Particle Detectors I

- Physics Cases and Detector Challenges
- Particle Interactions
- Tracking Detectors
- Calorimeters
- Reconstruction and Detector Concepts

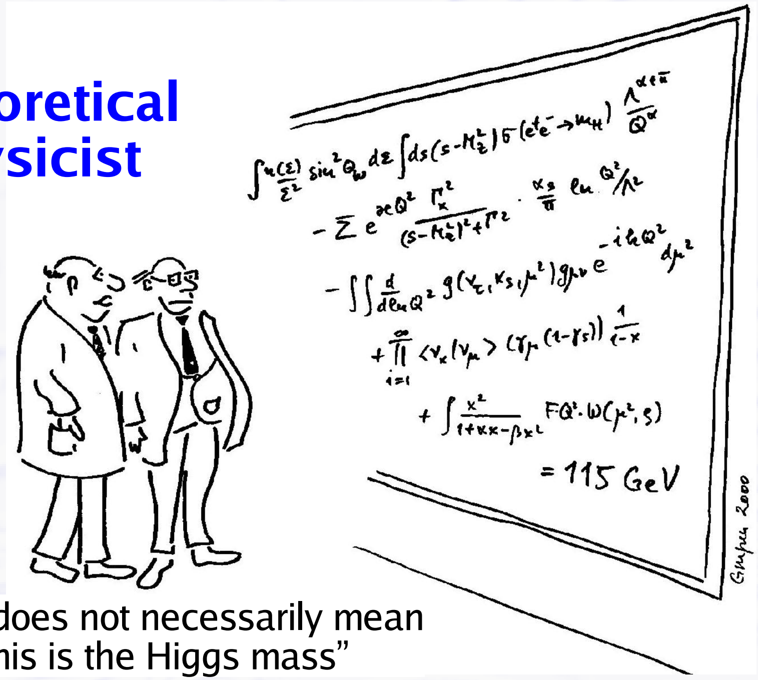
Day 1

Day 2

→ **can only give an incomplete overview of existing detectors and detector technology with slight focus on LHC detectors**

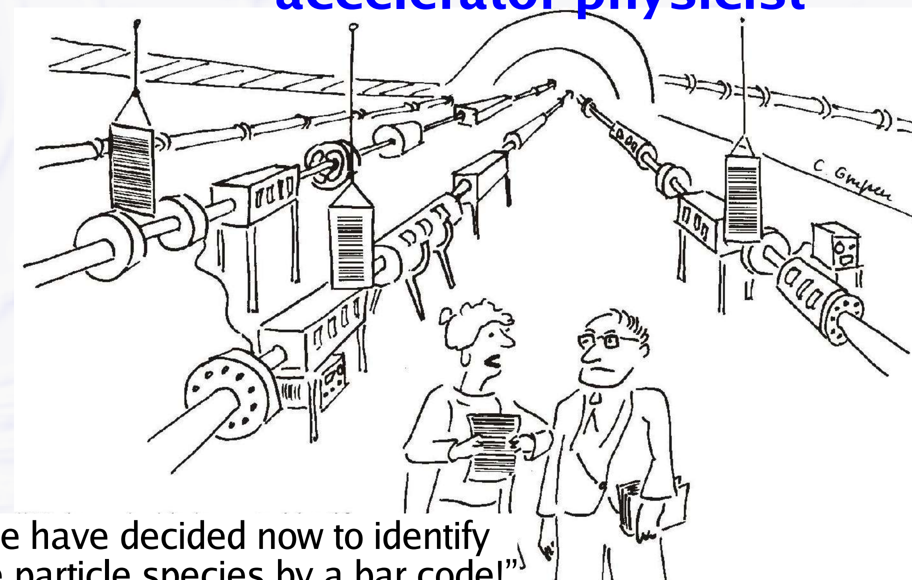
How (different) Physicicists See the World

theoretical physicist



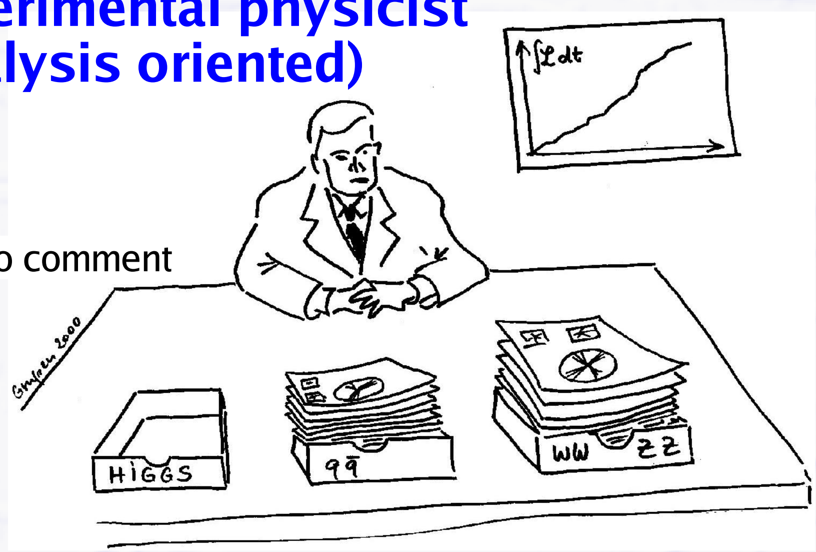
“This does not necessarily mean that this is the Higgs mass”

accelerator physicist



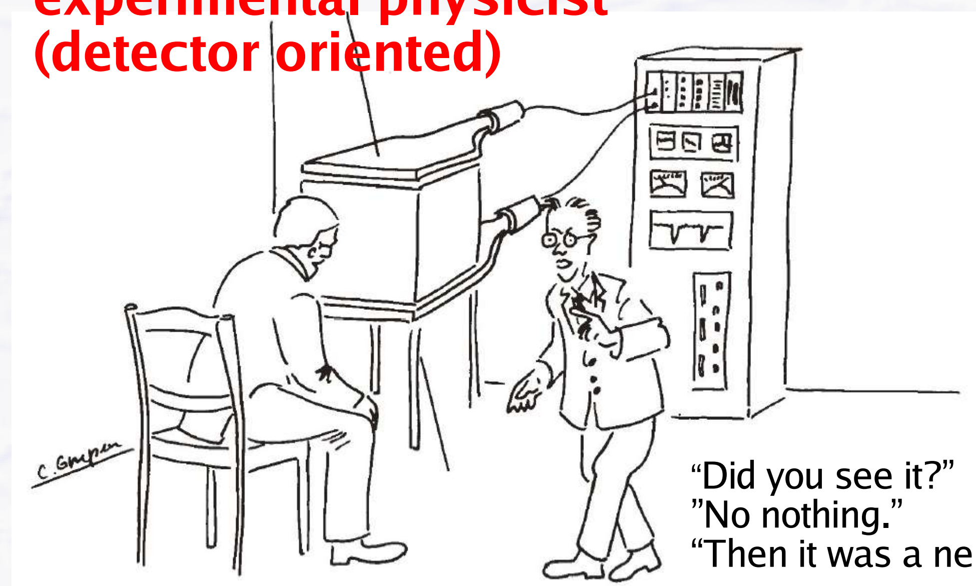
“We have decided now to identify the particle species by a bar code!”

experimental physicist (analysis oriented)



no comment

experimental physicist (detector oriented)



“Did you see it?”
”No nothing.”
“Then it was a neutrino!”

Cartoons by Claus Grupen

Physics Cases and Detector Challenges

- The High Energy Frontier
- LHC and ILC Physics Cases
- Detector Challenges

The High Energy Frontier

- **Accelerator projects on the market** (in very different states of development)
  - **LHC**
    - nominal LHC with 2 x 7 TeV and $L = 10^{34}\ cm^{-2}s^{-1}$
    - Super-LHC (SLHC) with 2 x 7 TeV and $L = 10^{35}\ cm^{-2}s^{-1}$
      - needs major detector upgrades and R&D on radiation hardness
    - Double-LHC (DLHC) with 2 x 14 TeV and $L = 10^{34}\ cm^{-2}s^{-1}$(?)
      - needs new superconducting magnets with B ~ 15 T, no R&D yet
  - **e^+e^- Linear Collider**
    - ILC with $\sqrt{s}$ = 500 GeV and $L = 2 - 5 \times 10^{34}\ cm^{-2}s^{-1}$, upgradable to 1 TeV
      - Global Design Effort (GDE) under way to prepare Technical Design Report until end of 2008
    - CLIC with $\sqrt{s}$ = 3 – 5 TeV and $L = 10^{35}\ cm^{-2}s^{-1}$
      - feasibility study under way, hope for positive results until 2010
  - **$\mu^+\mu^-$ Collider**
    - multi-TeV with $L = 10^{31}\ cm^{-2}s^{-1}$(?)
  - **LHeC (recent new proposal)**
    - LHC + 70 GeV e^- ring, $\sqrt{s}$ = 1.4 TeV (4.5x HERA), $L = 10^{33}\ cm^{-2}s^{-1}$ (20x HERA)

the only approved big project in high energy physics at present, under construction

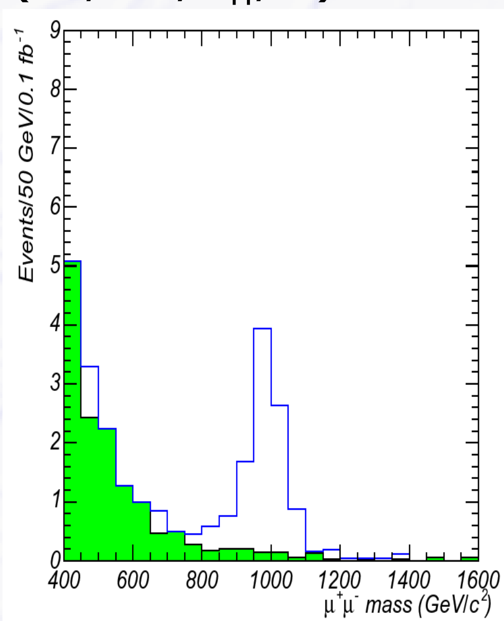
The Physics Case (LHC)

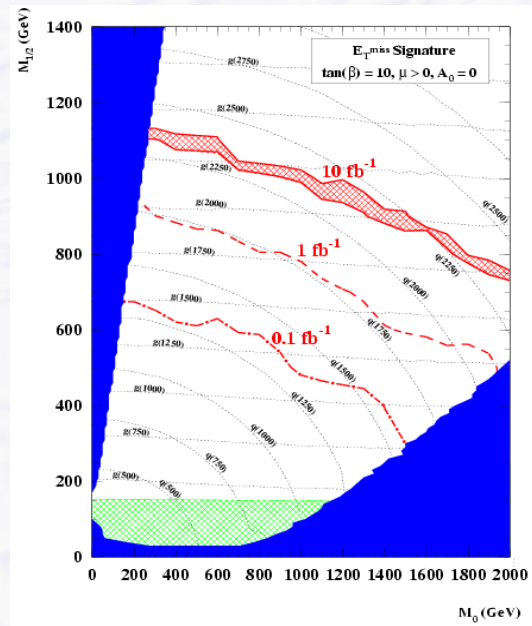
- **Possible discoveries with *O*(30) fb^{-1} (~2009/10)**

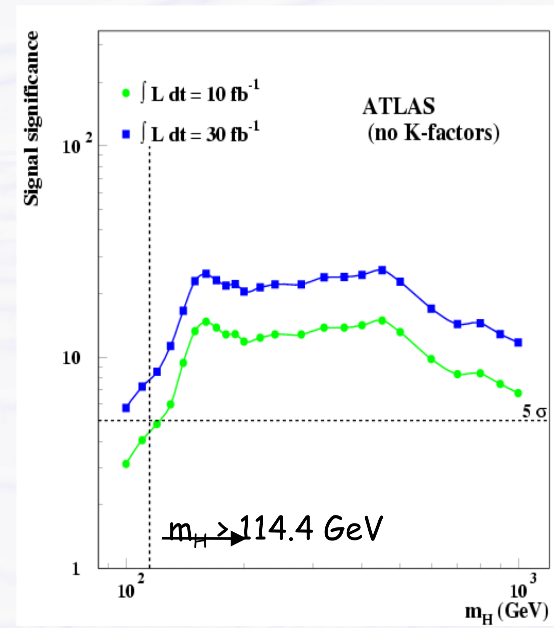
di-lepton resonance (Z',RS,Z_H,...)

inclusive SUSY

SM/MSSM Higgs







with 10 fb^{-1}:

$m<\sim 3$ TeV
dep. on model

$m_{sq,gl}<2\text{-}2.5$ TeV
in mSugra

full range

more easy...

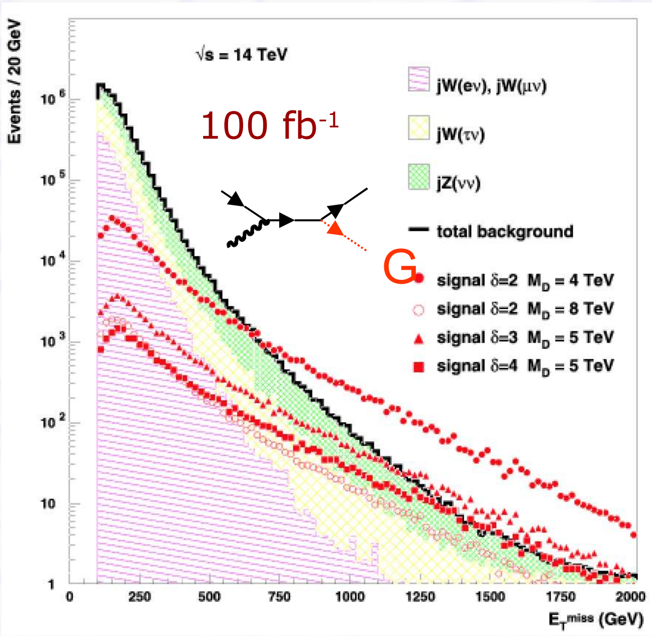
...more challenging

The Physics Case (LHC)

- **"Later" discoveries with *O*(100) fb^{-1}**

  in general more difficult: non-resonant hadronic or very rare leptonic final states will need more luminosity and better detector understanding

<u>Large Extra Dimensions (ADD)</u>



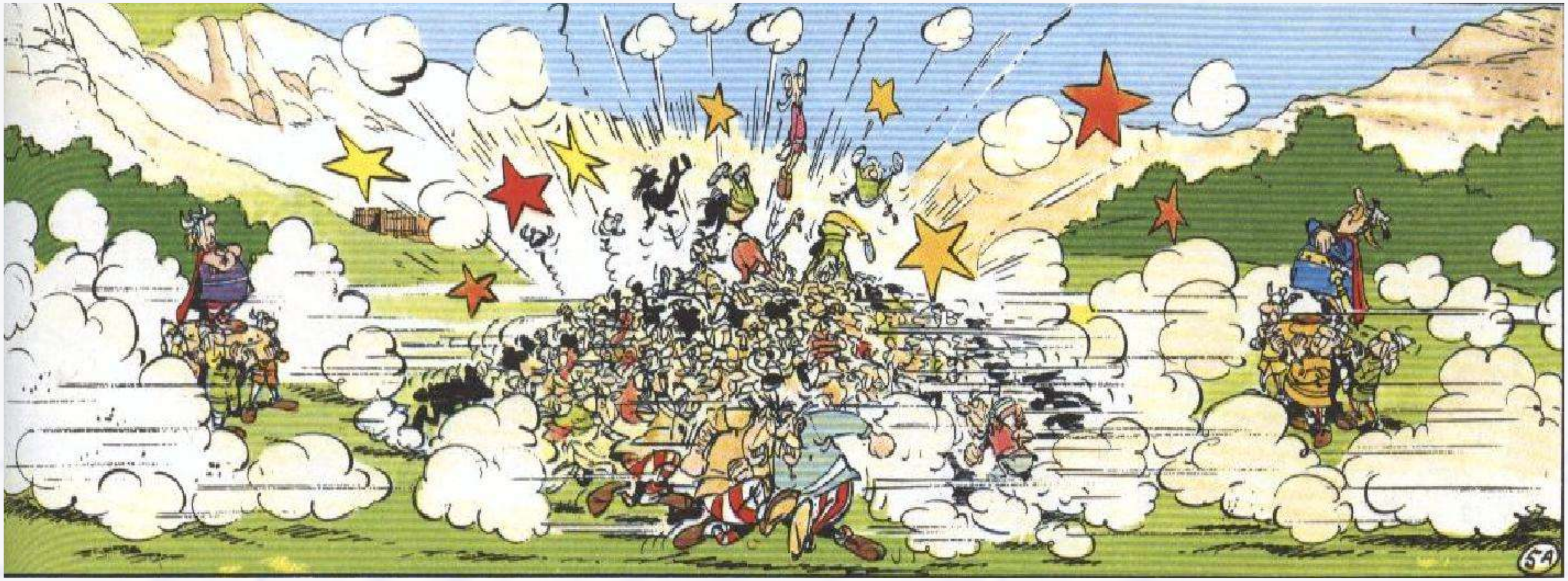
100 fb^{-1}	$\delta = 2$	$\delta = 3$	$\delta = 4$
M_D^{max}	9 TeV	7 TeV	6 TeV

<u>Strong EW Symmetry Breaking</u>

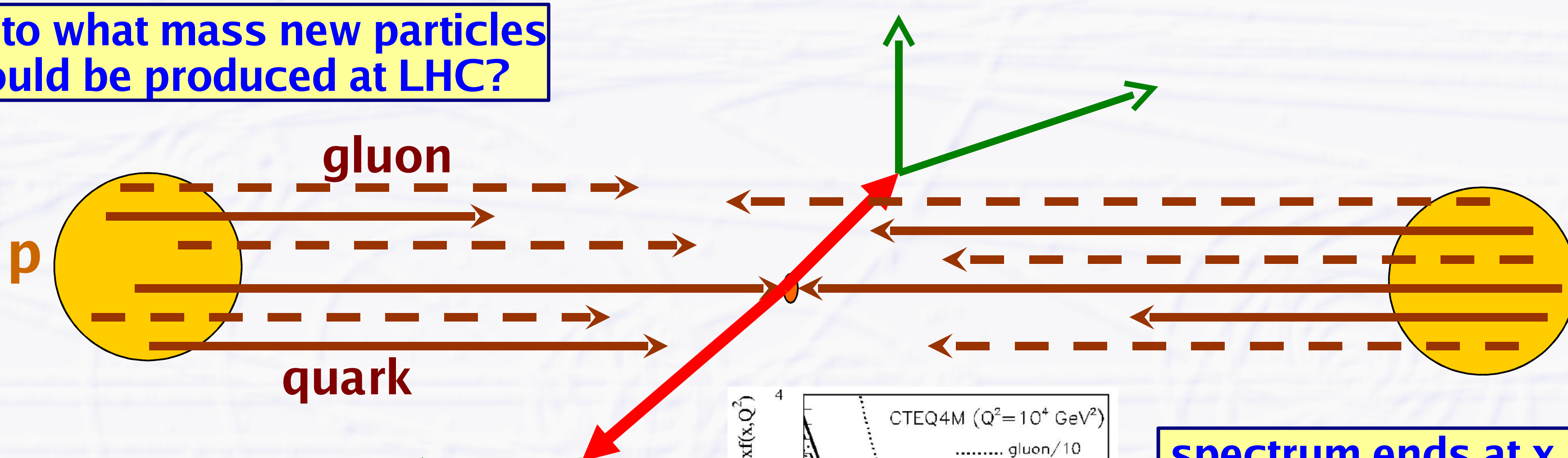
deviations from SM due to new interaction in $W_L W_L$ in absence of Higgs:

very challenging
sign. 2 lept + forw. jets + Emiss
possibly non-resonant

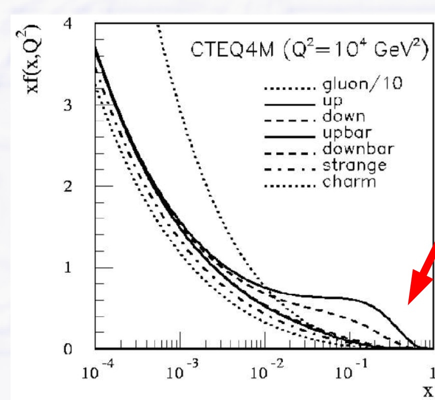
possibly only ~3σ with 100 fb^{-1}



Up to what mass new particles could be produced at LHC?



fraction x of proton momentum carried by partons



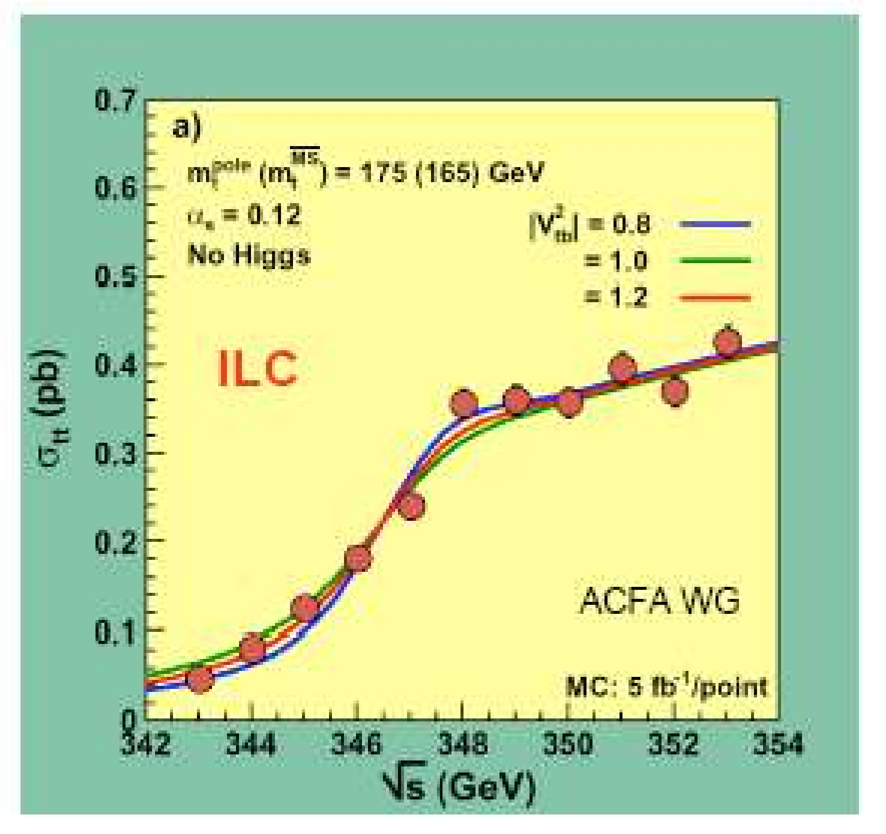
spectrum ends at x ~0.35

m_{max} = 0.35 x 7 TeV (p) ~ 2.5 TeV

The Physics Case (ILC)

- **Guaranteed and needed: Top mass**

  - top-quark could play a key role in the understanding of flavour physics
  - m_{top} fundamental parameter
  - Δm_{top} will limit many predictions



requires precise determination of its properties

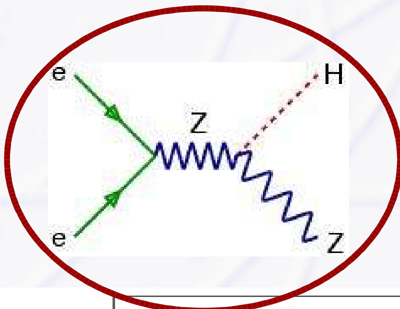
Energy scan of top-quark threshold:

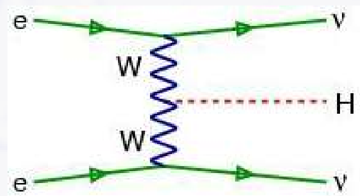
$\Delta M_{top} \approx 100$ MeV

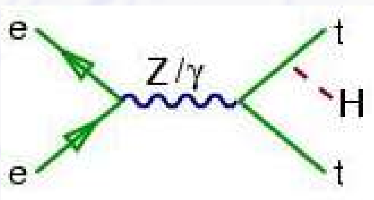
(dominated by theory)

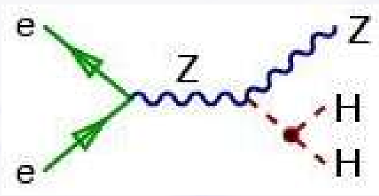
The Physics Case (ILC)

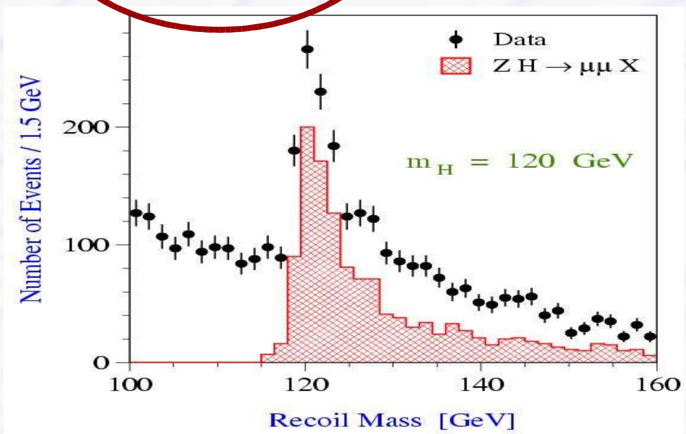
- **Precision Higgs physics**

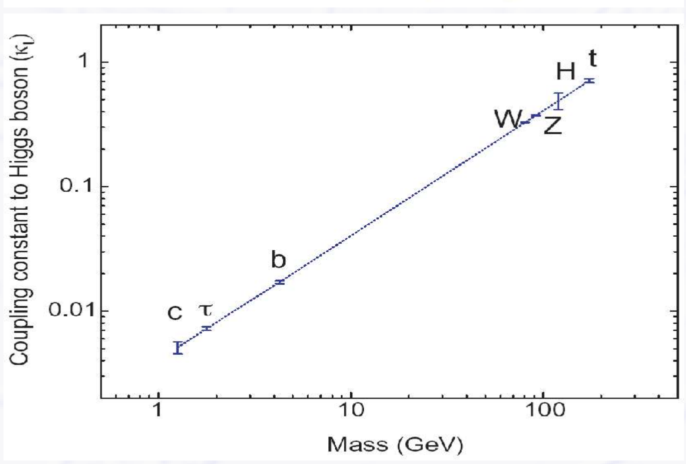










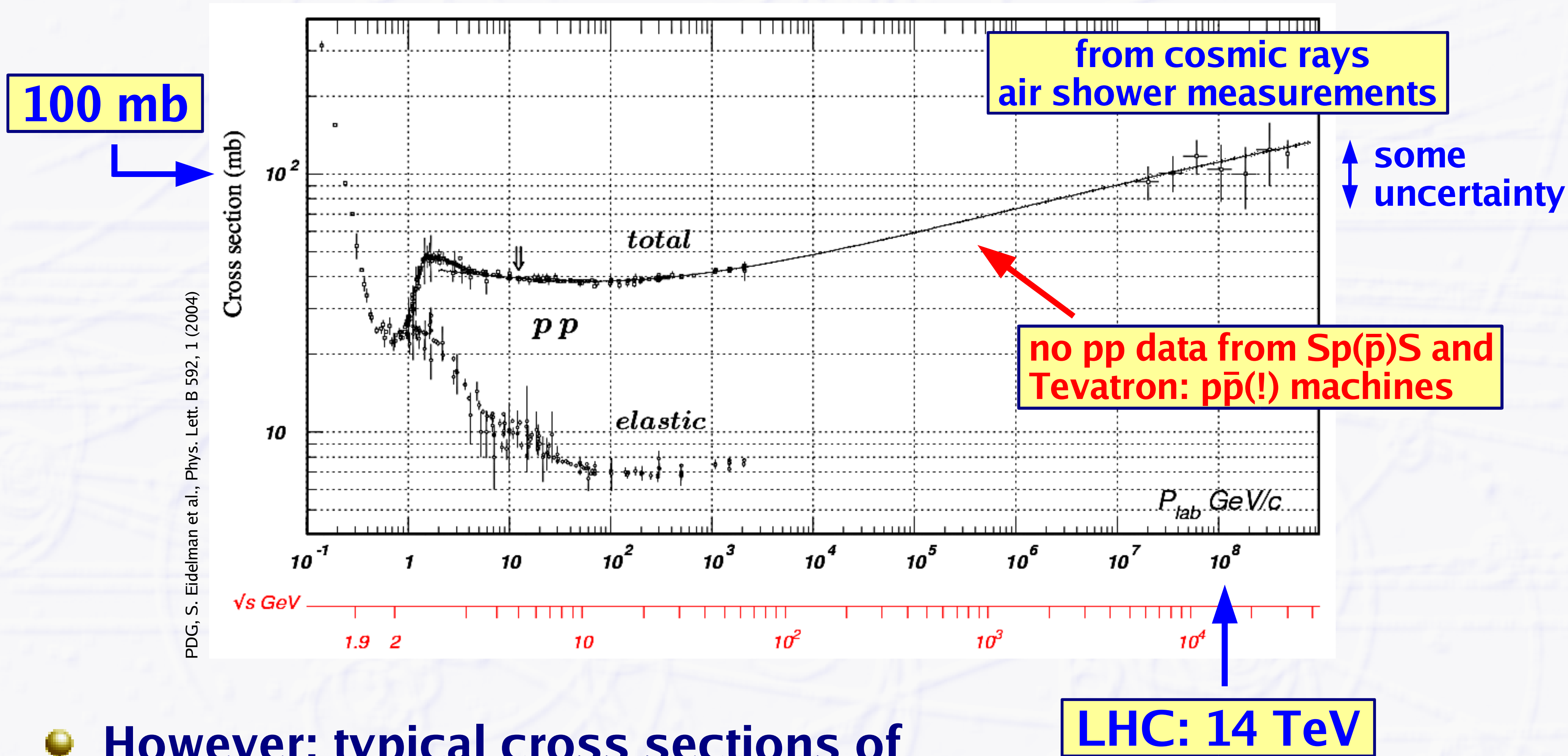


- decay-mode-independent observation
- mass (50 MeV)
- absolute couplings (Z,W,t,b,c,τ) (1-5%)
- total width (model-independent)
- spin, CP
- top Yukawa coupling (~5%)
- self coupling (~20%, 120-140 GeV)
- $\Gamma_{\gamma\gamma}$ at photon collider (2%)

fully establish Higgs mechanism!

pp Cross Section

- Total pp cross section at √s = 14 TeV is about ~100 mb

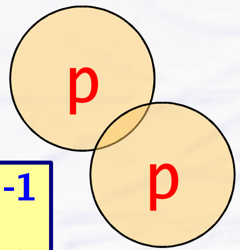


- However: typical cross sections of physics interest ~10...100 pb (and some < 1 pb)

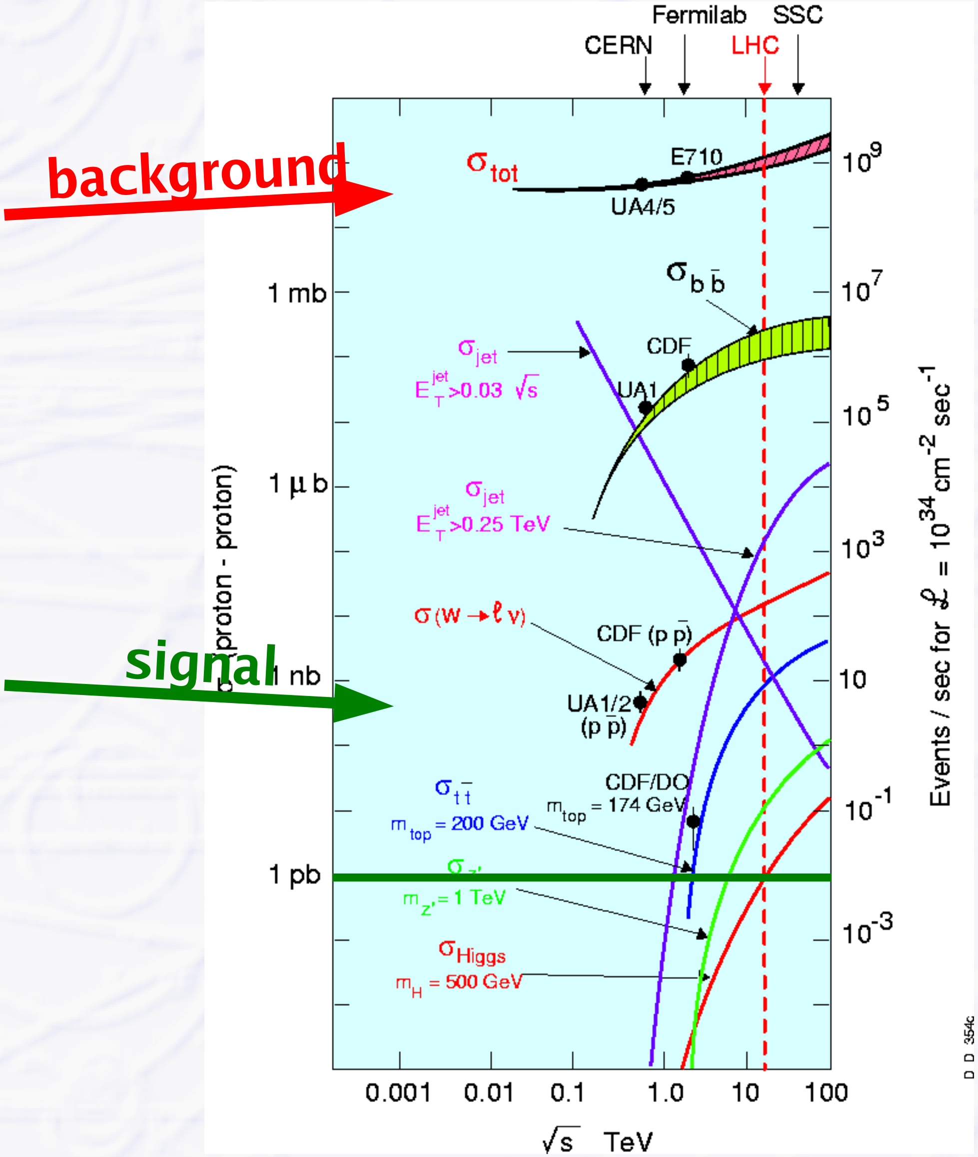
pp Physics Cross Sections

- **Many orders of magnitude between signal and background**

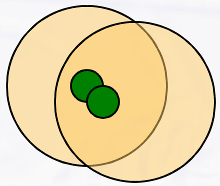
total inelastic cross section



$\sigma \sim 10^{-25}\ cm^{-2}s^{-1}$
(strong interaction)



point-like cross section



$\sigma \sim 10^{-37}\ cm^{-2}s^{-1}$
(electroweak interaction)

LHC Parameters

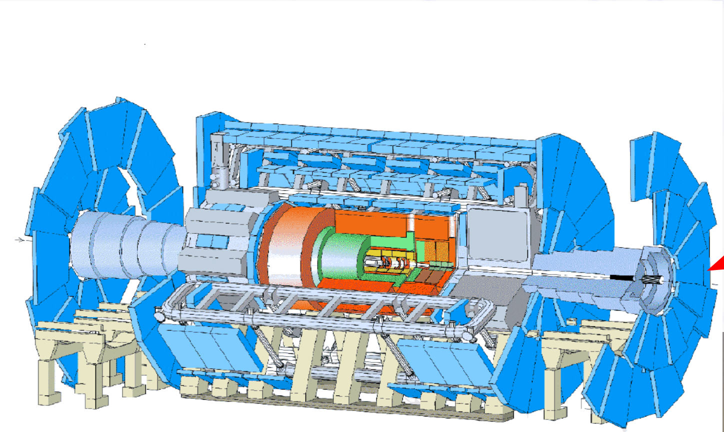
- Energy = 7 x Tevatron, luminosity = ~ 50-100 x Tevatron

	LHC (2007)	Tevatron (1987)	SppS (1981)
max. Energy (TeV)	7	1	0.450
circumference (km)	26.7	6.3	6.9
luminosity ($10^{30}cm^{-2}s^{-2}$)	10000	210	6
time between collisions (μs)	0.0025	0.396	3.8
crossing angle (μrad)	300	0	0
p/bunch (10^{10})	11	27/7.5	15/8
number of bunches	2808	36	6
beam size (μm)	16	34/29	36/27
filling time (min)	7.5	30	0.5
acceleration (s)	1200	86	10

Detector Challenges at LHC

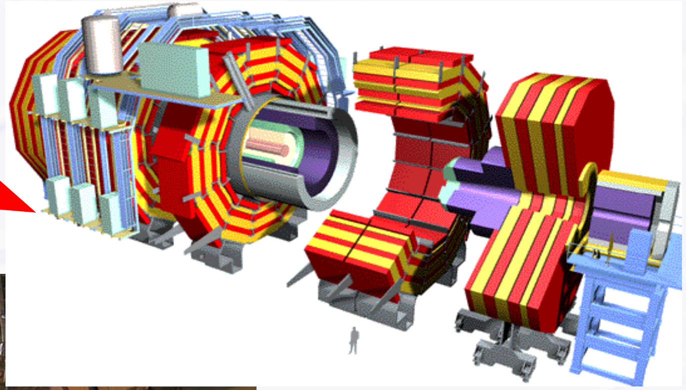
- Physics case (the driving force)
  - defines what type of accelerator/facility is needed
    - e.g. hadron/lepton collider, energy, luminosity
- Physics + accelerator parameters
  - define what type of detector is needed
- Detector requirements
  - High energy collisions
    - sufficiently high momentum resolution up to TeV scale
  - High luminosity
    - high rate capabilities and fast detectors because of high interaction rate
  - Large particle density
    - high granularity, sufficiently small detection units to resolve particles
  - At hadron colliders
    - radiation-hard detectors and electronics
      - radiation mainly due to many protons/neutrons emerging from the interactions not due to LHC machine backgrounds

LHC Detectors

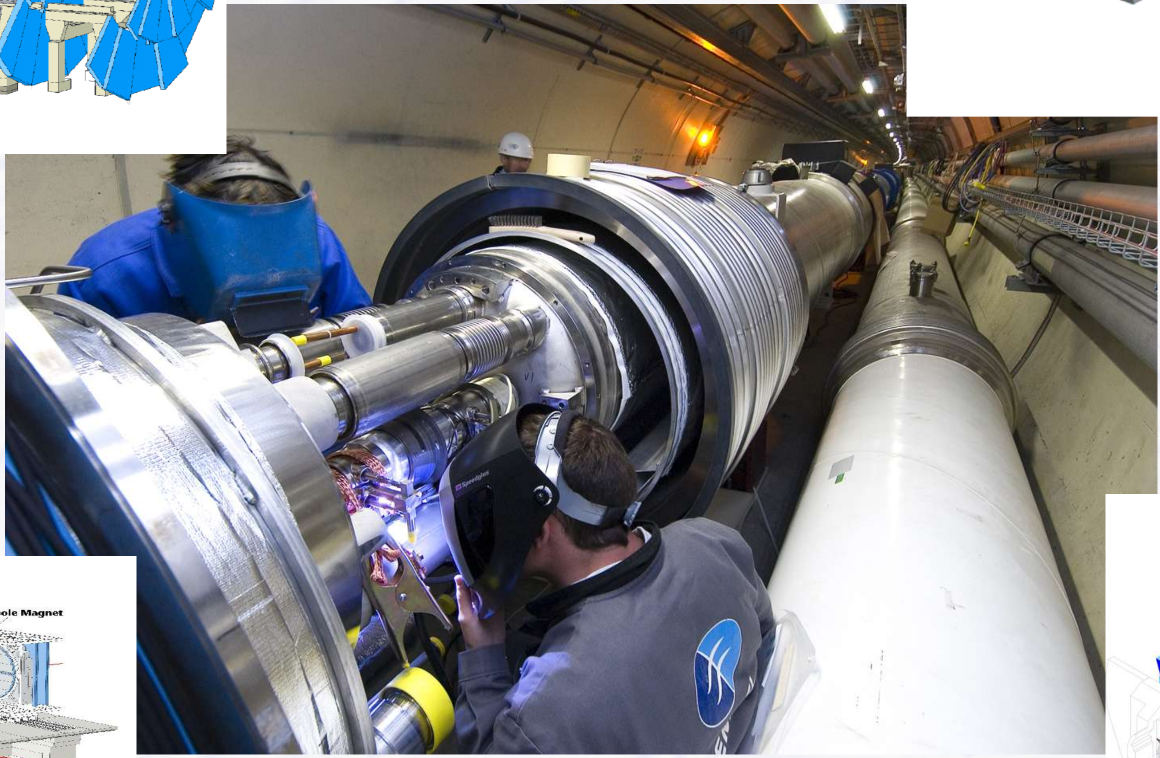


ATLAS

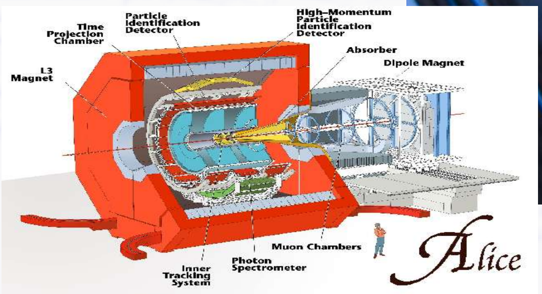
General purpose detectors (good for everything...)



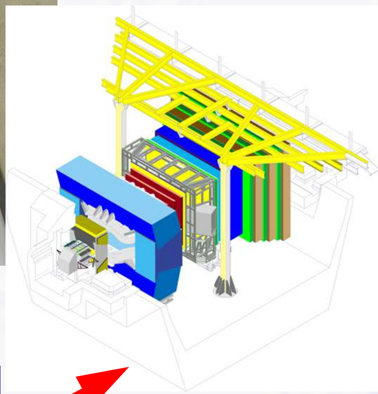
CMS



ALICE



LHCb

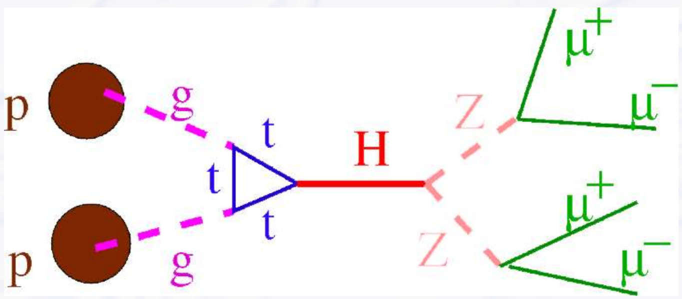


dedicated for Heavy Ion collisions

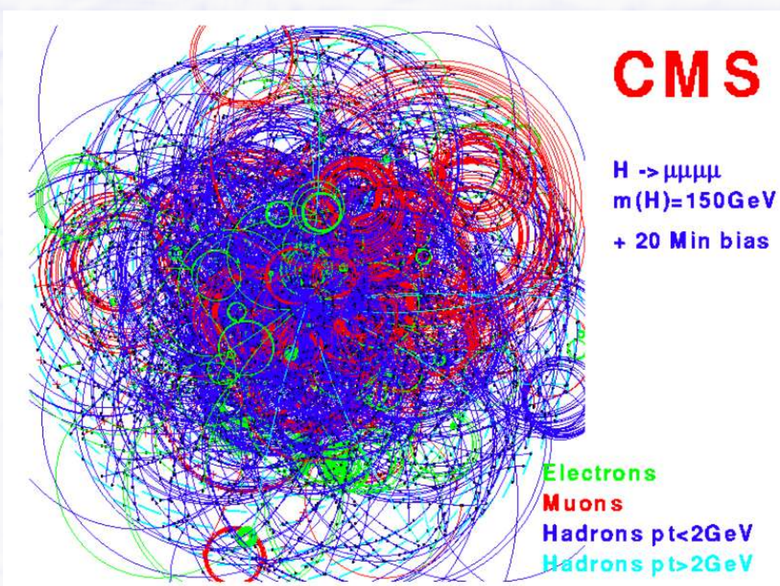
dedicated for b-physics

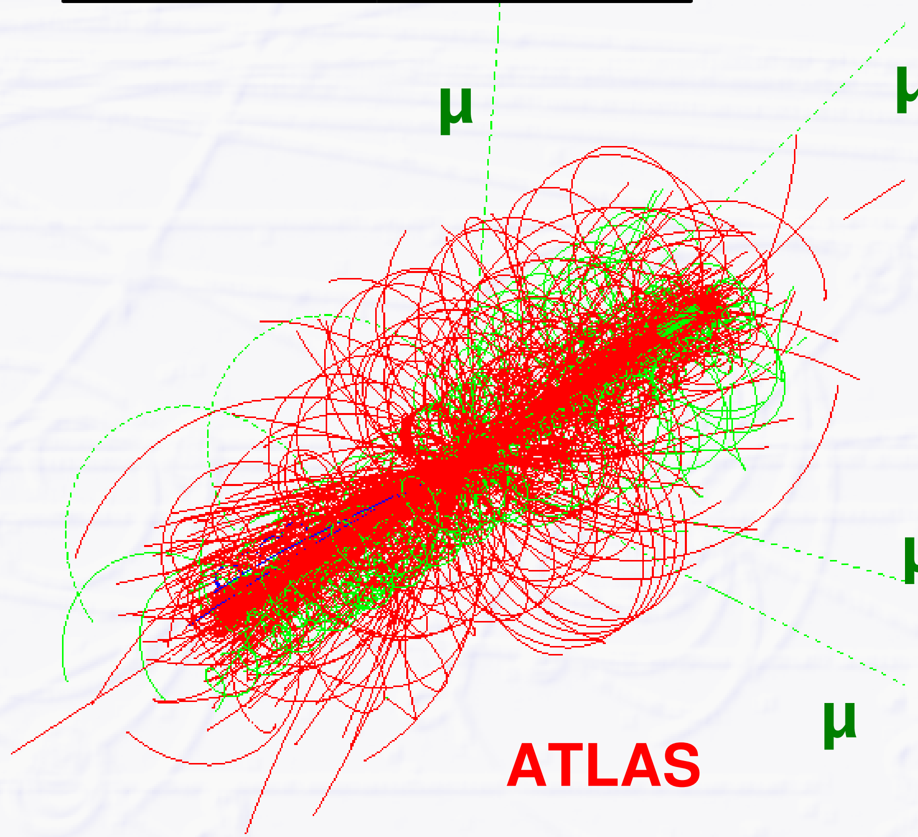
What we have to expect

- **One bunch crossing every 25 ns with ~20 interactions**
  - **1000 tracks per bunch crossing = 4 * 10^{10} tracks per second...**
  - **...and very often you're interested in a few tracks only...**



pp → H → ZZ → 4μ





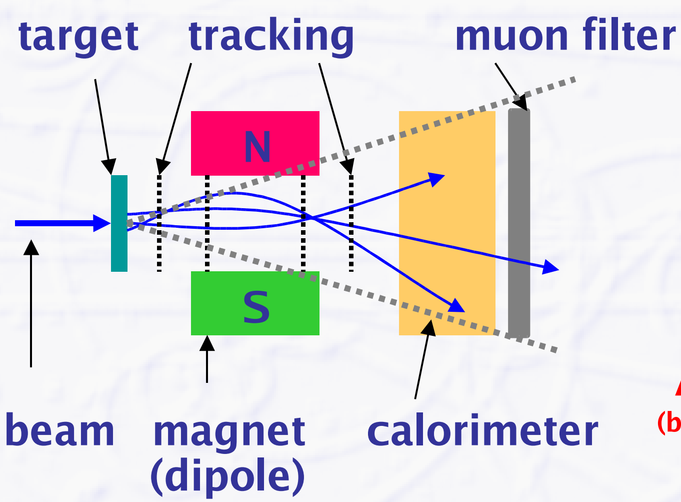
The Perfect Detector...

- ...should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get "4-momenta" of basic physics interaction)
  - efficiency:
    - not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, cables, electronics, mechanics)

Fixed target geometry

"Magnet spectrometer"

LHCb



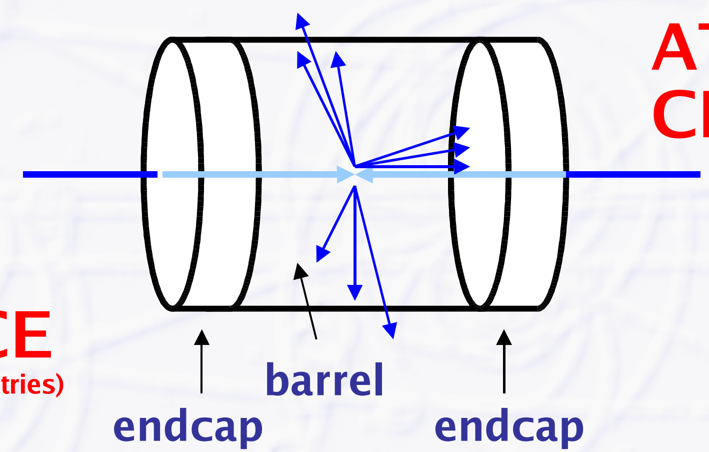
- Limited solid angle dΩ coverage
- rel. easy access (cables, maintenance)

ALICE
(both geometries)

Collider geometry

"4π multi purpose detector"

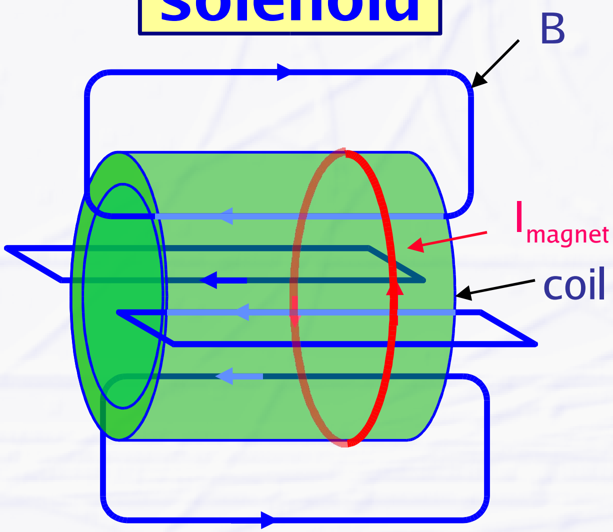
ATLAS
CMS



- "full" dΩ coverage
- very restricted access

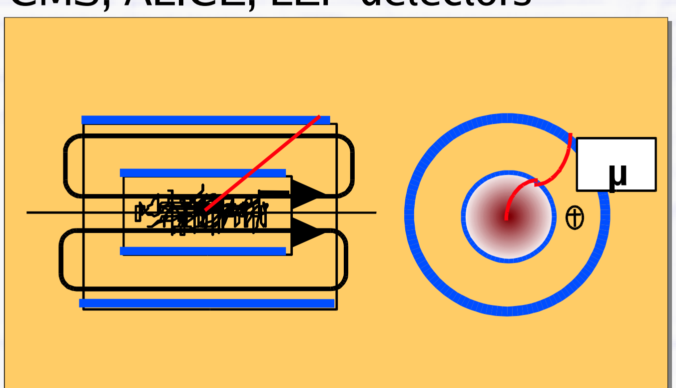
Magnet Concepts at LHC experiments

solenoid

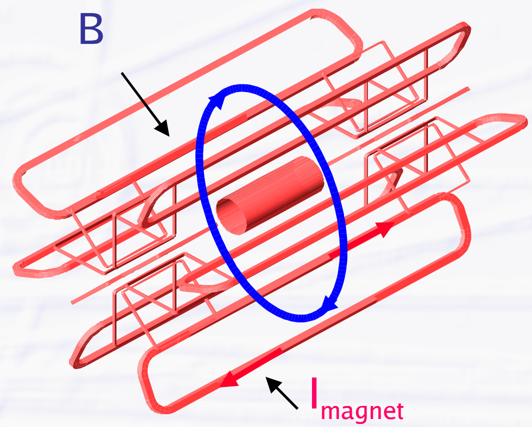


+ large homogenous field inside coil
- needs iron return yoke (magnetic shortcut)
- limited size (cost)
- coil thickness (radiation lengths)

CMS, ALICE, LEP detectors

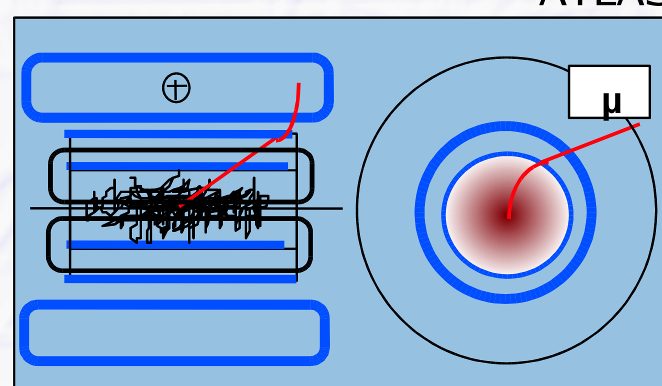


(air-core) toroid

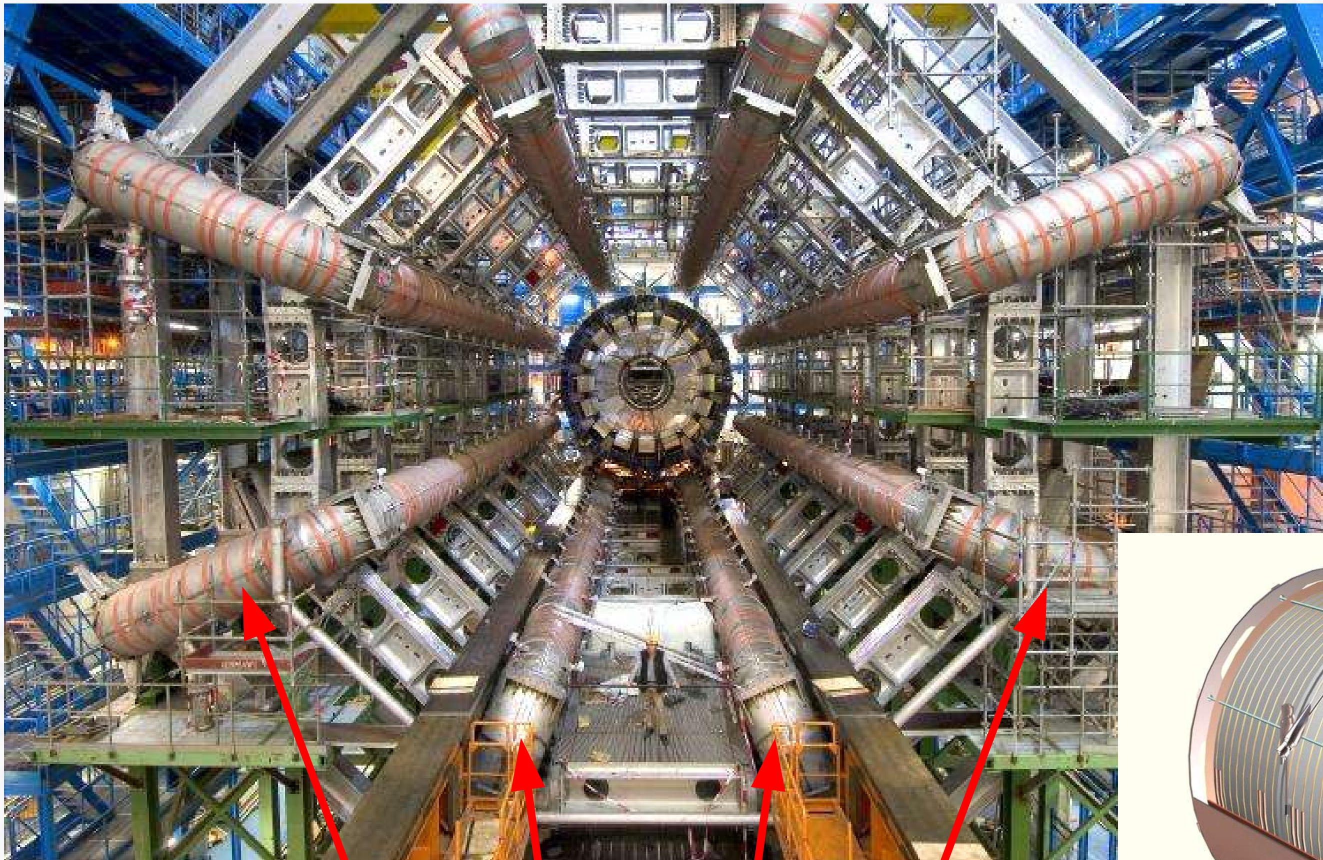


+ can cover large volume
+ air core, no iron, less material
- needs extra small solenoid for general tracking
- non-uniform field
- complex structure

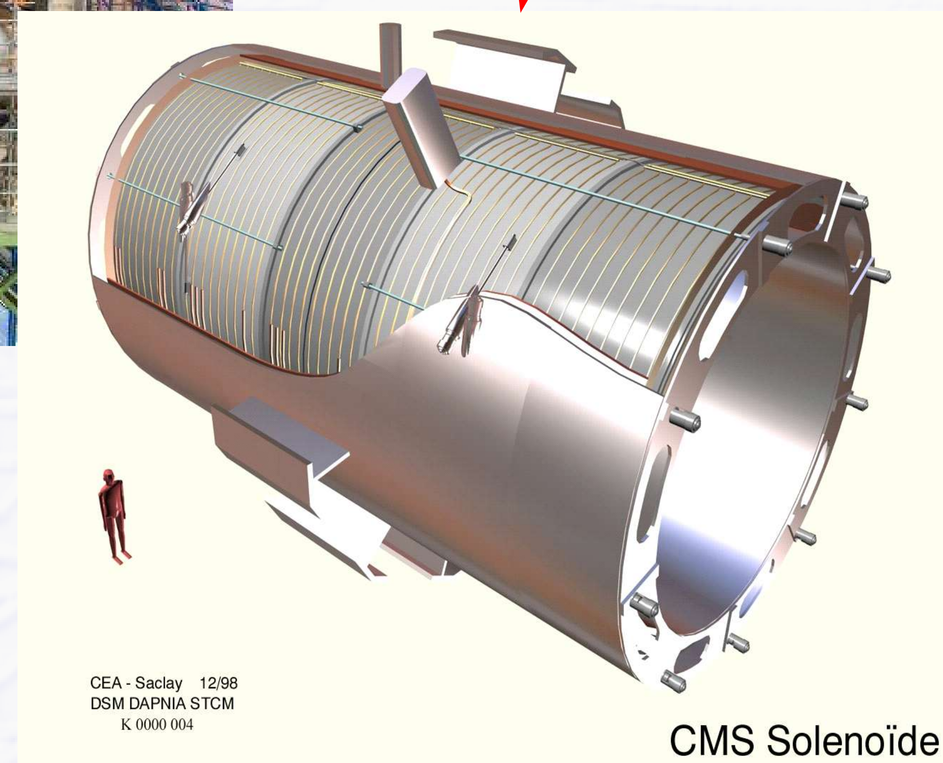
ATLAS



ATLAS and CMS Coils



CMS solenoid
(5 segments)



ATLAS toroid coils

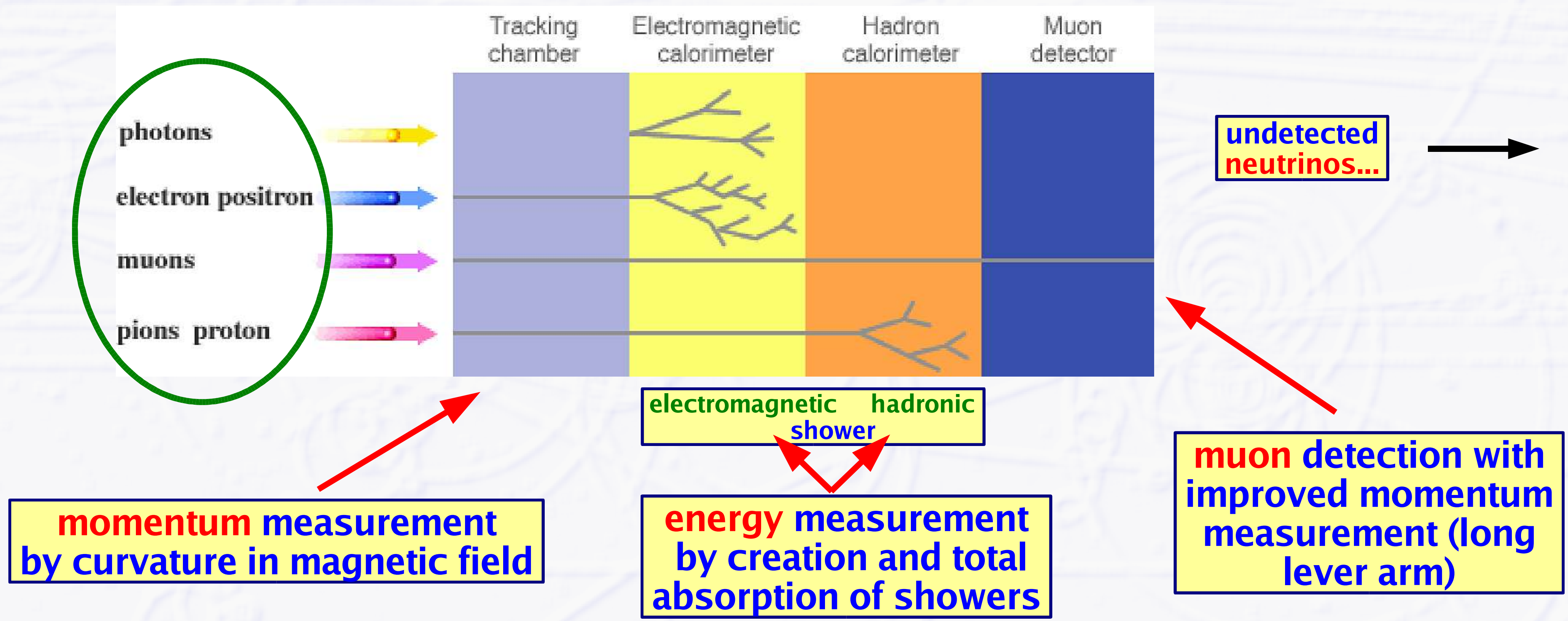
autumn 2005

Particle Interactions

- **Photon Interactions**
- **Charged Particle Interactions**
  - **Scattering, Ionization**
  - **Photon Emission: Čerenkov + Transition Radiation**

Particle Interactions

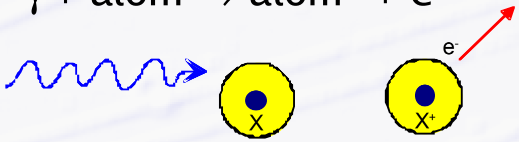
- **Particles cannot be seen/detected directly, we only can observe the result of their interactions with the detector (material)**
  - **Interactions are mainly electromagnetic**
    - **exceptions: strong interactions in hadronic showers (hadron calorimeters)**
      weak interactions at neutrino detection (not discussed here)



Particle Interactions – Photons

- **Photo effect**
  - ➜ used at various photo detectors to create electrons on photo cathodes in vacuum and gas or at semi conductors (surface)
    - Photo Multiplier Tubes (PMT)
    - photo diodes

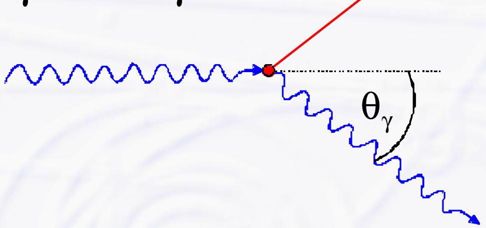
$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$



$$\sigma_{photo} \propto Z^5$$

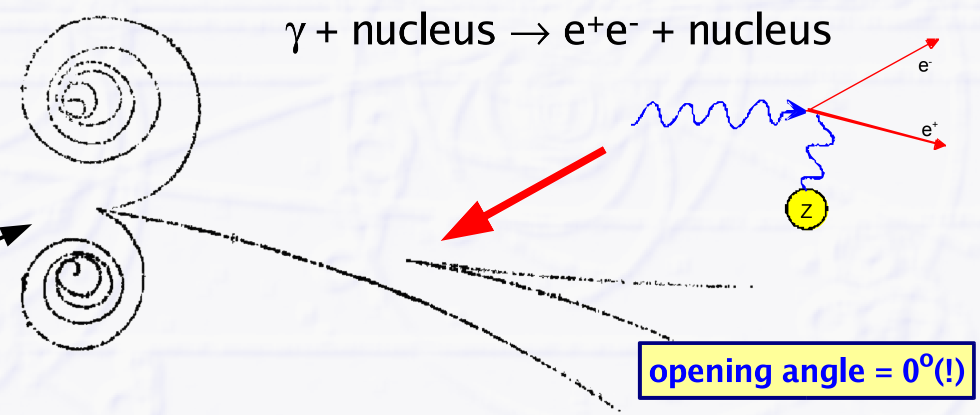
- **Compton scattering ($e^- \gamma$ scattering)**
  - ➜ not used for particle detection
    - but was/is used for polarization measurement of beams at e^+e^- machines and could be used to create high energy photons in a γγ - collider

$\gamma + e \rightarrow \gamma' + e'$



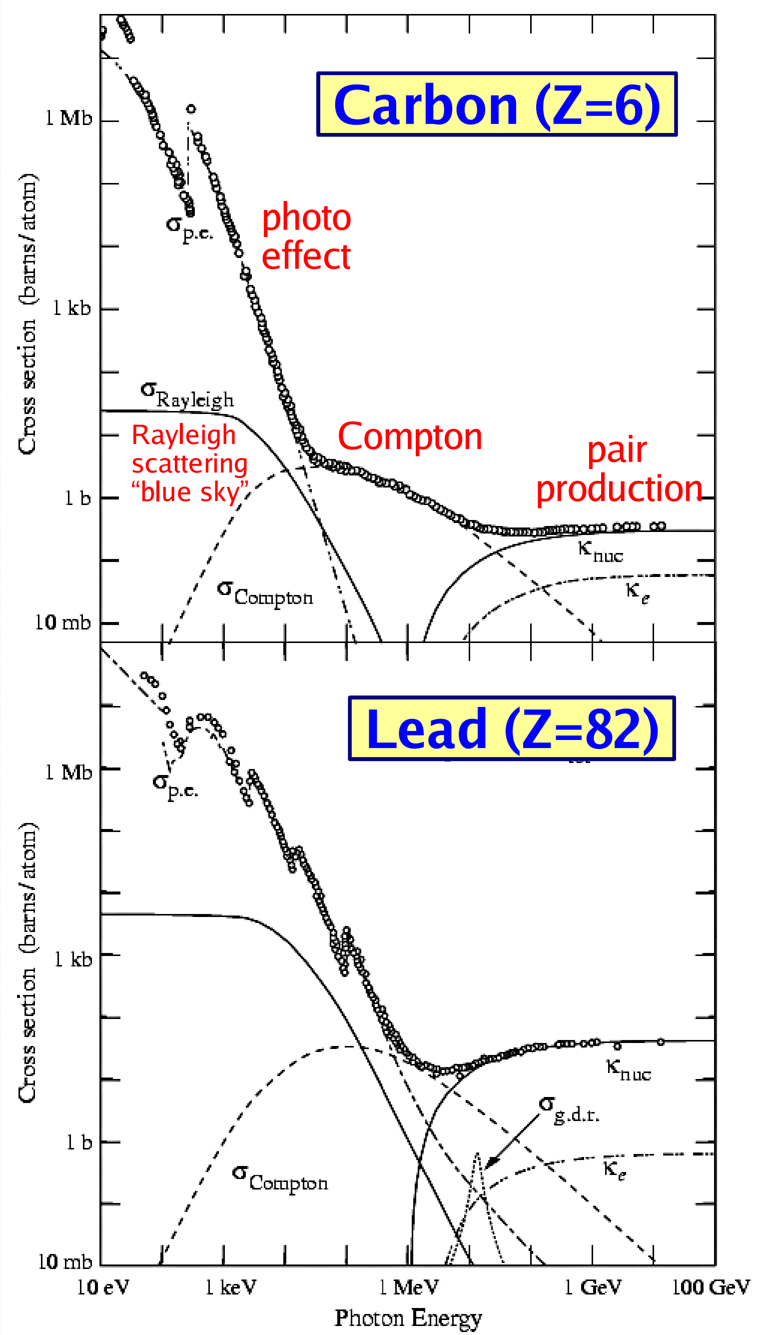
- **Pair production ($\gamma \rightarrow e^+e^-$)**
  - ➜ initiates electromagnetic shower in calorimeters, unwanted in tracking detectors

$\gamma + \text{nucleus} \rightarrow e^+e^- + \text{nucleus}$



$\gamma + e^- \rightarrow e^+e^- + e^- + \gamma$

Photon Interactions - Overview



- **Photo effect dominating at low γ energies (< some 100 keV)**
- **Compton scattering regime ~some 100 keV up to ~10 MeV**
  - exact energy domain depends on Z
    - low Z: wide energy range of Compton scat.
    - large Z: small energy range of Compton scat.
- **Pair production dominating at high energies (> ~10 MeV)**

$\sigma_{\text{p.e.}}$	=	Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh}	=	Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton}	=	Incoherent scattering (Compton scattering off an electron)
κ_{nuc}	=	Pair production, nuclear field
κ_e	=	Pair production, electron field
$\sigma_{\text{g.d.r.}}$	=	Photonuclear interactions, most notably the Giant Dipole Resonance [4]. In these interactions, the target nucleus is broken up.

Radiation Length

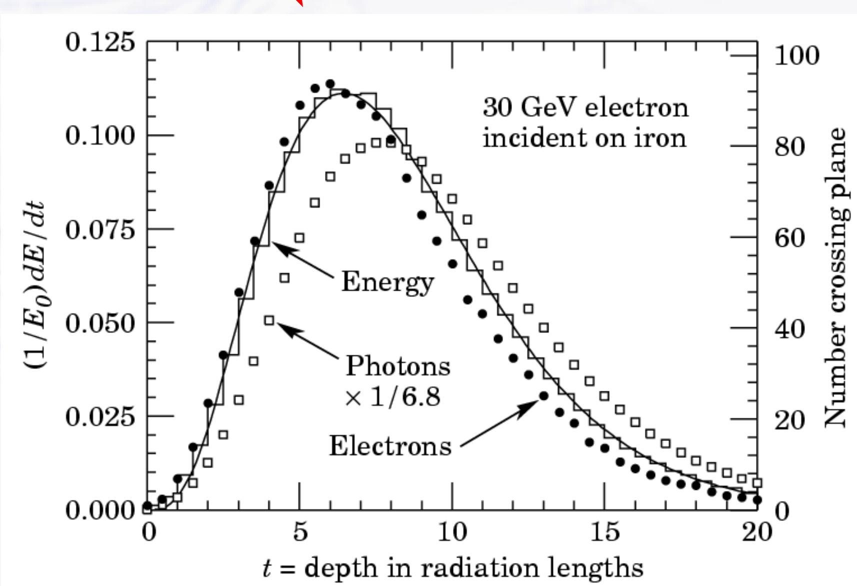
- Main energy loss of high energy electrons/photons in matter
  - Bremsstrahlung ($e^{\pm}$) and pair production (γ)
- Can characterize any material by its radiation length X_0
  - 2 definitions (for electrons and for photons)
    - X_0 = length after an electron looses all but 1/e of its energy by Bremsstrahlung
    - X_0 = 7/9 of mean free path length for pair prodution by the photon
- Very convienient quantity
  - Rather than using thickness, density, material type etc. detector
    - often expressed as % of X_0
  - tracking detectors should have X_0 as low as possible (<< 1 X_0)
    - ATLAS and CMS trackers: 30% - 130% X_0
    - not really "transparent", high probability to initiate electromagnetic showers in tracker far before electrons/photons reach calorimeters
      - "pre-shower" detectors in front of calorimter should detect and correct measured ECAL energy for such early showers
  - calorimeters should have X_0 as high as possible (typically 20...30 X_0)

Electromagnetic Cascades

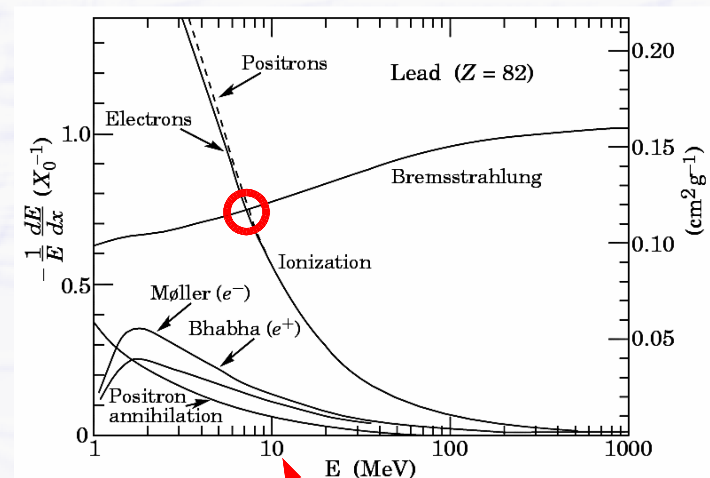
- **Starting from the first electron/photon an electromagnetic shower (cascade) develops in thick materials**
  - **shower maximum (peak of energy deposition) slightly energy dependent**

$$t_{max}[X_0] = \ln\frac{E_0}{E_c}\frac{1}{\ln 2}$$

E_c = critical energy where energy loss (Ionization) = energy loss (Bremsstrahlung)



O (5 - 10 X_0)

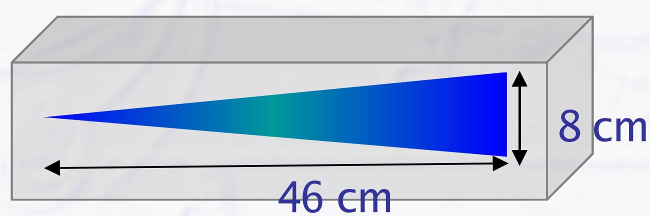


O (10 MeV)

transversal shower width given by Moliere radius

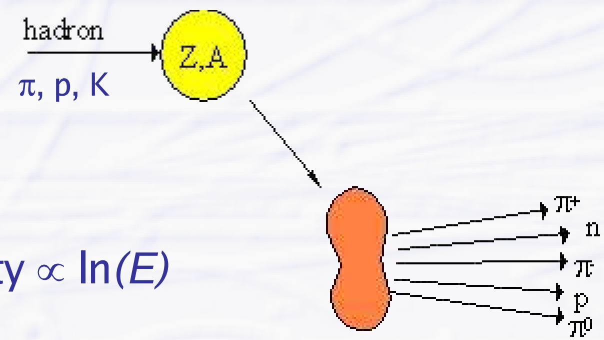
$$R_M = \frac{21\ MeV}{E_c} X_0$$

typically ~ 2 X_0

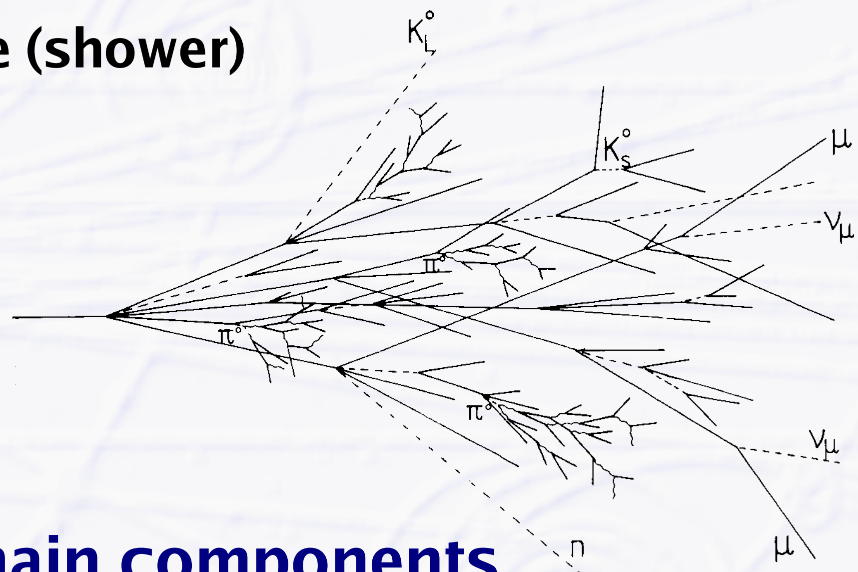


Nuclear Interaction Length

- **Similar as radiation length but for hadrons**
- **Strong interaction of hadron with nucleus**
  - **Development of hadronic cascade (shower)**



multiplicity ∝ ln(E)



C. Grupen

- **Hadronic showers have two main components**
  - **hadronic**
    - **charged hadrons, breaking up of nuclei (binding energy) nuclear fragments, neutrons**
  - **electromagnetic**
    - **decay of neutral pions: $\pi^0 \rightarrow 2\gamma$ (100% branching ratio)**

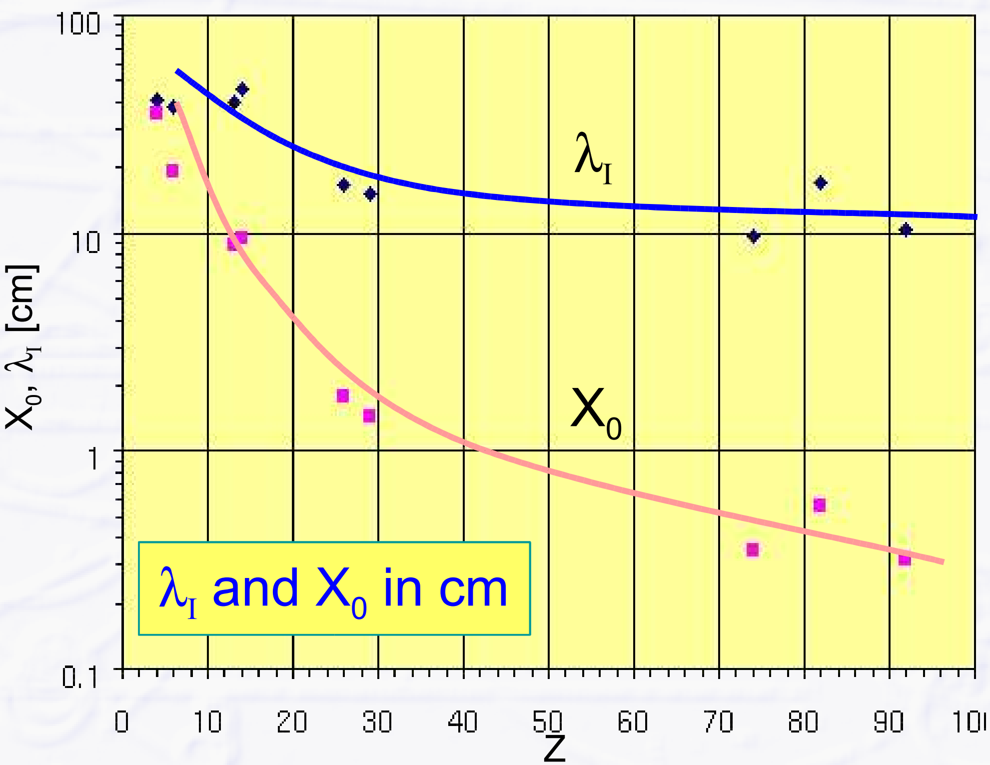
"invisible" energy = large energy fluctuations

Radiation and Nucl. Interaction Lengths

- **Typical radiation length**
  - **gases, e.g. Argon ~100 m**
  - **light materials, e.g. Aluminum, Silicon ~10 cm**
  - **heavier metals, e.g. Iron, Copper, Lead ~ 0.5 – 1.5 cm**

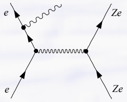
For Z > 6: $\lambda_I > X_0$

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_I [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0



Charged Particle Interactions

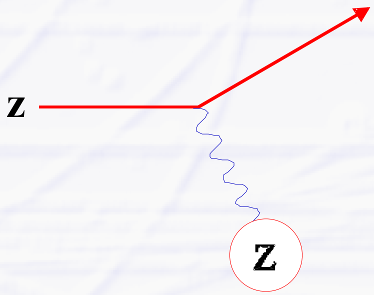
- (Multiple) elastic scattering with atoms of detector material
  - ➙ mostly unwanted, changes initial direction, affects momentum resolution
- Ionization
  - ➙ the basic mechanism in tracking detectors
- Photon radiation
  - ➙ Bremsstrahlung



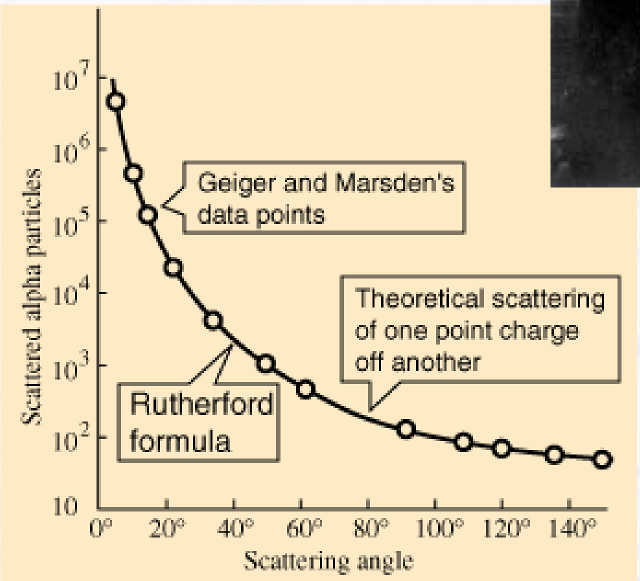
    - initiates electromagnetic shower in calorimeters, unwanted in tracking detectors
  - ➙ Čerenkov radiation
    - hadronic particle identification (ALICE),
      also in some homogeneous electromagnetic calorimeters (lead glass)
  - ➙ Transition radiation
    - electron identification in combination with tracking detector
- Excitation
  - ➙ creation of scintillation light in calorimeters (plastic scintillators, fibers)

Elastic Scattering

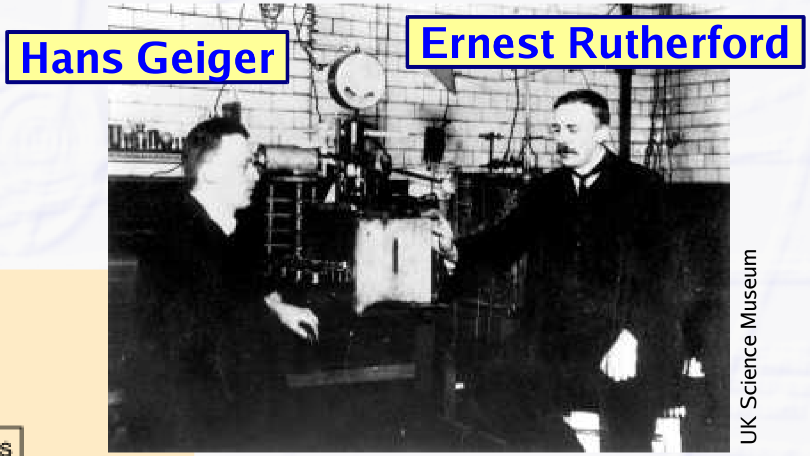
- **Most basic interaction of a charged particle in matter**
  - **elastic scattering with a nucleus = Rutherford (Coulomb) scattering**



$$\frac{d\sigma}{d\Omega} = 4zZr_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \Theta/2}$$



UK Science Museum

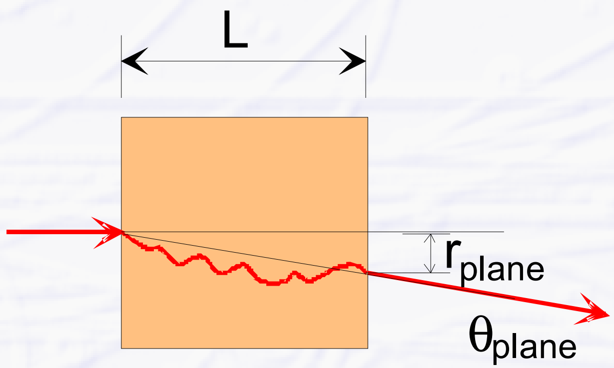


UK Science Museum

- **Approximations**
  - **non-relativistic**
  - **no spins**
- **Scattering angle and energy transfer to nucleus usually small**
  - **No (significant) energy loss of the incoming particle**
  - **Just change of particle direction**

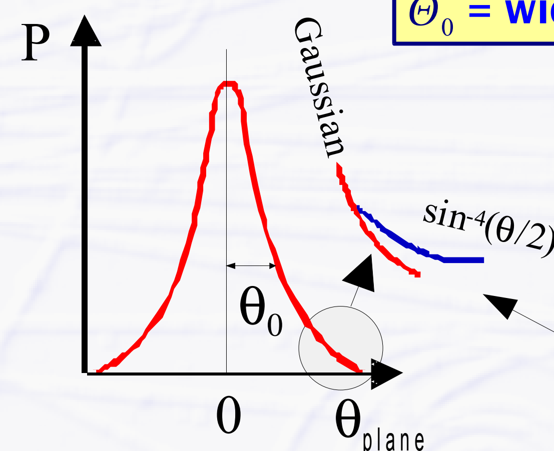
Multiple Scattering

- **If thick material layer: Multiple scattering**
  - after passing layer of thickness L particle leaves with some displacement r_{plane} and some deflection angle θ_{plane}



distribution of deflection angle

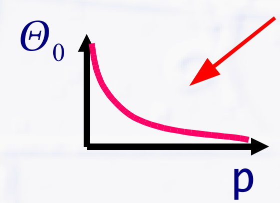
Θ_0 = width of distribution

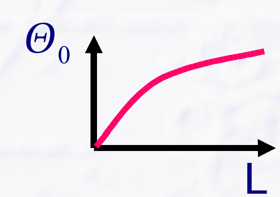


Gaussian is good approximation (except for tails)

- **Multiple scattering dominates momentum measurement for low momenta (see later)**

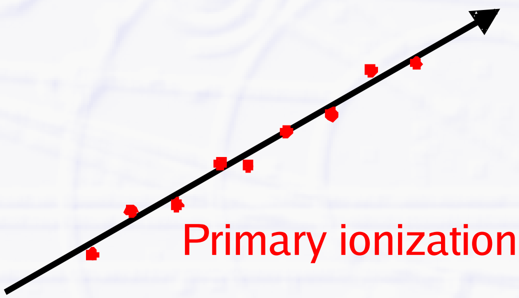
$$\Theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

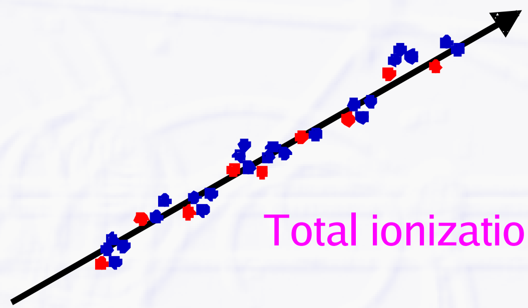




Ionization

- **Primary number of ionizations per unit length is Poisson-distributed**
  - typically ~30 primary interactions (ionization clusters) / cm in gas at 1 bar
- **However, primary electrons sometimes get large energies**
  - can make ionizations as well (secondary ionization)
  - can even create visible secondary track (“delta-electron”)
  - large fluctuations of energy loss by ionization





- Typically: total ionization = 3 x primary ionization
  - on average ~ 90 electrons/cm

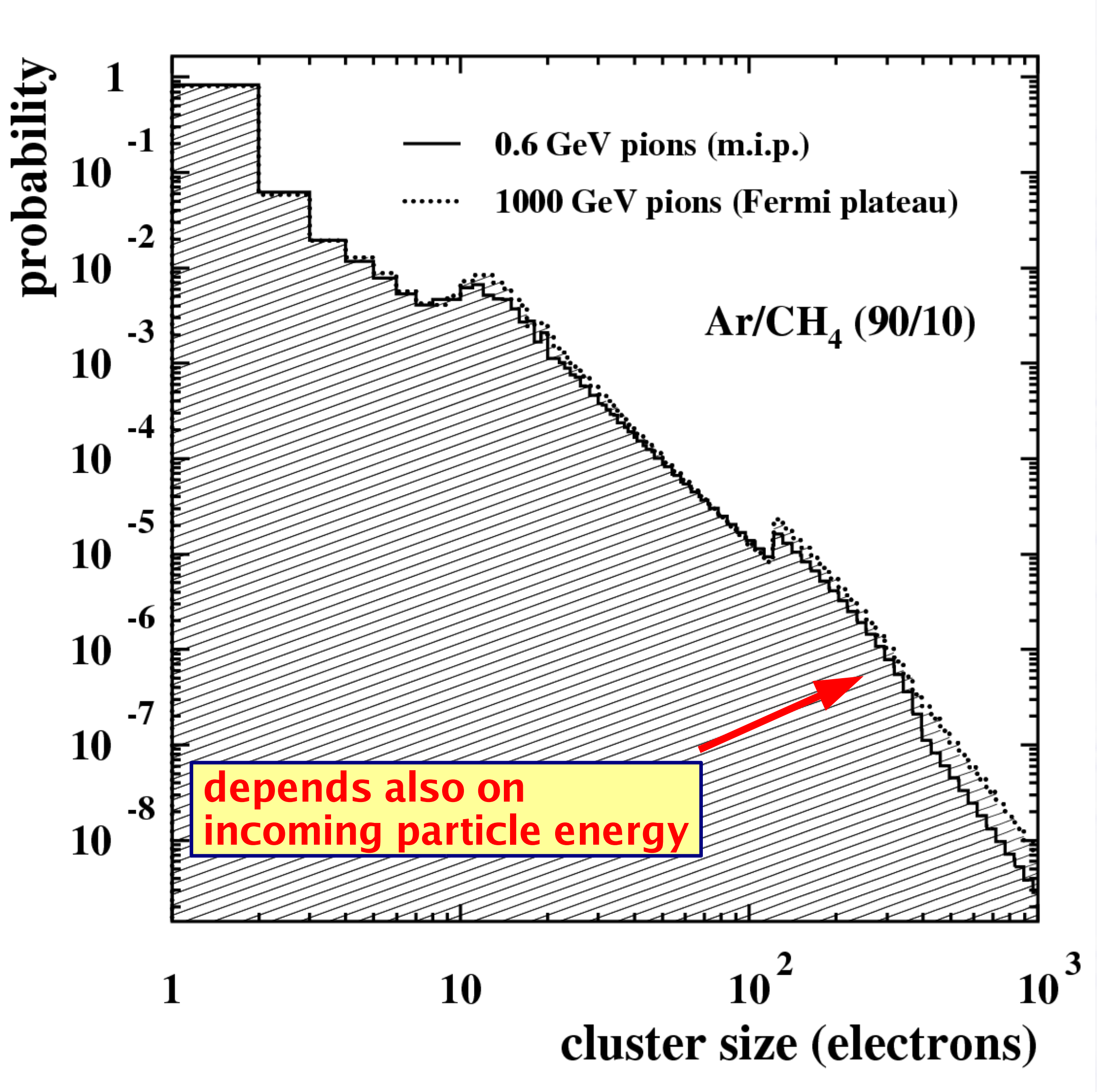
Ionization Cluster Size

- Probabilities (%) to create N_{el} electrons

	N_{el}	Ar	He
single el. →	1	65.6	76.6
multi el. cluster	2	15.0	12.5
	3	6.4	4.6
	4	3.5	2.0
	5	2.25	1.2
	6	1.55	0.75
	7	1.05	0.50
	8	0.81	0.36
	9	0.61	0.25
	10	0.49	0.19

data from H. Fischle et al., NIM A 301 (1991) 202

less multi-electron clusters at Helium (better!)

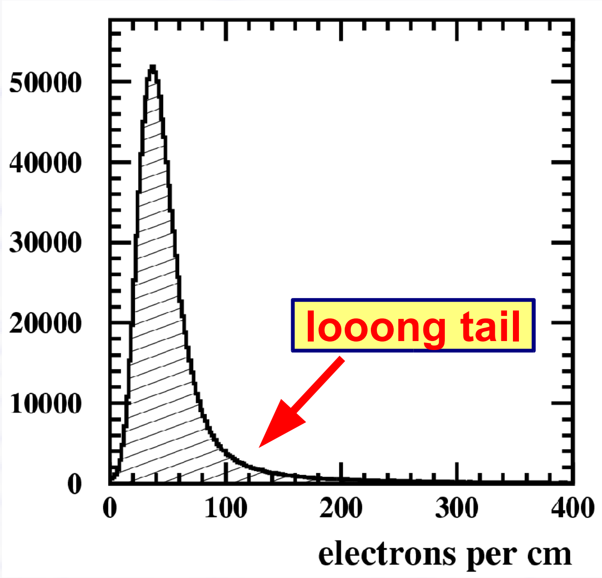


HEED cluster simulation (HEED written by I. Smirnov)

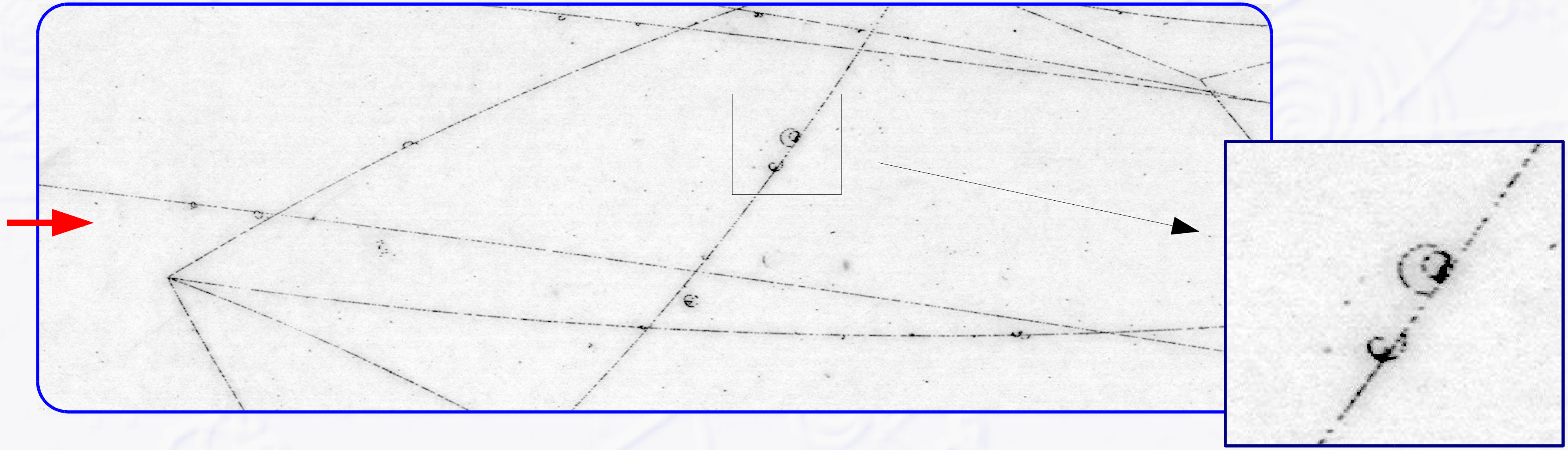
Energy Loss Distribution

- Cluster size fluctuations cause large variations of energy loss from track to track
  - Landau distribution
    - large broad peak (single or few el. clusters)
      - soft collisions, interaction with whole gas molecule
      - small energy transfer
    - looong tail (multi el. clusters, δ-electrons)
      - hard collisions, semi-free shell electrons
      - large energy transfer

1 cm sampling length



tracks in CERN 2m bubble chamber



Energy Loss Function (Bethe-Bloch)

- Mean energy loss as function of Q, βγ

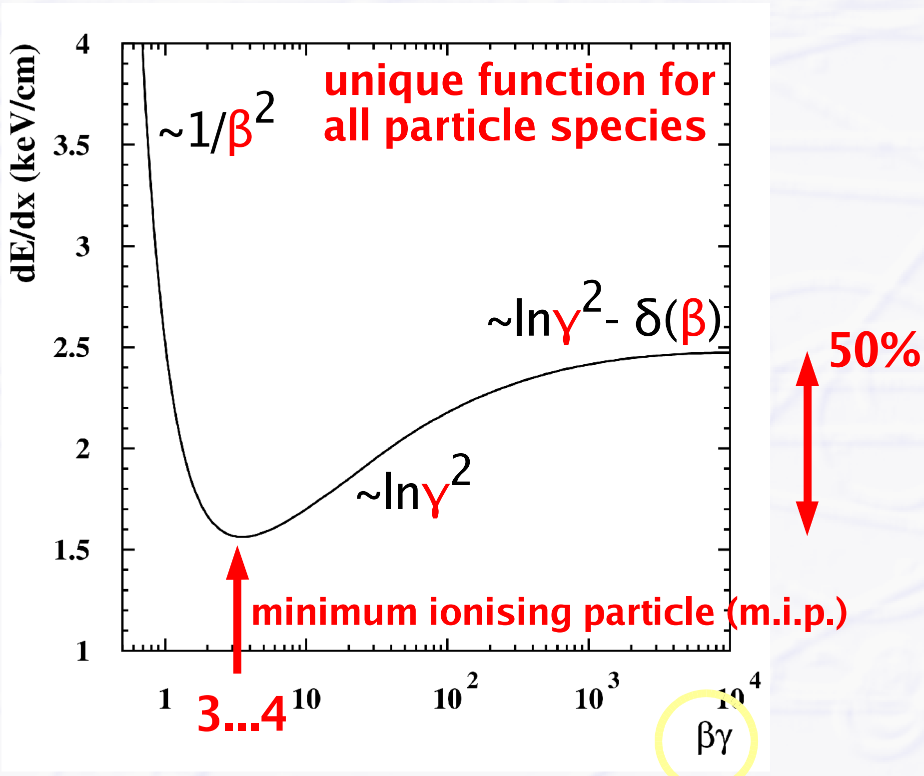
$$\langle dE/dx \rangle = \xi * 1/\beta^2 * Q^2 * [K + \ln Q^2 + \ln\gamma^2 - \beta^2 - \delta(\beta)]$$

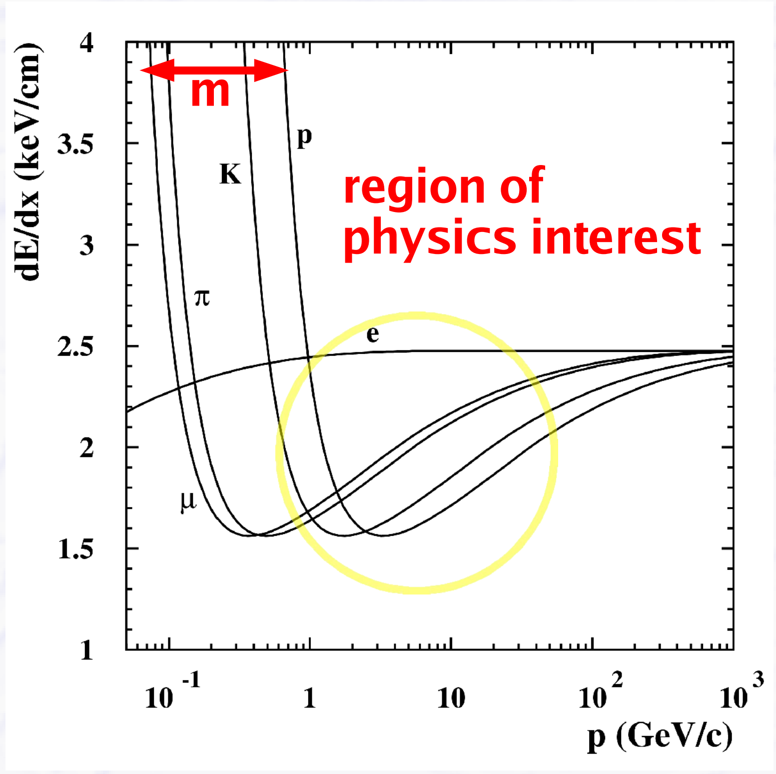
electron density of medium

classical Rutherford scattering

relativistic rise "Lorentz boost"

density effect: plateau due to polarization





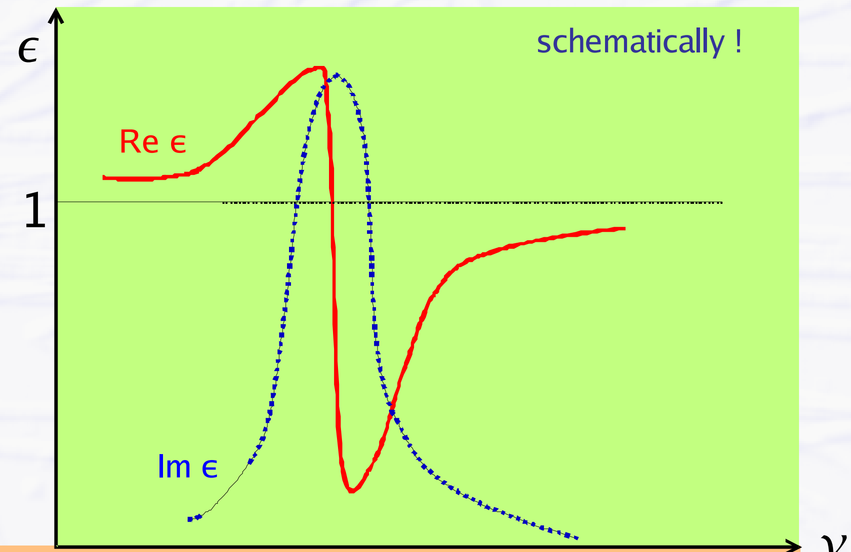
Energy Loss by Photon Emission

- **Ionization is one way of energy loss**
  - **emission of photons is another...**

Optical behaviour of medium is characterized by the (complex) dielectric constant ϵ

$\mathrm{Re}\,\sqrt{\epsilon} = n$ **Refractive index**

$\mathrm{Im}\,\epsilon = k$ **Absorption parameter**



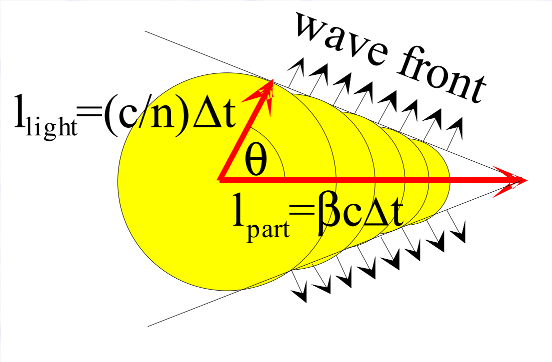
regime:	optical	absorptive	X-ray
effect:	Čerenkov radiation	ionization	transition radiation

Čerenkov Radiation

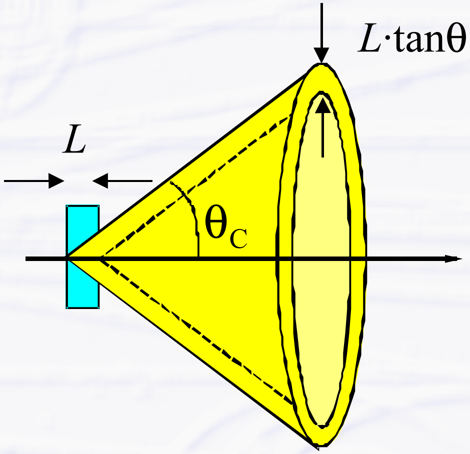
- Čerenkov radiation is emitted when a charged particle passes though a dielectric medium with velocity $\beta \geq \beta_{thres} = \frac{1}{n}$

  speed of light in medium

  - classical picture: wave front or cone under Čerenkov angle



$$\cos\Theta_C = \frac{1}{n\beta}$$



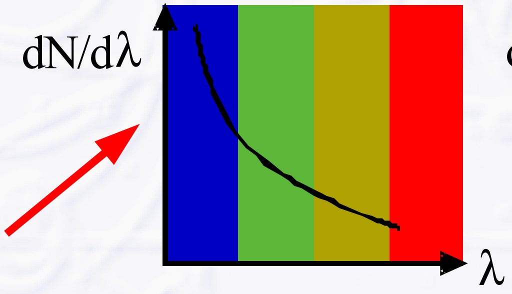
continuous wave front emission from track

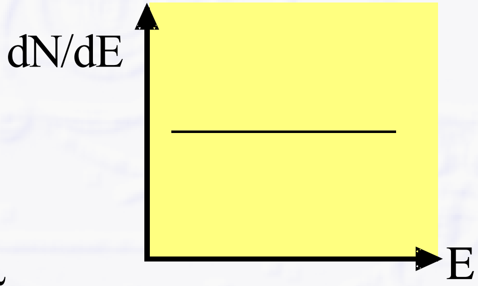
light cone emission when passing thin medium

  - number of emitted photons per unit length and unit wave length interval

$$\frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2} \qquad \frac{d^2N}{dx\,dE} = \text{const}$$

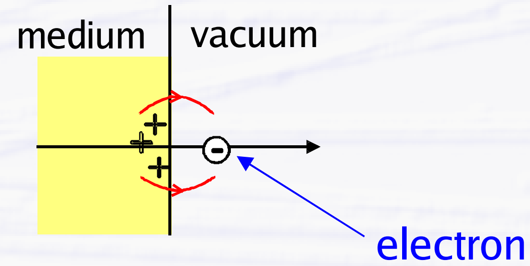
mainly UV photons!





Transition Radiation

- **Predicted by Ginzburg and Franck in 1946**
  - emission of photons when a charged particle traverses through the boundary of two media with different refractive index
  - (very) simple picture
    - charged particle is polarizing medium
    - polarized medium is left behind when particle leaves media and enters unpolarized vacuum
    - formation of an electrical dipol with (transition) radiation



- **Radiated energy per boundary** $W \propto \gamma$
  - only very high energetic particles can radiate significant energy
    - need about $\gamma > 1000$
      - in our present energy range reachable with accelerators only electrons can radiate
      - but probability to emit photons still small

$$N_{photons} \propto \alpha_{EM} \approx \frac{1}{137}$$

need many boundaries (foils, foam) to get a few photons