Gauge Bosons I

the W boson

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Unstable particles

- The wave function describing a decaying state is:

$$\psi(t)=\psi(0)e^{-i\omega_R t}e^{-t/2\tau}=\psi(0)e^{-t(iE_R+\Gamma/2)}$$

with E_R = resonance energy and τ = lifetime

- The Fourier transform gives: $$g(\omega)=\int_0^\infty \psi(t)e^{i\omega t}dt$$

The amplitude as a function of E is then:

$$\chi(E)=\int \psi(t)e^{iEt}dt=\psi(0)\int e^{-t\left[\left(\frac{\Gamma}{2}\right)+i\left(E_R-E\right)\right]}dt=\frac{K}{\left(E-E_R\right)-i\Gamma 2}$$

K= constant, E_R = central value of the energy of the state

But: $\chi(E)^*\chi(E)$ →

$$\sigma=\sigma_{max}\frac{\Gamma^2 4}{\left[\left(E-E_R\right)^2+\Gamma^2 4\right]}$$

Breit-Wigner

- The value of the peak cross-section σ_{max} can be found using arguments from wave optics:

$$\sigma_{max} = 4\pi \lambda\!\!\!^{-2} (2J+1)$$

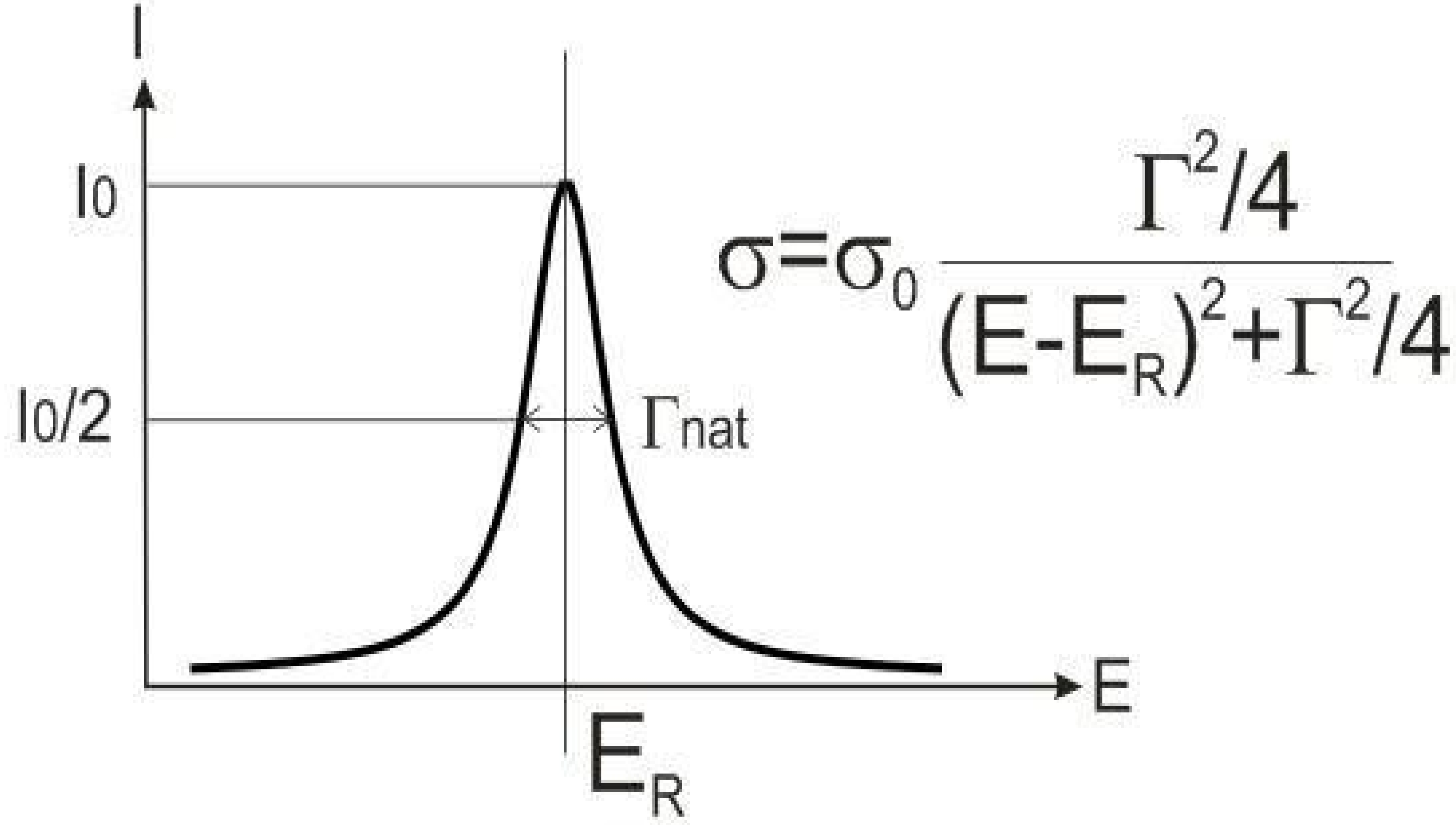
With $\lambda\!\!\!^{-}$ = wavelenght of scattered/scattering particle in cms

- Including spin multiplicity factors, one gets the **Breit-Wigner formula:**

$$\sigma = \frac{4\pi \lambda\!\!\!^{-2} (2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma^2 4}{\left[(E-E_R)^2 + \Gamma^2 4\right]}$$

s_a and s_b: spin s of the incident and target particles
J: spin of the resonant state

Breit-Wigner

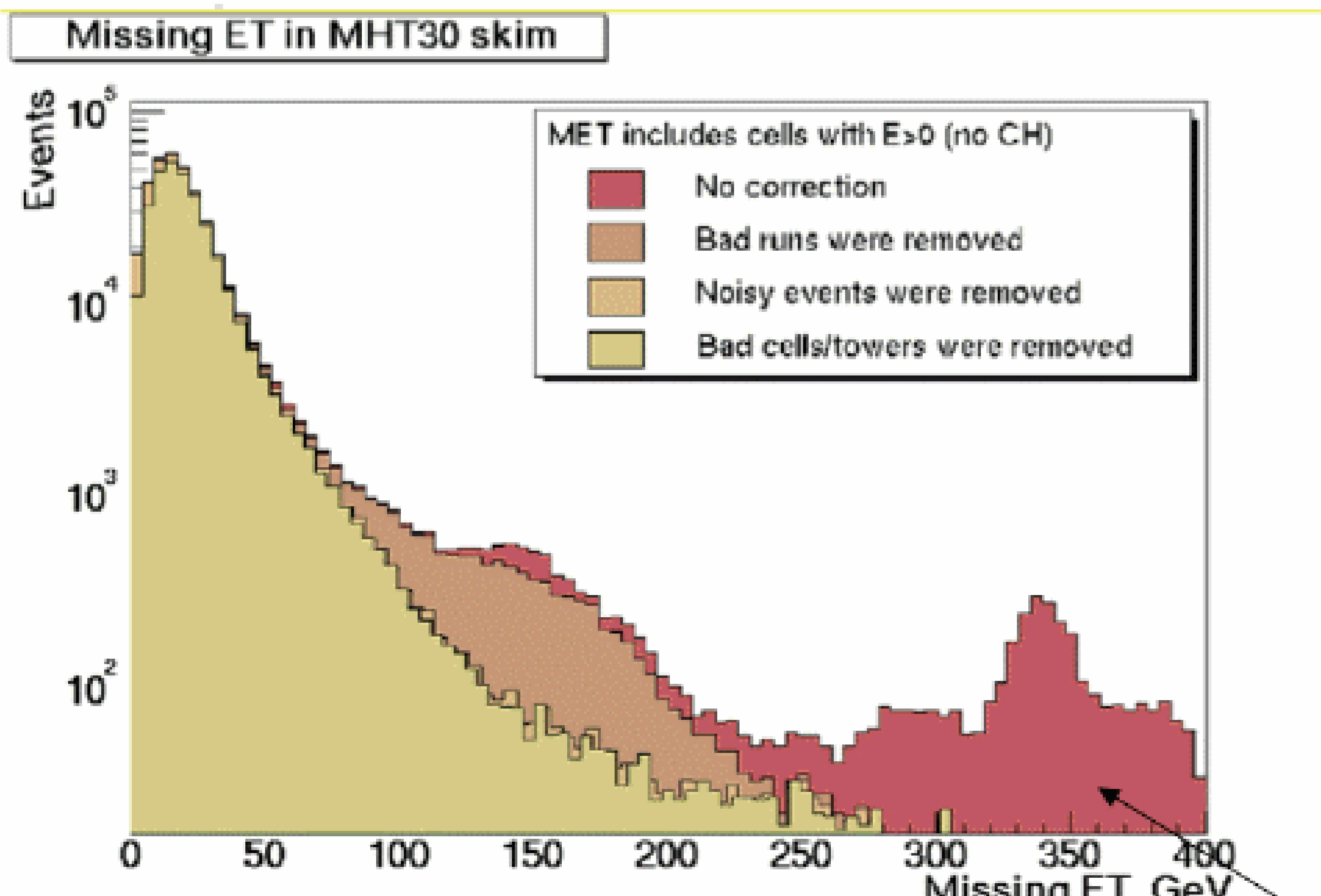


- Mean value of the Breit-Wigner shape is the mass of the resonance: $M=E_R$. Γ is the width of a resonance and is inverse mean lifetime of a particle at rest: $\Gamma = 1/\tau$

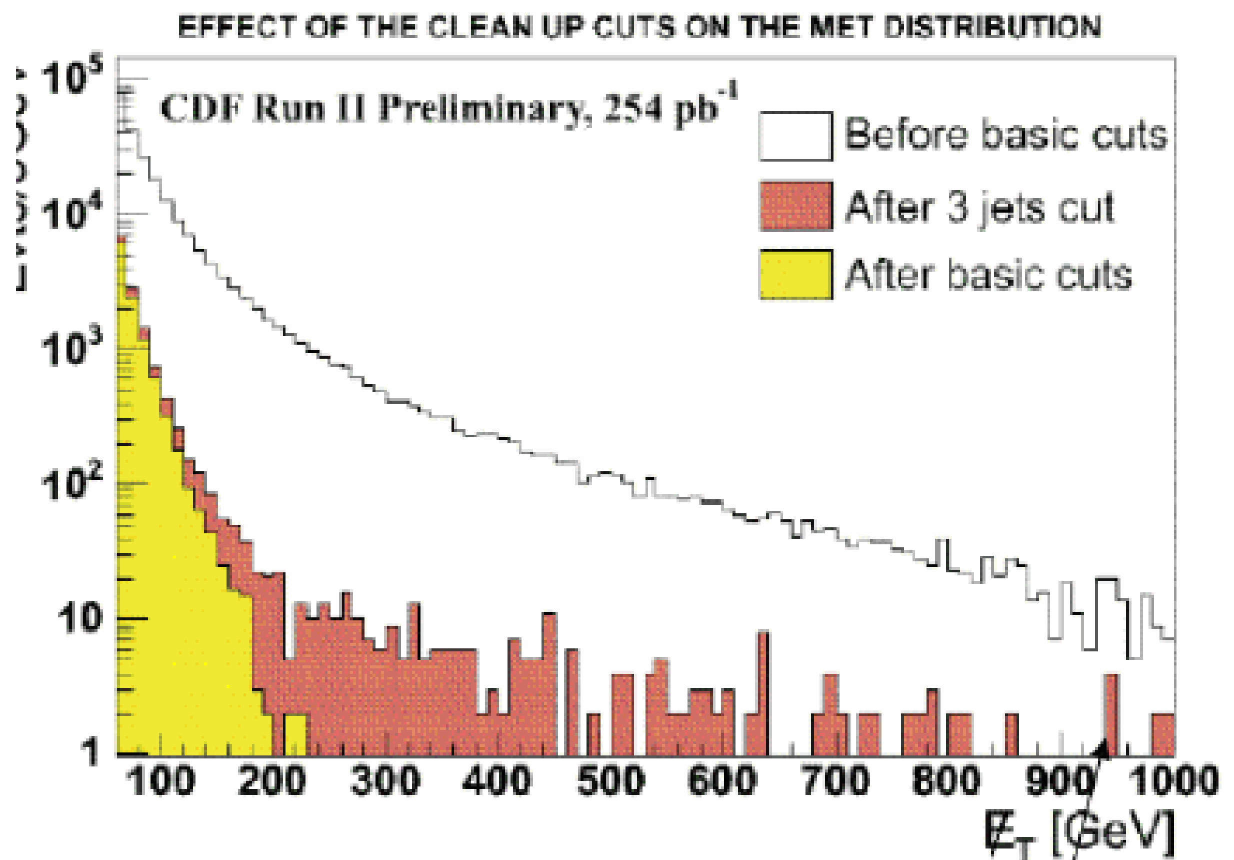
Missing Transverse Energy

- Missing energy is not a good quantity in a hadron collider as much energy from the proton remnants are lost near the beampipe
- Missing transverse energy (E_T) much better quantity
  - Measure of the loss of energy due to neutrinos
- Definition:
  - $\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ \mathrm{visible}} \vec{\mathrm{E}}_\mathrm{T}$
- Best missing E_T reconstruction
  - Use all calorimeter cells with true signal
  - Use all calibrated calorimeter cells
  - Use all reconstructed particles not fully reconstructed in the calorimeter
    - e.g. muons from the muon spectrometer

Missing Transverse Energy



MET, before corrections (Do)



MET, after corrections (CDF)

This is where new physics may sit

W leptonic widths

Masses (approximately)

$$M_W = \left(\frac{g^2 \sqrt{2}}{8 G_F} \right)^{1/2} = \sqrt{\frac{\pi \alpha}{\sqrt{2} G_F}} \frac{1}{\sin\theta_W} = \frac{37.3}{\sin\theta_W} \text{ GeV}$$

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

From the measured value of θ_W

$$\mathrm{M_W} = 80 \text{ GeV} \qquad M_Z \approx 91 \text{ GeV}$$

W. leptonic widths (equal one to each other, universality). From theory:

$$\Gamma_{e\nu} = \Gamma_{\mu\nu} = \Gamma_{\tau\nu} = \left(\frac{g}{\sqrt{2}} \right)^2 \frac{M_W}{24\pi} = \frac{1}{2} \frac{G_F M_W^3}{3\sqrt{2}\pi} \approx 225 \text{ MeV}$$

NB. In general, withds of interaction bosons are proportional to the cube of the mass

W hadronic widths

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$$m_t > m_W \;\Rightarrow\; \Gamma_{td} = \Gamma_{ts} = \Gamma_{tb} = 0$$

To compute widths in *qq one should take into account for*

- factor 3 since 3 colors
- mixing matrix

Two types of decays:

same family

different families (small width)

All non diagonal elements are small, so *W* decays to different families are suppressed

$$|V_{ub}| << 1 \;\Rightarrow\; \Gamma_{ub} \approx 0 \qquad |V_{cb}| << 1 \;\Rightarrow\; \Gamma_{cb} \approx 0$$

$$\Gamma_{us} \equiv \Gamma\left(W \to \bar{u}s\right) = 3 \times |V_{us}|^2\, \Gamma_{e\nu} = 3 \times 0.224^2 \times \Gamma_{e\nu} \approx 35 \text{ MeV}$$

Three colors

$$\Gamma_{cd} \equiv \Gamma\left(W \to \bar{c}d\right) = 3 \times |V_{cd}|^2\, \Gamma_{e\nu} = 3 \times 0.22^2 \times \Gamma_{e\nu} \approx 33 \text{ MeV}$$

$$\Gamma_{ud} \equiv \Gamma\left(W \to \bar{u}d\right) = 3 \times |V_{ud}|^2\, \Gamma_{e\nu} = 3 \times 0.974^2 \times \Gamma_{e\nu} = 2.84 \times \Gamma_{e\nu} \approx 640 \text{ MeV}$$

$$\Gamma_{cs} \equiv \Gamma\left(W \to \bar{c}s\right) = 3 \times |V_{cs}|^2\, \Gamma_{e\nu} = 3 \times 0.99^2 \times \Gamma_{e\nu} \approx 660 \text{ MeV}$$

$$\Gamma_W \approx 2.04 \text{ GeV}$$

W resonant production

Both *W* and *Z* can be produced at a collider quark-(anti)quark

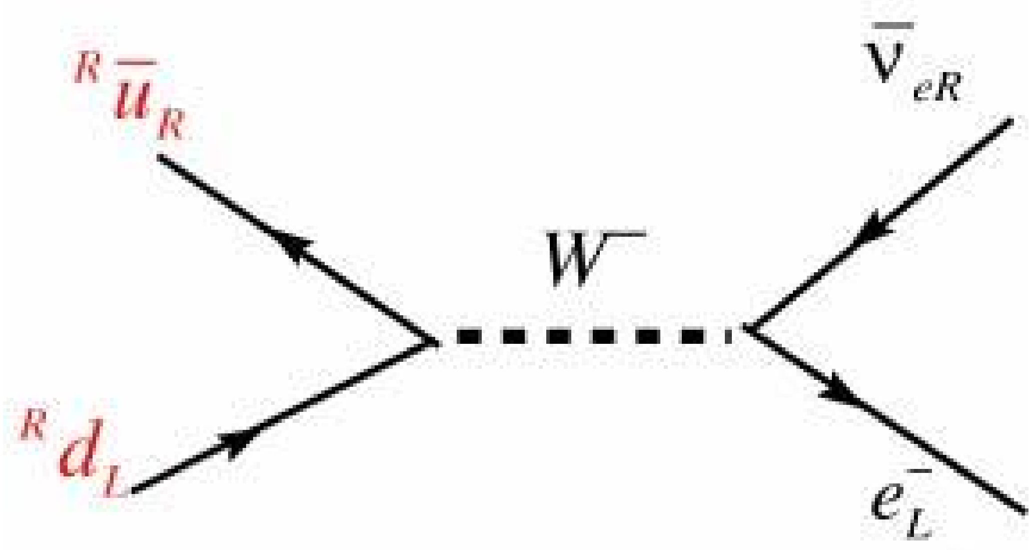
⇒ UA1 (CERN). Discovery in 1983

CM energy of quarks $$\sqrt{\hat{s}} = x_q x_{\bar{q}} \sqrt{s}$$

Main process:

$$\bar{u} + d \rightarrow e^- + \bar{\nu}_e$$

$$u + \bar{d} \rightarrow e^+ + \nu_e$$



They must have same **color**

They must have same **chirality**

W resonant production

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Close to resonance ⇒ Breit Wigner (like e^+e^-)

$$\bar{u}+d \rightarrow e^- + \bar{\nu}_e$$

$$\sigma\left(\bar{u}d \rightarrow e^-\bar{\nu}_e\right) = \frac{1}{9}\frac{3\pi}{\hat{s}}\frac{\Gamma_{ud}\Gamma_{e\nu}}{\left(\sqrt{\hat{s}}-M_W\right)^2+\left(\Gamma_W/2\right)^2}$$

Probability for **same colors**

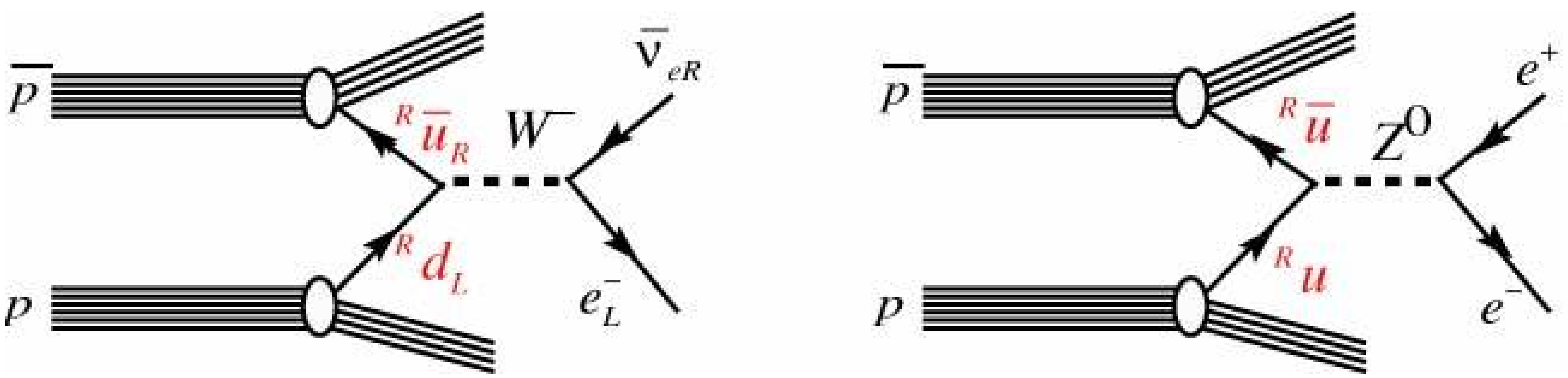
$$\sigma_{\max}\left(\bar{u}d \rightarrow e^-\bar{\nu}_e\right) = \sigma_{\max}\left(u\bar{d} \rightarrow e^+\nu_e\right)$$

$$= \frac{4\pi}{3}\frac{1}{M_W^2}\frac{\Gamma_{ud}\Gamma_{e\nu}}{\Gamma_W^2} = \frac{4\pi}{3}\frac{1}{81^2}\frac{0.640\times 0.225}{2.04^2}\left[\text{GeV}^{-2}\right]\times 388\left[\mu\text{b/GeV}^{-2}\right]\approx 8.8\text{ nb}$$

Small σ_{max}<<< $\sigma_{tot}\approx$100 mb. Weak interactions … are weak!

Cross sections

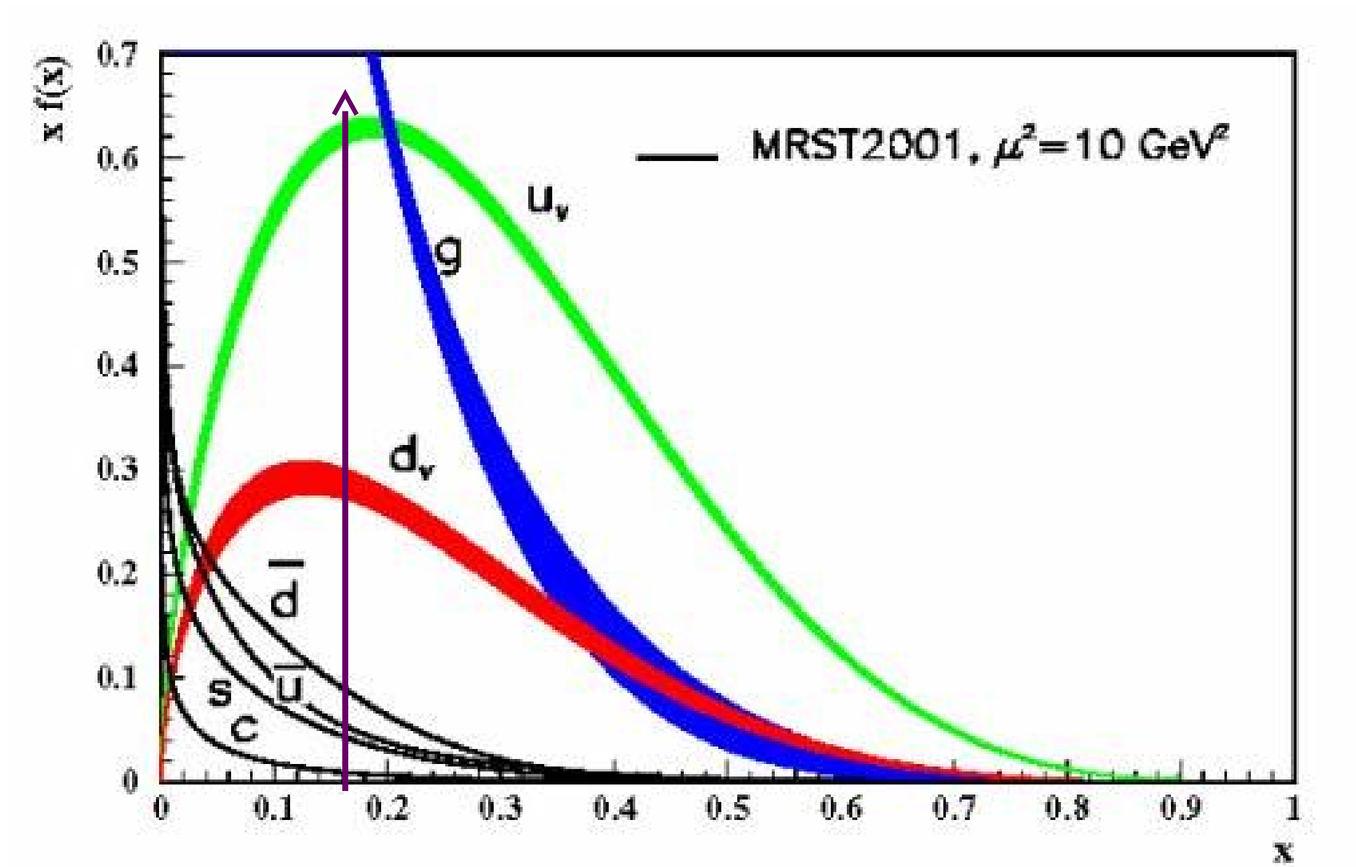
Beam of $\bar{p}$ = *partons* (*q, g, and some q*)



Consider fusion of a valence quark and antiquark

if $\sqrt{s}$=630 GeV, momentum fraction needed

$$< x > \approx \frac{M_W}{\sqrt{s}} \approx \frac{M_Z}{\sqrt{s}} \approx 0.15$$

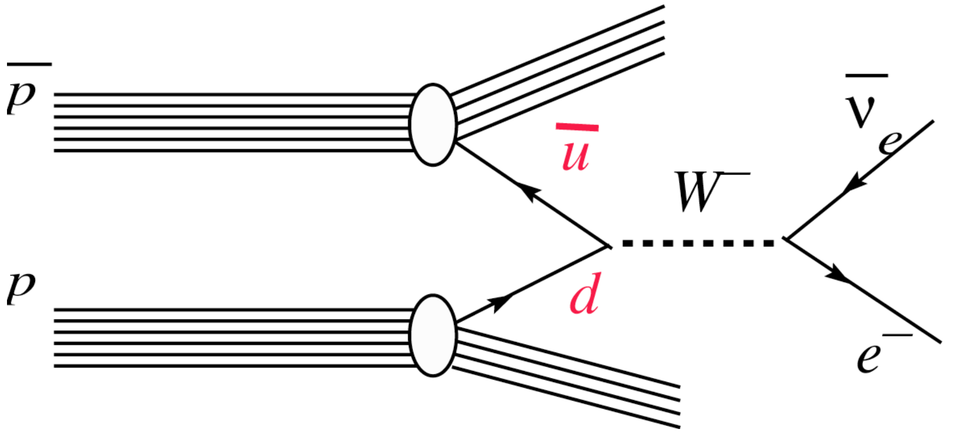


OK. A lot!

W production from $p\bar{p}$

Laboratory frame is the cm frame of $p\bar{p}$, not of $q\bar{q}$; this pair, and so also the *W* (*Z)* originated from it, have a different longitudinal motion from event to event

$$\hat{s} = x_d x_{\bar{u}} s$$



The cross section prediction (QCD and structure function uncertainties) was predicted to be √*s*=630 GeV:

$$\sigma\left(\bar{p}p \to W \to e\nu_e\right) = 530\,{}^{+170}_{-90}\ \text{pb}$$

(plus the analogue from $u\bar{d}$)

@ √*s*=630 GeV <*x*> = $M_W/\sqrt{s} \approx 0.15$, valence quarks dominate over sea quarks

Cross sections grow rapidly with energy, along with the posiibility to have some longitudinal moment for the boson

Resonant production of *W* and *Z*

In 1978 Cline, McIntire and Rubbia proposed to transform the proton collider SpS at CERN into a $p\bar{p}$ one, in which protons and antiprotons could flow in opposite directions, within the same (existing) magnetic structure, **thanks to CPT symmetry**.

The major problem which Rubbia and Van der Meer were able to solve was the “**cooling**” of particle beam bunches to dimensions small enough in the collision point.

In 1983 a luminosity of L=1032 m–2 s–1 was reached, sufficient to **discover W and Z**.

Signals

IVB production is a rare process 10^{-8} -- 10^{-9} ($\sigma_{tot}(pp) \approx$ 70 mb = 7×10^{10} pb)
[weak interaction is ...weak !]

Rejection power of the detector must be $> 10^{10}$

Most frequent final state: $q\bar{q}$

$$\sigma \cdot B(W \to q\bar{q}) = 3\sigma \cdot B(W \to l\nu_l) \quad 3 = \text{numero di colori}$$

Experimentally: $q \Rightarrow$ *jet*

Huge background from $gg \to gg, gq \to gq, \{g\bar{q} \to g\bar{q},\} q\bar{q} \to q\bar{q}$

Important kinematical quantity to neasure: *trasverse* momentum p_T = component of the momentum perpendicular to the beams

Leptonic states have a better S/B

$$\left.\begin{array}{lll} W \to e\,\nu_e & e & \text{isolated, high } p_T \\ W \to \mu\,\nu_\mu & \mu & \text{isolated, high } p_T \end{array}\right\} + \text{ high } p_T\,\nu = \text{high missing } p_T$$

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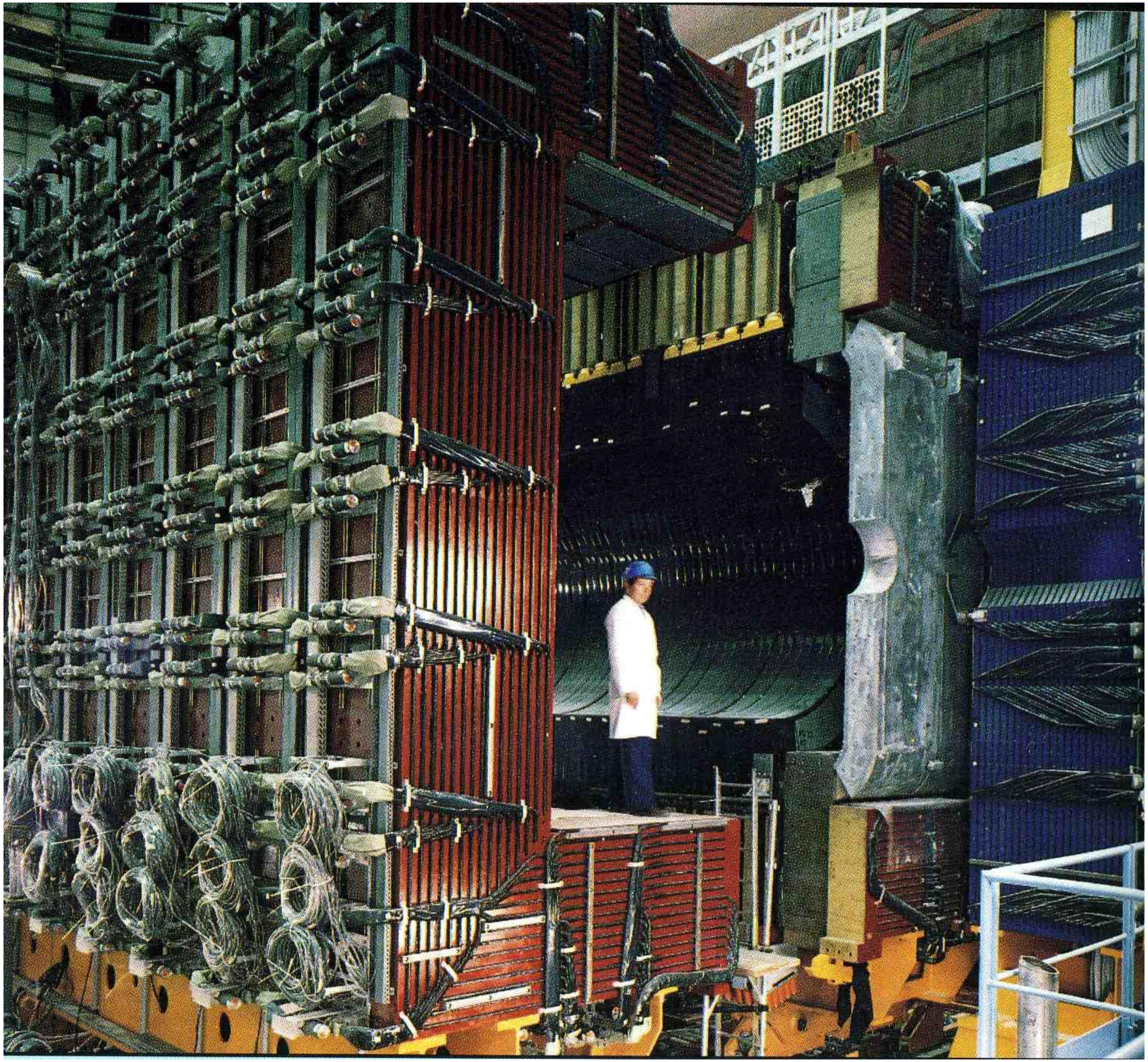
Building UA1



UA1. Central detector in the way to the museum

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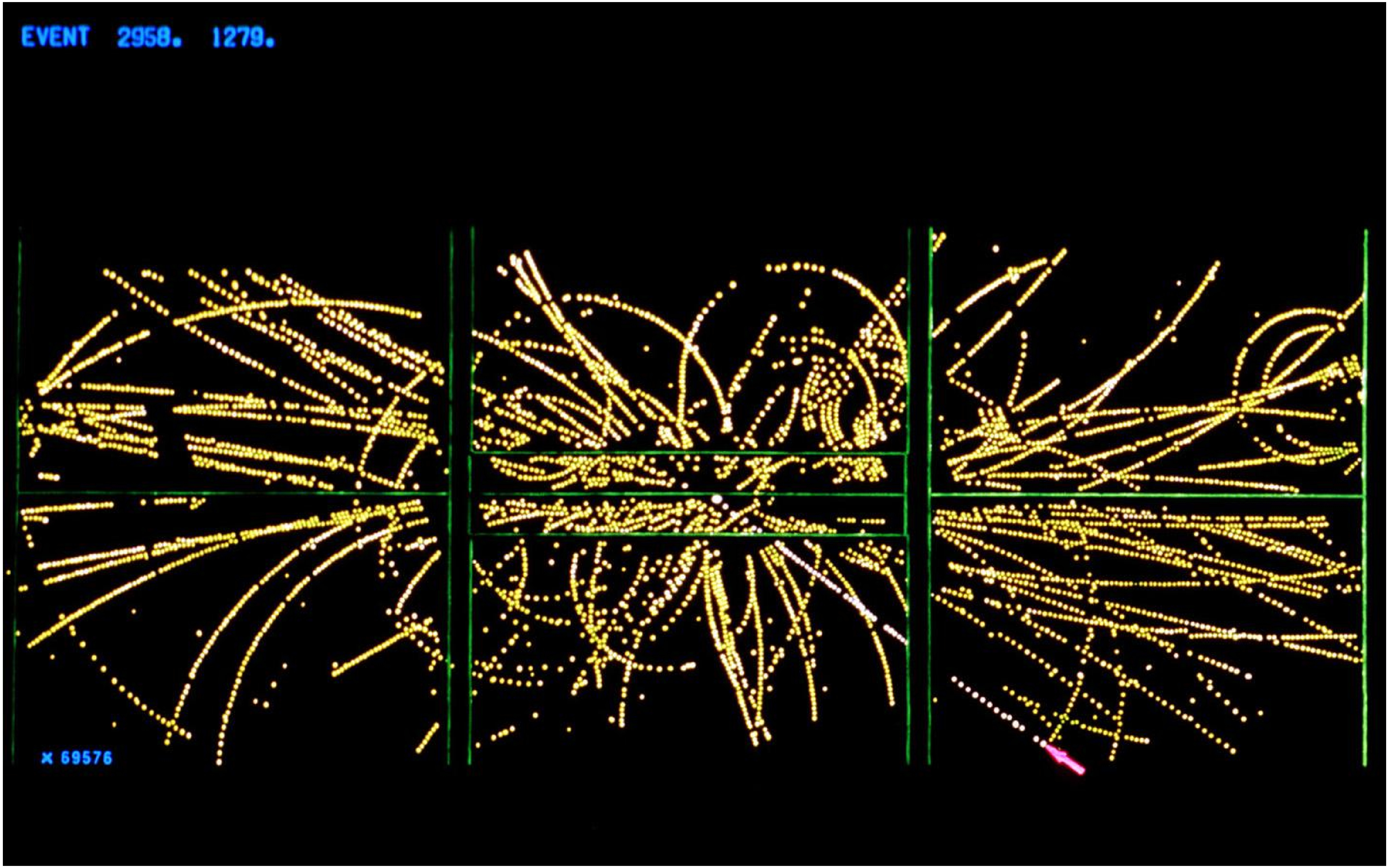
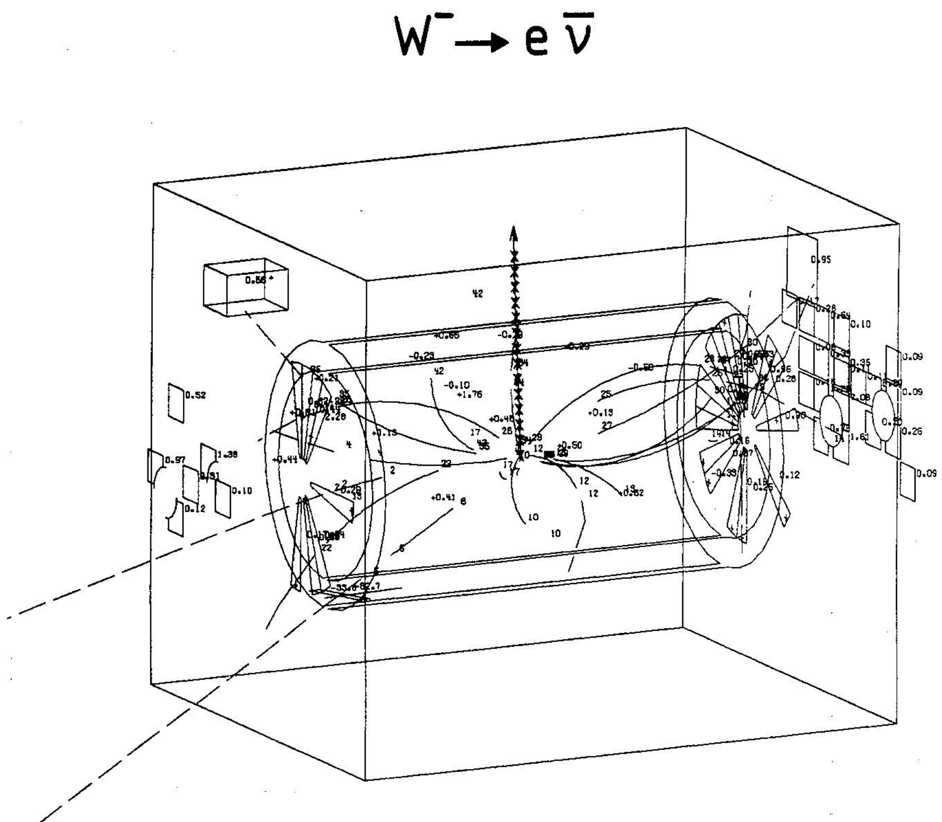
UA1. First W production



$W \to e\nu$

W appear in electromagnetic calorimeters as localised energy deposits in the opposite direction of the missing momentum



Vetoing tracks with p_T< 1 GeV cleans completely the event: what only survives are the electron and the“neutrino”

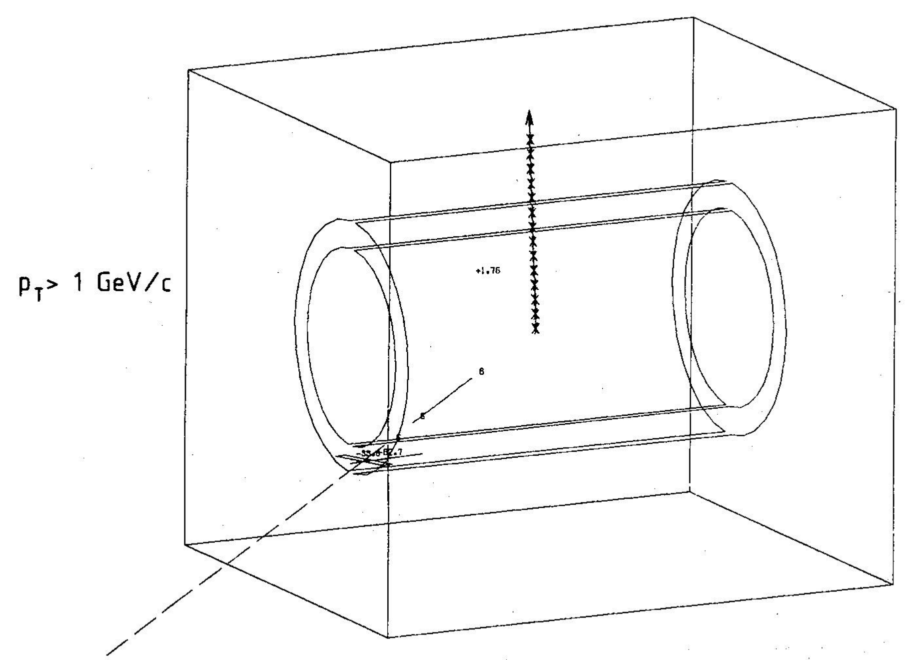
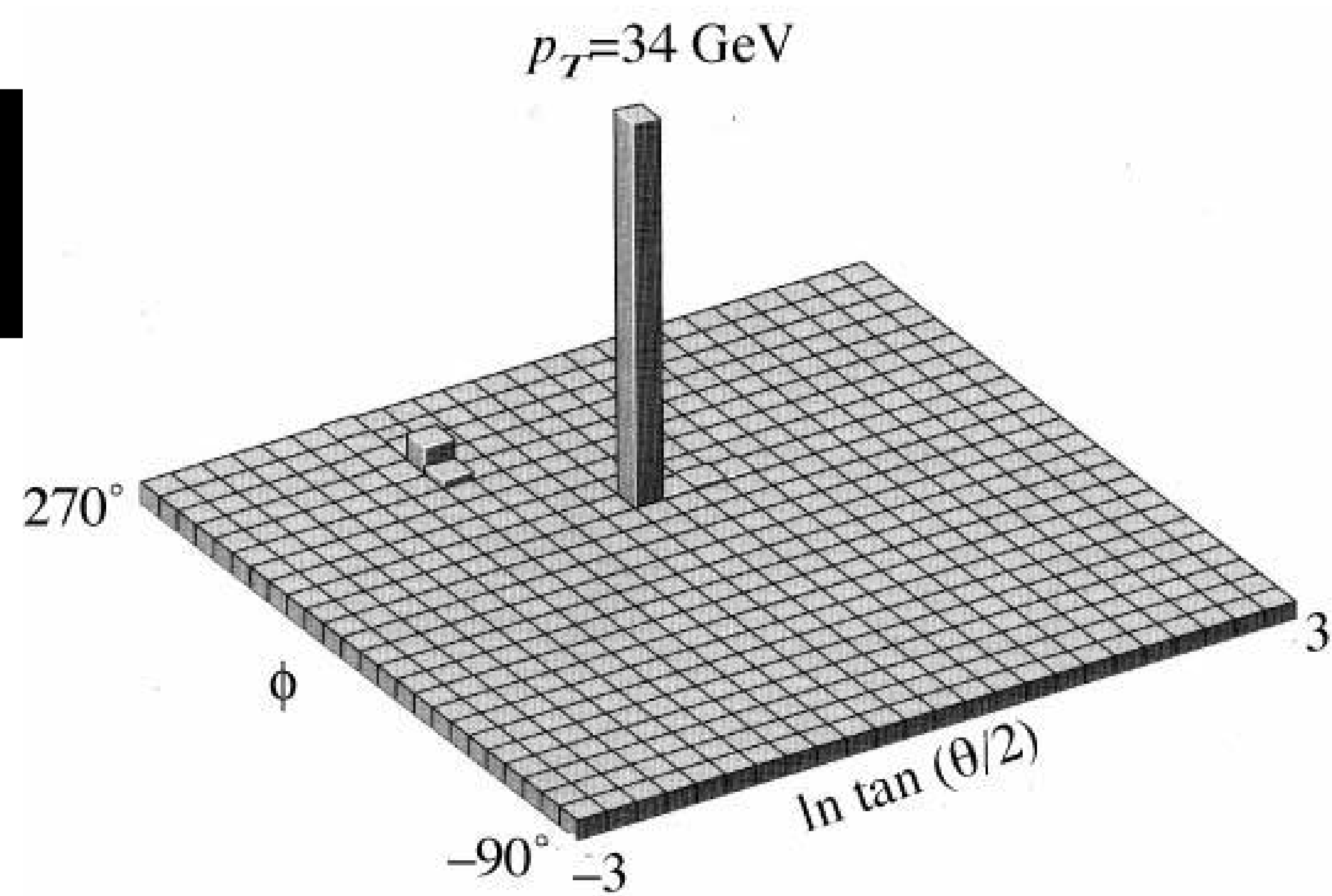


Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_T>1 GeV are shown.



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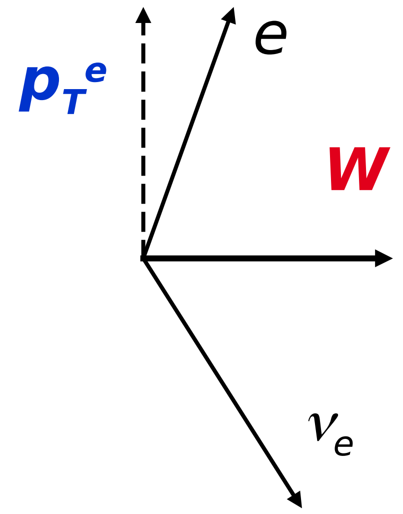
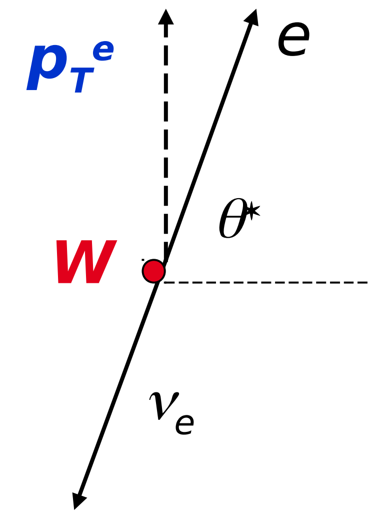
M_W measurement

$W \rightarrow l\ \nu_l$

Transverse momenta of q and e $\bar{q}$ are small, such that also that of the W is small.



LAB



CM. W

$p^e = m_W/2$

$\boldsymbol{p_T^e}$ is the same in the two reference frames = $(m_W/2)\sin\theta^*$

The angular distribution of the decay in the CM is known:

$$\frac{dn}{dq} \xrightarrow{\text{coordinate transf.}} \frac{dn}{dp_T} = \frac{dn}{dq}\frac{dq}{dp_T}$$

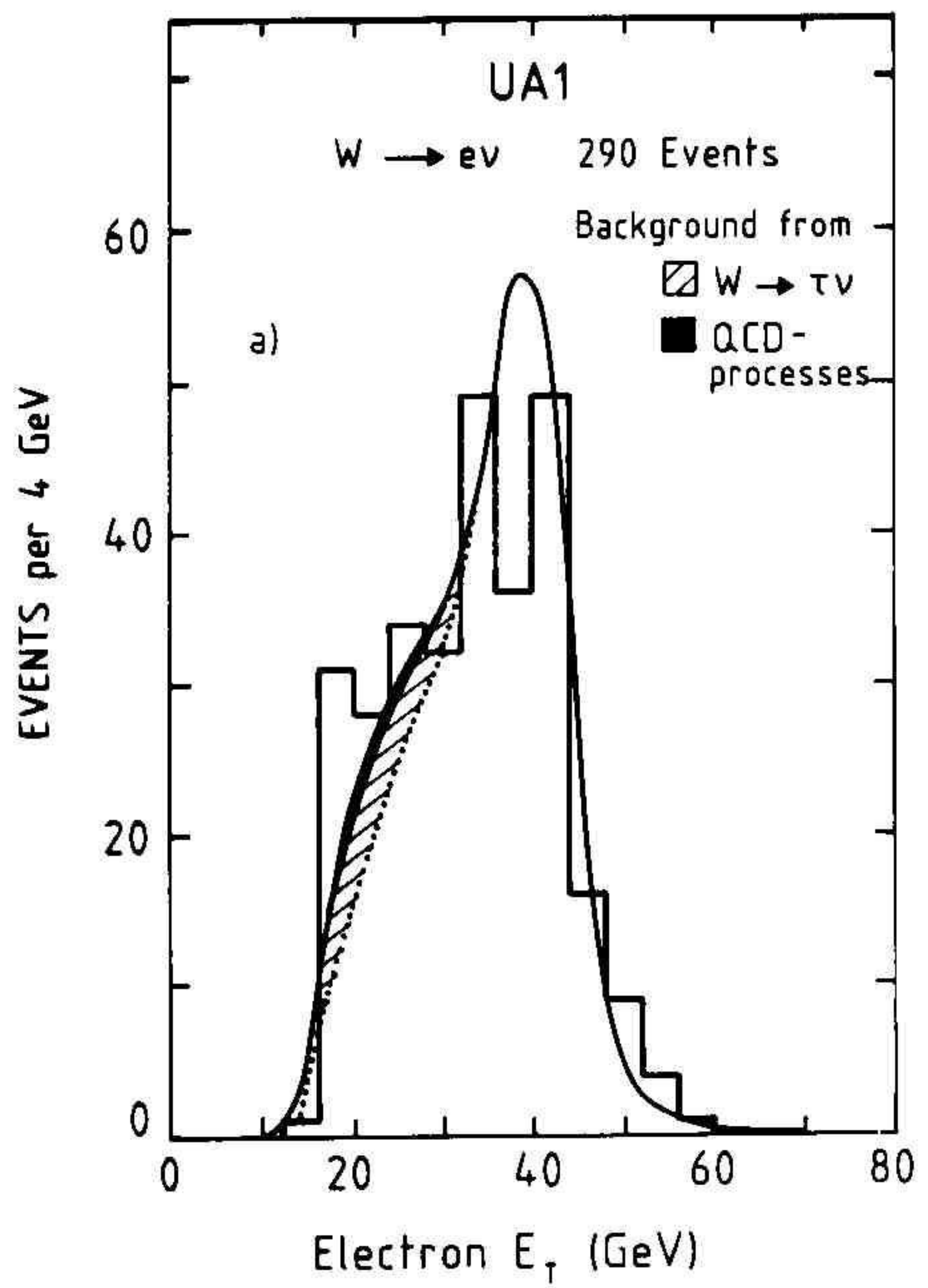
$$\frac{dn}{dp_T} = \frac{1}{\sqrt{\left(\frac{m_W}{2}\right)^2 - p_T^2}}\frac{dn}{dq}$$

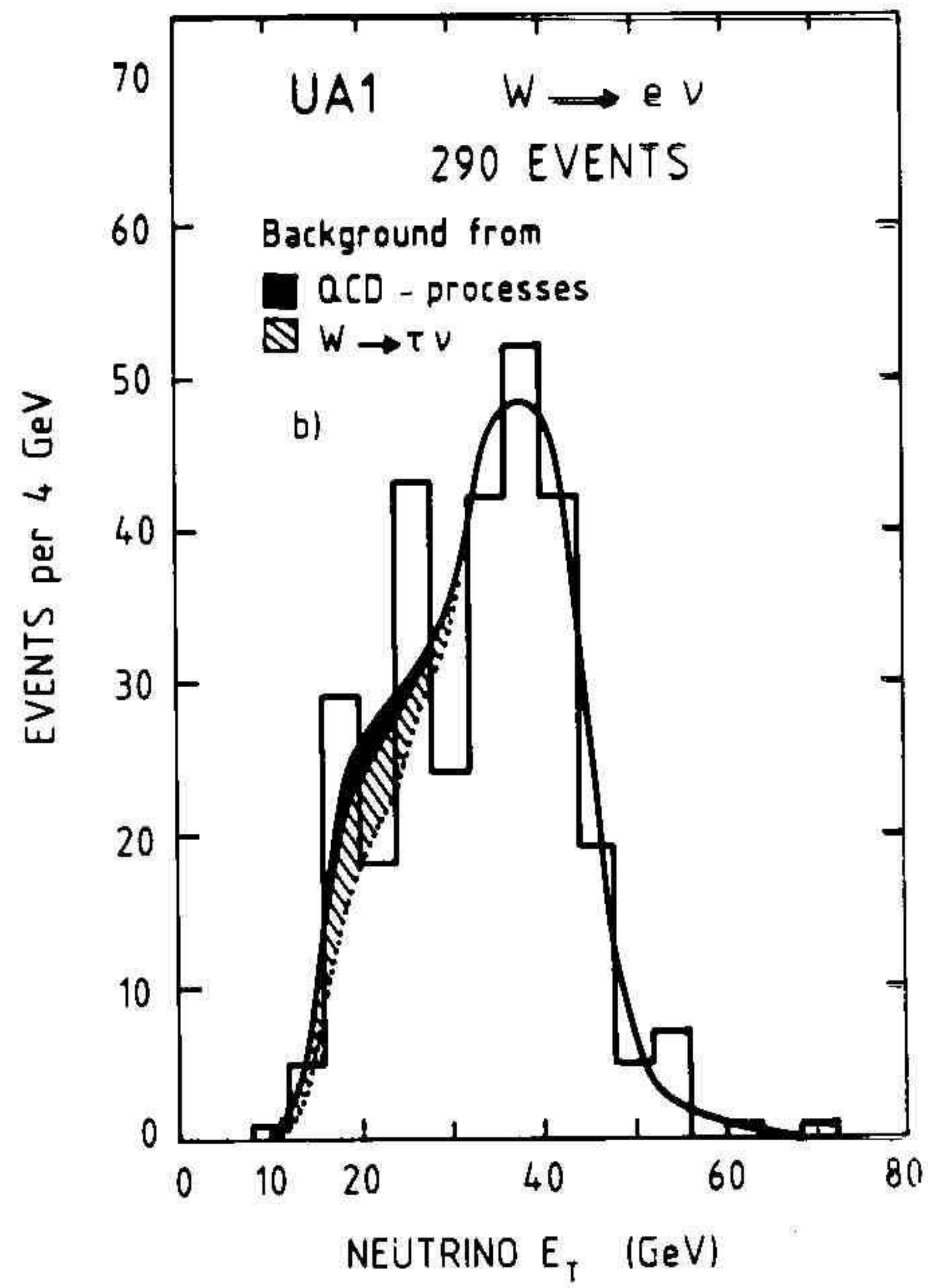
"Jacobian" peak for $p_T^e = m_W/2$

"Jacobian" peak for $p_T^{missing} = m_W/2$

Transverse motion of W ($p_T^W \neq 0$) smears the peak, but it doesn't cancel it. m_W measurement is based on the measurement of the peak energy (or the decreasing profile)

W's @ UA1

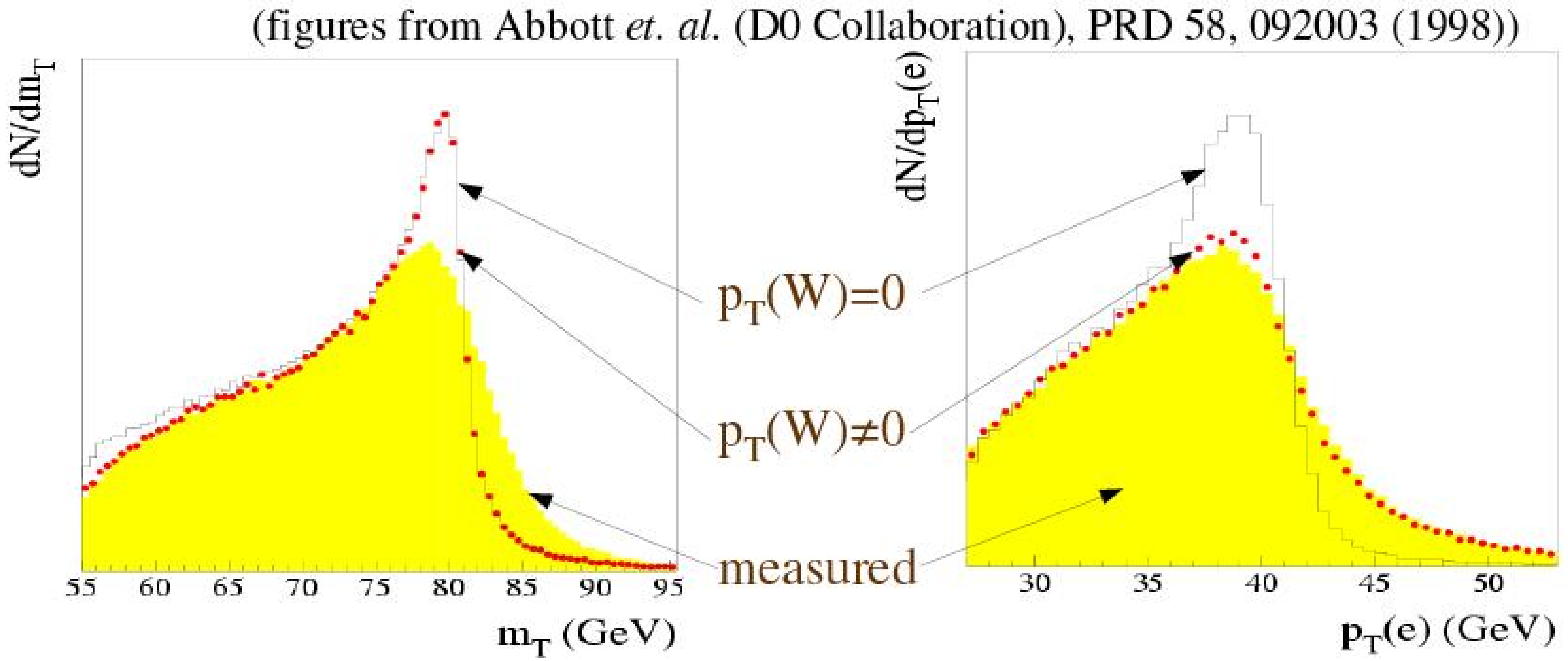




UA1 M_W**= 82.7±1.0(stat)±2.7(syst) GeV** Γ_W**<5.4 GeV**

UA2 M_W**= 80.2±0.8(stat)±1.3(syst) GeV** Γ_W**<7 GeV**

How to extract m_W



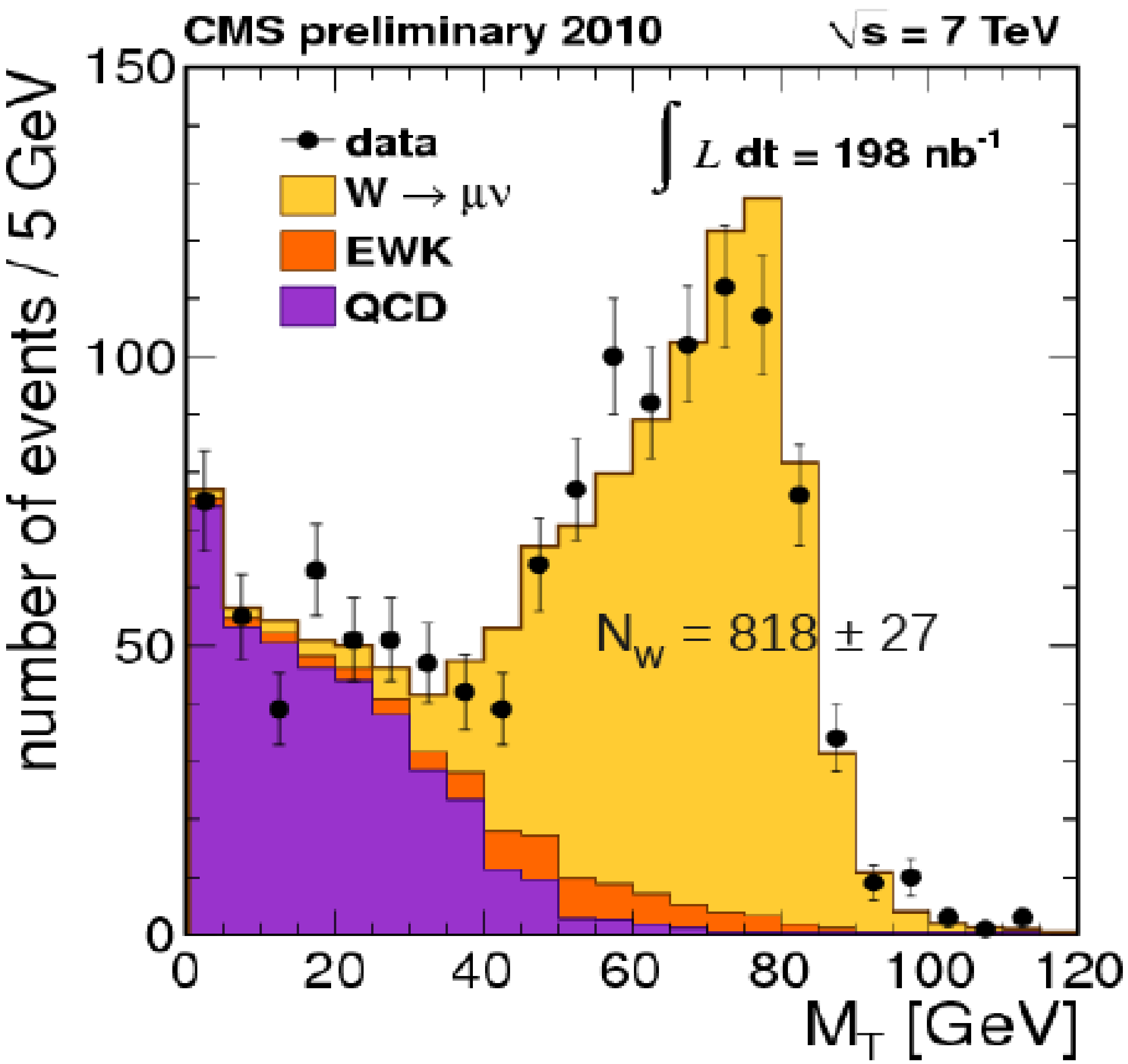
Alternatively can fit to

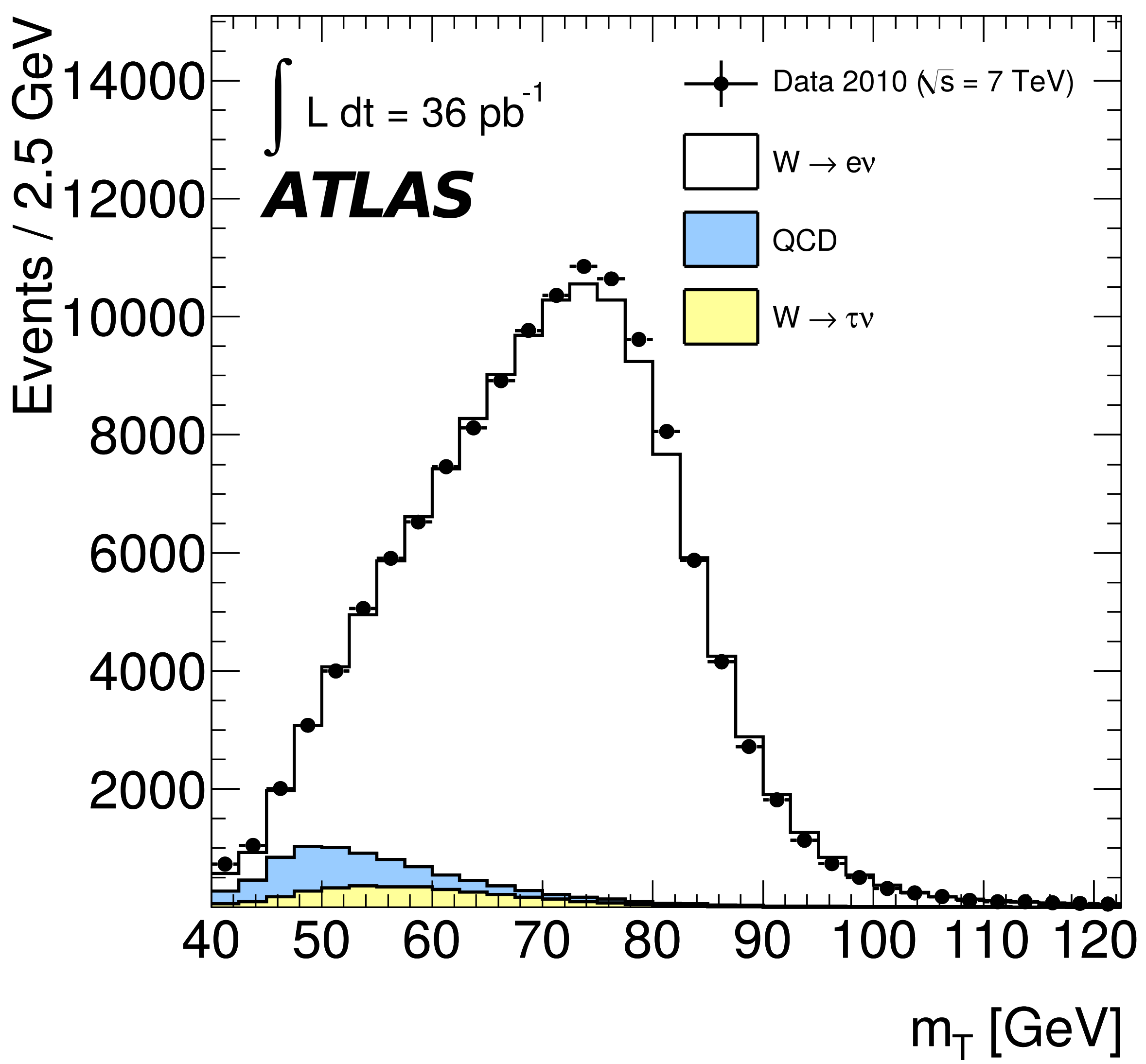
- Lepton p_T or missing E_T

Sensitivity different to different systematics

- Very powerful checks in this analysis:
  - Electrons vs muons
  - Z mass
  - m_T vs p_T vs ME_T fits
- The redundancy is the strength of this difficult high precision analysis

LHC signals of W's

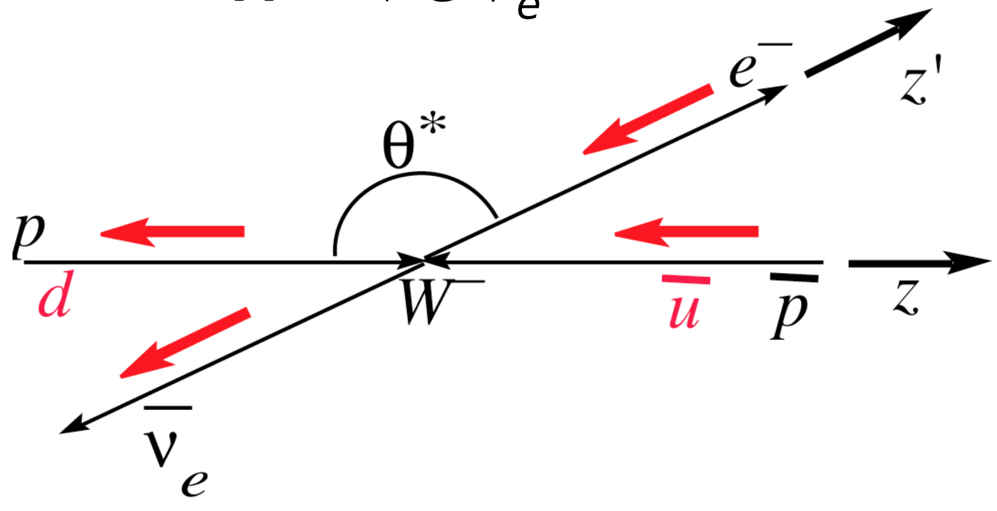




0.2-0.3 pb^{-1} yield clean signals of W's and Z's

W spin and polarisation

$W^- \to e^- \bar{\nu}_e$



In the *W* c.m. reference frame, electron's energy >> than its mass m_e. so chirality ≈ helicity

V–A ⇒ *W* couples only to

fermions with helicity –

antifermions with helicity +

Tot ang. mom. $J = S_W = 1$

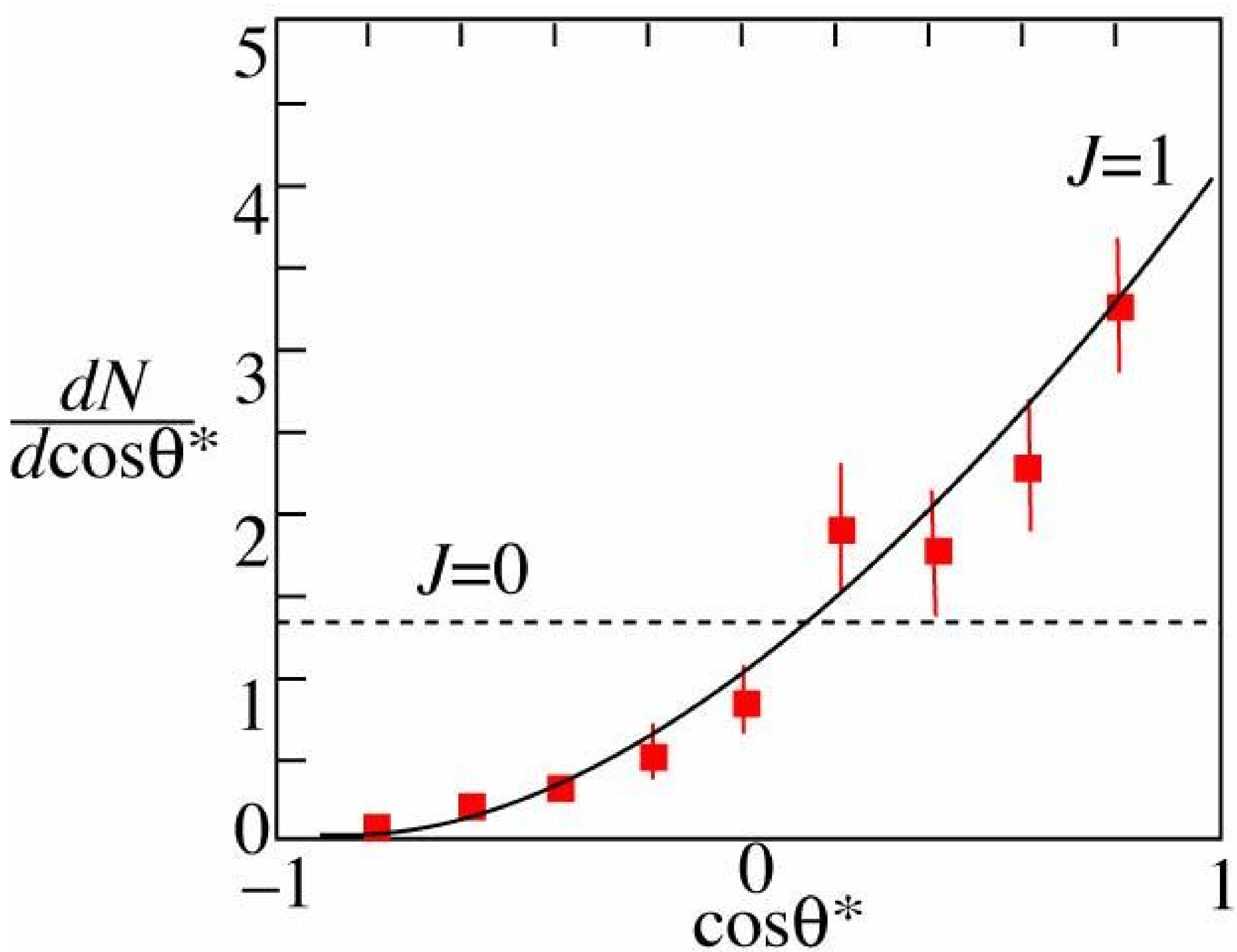
J_z (iniz.) = $\lambda = -1$

$J_{z'}$ (fin.) = $\lambda' = -1$

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

N.B. if instead *V+A:*

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



The forward backward asymmetry is a consequence of *P* violation

In order to distinguish *V–A* from *V+A* it is necessary to measure the electron polarization