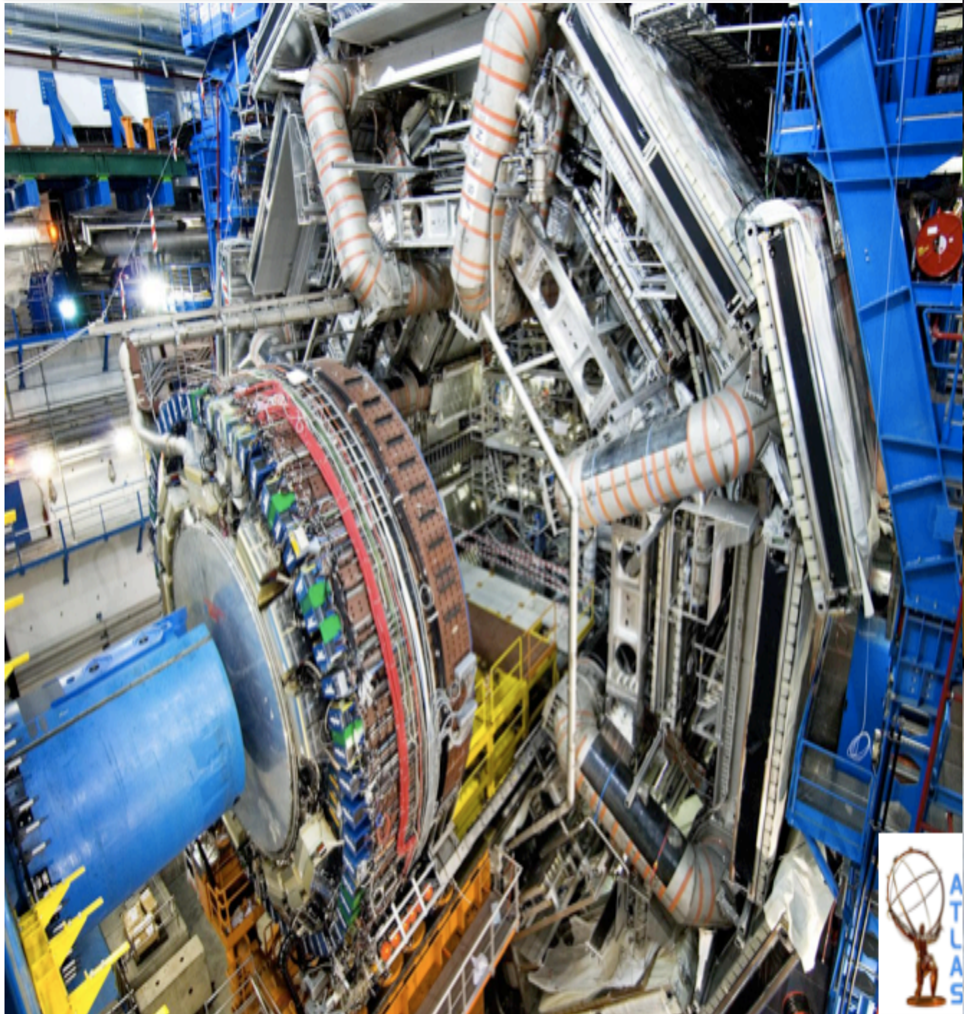
Muon Identification with ATLAS and CMS



Alan Poppleton CERN

Outline

- Motivation and basic concepts
  - Role of muons at the LHC
  - Muon system requirements
  - Muon Identification basics
  - Muon momentum measurement
- The ATLAS and CMS experiments
  - Conceptual design (>20 years ago)
  - Magnet systems
  - Muon detectors
- Reconstruction of Muons
  - Standalone in Muon Systems
  - Combined muons
  - ATLAS muon identification strategies
- First year of running
  - Performance determination with pp collision data
  - What to do with muons (and expect from muons)

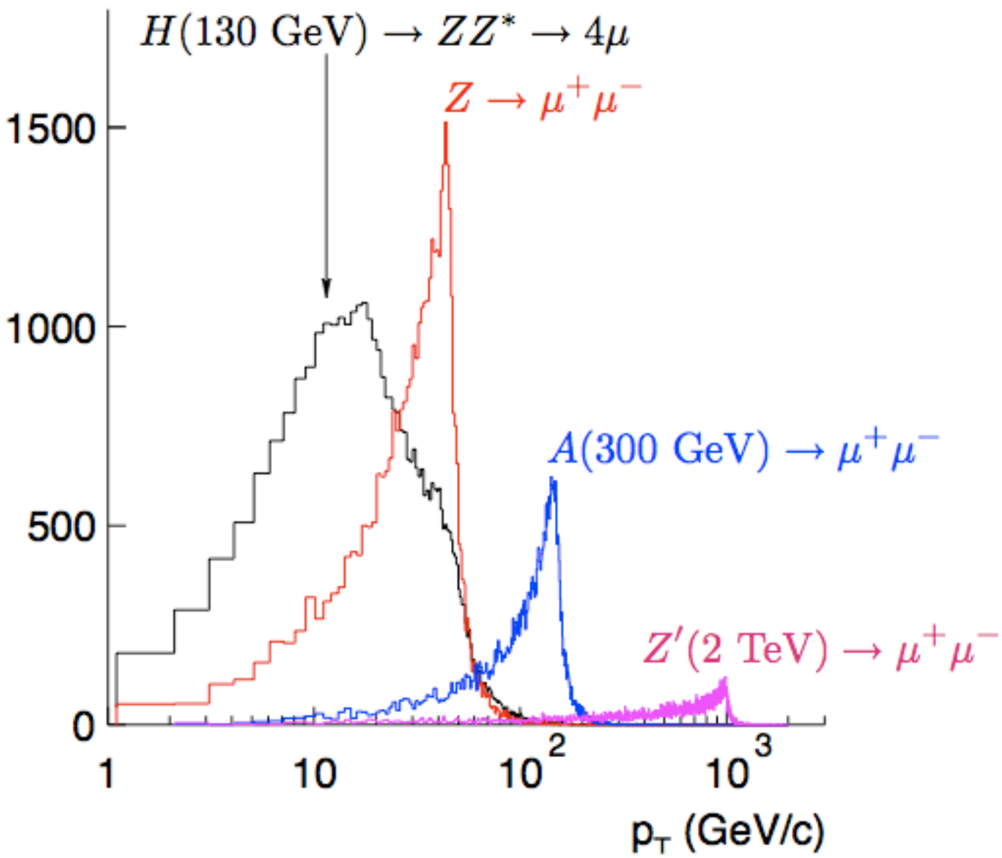
Role of Muons at the LHC

- Muons are the only charged primary collision products traversing the calorimeters
  - clean signature of muonic final states for discovering new physics
  - muons perhaps the cleanest signal for physics in early data

- Example physics processes with muonic final states:
  - $H \rightarrow Z Z^{*} \rightarrow \mu\mu\ell\ell$
  - $A \rightarrow \mu\mu$
  - $Z' \rightarrow \mu\mu$

- Good muon identification and reconstruction is crucial for physics at the LHC
  - dominant aspect of ATLAS and CMS designs (dimensions and mass)

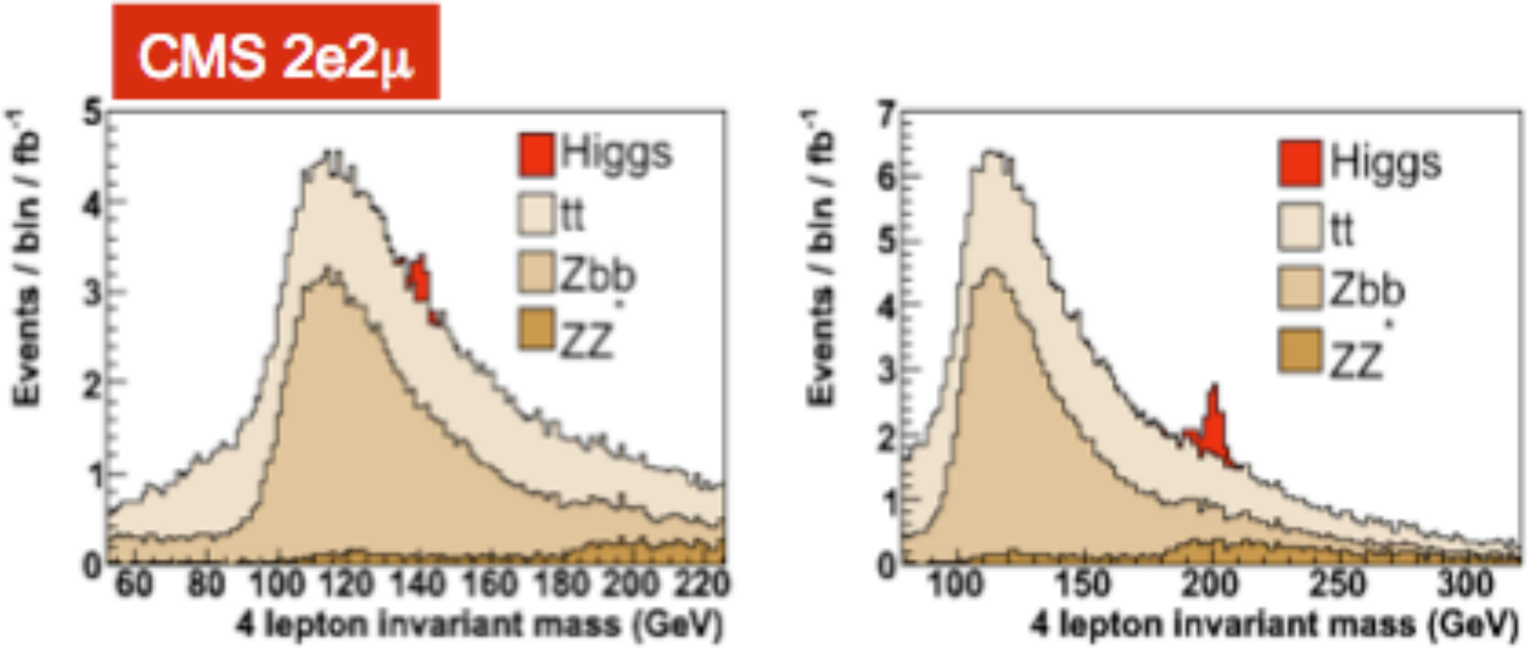
Characteristic Muon Momentum Spectra



Need for efficient muon detection and identification over wide momentum range!

Require precise muon momentum measurement

$$H \rightarrow Z Z^* \rightarrow \mu\mu\ell\ell$$



- rate of detectable Higgs production at LHC is predicted to be **12 orders of magnitude** below inelastic rate
- the low mass Higgs width is predicted to be much narrower than the experimental resolution

high precision momentum measurement helps resolve signal from background muons

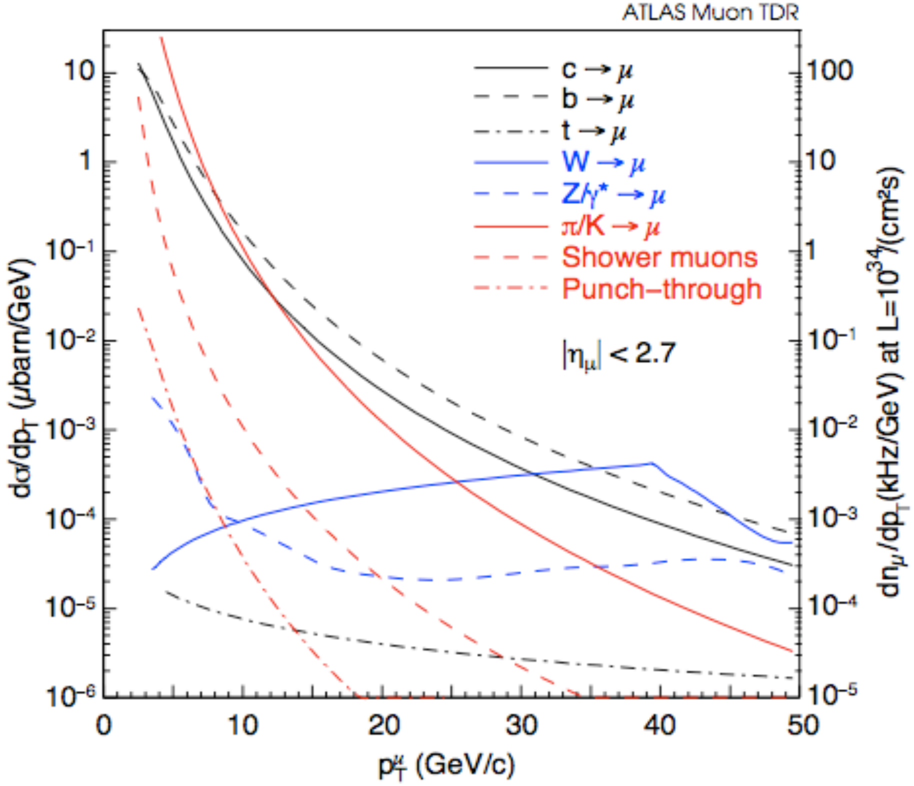
Muon system requirements

Basic concepts

- **Sufficient material** between Interaction Point (IP) and Muon Spectrometer (MS)
  - suppress hadronic punch-through and sail-through to well below rate of muons
  - in practice: ATLAS has at least 11 interaction lengths (λ) before entering MS
    CMS has ~10λ before MS, with at least 20λ from IP to MS exit
- Capability to operate in a **high radiation environment**
  - and accompanying high detector noise (occupancy from background)
- **Trigger chambers** to select single and multi-muon events
  - sufficient precision to ensure sharp p_T threshold at lower momenta
  - fast to give bunch crossing assignment
- **Standalone track reconstruction** capability (from trigger and precision chambers)
  - reliable association (match) to identify the corresponding inner detector track
  - muon momentum measurement
  - provides redundancy in case of problems in other sub-systems
    - otherwise facilitate calibration and alignment (detector understanding in general)
- **Combined momentum precision** (from all detector systems)
  - ~2% at low/intermediate momenta to distinguish multimuon mass peaks
  - ~10% at 1 TeV to give reliable charge determination up to kinematic limit

Muon Identification basics

Inclusive muon cross sections



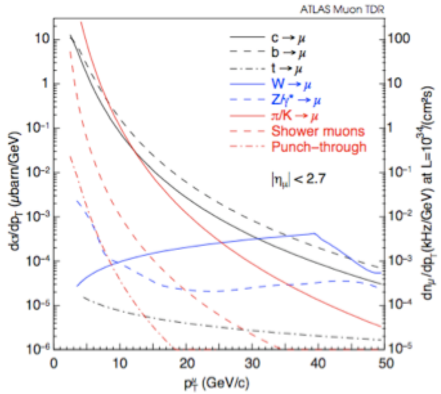
Muon identification tasks

- Identification of "prompt" muons from c, b, t, W, and Z/γ decays.
- Rejection of muon from π/K decays, shower muons, and hadronic punch-through.

Muon identification terminology

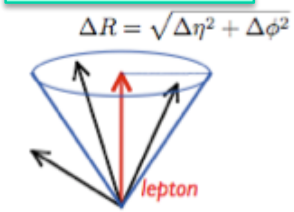
- **Non-muons:** tracks in the MS are essentially all muons
  - apart from very rare sail-through and low momentum hadronic punch-through
  - or fake tracks from unrelated background hits
- **Background muons** (to **prompt muons**): decays-in-flight, shower muons and beam halo (even cosmics)
  - reject from lack of projectivity to IP region or no match to inner track
  - distinguish by lower quality match with inner detector

The above MS tracks are collectively termed fakes



- **Indirect muons**: from b- and c- decay
  - distinguish production in jets using isolation criteria:
    - calo (energy in cone - around muon trajectory or around production direction)
    - track (multiplicity in cone around production direction)
  - belong to secondary vertex
    - b-tags from vertexing and impact parameter to beam-axis
- **Direct muons** are generally high p_T or isolated
  - W/Z and discovery physics

Isolation cone



Limiting factors for MS momentum measurement

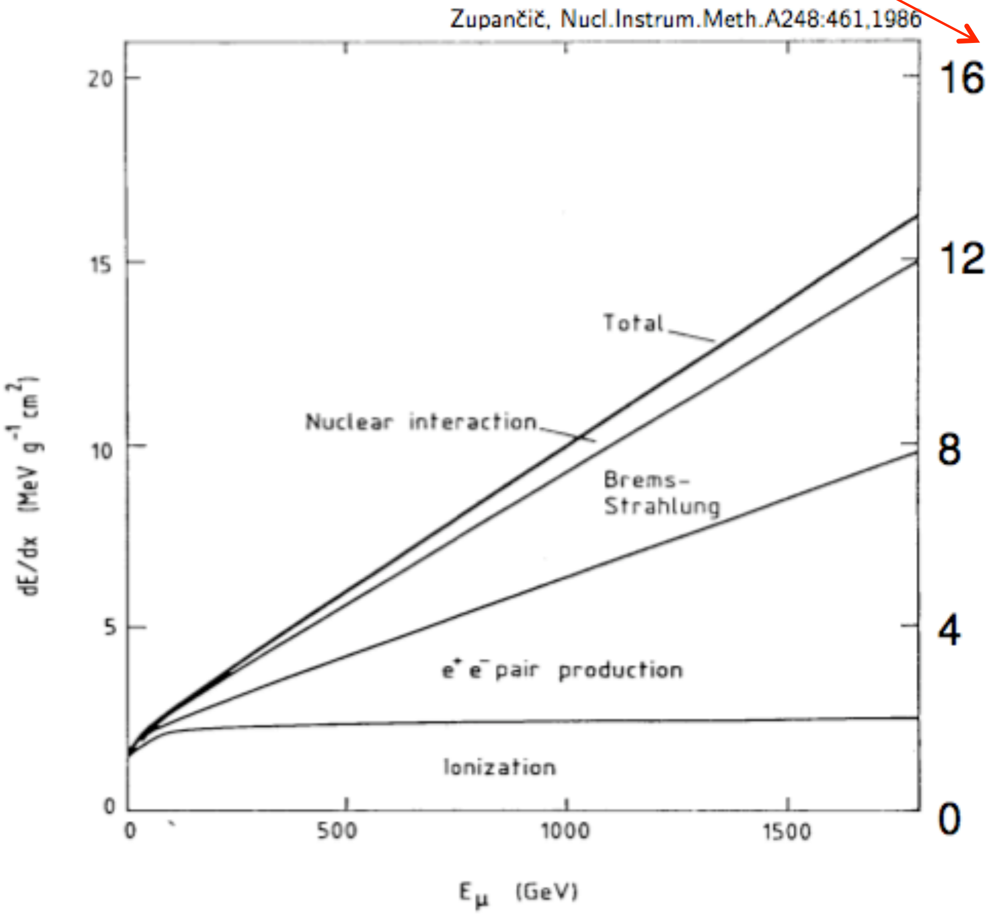
Limitations to standalone measurement

- Energy loss and energy loss fluctuations in the traversed material:
  - In particular material upstream in the calorimeters
- Field integral: the bending power (B.dl) of the muon system
- Multiple Coulomb scattering in the MS material
- Resolution and alignment precision of the muon chambers

remember final precision obtained after combination with ID

Energy loss front of the MS

Muon energy loss in GeV
for 1m thickness of iron
(taking Fe density into account)



High energy muons produce accompanying e/m showers

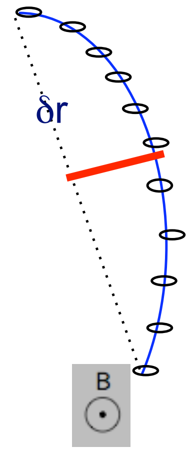
Momentum threshold for MS

- Interaction length of Fe ~ 0.17m
- Material in front of MS approximately equivalent to 1.9m Fe
- Minimum loss from ionization ~3GeV
- Significant increase in mean loss as momentum increases
- Most probable loss rises to >20 GeV at highest momenta
- However loss/momentum ratio decreases with muon energy
- In addition: muons need ~1GeV remaining momentum to avoid ranging out or being trapped in the MS magnetic field

Overall momentum threshold at ~4 GeV

Momentum measurement (1)

Solenoid: inner detector



- constant central field B along (z-)axis bends tracks in transverse projection
- curvature ρ inversely proportional to p_T
- **measure magnitude of sagitta** = $\delta r^2/8\rho = 0.3B\delta r^2/8p_T$ $\quad T.m^2.GeV^{-1}$
- High energy tracks are almost straight lines:

CMS ID:	B=4T, δr=1.4m	**sagitta ~ 0.3mm** for p_T = 1 TeV
ATLAS ID:	B=2T, δr=1m	**sagitta ~ 4×smaller**

Solenoid: flux return

CMS MS:	B~2T, δr=3m	**sagitta ~ 0.6mm** for p_T = 1 TeV

Toroid: barrel

- Field in ϕ direction, sagitta measures 1/p
- Path length = $\delta r/\sin\theta$ => **momentum precision proportional to $1/p_T$** *(as solenoid)*
- ATLAS mean field ~ 0.4T, field falls like 1/r, δr ~ 5m

ATLAS MS: **sagitta almost identical to that of CMS ID at η = 0**

Momentum measurement (2)

Barrel magnets

- forward tracks leave cylindrical volume endwise
  - without reaching full δr
- ID solenoids: **significant loss of precision for η>2**
- Barrel MS systems are at greater radius,
  - e.g. ATLAS barrel MS loses precision for η>1.3
- ATLAS adds endcap toroids to extend η coverage

Endcap Toroids

- ATLAS classical spectrometer: measure deflection rather than sagitta
  - measured from upstream to downstream of magnet
- exploit full bending power (B.dl) of magnet
  - long lever arm => more precise than sagitta measurement
  - cover to η = 2.7

  - **Note**: there is also a deflection contribution to the precision of combined CMS muons

Momentum measurement (3)

Coulomb scattering

- material thickness in MS ranges from O(1X_0) (ATLAS air core) to O(100X_0) (CMS flux return)
- most muons have momentum resolution limited by multiple Coulomb scattering

rms scattering angle $\sigma_\theta = 0.0136/(\beta cp) \times \sqrt{(l/X_0)}$ GeV^{-1}

- the momentum dependency cancels to give a lower limit to the relative sagitta precision
- i.e. **scattering adds a constant term to the p_T resolution**
- The magnitude of this term scales as $\sqrt{(\delta r/X_0)}$ / (B.dl)

MS: constant scattering term ~2% for ATLAS, ~8% for CMS

Conceptual design: >20 years ago

- Hadron colliders
  - **CERN-SPS** collider
    - 0.3 TeV per beam, low luminosity
  - **Fermilab Tevatron** under construction
    - up to 1 TeV per beam
  - **SSC 'super-collider'** planned and approved
    - 20 TeV per beam
  - Discovery potential remains for lower energy machines up to their energy reach
    - provided they deliver much higher integrated luminosity (compensate worse signal to background)
    - **idea to build LHC in LEP tunnel delivering very high luminosity at 7 TeV per beam**

Analogy with today:
Running collider + Imminent competition

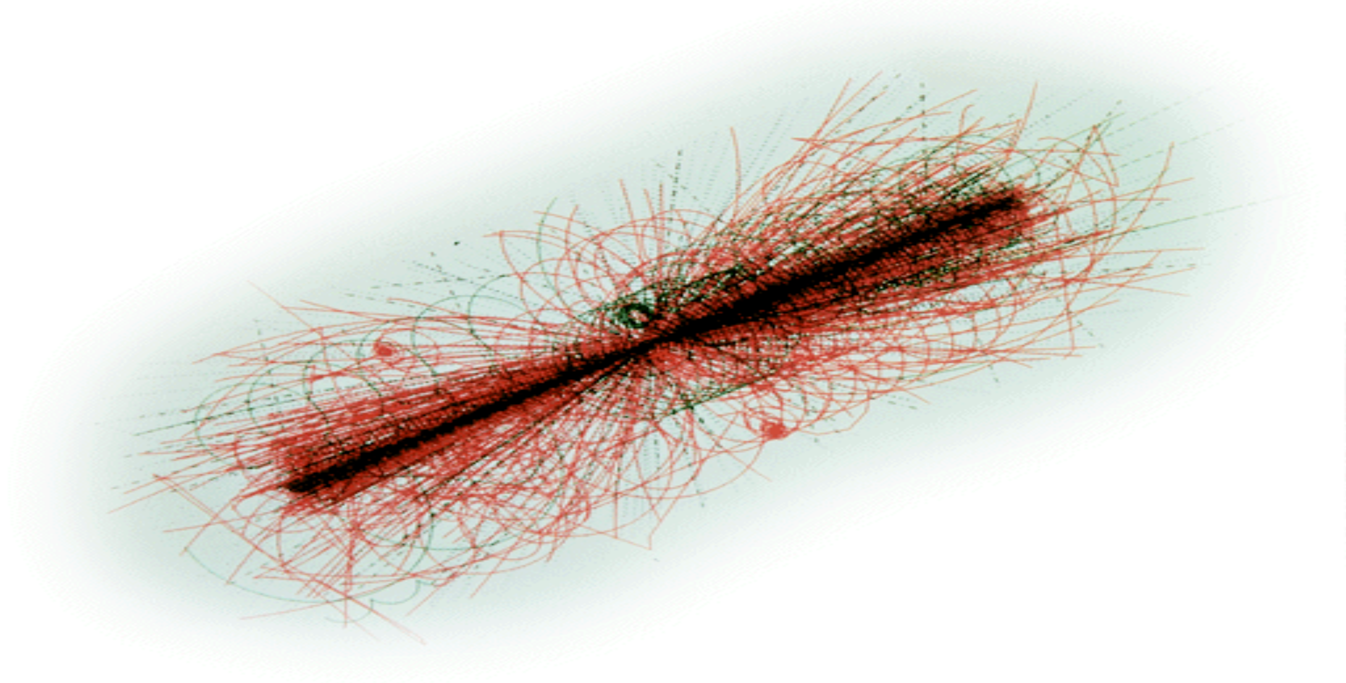
SPS collider experiments finished end-1990 (no longer competitive)
SSC canceled 1993

LHC lived on with **high luminosity design**, but **without the construction urgency**
Tevatron still running

- Major experiments at SPS
  - **UA2** specific detector capable of electron, photon and jet physics => sufficient to 'see' W/Z
  - **UA1** 'general purpose' => adding track charge/momentum measurement plus electron **and** muon lepton capability
  - W/Z discovery from high pt leptons (by UA1 as >double rate)

Lesson: provide equal opportunities for LHC experiments

Event pileup at high luminosity



- O(100) superimposed events per bunch crossing
- inner detector required to handle up to 10^4 tracks from 10^2 vertices
- idea of UA2-style specialist muon experiment:
  - ‘iron ball’ **surrounded by muon spectrometer**

ATLAS and CMS

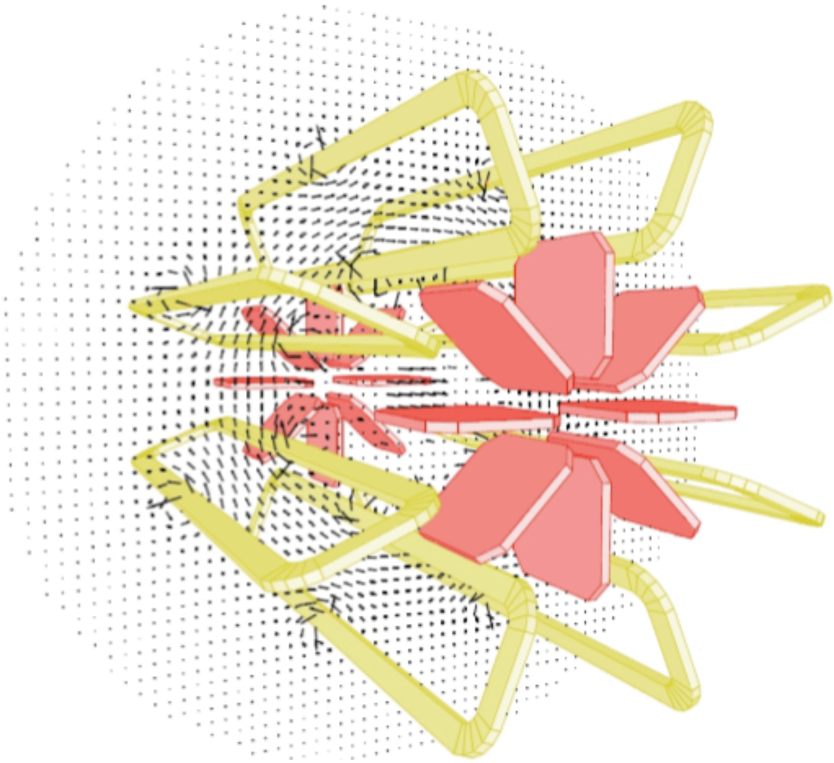
- Electron and muon capability quadruples Higgs->ℓℓℓℓ rate wrt single lepton specialist
  - the major LHC experiments focus on providing as complete as possible lepton performance

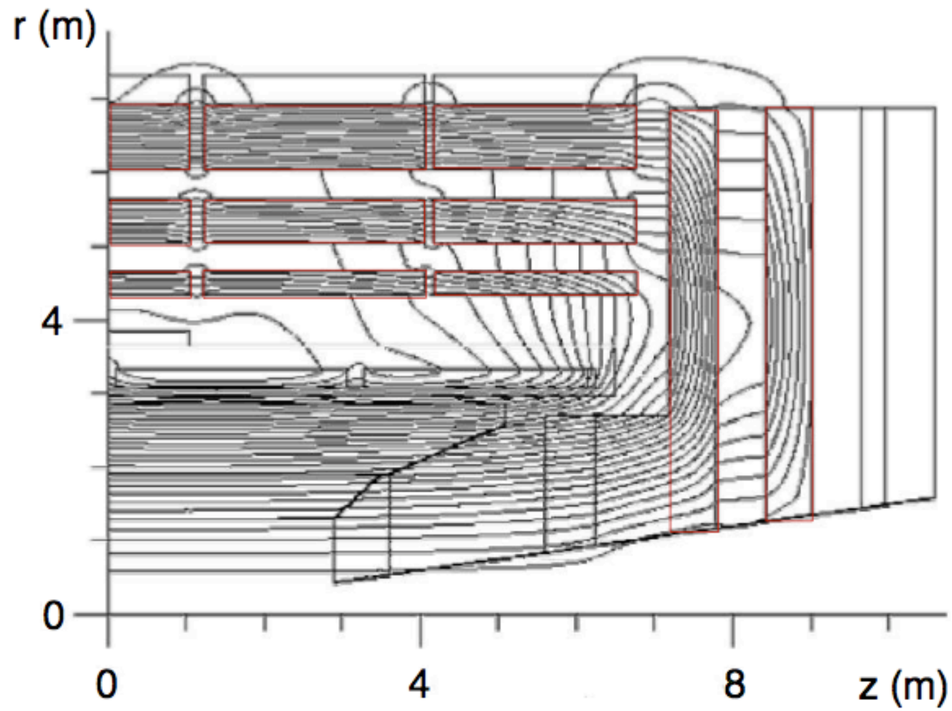
- ATLAS combination of:
  - External Muon Spectrometer concept from 'iron ball'
  - UA2 upgrade ideas for compact electron detection at high luminosity:
    - **Calorimeter radius chosen at minimum** giving sufficient granularity to handle high luminosity
    - because cost scales as $radius^3$

- CMS
  - Idea for a **large high-field solenoid** UA1-style general purpose experiment arose in mid-1980's
    - original magnet proposal very close to final design
  - Relatively compact by comparison to ATLAS

- External dimensions of both experiments driven by **muon system** (in particular the **magnets**)

Muon system magnets





◆ **ATLAS air core toroids**

=>large external dimensions

Advantages:

- ◆ air core (low material) => standalone precision
- ◆ acceptance out to high rapidity (endcaps)
- ◆ large measuring station separation isolates from accompanying e/m showers

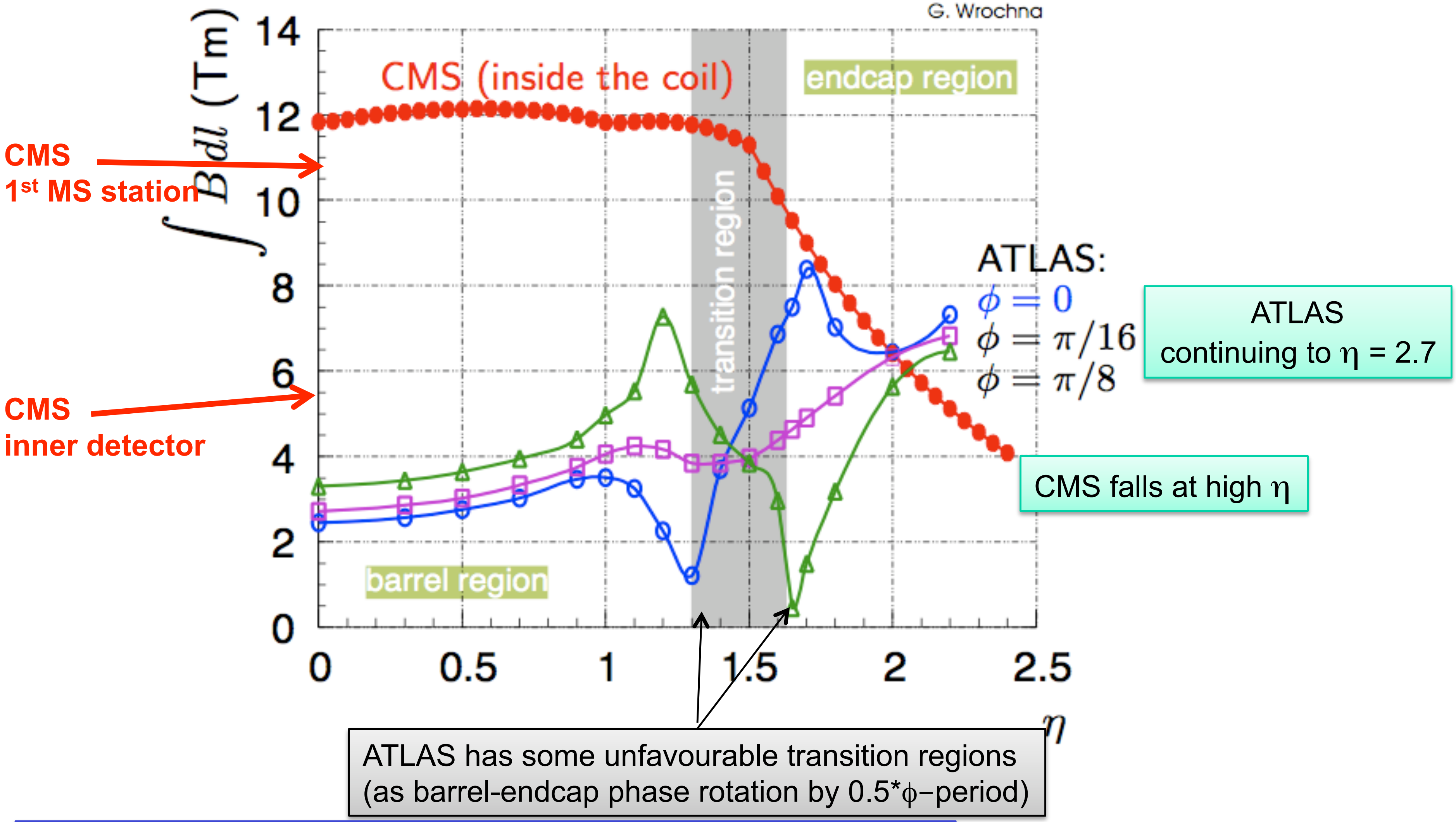
◆ **CMS instrumented iron return yoke**

=> compact dimensions

Advantages:

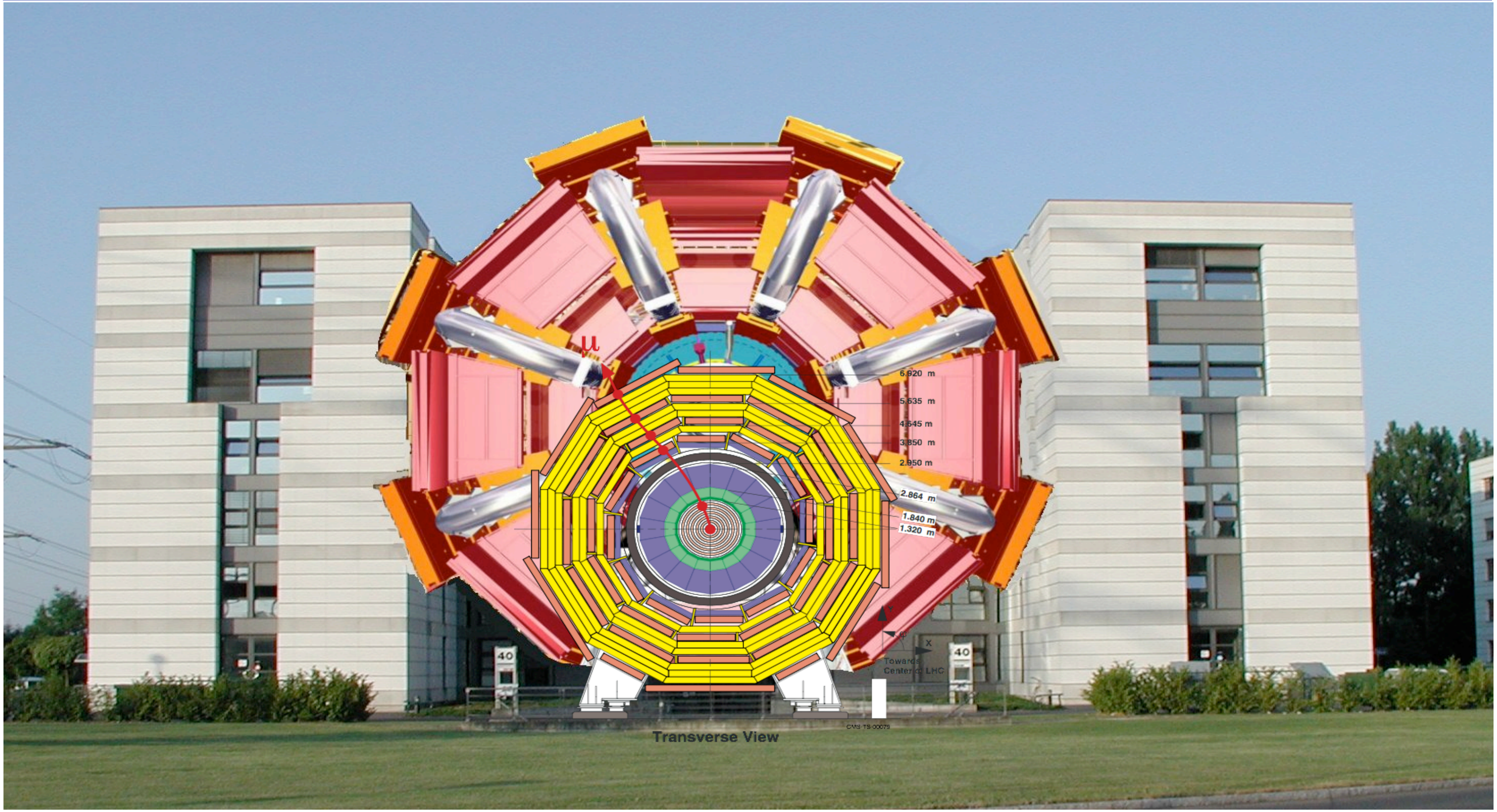
- ◆ compact design
- ◆ interleaved iron:
  - ◆ reduces neutron-induced cavern background
  - ◆ isolates stations from accompanying e/m showers

Bending power comparison



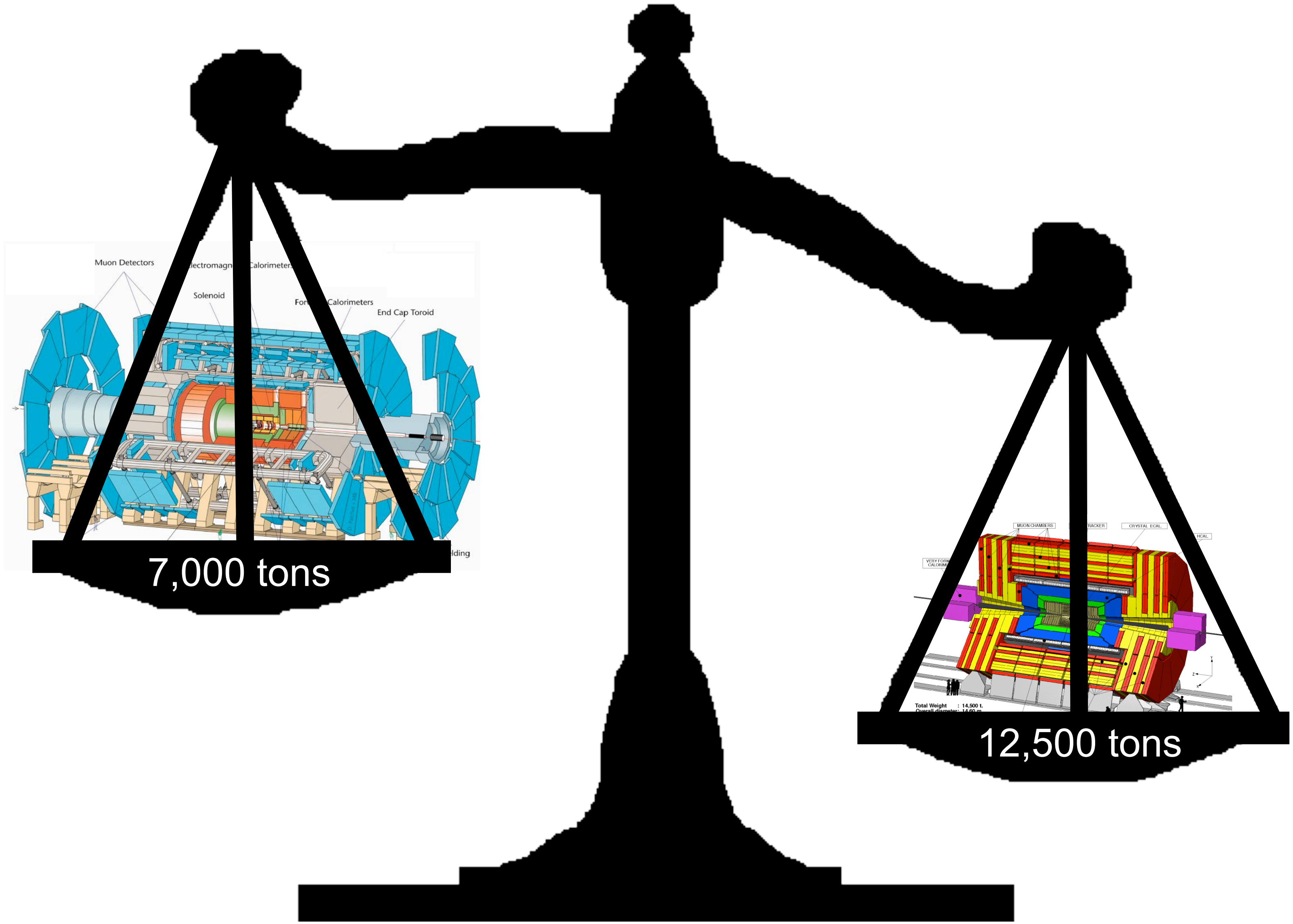
Combined MS + ID: significant increase in momentum precision
ATLAS adds independent 2T.m measurement
CMS approximate doubling of bending power

CMS: “C” stands for “Compact”

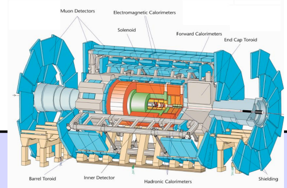


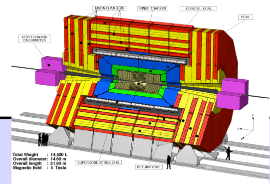
ATLAS is **2 times longer** and has **1.5 times the diameter** of CMS …

… but ATLAS has the ‘air core’



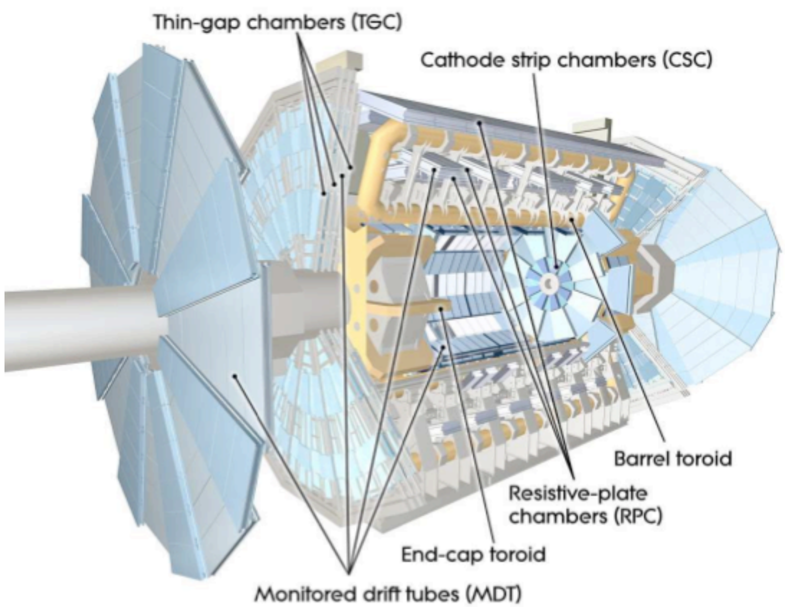
Summary of magnet concepts

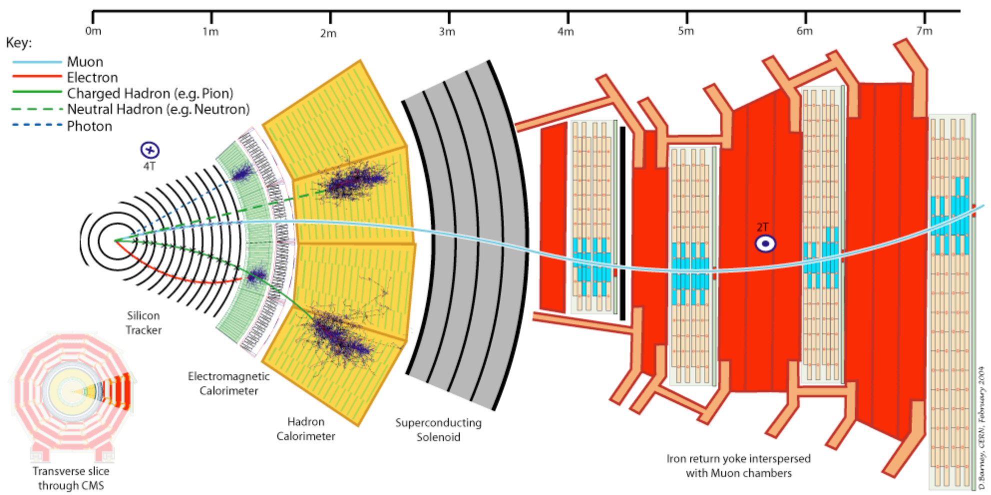




Concept	Focus on stand-alone muon reconstruction	Focus on high Bdl in the inner detector and overall compactness
Magnet system	2T solenoid placed inside e/m calorimeter flux return through hadron calo ID 2.2T.m Barrel toroid: ~3T.m InnerMiddleOuter stations Endcap toroids: ~7T.m line segments before/after	4T solenoid placed outside hadron calorimeter ID 5.6T.m Return yoke forms part of muon system MS standalone ~6T.m MS+ID combined ~12T.m
Muon system	3 stations RPC + TGC: triggers + 2nd coordinate MDT: precision measurements CSC: precision + 2nd coordinate	4 stations DT + CSC + RPC: triggers DT + CSC: precision + 2nd coordinate

MS stations (overview)





ATLAS

Barrel: 3 MDT multilayer stations
3 RPC layers for trigger

Endcap: 4 multilayer stations .
MDT multilayer wheels
CSC wheel at low radius
3 TGC wheels for trigger
Pseudorapidity coverage: $|\eta| \leq 2.7$
Optical station alignment to ~50μm

Both

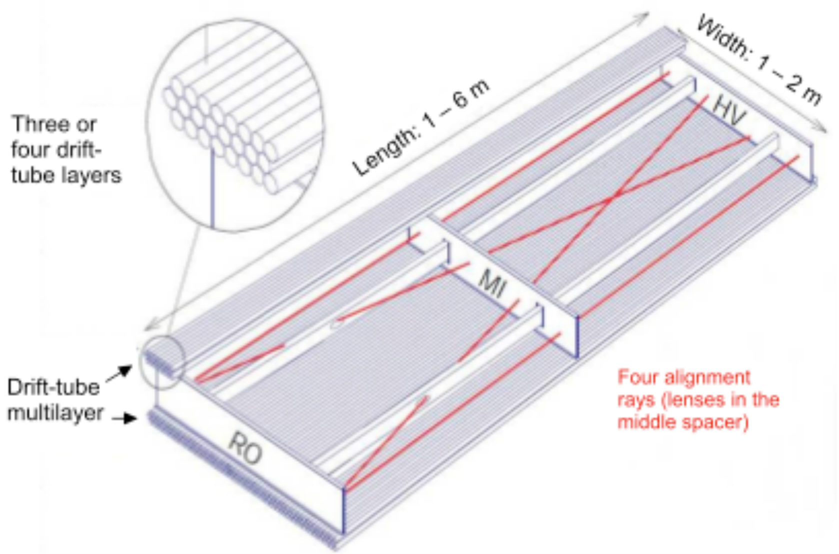
>20 precision hits O(100μm)
O(10mm) precision for 2nd coordinate

CMS

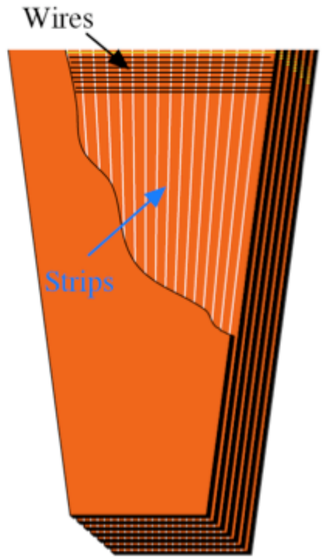
Barrel: 4 DT+RPC multilayer stations

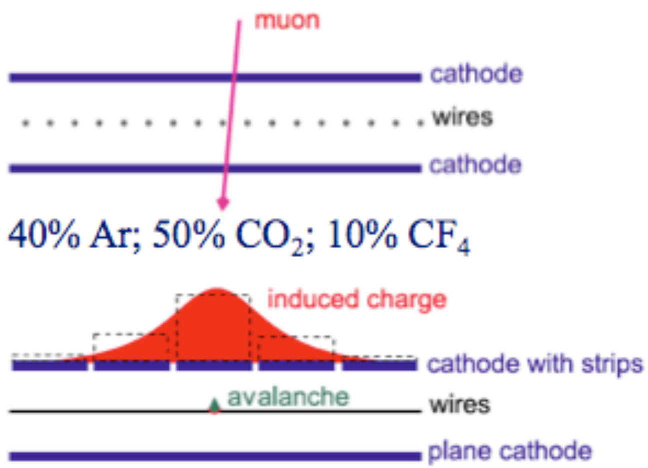
Endcap: 4 upper DT+RPC stations
4 lower DT+CSC stations
Pseudorapidity coverage: $|\eta| \leq 2.4$
Laser ID-MS alignment to ~200μm

Precision MS measurement technology



- ideal detector would be all solid state
  - silicon strip detectors
  - fast and precise
  - but we can only afford few × m^2
    - **reserve for ID**
- MS needs O(1000m^2) precision detectors
- **Drift tubes** are relatively cheap
  - offer ~100μm resolution
  - slow: ~1μs (40 bunch Xing)

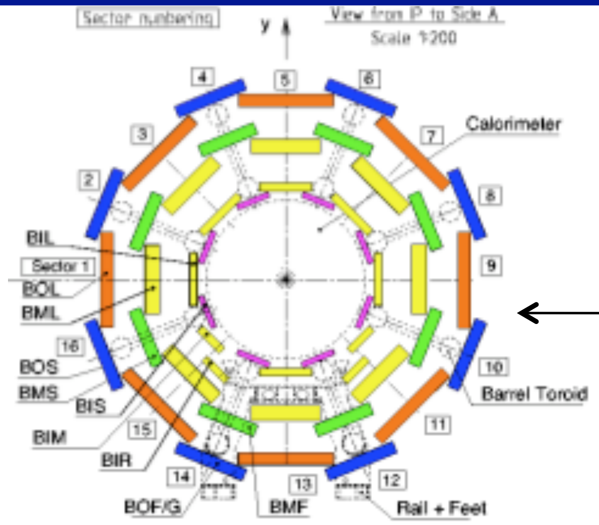




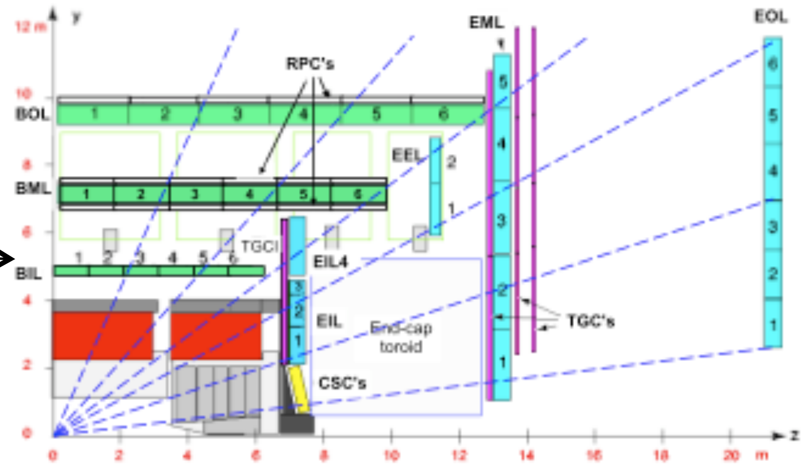
Cathode Strip Chambers

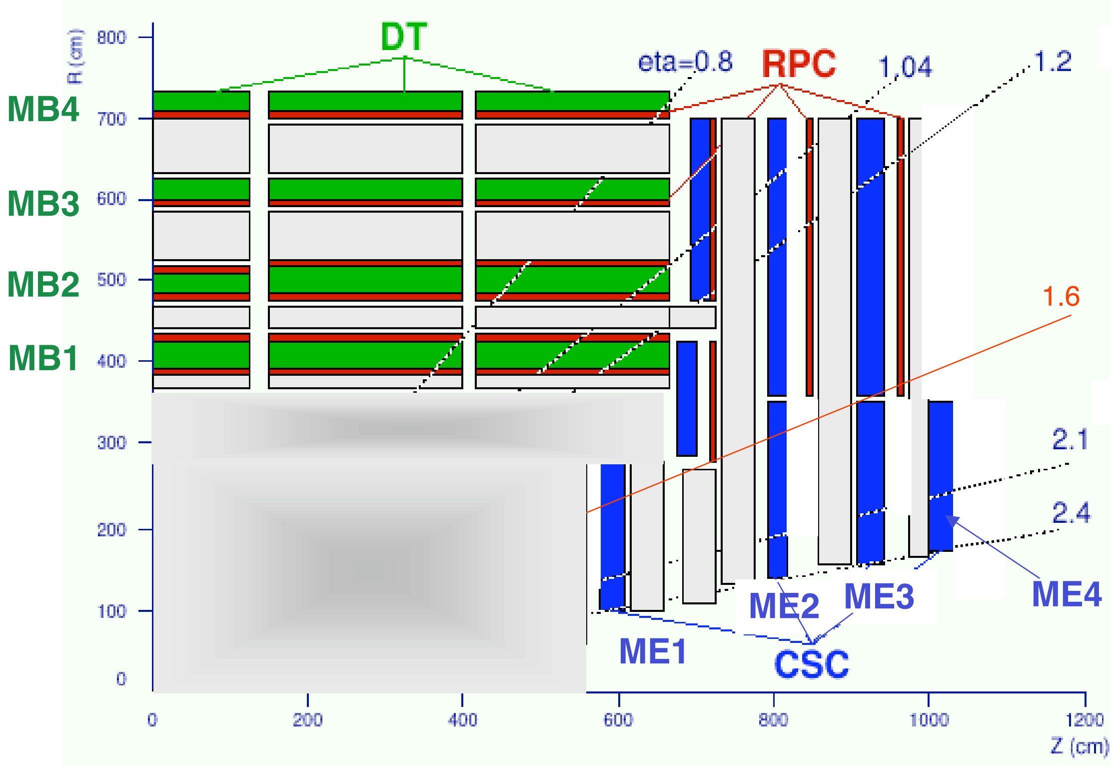
- more expensive than drift tubes
- measure charge weighted centroid
- precise ~ 70μm
- fast (resolve Xing)
- **use in high occupancy endcap zones**

Section through muon systems



ATLAS
Barrel + Endcap sections

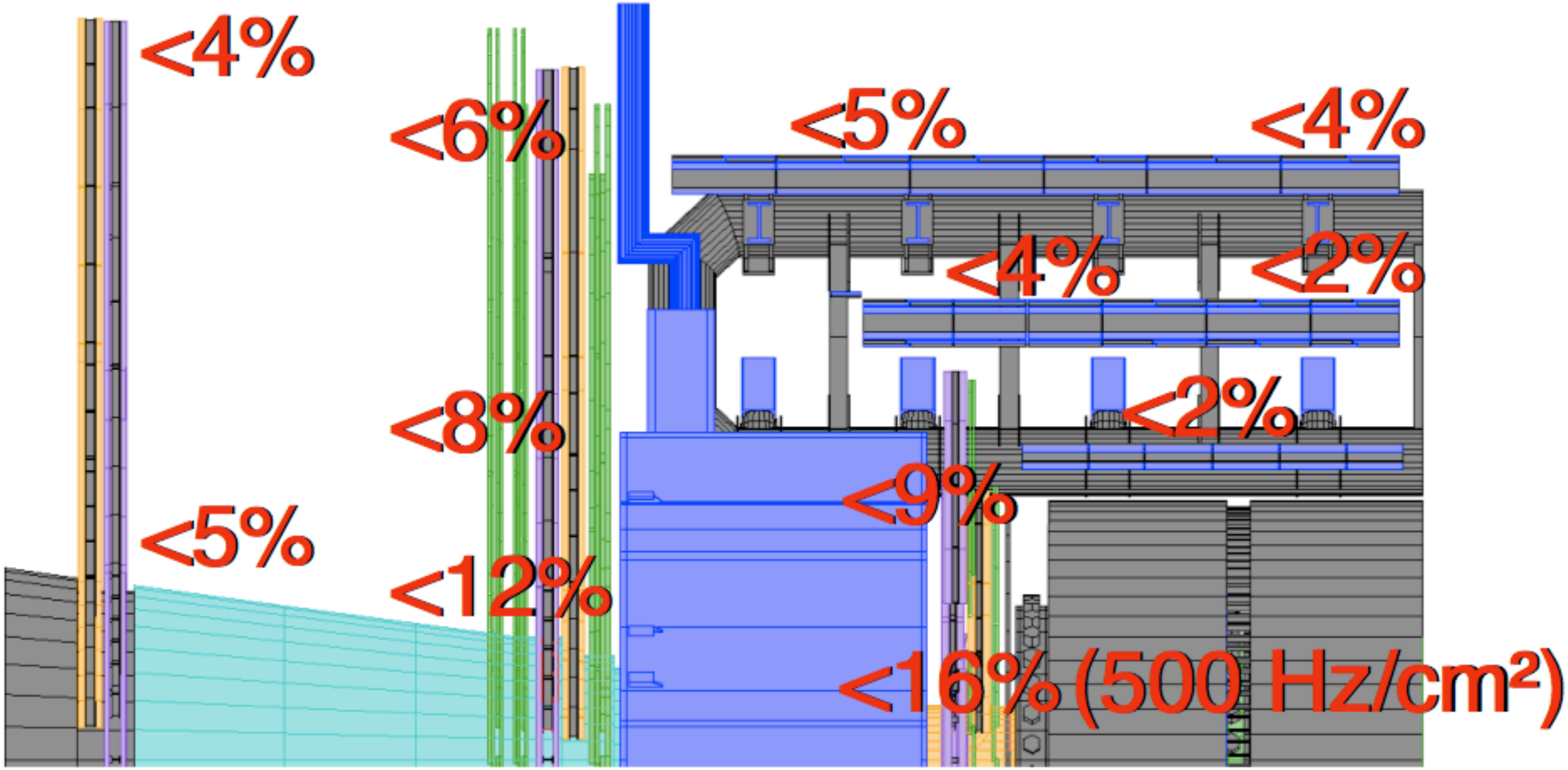




CMS
vertical section

Cavern background => high drift tube occupancies

Occupancies at $L = 10^{34}$ cm^{-2} s^{-1} in MDT chambers



ATLAS cavern background (~10×CMS)

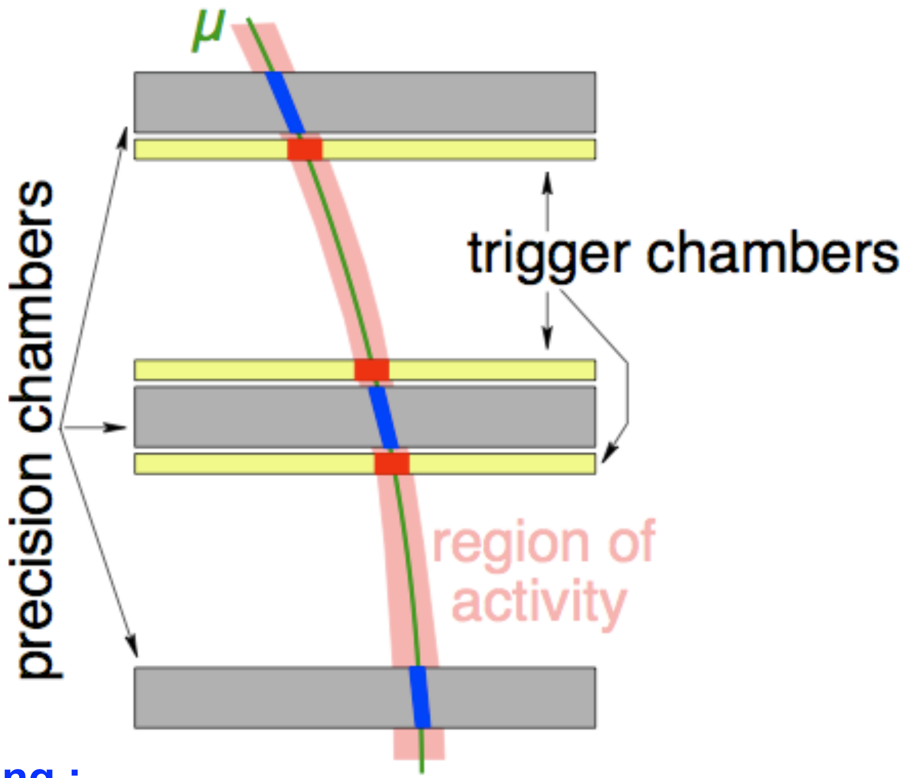
very low energy neutron/photon 'soup' induces high 'noise' rate

- pessimistic estimate (×5 'safety factor')
- Drift tubes most sensitive technology as large area with relatively long integration time
- MDT stations multi-layered (contain 6 or 8 detector layers)
    - offers robustness against accidental association of noise hits

Standalone reconstruction procedure

Both experiments apply the same strategy

- Define regions of activity from the **trigger chamber hits**
- Reconstruct **segments** in the appropriate multi-layer measurement stations
- Combine segments to form **tracks**
- Perform a **track fit** to the measurements to get precise track parameters



Straight-line multi-layer segment finding :

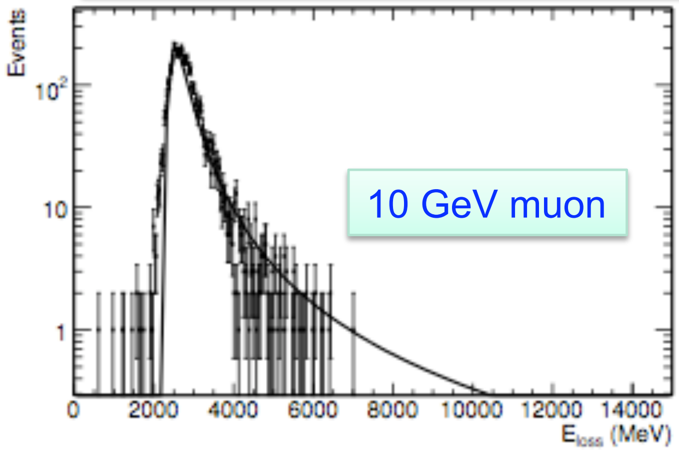
- simple pattern recognition
- resolves drift-sign ambiguity
- robust against high noise rate

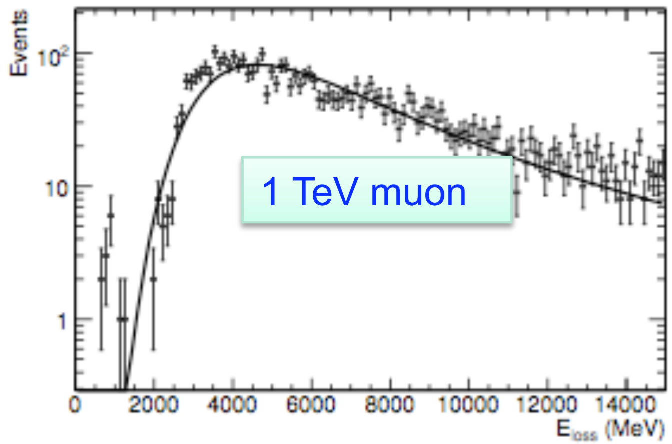
Correction for energy loss preceding MS

- ◆Energy deposition in upstream material follows a Landau distribution
- ◆Well approximated by Gaussian at low momenta
- ◆But long Landau tail at high momentum

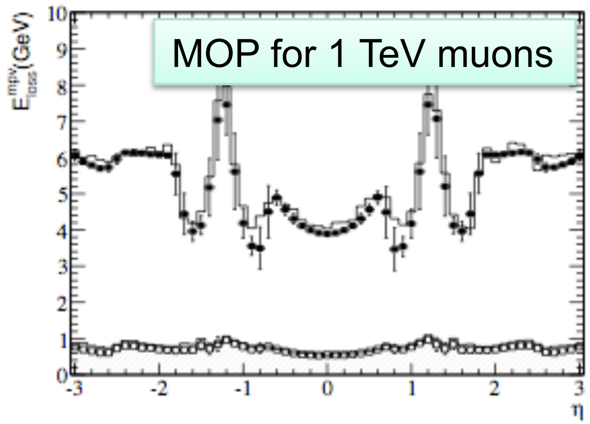
Upstream energy loss in ATLAS central barrel

i.e. where there's least material !





- Parametrize mean and most probable (MOP) energy loss fn(p_T,η)
- Also parametrize the rms width for use in track fitting
- Correct muon parameters at IP using truncated mean (between MOP and mean) and rms about this mean



Total before MS

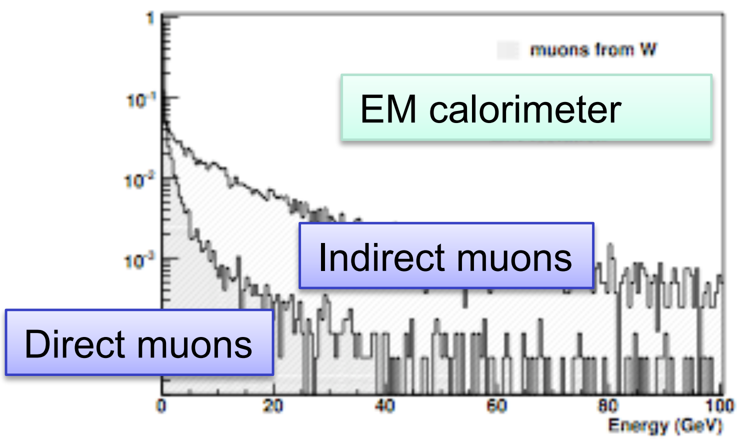
Total before hadron calorimeter

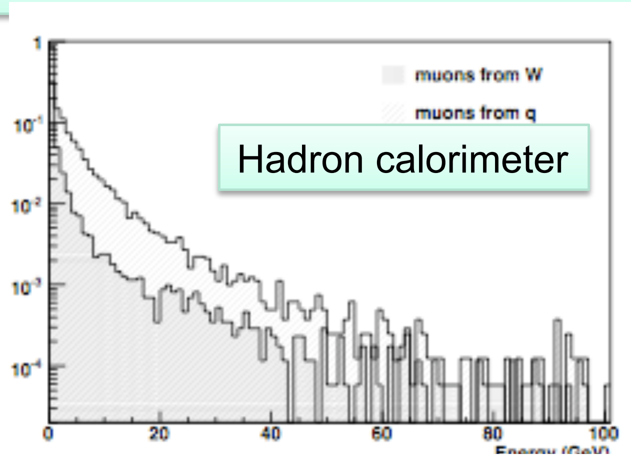
ATLAS apply a hybrid method

More precise at high momentum + suppresses tails (giving underestimated momentum)

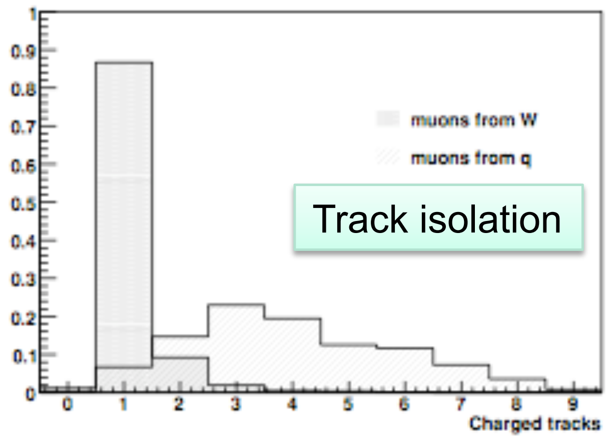
- Use measured energy from calorimeter for isolated muons **if measured to be in Landau tail**
- Otherwise **isolated muons** use a narrow MOP parametrization
- **Non-isolated and low p_T muons** use the previously described truncated mean parametrization

Calorimeter and track isolation





- Calorimeter isolation determined by the measured energy in a cone around the cells directly intersected by the muon
- Track isolation determined by the number of tracks in a cone around the muon direction extrapolated to the IP

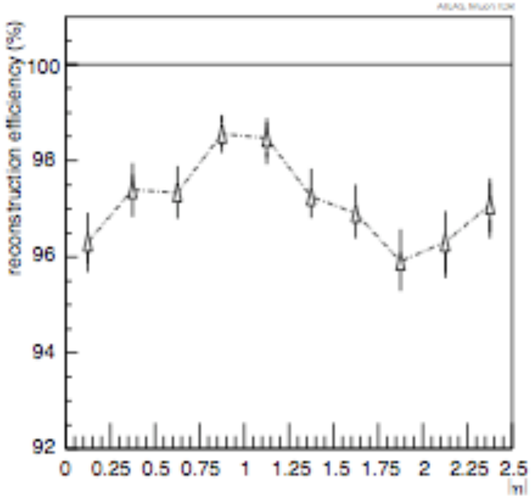


Standalone muon performance

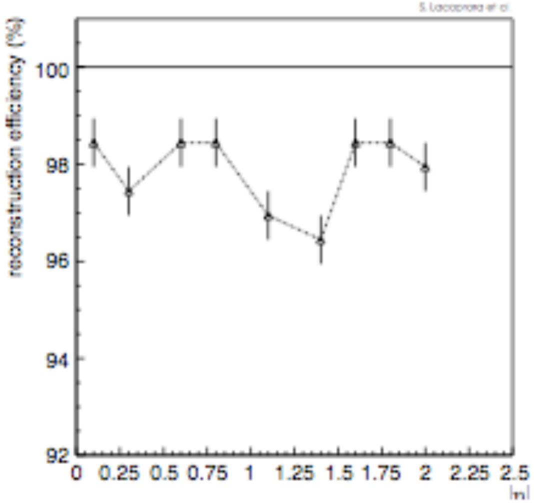
Track finding efficiency

- high efficiency ~96% for both experiments
  - losses due to service channels and support structures
  - additional losses near p_T threshold
- ATLAS:
  - small dead region at $|\eta| = 0$
  - some missing detectors during 1st year
  - =>additional efficiency loss for $|\eta|$~1.4

ATLAS



CMS

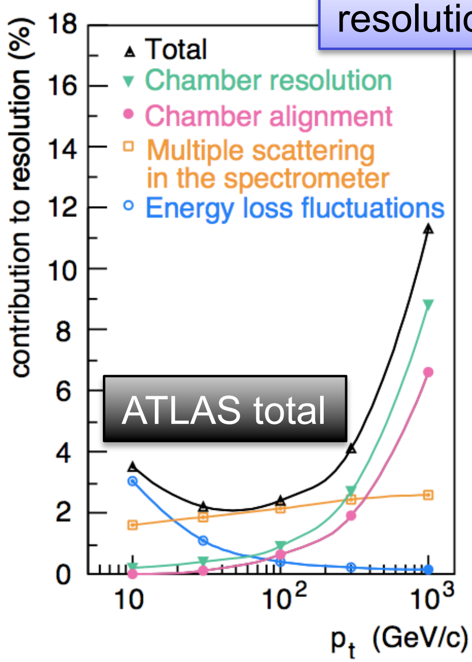


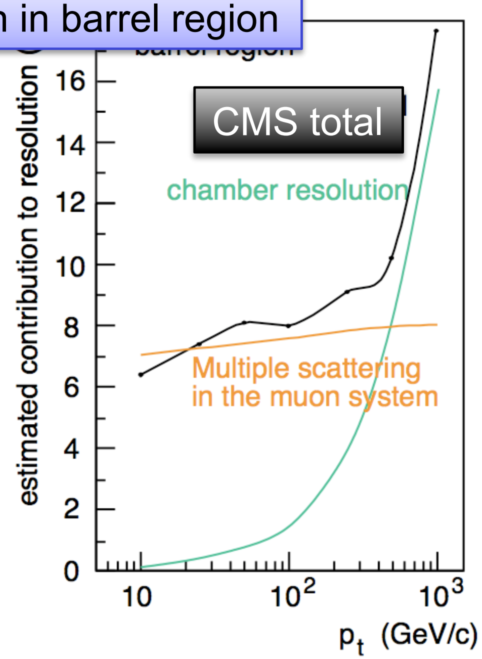
Momentum resolution

- Coulomb scattering dominates p_T < 200 GeV
- contribution from fluctuations in energy deposition in calorimeter at low p_T
- ATLAS: high standalone precision
  - 2-3 × more precise in barrel
  - precise endcap momentum up to $|\eta|$ = 2.7
- High precision:

means more care needed for energy loss treatment

resolution in barrel region





Search for low-beta particles

If they exist, split-SUSY predicted R-hadrons will penetrate to MS

characteristics

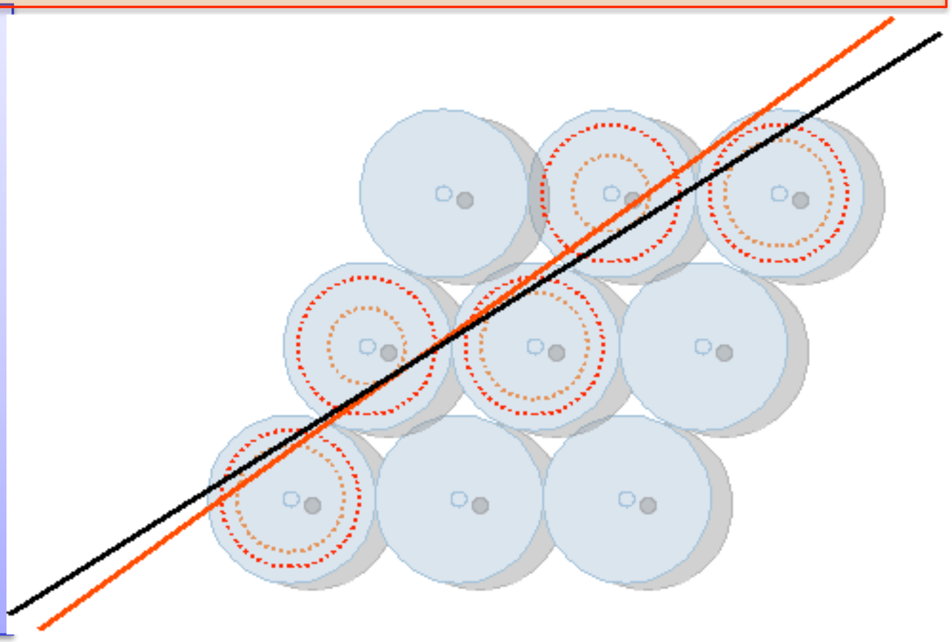
- Massive particles which strongly interact in calorimeter with dominant momentum transfer to another R-hadron (leading particle by kinematics and conservation law)
- expect significant calo energy loss which can be measured although no accurate predictions
- production track may be neutral or even of opposite charge

signature

- High momentum charged tracks in muon system with mass ~ momentum (i.e. slow)
- anomalous dE/dX in calorimeter

reconstruction (in ATLAS)

- Muons in MS have 15 to 60 ns delay wrt IP
- Slow particles have MDT offsets ~ few mm
- Standard reconstruction inefficient for $\beta<0.9$
- **Special algorithm** to find and associate segments using increased delay hypothesis
- **Special track fit** measures β (thus mass)
- Long path length in (and to) ATLAS MS gives an advantage for slow particle searches !



Track matching to inner detector

- the standalone MS track is extrapolated to represent the track at the IP (at the same origin as ID tracks)
- combined muons (paired ID-MS tracks) are identified using their match χ^2
  - by definition the difference between outer and inner measured track vectors (T) weighted by their summed covariance matrix (C)
- the 5 matched track-parameters give a χ^2 distribution for 5 degrees of freedom

Match χ^2

$$\chi^2_{match} = (T_{MS} - T_{ID})^T (C_{ID} + C_{MS} + C_{alignment})^{-1} (T_{MS} - T_{ID})$$

- an additional contribution is added to C to represent ID-MS misalignment
  - necessary to avoid losing high momentum matches - at least at start-up

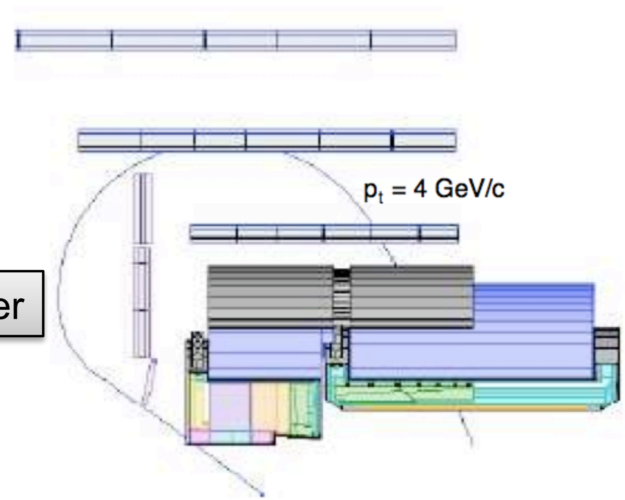
Fake rejection

- match χ^2 is a powerful discriminant against fakes
  - in principle 99.9% have $\chi^2 < 20$, but non-Gaussian behaviour leads to a ~5% tail beyond this cut-off
  - **at low momentum a good momentum match is crucial**
    - the other MS track parameter errors are large because of Coulomb scattering in the calorimeter
    - there is generally a high multiplicity of ID candidates which can give rise to ambiguities (e.g. jets)
- **incorrect (and ambiguous) matches are rare at high momentum**
  - well measured parameters from both systems
  - high momentum muons are generally isolated

Muon reconstruction seeded from inner detector

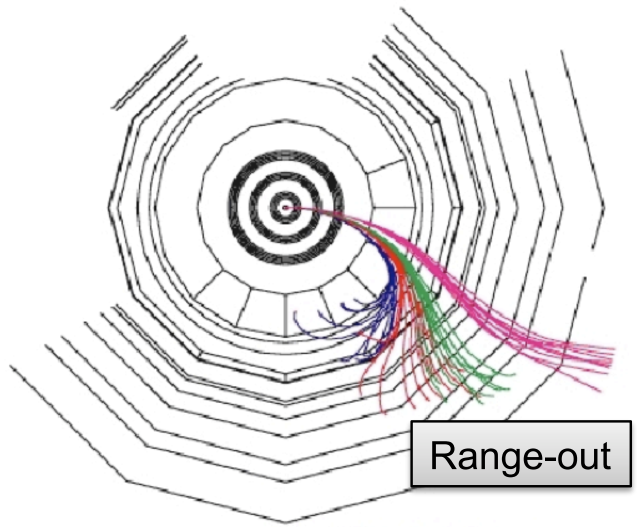
Soft muons

ATLAS



looper

CMS



p_t = 3.5, 4.0, 4.5, 6.0 GeV

- soft muons lose a significant fraction of their momentum in the calorimeters leading to high MS curvature
- back extrapolation is not very precise because of the large Coulomb scattering

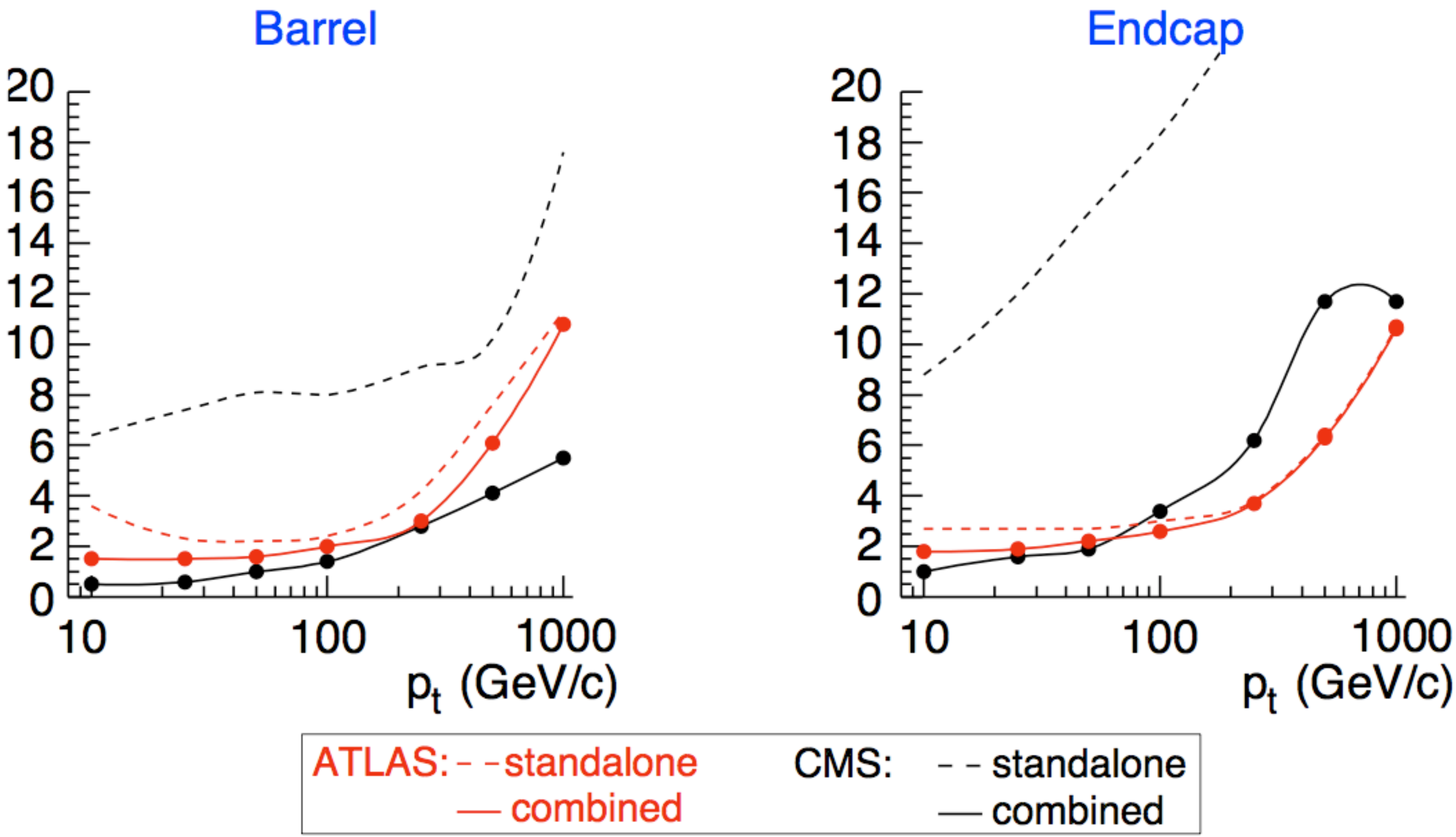
ID extension algorithm

- an efficient algorithm is to perform tracking from inside outwards
  - extrapolate into the sparsely populated MS to match segment-by-segment
- in general this approach yields the same muons with the same quality as the previous standalone method
- complements at higher momenta as increases the combined track finding efficiency, especially:
  - in less well-instrumented parts of the MS (e.g. regions with cracks for support structures)
  - in case of chamber inefficiency
  - high energy tracks showering in one or more muon stations
- the main disadvantage is the combinatorial increase in processing (from the ID multiplicity)

Combined momentum resolution

track fit to combined measurements gives the highest (final) precision

Both experiments fulfill the precision requirements for LHC physics



Tagged muons

Tagged muons are ID tracks that are muon candidates

- There remain a few % of signal muons without a good quality match and track fit
- These can be recovered by extrapolation from the ID to achieve the desired ~100% muon efficiency
- Typically these muons are in the tail of the Coulomb scattering and Landau energy loss distributions
- The parameters are correctly described by the ID
  - albeit with some loss of precision since there is no combined fit
- However there is inevitably a background from decay-in-flight polluting these tagged muons

Tag from calorimeter signal and unallocated MS segments

- tagging can be performed from a muon-like calorimeter signal
  - narrow and minimum ionizing through to the outer compartments
  - of particular relevance to the crack at η~0 in ATLAS
- the muon-ness is considerably strengthened when there are 'free' MS segments in the extrapolation window

Muon selection for analysis (ATLAS-style)

- End users just want to get the muons

- Merged muon collection
  - Merger of muons reconstructed by the different algorithms
  - Overlap removal to avoid double counting
  - Parameters etc taken from the highest quality track fit (or inner detector for tagged muons)

- ATLAS in the process of defining Loose, Medium and Tight standard selections
  - **Loose** maximizes efficiency without fake 'runaway' (nevertheless efficiency close to 100% for **|η|**< 2.7)
    - includes calo tagged muons to cover crack at **|η|**~0
    - track parameters may correspond to the inner detector track
  - **Tight** minimizes fake and background muons
    - provides high quality precise muons from combined fits (core of parameter resolution, ε >90%)
  - **Medium** sensible trade-off between the above
    - suitable for most analyses

- Physics analyses are expected to use the standard selections
  - with additional isolation etc cuts according to use-case
  - ask for more details in tutorial !

First year

Performance determination with pp collision data

- Determination of reconstruction efficiencies
  - One needs to know that there was a muon within an event and check whether it was reconstructed
- Determination of trigger efficiencies
  - Measure how often a well reconstructed muon fired the muon trigger
  - Important: The event must be triggered by something else than the muon under investigation to avoid a bias in the measured efficiency.
- Determination of the momentum scale and momentum resolution
  - Deduced from the peak position and width of known dimuon resonances.
- Measurement of fake rates
  - Difficult because one must know that there was no muon in the event although there was one reconstructed.

All the above as fn (p_T, η, ϕ)

First year

Performance measurements

- Have independent ID and MS detector systems each with standalone reconstruction
  - Match and compare tracks for efficiency measurement
  - Compare parameters for resolutions

- Dimuon resonances: $J/\psi \rightarrow \mu^+ \mu^-$, $\Upsilon \rightarrow \mu^+ \mu^-$, $Z \rightarrow \mu^+ \mu^-$
  - Check mean and width of mass peak consistent with simulation results

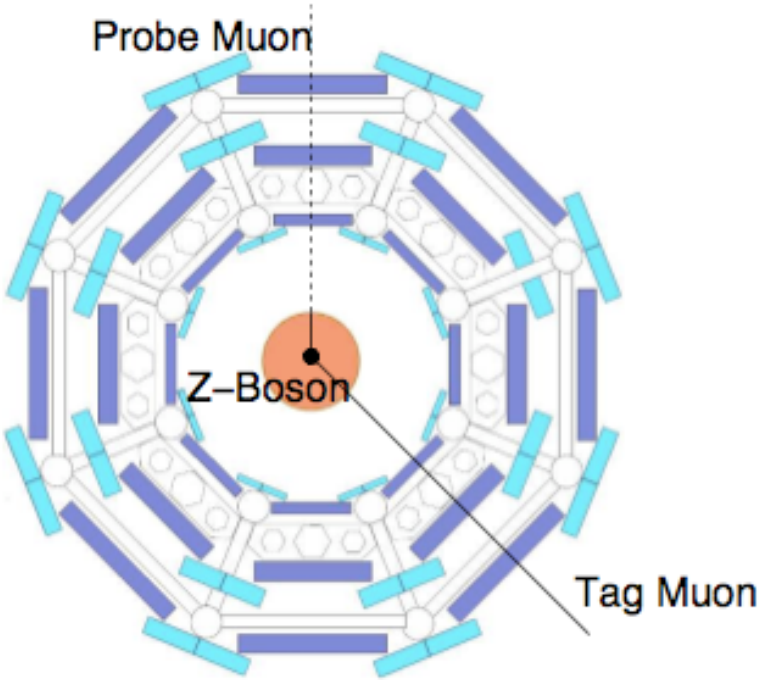
tag and probe method

example using $Z \rightarrow \mu^+ \mu^-$

- *Tag muon*
  - Event selected and/or triggered by tag muon
  - Isolated combined muon with $p_T > 20$GeV
- *Probe muon*
  - Inner detector track
  - Mass selection: m(tag, probe) ≈ m_Z

Measure how often the probe muon:

- **is reconstructed in the muon spectrometer**
- **passes the muon trigger**



First year

Performance determination with pp collision data

- Fake discrimination
  - $K^0 \rightarrow \pi^+\pi^-$ ('V-zero') decays in the ID
  - a prolific source of identified pions for misidentification studies

cosmics

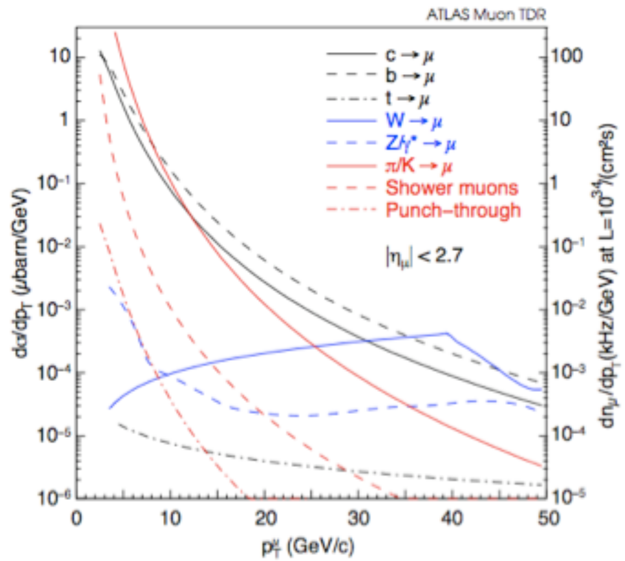
Of course we already have ~1 year of data with the fully installed detectors
e.g. efficiencies from 'up/down' tag and probe

Details in trigger, alignment and tutorial sessions

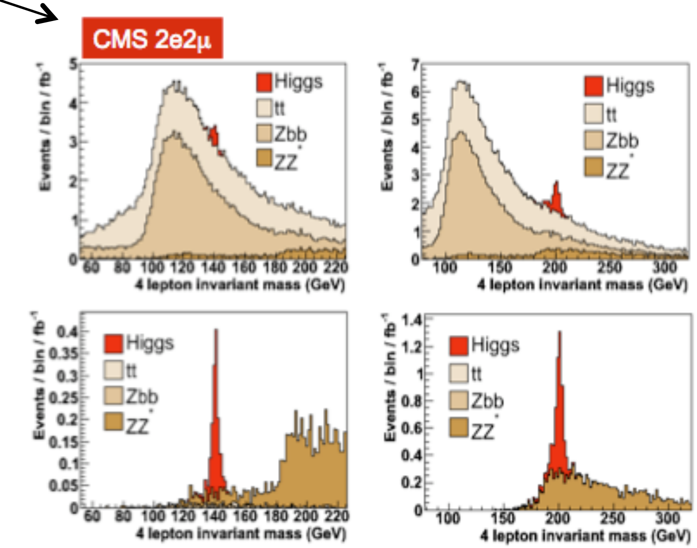
First year

Performance determination with pp collision data

- Inclusive muon cross-sections
  - Slide 7: inclusive cross-section predicted at 14 TeV
  - We will measure this at 8 to 10 TeV
    - With the prompt, indirect and direct contributions



- $H \rightarrow \mu\mu\ell\ell$ 10fb^{-1} at 14 TeV needed for clear discovery
  - The aggressive cuts applied in the CMS analysis indicate that an impressive background reduction is feasible
  - With limited data we should at least compare the performance of physics analysis cuts between data and Monte-Carlo
  - The backgrounds under the Higgs need to be understood as a prerequisite to any discovery



- Exclusion of 160 < m_H < 170 GeV
  - WW -> $\ell\ell$ with 200pb^{-1} at ~10 TeV

Concluding remarks

- Compared and overviewed the conceptually different layouts of ATLAS and CMS
  - Rather similar and fully adequate performance from the muon viewpoint
- Hardware ready and waiting for more exciting muon data than cosmic triggers
- Software robustness already tested
  - massive MonteCarlo productions
  - real-time cosmic data
- First data will be used for
  - MS alignment and calibration
  - Determining muon identification efficiency and momentum resolution
  - Understanding muon backgrounds
  - Inclusive SM muon cross-sections
- Muons prepared (and hoping) for an unexpectedly-early discovery at LHC !