# Concepts for Experiments at Future Colliders I

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Happy new year to all of you!

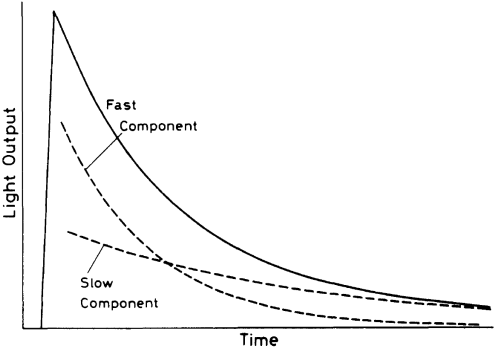
# Recapitulation of the previous lecture

## Scintillation counters

- Scintillation counters are important detectors for the active part of a calorimeter.
- Materials which emit a small flash of light when hit by radiation are used in scintillation counters.
- Important properties of the signal of a scintillation counter:
  - Above a certain minimum energy deposition, the amount of scintillation light is proportional to the deposited energy (in good approximation).
  - Fast response, i.e. the light signal is created a short time after the energy deposition.

## Time evolution of the scintillation light

- Scintillators are luminescent materials.
- If the emission of light happens within 10 ns, the process is called fluorescence.
- If the emission of light is delayed, the process is called phosphorescence.




- The time evolution of the light emission can be approximated by the superposition of two exponential distributions:

$$N_\gamma = A\exp\left(-\frac{t}{\tau_f}\right) + B\exp\left(-\frac{t}{\tau_s}\right);$$

$\tau_f$ Time constant of fast component.

$\tau_s$ Time constant of the slow component.

## Requirements for scintillation counters

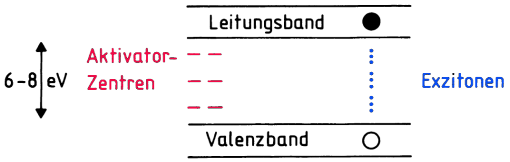
Good scintillation counters should have the following properties.

- High efficiency for the conversion of the deposited energy into scintillation light.
- The scintillator should be transparent for the scintillation light in order to allow for the transmission of the scintillation light.
- Emission of the scintillation light in a wavelength region for which efficient light detectors exist.
- Dominating fast component $\tau_f$.

## Anorganic scintillators

- Most of the anorganic scintillators are cristall of alkali halides mixed with small amounts of so-called activator impurities.
- Examples: NaI(Tl), CsI(Tl), $Bi_4Ge_3O_{12}$, $PbWO_4$.
- Many anorganic scintillators are hygroscopic, e.g. NaI, and have to be protected from humidity.
- CsI of BGO are examples of non- or weakly hygroscopic materials.

## Scintillation mechanism in anorganic scintillators



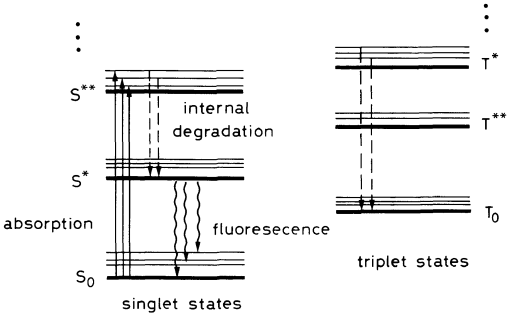

- Ionizing radiation can excite electrons into the conduction of exciton band.

- Light emitted in transition of electroncs from the conduction into the valence band is non-visible.
- Visible light is emitted in transitions from activator levels.
- Free holes of holes of excitons can ionize activator atoms. If an electron hit this atom, it can fill an excited activator state and return to the ground state by the emission of visible light.

## Organic scintillators

- Organic scintillators are aromatic hydrocarbons containing bound or condensated benzen ring structures.
- Organic scintillators have a small time constant in the ns range.
- The scintillation light is emitted in transitions of free valence electrons in $\pi$ orbitals of the molecules.

## Szintillation mechanism in organic scintillators




- Excitation of electron energy or vibrational level by ionizing radiation.
- Radiationless transition from a singlet excitation $S^{**}$ into $S^{*}$. within $<$10 ps.
- Large probability for a transition from $S^{**}$ into a lower vibrational level.

$\Rightarrow$ The scintillator is transparent for the emitted light because the vibrational level is above the ground state $S_0$.

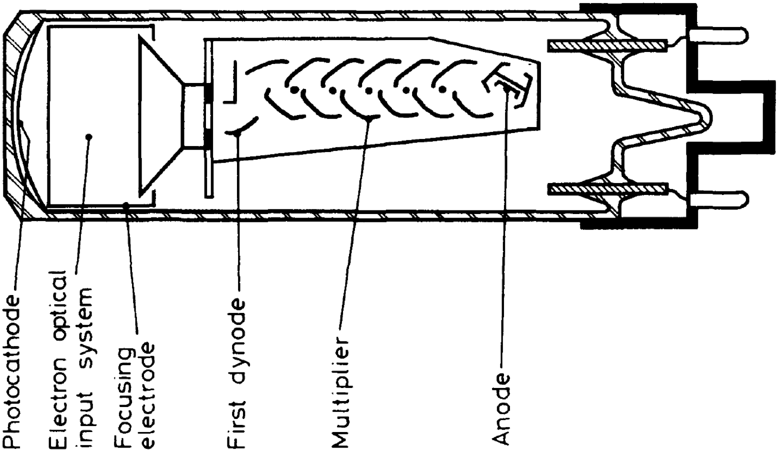
- Similar inner transitions from the excited triplet states.
- $T_0 \rightarrow S_0$ suppressed due to selection rules.
- $T_0 + T_0 \rightarrow S^* + S_0$+phonons, afterwards emission of scintillation light as described above.

## Plastic scintillators

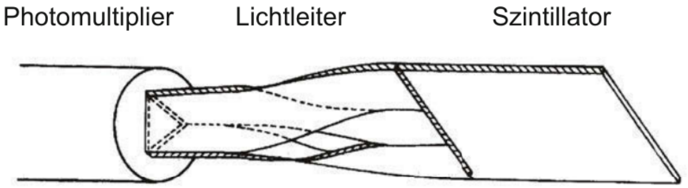
- Plastic scintillators are organic scintillators containe in a solid plastic.
- Frequently used plastics: polyvinyltoluene, polyphenylbenzene, polystyrene.
- Frequently used scintillators:
    - p-terphenyle ($C_{18}H_{14}$).
    - PDB ($C_{20}H_{14}N_2O$).
    - PPO ($C_{15}H_{11}NO$).

## Photomultipliers

- Photomultipliers are widely used for the detection of scintillation light.
- Yet they need a log of space and cannot be easily operated in large magnetic field. Hence several experiments used avalanche photodiodes or silicon photomultipliers. These two technologies will not be covered in the lecture due to lack of time.
- Schematic drawing of a photomultiplier.



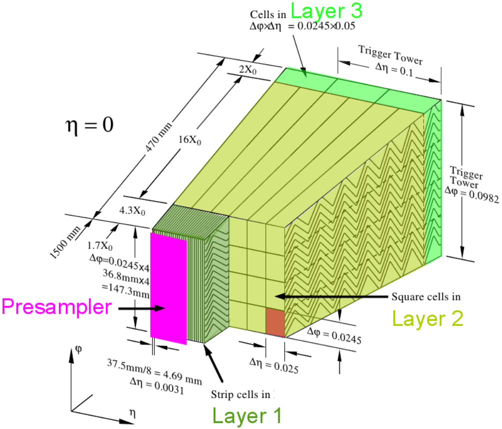
## Typical structure of a scintillation counter

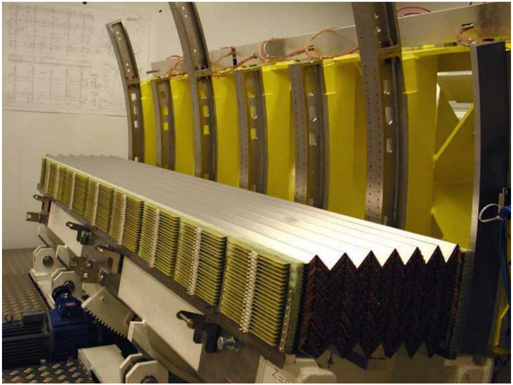



### Liquid argon as active medium

- Liquid argon is also used as active medium in calorimeters.
- Thanks to the large density of argon in liquid phase, many electrons are created by ionization radiation.
- In order to collect these electroncs, the liquid argon is contained between electrodes put under high voltage to collect the ionization charge.

## Electromagnetic calorimeter of the ATLAS experiment

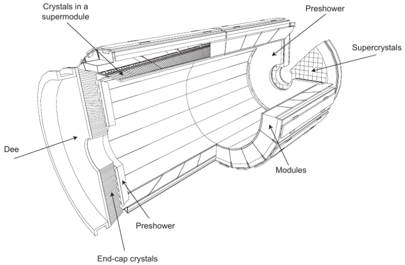


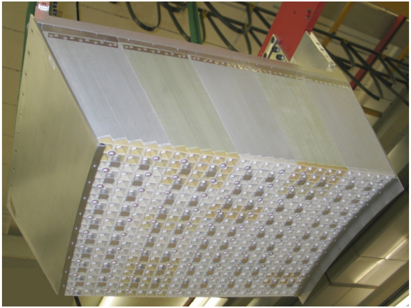



- Inhogeneous accordeon calorimeter with lead as passive material and liquid argon as active material.
- Accordeon structure to maximize the primary ionization path.
- Energy resolution:

$$\frac{\delta E}{E} = \frac{9\%}{\sqrt{E[\text{Gev}]}} \oplus 0,2\%$$

## Electromagnetic calorimeter of the CMS experiment



- Homogeneous $PbWO_4$ calorimeter.
- Detector material: scintillation $PbWO_4$ crystalls with high radiation hardness in order to maximize the energy resolution for photons:

$$\frac{\delta E}{E} = \frac{2,8\%}{\sqrt{E[\text{Gev}]}} \oplus \frac{120 \text{ MeV}}{E} \oplus 0,3\%$$

- Disadvantages:
  - No longitudinal segmentation $\Rightarrow$ poor angular resolution.
  - Small light yield requires read-out electronics with very high gain: avalanche photo diodes in the barrel, photomultipliers in the end caps.

# Recapitulation of the previous lecture

## Typical structure of hadron calorimeters

- Hadron calorimeters are sampling calorimeters.
- Choice of passive material with $\lambda_A$ not too different from $X_0$ to achieve a similar development of the hadronic and electromagnetic shower components.
- Good absorber: iron ($X_0$=1,8 cm, $\lambda_A$=17 cm).
- Alternative approach: compensating calorimeter.
  Choice of absorbers with high $Z$ (uranium, lead, wolfram) to suppress the signal yield for the electromagnetic component with respect to the hadronic component.

# Recapitulation of the previous lecture

## Calorimeter signals of electrons and hadrons

- Signal of a pion:

$$S(\pi) = (f_{em} \cdot \epsilon_{em} + f_h \cdot \epsilon_h) \cdot E,$$

  ($\epsilon$: detection efficiency).
- Signal of an electron:

$$S(e) = \epsilon_{em} \cdot E$$

- $\frac{e}{p}$ ratio:

$$\frac{S(e)}{S(\pi)} = \frac{\epsilon_{em} \cdot E}{(f_{em} \cdot \epsilon_{em} + f_h \cdot \epsilon_h) \cdot E} = \frac{\frac{\epsilon_{em}}{\epsilon_h}}{1 - f_{em}(1 - \frac{\epsilon_{em}}{\epsilon_h})},$$

  hence $\frac{S(e)}{S(\pi)}$=1, if $\epsilon_{em} = \epsilon_h$.
- Energy resolution:

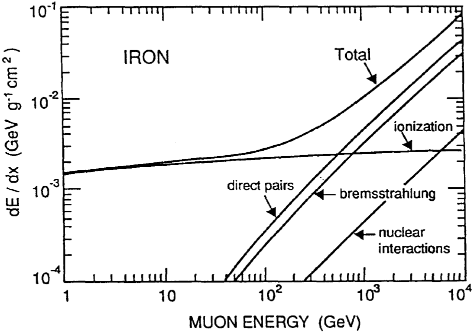
$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus b\left(\frac{\epsilon_{em}}{\epsilon_h}\right);$$

  $a \sim 50\%$, hence much larger than for electromagnetic calorimeters.
- The value of $\frac{\epsilon_{em}}{\epsilon_h}$ also influences the linearity of the calorimeter.

# Muon identification at hadron colliders

# Role of muons at hadron colliders

- Muons are the only charged primary collision products traversing the calorimeters.

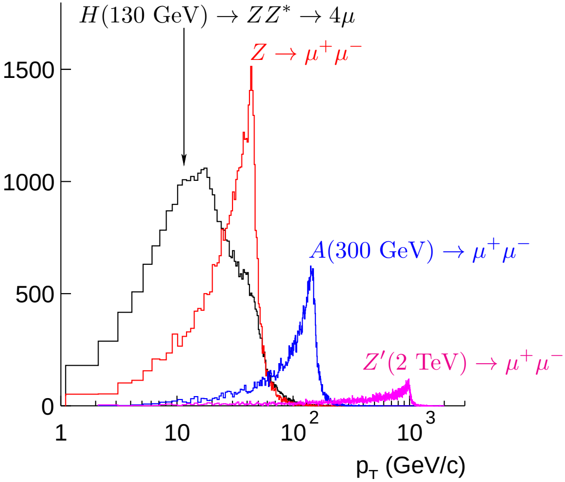



→ Clean signature of muonic final states.

- Example physics processes with muonic final states:
  - $H \to ZZ^* \to \mu\mu\ell\ell$,
  - $A \to \mu\mu$,
  - $Z' \to \mu\mu$.

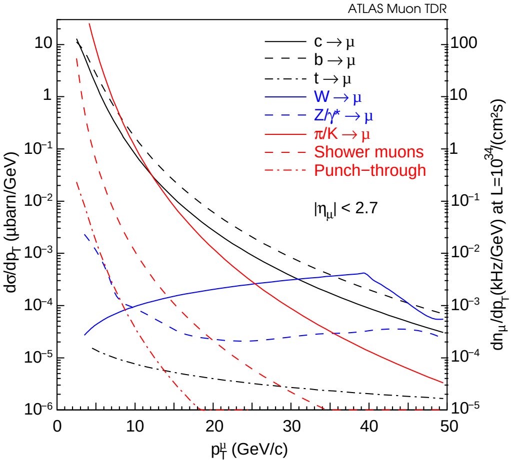
- Good muon identification and reconstruction is crucial for physics at the LHC.

# Characteristic muon momentum spectra




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

## Inclusive muon cross sections




### Muon identification tasks

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

# Muon identification strategy

## Muon identification concept

| Goal | Solution |
|---|---|
| Minimization of hadronic punch-through | Muon system surrounding the calorimeters |
| Suppression of muons from $\pi/K$ decays in flight | $p_t$ measurement in the muon system with $\frac{\Delta p_t}{p_t} \lesssim 10\%$ + requirement of a well matching inner-detector track |
| Suppression of shower muons | As $\pi/K \to \mu$ + requirement of a small energy deposit in the calorimeters |

# The ATLAS and CMS Muon Systems

# Limiting factors of the muon systems

**Energy loss in the calorimeters:**

- Energy loss $\sim$3 GeV with $\lesssim$20% fluctuation.
- Larger fluctuations can be measured by the calorimeters

$\rightarrow$ Neglible influence on $\frac{\Delta p_t}{p_t}$ for $p_t \gtrsim 10$ GeV/c.

**Multiple scattering (MS) in the calorimeters:**

- Negligible for ATLAS: $\frac{\Delta p_t}{p_t}|_{MS} \sim 10^{-3}$.

**Multiple scattering and bending power in the muon system:**

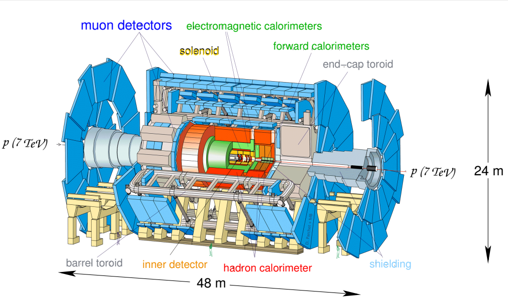
- $\frac{\Delta p_t}{p_t} \propto \frac{\sqrt{\text{material in the muon system } [X_0]}}{\int B\,dl}$.

**Resolution of the muon chambers:**

- Spatial resolution $\sigma$ of the muon chambers is the limiting factor for $\frac{\Delta p_t}{p_t}$ for high $p_t \sim 1$ TeV/c.
- $\frac{\Delta p_t}{p_t} \propto \sigma$ for $p_t \sim 1$ TeV/c.

## Two concepts for the muon system

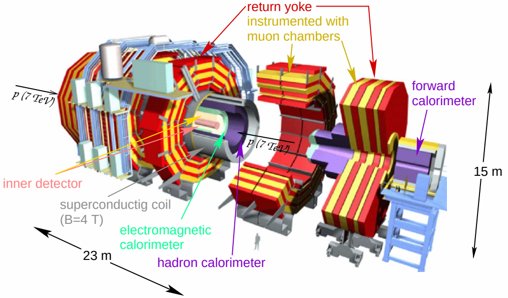
### ATLAS




- Focus on stand-alone muon reconstruction.

→ Air-core toroid → minimization of multiple scattering.

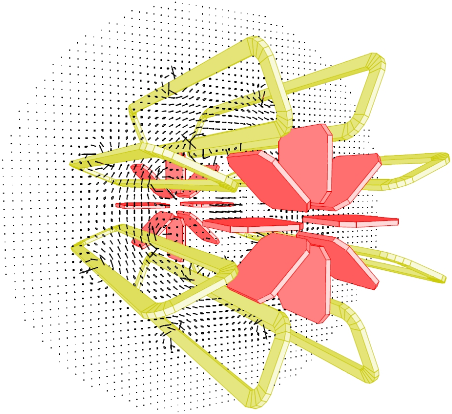
### CMS




- Focus on high $\int B\,dl$ in the inner detector and compactness.
- Instrumented return yoke of the solenoid to achieve high bending power.

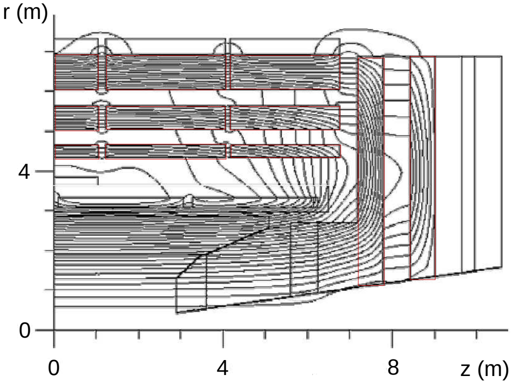
# Magnets

## ATLAS Air-Core Toroid



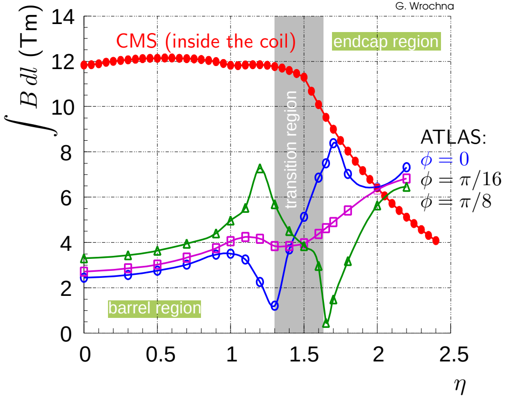
- No limitation of $\frac{\Delta p_t}{p_t}$ by MS.
- Accurate B-field measurement possible.
- Uniform $\frac{\Delta p_t}{p_t}$ independent of $\eta$.

## Iron Return Yoke of CMS Solenoid




- Uniform B field in the barrel.
- High bending power.
- Limitation of $\frac{\Delta p_t}{p_t}$ by MS.
- $\eta$ dependent $\frac{\Delta p_t}{p_t}$.

# Comparison of the magnetic field integrals




Barrel: $\approx 5\times$ higher bending power in CMS,
but $\approx 14\times$ larger multiple scattering.

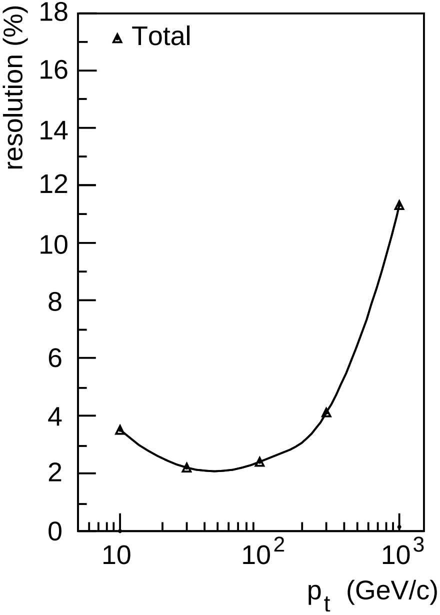
$\rightarrow$ $\approx 3\times$ worse $p_t$ resolution in CMS.

Endcap: similar bending powers,
$\approx 10\times$ large multiple scattering.

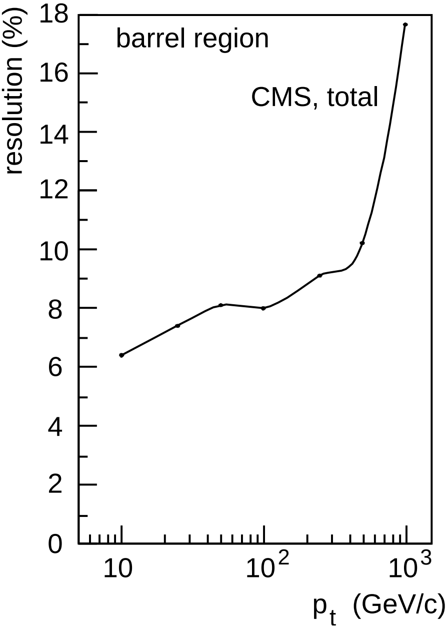
$\rightarrow$ $\approx 5\times$ worse $p_t$ resolution in CMS.

# Standalone transverse momentum resolution

ATLAS barrel standalone

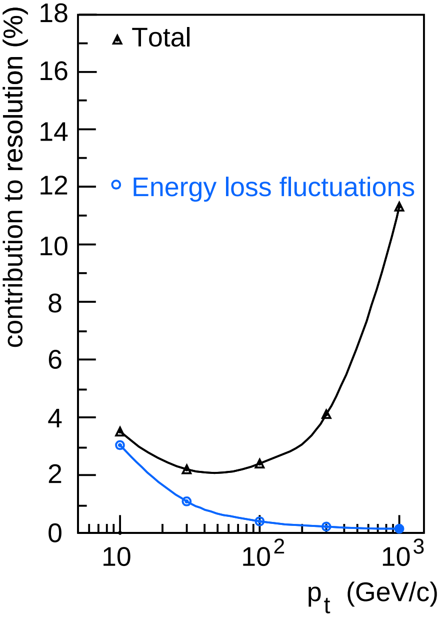



CMS barrel standalone

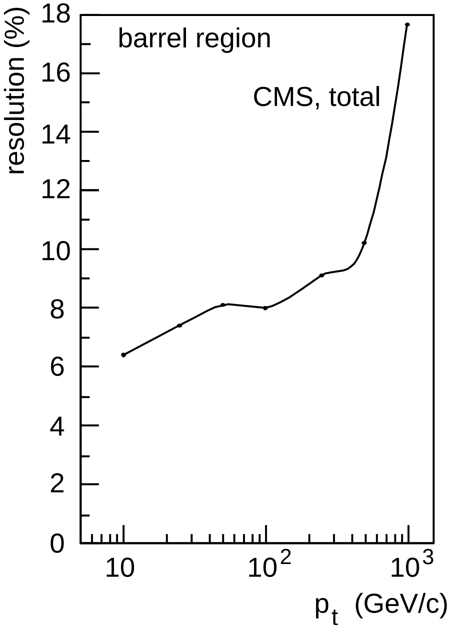


# Standalone transverse momentum resolution

ATLAS barrel standalone

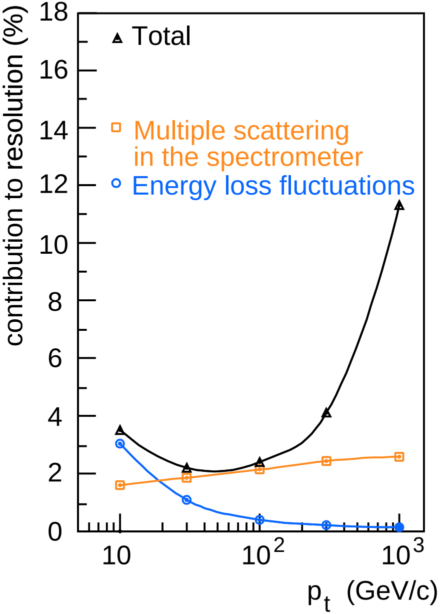



CMS barrel standalone

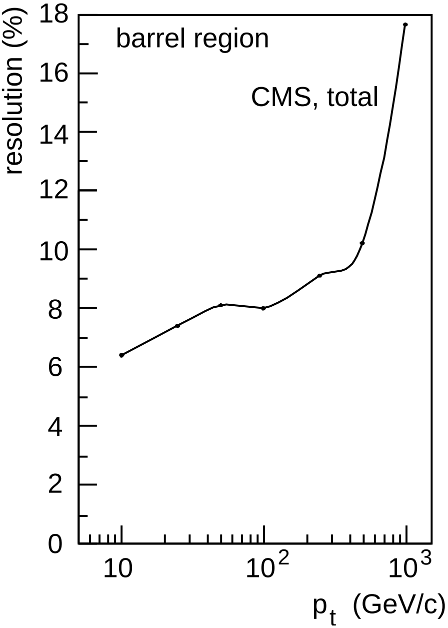


# Standalone transverse momentum resolution

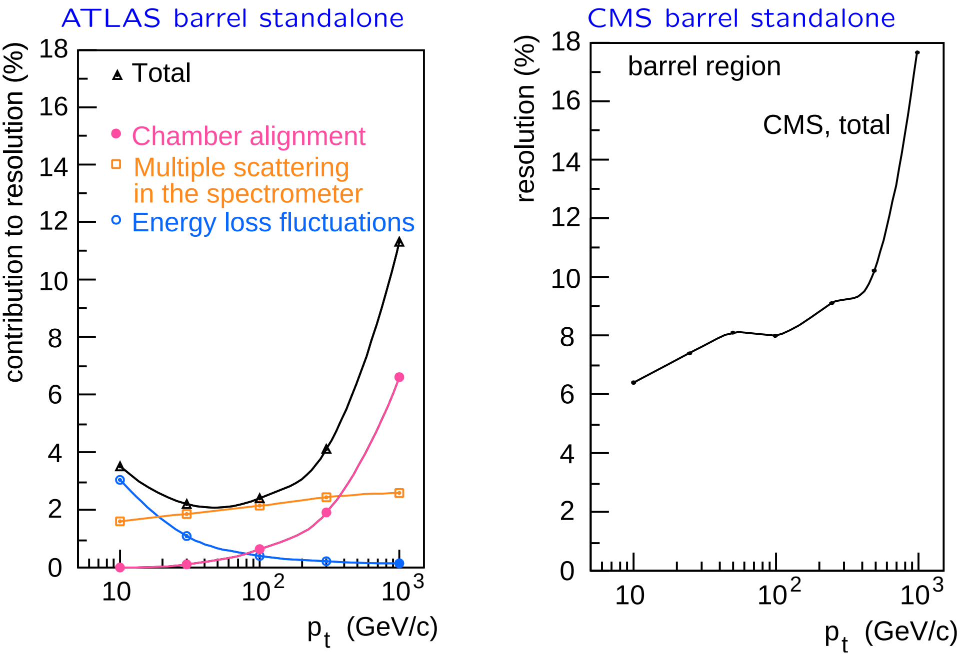
ATLAS barrel standalone




CMS barrel standalone

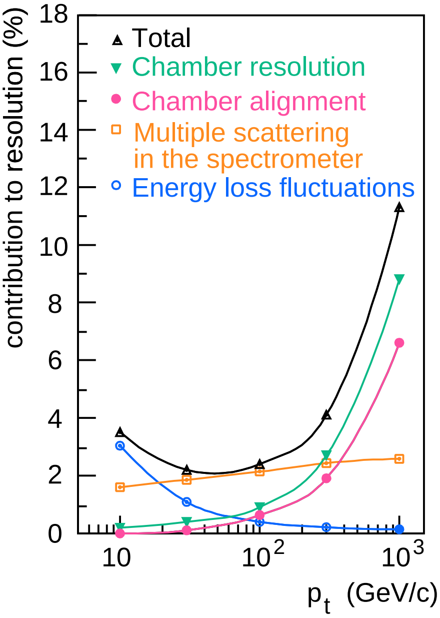


# Standalone transverse momentum resolution

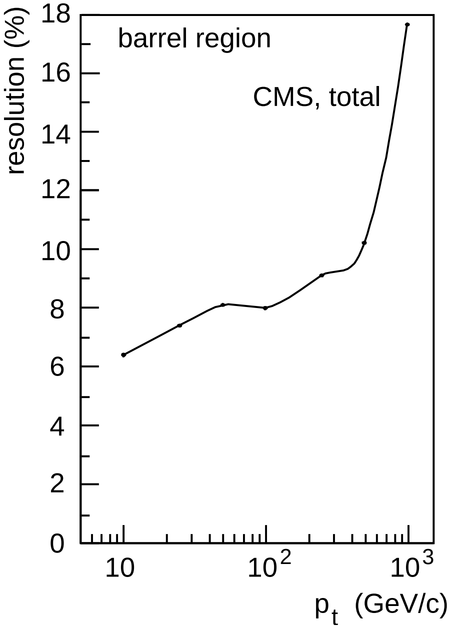


# Standalone transverse momentum resolution

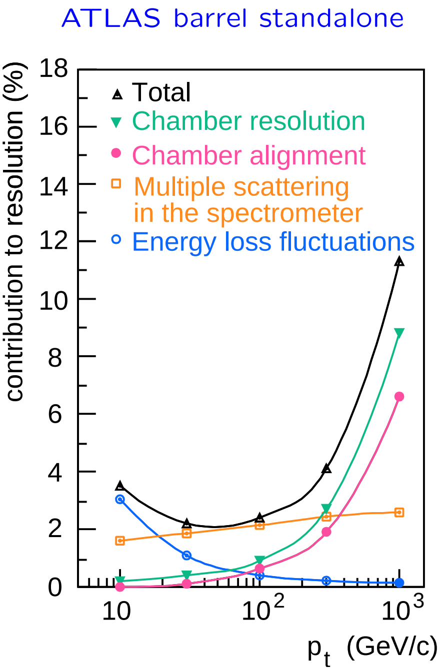
ATLAS barrel standalone

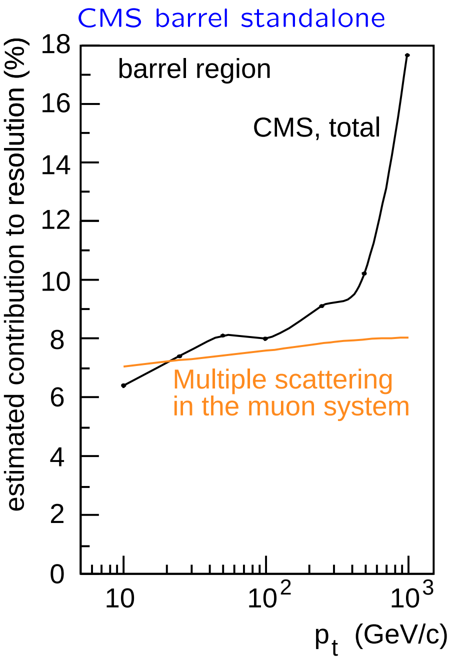



CMS barrel standalone

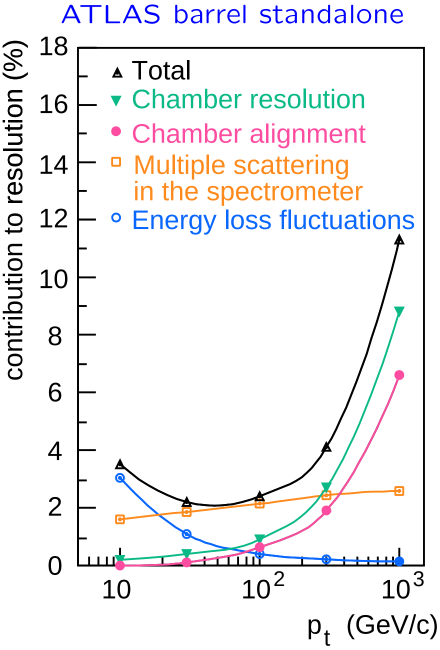


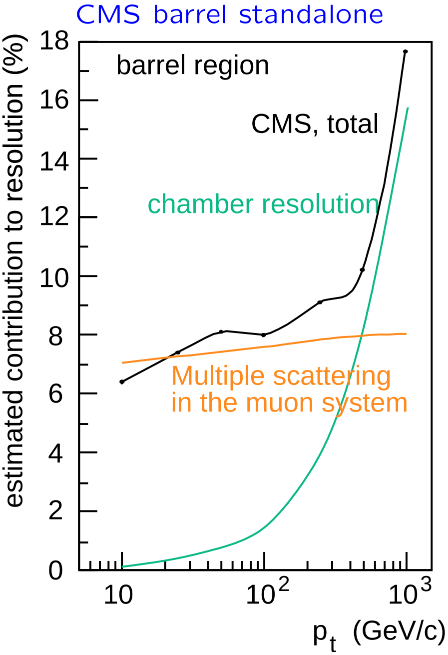
# Standalone transverse momentum resolution



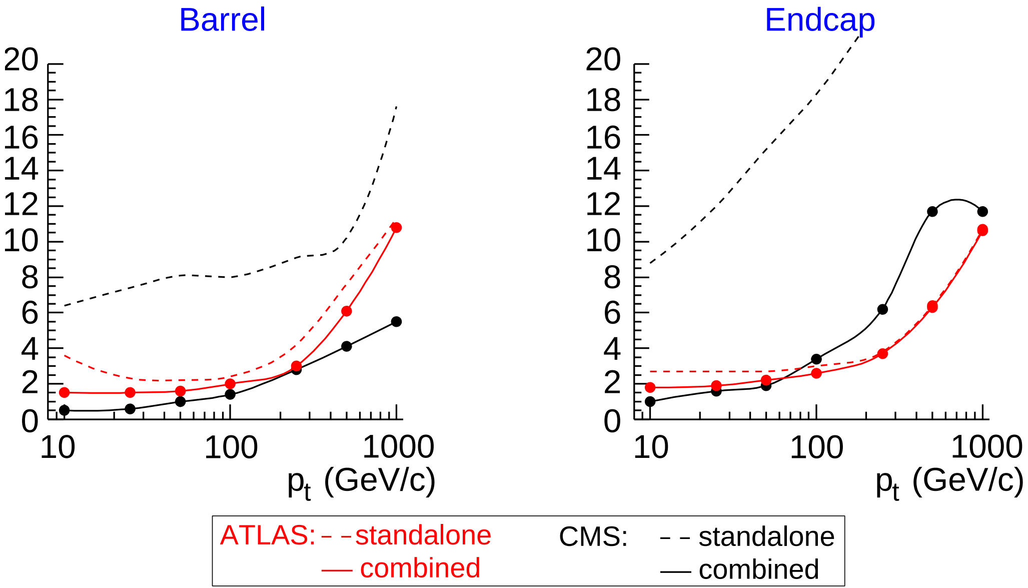
# Standalone transverse momentum resolution



# Combined transverse momentum resolution

Better resolution with muon systems and inner trackers




Better inner tracker resolution in CMS mainly due to higher B field.