Lecture:

Standard Model of Particle Physics

Heidelberg SS 2013

W- and Z-Bosons

Contents

- Discovery of “real” W- and Z-bosons
- Intermezzo: QCD at Hadron Colliders
- LEP + Detectors
- W- and Z- Physics at LEP
- W- and Z-Physics at Hadron Colliders (Tevatron+LHC)

Prediction of W and Z masses

SM predictions:

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

Measurement of Weinberg angle:

$$\sin^2\theta_W \approx 0.25 \quad \rightarrow \quad g \approx 0.6$$

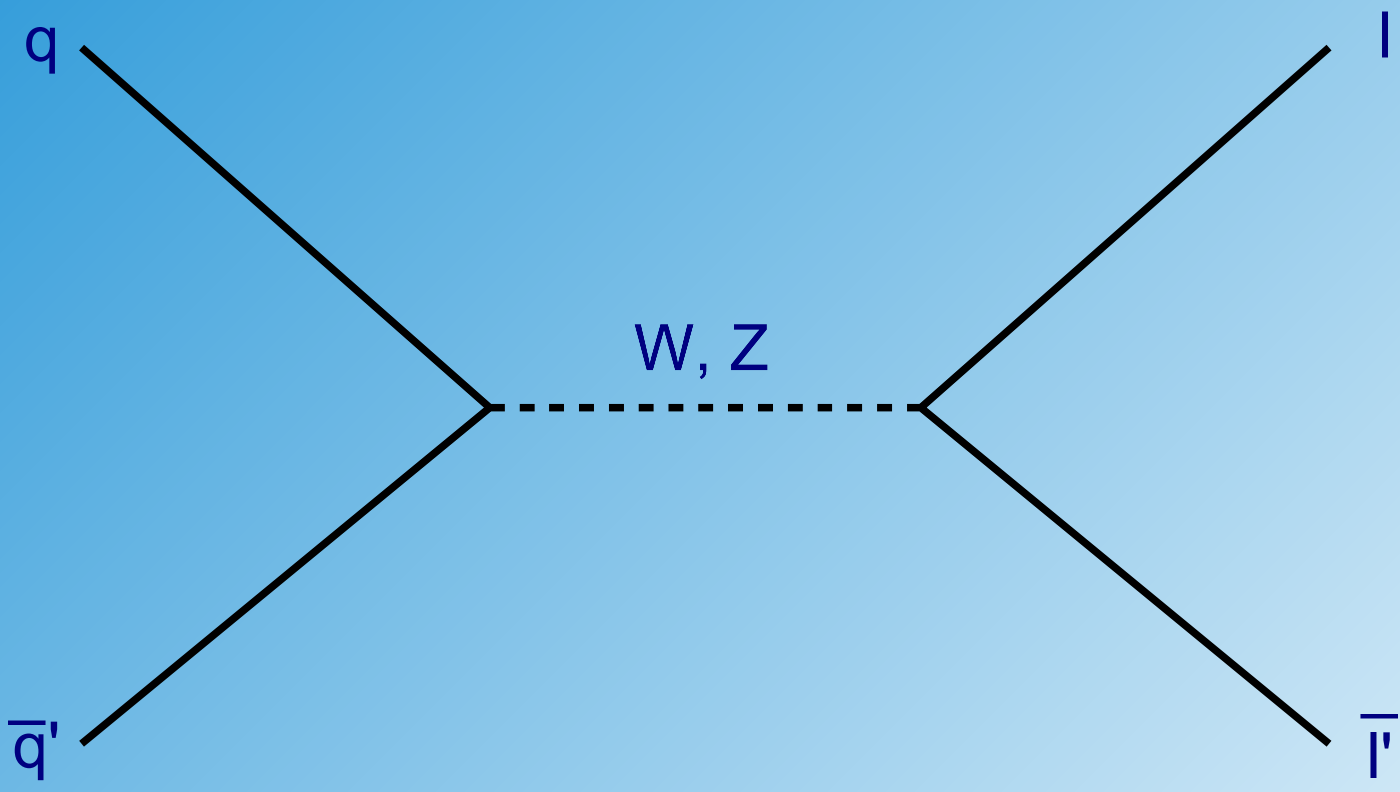
Low energy limit of W-propagator

$$G_F/\sqrt{2} = g^2/8 M_W^2 \quad \rightarrow \quad M_W \approx 80\, GeV$$

Relation from vector-boson mass matrix (Higgs mechanism)

$$\frac{M_W^2}{M_Z^2} = \frac{g^2}{g^2 + g'^2} = \cos^2\theta_W \quad \rightarrow \quad M_Z \approx 90\, GeV$$

W,Z Physics at Hadron Colliders



Intermezzo QCD

QCD Lagrangian (physical fields)

$$L_{phys} = -\frac{1}{4}F^{\alpha}{}_{\mu\nu}(x)F_{\alpha}{}^{\mu\nu}(x) + \sum_k \frac{i}{2}(\bar{q}_k(x)\gamma^{\mu}\nabla_{\mu}q_k(x) - \nabla_{\mu}\bar{q}_k(x)\gamma^{\mu}q_k(x)) \; .$$

vector coupling

Covariant derivative:

$$\nabla_{\mu}q(x) = \partial_{\mu}q(x) - i\,g\,G^{\alpha}_{\mu}(x)\hat{t}_{\alpha}q(x) \; ;$$

SU(3) group generators

Gluon field: non-abelian coupling

$$F^{\alpha}_{\mu\nu}(x) = \partial_{\mu}G^{\alpha}_{\nu}(x) - \partial_{\nu}G^{\alpha}_{\mu}(x) + g\,f^{\alpha}_{\beta\gamma}G^{\beta}_{\mu}(x)G^{\gamma}_{\nu}(x) \; ;$$

SU(3) structure constants

self coupling

SU(3) Group Representation

color states $r = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ $g = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$ $b = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

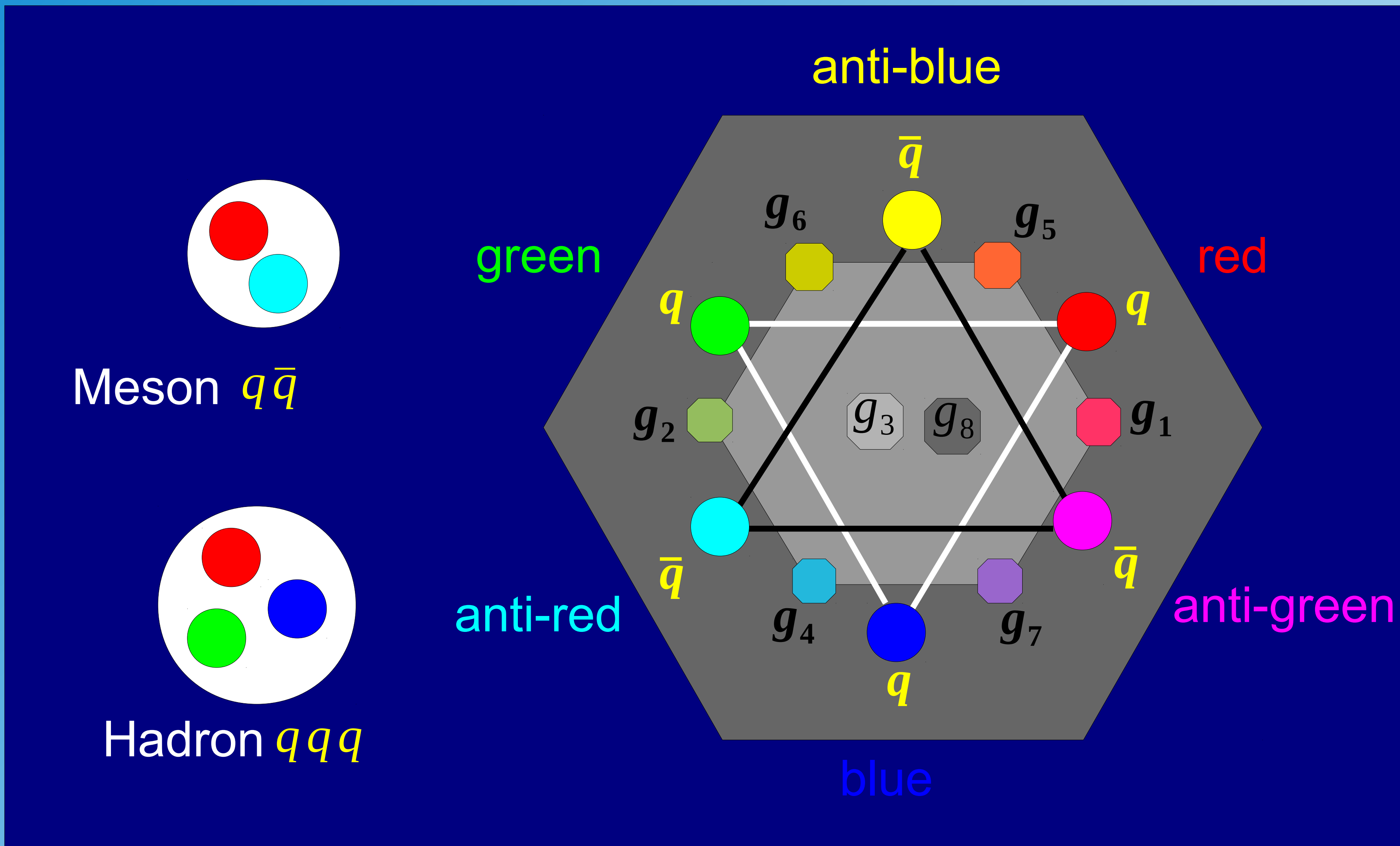
8 generators (N*N-1)

$$t_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad t_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad t_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

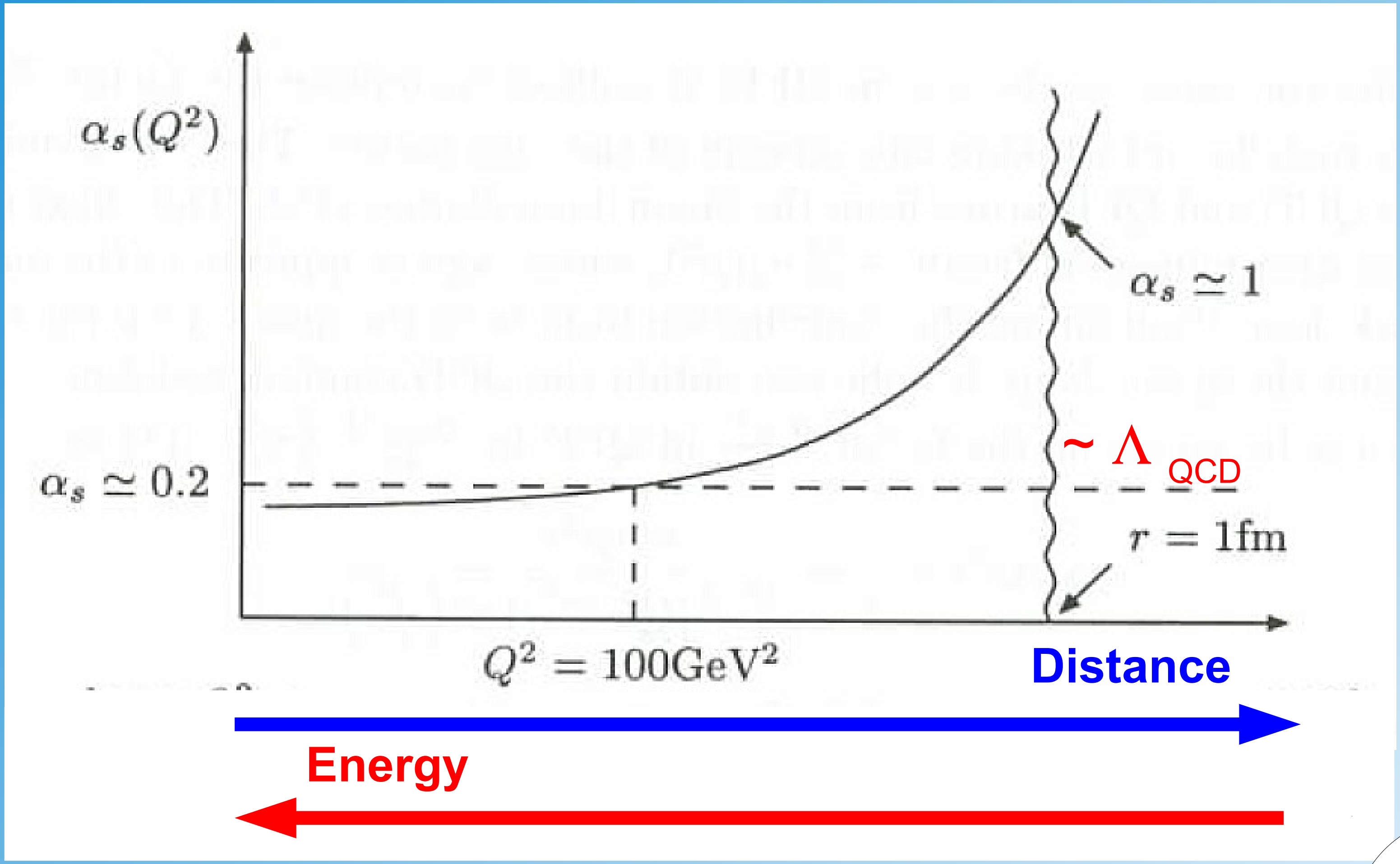
$$t_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad t_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad t_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$t_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad t_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Quantum Chromodynamics

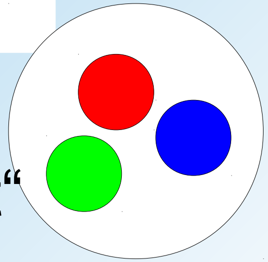


Running of alpha$_s$

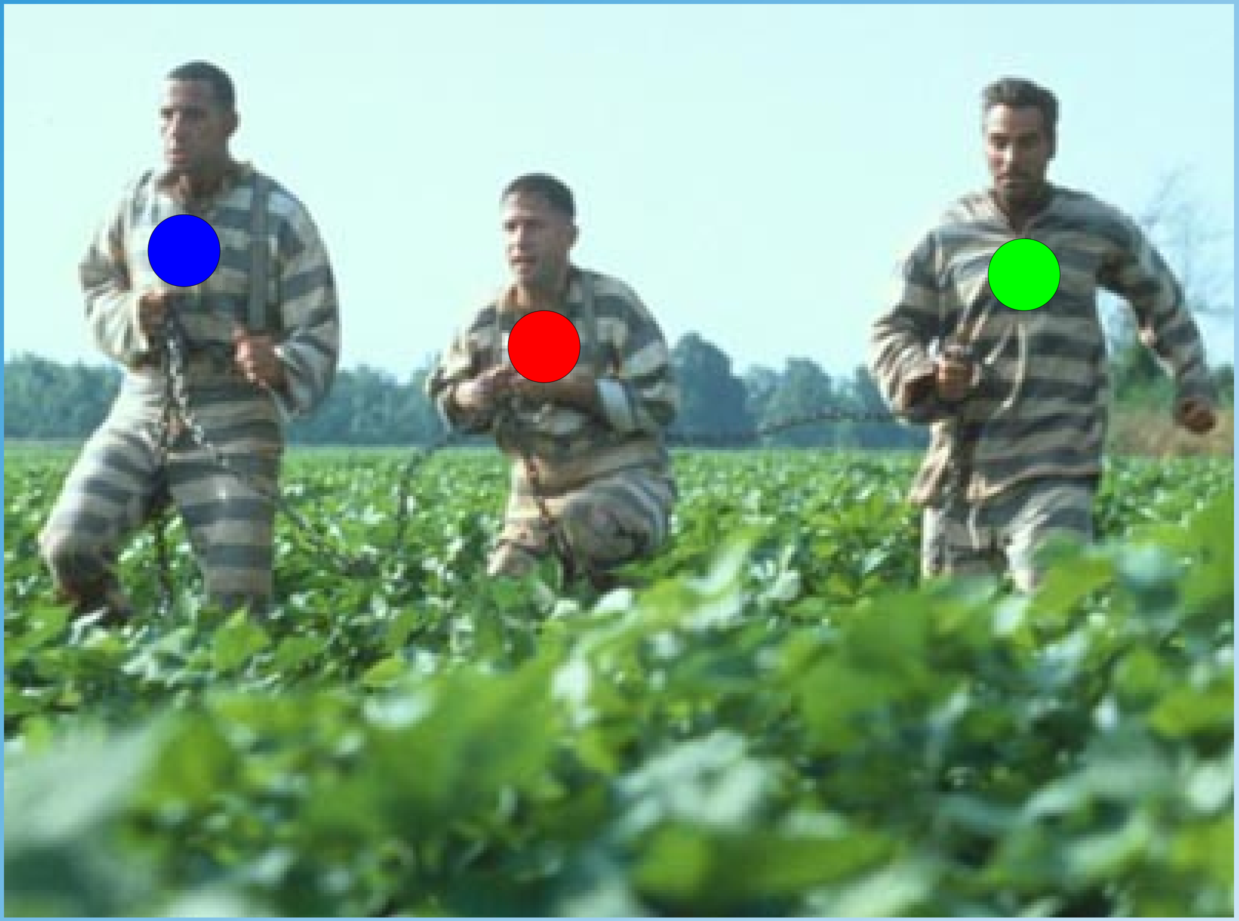


„Asymptotic Freedom“

„Confinement“



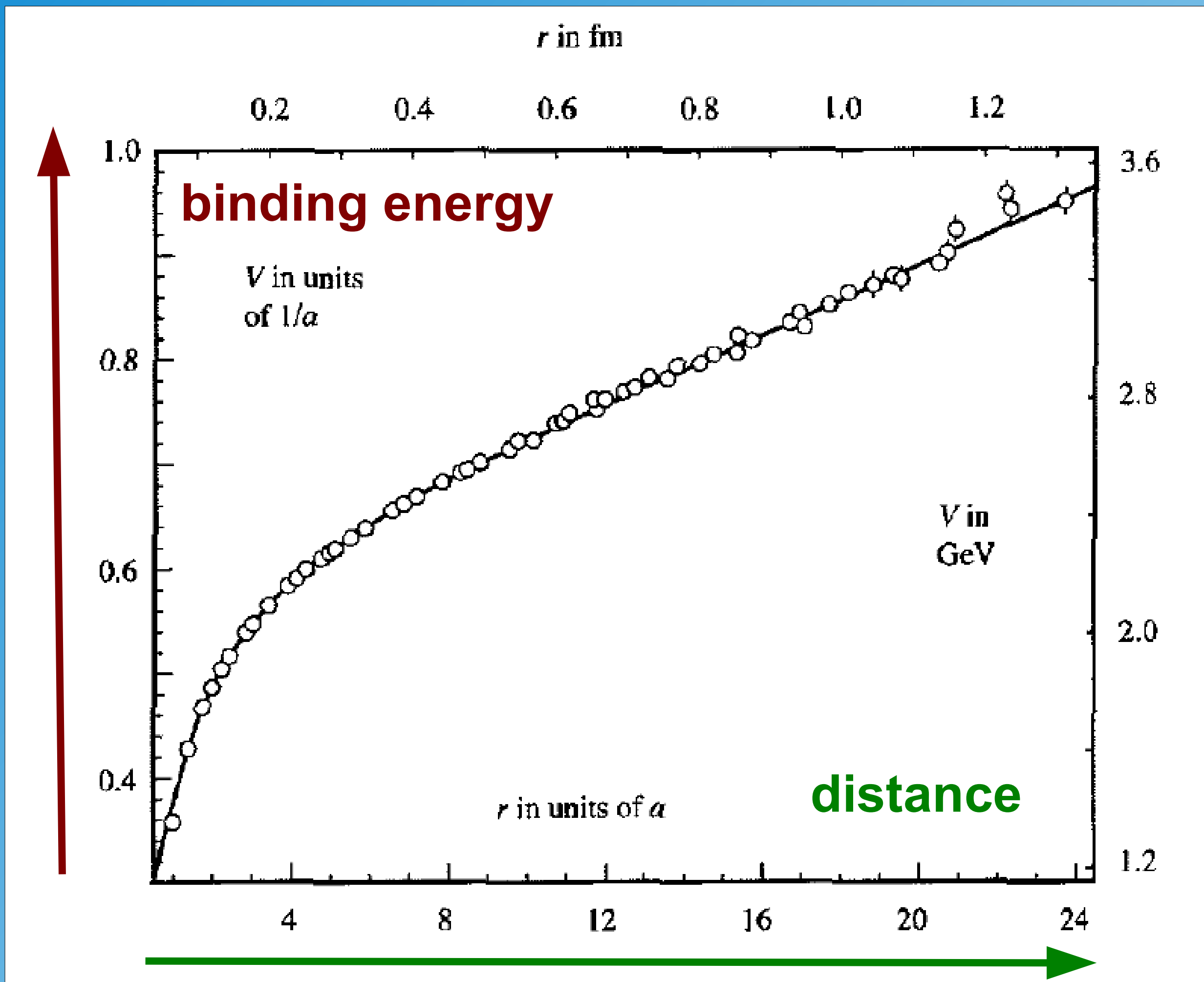
„Asymptotic Freedom“

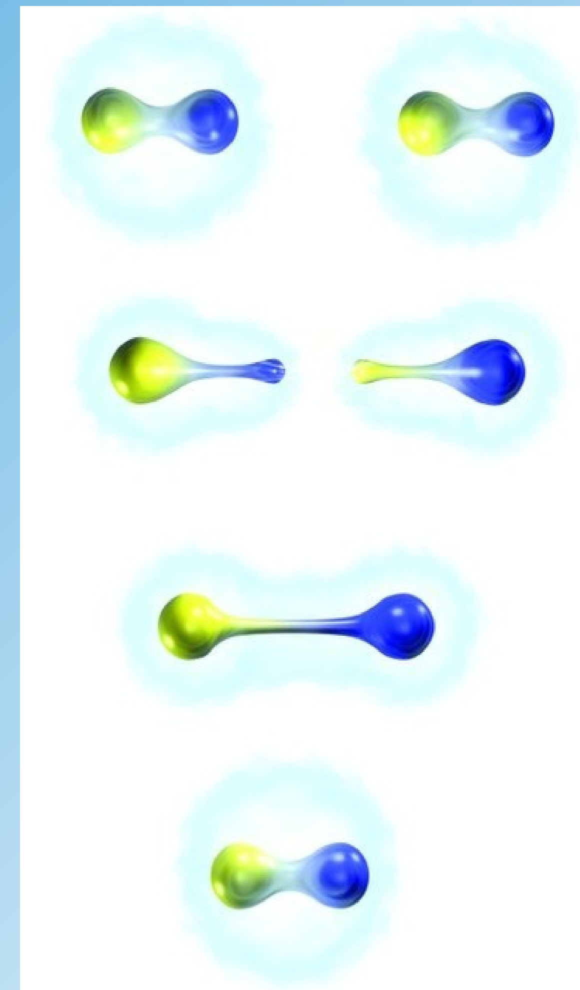


„Oh Brother, where art thou?“ (2000)

Confinement

The force between two quarks is 50000 N !!!





consequence: free quarks or gluons are not observable

Three-Jet Event at PETRA

Reaction:

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

- Hard gluon emission
  - calculable in pQCD
  - event topology
- Soft gluon emissions
  - parton showers (non-pQCD)
  - high particle multiplicities
  - collinear emissions makes "jet" structure
- Hadronisation
  - long distance scale
  - formation of hadrons from quarks and gluons

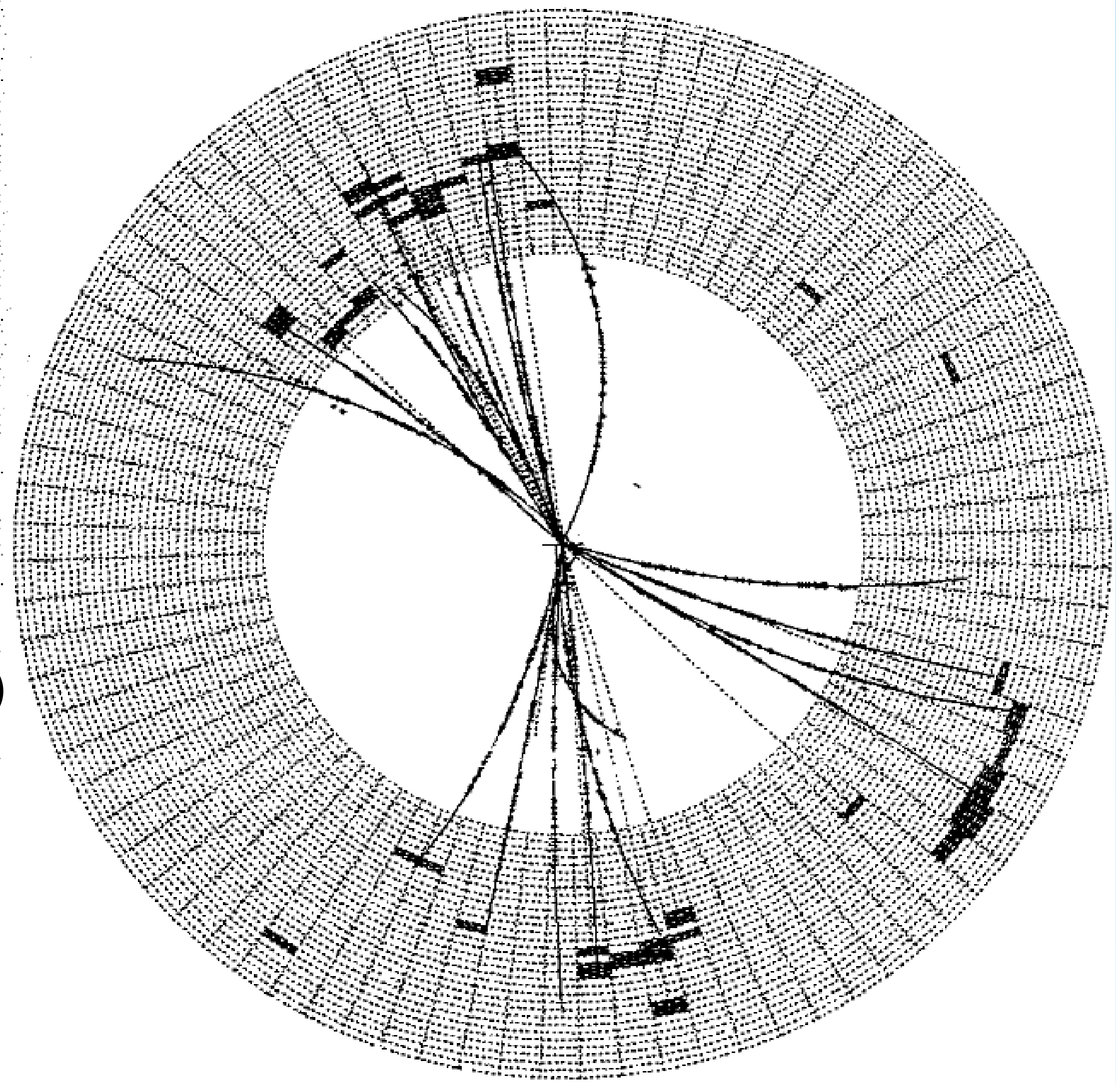
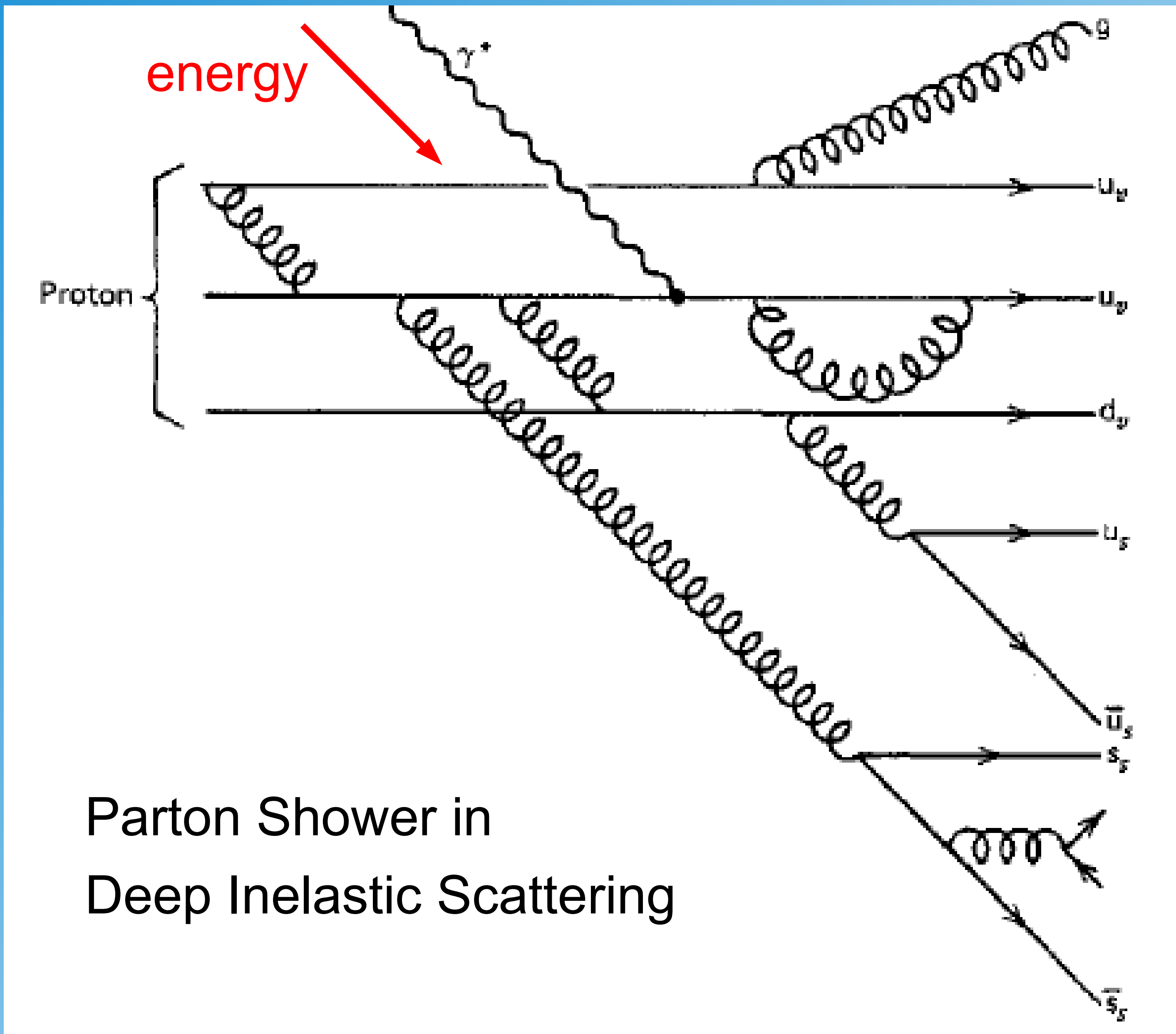


Fig. 11.12 A three-jet event observed by the JADE detector at PETRA.

Parton Showers

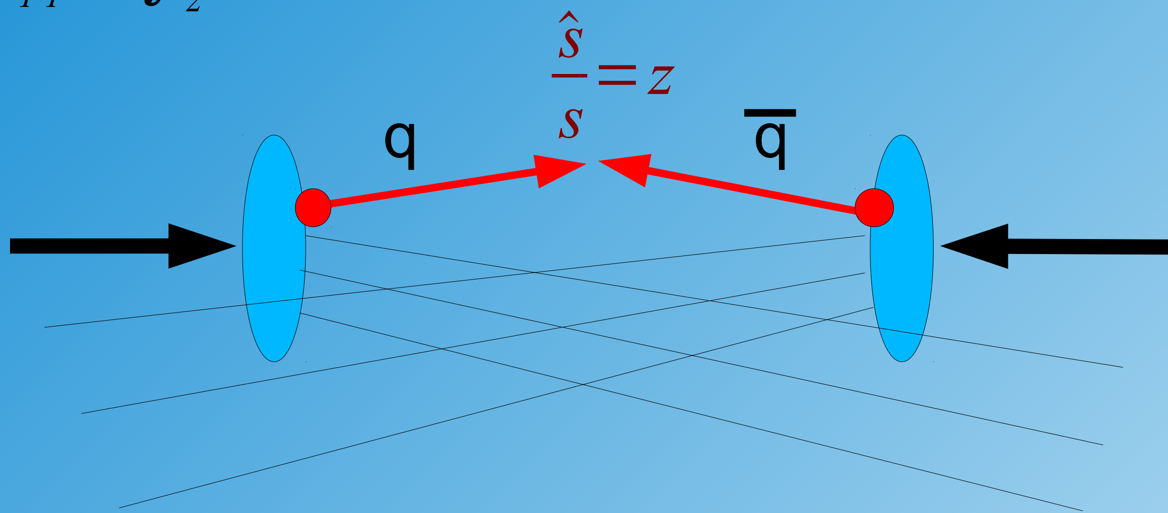


Parton Shower in
Deep Inelastic Scattering

Luminosity-Function

At Hadron Colliders: how to get from the proton to the parton?

$$L_{q\bar{q}} = \int_z^1 q(z/z_2)\bar{q}(z_2)\,dz_2/z_2 \quad \text{with} \quad z = z_1 z_2$$



s = total cms energy

$\hat{s}$ = cms energy of hard parton interaction

Parton density function $q = q(x,\mu^2)$

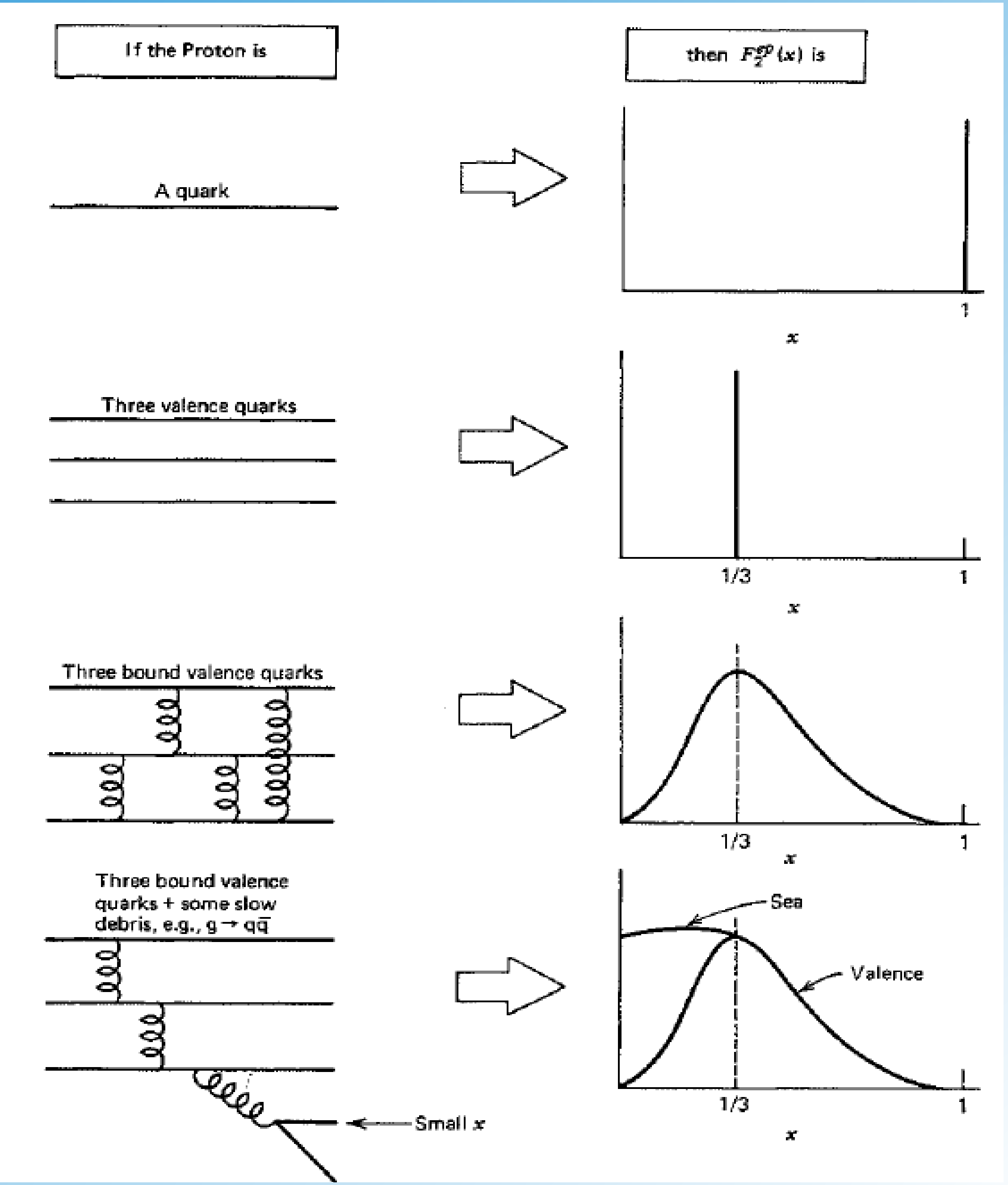
- In Lepton-Nucleon Scattering parton splitting (factorisation) scale $\mu = Q^2$
- **Question**: Which scale determines parton splitting in hadron-colliders?
- **Answer**: factorisation scale typically: $\mu_F = \hat{s}$

Input from lepton-nucleon scattering needed!

Parton Dynamics

- The x-dependence of $q(x,\mu)$ can not be calculated from first principles!

- Parton densities have to be measured by experiments
- Evolution of parton densities in Q^2 is described by DGLAP equations (splitting functions)



...coming back to W,Z Production

W,Z Production in Hadron Collisions

Reaction:

$q\,\bar{q} \rightarrow W\,(Z)\,X$

Collider energy:

$s^{1/2} \sim 500$ GeV

Boson masses

$M_{W,Z} \sim 100$ GeV

$M_{W,Z} \sim \hat{s} = x_1\,x_2\,s$

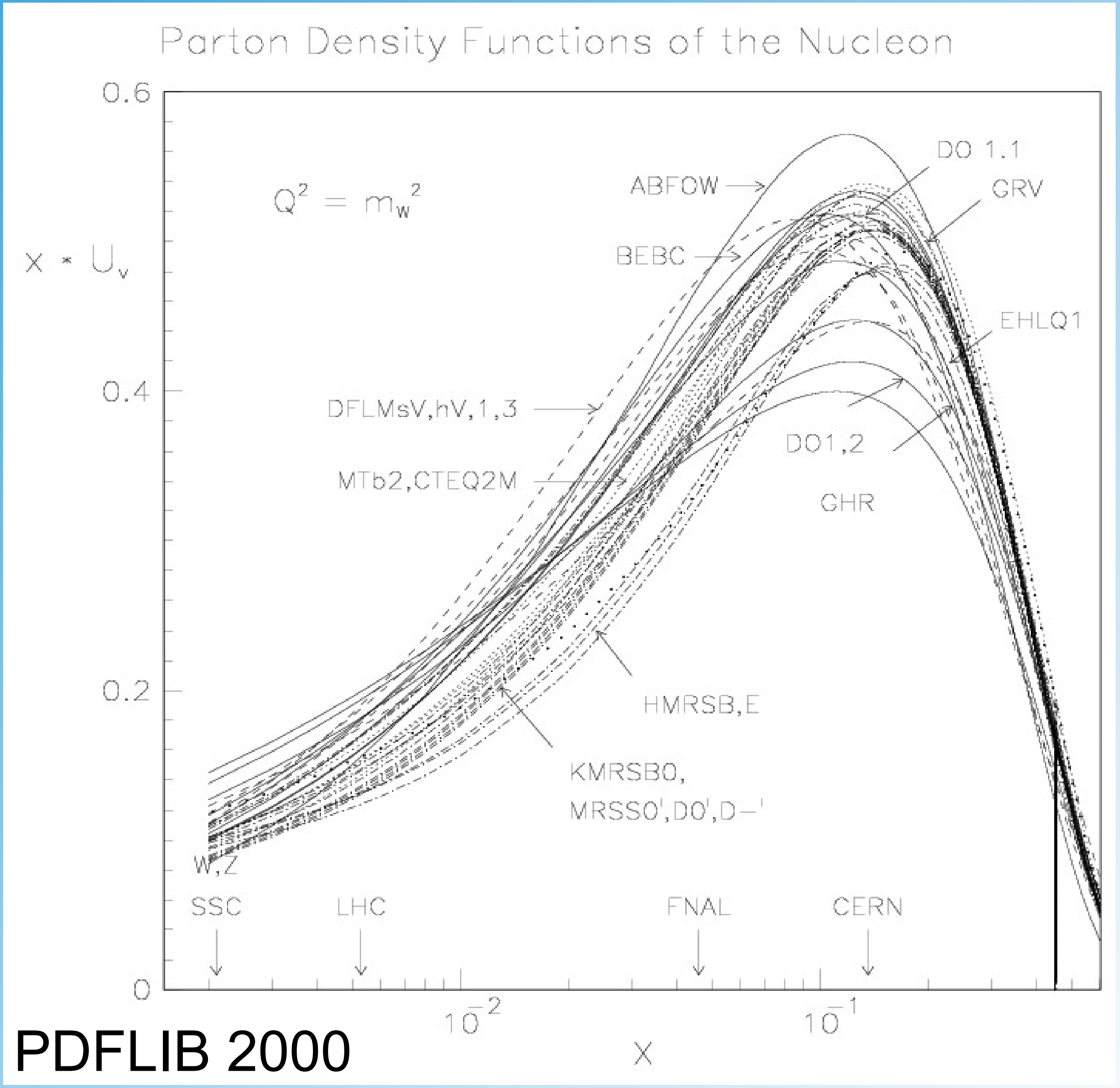
parton momentum fractions:

$x_1\,,\,x_2 \sim 0.2$

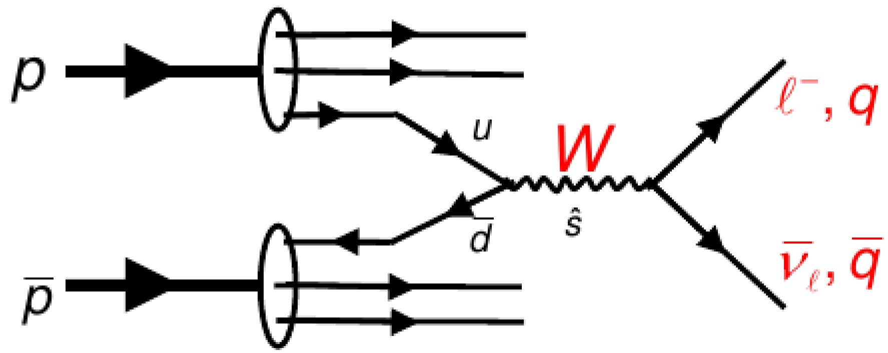
→ valence-quark region

$p\,\bar{p} \rightarrow W\,(Z)\,X$

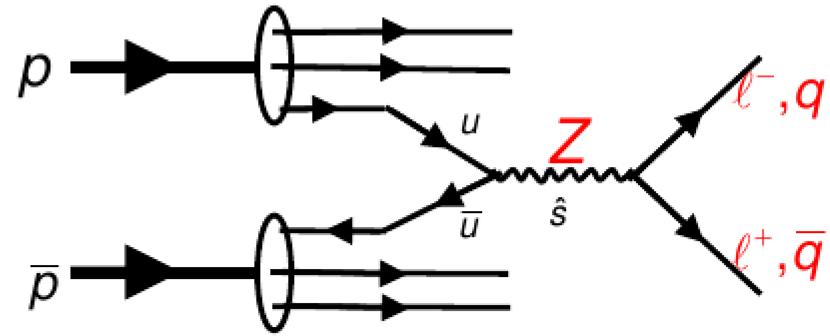
anti-protons needed!



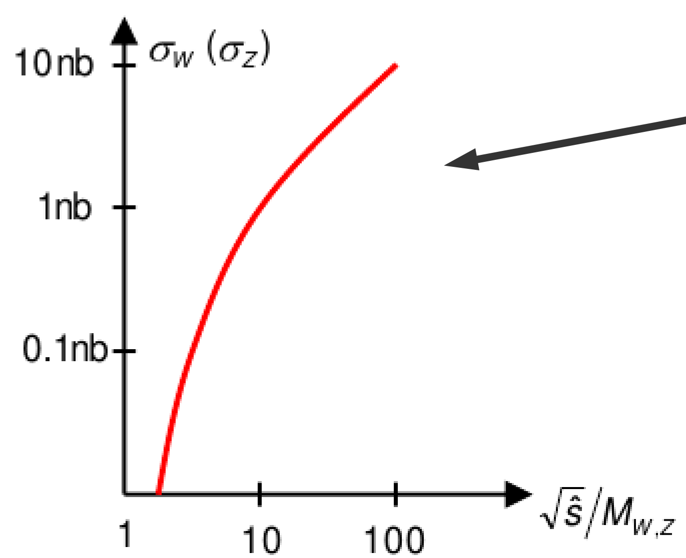
W,Z Cross Section



$$p\bar{p} \rightarrow W \rightarrow \ell \bar{\nu}_\ell + X$$



$$p\bar{p} \rightarrow Z \rightarrow f\bar{f} + X$$



Reasonable cross section of 0.1 nb at

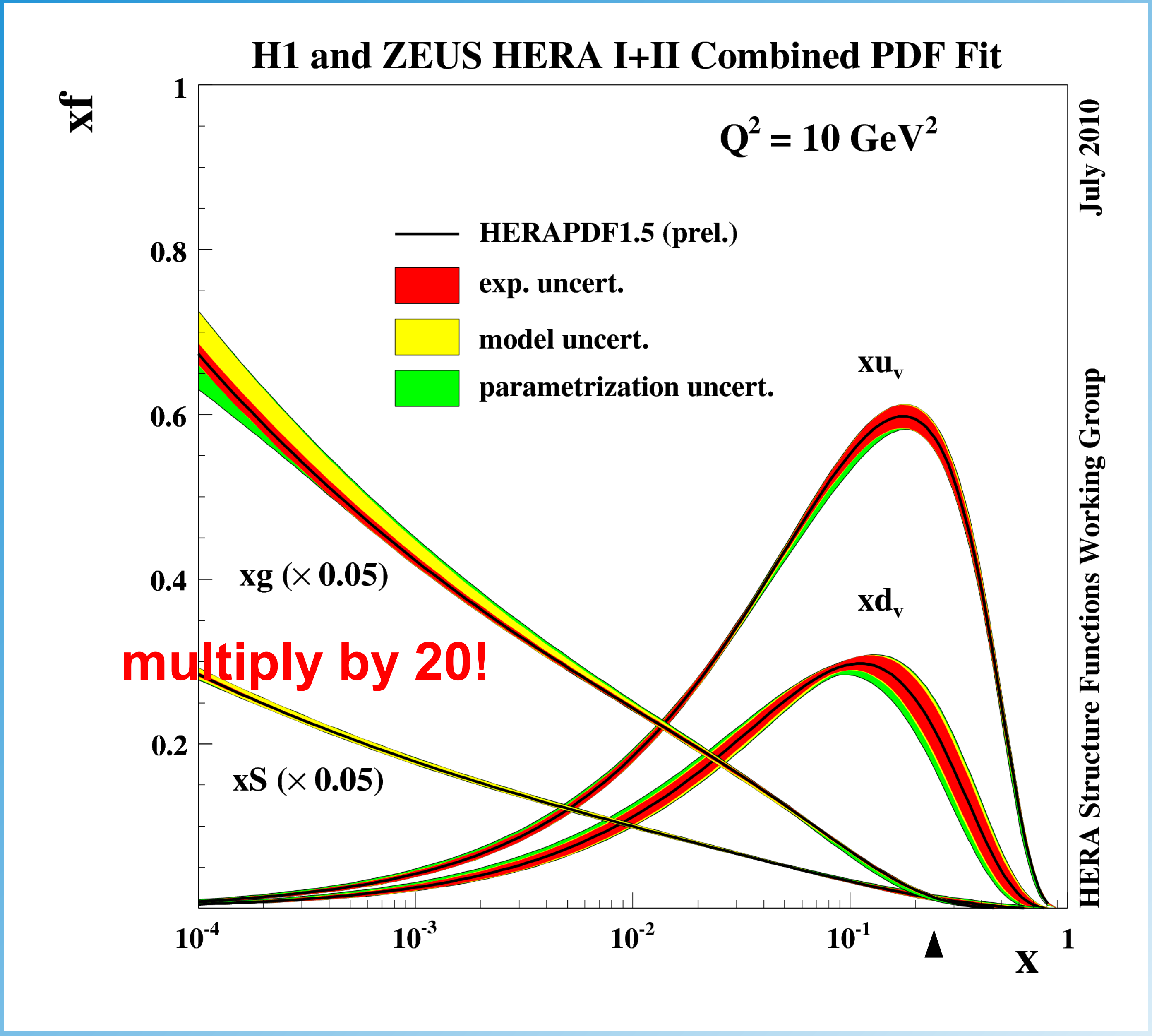
$s^{1/2}/M_W \sim 2$

Typically:

$x_1 , x_2 \sim 0.4$

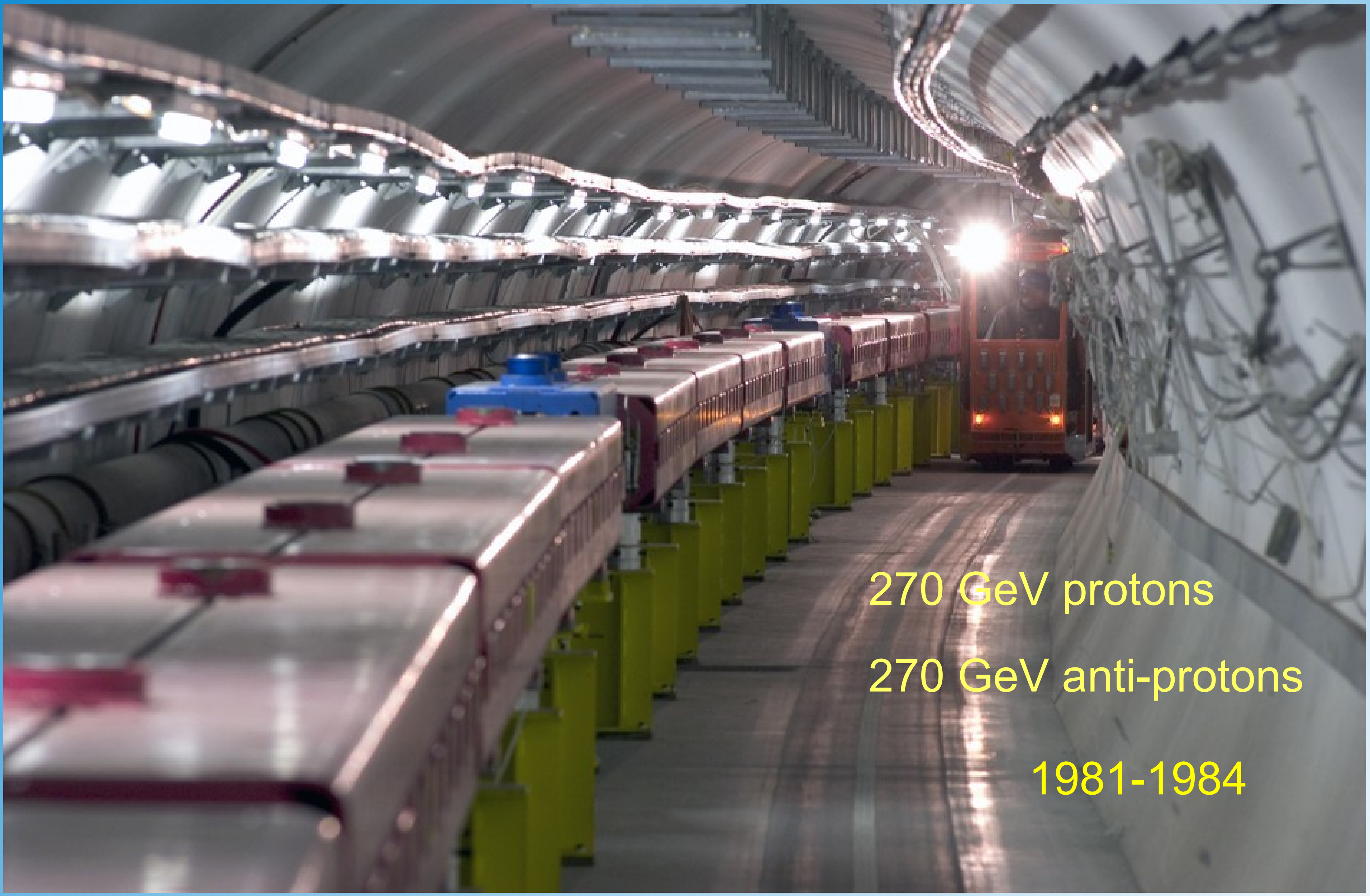
need high luminosity!

Proton Parton Densities



SPS energy

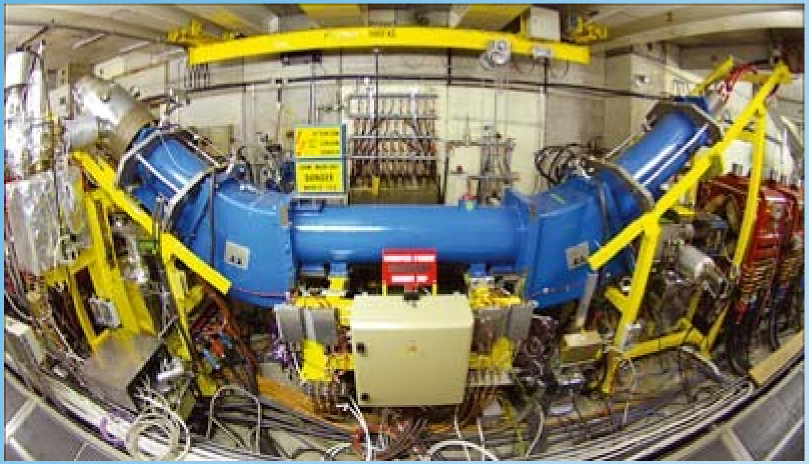
Super Proton (Antiproton) Synchrotron



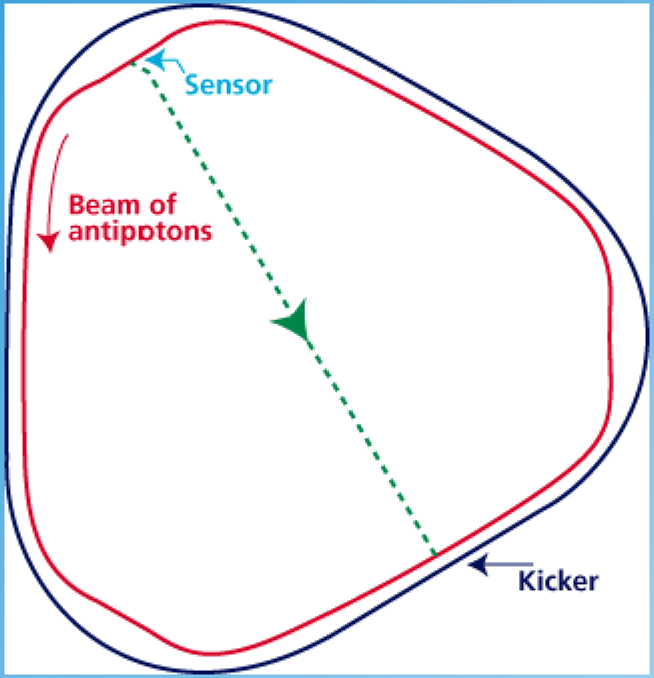
Cooling of Anti-protons

- High luminosities are obtained for small beam emittances !
- Antiprotons are hot after production!

electron cooling of anti-protons

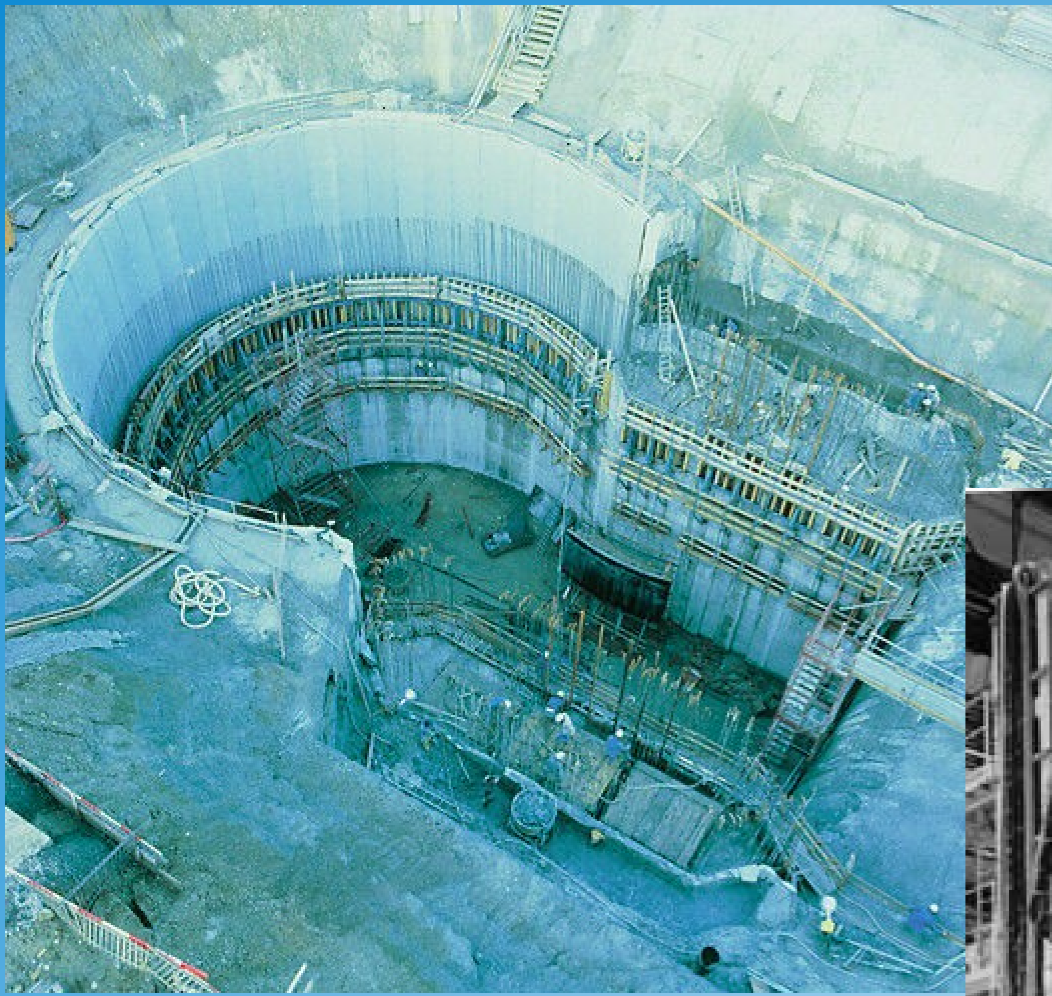


Stochastic cooling of anti-protons

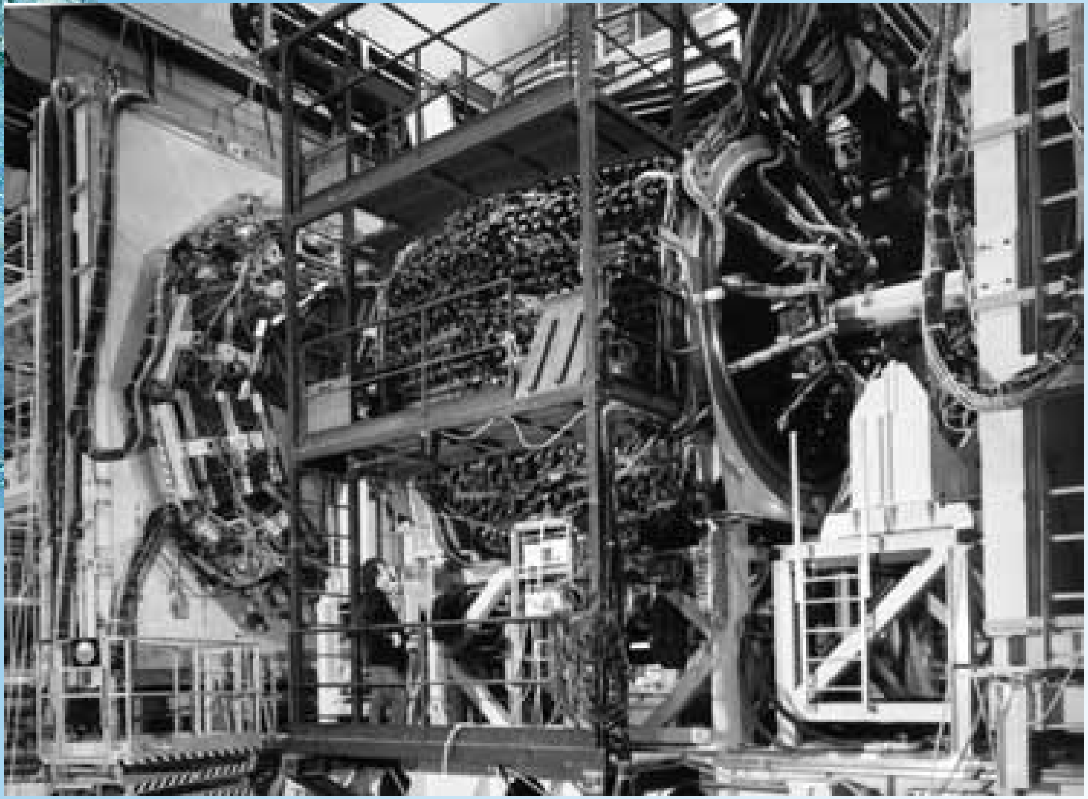


Simon van de Meer

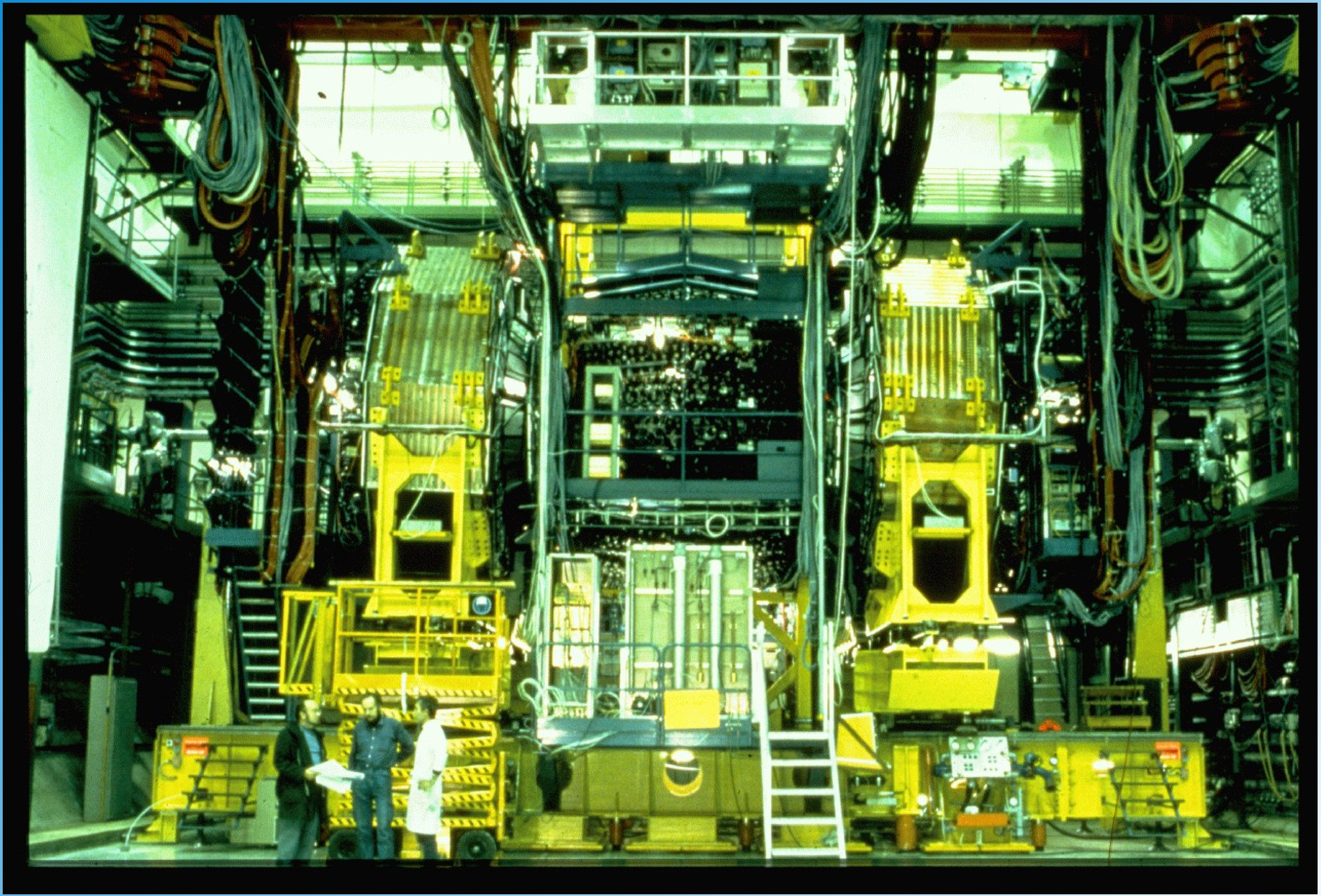
UA1 Experiment



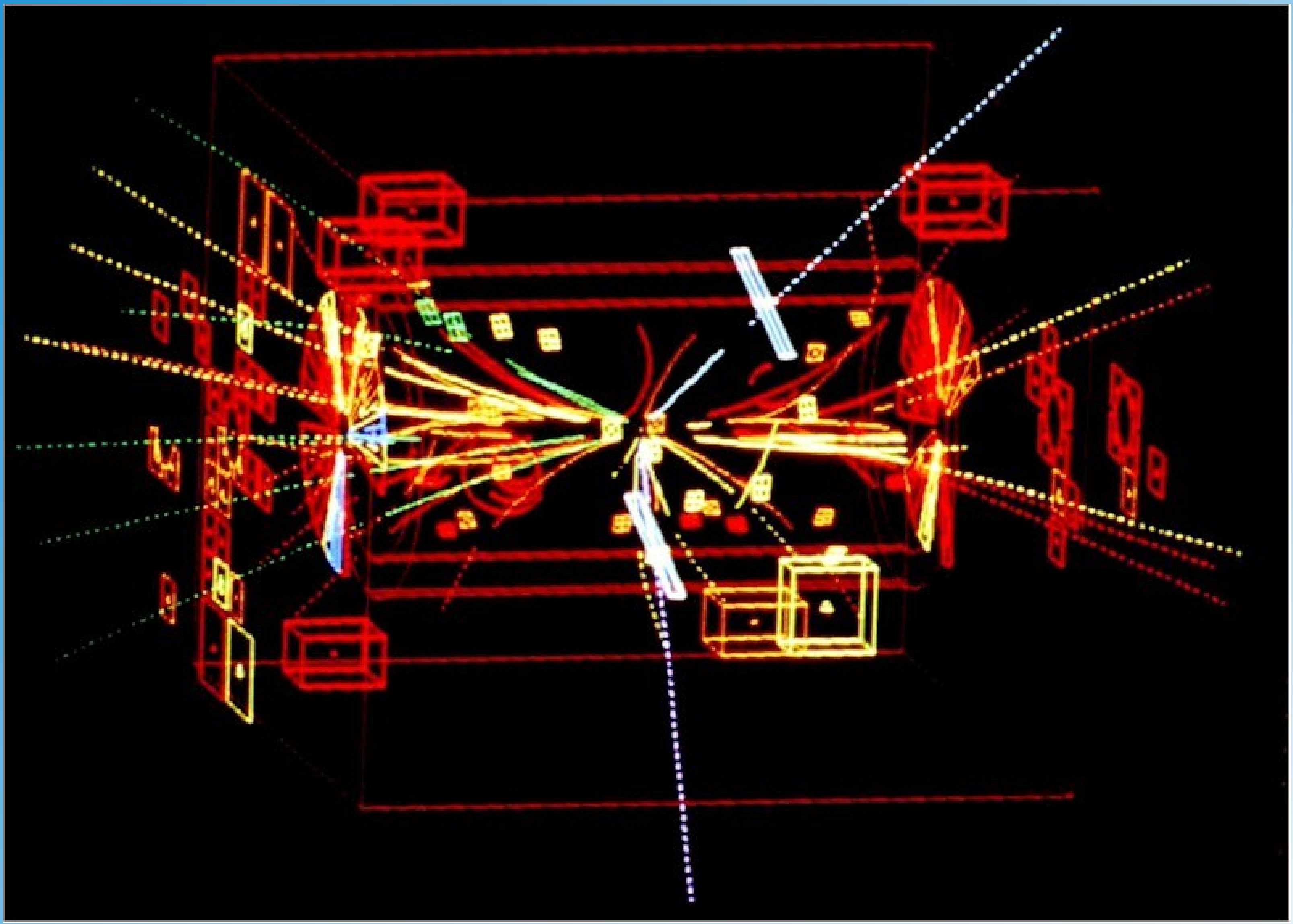
“modern” high energy collider experiment able to run at high collision rates (fast electronics)



UA2 experiment

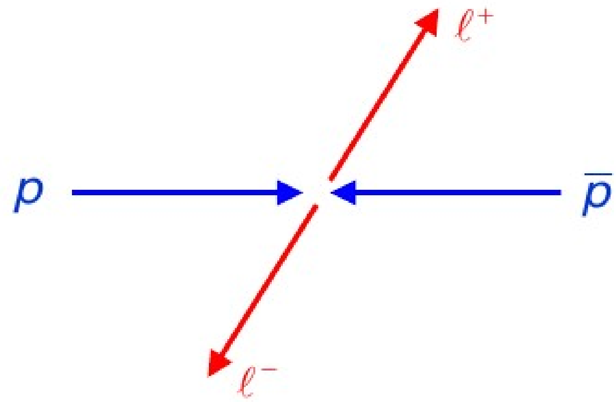


Candidate Z → ee



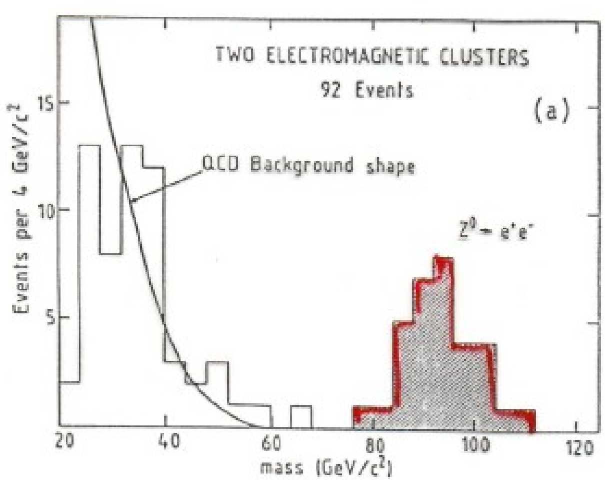
Z-candidate Event Signature

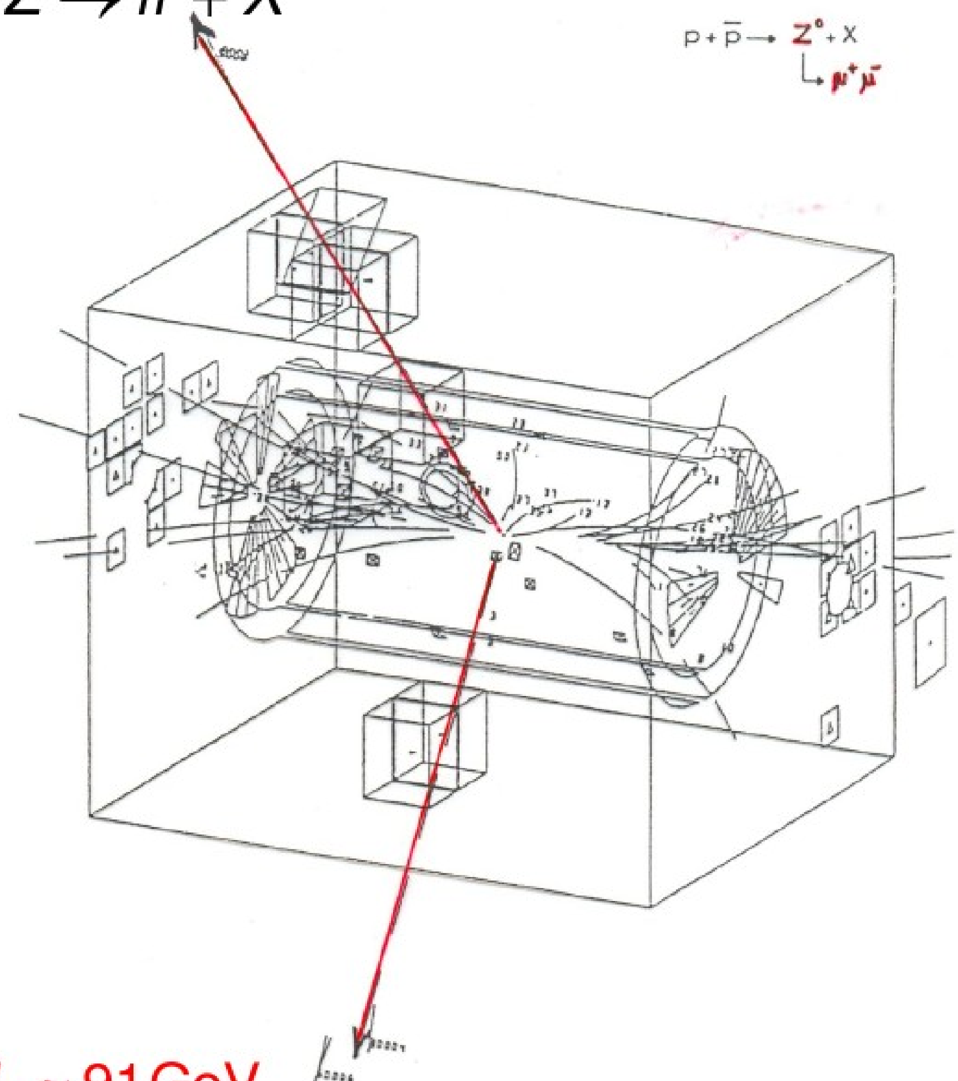
$$p\bar{p} \to Z \to f\bar{f} + X$$



High-energy lepton pair:

$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





$$M_Z \approx 91\,\text{GeV}$$

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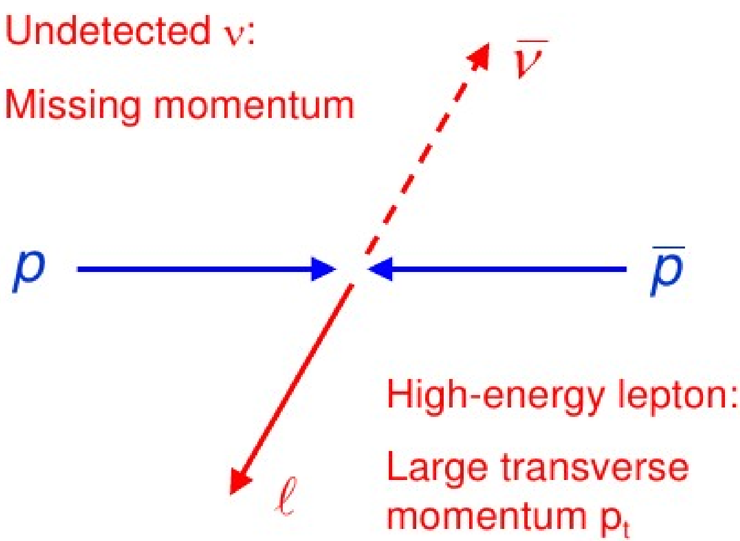
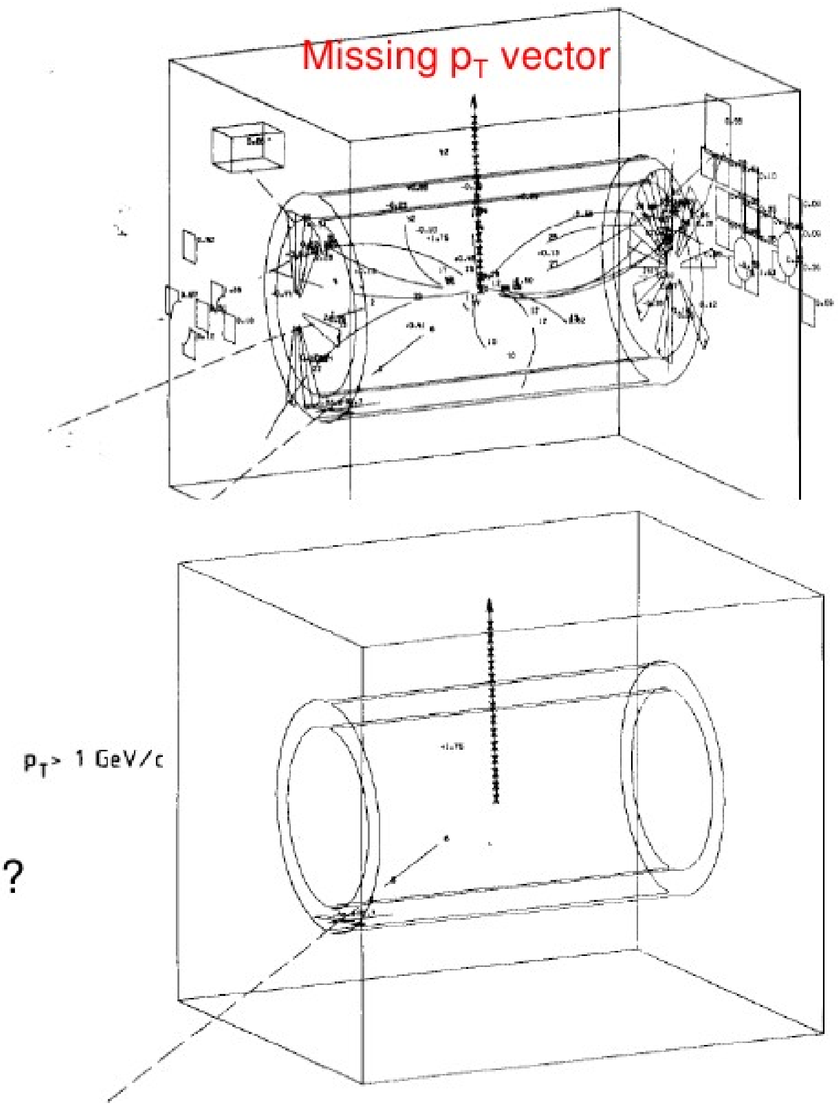
W-candidates

$$p\bar{p} \to W \to \ell \bar{\nu}_\ell + X \qquad W^- \to e\bar{\nu}$$





How can the W mass be reconstructed ?

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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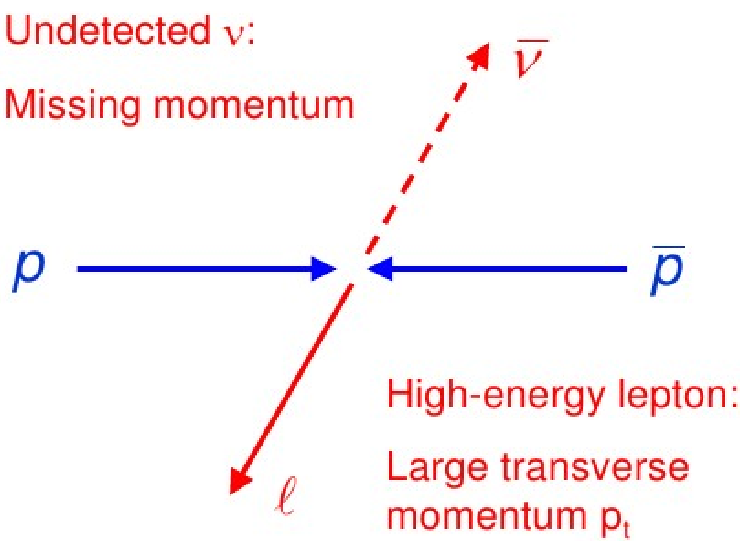
W-candidates

$$p\bar{p} \rightarrow W \rightarrow \ell \bar{\nu}_\ell + X$$

$W^- \rightarrow e\,\bar{\nu}$



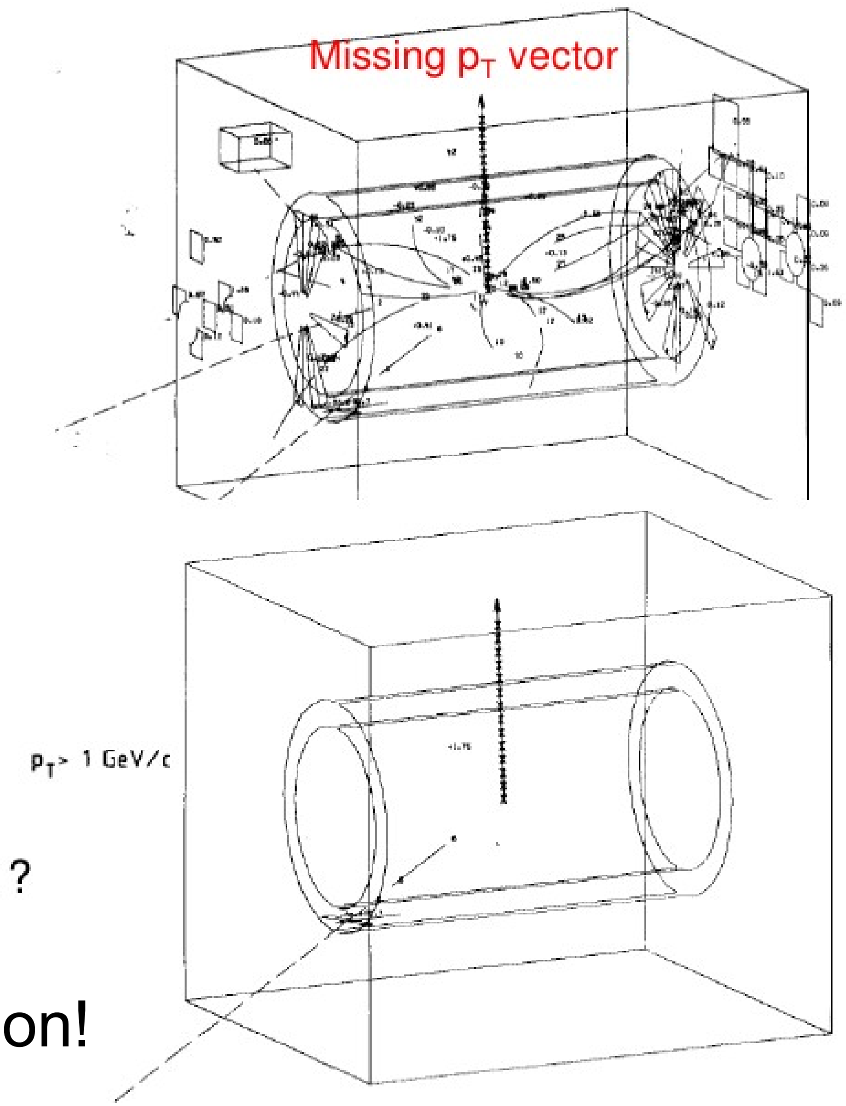


Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_t>1 GeV are shown.

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How can the W mass be reconstructed ?

exploit momentum conservation!

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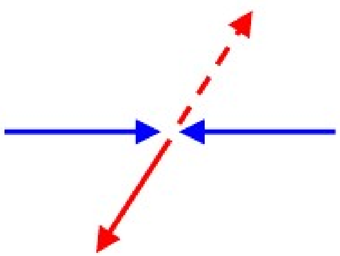
Kinematic Reconstruction of W-bosons

W mass measurement



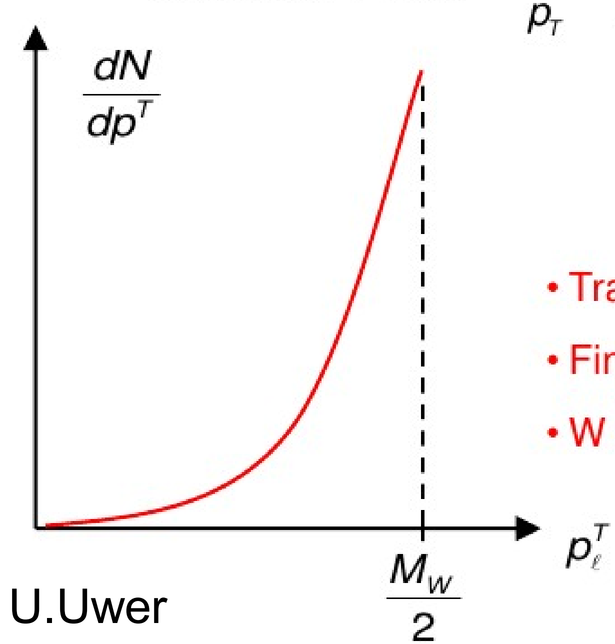
In the W rest frame:

- $|\vec{p}_\ell| = |\vec{p}_\nu| = \frac{M_W}{2}$
- $|p_\ell^T| \leq \frac{M_W}{2}$

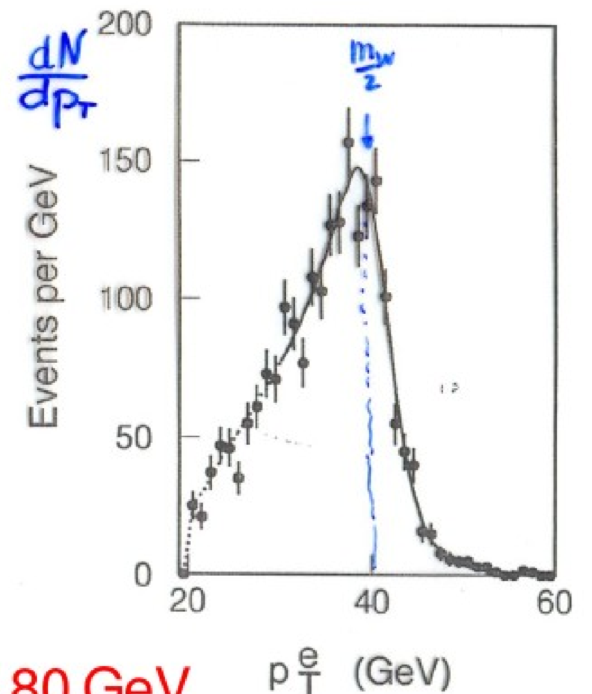
In the lab system:

- W system boosted only along z axis
- p_T distribution is conserved: maximum $p_T = M_W / 2$

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



- Trans. Movement of the W
- Finite W decay width
- W decay not isotropic



$M_W \approx 80$ GeV

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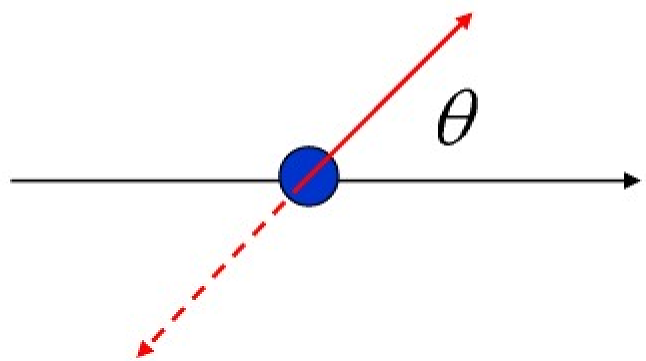
Jacobian Peak

Assume isotropic decay of the W boson in its CM system:

(Not really correct: W boson has spin=1 $\rightarrow$ decay is not isotropic!)

$$\frac{dN}{d\cos\theta} = const$$



$$\sin\theta = \frac{p_T}{p} = \frac{p_T}{M_w/2}$$

$$1-\cos^2\theta = \left(\frac{p_T}{M_w/2}\right)^2$$

$$d\cos\theta \sim \frac{p_T}{(M_W/2)^2}\frac{dp_T}{\cos\theta}$$

$$\frac{dN}{dp_T} = \left(\frac{dN}{d\cos\theta}\right)\cdot\boxed{\left(\frac{d\cos\theta}{dp_T}\right)} \sim \frac{2p_T}{M_W}\cdot\left(\frac{M_W^2}{4}-p_T^2\right)^{-1/2}$$

Jacobian

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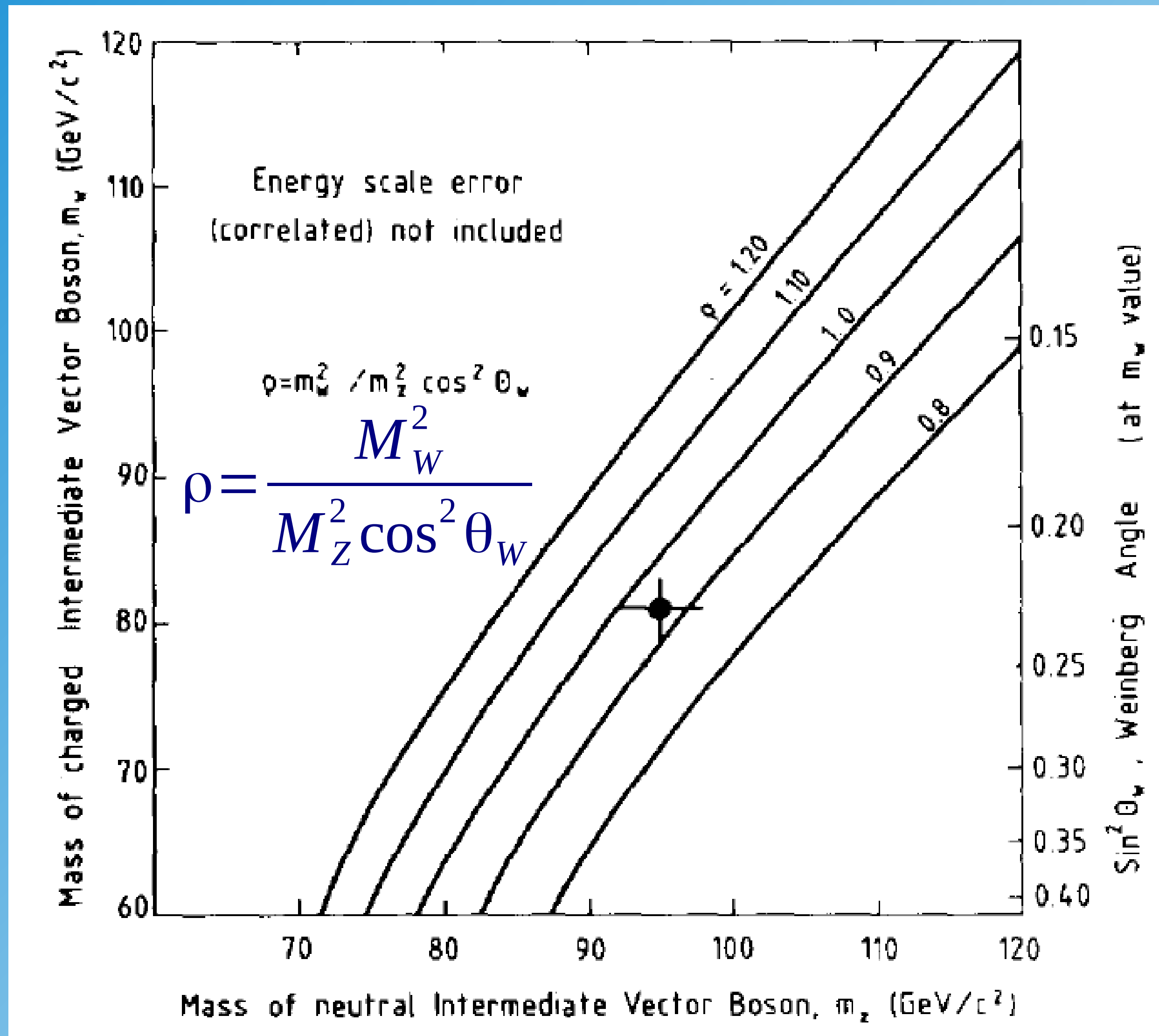
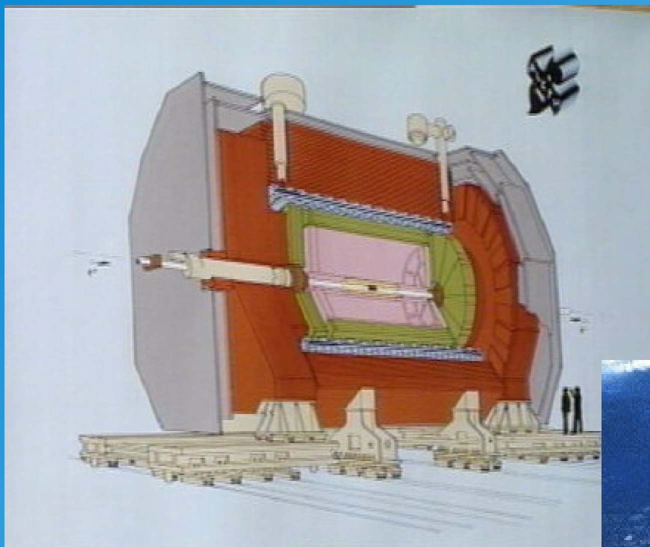
Final Result

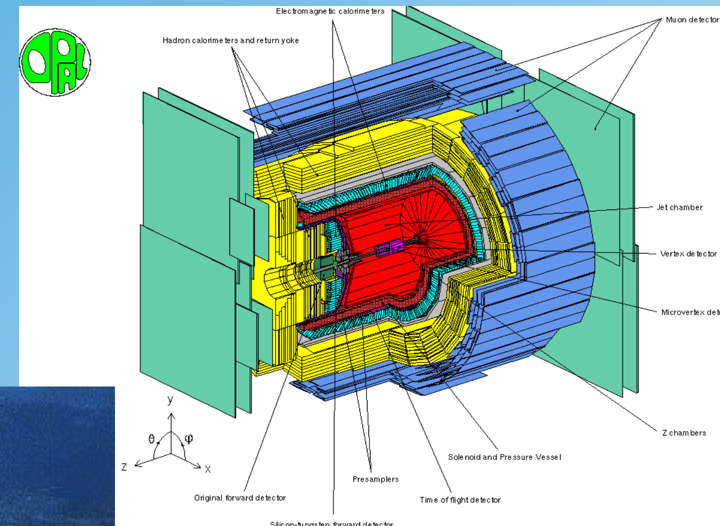


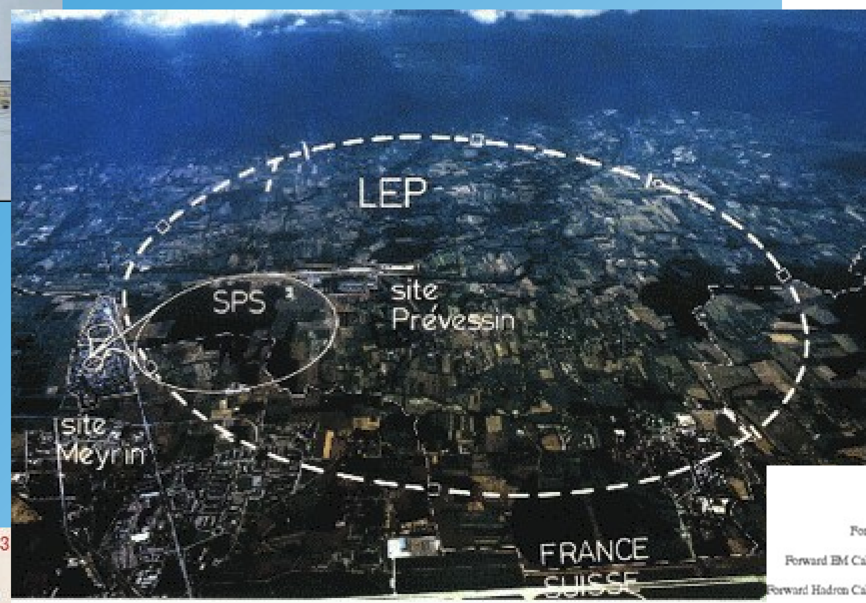
Rho parameter consistent with 1 → confirmation of the SM

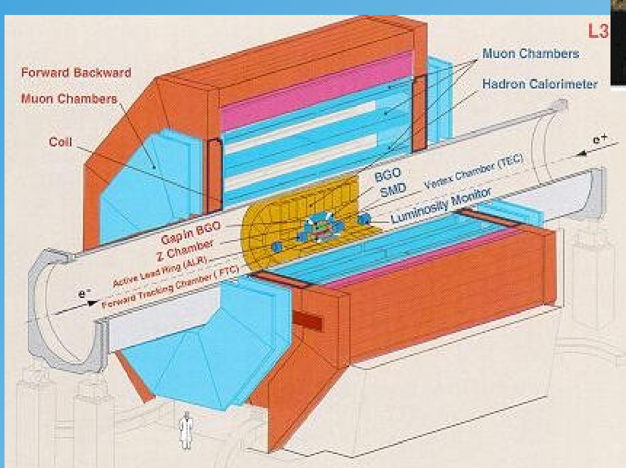
Nobel Prize for Physics 1984: C.Rubbia and S. van de Meer

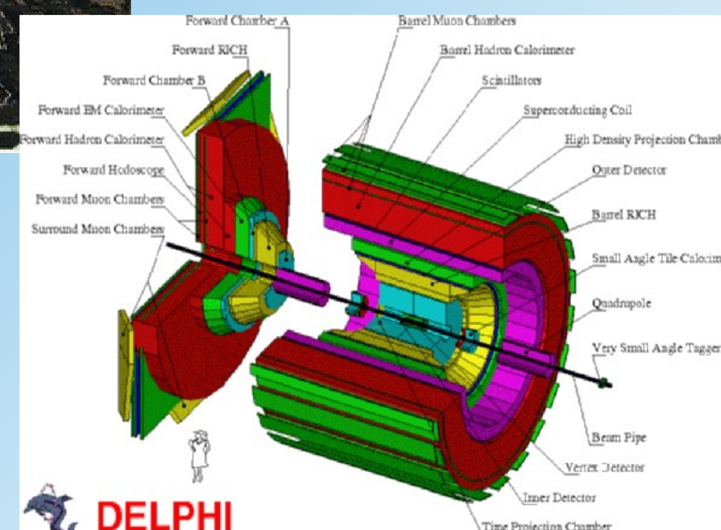
Large Electron Positron Collider







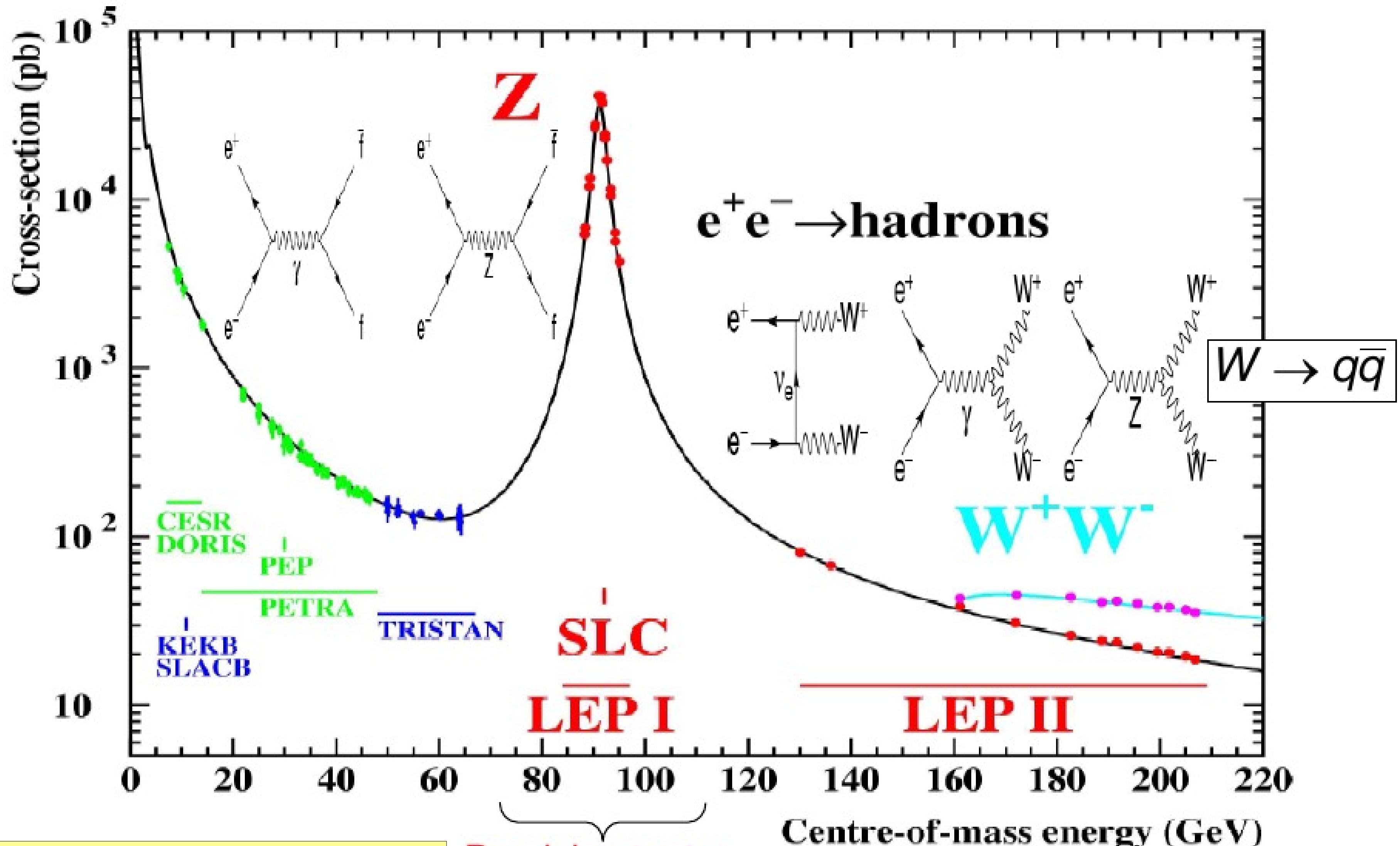




e^+e^- collider

$s^{1/2}$ = 90-200 GeV

Hadron Production in $e^+ e^-$



$M_Z = 91.1876 \pm 0.0021$ GeV

Precision tests of the Z sector

Tests of the W sector

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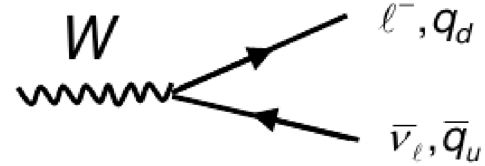
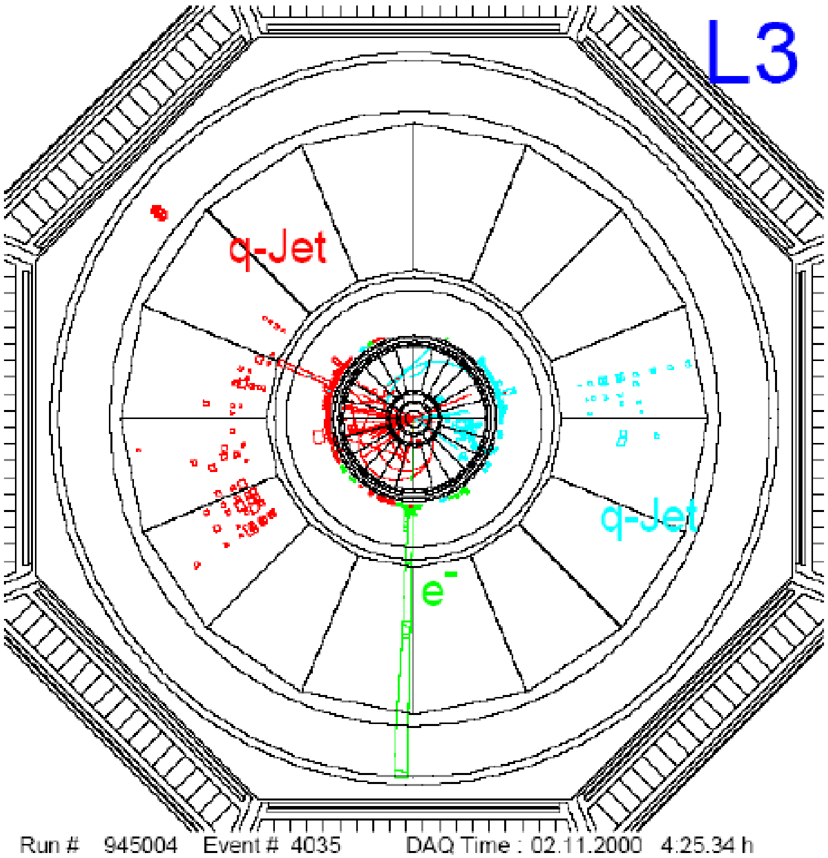
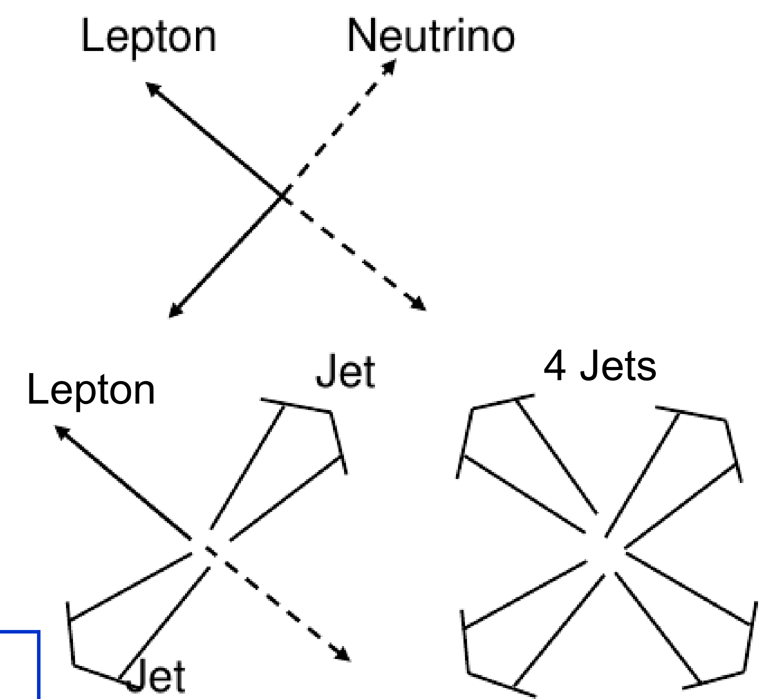
WW Pair Production at LEP

W decays





$$WW \rightarrow \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$



Easiest signature for a mass measurement:

$W_1 \rightarrow l\nu$ $W_2 \rightarrow$ JetJet: use JetJet invariant mass

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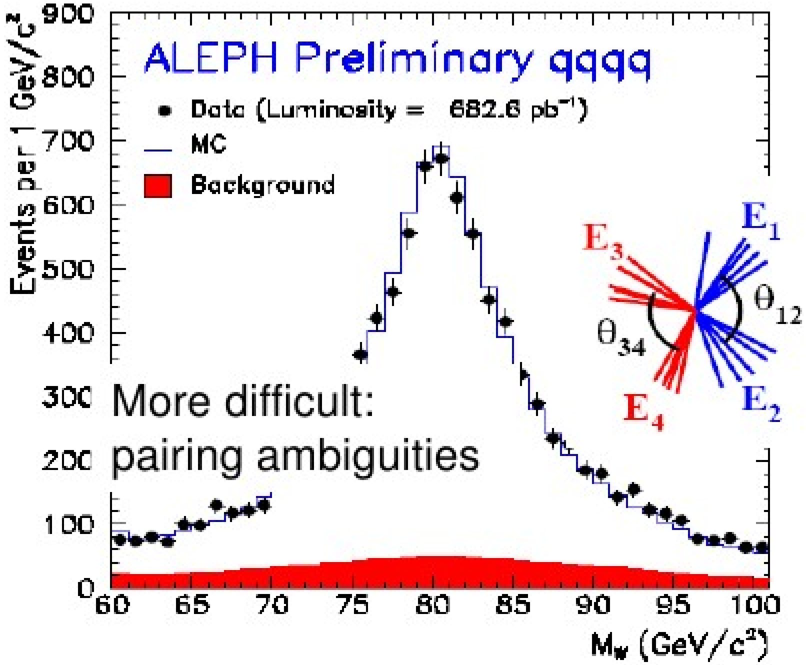
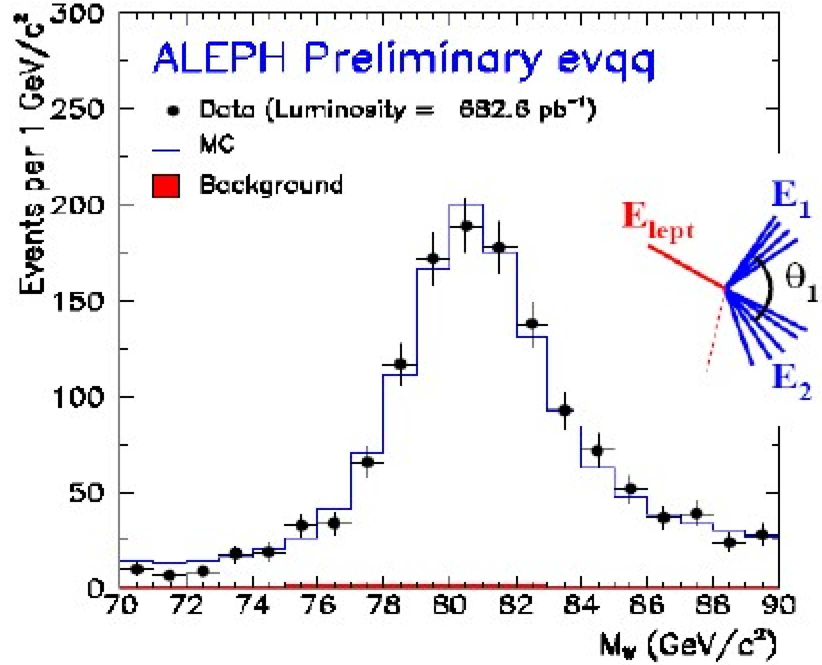
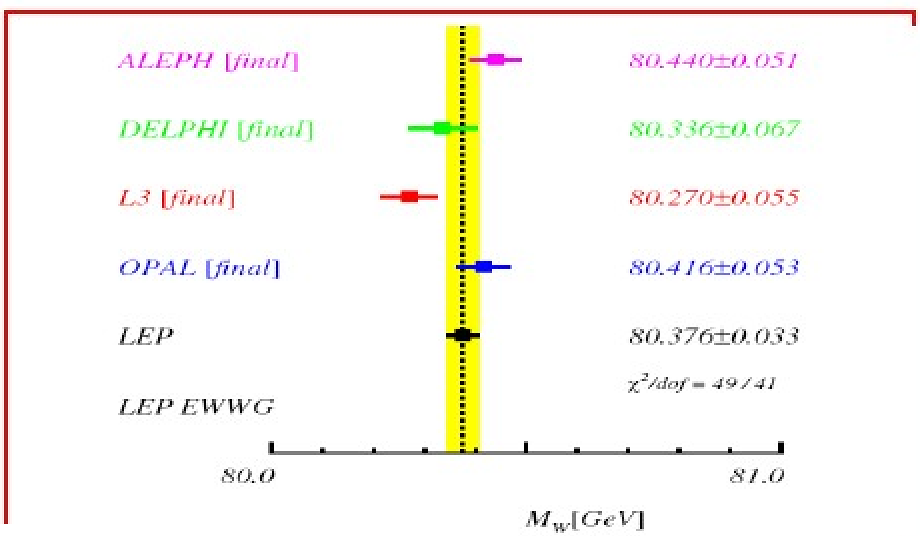
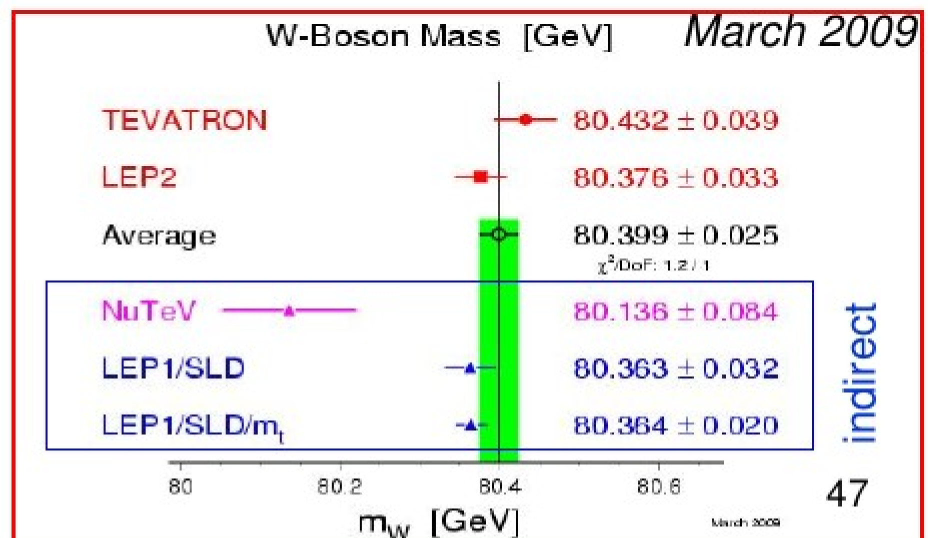
Invariant W mass recontruction

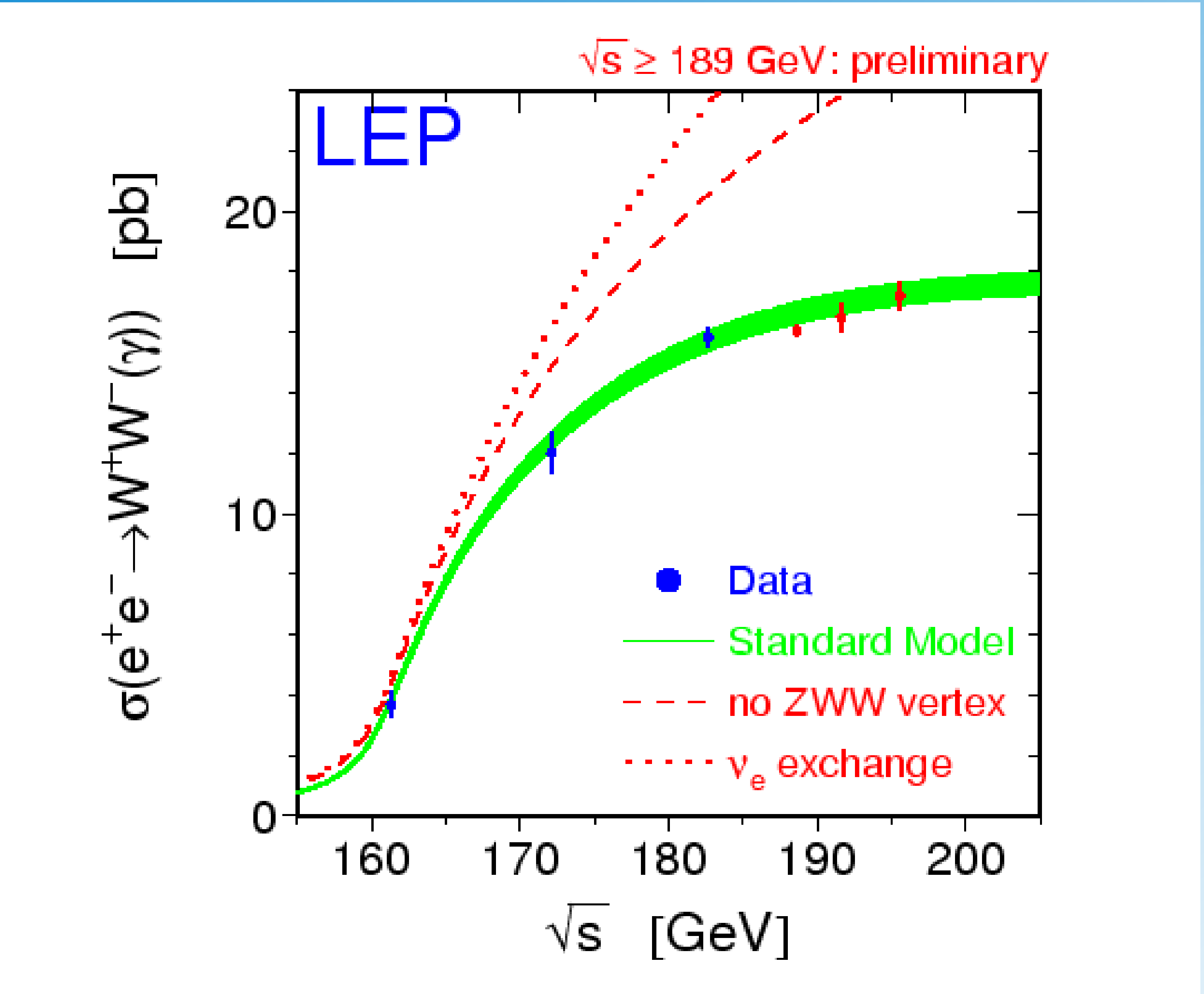




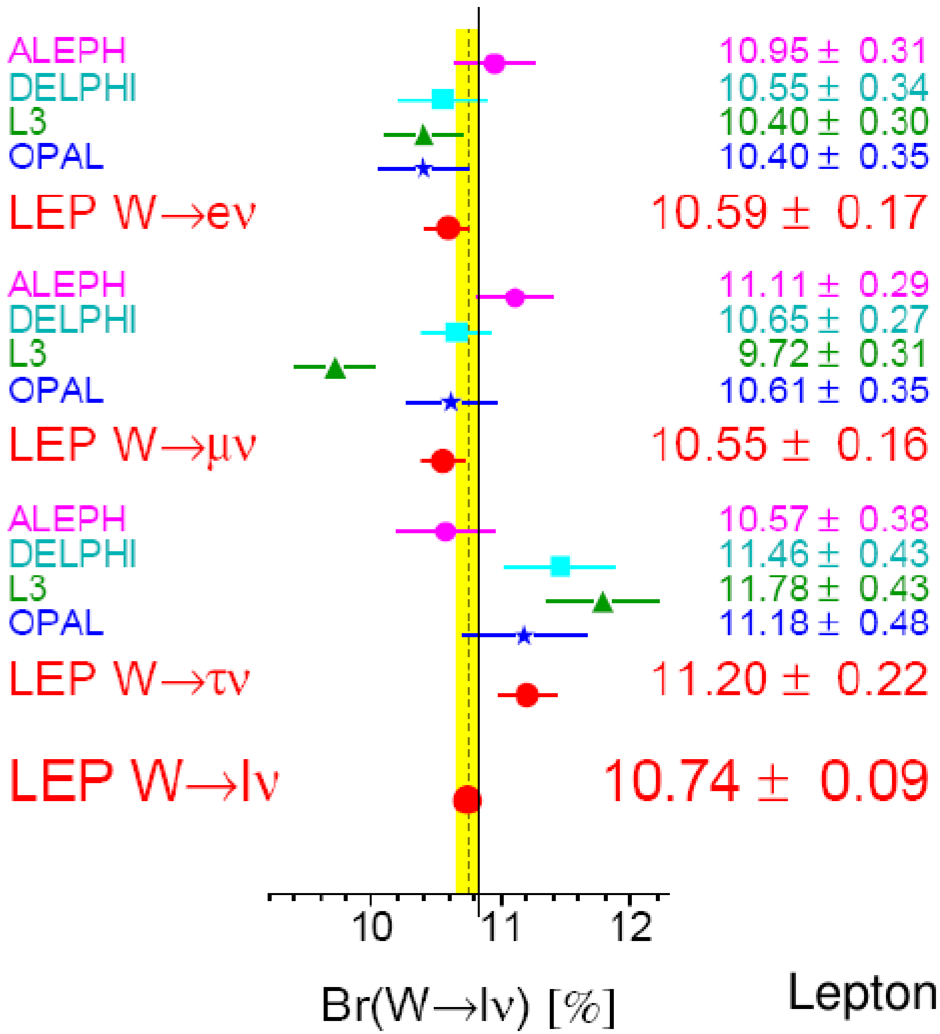




W-Pair Production at LEP2



W leptonic branching fractions

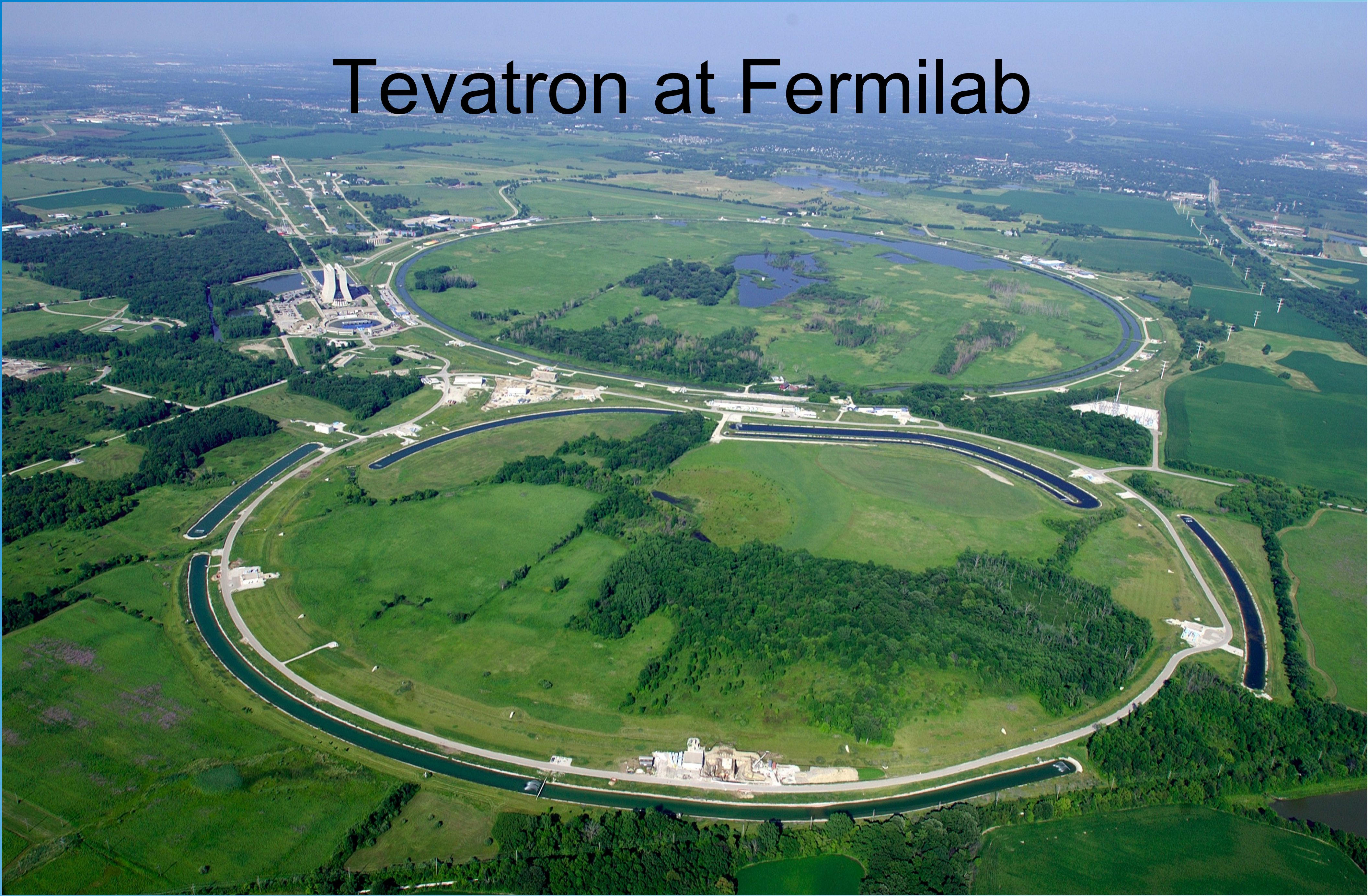


$$\Gamma_W = \frac{\sqrt{2}\, G_F\, m_W^3}{12\pi}$$

$$Br(W \to q\bar{q}) = (67.77 \pm 0.28)\%$$

Lepton universality tested to 2%

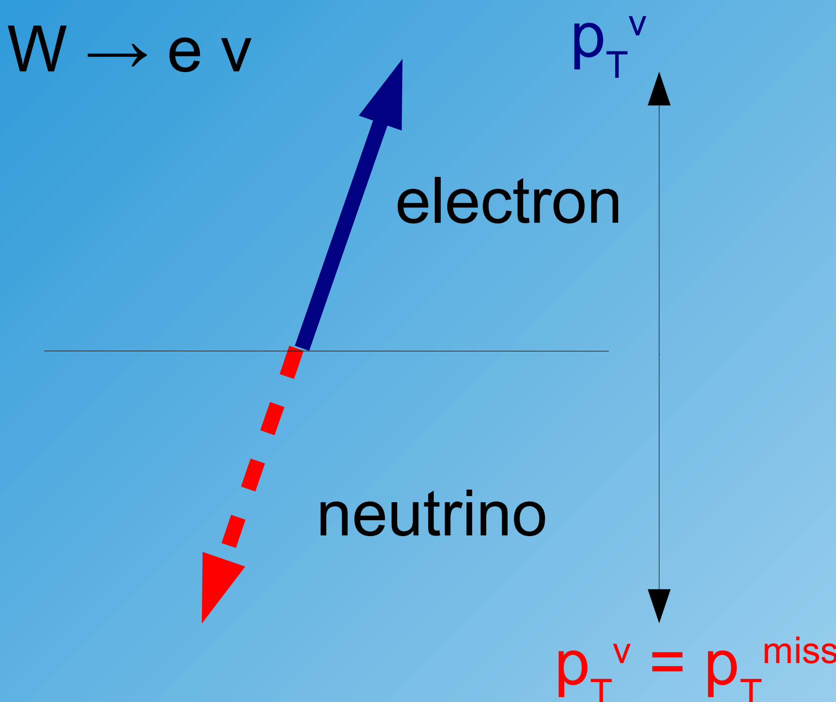
Tevatron at Fermilab

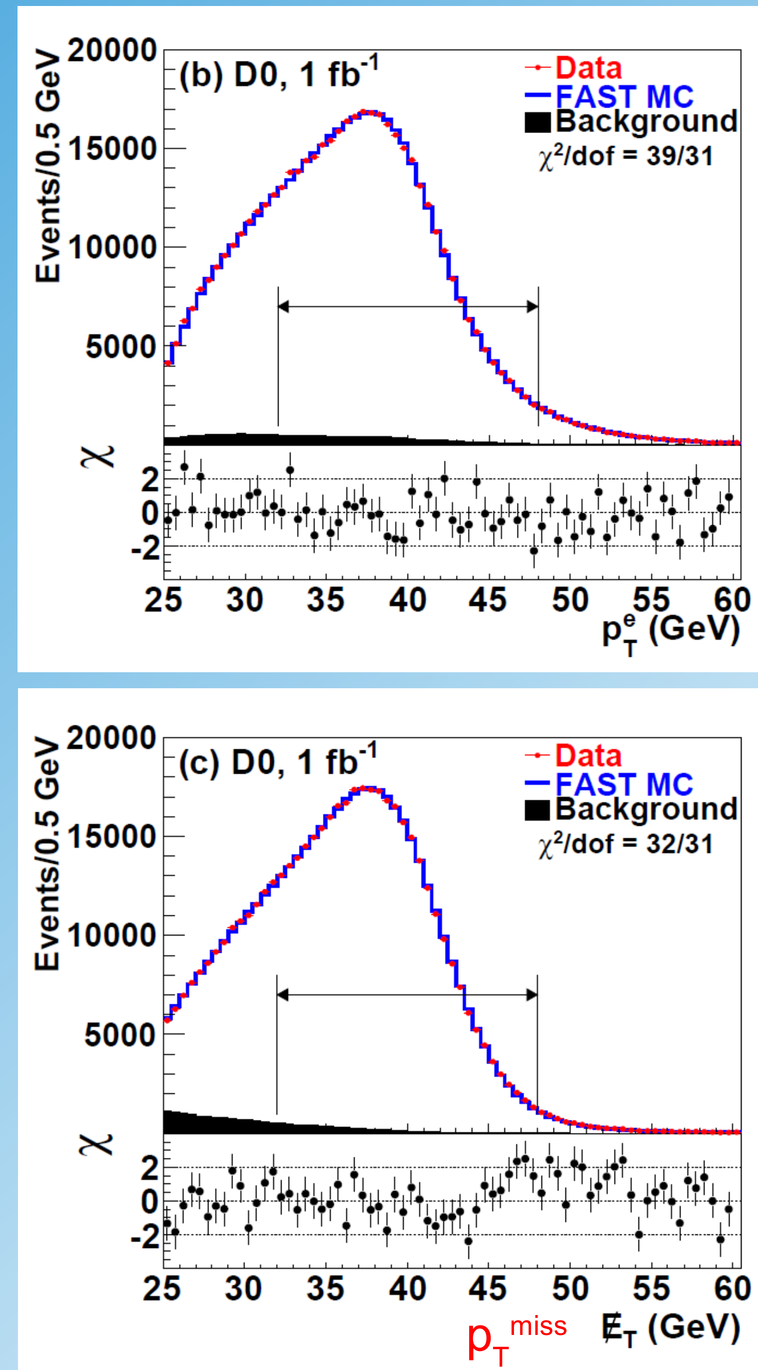


Proton – Antiproton Collider at $s^{1/2} = 2$ TeV

Missing Transverse Momentum

Jacobian peak at D0:

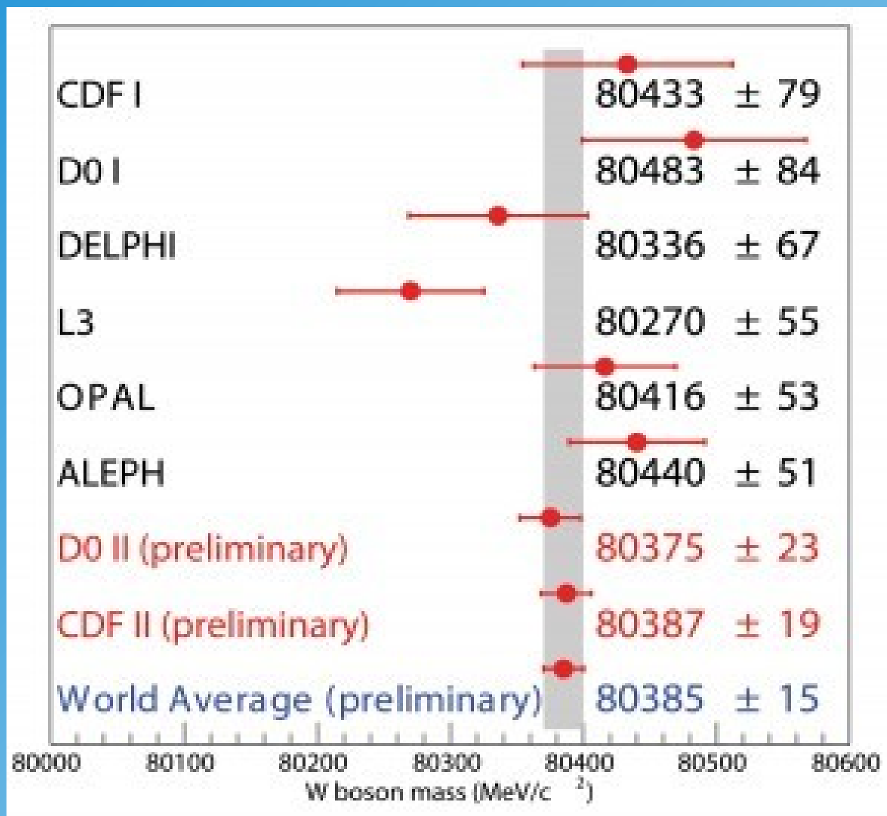




Latest Results W-mass

Method: normalise W-mass measurement to Z-mass measurement
and take input (precise Z-mass) from LEP

March 2012



} Tevatron Run 1

LEP2

} Tevatron Run 2

World Average

W-mass measurement important for Top and Higgs Mass predictions

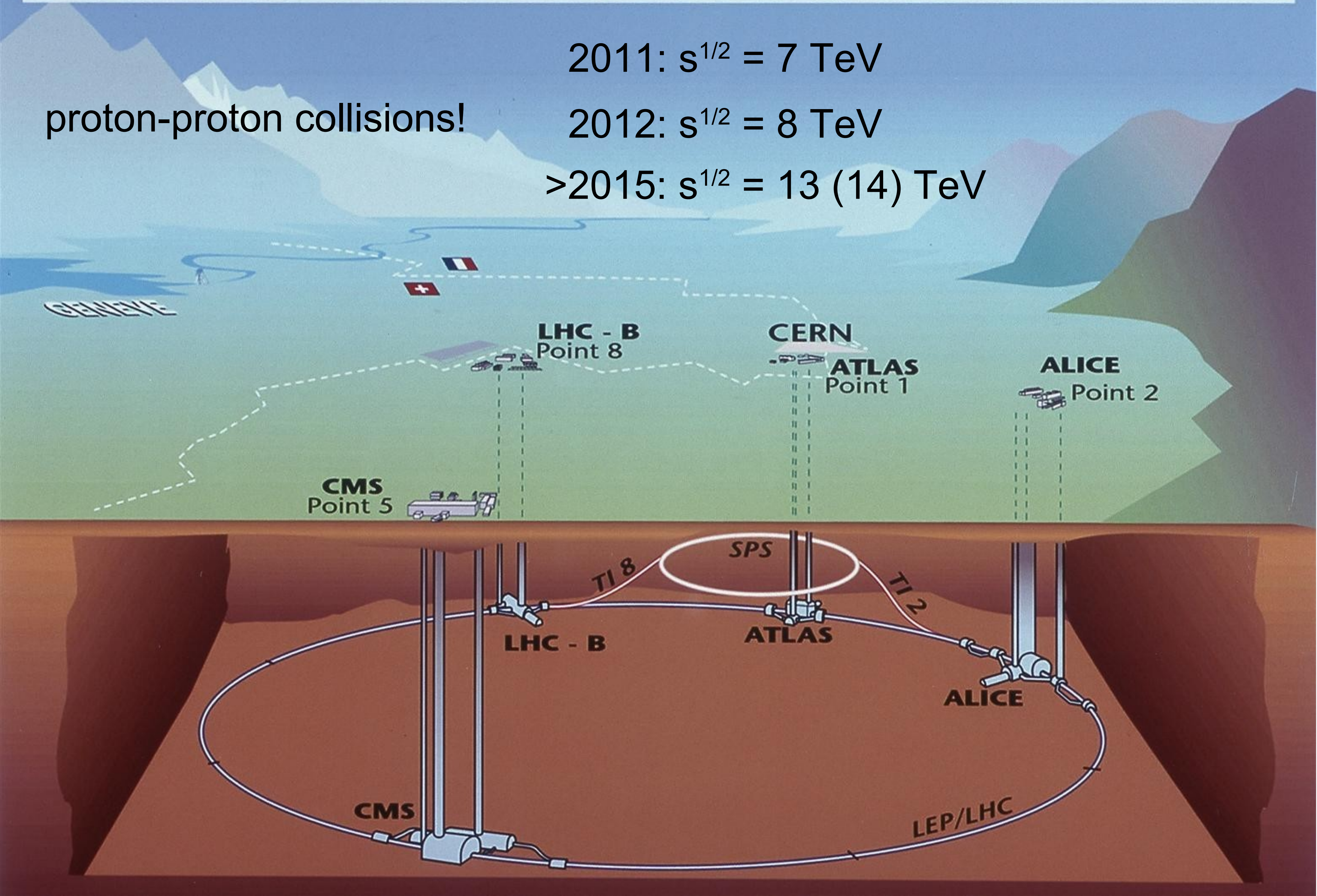
Overall view of the LHC experiments.

proton-proton collisions!

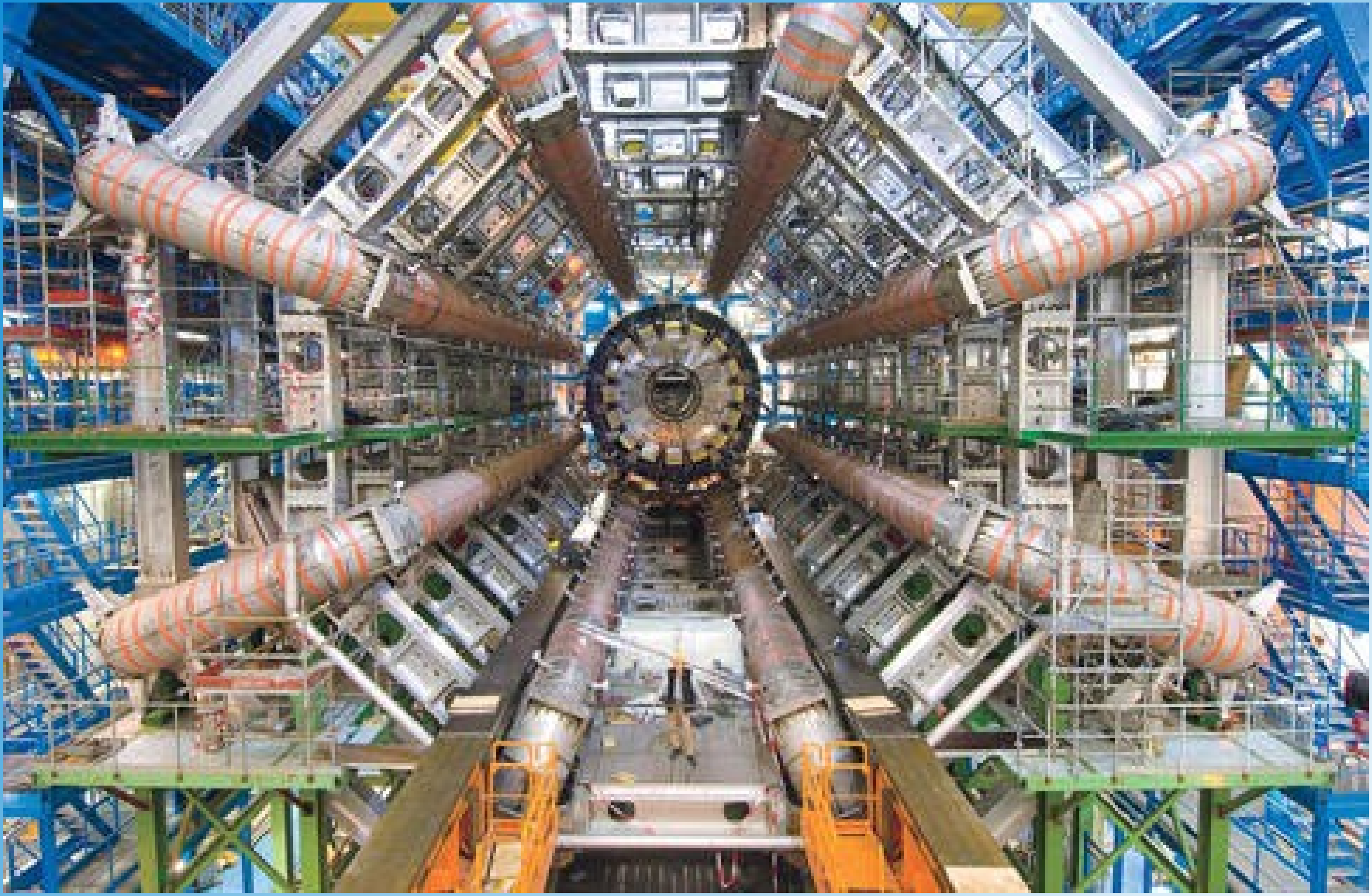
2011: $s^{1/2}$ = 7 TeV

2012: $s^{1/2}$ = 8 TeV

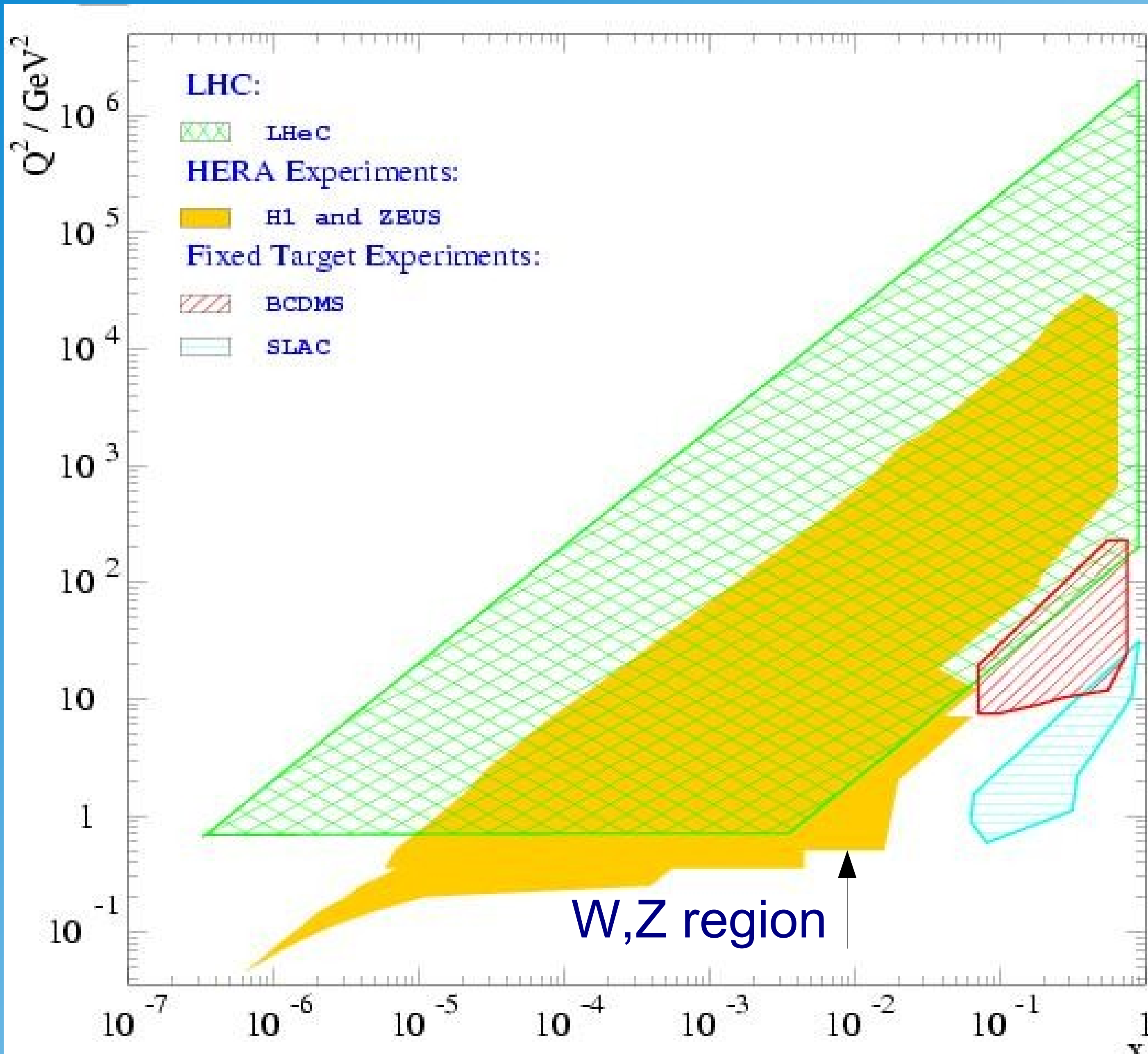
>2015: $s^{1/2}$ = 13 (14) TeV



ATLAS Detector

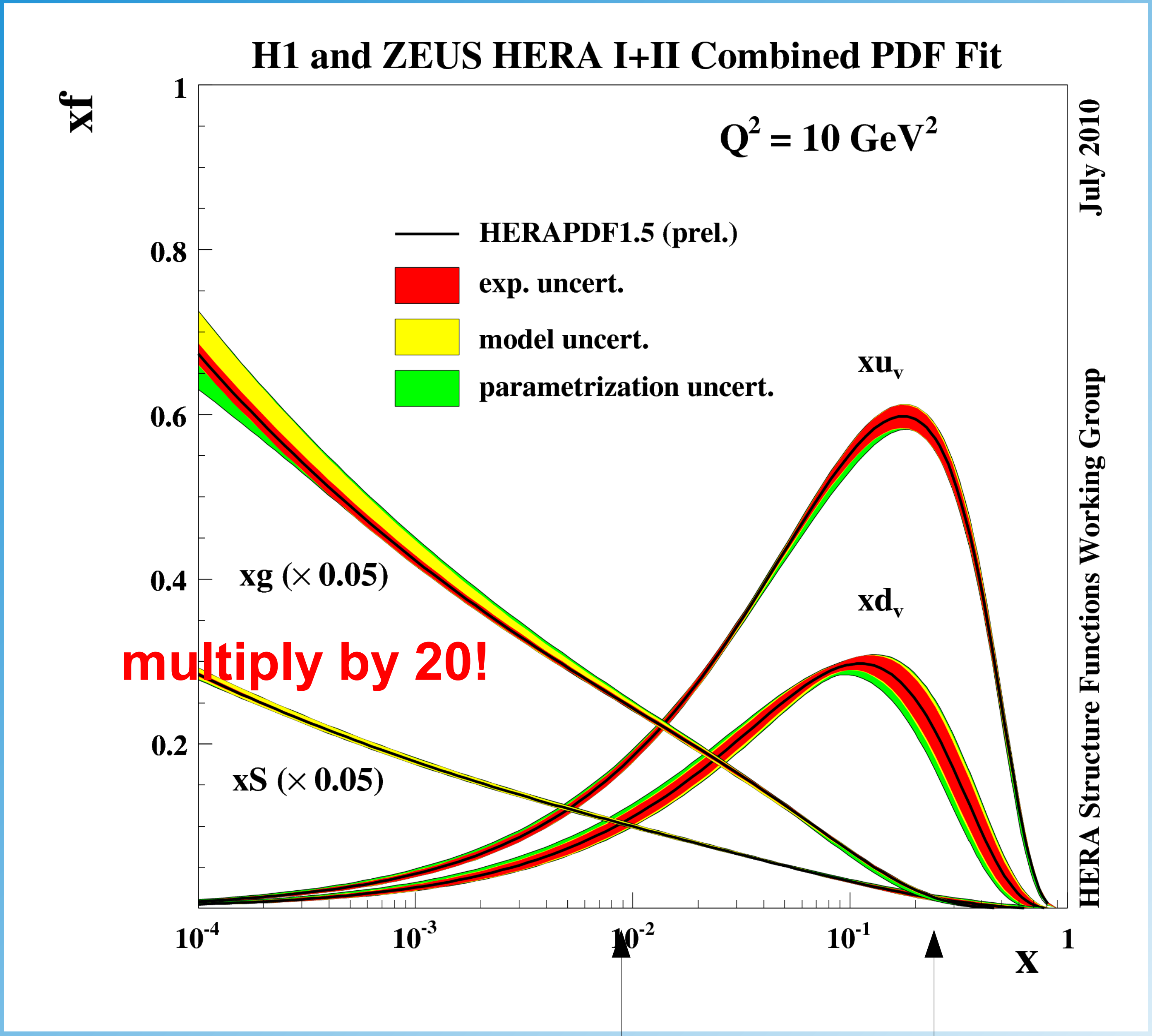


LHC Kinematic Plane



- W,Z production dominated by sea quarks
- low x-region very well constrained by HERA
- W,Z production can be used to measure proton-PDFs and LHC luminosity!

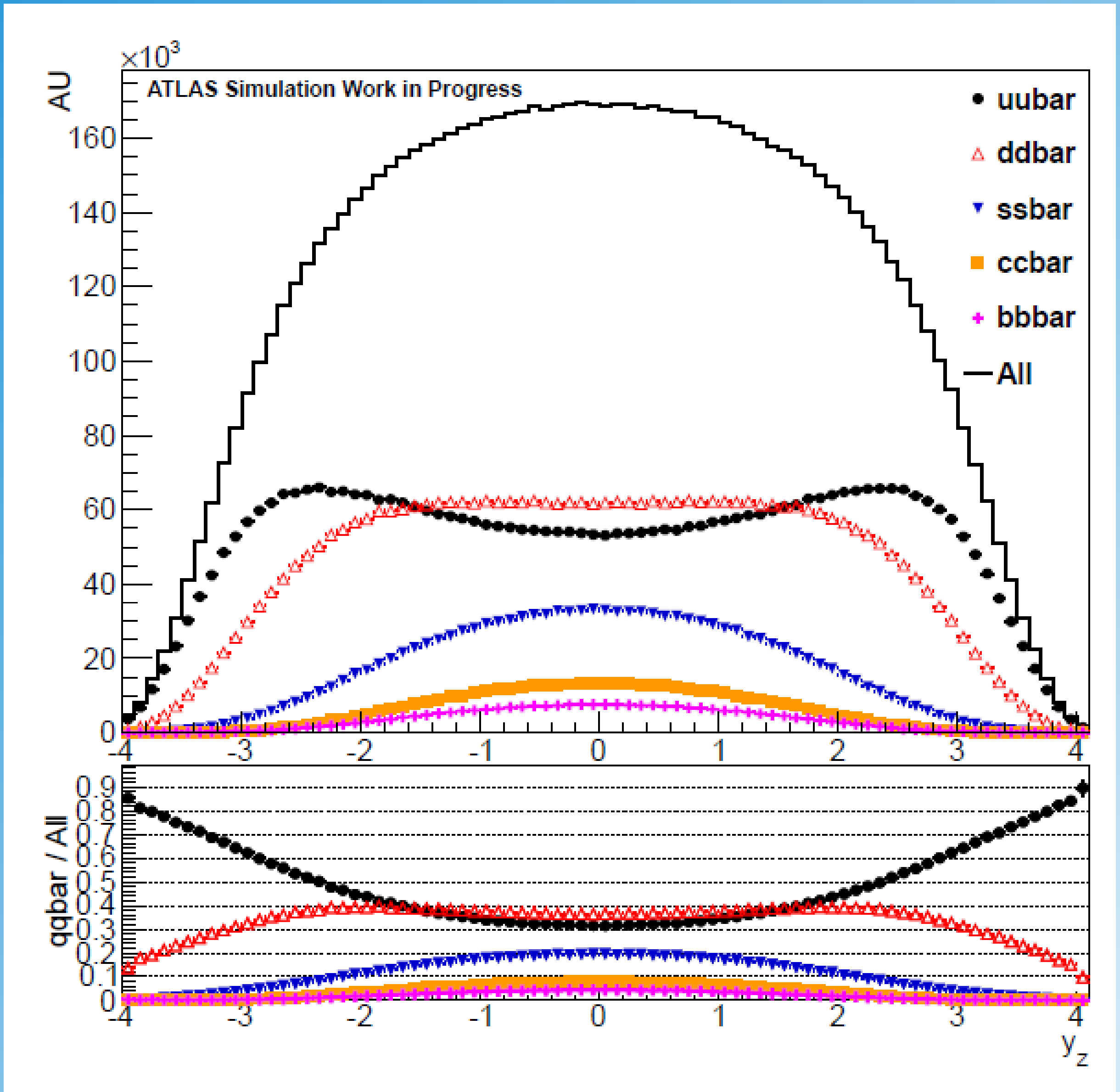
Proton Parton Densities



LHC energy SPS energy

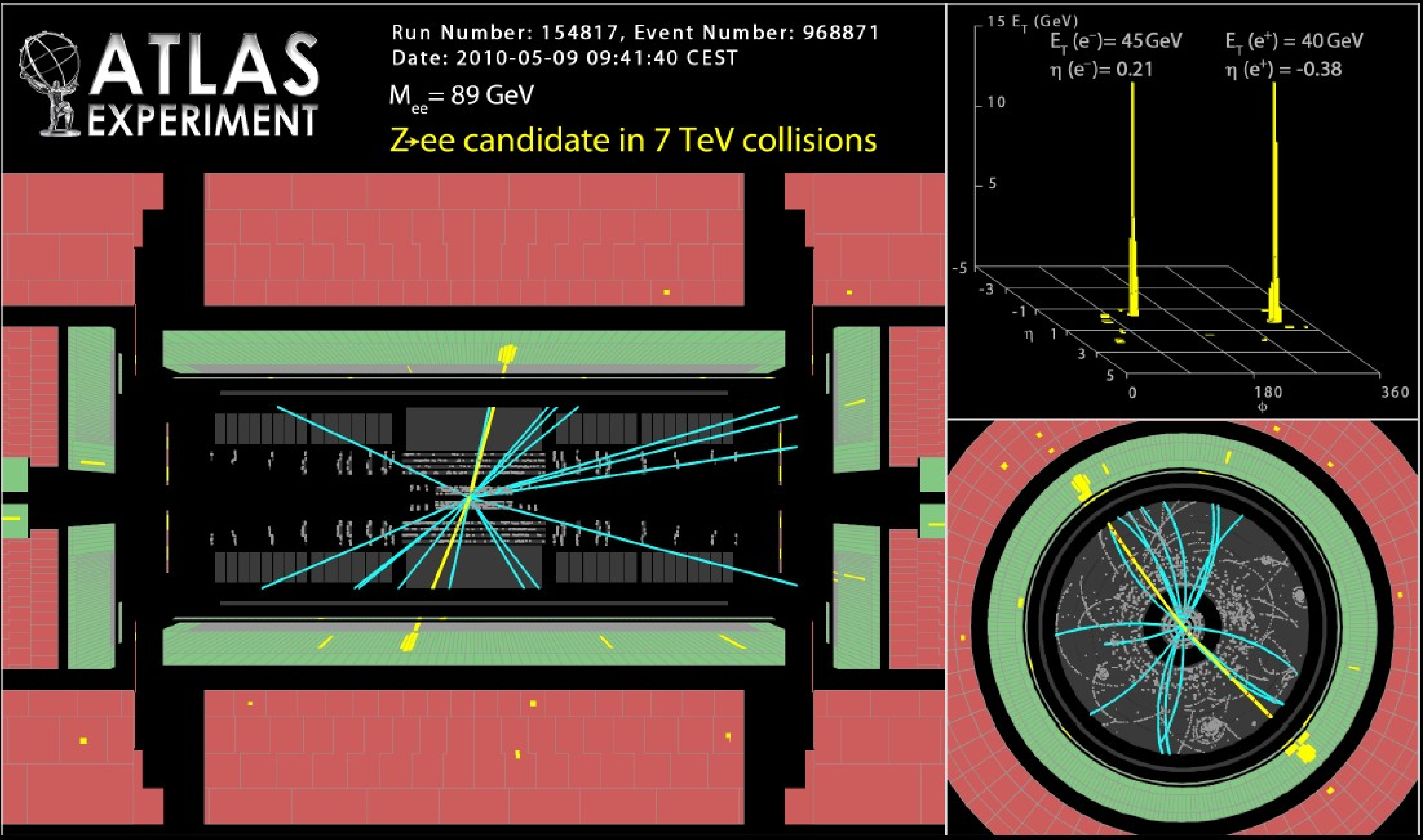
Quark Flavors in Z Production

q qbar → Z

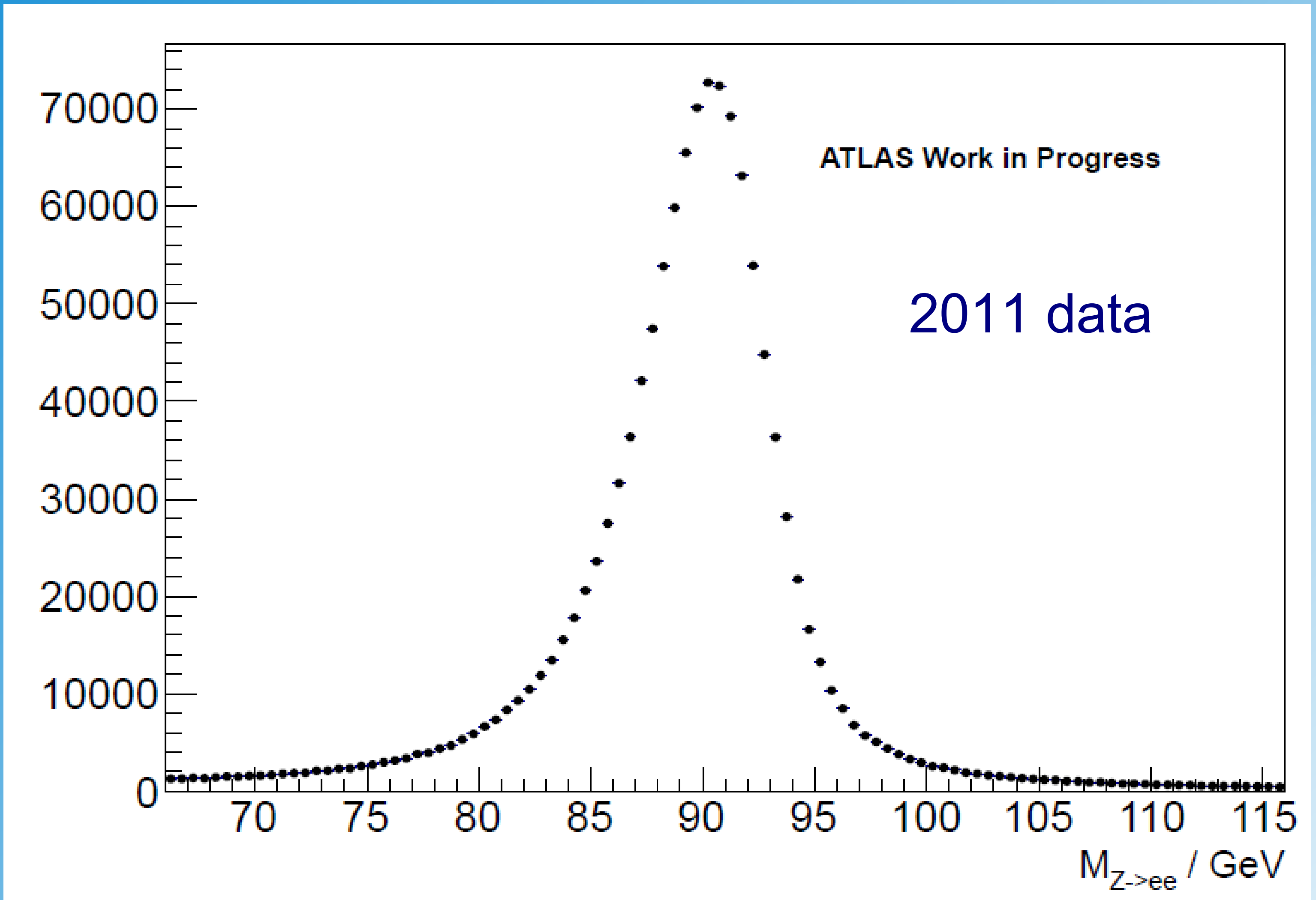


y_z = pseudorapidity of Z-boson: $y = -\ln \tan \theta/2$

Z → ee candidate at ATLAS



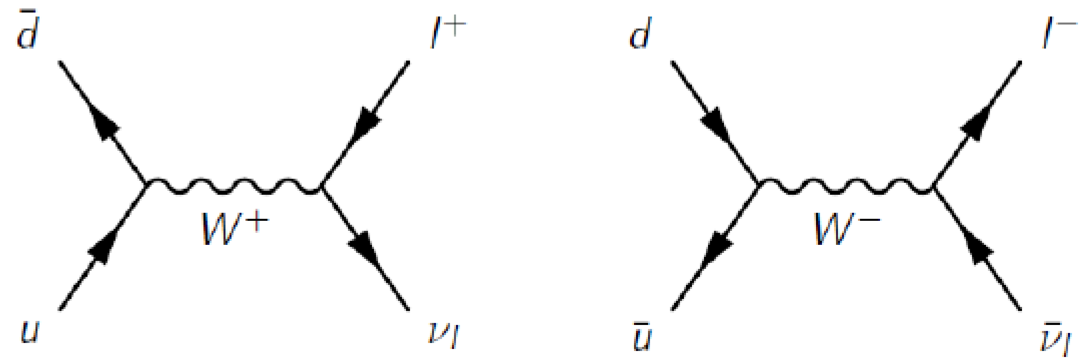
Z-Peak at ATLAS



LHC is a Vector-Boson factory!

W-Production at LHC

Valence quark + sea quark



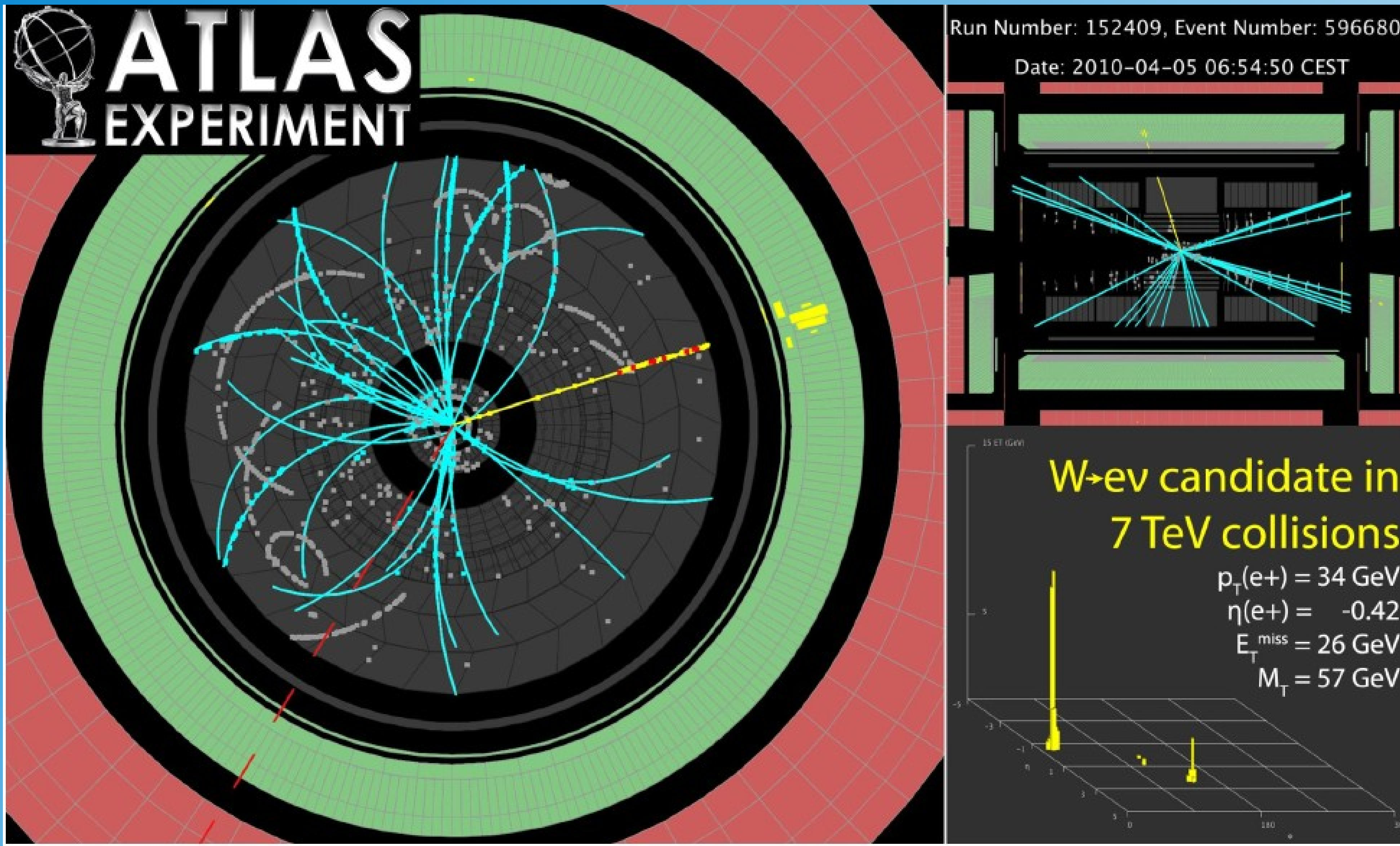
valence quark ratio u/d = 2 $\Rightarrow$ more W^+ than W^-

ATLAS 2010:

[nb]	Data
W^+	6.257±0.017(sta)±0.152(sys)±0.213(lum)±0.188(acc)
W^-	4.149±0.014(sta)±0.102(sys)±0.141(lum)±0.124(acc)
W	10.391±0.022(sta)±0.238(sys)±0.353(lum)±0.312(acc)

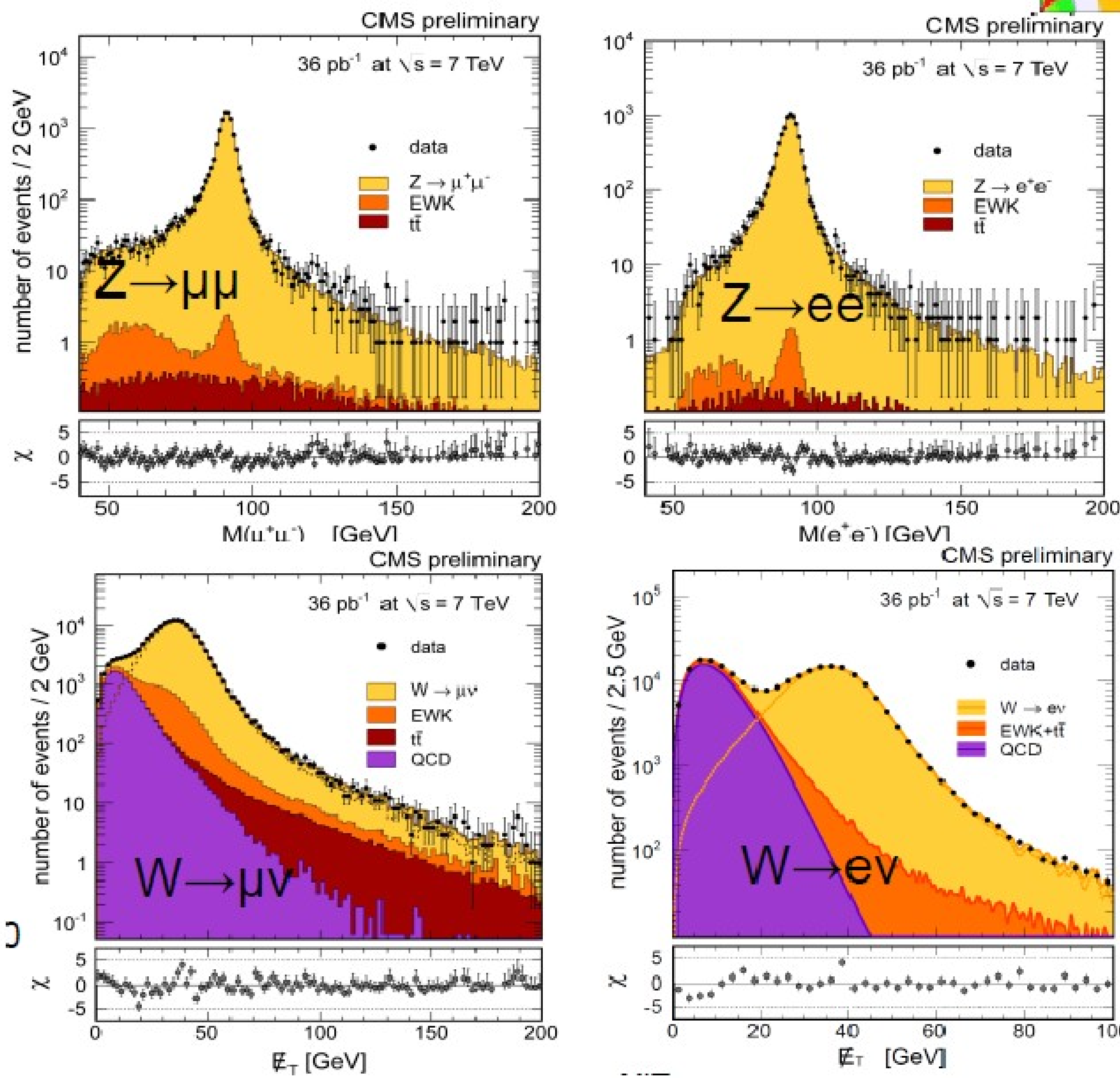
Charge Asymmetric! Tool to disentangle d and u valence quarks

W-boson Production at LHC



$u\,\bar{d} \rightarrow W^+ \rightarrow e^+\,\nu_e$ Anti-quarks from the sea! 12

Z and W production at LHC



P.Harris, Moriond 2011

Instead of E_{eT} use $\not{E}_T$ (i.e. $E_{\nu T}$)

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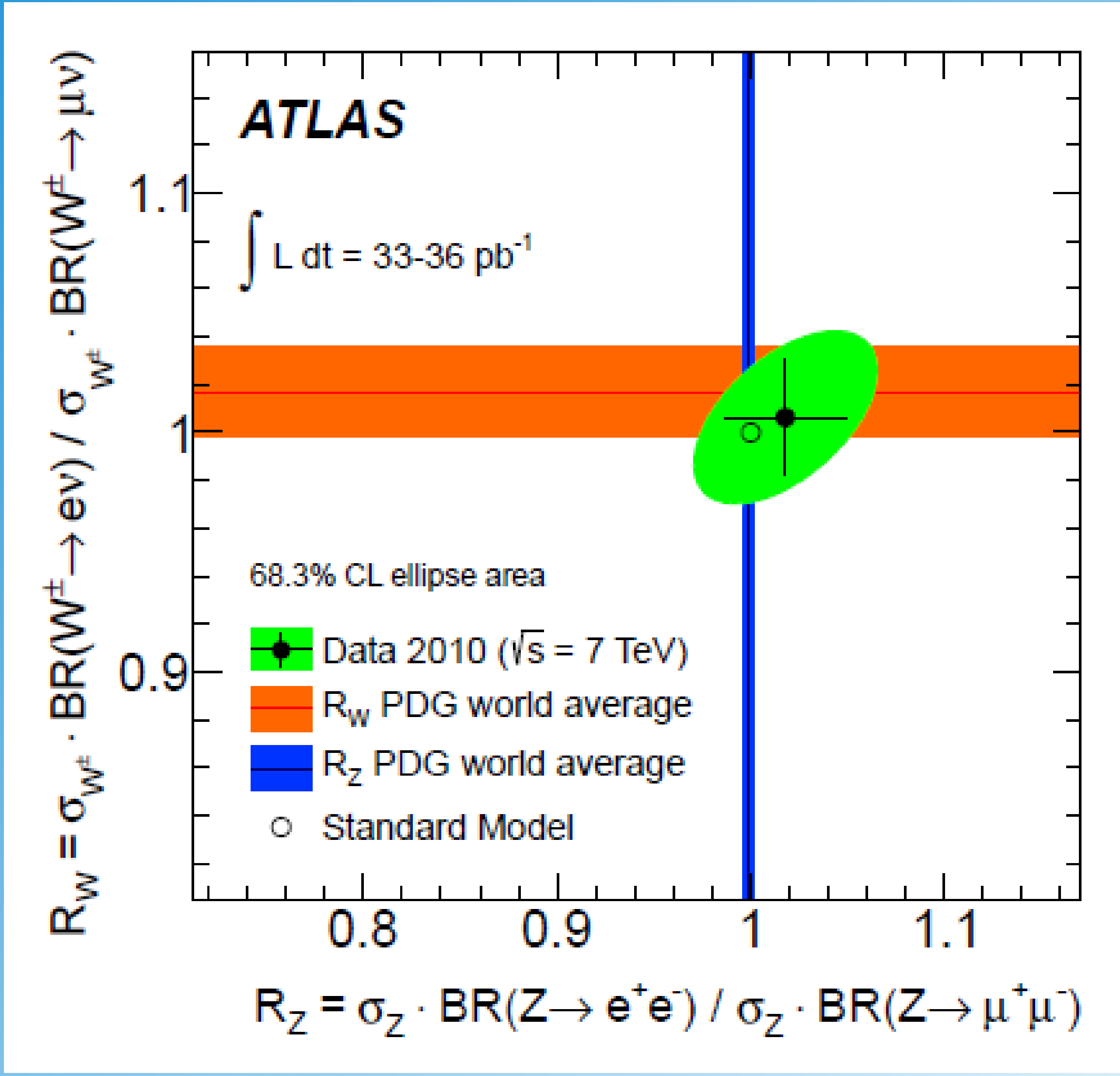
Lepton Universality Check at LHC



Summary

- W, Z boson discovered in 1983
- W, Z masses consistent with SM predictions
- Ratio of W and Z mass consistent with Weinberg angle measured in Neutral Currents
- Lepton universality tested in W, Z Decays
- $W^+ W^-$ pair production cross section measured. Confirmation of triple gauge couplings (WWZ)
- W and Z mass relevant for Higgs mass predictions