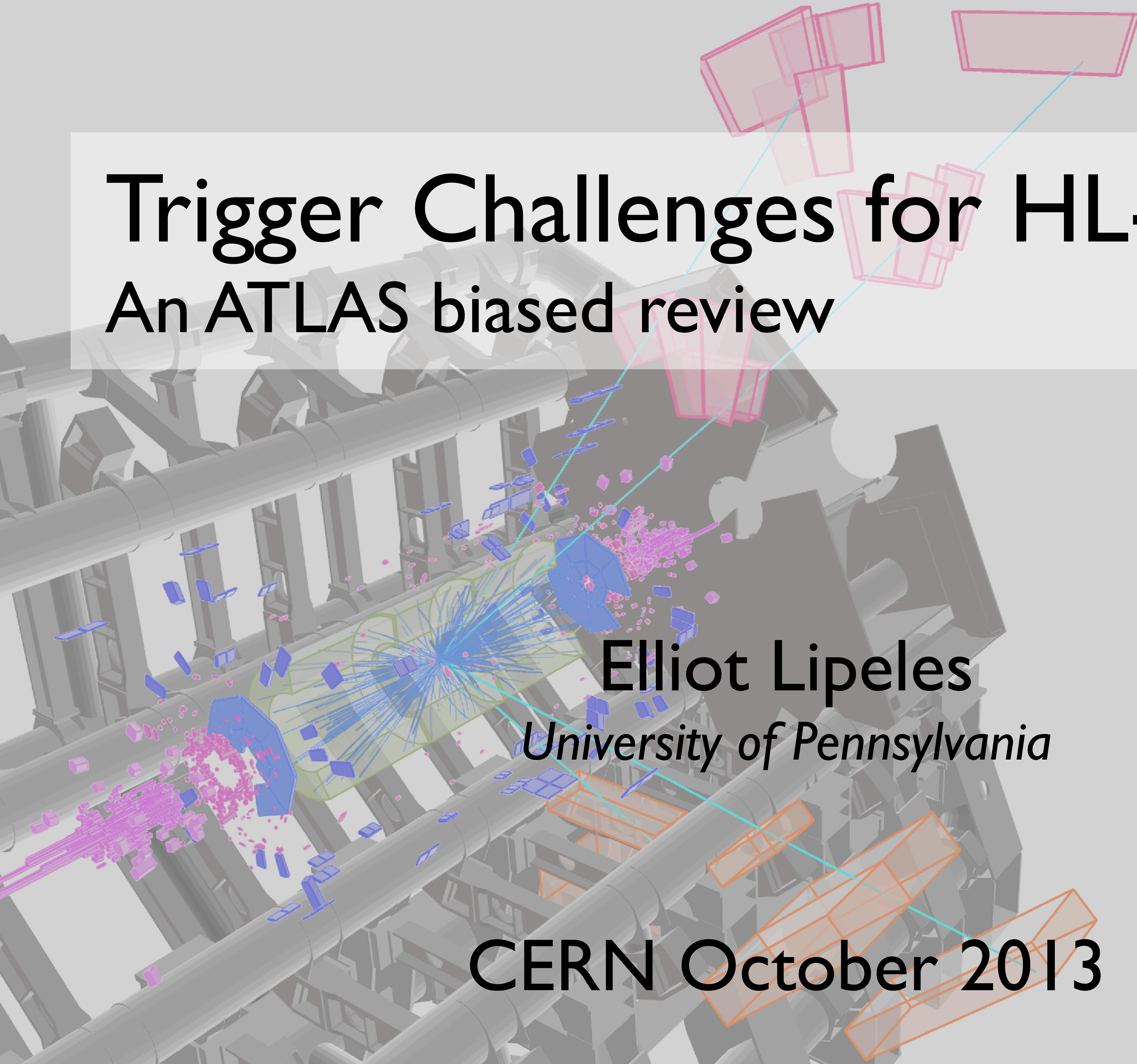
Trigger Challenges for HL-LHC

An ATLAS biased review



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CERN October 2013

Introduction

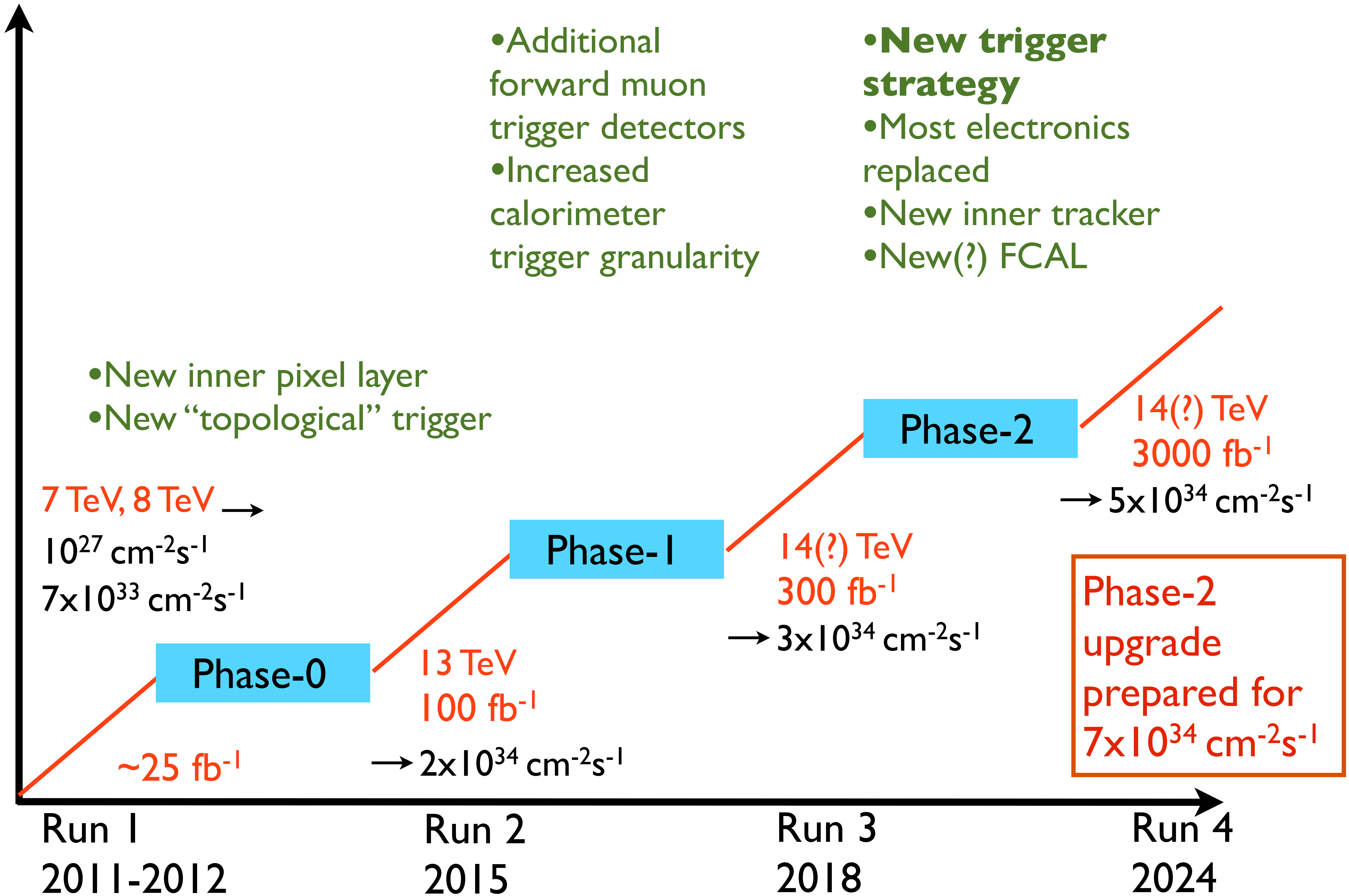
Context

- LHC Upgrade Program
- ATLAS trigger overview
- Planned ATLAS Phase-1 upgrades
- Problems with pile-up
- Physics requirements
  - The Higgs
  - BSM ... and the unknown

Track triggering

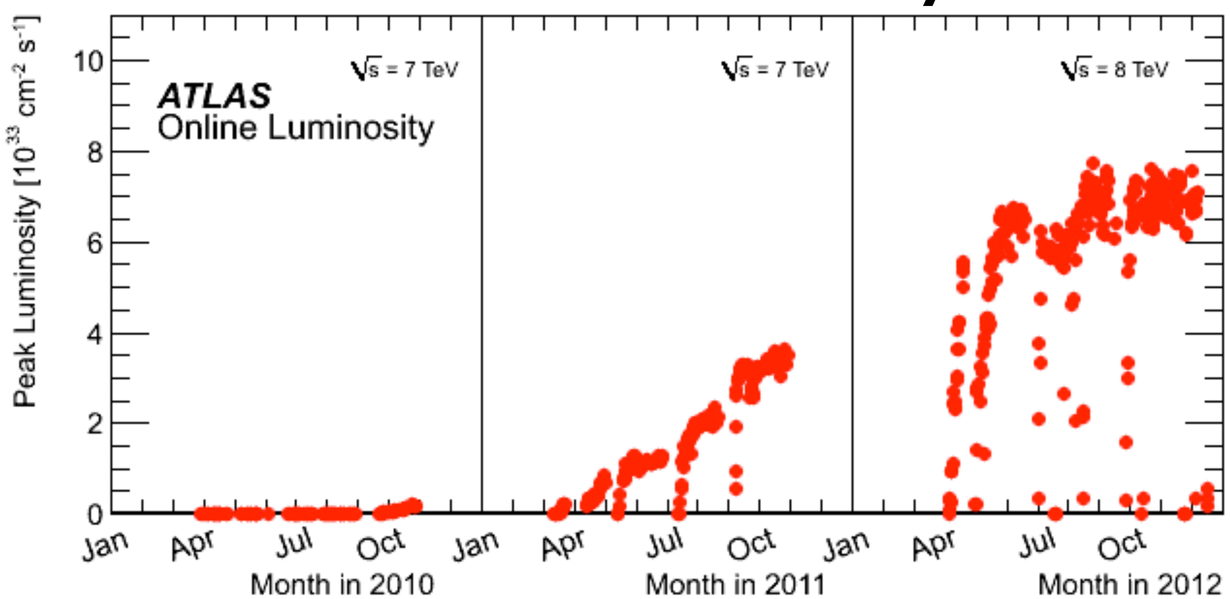
The current ATLAS plan

LHC Program and ATLAS Upgrades

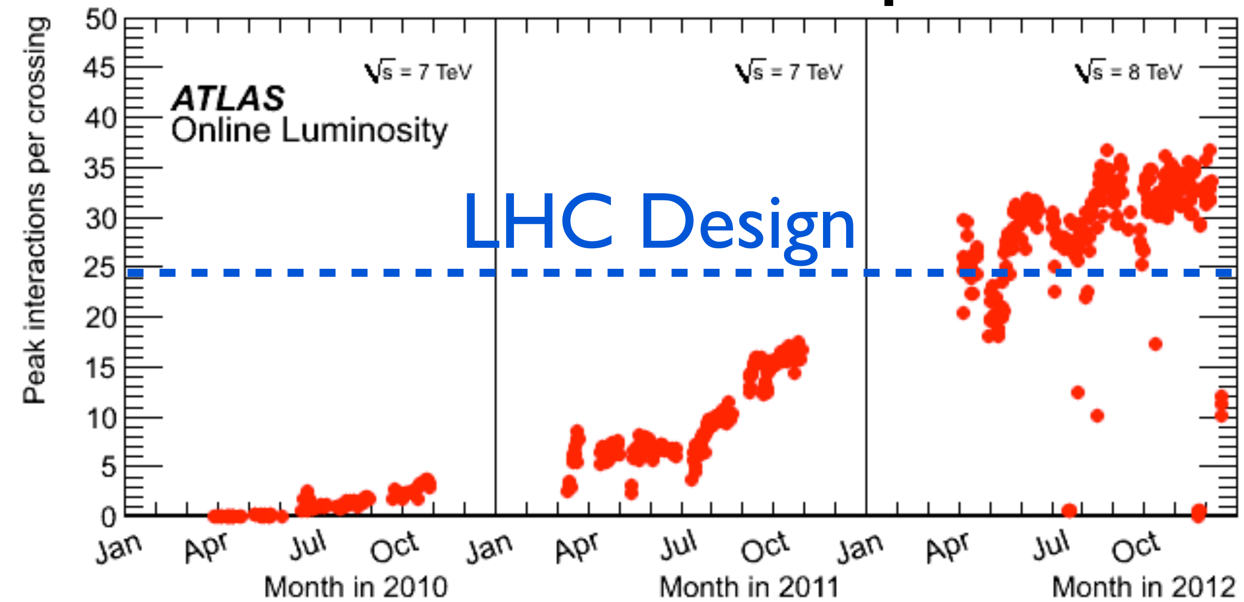


LHC Program and ATLAS Upgrades

Run I Luminosity



Run I Pile-up



	Luminosity	Bunch spacing	Pile-up
Run I	7×10^{33}	50 ns	~35
Run 2	2×10^{34}	25/50 ns	~55(or 80@50ns)
Run 3	3×10^{34}	25 ns	~80
Run 4	5×10^{34} (7×10^{34} w/ margin)	25 ns	~140 (200 w/margin)

Smaller bunch spacing means smaller ***in time*** pile-up

ATLAS trigger system overview

ATLAS Data Trigger Info

2012 reality

40 MHz

20 MHz

75 (100) kHz

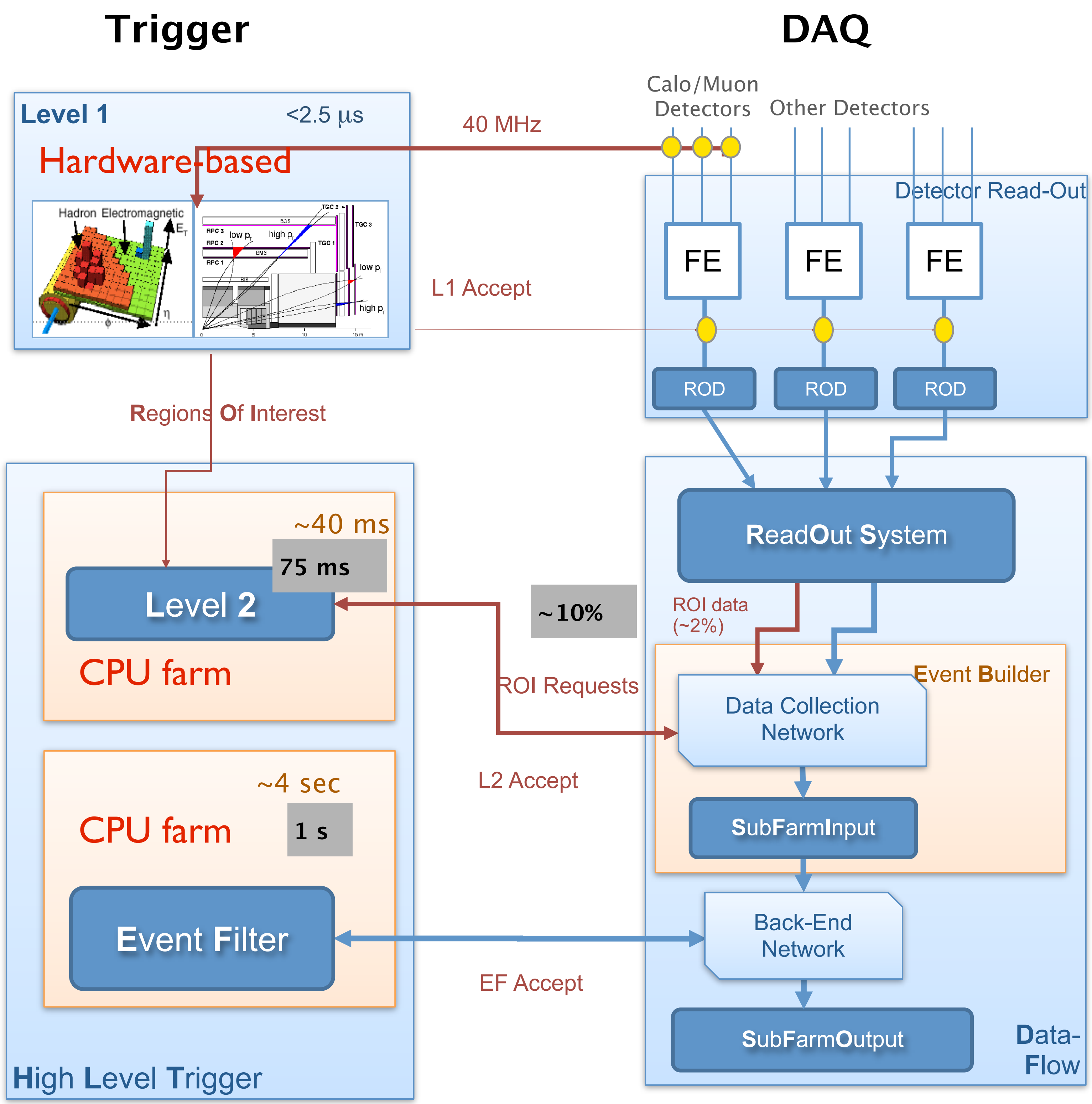
70 kHz

~ 4 kHz

6.5 kHz

Peak ~ 300 Hz

1 kHz



ATLAS Event 1.5 MB/25 ns

1.6 – 1.2 MB/50 ns

112 (150) GB/s

100 GB/s

~6 GB/s

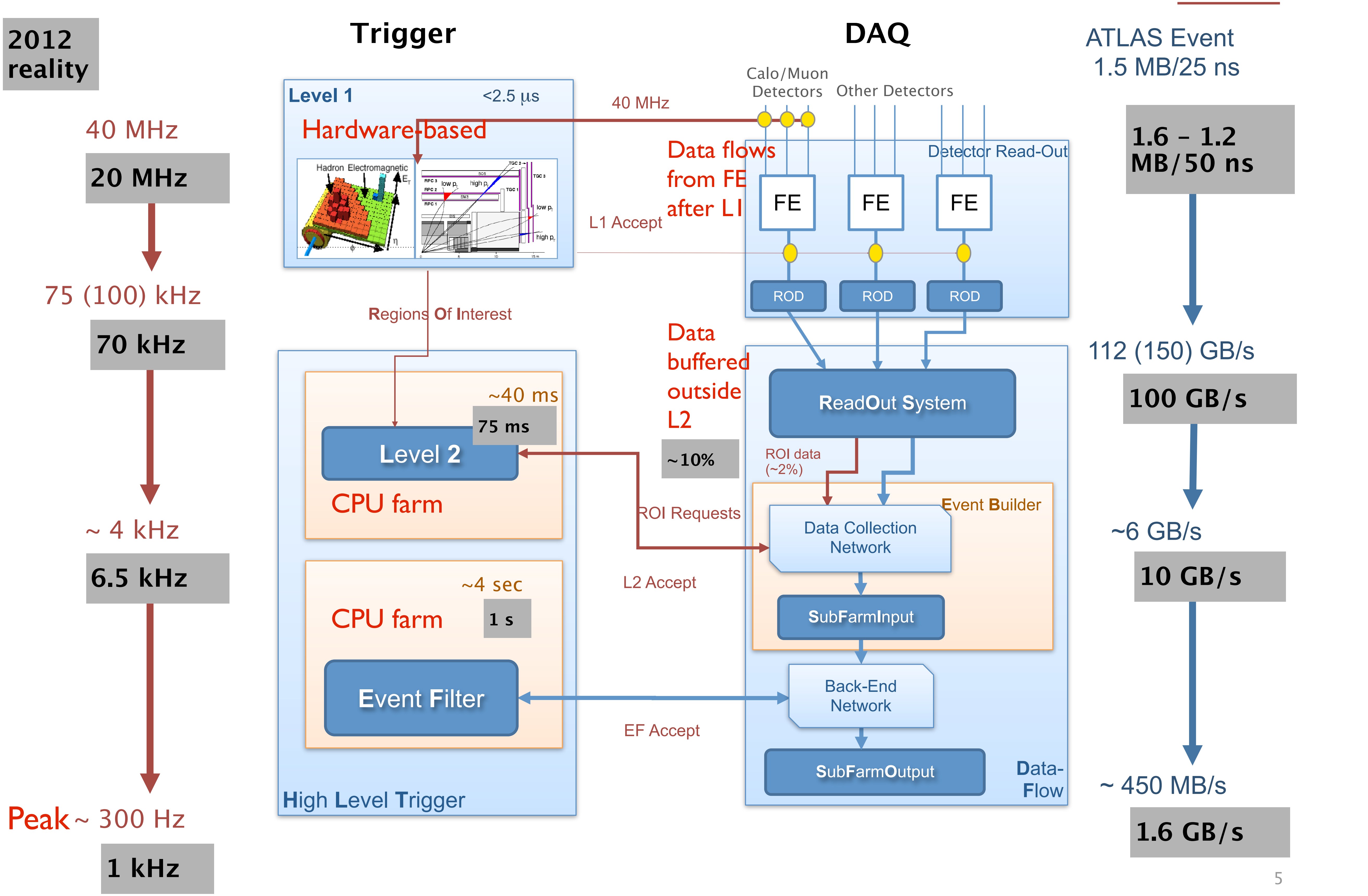
10 GB/s

~ 450 MB/s

1.6 GB/s

5

ATLAS trigger system overview



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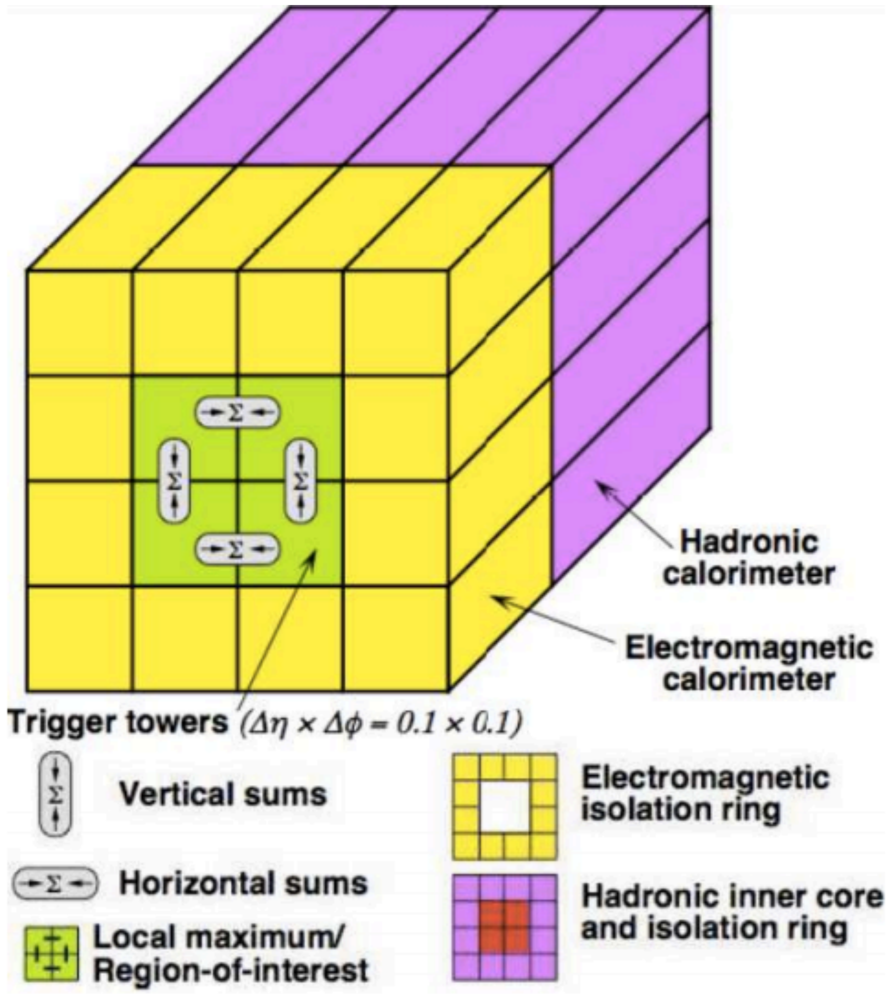
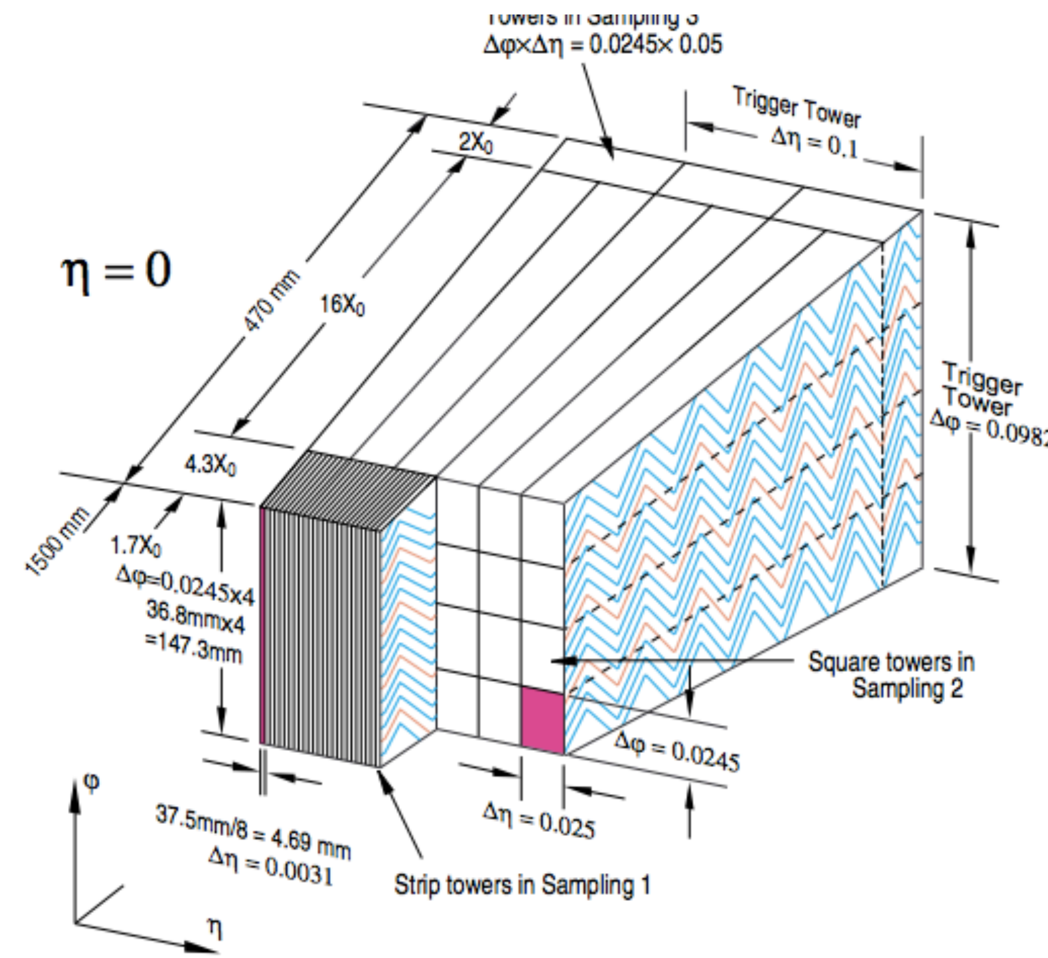
Calorimeter trigger vertical view





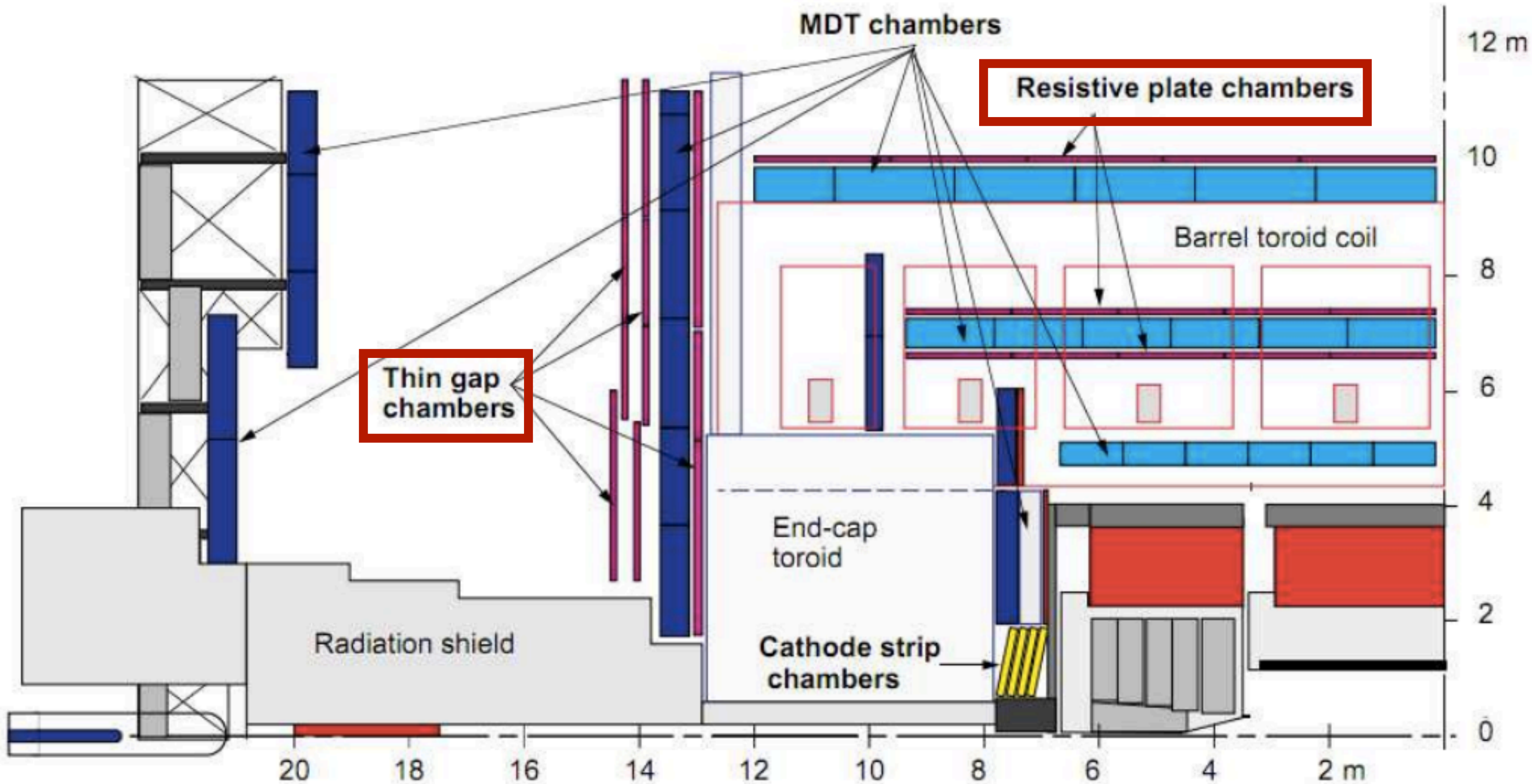
L1 Trigger: analog sums over...

- 0.1x0.1 for e/γ and τ
  - Isolation is possible
- ~0.2x~0.2 for jets, MET, sumET

HLT: L2 & EF Trigger:

- Full detector granularity same digitization as offline
- Track-shower matching
- Detailed shower shape cuts
- Reclustering jets
- Sharper turn-on curves

Calorimeter trigger vertical view



L1 Trigger:

- Fast Resistive Plate and Thin Gap Chambers
- Hardware pattern recognition

HLT: L2 & EF Trigger:

- Use slower more precise MDT chambers
- Combine with inner detector track
- L2 uses simplified B-field model
- EF uses full offline software

Lepton Trigger Rates

Electrons

Rates for $3x10^{34}$ $cm^{-2}s^{-1}$ (from ATLAS Phase-1 TDR)

This is well past the original design

2012 Menu | Planned 2015 Menu

Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Run 2	Offline p_T Threshold [GeV]	Rate [kHz]
EM18VH	25	130	EM30VHI	38	14
EM30	37	61	EM80	100	2.5
2EM10	2x17	168	2EM15VH I	2x22	2.9
EM total		**270**			**18**

Very High Single Electron Threshold

Muons

Rates for $3x10^{34}$ $cm^{-2}s^{-1}$ (from ATLAS Phase-1 TDR)

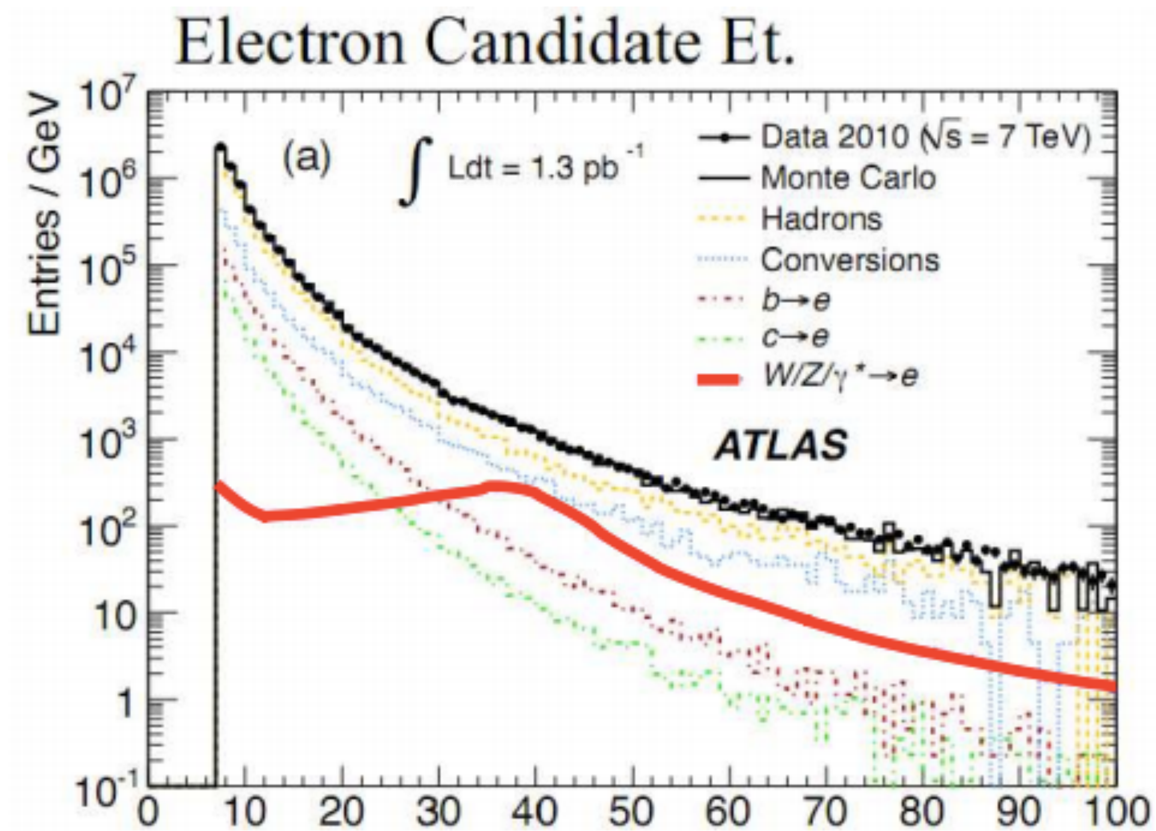
2012 Menu | Planned 2015 Menu

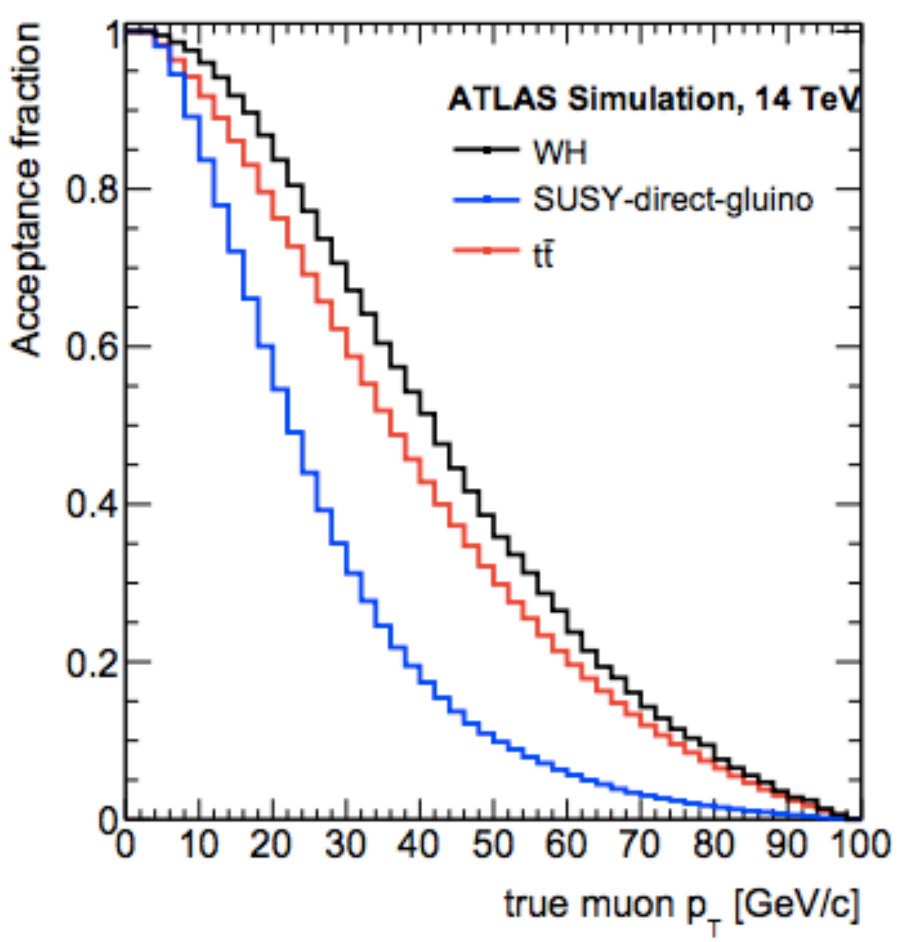
Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Run 2	Offline p_T Threshold [GeV]	Rate [kHz]
MU15	25	150	MU20	25	28
2MU10	2x12	14	2MU11	2x12	4.0
Muon total		**164**			**32**

Very High Single Muon Rate

Single Lepton Motivation

The peak of the lepton energy from W and Z is around 35 GeV, so a cut at ~35 GeV gives a 50% acceptance



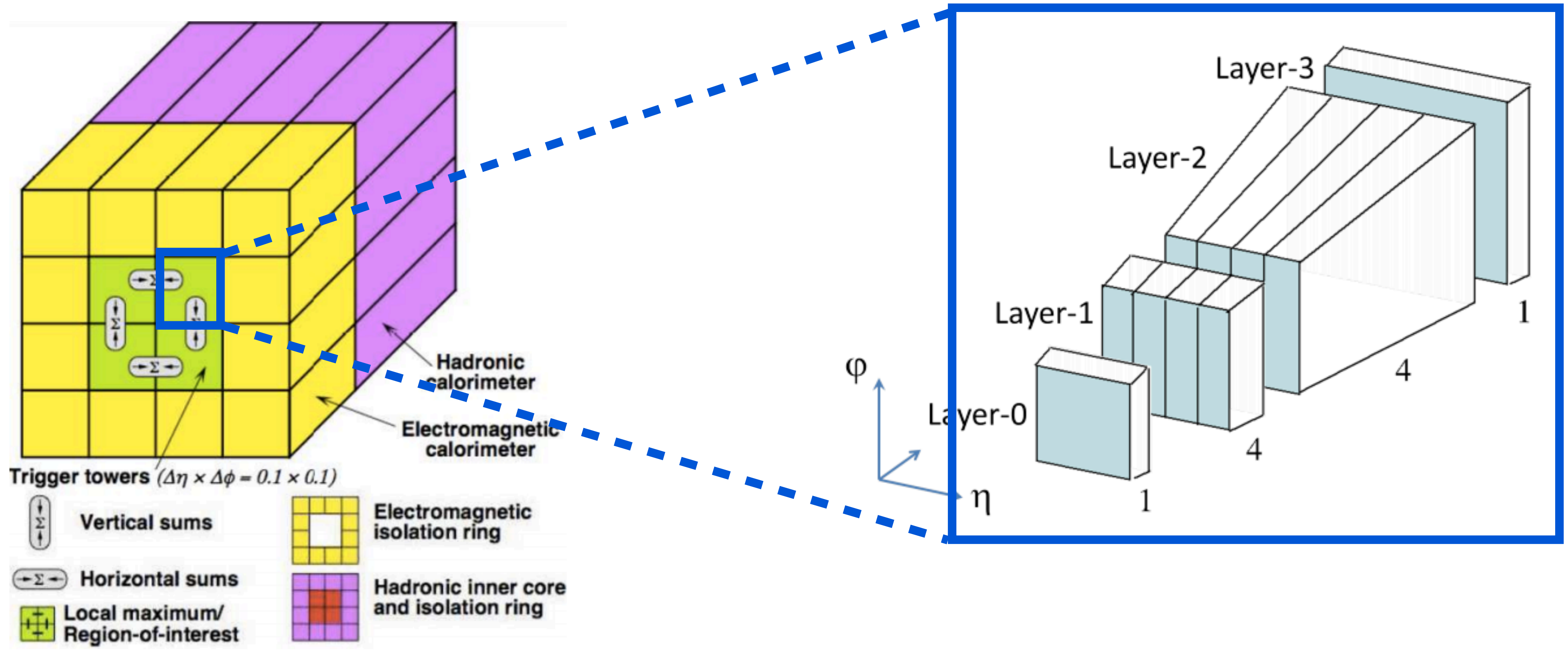


Acceptance increase from lowering threshold from 30 GeV to 20 GeV is 1.3-1.8 for WH, tt, and a SUSY model

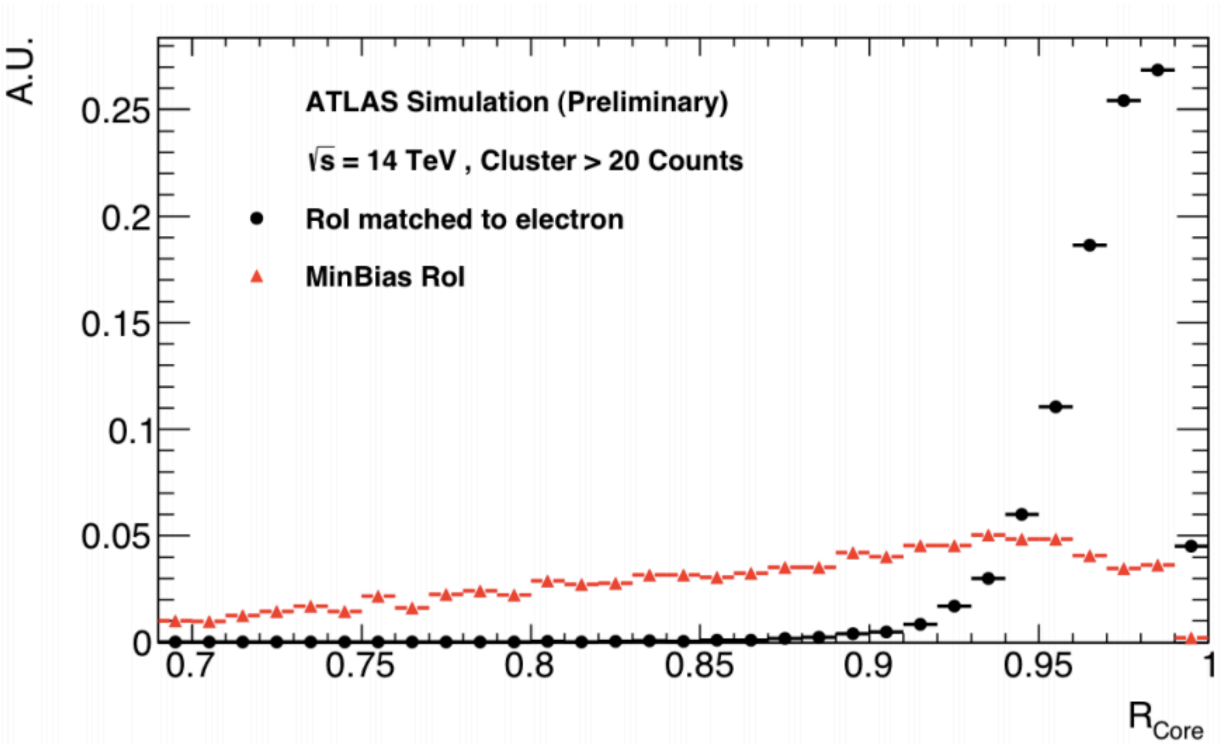
We would like to maintain sensitivity/ flexibility for the unknown

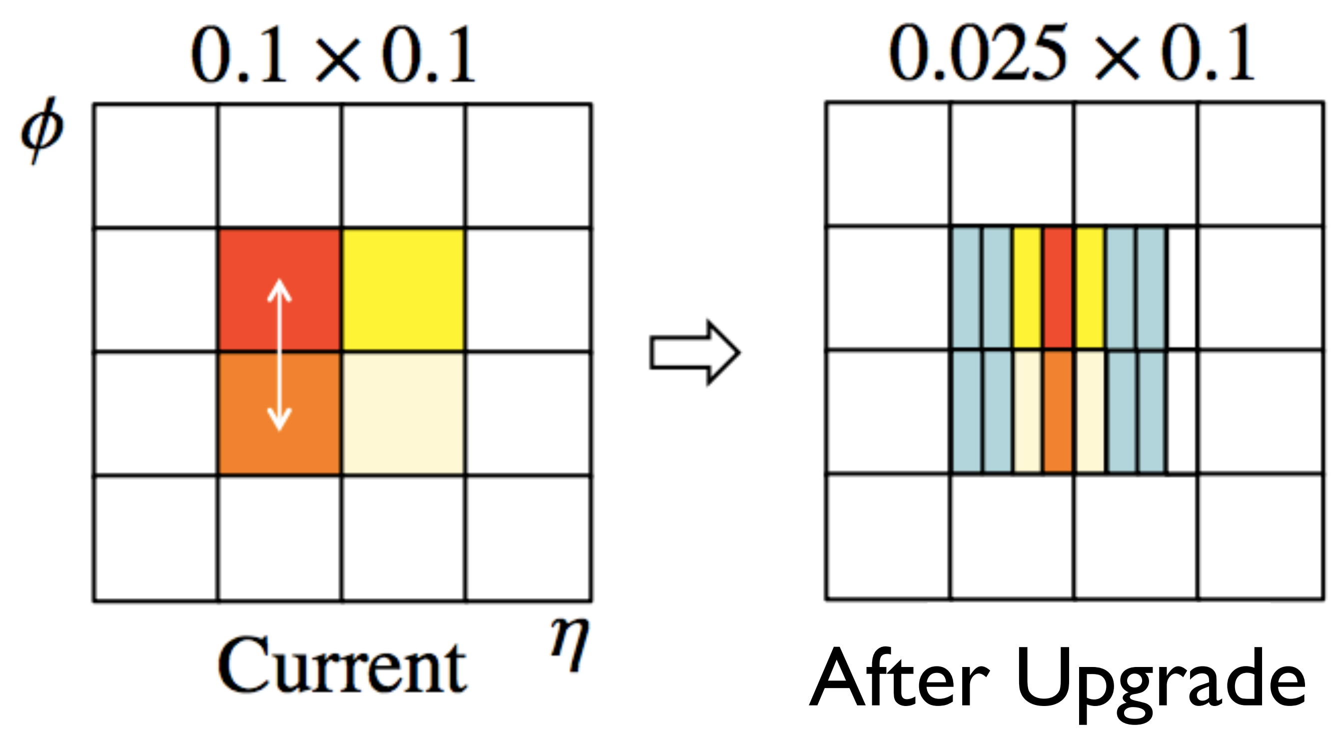
Phase-1 L1Calo Trigger Upgrade

Granularity Improvement



Cut on shower shapes





Phase-1 Muon Trigger Upgrade

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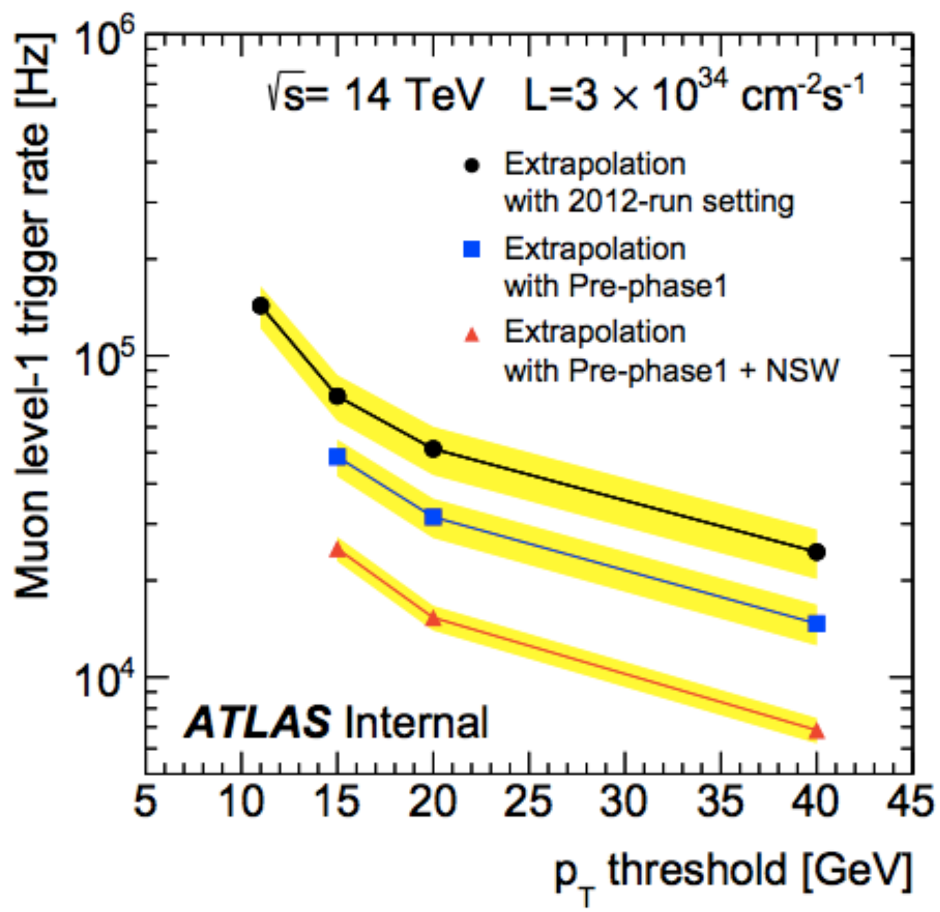
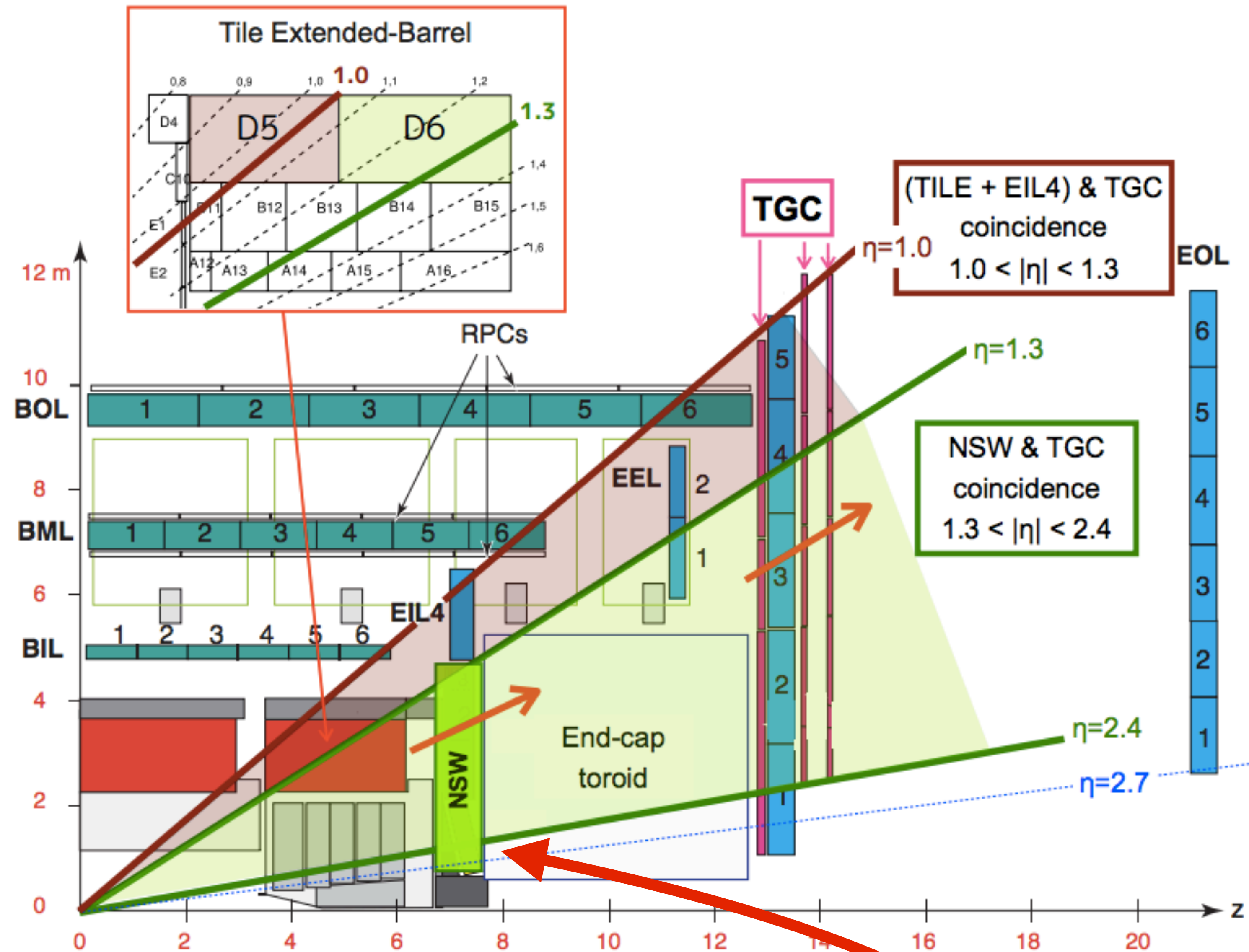
Rates driven by

- Resolutions (muons below the nominal threshold)
- Fakes (charged particles not associated with the collision)





Rates at $3x10^{34}$ cm^{-2}s^{-1}
51 KHz for 2012 Configuration
32 KHz for 2015 Configuration
15 KHz with "New Small Wheel"

Lepton Trigger Rates

Electrons

Rates for 3×10^{34} cm^{-2}s^{-1} (from ATLAS Phase-1 TDR)

2012 Menu: Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Planned 2015 Menu: Run 2	Offline p_T Threshold [GeV]	Rate [kHz]	Planned 2018 Menu: Run 3	Offline p_T Threshold [GeV]	Rate [kHz]
EM18VH	25	130	EM30VHI	38	14	EM25VHR	32	14
EM30	37	61	EM80	100	2.5	EM80	100	2.5
2EM10	2x17	168	2EM15VH I	2x22	2.9	2EM12VHR	2x19	5.0
EM total		**270**			**18**			**20**

Both e and mu Rates Reduced

Electron Threshold still somewhat high

Muons

Rates for 3×10^{34} cm^{-2}s^{-1} (from ATLAS Phase-1 TDR)

2012 Menu: Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Planned 2015 Menu: Run 2	Offline p_T Threshold [GeV]	Rate [kHz]	Planned 2018 Menu: Run 3	Offline p_T Threshold [GeV]	Rate [kHz]
MU15	25	150	MU20	25	28	MU20	25	15
2MU10	2x12	14	2MU11	2x12	4.0	2MU11	2x12	4.0
Muon total		**164**			**32**			**19**

With Phase-1 Upgrade

Lepton Trigger Rates

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Electrons

Rates for 3x10^{34} cm^{-2}s^{-1} (from ATLAS Phase-1 TDR)

2012 Menu			Planned 2015 Menu			Planned 2018 Menu			Crude Rates for 7x10^{34} cm^{-2}s^{-1}
Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Run 2	Offline p_T Threshold [GeV]	Rate [kHz]	Run 3	Offline p_T Threshold [GeV]	Rate [kHz]	
EM18VH	25	130	EM30VHI	38	14	EM25VHR	32	14	33 KHz
EM30	37	61	EM80	100	2.5	EM80	100	2.5	6 KHz
2EM10	2x17	168	2EM15VH I	2x22	2.9	2EM12VHR	2x19	5.0	12-27 KHz
EM total		**270**			**18**			**20**	51-66 KHz

Muons

Rates for 3x10^{34} cm^{-2}s^{-1} (from ATLAS Phase-1 TDR)

2012 Menu			Planned 2015 Menu			Planned 2018 Menu			Crude Rates for 7x10^{34} cm^{-2}s^{-1}
Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Run 2	Offline p_T Threshold [GeV]	Rate [kHz]	Run 3	Offline p_T Threshold [GeV]	Rate [kHz]	
MU15	25	150	MU20	25	28	MU20	25	15	35KHz
2MU10	2x12	14	2MU11	2x12	4.0	2MU11	2x12	4.0	9-22 KHz
Muon total		**164**			**32**			**19**	44-57 KHz

With Phase-1 Upgrade

Please note these are my crude numbers

Problems with pile-up

One might think we can make it up with l+X triggers (where X=jets, met, more leptons,...)

Multiobject triggers scale badly with pile-up...

If p is the probability that a single collision produces object passing a given threshold

Then the trigger rate for that object is

$$\text{Rate} = p\mu f$$

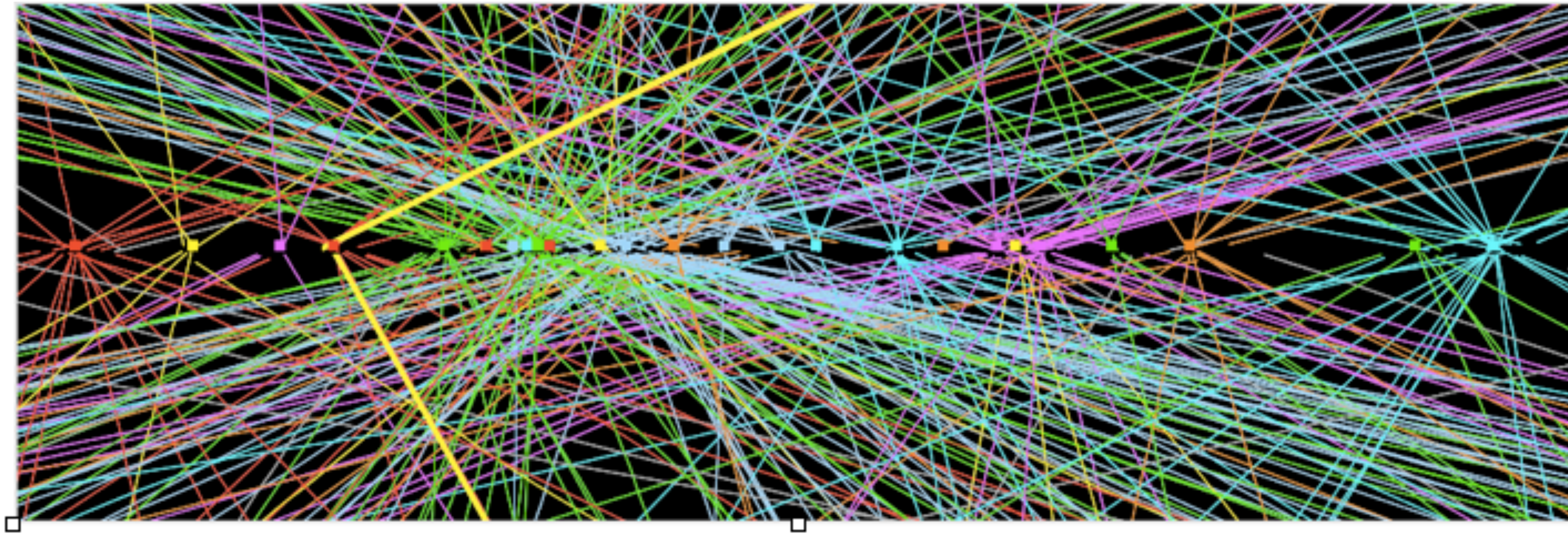
where f is the frequency of crossings and μ is the number of collisions per crossing

The rate for a coincidence of two such objects is approximately

$$\text{Rate} = \frac{1}{2}(p\mu)^2 f$$

I.e. it grows with the square of μ, and worse for more objects!!!

More pile-up problems



Pile-up will degrade

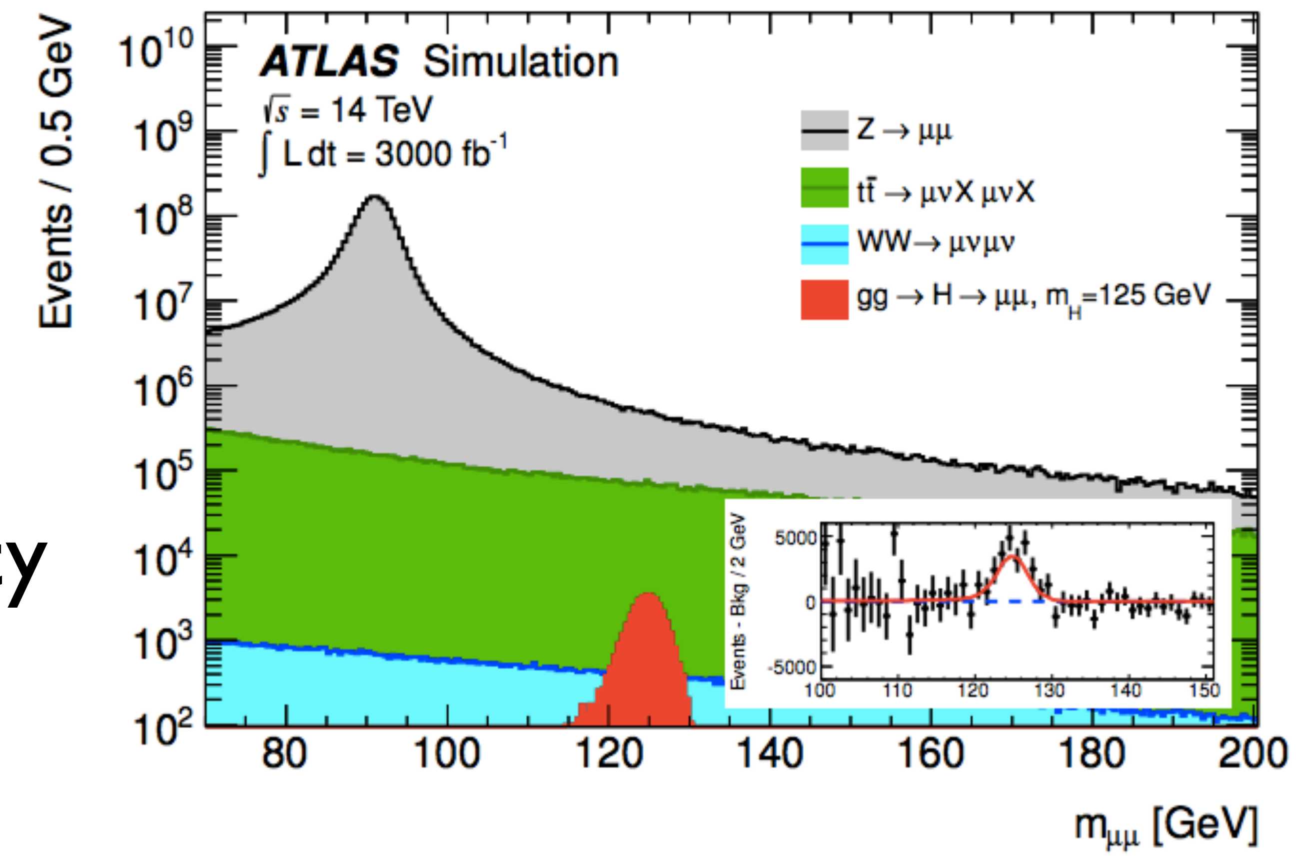
- Calorimeter Isolation (used at L1 for 2015 electrons)
- Missing Energy
- Jets (creates fake "pile-up jets")
- Cavern Background

Tracking is used increasingly in offline analysis to cope with pile-up (jet vertex association, track isolation, track MET, ...)

Selected Higgs Physics

$H \to \mu\mu$

Could use a dimuon trigger, but then you pay ϵ^2 instead of $1-(1-\epsilon)^2$ which could be order 50% loss of efficiency



$H \to \tau\tau$

In particular, VBF channel has moderate p_T and forward jets. High multiplicity does not scale well with pile-up

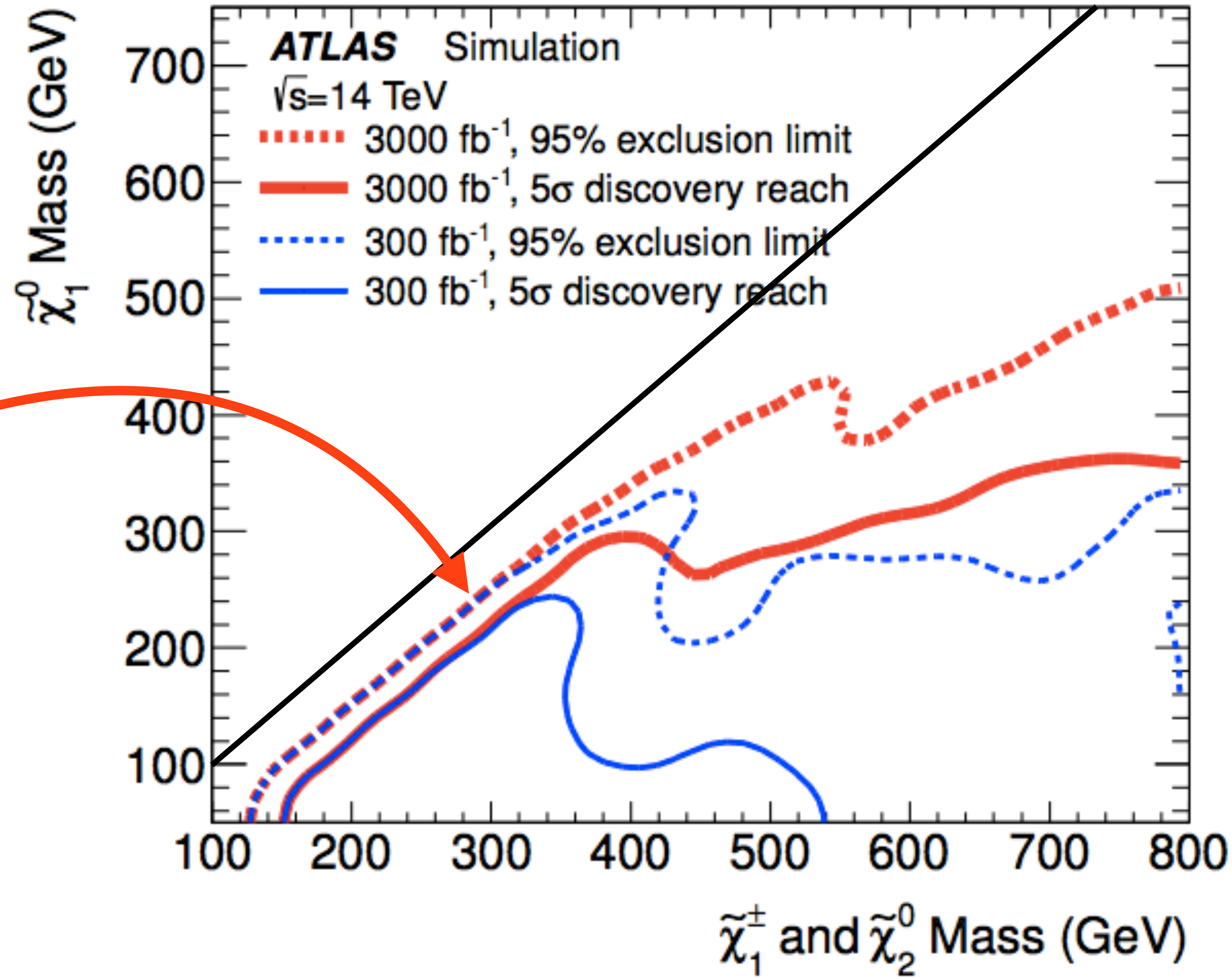
$HH \to bb\tau\tau$ and other self-coupling channels all have relatively low p_T objects. Many possible channels still being explored

$WH \to l\nu + X$ serves as an inclusive Higgs trigger for BSM decays

Chargino Search

One of the compelling physics cases for HL-LHC

This region just below the kinematic boundary has low p_T leptons



Also still a lot of thinking going on about how to address these kinematic boundaries

Issues Entering Phase-2

Issues:

- Overall rates are large
- Muon resolution limits largest possible p_T cut
- Calorimeter isolation degrades, track isolation could help
- Missing energy degrades (less useful in combinations)
- Fake jets, which forces larger jet threholds
- Multiobject triggers increasingly from coincidences

Goals:

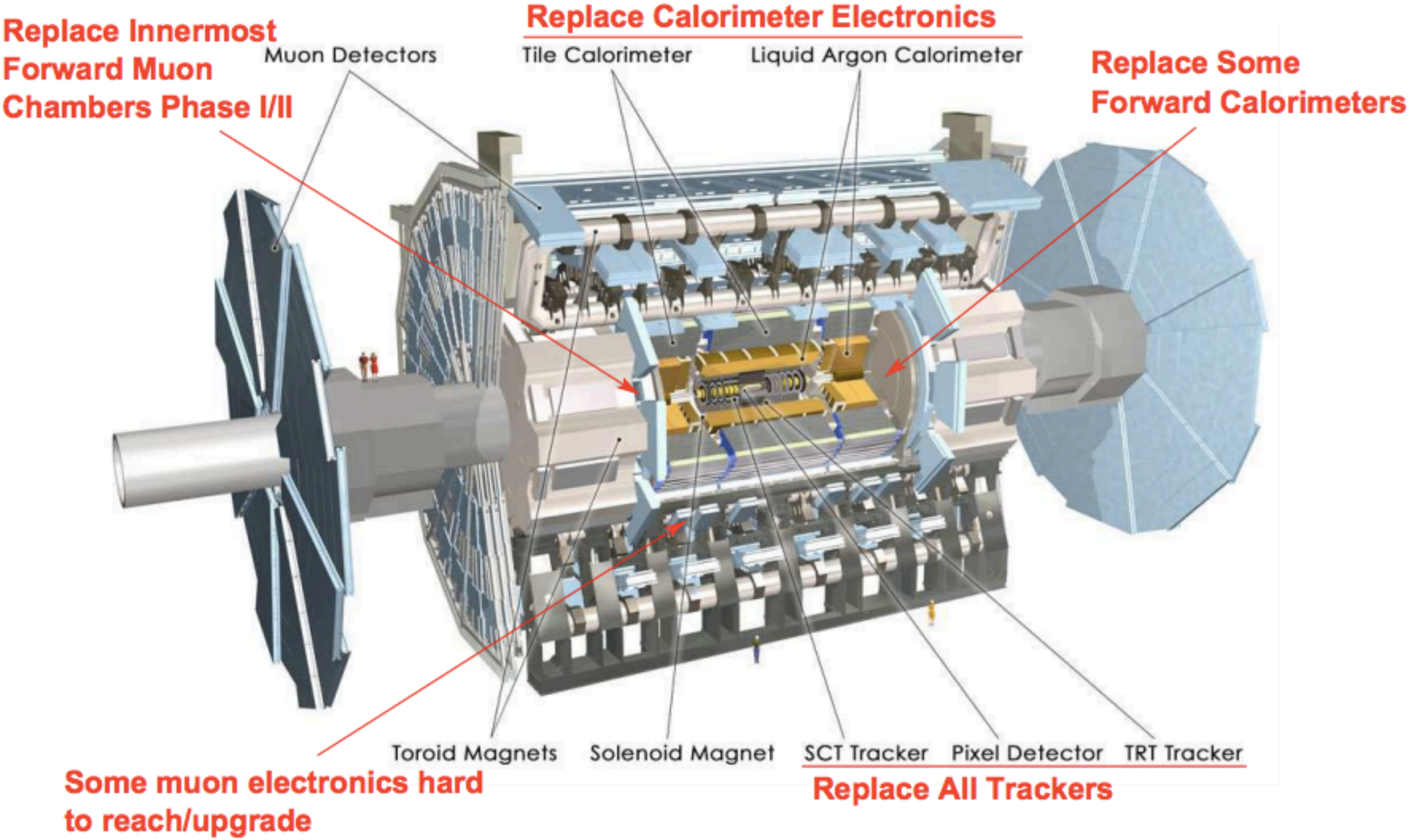
- Would like to maintain lower p_T leptons at least to HLT
- We are searching for the unknown, it might be at high $p_{T,}$ but it might be at moderate p_T and rare...

Trigger Strategies:

- Two-stage hardware triggers (with tracking)
- Self-seeded track triggers

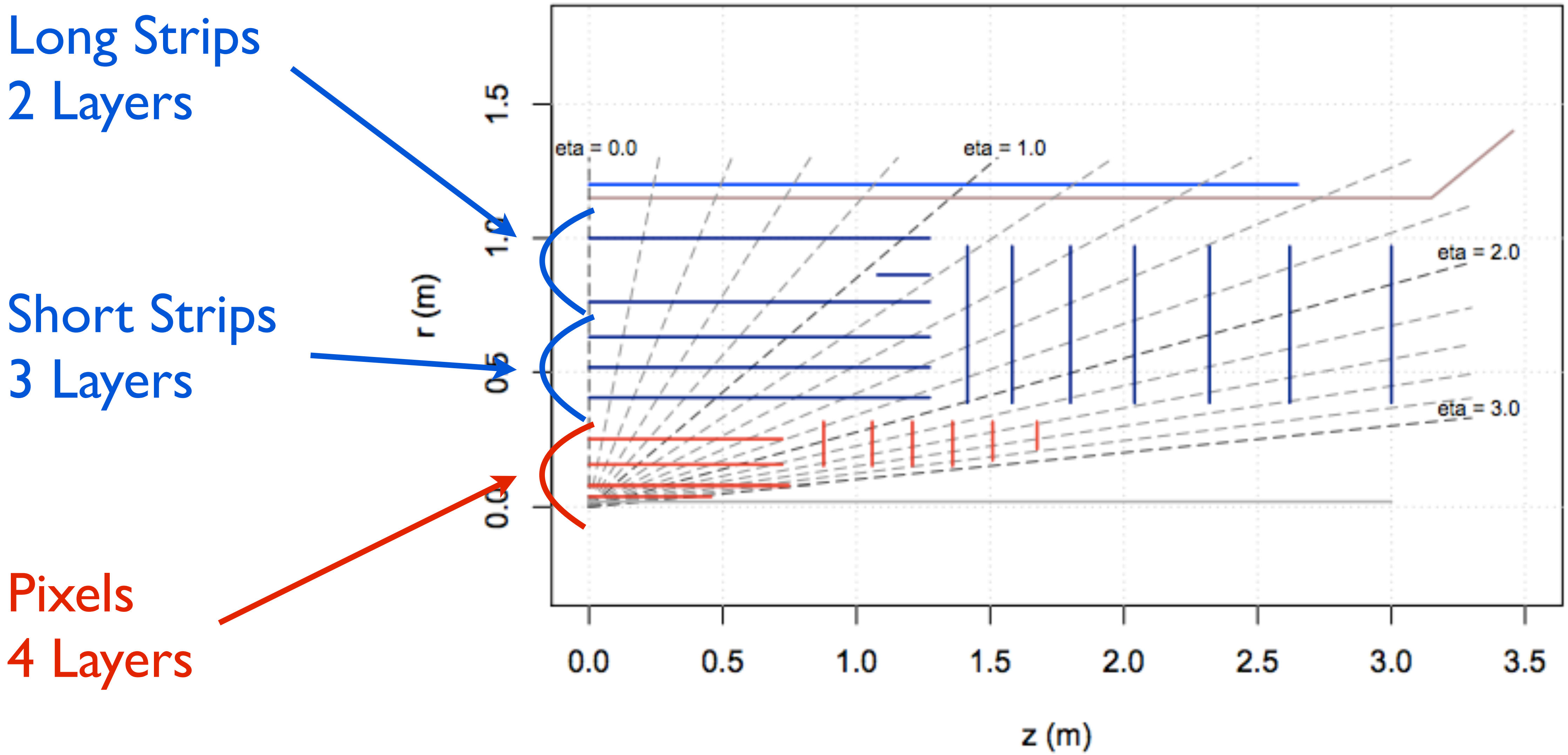
Track Triggering

Overview of Phase-2 Upgrade



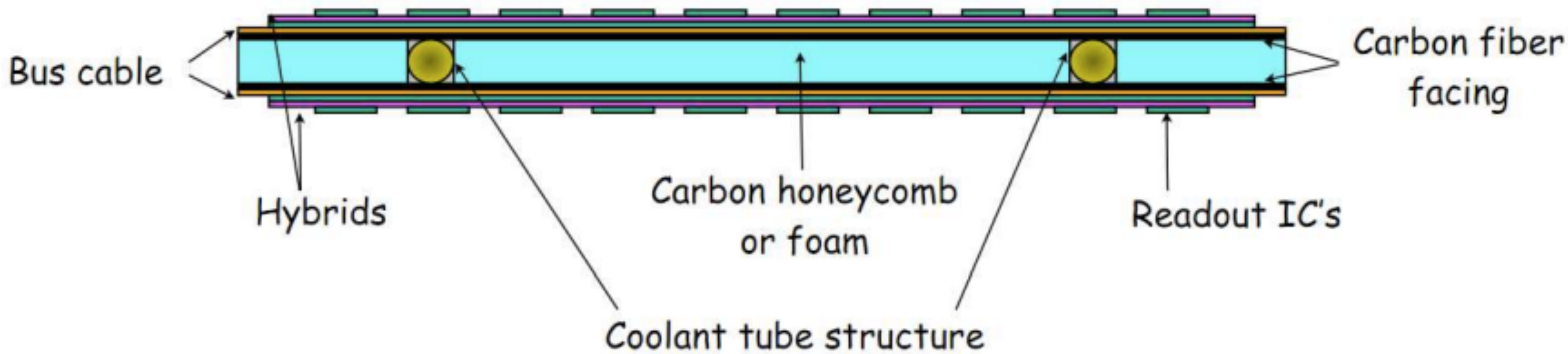
Baseline Tracker Layout

All Silicon Tracker



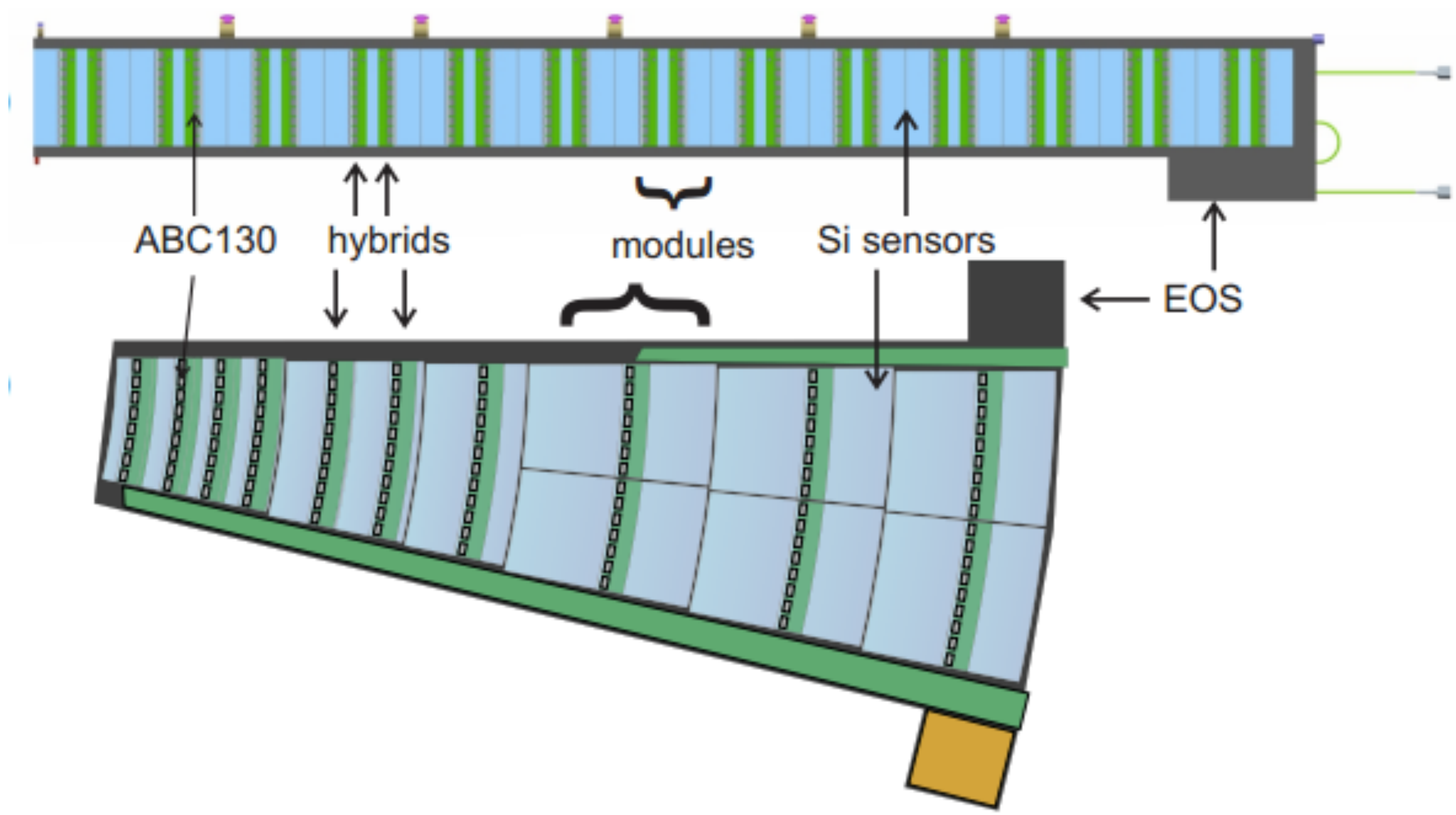
- Alternative optimizations still being studied (resolution, fakes, material)
- Strips are designed to have one-side as a low angle stereo
- Details in Phase-2 "Letter of Intent"

Strips design



Barrel →

Endcap →



Track Trigger Challenges

Detector:	Silicon area [m^2]	Channels [10^6]
Pixel barrel	5.1	445
Pixel end-cap	3.1	193
Pixel total	**8.2**	**638**
Strip barrel	122	47
Strip end-cap	71	27
Strip total	**193**	**74**

Huge Channel Counts

Pixels

Strips

with a 40 MHz beam crossing rate!

Data Flow

- Read out at 40 MHz is a non-starter due to material in power and cooling
- Current planned readout rate is 200 KHz
- **Need to filter to reduce data flow**

Filtering Options

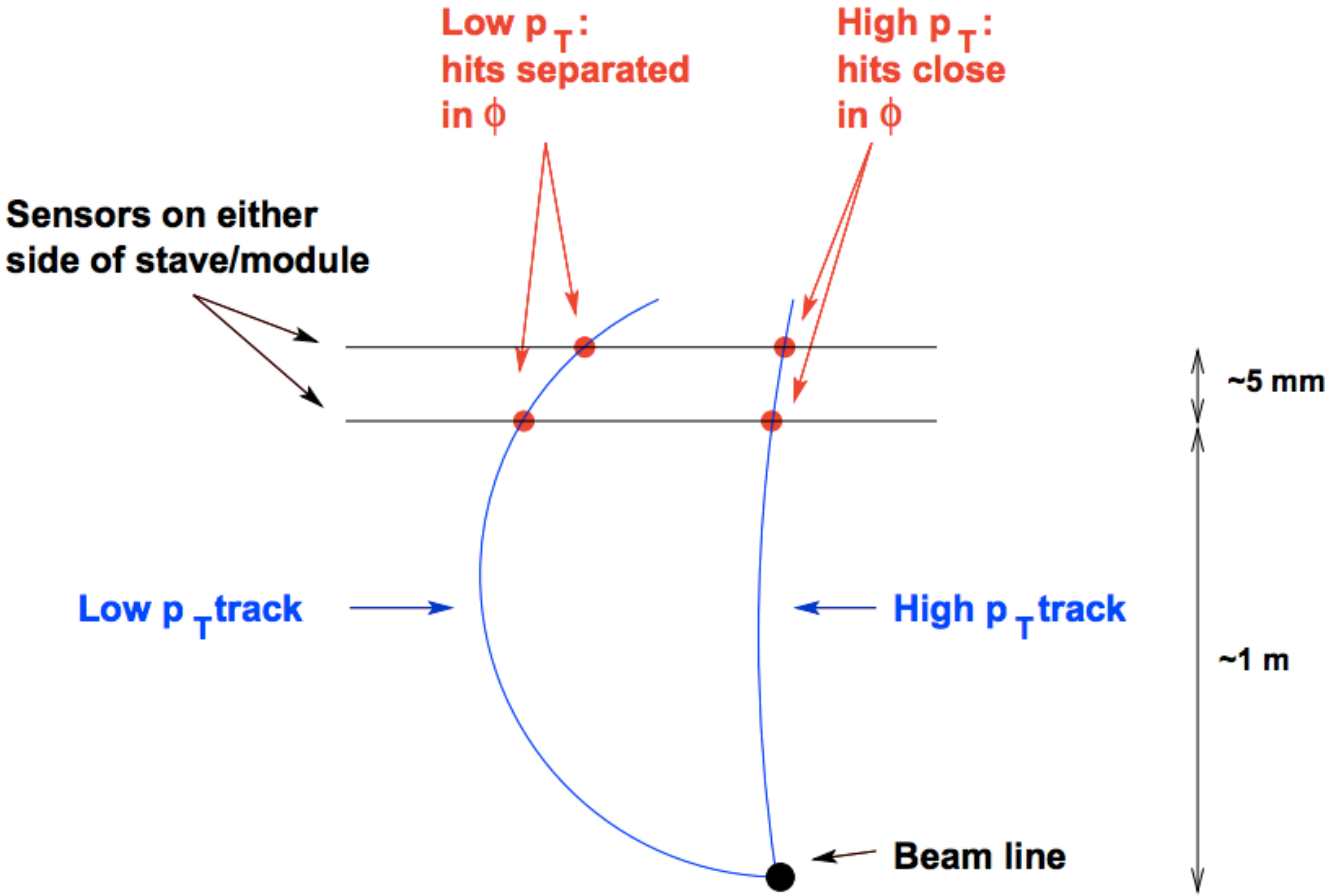
1. Filter on p_T
2. Filter on Region

Filtering on p_T:

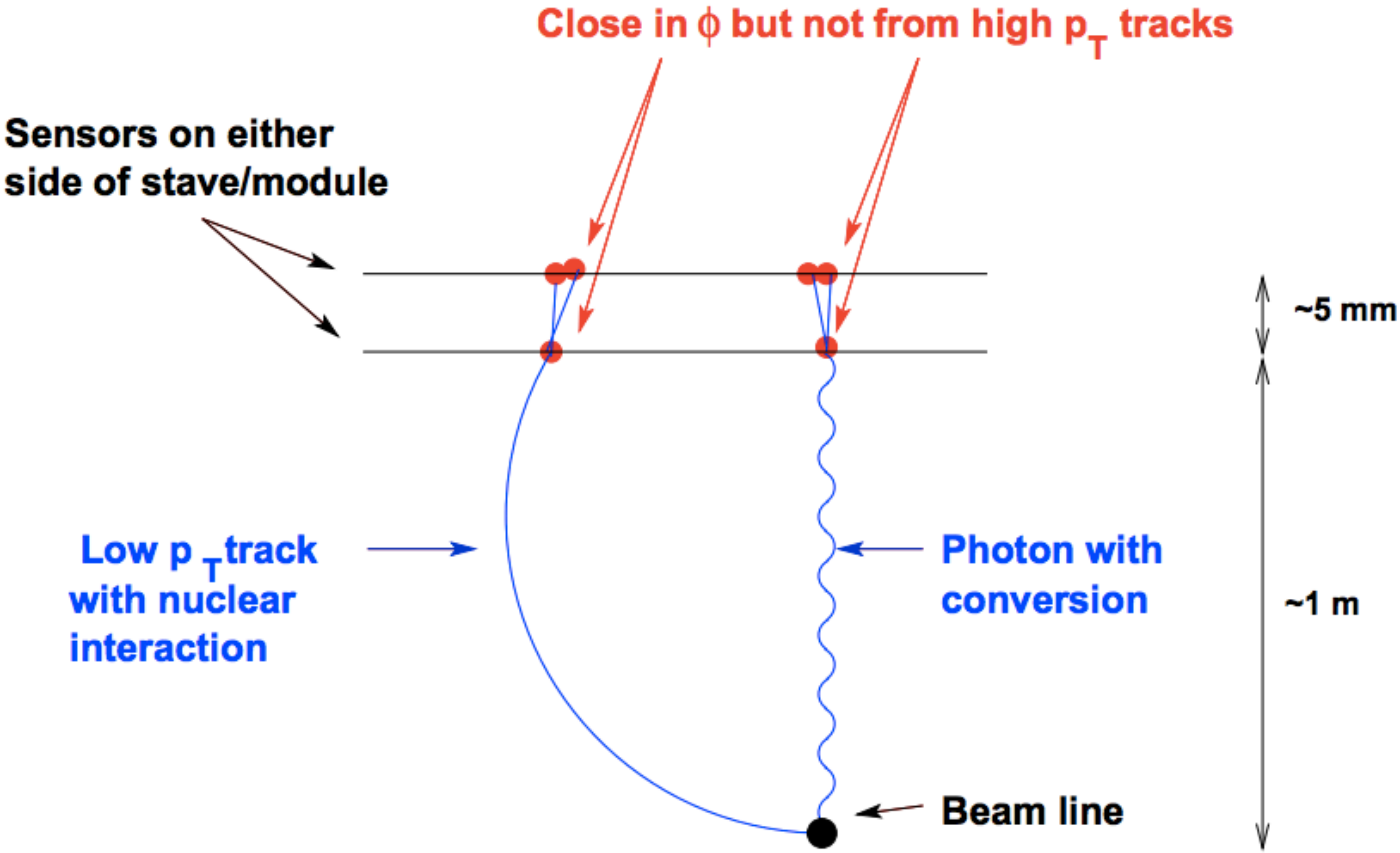
unseeded, doublet, push model

Reducing the data flow: Filtering on p_T

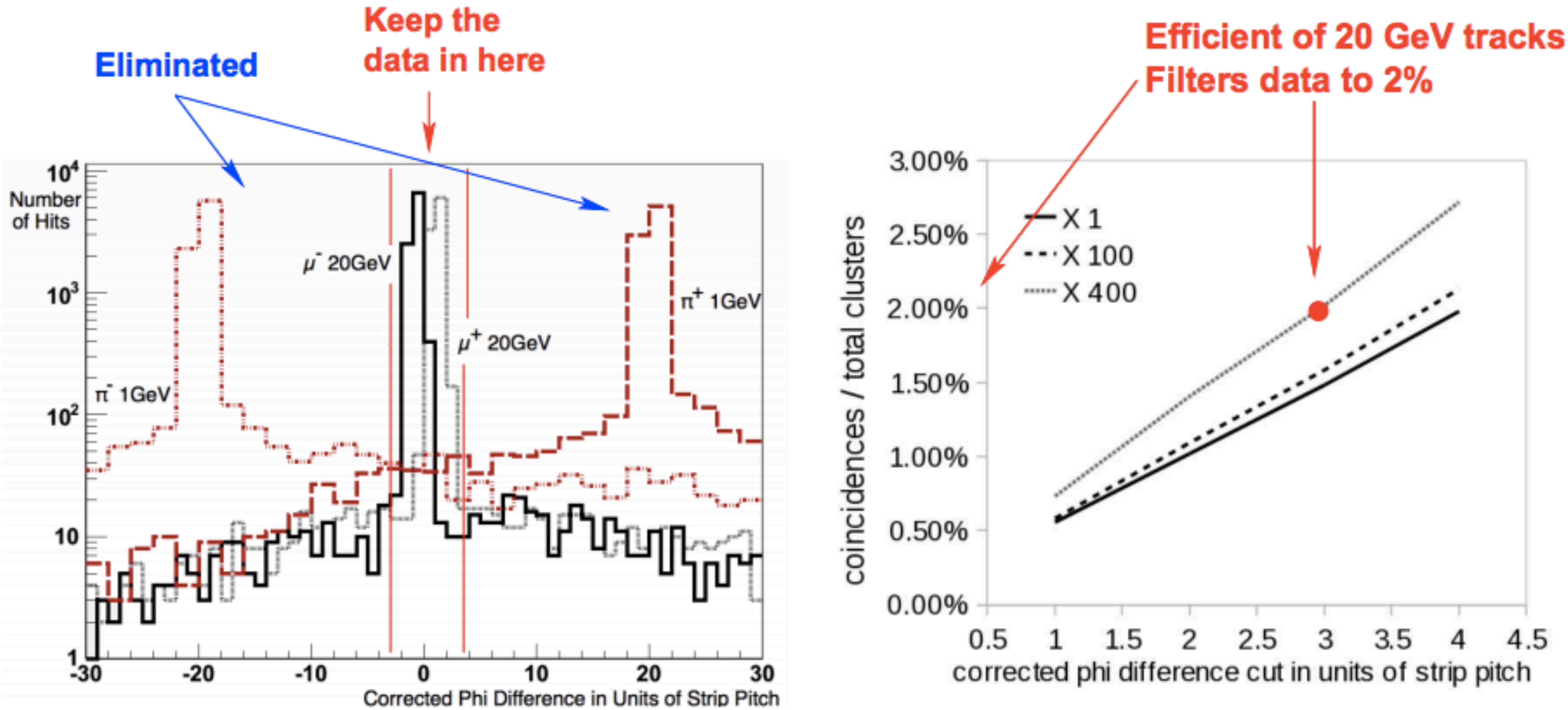
"Unseeded"/Doublet Method



Other sources of doublet coincidences



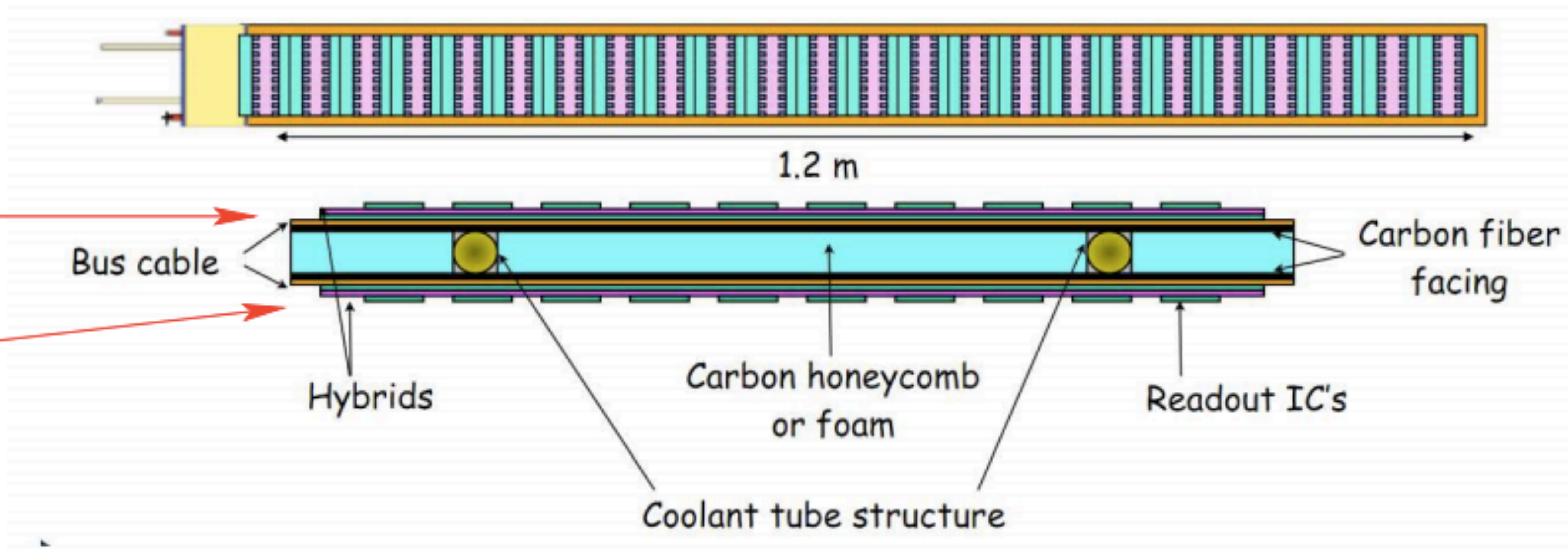
Doublets: The data reduction



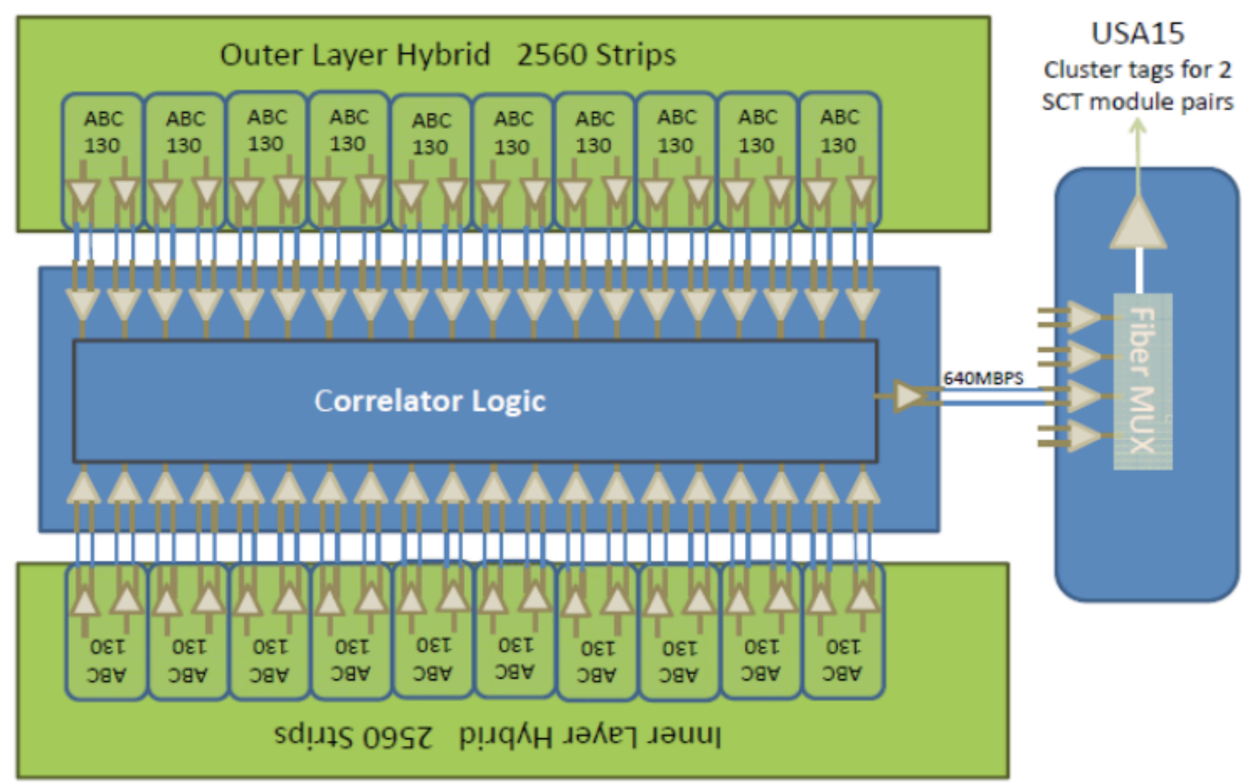
- Two-trigger layers at 0.8 m and 1.0 m have roughly double the readout rate as an offline only design
- Total bandwidth for outer layer with doublet readout is comparable to an inner layer without
- Must eliminate stereo angle for outer layers (impact not that serious)

Communication between the two-sides

Need to get from here to here



- Add wrap around cable with a high-speed serial interconnect for each 128 channels
- Add correlator chip for each ~10 cm module



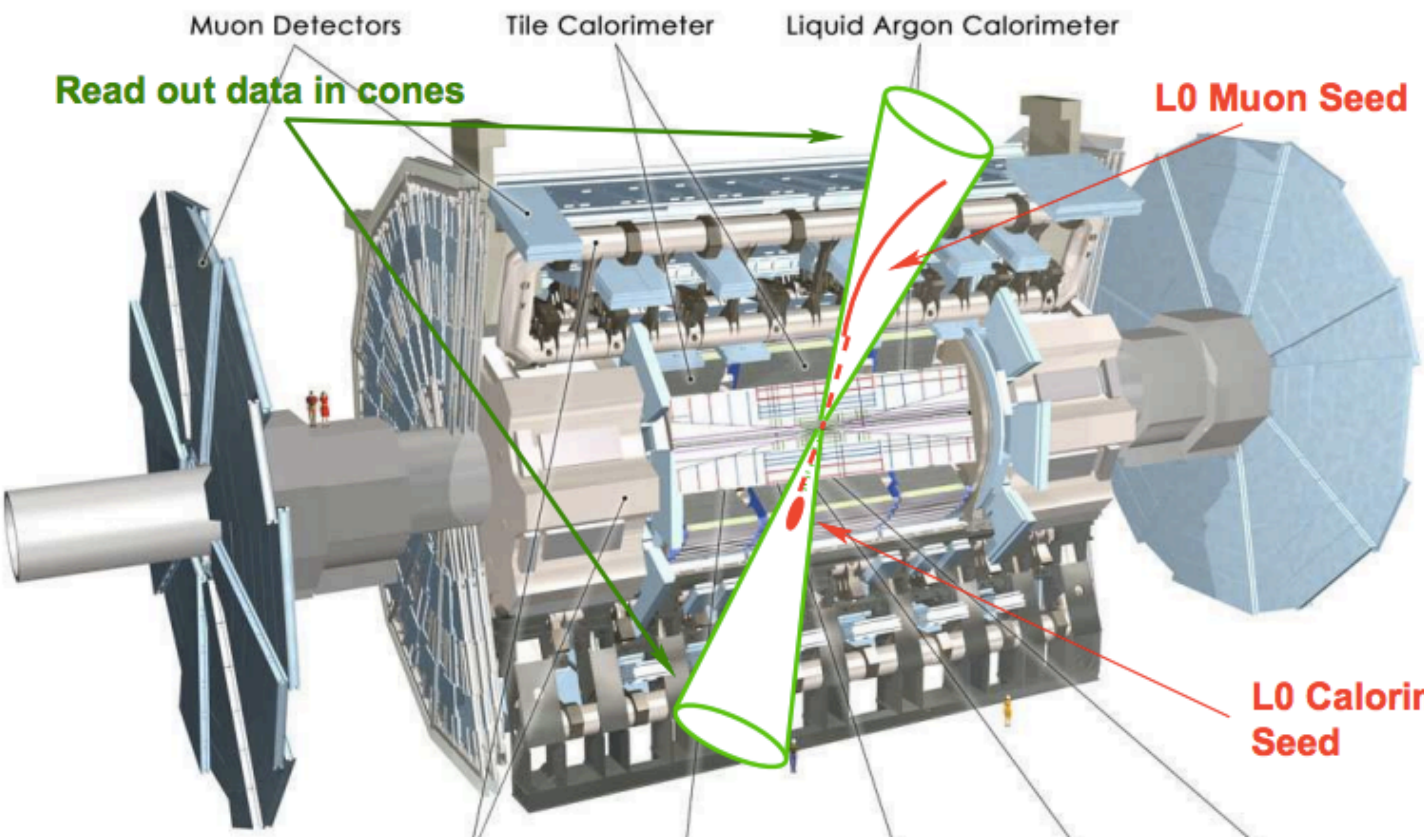
Filting on Region:

Two-level trigger, Pull method

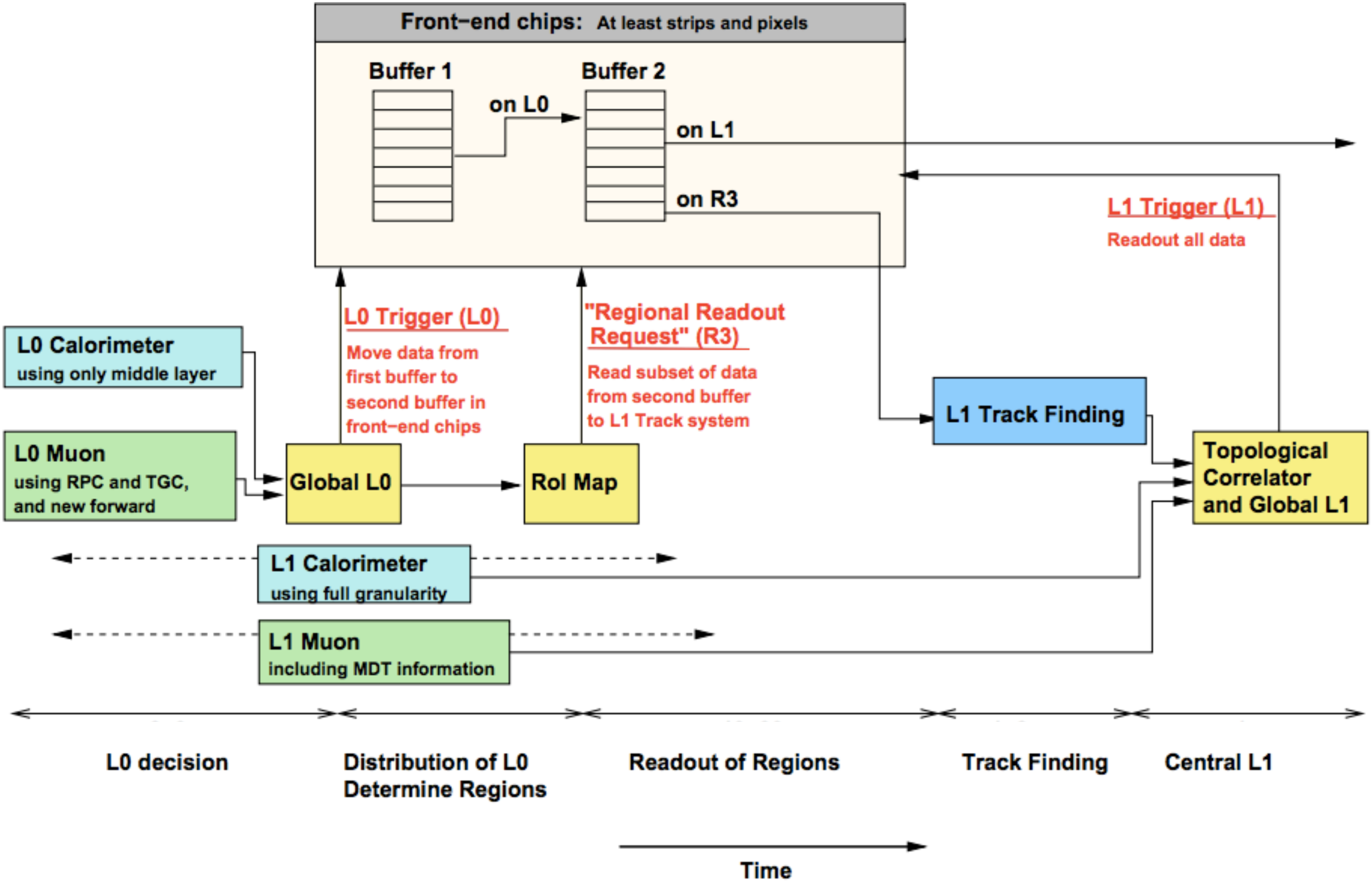
Reducing the data flow: Region method

Two-level trigger: L0 and L1

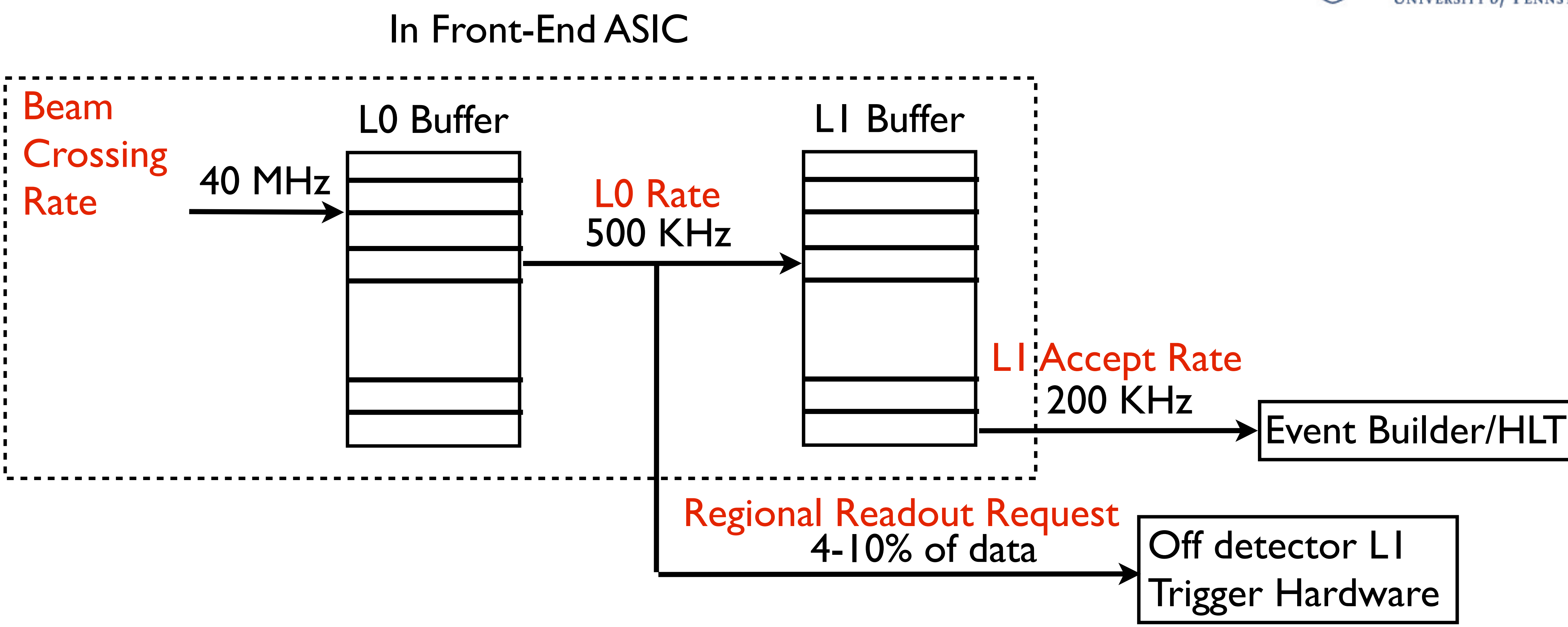
- **L0** uses calorimeter and muon system to define regions of interest (RoIs)
- **L1** extracts tracking for just RoIs from detector front-ends



Two-buffer scheme



Two-buffer scheme



Bandwidth = L1 Rate + L0 Rate × fraction of data in RoI

Nominal parameters:

L0 Rate = 500 KHz, L1 Rate = 200 KHz, RoI fraction = 10%

$$\text{L0 Latency} = \frac{\text{L0 Buffer length (in events)}}{\text{Beam Crossing rate}} \approx \frac{128}{40\text{MHz}} \approx 3.2\mu s$$

$$\text{L1 Latency} = \frac{\text{L1 Buffer length (in events)}}{\text{L0 Rate}} \approx \frac{128}{500\text{KHz}} \approx 256\mu s$$

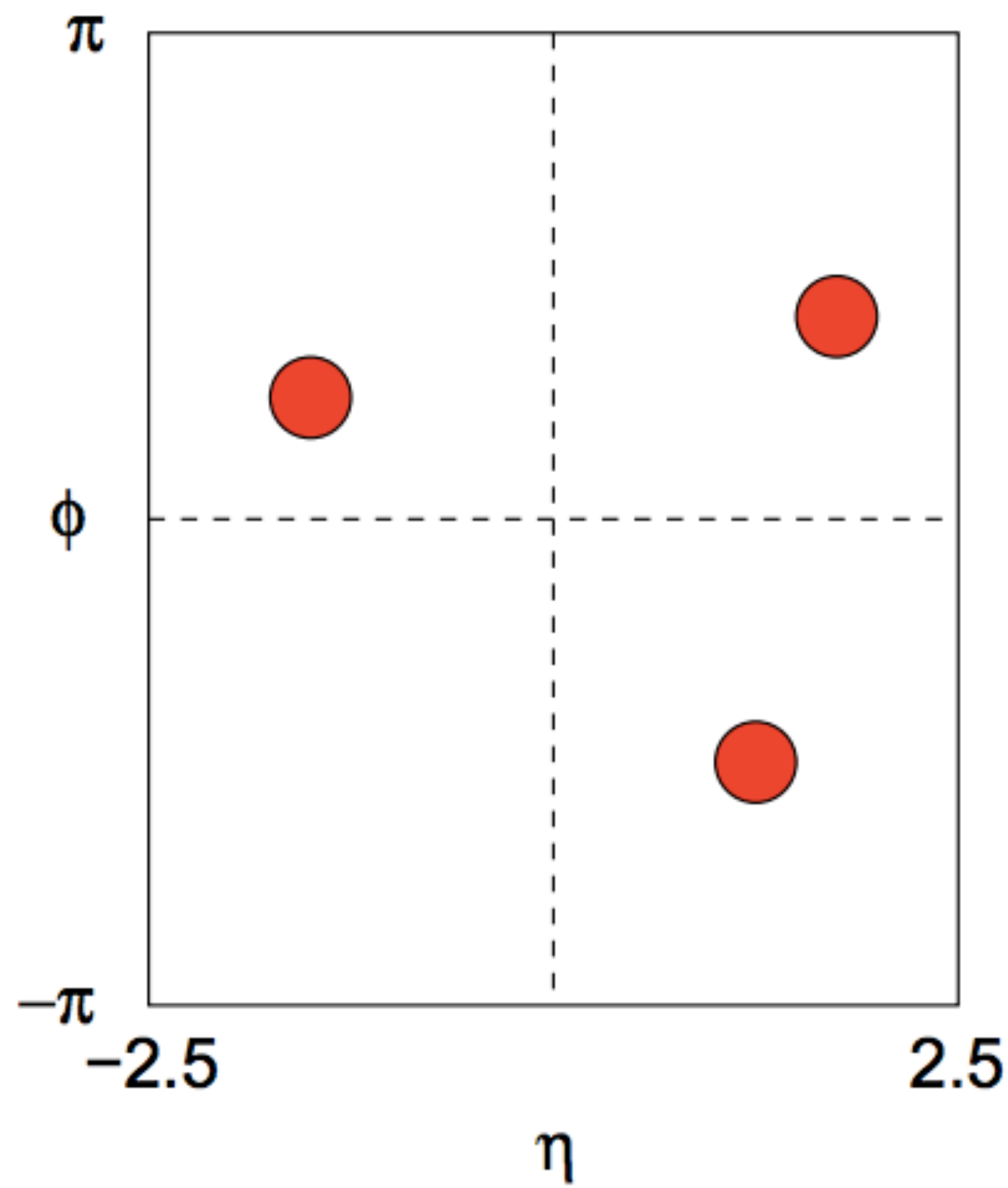
Data Reduction from Regions

Consider cones in $\eta - \phi$ space

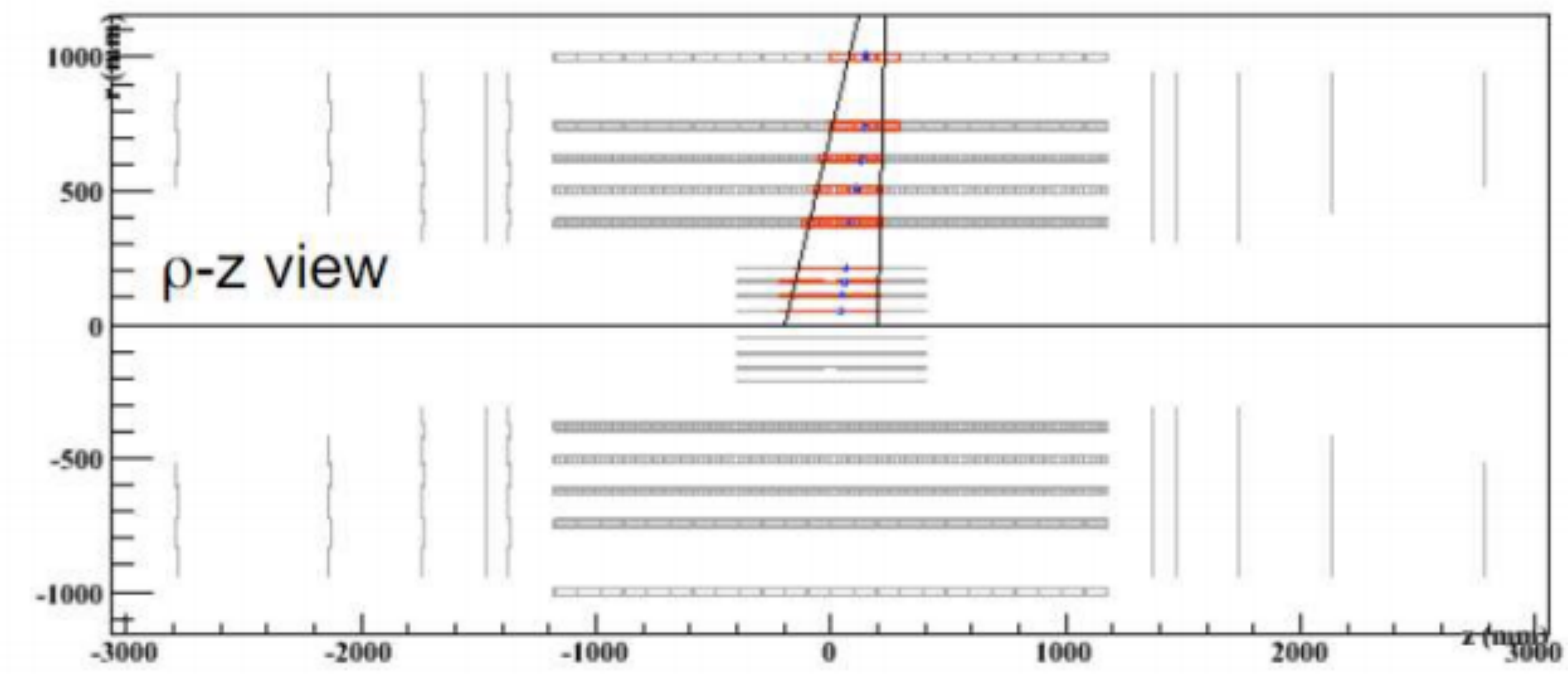
- Typical cones size used for isolation are $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.2 - 0.4$
- Fractions of tracking volume in a cone of $\Delta R < r$ is

$$\frac{\pi r^2}{(\eta \text{ range}) \times (\phi \text{ range})}$$

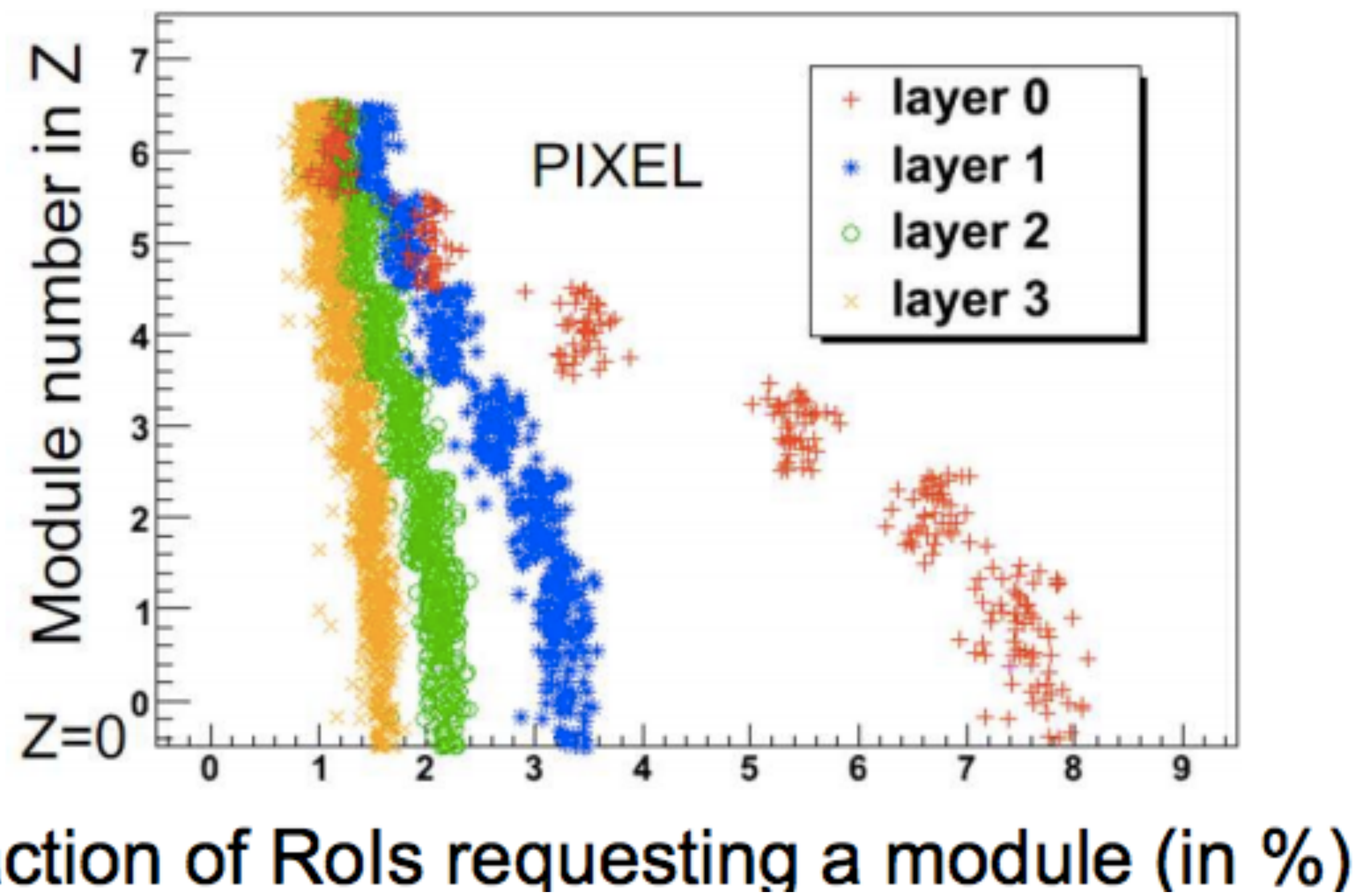
- For a cone of $\Delta R < 0.2$ this is 0.4%
- This allows for a large number of RoIs and a safety margin to fit in 10% RoI request fraction



Data Reduction from Regions



A tricky challenge



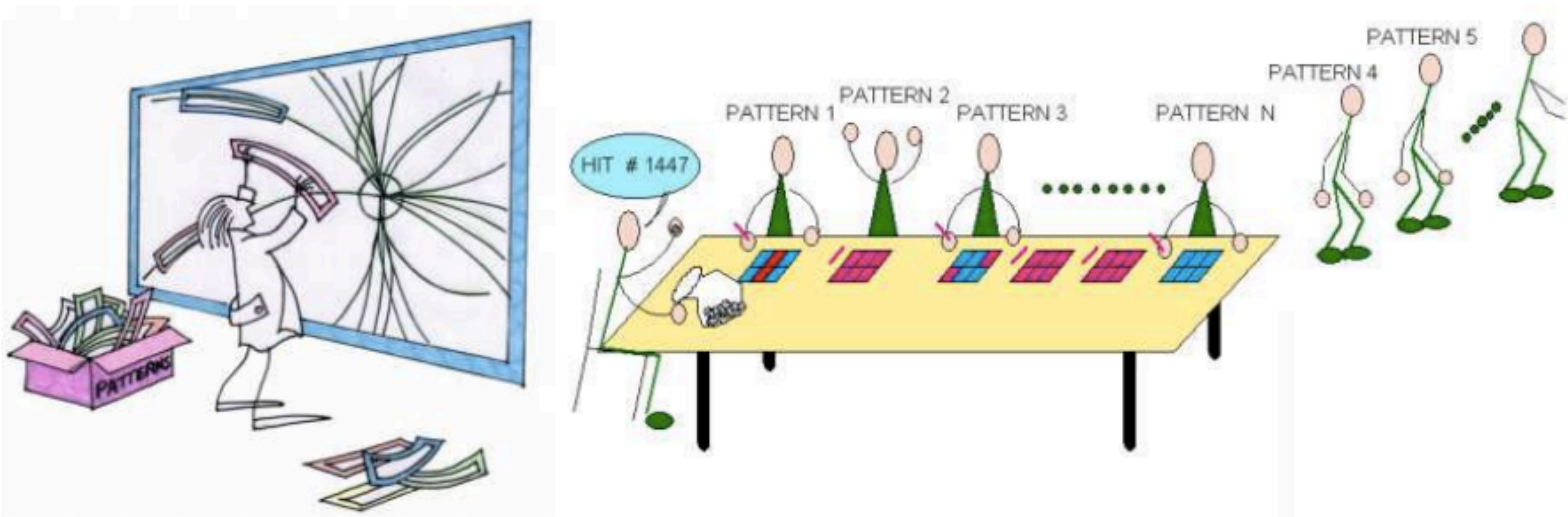
- Because of beam spot spread, RoI need to be elongated along beam direction

- Large request rate for central wafers in inner pixel layers

Finding tracks...

Both methods are about getting the data out of the detector

Still need to find the tracks ⇒ Content Addressable Memory (CAM)



- Technology has been used in many places : CDF SVT, H1, ...
- FTK: ATLAS is implementing a preprocessor for the level-2 trigger which gets tracks with near-offline quality at the current 100 KHz L1 output rate
- More advanced ideas involving 3-d chips are being explored

Comparing the Methods

Doublet Method

- Delivers: High-pT tracks for all crossings
- Latency: Could fit within short latency specifications
- Effects on tracking system:
  - Requires development of fast readout chain
  - Requires removal of stereo angle on trigger-layer strips

Region of Interest Method

- Delivers: All momentum tracks in regions for selected events
  - Also gives vertex information
- Latency: Needs replacement of all electronics in the system
  - Almost all electronics already planned to be replaced
  - Large latency allows for more processing of the other detector information
    - Inclusion of muon monitored drift tube (MDT) information
    - Inclusion of fine granularity calorimeter information
- Effects on tracking system:
  - Only affects buffers and readout logic in the front-end chips

More on the ATLAS L0/L1 Plan

Constraints on the latency and rates

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Constraints:

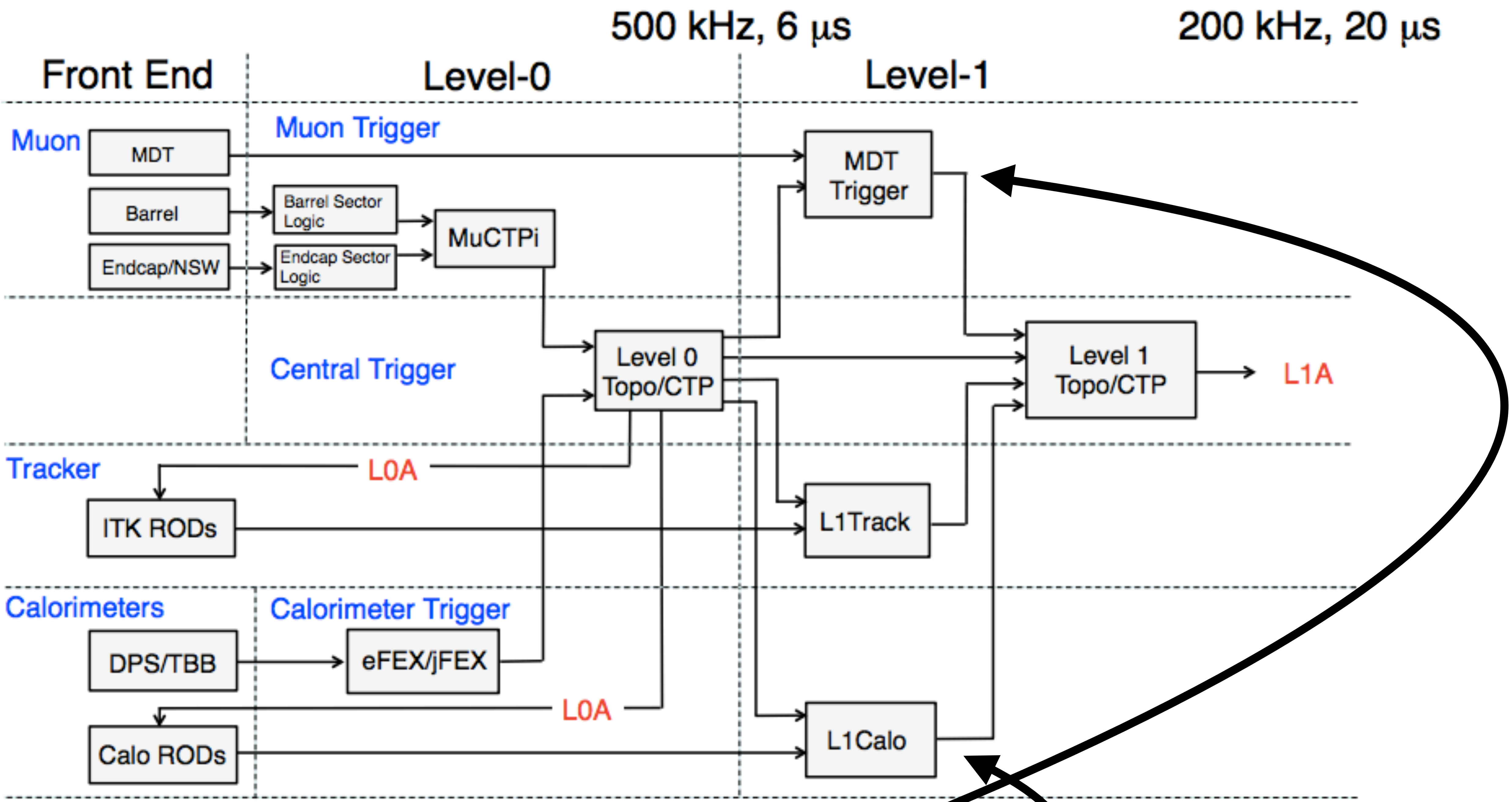
Detector	Max. Rate	Max. Latency
MDT	$\sim 200\,\text{kHz}$	$\sim 20\,\mu\text{s}$
LAr	any	any
TileCal	$> 300\,\text{kHz}$	any
ITK	$> 200\,\text{kHz}$	$< 500\,\mu\text{s}$

- Assumes LAr plan to go to full 40 MHz digital readout
- MDT Chambers will replace all accessible electronics
  - Limit is from difficult to reach inner barrel layers which will not be replaced

Plan:

	Rate	Latency
L0	500 KHz	6 μs
L1	100 KHz	14 μs

Two-layer scheme from Letter of Intent



Specifically envisions MDT muon trigger and a fine granularity L1Calo

Resulting Rates

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Object(s)	Trigger	Estimated Rate no L1Track	Estimated Rate with L1Track
e	EM20	200 kHz	40 kHz
γ	EM40	20 kHz	10 kHz*
μ	MU20	$>$ 40 kHz	10 kHz
τ	TAU50	50 kHz	20 kHz
ee	2EM10	40 kHz	small
$\gamma\gamma$	2EM10	as above	small
$e\mu$	EM10_MU6	30 kHz	small
$\mu\mu$	2MU10	4 kHz	small
$\tau\tau$	2TAU15I	40 kHz	small
Other	JET + MET	$\sim$ 100 kHz	$\sim$ 100 kHz
Total		$\sim$ 500 kHz	$\sim$ 200 kHz

Numbers only assume affect of L1 Track (no L1Calo and L1Muon except the photon which assumes L1 Calo)

Conclusion

HL-LHC poses significant challenges:

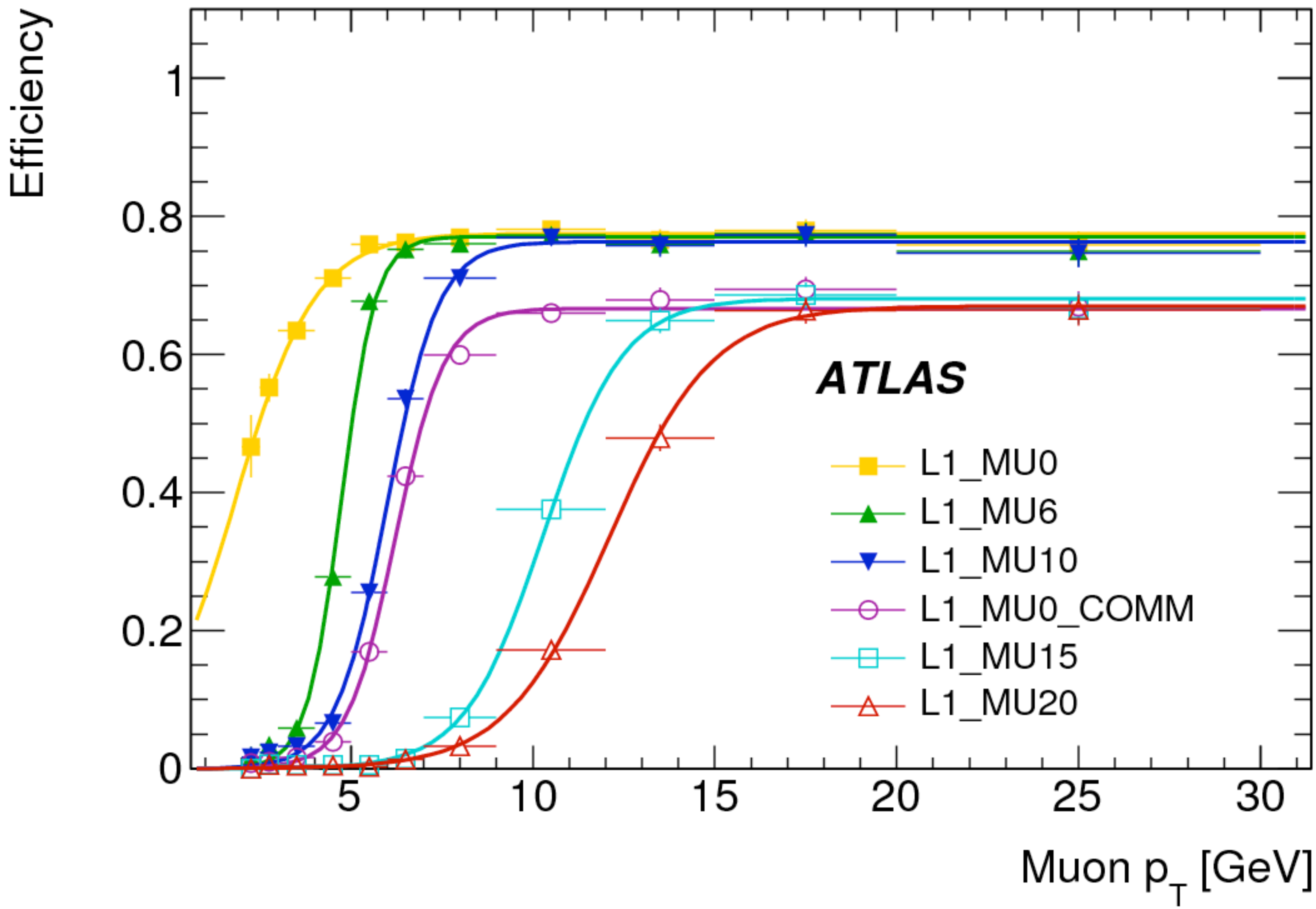
- Overall event rates
- Pile-up
  - Isolation, MET are degraded, Fake jets
  - Coincidences for multiobjects increase
- *Flexibility is a key design criterion*
  - Parts of the detector will be run at ~5 times their design luminosity ~30 years after their design

Addressing the challenges:

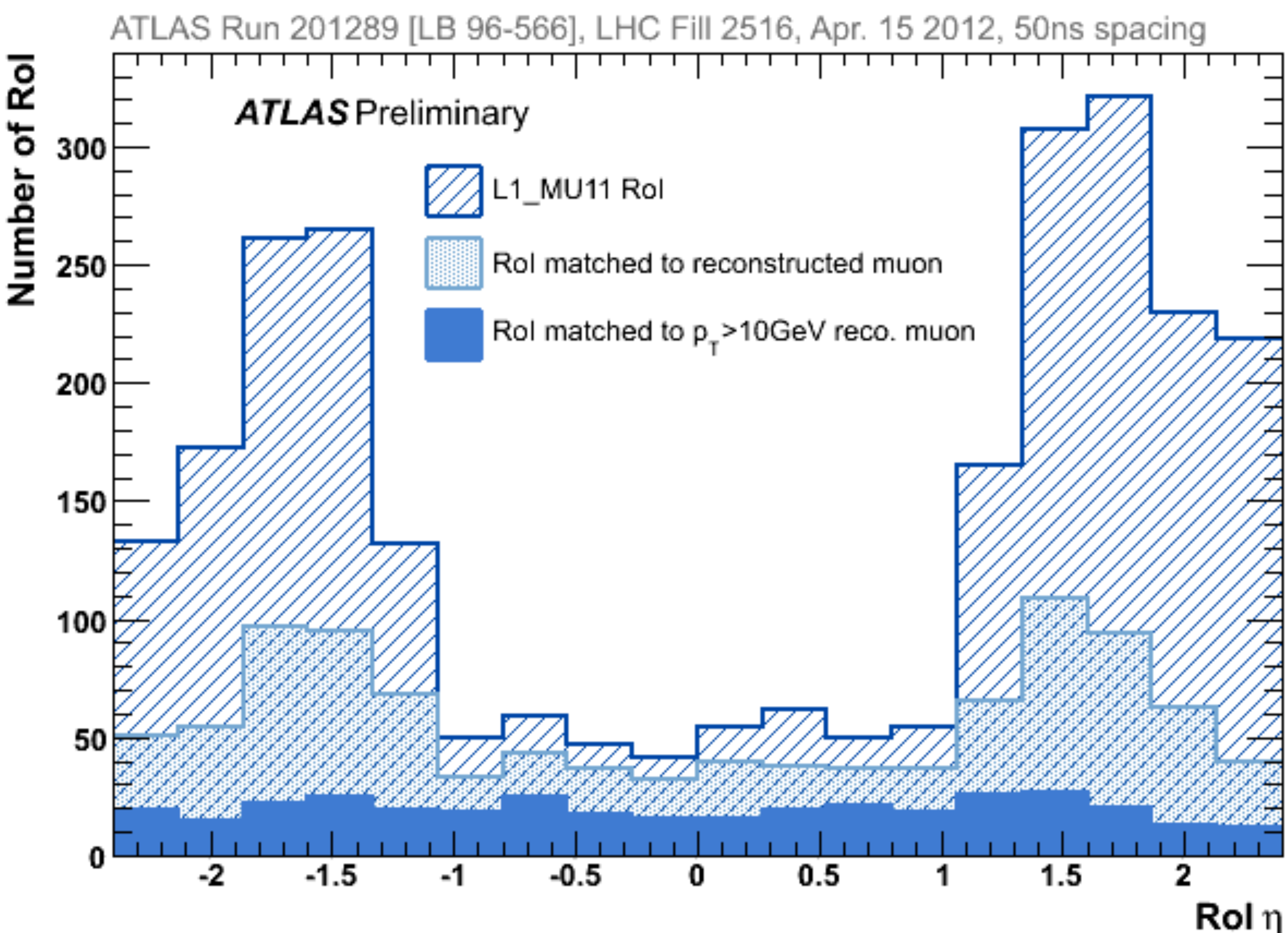
- ATLAS has outlined a planned to address these challenges based on a two-stage design
  - Meets challenges while potentially improving (reducing) some thresholds to get back acceptance
- A self-seeded (doublet) method is also being investigate

Begin Backup

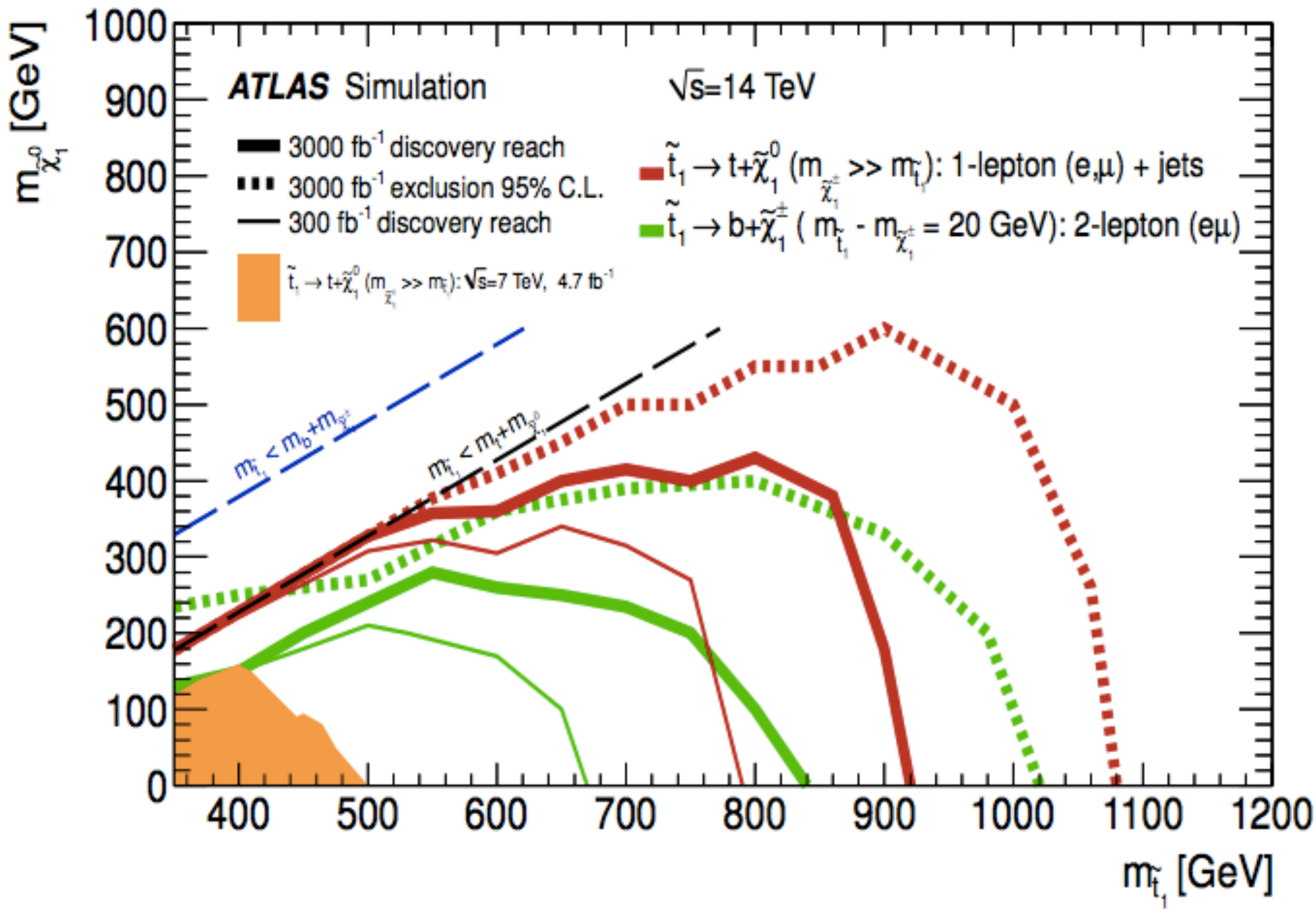
Muon Turn-on curves from 2011



Muon Eta Distribution from 2011



Stop search


ATLAS Simulation
√s=14 TeV
3000 fb⁻¹ discovery reach
3000 fb⁻¹ exclusion 95% C.L.
300 fb⁻¹ discovery reach
$\tilde{t}_1 \to t+\tilde{\chi}_1^0$ ($m_{\tilde{\chi}_1^\pm} >> m_{\tilde{t}_1}$): √s=7 TeV, 4.7 fb⁻¹
$\tilde{t}_1 \to t+\tilde{\chi}_1^0$ ($m_{\tilde{\chi}_1^\pm} >> m_{\tilde{t}_1}$): 1-lepton (e,μ) + jets
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm$ ($m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm}$ = 20 GeV): 2-lepton (eμ)
$m_{\tilde{t}_1} < m_b+m_{\tilde{\chi}_1^\pm}$
$m_{\tilde{t}_1} < m_t+m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
100
200
300
400
500
600
700
800
900
1000
1100
1200