Upgrade of the ATLAS Muon Spectrometer for Operation at the HL-LHC

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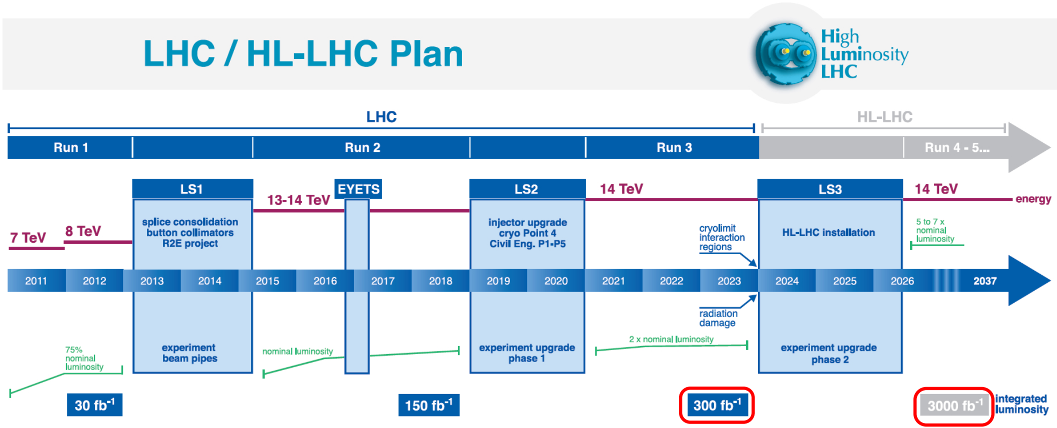
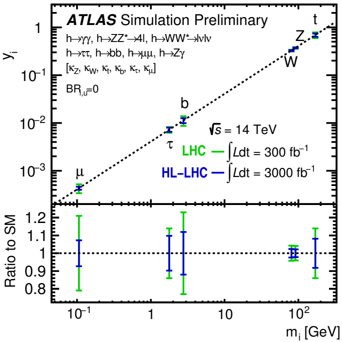
The roadmap to High-Luminosity LHC



- Plan to increase the LHC luminosity by an order of magnitude.
- Physics motivation with selected examples on the next 3 slides.
- Increase of the particle fluxes/rates by an order of magnitude from the LHC to the HL-LHC requires a major detector upgrade.
- Muon spectrometer upgrade in two steps during long shut downs 2 and 3.

Higgs physics at the HL-LHC

- Precision measurements of Higgs boson couplings and spin-CP quantum numbers as a probe for physics beyond the Standard Model.

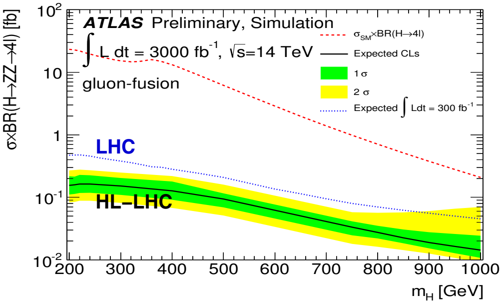


Measurement of deviations of Higgs couplings from SM values with per-cent precision at the HL-LHC.

Search for deviations from SM and for rare and invisible Higgs decays.

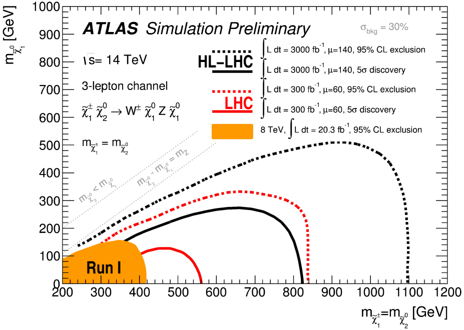
Evidence for Higgs boson self-coupling possible at the HL-LHC.

- 3-4 times higher sensitivity in direct searches for additional Higgs bosons at the HL-LHC than the LHC.



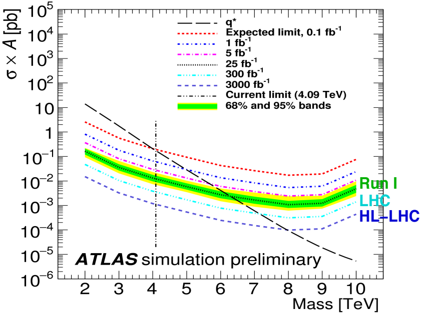
Supersymmetric and other new particles at the HL-LHC

Search for supersymmetric particles



- Much larger area of the SUSY parameter space accessible at the HL-LHC than at the LHC.
- Sensitivity to 1.5 times larger neutralino and chargino masses in WZ-mediated SUSY at the HL-LHC than the LHC.
- If SUSY is found at the LHC, the HL-LHC needed to study its exact nature.

Model independent search for heavy resonances (di-jet, di-photon $\ell\ell$, tt)



- Search performed in several final states, e.g. di-jet, di-photon, di-lepton, $t\bar{t}$.
- Di-jet resonances predicted by several theories, e.g. excited quarks, quantum black holes.
- 4 times higher sensitivity to di-jet resonances at the HL-LHC than at the LHC.

Dark matter at the HL-LHC

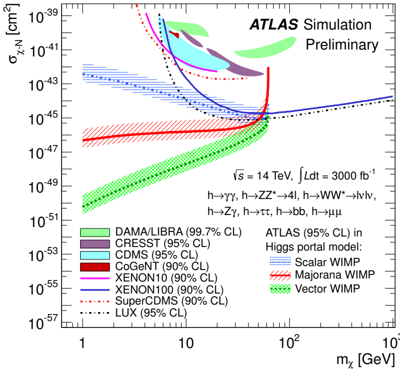
Search for dark matter in Higgs boson decays

- Signature of Higgs boson decays into dark matter: $H \to invisible$.
- Direct search in vector boson fusion and W/Z associated Higgs boson production.

  95% confidence upper limits on BR($H \to inv.$)

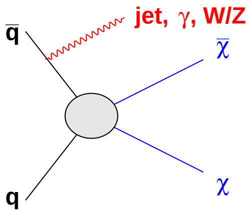
Run I	LHC	HL-LHC
0.49	0.22	0.13

- Indirect search via precision measurement of Higgs boson couplings.

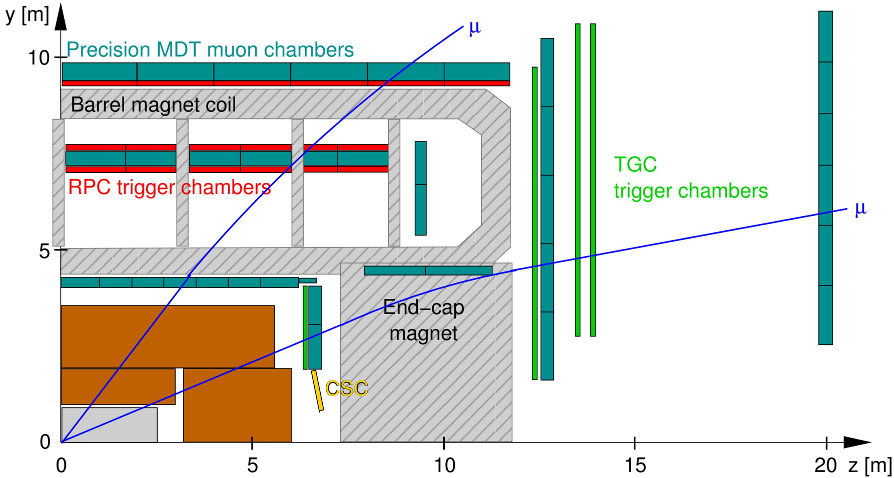


Search for dark matter production in association with Standard Model particles

Similar increase in sensitivity from LHC to HL-LHC as above.

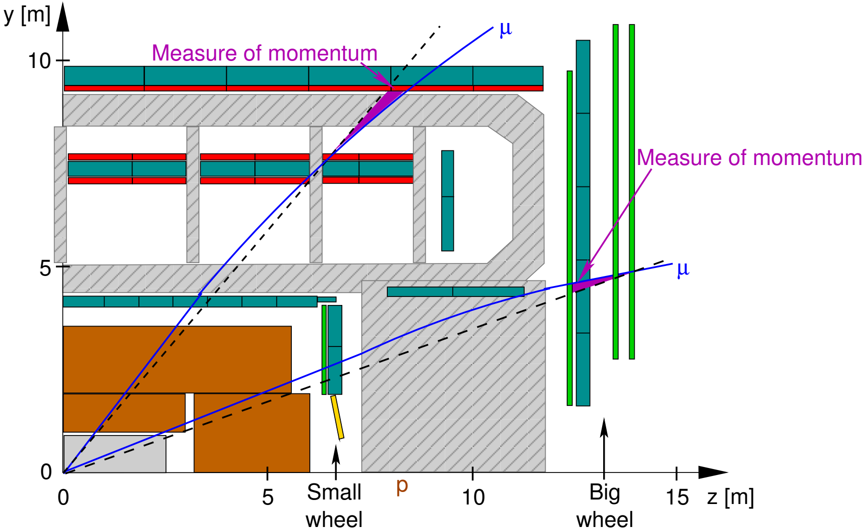


The ATLAS muon spectrometer at the LHC



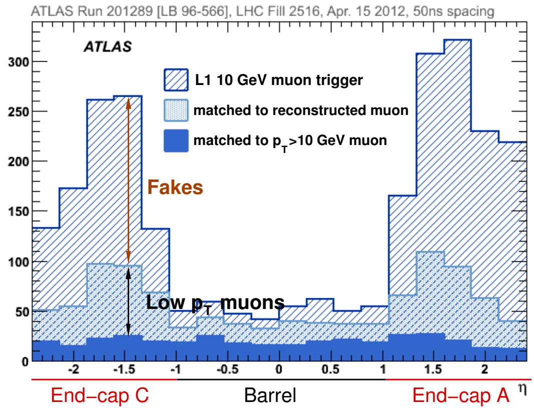
- Fast trigger chambers: RPC, TGC
  ($<$10 ns time resolution, moderate spatial resolution $\sim$mm-cm).
- High-resolution tracking detectors: CSC, MDT (40 μm spatial resolution).
- Optical alignment system with 50 μm resolution.
- Pseudorapidity coverage: $|\eta| < 2.7$.

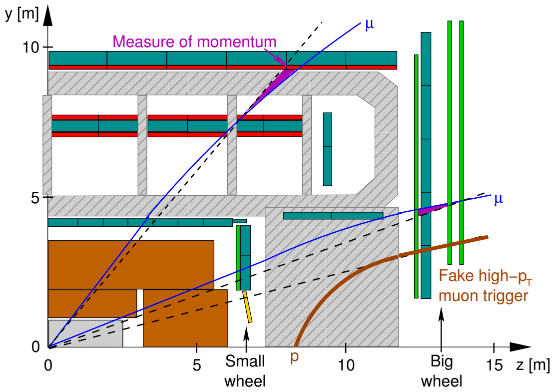
The ATLAS 1st level muon trigger in LHC run I



- ATLAS uses as 3-level trigger system.
- The level-1 high p_T muon trigger built out of a coincindence of three RPCs in the barrel or three TGCs in the big end-cap wheel.
- Muon momentum estimate from the size of the deviation of hits from an infinite momentum track from the interaction point.

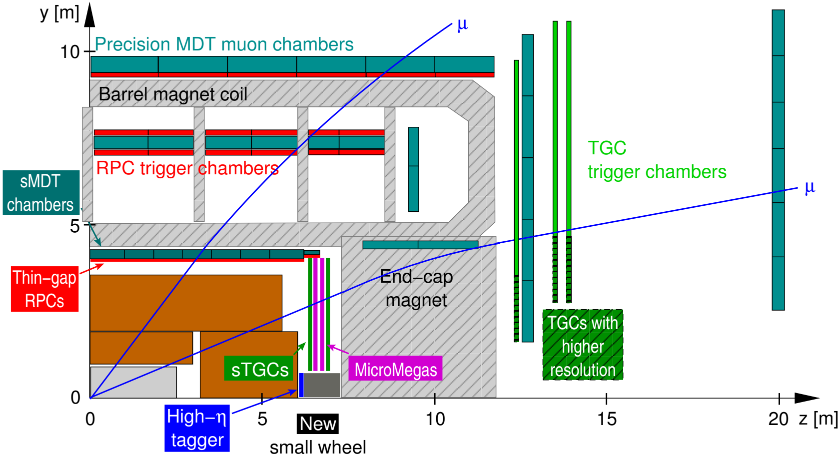
Sources of 1^{st} level muon triggers in LHC run I





- Muon trigger rate dominated by fake triggers in the end-caps caused by charged particle not emerging from the interaction point.
- Real muon triggers contaminated with sub-p_T-threshold muon due to the reduced momentum resolution caused by the moderate spatial resolution of the trigger chambers.

The ATLAS muon spectrometer at the HL-LHC

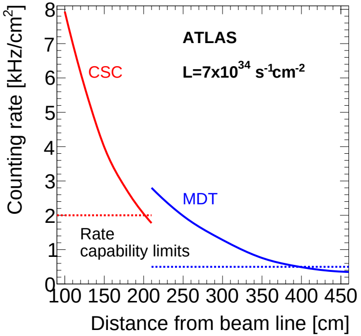


- New small wheel with high-resolution trigger chambers to reject fake muon triggers and improve momentum resolution at trigger level.
- New TGCs with higher resolution to cope with background at $|\eta| \sim 2.7$.
- New thin-gap RPCs to close acceptance gaps of the barrel muon trigger.
- New sMDT chambers to free space for new RPCs.
- High-η tagger to identify muons up to $|\eta| = 4.0$.

\+ New on- and off-chamber electronics for new trigger architechture.

New small end-cap wheels

Extrapolated hit rates



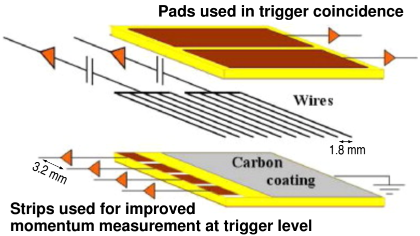
- The ATLAS muon spectrometer is operated in a large background of neutrons and γ rays.
- At the HL-LHC the background rates in the present small wheels would exceed the rate capabilities of the CSC and MDT chambers.

$\Rightarrow$ New small wheels with chambers with increased high-rate capability:

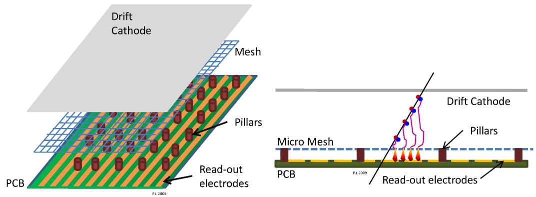
- Small strip TGCs (sTGCs) for triggering,
- MicroMegas for triggering and precision tracking.

Installation 2019-2020 during LS2.

sTGC schematic



Micromegas schematic



Mode of safe RPC operation at the HL-LHC

RPC rate estimates [Hz/cm^2] for HL-LHC

$\eta=-1$ $\eta=0$ $\eta=1$

Sector Φ Id.	-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	319	262	281	210	135	106	119	95		57	57	66	106	114	118	127	199	258	251	266	168
01.02	273	262	283	203	148	124	121	133		71	67	70	118	134	131	138	201	275	260	277	176
2	157	191	176	129	102	84	72	58	51	52	42	45	57	74	87	98	130	193	183	142	107
03.01	277	276	263	184	138	120	111	111	63	63	60	66	122	117	106	117	193	307	251	271	165
03.02	280	227	258	196	141	120	144	114	79	70	70	65	113	119	142	123	193	294	227	279	167
4	105	155	148	141	94	78	61	71	38	49	43	38	68	63	86	101	149	183	163	105	101
05.01	159	161	245	129	98	96	131	118	64	56	56	64	116	165	96	128	173	270	161	159	139
05.02	211	185	221	147	102	98	127	133	72	57	58	66	103	127	101	131	187	250	238	264	148
6	163	174	194	152	98	89	84	89	72	55	49	55	79	76	99	116	177	187	212	156	122
07.01	285	245	269	178	144	120	122	106		71	73		114	130	116	138	173	244	250	285	171
07.02	305	241	201	189	132	104	120	101		69	72		98	107	105	142	172	259	257	260	163
8	136	183	182	150	96	79	75	65	46	53	51	50	63	69	79	101	157	183	181	145	110
09.01	298	230	281	192	145	109	139	111		43	60		99	125	116	126	184	264	244	277	169
09.02	324	240	268	191	133	89	100	96		54	63		92	104	89	128	175	266	247	273	163
10	163	187	193	137	92	80	63	66	43	40	38	46	60	64	75	96	138	181	188	159	107
11.01	288	228	222	147	90	78	76	81		37	40		78	88	86	88	138	212	200	259	132
11.02	183	180	147	98	72	62	52	53		31	29		47	58	54	66	91	141	149	173	91
12						74	75	62	48	34	34	48	70	81	74						60
13.01	272	260	236		131	95	89	78	40	38	44	47	81	89	92	115		232	245	298	139
13.02	279	246	245		97	90	98	80	45	45	47	53	87	96	90	102		235	212	275	137
14						133	64	60	48	38	38	46	59	64	127						70
15.01	183	206	139	106	71	66	62	46		36	33		47	55	80	81	97	146	162	183	97
15.02	171	148	230	153	108	92	96	70		41	40		70	99	104	100	147	231	148	171	124
16	161	200	202	162	101	83	51	70	52	55	47	46	72	51	81	96	165	195	194	144	115
Average	214	208	218	156	111	94	90	82	52	49	48	52	80	90	96	111	160	224	206	206	128

RPC unit Id. along Z direction; φ

Rate above limit of safe operation

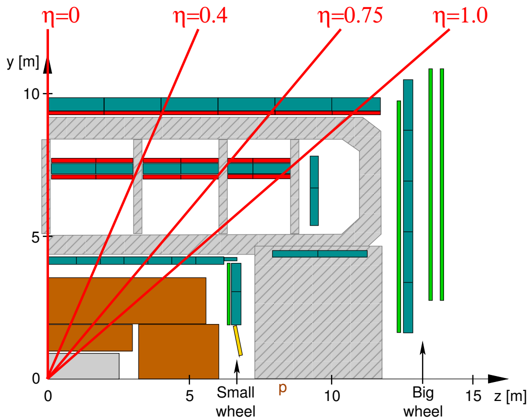
- Longevity of the RPCs depends on the charge accumulated during ten years of HL-LHC operations.
- According to irradiation tests in the GIF limit for safe operation of present RPCs: 100 Hz/cm^2.

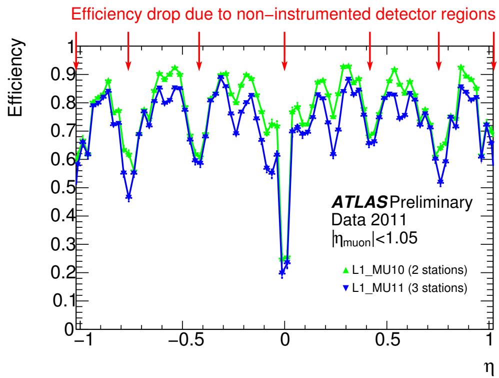
Limit exceeded by up to a factor of 2 at $|\eta| \gtrsim 0.7$!

- Plan to reduce operating voltage to keep the gap currents/accumulated charge within the safety margin.

⇒ Reduced gas gain/pulse heights lead to inefficiencies as the preamplifiers cannot be replaced by more sensitive ones.

Barrel muon trigger coverage

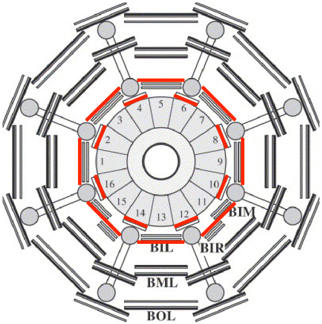




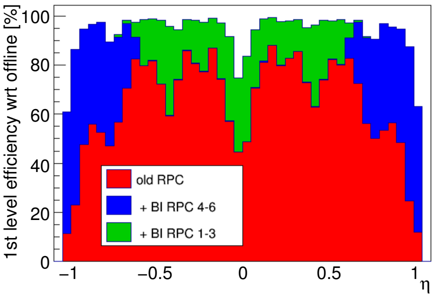
The high p_{T} muon trigger acceptance is limited to $\approx 72\%$ due to non-instrumented regions of the muon spectrometer.

- $\eta = 0$: Non-instrumented region of the spectrometer to provide space for services of the inner detector and the calorimeters.
- $\eta = 0.4$, 0.75, 1.0: Non-instrumented region due to toroid and rib structures.

Reinforcement of the barrel muon trigger

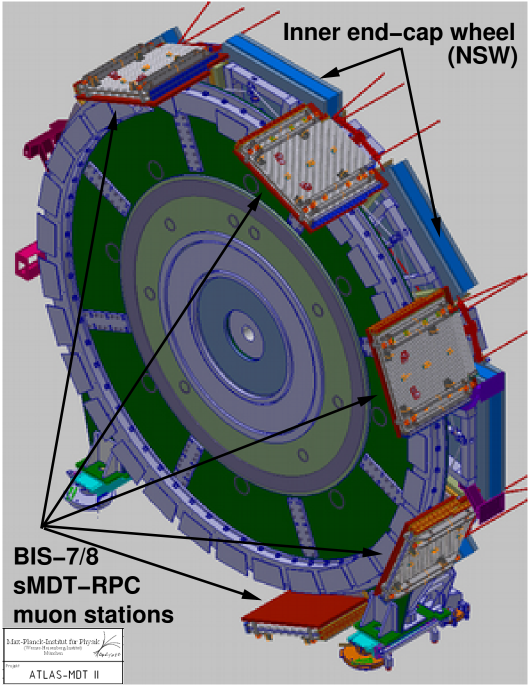


- Installation of additional RPCs with increased high-rate capability in the inner barrel layer to recuperate the reduced muon trigger efficieny.
- Replacement of MDT chambers with sMDT chambers in small barrel sectors to free space for RPCs.
- Pilot project: BIS-7/8.



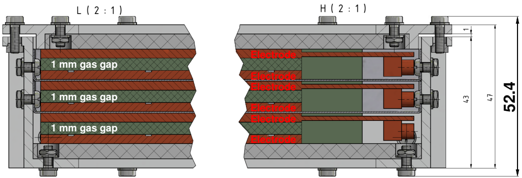
Installation of trigger chambers in BI closes acceptance gaps and recuperates RPC inefficiencies!

Barrel upgrade pilot project

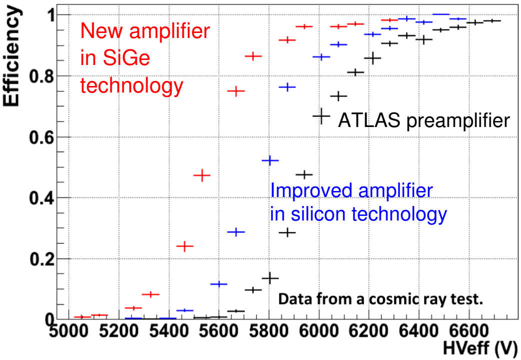


- 16 new muon stations inside the barrel toroid coils at the boundary between barrel and end caps.
- Purposes:
  - Improvement the selectivity of the muon trigger in the barrel end-cap transition region.
  - Increase of high-rate capability.
- Technology: Integrated sMDT-RPC chambers.
  - sMDT chambers for precision tracking.
  - New thin-gap resistive plate chambers (RPC) for triggering.
- Installation during LS2 (2019-2020).

Thin-gap RPCs



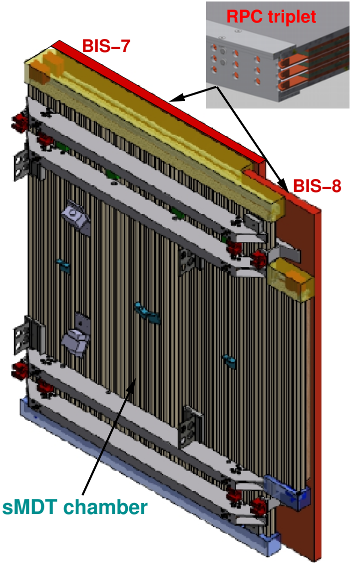
Very challenging space constraints: ~5 cm space for a triplet of 1 mm gas gaps.



A new highly sensitive low-noise preamplifier in SiGe technology allows the efficienct operation at 4 times smaller gas gain than with the current ATLAS preamplifier.

⇒ >4 times greater high-rate capability, which is substantially more than required.

sMDT chambers



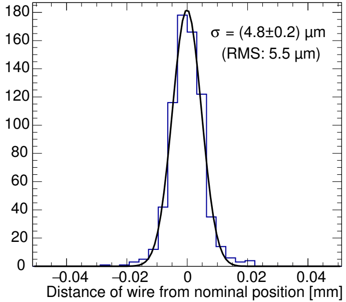
Characteristics of sMDT chambers

- Monitored drift-tube chambers with 15 mm diameter tubes instead of 30 mm diameter tubes as currently in ATLAS.

$\Rightarrow$ 10 times greater high-rate capability than present ATLAS chambers.

Unprecedented wire positioning accuracy of 5 μm

(4 times higher accuracy than in present MDT chambers)



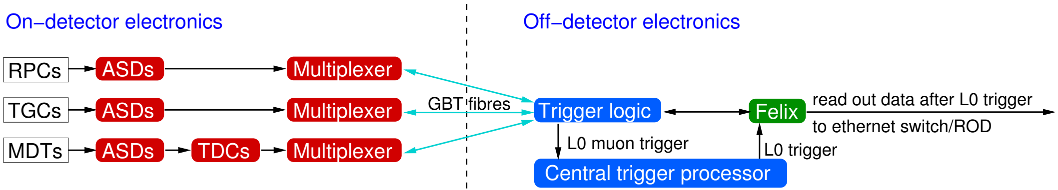
- Further details: H. Kroha's presentation.

ATLAS trigger scheme for HL-LHC

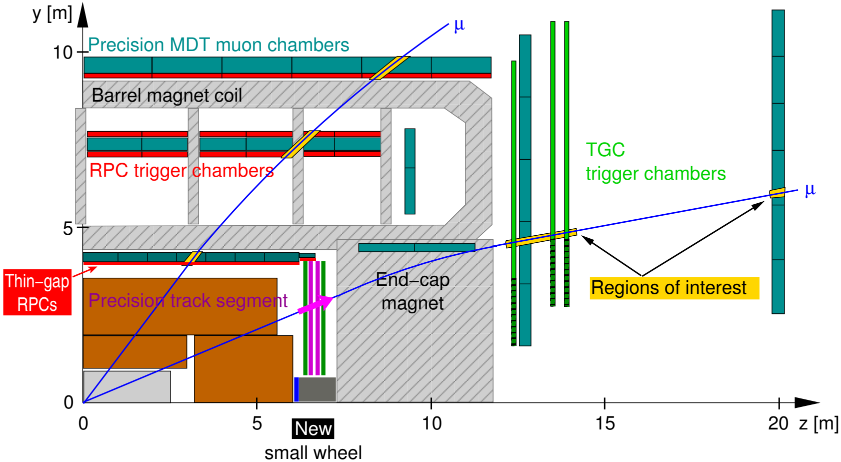
- New trigger scheme:
  - Only two trigger levels: level 0 (L0) and high-level trigger (HLT).
  - L0 rate: 1 MHz. L0 latency: 6-10 μs.

$\Rightarrow$ In this scheme all muon chambers have to send their data off to USA15 continuously for further processing.

$\Rightarrow$ New on-chamber (MDT ASD and TDC chips, multiplexers) and off-chamber electronics (trigger logic, Felix) needed!



The ATLAS 1^{st} level muon trigger at the HL-LHC

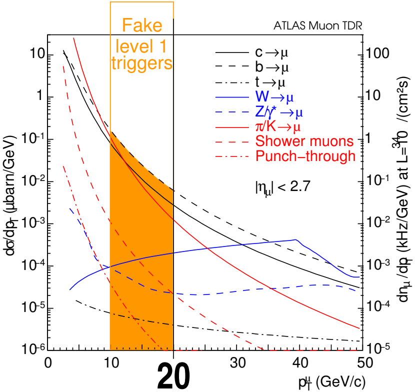


Processing step | Time after pp collision

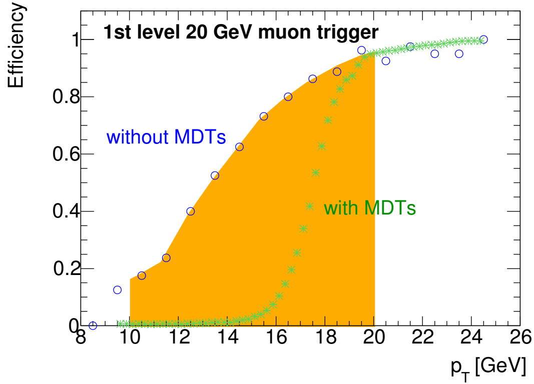
1. Continuous stream of muon hit data to off-detector trigger logic. 1 μs
2. Pre-muon-trigger based on coincidences of trigger-chamber hits in the inner, middle, and outer layers. 2 μs
3. Use of precision NSW and MDT hits for the refinement of muon p_{T} measurement in regions of interest defined by the trigger chambers. 3 μs
4. Final muon trigger based on refined momentum measurement. 6 μs

Reason for integrating MDT data in the 1^{st} trigger level

Inclusive muon cross section



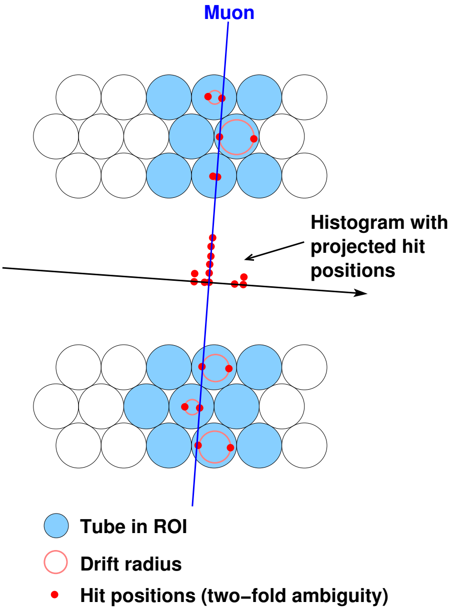
Muon first-level trigger efficiency



- The interesting electroweak physics is mainly at $p_{\mathrm{T}} > 20$ GeV.
- The inclusive muon cross section is very steeply rising with decreasing p_{T}.
- Present 1^{st} level 20 GeV muon trigger accepts a lot of muons with 10 GeV< p_{T} <20 GeV due limited spatial resolution of trigger chambers.

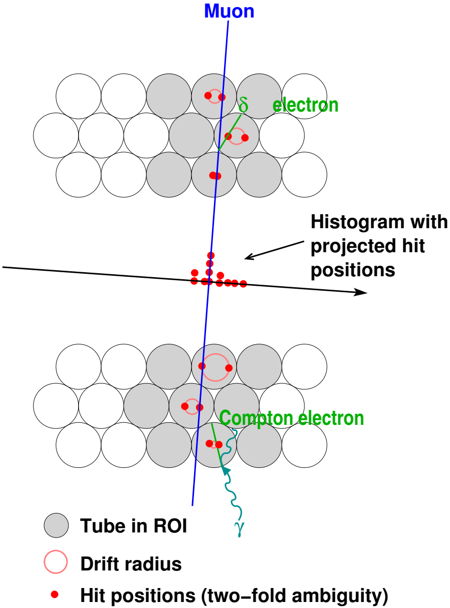
⇒ Sharpening of trigger turn-on curve by the use of precision muon drift-tube (MDT) chambers to limit the trigger rate.

MDT trigger: fast track reconstruction algorithm



- Restrict pattern recognition to the ROI.
- Incident angle is known from trigger chambers (with 3 mrad resolution).
- Project hits into the plane perpendicular to the trigger chamber track and fill the into a histogram.
- Correct hit pattern leads to the highest peak in the histogram (ideally with 6 hits).
- Final track: straight line fitted to the correct hit pattern.

MDT trigger: fast track reconstruction algorithm



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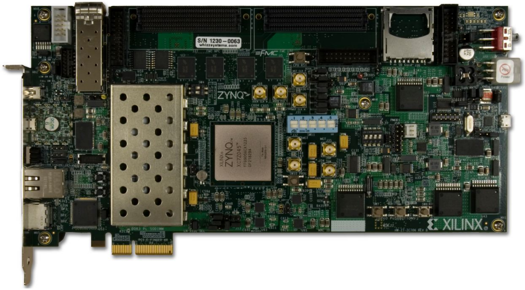
- Correct hit pattern leads to the highest peak in the histogram (ideally with 6 hits).
- Final track: straight line fitted to the correct hit pattern.

In practice there are less than 6 hits due to

- the dead area introduced by the tube walls,
- masking of muon hits by δ and Compton electrons.

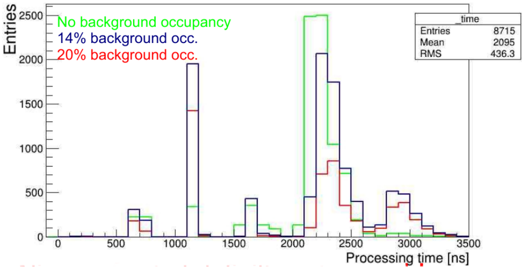
First timing study results

Demonstrator hardware



- Plan to use a microprocessor for fast floating point operations.
- Demonstrator hardware: Xilinx Evaluation Kit ZC806 (SoC Zynq-7045 with 1 GHz ARM Cortex-A9).
- Algorithm programmed in ARM assembler.

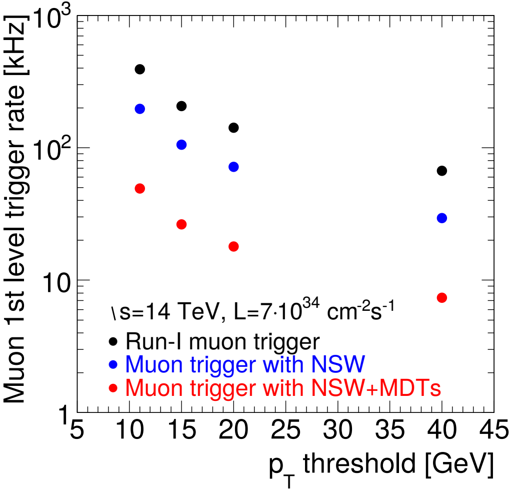
Test under realistic background conditions



- Test with experimental data recorded in CERN's gamma irradiation facility.
- Processing time $< 3.5\ \mu s$ even at 20% occupancy!

Single-muon trigger rates at the HL-LHC

Single-muon trigger rates
(estimated from run-I data)



- Unacceptably high rate of run-I 20 GeV muon trigger: ∼150 kHz.
- Removal of fake triggers by including the NSW in the trigger coincidence.

  ⇒ Rate reduced to ~ 70 kHz.
- Sharpening of the turn-on curve with MDT data reduces trigger rate to ~ 18 kHz.

⇒ ~ 150 kHz free for other triggers!

Black and blue points from
https://twiki.cern.ch/twiki/pub/AtlasPublic/MuonTriggerPublicResults/NSWRate.eps

Summary

- LHC and HL-LHC will dominate accelerator particle physics for the next two decades.
- Upgrade of the ATLAS detector to fully exploit the HL-LHC's physics potential.
- The upgrade of the muon spectrometer driven by the need for a highly efficient and selective single muon trigger:
    - New small wheel to reject fake muon trigger.
    - New RPCs in the inner barrel to maximize acceptance.
    - Inclusion of MDT data in the 1^{st} level muon trigger to maximize selectivity.