# DISCOVERY OF THE WEAK BOSONS

# Resonance production cross sections

- **A general formula for vector resonance production:**

$$\sigma(s) = \frac{12\pi}{s} \frac{\Gamma_{f_1 f_2} \Gamma_{f_3 f_4}}{(s - M_0^2)^2 + s^2 \Gamma_{tot}^2 / M_0^2}$$

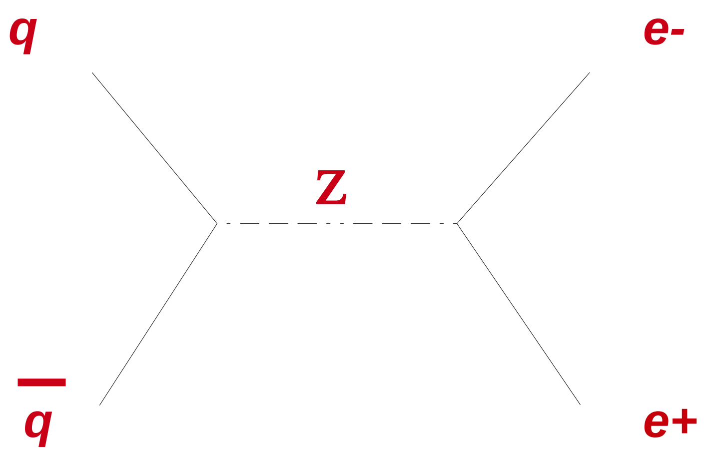
- where: $\Gamma_{f_i f_j} = \Gamma_{tot} \times BR(f_i f_j)$

- **Tree level Standard Model formulae** for the widths into given fermion (of given color!):

$$\Gamma_{W \to f_i f_j} = \frac{G_F}{\sqrt{2}} \frac{M_W^3}{6\pi} \qquad \Gamma_{Z \to f \bar{f}} = \frac{G_F}{\sqrt{2}} \frac{M_Z^3}{6\pi} (v_f^2 + a_f^2)$$

# Resonance production in hadron collisions

Using the example of the Z, the production process is:




- But quarks are not free! For each collision, a quark is "picked" in each hadron, carrying a momentum fraction **x** of the hadron energy

- Parton distribution functions were introduced in the QCD course

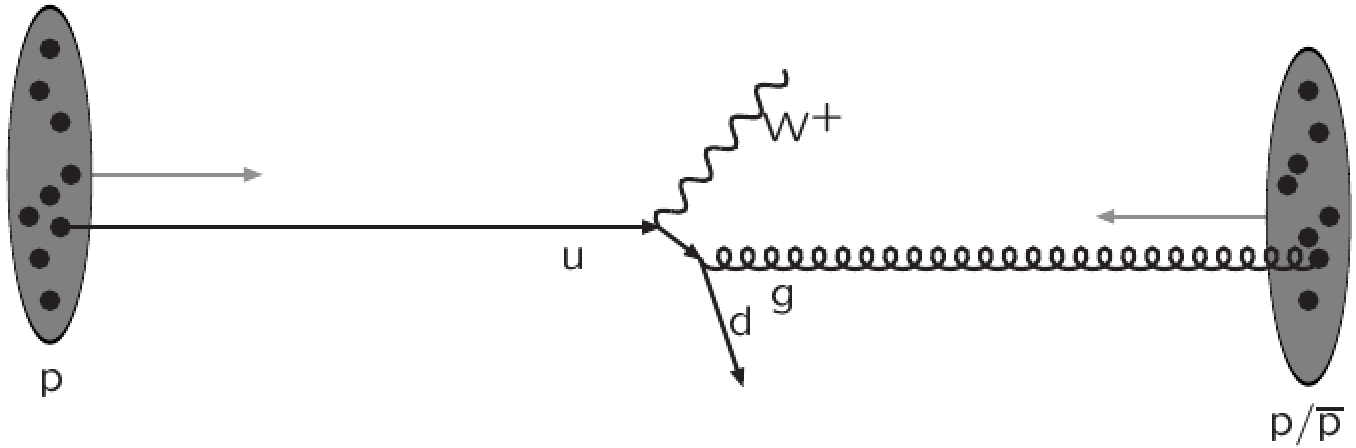
# Scenario of a hadron-hadron collision

Warning: schematic only, everything simplified, nothing to scale, . . .


Incoming beams: parton densities

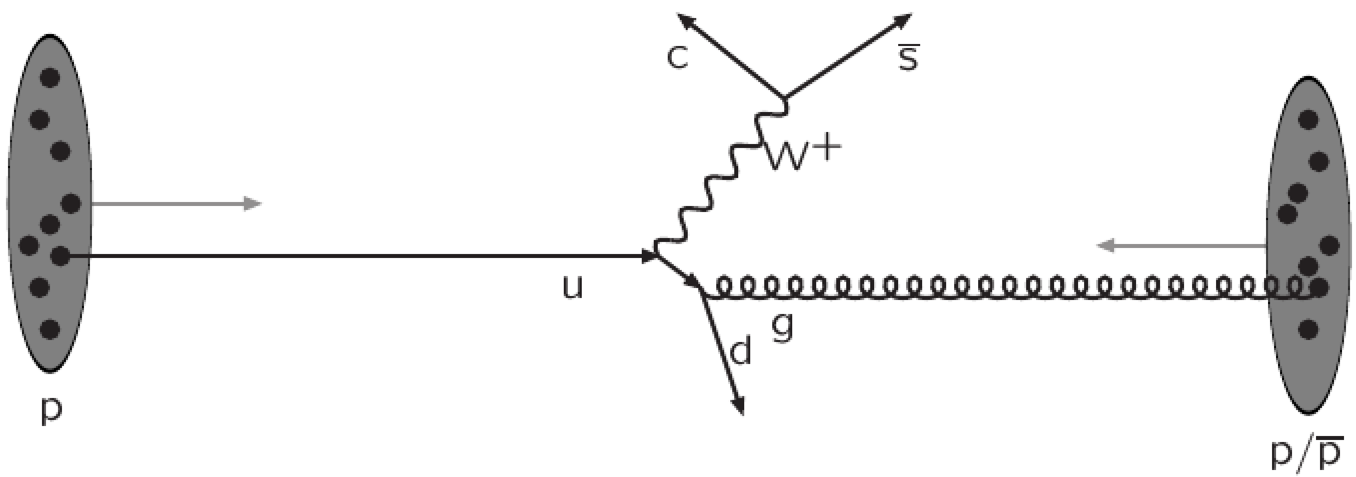
(T. Sjostrand)

# Scenario of a hadron-hadron collision



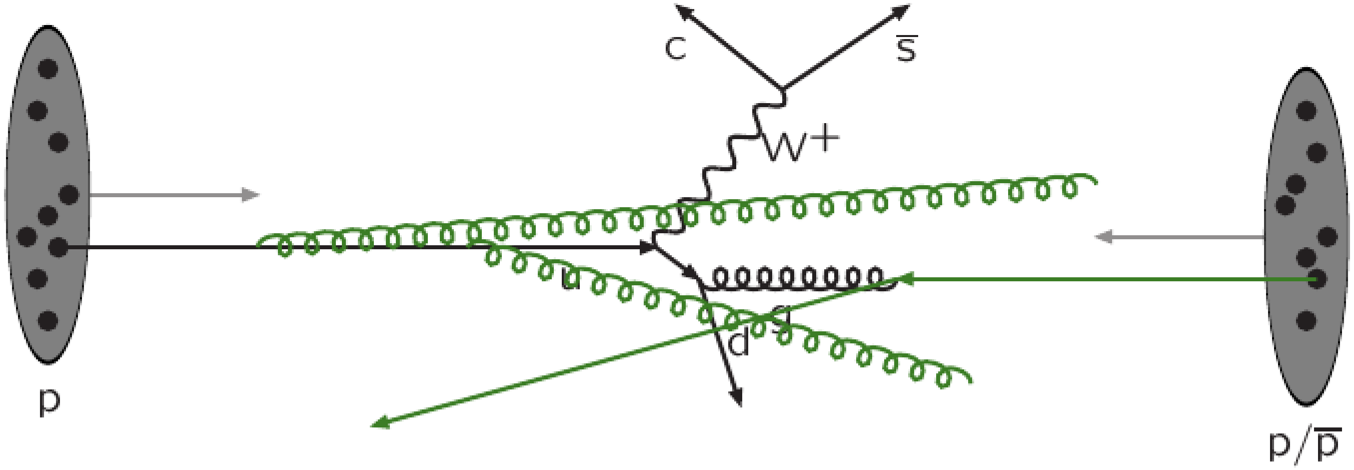

Hard subprocess: described by matrix elements

# Scenario of a hadron-hadron collision



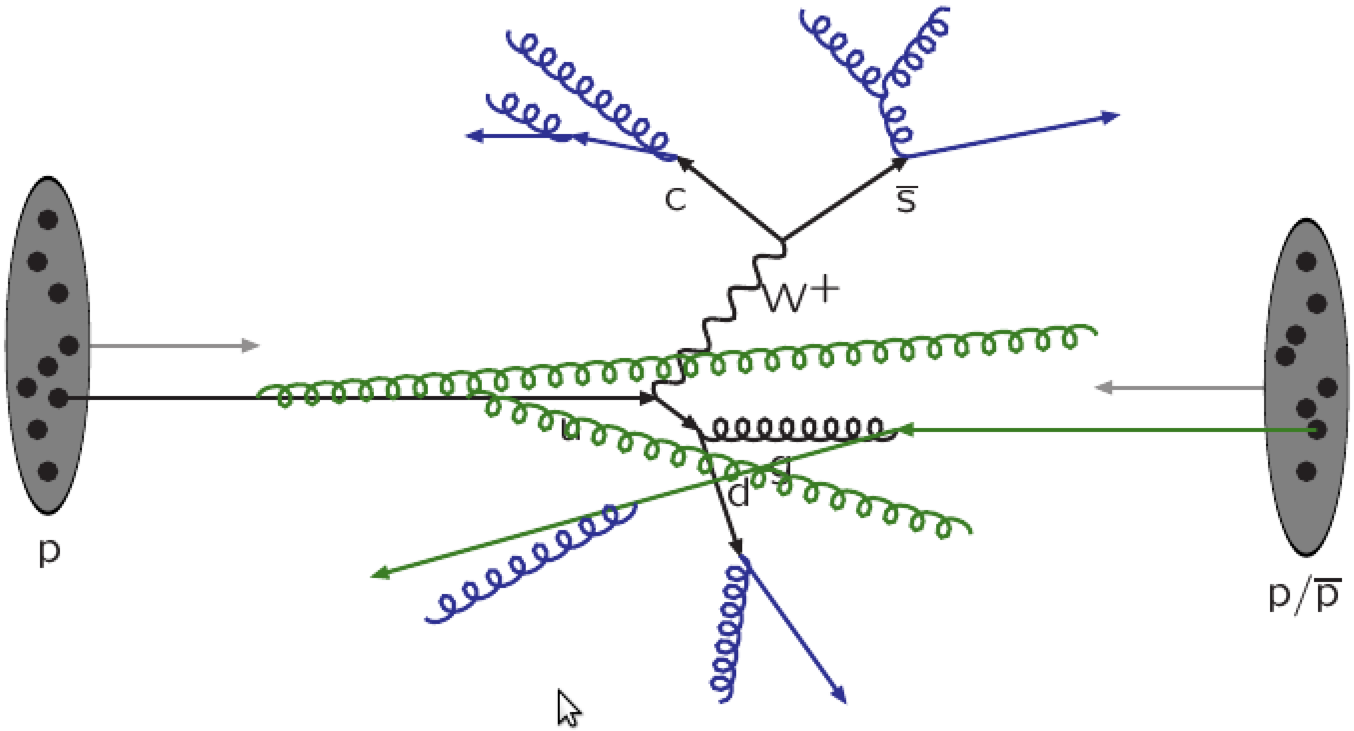

Resonance decays: correlated with hard subprocess

# Scenario of a hadron-hadron collision



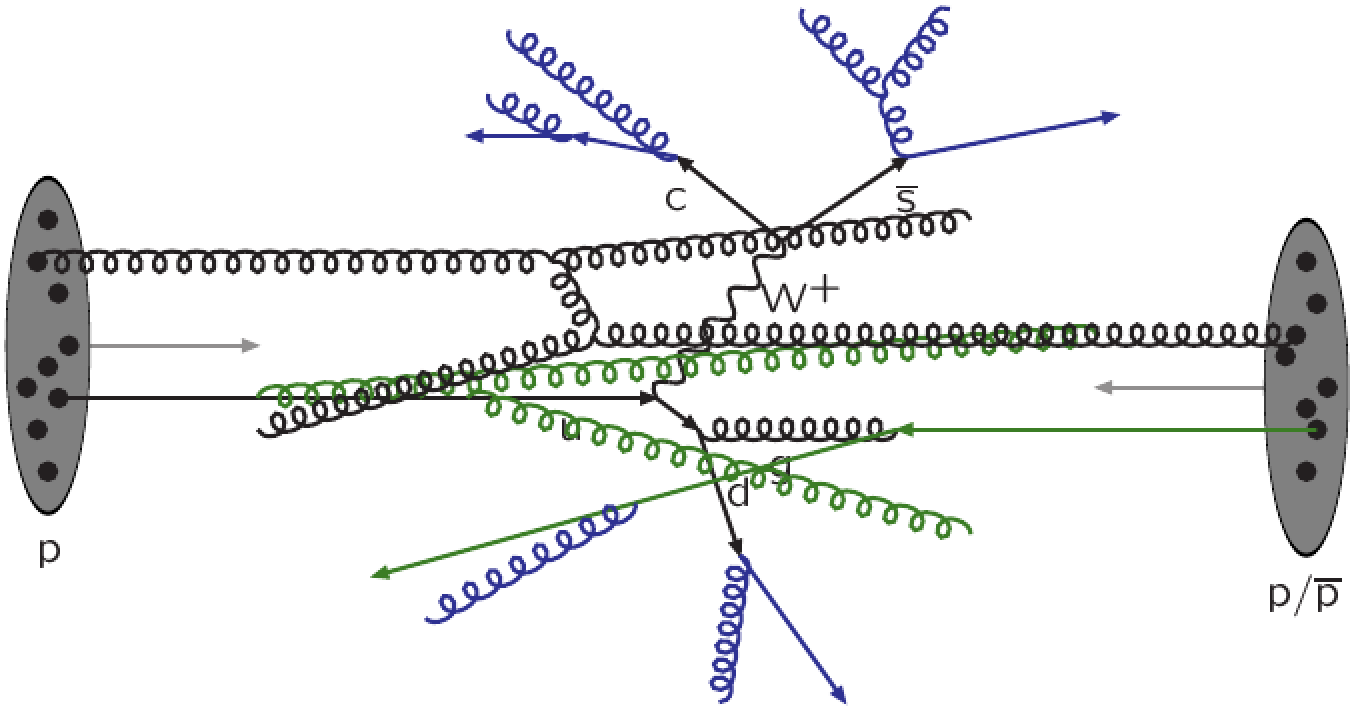

Initial-state radiation: spacelike parton showers

# Scenario of a hadron-hadron collision



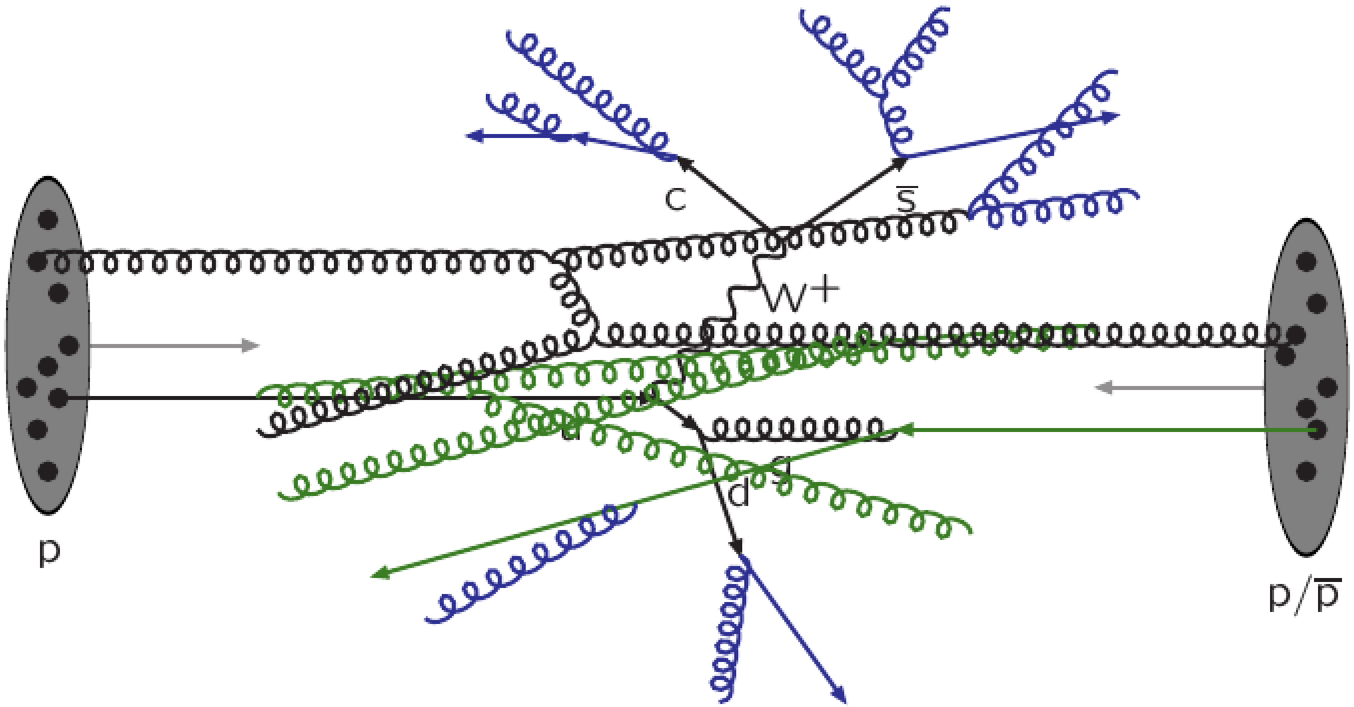

Final-state radiation: timelike parton showers

# Scenario of a hadron-hadron collision



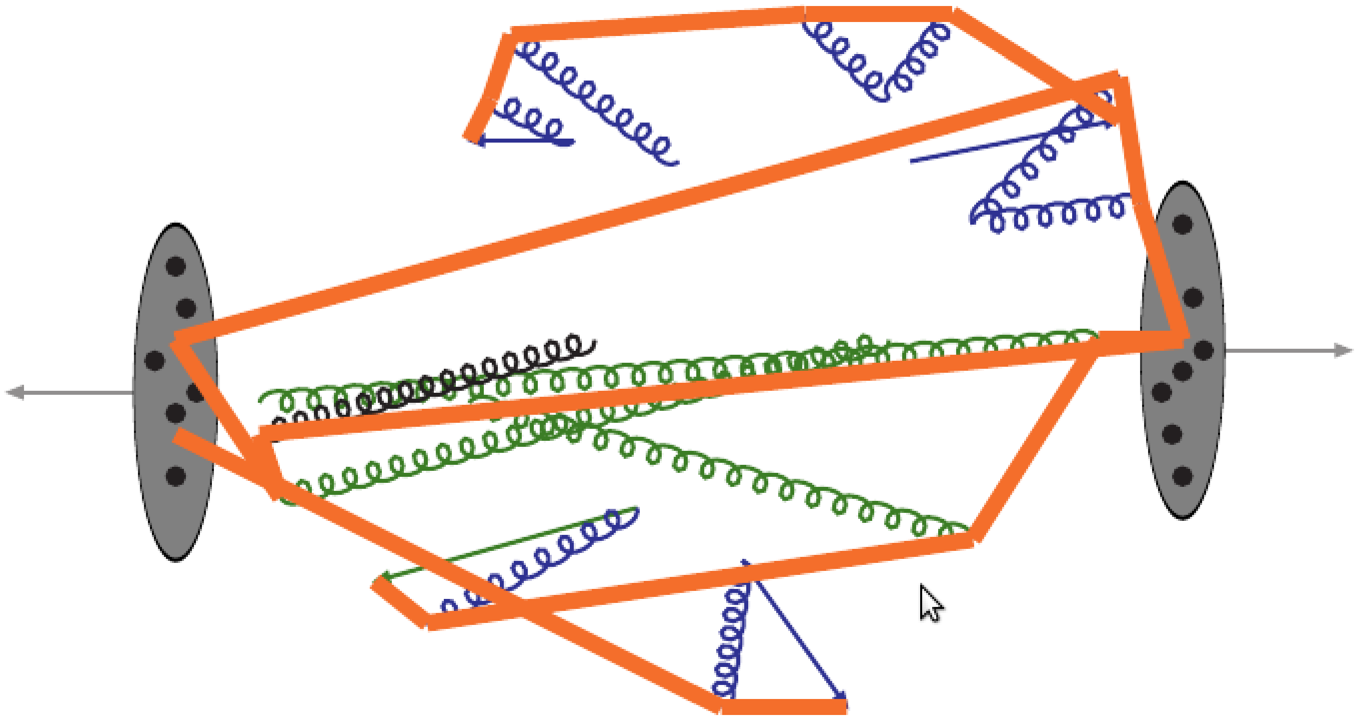

Multiple parton–parton interactions . . .

# Scenario of a hadron-hadron collision




. . . with its initial- and final-state radiation

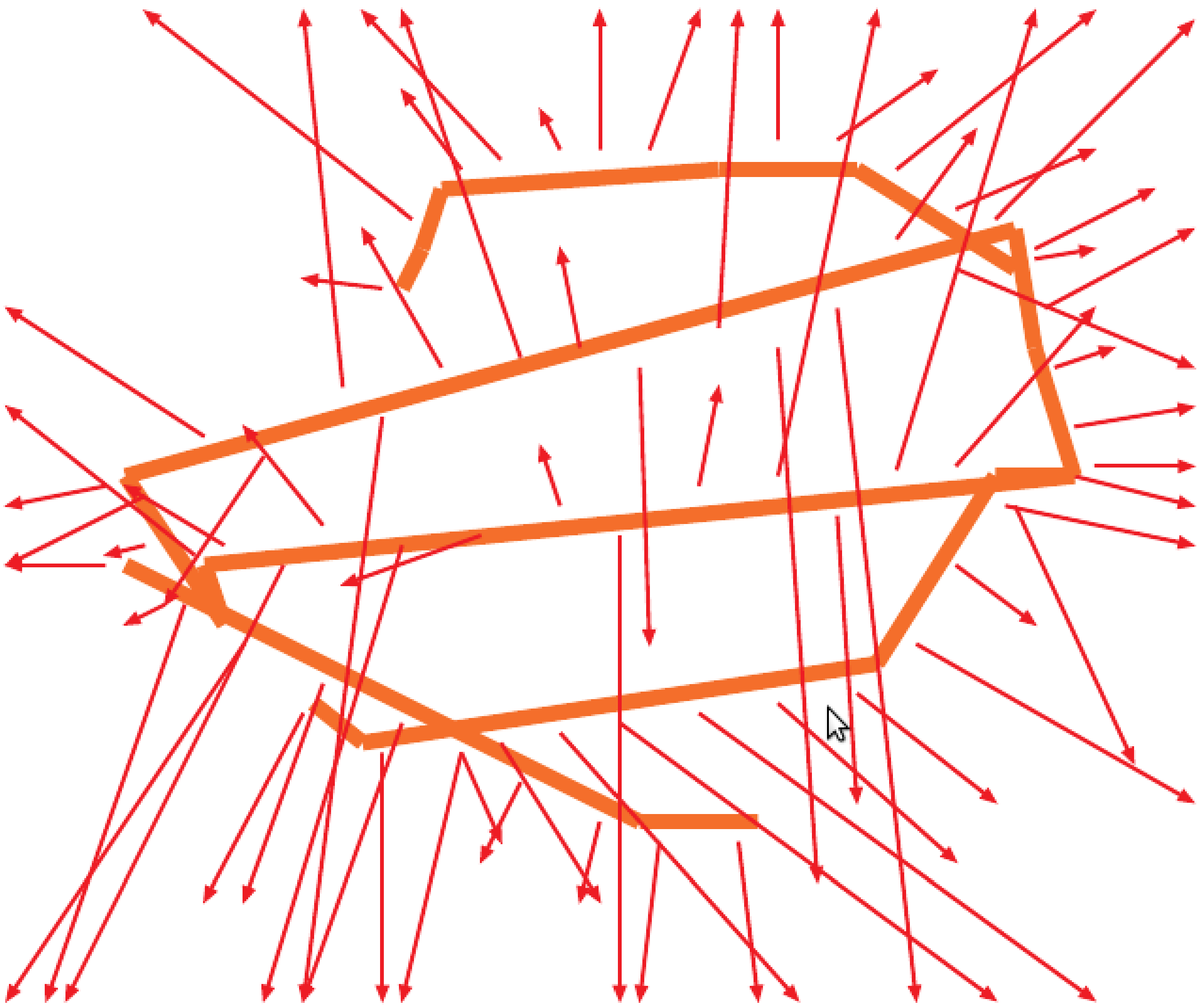
# Scenario of a hadron-hadron collision



Everything is connected by colour confinement strings

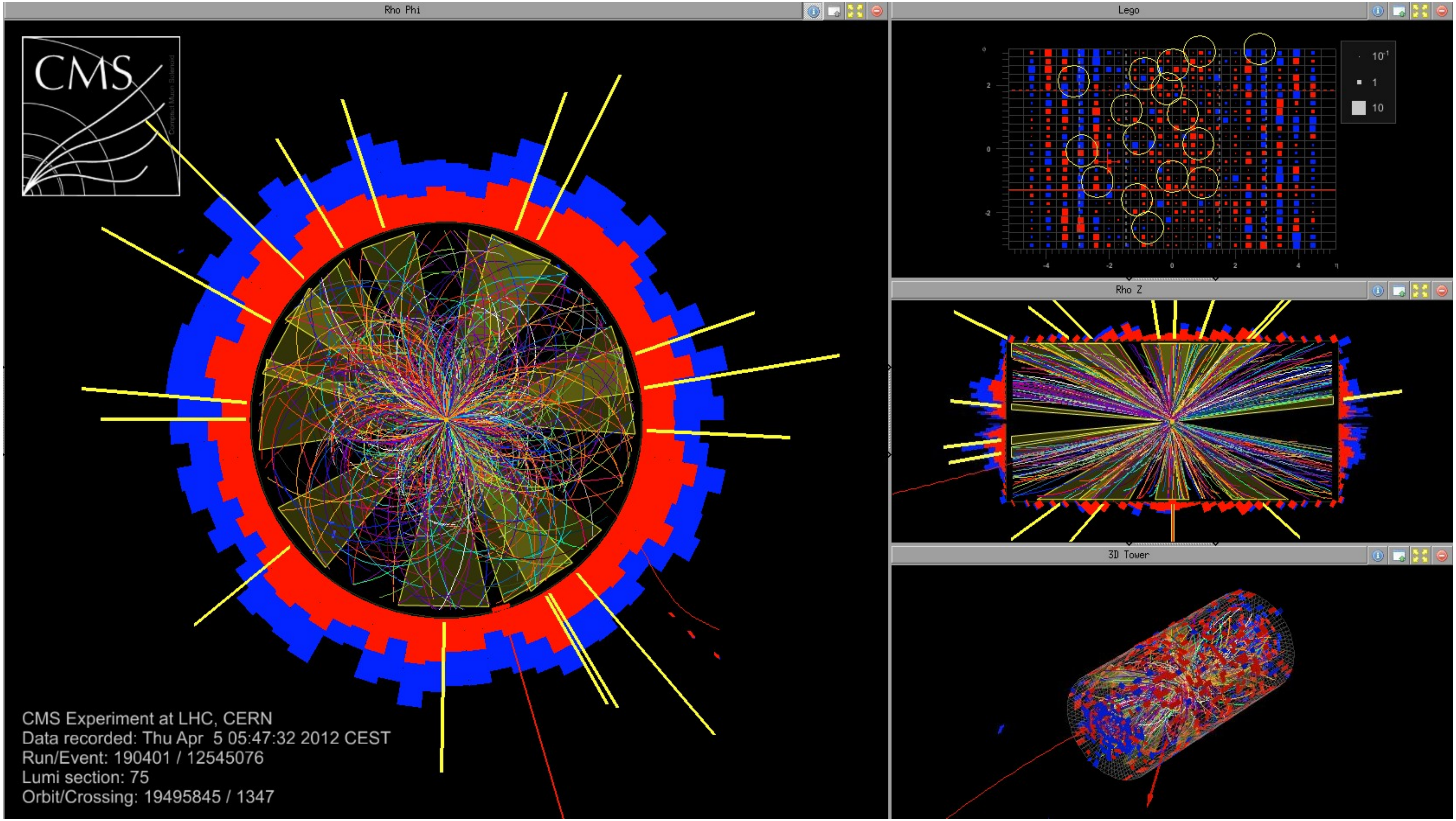
Recall! Not to scale: strings are of hadronic widths

# Scenario of a hadron-hadron collision



The strings fragment to produce primary hadrons

# A proton-proton event in CMS



# Lessons

- A hadron-hadron collision is a very complex process!
  Of interest for us in the following:

  - The "hard process" (e.g, W or Z resonance production) is accompanied by much other, mostly decorrelated activity that also leave signals in the detector

  - Colliding protons are not like protons at rest. When 2 protons move towards eachother, the quarks on each side start interacting
    - Emitting gluons : **q → q g**
    - The gluons then also take part in the interaction, and can split into new quarks, e.g
      **g → u ubar**
      **g → d dbar**
      **g → s sbar**
      **g → c cbar**
      **g → b bbar**

**Resulting in a complex "soup" of gluons and quarks of all flavours!**

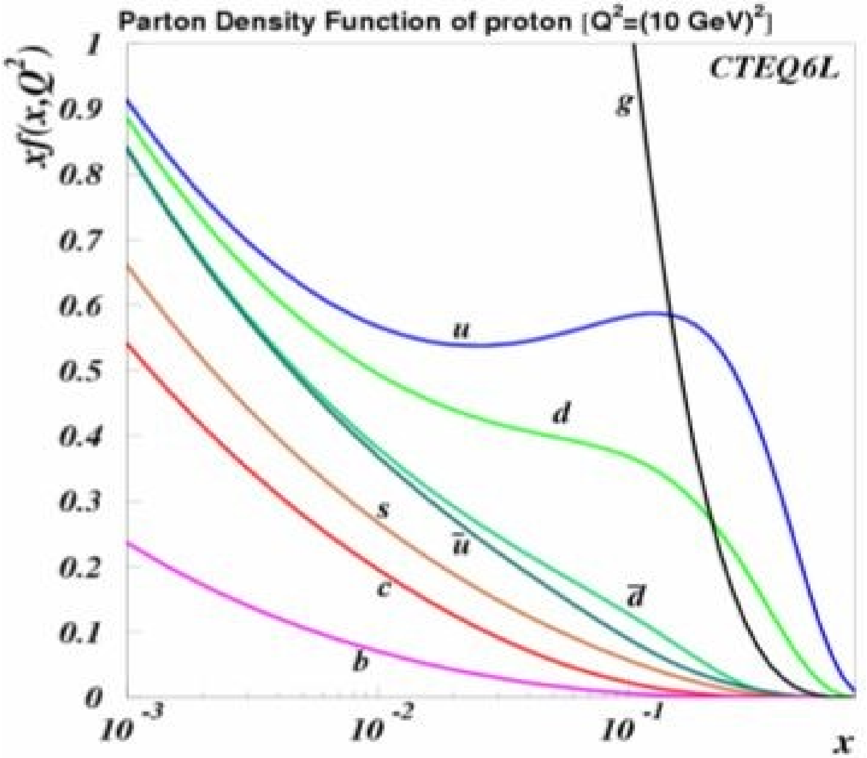
# Resonance production in hadron collisions

- The proton can a priori contain $u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, g...$ It has to remain a **(u,u,d)** hadron overall, implying so-called "sum-rules", for example:

$$\int [u(x)-\bar{u}(x)]dx=2 \qquad \int [d(x)-\bar{d}(x)]dx=1 \qquad \int [s(x)-\bar{s}(x)]dx=0$$

- The measured proton PDFs:

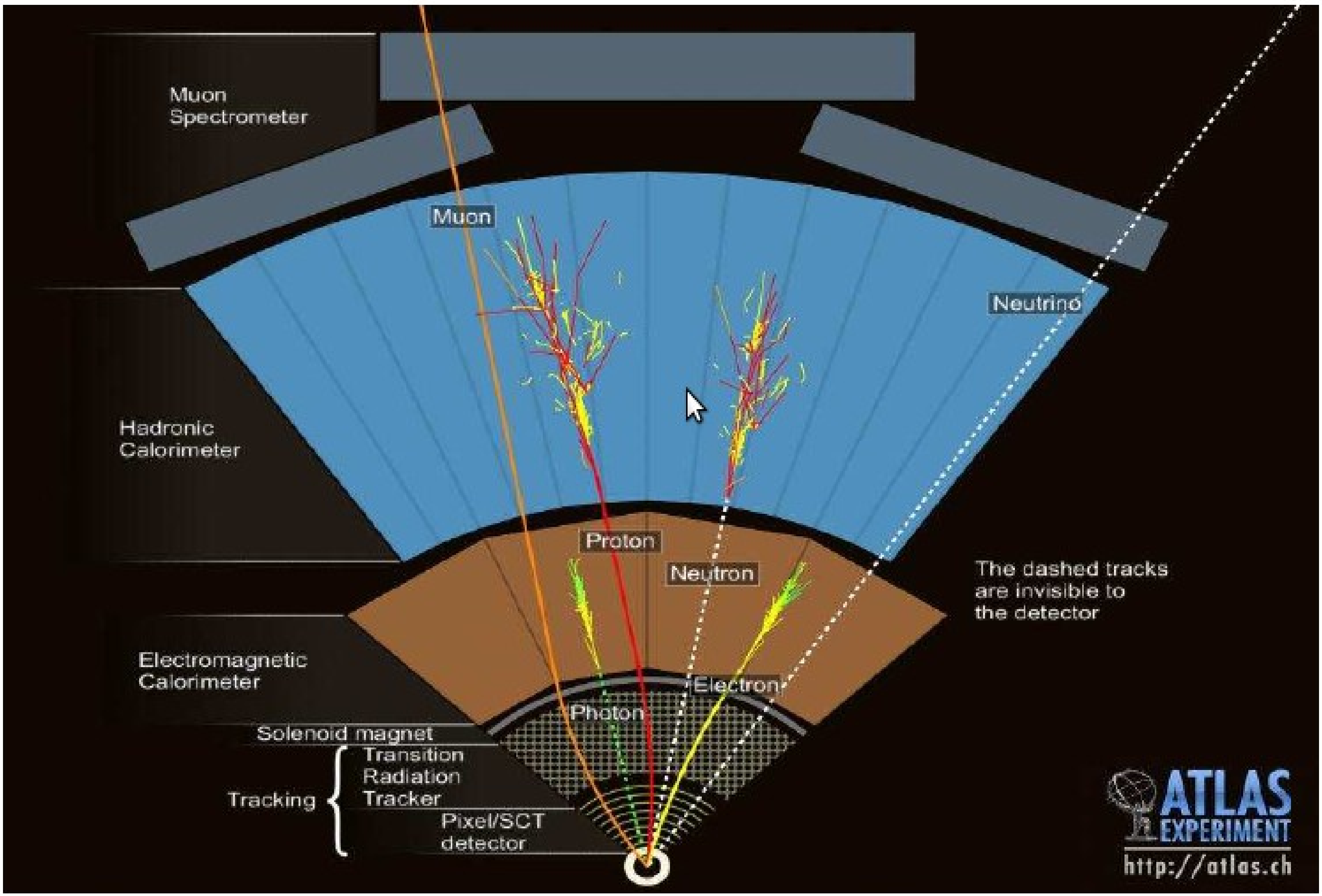
  (anti-proton PDFs obtained by c.c)




- Overall cross section:

$$\sigma = \sum_q \int dx_1 dx_2 q(x_1) \bar{q}(x_2) \sigma_{q\bar{q} \to l^+ l^-}(x_1 x_2 s)$$

# A very brief reminder of detection methods...



# Experimental set-up

- Proton and anti-proton beam, at a centre-of-mass energy of 540 GeV
- Two “multipurpose” detectors, UA1 and UA2, built around the interaction point

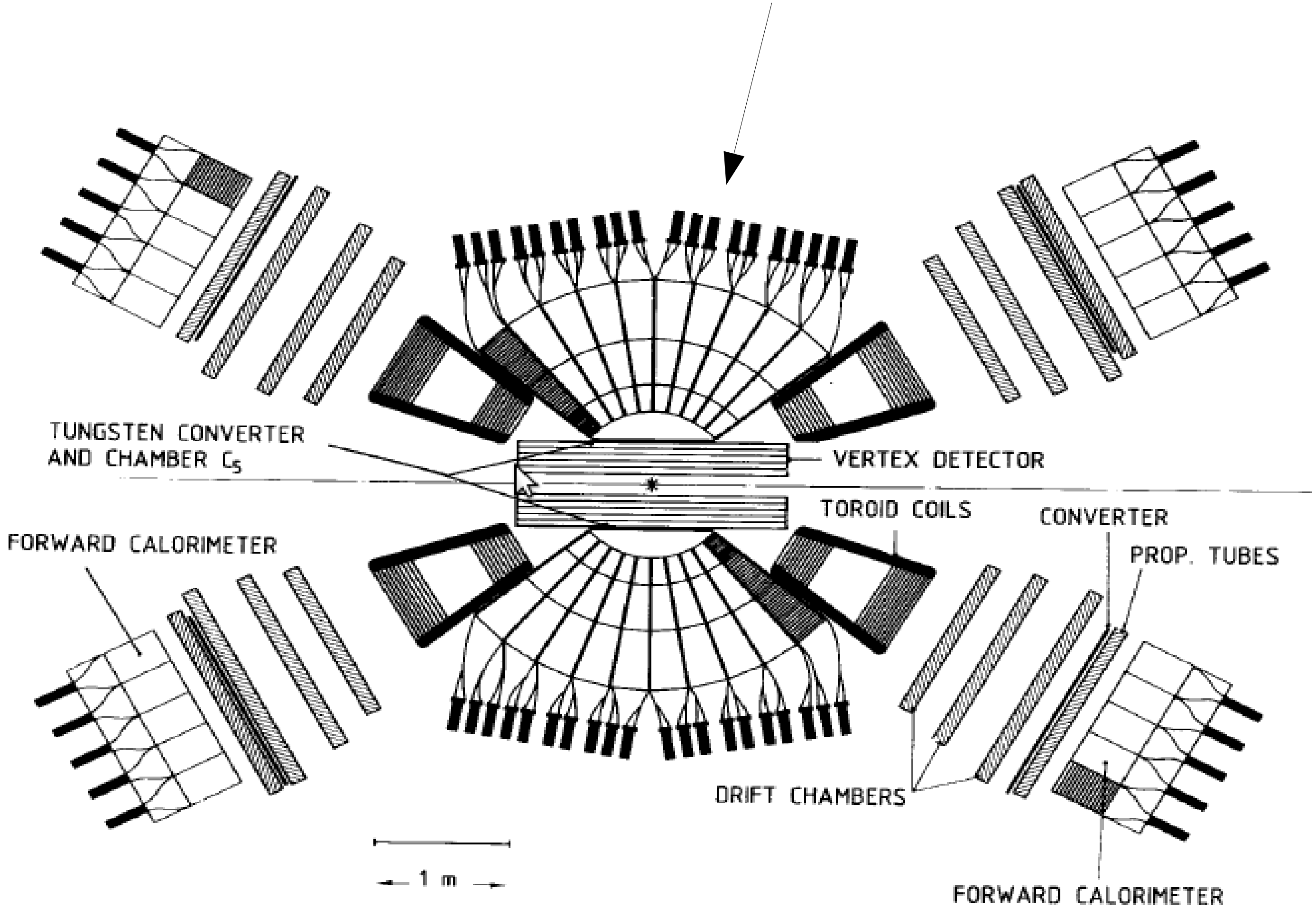
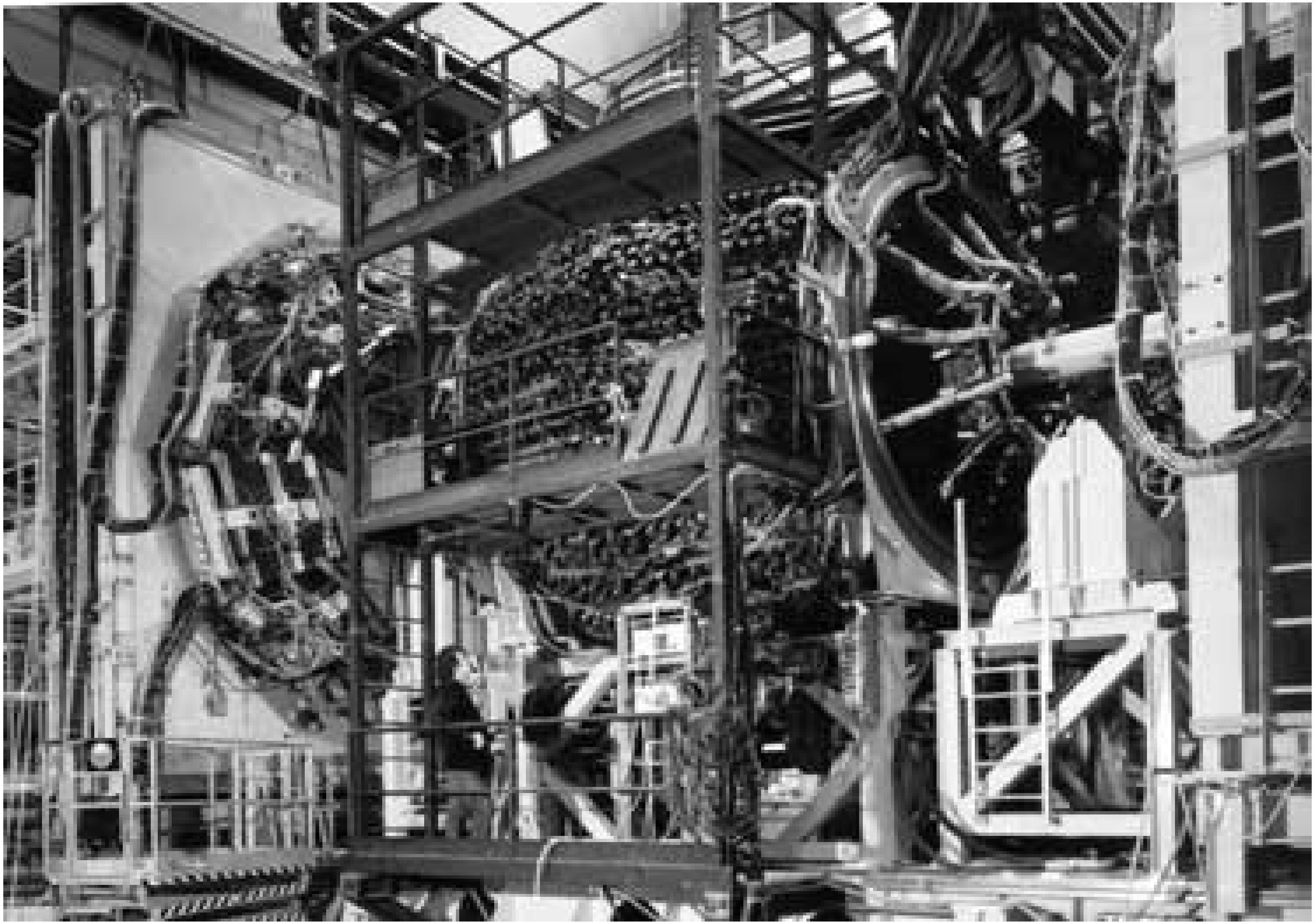


Fig. 1

# The real detector



# How to measure the W and the Z?

- **For the Z boson it is easy, at least in principle**
  - Both decay leptons are measured in the calorimeters
  - We can then combine their four-momenta and compute the invariant mass of the pair
  - The distribution of this invariant should display a peak at the resonance. The position of the peak will give the resonance mass.

- **And for the W?**
  - We measure one decay lepton; the neutrino escapes
  - We can however estimate the transverse momentum of the neutrino, by summing all measured signals in the calorimeter and imposing momentum conservation in the transverse plane!
    - Initial state has $p_T = 0$; and momentum is conserved
    - So we can use $p_T(\nu) = -\sum_i \vec{p}_{T,i}$

# How to measure the W and the Z?

- **(W continued)**
  - The transverse momentum distributions of the charged lepton and neutrino are sensitive to the W boson mass!
  - Suppose the W is produced with longitudinal momentum (induced by the proton PDFs), and with small transverse momentum. Then in the W rest frame we have

$$\frac{d\sigma}{d\cos\theta} \sim 1+\cos^2\theta$$

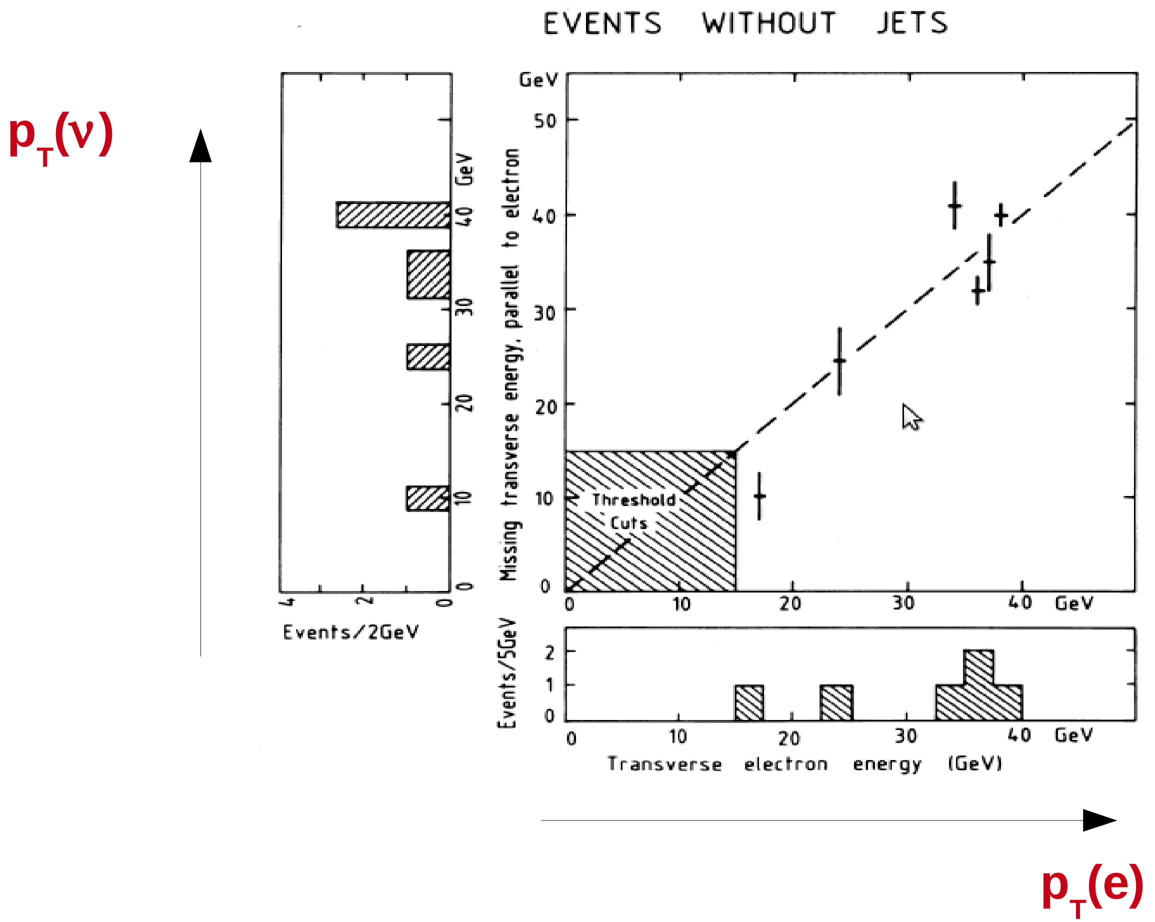
  - Change variables to $p_T = \frac{M_W}{2}\sin\theta$

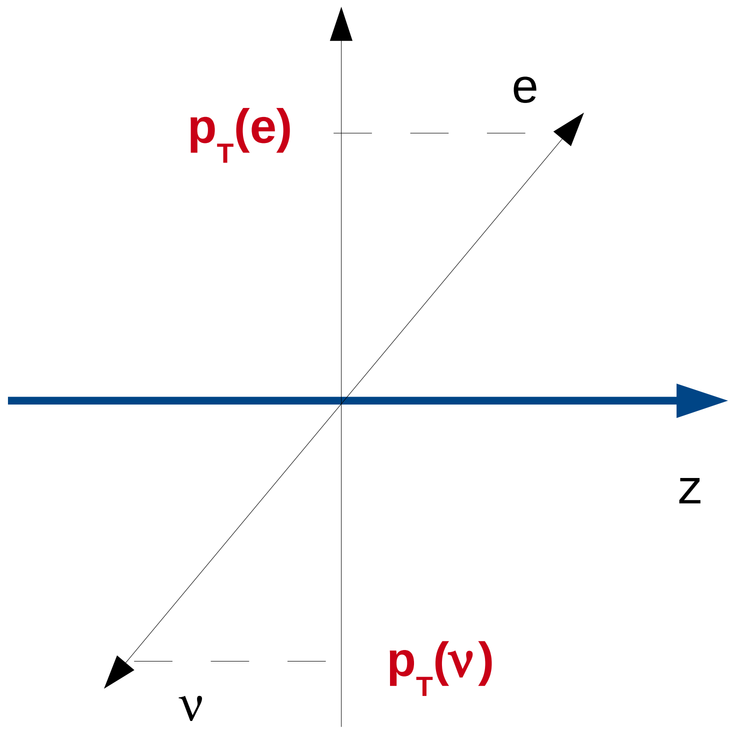
and obtain : $\frac{d\sigma}{dp_T} \sim \frac{p_T/M_W-(p_T/M_W)^3}{\sqrt{1-(2p_T/M_W)^2}}$ diverges at $p_T = \frac{M_W}{2}$

  - Actually the divergence is cured by many effects, but a peak remains, allowing to estimate Mw from the distribution.

# The discovery papers : 1983

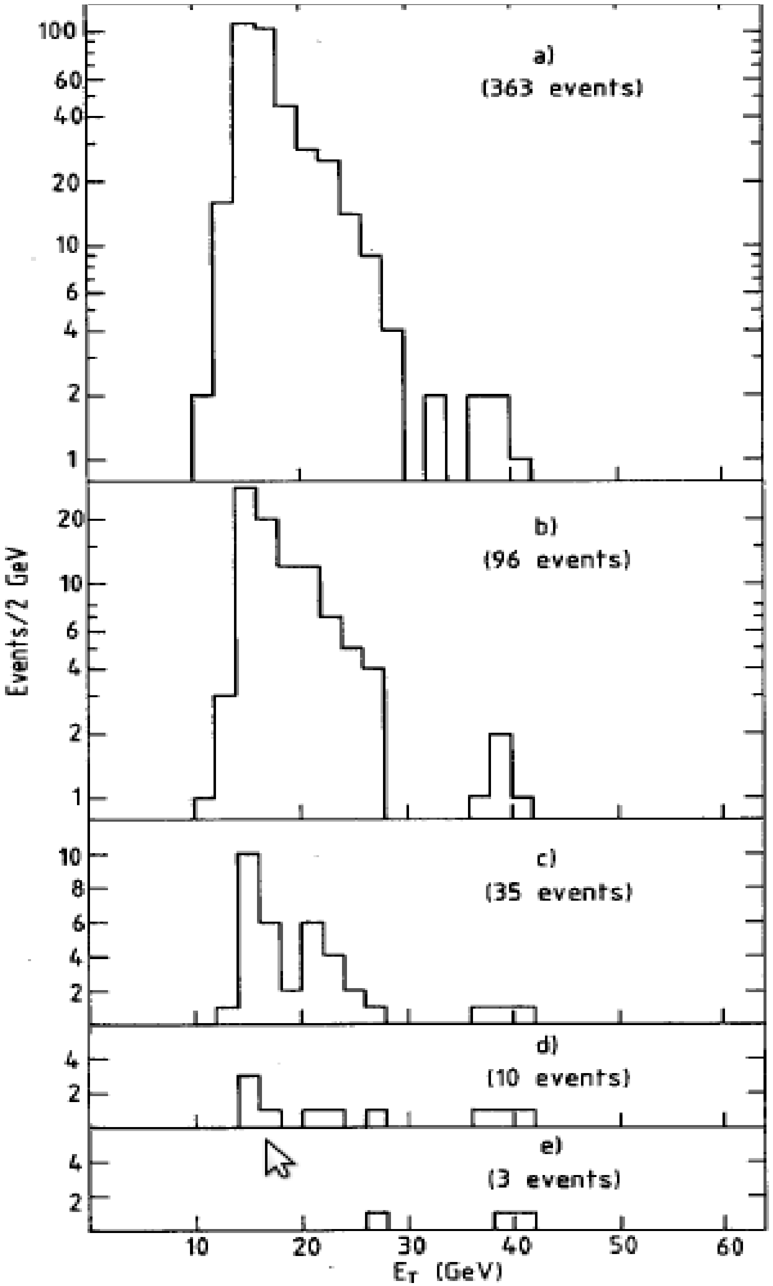
- In order of appearance!
- January 1983 : UA1 announces W discovery



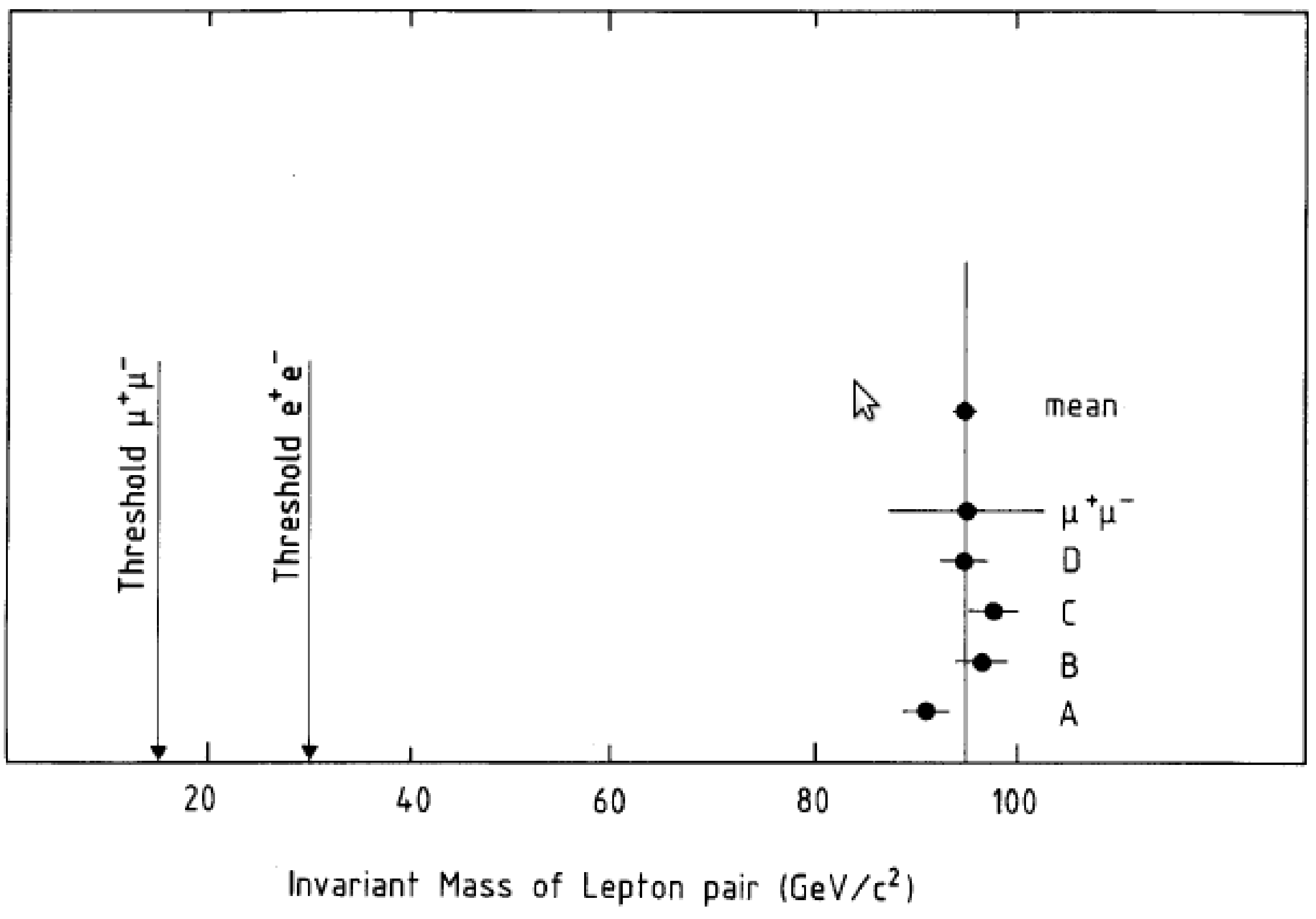
# The discovery papers : 1983

- February 1983 : UA2 announces W discovery
- Here an example of how events are selected from the background:
  - Cut 1 : selection of a high energy cluster in the EM calorimeter
  - Cut 2 : cluster matched to a track
  - Cut 3 : energy deposit in the “pre-shower” detector
  - Cut 4 : only one such deposit
  - Cut 5 : final reconstruction quality cuts



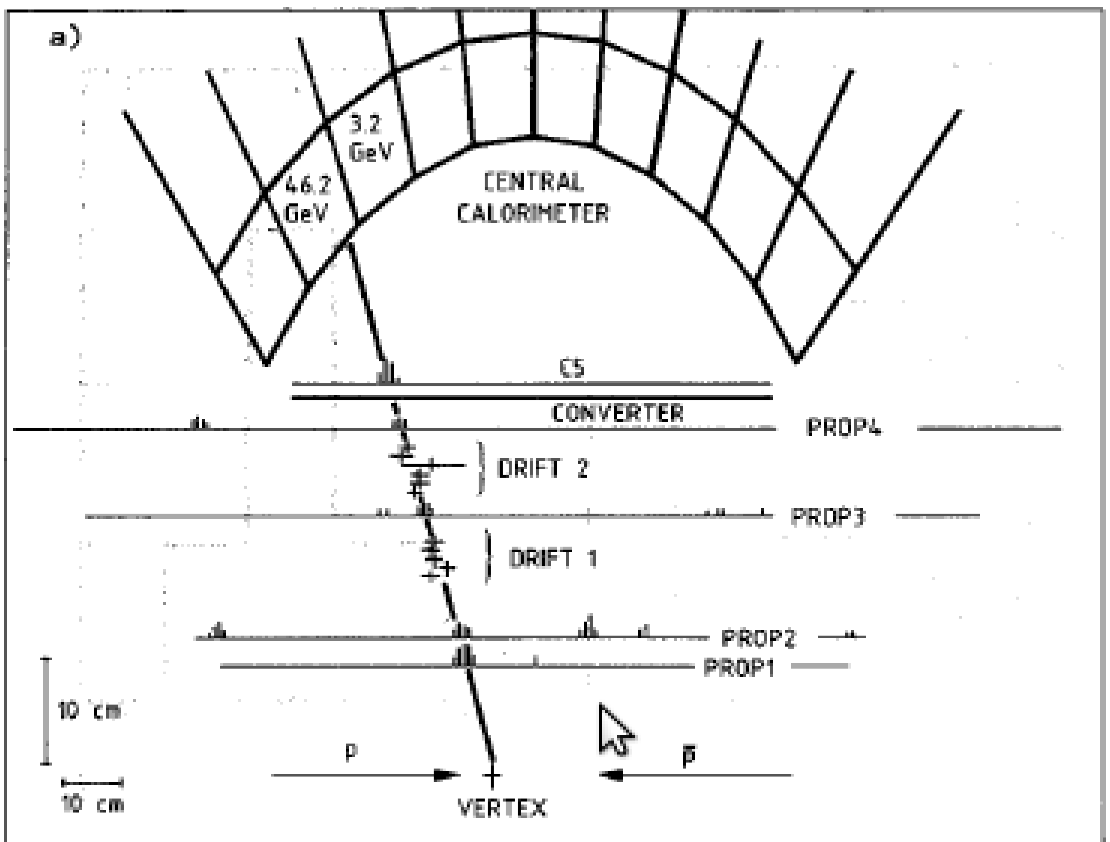
# The discovery papers : 1983

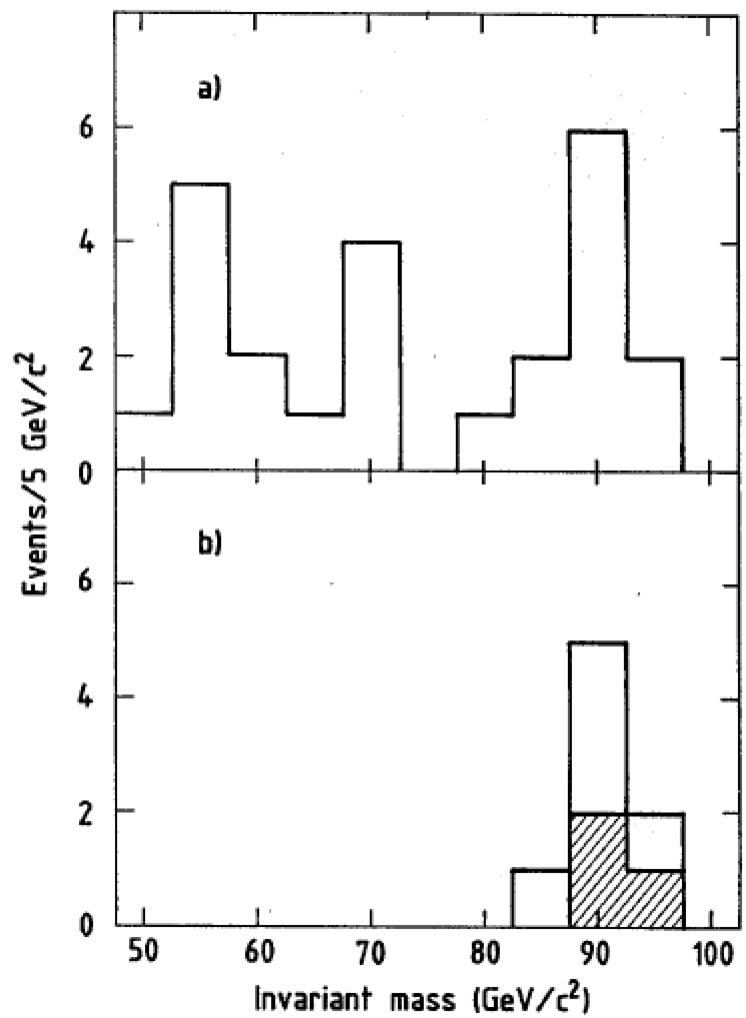
- June 1983 : Z discovery in UA1



# The discovery papers : 1983

- August 1983 : UA2 follows



# Implications / status of the SM

- Confirmation of the existence of the gauge bosons!
  Meaning : establish the pole of their propagator, in contrast to the neutrino experiments.

- Masses measured:

  - **$M_W$ = 81 +- 3 GeV**

  - **$M_Z$ = 92 +- 2 GeV** **in agreement** with the estimation based on **$\sin^2\theta_W$**

- We have now established the nature of the weak force, and confirmed the SU(2)xU(1) hypothesis. What will follow in the next decade is a thorough exploration of all possible observables, verifying consistency and searching for the missing pieces.

# First "precision tests" of the Standard Model

- Let us see if we can go further! Using the expressions given previously:

  - Combining $G_F$ and $M_W$ provides a new measurement of $\sin^2\theta_W$:

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8\sin^2\theta_W M_W^2} \longrightarrow \sin^2\theta_W = 0.227 \pm 0.015$$

  - We can test the ρ parameter using the independent measurements of $M_W$, $M_Z$ (the present discoveries) and $\sin^2\theta_W$ (from the NC/CC measurement):

$$\rho = \frac{M_W^2}{M_Z^2\cos^2\theta_W} \longrightarrow \rho = 1.01 \pm 0.05$$

**We are already testing the Higgs sector!**