Lecture:

Standard Model of Particle Physics

Heidelberg SS 2012

W- and Z-Bosons

Tippübersicht • 1. Spieltag

Pos	+/-	Name	POL 1:1 GRI	RUS 4:1 TSCH	NIE 0:1 DEN	DEU 1:0 POR	SPA 1:1 ITA	IRL 1:3 KRO	FRA 1:1 ENG	UKR 2:1 SWE	Pkt	Siege	Ges
1.	•	das	1:0	1:0 2	3:1	2:1 3	2:1	0:1 2	1:1 4	1:0 3	14	0,50	14
1.	•	Nikolai	1:1 4	2:1 2	3:0	3:1 2	3:1	1:1	2:2 2	2:1 4	14	0,50	14
3.	•	DanielW			2:0	1:0 4	1:1 4	0:1 2	1:2	1:0 3	13		13
3.	•	Jo	1:1 4	0:1	3:1	2:1 3	3:1	1:2 2	1:2	2:1 4	13		13
5.	•	B.Knorr	1:2	0:2	3:2	2:1 3	1:1 4	1:2 2	2:2 2	0:2	11		11
6.	•	Tango12	2:1	2:1 2	3:0	3:1 2	1:0	1:2 2	2:1	2:1 4	10		10
7.	•	F.Foerster	2:0	2:0 2	3:0	4:1 2	1:0	0:1 2	2:1	1:0 3	9		9
7.	•	Neues-Omma-Sofa	3:1	1:0 2	3:0	2:1 3	1:0	1:1		2:1 4	9		9
7.	•	SteffenSchmidt	2:1	1:1	2:0	2:0 2	3:1	0:2 3	1:1 4	0:2	9		9
10.	•	faco	1:2	3:0 3	2:1	2:1 3	2:1	1:22 2	2:3	1:3	8		8
10.	•	Jiri	2:0	1:1	3:0	3:1 2	2:2 2	1:2 2	2:2 2	1:1	8		8
10.	•	Mattia	1:0	1:0 2	1:0	1:0 4	1:0	0:1 2	1:0	1:1	8		8
10.	•	W.Rodejohann	2:0	1:1	3:1	3:1 2	1:1 4	1:2 2	2:0	1:1	8		8
14.	•	tuti	0:2	1:0 2	2:0	2:1 3	1:3	0:1 2	2:3	1:2	7		7
15.	•	S.Dittmeier	2:1	1:0 2	3:1	2:0 2	2:1	0:3 2	3:1	0:0	6		6
16.	•	CarloL	0:0 2	2:2	2:0	2:1 3	3:0	1:1	3:2	0:1	5		5
17.	•	Higgs125	0:0 2	1:1	3:1	2:2	0:0 2	2:1	1:2	1:2	4		4
18.	•	ssb	1:0	0:2	3:1	2:1 3	3:1	0:0	0:1	1:2	3		3
19.	•	Knarf									0		0

Tippübersicht • 2. Spieltag

Pos	+/-	Name	GRI 1:2 TSCH	POL 1:1 RUS	DEN -:- POR	NIE -:- DEU	ITA -:- KRO	SPA -:- IRL	UKR -:- FRA	SWE -:- ENG	Pkt	Siege	Ges
1.	2 ↑	DanielW	0:0	1:1 4	-:-	-:-	-:-	-:-	-:-	-:-	4	0,25	17
1.	2 ↑	Jo	1:2 4	1:2	-:-	-:-	-:-	-:-	-:-	-:-	4	0,25	17
3.	2 ↓	das	1:0	1:2	-:-	-:-	-:-	-:-	-:-	-:-	0	0,50	14
3.	2 ↓	Nikolai	2:1	1:2	-:-	-:-	-:-	-:-	-:-	-:-	0	0,50	14
5.	2 ↑	SteffenSchmidt	0:2 2	2:2 2	-:-	-:-	-:-	-:-	-:-	-:-	4	0,25	13
6.	•	Tango12	0:2 2	0:2	-:-	-:-	-:-	-:-	-:-	-:-	2		12
7.	7 ↑	tuti	1:0	1:1 4	-:-	-:-	-:-	-:-	-:-	-:-	4	0,25	11
8.	3 ↓	B.Knorr	2:1	1:2	-:-	-:-	-:-	-:-	-:-	-:-	0		11
8.	2 ↑	Mattia	0:1 3	0:1	-:-	-:-	-:-	-:-	-:-	-:-	3		11
10.	•	Jiri	0:2 2	0:2	-:-	-:-	-:-	-:-	-:-	-:-	2		10
11.	4 ↓	F.Foerster	1:1	0:1	-:-	-:-	-:-	-:-	-:-	-:-	0		9
11.	4 ↓	Neues-Omma-Sofa	1:0	0:2							0		9
13.	3 ↓	faco	2:1	0:3	-:-	-:-	-:-	-:-	-:-	-:-	0		8
13.	3 ↓	W.Rodejohann	1:1	1:2	-:-	-:-	-:-	-:-	-:-	-:-	0		8
15.	•	S.Dittmeier	2:1	1:0	-:-	-:-	-:-	-:-	-:-	-:-	0		6
16.	•	CarloL	1:0	1:2	-:-	-:-	-:-	-:-	-:-	-:-	0		5
17.	•	Higgs125	1:1	1:3	-:-	-:-					0		4
18.	•	ssb	1:0	2:1	-:-	-:-	-:-	-:-	-:-	-:-	0		3
19.	•	Knarf									0		0

Gesamtübersicht

		Spieltage							Gesamt	
Pos.	Teilnehmer	Fr	1	2	3	Vi	Ha	Fi	Sg	Pkt
1.	DanielW	0	13	4					0,25	17
1.	Jo	0	13	4					0,25	17
3.	das	0	14	0					0,50	14
3.	Nikolai	0	14	0					0,50	14
5.	SteffenSchmidt	0	9	4					0,25	13
6.	Tango12	0	10	2						12
7.	tuti	0	7	4					0,25	11
8.	B.Knorr	0	11	0						11
8.	Mattia	0	8	3						11
10.	Jiri	0	8	2						10
11.	F.Foerster	0	9	0						9
11.	Neues-Omma-Sofa	0	9	0						9
13.	faco	0	8	0						8
13.	W.Rodejohann	0	8	0						8
15.	S.Dittmeier	0	6	0						6
16.	CarloL	0	5	0						5
17.	Higgs125	0	4	0						4
18.	ssb	0	3	0						3
19.	Knarf	0	0	0						0

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:

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

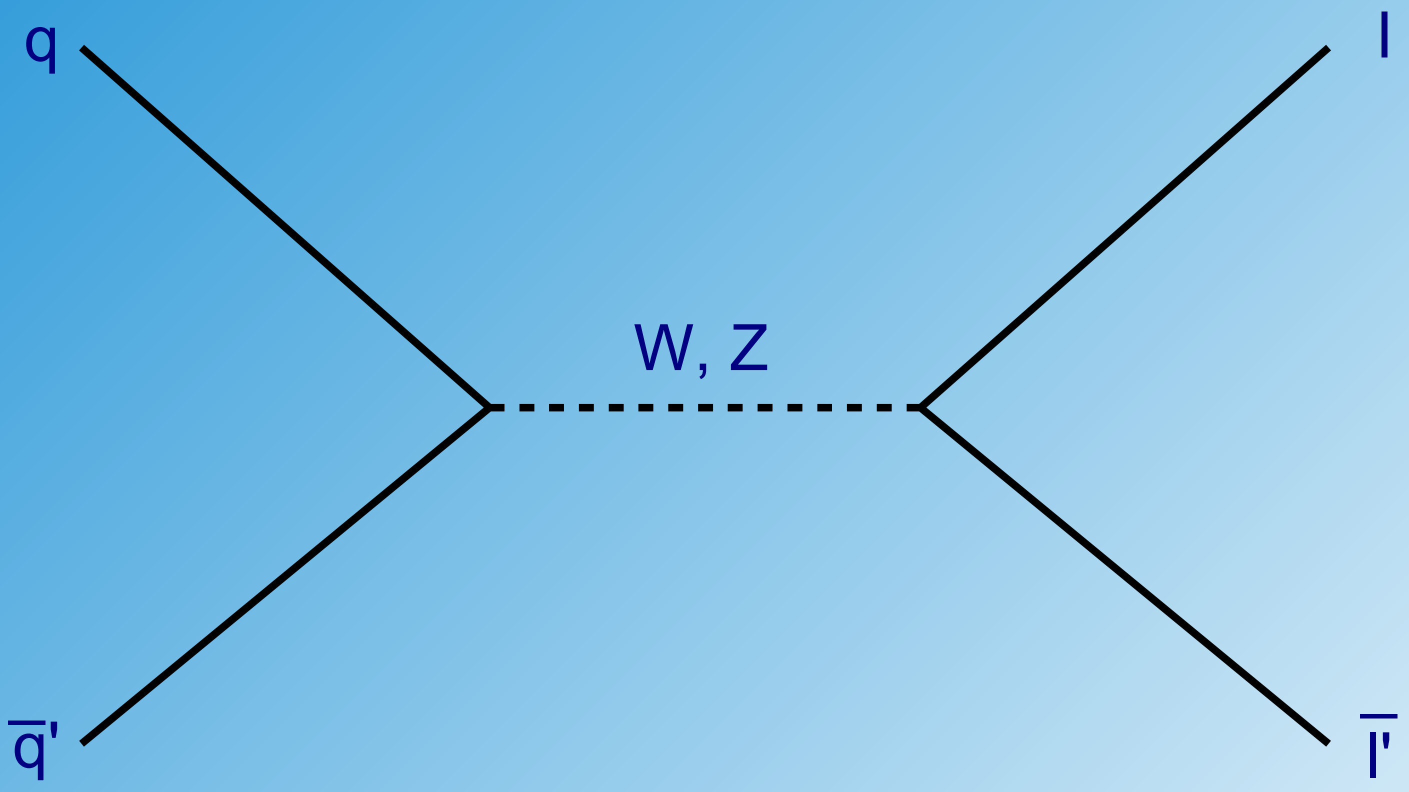
Low energy limits of W-propagator

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

Relation from vector-boson mass matrix

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

W,Z Physics at Hadron Colliders



Intermezzo QCD

QCD Lagrangian (physical fields)

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

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

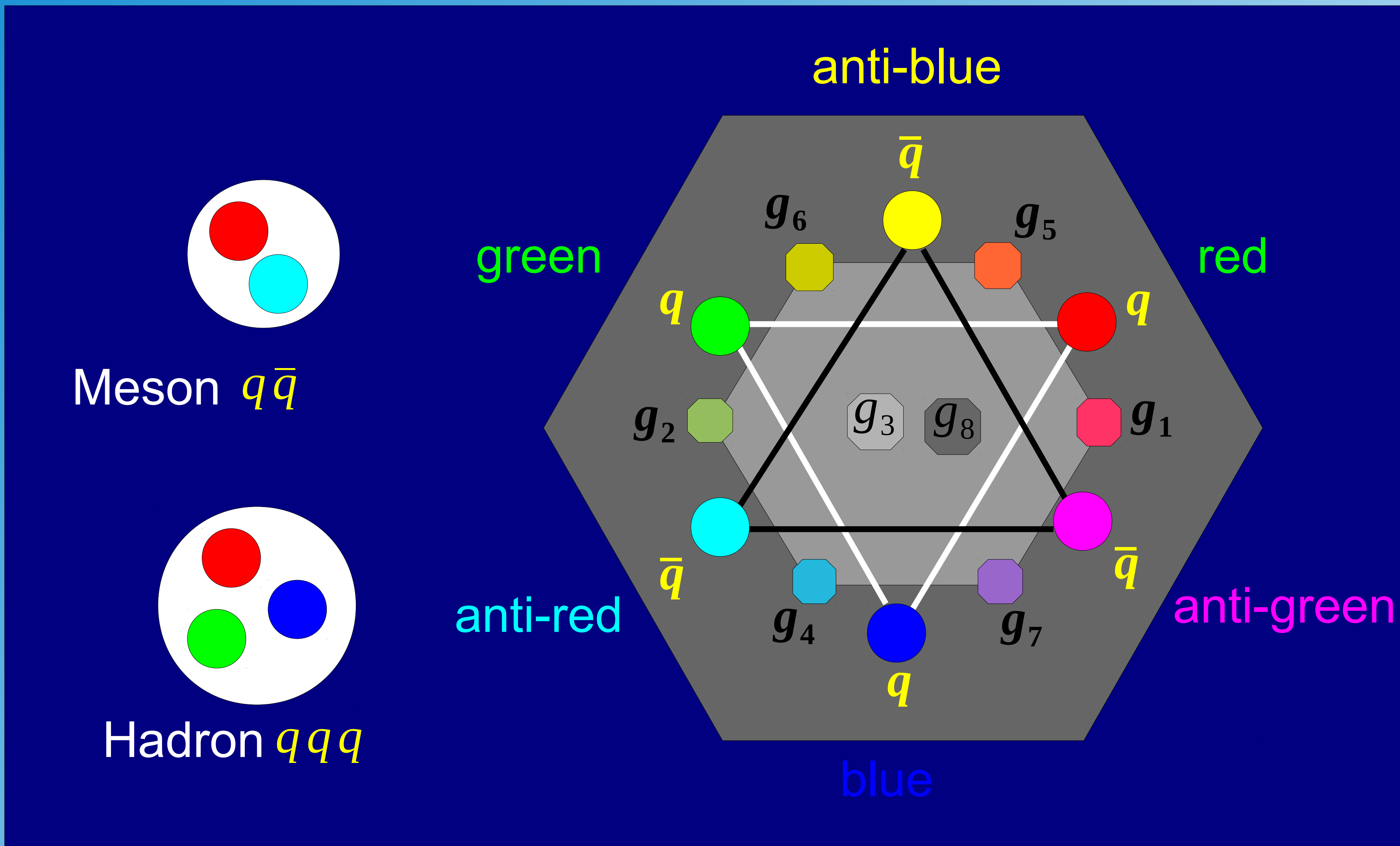
8 generators (N*N-1)

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

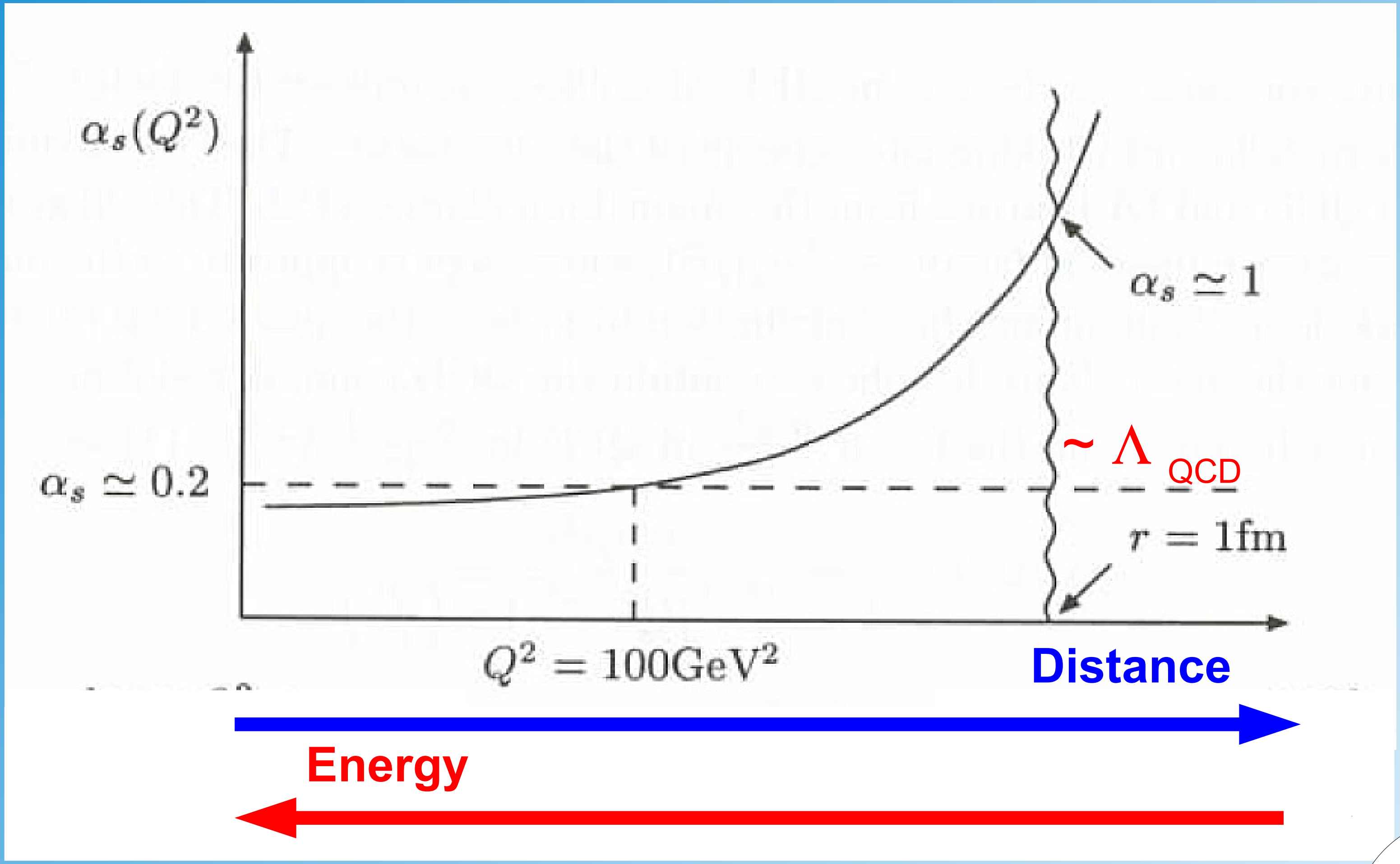
$$t_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad t_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad t_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

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

Quantum Chromodynamics

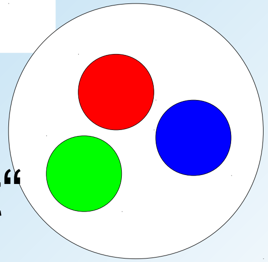


Running of alpha$_s$



„Asymptotic Freedom“

„Confinement“

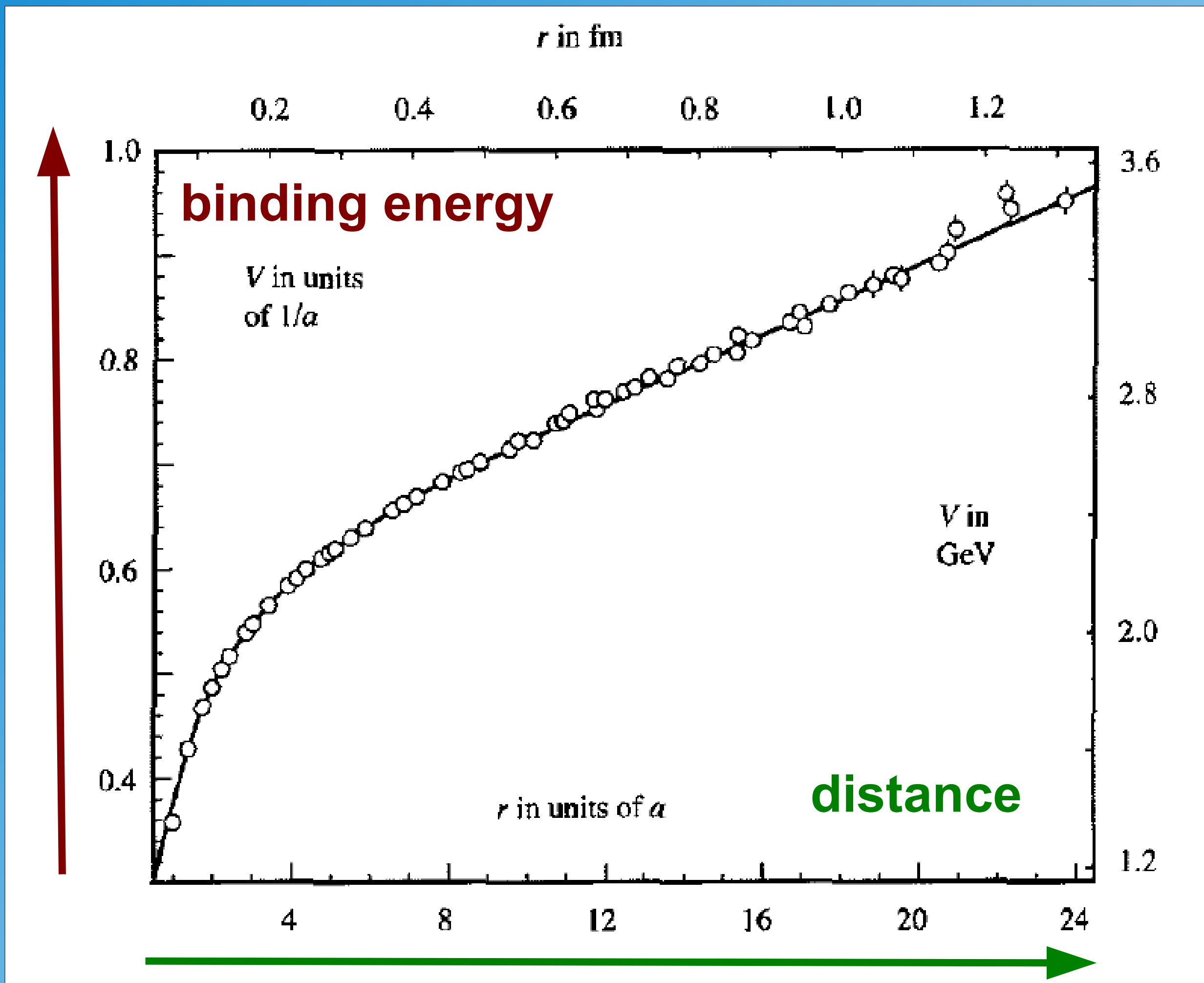


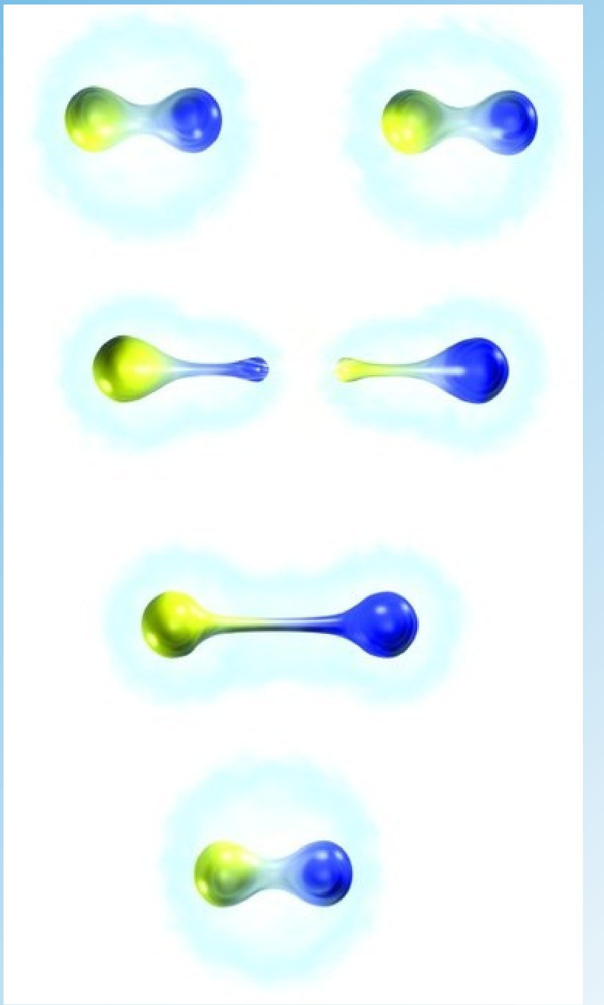
„Asymptotic Freedom“

„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 lead to “jet” structure
- Hadronisation
  - long distance scale
  - formation of hadrons from quarks and gluons

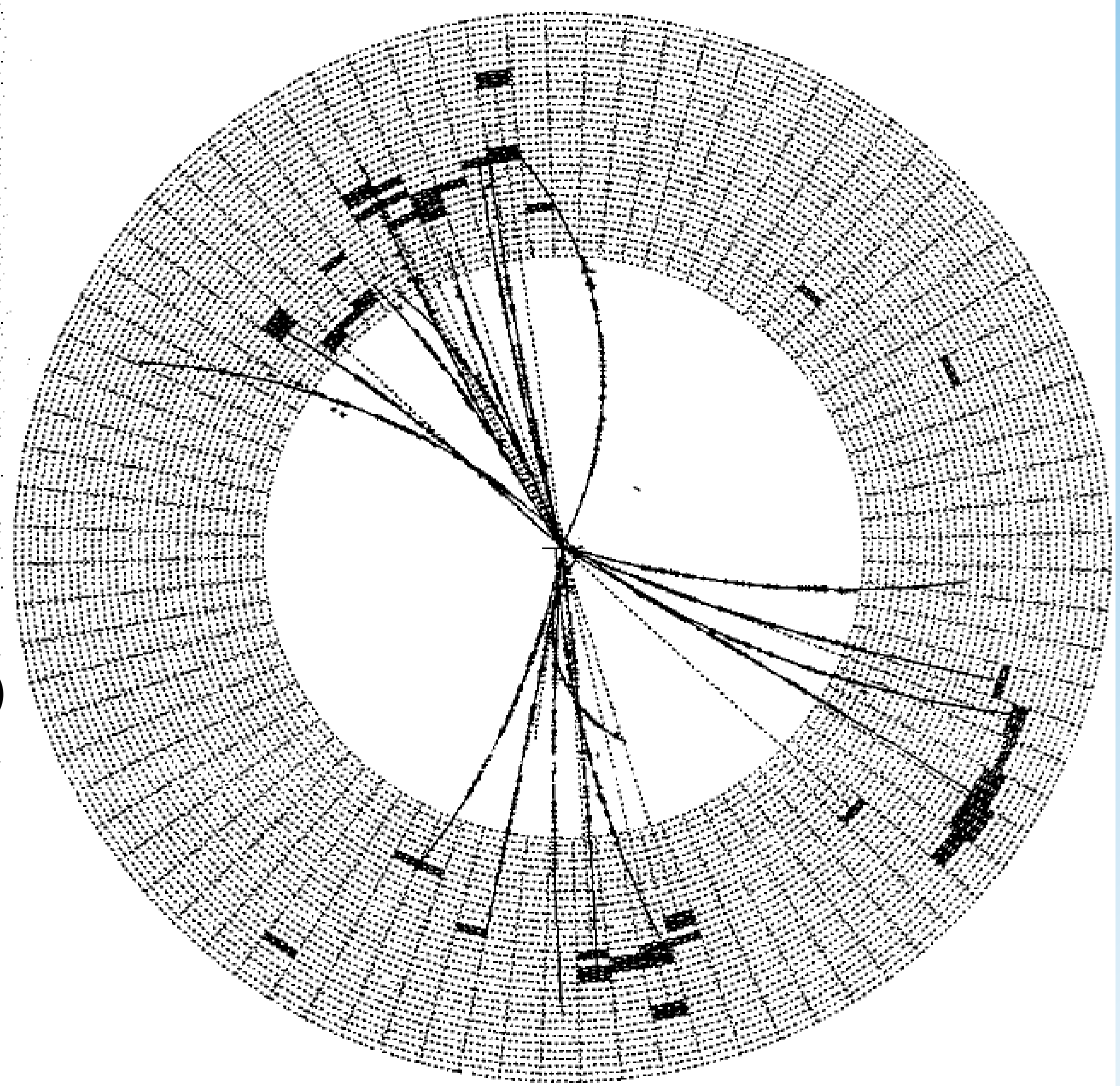
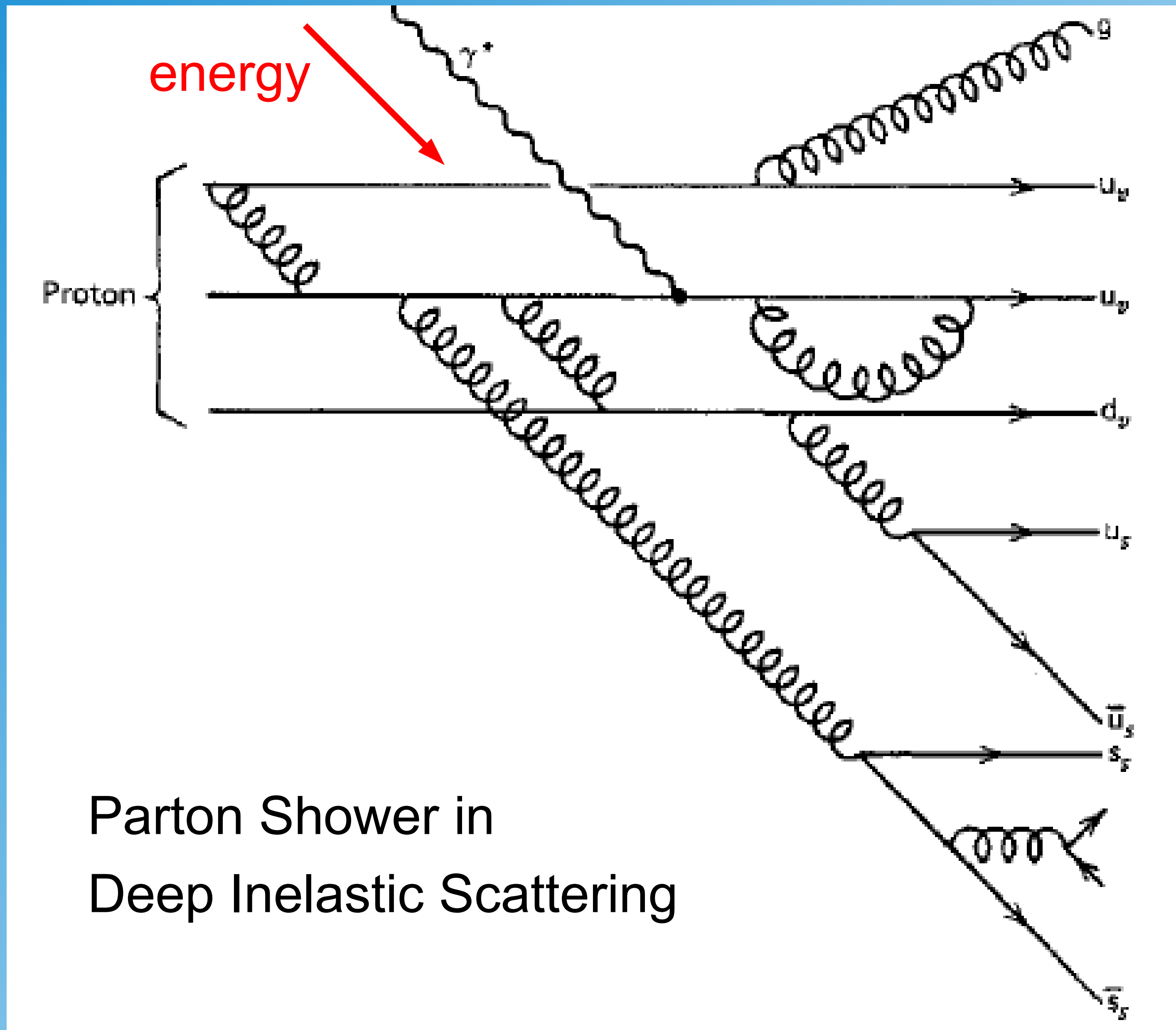


Fig. 11.12 A three-jet event observed by the JADE detector at PETRA.

Parton Showers

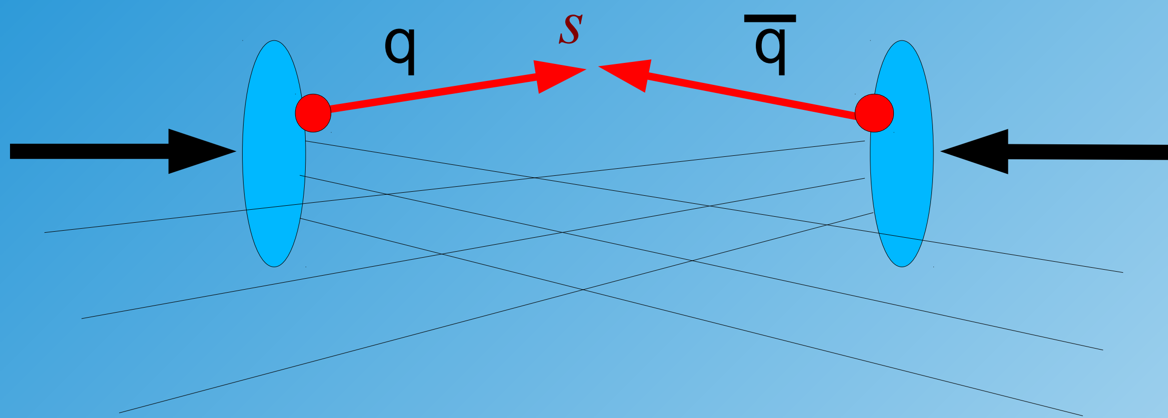


Luminosity-Function

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

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

$$\frac{\hat{s}}{s} = z$$



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?

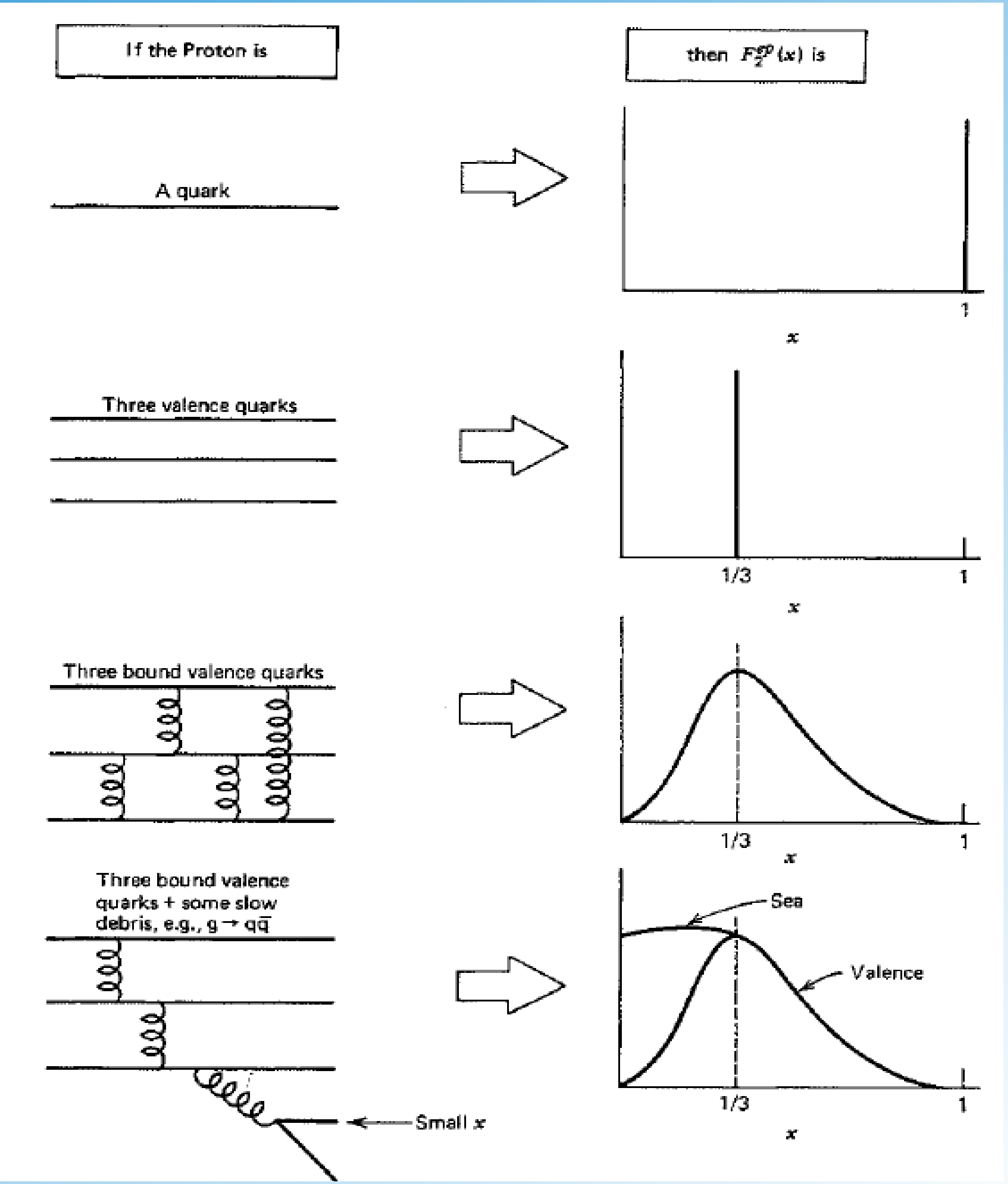
Answer: factorisation scale typically: $\mu_F = \hat{s}$

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)



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

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

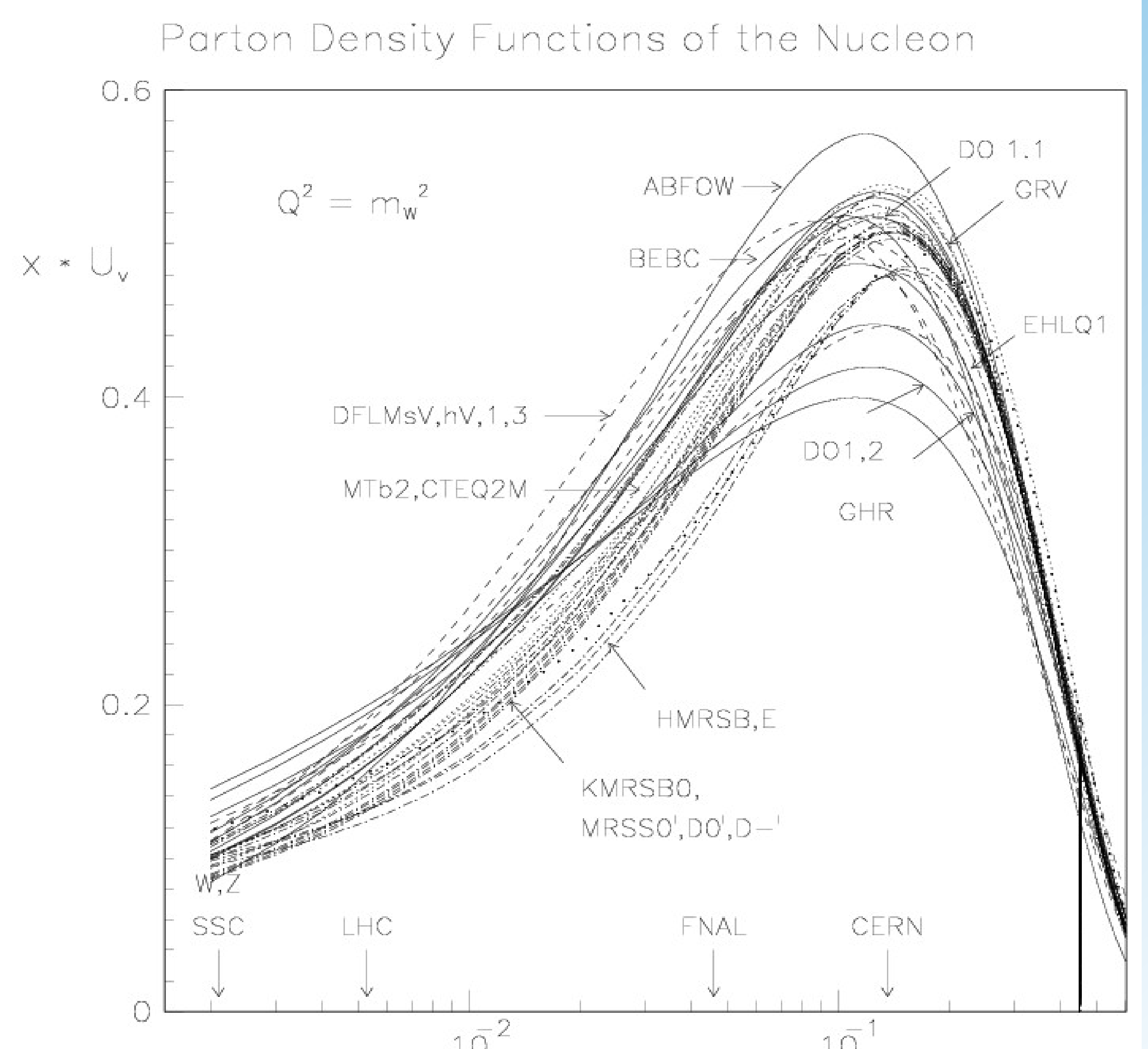
parton momentum fractions:

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

→ valence-quark region

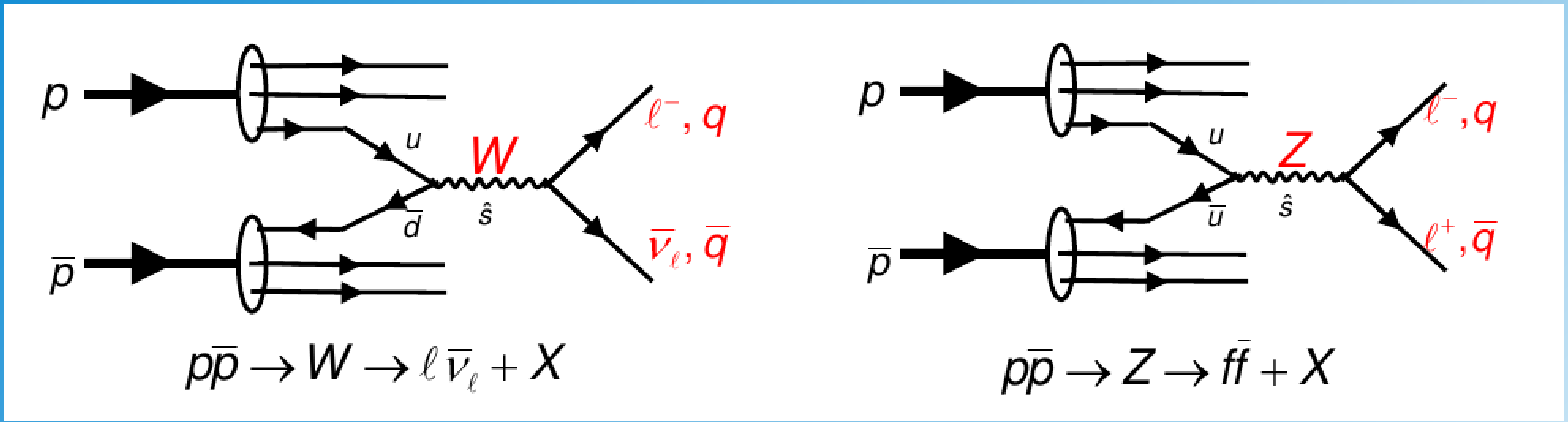
$p\,\bar{p} \rightarrow W\,(Z)\,X$

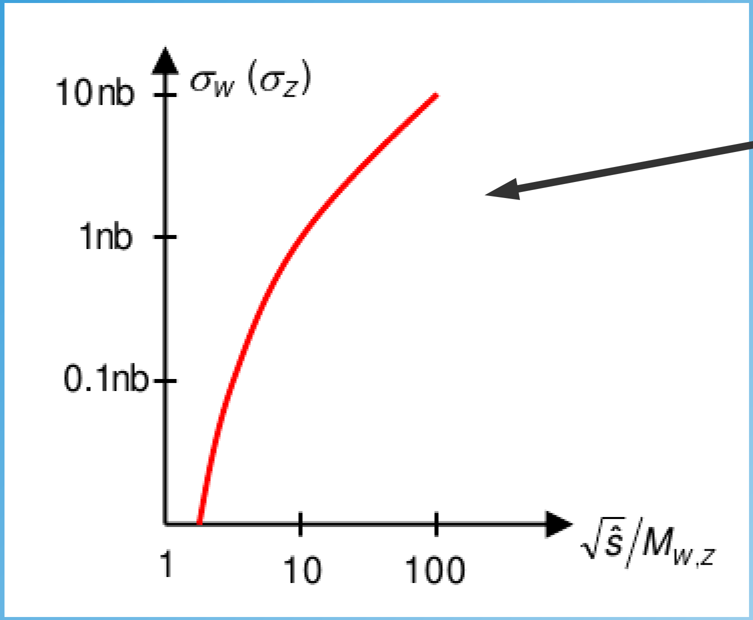
need anti-protons!



PDFLIB 2000

W,Z Cross Section





Reasonable cross section of 0.1 nb at

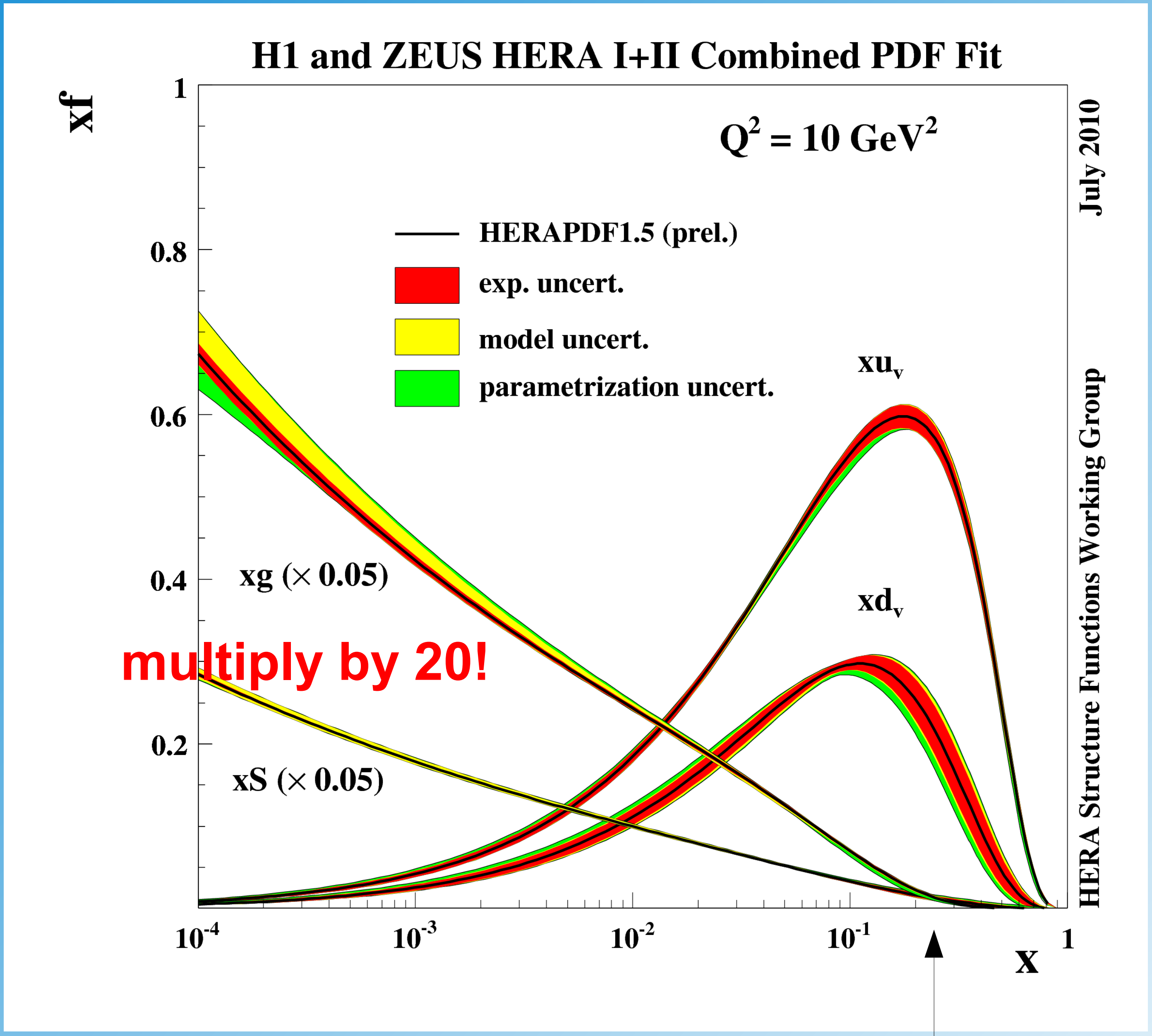
$s^{1/2}/M_W \sim 2$

Typically:

x_1 , $x_2 \sim 0.4$

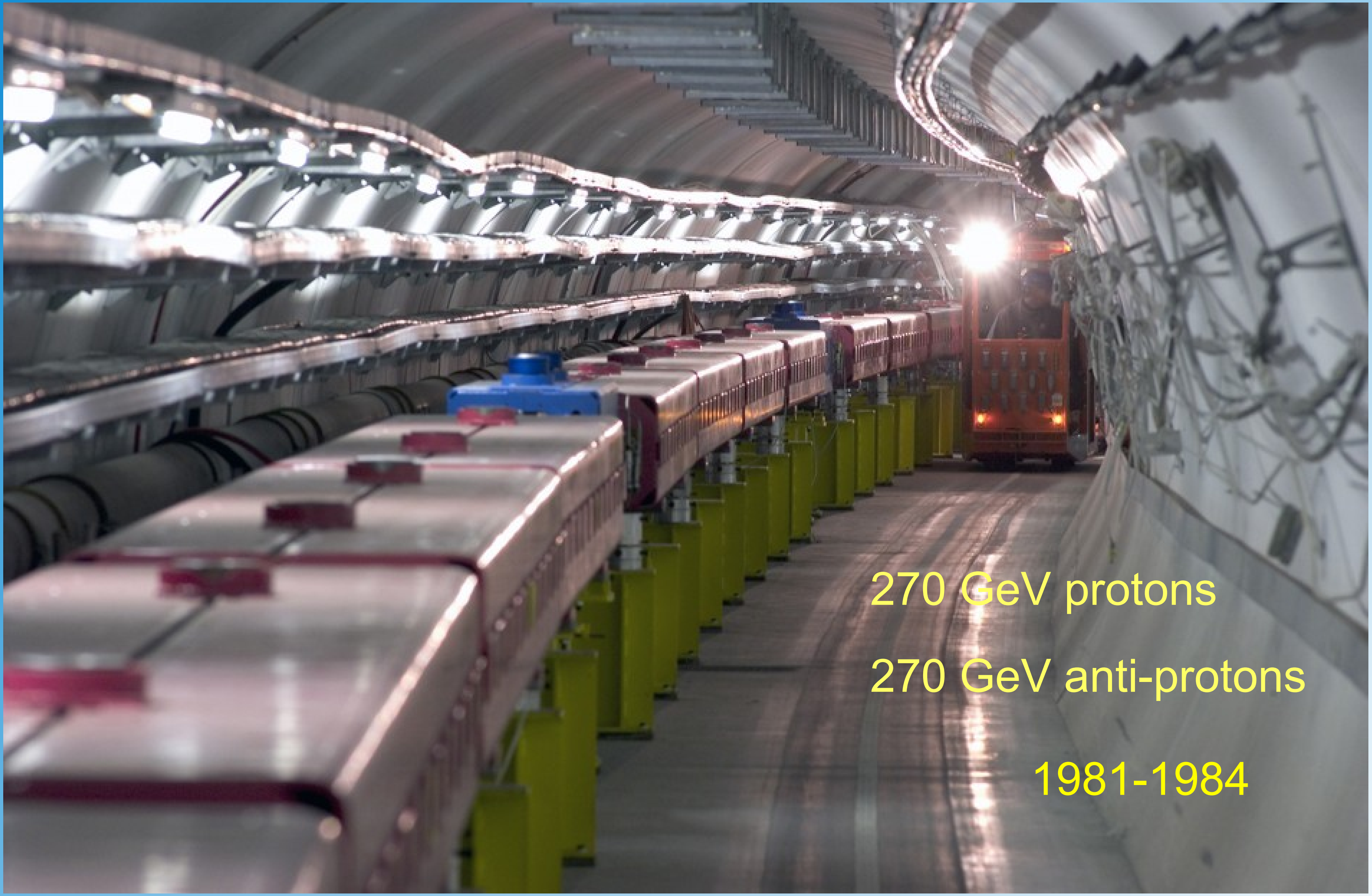
need high luminosity!

Proton Parton Densities



SPS energy

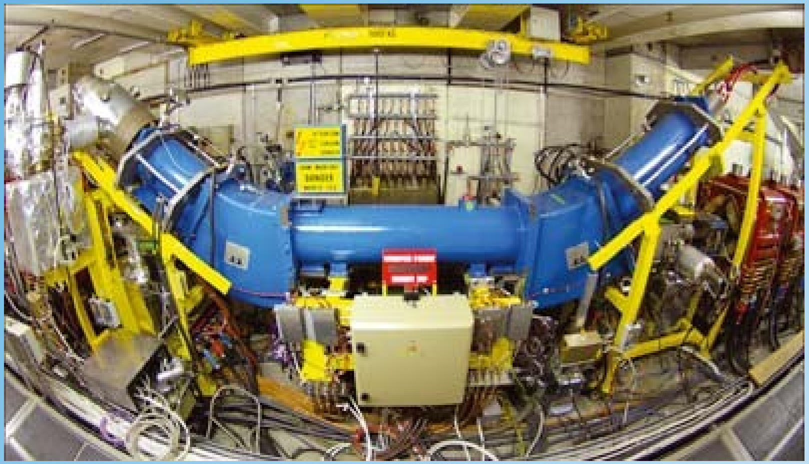
Super Proton (Antiproton) Synchrotron



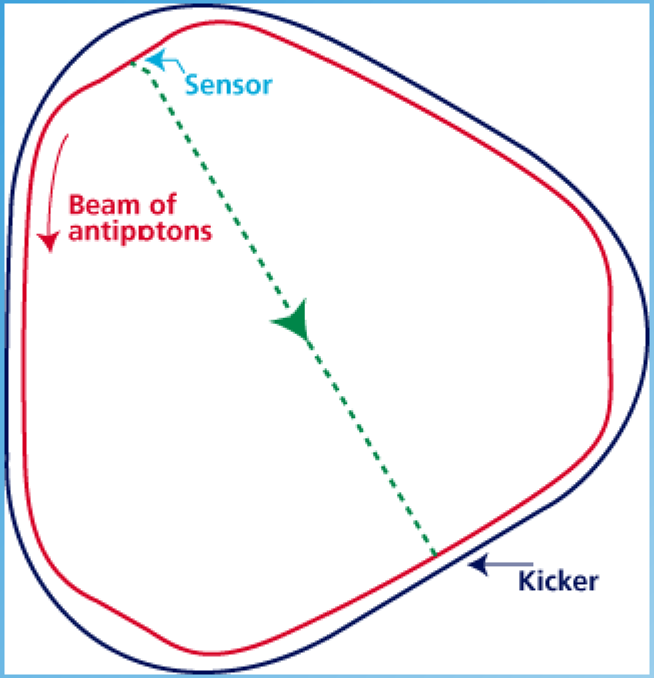
Cooling of Anti-protons

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

electron cooling of anti-protons

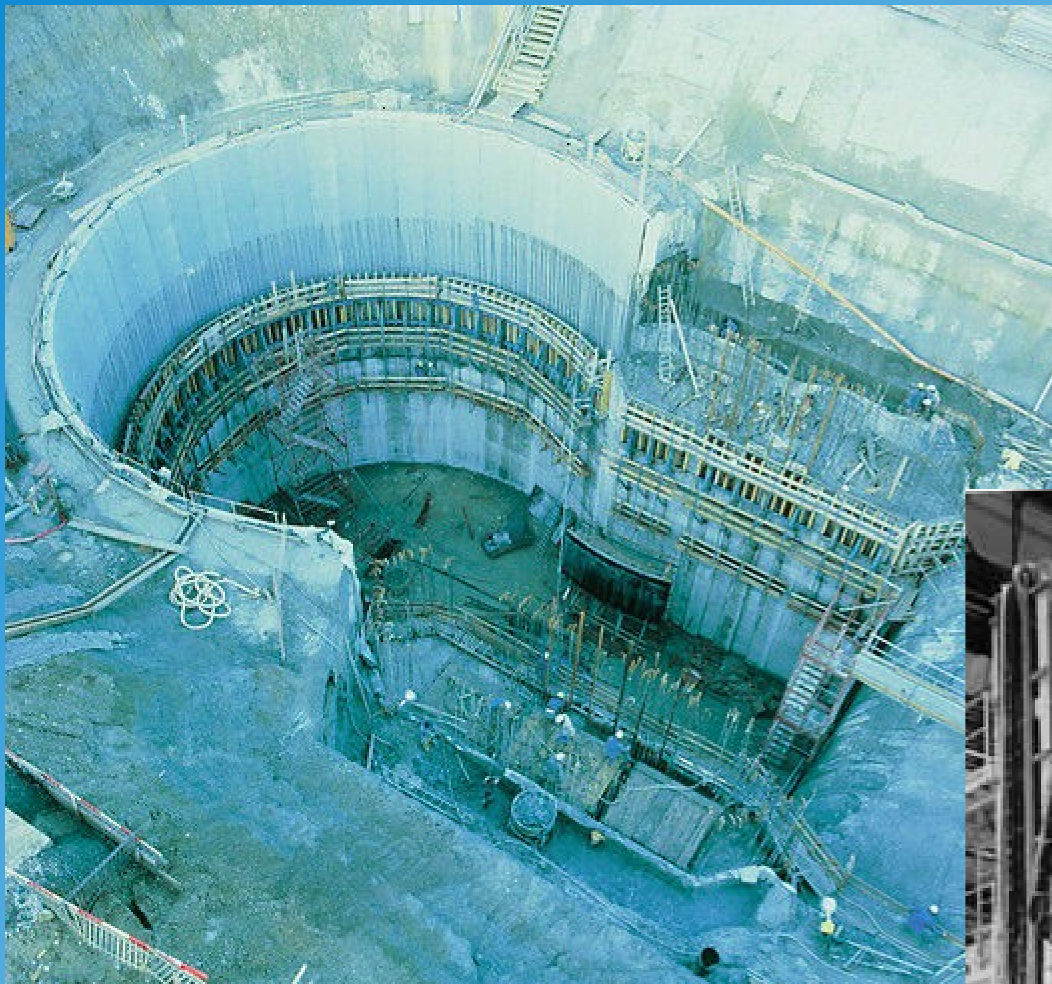


Stochastic cooling of anti-protons

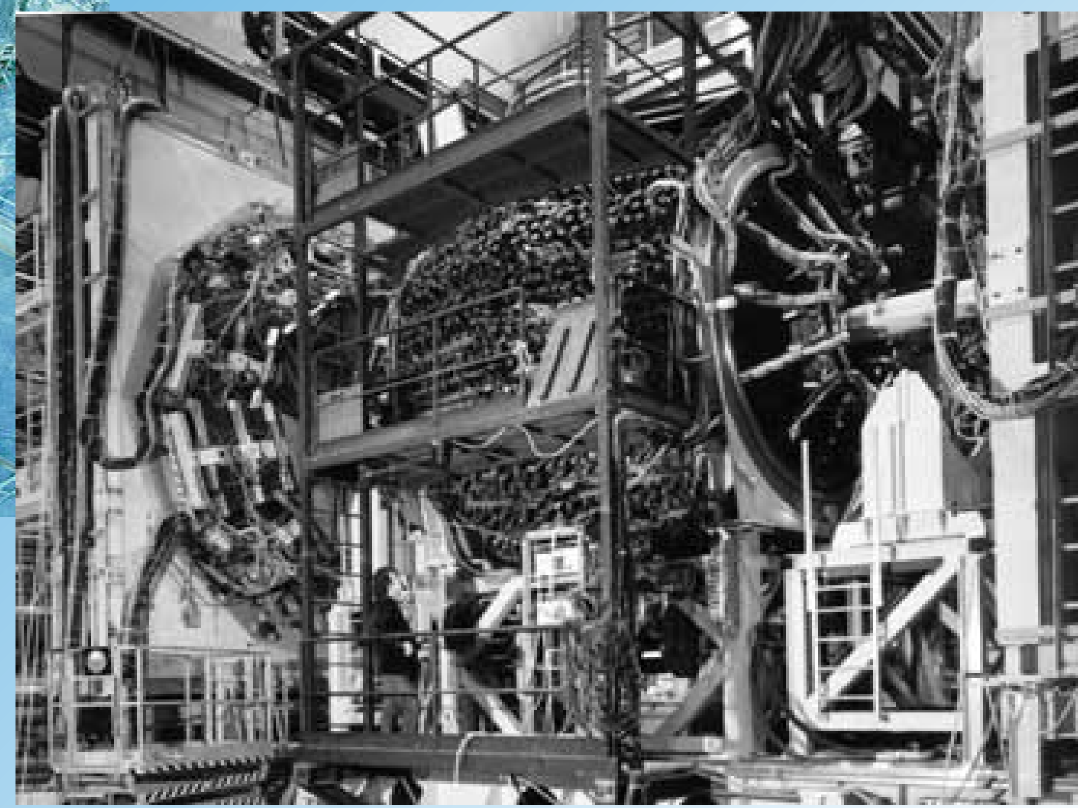


Simon van de Meer

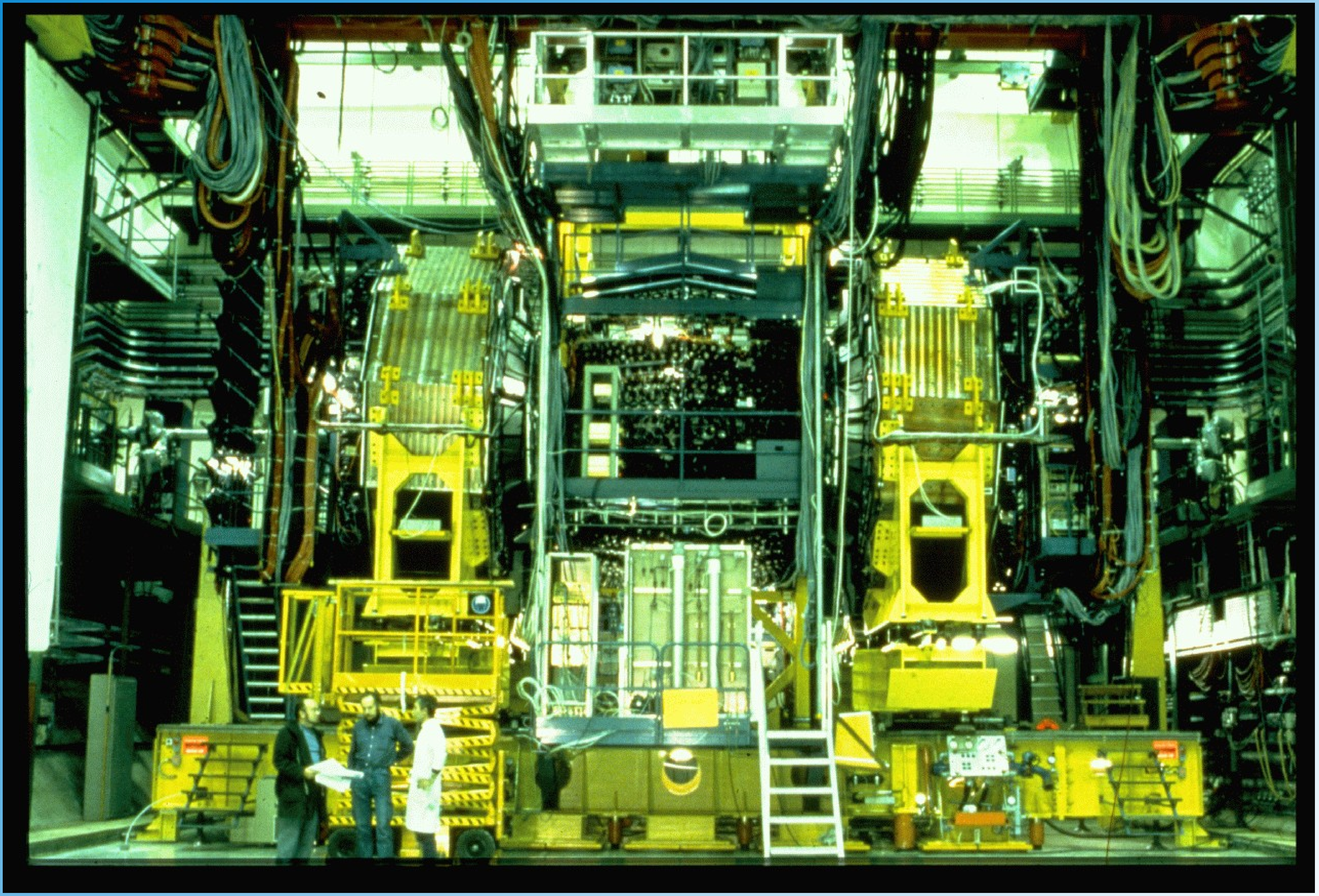
UA1 Experiment



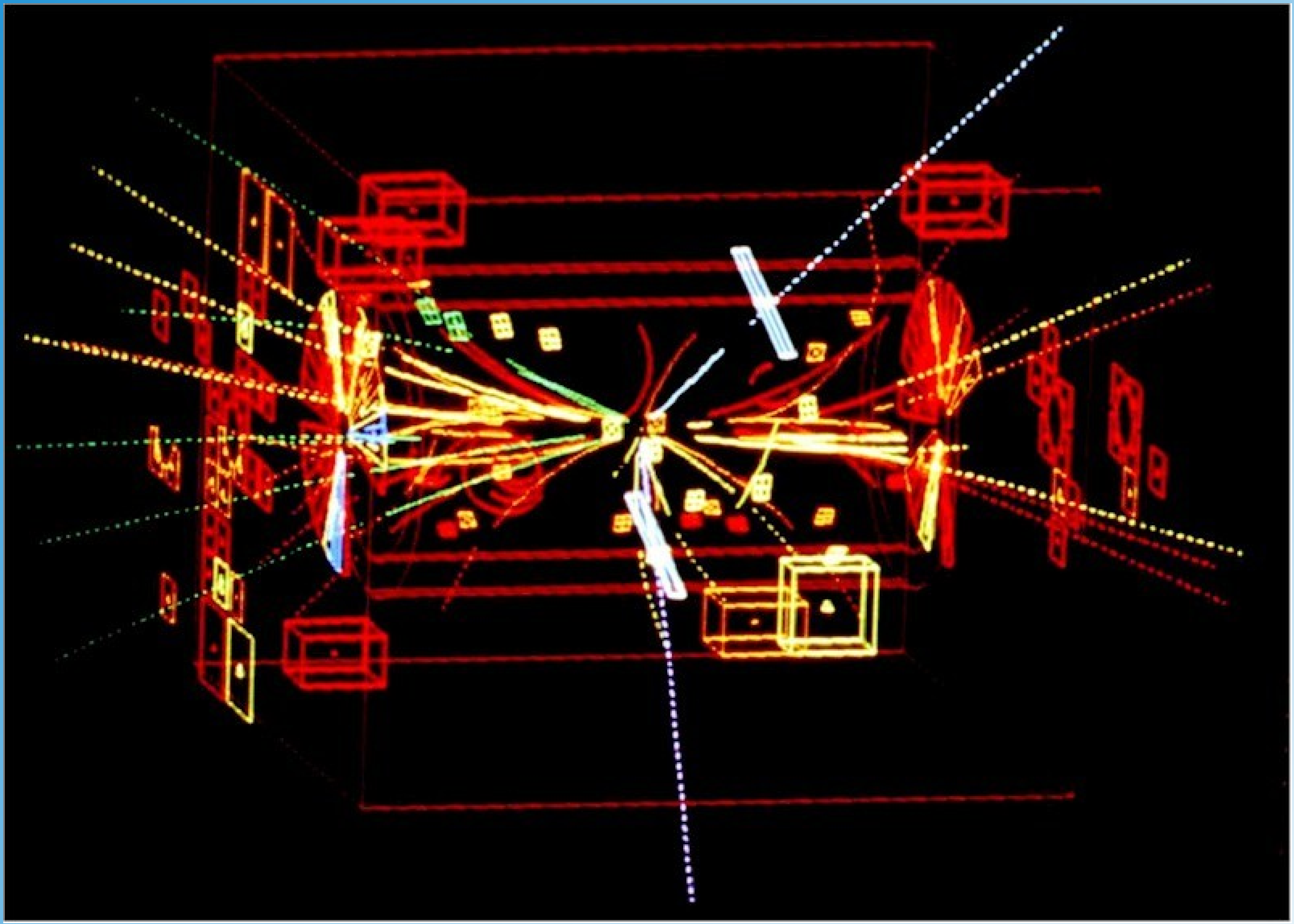
“modern” high energy collider experiment able to run at high collision rates (fast electronics)



UA2 experiment

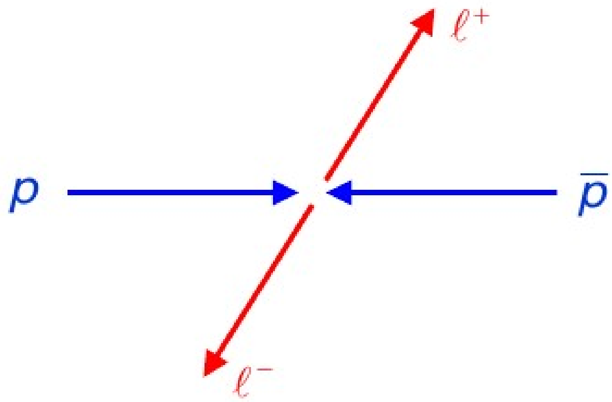


Candidate $Z \rightarrow ee$



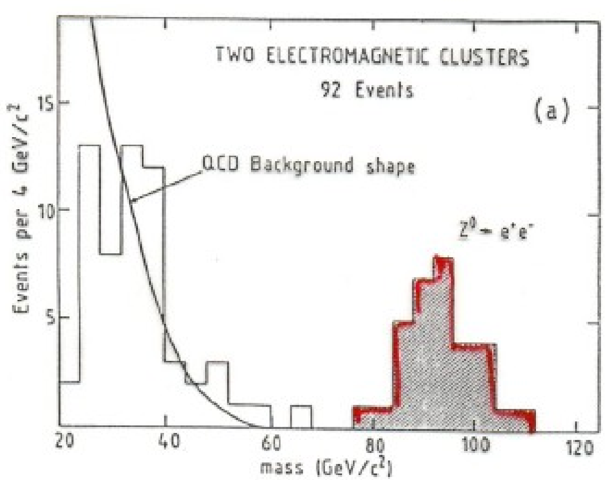
Z-candidate Event Signature

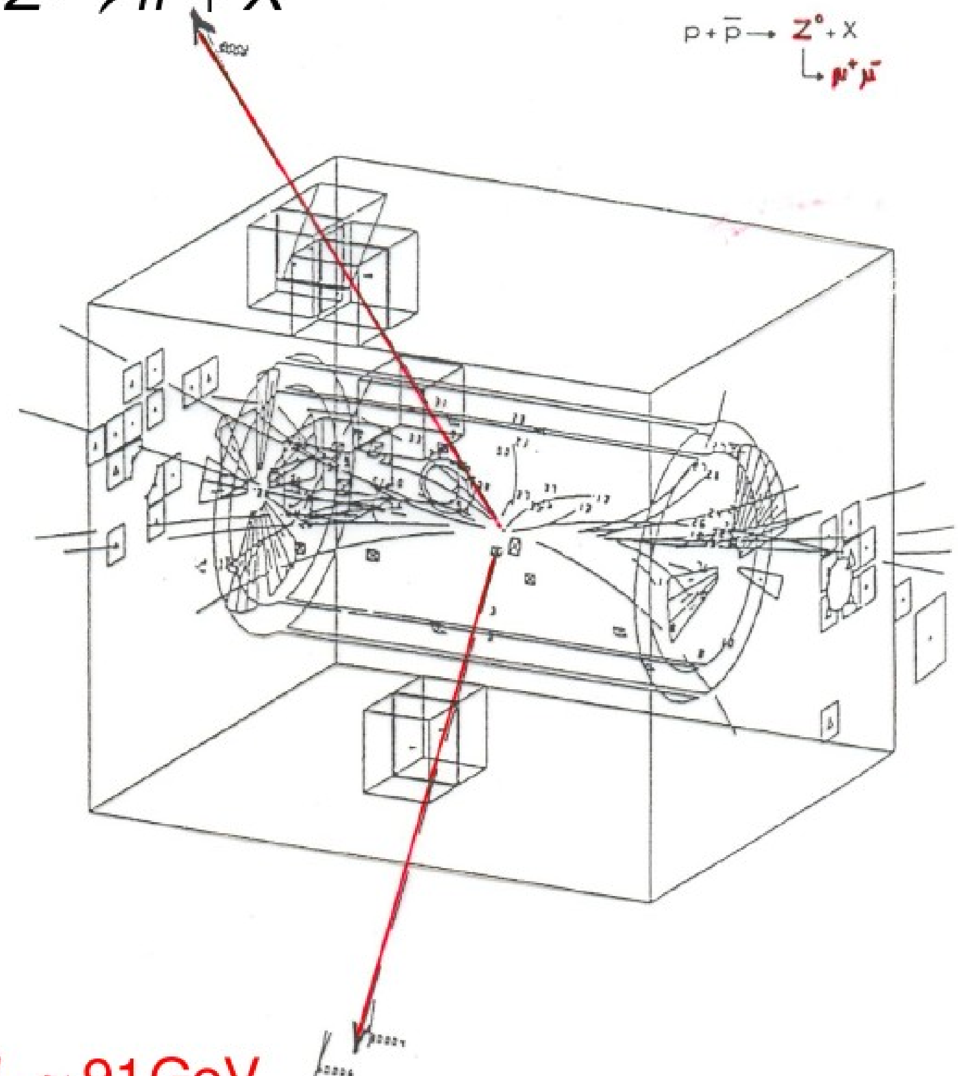
$$p\bar{p} \to Z \to f\bar{f} + X$$



High-energy lepton pair:

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





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

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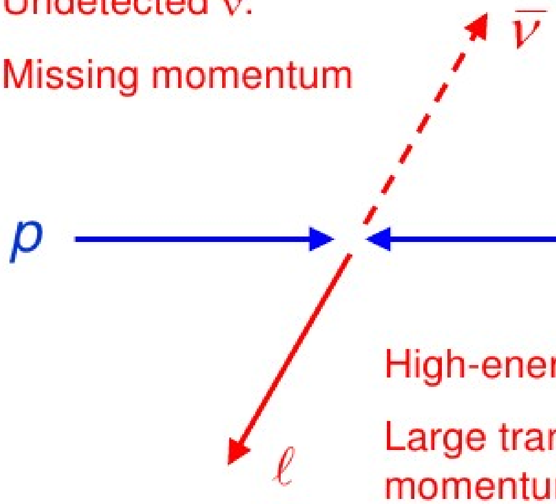
W-candidates

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

Undetected ν:

Missing momentum



High-energy lepton:

Large transverse momentum p_t

How can the W mass be reconstructed ?

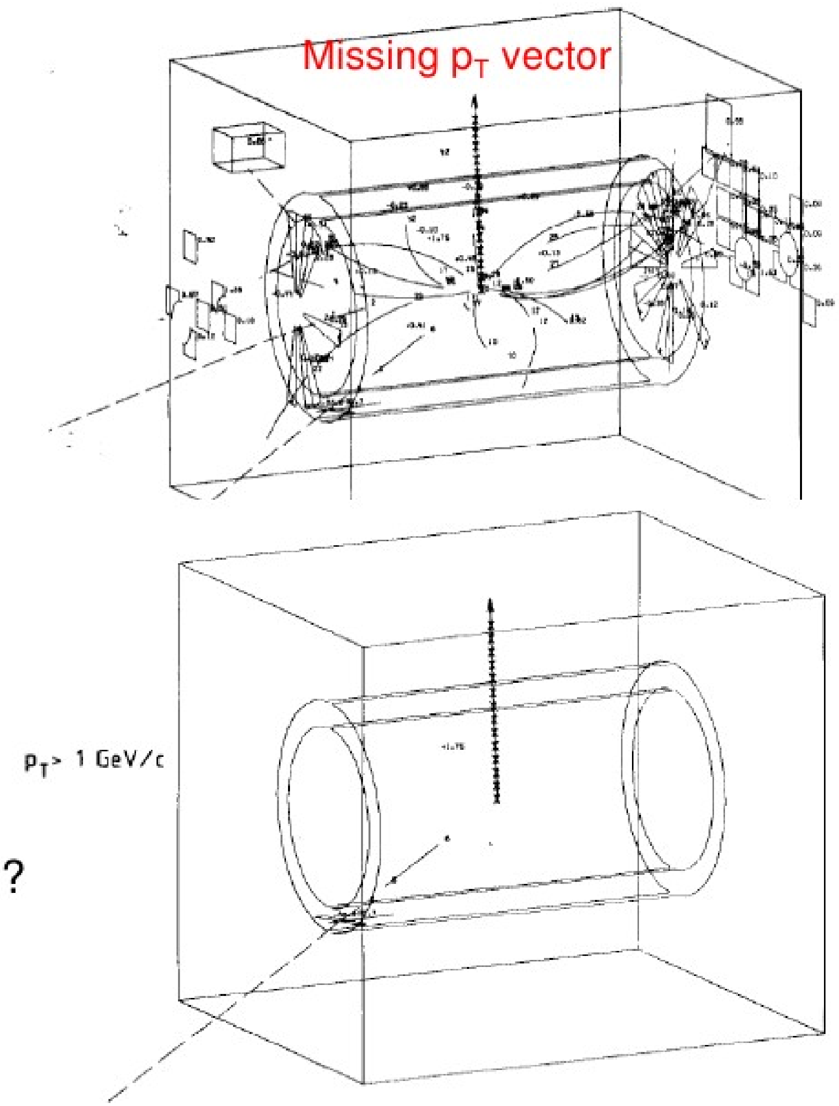


Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_t>1 GeV are shown.

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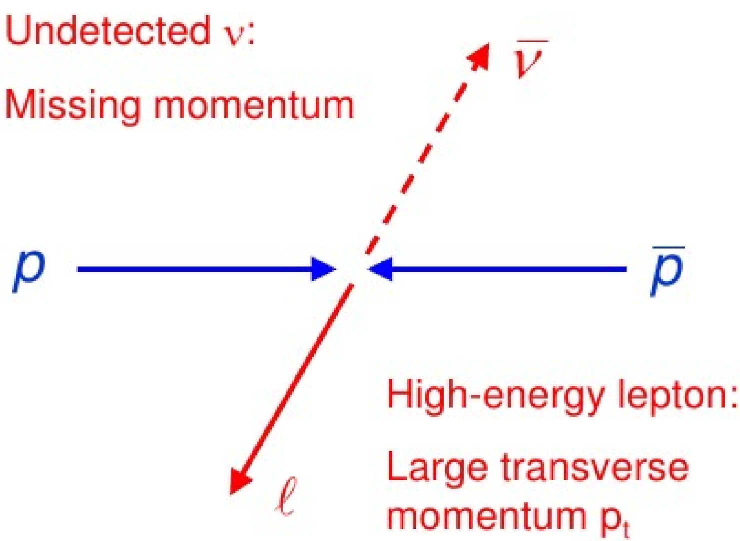
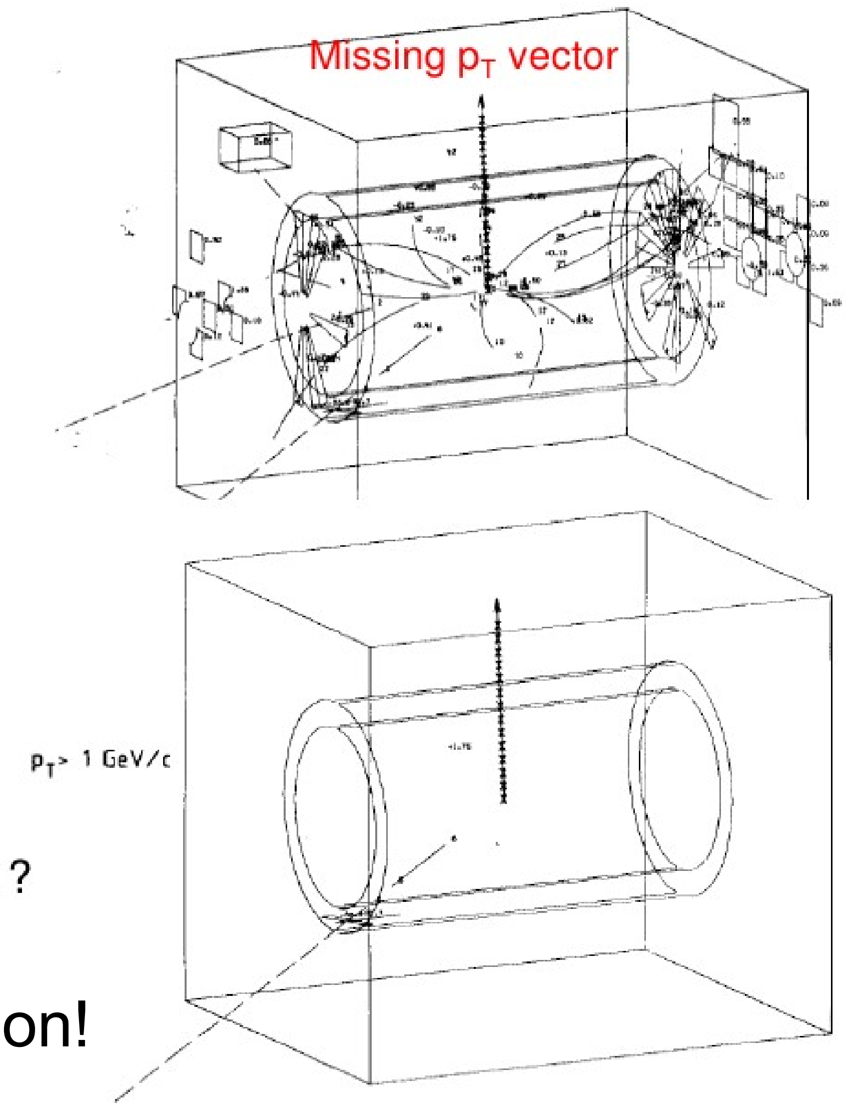
W-candidates

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





How can the W mass be reconstructed ?

exploit momentum conservation!

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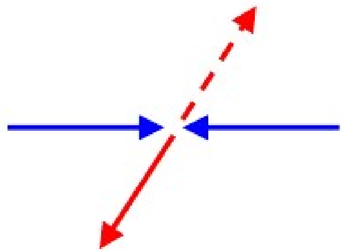
Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_t>1 GeV are shown.

9

Kinematic Reconstruction of W-bosons

W mass measurement



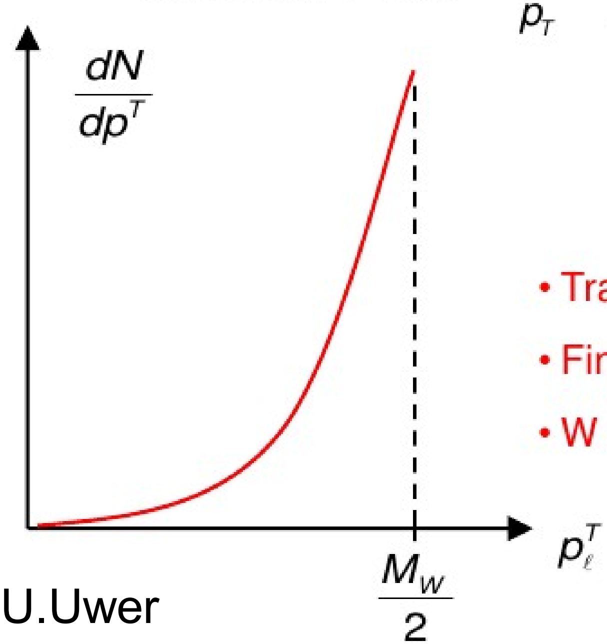
In the W rest frame:

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

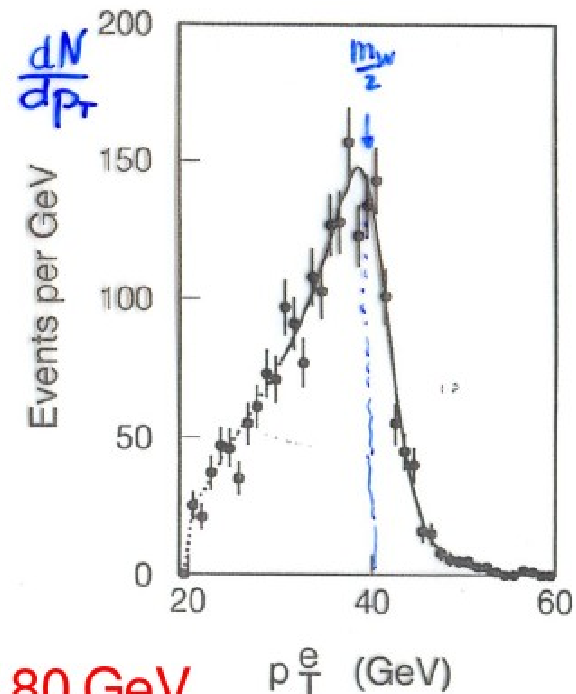
In the lab system:

- 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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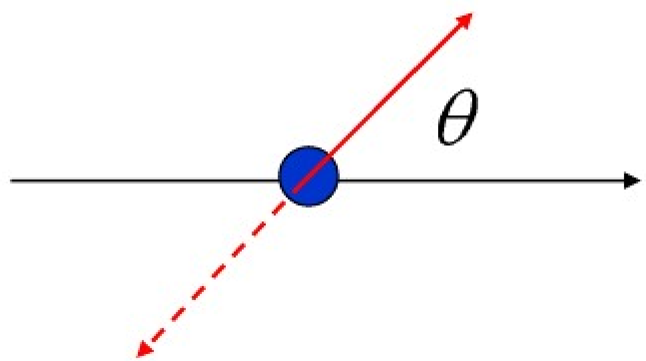
10

Jacobian Peak

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

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

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



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

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

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

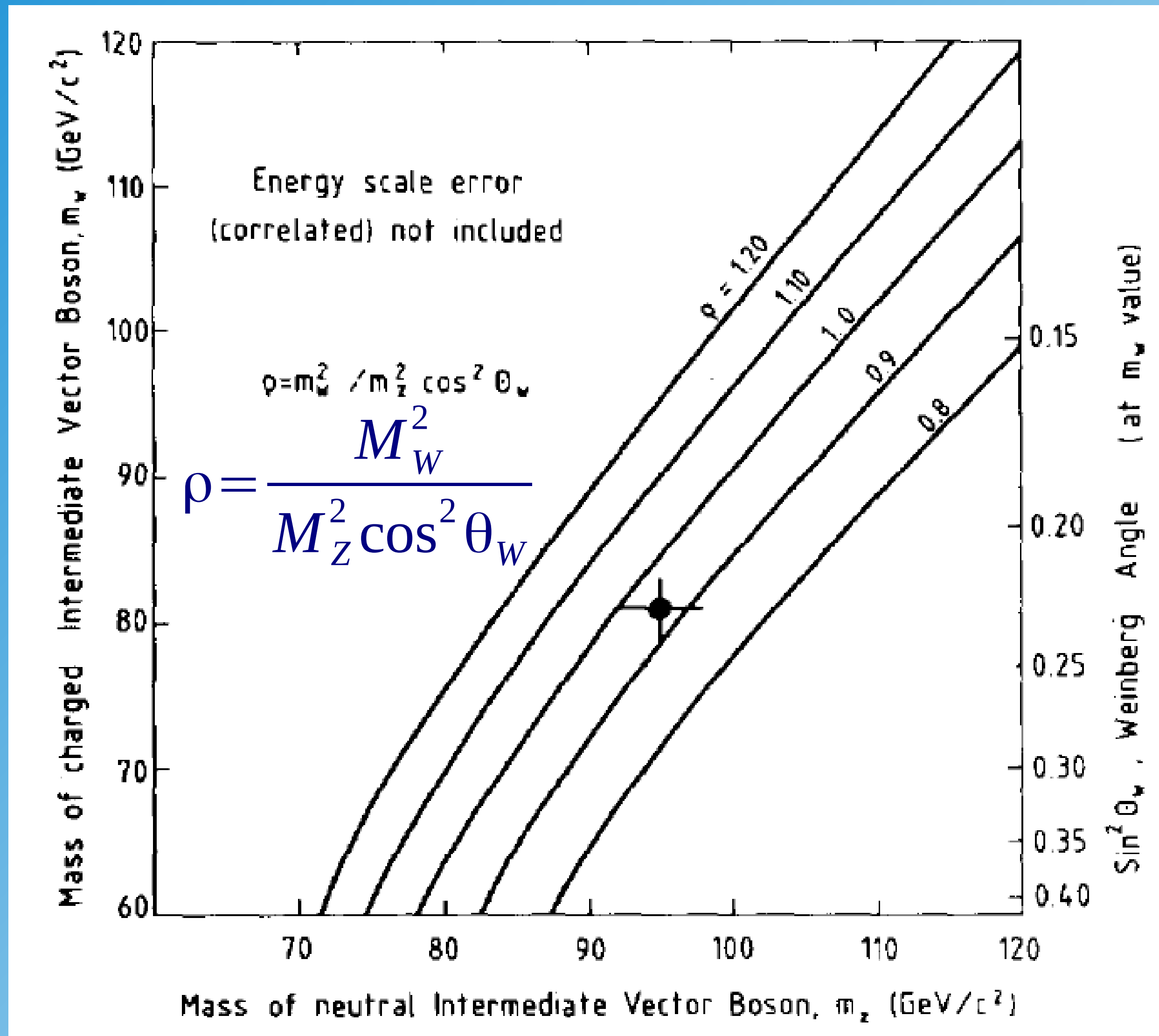
$$\frac{dN}{dp_T} = \left(\frac{dN}{d\cos\theta}\right)\cdot\boxed{\left(\frac{d\cos\theta}{dp_T}\right)} \sim \frac{2p_T}{M_W}\cdot\left(\frac{M_W^2}{4}-p_T^2\right)^{-1/2}$$

Jacobian

U.Uwer

11

Final Result

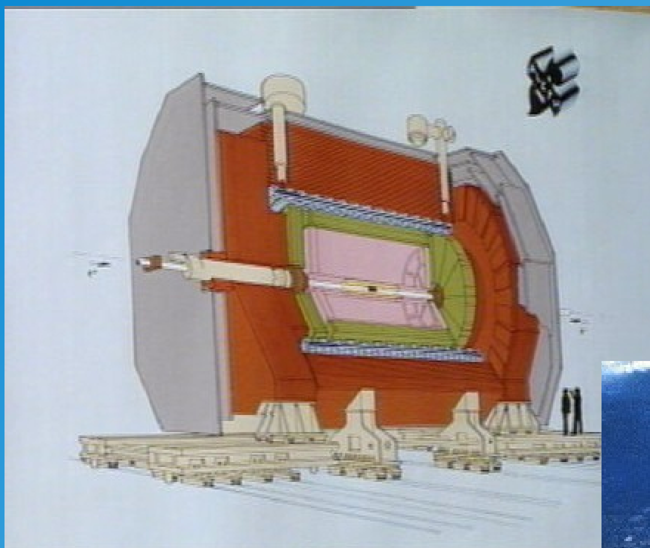


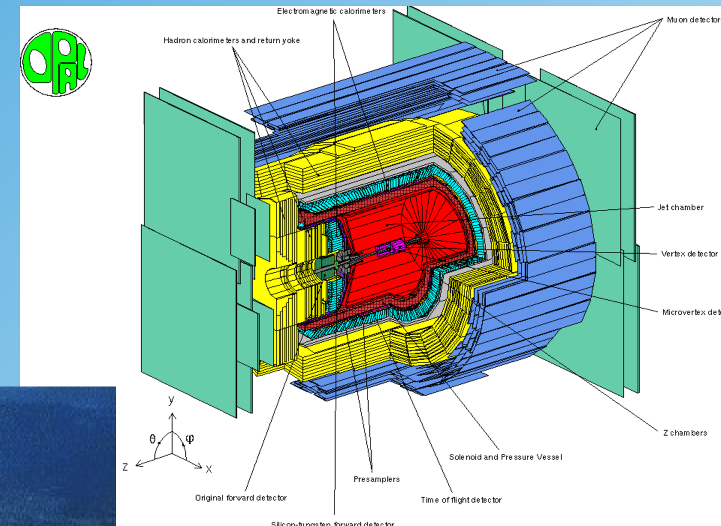
$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$

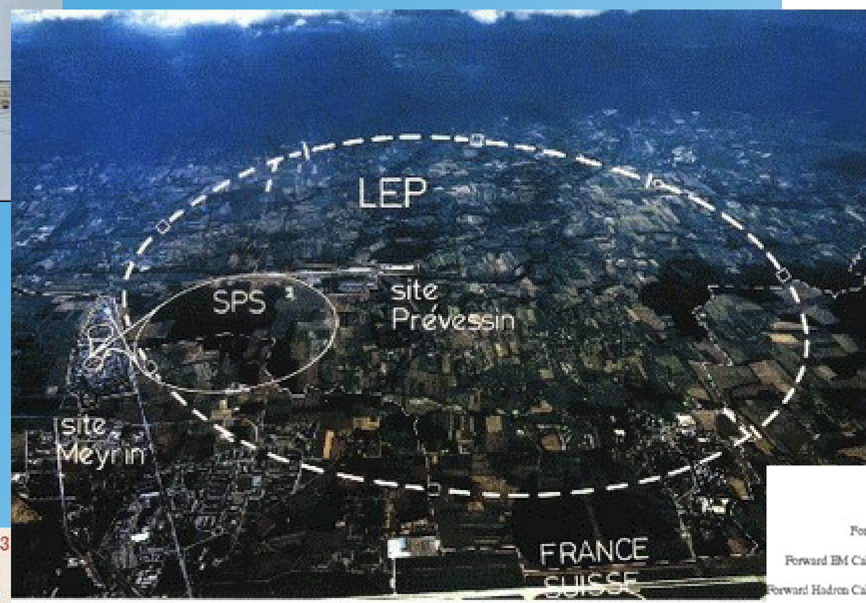
Rho parameter consistent with 1 → confirmation of the SM

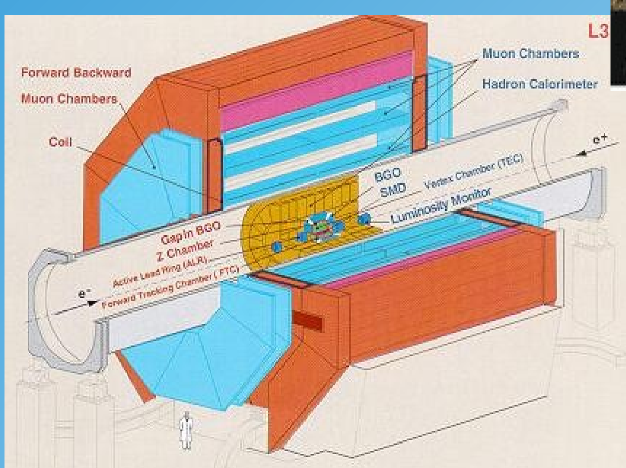
Nobel Prize for Physics 1984: C.Rubbia and S van de Meer

Large Electron Positron Collider



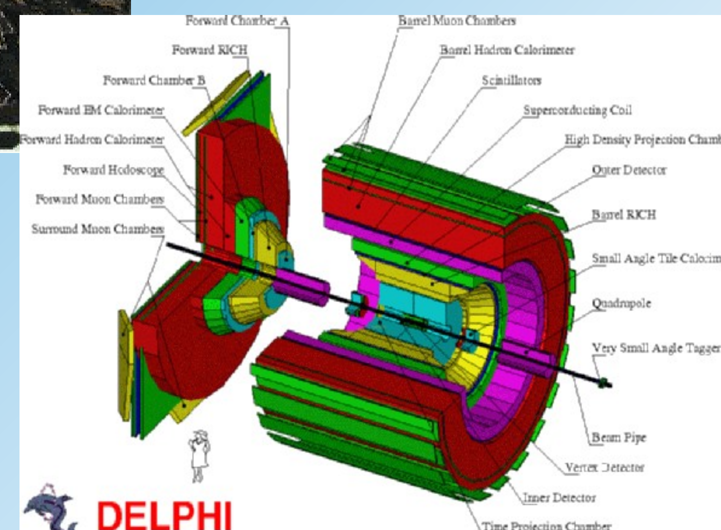




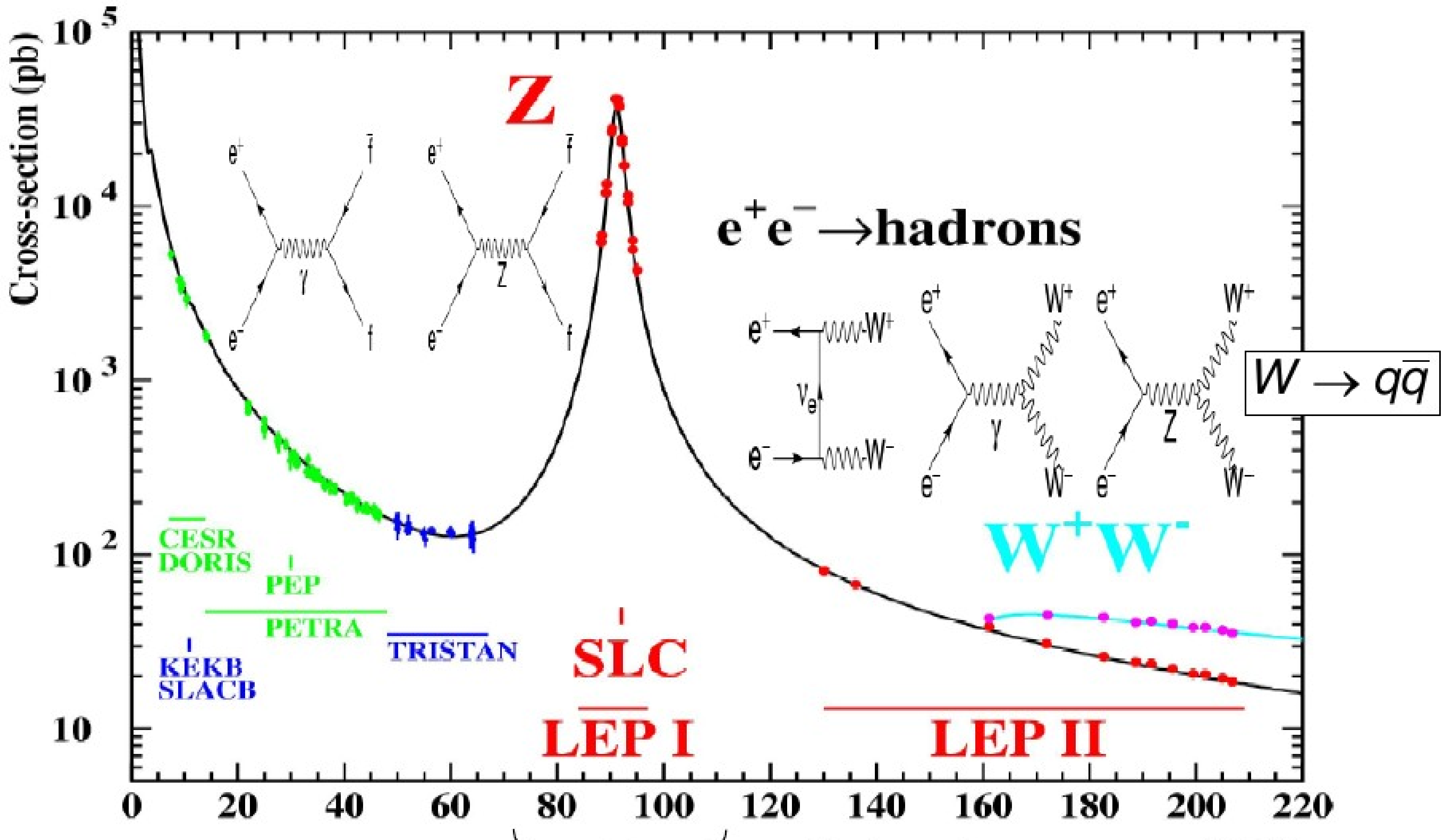


$e^{+}e^{-}$ collider

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



Hadron Production in $e^+ e^-$



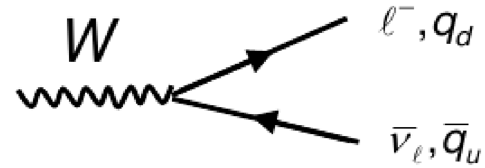
$M_Z = 91.1876 \pm 0.0021$ GeV

Precision tests of the Z sector

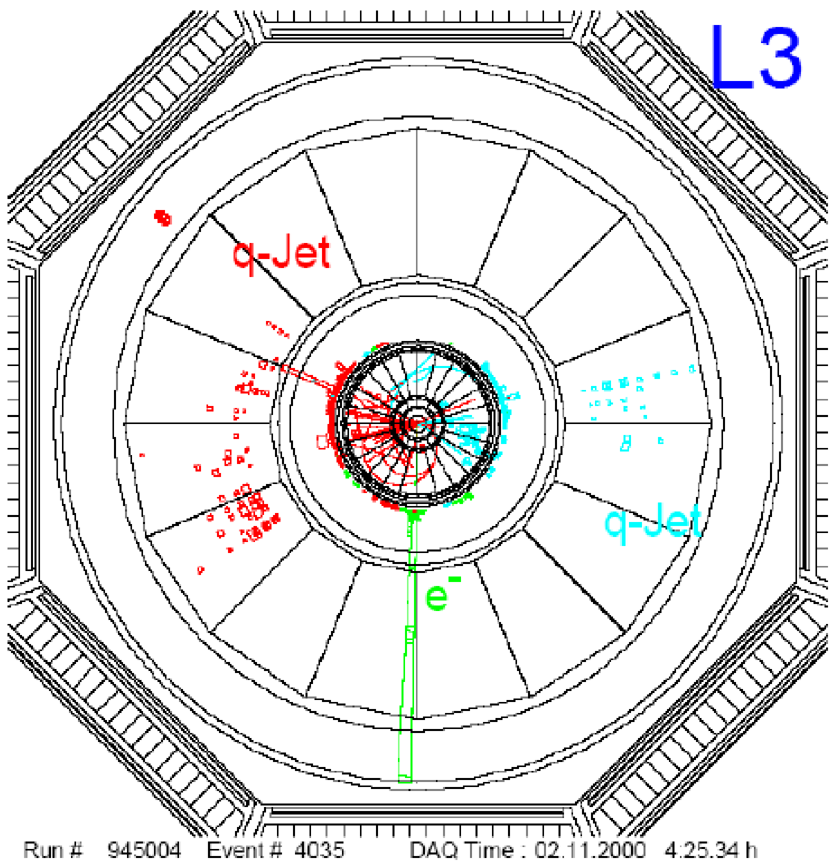
Tests of the W sector

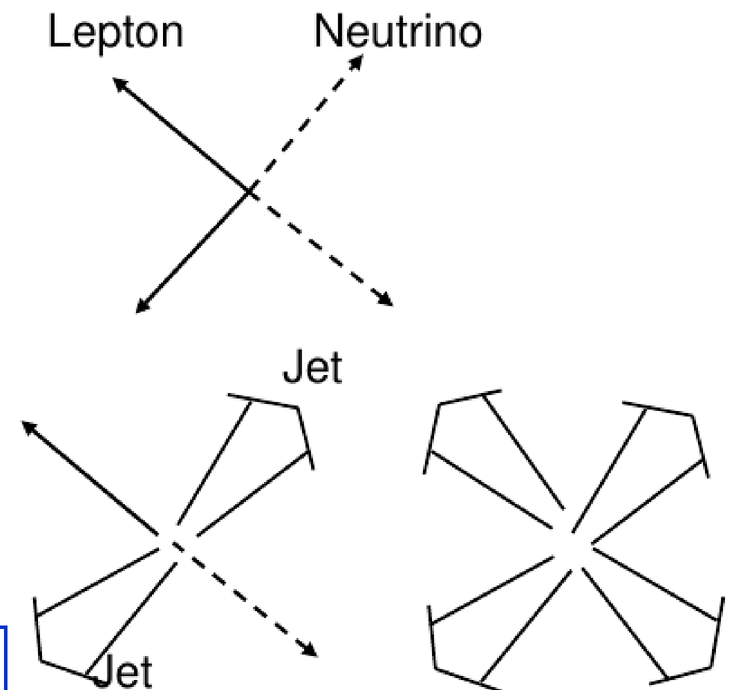
WW Pair Production at LEP

W decays



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





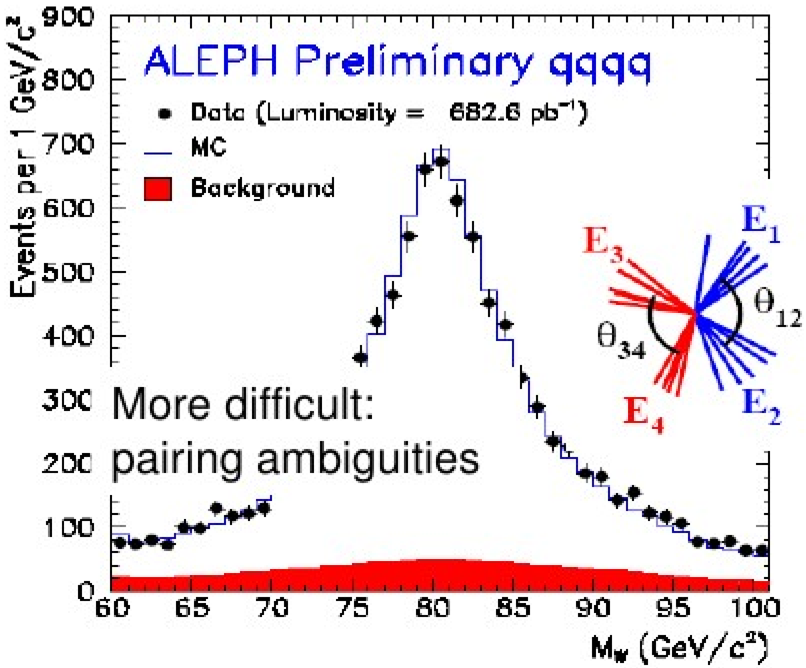
Easiest signature for a mass measurement:

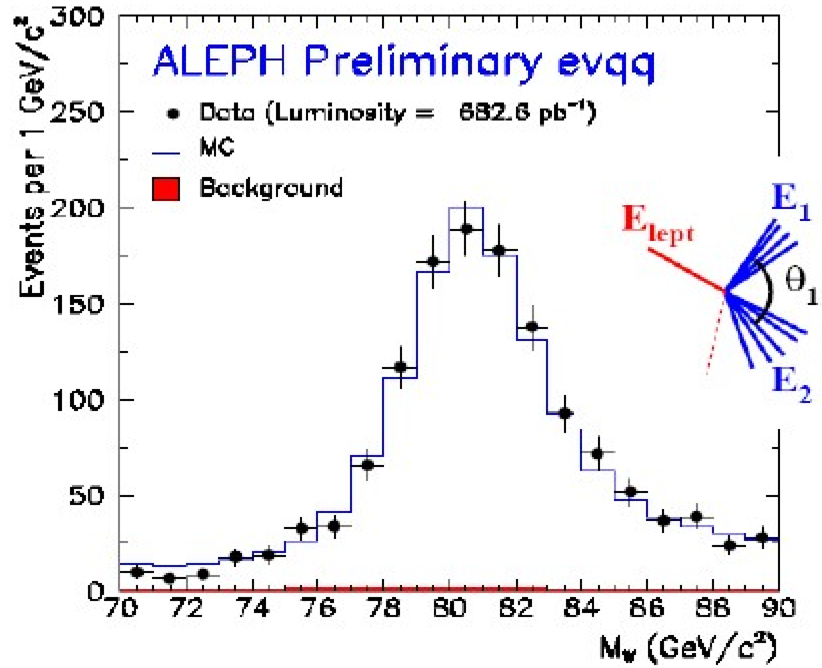
$W_1 \rightarrow l\nu$ $W_2 \rightarrow$ JetJet: use JetJet invariant mass

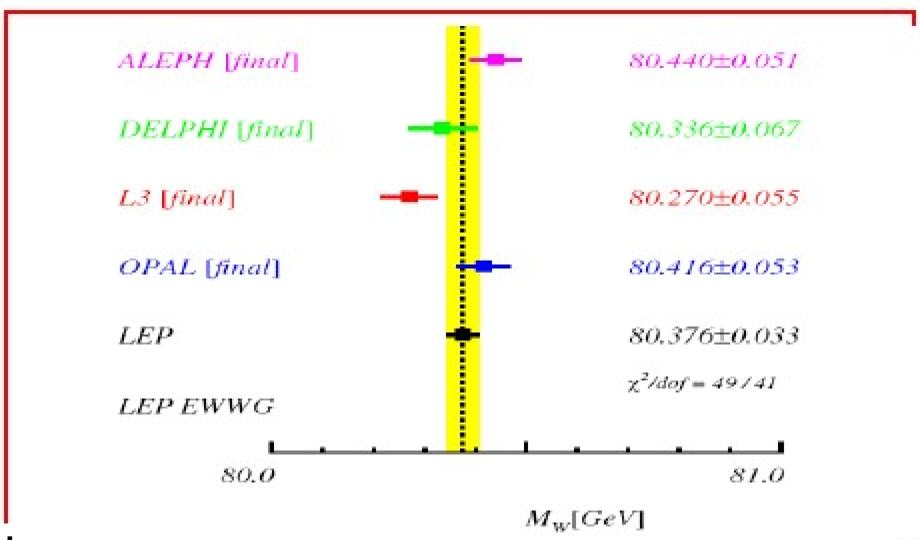
45

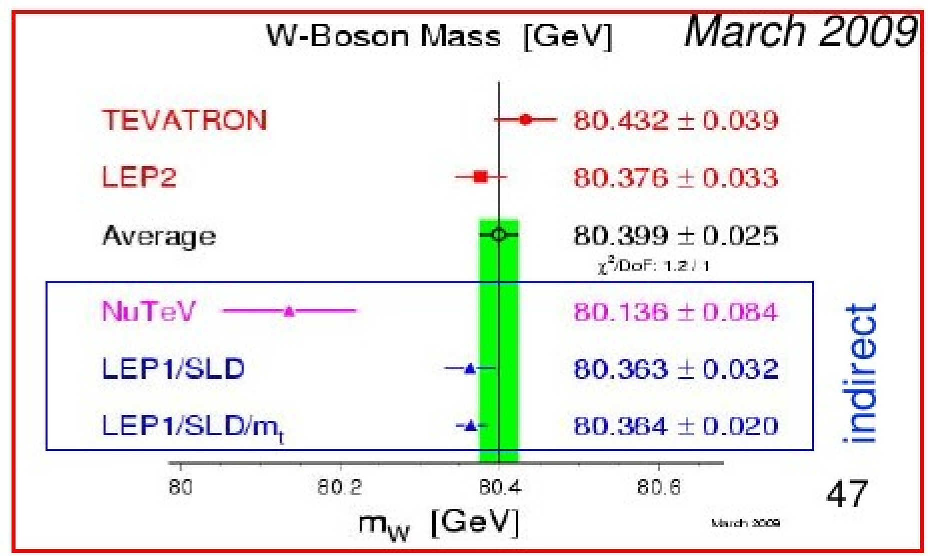
U.Uwer

Invariant W mass recontruction

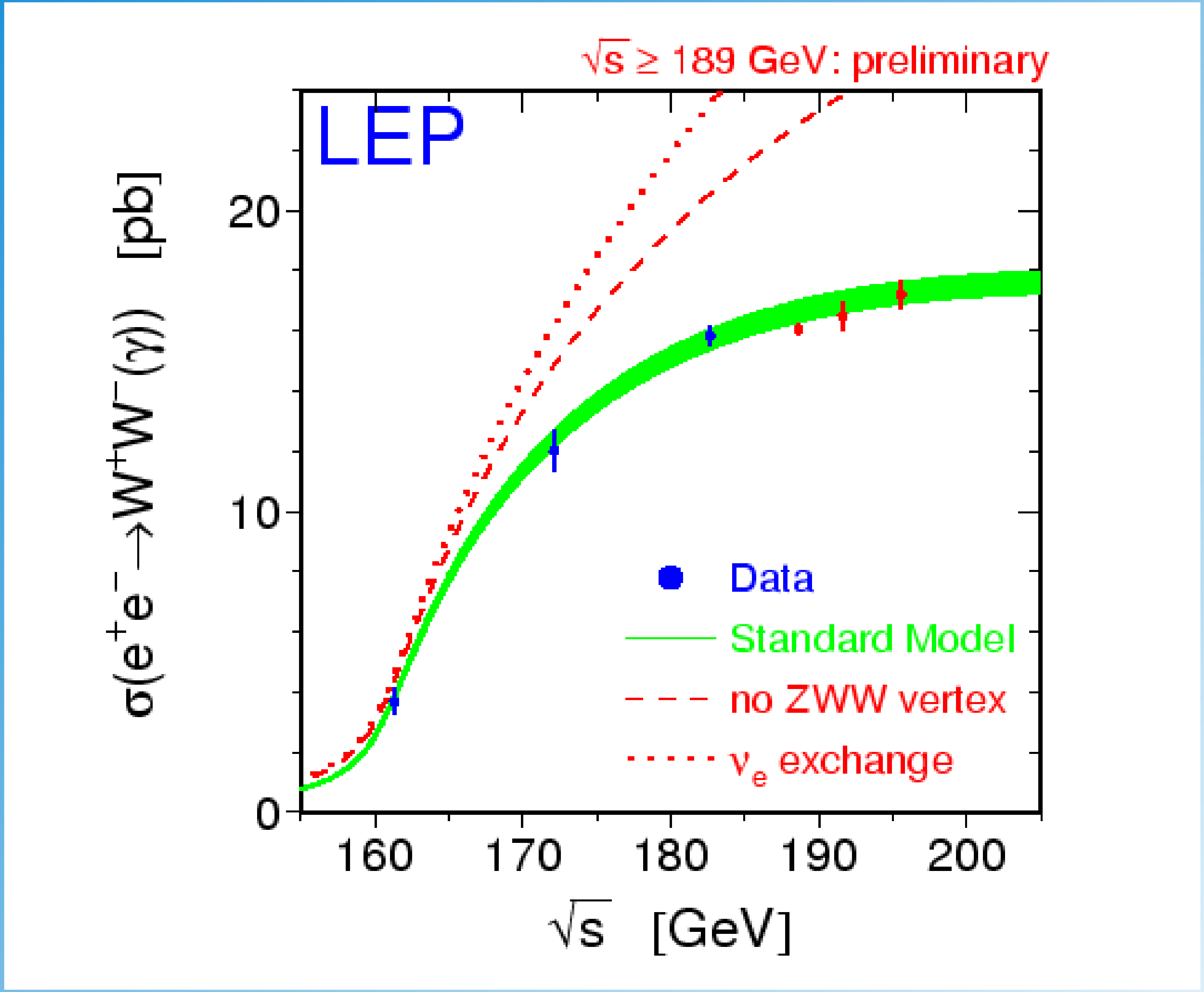




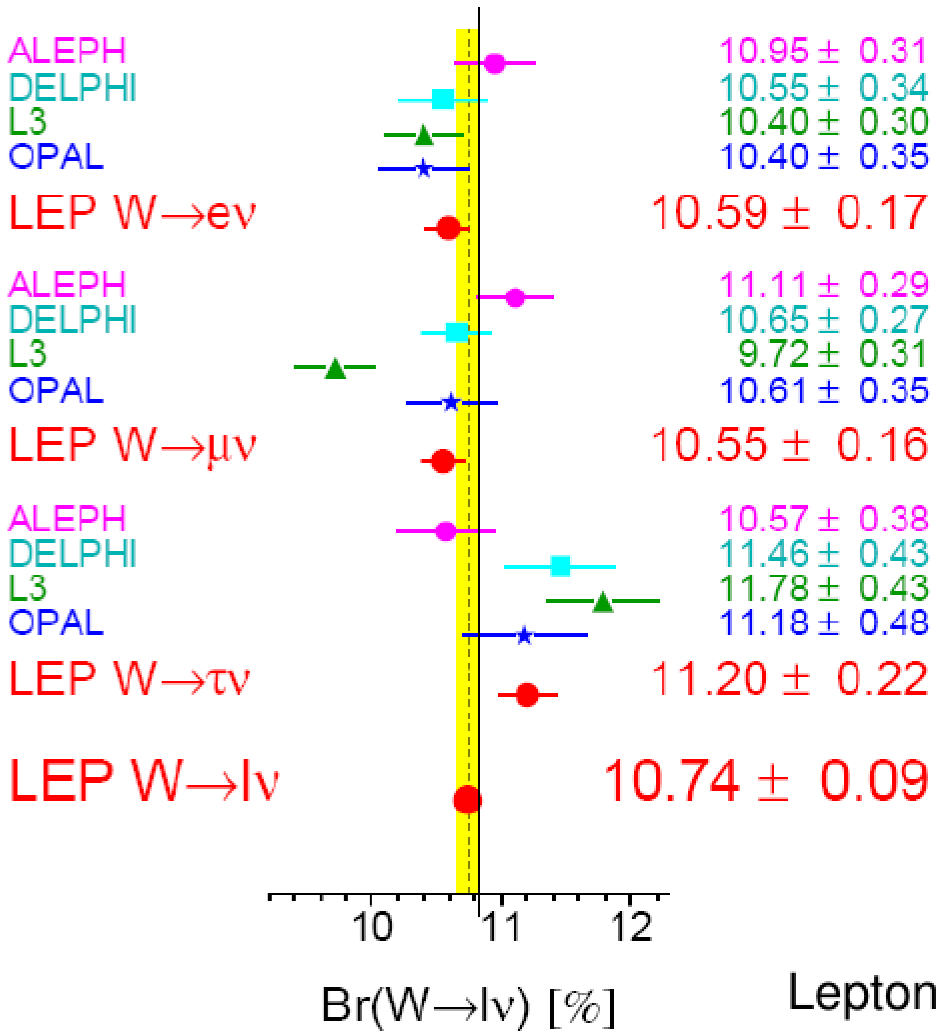




W-Pair Production at LEP2



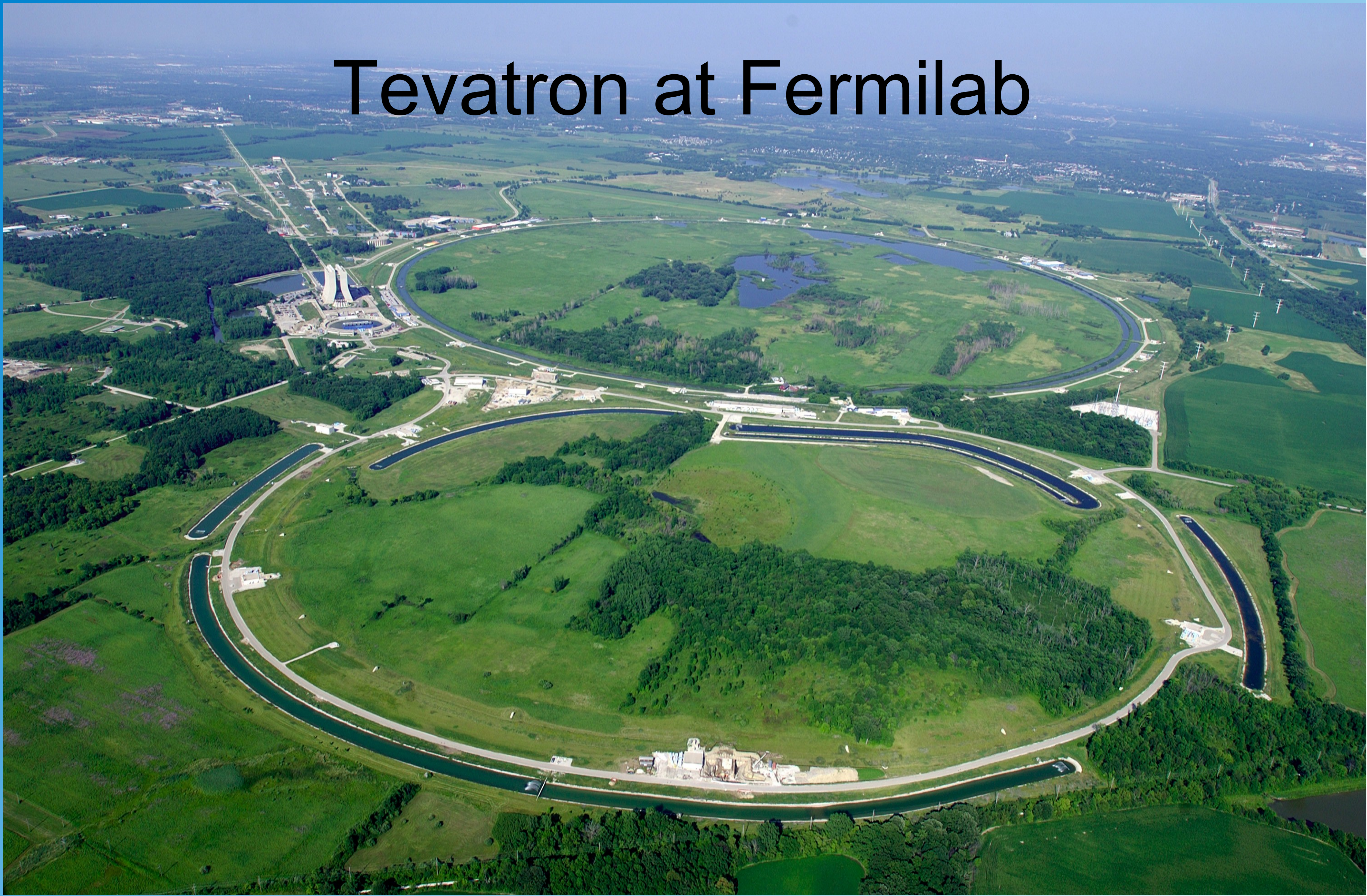
W leptonic branching fractions



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

Lepton universality tested to 2%

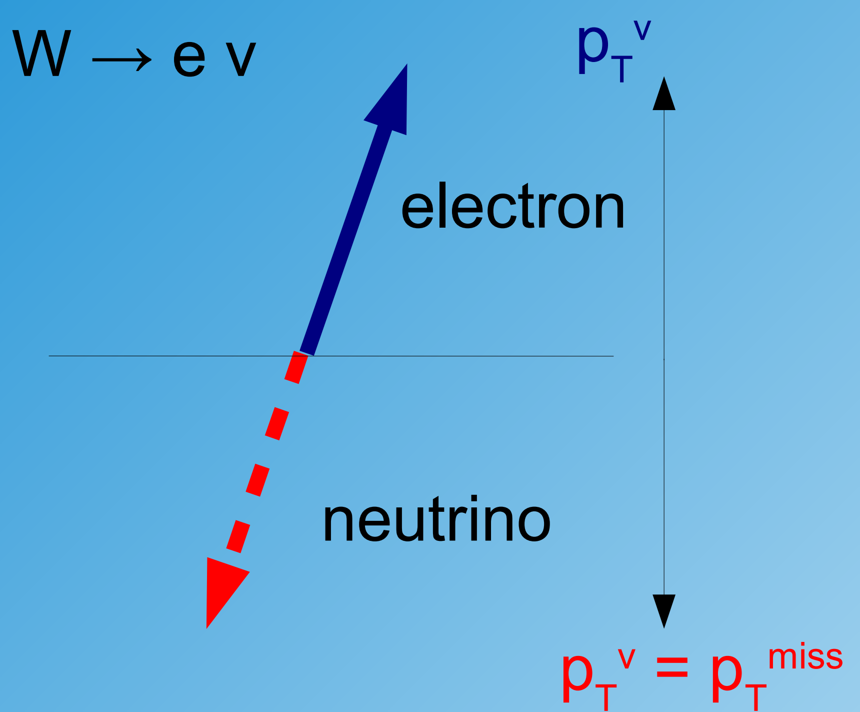
Tevatron at Fermilab

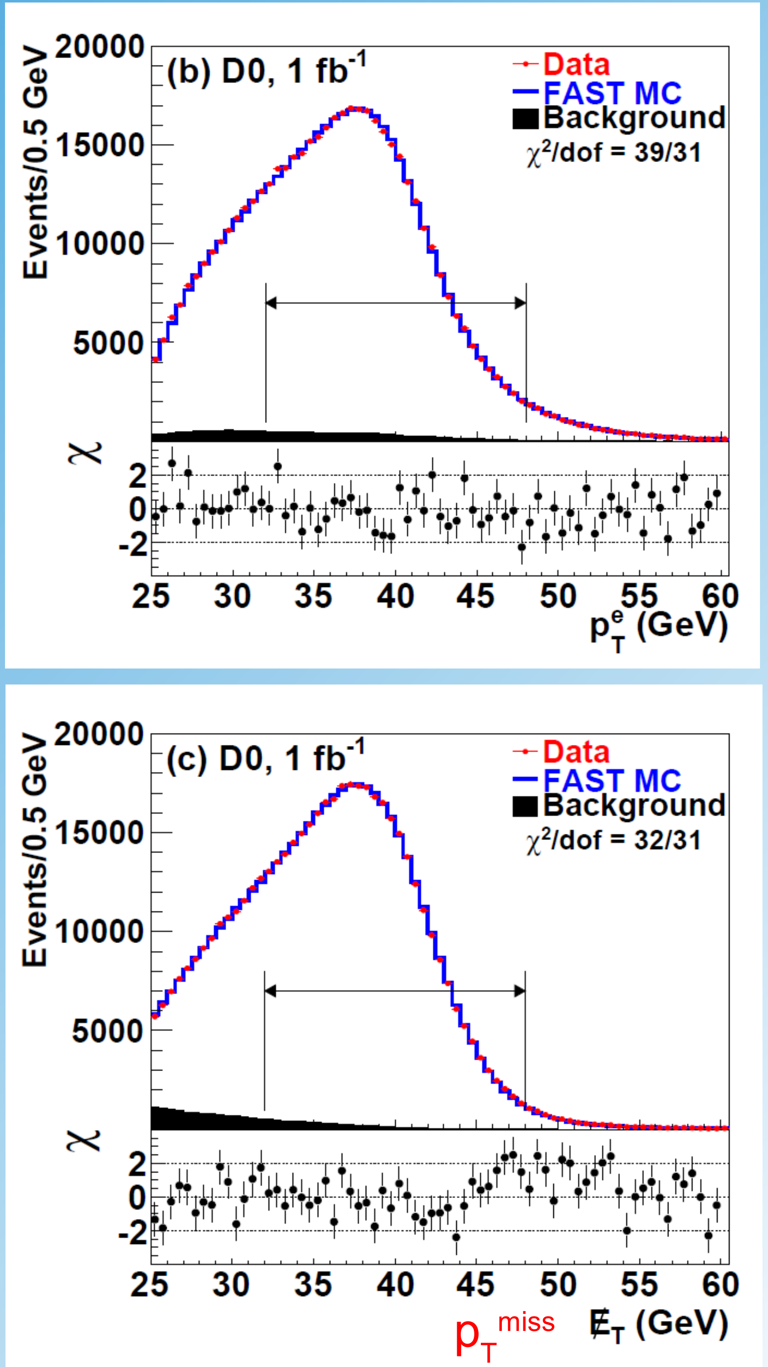


Proton – Antiproton Collider at $s^{1/2}$ = 2 TeV

Missing Transverse Momentum

Jacobian peak at D0:

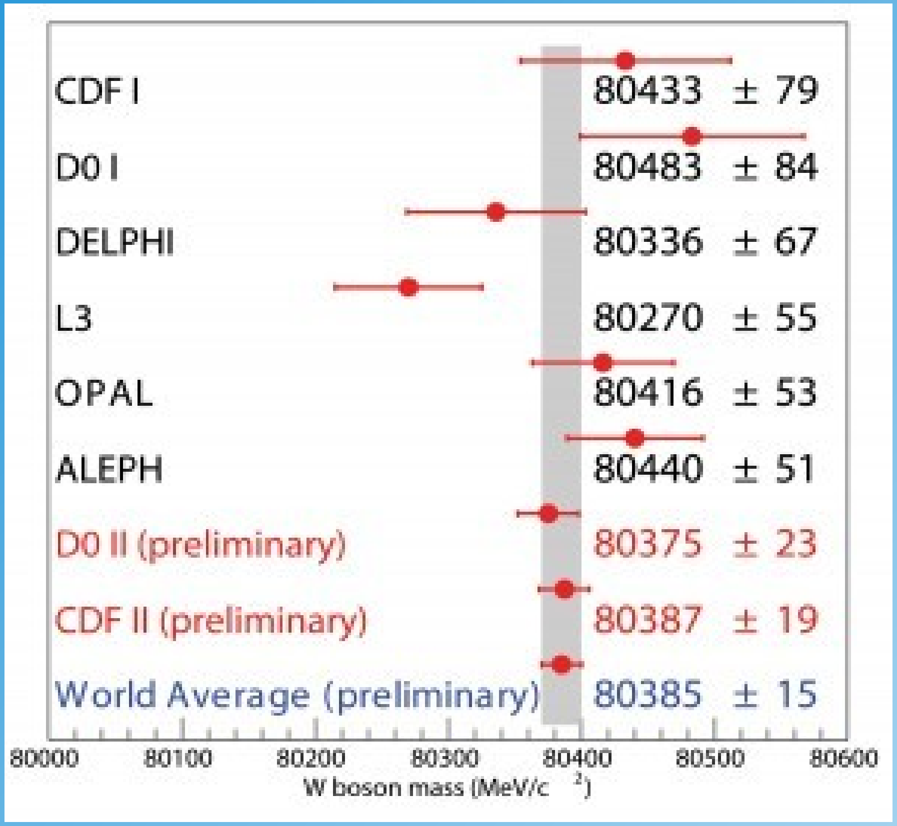




Latest Results W-mass

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

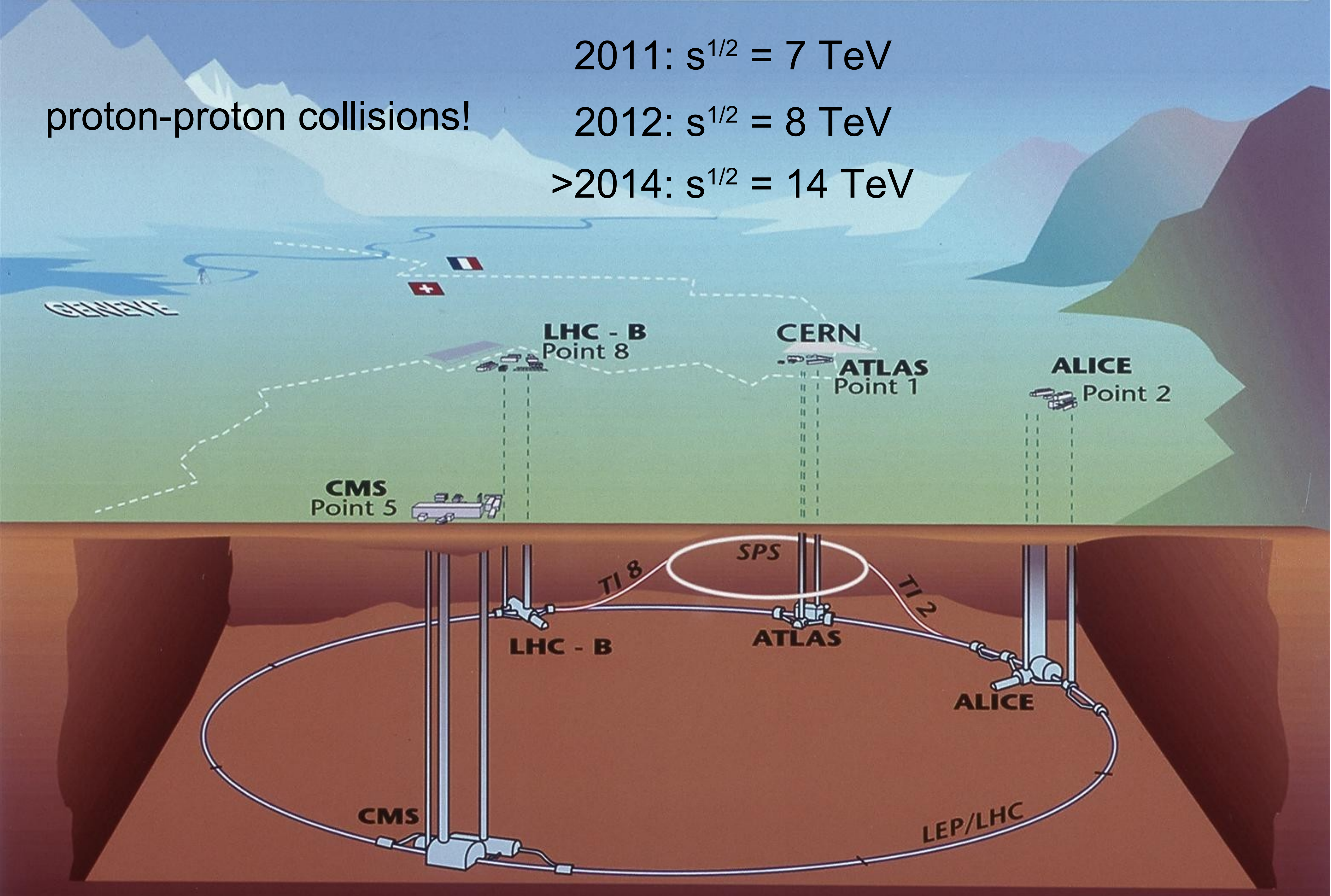
Overall view of the LHC experiments.

proton-proton collisions!

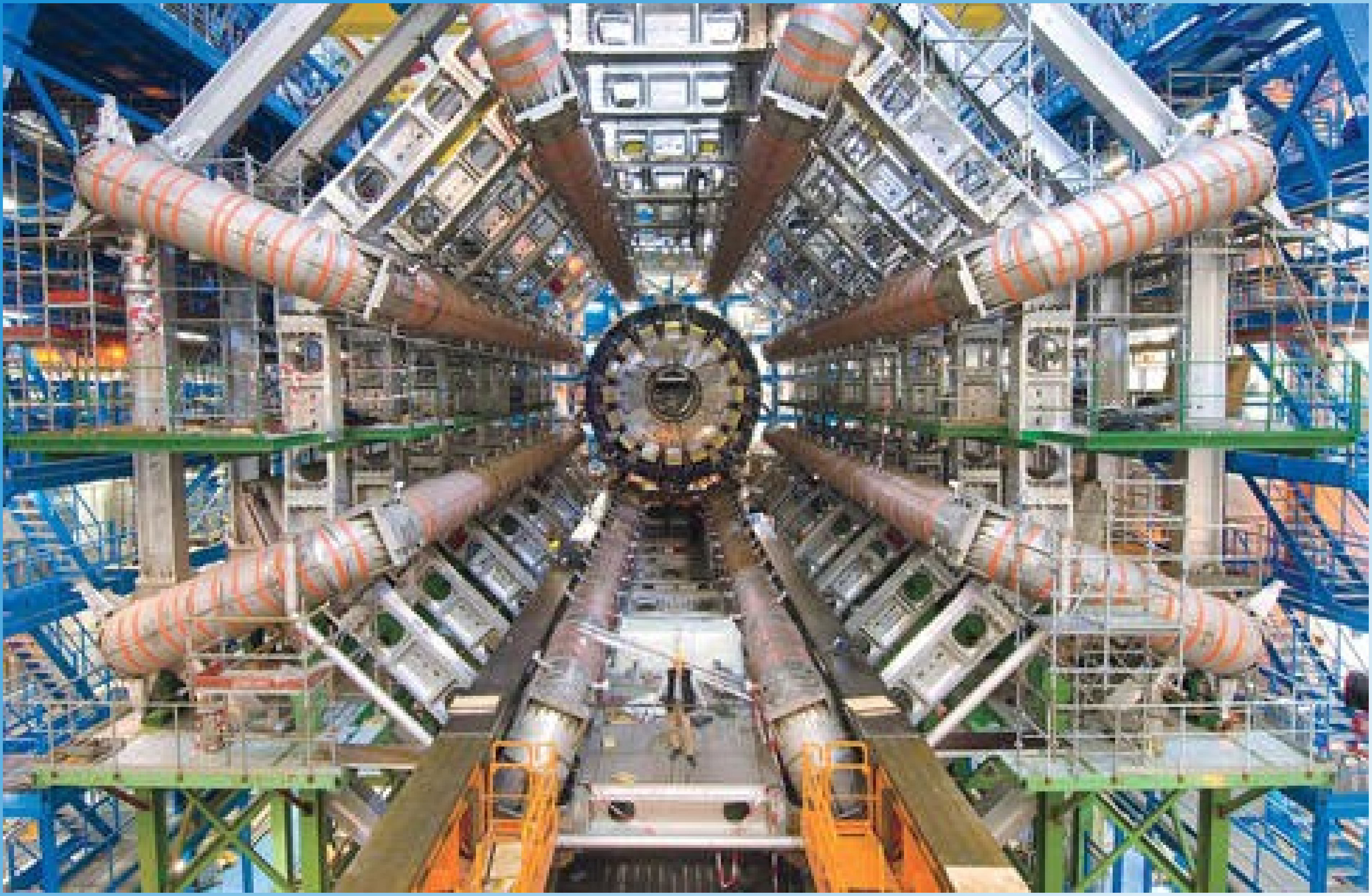
2011: $s^{1/2}$ = 7 TeV

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

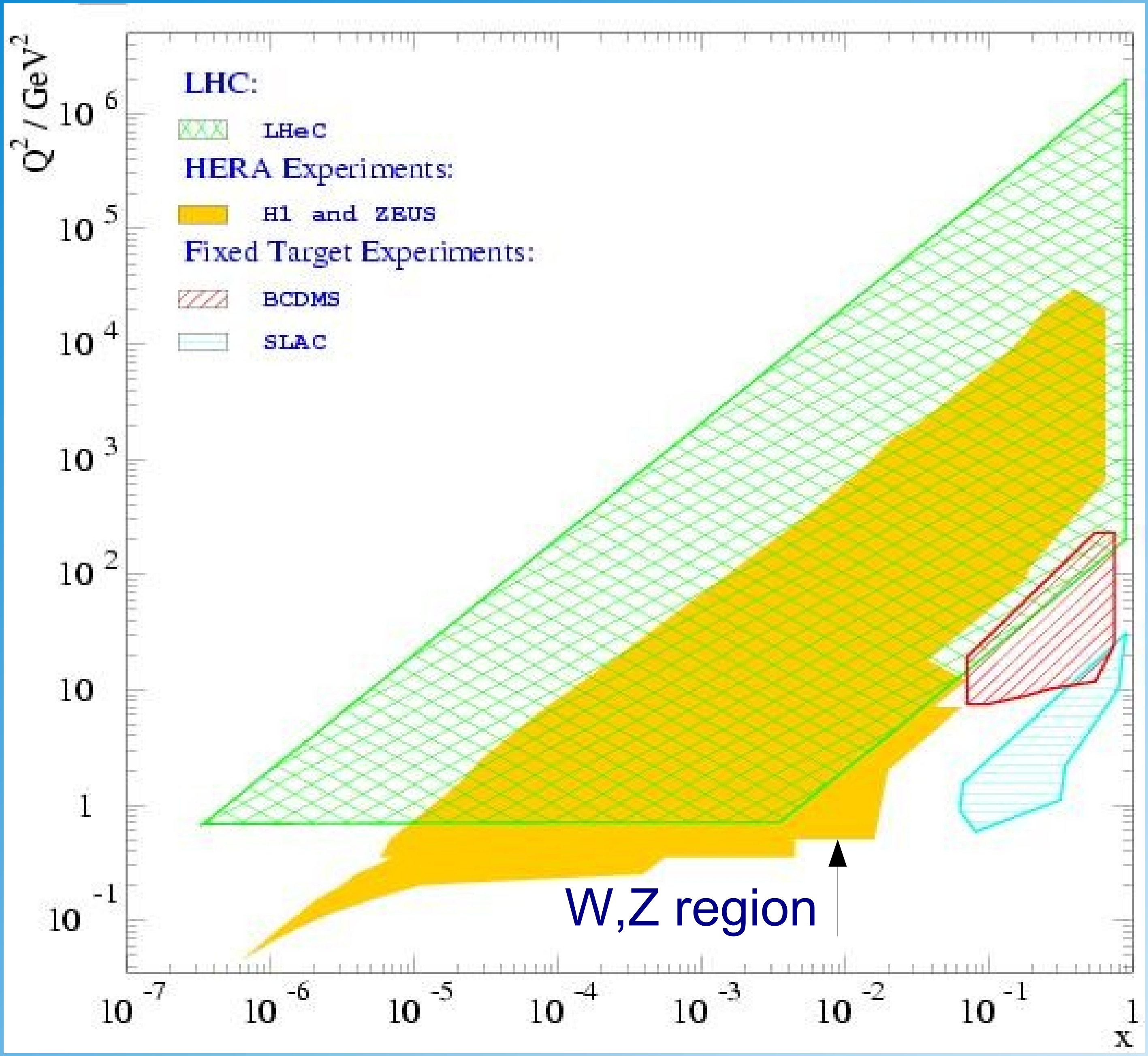
>2014: $s^{1/2}$ = 14 TeV



ATLAS Detector

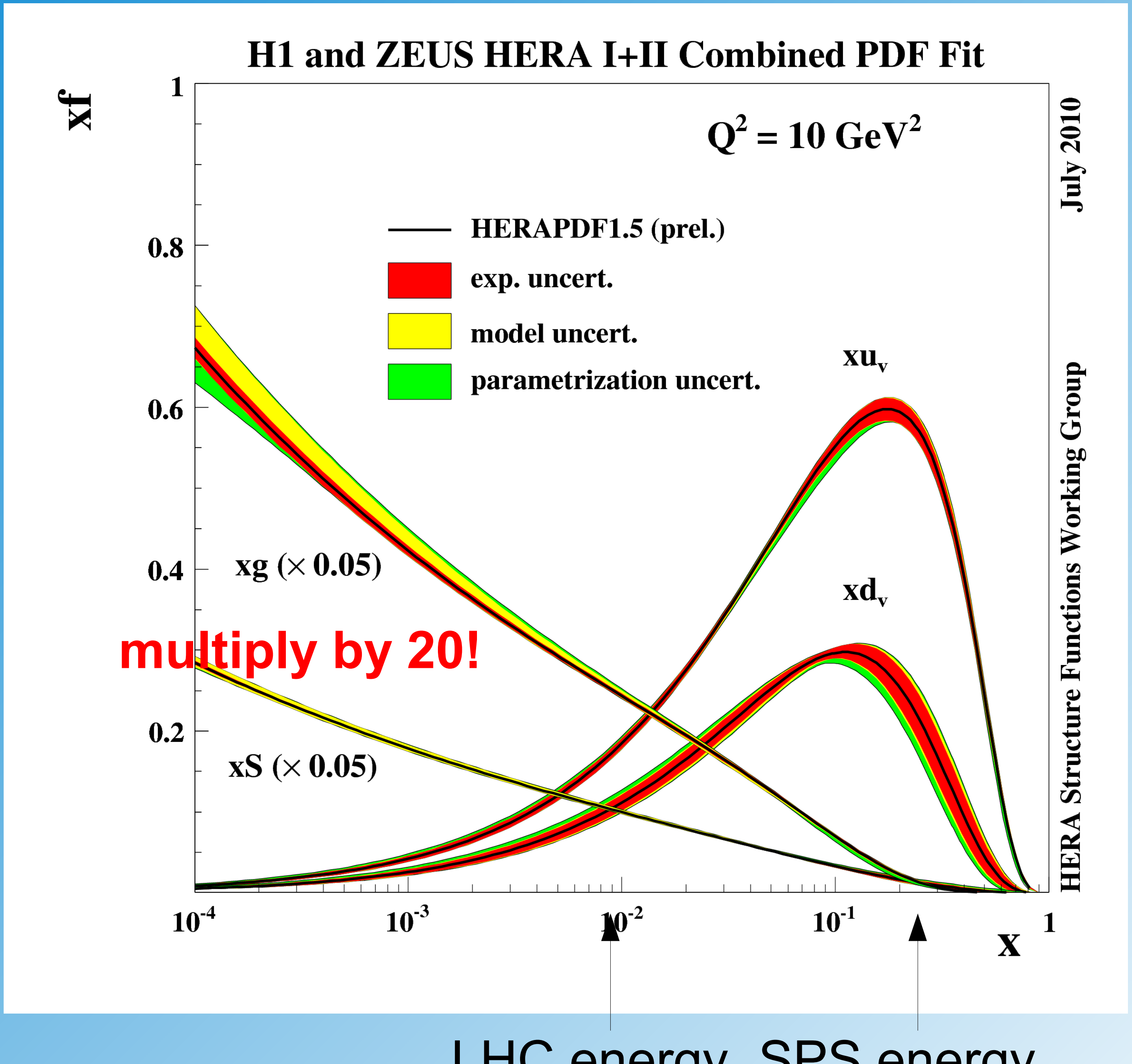


LHC Kinematic Plane



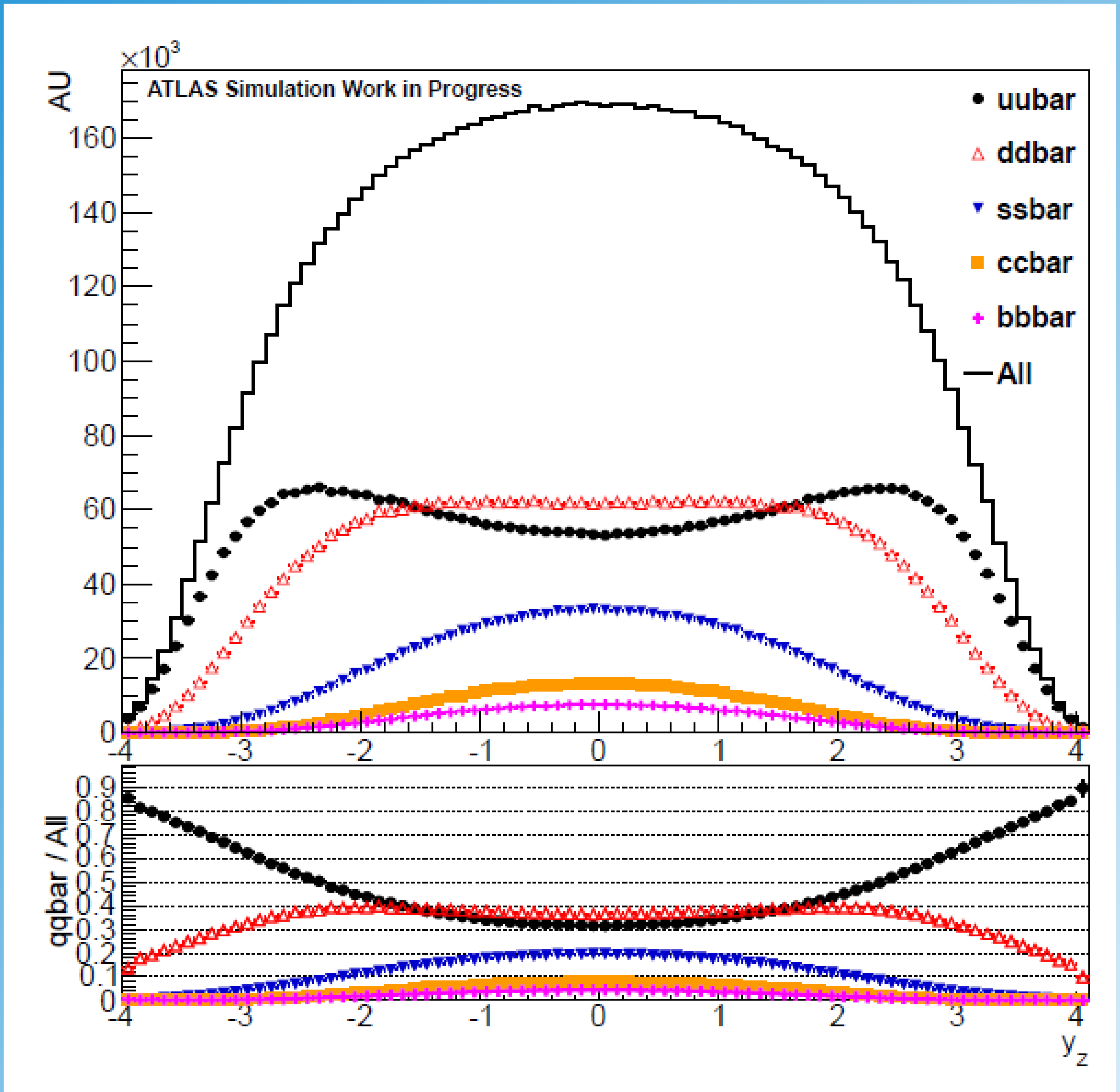
- W,Z production dominated by sea quarks
- low x-region very well constrained by HERA
- W,Z production can be used to measure proton-PDFs and LHC luminosity!

Proton Parton Densities



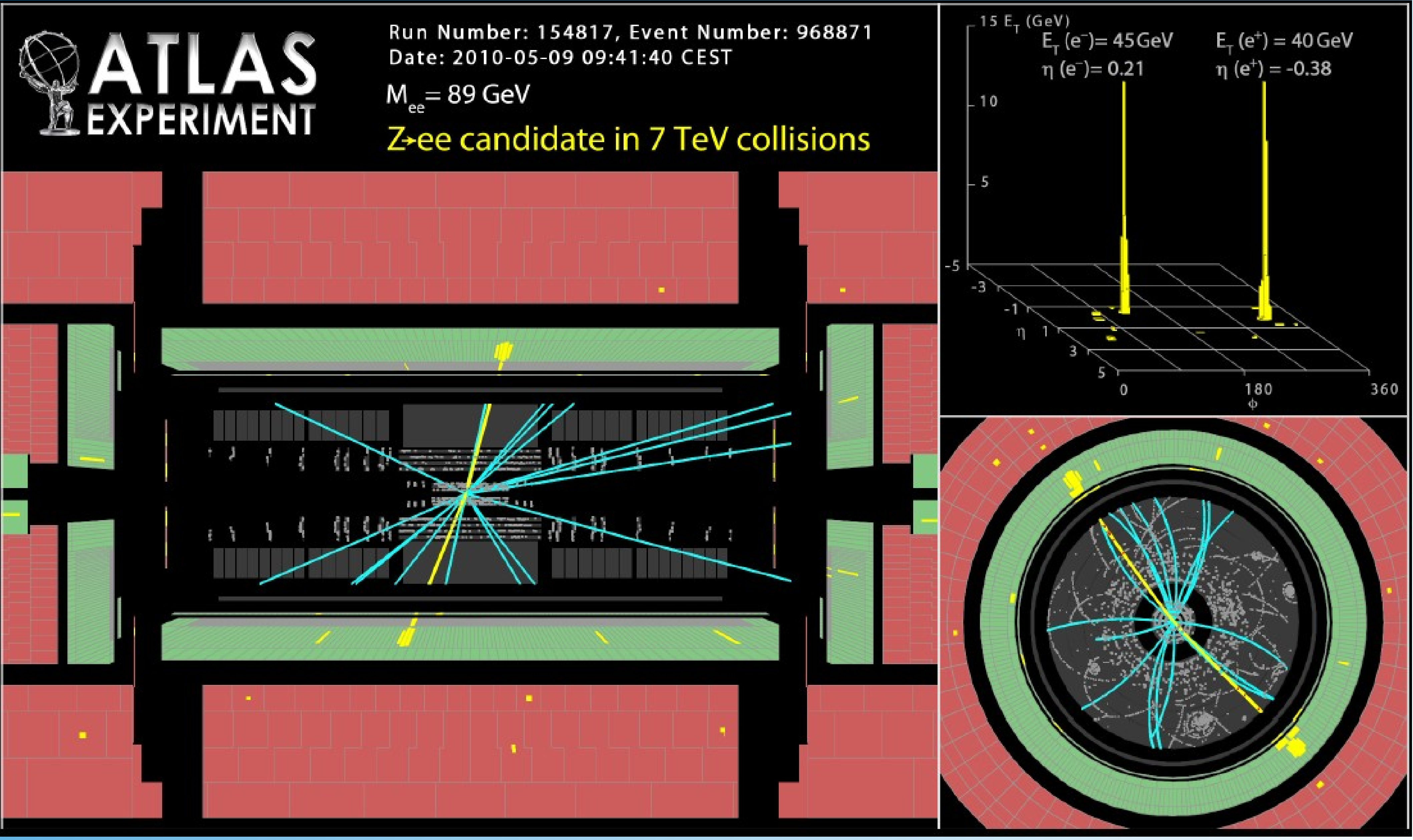
Quark Flavors in Z Production

q qbar → Z

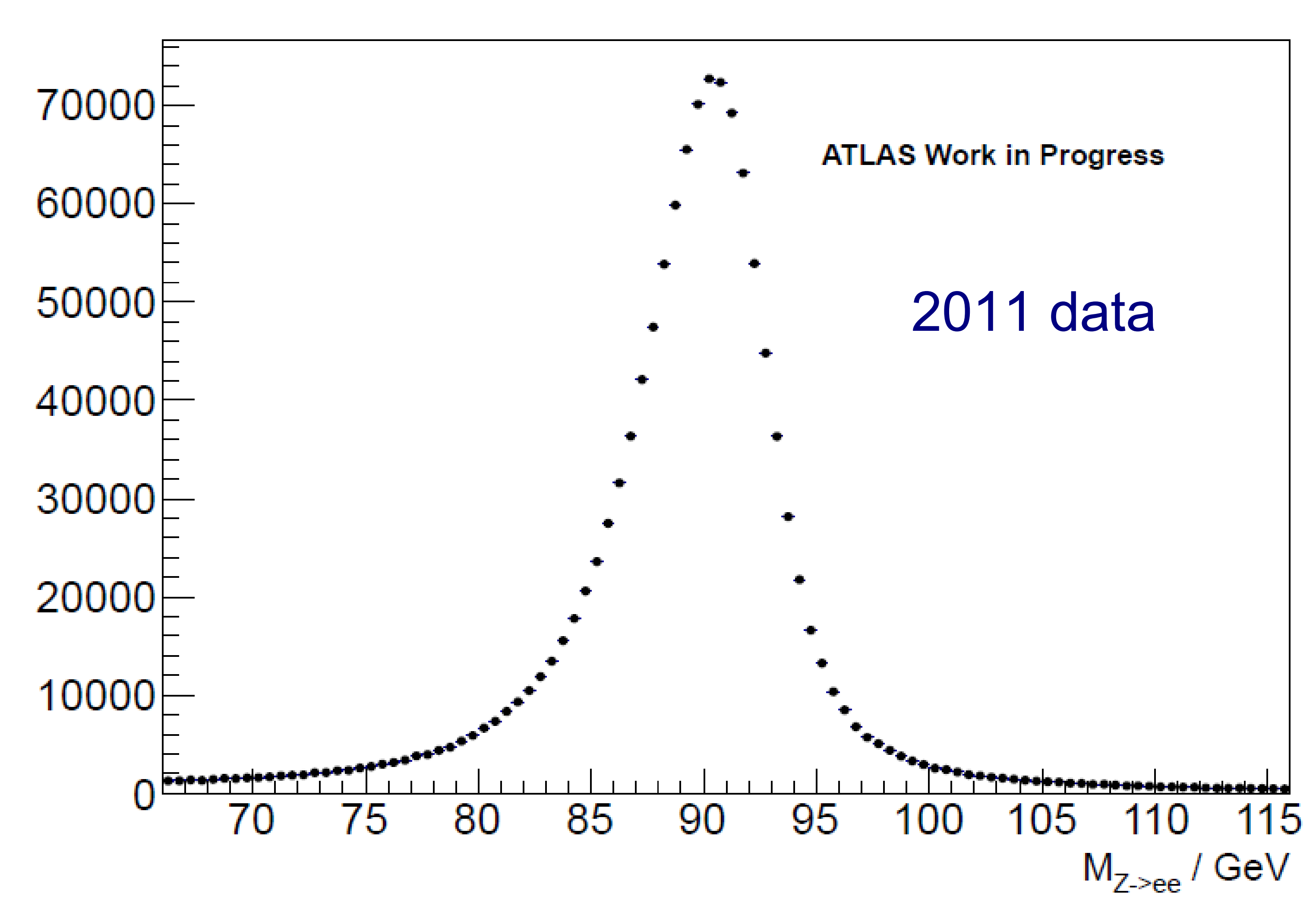


y_z = pseudorapidity of Z-boson: $y = -\ln \tan \theta/2$

Z → ee candidate at ATLAS



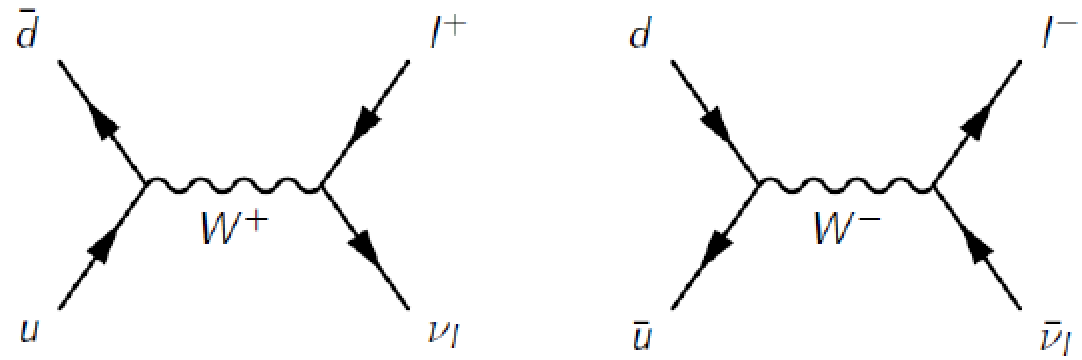
Z-Peak at ATLAS



LHC is a Vector-Boson factory!

W-Production at LHC

Valence quark + sea quark



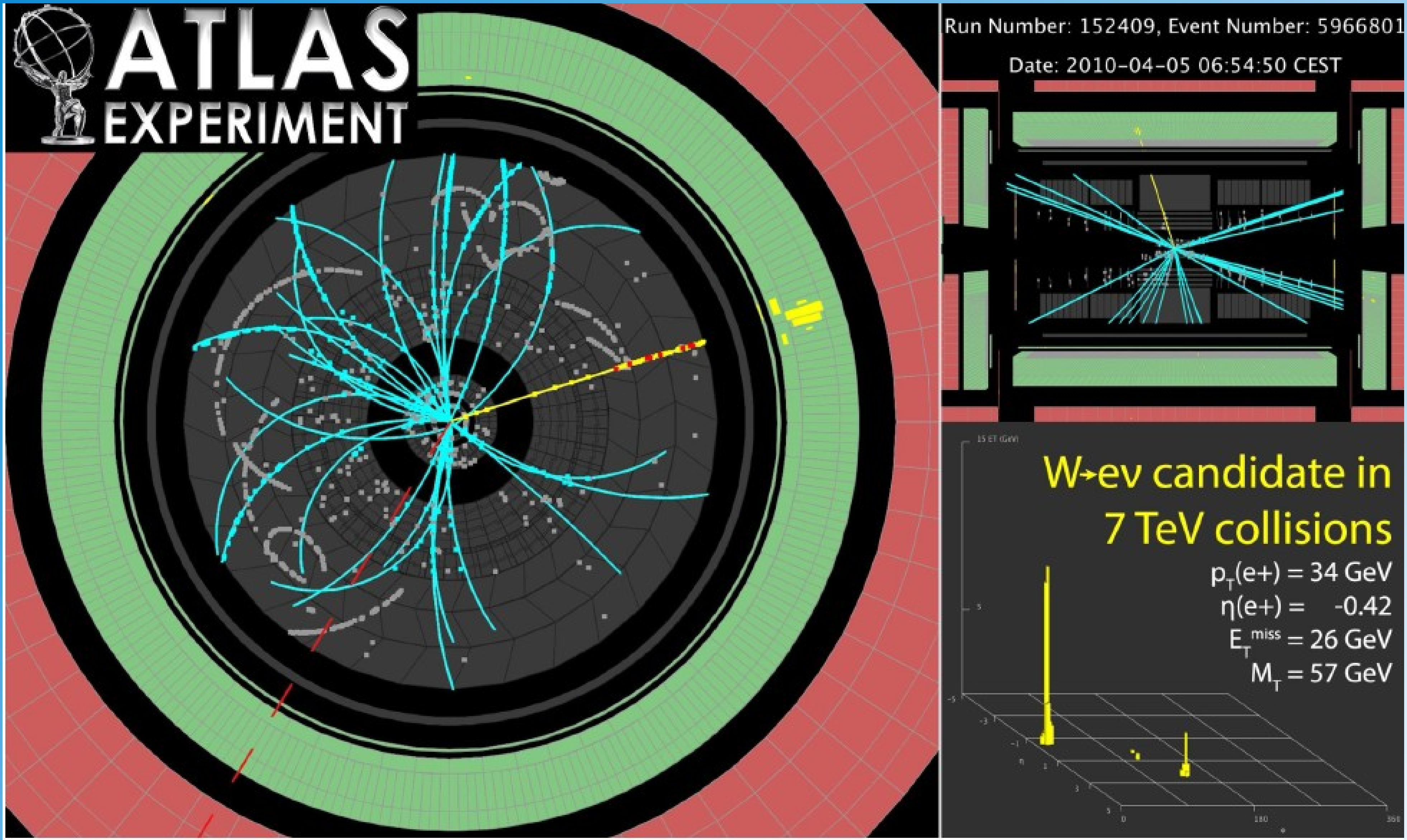
valence quark ratio u/d = 2 $\Rightarrow$ more W^+ than W^-

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)

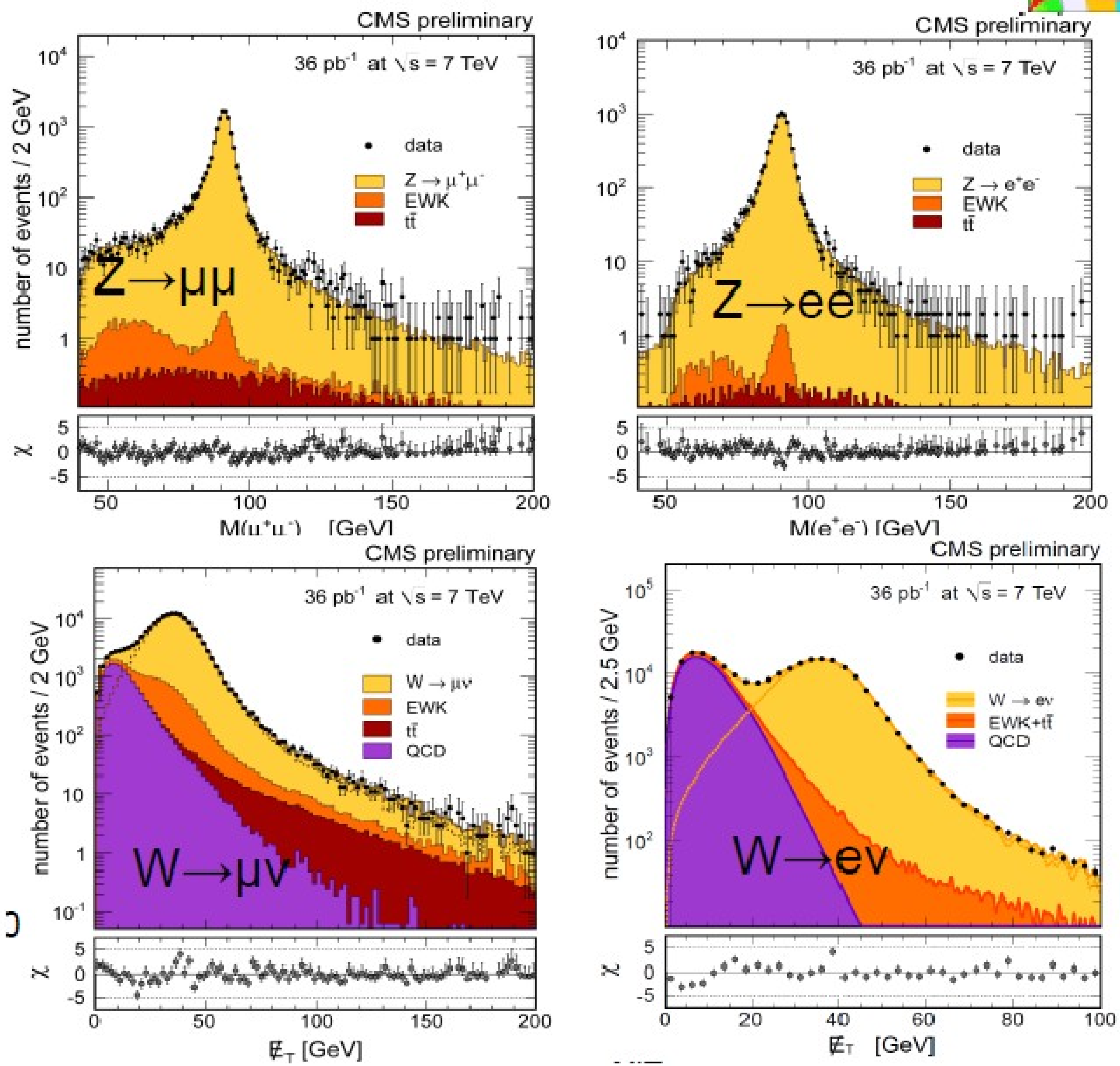
Charge Asymmetric! Handle to disentangle d and u valence quarks

W-boson Production at LHC



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

Z and W production at LHC

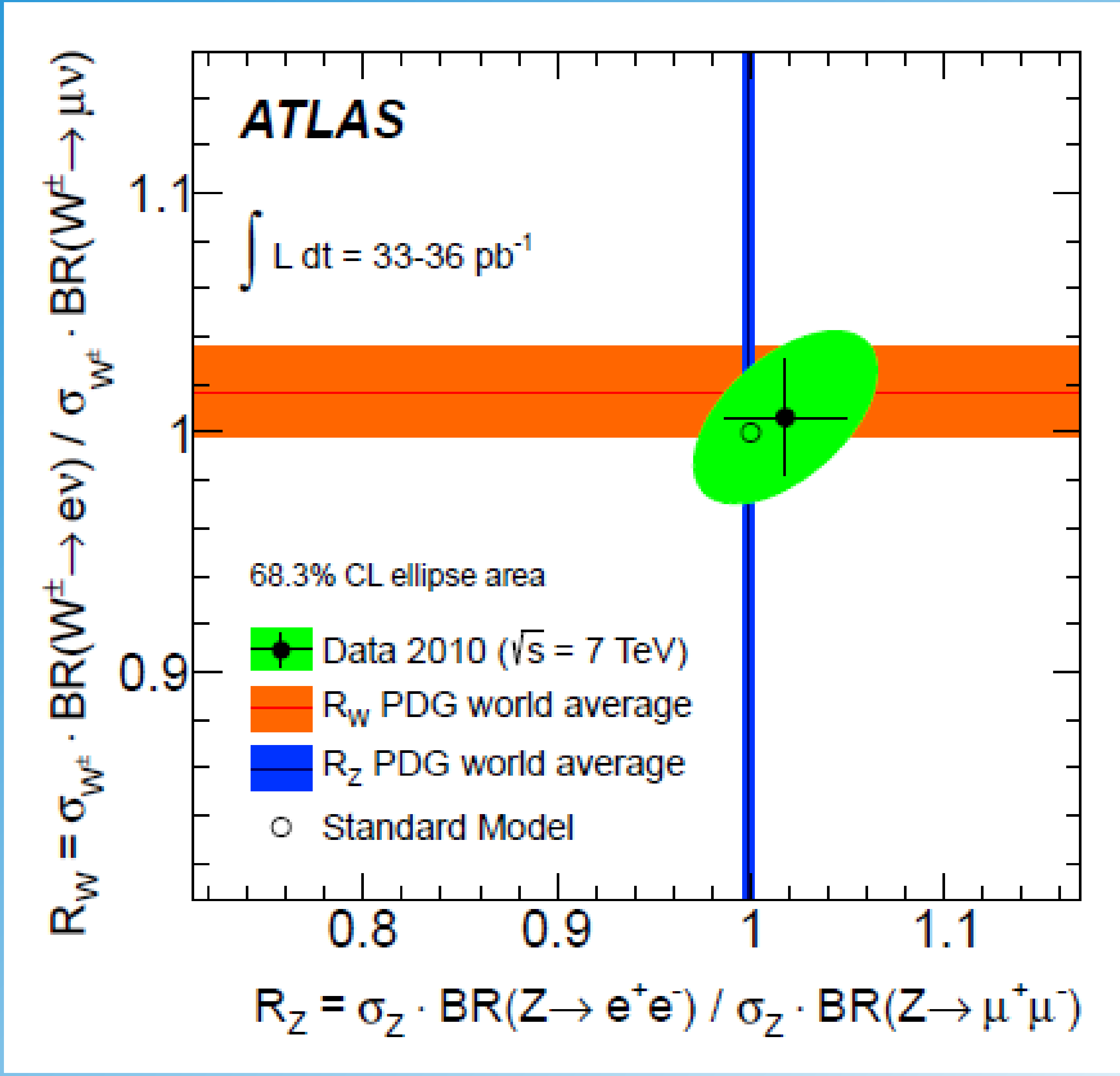


P.Harris, Moriond 2011

Instead of E_{eT} use E_T (i.e. $E_{\upsilon T}$)

14

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