The discovery of W and Z

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Outline

- The Standard Model
  - Electro-Weak unification
  - The Higgs mechanism
- The $Sp\bar{p}S$ accelerator
  - Stochastic cooling
- The detectors
  - UA1
  - UA2 (in backup slides)
- The W and Z observation

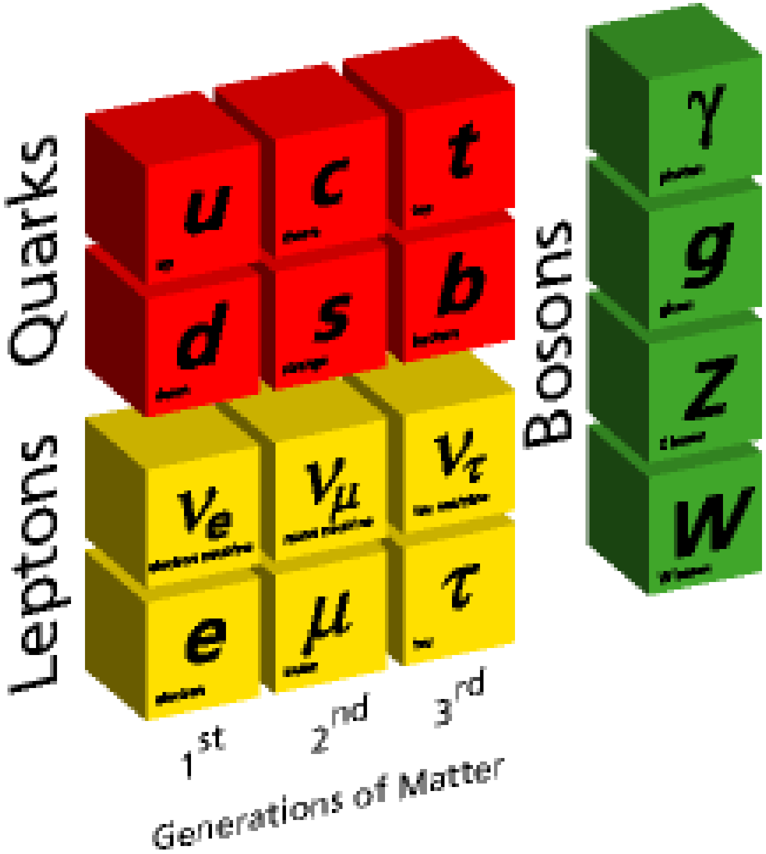
Rubbia
(physicist)

Van der Meer
(engineer)

Introducing the Standard Model

- Warning: you still don't know what is a gauge theory (and why it is so important to know what it is)
  - You will not learn it now
  - Although I will try to give a qualitative idea at the blackboard

The Standard Model



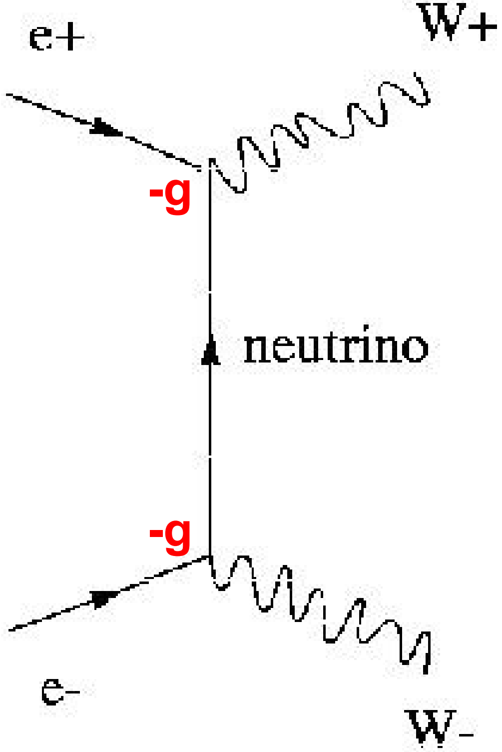
- Forces are carried by bosons: photons, W/Z, gluons, gravitons
- Matter (fermions) is composed of quarks (sensitive to QCD) and leptons (neutral to QCD), grouped in 3 generations
- What we call “Standard Model” of High Energy Physics is Electro-Weak Theory (with Higgs mechanism) + QCD
  - Gravity is not really included!

Electro-Weak Unification

- QED is a gauge theory
- Gauge theories imply mass=0 for the force carriers (example: the photon in QED)
- At least two weak force carriers exist, both charged (W^+ and W^-) because weak decays change the charge:
  - $n \rightarrow p e \bar{\nu}$ interpreted as $n \rightarrow p W^{-(*)}$ plus $W^{-(*)} \rightarrow e \bar{\nu}$
- The phenomenology of the weak interaction suggests that the range is short, which can come in a natural way if the force carriers are quite massive (Yukawa)
- So, weak interaction seemed not to be explainable with a gauge theory, at first

Electro-Weak Unification

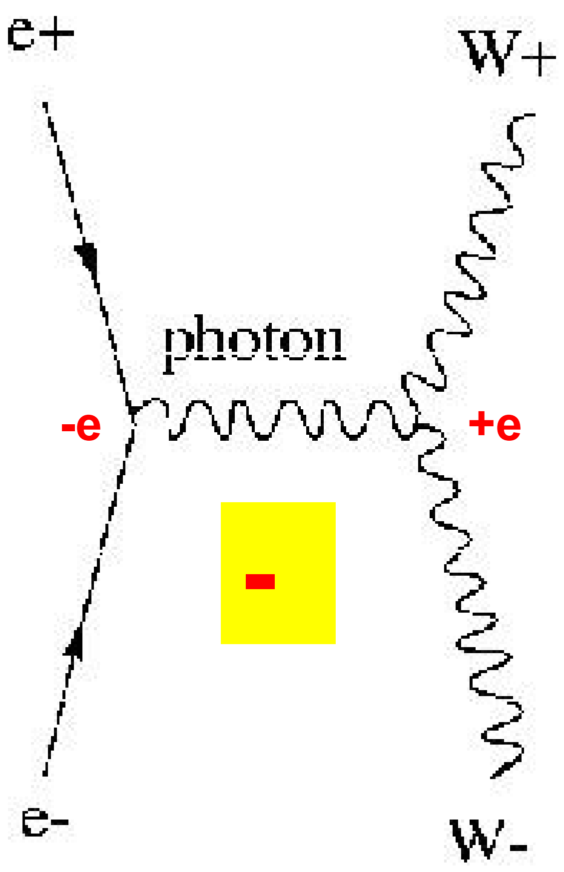
- Why a gauge theory is desirable: because its symmetries provide cancellations of terms that would otherwise diverge
- A non-gauge quantum field theory will always contain somewhere some divergence that you cannot cancel

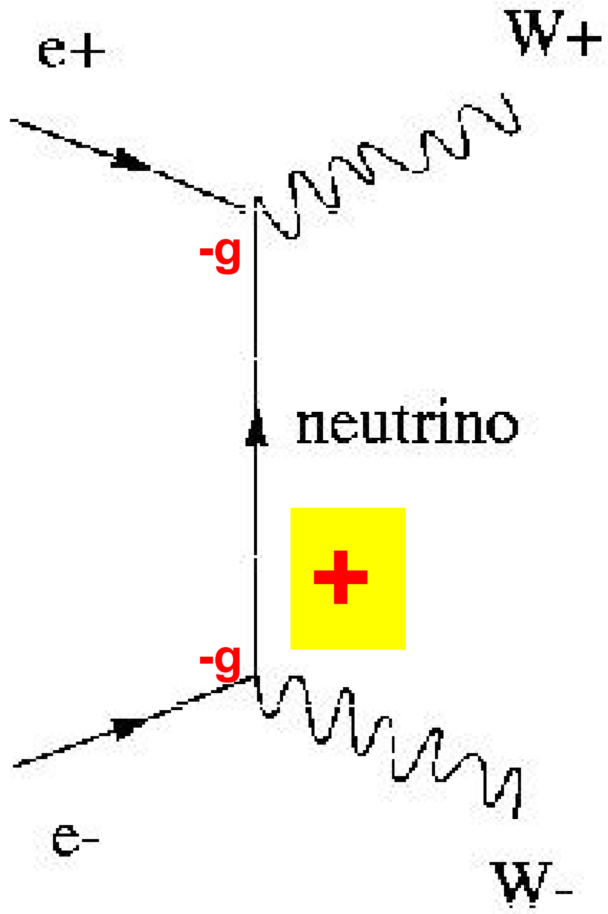


Example: if you calculate the probability that this process occurs in an e^+e^- collision, you get that above some energy the probability becomes >100%, i.e. $\sigma(e^+e^- \rightarrow W^+W^-) > \sigma(e^+e^- \rightarrow \text{anyth.})$! This is nonsense...

Electro-Weak Unification

- A suggestive coincidence: if you assume g~e, summing the amplitudes of these two diagrams gives a cancellation up to some higher energy:



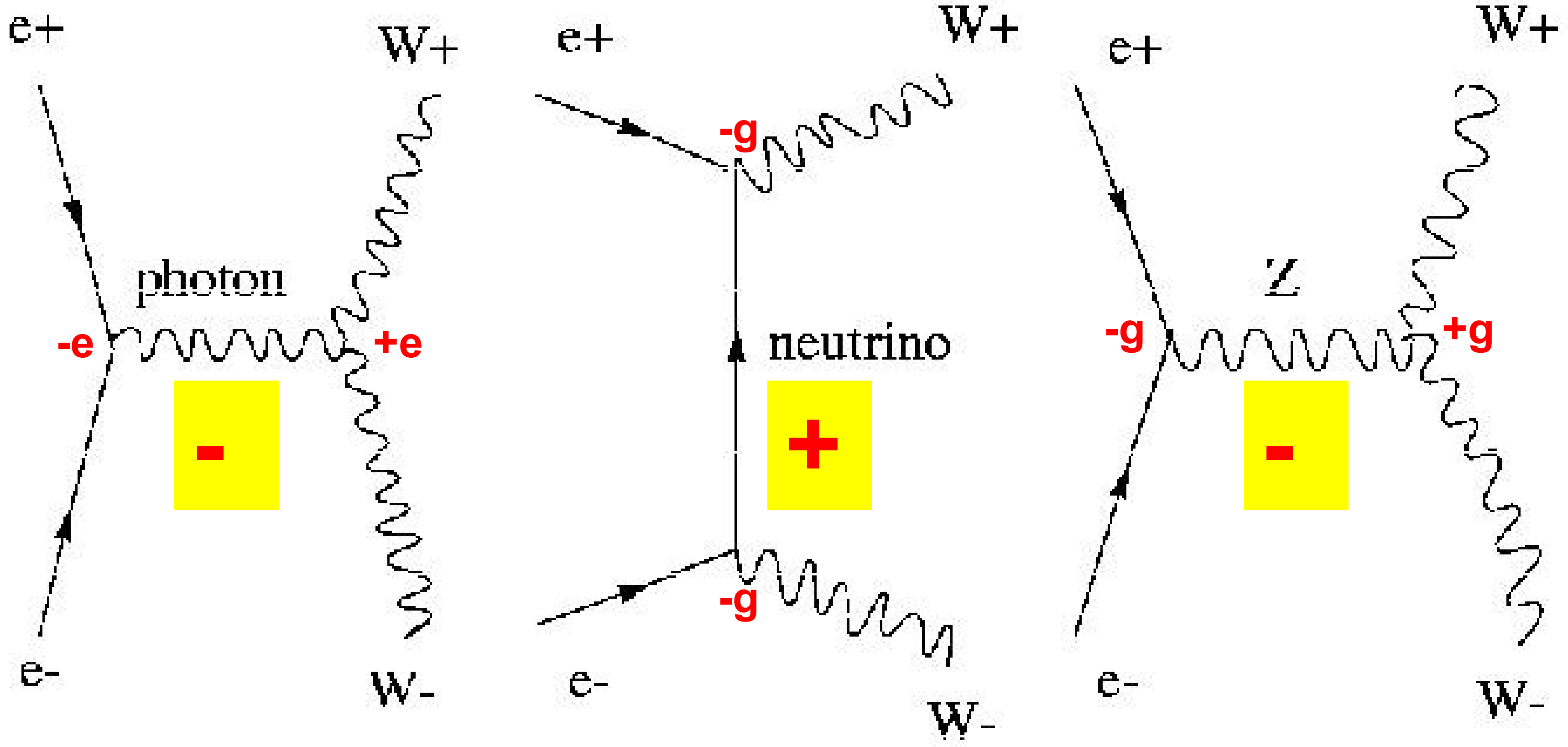


This delays the problem to higher energy, but does not solve it...

Question: does the process on the left diverge?

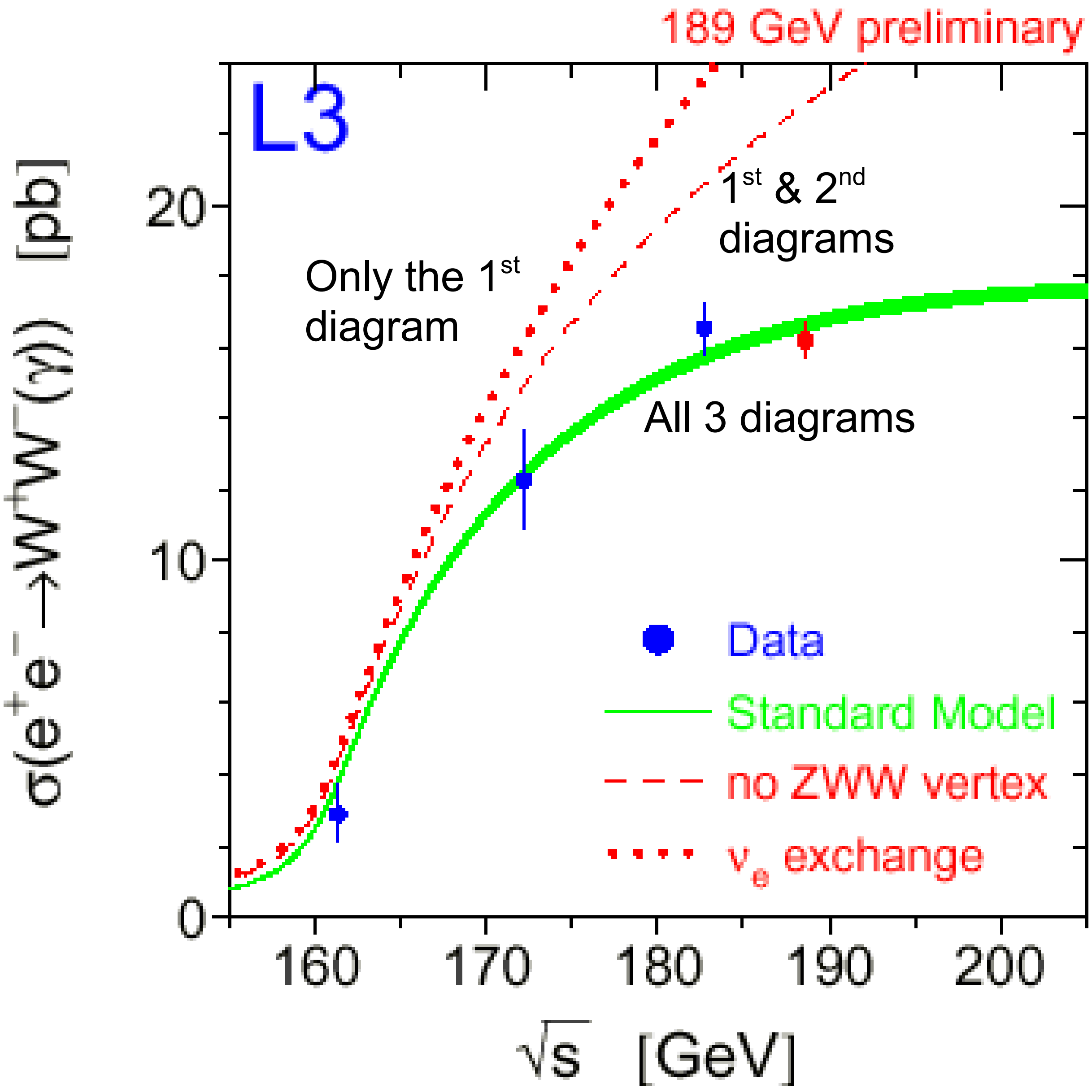
Electro-Weak Unification

- Hypothesis by Glashow, Salaam, Weinberg (1967): a new process where a new boson is present in the intermediate state (so that the sign of the amplitude is the same as for the diagram with the photon)



Experimental check

(many years later)

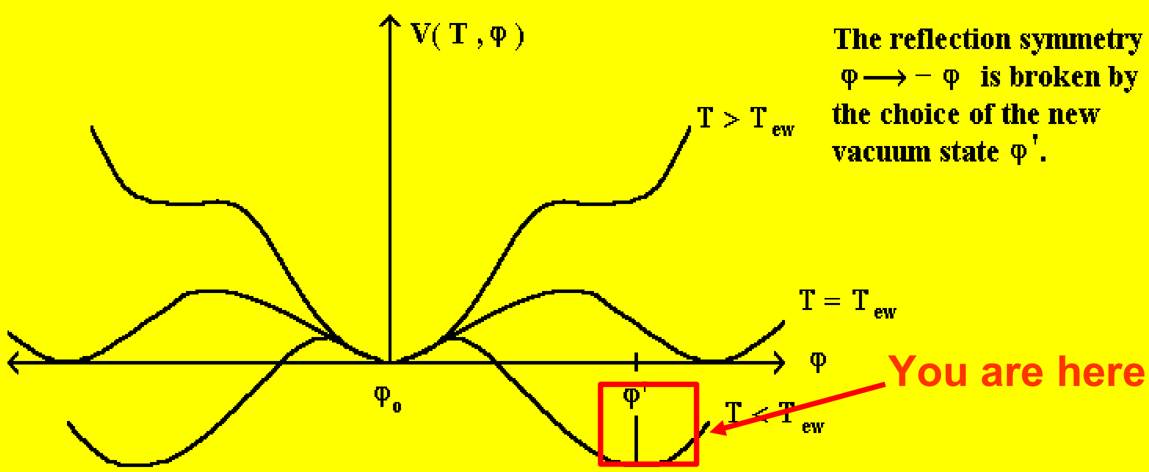


Electro-Weak Unification

- If g~e, and if γ, W and Z masses are roughly equal, then there is a cancellation
- But of course these masses are not similar at all
  - photon is massless
  - W is heavy; if not, weak force would have long range
  - Z is heavy too, otherwise we would have observed it since long time, exactly as the photon
- But when you consider energies $>>M_W, M_Z$, you get the desired cancellation and your theory has a perfect symmetry between the EM and the Weak aspects

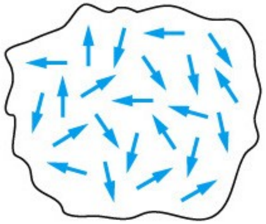
The Higgs mechanism
(= Spontaneous Symmetry Breaking)

- Basic idea: the lagrangian of a theory can have a symmetry which is not a symmetry of the ground state
- At low energy we are close to the ground state, and only at very high energy we can notice the symmetry
- Analogy: ferromagnetism versus temperature

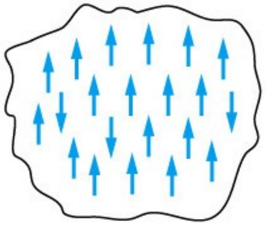


The reflection symmetry $\varphi \longrightarrow -\varphi$ is broken by the choice of the new vacuum state φ'.

You are here



$T > T_c$
perfect isotropy



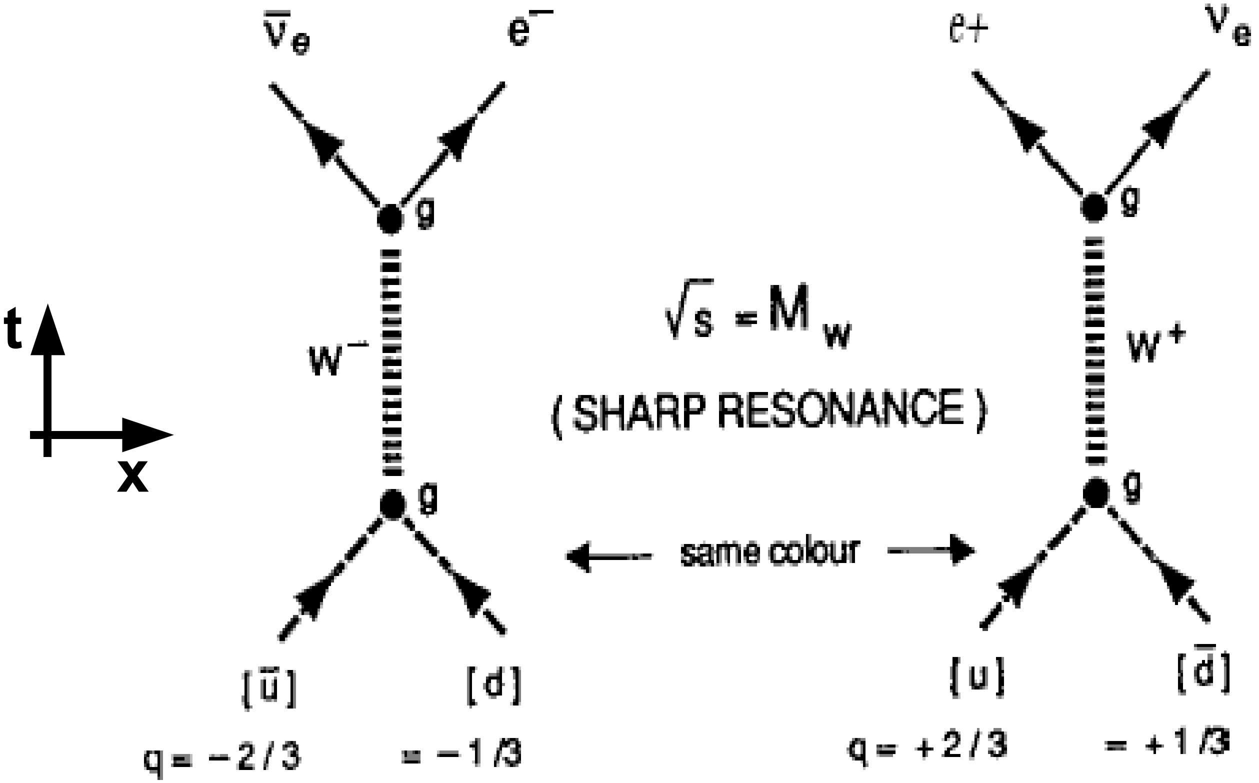
$T < T_c$
one direction prevails
(but it is not special!)

Prediction of the W and Z masses

- Remember: $G_F \sim (g/M_W)^2$
  - To be precise: $G_F/\sqrt{2} = g^2/8M_W^2$
  - G_F is known with high precision from the measurement of the muon mass and lifetime: 1.16×10^{-5} GeV^{-2}
  - The EW unification predicts $g = e \sin\theta_w$, where θ_W is the rotation between the original W^0 and the observable Z
  - $\sin^2\theta_w$ was measured by the NC/CC ratio in neutrino/nucleon experiments: $\sin^2\theta_w \sim 0.23$
- → prediction for the W mass: ~80 GeV
- → prediction for the Z mass: $\boxed{M_Z = M_W/\cos\theta_w} \sim 90$ GeV

You will do the math yourselves next year...

W production and detection in hadronic collisions

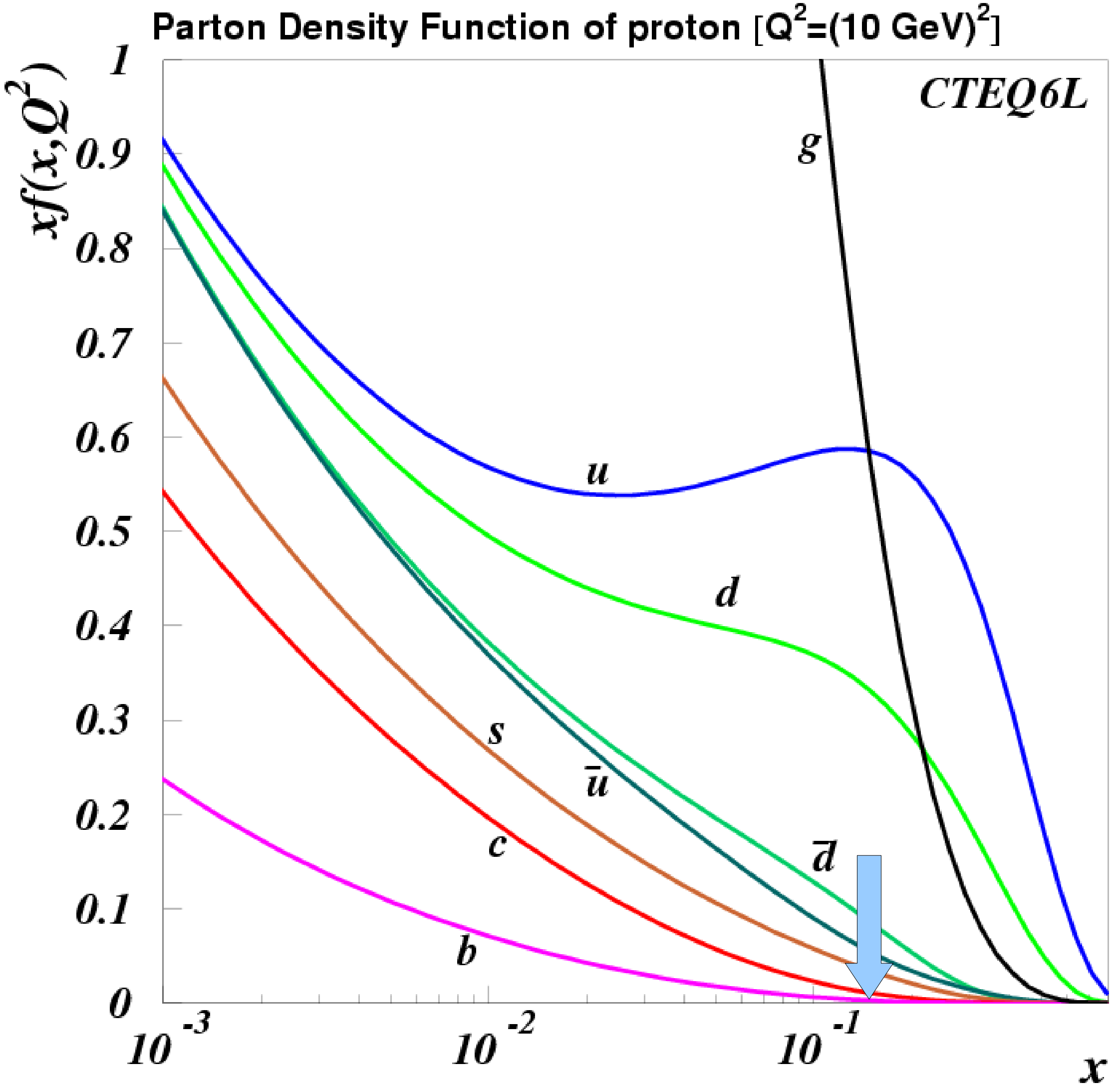


Leptonic decays are a clean signature against the huge hadronic background (see the techniques for e,μ detection in previous lectures)

$$\sigma(q\bar{q} \rightarrow W) = \tfrac{3}{4}\pi\lambda^2\Gamma_i\Gamma/[(E-m_W)^2+\Gamma^2/4]$$

But we are colliding protons, not quarks... What is the c.m. energy of the quark-antiquark collision?

Parton Density Functions



There is an online calculator for PDFs:
http://durpdg.dur.ac.uk/hepdata/pdf3.html

- They give the probability of finding a parton with a certain x (= P_q/P_p) for a given Q^2 of the interaction
- They can be measured in Deep Inelastic Scattering with leptons and neutrinos
- $s_{q1,q2}=s_{p1,p2}x_{q1}x_{q2}$
- New accelerator that collided $p\bar{p}$ at 540 GeV: to create a particle of M~80 GeV, u,d,$\bar{u}$,$\bar{d}$ quarks with x>0.15 are able to contribute

Proton-antiproton colliders

- There was already a proton accelerator of the right energy at CERN, the SPS (still in operation nowadays...)
  - Mostly used for fixed-target experiments
- Rubbia proposed to operate it as $p\bar{p}$ collider
  - It was then used this way for several years, then returned back to its original proton-only vocation when a much larger proton-antiproton collider started operating in the US (Tevatron, still in activity)
  - Now it is also the injector for LHC

How to produce antiprotons

- Some of the protons are shot against a target, producing a lot of hadrons; among them, some antiprotons
- Magnetic selection of antiprotons by their mass and charge sign

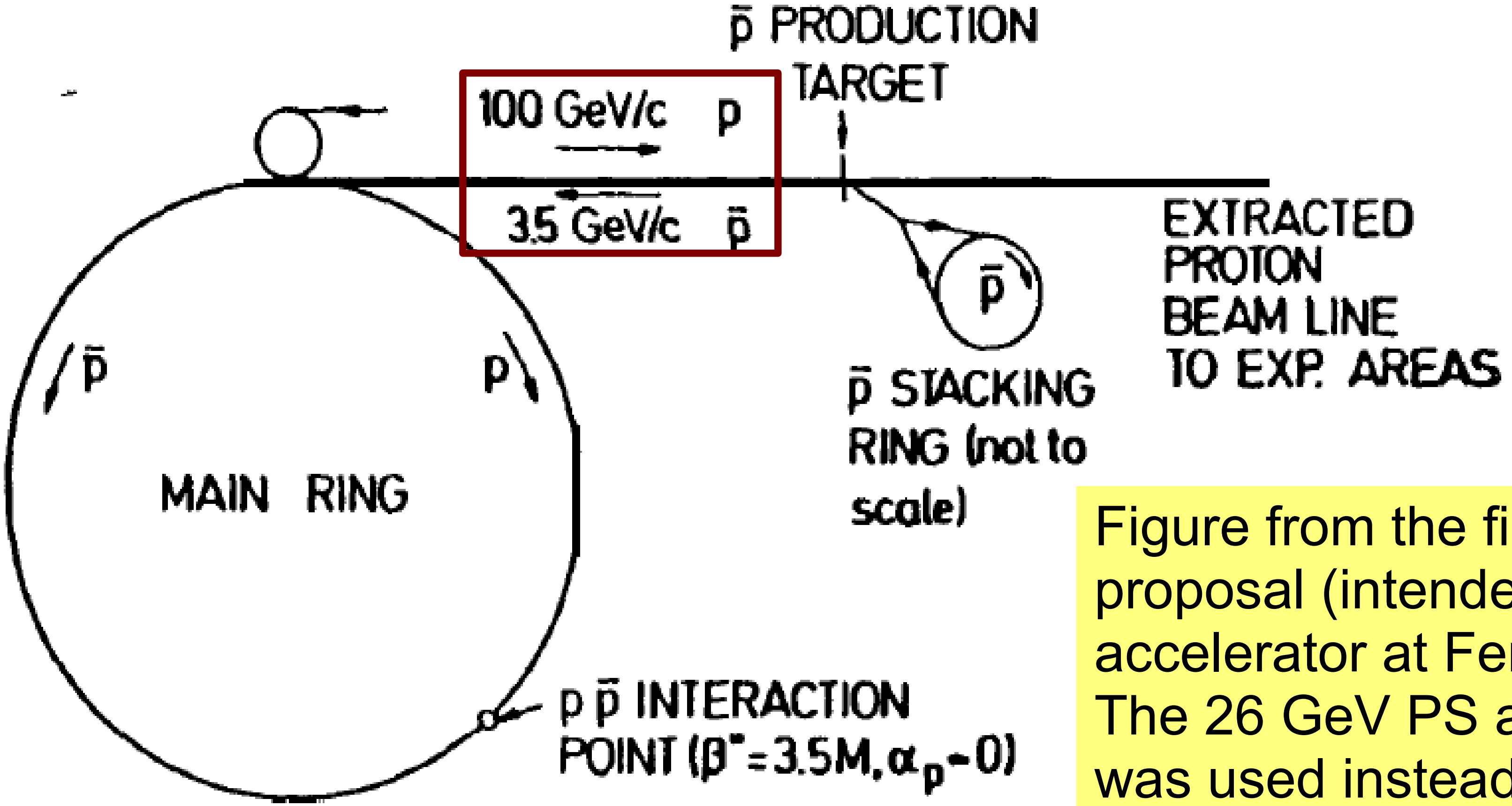
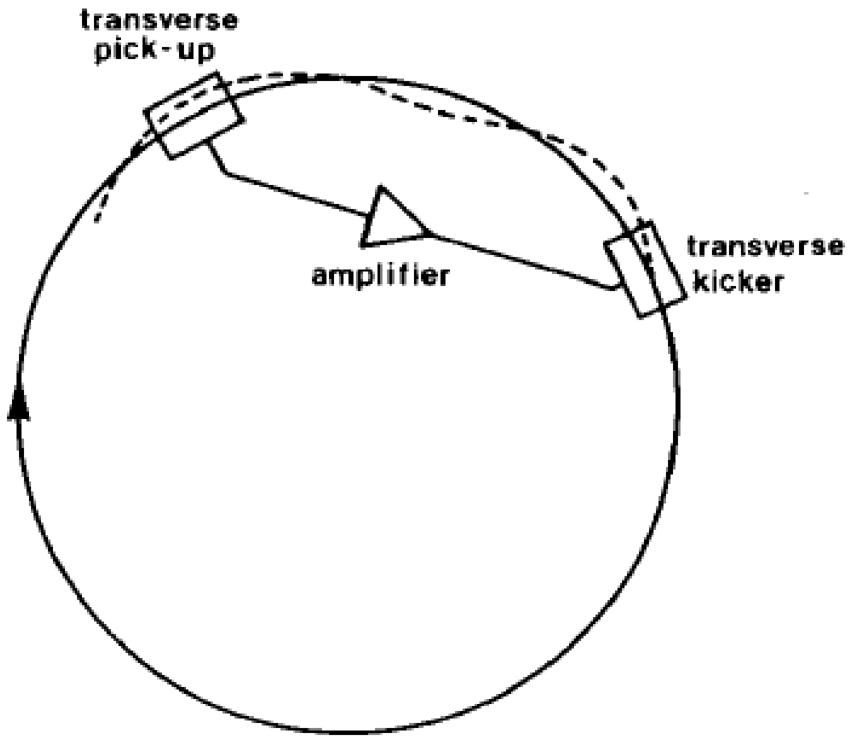


Figure from the first proposal (intended for an accelerator at Fermilab). The 26 GeV PS at CERN was used instead.

The problem with antiprotons

- The production mechanism gives a broad momentum spectrum
- We don't want to be too selective: we need as many antiprotons as we can, so our momentum filter must have large acceptance
- We need to squeeze as much as possible, simultaneously:
  - the spatial distribution, in order to increase the collision probability when the antiproton beam meets the proton beam
  - the momentum distribution, otherwise some particles will be badly out of phase with the RF accelerating fields
  - this is called **phase space reduction**
- But wait, how can we do that? Liouville Theorem demonstrates that a conservative force (like the electric and magnetic fields that we can use to manipulate the beam) can not change in any way the density of the phase space

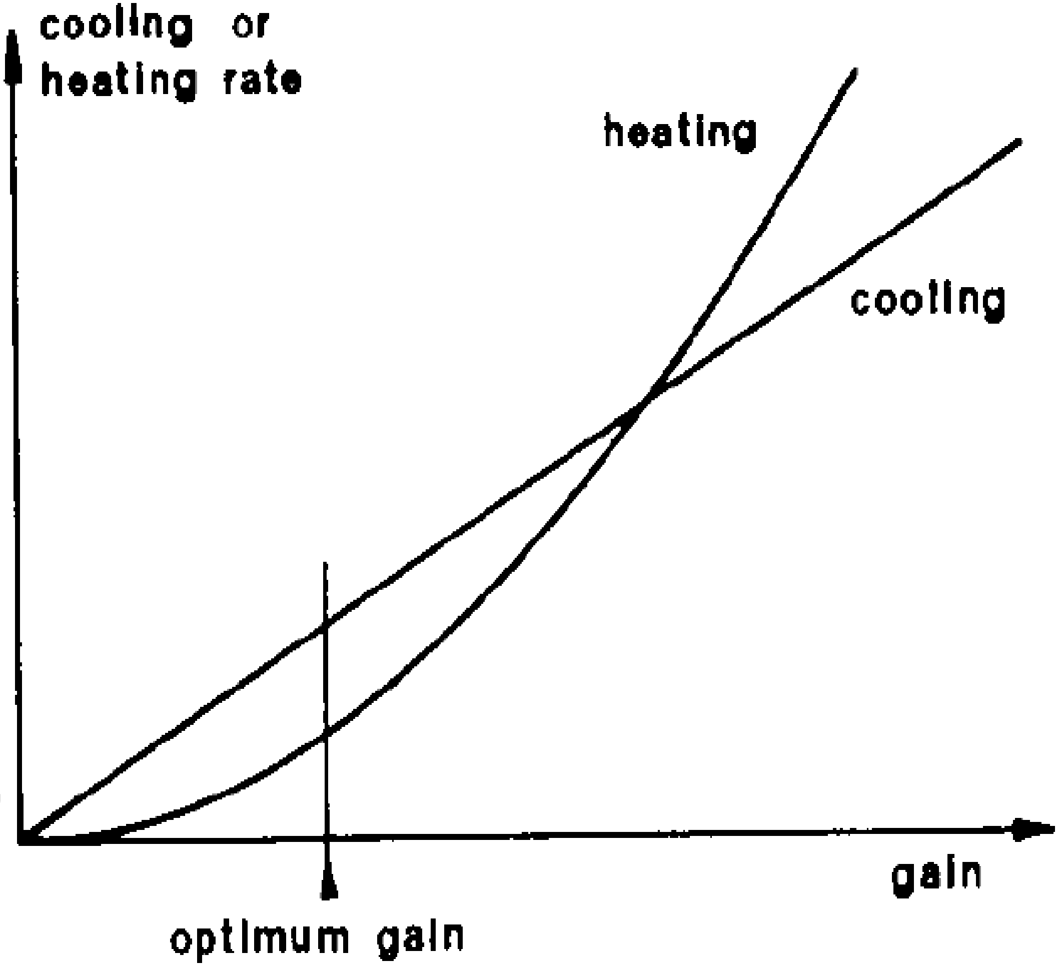
The Stochastic Cooling (1)



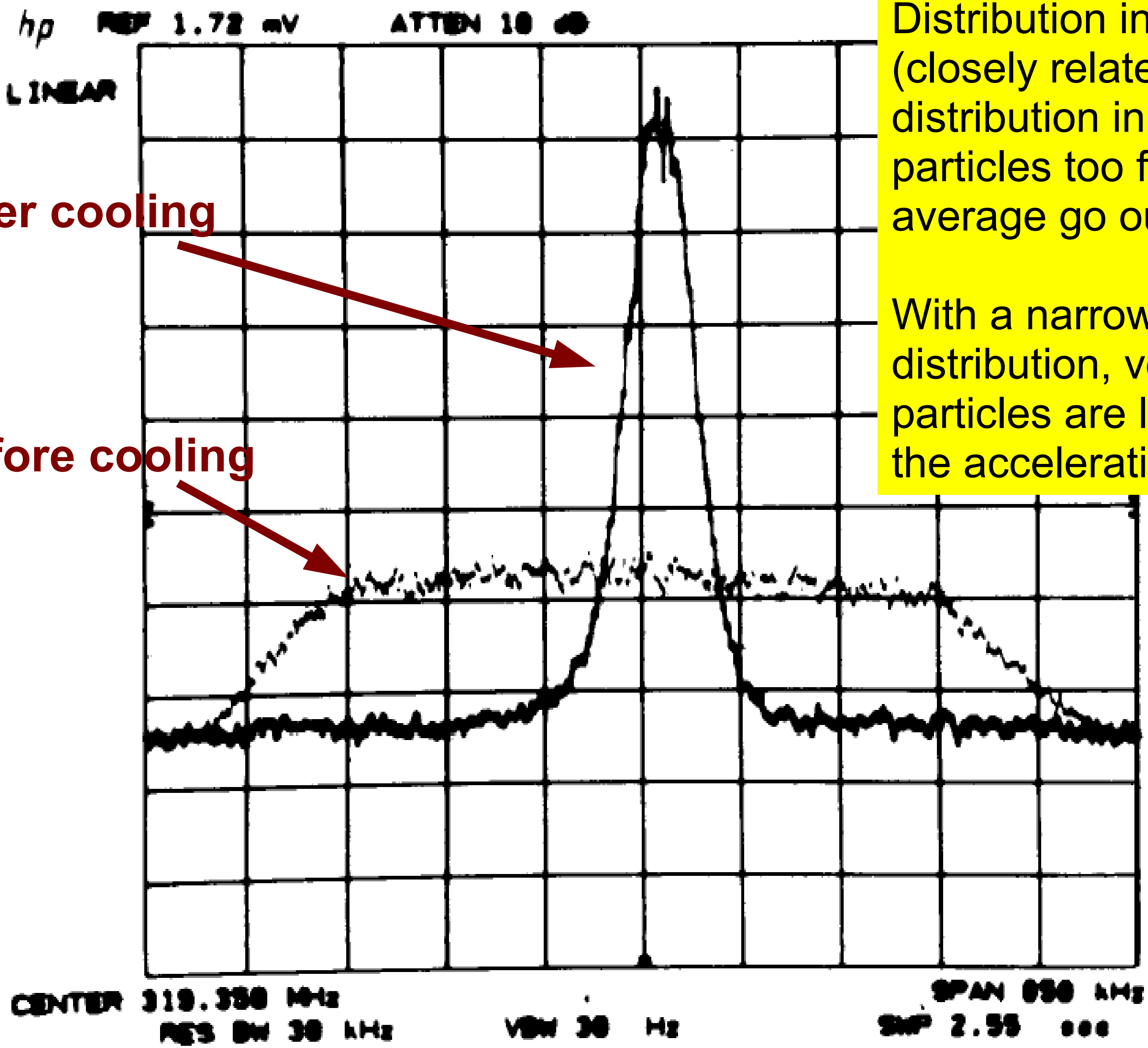
- At each passage of a particle, the **pick-up** gives a signal proportional to the distance of the particle from the perfect orbit
- The **kicker** receives this signal (before the particle arrives) and pushes the particle towards the ideal orbit with a strength proportional to *{signal from the pick-up} x {gain of the amplifier}*
- If the particles were very sparse and the electronics fast enough to handle them one by one, this would be the end of the story; but how can this work with 10^{12} antiprotons?

The Stochastic Cooling (2)

- Any particle receives a correction which depends on its own signal, and on the other particles' signals: the system's “temperature”
  - $T \sim \langle p_T^2 \rangle - \langle p_T \rangle^2$
- So, there are two competing effects from the kicker: the **cooling** is linear with the gain G between pick-up and kicker, while the **heating** goes as G^2
- The $\langle p_T^2 \rangle$ term is dominated by the “hottest” single particle, not so for the $\langle p_T \rangle^2$ term



We can tune the gain: we choose to maximize the difference in favour of cooling



After cooling

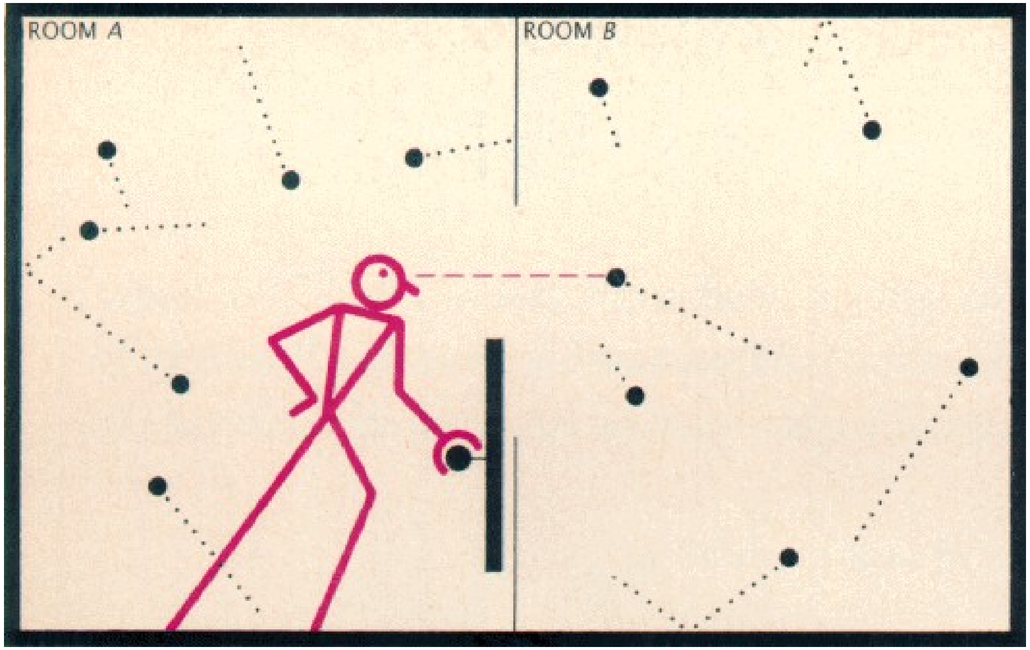
Before cooling

Distribution in frequency (closely related to the distribution in momenta: particles too far from the average go out of phase)

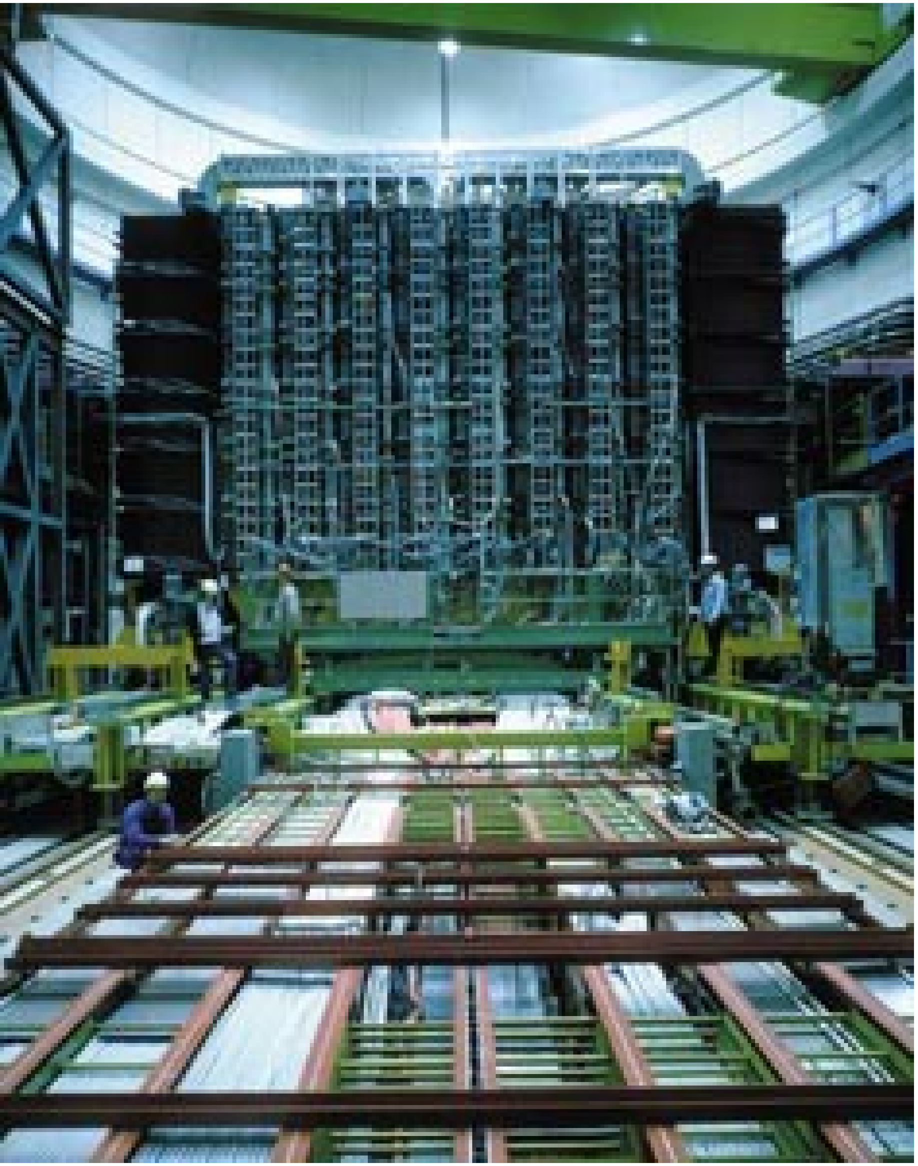
With a narrow frequency distribution, very few particles are lost during the acceleration steps

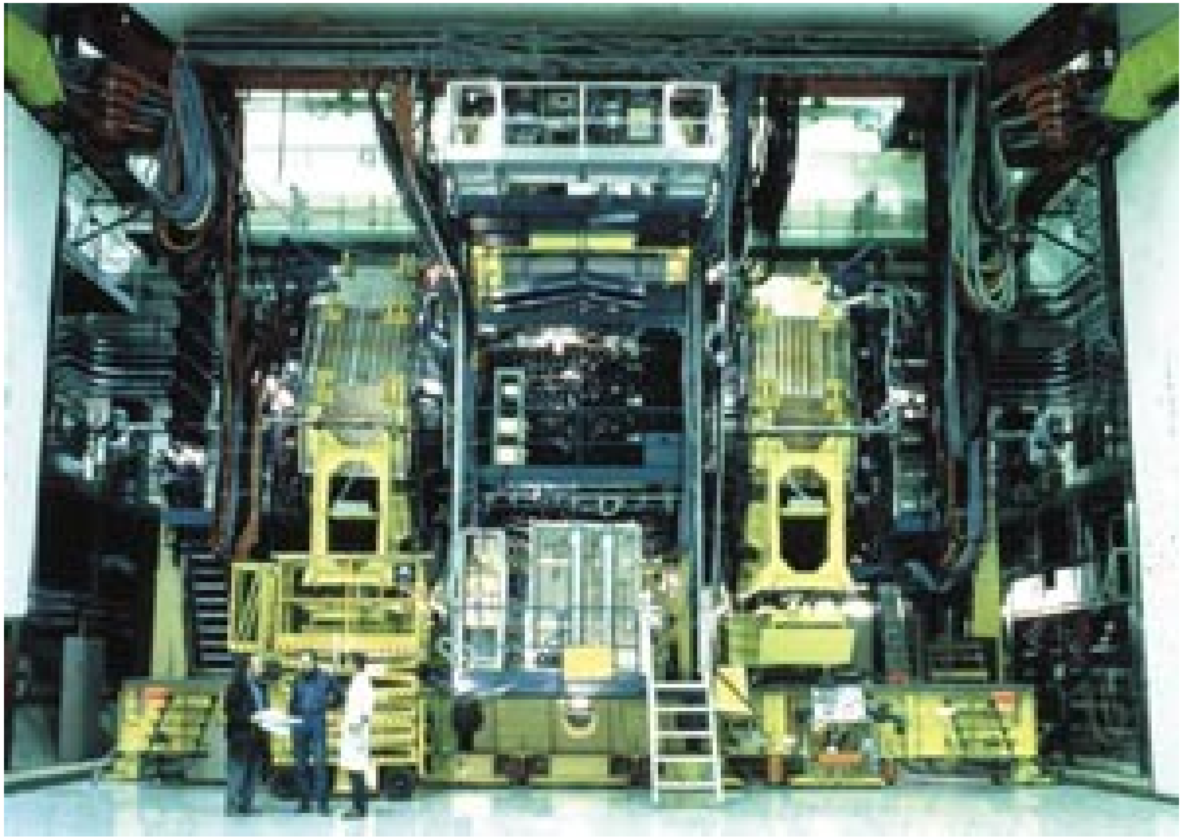
So we violate Liouville theorem. How is it possible?

- It applies only to closed system. Is this system closed?
- In some sense, we have a “Maxwell's demon” which chooses one by one the particles to be moved around
- The analogy is even more appropriate if you consider that the entropy of the beam decreases in the process



The UA1 and UA2 detectors

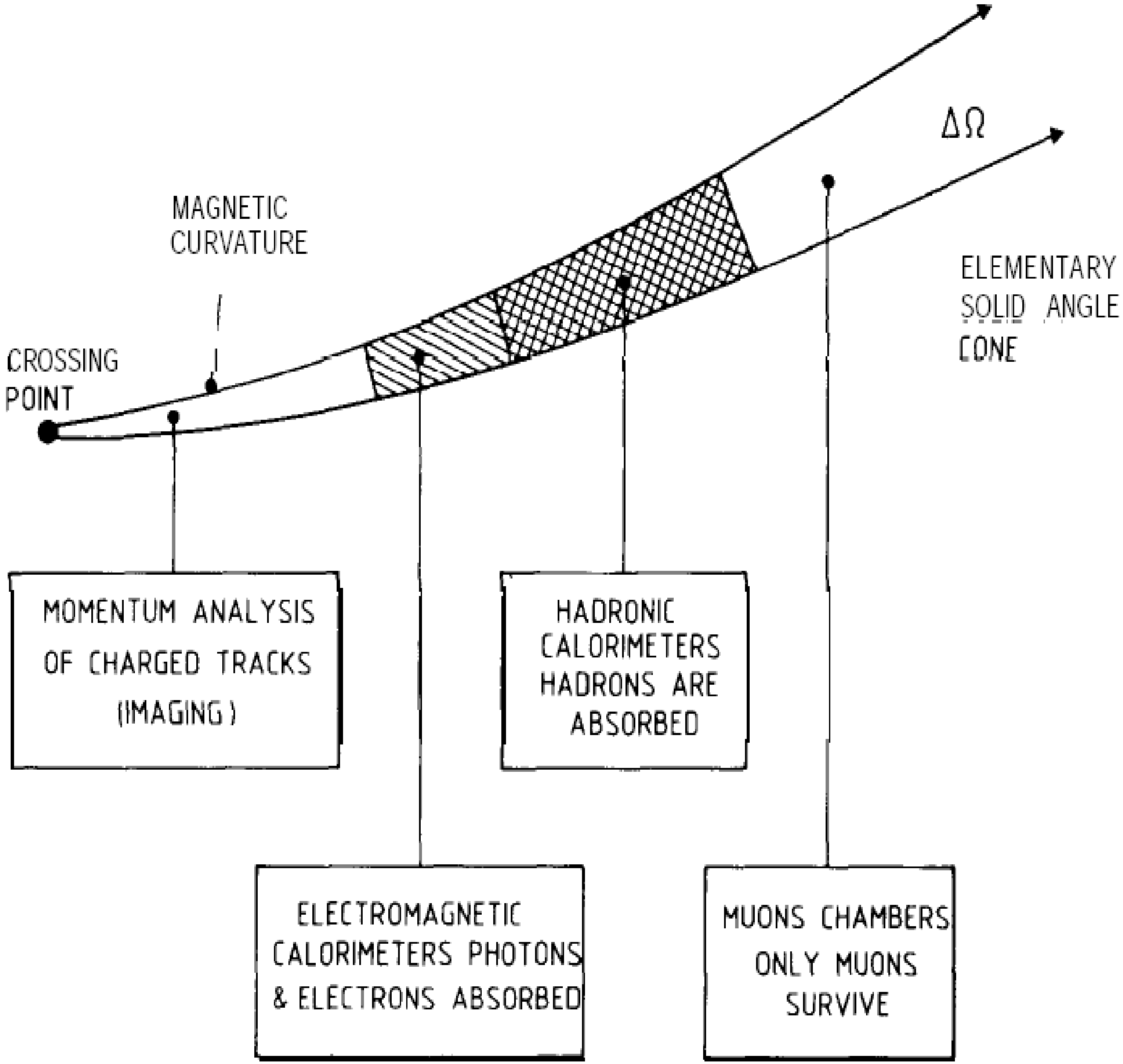




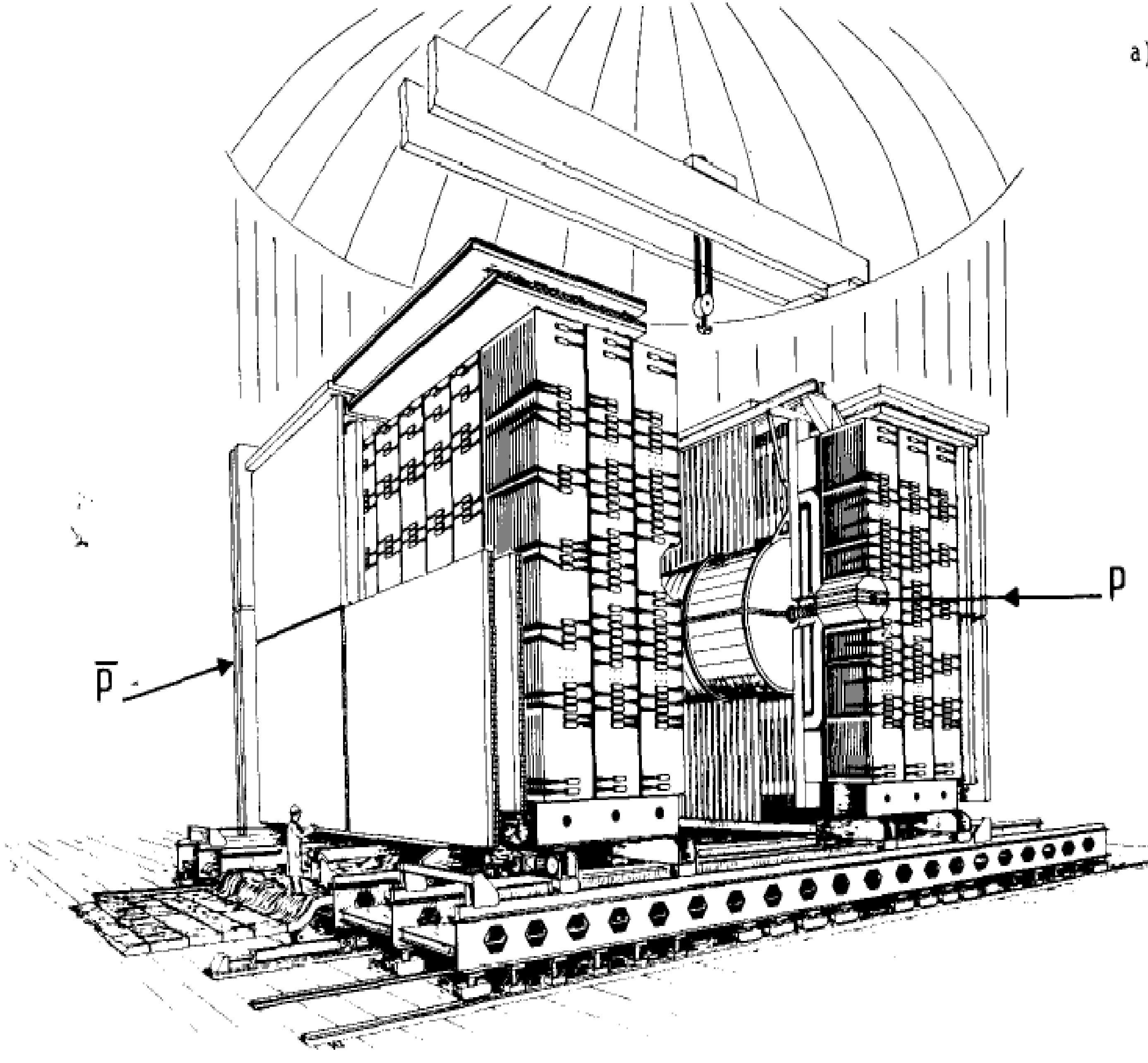
Different collision points in the SPS tunnel

Two different “multi-purpose” detectors (like Mark I at SPEAR), with different technological choices in order to be as complementary as possible

General structure
(note: very similar in modern detectors)



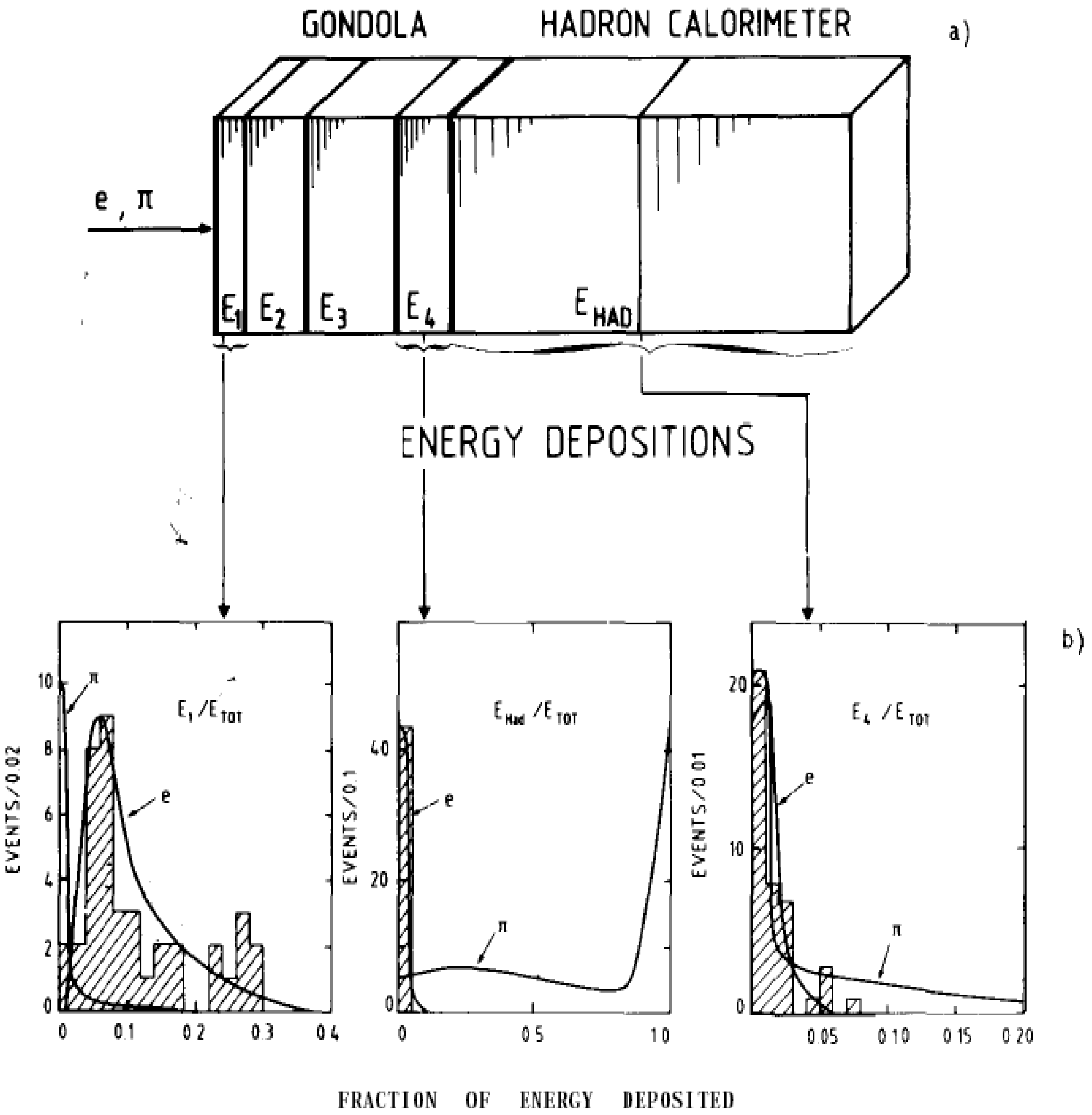
The UA1 detector



- Magnetic field (horizontal, 0.7 Tesla)
- Emphasis on good momentum resolution (→high precision tracking)
- Electromagnetic calorimeters (e/γ id.): alternated layers of <u>lead</u> (high Z) and scintillator
- Hadronic calorimeter: alternated layers of <u>iron</u> and scintillator
- Hermetic
- Muon chambers: drift chambers external to the rest of the detector

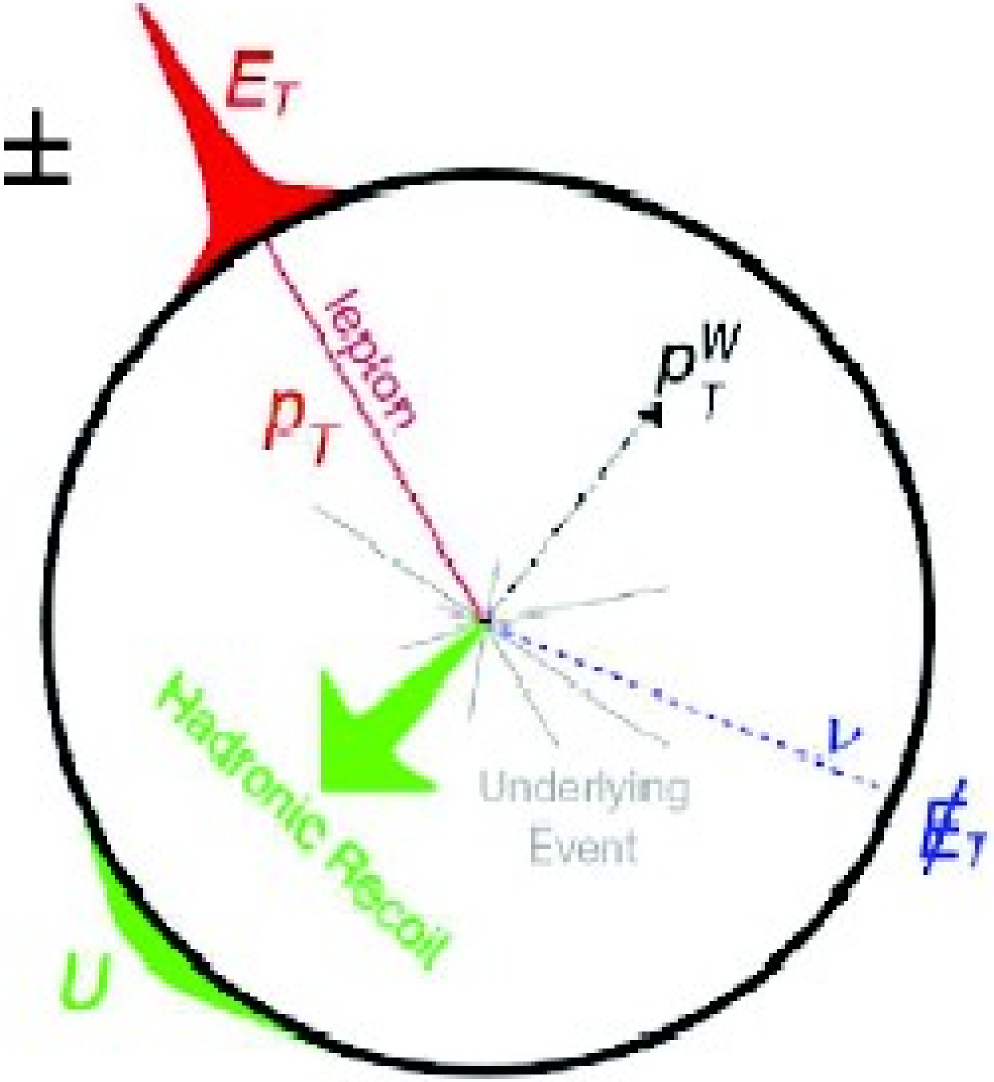
Electron/hadron discrimination

(UA1)

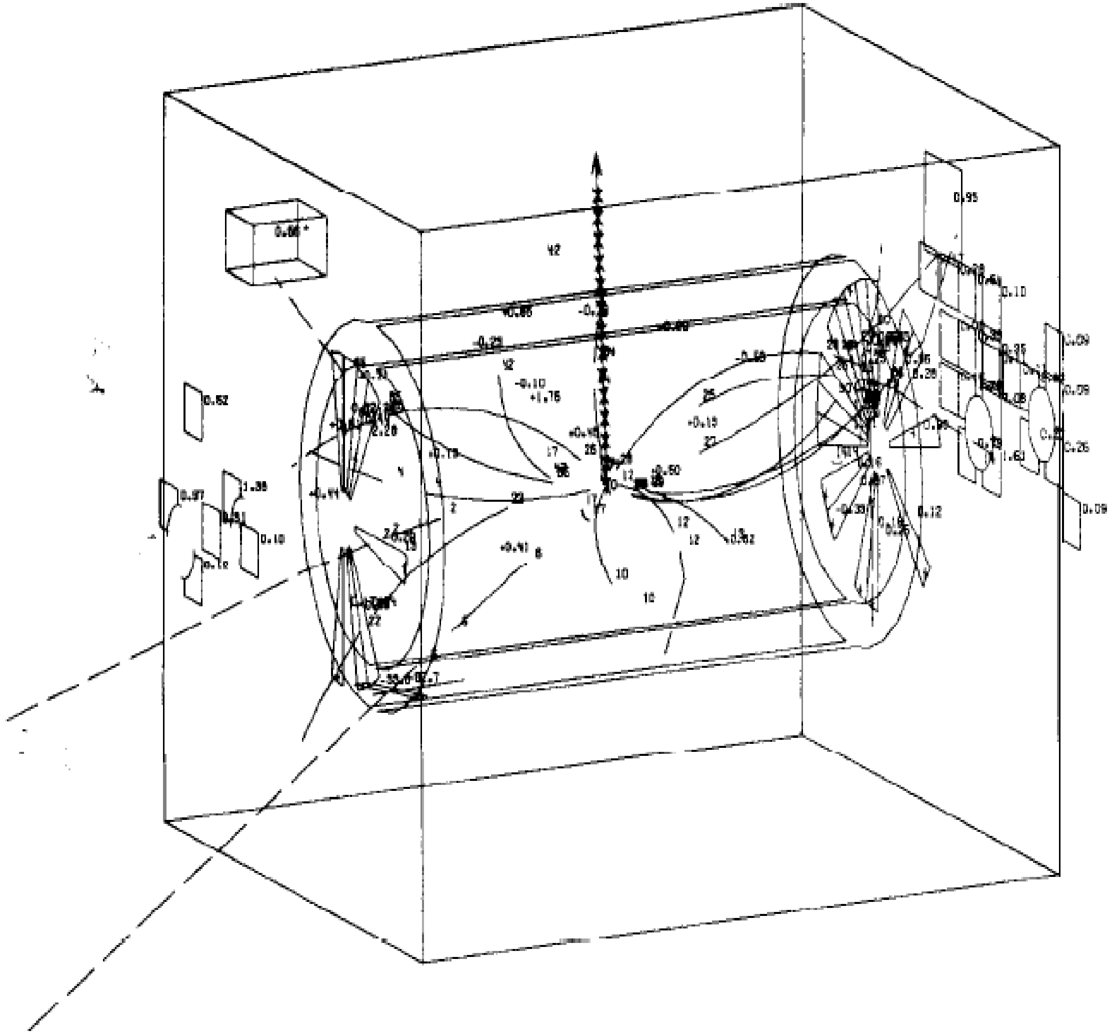


Generic final state of a W event

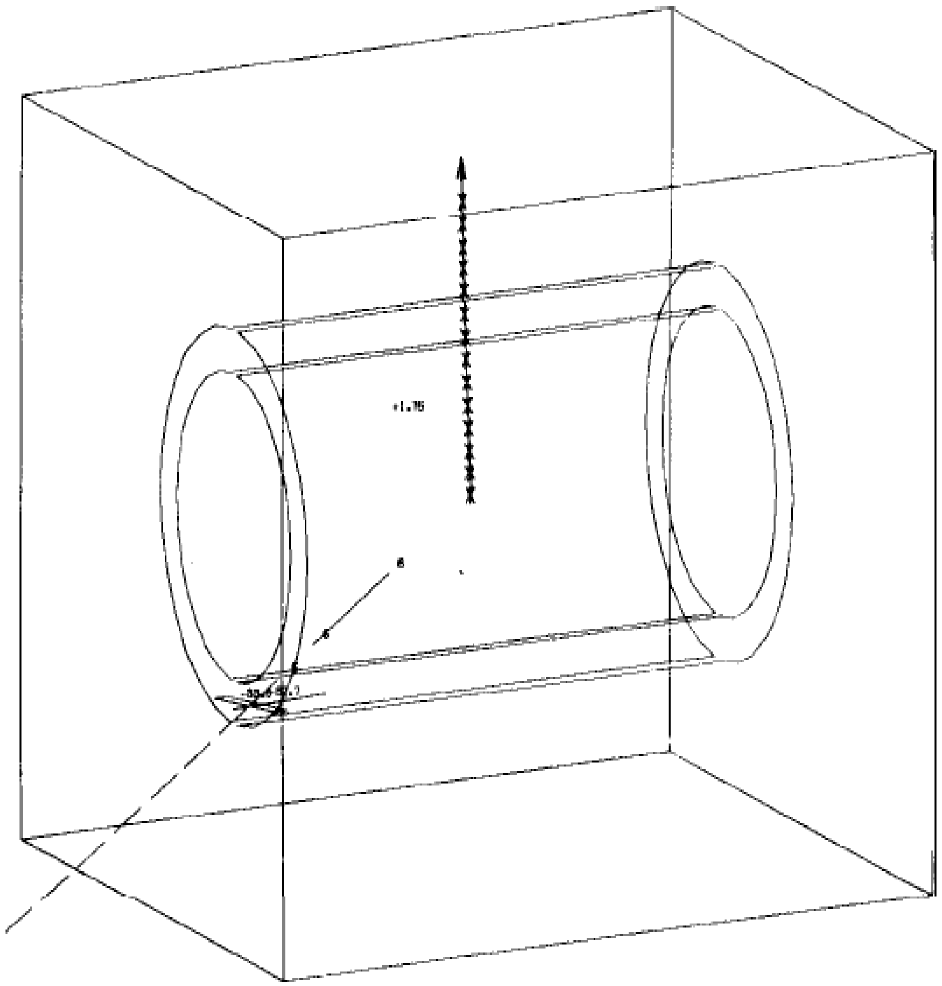
$W^{\pm}$



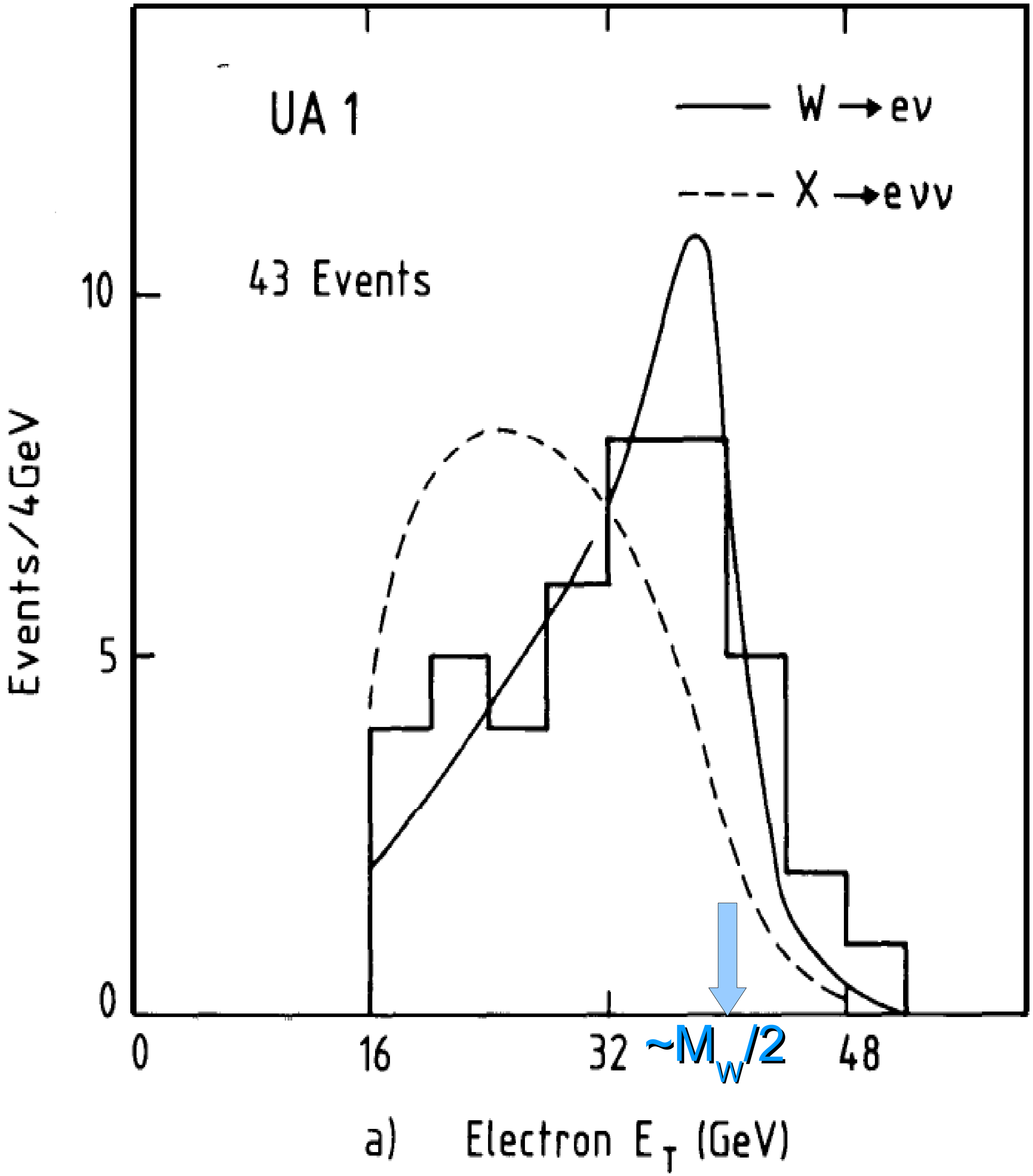
stolen to T. Dorigo



All charged tracks are displayed



Only P_T>1 GeV

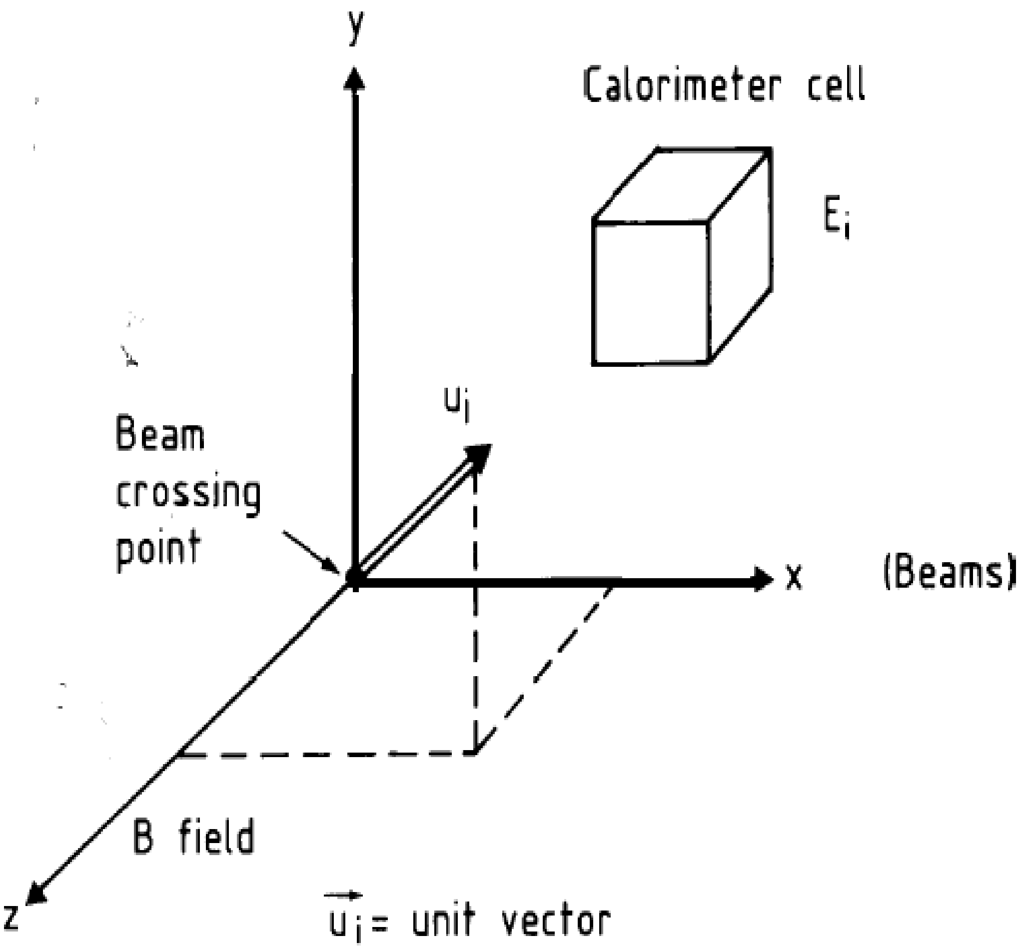


- If you could plot E in the W rest frame, you would get a **gaussian** centered around $M_W/2$
- This distribution comes from the fact that we plot $E_T = E \sin\theta$ (remember: the longitudinal boost of q and $\bar{q}$ is unknown)
- How to know that the new particle is a W and not, for example, a new heavy lepton?
- This plot shows that the 2-body decay (as expected for a W) is more compatible than the 3-body decay (like a new lepton: remember the μ)

Missing (transverse) momentum method

- Neutrinos have negligible interaction probability
- Ideally, by detecting all the other particles in the event, you can infer the existence (and measure the momentum) of a non-interacting particle by **momentum conservation**
  - This means that the detector has to be as hermetic as possible: any particle escaping (down the beam pipe or in a crack) will degrade the missing momentum determination
  - Calorimeter noise (= fake particles) also degrades it
- The missing momentum method works very well in e^+e^- colliders, while in pp and $p\bar{p}$ colliders only the missing **transverse** momentum (2D projection) is used
  - (you know why)

CONSTRUCTION OF ENERGY VECTORS



$\vec{u}_i$ = unit vector

$\vec{E}_i = E_i \vec{u}_i$

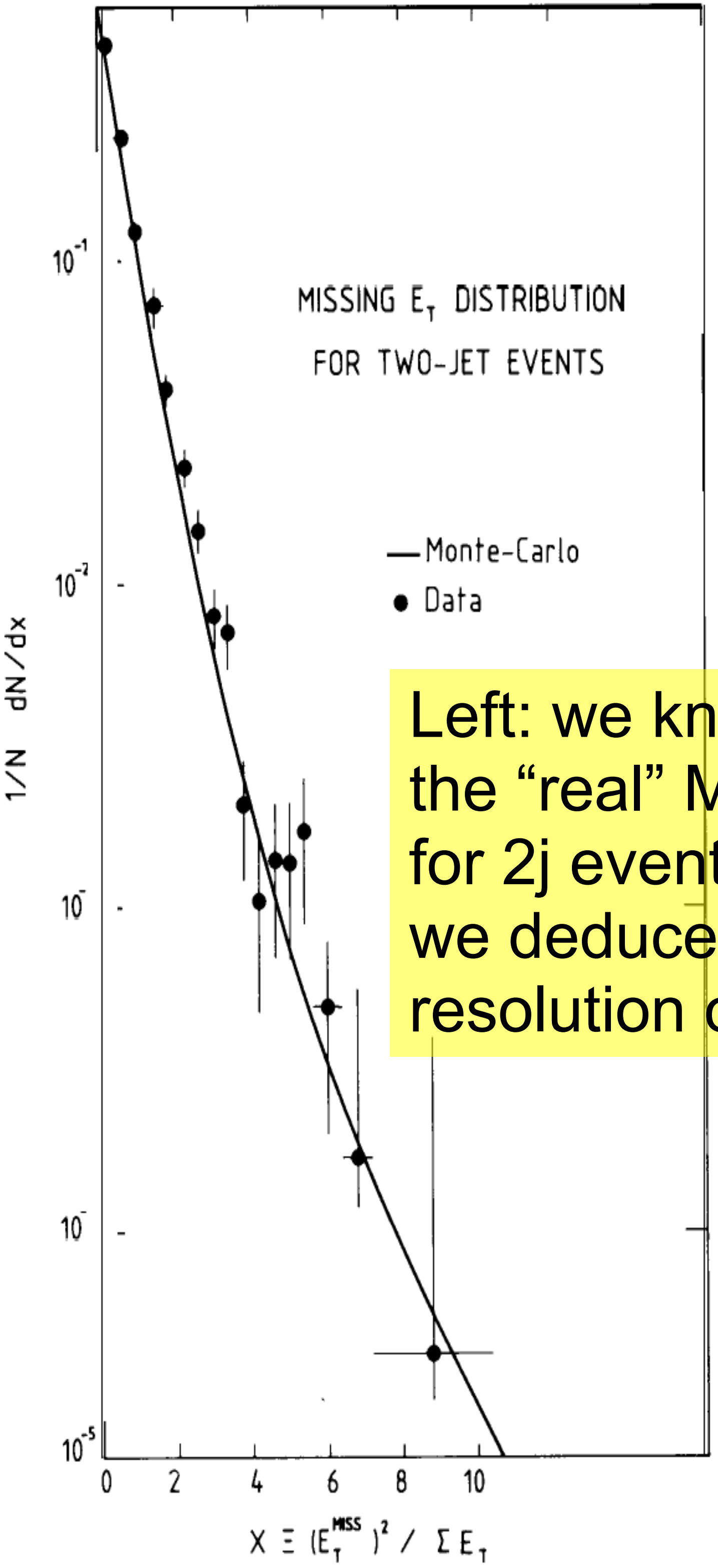
Momentum conservation (ideal detector) $\longrightarrow \sum_i \vec{E}_i = 0$

$\Delta\vec{E}_m = \sum \vec{E}_i$

The method is often called of “missing energy”, instead of “missing momentum”, because calorimeters are used (which block all particles – apart from muons – and measure their total <u>energies</u>).

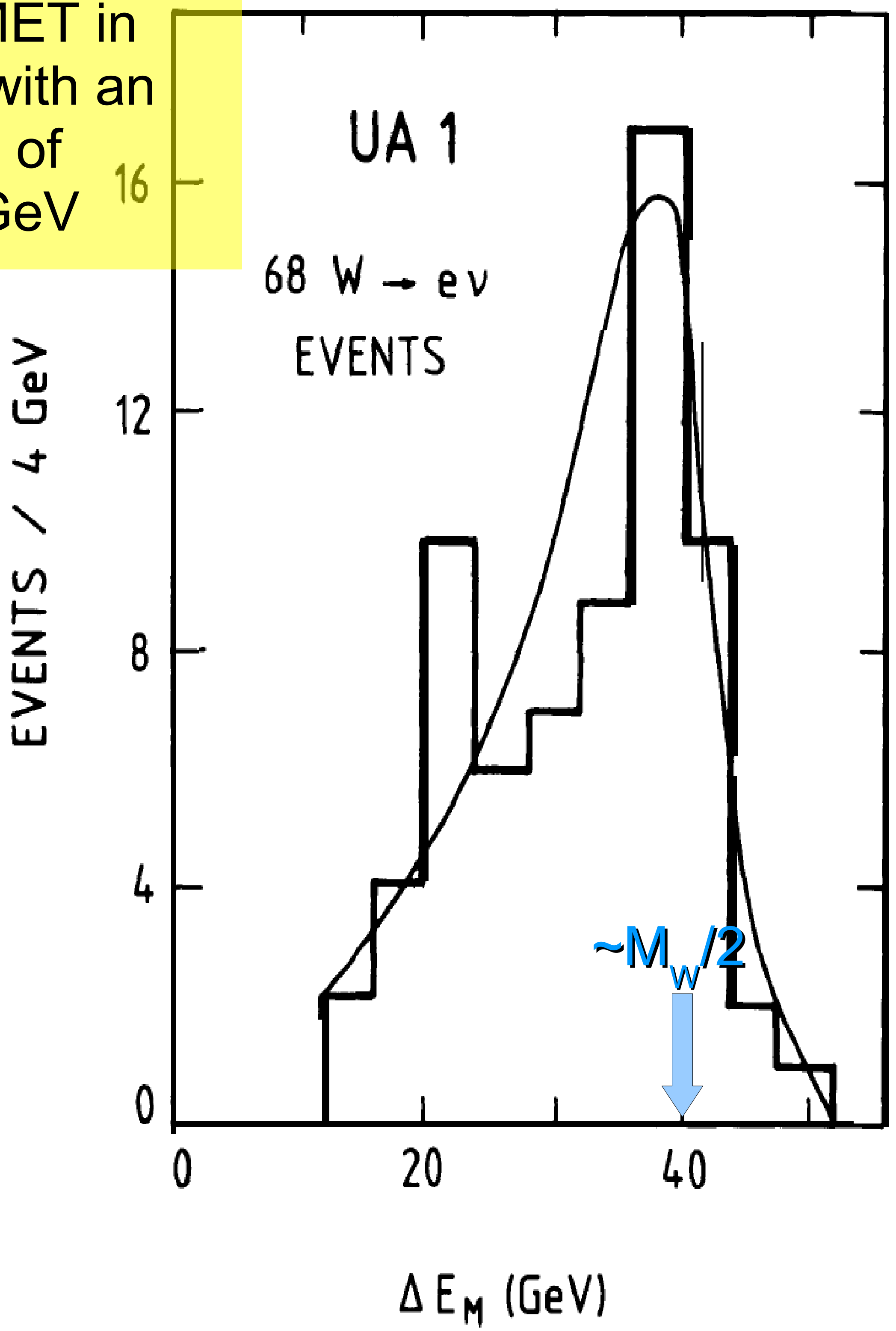
MET is the standard acronym for Missing Energy in the Transverse plane.

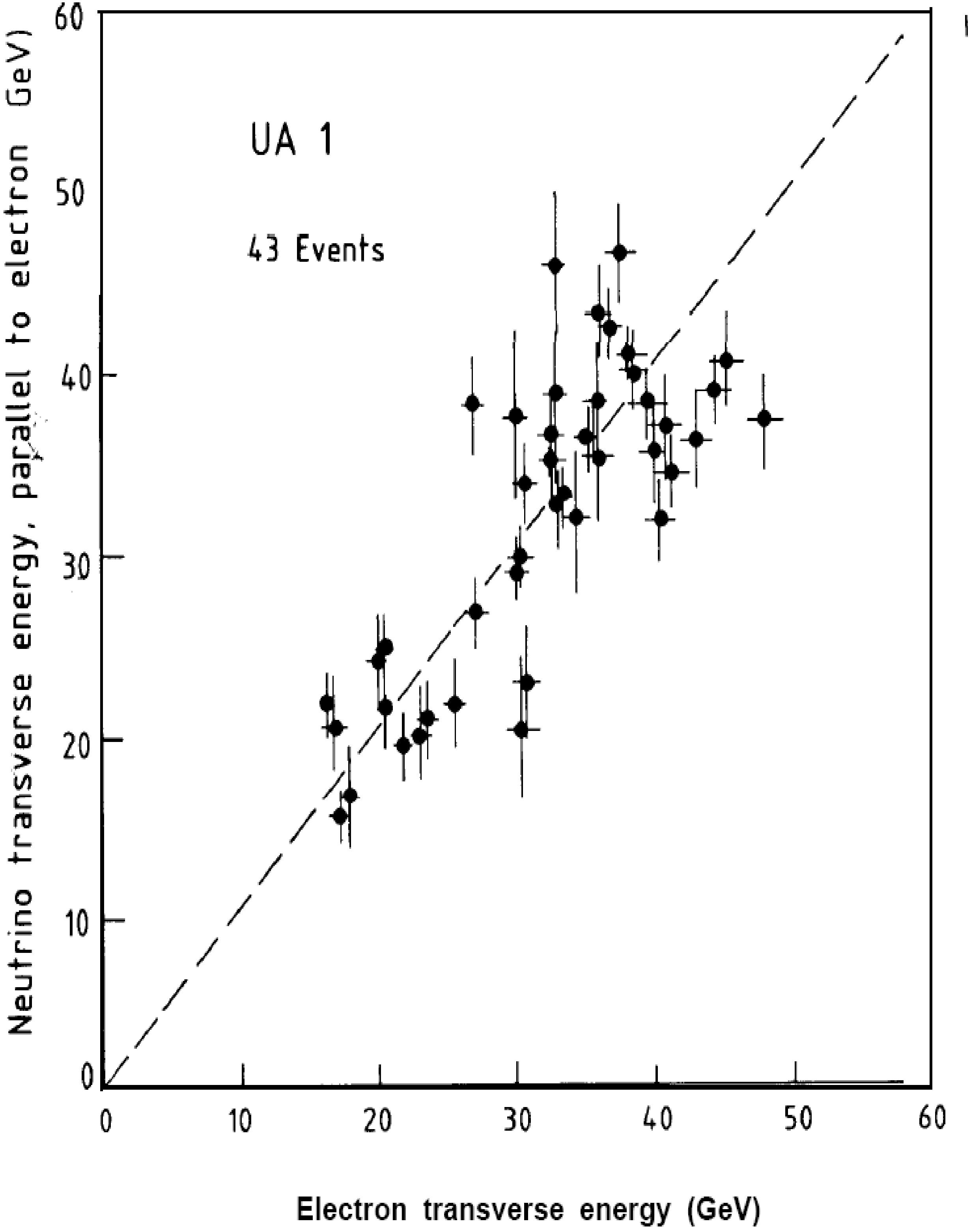
Question: why not using the information (momentum) from the Tracking system? Note: Δp/p from magnetic bending is smaller than ΔE/E from calorimeter, for low p&E



Left: we know that the “real” MET is 0 for 2j events, and we deduce the resolution on MET

Right: MET in events with an electron of E_T>15 GeV





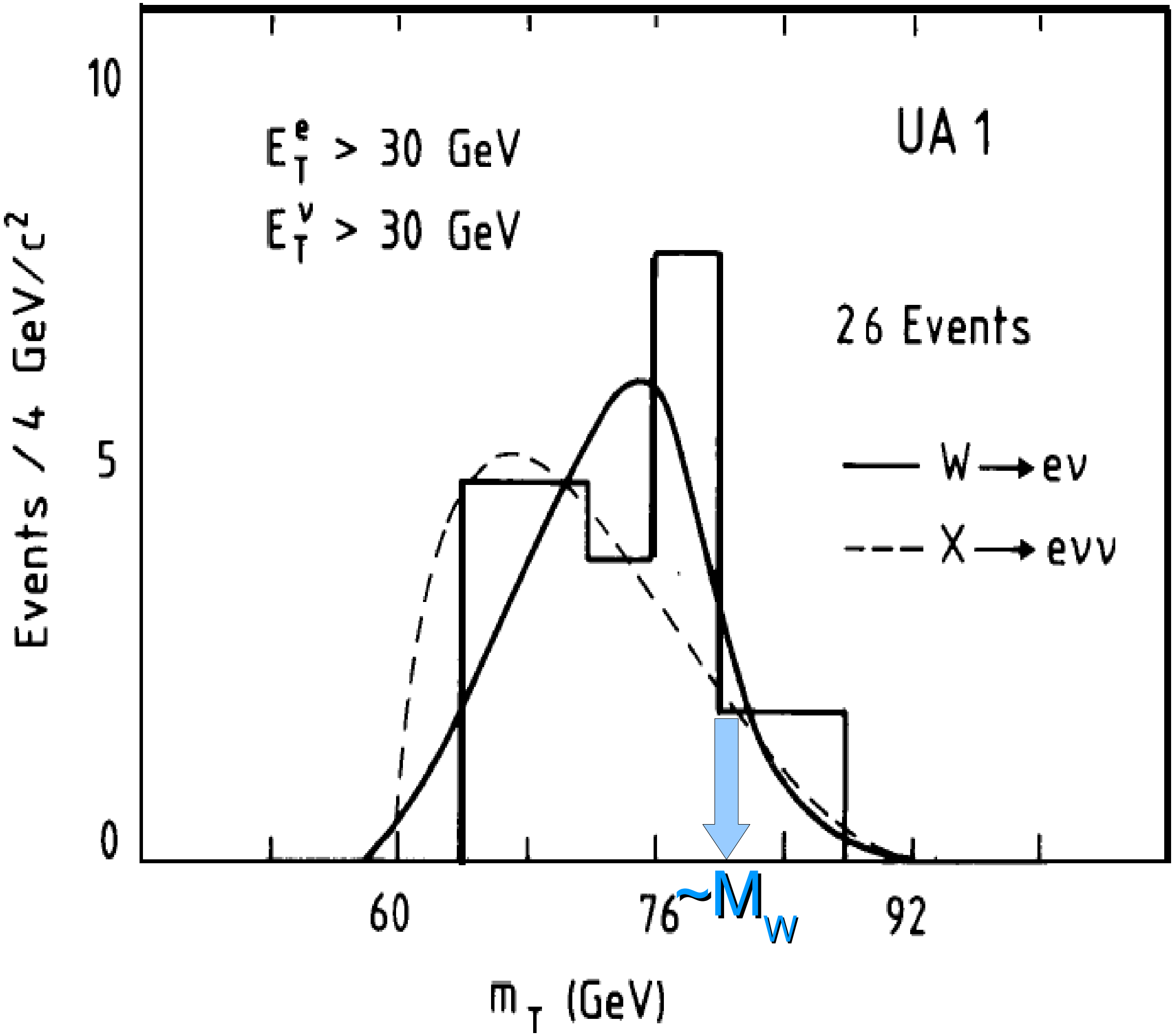
From this correlation it is evident that the electron and the invisible particle(s) are produced back-to-back

Question: why aren't they distributed exactly along the line?

Measuring the W mass

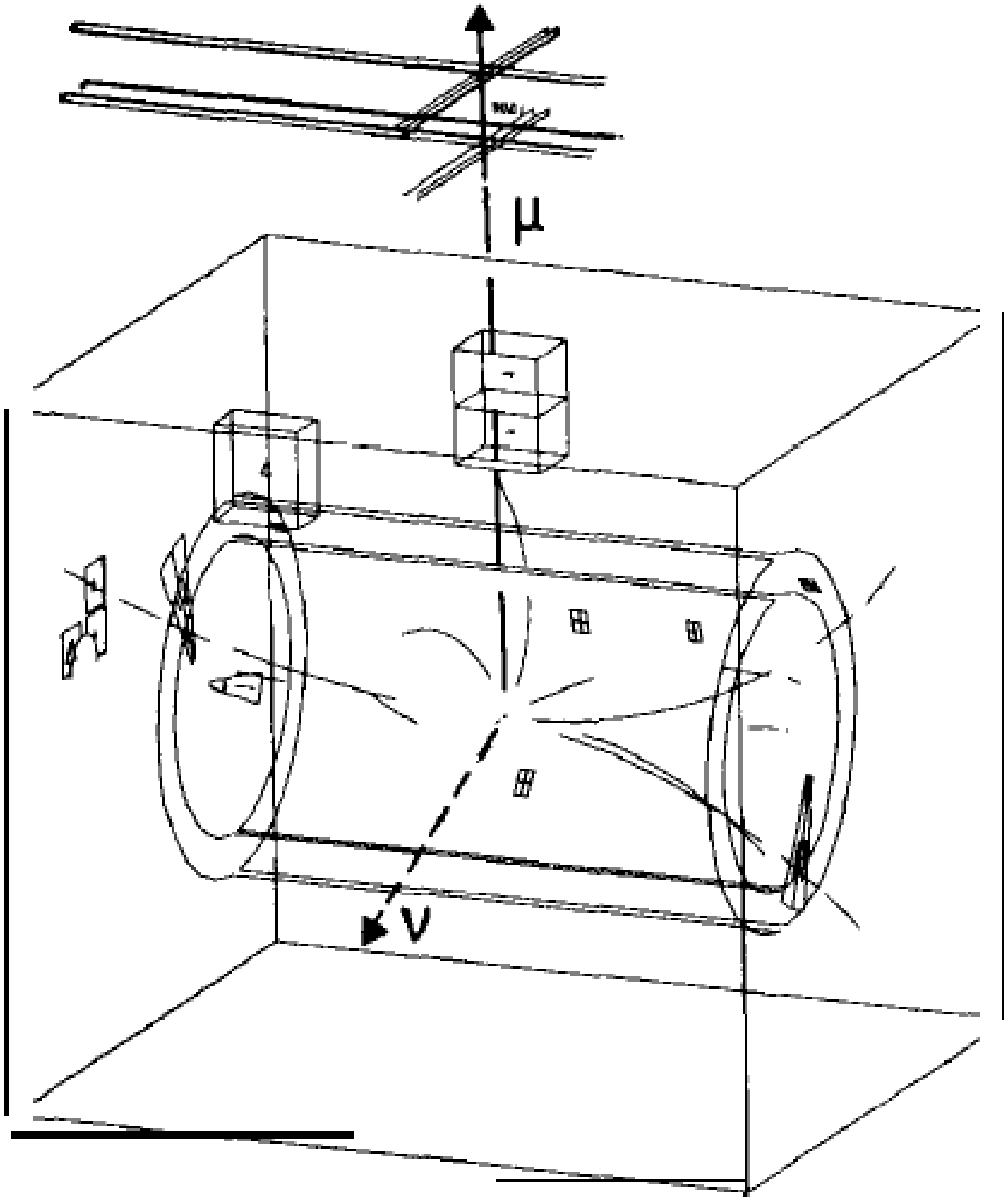
- In absence of resolution effects and for $P_T^W=0$, the distributions of E_T and MET would both have a sharp edge at $M_W/2$

- Other useful variable, insensitive to P_T^W: the “transverse mass” (i.e. invariant mass in the 2D transverse plane)
  - Question: why is it insensitive to P_T^W?



$$m_t^{\,2} = \left(E_{e,t} + E_{\nu,t}\right)^2 - \left(\vec{E}_{e,t} + \vec{E}_{\nu,t}\right)^2 = 2 p_t^{\,e} p_t^{\,\nu}\left(1 - \cos\phi_{\nu e}\right) = 4 p_t^{\,e} p_t^{\,\nu} \sin^2\frac{\phi_{\nu e}}{2}$$

Muonic decay



- Tracking (muons): $\sigma_p/p \sim p$
- Calorimeters (electrons): $\sigma_E/E \sim 1/\sqrt{E}$

At low energy, the tracking measurement is more precise; but for high energies it's the opposite. The muonic sample was not competitive for the extraction of M_W, but confirmed the *lepton universality* of the W: $BR(W \rightarrow e\nu_e) = BR(W \rightarrow \mu\nu_\mu)$

If this particle is really the mediator of the weak force...

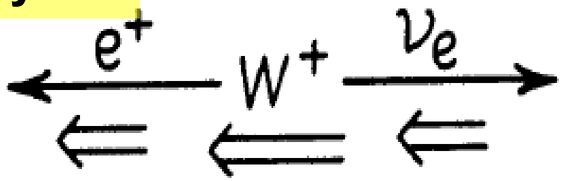
- ...it has to exhibit the most peculiar property of this force: parity violation (and charge conjugation violation)
  - Particles couple to the W only if they are left-handed (LH), i.e. helicity<0, anti-particles only if they are right-handed (RH), i.e. helicity>0
- And if it is the W of the EW theory, it must have spin 1
  - In the next slide we put these two informations together in order to see how to get a clear experimental signature of the nature of W

Asymmetry in the lab system

Production:

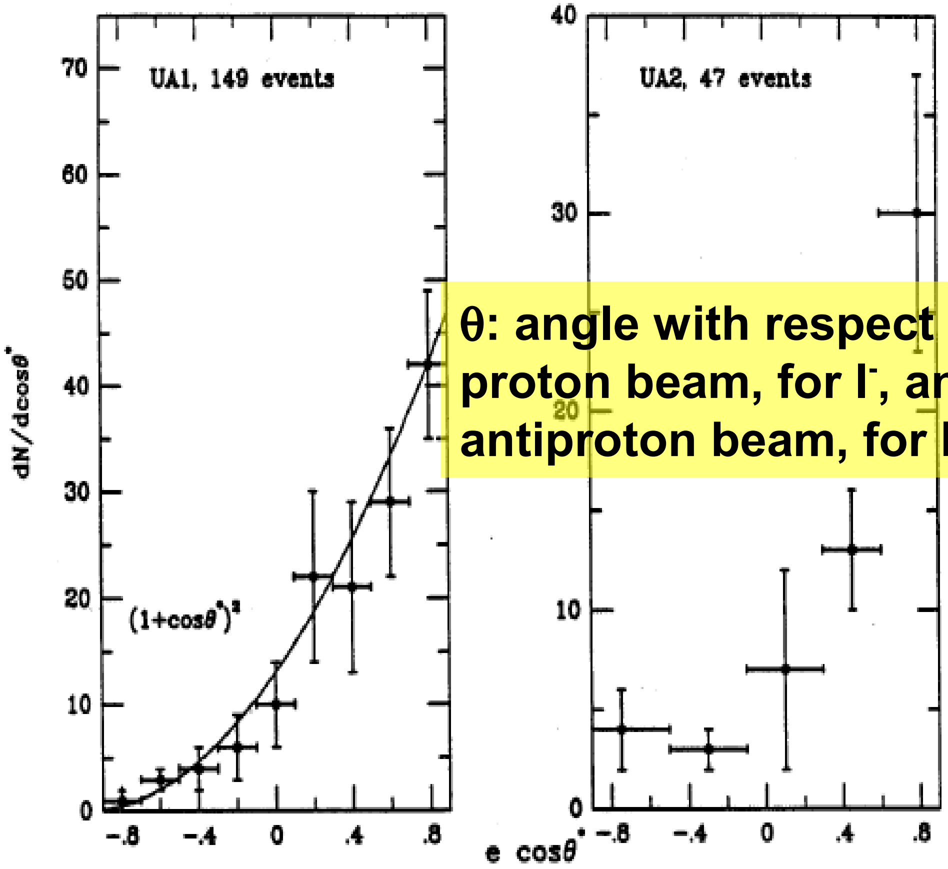
Figure 10.4
Polarized W^+ produced in a $p\bar{p}$ collider.

Decay:



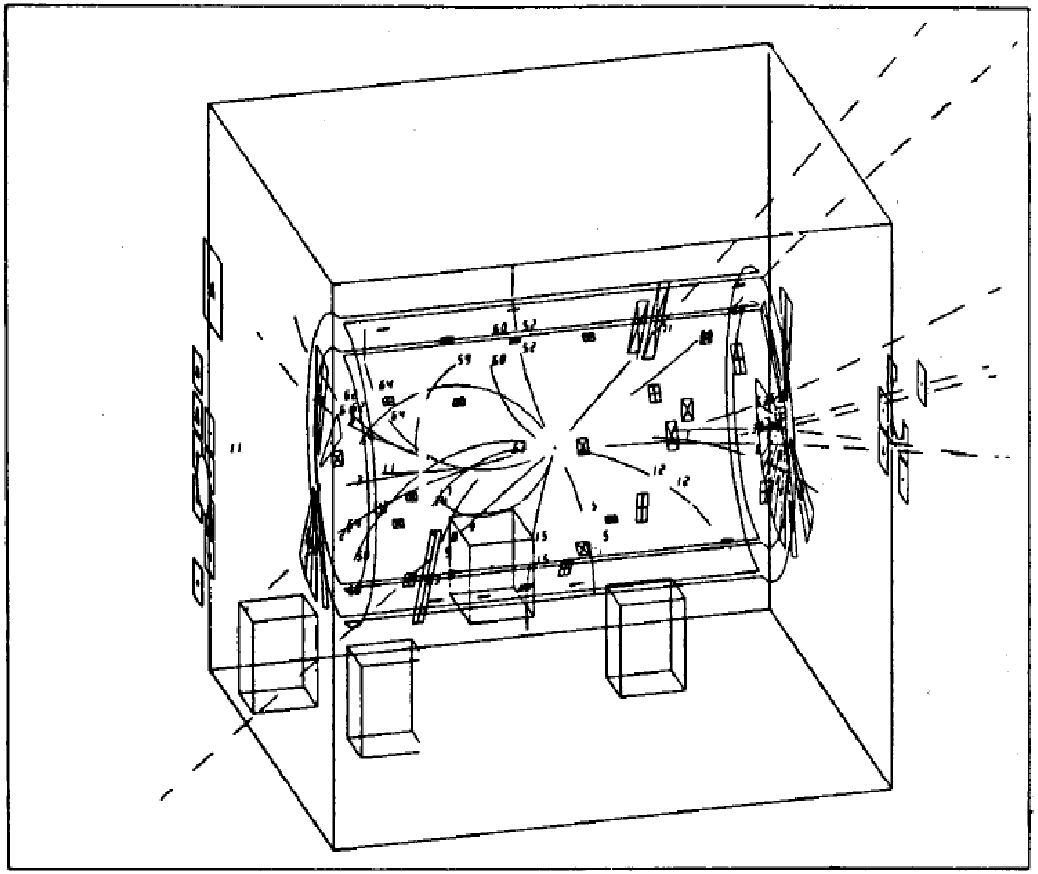
Remember: particles (u,ν) are LH, i.e. have negative helicity, i.e. their spin points oppositely to the momentum; antiparticles ($\bar{d}$,e^+) are RH: spin and momentum are parallel

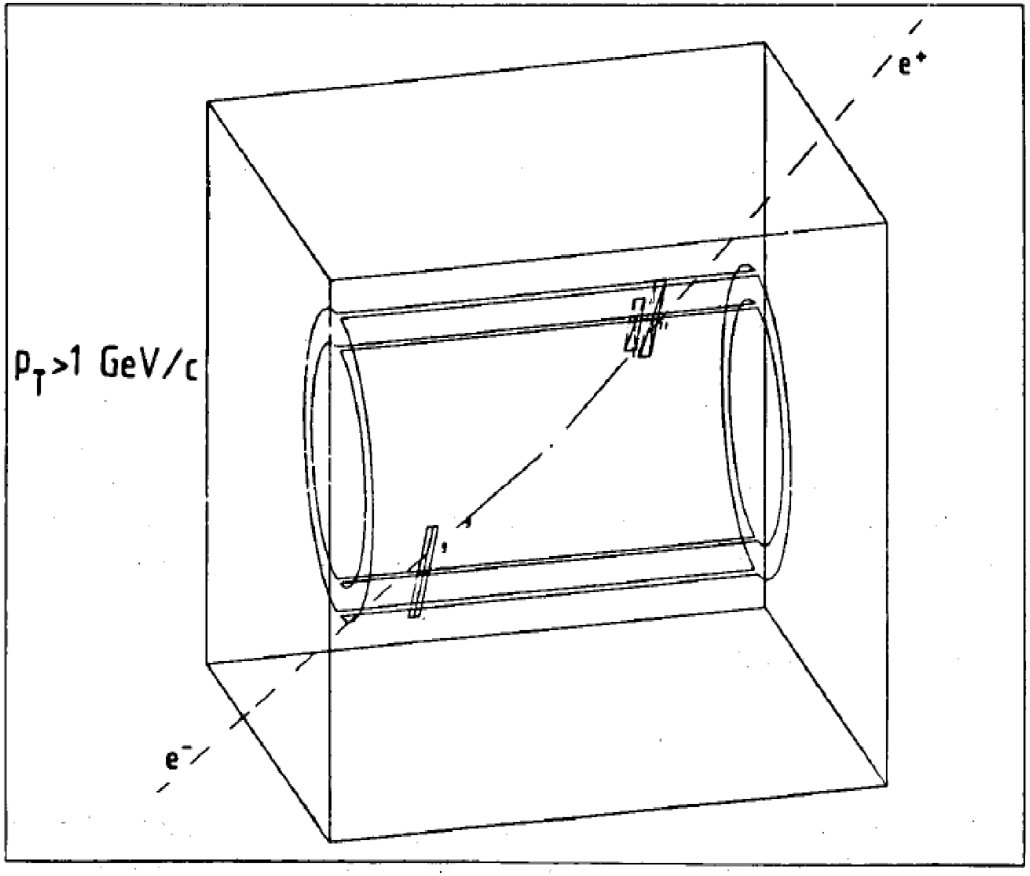
From the figure on the left (and drawing the equivalent figure for W^-) you expect that positive leptons tend to follow the antiproton direction, negative leptons the proton direction



θ: angle with respect to the proton beam, for l^-, and the antiproton beam, for l^+

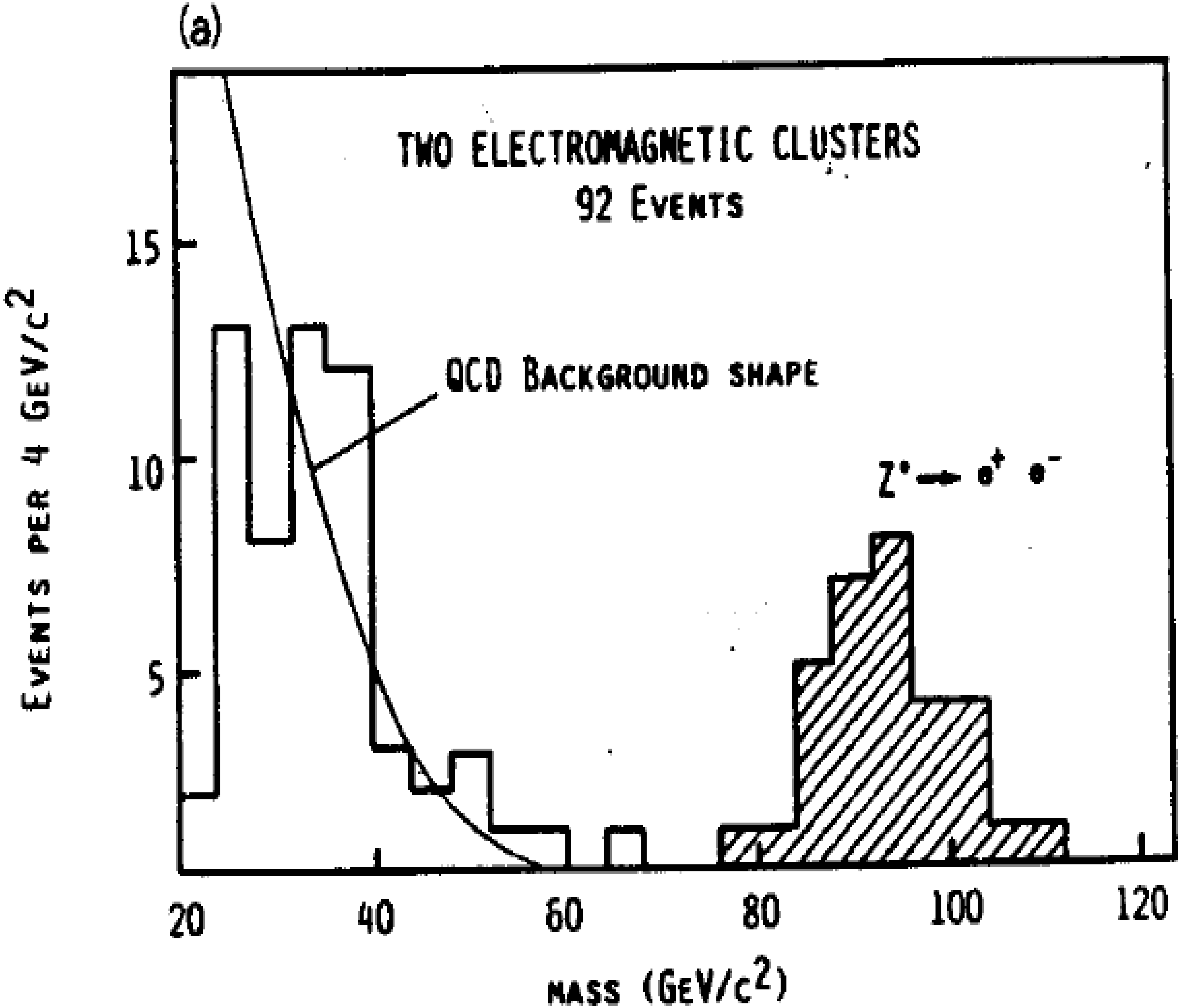
Z discovery (1)





Very clear signature: 2 high energy leptons with opposite charge, no missing energy

Z discovery (2)



Conclusions

- The observation of W and Z, with the correct masses and couplings, was one of the most crucial proofs for the SM
- Why Rubbia won the Nobel: for having figured out an experiment able to give an **unambiguous (yes/no) answer** to the question “Do the W and Z of SM exist?”
  - Note: SM is <u>not</u> the Final Theory, but any conceivable new theory has to explain the SM as its low-energy limit
- This needed also genius from the **engineering** part (and this is why Van der Meer got a Nobel too)
- A particle physicist (including theorists) in the LHC era needs to understand the basics of **hadron collider physics**. The hadron collider physics of today was born with the SppS; UA1/UA2 are the grandfathers of CMS/ATLAS

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- Rubbia's and Van der Meer's Nobel Lectures:
  - http://nobelprize.org/nobel_prizes/physics/laureates/1984/

Appendix: the UA2 detector

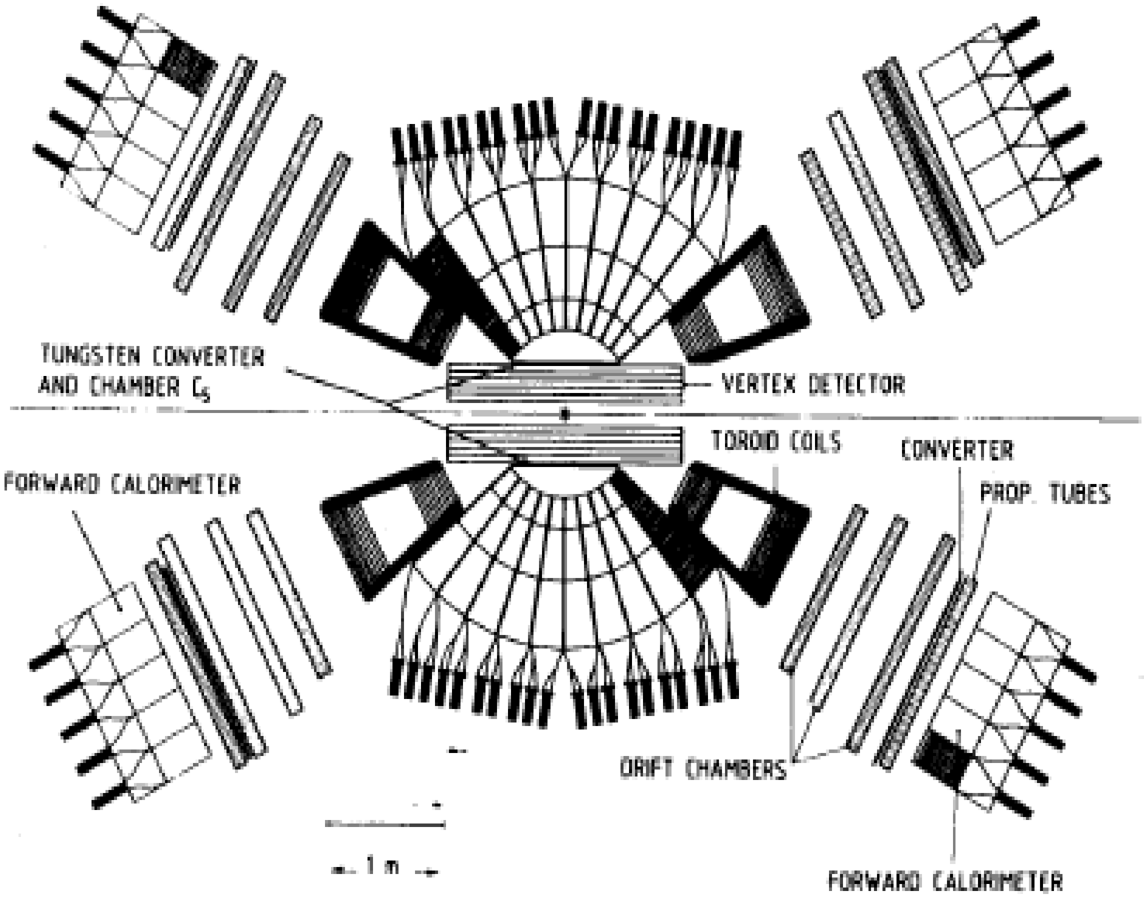

Fig. 1. The UA2 detector: Schematic cross section in the vertical plane containing the beam.

Main differences with respect to UA1:

- No muon chambers
- Emphasis for tracking on good position resolution ("Vertex detector")
- Magnetic bending only in the forward direction, where the W decay asymmetry is maximal
- Less hermetic than UA1