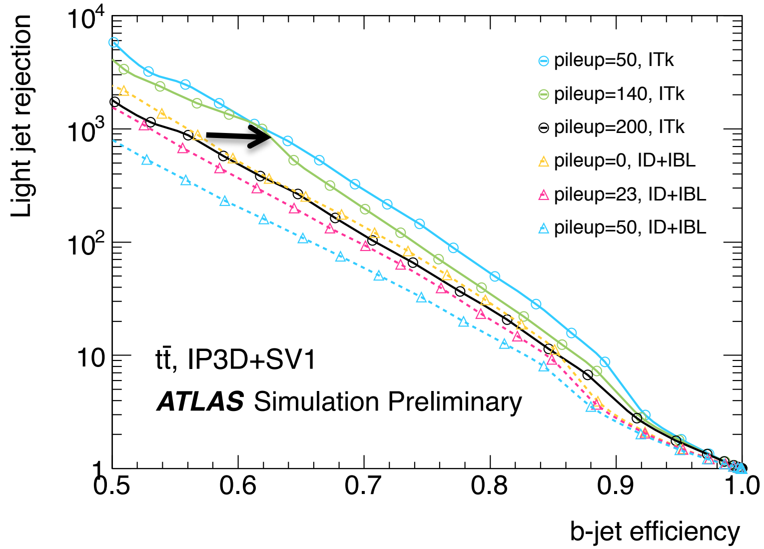
- Preliminary studies with CMS Phase 1 detector
  - Tracking acceptance covers flat luminous region
  - No significant tracking efficiency difference at 140 PU
  - Vertex finding efficiency decrease & number of merged vertices increase for Gaussian density
- Track association to primary and secondary vertices will be more efficient with flat density
  - Improved corrections to calorimeter energies
  - Improved b-tagging efficiency. Ex. a 10% gain as shown in right bottom plot will increase 2b-tagging efficiency by ~ 40 %



Scenarios of interaction density / crossing
S. Fartouk presentation at ECFA workshop

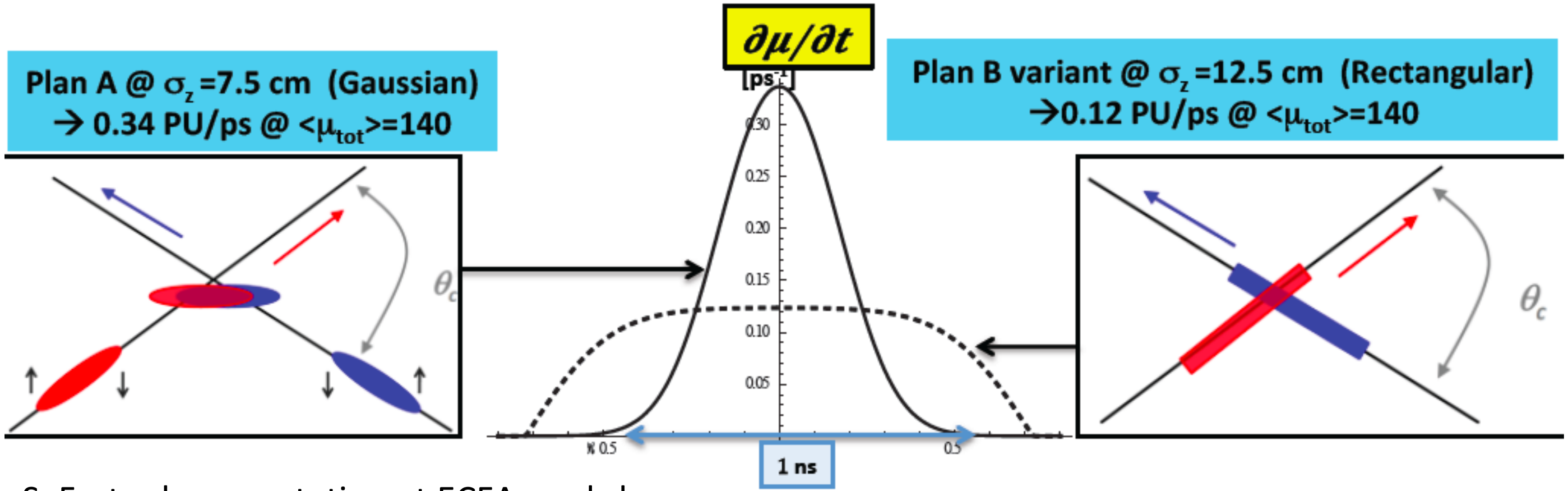






Another means of pile-up mitigation: precise timing

- Tracking does not allow to mitigate PU effect due to neutral particles
  - Limiting performance for photon and Jet ID and energy resolution at high PU
  - Precise timing measurement in front or within calorimeters with ~ 30 ps could allow to significantly reduce number of fakes and background
  - This would depend both on z and timing distributions of the collisions in the bunch crossings
  - More studies to estimate benefit and R&Ds are on-going to develop technical solutions



S. Fartouk presentation at ECFA workshop

Concluding remarks

- Phase 1 upgrades are needed to maintain performance beyond 1 x 10^{34} Hz/cm^2 , PU ~ 25
- With these upgrades ATLAS and CMS will be able to operate with good performance up to PU of ~ 70 and integrated luminosity ~ 500 fb^{-1}
- For Phase 2 HL-LHC physics program ATLAS and CMS are preparing for operation up to 140-200 PU - but with luminosity leveling depending on performance at high PU
  - Present simulations assume 5 x 10^{34} Hz/cm^2, 140 PU with a Gaussian luminous region
- A lot of work is ongoing to understand the limitations with Phase 1 detectors and benefits with Phase 2 upgrades
  - Important effort to develop and tune data reconstruction and physics analyses
- A flat density luminous region scenario as presented at the ECFA workshop could be effective to allow detectors to run at higher PU
  - But limitation might remain due to neutral particles - collision time dispersion & precision timing could be a mean to mitigate this PU effect

It is essential that Accelerator & Experiments investigate all opportunities to mitigate PU effects to fully profit from the LHC High Luminosity potential