

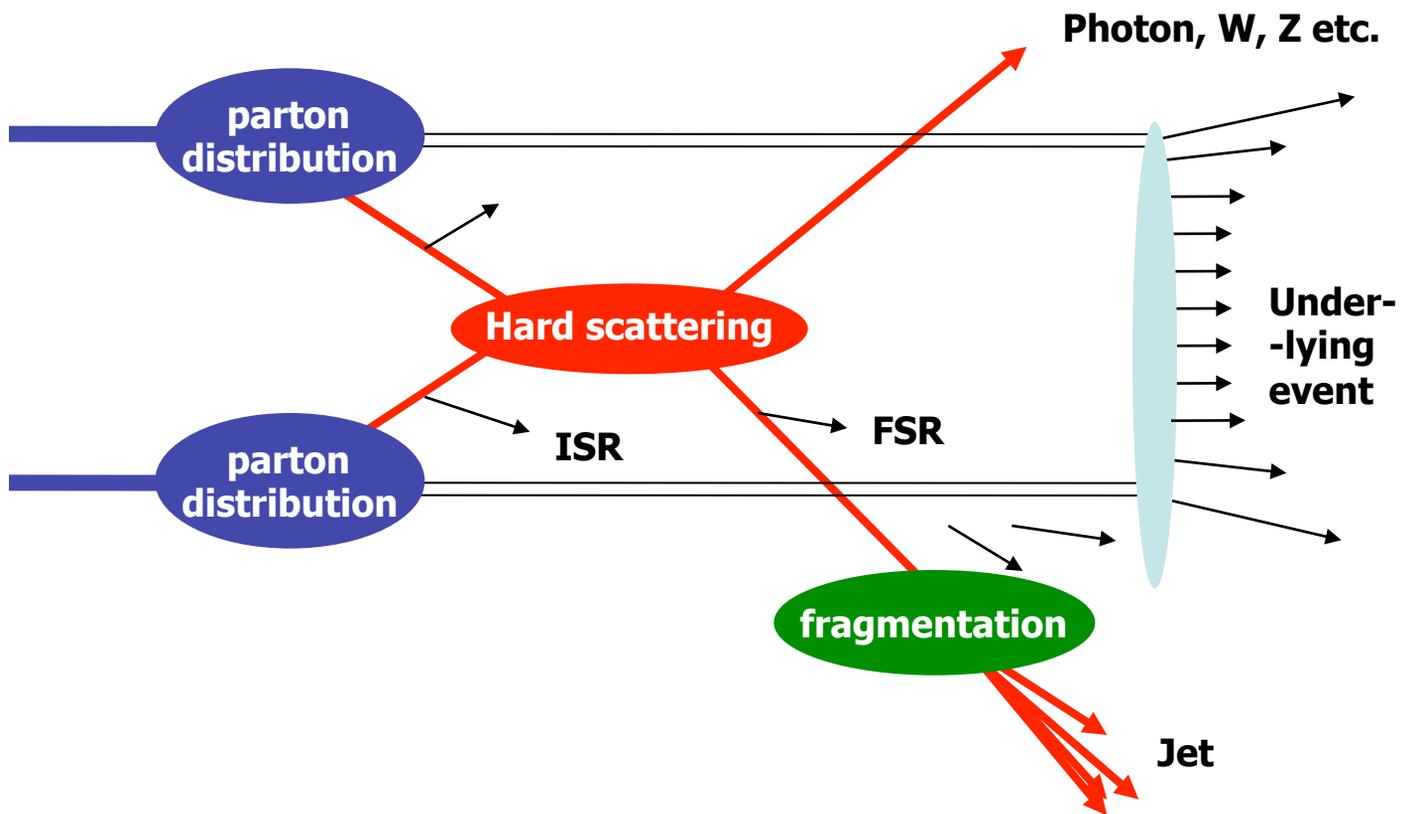
Capitolo 9 : Scoperta dei Bosoni W e Z

Corso di Fisica Nucleare e
Subnucleare II

Professor Carlo Dionisi

A.A. 2012-2013

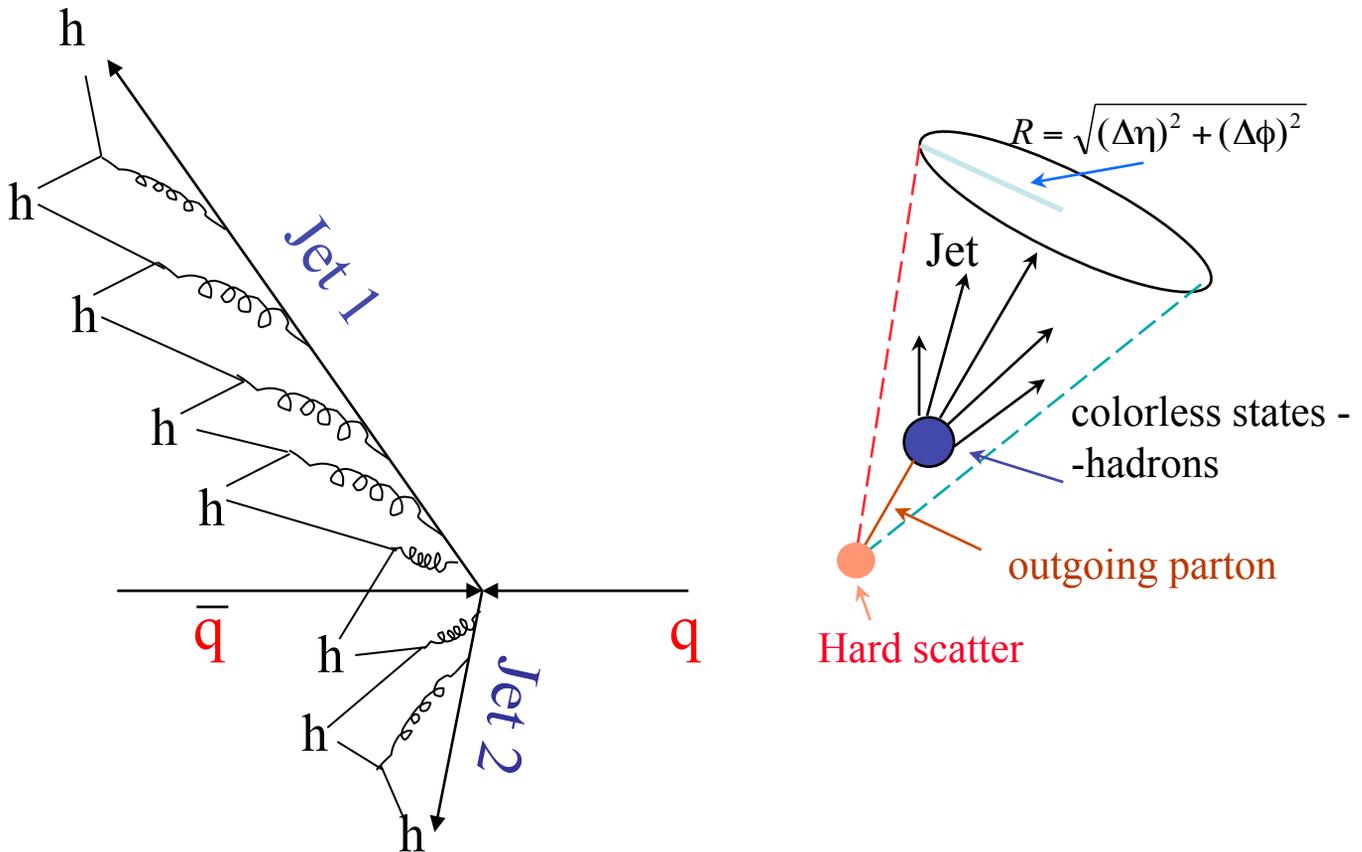
Collisioni Adrone-Adrone



- **Caratteristiche:**

- La σ dell'urto hard è mediata sulle pdf
- Gli stati iniziali e finali possono emettere gluons
- Gli stati finali colorati frammentano a formare dei "jets"
- Underlying event dai residui di proton/p-bar

Collisioni Adrone-Adrone

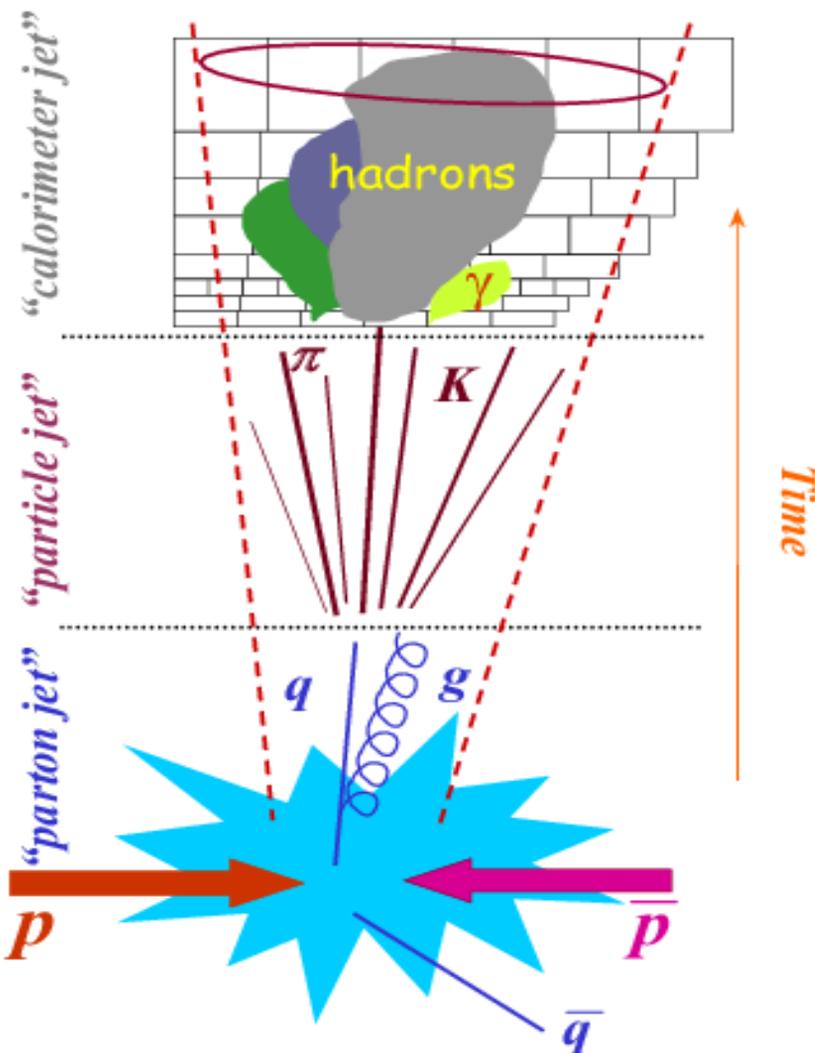


- **Fragmentation (hadronization):**

- Final state quarks or gluons produced by the hard scattering produce lots of radiation (a_s is large!)
- Recombine to form a colorless spray of approximately collinear hadrons: **a jet**
- Jets are an experimental signature of quarks and gluons and are observed as localized energy deposits in the calorimeters

Jets

A jet is a composite object:



- **complex underlying physics**

- events contain spectator interaction
- processes connected via color
- hadron fragmentation
- different type of jets: $q, g, b/c$

- **complex detector properties**

- non-linear detector properties
- non-instrumented regions

Jet Corrections

Calorimeter Jets:

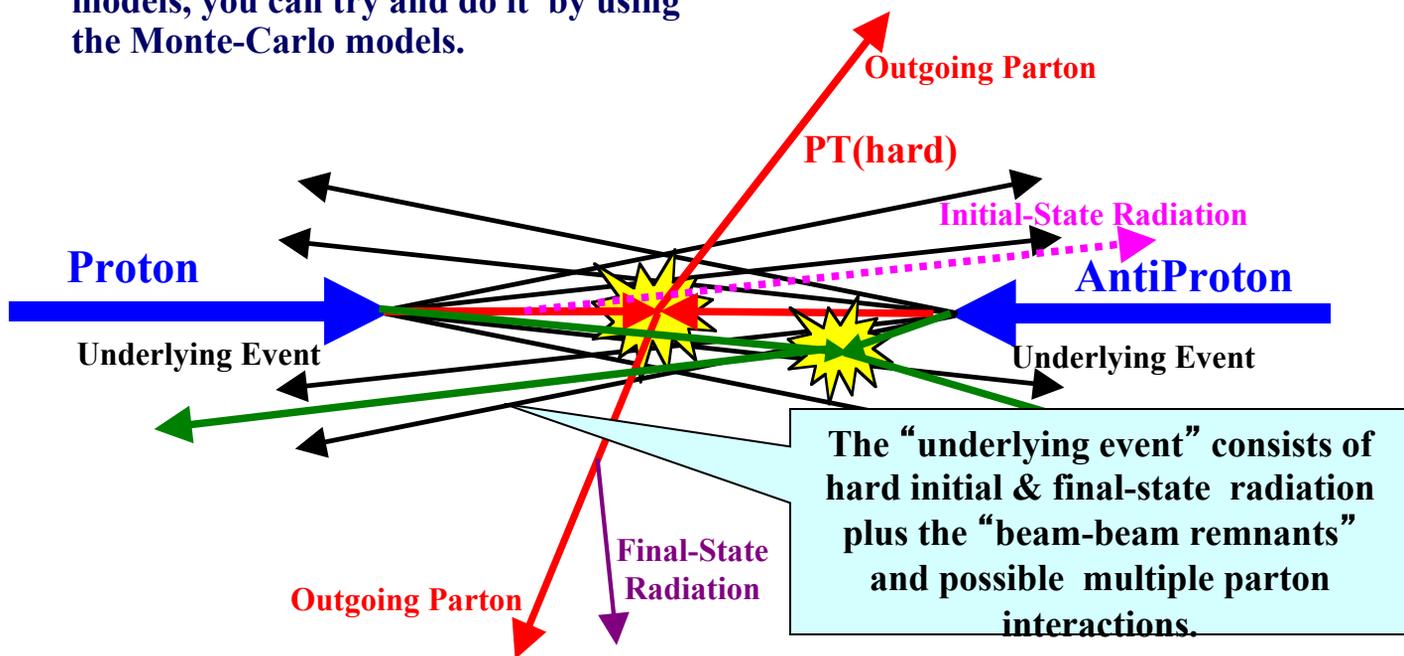
- We measure “jets” at the “hadron level” in the calorimeter.
- We certainly want to correct the “jets” for the detector resolution, non linearity, efficiency and holes.
- Also, we must correct the “jets” for “pile-up”.
- Must correct what we measure back to the true “particle level” jets!

Parton Level Jets:

- Do we want to use our data to try and extrapolate back to the parton level?
- This also cannot really be done but, again if you trust the Monte-Carlo models, you can try and do it by using the Monte-Carlo models.

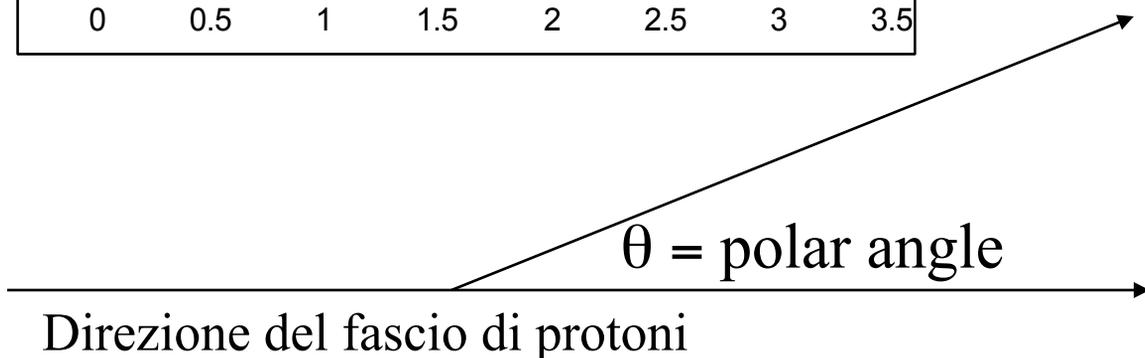
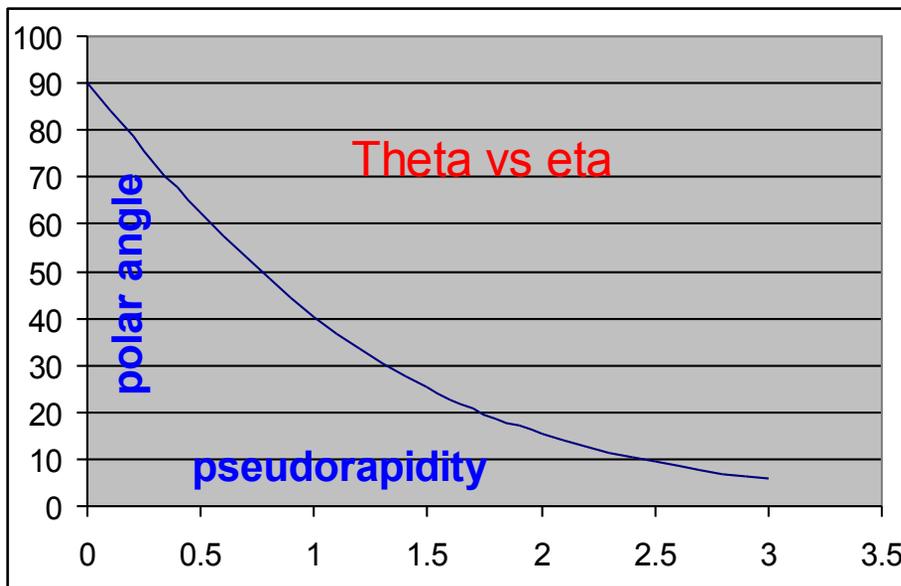
Particle Level Jets:

- Do we want to make further model dependent corrections?
- Do we want to try and subtract the “underlying event” from the “particle level” jets.
- This cannot really be done but, if you trust the Monte-Carlo models modeling of the “underlying event”, you can try and do it by using the Monte-Carlo models (use PYTHIA Tune A).

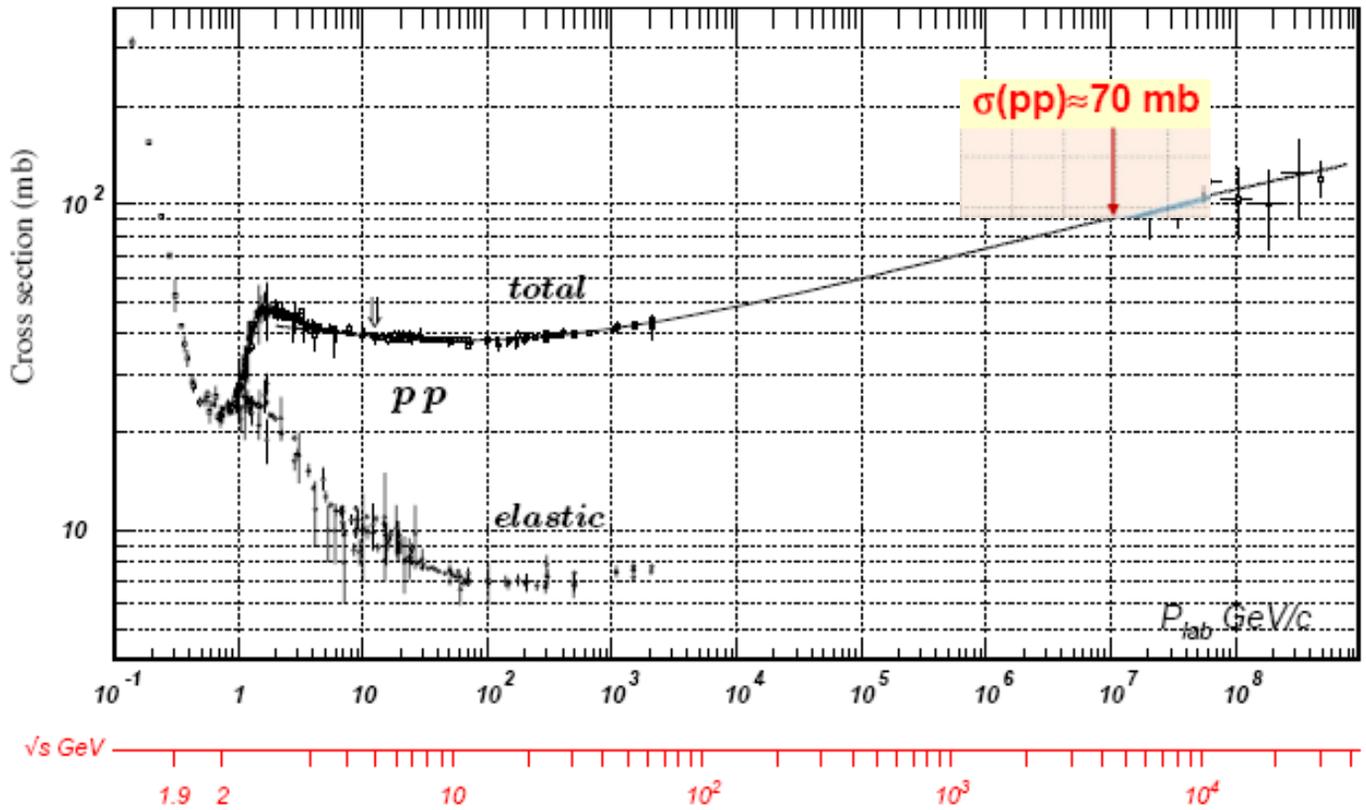


Variabili Utili

- Anche se l'urto protone-antiprotone e' nel CM, **NON LO E'** lo scattering hard tra i partoni!
 - La collisione Hard e' tipicamente “boosted” lungo i fasci di una quantita' NON nota!
 - La soluzione e' quella di usare variabili che hanno una sensibilita' piccola al boost longitudinale:
 - Transverse energy: $E_T = E \sin q$
 - Rapidity $y = \frac{1}{2} \ln[(E+p_z)/(E-p_z)]$
 - pseudo-rapidity $\eta = \ln(\tan(q/2))$ for $m=0$



Sezione d'urto pp



◆ Numero di interazioni per ogni incrocio dei fasci:

• Interazioni / sec:

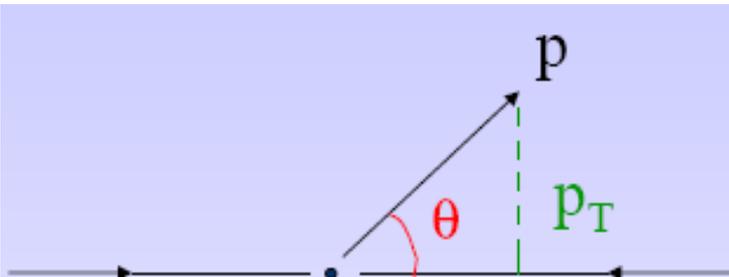
- Lum = $1034 \text{ cm}^{-2} \text{ s}^{-1} = 107 \text{ mb}^{-1} \text{ Hz}$
- $\sigma(pp) = 70 \text{ mb}$
- rate di interazione, $R = 7 \times 10^8 \text{ Hz}$

• Eventi / beam crossing

- $\Delta t = 25 \text{ ns} = 2.5 \times 10^{-8} \text{ s}$
- interazioni / crossing = 17.5

◆ Un evento di “Higgs” + 20 interazioni di “ minimum bias “

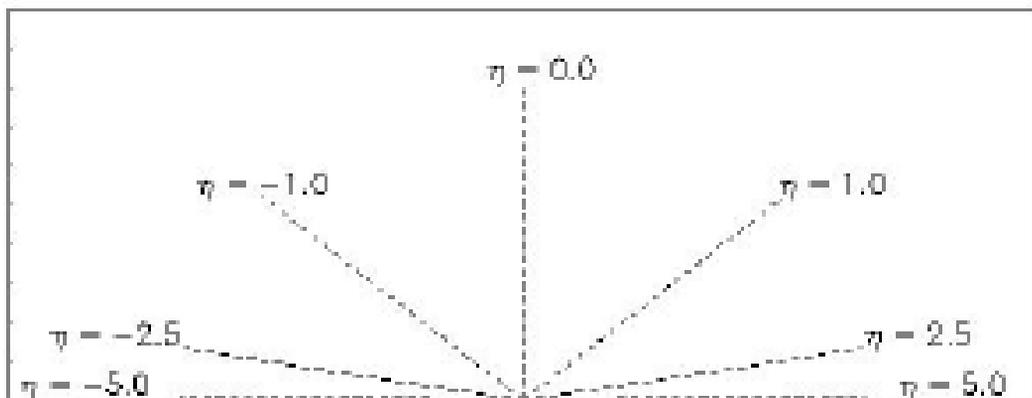
Variabili usate nelle interazioni p-p



Transverse momentum
(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

(Pseudo)-rapidity: $\eta = -\ln \tan \frac{\theta}{2}$



$$\theta = 90^\circ \rightarrow \eta = 0$$

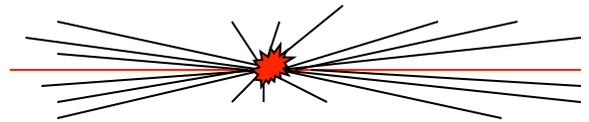
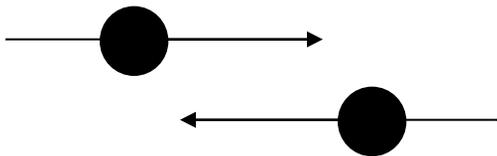
$$\theta = 10^\circ \rightarrow \eta \cong 2.4$$

$$\theta = 170^\circ \rightarrow \eta \cong -2.4$$

Due classi di Interazione

Inelastic low - P_T pp collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as “ a whole ” \rightarrow small momentum transfer ($\Delta p \approx \hbar / \Delta x$) \rightarrow particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)



$\langle p_T \rangle \approx 500 \text{ MeV}$ of charged particles in final state

$$\frac{dN}{d\eta} \approx 7$$

charged particles uniformly distributed in ϕ

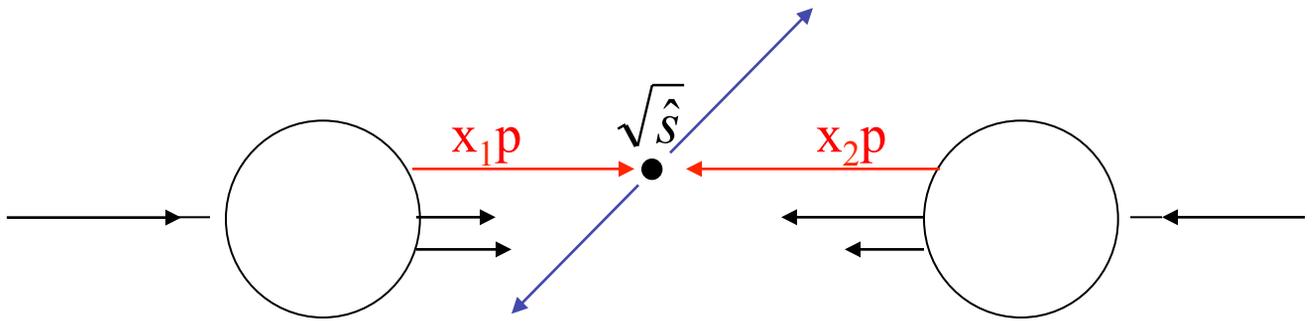
Most energy escapes down the beam pipe.

These are called **minimum-bias events** (“ soft “ events).

They are the large majority but are not very interesting.

the hard scattering process:

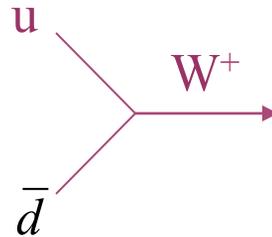
Monochromatic proton beam can be seen as **beam of quarks and gluons** with a wide band of energy. Occasionally **hard scattering** (“head on”) between constituents of incoming protons occurs.



Interactions at small distance \rightarrow large momentum transfer \rightarrow
 \rightarrow massive particles and/or particles at large angle are produced.

These are interesting physics events but they are **rare**.

Ex. $u + \bar{d} \rightarrow W^+$

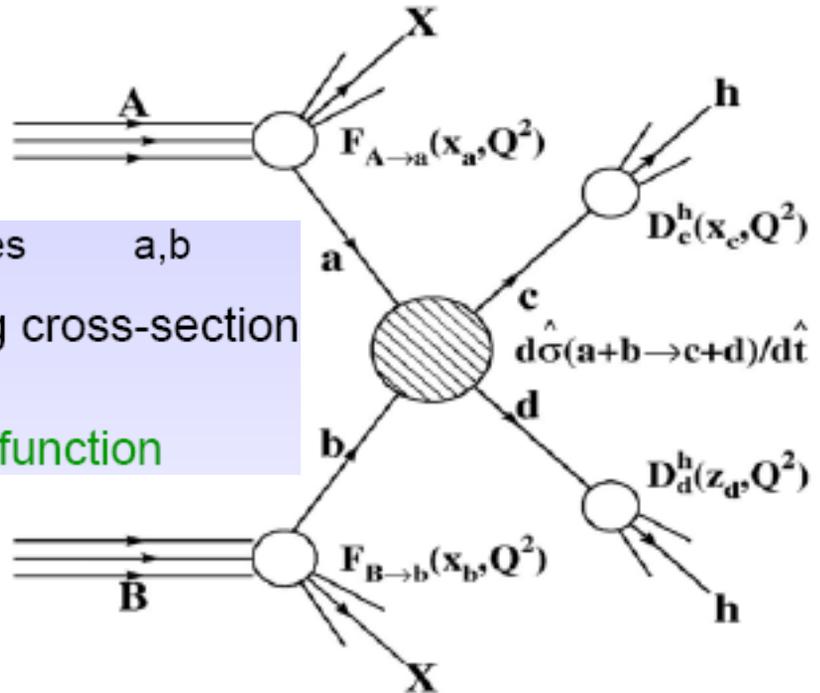


$$\sigma(pp \rightarrow W) \approx 150 \text{ nb} \approx 10^{-6} \sigma_{\text{tot}}(pp)$$

Calculation of cross sections

Sum over initial partonic states a, b
 $\hat{\sigma}_{ab} \equiv$ hard scattering cross-section

$f_i(x, Q^2) \equiv$ parton density function



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

- effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than \sqrt{s} of colliding beams:

$$\left. \begin{aligned} \vec{p}_a &= x_a \vec{p}_A \\ \vec{p}_b &= x_b \vec{p}_B \end{aligned} \right\} p_A = p_B = 7 \text{ TeV} \quad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x \sqrt{s}$$

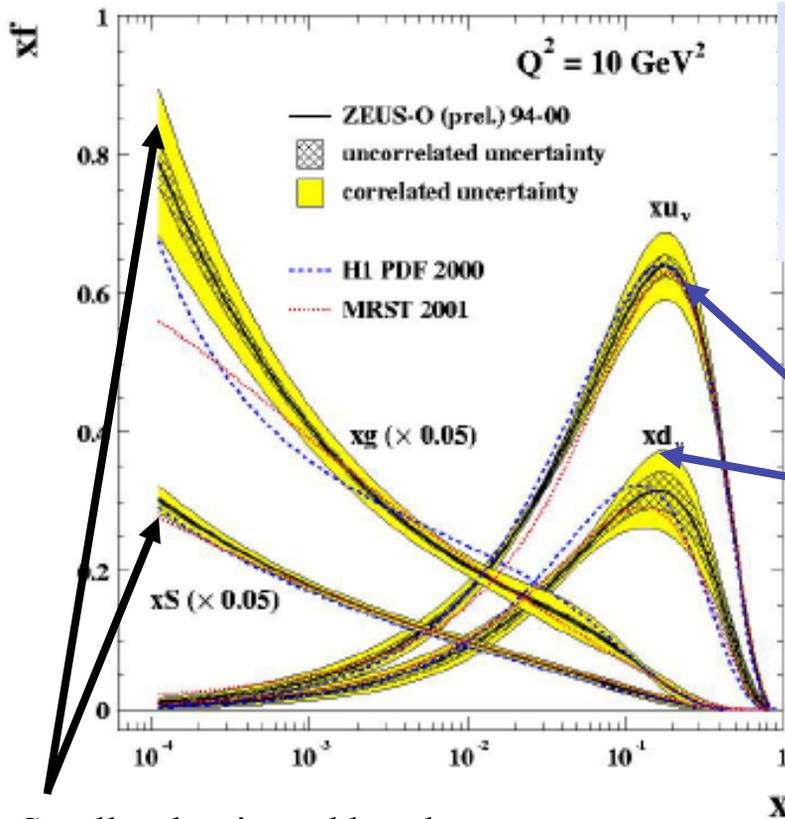
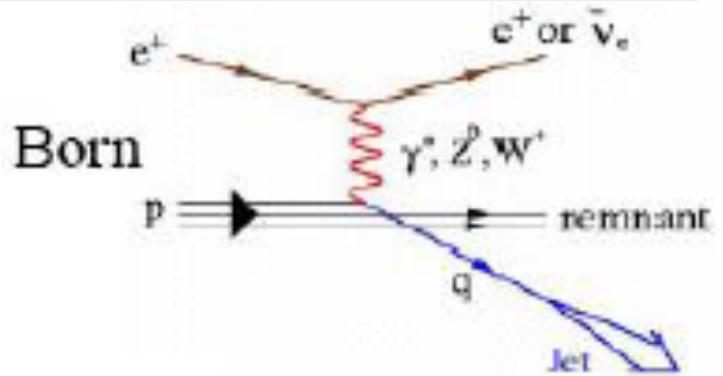
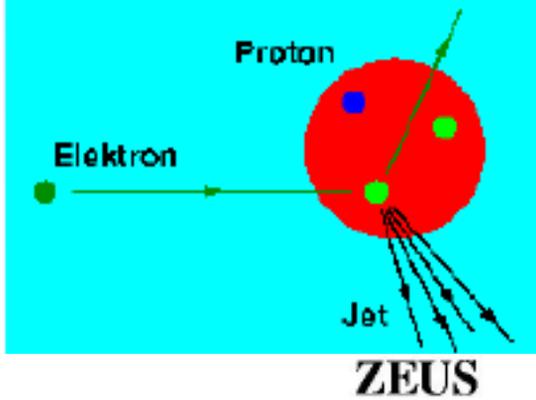
if $x_a \approx x_b$

- to produce $m \approx 100 \text{ GeV}$ $x \sim 0.01$
- to produce $m \approx 5 \text{ TeV}$ $x \sim 0.35$

From where do we know the x-values?

The structure of the proton is investigated in Deep Inelastic Scattering experiments:

the HERA ep collider at DESY/Hamburg
 Scattering of 30 GeV electrons on 900 GeV protons:
 → Test of proton structure down to 10^{-18} m



Parton density functions (pdf):

u- and d-quarks at large x-values

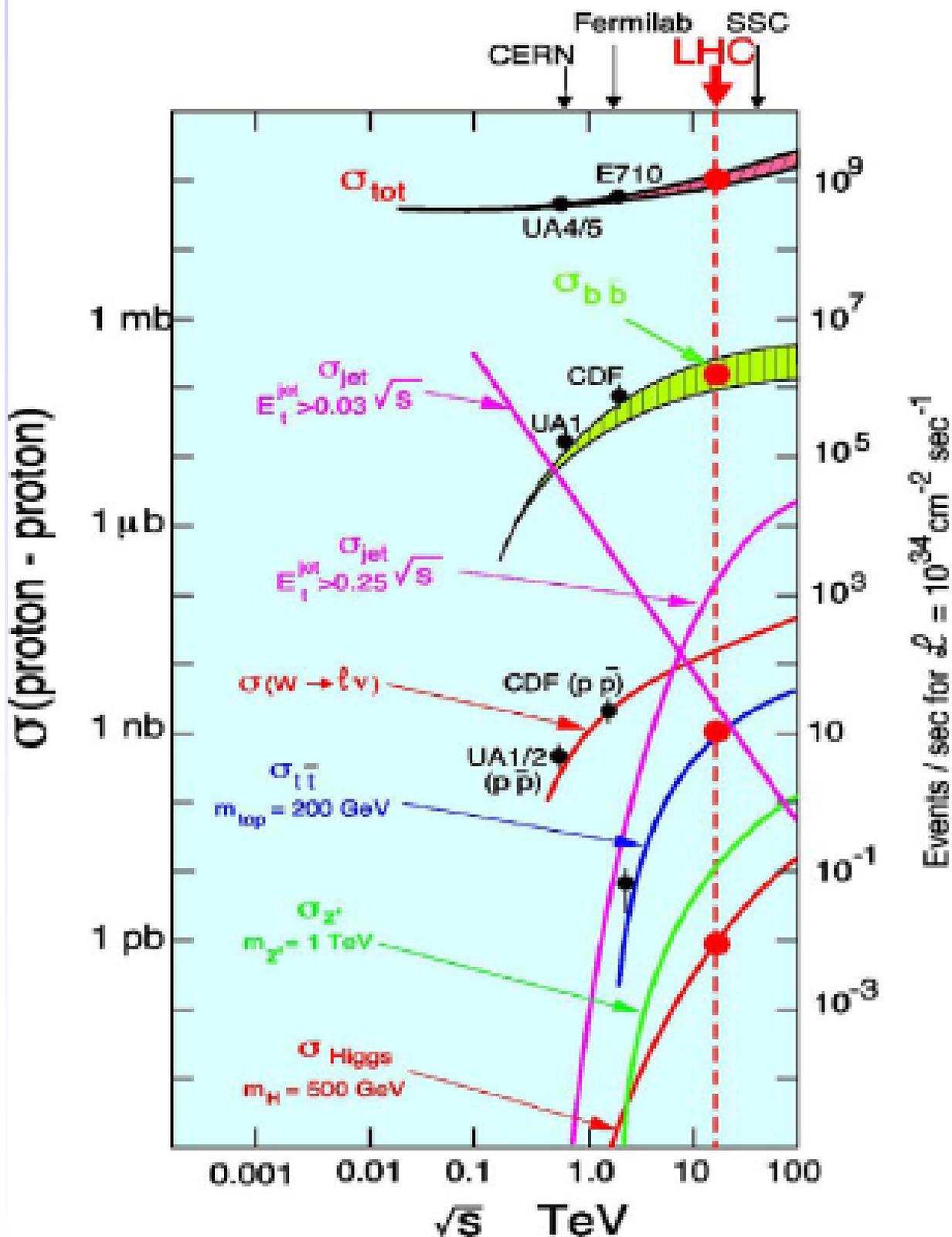
Gluons dominate at small x !!

Uncertainties in the pdfs, in particular on the gluon distribution at small x

Large x dominated by valence quarks

Small x dominated by gluons and sea quarks

Cross Sections



Luminosity

The rate of produced events for a given physics process is given by:

$$N = L \sigma$$

L = Luminosity
 σ = cross section

dimensions: $s^{-1} = cm^{-2} s^{-1} \cdot cm^2$

- L = $2 \cdot 10^{32} cm^{-2} s^{-1}$ design value for Tevatron Run II
- L = $10^{33} cm^{-2} s^{-1}$ planned for the initial phase of the LHC (1-2 years)
- L = $10^{34} cm^{-2} s^{-1}$ LHC design luminosity, very large !!
(1000 x larger than LEP-2, 50 x Tevatron Run II design)

Production Rates

Rates for L = $10^{34} cm^{-2} s^{-1}$: (LHC)

• Inelastic proton-proton reactions:	$10^9 / s$
• bb pairs	$5 \cdot 10^6 / s$
• tt pairs	$8 / s$
• $W \rightarrow e \nu$	$150 / s$
• $Z \rightarrow e e$	$15 / s$
• Higgs (150 GeV)	$0.2 / s$
• Gluino, Squarks (1 TeV)	$0.03 / s$

LHC is a factory for:
top-quarks, b-quarks, W, Z, Higgs,

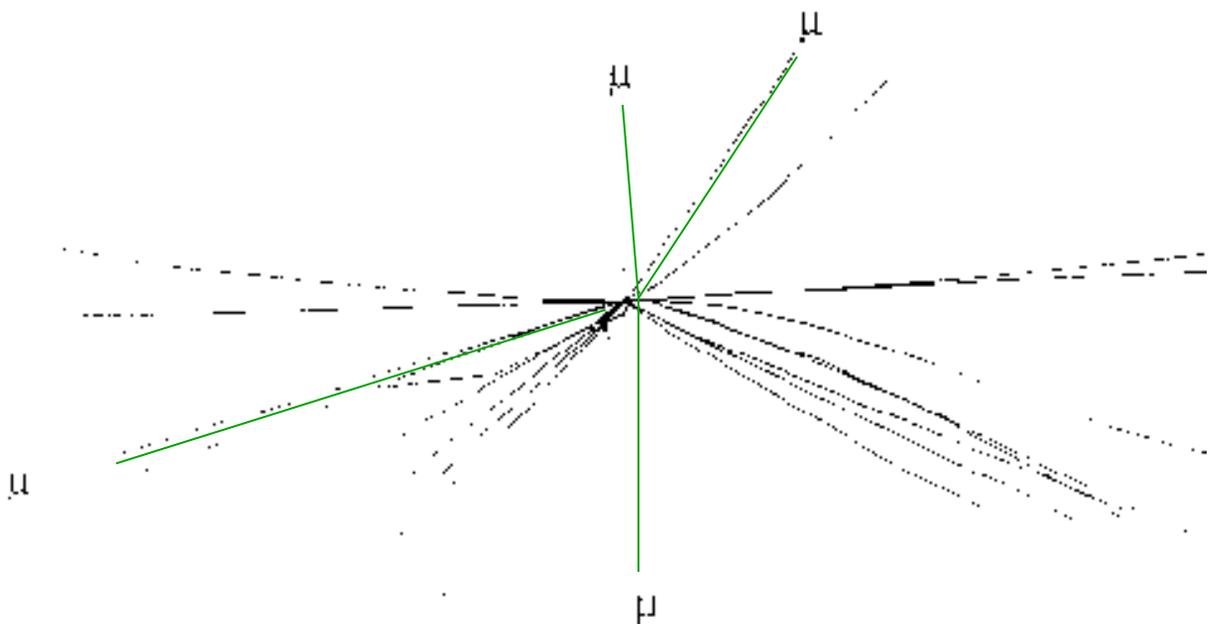
Simulation of CMS inner detector

30 minimum bias events +

$H \rightarrow ZZ \rightarrow 4\mu$

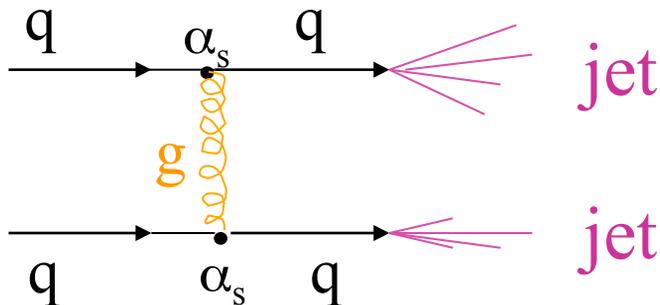


all charged particles with $|\eta| < 2.5$



reconstructed tracks with $p_t > 2.0$ GeV

- ② Common to all hadron colliders:
 high- p_T events dominated by **QCD**
jet production:



- **Strong production** \rightarrow **large cross-section**
- **Many diagrams** contribute: $qq \rightarrow qq$,
 $qg \rightarrow qg$, $gg \rightarrow gg$, etc.
- Called “ **QCD background** “

Most interesting processes are rare processes:

- involve **heavy particles**
- have **weak cross-sections** (e.g. W production)
- To extract signal over QCD jet background must look at decays to photon and leptons
 \rightarrow **pay a prize in branching ratios**

Detectors Characteristics

Don't know how New Physics will manifest

→ detectors must be able to detect as many particles and signatures as possible:

⇒ $e, \mu, \tau, \nu, \gamma, \text{jets, b-quarks, } \dots$
“multi-purpose” experiments.

- Momentum / charge of **tracks and secondary vertices** (e.g. from b-quark decays) are measured in **central tracker**. Excellent momentum and position resolution required.
- Energy and position of **electrons and photons** measured in **electromagnetic calorimeters**. Excellent resolution and particle ID required.
- Energy and position of **hadrons and jets** measured mainly in **hadronic calorimeters**. Coverage over $|\eta| < 5$ and granularity are required.
- **Muons** identified and momentum measured in external **muon spectrometer** (+ central tracker). Excellent resolution over $5 \text{ GeV} < p_T < \sim \text{TeV}$ required.
- **Neutrinos** “detected and measured” through measurement of missing transverse energy E_T^{miss} .

Detection and measurement of neutrinos

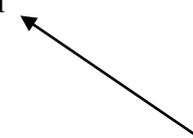
- Neutrinos traverse the detector without interacting
→ not detected directly

- Can be detected and measured asking:

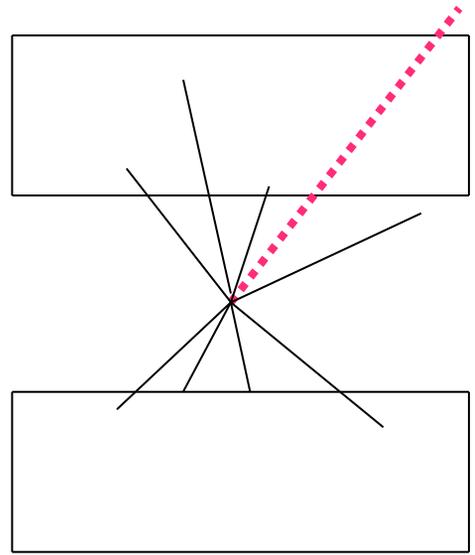
$$\vec{E}_f, \vec{P}_f = \vec{E}_i, \vec{P}_i$$



total energy, momentum
reconstructed in final state



total energy, momentum
of initial state



-- e^+e^- colliders: $E_i = \sqrt{s}$, $\vec{P}_i = 0$

→ if a neutrino produced, then $E_f < E_i$ (→ **missing energy**)

and $\vec{P}_f \neq 0 \rightarrow \vec{P}_\nu = -\vec{P}_f \quad E_\nu = |\vec{P}_\nu|$

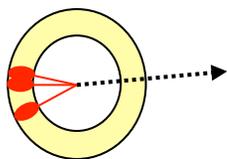
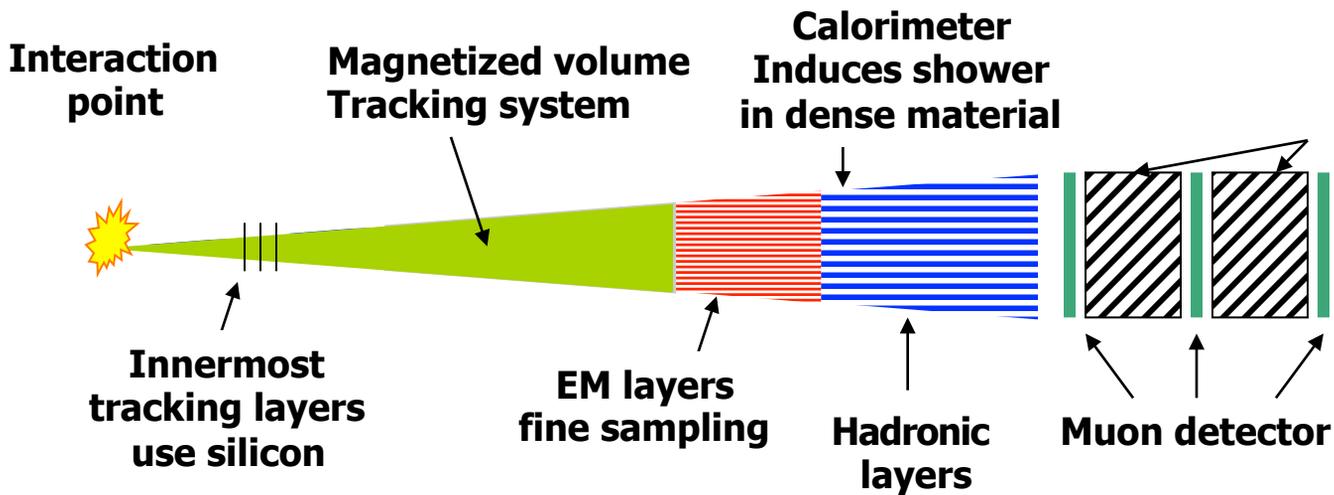
-- **hadron colliders**: energy and momentum of initial state (energy and momentum of interacting partons) not known.

However: **transverse momentum** $\vec{P}_{Ti} = 0$

→ if a neutrino produced $\vec{P}_{Tf} \neq 0$ (→ **missing transverse momentum**) and

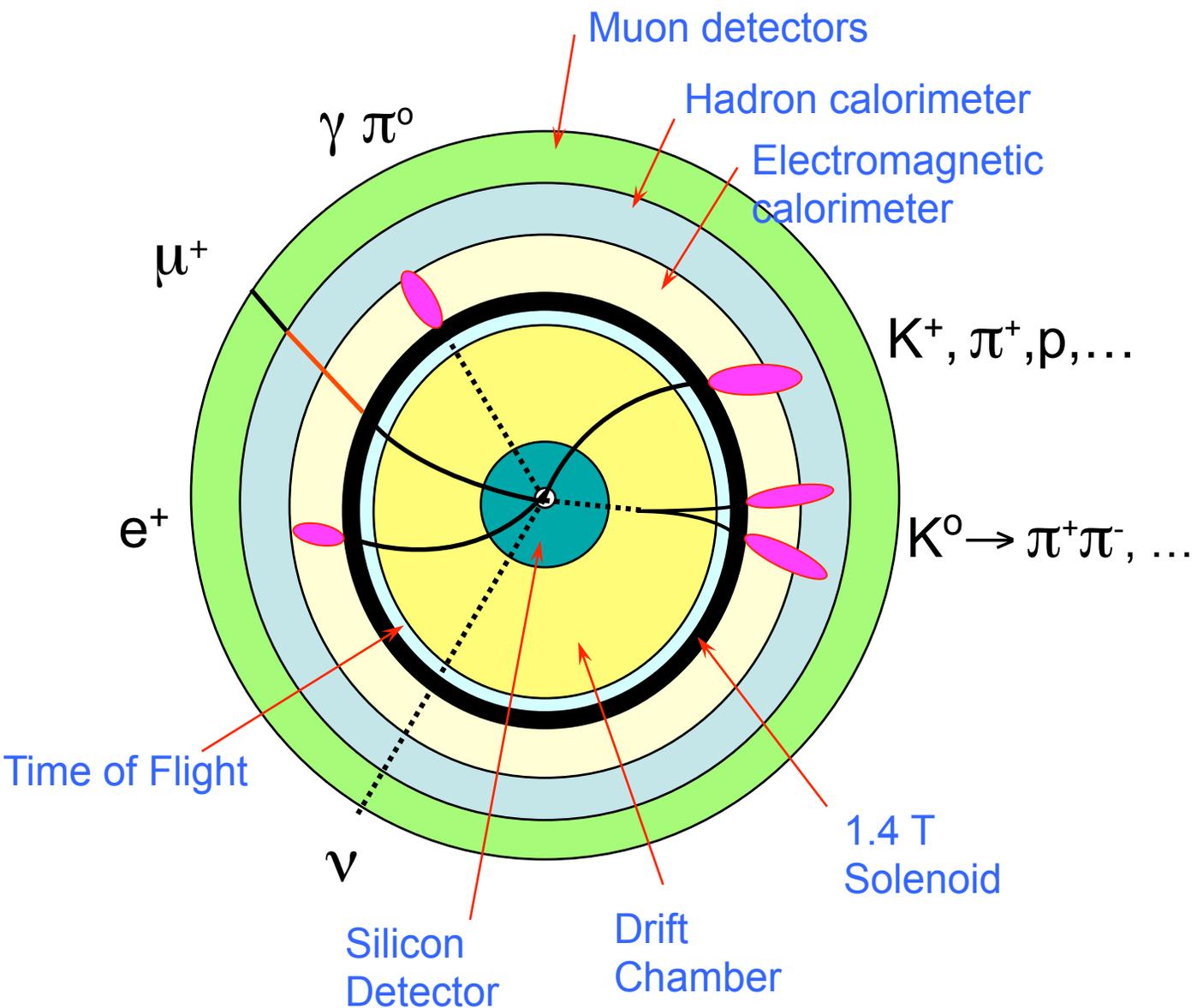
$$|\vec{P}_{T\nu}| = |\vec{P}_{Tf}| = E_T^{\text{miss}}$$

Specifiche per il rivelatore



“Missing transverse energy”
Signature of a non-interacting (or weakly interacting) particle like a neutrino

Specifiche per il rivelatore



Specifiche per il rivelatore

Il rivelatore deve identificare e misurare gli oggetti elementari a $\sqrt{s} \approx 100$ GeV, leptoni e partoni

elettroni e fotoni

calorimetro “elettromagnetico”

muoni

assorbitore massiccio + grandi camere traccianti

quark e gluoni (jet)

calorimetri (elettrom. e adronico) + camere a immagine

leptoni t

forma del jet per $t \rightarrow$ adroni

neutrini

sbilancio del momento \rightarrow ermeticità del rivelatore

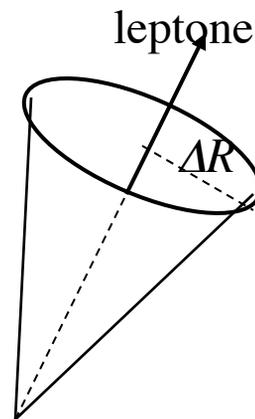
ISOLAMENTO di un leptone

definito nello spazio (azimut, rapidità) = $(F, h = \ln \operatorname{tg} q)$

si chiede che il flusso di energia in un cono di semiapertura ΔR sia inferiore a una soglia

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

I valori della soglia e di ΔR si fissano dallo studio dei dati i



Identificazione delle particelle

ELETRONI

Fondo principale: overlap π^\pm (n) π^0 nei jet

Isolamento discrimina ad alto p_T (reiezione 40.000 rispetto a jet)

Difficile vicino a jet, fisica b e t

μ

Fondo principale: μ da decadimenti K e π

Isolamento, alto p_T , relativamente facile

Possibile dentro jet, fisica b e t

$t \Rightarrow$ adroni

Fondo principale: jets di QCD

Discriminazione in base alla forma del jet (difficile)

magrezza del jet

molteplicità carica

NEUTRINI

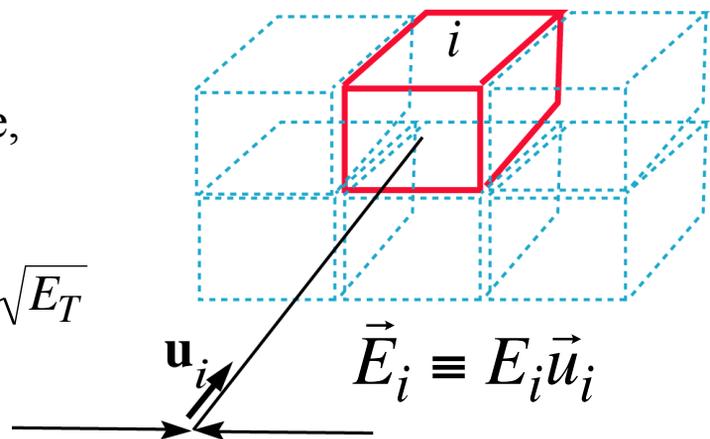
Energia trasversale mancante, per calorimetro ermetico e omogeneo

$$E_T^{miss} \equiv p_T^{miss} = -\sum_i \vec{E}_i^T - p_\mu^T$$

UA1 è ermetico nel piano trasversale, non nella direzione dei fasci

$\frac{dn}{dp_T^{miss}}$ gaussiana

$$\sigma(p_T^{miss}) = 0.7\sqrt{E_T}$$



Calorimetria

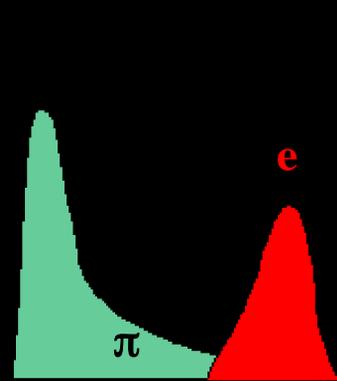
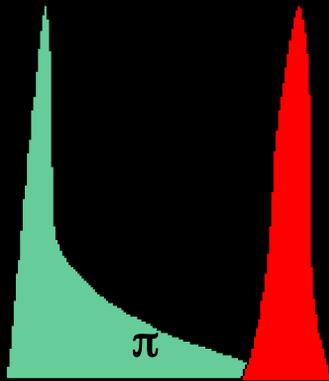
Richiesta base: separazione e/p.

Scelta base: **risoluzione** / **granularità**

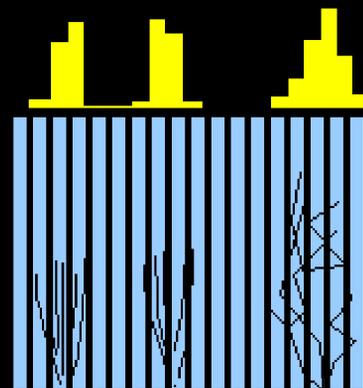
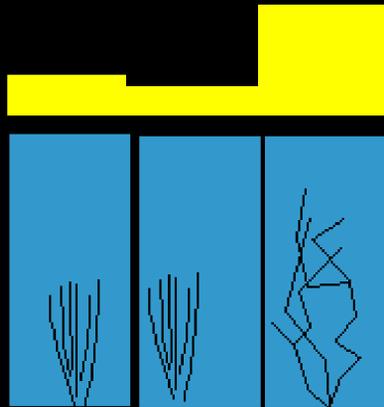
$$\frac{1\%}{\sqrt{E}} \leq \frac{\Delta E}{E} \leq \frac{6\%}{\sqrt{E}}$$

$$\frac{16\%}{\sqrt{E}} \leq \frac{\Delta E}{E} \leq \frac{20\%}{\sqrt{E}}$$

risoluzione



granularità
(importante
nei jet densi)



L3: BGO
OPAL: Pb glass
DELPHI on End caps

ALEPH: Tubes
DELPHI: HPC

Scoperta del W e dello Z

Riassumiamo le formule ricavate nel capitolo 8. Come abbiamo visto, le prime indicazioni sui valori delle masse del W e dello Z furono derivate dalla determinazione del $\sin\theta_W$ ricavato a sua volta dalle misure del rapporto NC su CC dalle interazioni di neutrini e anti-neutrini su nucleoni e, in modo molto più preciso, su elettroni.

$$R_\nu = \left(\frac{NC}{CC} \right)_\nu = \frac{1}{2} - \sin^2 \theta_W + \frac{20}{27} \sin^4 \theta_W$$
$$R_e = \left(\frac{NC}{CC} \right)_e = \frac{1}{2} - \sin^2 \theta_W + \frac{20}{9} \sin^4 \theta_W$$

Abbiamo visto che il Modello Standard contiene i mesoni vettori di gauge

W_μ^i ($i = 1, 2, 3$) $T^W=1$, corrisponde a SU(2),
costante di accoppiamento g

B_μ $T^W=0$, corrisponde a U(1),
costante di accoppiamento g'

E che l'Angolo di Weinberg è dato dal rapporto delle due costanti
$$\theta_W = \tan^{-1} \frac{g'}{g}$$

Inoltre, i bosoni vettori fisici si ottengono con una rotazione θ_W

$$\begin{pmatrix} Z_\mu^0 \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}$$

Ricordiamo anche che la carica del positrone e' :

$$e = g \sin \theta_W = g' \cos \theta_W$$

L'angolo di Weinberg mette anche in relazione le masse dei due bosoni vettori W e Z:

$$\cos \theta_W = \frac{M_W}{M_Z}$$

$$e^2 = g^2 \sin^2 \theta_W \quad g^2 = \frac{8}{\sqrt{2}} G_F M_W^2$$

SU(2)xU(1) prevede quindi a livello albero


$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin \theta_W} = \frac{37.2810 \pm 0.0003}{\sin \theta_W}$$

Da DIS di ν_μ $\sin^2 \theta_W = 0.232 \pm 0.006 \Rightarrow M_W = 77.67 \text{ GeV}$

Ma bisogna tener conto di grafici di ordine superiore, sensibili a m_t

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{1 - \Delta r} \frac{1}{\sin \theta_W},$$

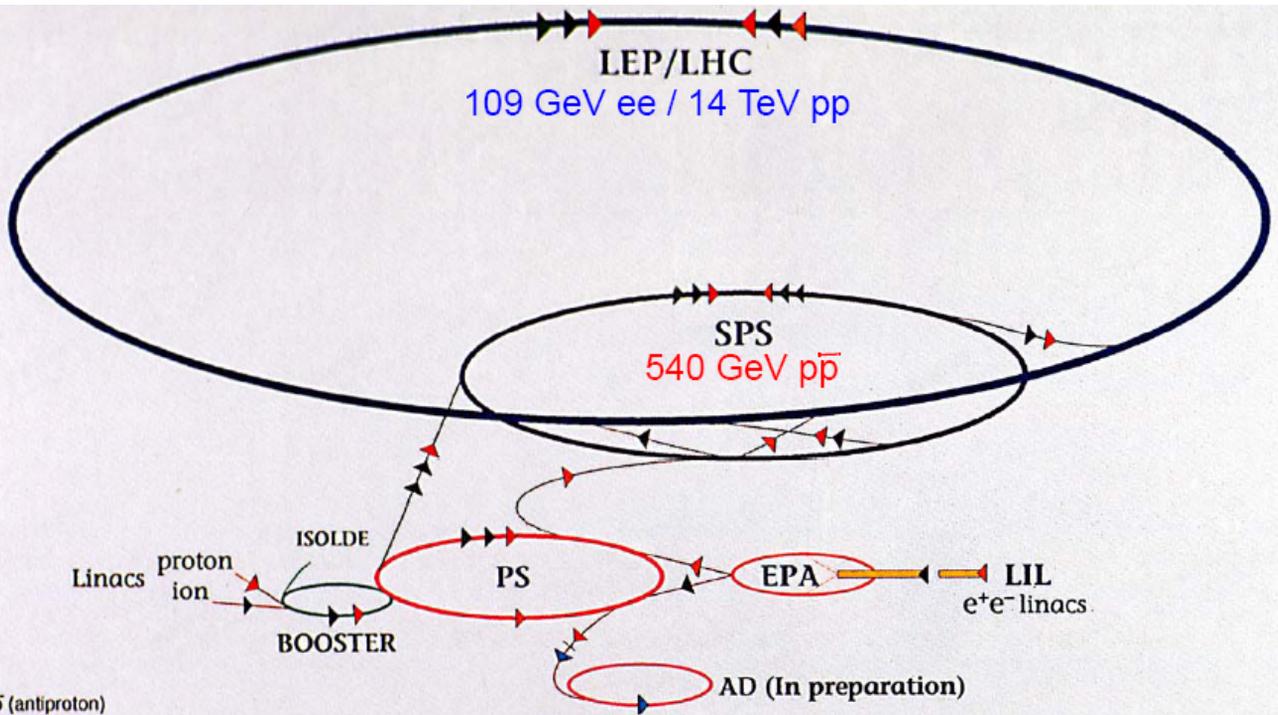
$$\Delta r = 0.0711 \pm 0.0013 \quad \text{calcolato per } m_t = 40 \text{ GeV}$$

$$M_W = 80.3 \pm 0.9 \text{ GeV}$$

$$\sigma(\bar{p}p \rightarrow W \rightarrow e\nu_e) = 530^{+170}_{-90} \text{ pb} \quad @ 630 \text{ GeV}$$

Questo valore della massa era fuori dalla portata degli acceleratori di fine anni 70. C. Rubbia e S. Van der Meer convinsero le autorità del CERN a trasformare l'SPS in un collisionatore protoni-antiprotoni : l'Sp-pbarS.

I protoni venivano usati per creare gli antiprotoni che venivano catturati e accumulati. Gli antiprotoni rientravano poi nel SPS nella direzione opposta. Il problema più difficile era quello di comprimere gli antiprotoni fino a produrre un significativo rate di interazione con il fascio di protoni. Questo fu realizzato da S. Van der Meer con la tecnica da lui inventata e nota come "stochastic cooling". Il collisionatore fu completato nel 1982 e con una luminosità totale di 18 nb^{-1} a una energia del centro di massa di 540 GeV, UA1 riportò la prima evidenza del W e dello Z.



Il primo periodo del collider

Il collider diede dati a UA1 e UA2 dal 1981 al 1985

Furono scoperti i bosoni intermedi W e Z

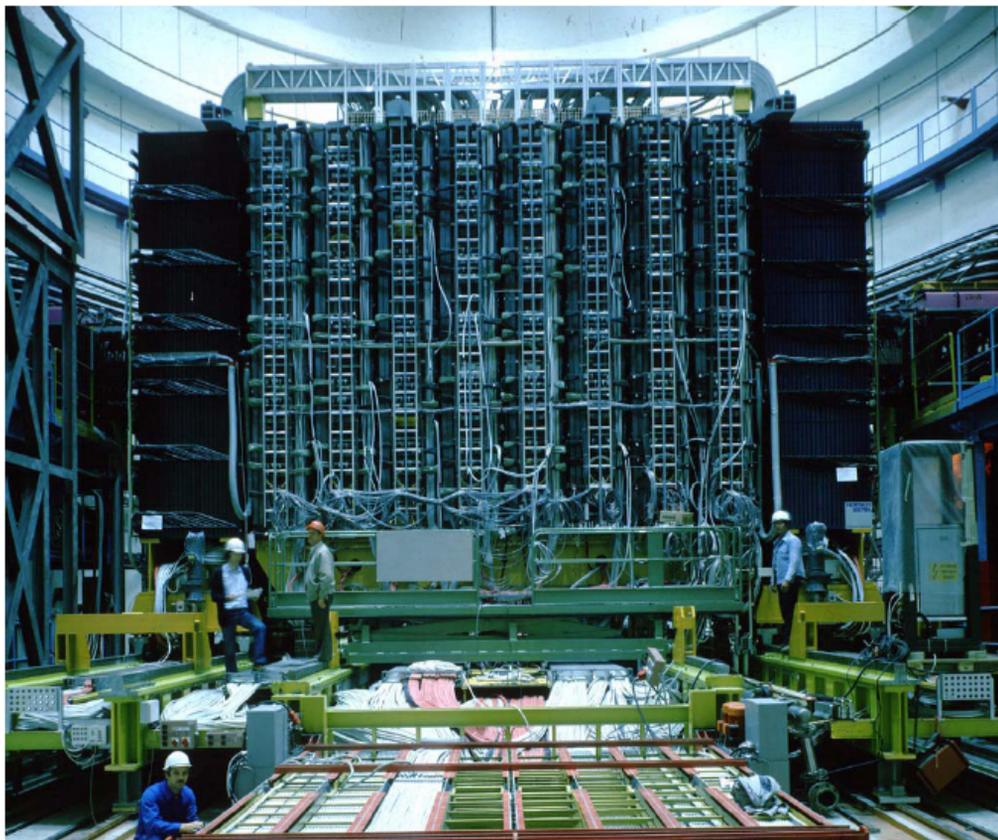
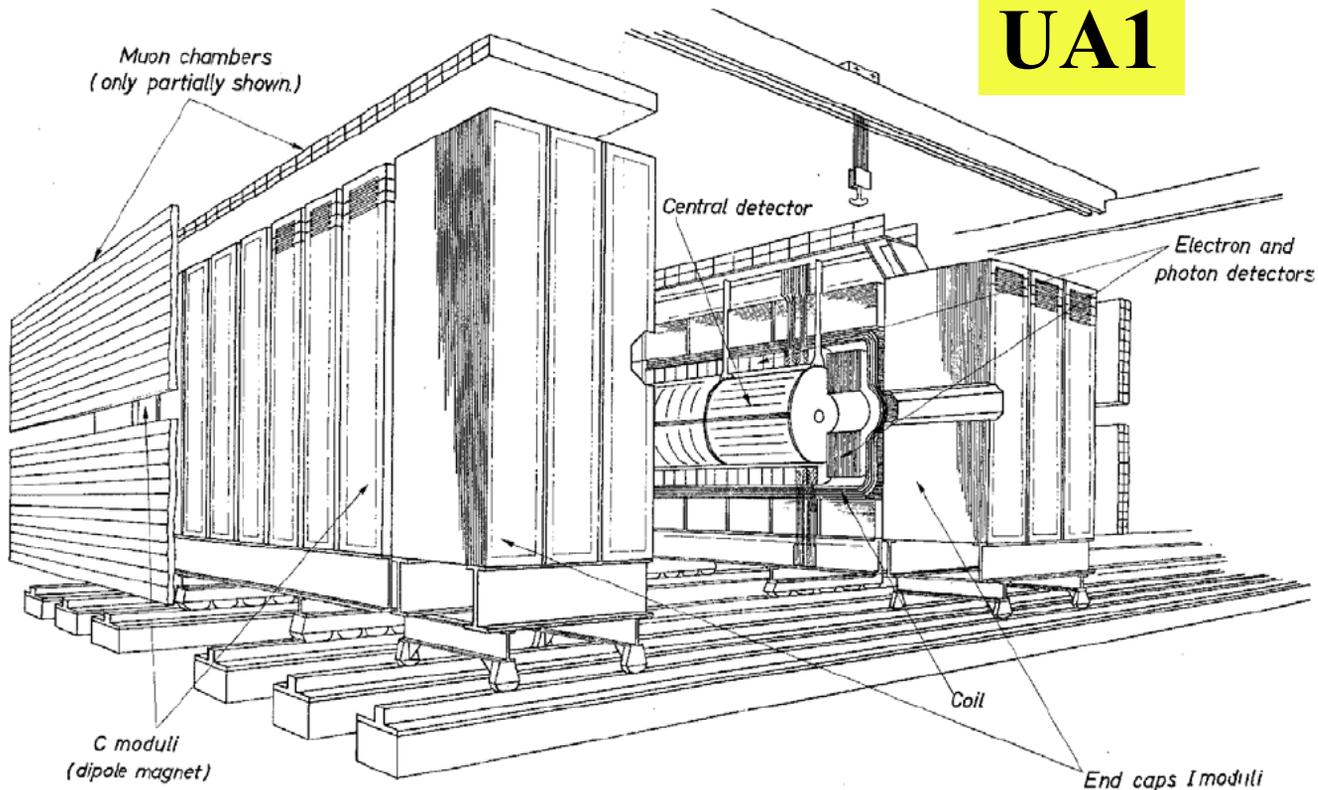
statistica finale di UA1: 366 W^\pm e 52 Z

Furono verificate le previsioni fondamentali del Modello Standard

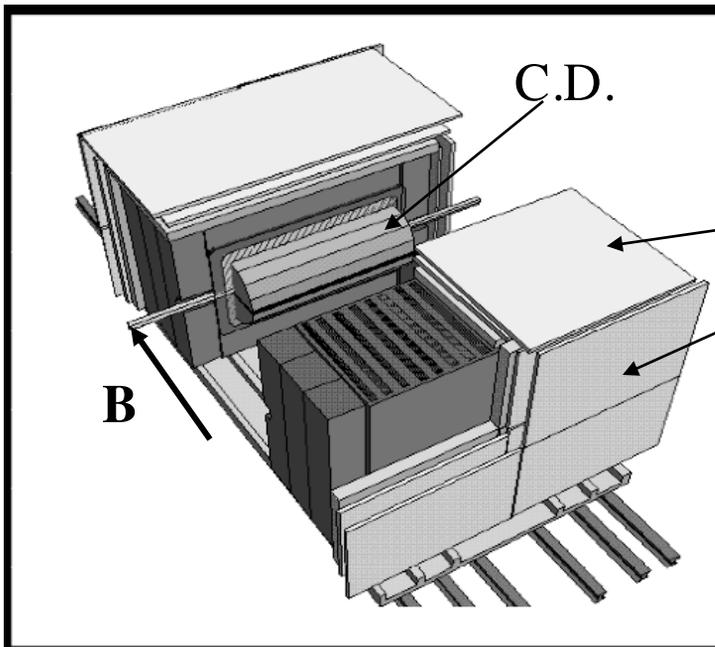
a parte il bosone di Higgs (non scoperto ancora oggi)

I dati raccolti dagli esperimenti corrispondono a **50×10^9 collisioni**

$\sqrt{s}(\text{GeV})$	$\int Ldt \text{ (nb}^{-1}\text{)}$
546	118
630	568
<i>totale</i>	686

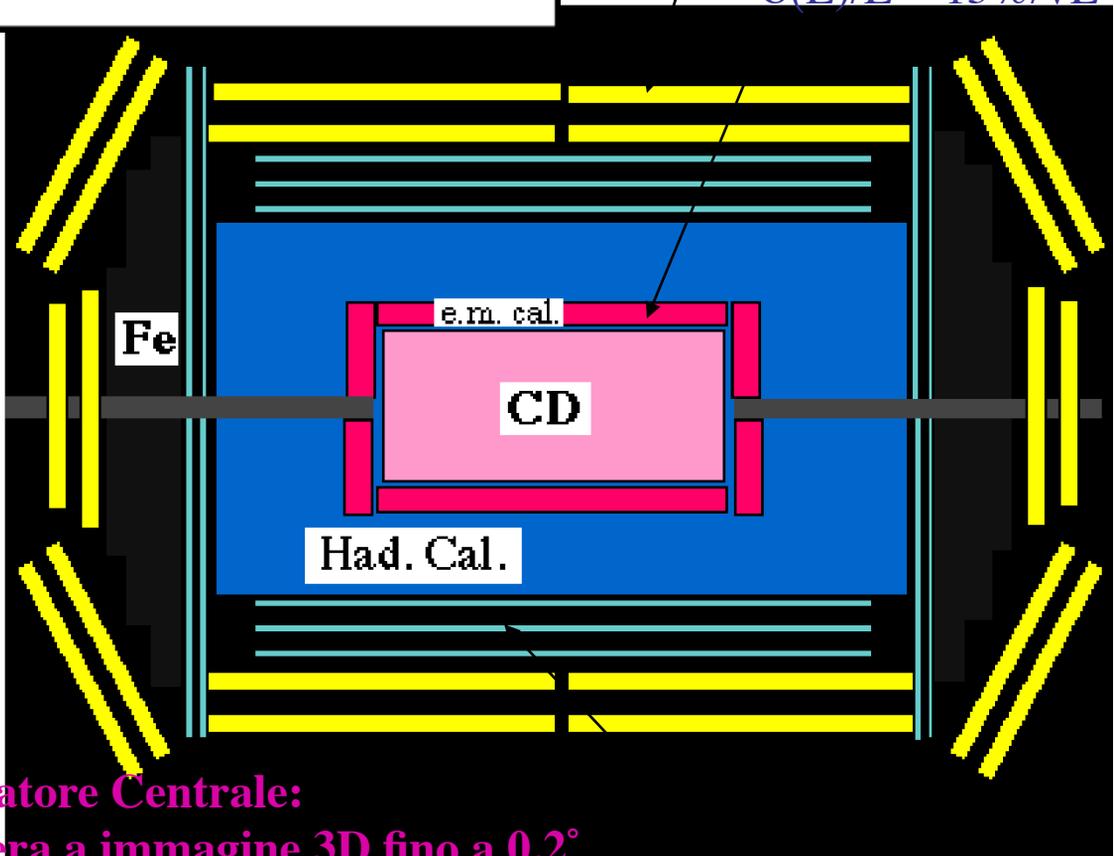


UA1



muon drift chambers

calorimetro e.m.
 $\sigma(E)/E = 15\%/\sqrt{E}$

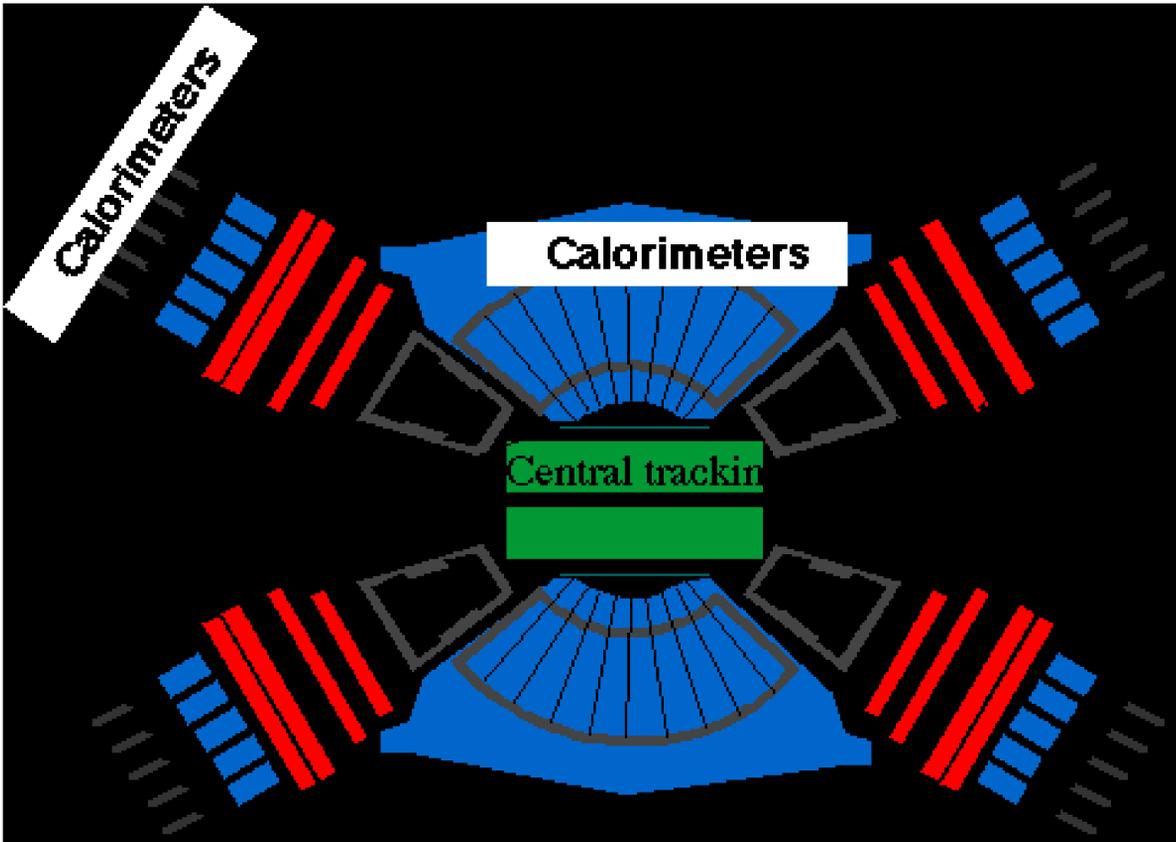


assorbitori di Fe magnetizzato

Rivelatore Centrale:
Camera a immagine 3D fino a 0.2°
Campo magnetico normale ai fasci
 $B = 0.7 \text{ T}$
 $\sigma(p)/p = 0.5\% p \text{ (GeV)}$

Calorimetri in avanti

$$\Delta\theta \otimes \Delta\Phi \ 3.5^\circ \otimes 15^\circ$$



Non ermetico

Tracking in campo **B** solo in limitato angolo solido

Ottima calorimetria, sia in granularità sia in risoluzione

Preshower

Calorimetro centrale

$$\Delta\theta \otimes \Delta\Phi \ 10^\circ \otimes 15^\circ$$

longitudinalmente: 1 em (17 RL) + 2 adron. (2 abs. lengths

risol. elettromagnetico $\sigma(E)/E = 15\%/\sqrt{E}$

risol. adronico $\sigma(E)/E = 32\%/(E)^{1/4}$

Incertezza sulla scala dell'energia (e massa)

Naturalmente ne` UA1 nè UA2 misurano direttamente l'energia persa dalla (dalle) particella(e), ma la luce da essa prodotta in strati di materiale scintillatore. A catena e' :

Energia persa nello scintillatore⇒Luce⇒in parte raccolta dalle guide di luce e portata ai fotomoltiplicatori⇒fotoelettroni prodotti al fotocatodo⇒moltiplicati dai dinodi⇒conversione analogico-digitale

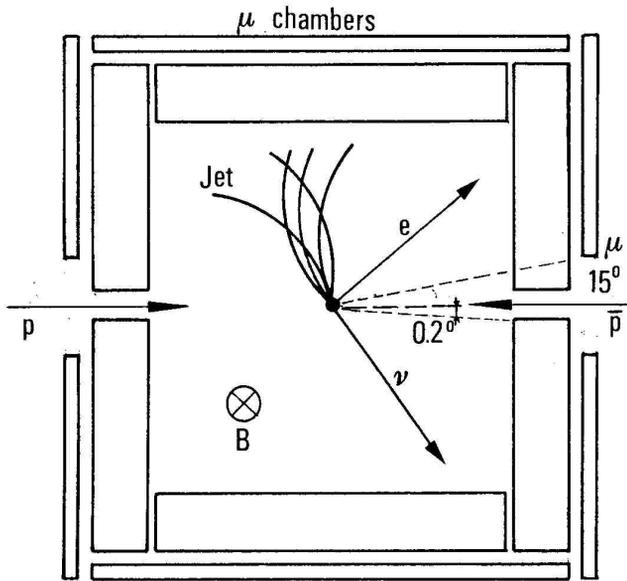
Tutta la catena deve essere calibrata su fasci di e e π di energia nota

Ma le costanti di calibrazione non sono costanti, variano nel tempo (invecchiamento dei materiali, danneggiamento da radiazione, ecc.)
necessario monitoraggio in linea (flasher, sorgenti radioattive,..)

UA1. Grandi moduli. Calibrazione su fascio solo inizialmente
⇒ incertezza scala $\pm 3\%$

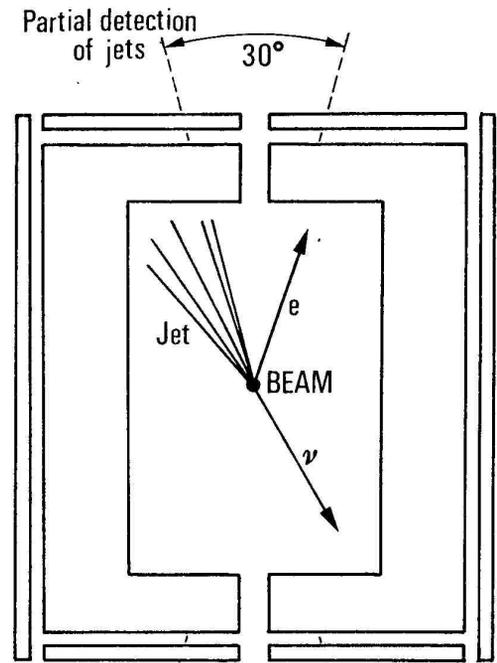
UA2. Piccoli moduli. Calibrazione periodica su fascio
⇒ incertezza scala $\pm 1.6\%$

Schema degli eventi

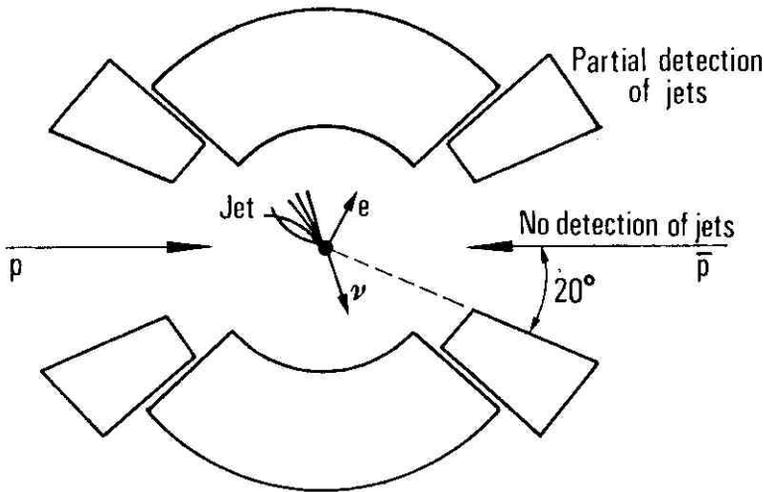


Longitudinal view

UA1

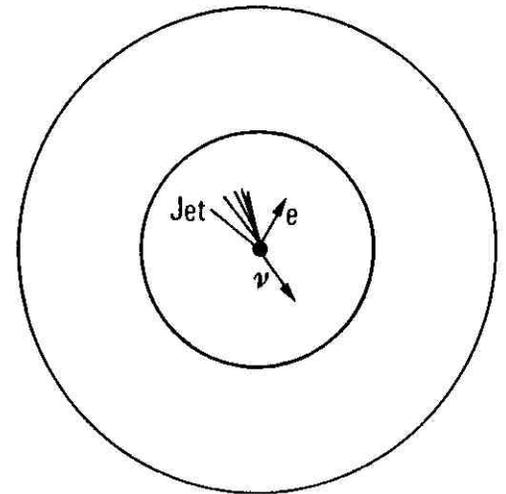


Transverse view



Longitudinal view

UA2



Transverse view

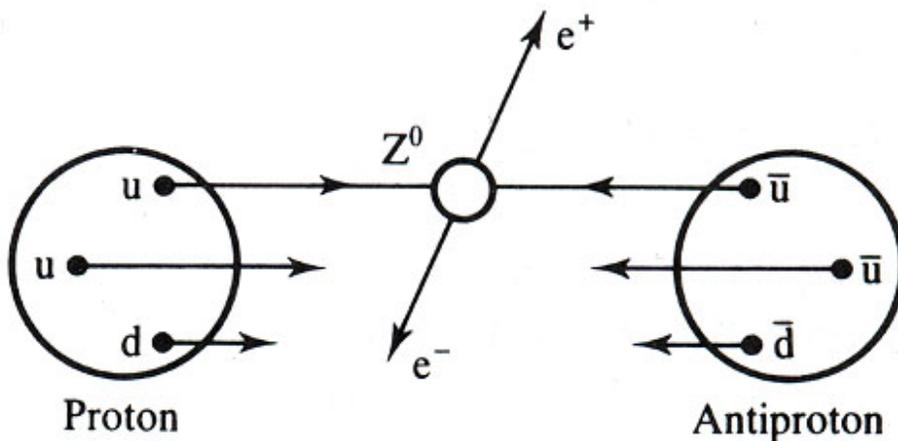
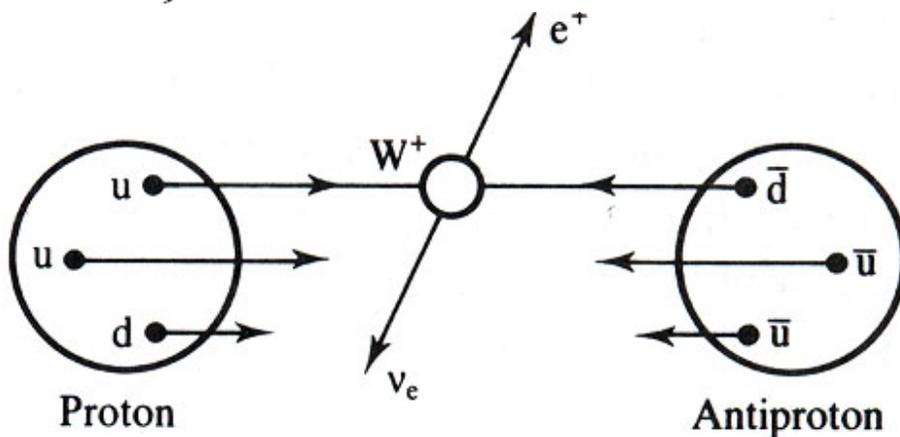
Produzione di $W^{(+, -)}$ e Z^0 in Collisioni Adroniche

Osservati per la prima volta al collisionatore p-pbar al CERN nel 1983.

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e, \mu^+ + \nu_\mu$$

$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}_e, \mu^- + \bar{\nu}_\mu$$

$$\left. \begin{array}{l} u + \bar{u} \\ d + \bar{d} \end{array} \right\} \rightarrow Z^0 \rightarrow e^+ e^-, \mu^+ \mu^-$$



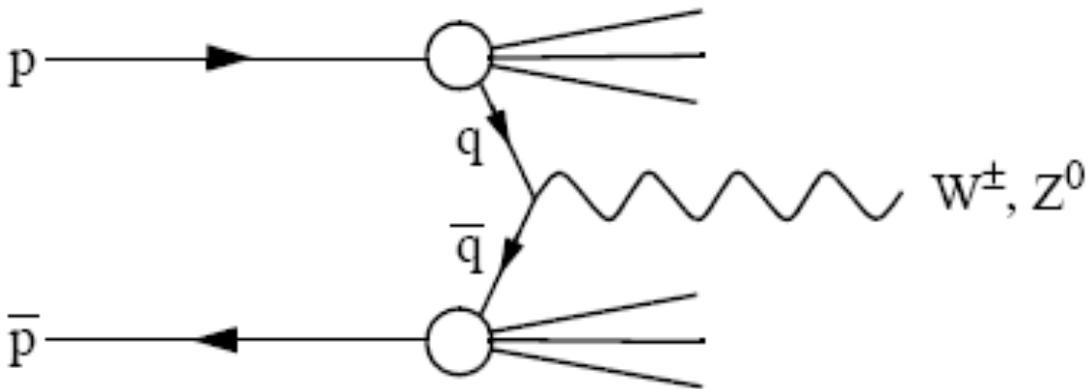
Produzione:

nei collisori adronici SPSC e Tevatron, vedi dopo, i bosoni W e Z sono prodotti da annichilazioni quark-antiquark:

$$u + \bar{d} \rightarrow W^+ , \quad d + \bar{u} \rightarrow W^-$$

$$u + \bar{u} \rightarrow Z^0 , \quad d + \bar{d} \rightarrow Z^0$$

Meccanismo di produzione di W e Z :



Decadimenti: I bosoni W e Z decadono nel 70% dei casi in adroni che alle energie di 540 GeV non si possono identificare dagli altri adroni creati nelle collisioni protone-antiprotone. Si cerca invece di identificarli dai loro decadimenti leptonici.

$$\bar{p} + p \rightarrow W^+ + X$$

$$\quad \quad \quad \searrow \rightarrow q' + \bar{q}$$

$$\bar{p} + p \rightarrow W^+ + X$$

$$\quad \quad \quad \searrow \rightarrow l^+ + \nu_l$$

$$\bar{p} + p \rightarrow W^- + X$$

$$\quad \quad \quad \searrow \rightarrow q' + \bar{q}$$

$$\bar{p} + p \rightarrow W^- + X$$

$$\quad \quad \quad \searrow \rightarrow l^- + \bar{\nu}_l$$

$$\bar{p} + p \rightarrow Z^0 + X$$

$$\quad \quad \quad \searrow \rightarrow q + \bar{q}$$

$$\bar{p} + p \rightarrow Z^0 + X$$

$$\quad \quad \quad \searrow \rightarrow l^+ + l^-$$

Vite medie: le vite medie di W e Z sono dell'ordine di 10^{-25} s e quindi NON visibili direttamente negli esperimenti.

Discovery of the W Boson

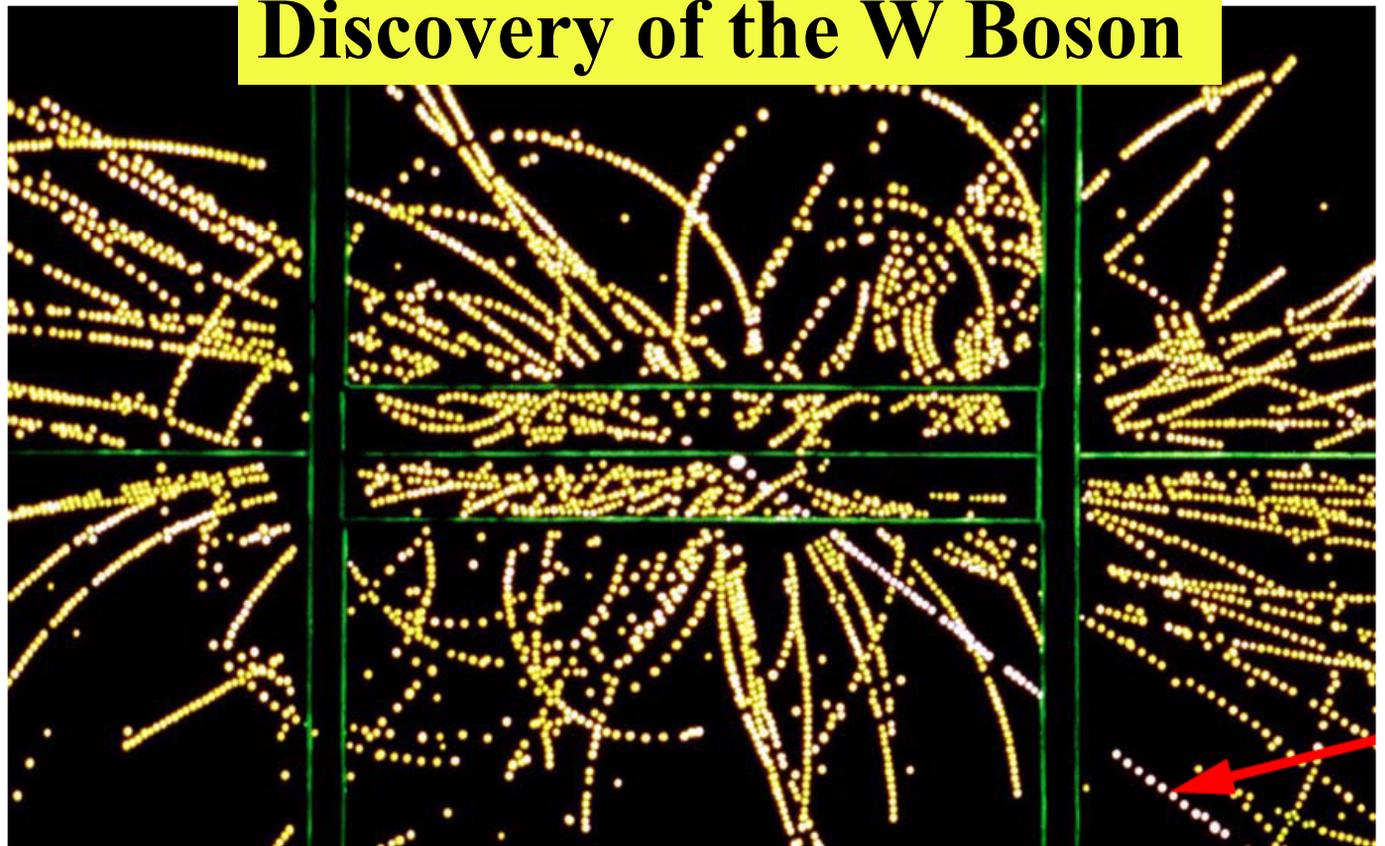


Figure 82: A W event observed by the UA1 detector in 1982. A high transverse momentum electron is indicated by the arrow.

The signature of a W boson is:

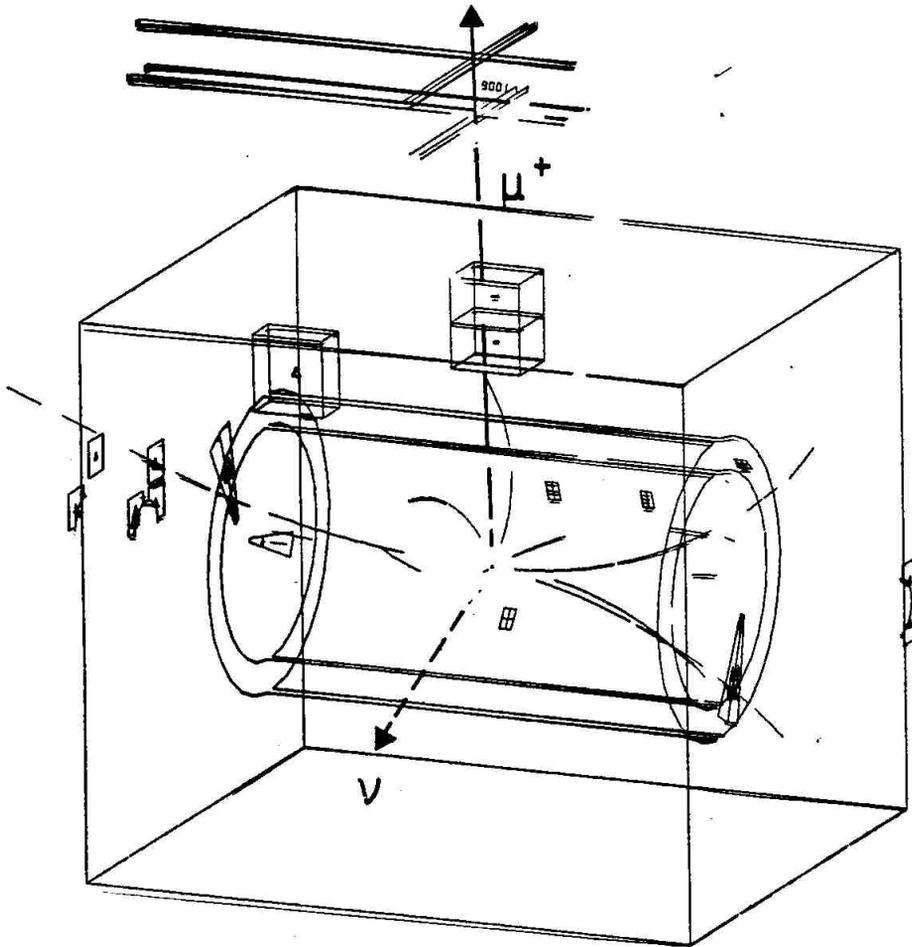
- a lepton with **large momentum** ($>10 \text{ GeV}/c$) emitted at a wide angle to the beam ($>5^\circ$).
- large “**missing transverse momentum**” carried away by the neutrino.

Transverse Energy: $E_T = E \sin \theta$

Transverse Momentum: $P_T = P \sin \theta$

where θ is the angle to the colliding beams.

Evento $W \rightarrow \mu\nu$ (solo UA1)

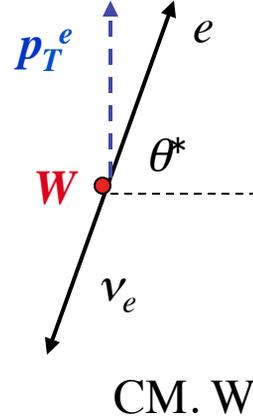
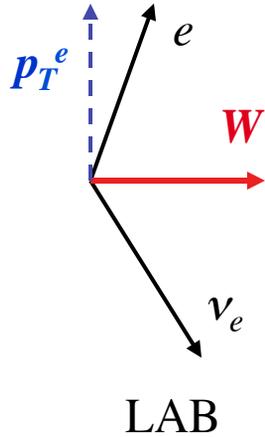


Misura di M_W

$$W \rightarrow l \nu_l$$

trascurando il moto trasversale della W (piccolo)

$$p^e = m_W/2$$



p_T^e è il medesimo nei due riferimenti = $(m_W/2) \sin \theta^*$

Distribuzione angolare di decadimento nel CM nota

$$\frac{dn}{d\theta^*} \xrightarrow{\text{trasf. coordinate}} \frac{dn}{dp_T} = \frac{dn}{d\theta^*} \frac{d\theta^*}{dp_T}$$

$$\frac{dn}{dp_T} = \frac{1}{\sqrt{\left(\frac{m_W}{2}\right)^2 - p_T^2}} \frac{dn}{d\theta^*}$$

Picco “Jacobiano” per $p_T^e = m_W/2$

Picco “Jacobiano” per $p_T^{\text{missing}} = m_W/2$

Il moto trasversale della W ($p_T^W \neq 0$) sbrodola il picco, ma non lo cancella. La misura della m_W si basa sulla misura dell'energia del picco o del suo fronte di discesa

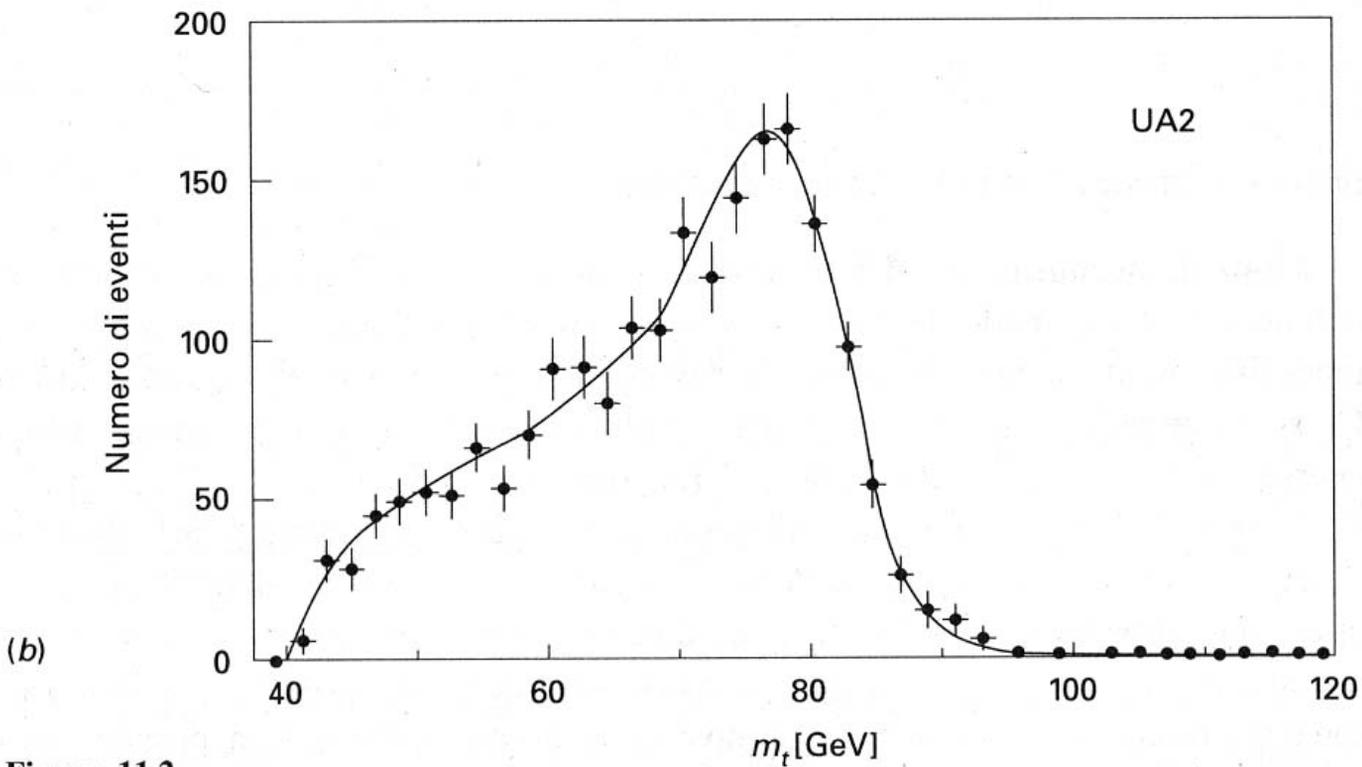
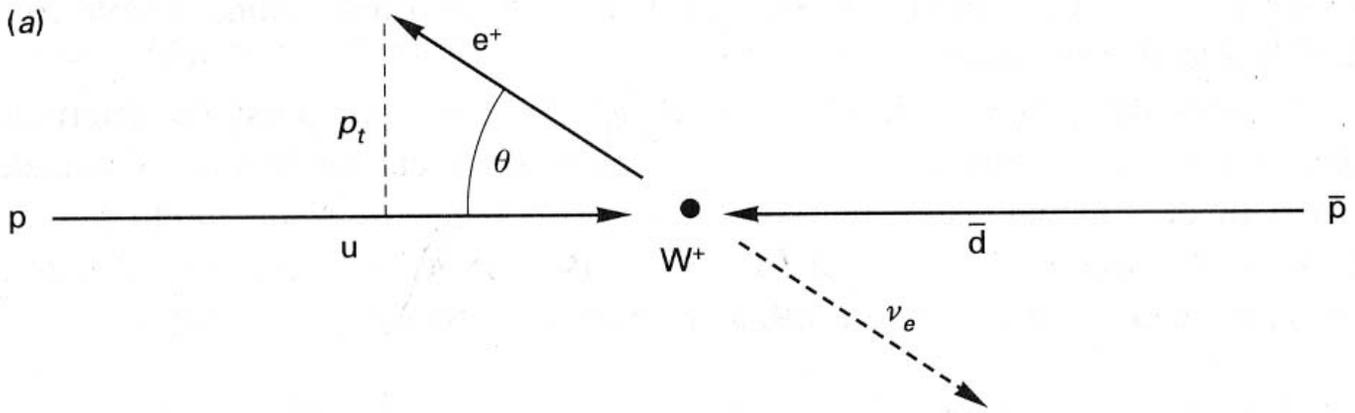


Figura 11.2

(a) Cinematica del decadimento $W^+ \rightarrow e^+ + \nu_e$. Il valore massimo possibile per l'impulso trasverso p_t del e^+ è $M_W c/2$. (b) Distribuzione della "massa trasversa" $m_t = 2p_t/c$ di e^+ ed e^- , nel processo $q_1 + \bar{q}_2 \rightarrow e^\pm + \text{"nulla"}$, dall'esperimento UA2 al CERN [A192b]. (La scala in ascissa è suddivisa in intervalli di 2 GeV ciascuno).

→ $E_T = P_T$ if the mass of a particle is small compared to its energy.

→ If the **momentum of all particles** in a collision is added up the result should be **zero** (momentum conservation). Neutrinos can, however, not be detected and if the total momentum is different from zero the event is said to have **missing momentum** (or missing energy).

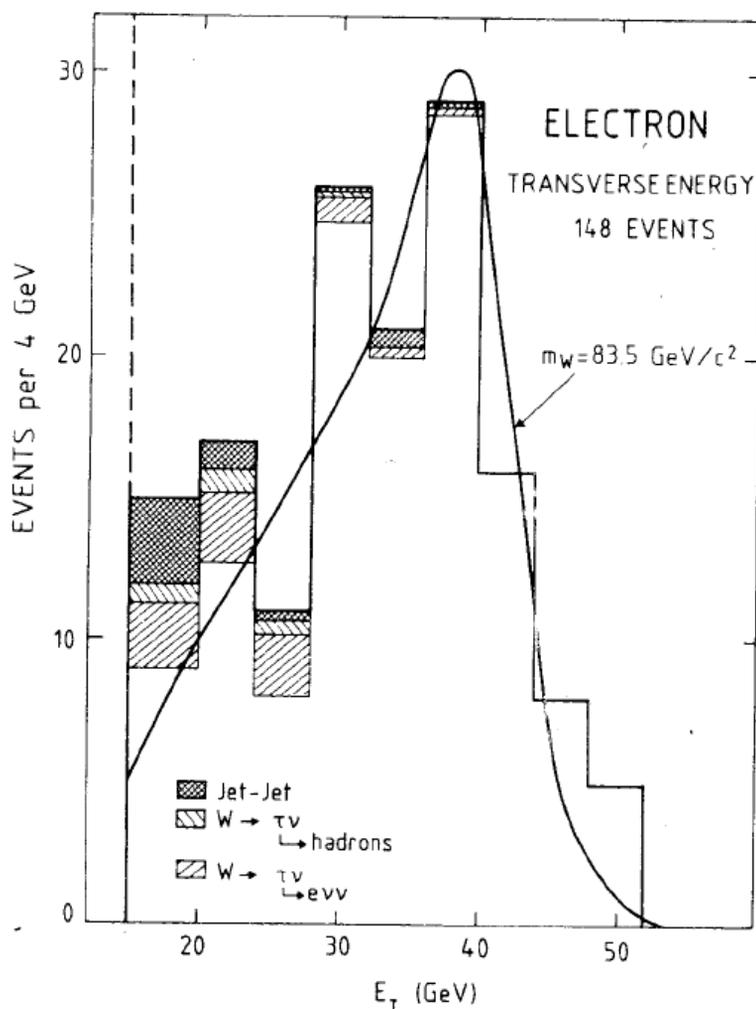


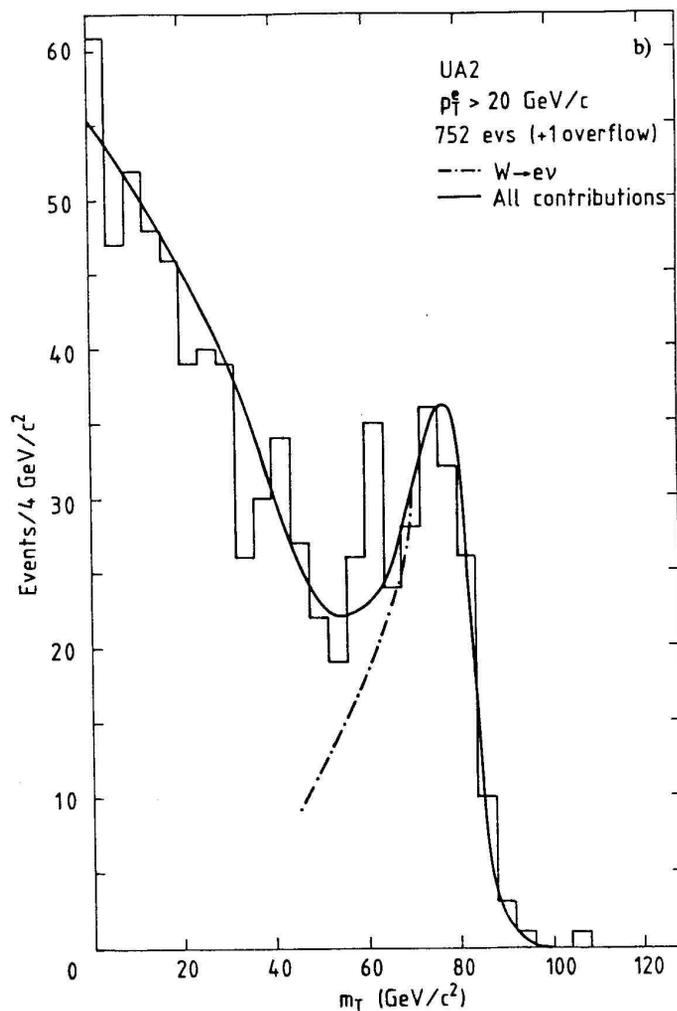
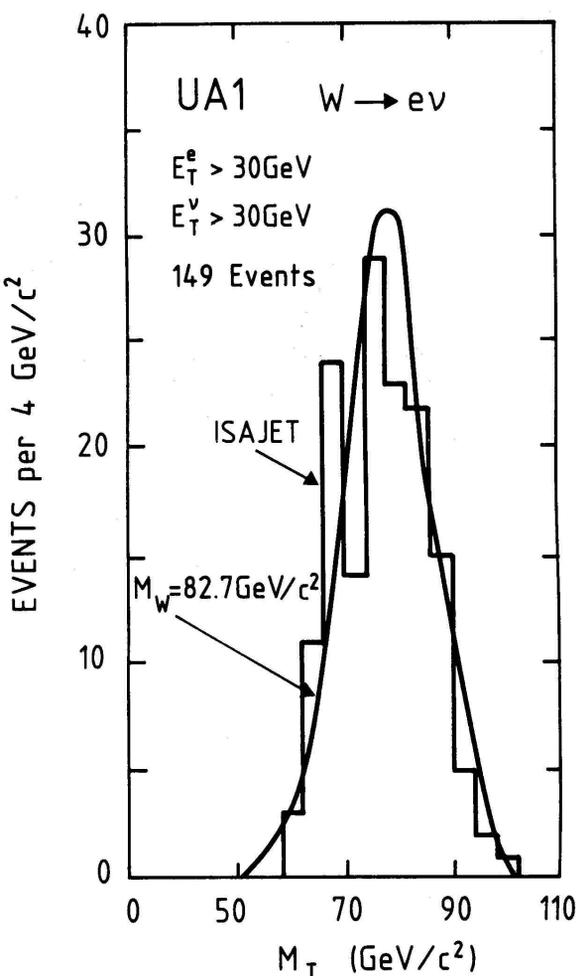
Figure 83: The UA1 transverse energy distribution of electrons in events with more than 15 GeV missing energy.

Massa trasversale

$$M_T^{lv} \equiv \sqrt{2p_T^l p_T^v (1 - \cos \phi)}$$

ϕ angolo tra elettrone e neutrino

nel piano trasverso



UA1

$M_W = 82.7 \pm 1.0(\text{stat}) \pm 2.7(\text{syst}) \text{ GeV}$

$\Gamma_W < 5.4 \text{ GeV}$

UA2

$M_W = 80.2 \pm 0.8(\text{stat}) \pm 1.3(\text{syst}) \text{ GeV}$

$\Gamma_W < 7 \text{ GeV}$

UA2 ha miglior controllo della calibrazione del calorimetro.
Piccole celle, calibrate su fascio periodicamente

Per entrambi errore sistematico
incertezza su scala dell'energia

→ From the first 148 electron and 47 muon events recorded by the UA1 it was estimated that

$$M_W = 83,5 \pm 2,8 \text{ GeV} \quad \Gamma_W \leq 6,5 \text{ GeV}$$

→ W bosons can be pair-produced in e^+e^- annihilation. From measurement at the LEP accelerator, the W mass and width is now estimated to be

$$M_W = 80,43 \pm 0,05 \text{ GeV} \quad \Gamma_W = 2,1 \pm 0,1 \text{ GeV}$$

→ The branching ratios of the leptonic decay modes of the W^\pm have been measured to be about 11% for each lepton generation.

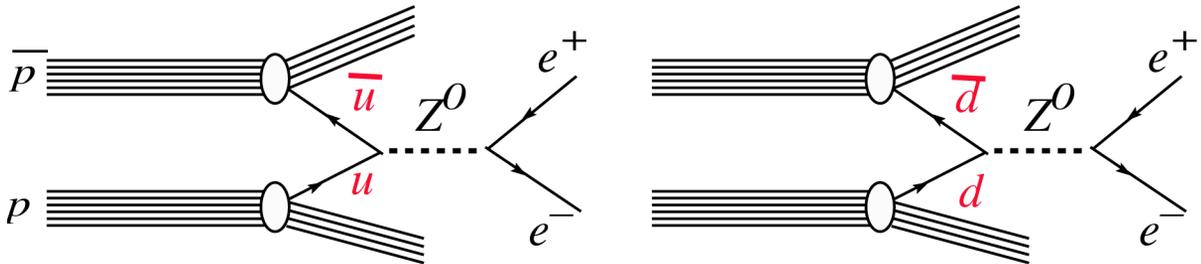
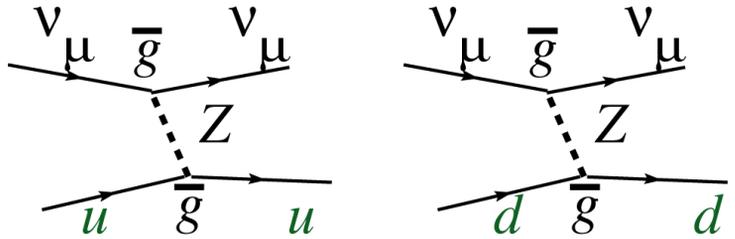
Aspettative per lo Z

SU(2)XU(1) predice massa e larghezza della Z

$$M_Z = \frac{M_W}{\cos \theta_W} = 91.6 \pm 0.7 \text{ GeV}$$

$$\Gamma_Z = 2.54 \text{ GeV}$$

L'annichilazione di un quark e un antiquark in Z^0 è descritta dagli stessi grafici che descrivono $\nu_\mu N \rightarrow$ adroni (senza μ)



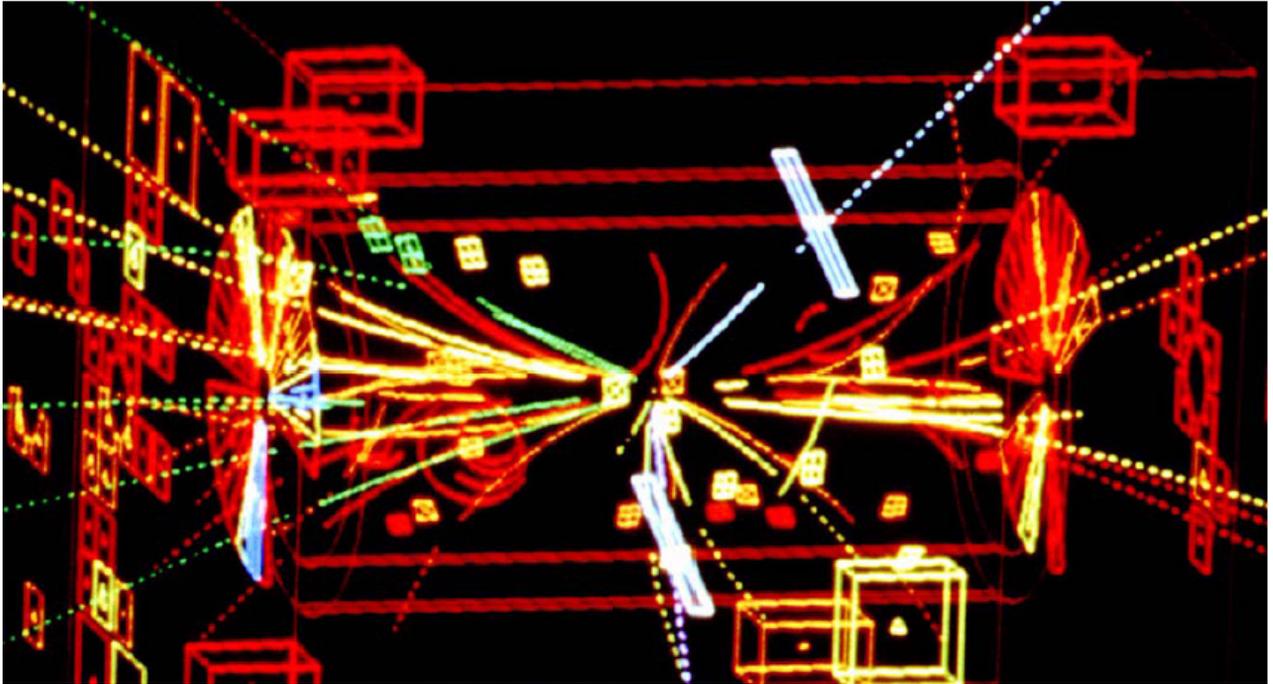
Altri stati finali $\mu^+\mu^-$, $\tau^+\tau^-$, qq_{bar}

Il calcolo di QCD (incertezze) della sezione d'urto da

$$\sigma(\bar{p}p \rightarrow Z \rightarrow e^+e^-) = 35^{+17}_{-10} \text{ pb} \quad @ 630 \text{ GeV}$$

Un ordine di grandezza più piccola che per la W, ma stati finali con 2, non 1 particella carica

DISCOVERY OF THE Z BOSON

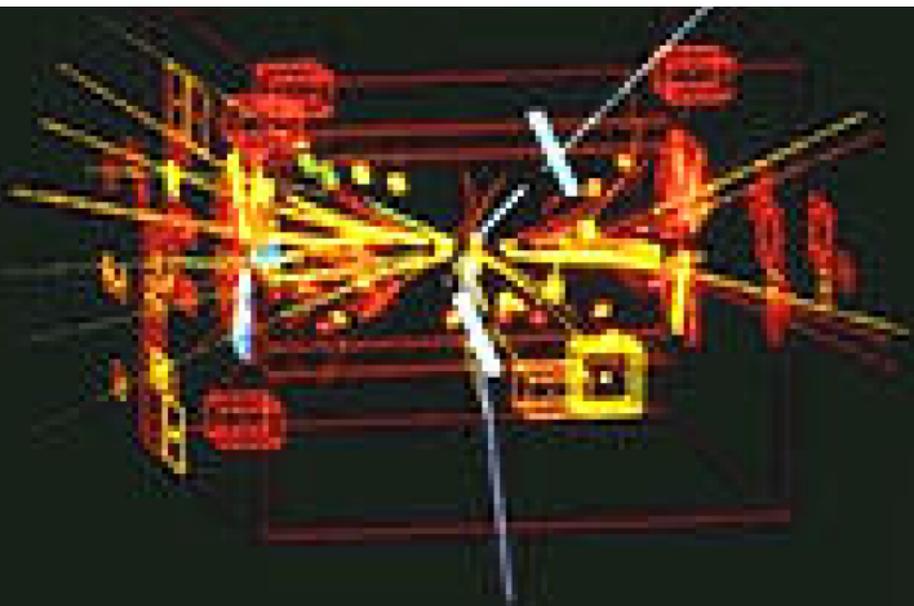


→ The signature of a Z^0 boson created in $p\bar{p}$ collision is a **pair of leptons** with large transverse momenta.

→ The mass of the Z^0 is given by the invariant **mass of the leptons**:

$$M_Z^2 = 2 E_l E_{\bar{l}} (1 - \cos \varphi) \quad \text{if } m_l=0$$

DISCOVERY OF THE Z BOSON



Misura di M_Z

$$Z^0 \rightarrow e^+ e^-, \quad \mu^+ \mu^-$$

$$\begin{aligned} m^2 &= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = \\ &= E_1^2 + E_2^2 + 2E_1 E_2 - p_1^2 - p_2^2 - 2p_1 p_2 \cos \theta \\ &\cong 2E_1 E_2 (1 - \cos \theta) \end{aligned}$$

$$m^2 \cong 4E_1 E_2 \sin^2 \theta / 2$$

$$\frac{\sigma_m}{m} = \sqrt{\left(\frac{\sigma(E_1)}{E_1}\right)^2 + \left(\frac{\sigma(E_2)}{E_2}\right)^2 + \left(\frac{\sigma(\theta)}{\tan \theta / 2}\right)^2}$$

$$\frac{\sigma_m}{m} = \sqrt{\left(\frac{\sigma(E_1)}{E_1}\right)^2 + \left(\frac{\sigma(E_2)}{E_2}\right)^2 + \left(\frac{\sigma(\theta)}{\tan \theta / 2}\right)^2}$$

$$\theta \geq 100^\circ \quad \tan \frac{\theta}{2} \approx O(1)$$

$$\theta \text{ misurato dalla misura delle tracce} \quad \sigma(\theta) \approx 10^{-2}$$

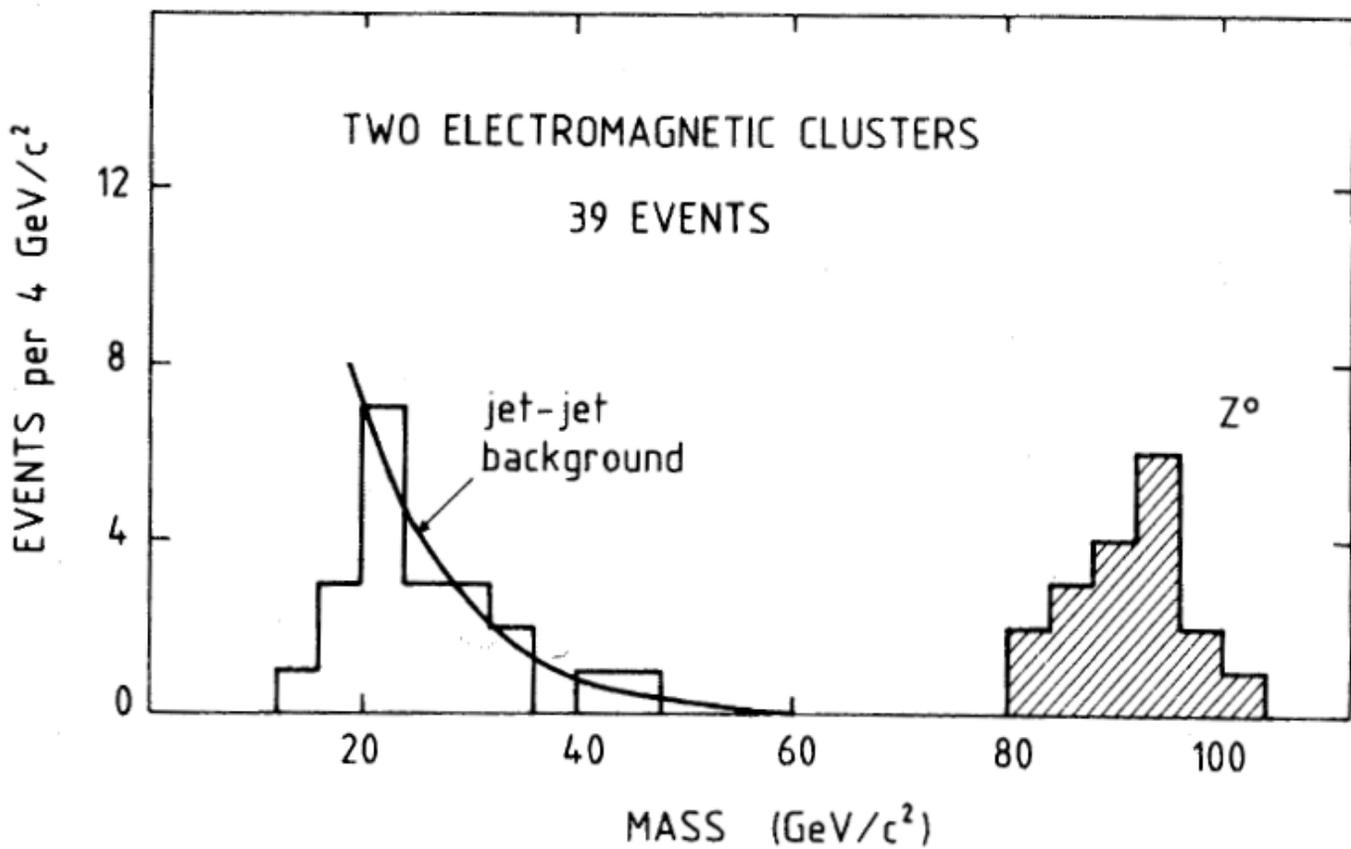


Figure 88: The UA1 mass distribution of pairs of electrons
 → From the first 18 electron and 10 muon events recorded by the UA1 it was estimated that

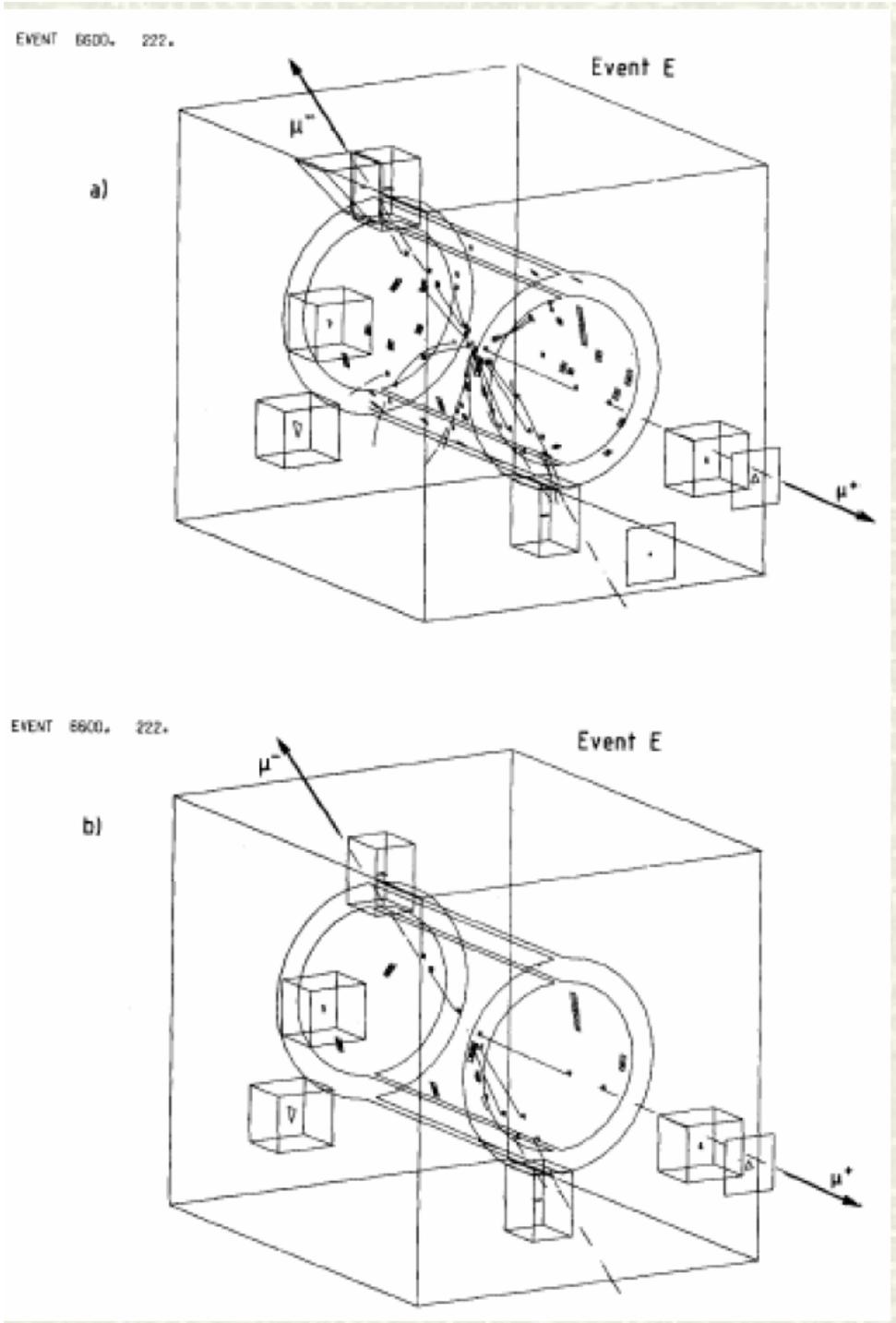
$$M_Z = 93,0 \pm 1,4 \text{ GeV} \quad \Gamma_Z \leq 8,1 \text{ GeV}$$

→ From measurement at the LEP accelerator, the Z mass and width is now estimated to be

$$M_Z = 91,188 \pm 0,002 \text{ GeV} \quad \Gamma_Z = 2,495 \pm 0,002 \text{ GeV}$$

The branching ratios of the leptonic decay modes of the Z are measured to be about 3% for each lepton.

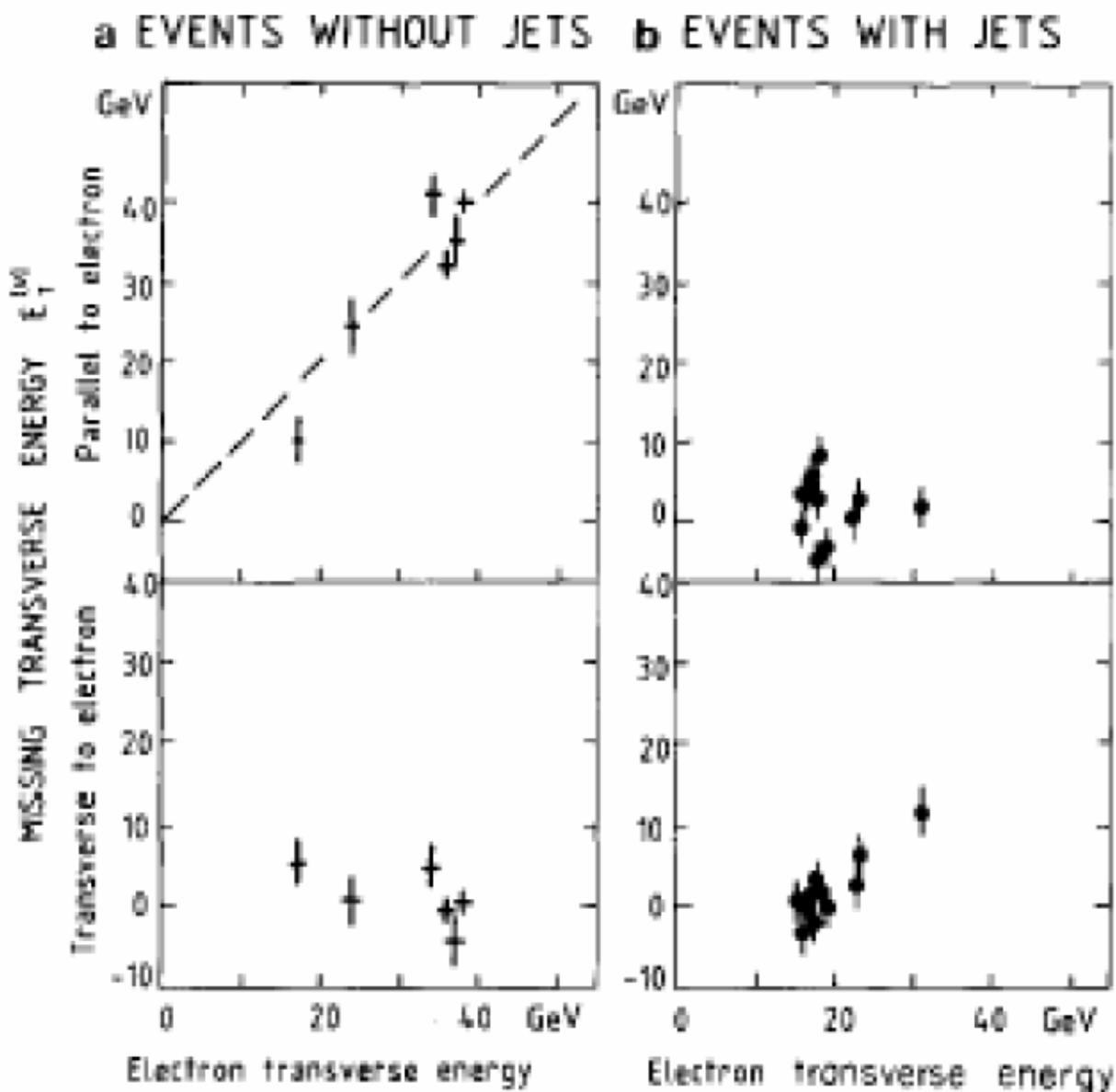
UA1 results



Missing energy

Events without jets:

- From the momentum conservation it was found that the missing neutrino is antiparallel to the electron
- Missing transverse energy is proportional to the electron transverse energy

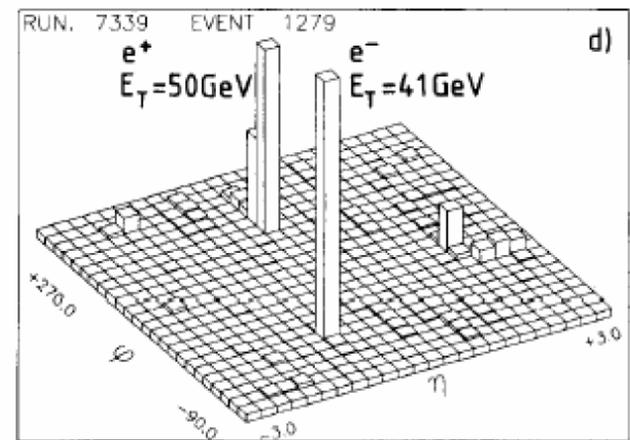
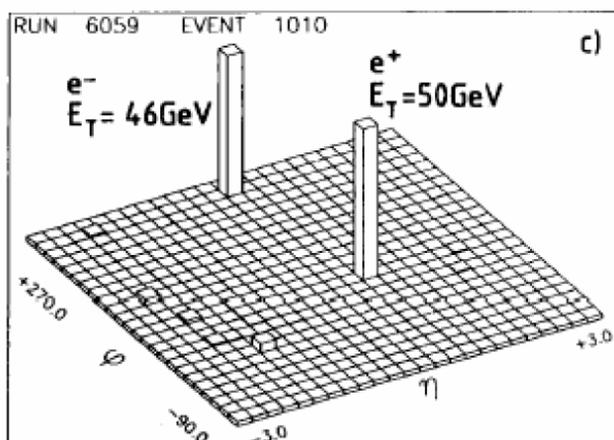
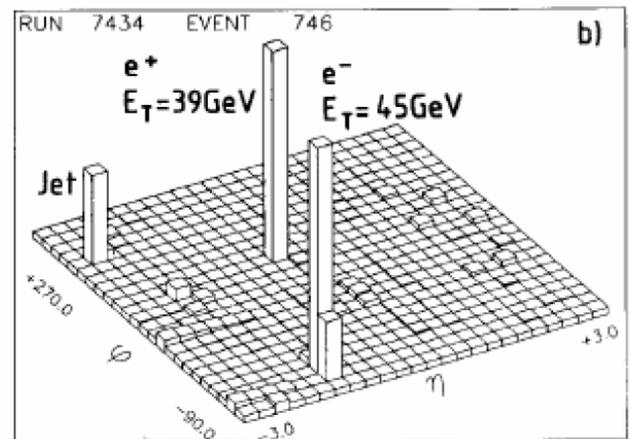
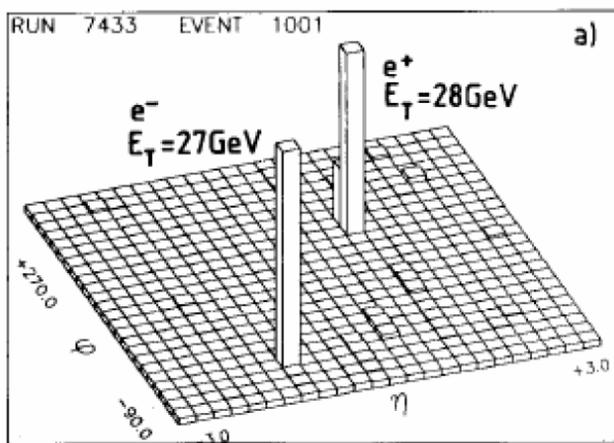


UA1 experiment

Lego plot for 4 UA1 candidates shows isolated high-energy electron and positron tracks:

pseudorapidity

$$\eta = -\ln(\tan(\theta/2)).$$

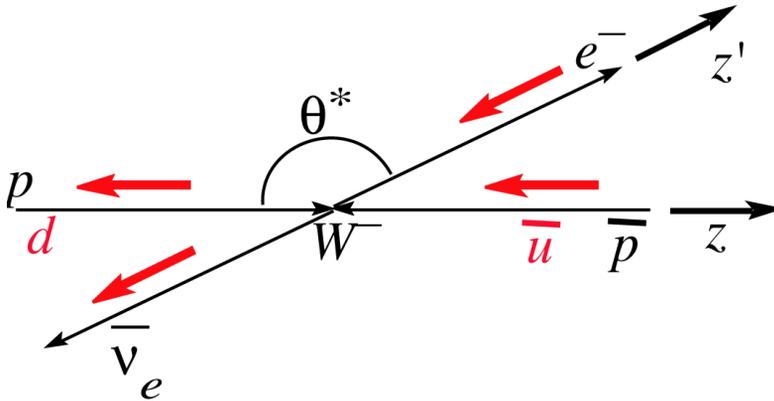


Polarizzazione della $W \Rightarrow e\nu_e$

Nel riferimento del c.m. della W :

l'energia dell'elettrone $\gg m_e$. chiralità \approx elicità

$V-A \Rightarrow W$ si accoppia solo a fermioni con elicità -
antifermioni con elicità +



Mom. ang. tot. $J=S_W=1$

J_z (iniz.) = $\lambda = -1$

J_z (fin.) = $\lambda' = -1$

$$\frac{d\sigma}{d\Omega} \propto \left[d_{-1,-1}^1 \right]^2 = \left[\frac{1}{2} (1 + \cos \theta^*) \right]^2$$

N.B. Se fosse stato $V+A$ $\frac{d\sigma}{d\Omega} \propto \left[d_{1,1}^1 \right]^2 = \left[-\frac{1}{2} (1 + \cos \theta^*) \right]^2$

L'asimmetria avanti-indietro è conseguenza della violazione di P

Per distinguere $V-A$ da $V+A$ sono necessarie misure di polarizzazione dell'elettrone

Polarizzazione della $W \Rightarrow e \nu_e$

Selezionati 132 eventi con carica dell'elettrone ben definita e p_L^{ν} ben determinato dalla cinematica

$$\frac{d\sigma}{d\Omega} \propto [d_{-1,-1}^1]^2 = \left[\frac{1}{2} (1 + \cos \theta^*) \right]^2$$

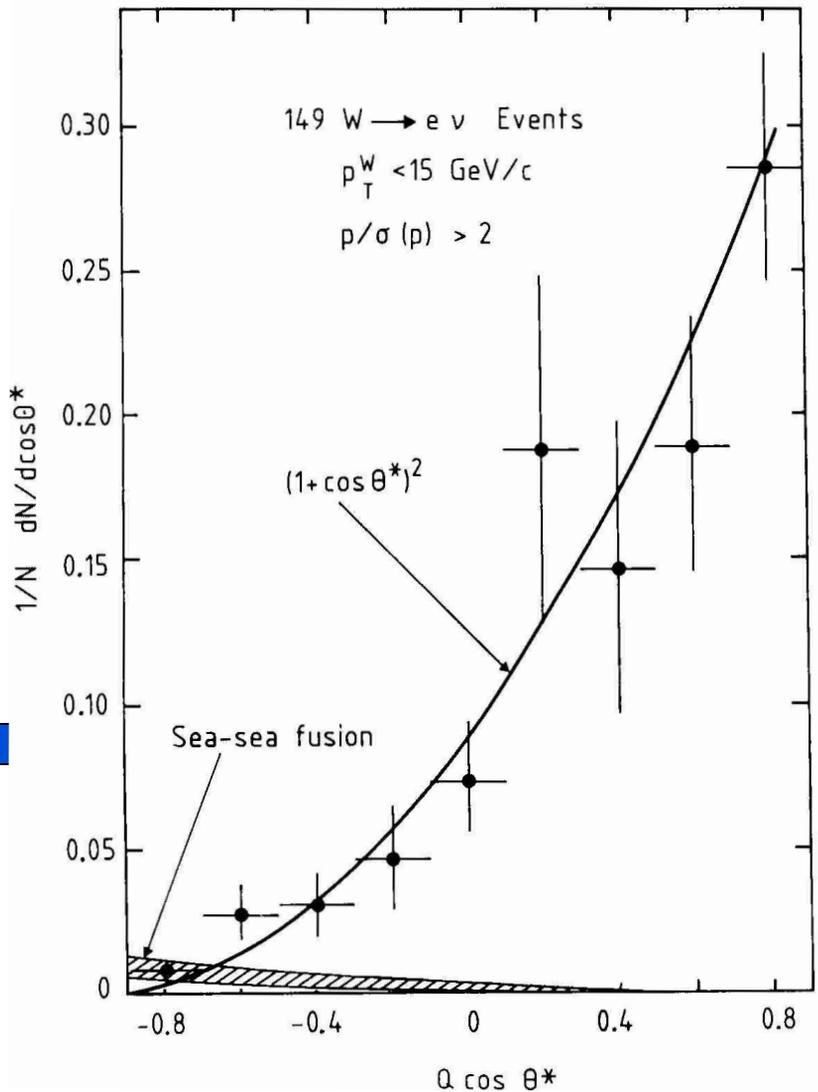
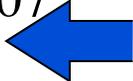
$$\langle \cos \theta^* \rangle = \frac{\langle \lambda \rangle \langle \lambda' \rangle}{J(J+1)}$$

$$J=1 \quad \langle \cos \theta^* \rangle = \frac{1}{2}$$

$$J=0 \quad \langle \cos \theta^* \rangle = 0$$

$$J > 1 \quad \langle \cos \theta^* \rangle \leq \frac{1}{6}$$

$$\langle \cos \theta^* \rangle = 0.43 \pm 0.07$$



cioè $J=1$ e elicità massima ($\lambda, \lambda' = \pm 1$)

Conclusioni

La teoria di Fermi delle interazioni deboli a quattro fermioni, includendo la teoria V-A delle interazioni corrente-corrente, e' sostituita dalla teoria unificata delle interazioni elettromagnetiche e deboli sviluppata da **Glashow, Weinberg a Salam**.

Due aspetti importanti della teoria elettrodebole:

i) la rottura spontanea della simmetria, che da' le masse ai bosoni vettori;

ii) La rinormalizzabilita' della teoria, che rimuove gli infiniti nel calcolo delle ampiezze dei processi di interazione; sono stati risolti con successo rispettivamente da **Higgs e da 'T Hooft**.

La validita' della teoria e' stata provata:

i) dalla scoperta delle correnti neutre da parte dell' esperimento **Gargamelle** al CERN (il primo grande successo del CERN);

ii) dalla osservazione dei Bosoni W e Z agli esperimenti **UA1 e UA2** di nuovo al CERN.

Bibliografia

- Pag 320-338 capitolo 9 di:
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