Discovery of the W and Z Boson

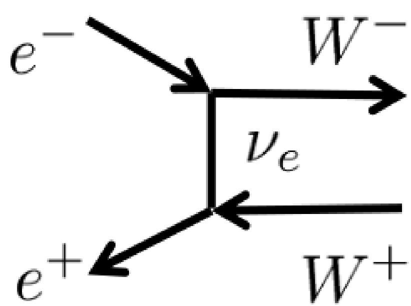
Status: 1969 Glashow, Salam and Weinberg postulated electroweak unification
W, Z particles were predicted.

1973 Discovery of CC interactions, rate of CC and NC gave indication for heavy
W, Z bosons (60-100 GeV)

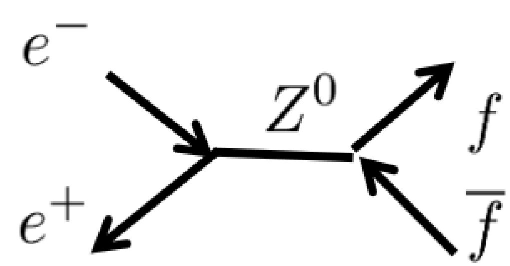
This was a planed discovery! (Carlo Rubbia, Simon van der Meer)

Which accelerator/collider can be used to generated heavy W, Z bosons?

a) e^+e^- collider



$\sqrt{s} > 2\, m_W$



$\sqrt{s} > m_Z$

Caveat: LEP (large electron positron) collider was under construction, but started only
in 1989. No e^+e^- collider with sufficient energy available in mid 70ies

Discovery of the W and Z Boson

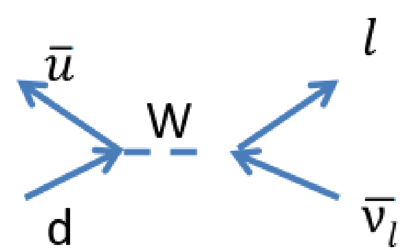
b) p on fixed target experiment

Highest energy accelerator at that time:
SPS (Super Proton Syncroton) @ 318 GeV, working in fixed target mode.

(ignoring that quarks/gluons in proton carry only fractional momentum of quarks):

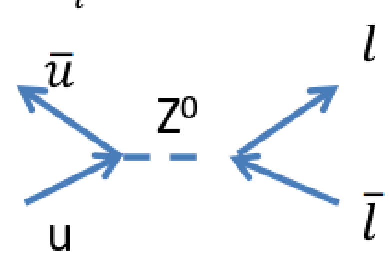
$\sqrt{s} = \sqrt{2Em_t}$ ~ 25 GeV < m(Z/W) m_t: mass of target particle, proton or neutron

⟹ too low energy!

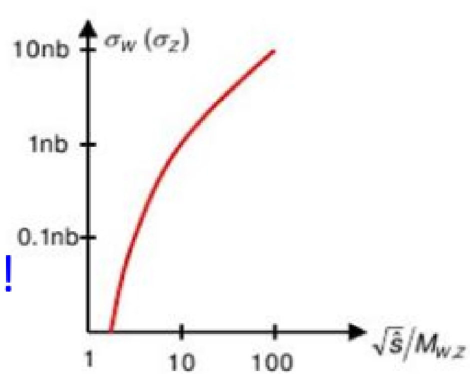


c) Idea: build proton-antiproton collider

Technical possible SP$\bar{P}$S with $\sqrt{s} = 540$ GeV



$\hat{s} = x_q x_q s$ mit $\langle x_s \rangle \sim 0.12$
$= (65 \text{ GeV})^2$



Expected cross section very small !

pp vs. p anti-proton collider

- proton - proton collider, require one valence quark and one sea quark
  sea quarks have lower x values, thus higher CME required

- proton – antiproton collider can use same magnetic field to accelerate
  both particle beams

How to create large amounts of anti-protons?

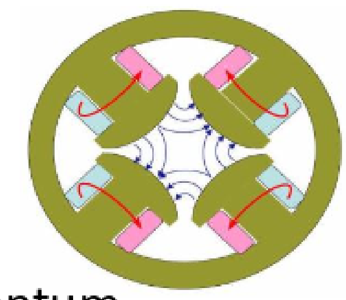
- Hydrogen gas is an „infinite“ source of protons, can be accelerated and energy filtered
  to be stored in dense bunches of same energy and direction/phase

- Antiprotons are produced by colliding protons on a copper target $n(\bar{p})/n(p) \sim 10^{-6}$
  Antiprotons cover huge range of momentum and angular distributions

  Technical challenge: How to get coharent antiproton buches
  (simple filtering would add even more ineffiency)
  → stochastical cooling (Simon van der Meer)

Stochastical Cooling

Quadrupol magnets keep average beam position centered.

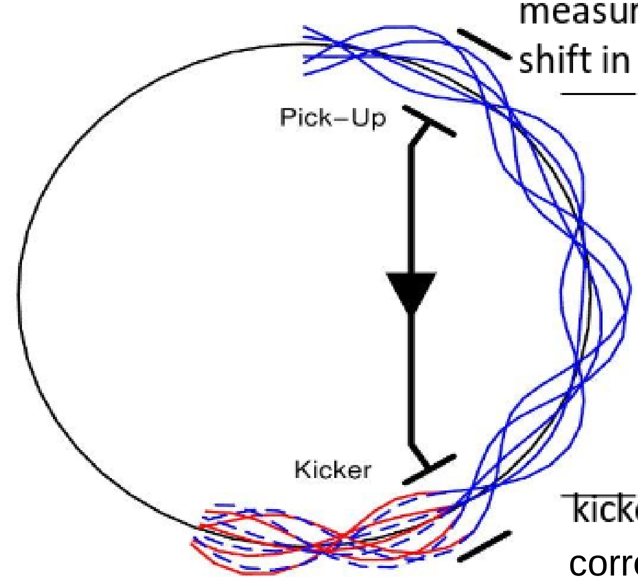


However individual particles which have some spread in momentum, will do betatron oscillation.

Important feature: circumference ≠ nλ

> Van der Meer showed, correcting the average of a particle bunch, will on long term uniformise the particles in the bunch (spread in momentum and direction reduced)

pick.-up:
measure average
shift in mean position



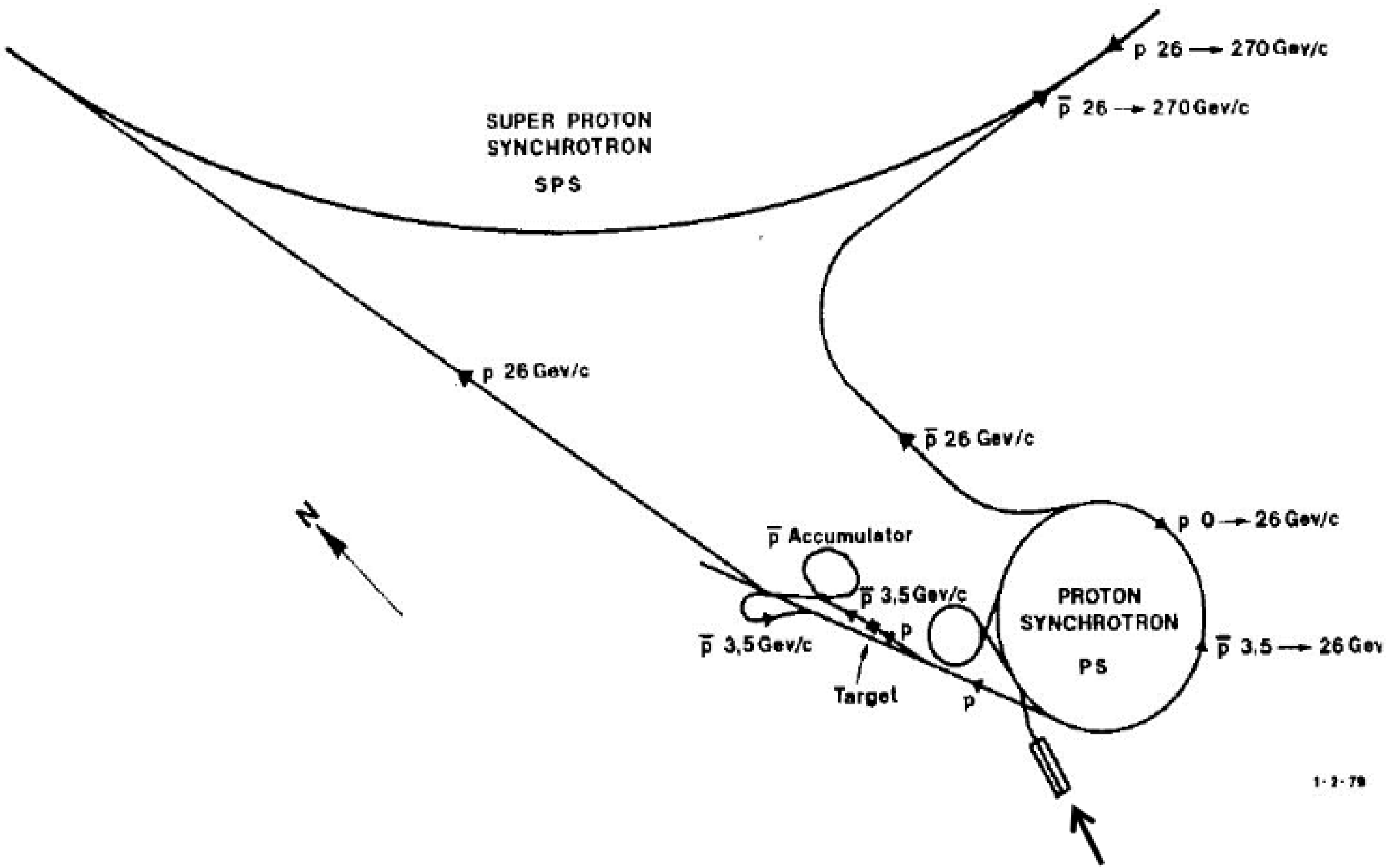
kicker:
correct average
shift in mean position

Short distance between pick-up and kicker ⟺ same statistical composition

Long distance between kicker and pick-up ⟺ randomizing of statistical composition due to different momenta

➡ This idea was mandatory for any future proton-antiproton collider!

$Sp\bar{p}S$ Accelerator Complex



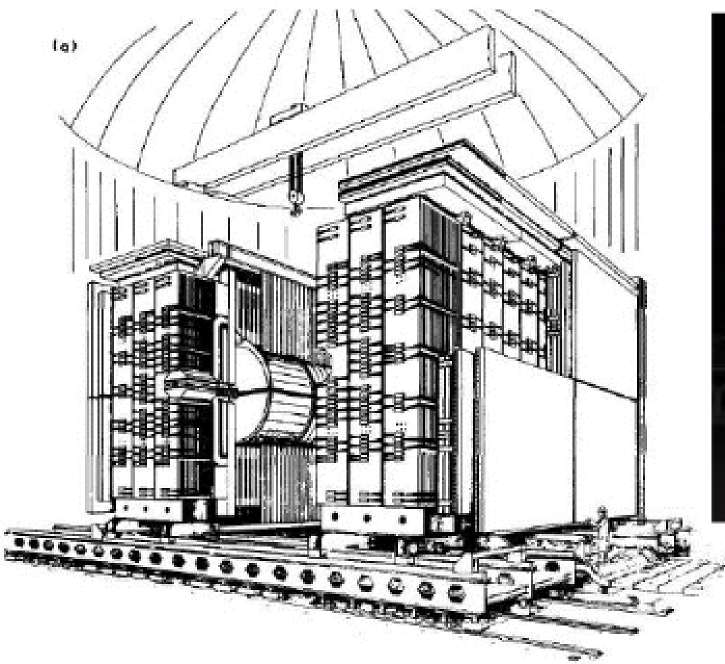
Helium-bottle

Experiments at SP$\bar{P}$S

Two experiments are located at SPPS: UA1, UA2

Start of data-taking in 1981

Schematic view of UA1 - Detector



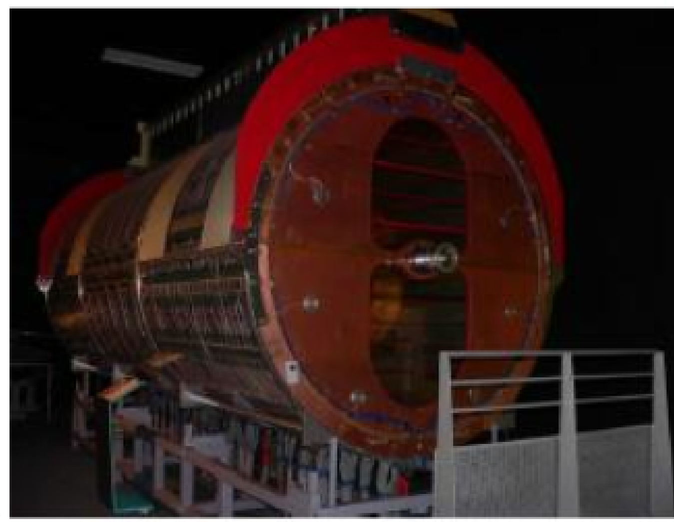
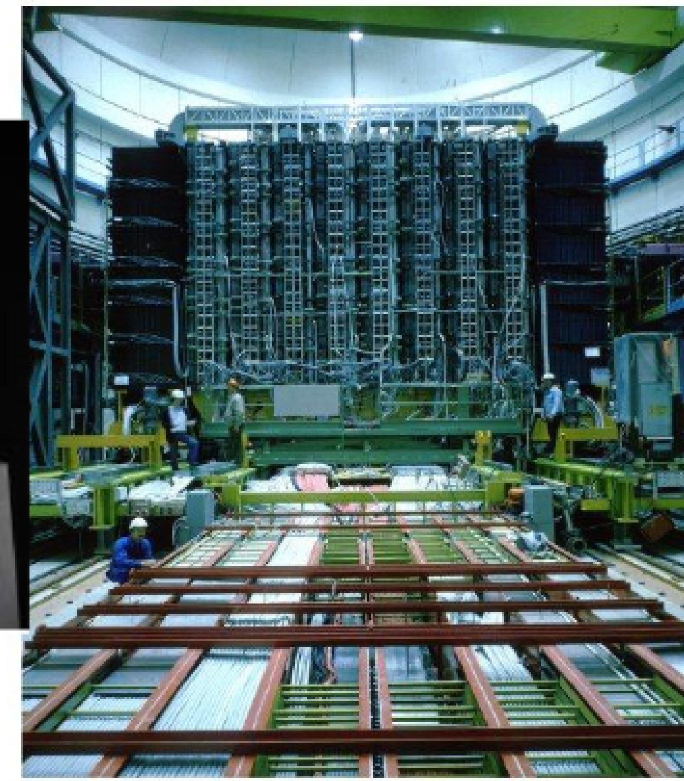


foto of UA1 drift chamber

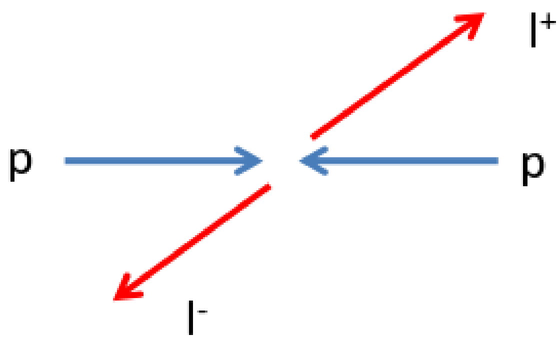
foto of closed UA1 experiment



UA1 was the better detector and thus provided the results a bit faster than UA2.

UA1 famous for discovery of W and Z boson, UA2 almost unkown.

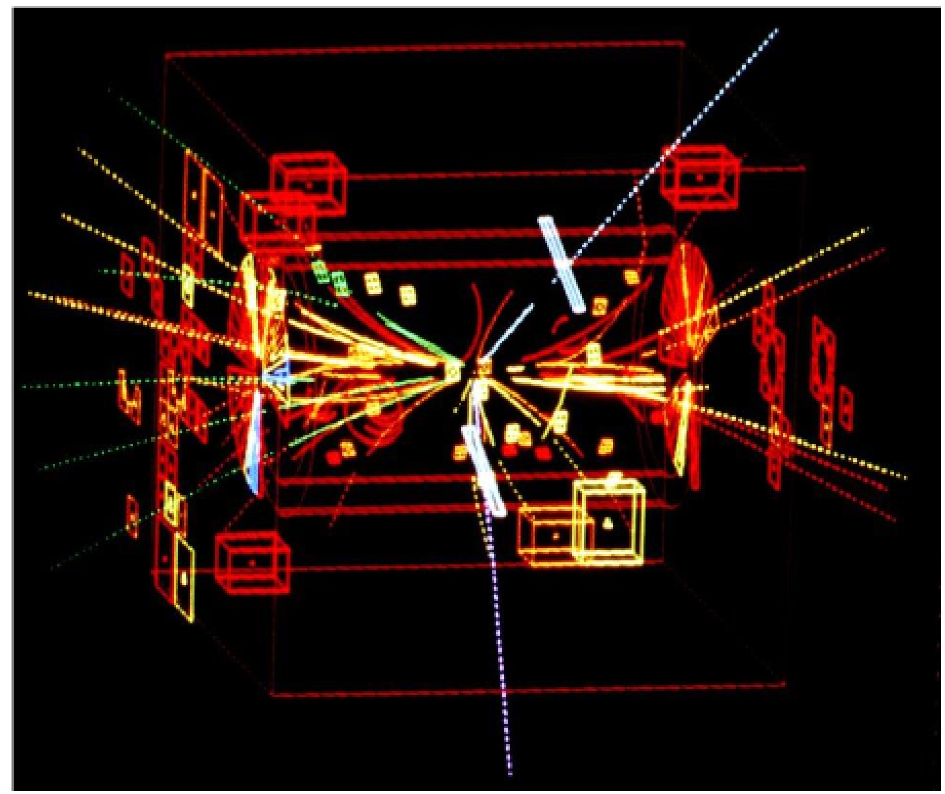
Discovery of Z Boson



Heavy particles are produced „almost“ at rest

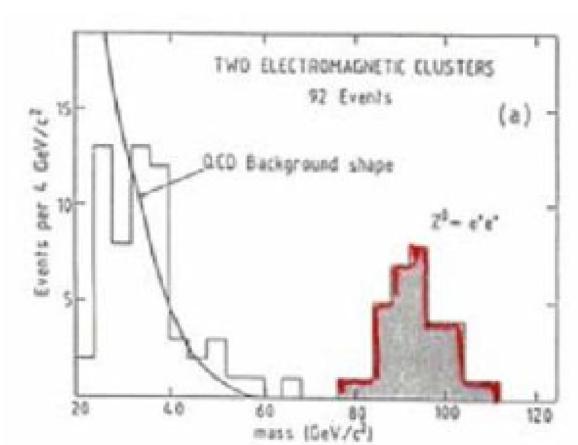
Largest cross-section for $x_1 \sim x_2$!

$Z \rightarrow e^+ e^-$



high energy lepton pair

$m_{ll}^2 = (p_{l+} + p_{l-})^2 = M_Z^2$

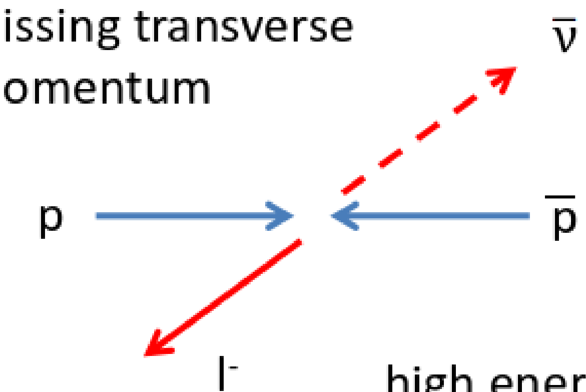


$M_Z \sim 91$ GeV

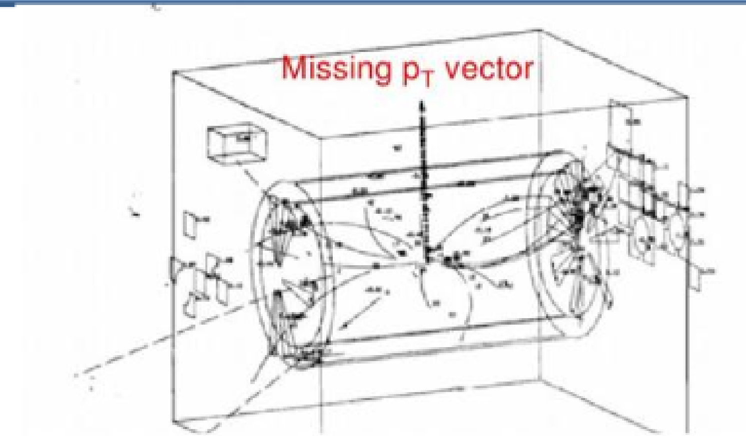
Signature of W Decays

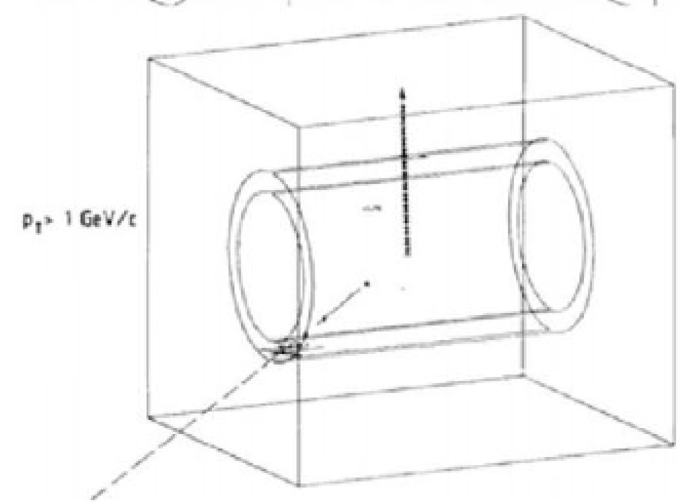
$p\bar{p} \rightarrow W \rightarrow l\bar{\nu}$

missing transverse momentum



high energy lepton
large transverse momentum



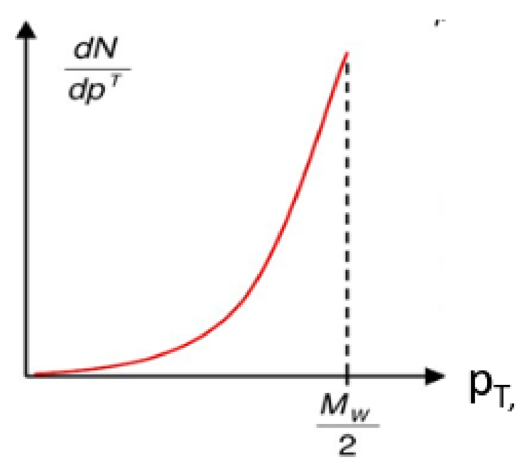


In W rest frame, lepton and neutrino back-to-back:

$|p_l| = |p_\nu| = M_W/2$

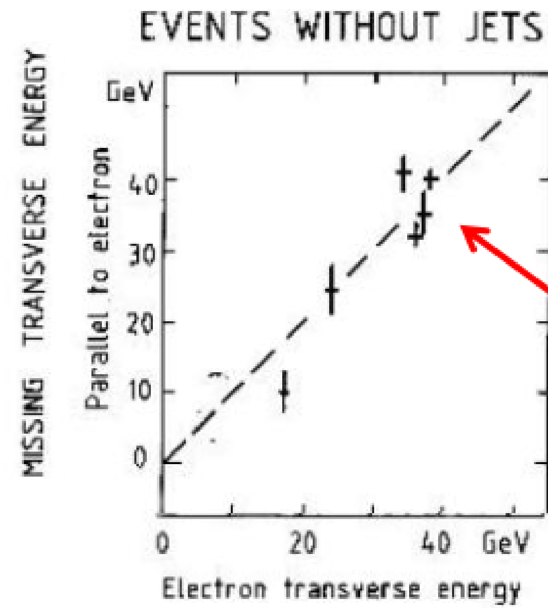
boost in z-direction: $|p_{T,l}| = |p_{T,\nu}| < M_W/2$

Jacobian Peak: $\frac{dN}{pT} \sim \frac{2p_T}{M_W}\left(\frac{M_W{}^2}{4} - p_T{}^2\right)^{-\frac{1}{2}}$



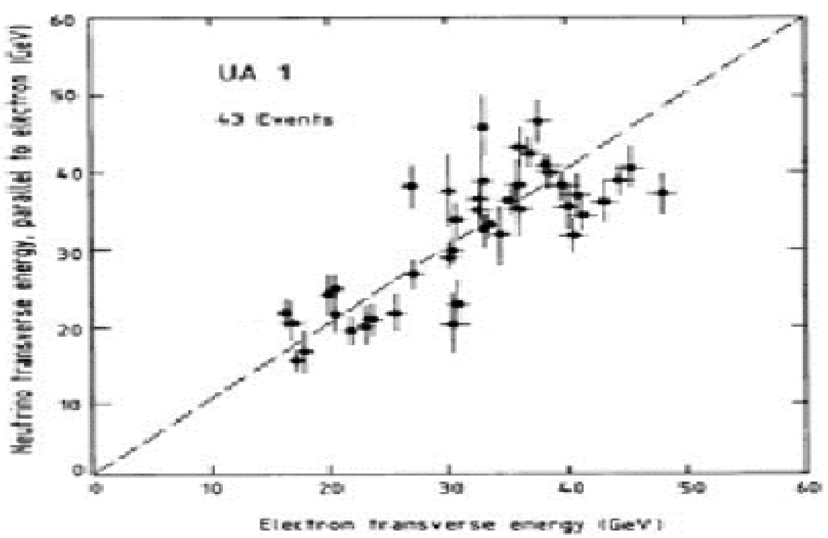
Discovery of W Boson

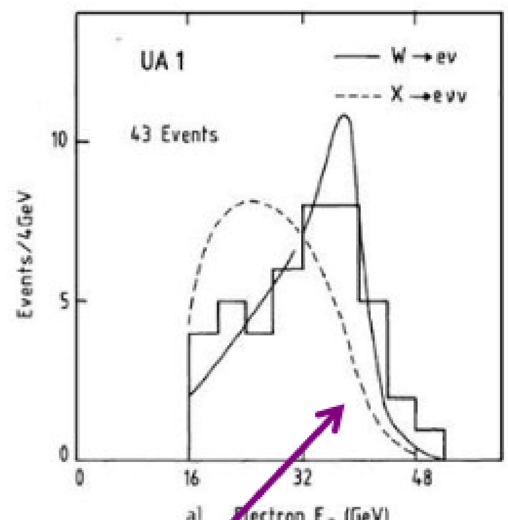
First analysis (5 events) - 1982:
select isolated high transverse energy lepton



distribution peaks at ~ 40 GeV

Updated analysis (43 events) - 1983





→ m_W~ 80 GeV

Distribution smeared out due to trans. Momentum of W, finite decay width, non istrop decay

Nobel Prize in 1984

Carlo Rubbia

Simon van der Meer

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*

Helicity Eigenstates

$[u_1, u_2]$: sub-space of particle spinors

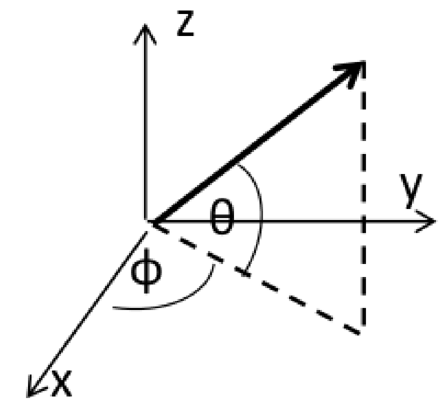
$[v_1, v_2]$: sub-space of antiparticle spinors

Freedom of rotation in both sub-spaces

➡ resolve for both sub-spaces: $\boldsymbol{\Sigma}\,\mathbf{P}\begin{pmatrix} a \\ b \end{pmatrix} = h\begin{pmatrix} a \\ b \end{pmatrix}$ $\quad h=\pm 1$

➡ 4 common Eigenstates for E, p, h:

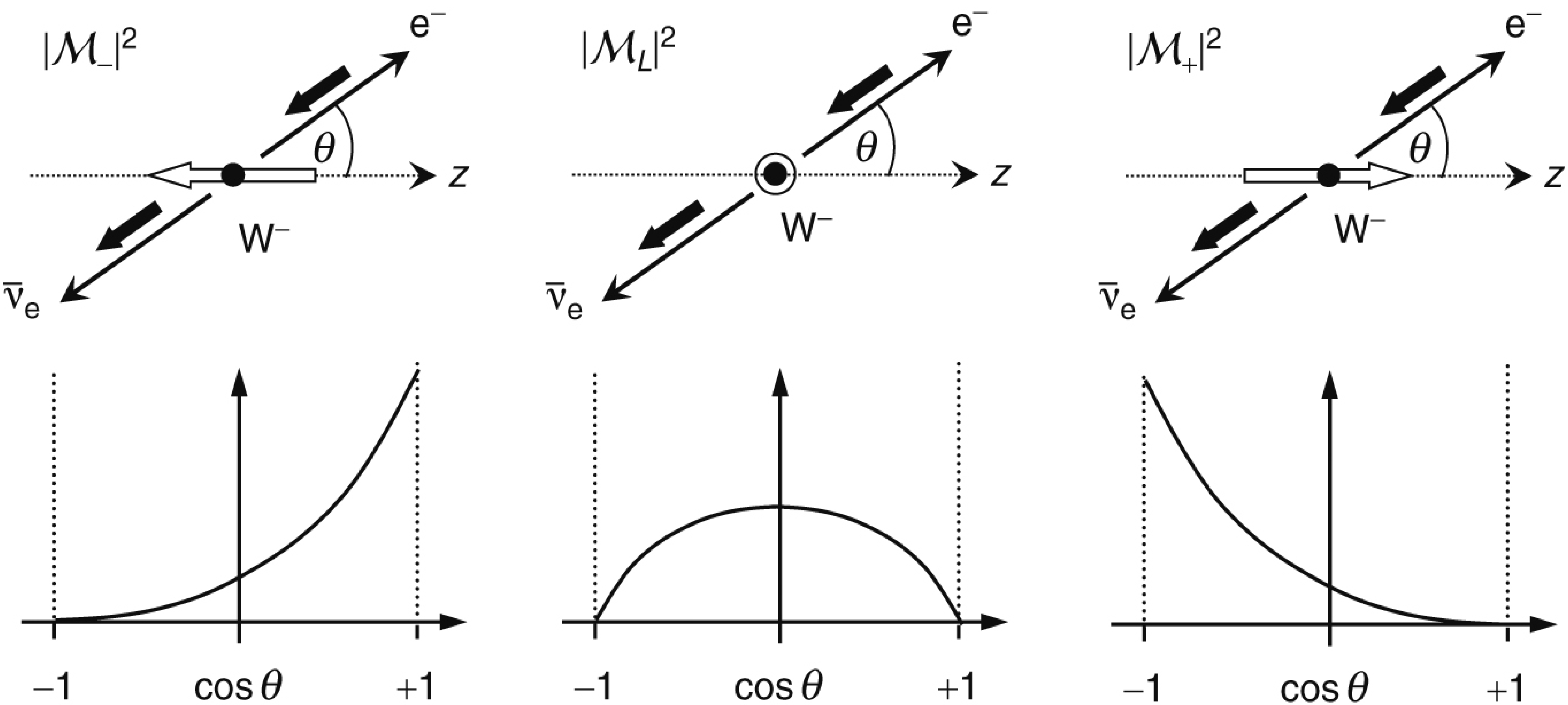
$$\vec{p} = |\vec{p}|\begin{pmatrix} \sin\theta\cos\varphi \\ \sin\theta\sin\varphi \\ \cos\theta \end{pmatrix}$$

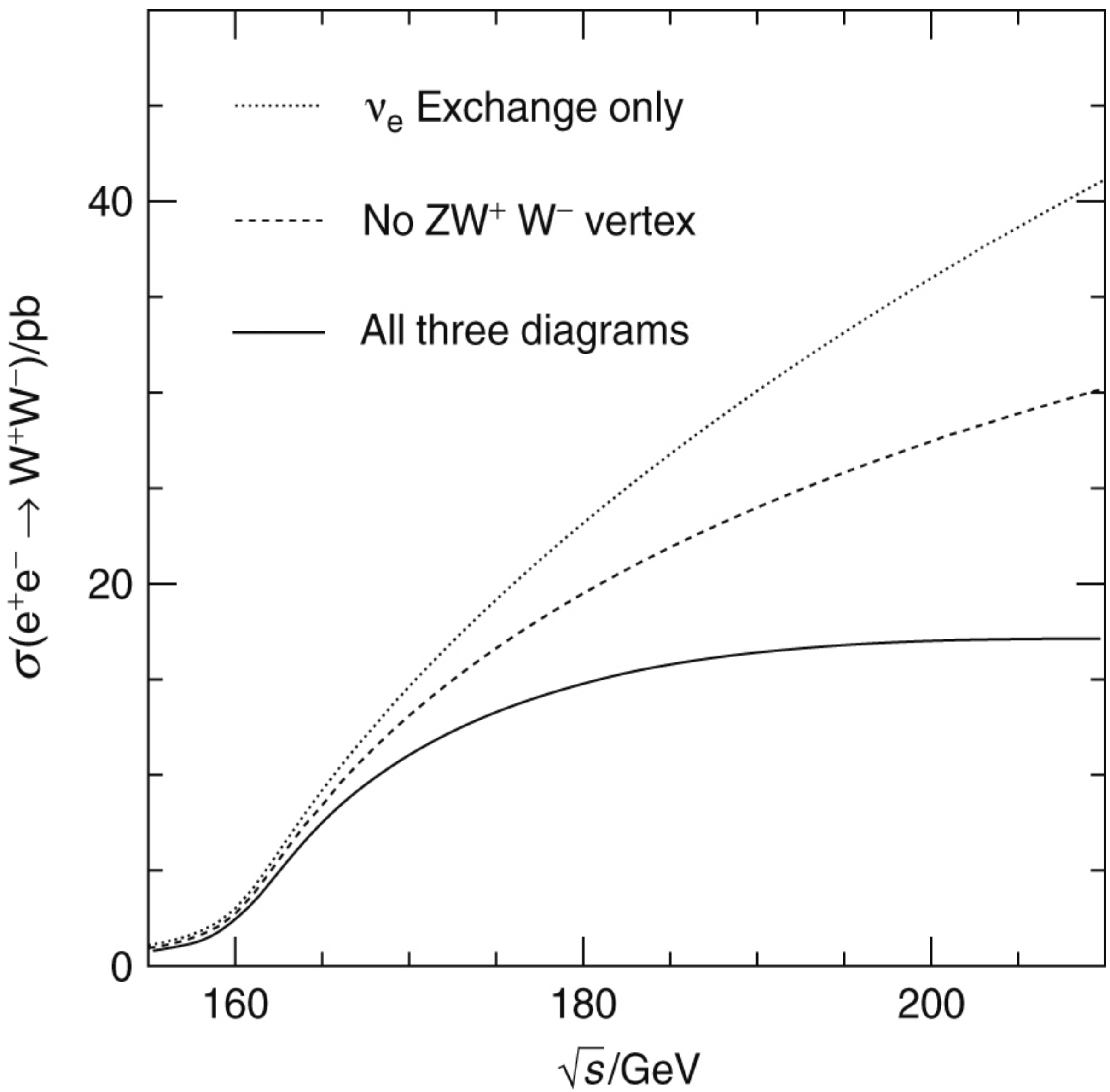


$$u_{h=1} = \sqrt{E+m}\begin{pmatrix} \cos\theta/2 \\ e^{i\varphi}\sin\theta/2 \\ \frac{|\vec{p}|}{E+m}\cos\theta/2 \\ \frac{|\vec{p}|}{E+m}e^{i\varphi}\sin\theta/2 \end{pmatrix} \qquad u_{h=-1} = \sqrt{E+m}\begin{pmatrix} -\sin\theta/2 \\ e^{i\varphi}\cos\theta/2 \\ \frac{-|\vec{p}|}{E+m}\sin\theta/2 \\ \frac{-|\vec{p}|}{E+m}e^{i\varphi}\cos\theta/2 \end{pmatrix}$$

$$v_{h=1} = \sqrt{E+m}\begin{pmatrix} \frac{|\vec{p}|}{E+m}\sin\theta/2 \\ \frac{-|\vec{p}|}{E+m}e^{i\varphi}\cos\theta/2 \\ -\sin\theta/2 \\ e^{i\varphi}\cos\theta/2 \end{pmatrix} \qquad v_{h=-1} = \sqrt{E+m}\begin{pmatrix} \frac{|\vec{p}|}{E+m}\cos\theta/2 \\ \frac{|\vec{p}|}{E+m}e^{i\varphi}\sin\theta/2 \\ \cos\theta/2 \\ e^{i\varphi}\sin\theta/2 \end{pmatrix}$$

Distribution of decay particles of W decay for diff. W polarisation





ν_e Exchange only
No $ZW^+ W^-$ vertex
All three diagrams
40
20
0
160
180
200
$\sqrt{s}$/GeV
$\sigma(e^+e^- \to W^+W^-)$/pb