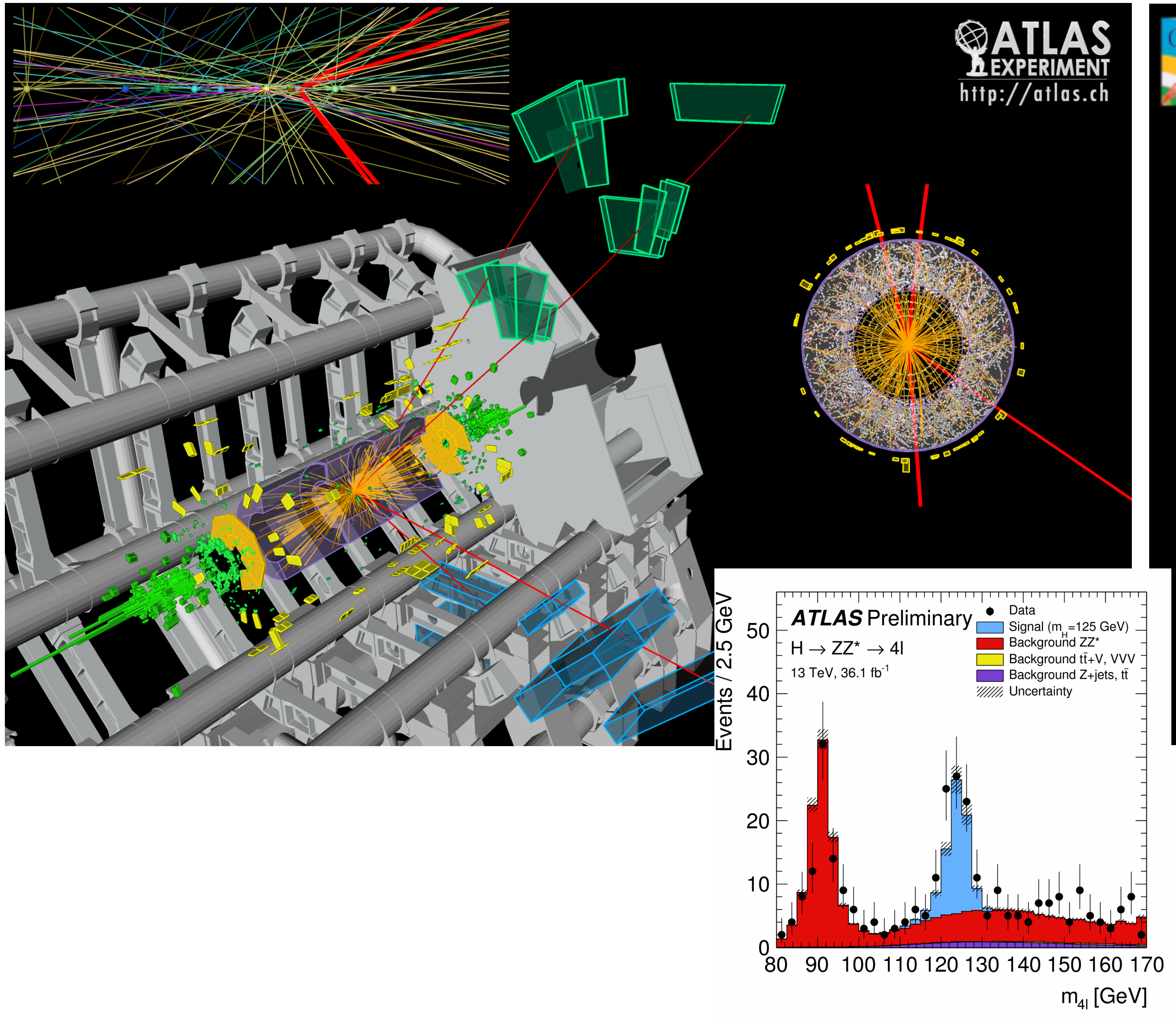
WEIZMANN INSTITUTE OF SCIENCE

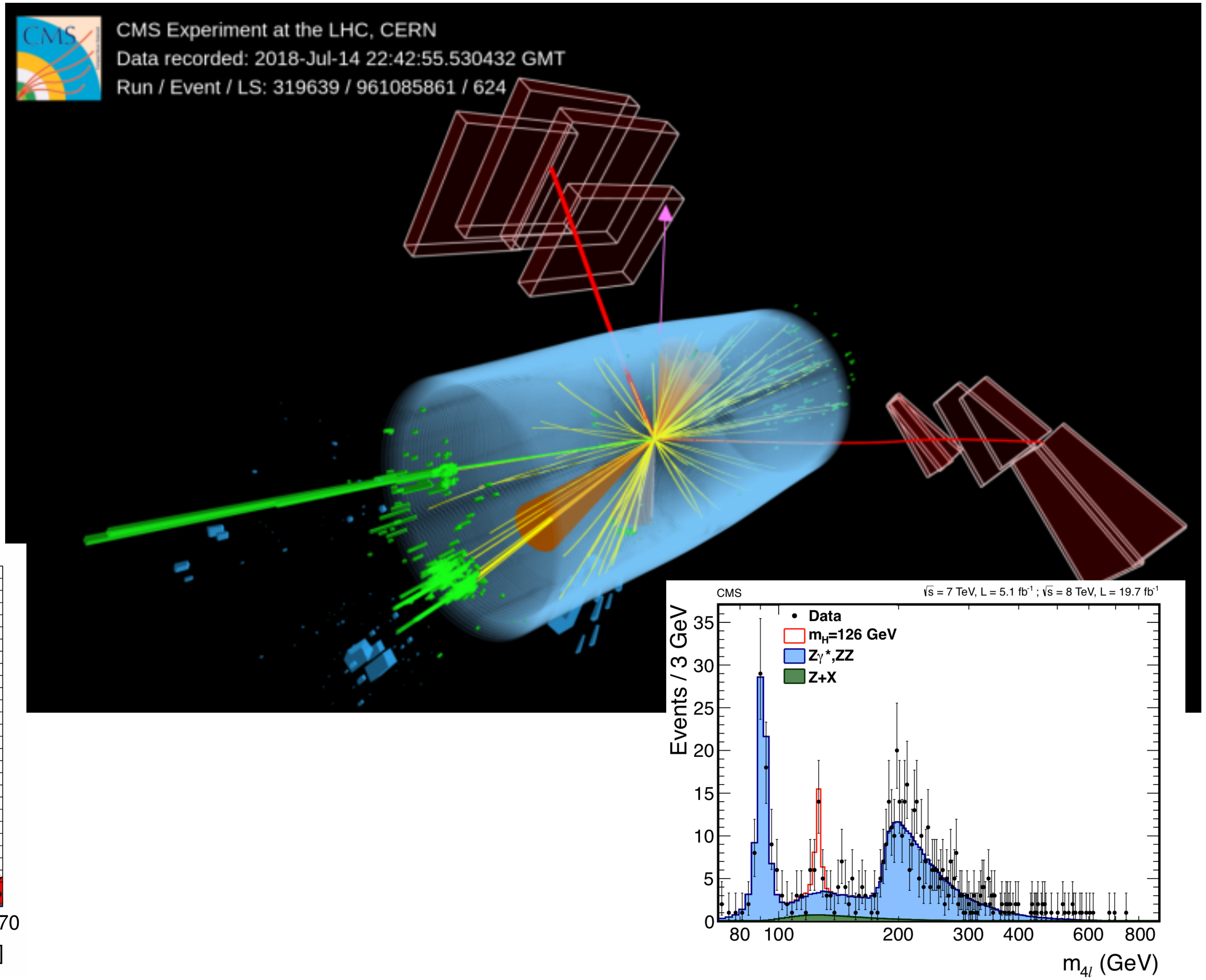
Gaseous Detector for Muon Spectrometer

Current state of the art

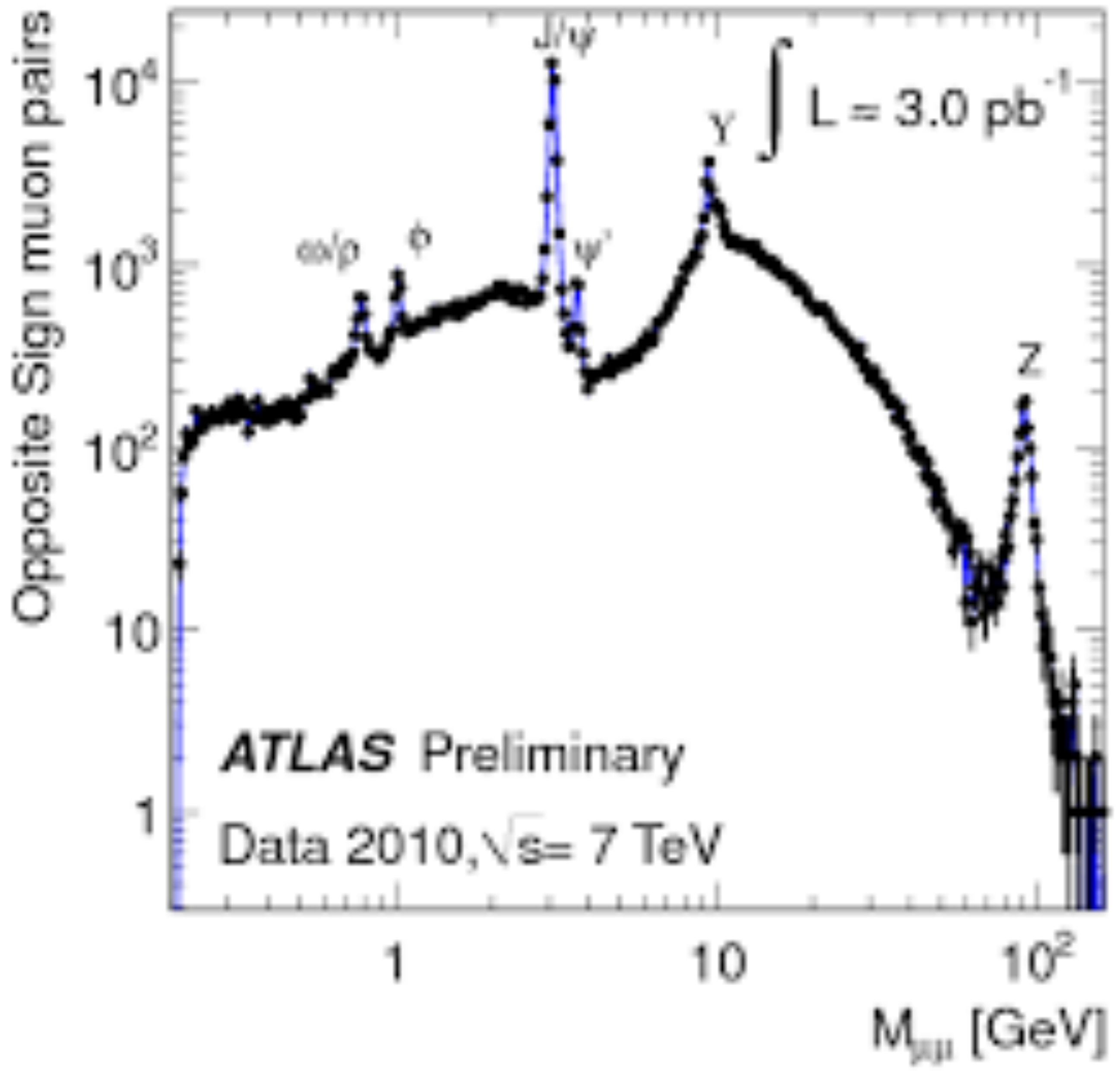
Shikma Bressler I CEPC 2025 I November 6-10, 2025

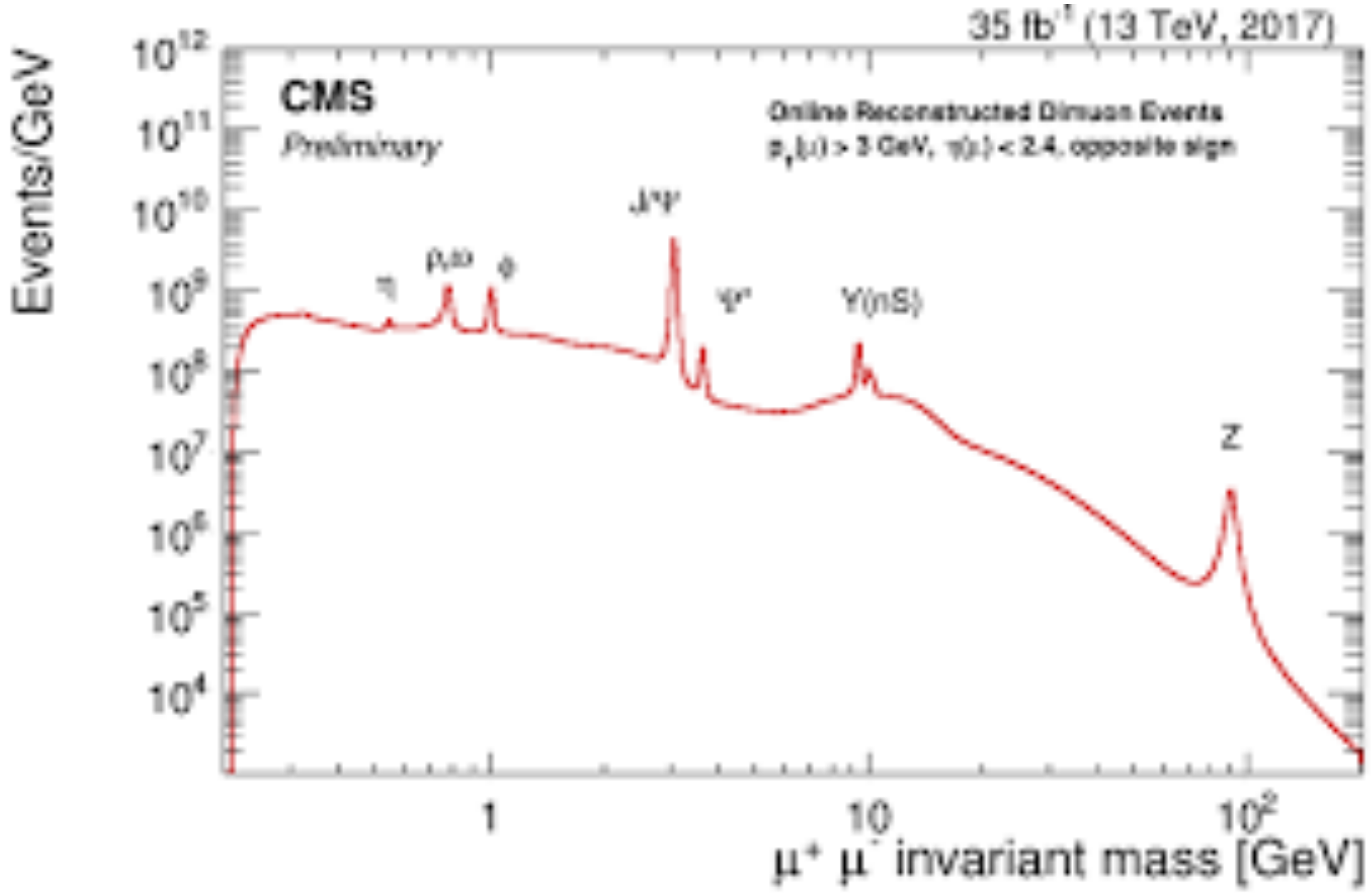
The role of μ's in HEP

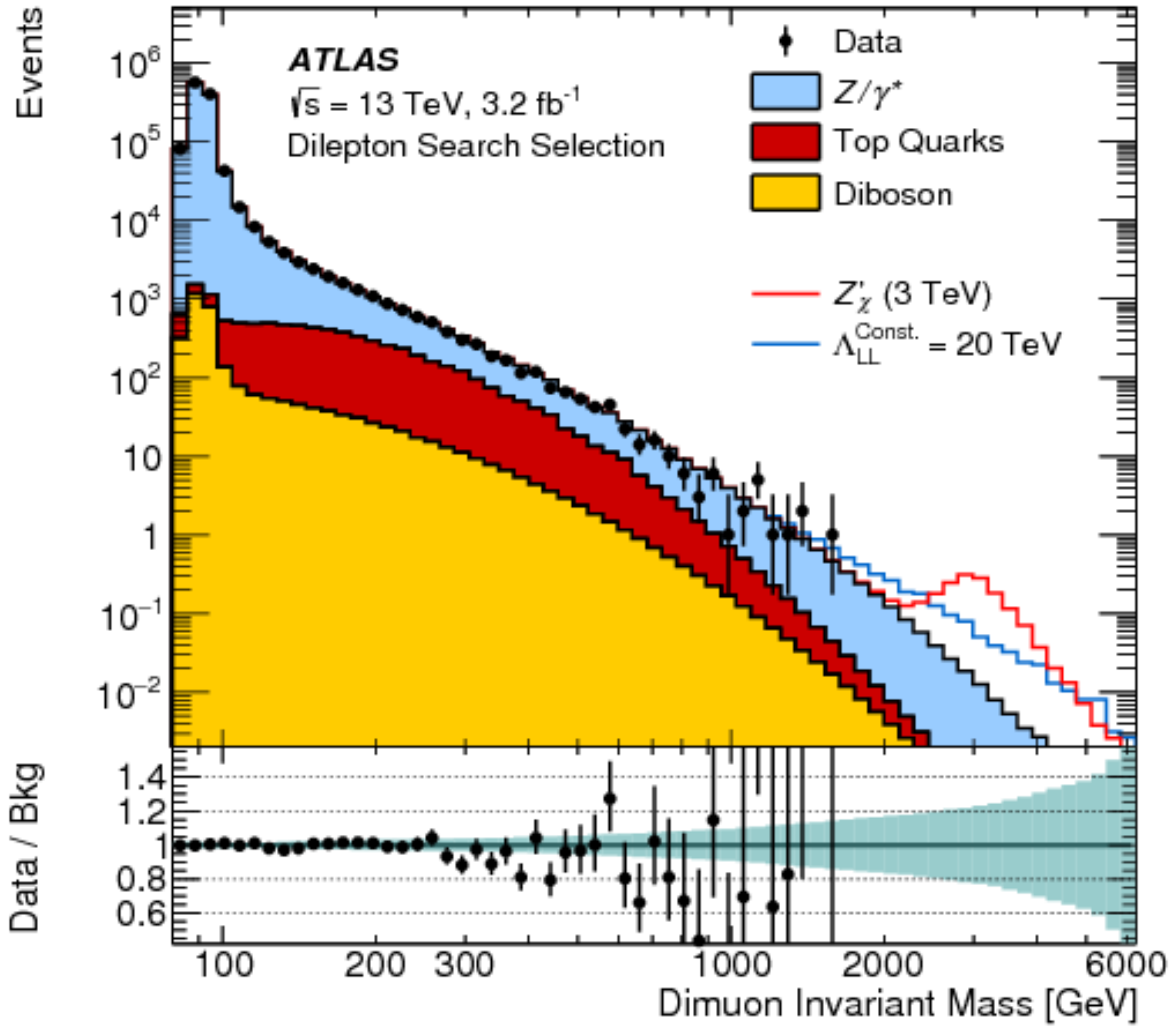




The role of μ's in HEP

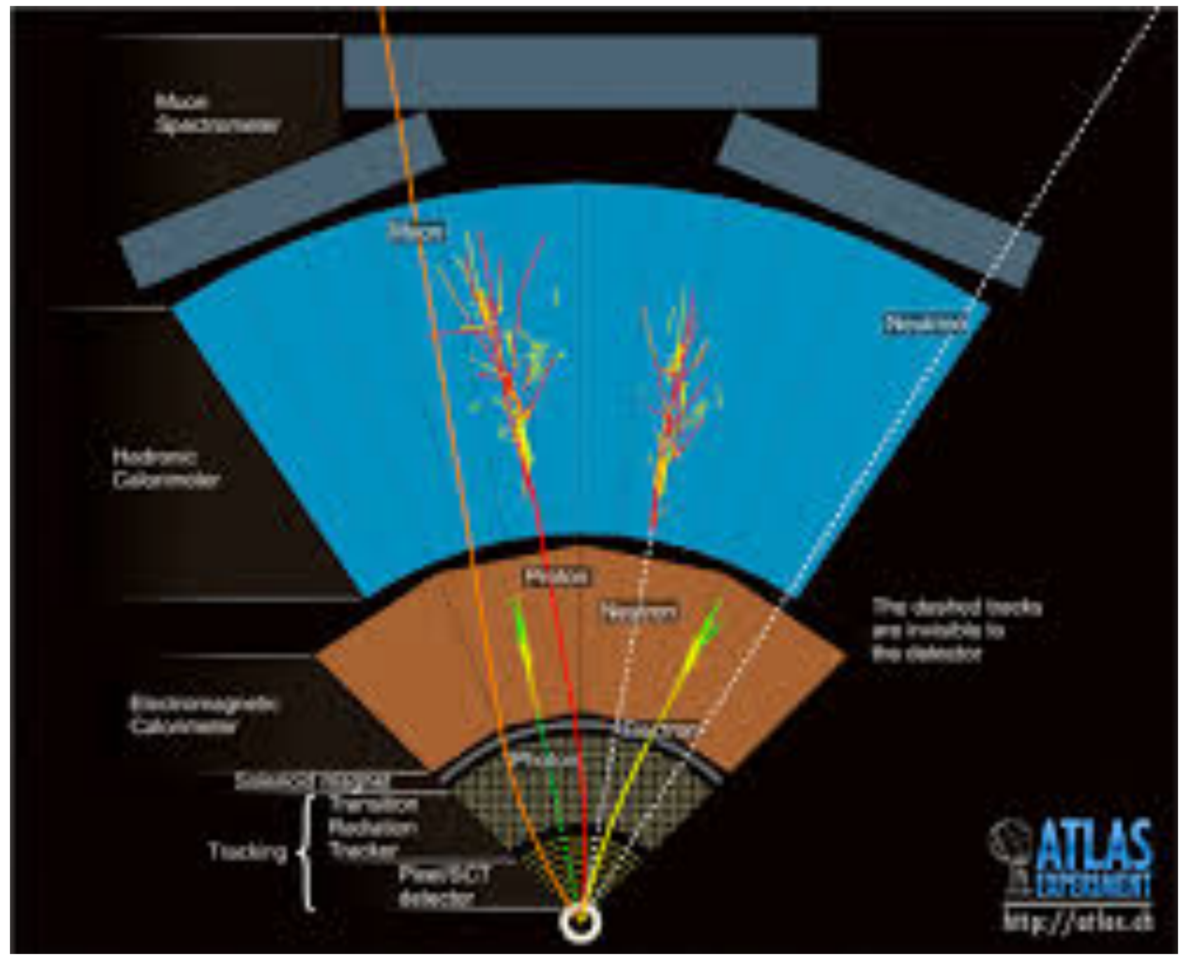


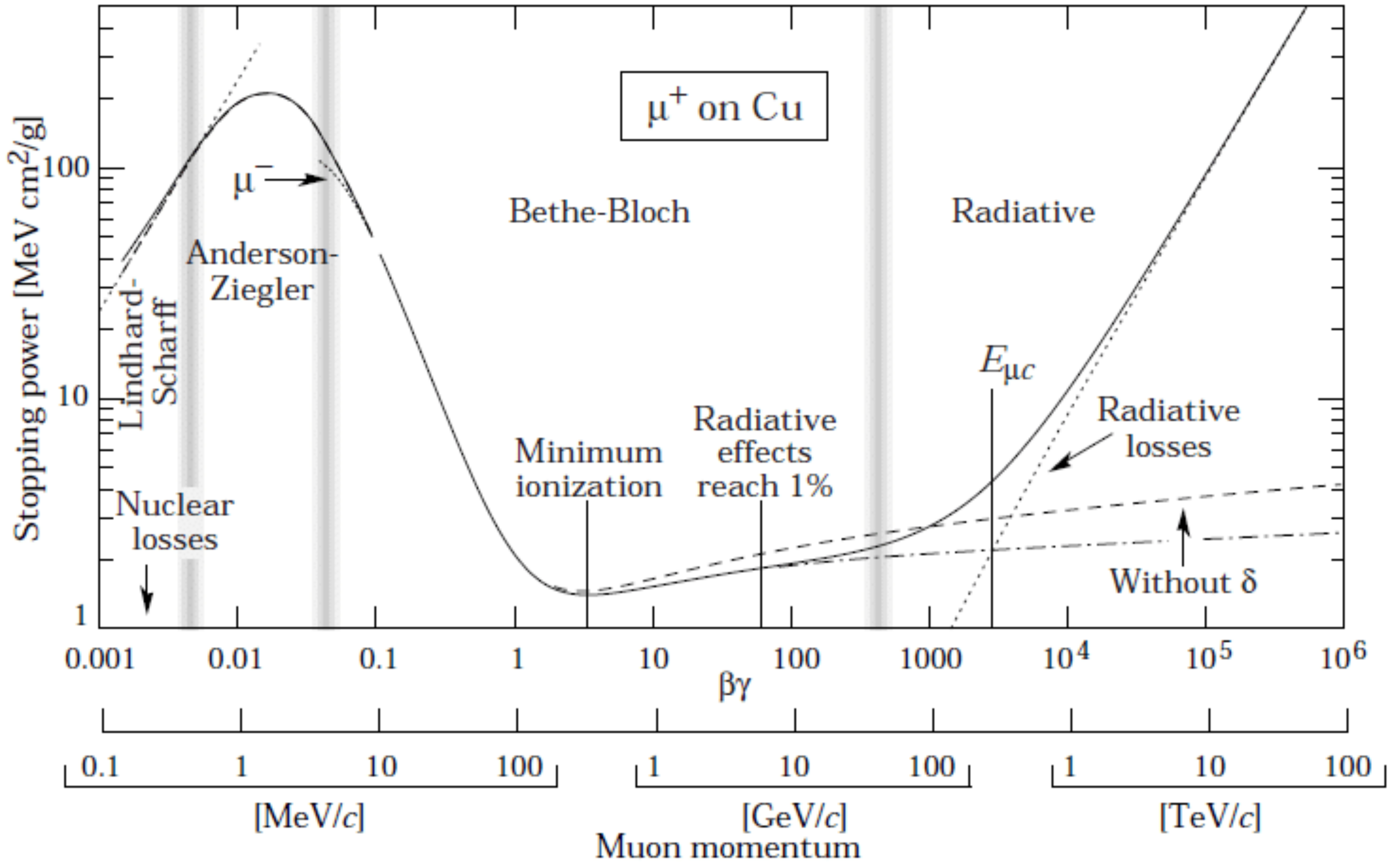


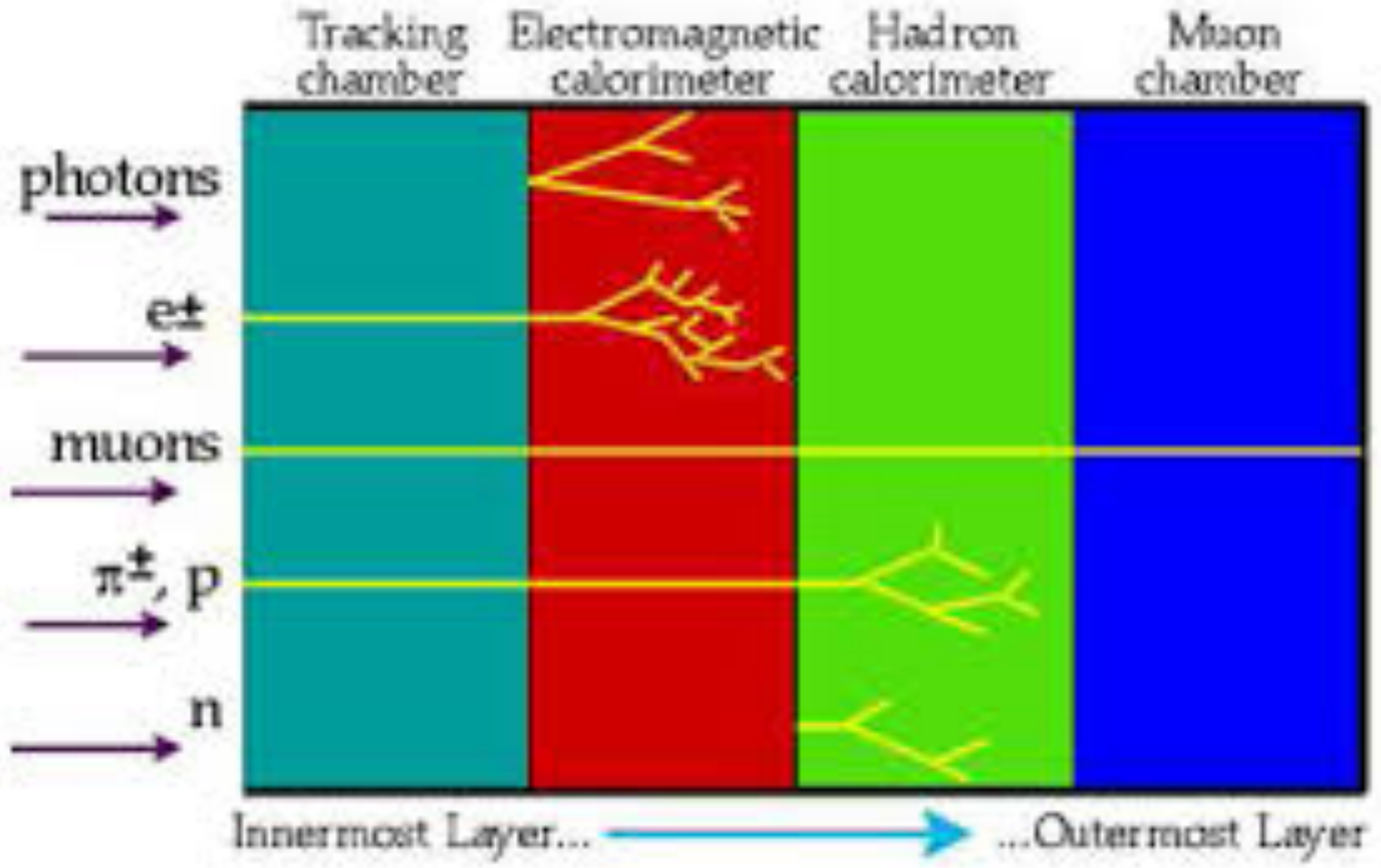


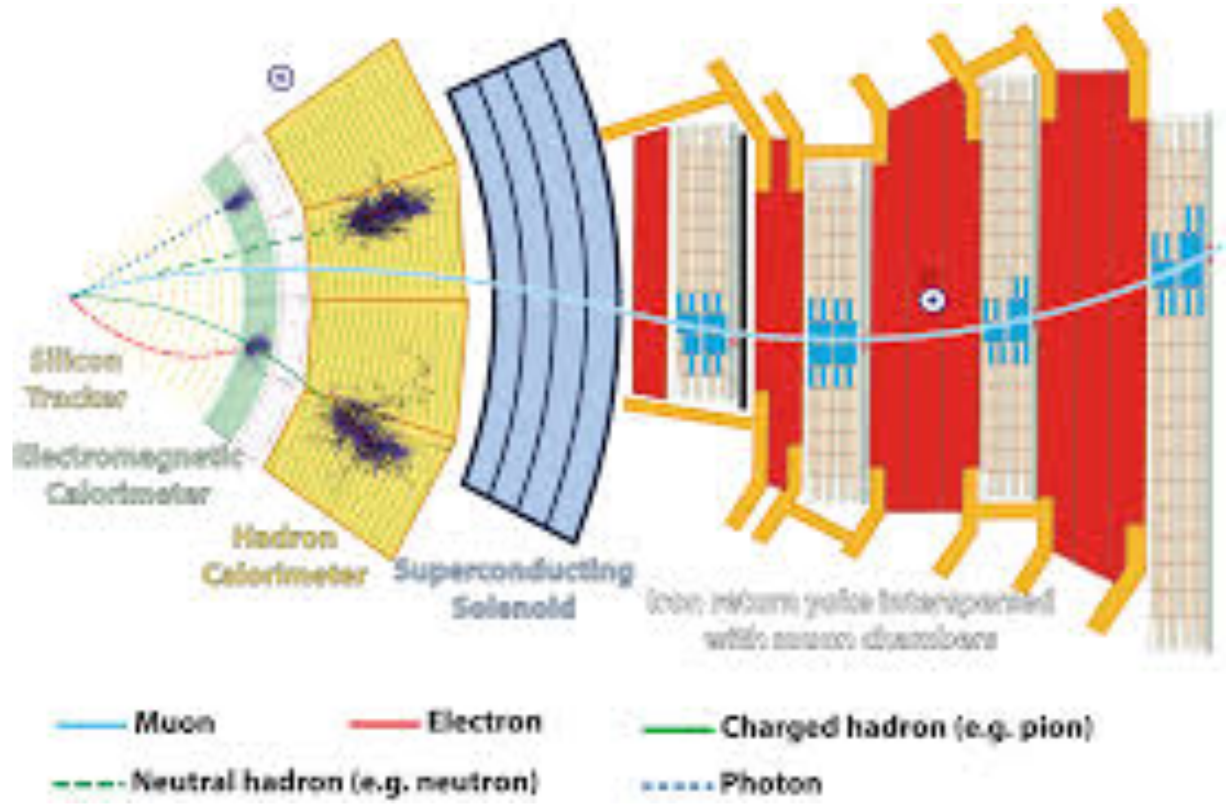
μ Interaction & Detection

- μ's are Minimum Ionizing Particle (MIPs)
- Traverse thought the entire detectors
- μ-spectrometers are placed at the external layer
- Large area coverage → expensive → gaseous detectors





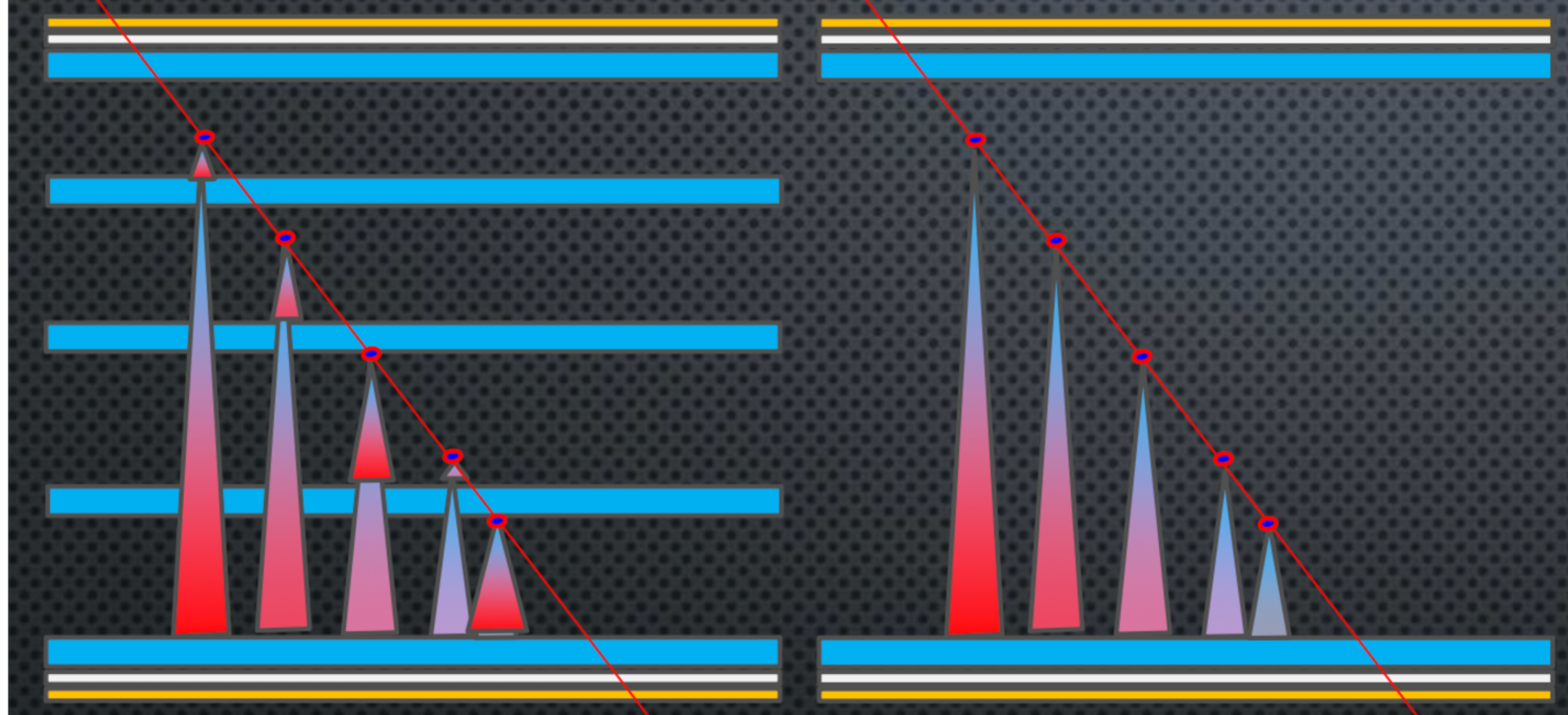




Gaseous Detector Technologies

From Giulio Aielli

RESISTIVE PLATE CHAMBERS AT A GLANCE



RPC and MRPC Common features

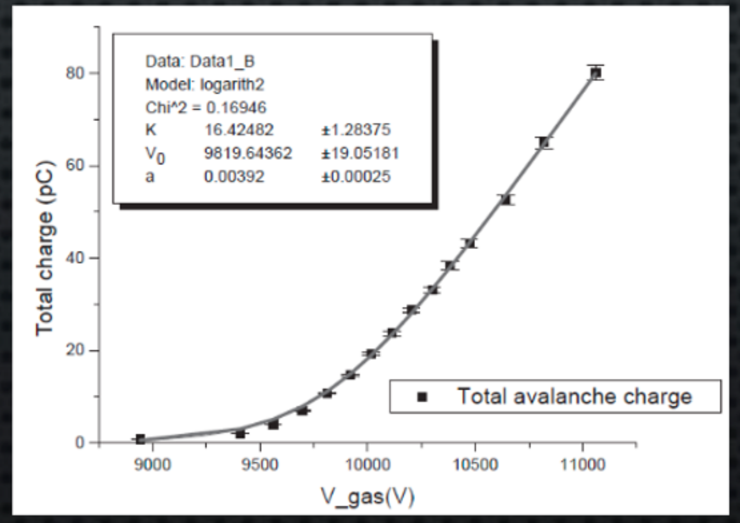
- Target and amplification coincide
- uniform field → prompt signal
- Target and amplification coincide
- high R electrodes → Spark less
- Uniform electrode → simple
- Working at atm. Pressure → simple
- Min 1 mm of target for full eff.
- Thin 0.1mm 2D localization
- Very quenching and electronegative Gases

Feature	RPC	vs	MRPC
# of gaps →	1	–	4 to tens
$\rho(\Omega\ \mathrm{cm})$ →	5×10^{10}	–	5×10^{12}
Module size →	2 m^2	–	0.1 m^2
$\mathrm{Hz/cm}^2$ →	10^4	–	5×10^2
σ_t →	500 ps	–	50 ps

$$Q(V) = \ln\left(1 + e^{a(V-V_0)}\right)$$
$$Q(x) = \ln(1 + e^{ax})$$

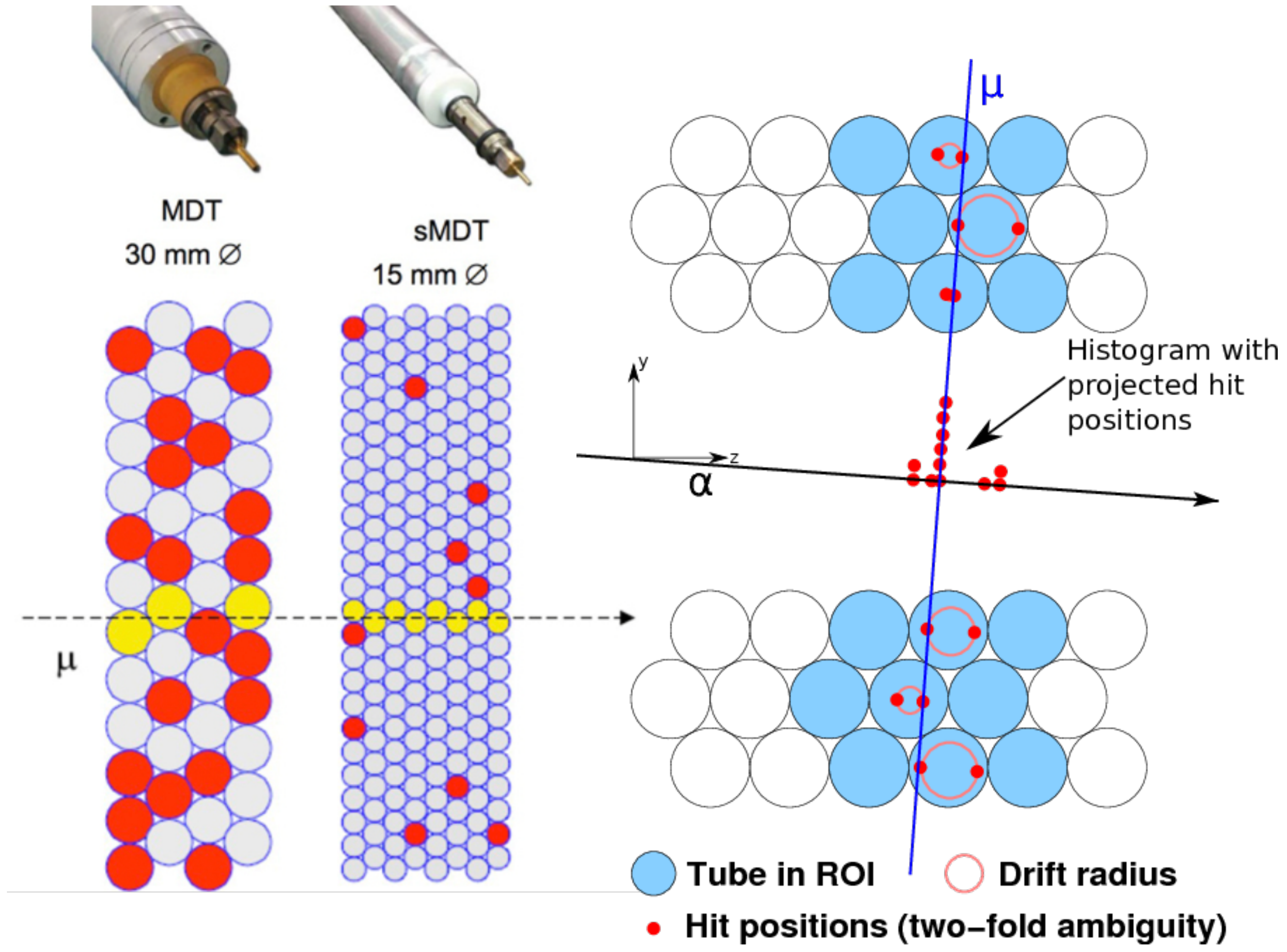
Integral logistic growth

G. Aielli et al NIM A 508 (2003) 6–13

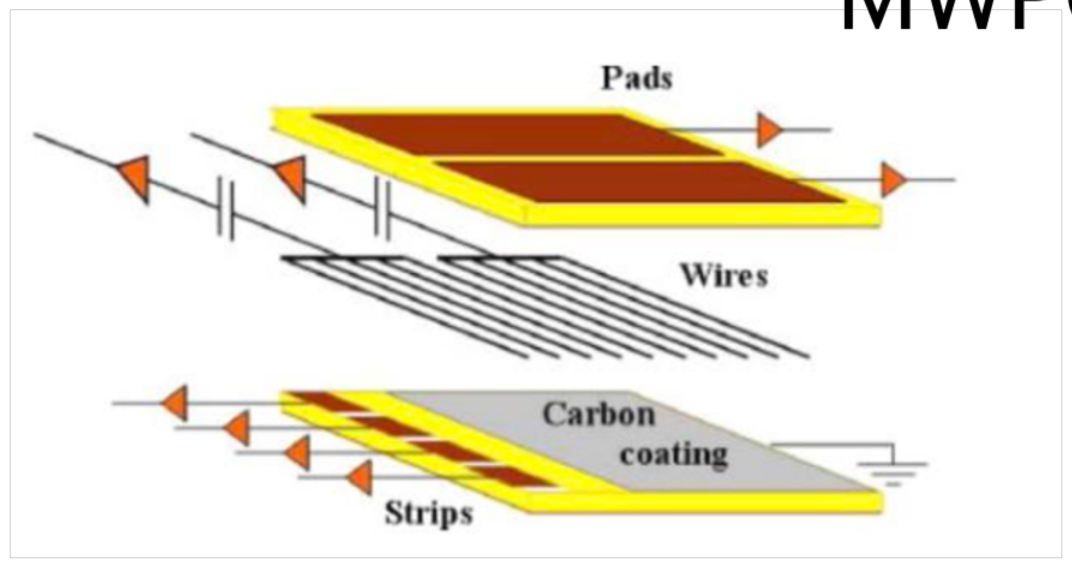


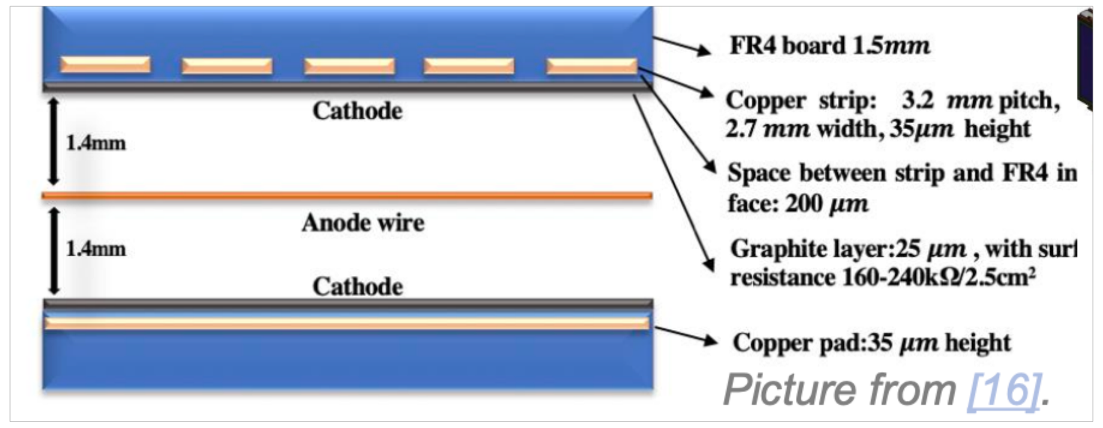
Gaseous Detector Technologies

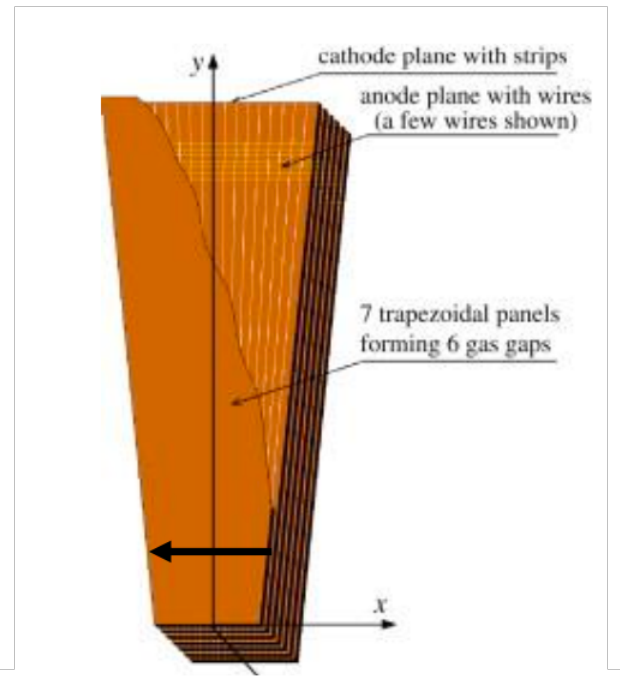
Tubes

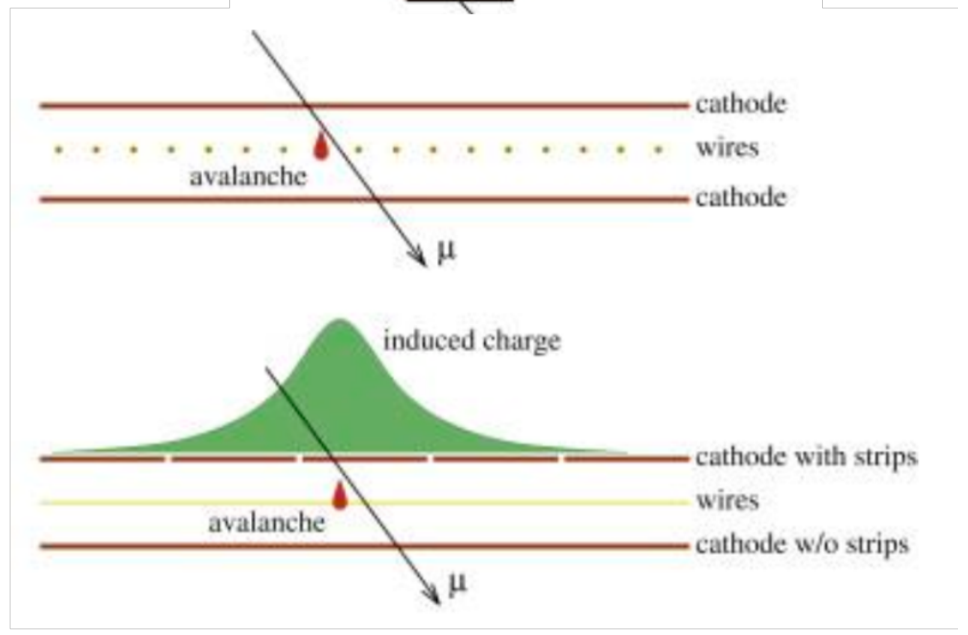


MWPC









From Peter Wintz

CSC/TGC

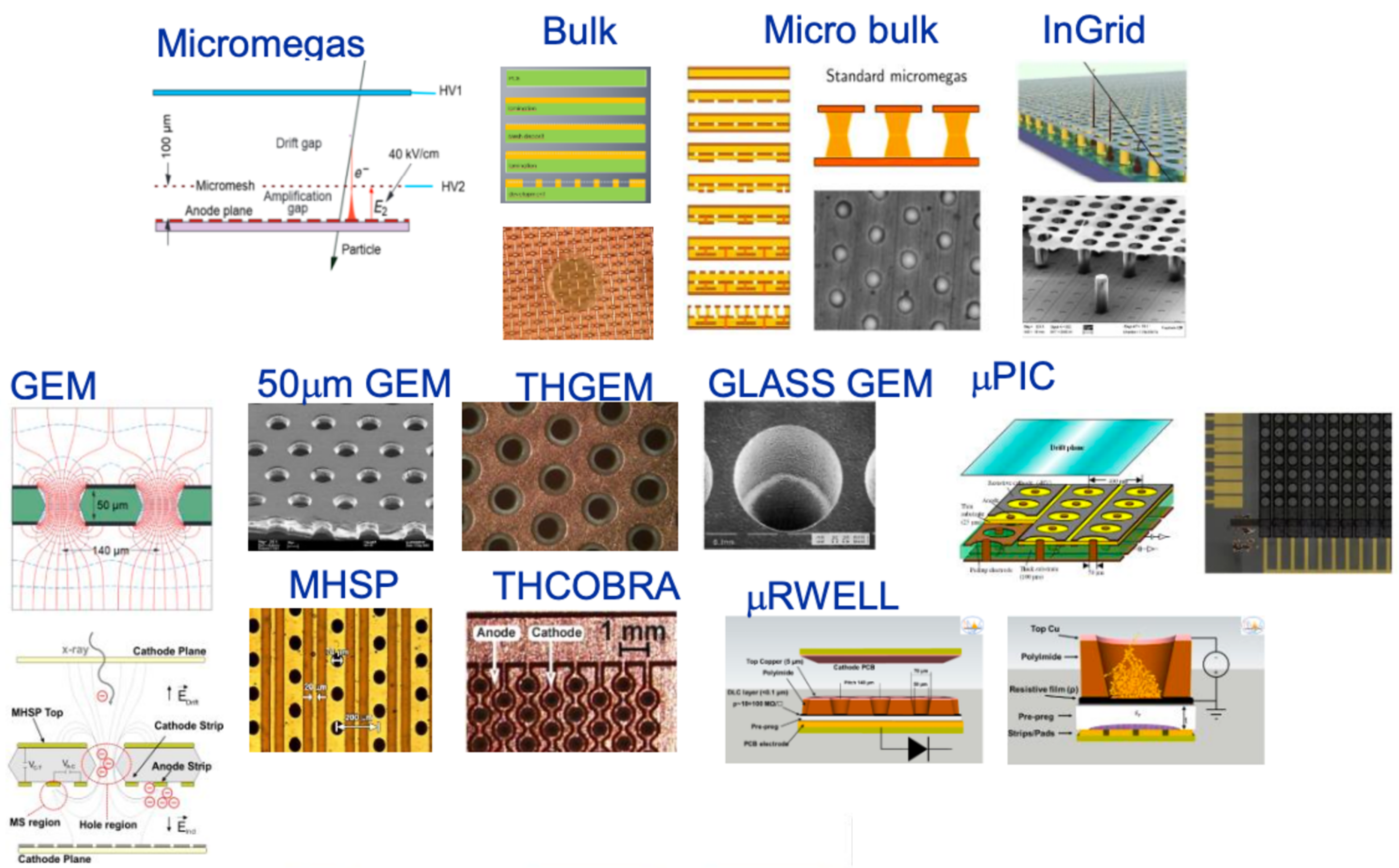
- Low X/X0 TGC layers for central tracking regions?

Wires

- New wire materials new alloy, metallized carbon wire, ..
- Specific topic: wire corrosion, coating quality, ..

Gaseous Detector Technologies

From Eraldo Oliveri



High Rate Capability	Up to MHz/mm^2 (MIP)
High Gain	Up to 10^5 -10^6
High Space Resolution	<100μm
Good Time Resolution	In general few ns , sub-ns in specific configuration
Good Energy Resolution	10-20% FWHM @ soft X-Ray (6KeV)
Excellent Radiation Hardness	
Good Ageing Properties	
Ion Backflow Reduction	% level sort of easy, below % in particular configuration
Photon Feedback Reduction	
Large size	m^2
Low material budget	
Low cost	

- R&D on: timing, stability, resistive materials, upscaling,

ATLAS - LHC

- From ATLAS Muon TDR, 1997
- Physics requirements

  - Resolution: momentum and mass resolutions at the level of 1% are essential for the reconstruction of narrow two- and four-muon final states on top of high background levels, such as the intermediate mass Higgs, and for reliable charge identification. A transverse momentum resolution that is constant over the full rapidity range is desirable.
  - Second-coordinate measurement: a measurement of muon tracks in the non-bending projections with an r.m.s. spatial resolution of 5–10 mm is required for safe track reconstruction and reliable momentum determination.
  - Rapidity coverage of track reconstruction: all physics channels profit from a pseudorapidity coverage up to $|\eta| \approx 3$ and good hermeticity, in particular rare high-mass processes.
  - Trigger selectivity: transverse momentum thresholds of 10–20 GeV are adequate for high-mass states, which will be in the focus of LHC physics at nominal luminosity. Lower thresholds of $p_T \approx 5$ GeV are required for CP violation and beauty physics.
  - Trigger coverage: adequate trigger efficiencies can be obtained with a pseudorapidity coverage smaller than that of the precision chambers. The actual requirements are mostly determined by processes at the opposite ends of the LHC mass scale: the need for good acceptance for rare high-mass Higgs particles, and the need for very high statistics to study small rate asymmetries due to CP violation in the B sector. A trigger coverage of $|\eta| < 2.4$ is found to be sufficient.
  - Bunch-crossing identification: the LHC bunch-crossing interval of 25 ns sets the scale for the required time resolution of the first-level trigger system.

→ ~hundred μm / hit

→ Radiation hardness & rate capabilities

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→ ~hundred μm / hit

→ Radiation hardness & rate capabilities

→ Sharp turn on curve

→ Fast response & fast elx decision

ATLAS - LHC

- Gaseous solutions
- Long lever arm for sufficient banding in the magnetic field
- Two technologies for triggering
  - RPC - Barrel
  - TGC - Endcap
- Two technologies for precision
  - MDT - Barrel & Endcap
  - CSC - Inner Endcap

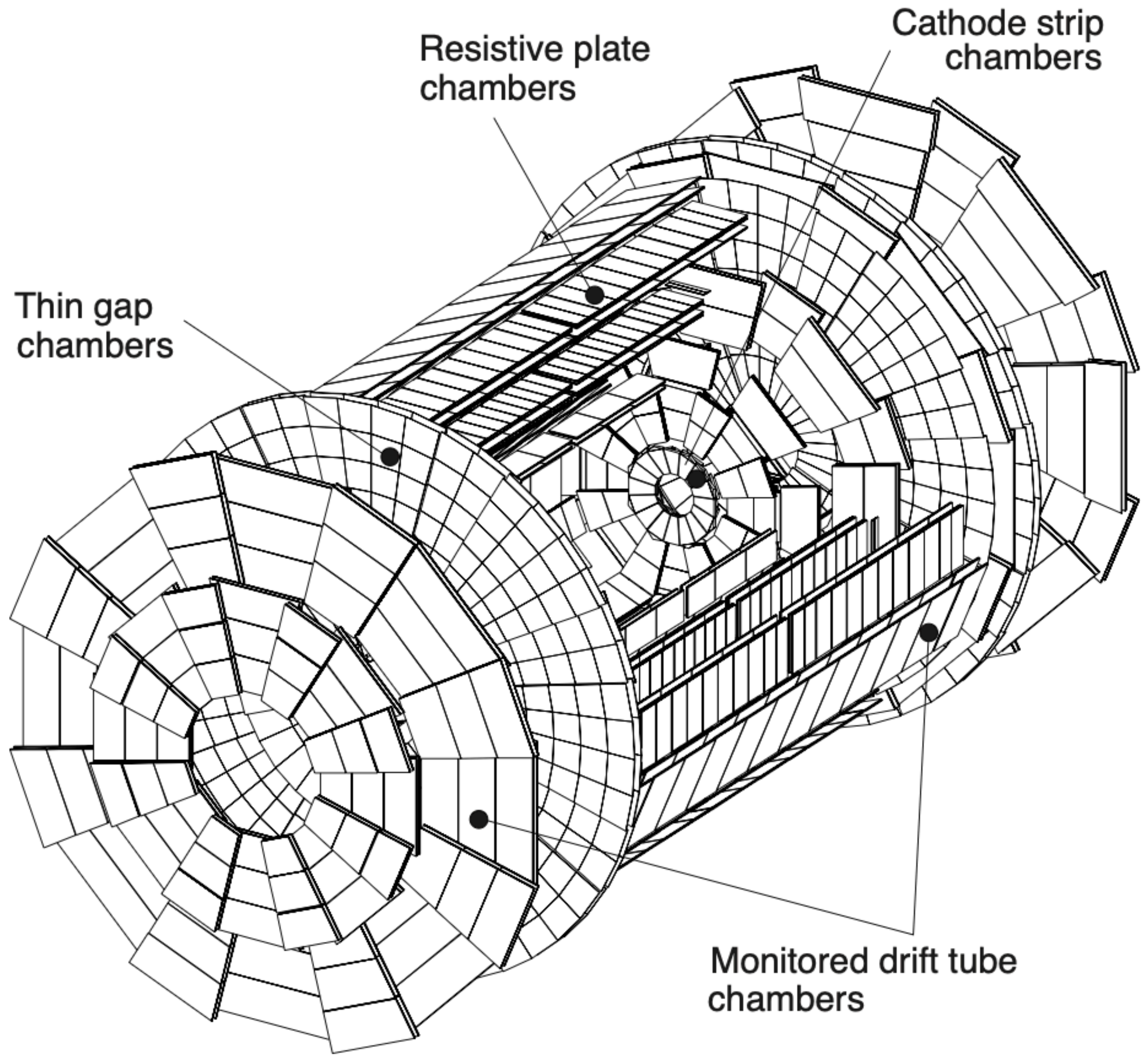
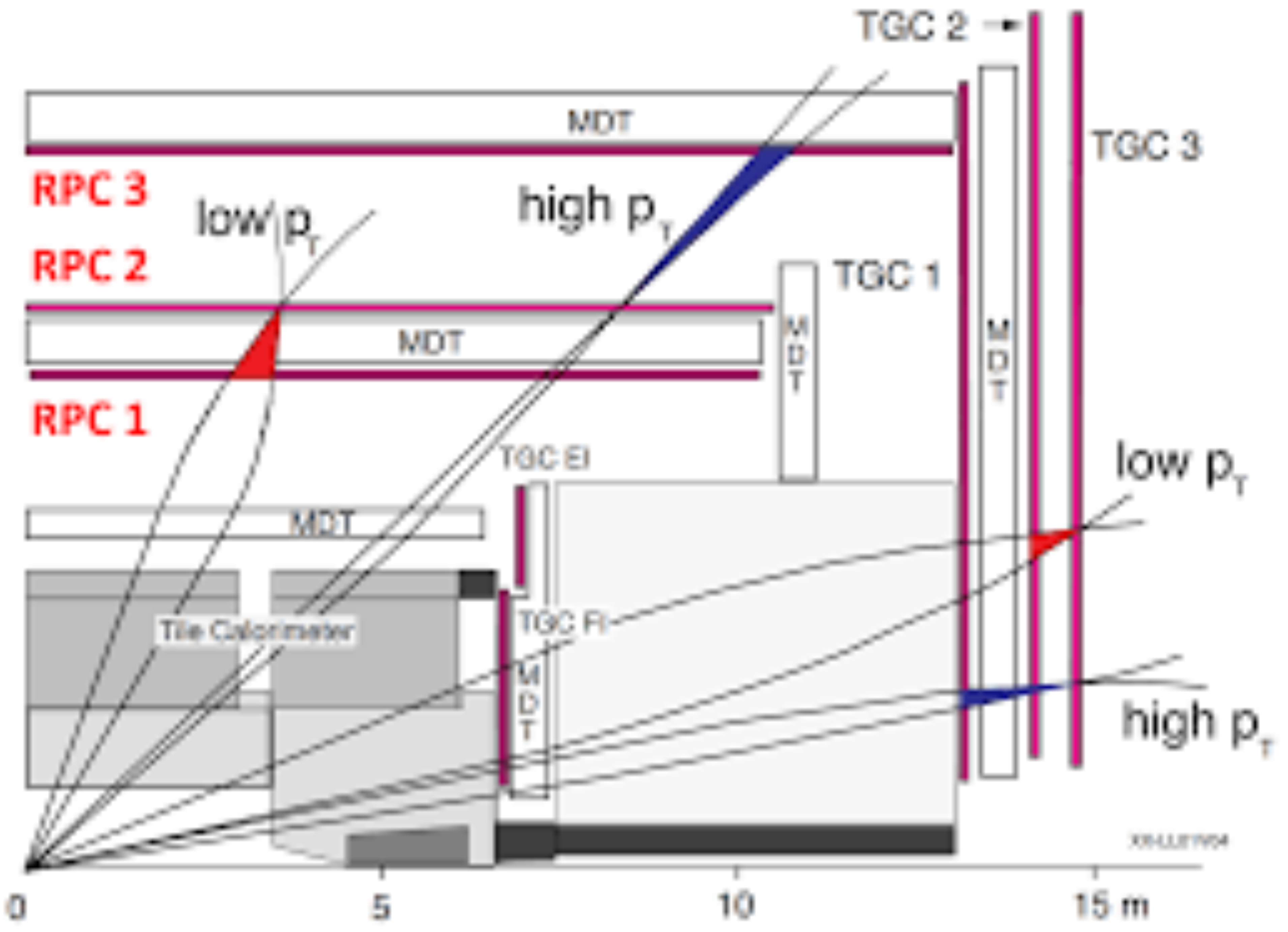


Figure 1-6 Three-dimensional view of the muon spectrometer instrumentation indicating the areas covered by the four different chamber technologies

ATLAS - Trigger & Reco. scheme



- Reconstruction
  - From inner tracks extrapolated to muon stations and corrected with MDT segments
  - Muon segments extrapolated to inner tracks
- Trigger
  - LVL 0 - hardware based
  - High LVL - software

CMS - LHC

- From CMS Muon TDR, 1997
- Physics requirements

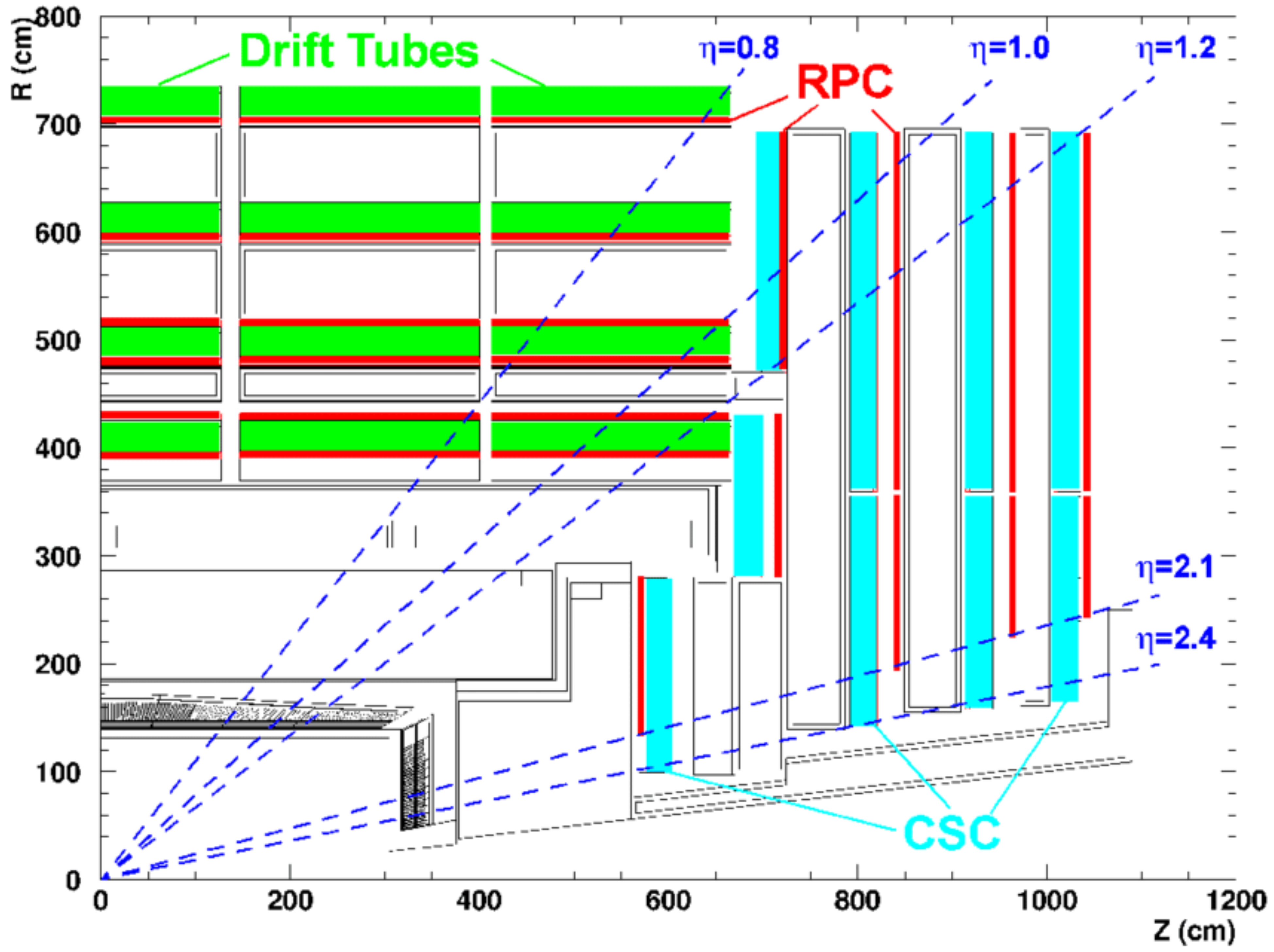
The muon system has three purposes: muon identification, muon trigger, and muon (signed) momentum measurement. Performance requirements follow the physics goals, including the maximum reach for unexpected discoveries, and the background environment of LHC at its highest luminosity. A robust 4 T solenoid-based system is the key to the CMS design. Comprehensive simulation studies have indicated that the physics goals can be achieved if the muon detector has the following functionality and performance:

- MUON IDENTIFICATION: at least 16 λ of material is present up to η=2.4 with no acceptance losses.
- MUON TRIGGER: the combination of precise muon chambers and fast dedicated trigger detectors provide unambiguous beam crossing identification and trigger on single and multimuon events with well defined p_T thresholds from a few GeV to 100 GeV up to η=2.1.
- STANDALONE MOMENTUM RESOLUTION from 8 to 15% $\delta p_T/p_T$ at 10 GeV and 20 to 40% at 1 TeV.
- GLOBAL MOMENTUM RESOLUTION after matching with the Central Tracker: from 1.0 to 1.5% at 10 GeV, and from 6 to 17% at 1 TeV. Momentum-dependent spatial position matching at 1 TeV less than 1 mm in the bending plane and less than 10 mm in the non-bending plane.
- CHARGE ASSIGNMENT correct to 99% confidence up to the kinematic limit of 7 TeV.
- CAPABILITY OF WITHSTANDING the high radiation and interaction background expected at the LHC.

→ Material to block other particles

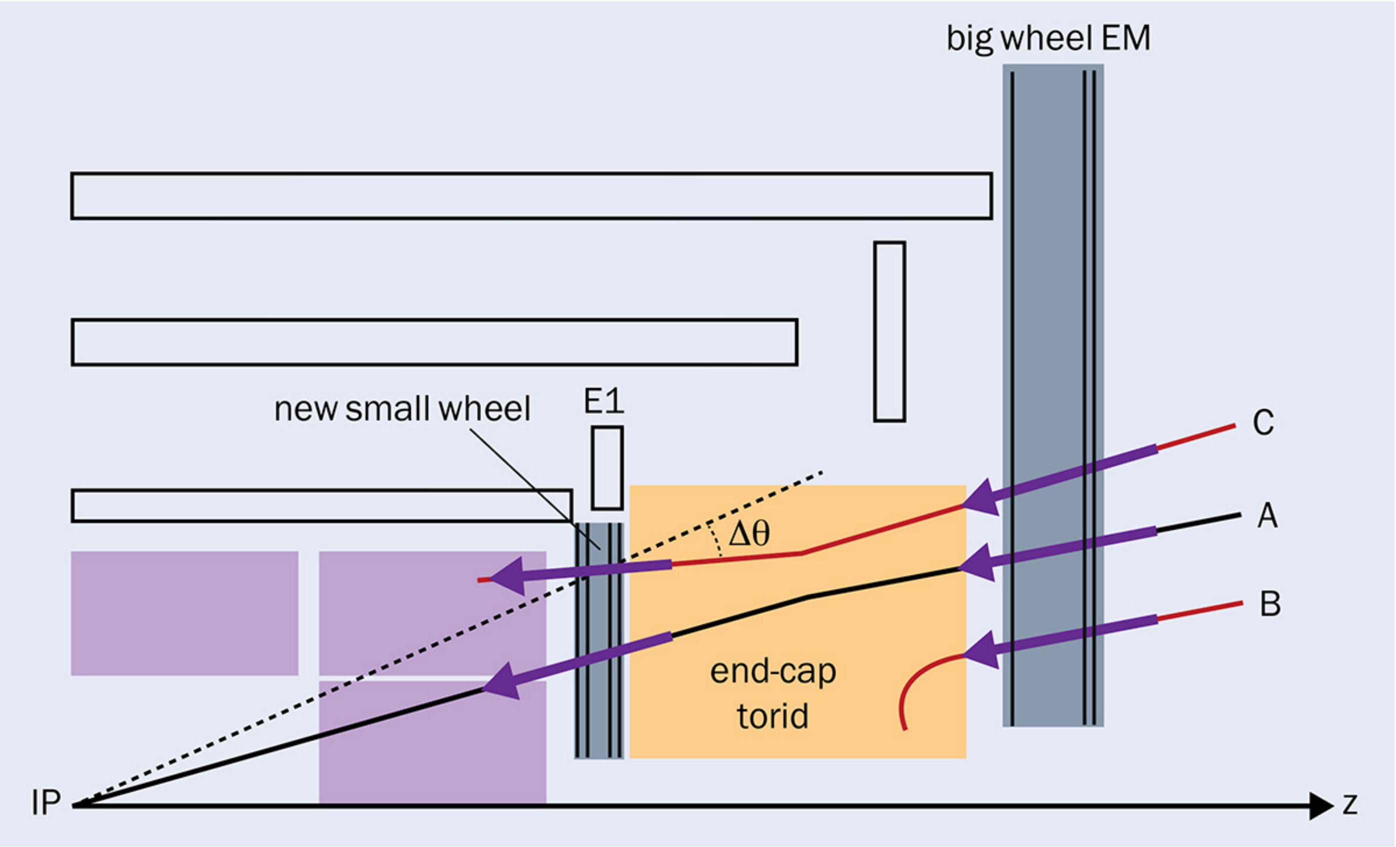
CMS - LHC

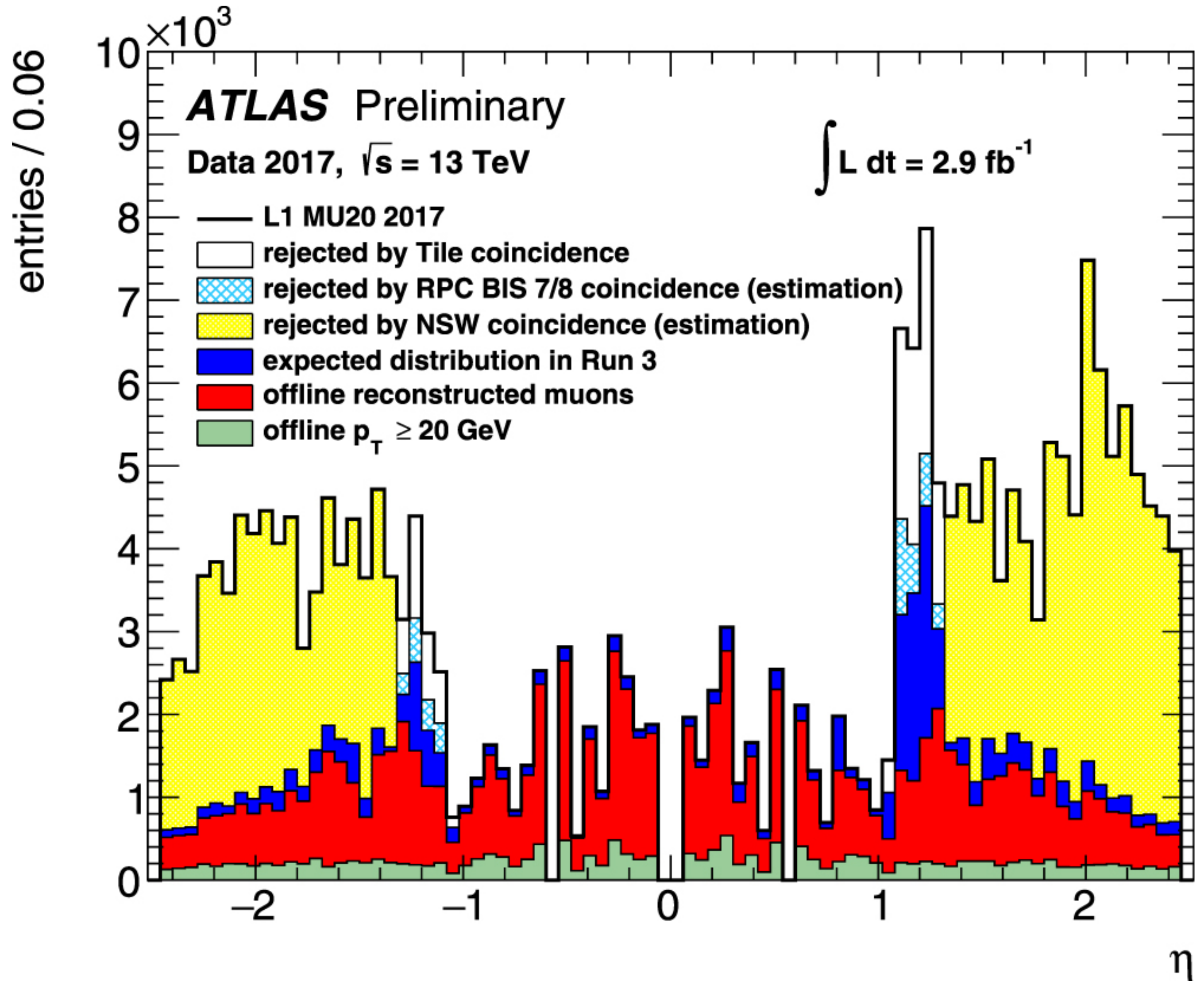
- Gaseous solutions
- Technologies used for tracking and triggering
  - Drift Tubes - Barrel
  - CSC - Endcap
  - RPC - Barrel & Endcap



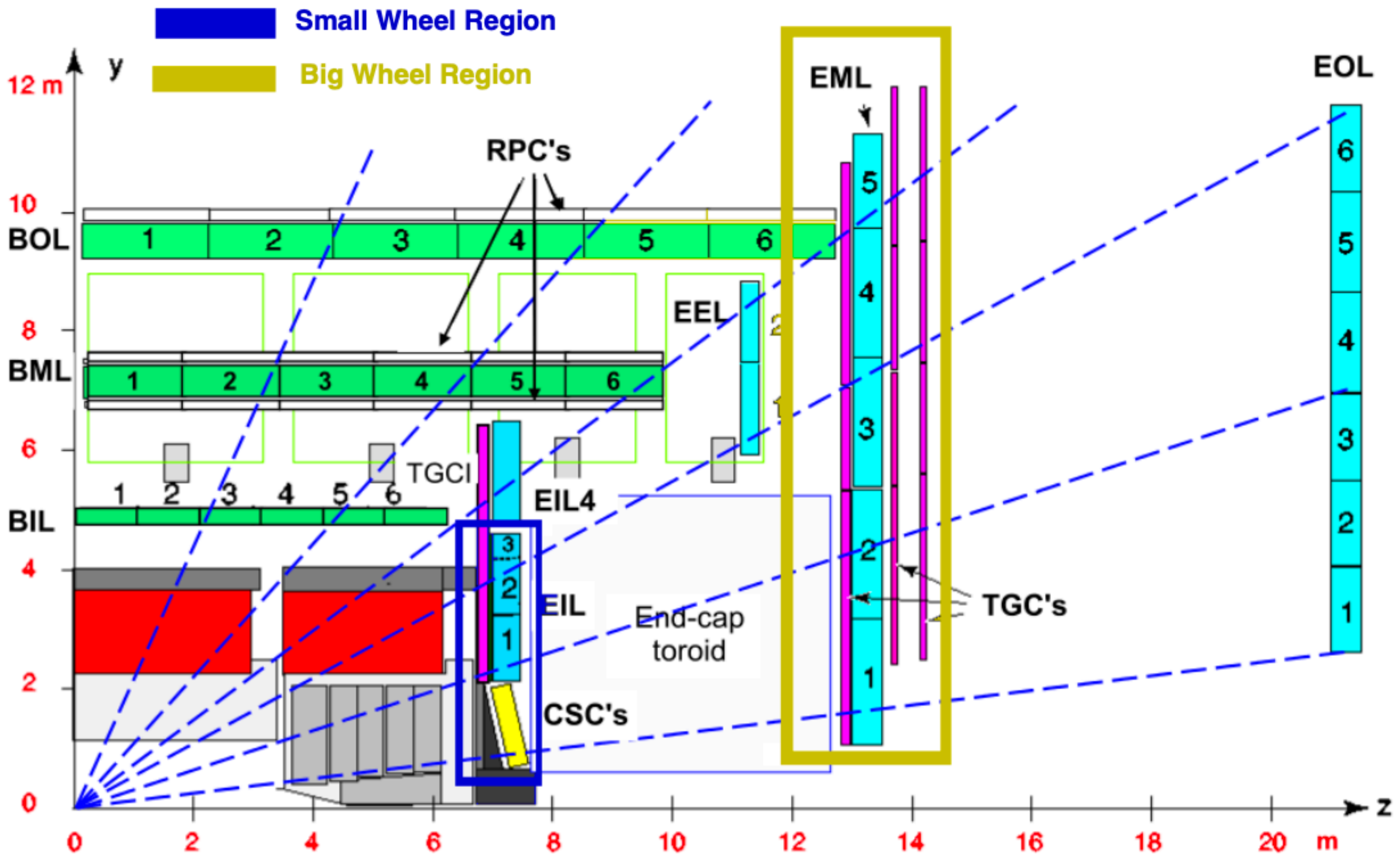
ATLAS - HL-LHC

- Higher luminosity
- Higher background
- Higher radiation
- &aging





- ATLAS upgrade in two phases
  - **Phase I - New Small Wheel**
  - Phase II - TGC EI, MDT to sMDT, new RPC, elx.



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- Expected hit rate in Run-4 extrapolated from Run-2 (I. Ravinovich)
- Up to 2 kHz/cm² in the big wheel inner ring region (6 C/cm integrated charge)
- Up to 450 Hz/cm² in the EIL4 region

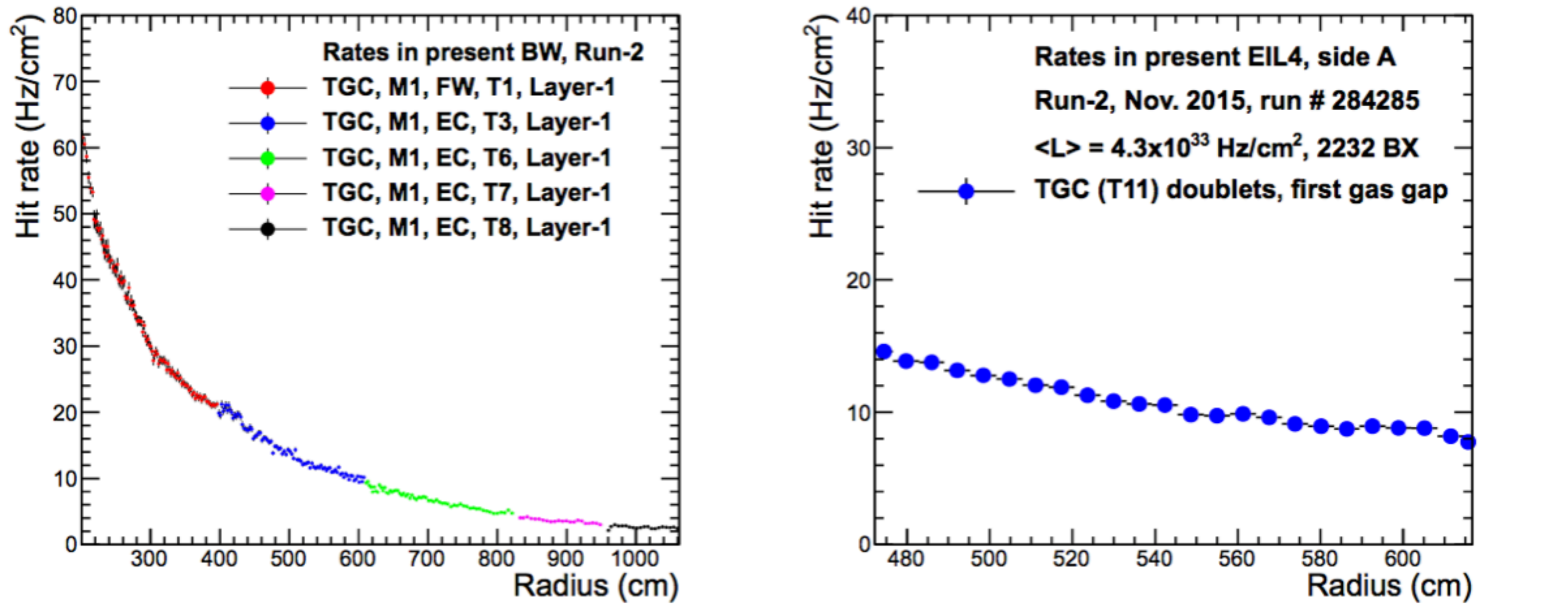
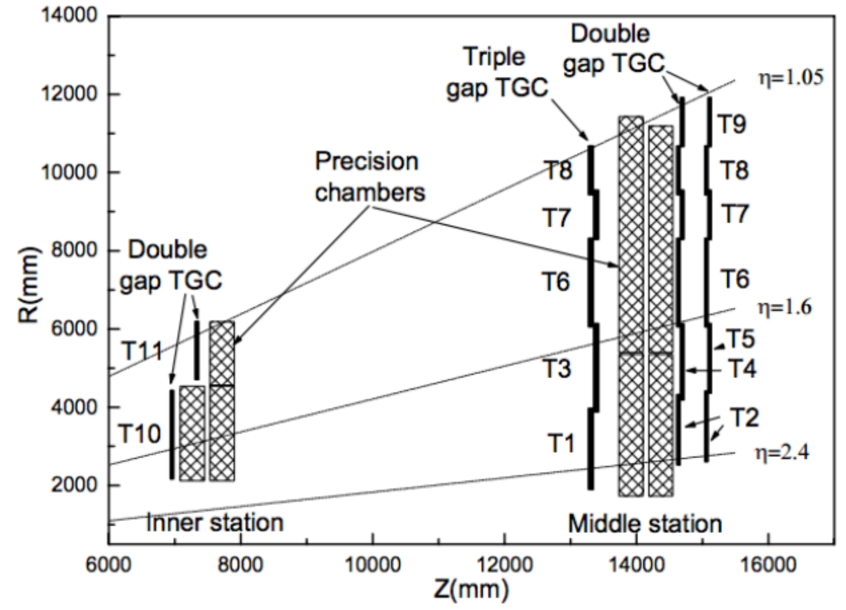


Figure 7.1: Measured TGC hit rates on the M1 wheels (left) and the EIL4 chambers (right) at a luminosity of 4.3×10^{33} cm^{-2} s^{-1}.



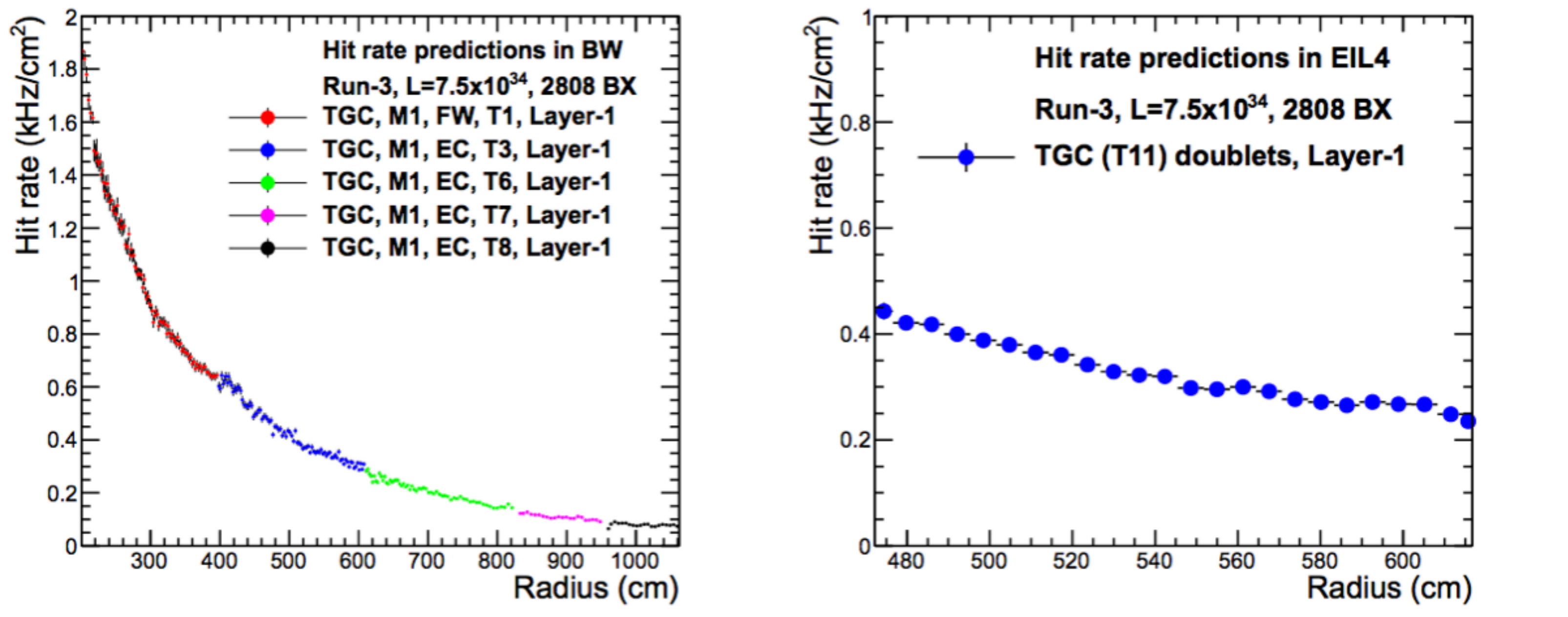


Figure 7.2: Expected TGC hit rates on the M1 wheels (left) and the EIL4 chambers (right) at a luminosity of 7.5×10^{34} cm^{-2} s^{-1}.

ATLAS - HL-LHC

- Higher luminosity
- Higher background
- Higher radiation
- &aging

- ATLAS upgrade in two phases
  - Phase I - New Small Wheel
  - **Phase II - TGC EI, MDT to sMDT, new RPC, elx.**

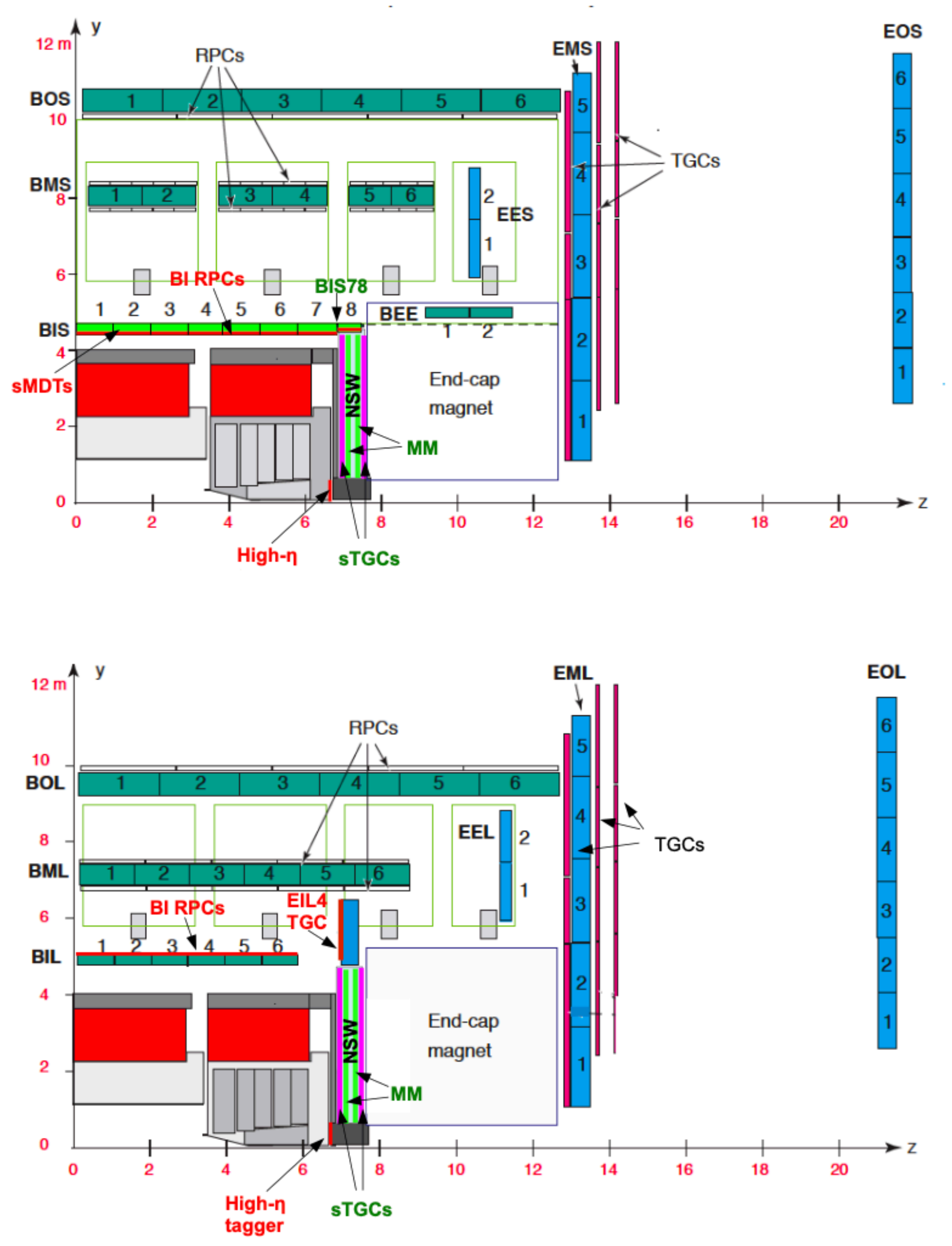


Figure 1.3: Two *R-Z* views of the Phase-II ATLAS muon spectrometer layout showing a small sector (top) and a large sector (bottom). The drawings show the new detectors to be added in the Phase-II upgrade, including the addition of the high-η tagger (red text: BI RPC, sMDT, EIL4 TGC, high-η tagger), those to be installed during LS2 (green text: Micromegas and sTGC in the New Small Wheel and BIS78 RPC and sMDT), and those that will remain unchanged from the Run 1 layout (black text).

CMS - HL-LHC

- Higher luminosity
- Higher background
- Higher radiation
- &aging

- CMS upgrade
  - iRPC, GEM, elx.

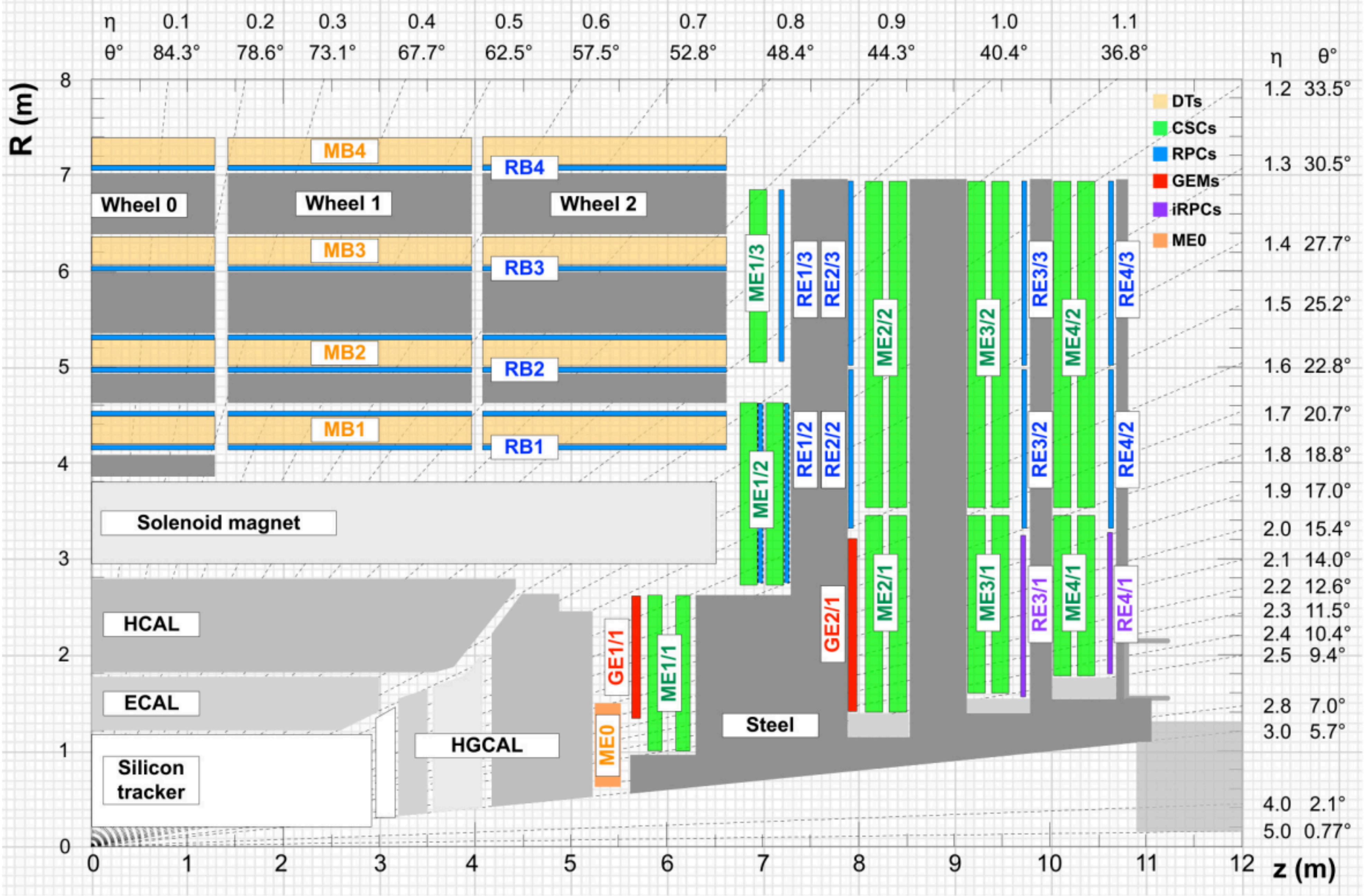


Figure 1. Quadrant of a section of the CMS muon spectrometer, showing the Phase-1 muon stations and the new stations after the Phase-2 upgrade (in red, violet and orange) [2].

Future

From Maxim Titov

Accelerator & Time scale	Application	Technology	Detector size & Module size	Requirements	Special requirements
LHeC	Muon system for Tracking & Triggering	RPC/MDT	Total: 400 m^2 Module: 2-5 m^2	Max rate: 3 kH_z/cm^2 Spatial res: 1 mm/80 μm Time res ~0.4 ns Rad. Hard: 0.3 C/cm^2	
FCC-ee/CEPC >2030	IDEA pre shower for Tracking	μRWELL	Total: 225 m^2 Module: 0.25 m^2	Max rate:10 kH_z/cm^2 Spatial res ~60-80 μm Time res: 5-7 ns Rad. Hard < 100 mC/cm^2	
FCC-ee/CEPC >2030	IDEA muon system for Tracking & Triggering	μRWELL	Total: 3000 m^2 Module: 0.25 m^2	Max rate < 1 kH_z/cm^2 Spatial res ~ 150 μm Time res: 5-7 ns Rad. Hard < 10 mC/cm^2	
FCC-hh > 2050	Muon system for Tracking & Triggering	MDT/RPC/MPGD/CSC	Total: ~ 3000 m^2	Max rate < 500 kH_z/cm^2 Spatial res <100 μm Time res ~3 ns Rad Hards ~1 C/cm^2	Redundant tracking and triggering
Muon Collider > 2050	Muon system for Tracking & Triggering	RPC/fast timing MPGD	Total: 3500 m^2 Module: 0.3-0.4 m^2	Max rate < 100 kH_z/cm^2 Spatial res < 100 μm Time res <10 ns Rad Hards < C/cm	Redundant tracking and triggering

Future

- Nothing decided yet
- All options are on the table
- continues development of most gaseous detector types
  - Higher precision
  - Towards pico second timing
  - Better stability
- New production techniques
- New materials
- Detailed comparison of the different technologies under identical conditions