Calorimetry

in particle physics experiments

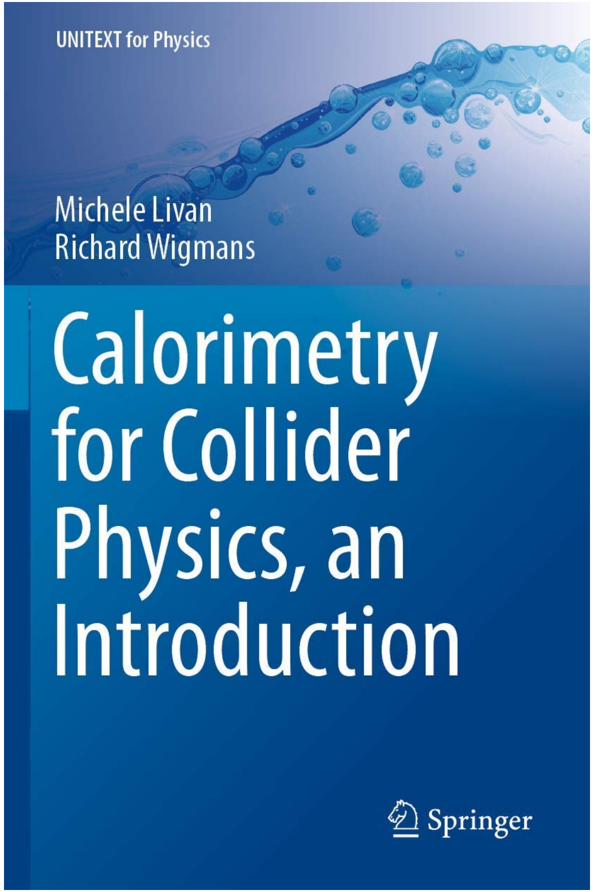
1.

Why Calorimetry? Motivation and Historical Landscape

Course roadmap

- **Week 1 (Foundations)**
  - ✓ Lecture 1: Why calorimetry?
  - ✓ Lecture 2: EM shower physics
- **Week 2 (Physics depth)**
  - ✓ Lecture 3: Hadronic shower physics
  - ✓ Lecture 4: Energy resolution from first principles
- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies (real-life EM and Hadronic calorimeters)
  - ✓ Lecture 6: Calorimeter Design
- **Week 4 (Systems & Future)**
  - ✓ Lecture 7: Signal chain, readout, calibration
  - ✓ Lecture 8: Future calorimetry

Resources



UNITEXT for Physics

Michele Livan
Richard Wigmans

Calorimetry for Collider Physics, an Introduction

Springer

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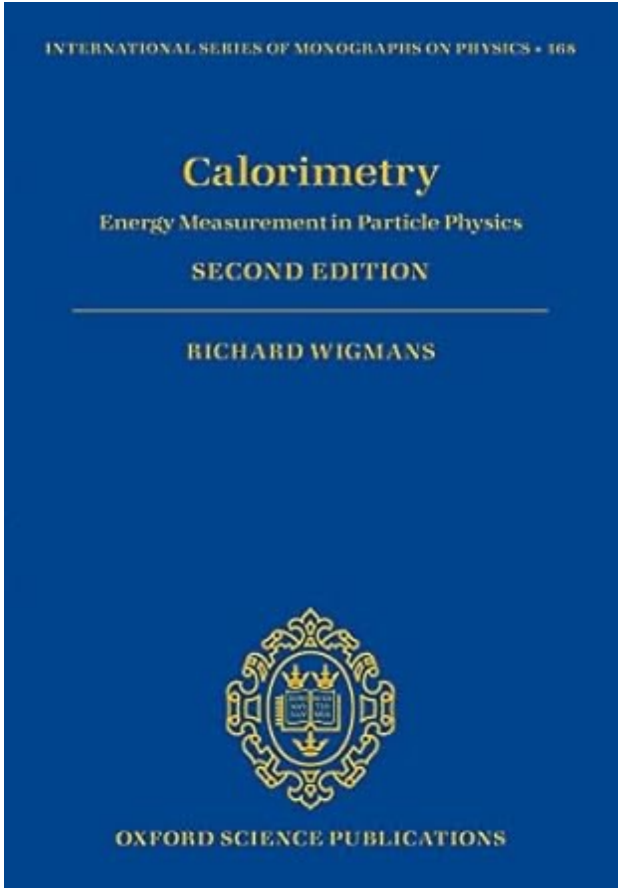

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Calorimetry

Energy Measurement in Particle Physics

SECOND EDITION

RICHARD WIGMANS

OXFORD SCIENCE PUBLICATIONS

https://academic.oup.com/book/26593

Today’s Lecture

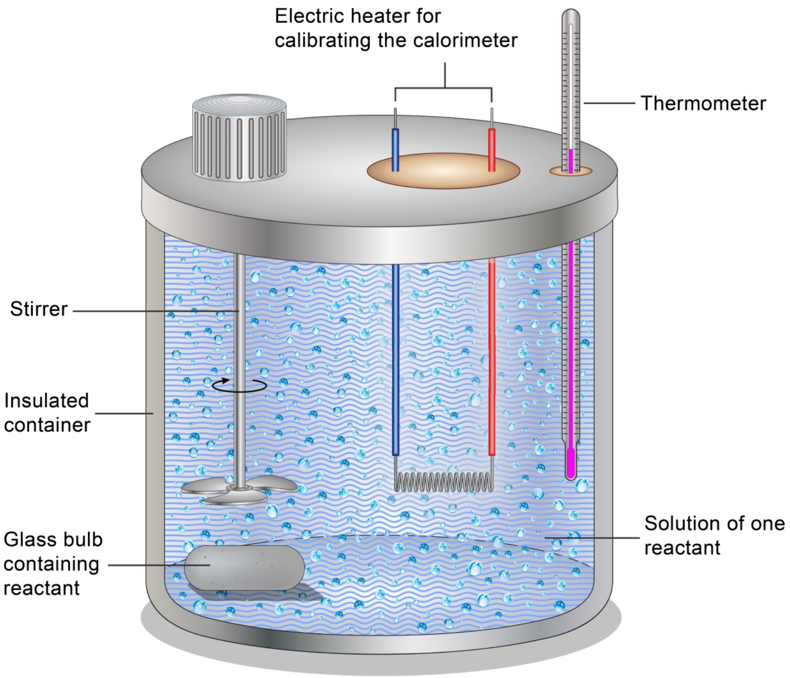
- **Week 1 (Foundations)**
  - ✓ Lecture 1: Why calorimetry?
    - *1.1 Why calorimetry?*
    - *1.2 Calorimeters in Detector Systems*
    - *Intermezzo: Coordinate system & Cross-section & Hadron vs Lepton Colliders*
    - *1.3 Historical Development*
  - ✓ Lecture 2: EM shower physics

1.1

Why Calorimetry?

What is a (generic) calorimeter?

- **In general: an apparatus used to measure the transfer of heat (energy) involved in a chemical reactions or physical changes**
  - ✓ E.g. a thermally hermetic box with a substance of which we want to measure the temperature, equipped with a thermometer
    - 1 calorie (4.185 J) = energy necessary to increase of one degree the temperature of 1 g of water at 15 C
- **In particle physics: a detector which measures the energy carried by a particle**
  - ✓ In particle physics the energy of a particle is measured in eV
    - 1 eV = energy acquired by one electron accelerated by a difference of potential of 1 V
    - 1 MeV = 10^6 eV; 1 GeV = 109 GeV; 1 TeV = 10^{12} eV

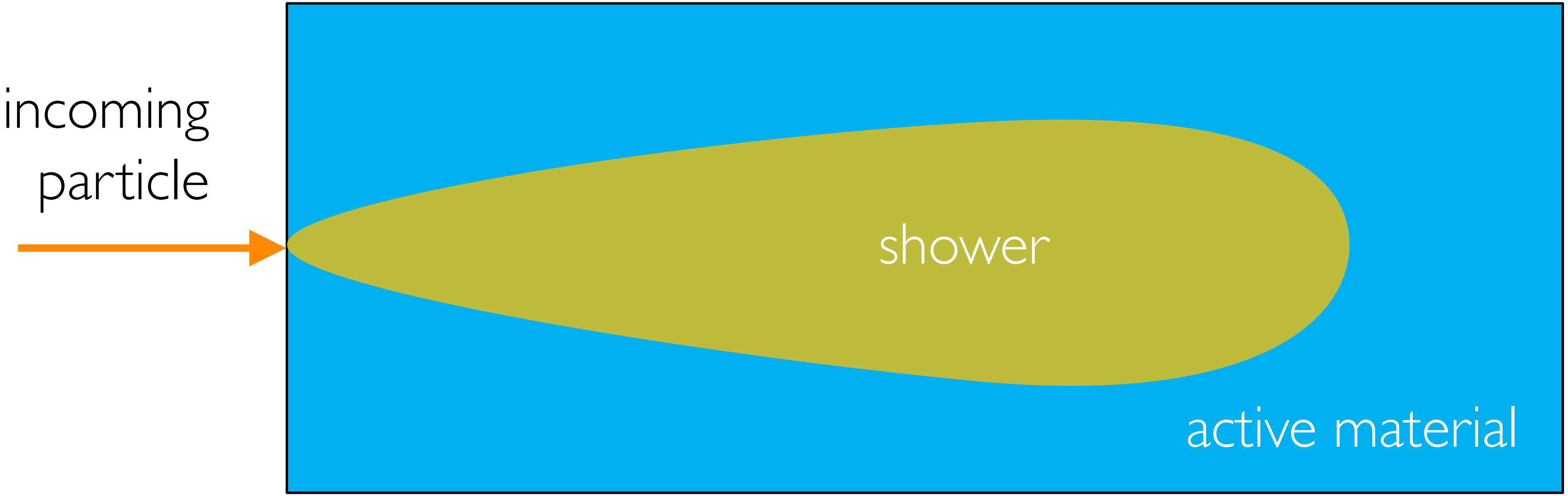


HEP, SI and “natural” units

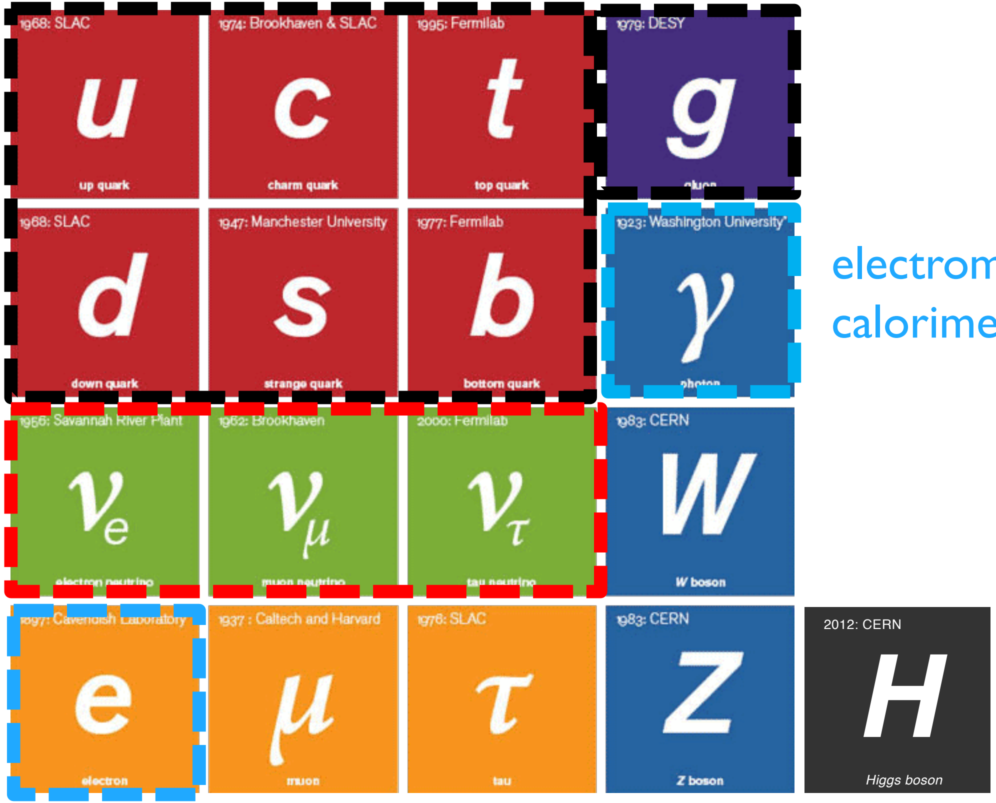
Quantity	HEP units	SI units
length	1 fm	10^{-15} m
charge	e	$1.602\square 10^{-19}$ C
energy	1 GeV	1.602×10^{-10} J
mass	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = h/2\pi$	6.588×10^{-25} GeV s	1.055×10^{-34} Js
c	2.988×10^{23} fm/s	2.988×10^{8} m/s
$\hbar c$	197 MeV fm	…
	“natural” units ($\hbar = c = 1$)	
mass	1 GeV	
length	1 GeV^{-1} = 0.1973 fm	
time	1 GeV^{-1} = 6.59×10^{-25} s	

What is a (particle physics) calorimeter?

- **A detector for energy measurement ** via total absorption of particles**
  - ✓ What particle can we use a calorimeter for? It depends on energy loss mechanisms
    - Example: a 10 GeV muon loses energy mainly by ionization, to absorb all the energy one needs ~9 m of iron
    - High energy electrons, photons, hadrons can deposit their energy much more efficiently...



What particle do we measure with calorimeters?



hadronic calorimeter (quarks and gluons form hadron jets)

electromagnetic calorimeter

"invisible": missing energy

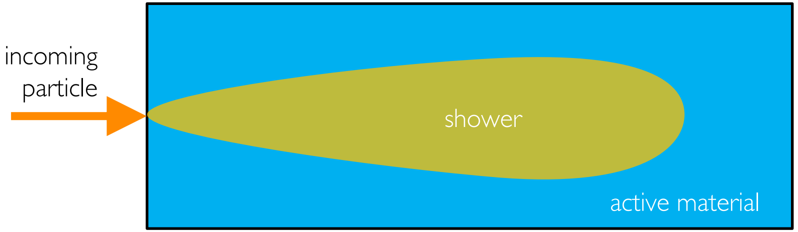
electromagnetic calorimeter

Note that at energy > 1 TeV muon calorimetry becomes possible as muons in lead/iron undergo interaction processes where the energy loss is proportional to the muon energy

What is a calorimeter?

- **A detector for energy measurement** via total absorption of particles**
- **Principles of operation:**

1. Incoming particle initiates a "particle shower"
   - Shower properties depend on particle type and detector material
     - Electrons & photons → Electromagnetic shower → Electromagnetic calorimeter
     - Hadrons → Hadronic shower → Hadronic calorimeter
2. Energy is deposited in "active" regions
   - Different calorimeters use different kind of signals
     - Ionization charge, atom excitation (scintillation light), Cherenkov light, …
3. Signal is "proportional" to energy released
   - Proportionally → calibration
   - Shower containment

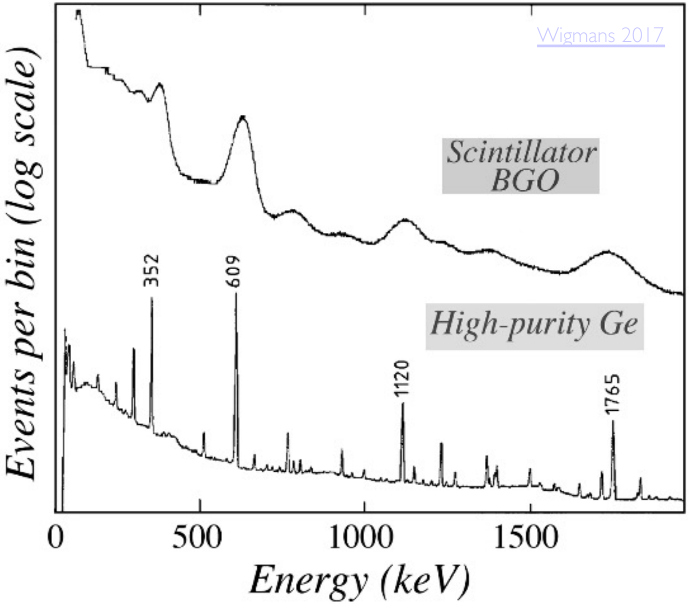


* *Also sensitive to particle position: fundamental for neutral particles!*

* *Segmentation allows particles identification and more!*

Why calorimetry? Neutral particles are invisible to trackers

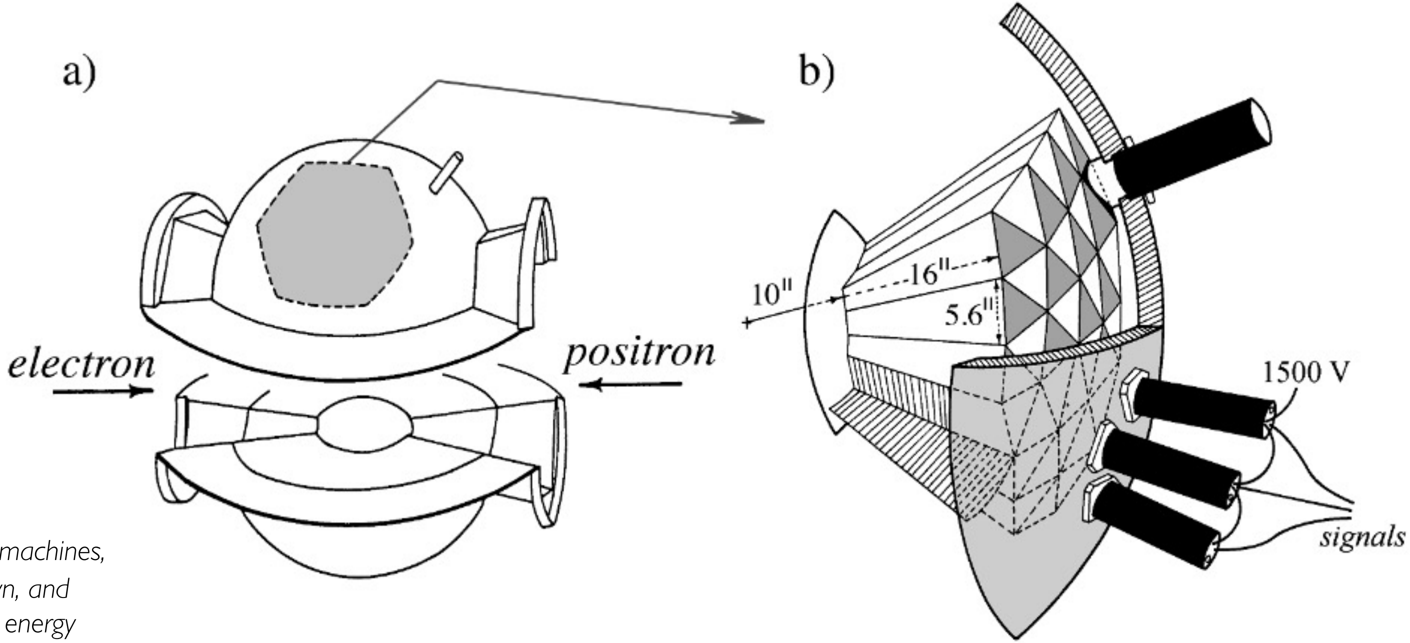
- Neutral particles are invisible to tracking detectors!
  - ✓ Historical use cases from nuclear physics
    - e.g. spectroscopy of excited states which decay into X + nπ^0
  - ✓ In general, detector of neutrals (e.g. γ, neutrons) or neutral products ($\pi^0 \rightarrow \gamma\gamma$)
  - ✓ Pioneer measurements in early 1950s with calorimeters based on crystals such as NaI(Tl) used as γ-ray detectors
  - ✓ Following milestone around 1965, when semiconductor detectors for γ-ray detection made their appearance



Why calorimetry? Missing energy reconstruction

- Missing (transverse) energy as signature of undetectable particles
- Kinematic closure of event * allows for measurement of the event energy flow
  - ✓ Requirement: hermetic (4π) calorimetric coverage

Example of one of the first $4\boldsymbol{\pi}$ hermetic calorimeter: Crystal Ball at SLAC e+e– **SPEAR, a** NaI(Tl) Crysal calorimeter

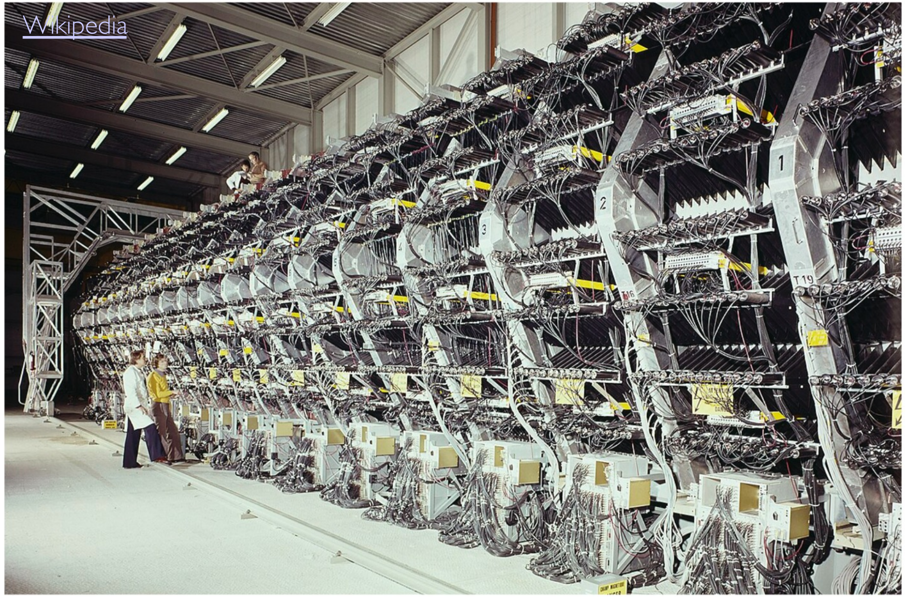


Wigmans 2017

** Particularly important at e^+e^- collider machines, where energy of collision is well known, and collision produces particles with total energy equal to the center-of-mass energy*

Why calorimetry? Detect neutrinos

- Late 60's - early 70's saw advent of intense high energy neutrino beam
- Need for highly massive detectors to study neutrinos interaction (cross section extremely small ~10^{10} smaller than hadron interaction cross-sections)
  - ✓ *Detector also acting as target to study inelastic process*
  - ✓ *Detector should be uniformly sensitive to reaction products!*


Wikipedia

CDHS (CERN-Dortmund-Heidelberg-Saclay) neutrino experiment
Designed to study deep inelastic neutrino interactions in iron.
The detector had a mass of 1250 tons and combined the functions of a muon spectrometer and hadron calorimeter. It consisted of 19 magnetized iron modules, separated from each other by wire drift chambers.

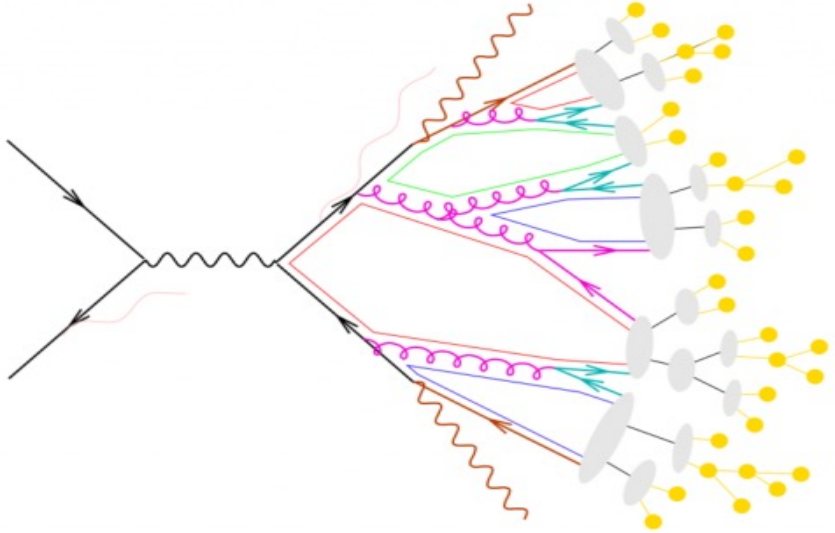
Why calorimetry? Measure hadronic jets

- QCD asymptotic freedom and confinement:
  - ✓ at short distances strong interactions weak, quarks and gluons essentially free particles;
  - ✓ at large distances, higher-order diagrams dominate, interaction very strong (perturbative regime fails, effective models needed)

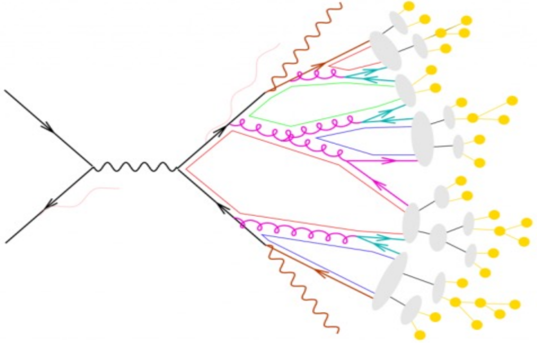
quark-quark effective potential

$$V_s = \underbrace{-\frac{4}{3}\frac{\alpha_s}{r}}_{\text{single gluon exchange}} + \underbrace{kr}_{\text{confinement}}$$

- Quarks and gluons hadronise into collimated jets
  - ✓ Jet retains direction and energy of parent parton
  - ✓ Moving from description of the single particles to measurement of global characteristics (energy flow, missing energy, jets energy)



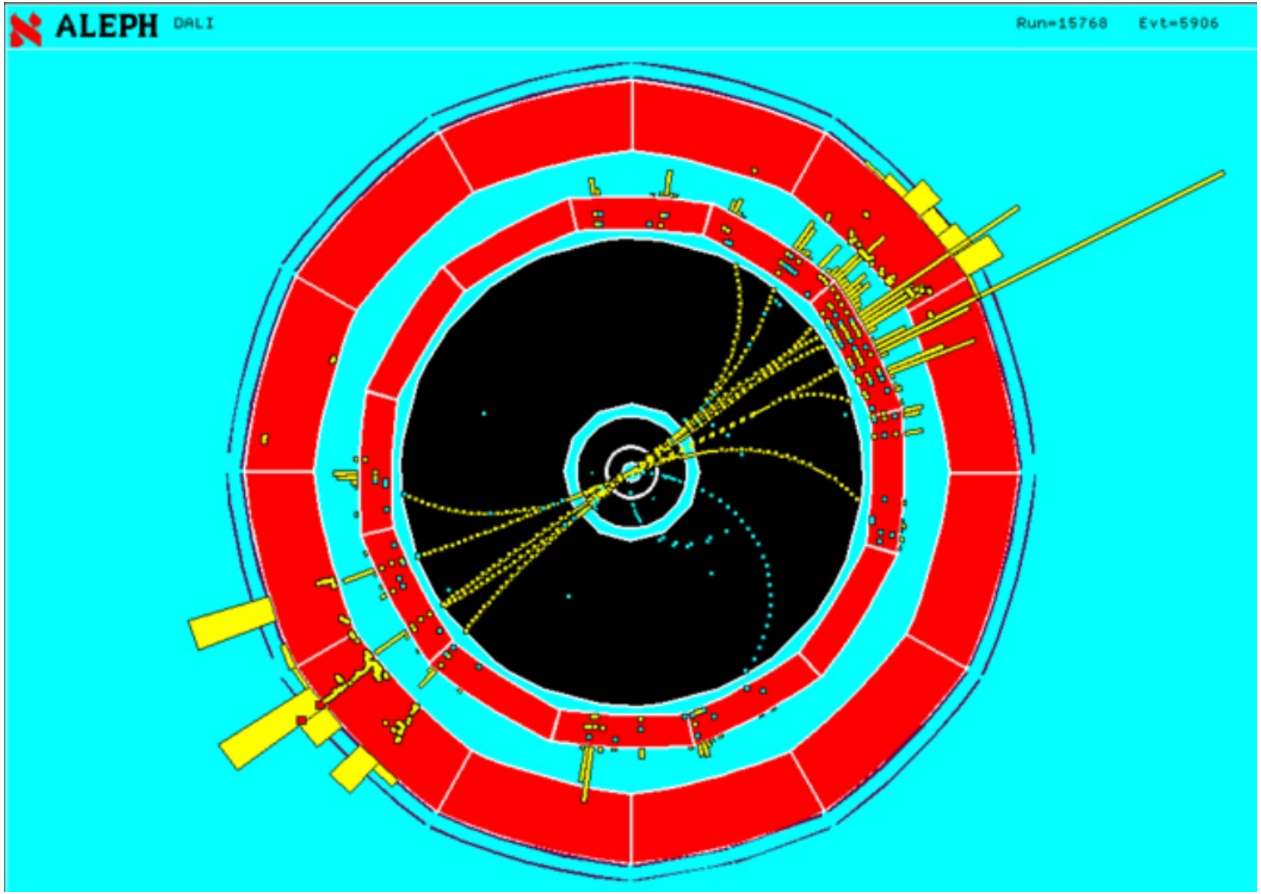
Why calorimetry? Measure hadronic jets



$$e^+e^- \rightarrow Z \rightarrow q\bar{q}$$

Discovery of jet-like events in e^+e^- collisions at SLAC in 1975 stimulated community to introduce calorimeters:

- better energy resolution than magnetic spectrometers
- capability of measuring the energy of charged as well as neutral particle



Why measure particle *energy* with a calorimeter?

- Fundamental contrast with spectrometers: calorimeters *absorb* rather than *deflect*
  - ✓ Spectrometer: particle survives, momentum measured from curvature
  - ✓ Calorimeter: particle destroyed, energy inferred from shower total

- Energy (momentum) resolution

Calorimeter

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

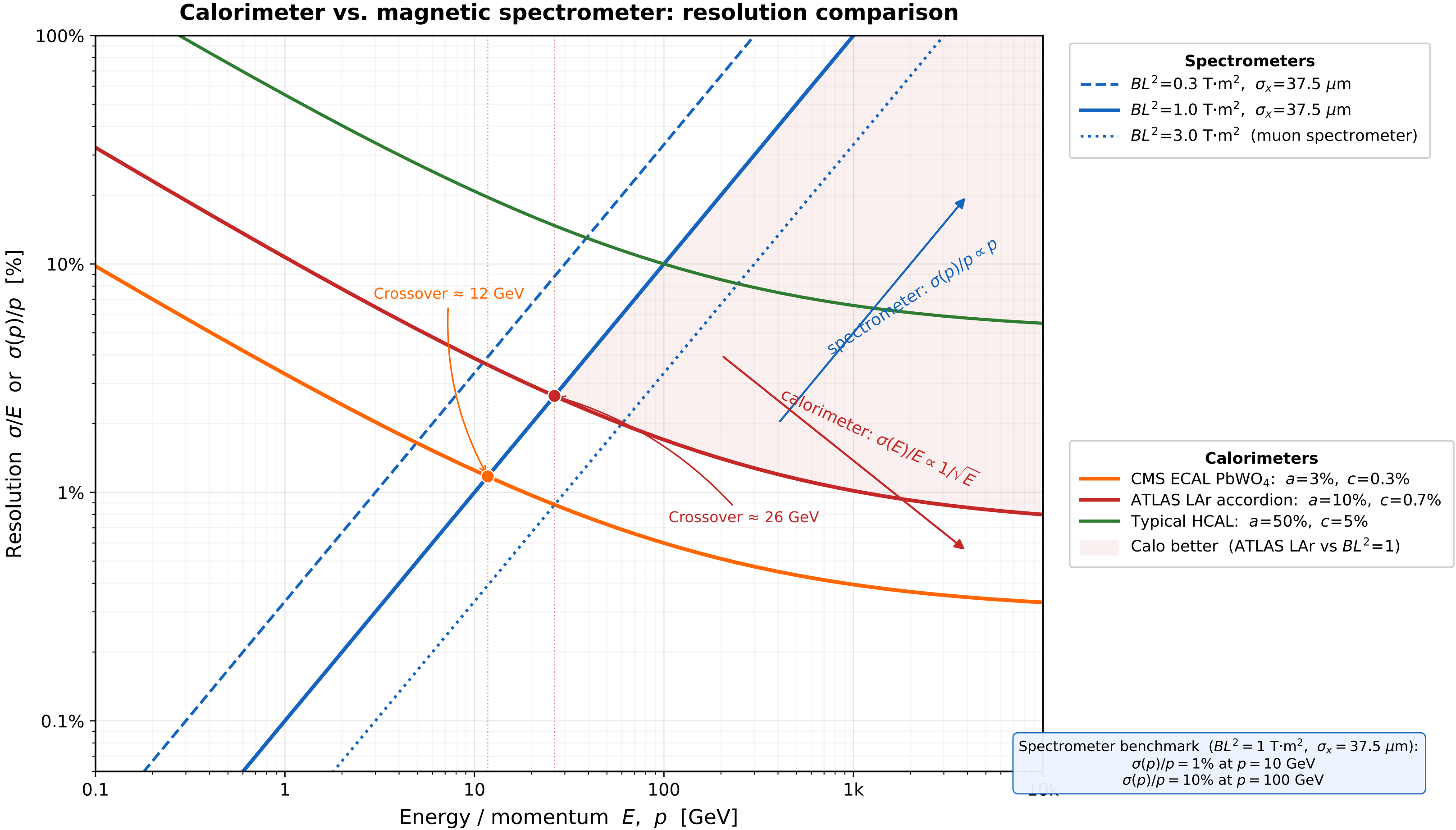
$$\frac{\sigma(E)}{E} \simeq \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad E[\mathrm{GeV}]$$

Spectrometer

$$\frac{\sigma(p)}{p} \propto p$$

$$\frac{\sigma(p)}{p} \simeq \frac{8\,\sigma_x\,p}{0.3\;B\,L^2}, \quad p\;[\mathrm{GeV}],\; B\;[\mathrm{T}],\; L\;[\mathrm{m}],\; \sigma_x\;[\mathrm{m}]$$

Calorimeters vs. magnetic spectrometers

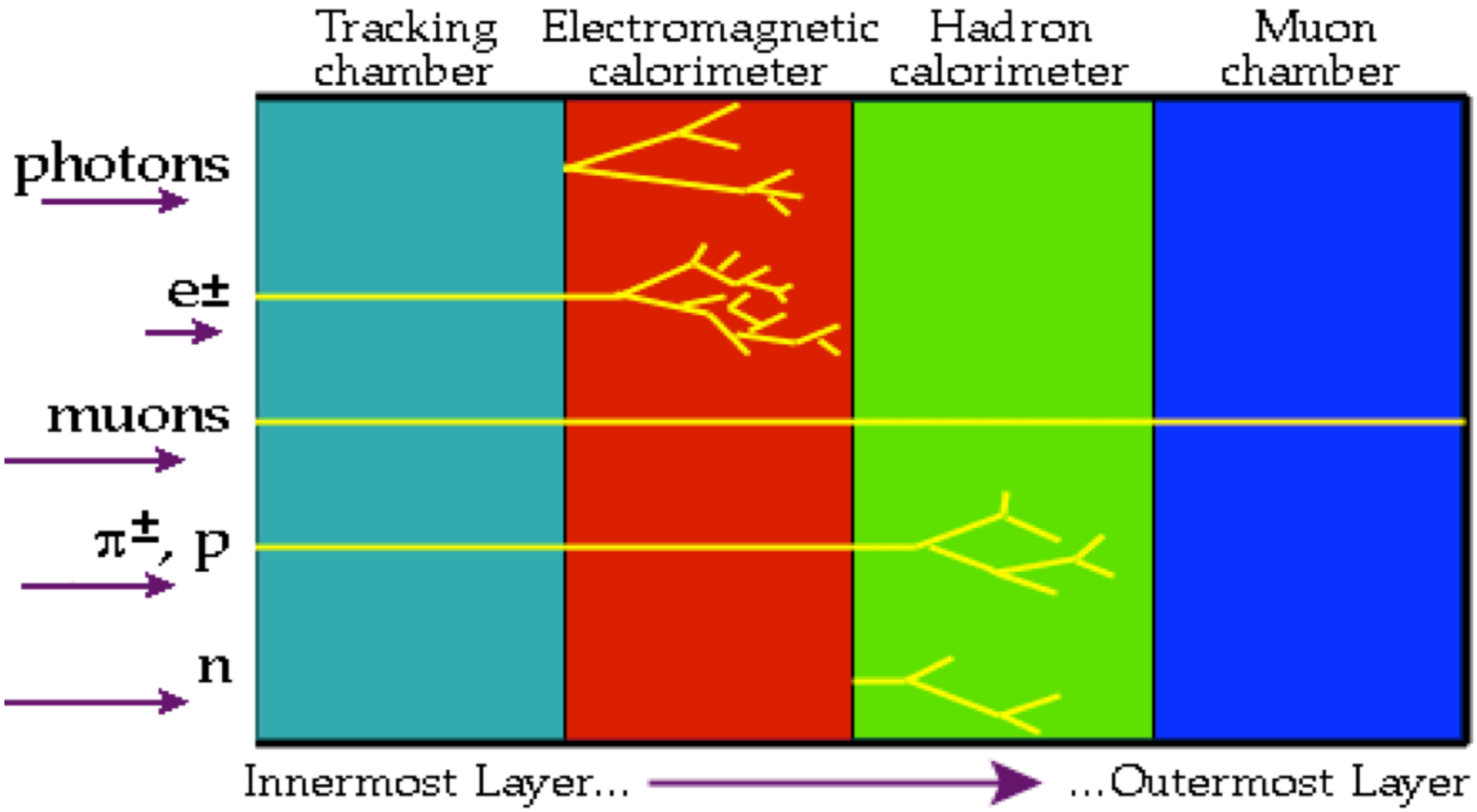

Calorimeter vs. magnetic spectrometer: resolution comparison

Spectrometer benchmark ($BL^2 = 1$ T·m^2, $\sigma_x = 37.5$ μm):
$\sigma(p)/p = 1\%$ at $p = 10$ GeV
$\sigma(p)/p = 10\%$ at $p = 100$ GeV

1.2

Calorimeters in Detector Systems

How do we “see” particles?



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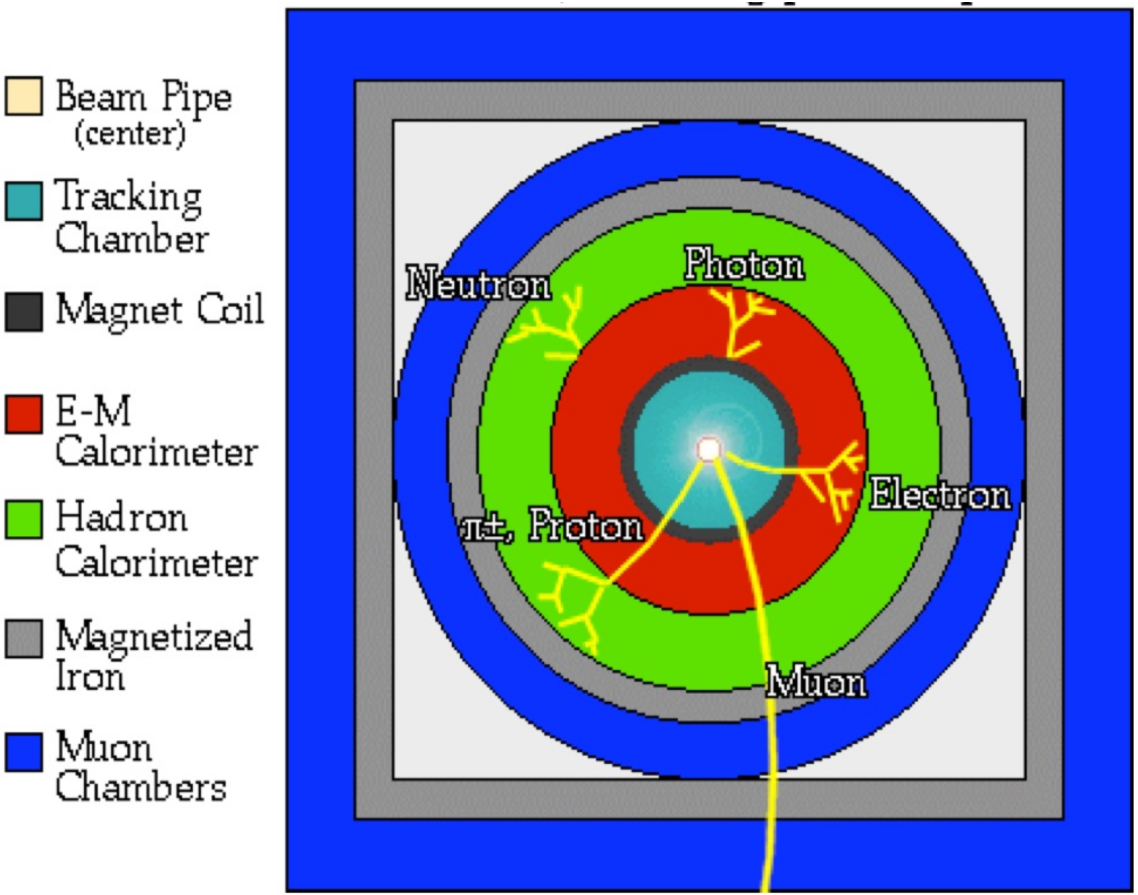
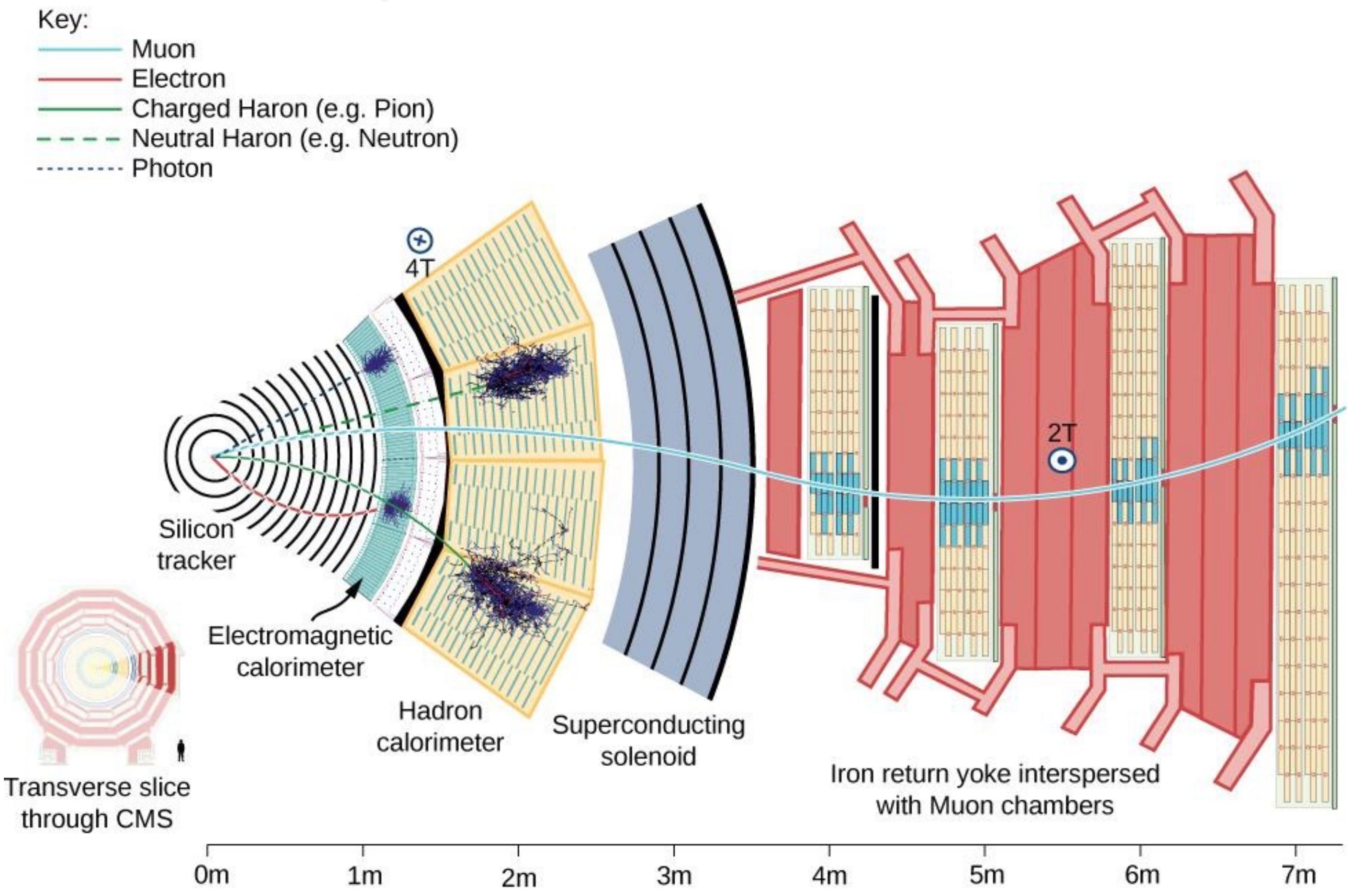


How do we "see" particles?



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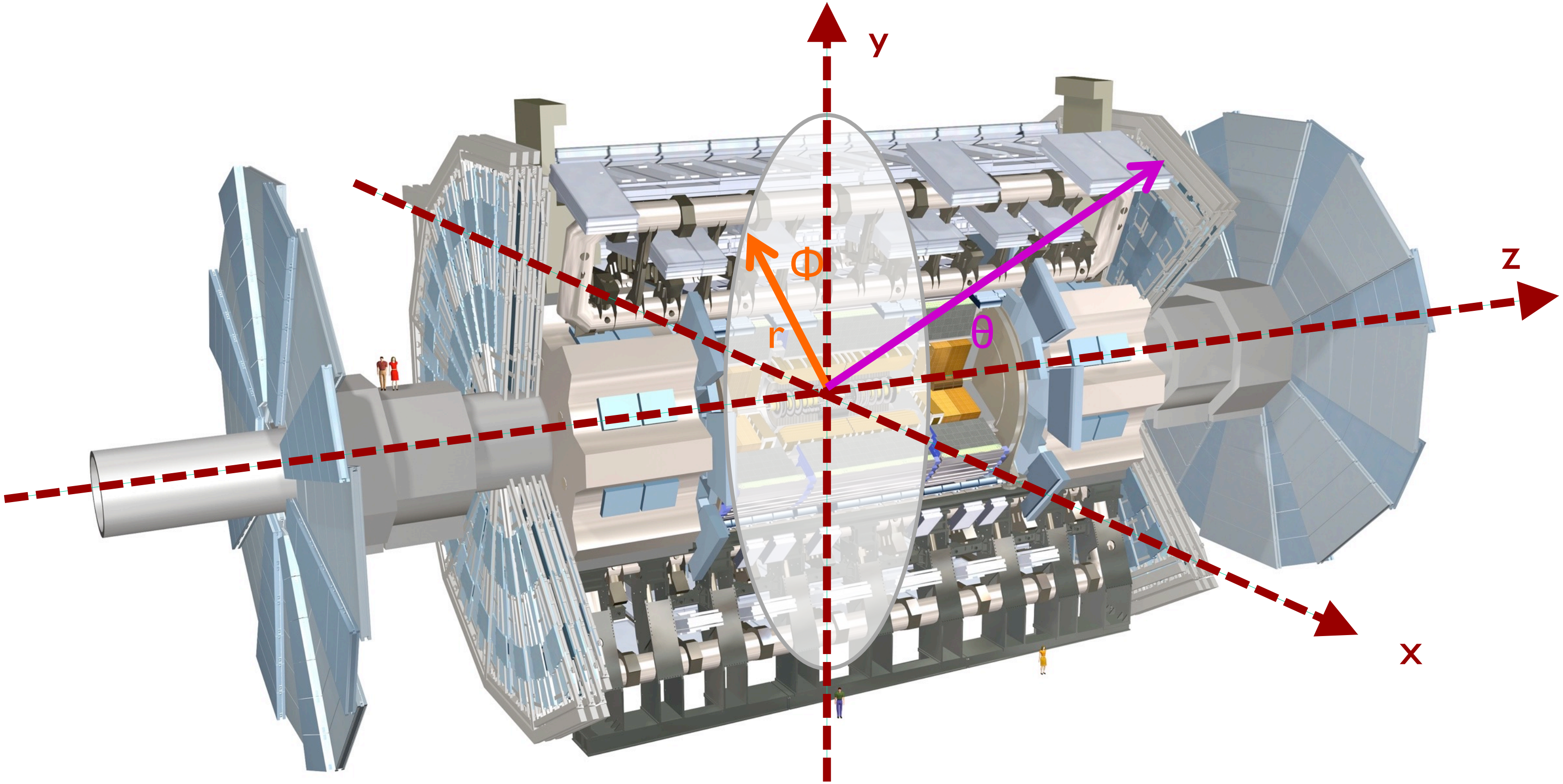
Coordinate system &

Cross-section &

Hadron vs Lepton Colliders

Collider experiment coordinates



Rapidity

Lorentz factor $$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \cosh\varphi$$ Hyperbolic cosine of “rapidity”

$$E = m\cosh\varphi$$
$$|\vec{p}| = m\sinh\varphi$$

$$\varphi = \tanh^{-1}\frac{E}{|\vec{p}|} = \frac{1}{2}\ln\frac{E+|\vec{p}|}{E-|\vec{p}|}$$

- Particle physicists prefer to use modified rapidity along beam axis

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

Pseudorapidity

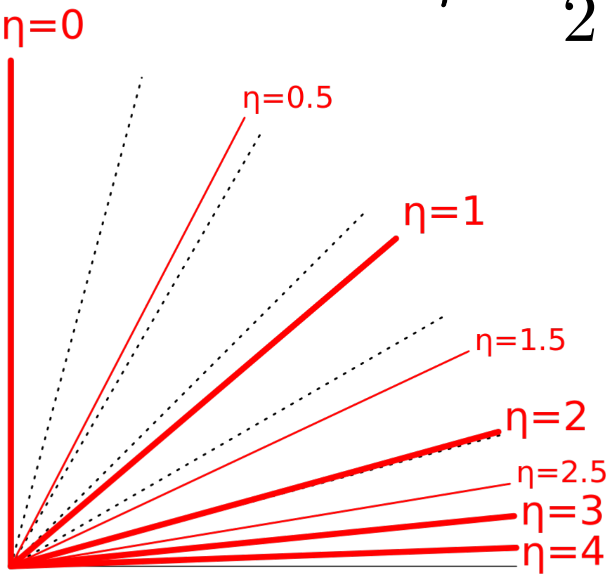
$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

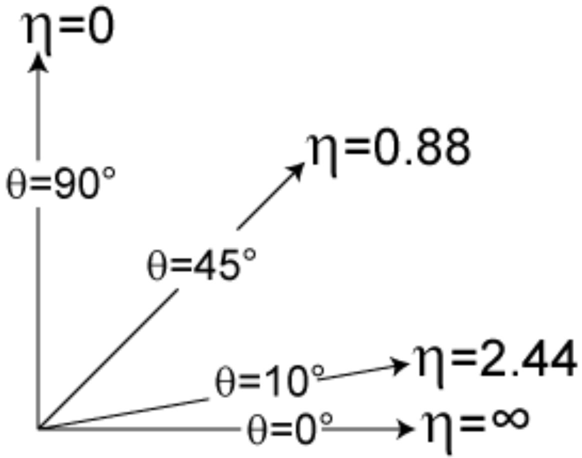
$$\eta = \frac{1}{2} \ln \left(\tan \frac{\theta}{2} \right)$$

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

$$\eta \simeq y$$

if E >> m





Transverse variables

- At hadron colliders, a significant and unknown fraction of the beam energy in each event escapes down the beam pipe.
- Net momentum can only be constrained in the plane transverse to the beam z-axis!

$$\sum p_T(i) = 0$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\begin{aligned} p_x &= p_T \cos\phi \\ p_y &= p_T \sin\phi \\ p_z &= p_T \sinh\eta \end{aligned}$$

$$|p| = p_T \cosh\eta$$

$$E_T = \frac{E}{\cosh\eta}$$

Missing transverse energy and transverse mass

- If invisible particle are created, only their transverse momentum can be constrained: missing transverse energy

$$E_T^{\mathrm{miss}} = \sum p_T(i)$$

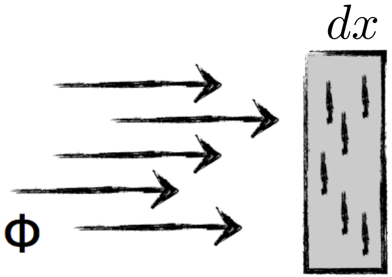
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can be constrained with the transverse mass quantity

$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)] \end{aligned}$$

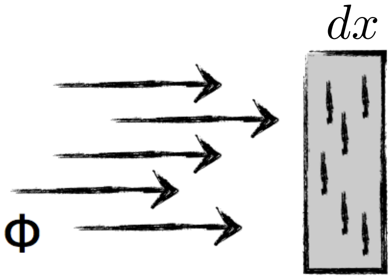
if $m_1 = m_2 = 0$ $\quad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$

Interaction cross section

Flux $$\Phi = \frac{1}{S}\frac{dN_i}{dt}$$ [L^{-2} t^{-1}]



Interaction cross section

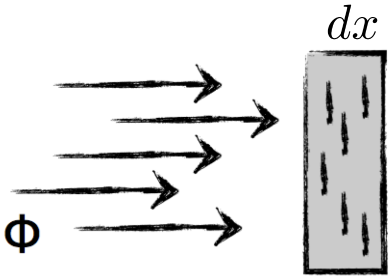


Flux $$\Phi = \frac{1}{S}\frac{dN_i}{dt}$$ [L^{-2} t^{-1}]

area obscured by target particle

Reactions per unit of time $$\frac{dN_{\mathrm{reac}}}{dt} = \underbrace{\Phi}_{[L^{-2}\,t^{-1}]}\overbrace{\underbrace{\sigma}_{[?]}\underbrace{N_{\mathrm{target}}}_{[L^{-1}]}\underbrace{dx}_{[L]}}$$ [t^{-1}]

Interaction cross section



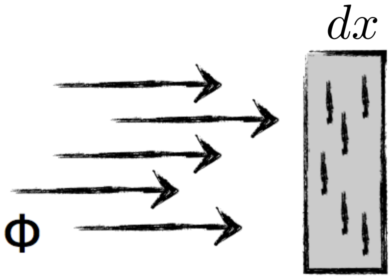
Flux $$\Phi = \frac{1}{S}\frac{dN_i}{dt}$$ $[L^{-2}\, t^{-1}]$

Reactions per unit of time
$$\frac{dN_{\text{reac}}}{dt} = \underbrace{\Phi \sigma}_{W_{if}} \overbrace{\sigma N_{\text{target}} dx}^{\text{area obscured by target particle}}$$ $[t^{-1}]$

$[L^{-2}\, t^{-1}]$ $[?]$ $[L^{-1}]$ $[L]$

Reaction rate per target particle $$W_{if} = \Phi\sigma$$ $[t^{-1}]$

Interaction cross section



Flux $\Phi = \frac{1}{S}\frac{dN_i}{dt}$ $[L^{-2}\,t^{-1}]$

Reactions per unit of time

$$\frac{dN_\mathrm{reac}}{dt} = \Phi\overbrace{\sigma N_\mathrm{target}\,dx}^{\textit{area obscured by target particle}} \qquad [t^{-1}]$$

$$\underbrace{[L^{-2}\,t^{-1}]\quad[?]}\qquad [L^{-1}]\qquad [L]$$

Reaction rate per target particle $W_{if} = \Phi\sigma$ $[t^{-1}]$

Cross section per target particle

$$\sigma = \frac{W_{if}}{\Phi} \qquad [L^2]$$

= reaction rate per unit of flux

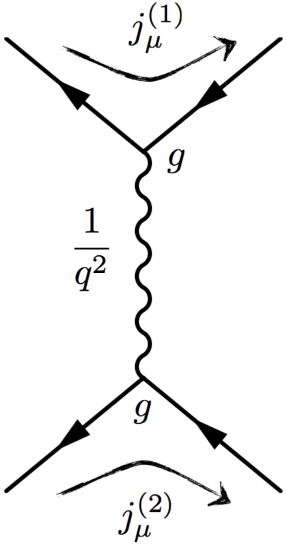
1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

Fermi Golden Rule

From non-relativistic perturbation theory…

$$\overbrace{W_{if}}^{\textit{transition probability}} = \frac{2\pi}{\hbar}\overbrace{|M_{if}|}^{\textit{matrix element}}{}^2\,\overbrace{\frac{dN}{dE_f}}^{\textit{energy density of final states}}$$

[t⁻¹] [E] [E⁻¹]

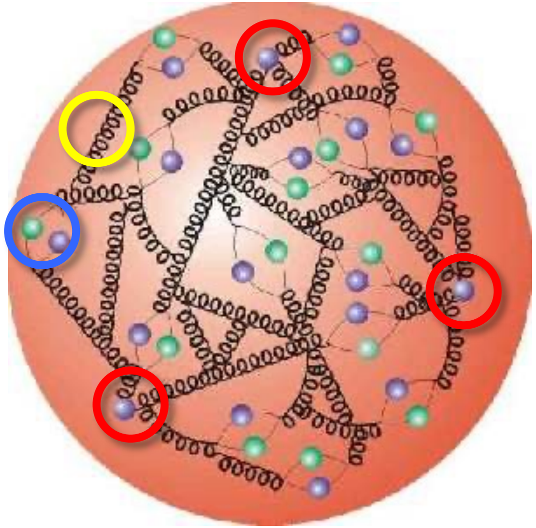


$$M_{if} = -i\int j_\mu^{(1)}\left(\frac{1}{q^2}\right)j_\mu^{(2)}d^4x$$

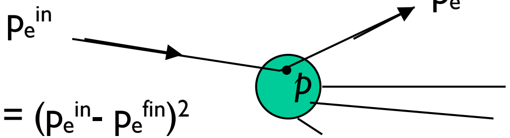
$$\sigma \sim |M_{if}|^2 \sim g^4\left(\frac{1}{q^4}\right)$$

About the inner life of a proton

- ***p*rotons have substructures**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (colored) quarks bound by gluons
  - ✓ Gluons (colored) have self-interactions
  - ✓ Virtual quark pairs can pop-up (sea-quark)
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions

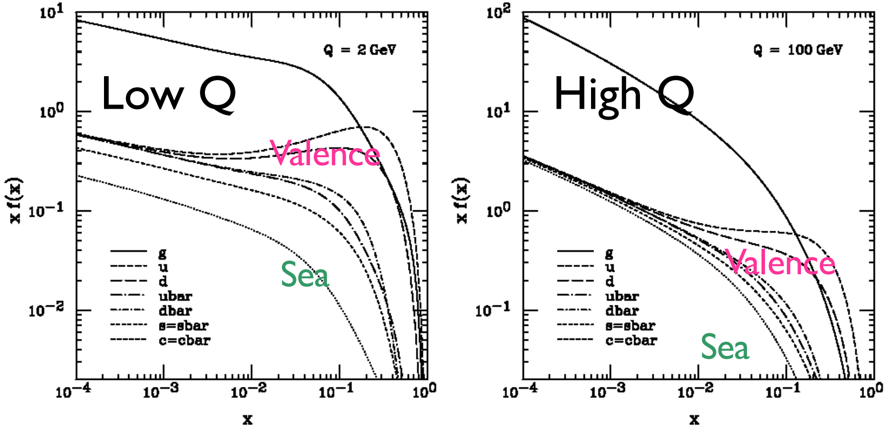


- **Parton energy not 'monochromatic'**
  - ✓ Parton Distribution Function
    - PDF = $q(x,Q^2)$, q = u,d,s,..g

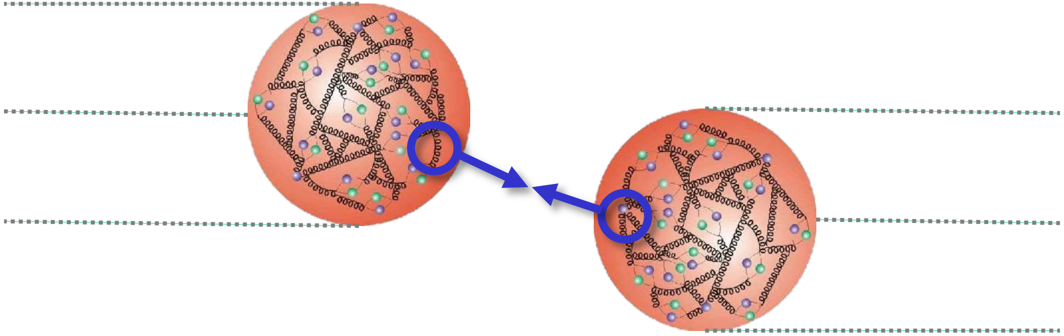


$Q^2 = (p_e^{in} - p_e^{fin})^2$

- **Kinematic variables**
  - ✓ Bjorken-x: fraction of the proton momentum carried by struck parton
    - $x = p_{parton}/p_{proton}$
  - ✓ Q^2 : 4-momentum^2 transfer

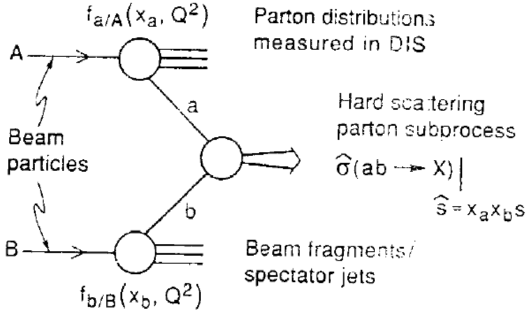


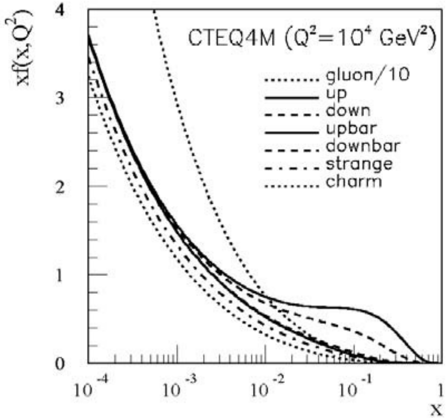
Cross sections at a proton-proton collider



$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x, Q^2) f_b(x, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$



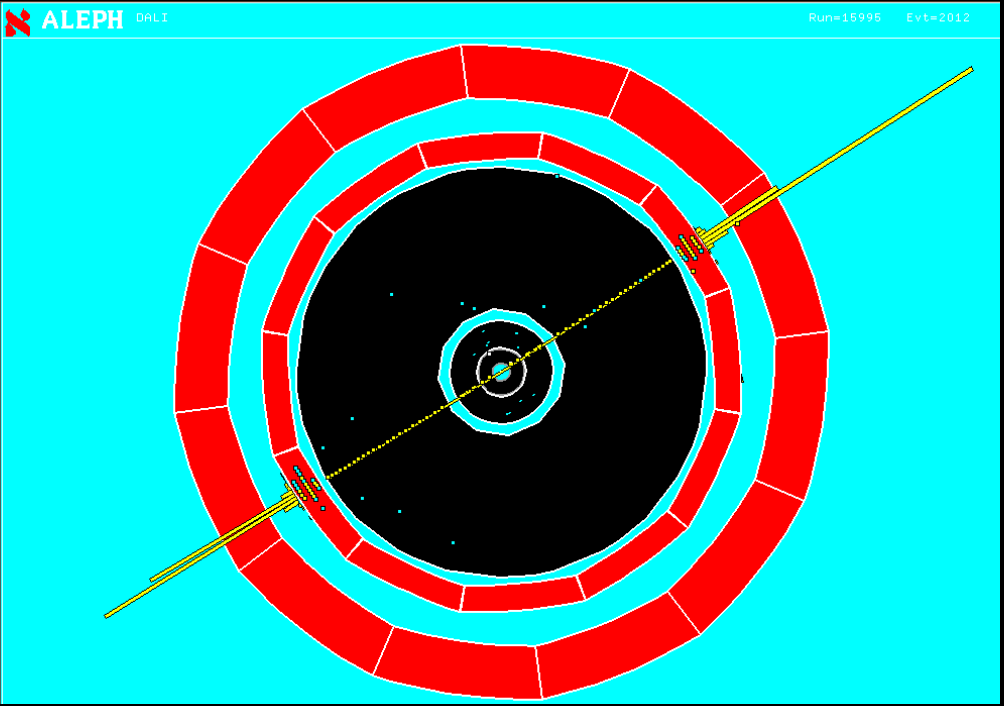


Example: to produce a particle with mass m = 100 GeV

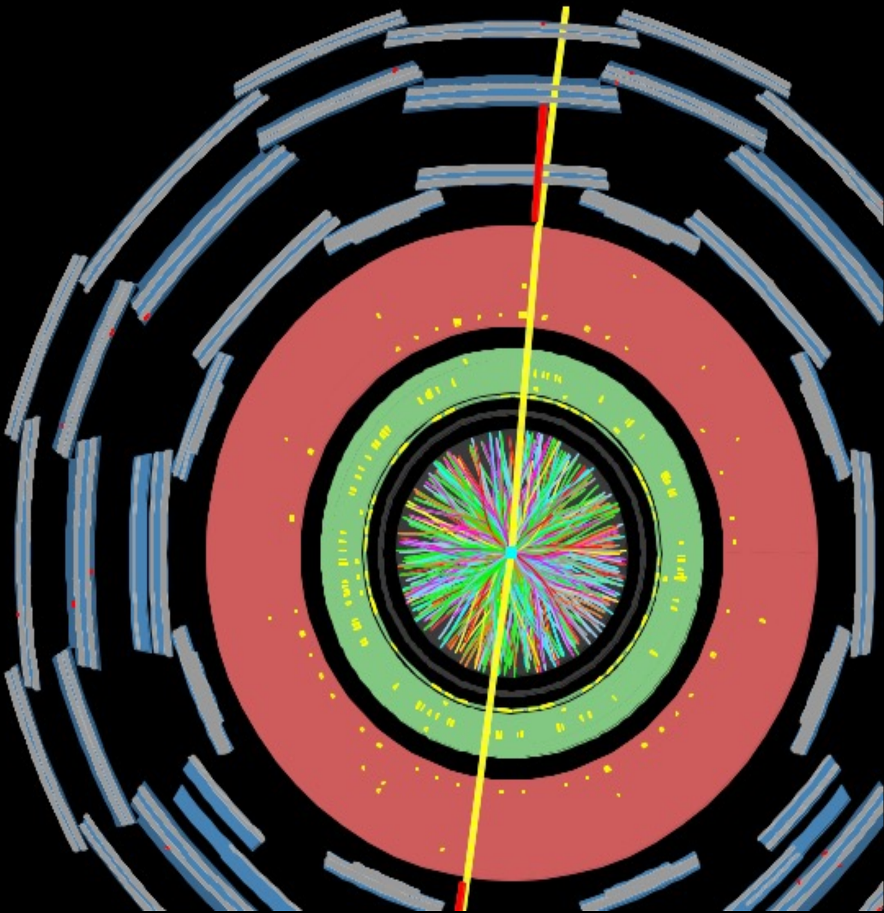
$\sqrt{\hat{s}}$ = 100 GeV

$\sqrt{s}$ = 14 TeV → $x_a x_b$ = 0.007

A Z→e^+e^- event at LEP and ad LHC



ALEPH @ LEP

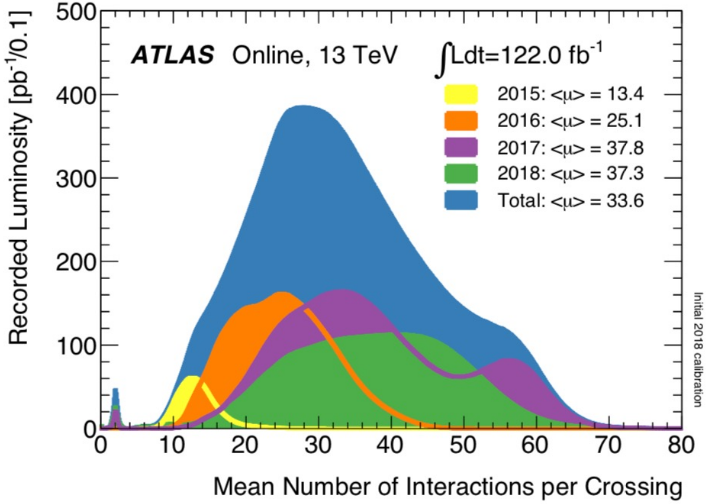


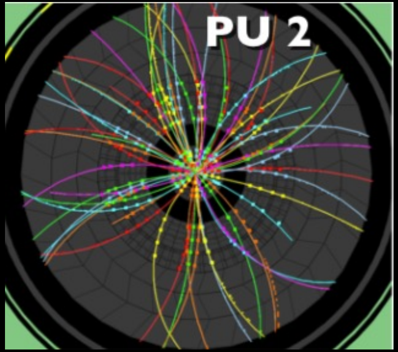
ATLAS @ LHC

Pile-Up

$$\mathcal{L} = \frac{1}{4\pi}\frac{f\,k\,N_1 N_2}{\sigma_x \sigma_y}$$

PU = number of inelastic interactions per beam bunch crossing





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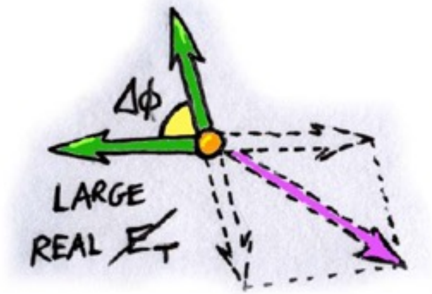
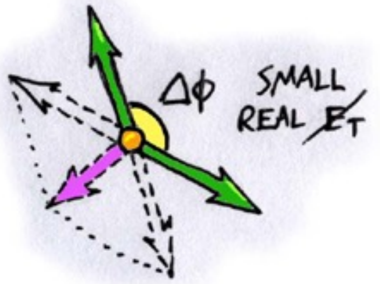
back to

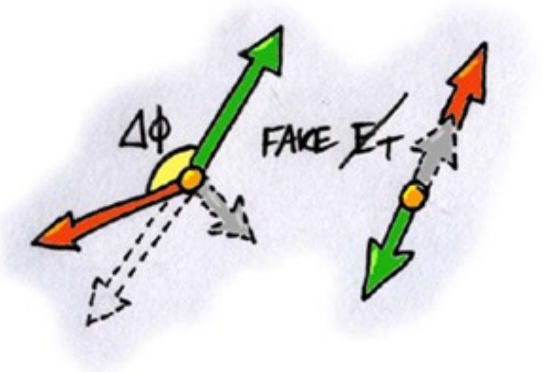
Calorimeters in Detector Systems

Neutrino (and other invisible particles) at colliders

- Interaction length $\lambda_{int} = A/(\rho\ \sigma\ N_A)$
- Cross section $\sigma \sim 10^{-38}\ \text{cm}^2 \times E$ [GeV]
  - ✓ This means 10 GeV neutrino can pass through more then a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse) energy*







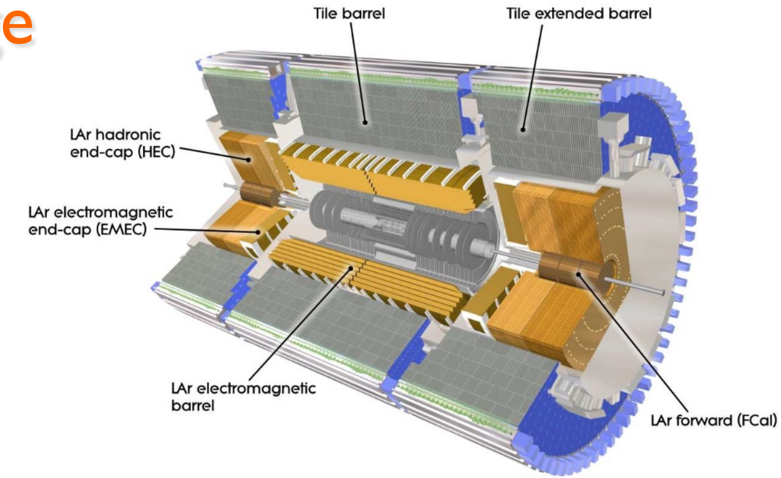
- Missing energy resolution depends on
  - ✓ Detector acceptance (e.g. calorimeter coverage)
  - ✓ Detector noise and energy resolution

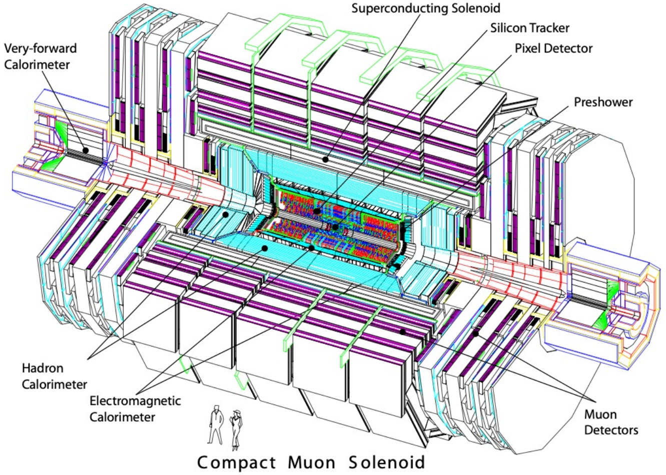
Missing energy vs. hermetic coverage

$$\vec{E}_{(T)}^{\text{miss}} = -\sum_{\text{visible}} \vec{p}_{(T)}$$

- **True if ALL particles detected**
  - ✓ Un-instrumented regions (cracks, supports, services) create “fake” missing energy
  - ✓ Crack calibration and inter-module corrections: ongoing experimental challenge
- Missing energy resolution drives detector hermeticity requirements
- Pseudorapidity coverage at LHC: |η| up to 4.9 (ATLAS), 5.2 (CMS)
  - ✓ Forward calorimeters essential!

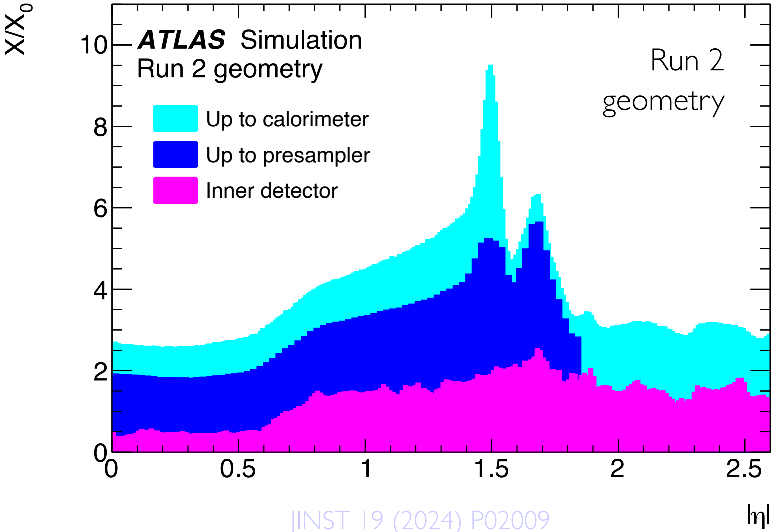
$$\sigma\left(E_{(T)}^{\text{miss}}\right) \simeq a \cdot \sqrt{\sum E_{(T)}}$$





Energy resolution vs. upstream material

- Calorimeter in HEP experiment don’t live in vacuum!
- Ideally, minimum material budget in front of ECAL
  - ✓ Position of tracker solenoid (ECAL before or after the tracker?)
  - ✓ Tracker material causes upstream losses (and resolution degradation)
  - ✓ ATLAS and CMS material ~ 0.1-0.5 X_0 at η=0, up to 1-2 X_0 at |η|~2



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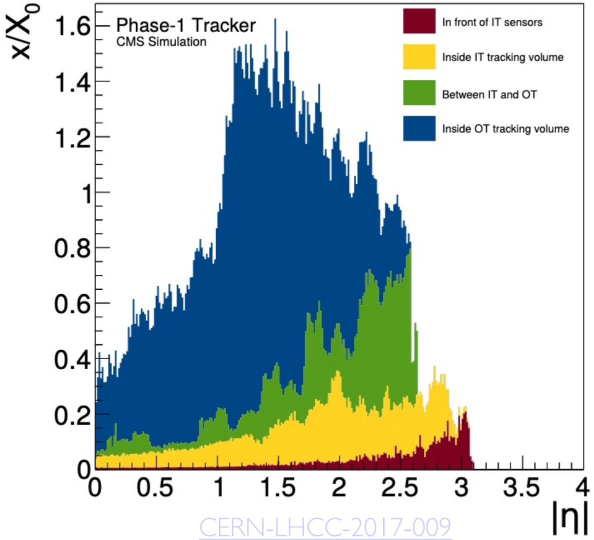


CERN-LHCC-2017-009

So, why calorimeters?

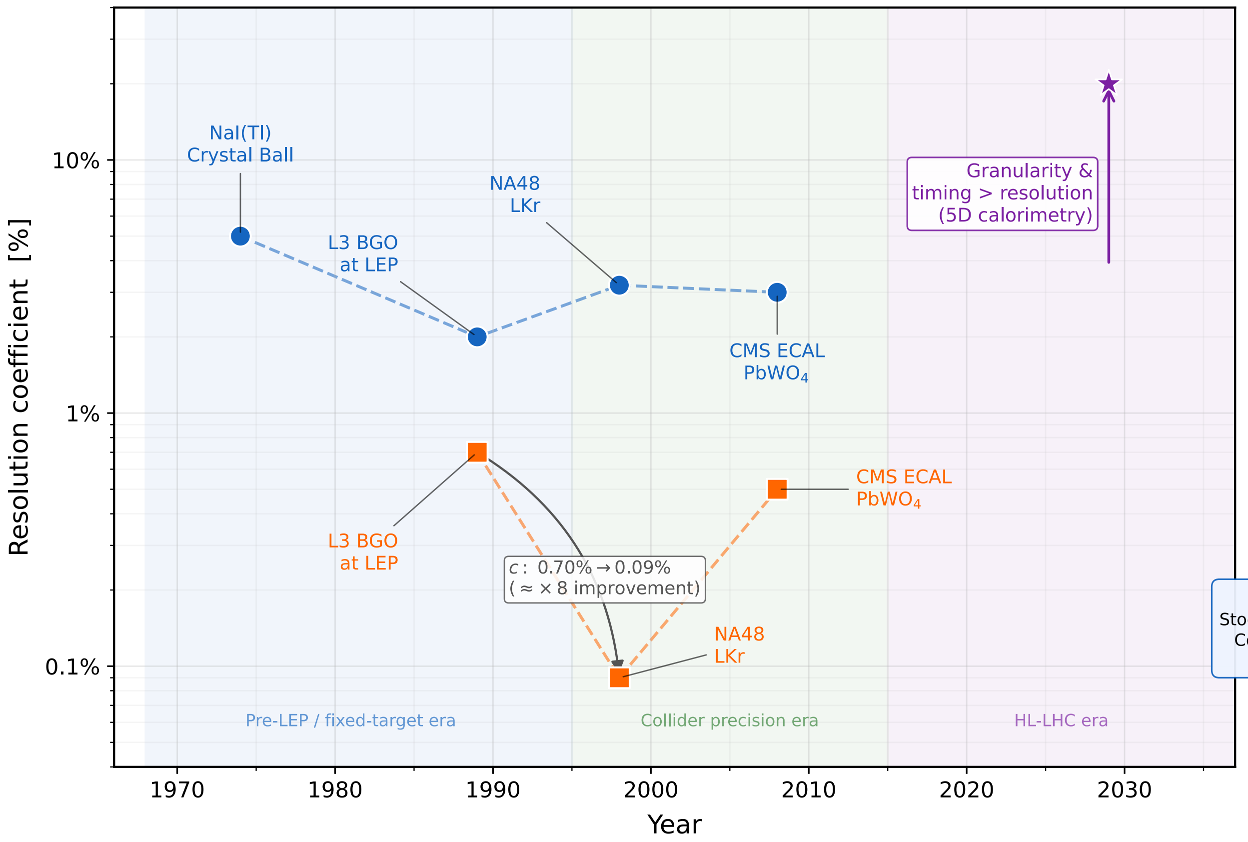
- Sensitive to all type of particles, charged and neutrals
- Can measure energy, but also position, direction, time and identify particles (e.g. thanks to segmentation)
- Can be used in trigger systems: signal is generally fast and easy to process
- Shower length increases as log E, thus detector thickness need only increases logarithmically with particle energy (while it increase ~linearly for spectrometers): compact detectors

1.3

Historical Development

The EM resolution frontier

Fifty years of EM calorimeter progress: $\sigma(E)/E = a/\sqrt{E} \oplus c$



$$\frac{\sigma(E)}{E} \simeq \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$\sigma(E)/E = a/\sqrt{E\,[\text{GeV}]} \oplus b/E \oplus c$
Stochastic term a: sampling/shower fluctuations
Constant term c: calibration, non-uniformity, radiation damage

- Each step was driven by a specific physics need!

Three physics problems that drove EM calorimeter design

- **Measure the W boson mass with per-mille precision**
  - ✓ $W \to e\nu$ at the Tevatron: electron E_T from EM calorimeter; energy scale calibrated on $Z \to ee$ (M_Z known from LEP)
    - Precision sampling EM calorimetry (CDF/D0, $c < 0.5\%$)

- **Measure rare kaon and B-meson decays in fixed-target experiments**
  - ✓ Required rejection (reconstruction) of large $\pi^0 \to \gamma\gamma$ backgrounds
    - Precision liquid homogeneous calorimetry (NA48 LKr, 1998): $c = 0.09\%$
    - Precision crystals homogeneous calorimeters (BaBar and Belle, 1999–2010): $\sigma(E)/E \sim 2.5\%$ at 1 GeV;

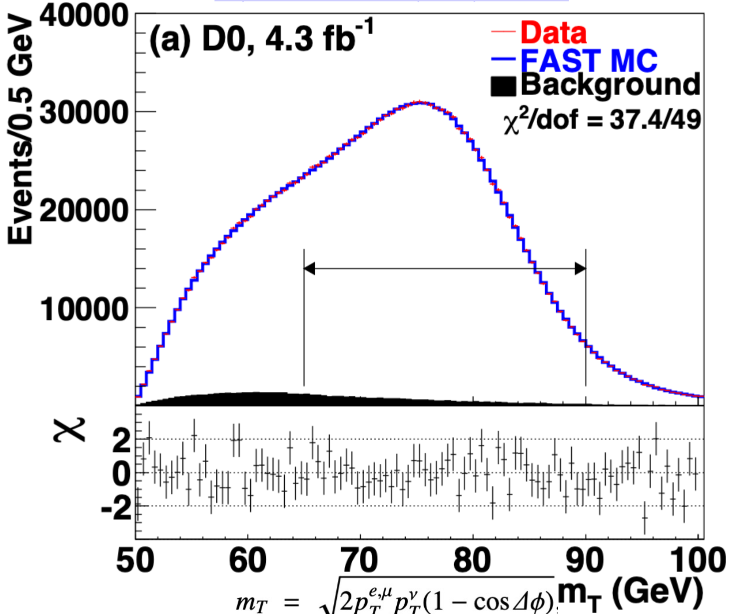
- **Discover and characterise the Higgs boson via $H \to \gamma\gamma$ at the LHC**
  - ✓ Di-photon mass resolution $\sigma(m_{\gamma\gamma})/m_{\gamma\gamma} < 1\%$ required $\sigma(E)/E$ constant term $c < 0.5\%$
    - Radiation-hard crystal calorimetry (CMS ECAL $PbWO_4$, 2008)
    - Resolution is not the full story… (ATLAS LAr/Pb + segmentation, 2008)

W boson mass: precision EM calorimetry at hadron colliders

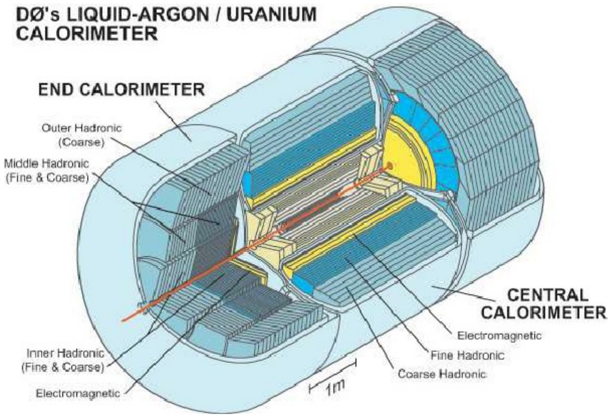
- **W mass as an electroweak precision observable**
  - ✓ m_W predicted by SM loop corrections involving m_{top} and m_H: independent measurement tests EW self-consistency
  - ✓ Tevatron goal (CDF, D0, 1987–2011): $\delta m_W \sim 20$ MeV
  - ✓ $\sigma(E)/E$ at 40 GeV governs the sharpness of the Jacobian edge in $m_T \rightarrow$ limits δm_W

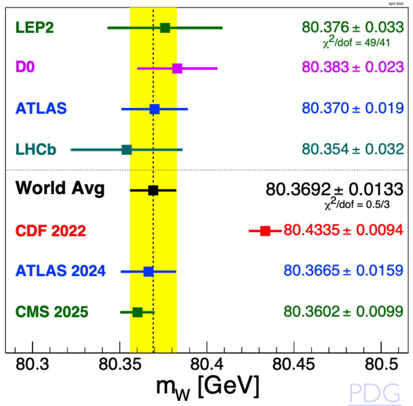
- **W→eν at CDF and D0: a calorimeter-driven measurement chain**
  - ✓ Electron E_T from EM calorimeter + ν from MET → transverse mass m_T peaks at m_W; fit the Jacobian edge to extract m_W
  - ✓ Energy scale calibrated in situ with Z→ee (m_Z from LEP, known to 2 MeV) → constant term c controls calibration transfer from 91 to 80 GeV
    - CDF Pb-scintillator (c ~ 2%)
    - D0 uranium-LAr (c ~ 0.3%)
  - ✓ Energy scale one of the dominant δm_W systematic

Phys.Rev.Lett. 108 (2012) 151804



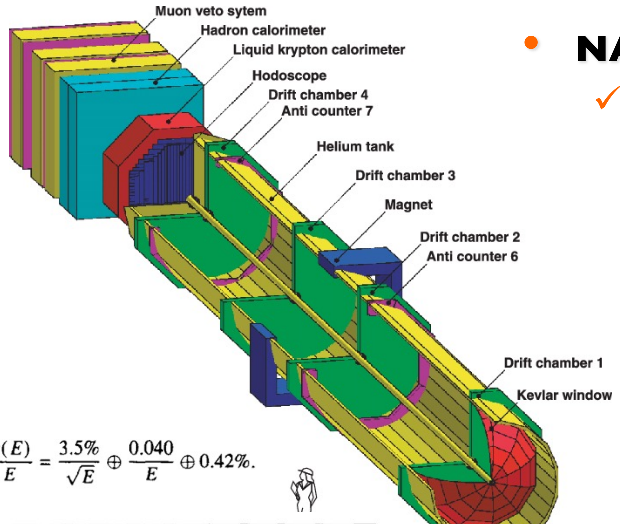
$$m_T = \sqrt{2 p_T^{e,\mu} p_T^{\nu}(1-\cos\Delta\phi)}$$



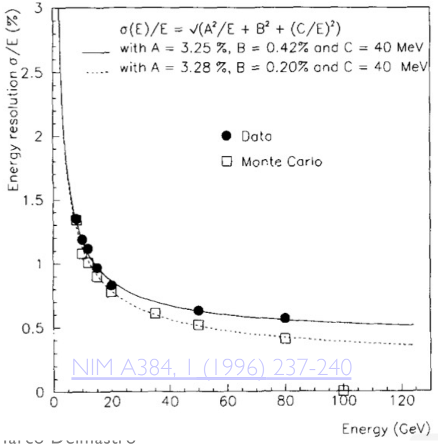


PDG

Rare kaon decays: precision EM calorimetry



$$\frac{\sigma(E)}{E} = \frac{3.5\%}{\sqrt{E}} \oplus \frac{0.040}{E} \oplus 0.42\%.$$

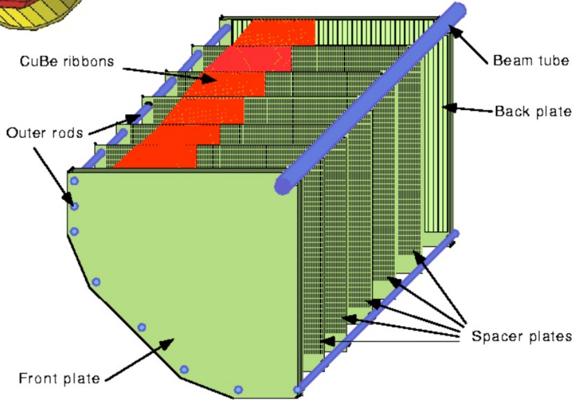


NIM A384, 1 (1996) 237-240

- **NA48 at CERN SPS (1997–2002)**
  - ✓ Physics: direct CP violation in $K^0 \to \pi^+\pi^-$ and $K^0 \to \pi^0\pi^0 \to 4\gamma$

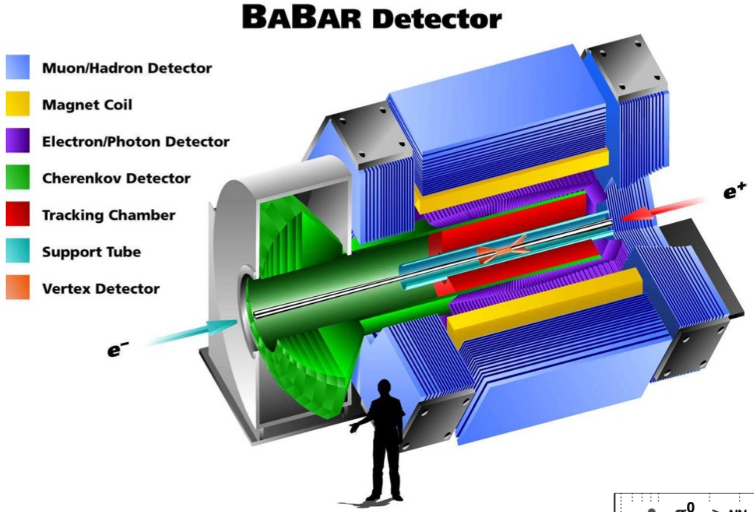
$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Bigg/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}$$

$$\approx 1 - 6 \times \mathrm{Re}(\epsilon'/\epsilon).$$



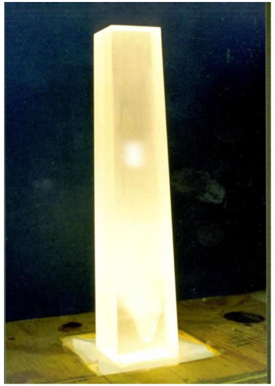
- ✓ Result: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4} \neq 0$
  - Confirmed direct CPV (2001)
- ✓ Demand: reconstruct $\pi^0 \to \gamma\gamma$ pairs at low energy with tiny constant term (long stability)
- ✓ Answer: quasi-homogeneous liquid krypton calorimeter
  - $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 0.09\% \oplus 42\ \mathrm{MeV}/E$

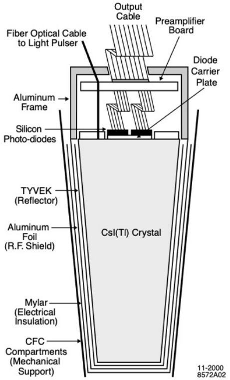
Rare B-meson decays: precision EM calorimetry

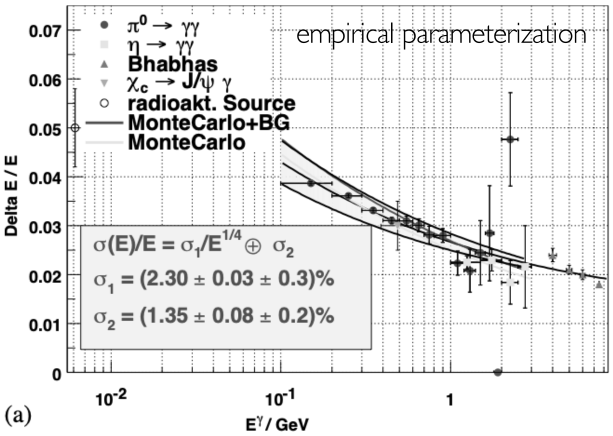


BaBar (SLAC) and Belle (KEK) (1999–2010)

- ✓ Physics: CP violation in $B \to J/\psi\, K^0$, time-dependent asymmetries; $B \to \pi^0\pi^0$, η_c
- ✓ Demand: low-energy γ reconstruction ($\pi^0 \to \gamma\gamma$, $E\gamma \sim 20$–200 MeV) in high-rate environment
- ✓ Answer: CsI(Tl) crystals
  - σ(E)/E ≈ 2.5% at 1 GeV; 6580 (BaBar) / 8736 (Belle) crystals
  - c ~ 1–2% for B→Xγ where X is a kaon resonance (softer constraint than NA48 but same motivation)



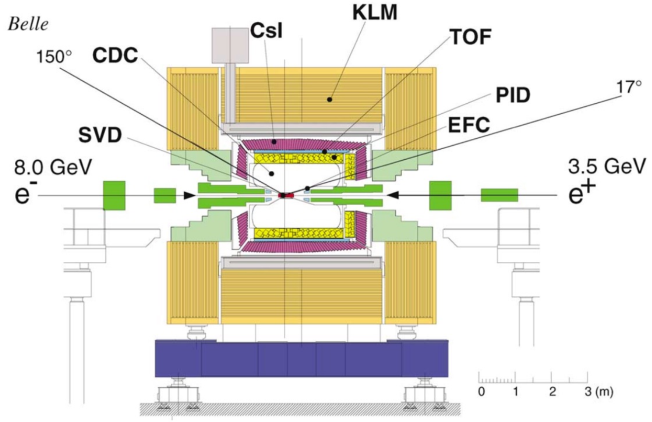




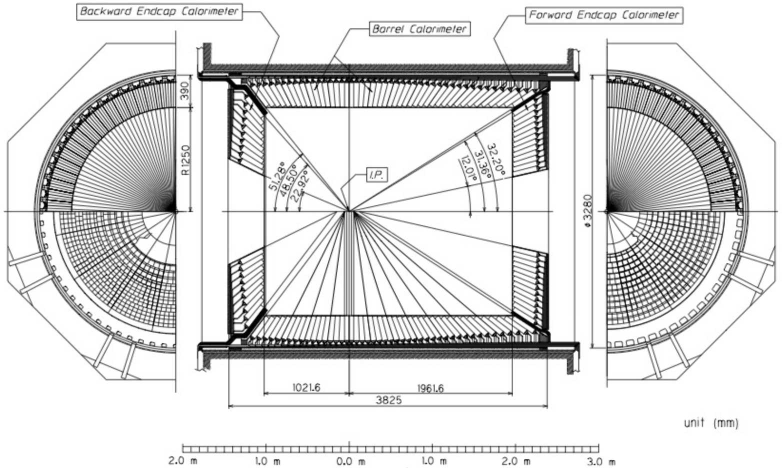
empirical parameterization

IEEE NSS 2005

Rare B-meson decays: precision EM calorimetry



BELLE CsI ELECTROMAGNETIC CALORIMETER



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  - ✓ Answer: CsI(Tl) crystals
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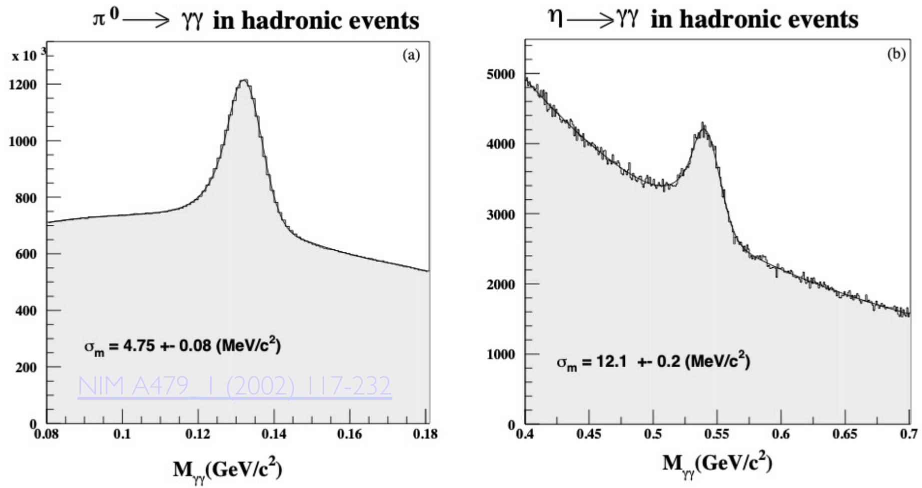
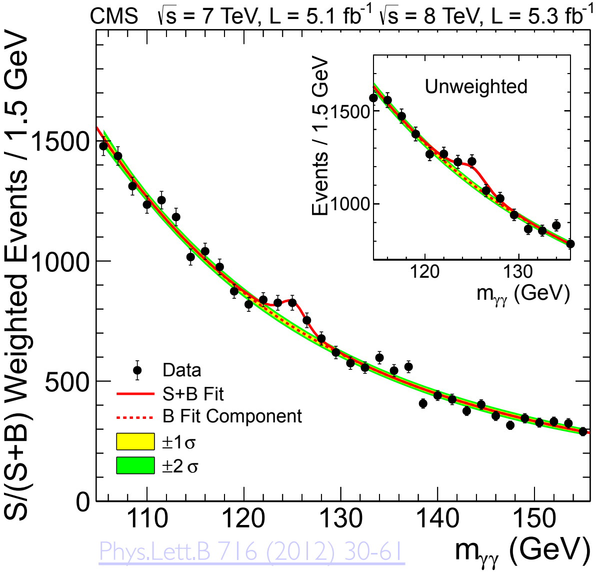


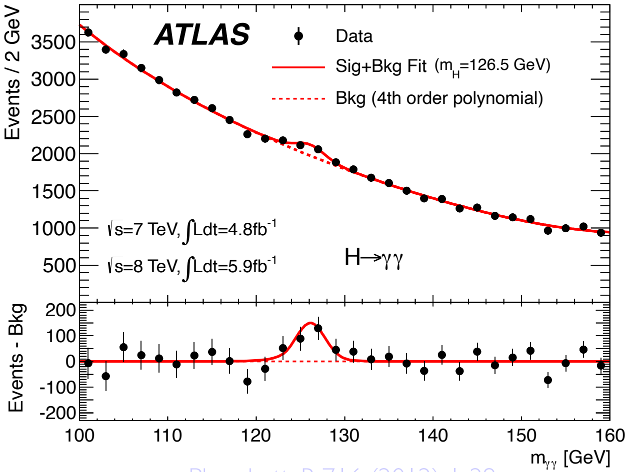
NIM A479_1 (2002) 117-232

H→γγ discovery at LHC: energy resolution (and more)

- **CMS (2012)**
  - ✓ Physics: Needed to resolve 125 GeV peak against background
  - ✓ Required a ~3%, c < 0.5%
  - ✓ Answer: PbWO4 crystals
- **ATLAS (2012)**
  - ✓ Physics: Same need, different choice (resolution is not everything)
  - ✓ Required excellent uniformity + particle identification capability (accepting a~10%)
  - ✓ Answer: LAr/Pb sampling + fine segmentation



Phys.Lett.B 716 (2012) 30-61



Phys. Lett. B 716 (2012) 1-29

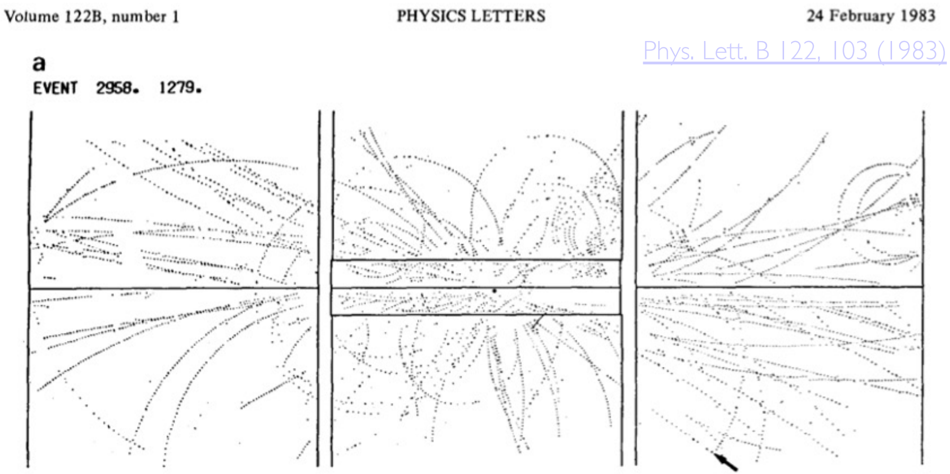
Three physics problems that drove HCAL design

- **Find W and Z bosons at a hadron collider**
  - ✓ W → eν reconstruction requires MET in hadronic events
    - Hermetic 4π iron-scintillator calorimetry (UA1/UA2, 1983)

- **Measure hadronic energy without bias from shower composition**
  - ✓ Fluctuating EM/hadronic fraction causes irreducible non-linearity if e/h ≠ 1
    - Compensating calorimetry (ZEUS, 1992)

- **Reconstruct complex LHC events with many overlapping particles**
  - ✓ Good hadronic resolution hard to achieve; use combination of tracker + ECAL + HCAL information per particle in jets (particle flow)
    - Extreme segmentation (CMS; HGCAL)

Finding W bosons at a hadron collider



Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

Phys. Lett. B 122, 103 (1983)

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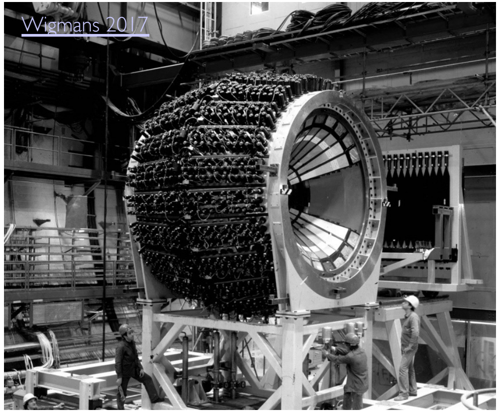
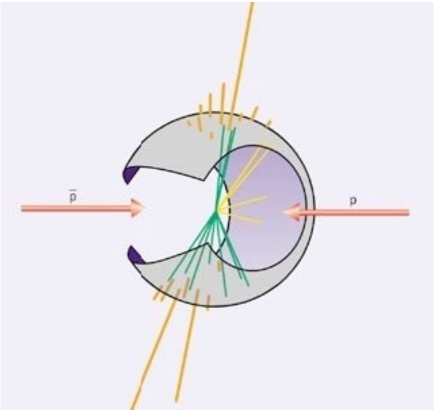


Wigmans 2017

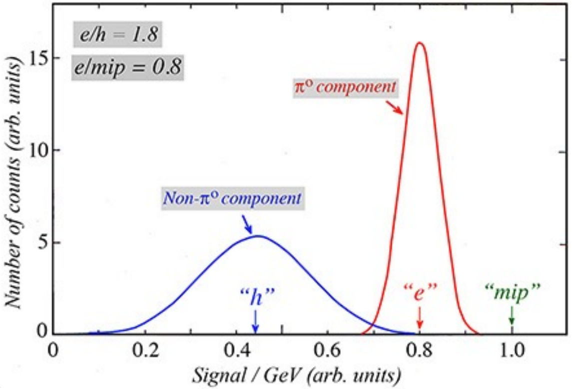


- **UA1 and UA2 at CERN SppS collider (1983)**
  - ✓ Physics: W → eν → electron from W decay + large MET from neutrino, against ~300 GeV hadronic activity
  - ✓ Challenge: MET only meaningful if ALL particles detected → any uninstrumented gap creates fake MET
  - ✓ Answer: iron-scintillator HCAL with full 4π coverage, ~700 projective towers, |η| < 3
- **W/Z discovery (Nobel 1984)**
  - ✓ MET significance > 4σ per event → calorimetric MET proven as a physics observable
  - ✓ Concept generalised: every subsequent hadron collider experiment adopted hermetic calorimetry → standard for SUSY, DM, top, W mass at LHC

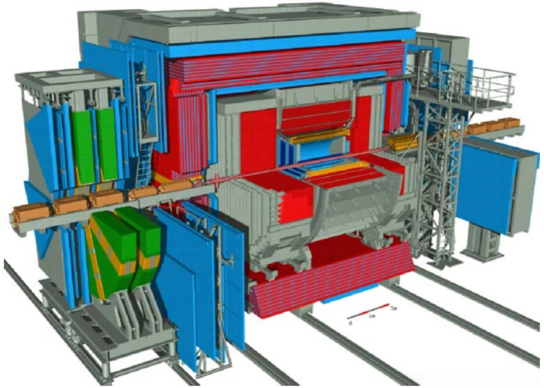
Hadronic energy without bias: e/h problem and compensation

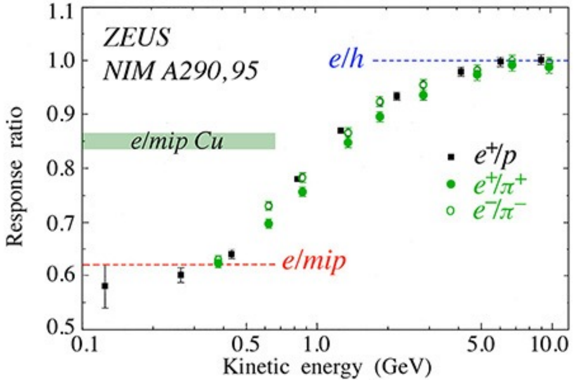
- **The e/h problem (Wigmans, 1987)**
  - ✓ e = calorimeter response to electrons; h = response to hadrons
  - ✓ Hadronic showers: ~30% of energy "invisible" (nuclear binding, slow neutrons) → h < e → e/h > 1
  - ✓ EM fraction f_{EM} fluctuates event-to-event → if e/h ≠ 1: non-linear response + irreducible constant term in σ(E)/E
- **Wigmans' insight: choose passive absorber material to obtain e/h = 1 ("compensation")**
  - ✓ ^{238}U absorber: neutron-induced fission releases ~8 MeV/fission → compensates invisible nuclear binding energy loss

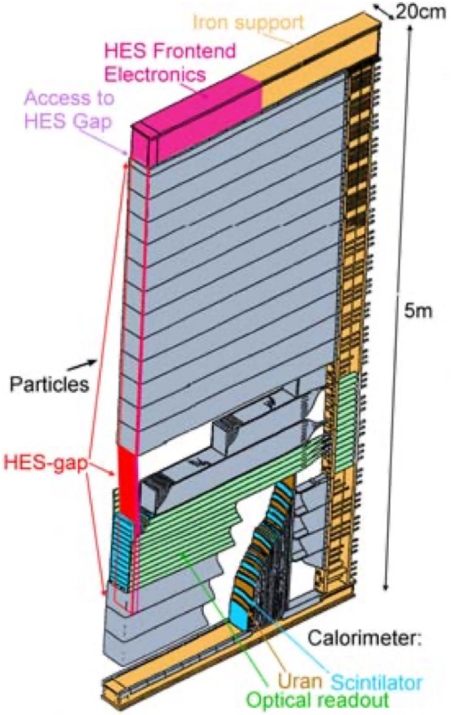
arXiv:1712.05494



- **ZEUS at HERA (1992): uranium/scintillator compensating calorimeter**
  - ✓ e/h = 1.00 ± 0.02
  - ✓ σ(E)/E = 35%/√E for hadrons (purely stochastic, no constant term!)



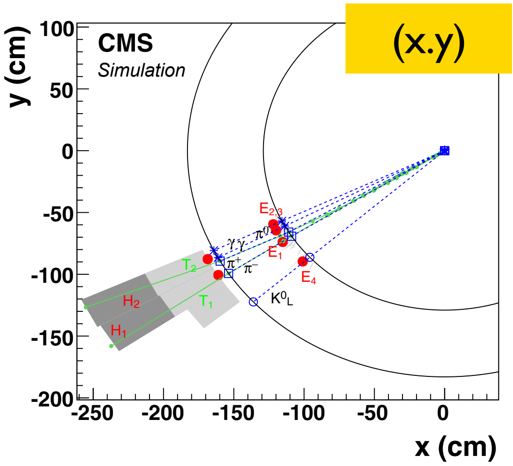


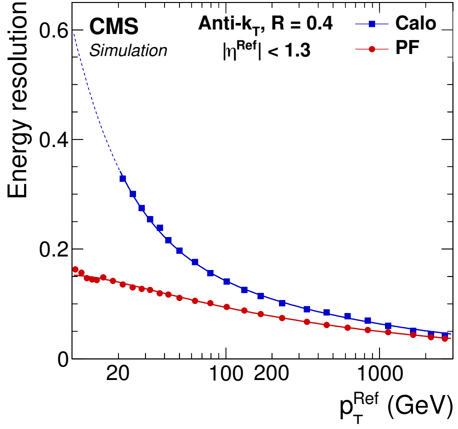


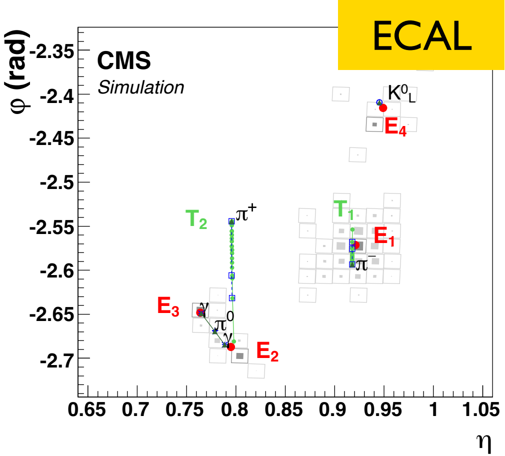
Reconstructing complex LHC events: “particle flow”

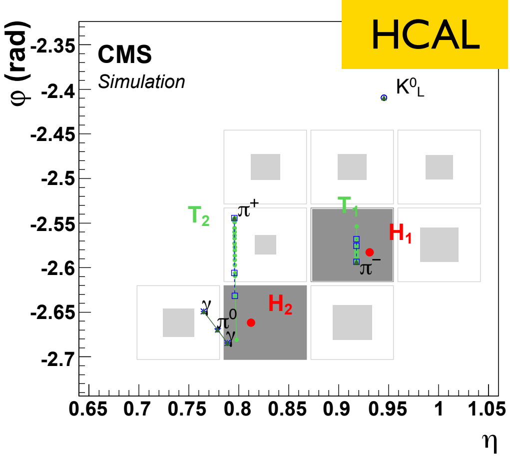
- **The problem: HCAL alone gives poor jet resolution**
  - ✓ ~65% of jet energy is charged hadrons — better measured by tracker than HCAL
  - ✓ Only ~35% (neutral hadrons) truly needs HCAL — resolution matters less once charged/EM parts subtracted
- **Particle flow algorithm (CMS, 2010): combine sub-detectors per particle**
  - ✓ Tracker → charged hadrons; ECAL → photons; HCAL → neutral hadrons only
  - ✓ Jet energy resolution: σ/E ~ 15% → 10% at 100 GeV — requires fine HCAL granularity to separate charged from neutral deposits
    - True particles in blue; Reconstructed tracks and tracker hits (+extrapolation) in green;
    - Cluster seeds in dark grey; Other cluster cells in light grey; Cluster position in red;
    - Symbols indicate the positions of the true particles
- **CMS HGCAL (HL-LHC target, 2029…): “5D” calorimetry**
  - ✓ 6M channels, 50 longitudinal layers, Si + scintillator; position σ(x,y) < 1 mm; timing σ(t) < 50 ps
  - ✓ a ~ 20%/√E but adds position + timing: pile-up rejection in 5 dimensions (x, y, z, t, E)

arXiv:1706.04965









What did we learn today?

- **Week 1 (Foundations)**
  - ✓ Lecture 1: Why calorimetry?
    - *1.1 Why calorimetry?*
      - *Essential to measure energy (but also position and other properties) of neutral particles*
      - *Essential to detect invisible particle at colliders and neutrinos*
      - *Essential to measure properties of QCD jets*
      - *Most precise detector for high energy/momentum measurement*
    - *1.2 Calorimeters in Detector Systems*
      - *Calorimeters always come after some kind of tracking device (material in front!)*
      - *Needs to be "hermetic" to allow for missing energy measurement*
      - *Size scale logarithmically with energy, can be compact devices*
      - *Calorimeter signals are fast: essential for triggering purposes*
    - *Intermezzo: Coordinate system & Cross-section & Hadron vs Lepton Colliders*
    - *1.3 Historical Development*
      - *Most improvements in calorimeter design was driven by specific physics needs!*
  - ✓ Lecture 2: EM shower physics