ECFA workshop,
Aix-les-Bains 3-6 October 2016

ATLAS Muon upgrade for HL-LHC overview and performance

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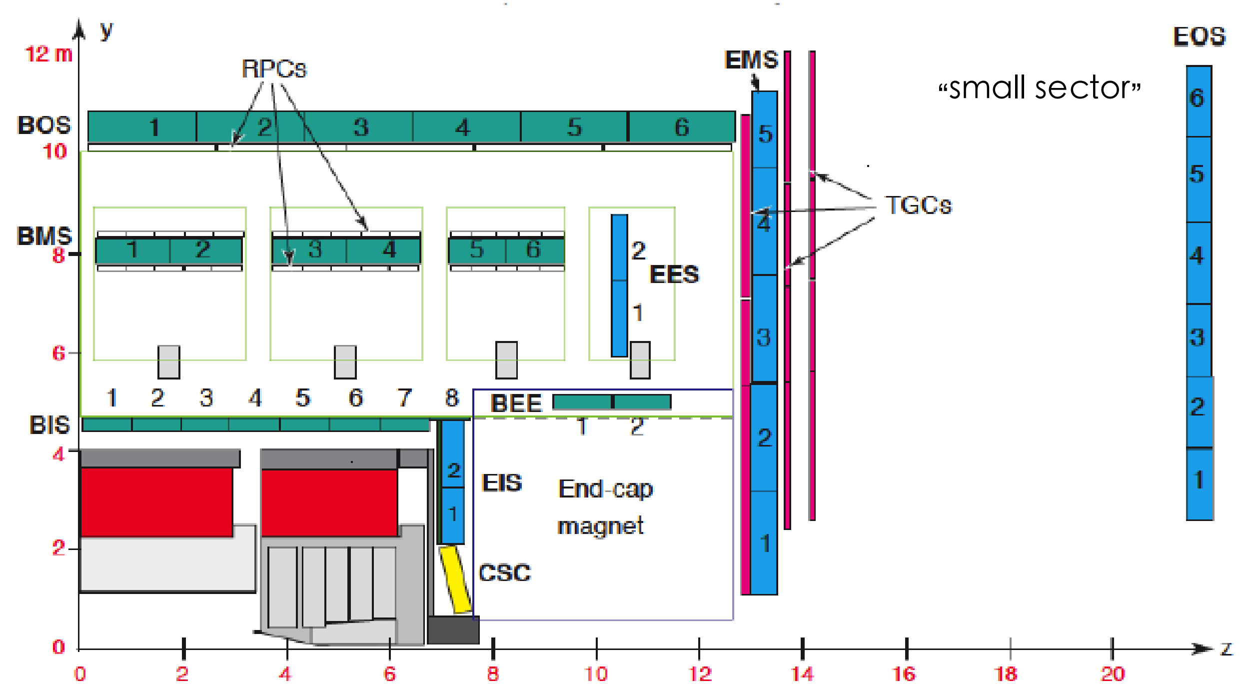
On behalf of the ATLAS Muon Collaboration

ATLAS Muon Spectrometer at LHC

- Air-core magnetic system
  stand-alone momentum measuement for $|\eta|<2.7$
- Trigger chambers,
  timing resol. <10 ns
  RPC (barrel), TGC (endcaps)
- Precision chambers
  superpoint resolution <40 μm
  MDT, CSC



Working well in 2016 at $L=10^{34}$ cm^{-2} s^{-1}

what should we change for HL-LHC ?

Phase-I Upgrade

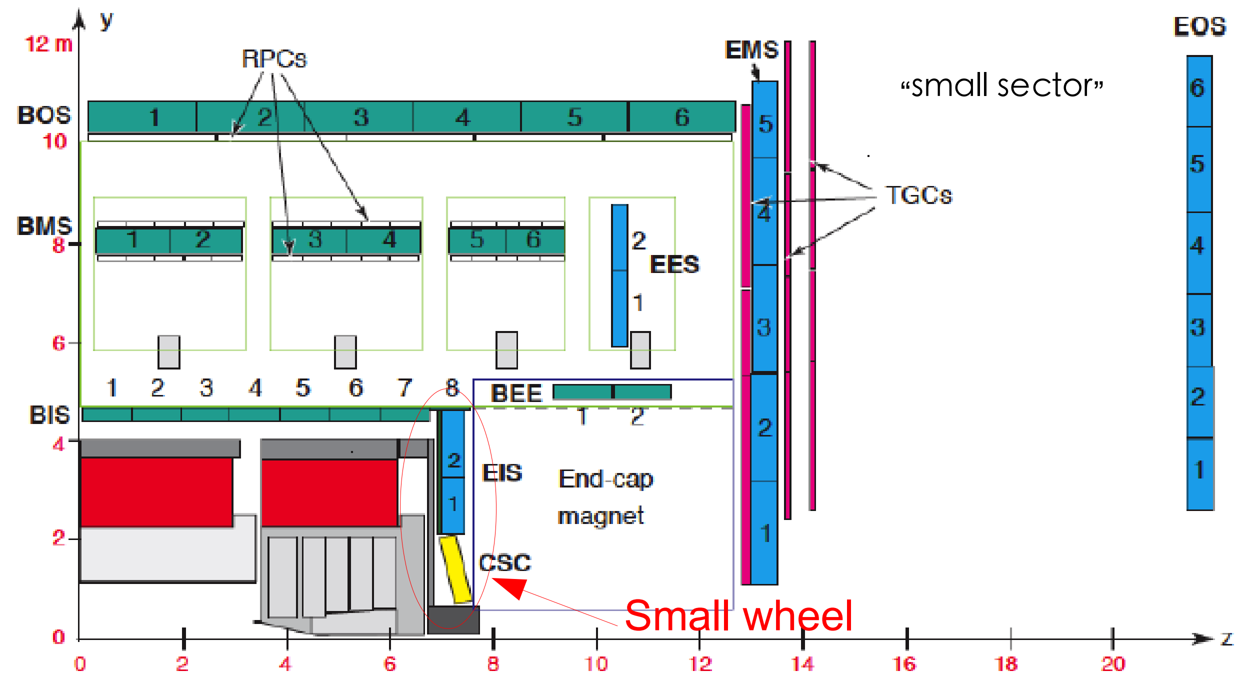
Phase-I upgrade: 2019-2020

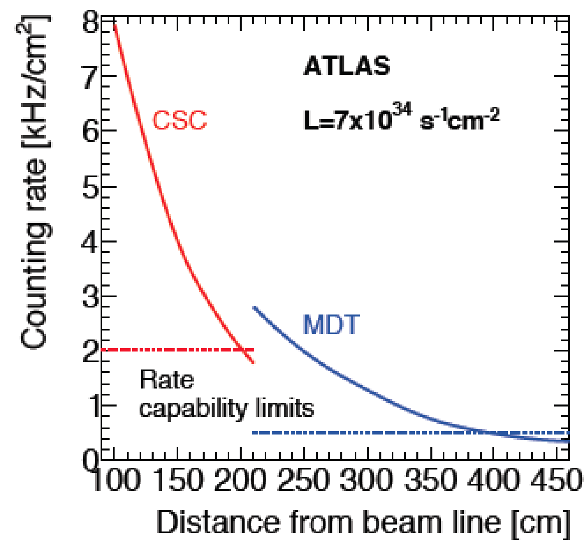
New Small Wheel (NSW)

Motivations:

- Hit rate on Small Wheel will exceed CSC and MDT limits

- Need to keep the L1 trigger rate within the budget allocated to muons without increasing p_T thresholds: add coincidence with segment in small wheel to reduce the fake muon rate





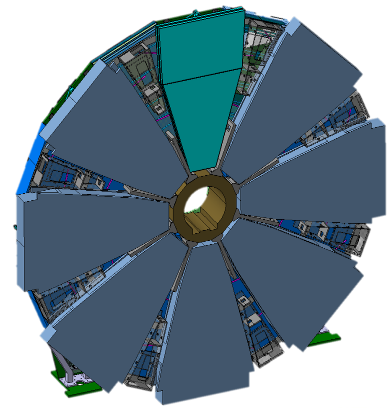
Phase-I Upgrade : New Small Wheel

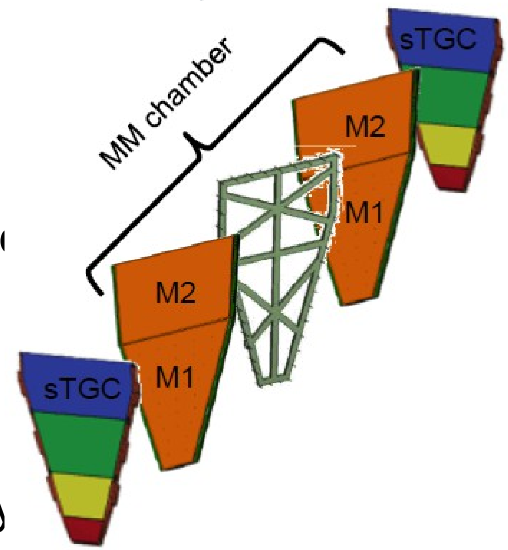
New Small Wheel

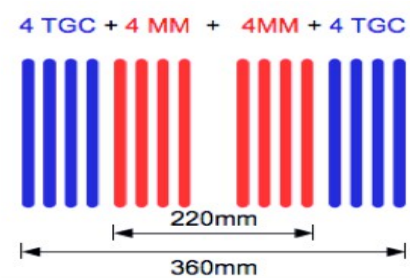
- small-gap TGC
  good timing for trigger
- Micro-Megas
  precision mesurement

- 8+8 points on track
- Super-point resolution ~30 μm
- Anglular measurement used
  in Level-1 trigger (resol. <1 mra
  to reject fakes and improve
  momentum resolution

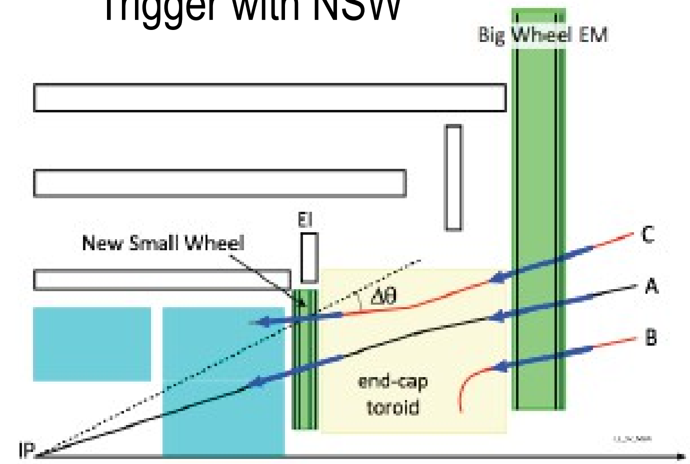
- First module-0 prototypes
  produced and tested succesfully
- Series production in 2017

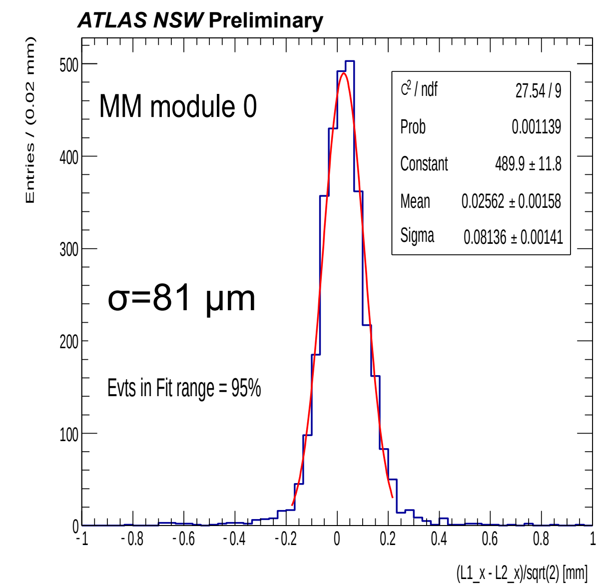






Trigger with NSW





Phase-II upgrade projects

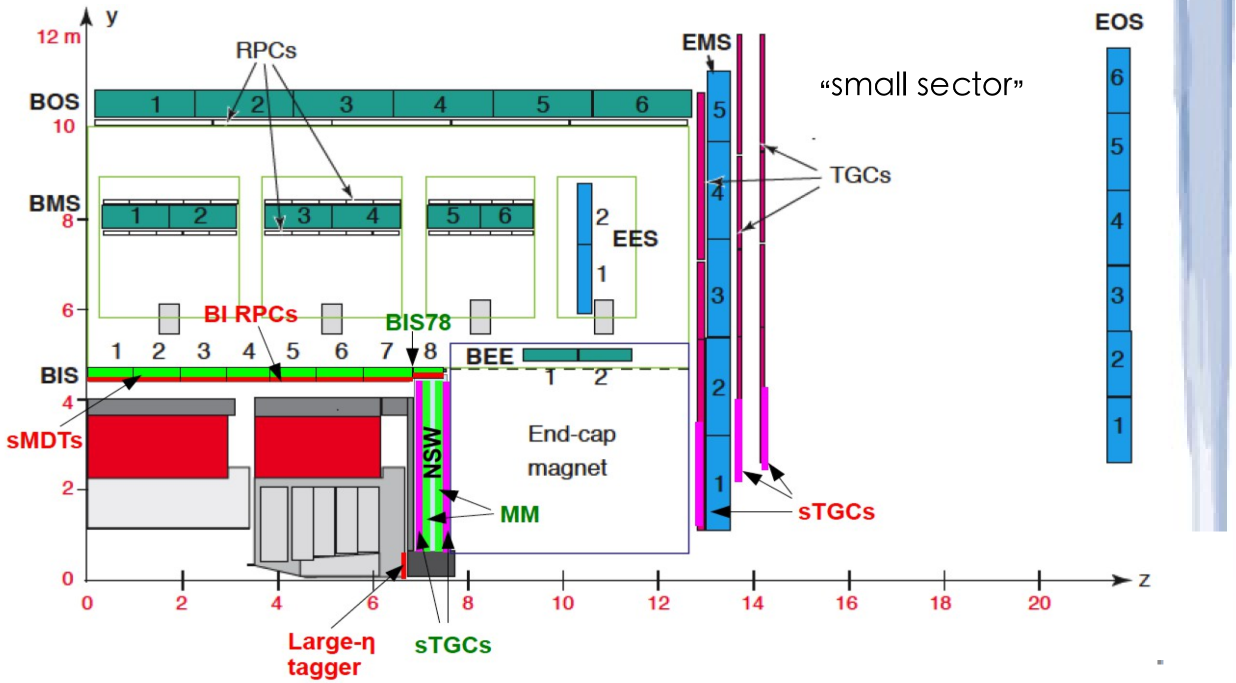
Projects in ATLAS Scoping Document :
CERN-LHCC-2015-020

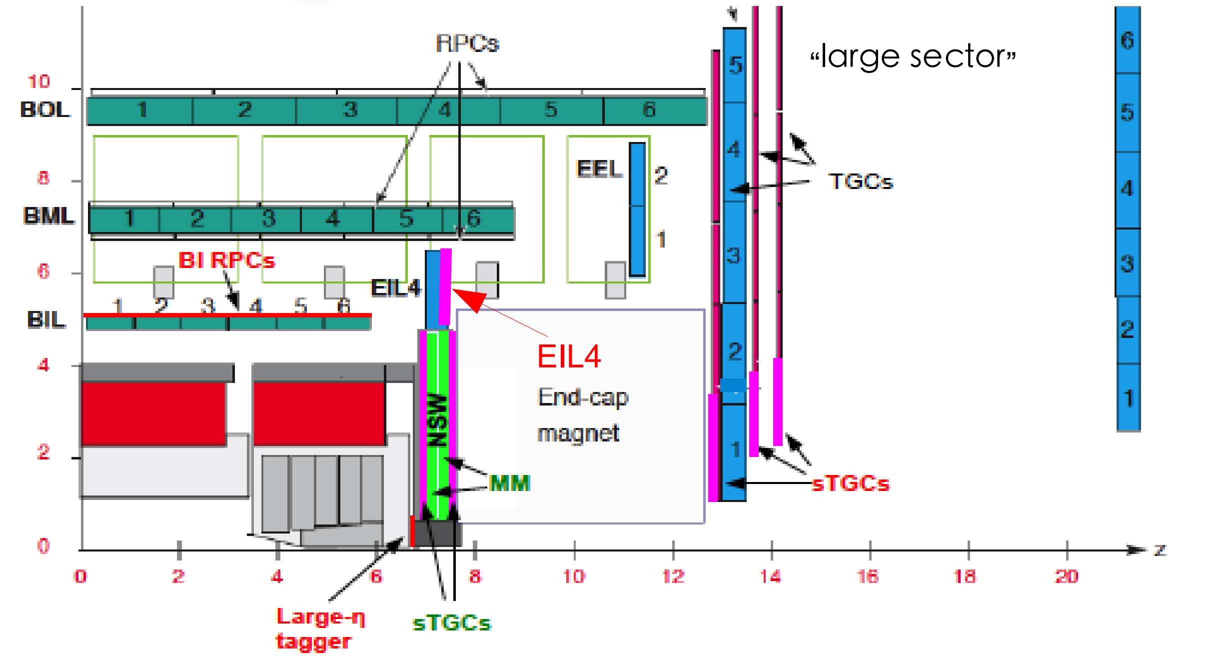
- Phase-II ATLAS trigger/DAQ :
  Level-0 trigger rate = 1 MHz
  (or even more)
  => Replacement of electronics for MDT, RPC, TGC
  => Profit to improve trigger and introduce a trigger based on MDT
  See talk by Y. Horii

- Improve barrel trigger:
  => 4th layer of new type RPC
  => small-MDT (sMDT) chambers in BI for "small sectors"

- Large-η tagger

- Options to replace TGCs in strategic places to improve trigger:
  => inner layer of big wheel (EM)
  => EIL4 chambers





Barrel Trigger: RPC rate limitations

- Present ATLAS RPC :
  from tests at GIF++ the current limit for stable operation is equivalent to 100 Hz/cm^2 at standard HV

- Map with extrapolated rates (including a safety facotor ~2) rates up to 300 Hz/cm^2

- “Safe operating mode”: reduce HV in regions with high rates to reduce currents.
  The price is a significant reduction of hit efficiency, From ~95% at η=0 to 60-80% at |η|=1

Hz/cm² @L=7x10^{34} cm^{-2}s^{-1}

φ chamber index

Sector Φ Id.	RPC unit Id. along Z direction -6.2	-6.1	-5.0	-4.0	-3.2	-3.1	-2.2	-2.1	-1.2	-1.1	1.1	1.2	2.1	2.2	3.1	3.2	4.0	5.0	6.1	6.2	Average
01.01	342	280	301	225	145	114	128	101		61	61	71	113	122	127	136	214	276	269	285	180
01.02	293	281	303	218	159	133	129	143		76	71	75	127	143	140	148	215	295	278	297	188
2	168	204	188	138	109	90	77	63	55	56	45	48	61	79	94	104	140	207	196	152	115
03.01	297	296	281	198	148	128	119	119	68	67	65	71	131	125	114	125	207	329	268	290	177
03.02	300	243	277	210	151	129	155	122	85	75	75	70	122	127	152	132	207	315	243	299	179
4	112	166	158	151	101	83	65	77	41	53	46	41	73	68	92	108	160	196	175	112	101
05.01	171	173	263	138	105	102	140	127	68	60	60	69	124	177	102	137	185	290	173	171	149
05.02	227	198	237	158	109	105	136	143	77	61	63	71	111	136	108	141	200	267	255	282	159
6	175	186	208	163	105	95	90	95	77	59	52	59	84	81	106	124	189	200	227	167	131
07.01	305	263	288	191	154	129	131	114		76	78		122	139	124	148	185	261	268	305	183
07.02	327	258	216	203	141	112	129	108		74	77		105	114	112	152	184	278	276	279	175
8	146	196	195	161	103	85	80	70	50	57	54	54	67	74	85	108	168	196	194	156	118
09.01	319	246	301	206	155	117	149	119		46	64		106	134	124	135	197	283	262	297	181
09.02	347	258	287	205	143	95	107	103		58	67		99	112	95	137	188	285	265	292	174
10	174	201	207	147	99	86	68	71	46	43	41	50	64	69	80	103	148	193	201	170	115
11.01	308	244	237	157	97	84	81	87		40	43		83	94	92	94	148	227	215	278	132
11.02	196	193	157	105	78	66	55	57		33	31		50	62	58	71	98	151	160	185	98
12						80	81	66	51	36	36	51	75	87	80						64
13.01	291	278	253		140	102	96	84	43	41	47	50	87	95	99	123		249	263	319	149
13.02	299	264	262		104	97	105	86	49	48	50	56	93	103	97	110		252	227	294	146
14						142	68	64	52	41	40	49	63	68	136						76
15.01	196	221	148	113	76	71	67	49		38	36		50	59	86	87	104	156	173	196	104
15.02	183	159	246	164	116	98	103	75		44	43		75	106	112	107	158	248	159	183	133
16	173	214	216	173	108	89	54	75	56	59	50	50	77	54	87	103	177	209	208	154	124
Average	229	223	234	167	118	101	96	88	56	52	51	56	86	97	103	118	171	240	221	221	137

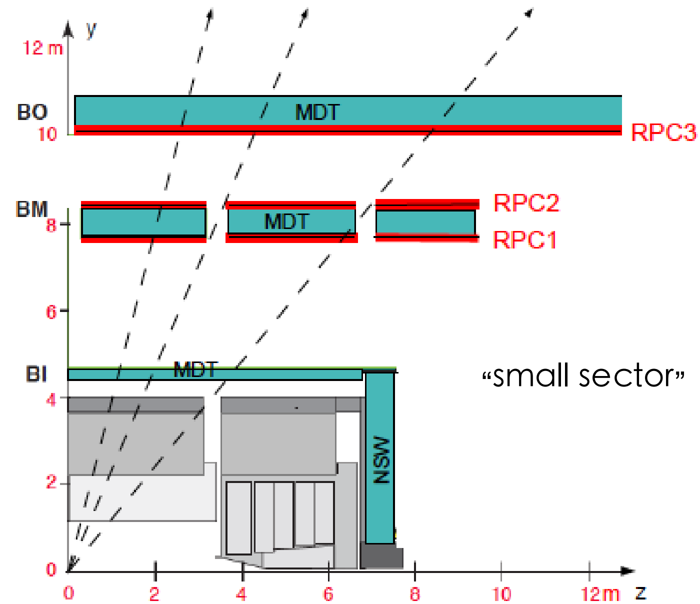
η=-1 η=0 η=1

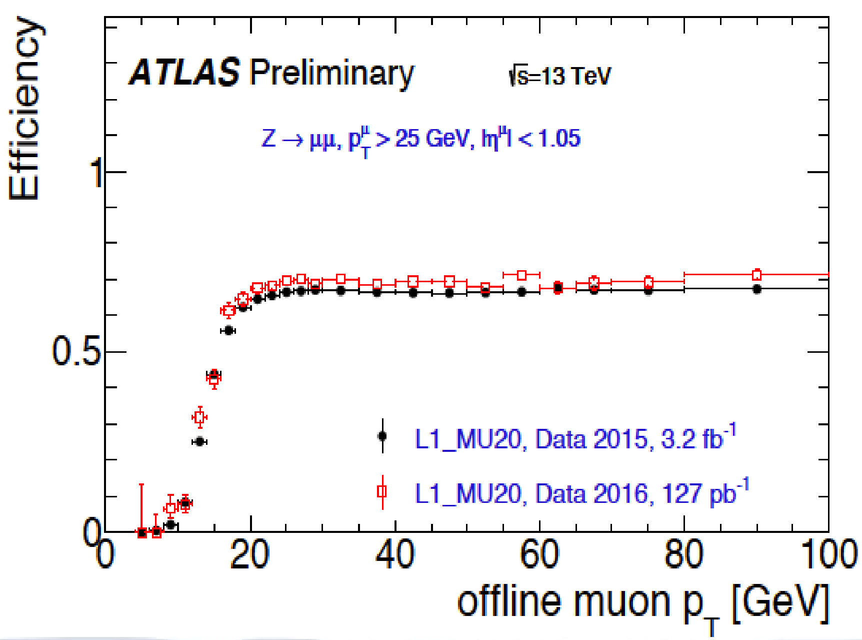
Barrel Trigger: Acceptance limitations

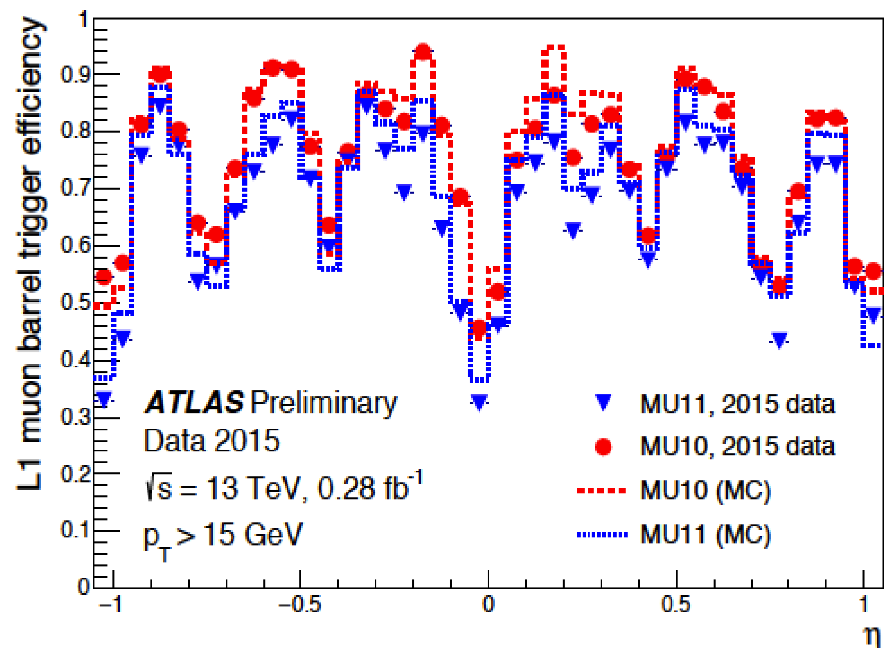
- Present Barrel trigger requires a coincidence between three RPC doublet layers: RPC1,2,3

- Acceptance holes in “small sectors” caused by supports of magnet coils

- Limited redundancy : will not work in “safe operating mode'







Barrel Trigger: BI RPC layer

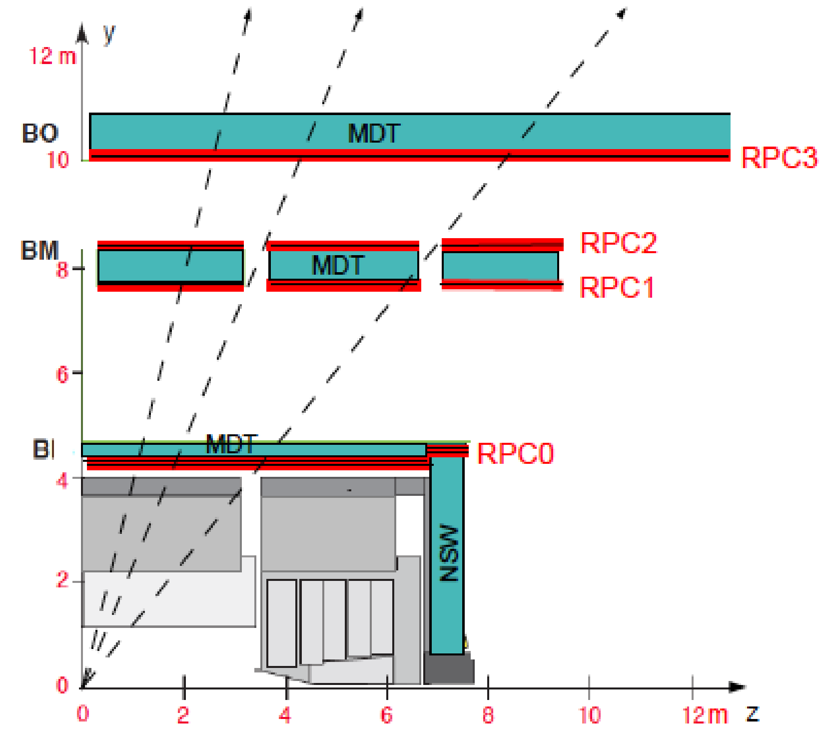
- Solution: introduce a new RPC triplet (RPC0) on barrel inner (BI)

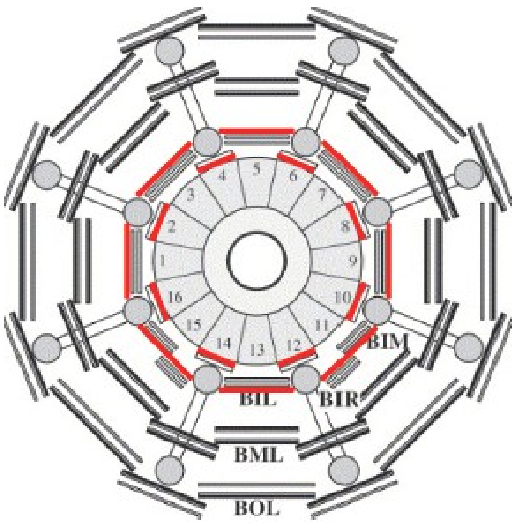
- New small-gap RPCs with higher rate capability

- Need to replace MDT in small sectors with small-MDTs to make room for RPCs

- Pilot Phase-I upgrade project
  BIS78 (1<|eta|<1.2)
  RPC+sMDT chambers

See talk by H. Kroha

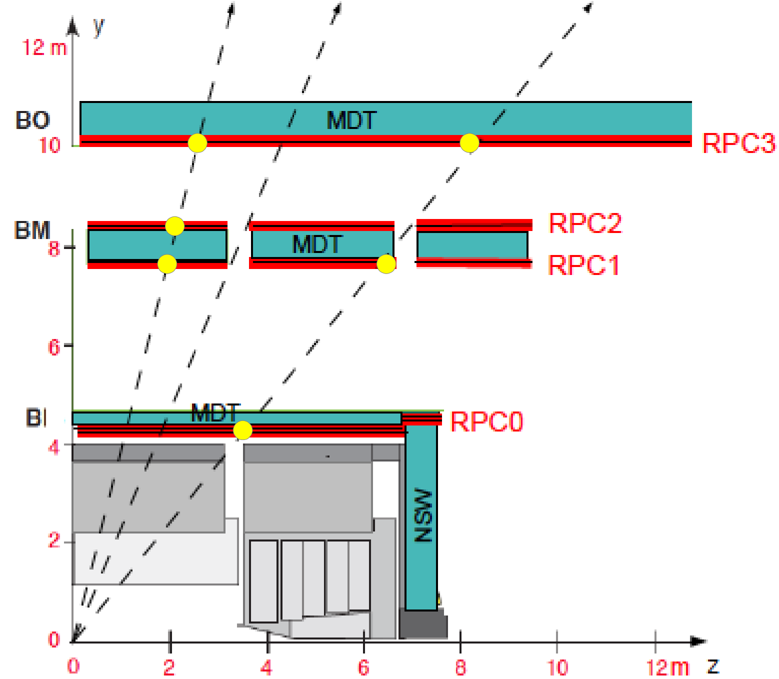


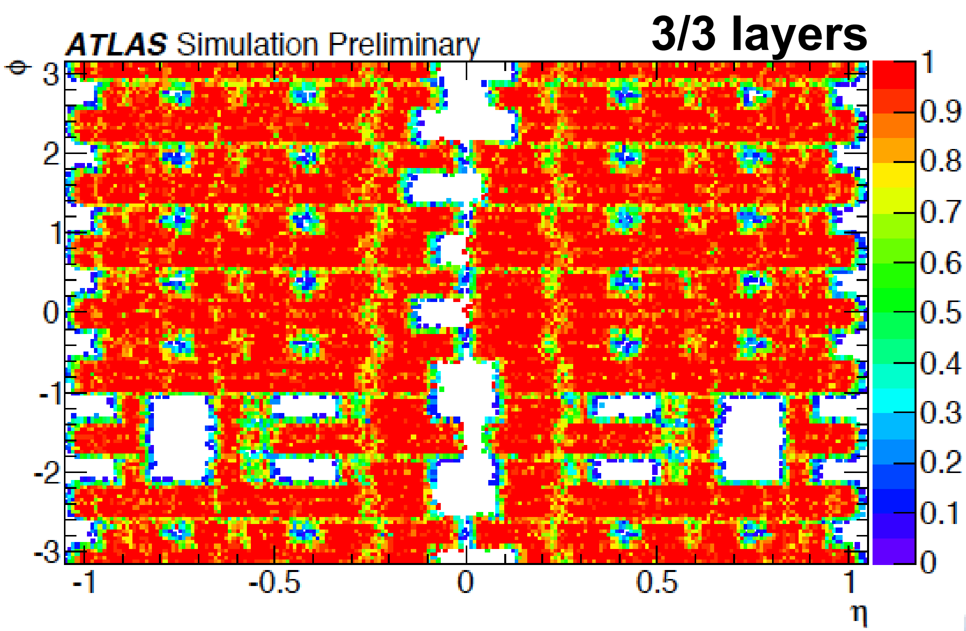


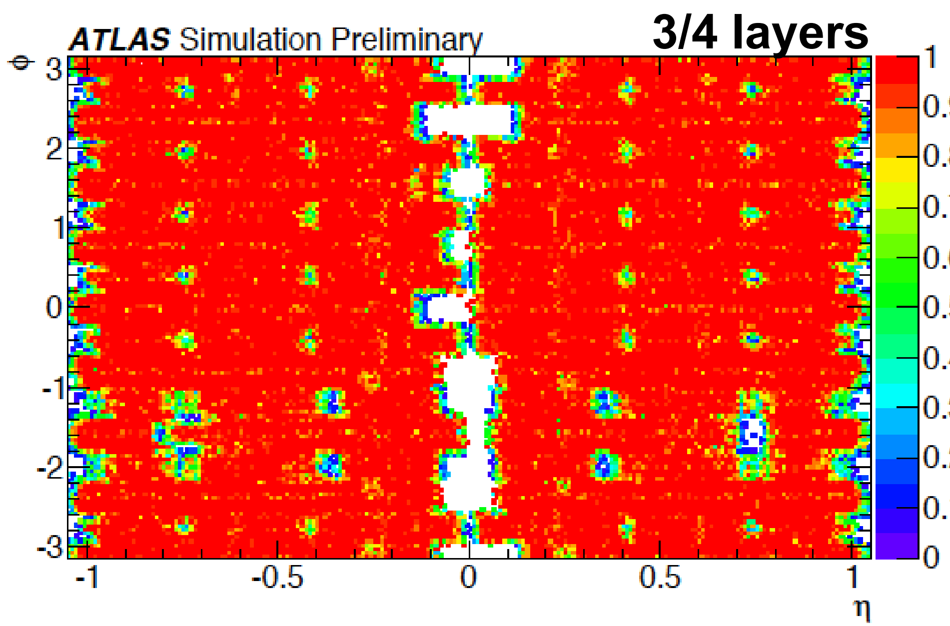
Barrel Trigger: acceptance

More flexible trigger logic:

- Replace 3-out-of-3 layers requirement with 3-out-of-4 layers
  Acceptance 80% → 92%





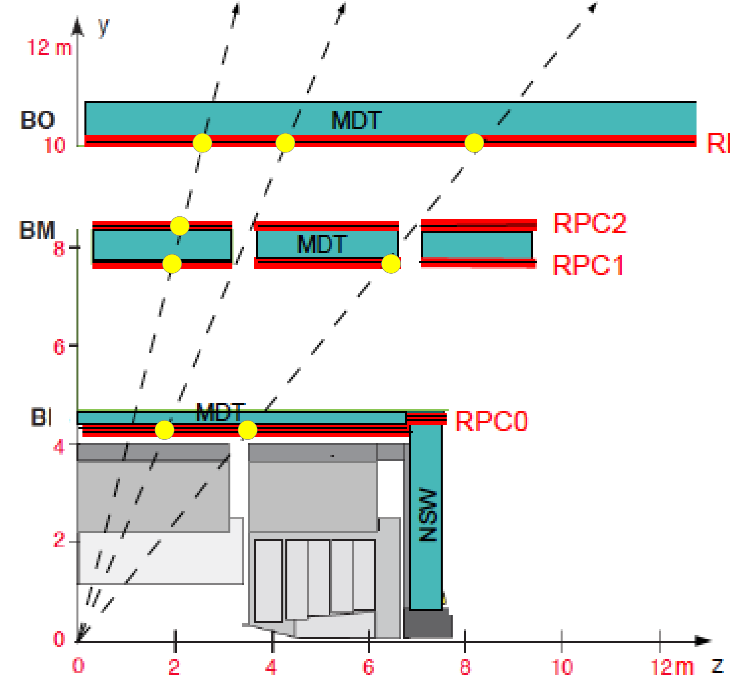


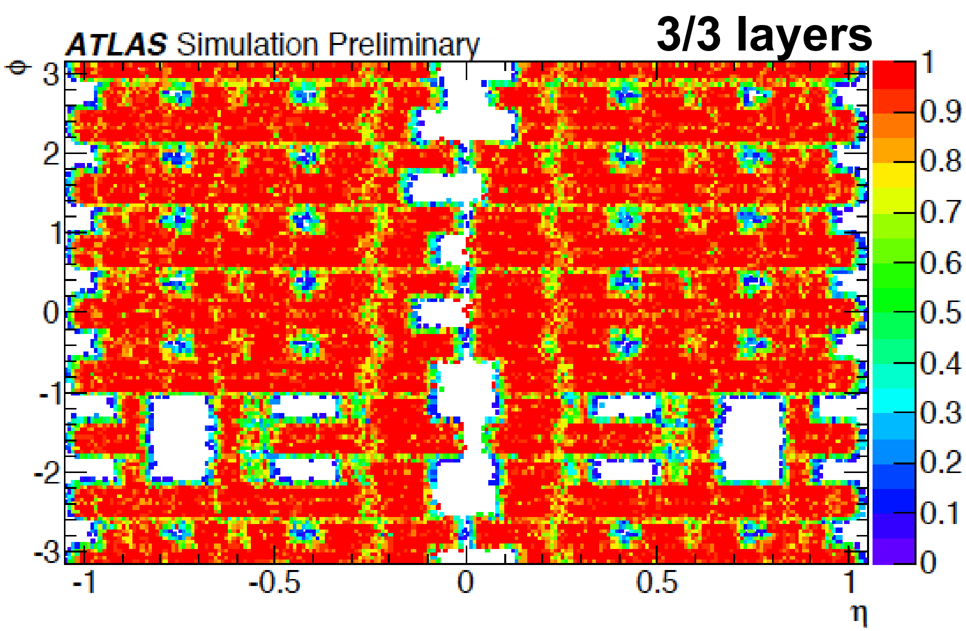
Barrel Trigger: acceptance

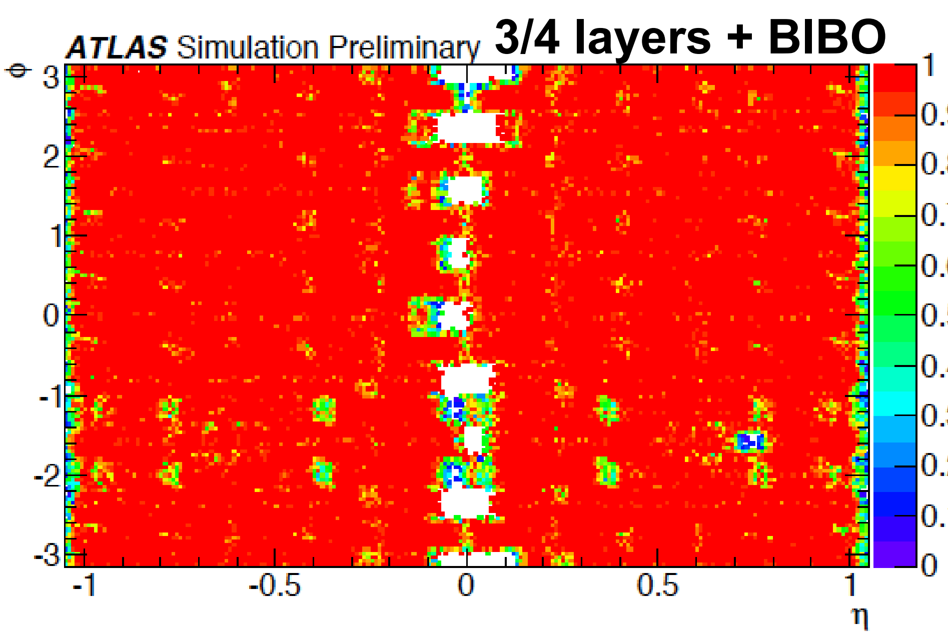
More flexible trigger logic:

- Replace 3-out-of-3 layers requirement with 3-out-of-4 layers
  Acceptance 80% → 92%

- Adding also two-station coincidences BI-BO (RPC0-RPC3)
  Acceptance → 96%
  2-station coincidences can be limited to areas with limited acceptance to reduce trigger rate







Barrel Trigger: efficiency x acceptane

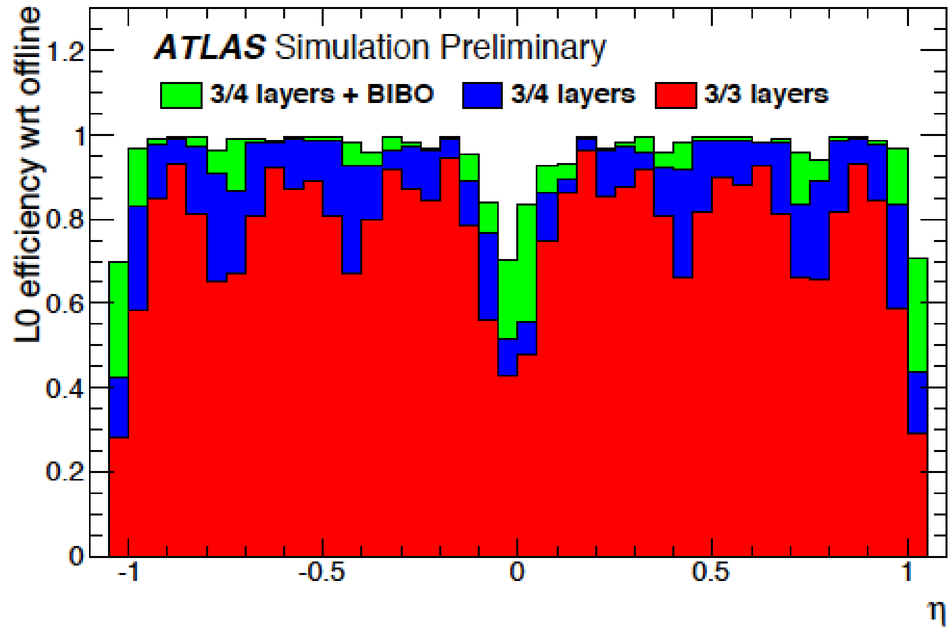
- Robustness against reduction of efficiency of old RPCs

- Scenario with HV reduction to keep old-RPC currents below safe-operation limits at HLLHC (with safety factor ~2 on rates)

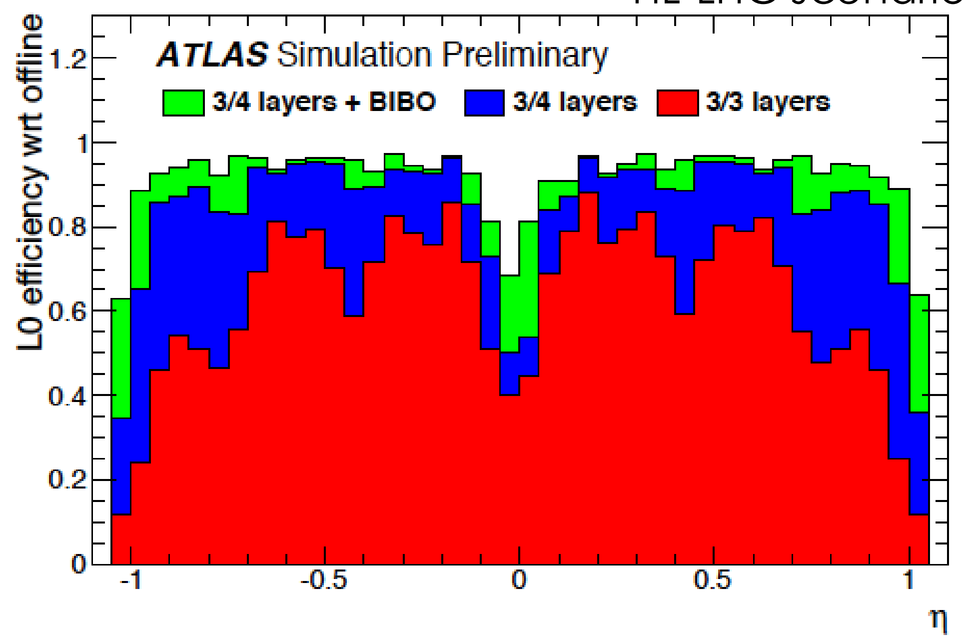
- Efficiency x Acceptance of new trigger remains above 90%

- Trigger rate for p_T>20 GeV of order 60 kHz @L=$7.5 \times 10^{34} cm^2 s^{-1}$ (barrel only)

100% RPC efficiency



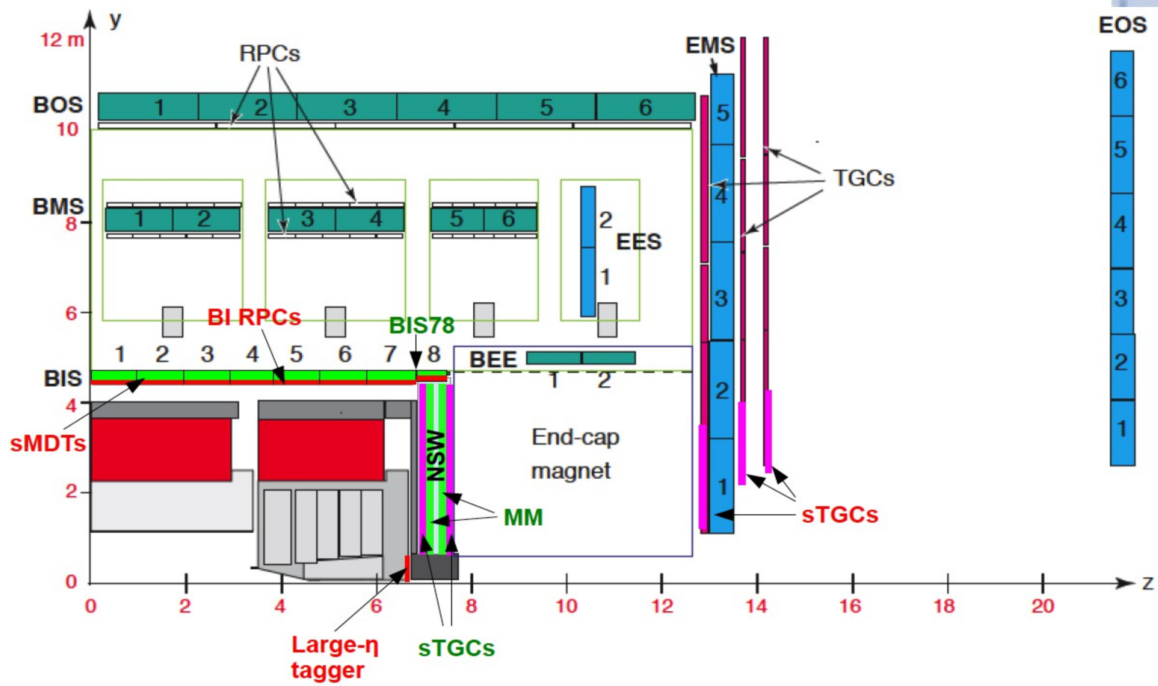
HL-LHC scenario



Large-η tagger

- Profit from η extension of inner tracker from η=2.5 to 4.0: to extend the muon acceptance from 2.7 to 4.0

- B-field integral becomes zero between η=2.7 and η=3.2 No momentum measurement from muon system in the large η region



Large-η extension: initial options

1) μ tagger

2) 2nd tracker

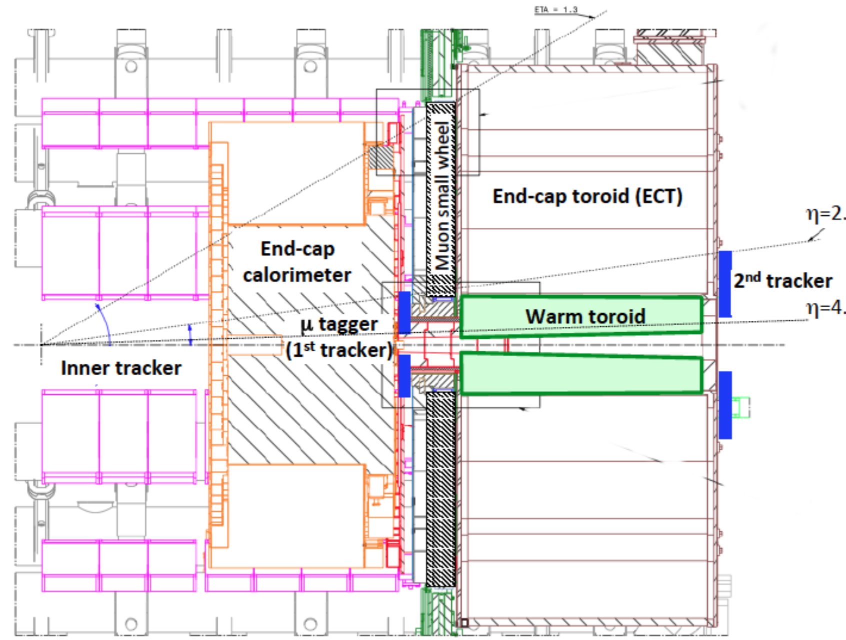
3) Warm Toroid (WT)
magnetized JTT shielding
(Iron, 4.5m x 1.5 T)

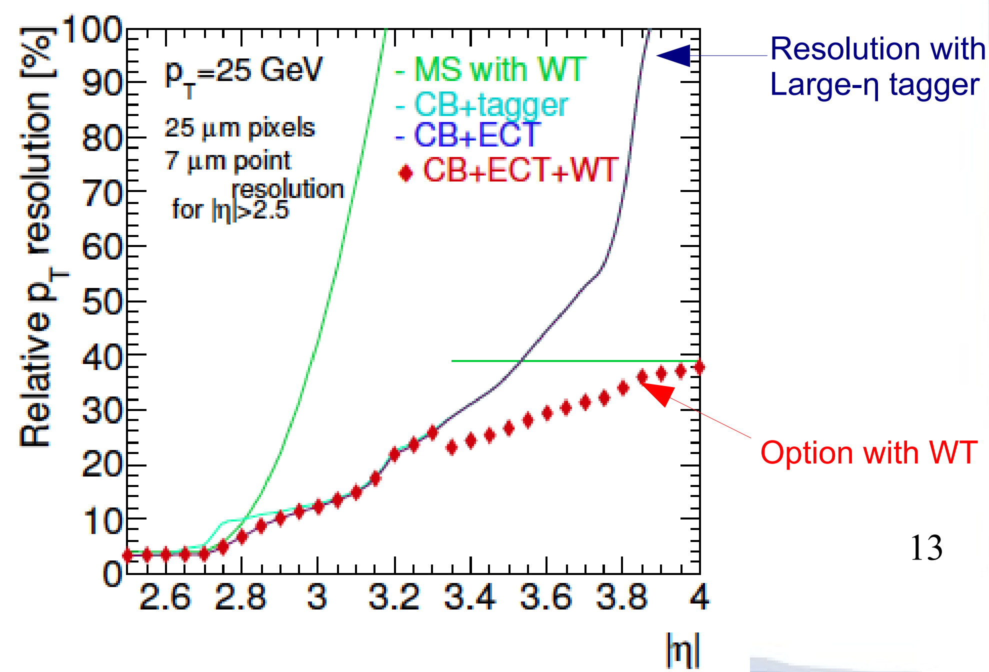
- WT implies significant cost and complication and moderate resolution due to multiple scattering in Iron.

- 2nd tracker does not look very useful

- Simple tagger looks more promising and is currently under study

Space for tagger considered in the design of new shielding for Phase-I upgrade





Large-η Tagger

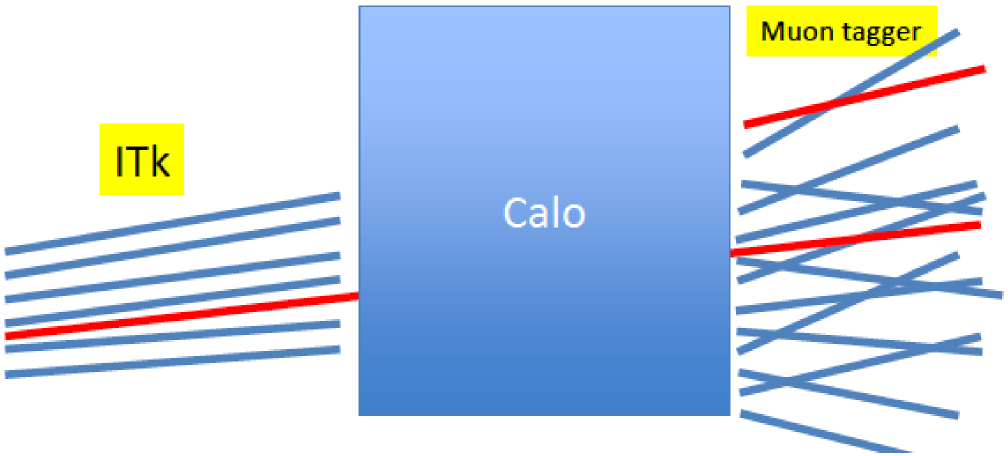
Large eta Tagger:
Select "pointing" track segments
to be matche with high-pT tracks

- Limited space available
  (thickness ~5 cm)

- Harsh radiation environment:
  up to ~10 MHz/cm^2 for η=4

- Require ~5 planes with
  pixelized readout
  at η=4 pixels of 3mm^2 for 4% occupancy
  Angle resolution ~10 mrad

- Possible technologies:
  - Large silicon pixels
  - MPGD with pixel readout:
    Micro Megas with pixel readout
    μ-PIC
    μRwell



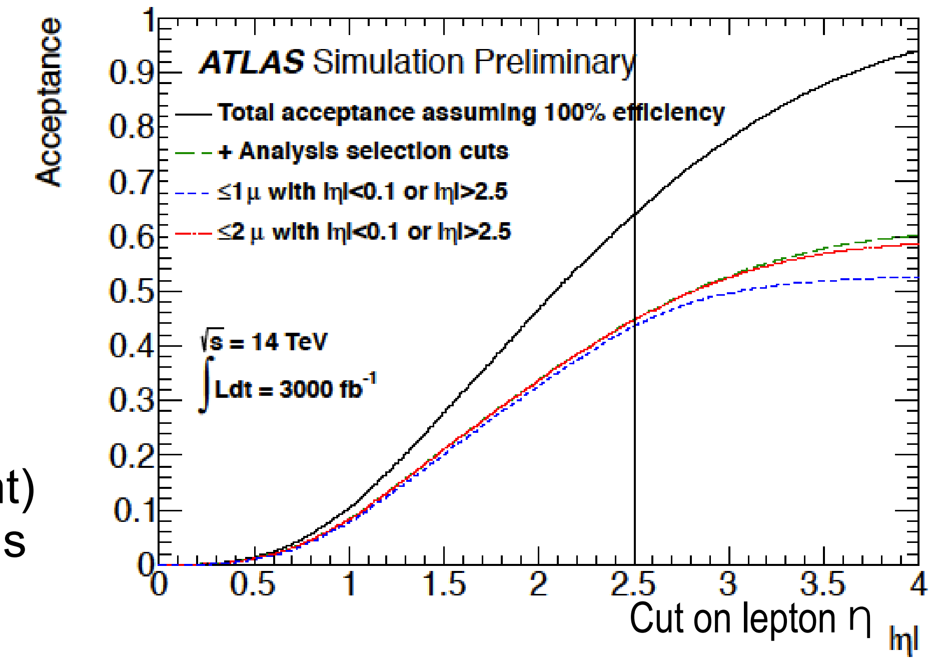
Large-η tagger: physics

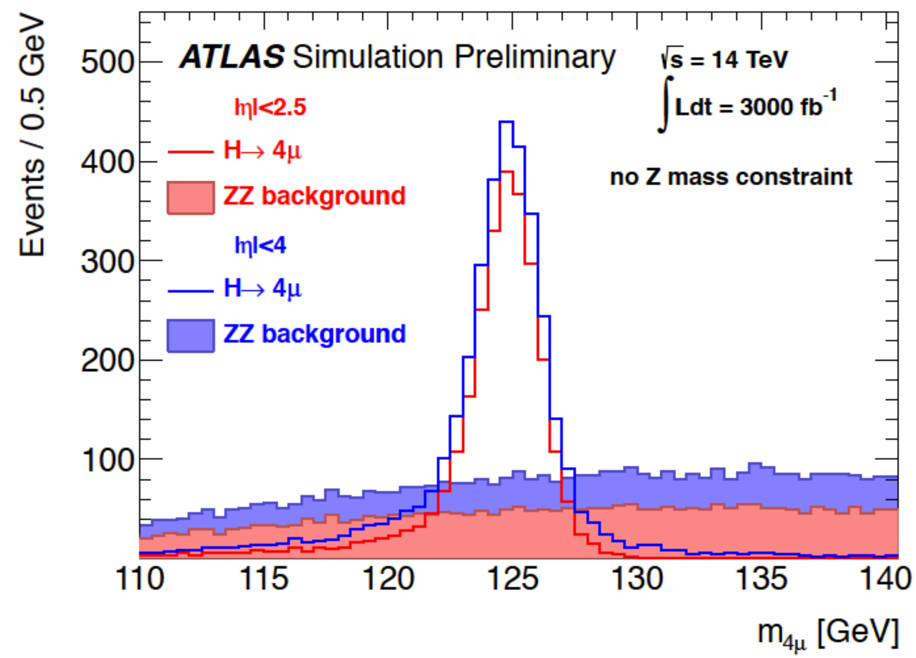
What is the physics impact ?
(studies from Scoping Document)

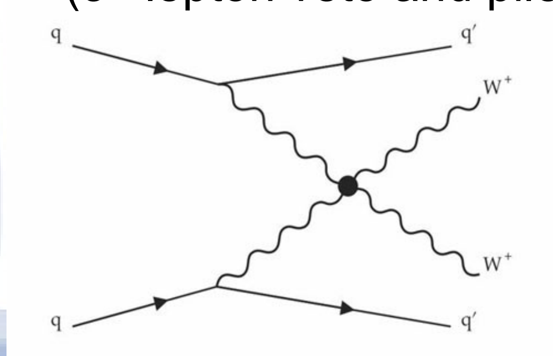
In general acceptance increases for all channels. But momentum resolution may be a problem.

- 1) H->4l
  20% increase of acceptance
  Δμ/μ: 2.4% => 2.2% (10% improvement)
  Larger impact for differential distributions

- 2) boson-boson scattering: W^+W^+jj
  - same charge leptons
  - veto on 3rd lepton reduces WZ bkg: by a factor 2 going from η<2.5 to η<4
  - Δσ/σ : 13% → 5.9% with large-eta extension (3rd lepton veto and pileup jet cleaning)

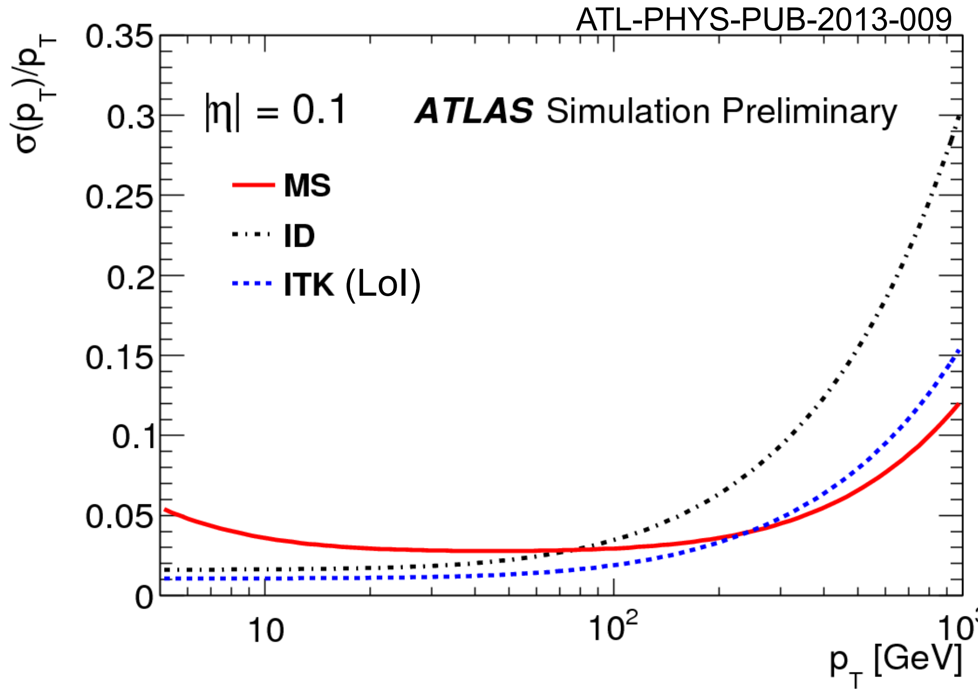


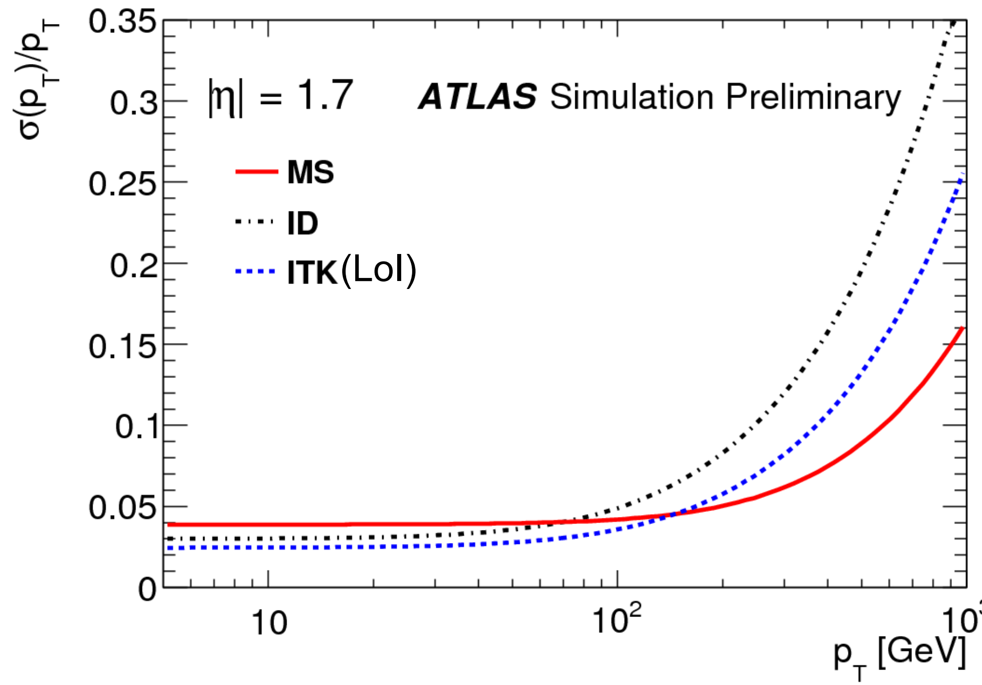




Muon momentum reconstruction

- Upgrades of Muon Spectrometer not expected to change significantly momentum resolution
- New tracker, ITK : improvement of resolution and eta coverage over present ID
  => impact on Combined (ITK+MS) momentum measurement
  => extension of coverage to higher eta
- Previous studies (ECFA'13, Scoping Doc.) based on parametrizations of standalone ITK simulations
- Region in which the Inner tracker has better momentum resolution than muon spectrometer is extended toward higer p_T





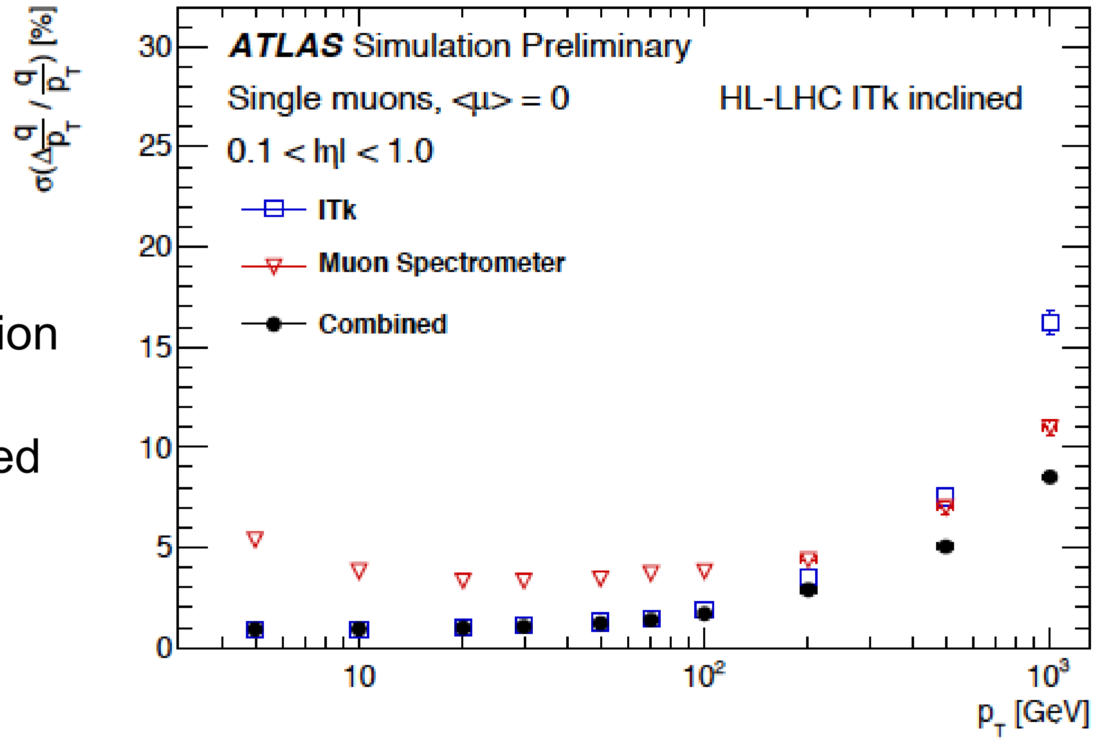
Muon momentum reconstruction

New studies with full simulation and detailed ITK layouts

Resolution for combined muons:

- low-pT: 1 - 2% for 0<|η|<2
  (compare to present 1.5 – 3%)

- Significant improvement in resolution for p_T < 200-500 GeV (dep. on η)
  At higher p_T resolution is dominated by Muon Spectrometer



Conclusions

Large upgrade programme for Muon Spectrometer for HL-LHC

Main upgrade items:

- Electronics replacement for all chambers (MDT, TGC, RPC)
  => allow to run at higher trigger rates, use improved trigger logics
- MDT trigger
  => more selective trigger, more redundant system
- Improvement of the trigger barrel region with new layer of RPC and with sMDT
  => higher acceptance, robustness against aging/rate issues with old RPCs
- Under discussion
  - large-η tagger: will extend acceptance in η, needs detector R&D...
  - TGC replacement in some critical chambers

Basic goal:
keep same performance as today in a much more difficult environment

Extra bonus:
higher trigger efficiency, larger eta coverage, better momentum resolution

Backup Material

Momentum Resolution from Scoping Document

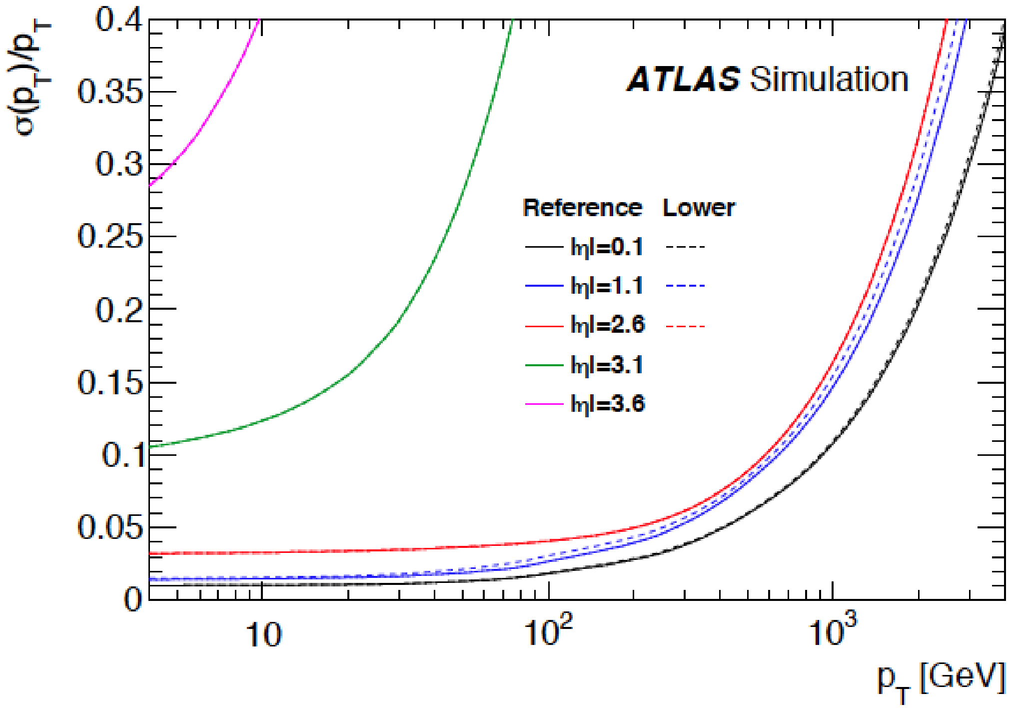


Figure 85. Momentum resolution combining the ITk and muon spectrometer measurements at several η values for the Reference and Low scenarios.

H->4μ with eta extension

Table 28. Reconstructed Higgs boson mass and width for $H \to ZZ^{(*)} \to 4\mu$ in rapidity bins defined by the muon with the largest $|\eta|$ value for the Reference layout. The numbers are obtained from a fit of a Gaussian distribution in $\pm 1.5\sigma$ around the Higgs boson mass. The uncertainty given is the uncertainty of the fit result.

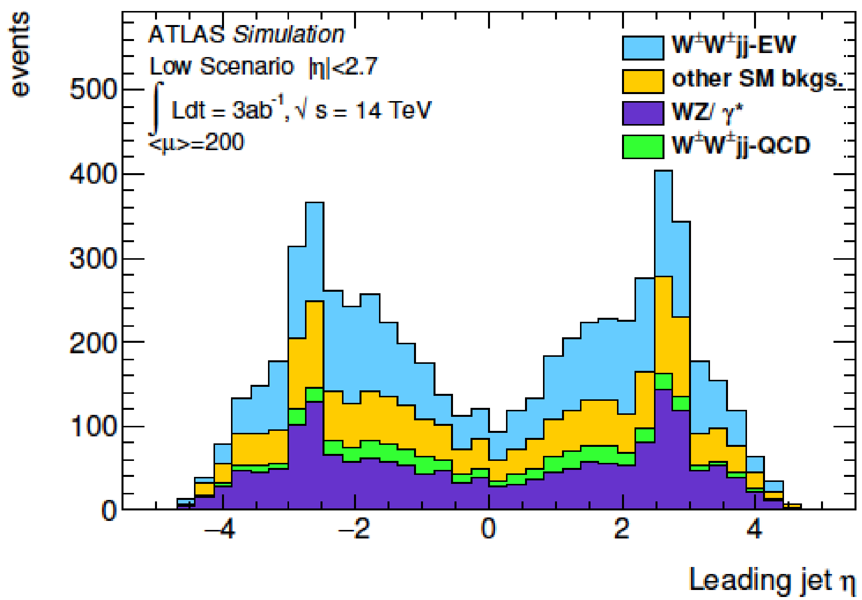
Coverage	Mass (GeV)	Width (GeV)
$\lvert\eta^{\mu}_{\max}\rvert < 2.7$	124.95 ± 0.01	1.11 ± 0.01
$2.7 < \lvert\eta^{\mu}_{\max}\rvert < 3.2$	125.31 ± 0.07	2.53 ± 0.08
$3.2 < \lvert\eta^{\mu}_{\max}\rvert < 4.0$	125.89 ± 0.17	4.61 ± 0.23

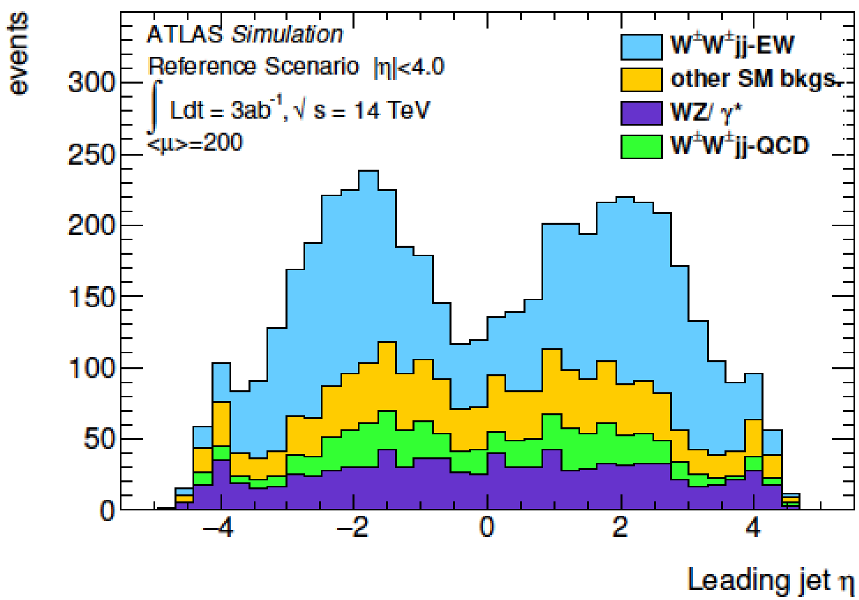
Table 29. Expected number of events in a region of $\pm 1.5\sigma$ around the Higgs peak for $3000\ \mathrm{fb}^{-1}$ of data in the $H \to 4\mu$ and $ZZ^{(*)} \to 4\mu$ channel for the various layouts. The last row shows the relative uncertainty on the signal strength. As the width is very similar in the three layouts for $|\eta| < 2.7$ the width as obtained from a fit in the Reference layout is used here. The uncertainties correspond to the statistical uncertainties.

Scenario	$H \to 4\mu$	$ZZ^{(*)} \to 4\mu$	$\Delta\mu/\mu$
Reference	2551 ± 51	741 ± 27	0.022
Middle	2104 ± 46	351 ± 19	0.024
Low	2014 ± 45	336 ± 18	0.024

W+W+jj with eta extension

Selection	Electroweak Signal Region
Number of leptons	2
Number of jets	≥ 2
Third lepton veto	remove events with $\geq$ 3 veto-leptons
Di-lepton invariant mass $m_{\ell\ell'}$ (GeV)	> 20
Z-veto (GeV)	$\|m_{e,e} - m_Z\| > 10$
Di-jet invariant mass $m_{j,j}$ of highest p_T jets (GeV)	> 500
$\Delta\eta_{j,j}$ of highest p_T jets	> 2.4
E_T^{miss} (GeV)	> 40





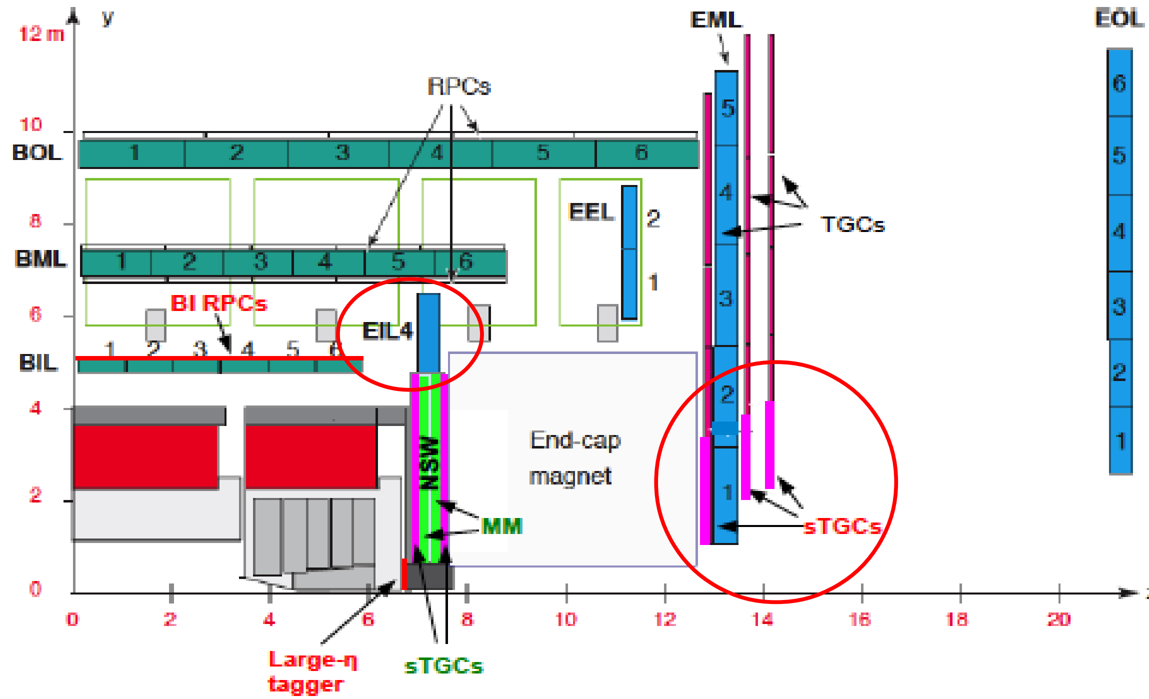
Replacement of TGC chambers

TGC rate capability is sufficient for HL-LHC

Two options under study.

1) from LoI, Scoping Doc.:
   Replacement of inner ring of "Big Wheel" with TGCs (sTGCs) with Improved spatial resolution

   Main goal is improve trigger selectivity in forward region. From latest studies it may not be necessary



2) EIL4 chambers,
   1<|η|<1.3 only on "large" ϕ sectors.
   Currently only one TGC doublet, with coarse resolution in trigger readout:
   Trigger with weak inner-plane coincidence.
   Proposal to replace with triplet with better granularity to improve the trigger selectivity.
   Would bring to same level of fake rejection as in NSW and in "small" sectors (BIS78).