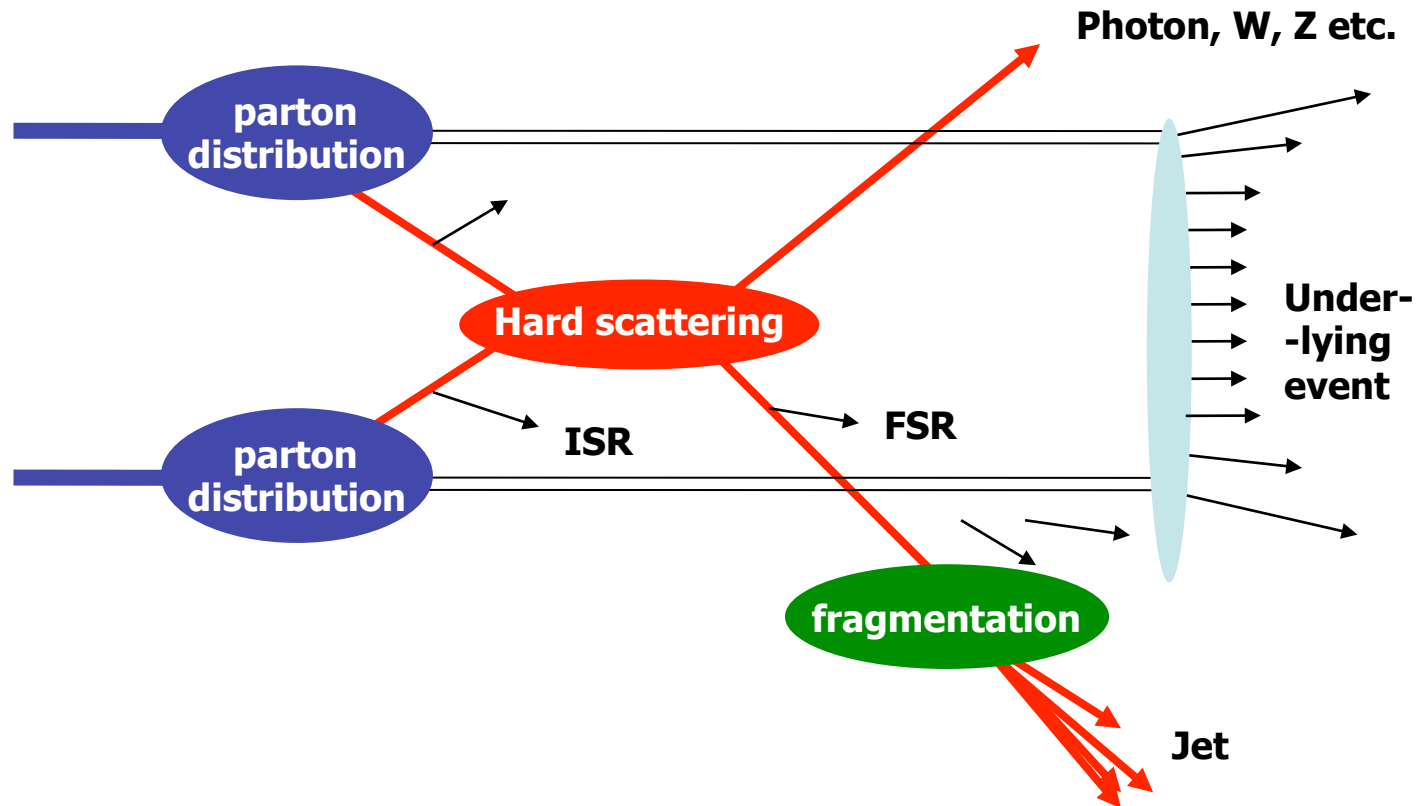


Collisioni adroniche e  
produzione di W/Z  
ai collider da SppS a LHC

# Collisioni Adroniche

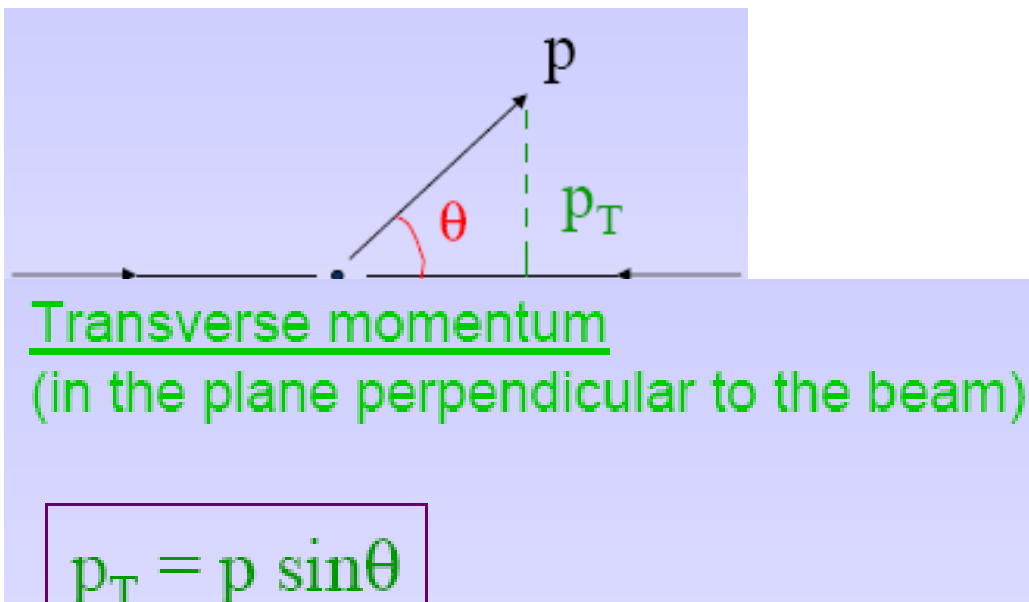


- Due classi di eventi
  - Processi “soft” a piccolo momento trasferito, caratterizzate dalla emissione di particelle a basso momento trasverso (QCD)
  - Processi “hard” a grande momento trasferito dove e’ possibile osservare la produzione di getti di particelle adroniche, fotoni, bosoni vettori etc. (QCD+EWK)
- Anche nei processi “hard” la grande maggioranza delle particelle emesse sono prodotte dal riarrangiamento dei flussi di colore dei partoni nelle particelle dei fasci (beam remnants) per ottenere stati finali “bianchi”. Si produce quindi il così detto “underlying event”



# Variabili Cinematiche

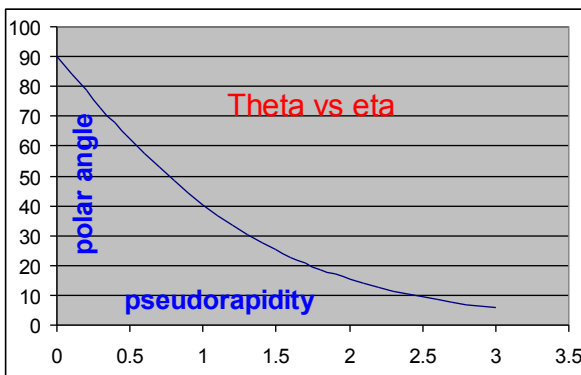
- Il centro di massa delle collisioni elementari ha in genere un moto non trascurabile lungo l'asse dei fasci (protoni = oggetti complessi)
- Utilizziamo il piano trasverso ai fasci:



- $p_T$  e' invariante rispetto al boost del c.m.
- Si sfrutta la conservazione del momento nel piano trasverso (=0 nello stato iniziale) per rivelare la presenza di particelle non-interagenti
- Energia trasversa  $E_T = E * \sin \theta$

# Variabili cinematiche – Rapidita'

- L'angolo polare  $\theta$  non è invariante rispetto a boost lungo Z così come non lo è la distanza angolare  $\Delta\theta_{i,j}$  tra due particelle  $i,j$ .



$\theta = \text{polar angle}$

Direzione del fascio di protoni

- Si introduce la rapidita':

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right).$$

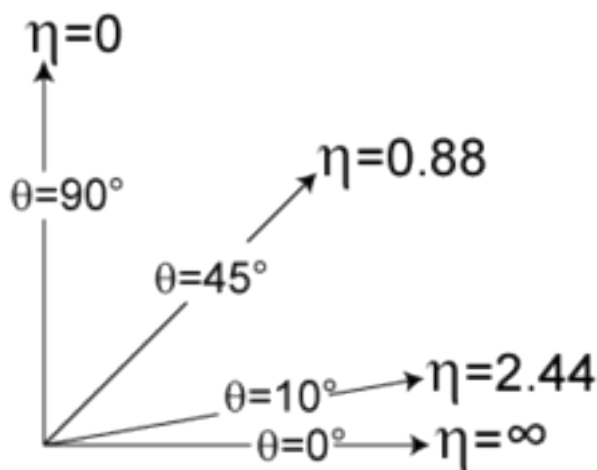
- Applicando un boost di Lorentz ( $\beta$ ):

$$y \rightarrow y' = y + \frac{1}{2} \ln \left( \frac{1 - \beta}{1 + \beta} \right)$$

- Dunque  $\Delta y = y_i - y_j$  e' una misura Lorentz invariante della "distanza" tra due particelle  $(i,j)$ .

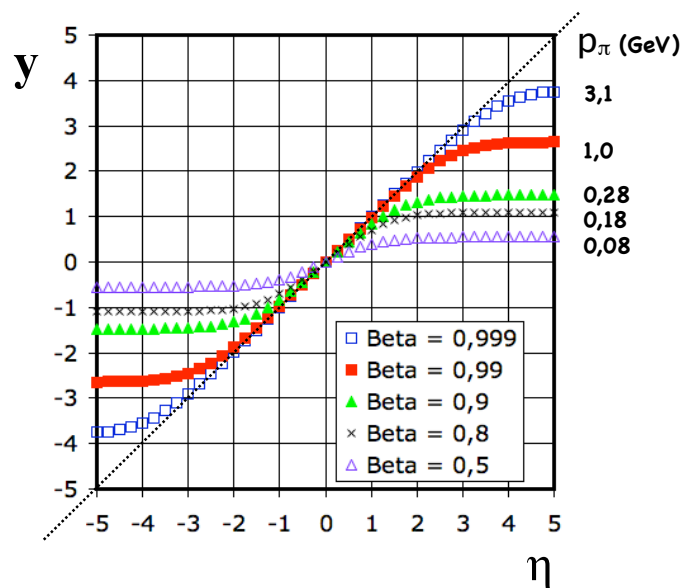
# Variabili cinematiche – Rapidita'

- Per particelle mass-less o altamente relativistiche e' conveniente utilizzare la pseudo-rapidita'  $\eta$



$$\eta \equiv -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right],$$

$$y = \ln \left( \frac{\sqrt{m^2 + p_T^2 \cosh^2 \eta} + p_T \sinh \eta}{\sqrt{m^2 + p_T^2}} \right)$$

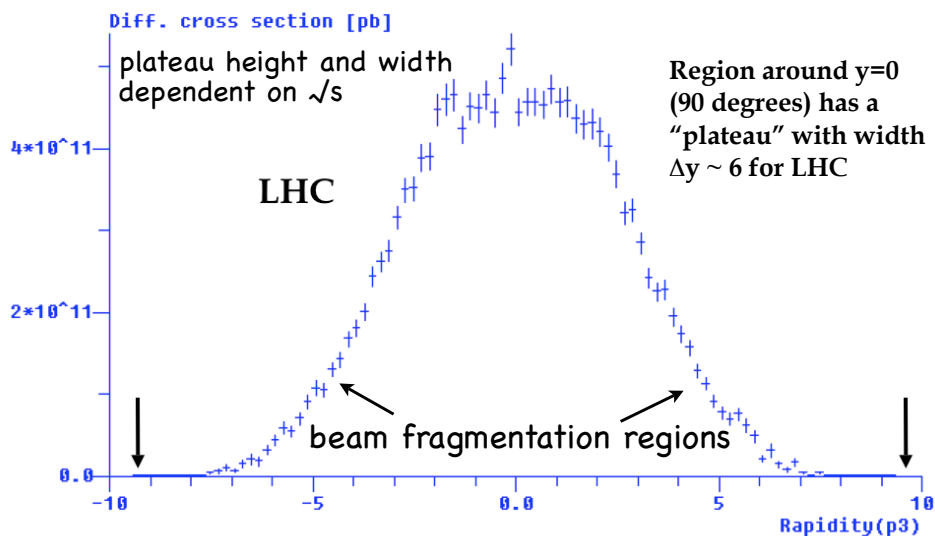


- Per  $m \ll p_T$   $y \rightarrow \eta$
- Dunque definiamo una distanza 2D tra due particelle tipicamente come:

$$\Delta R = \sqrt{[(\Delta \eta)^2 + (\Delta \phi)^2]}.$$

# Rapidity Plateau

- L'emissione di particelle è circa costante in rapidità all'interno del range cinematicamente permesso
- Spazio delle fasi invariante  $d\tau$  proporzionale a  $dy$ :  $d\tau = 1/2 dp_T^2 d\Phi dy$
- Se matrix-element costante con  $y$ 
$$d\sigma = |M|^2 d\tau$$
- La sez. d'urto sarà circa costante in  $y$



# Relazioni cinematiche

Given the definition  $y = \frac{1}{2} \cdot \ln[(E+p_z)/(E-p_z)]$ , there is a maximum value for the rapidity, which depends on the beam energy.

We can simply calculate it for a "forward elastically scattered" beam protons (i.e.  $\theta \approx 0$  degrees and  $p_z \approx p_{\text{beam}}$ ):

$$y = \frac{1}{2} \cdot \ln \frac{(E+p_z)}{(E-p_z)} = \frac{1}{2} \cdot \ln \frac{(E+p_z)}{(E-p_z)} \cdot \frac{(E+p_z)}{(E+p_z)} = \frac{1}{2} \cdot \ln \frac{(E+p_z)^2}{(E^2-p_z^2)}$$

$$y_{\text{max}} = \frac{1}{2} \cdot \ln \frac{(2p_{\text{beam}})^2}{m_p^2} = \ln \frac{2p_{\text{beam}}}{m_p} = \ln \frac{\sqrt{s}}{m_p}$$

only log dependence on beam energy

Therefore,

at LHC:  $y_{\text{max}} \approx \ln(14\text{TeV}/1\text{GeV}) \approx \ln 14000 \approx 9.5$

at Tevatron:  $y_{\text{max}} \approx \ln(2\text{TeV}/1\text{GeV}) \approx \ln 2000 \approx 7.6$

$$q_1 = \frac{1}{2}\sqrt{s} (x_1, 0, 0, x_1)$$

$$q_2 = \frac{1}{2}\sqrt{s} (x_2, 0, 0, -x_2)$$

The rapidity for the system  $q_1+q_2$  is:

$$y = \frac{1}{2} \ln[(E+p_z)/(E-p_z)] = \frac{1}{2} \ln(x_1/x_2)$$

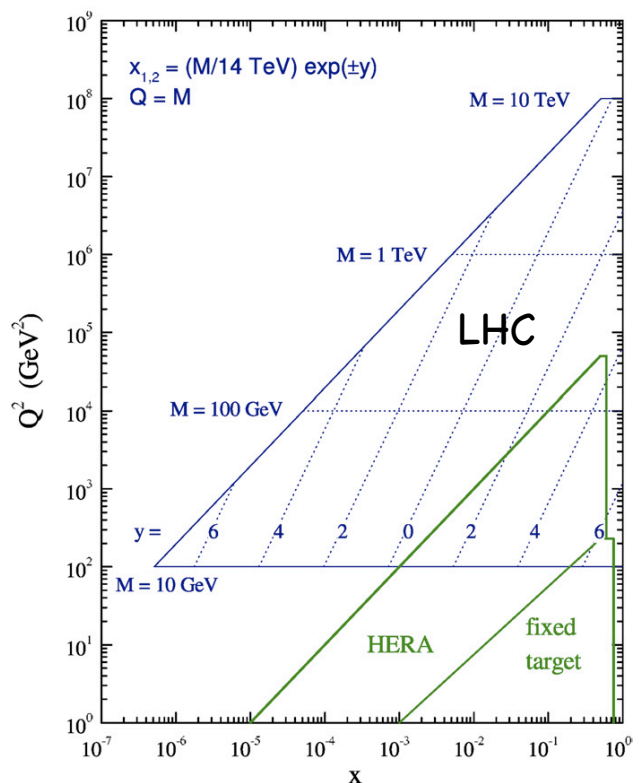
Hence:  $x_1 = x_2 e^{2y}$

and using  $\hat{s} = M^2 = x_1 x_2 s$ , we obtain:

$$x_1 = (M/\sqrt{s}) \cdot e^{+y} \quad \text{and} \quad x_2 = (M/\sqrt{s}) \cdot e^{-y}$$

Therefore, different values of M and y probe different values of  $x_1$  and  $x_2$  of the colliding beams.

In general, for ANY final state with a given y and M values, in the plot on the right, there will be two (dashed) lines that give the x values at which the protons are probed



# Conclusioni

- La produzione di particelle soft avviene a tutte le rapidità (ma si concentra in avanti in  $\theta$ : intervalli costanti in  $y$  corrispondono a intervalli sempre più piccoli nel laboratorio )
- Per la produzione di particelle pesanti siamo interessati alla zona “centrale” nel rivelatore, ovvero le zone corrispondenti a  $y$  piccolo (ad es.  $|y| < 1.5$ )
- Più pesante  $\rightarrow$  più “centrale”

# Underlying Event

The total antiproton-proton cross section is the sum of the elastic and inelastic components,  $\sigma_{\text{tot}} = \sigma_{\text{EL}} + \sigma_{\text{IN}}$ . Three distinct processes contribute to the inelastic cross section: single diffraction, double-diffraction, and everything else (referred to as “non-diffractive”). For elastic scattering neither of the beam particles breaks apart (*i.e.* color singlet exchange). For single and double diffraction one or both of the beam particles are excited into a high mass color singlet state (*i.e.*  $N^*$  states) which then decay. Single and double diffraction also correspond to color singlet exchange between the beam hadrons. When color is exchanged the outgoing remnants are no longer color singlets and one has a separation of color resulting in a multitude of quark-antiquark pairs being pulled out of the vacuum. The non-diffractive component,  $\sigma_{\text{ND}}$ , involves color exchange and the separation of color. However, non-diffractive collisions have both a soft and hard component. Most of the time the color exchange between partons in the beam hadrons occurs through a soft interaction (*i.e.* no high transverse momentum) and the two beam hadrons ooze through each other producing lots of soft particles with a uniform distribution in rapidity and many particles at small angles to the beam. Occasionally, there is a hard scattering among the constituent partons producing outgoing particles and “jets” with high transverse momentum.

- The underlying event (UE) consists of the beam-beam remnants (BBR) and the multiple parton interactions (MPI) that accompany a hard scattering. The UE is an unavoidable background to hard-scattering collider events. To study the UE we use MB data, however, MB and UE are not the same object. The majority of MB collisions are soft, while the UE is studied in events in which a hard scattering has occurred. One uses the structure of the hard hadron-hadron collision to experimentally study the UE.

# Minimum Bias (MB)

- La vastissima maggioranza della sezione d'urto inelastica protone-protone ( $\sim 50$  mb su 70 al TeVatron, 80/100 a LHC!) e' costituita da interazioni soffici (produzione di particelle di basso impulso trasverso)

Process	Cross-section (mb)	
	PHOJET	PYTHIA
non-diff.	69	55
single diff.	11	14
double diff.	4	10
central diff.	1	-
total inelastic	85	79
elastic	35	23
total	120	102

The diagram shows three boxes labeled 'Single Diffractive', 'Double Diffractive', and 'Non Diffractive'. Arrows from the 'Single Diffractive' and 'Double Diffractive' boxes point to the  $\sigma_{sd}$  and  $\sigma_{dd}$  terms in the equation below. An arrow from the 'Non Diffractive' box points to the  $\sigma_{nd}$  term.

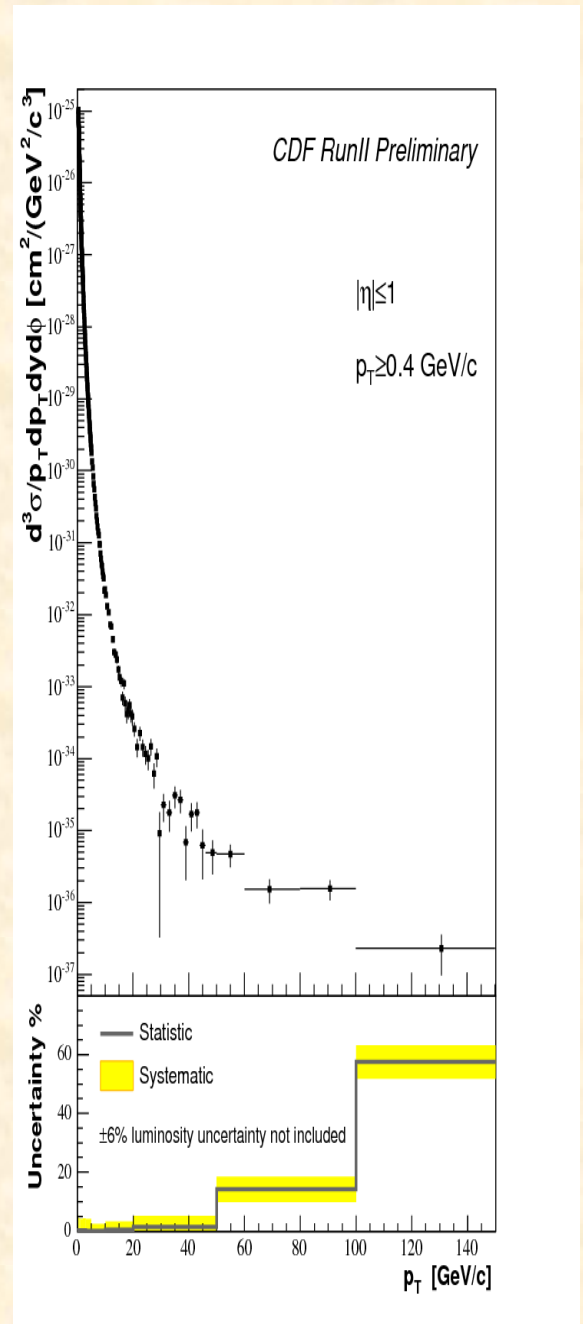
$$\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$

- Minimum bias : eventi raccolti senza richieste particolari di segnali sul rivelatore, storicamente richiedendo la coincidenza di segnali sui due lati del rivelatore (indicando che sia il protone che l'anti-protone si sono "rotti")



# Misura della sezione d'urto di MB a CDF

- Eventi caratterizzati da bassa molteplicita' carica e basso  $P_T$
- Misura recente di CDF utilizza dati a bassa luminosita' istantanea (max 1 interazione per evento)
- Trigger richiede un numero molto basso di hit nel calorimetro (efficienza calcolata utilizzando 0 bias event  $\rightarrow$  random trigger)
- La sezione d'urto di questo processo e' stato misurato su 13 ordini di grandezza!
- Studio importante anche nella prima fase di LHC. Trigger dedicati  $\rightarrow$  basati su scintillatori che si buttano dopo i primi mesi di operazione (danneggiamento da radiazione)

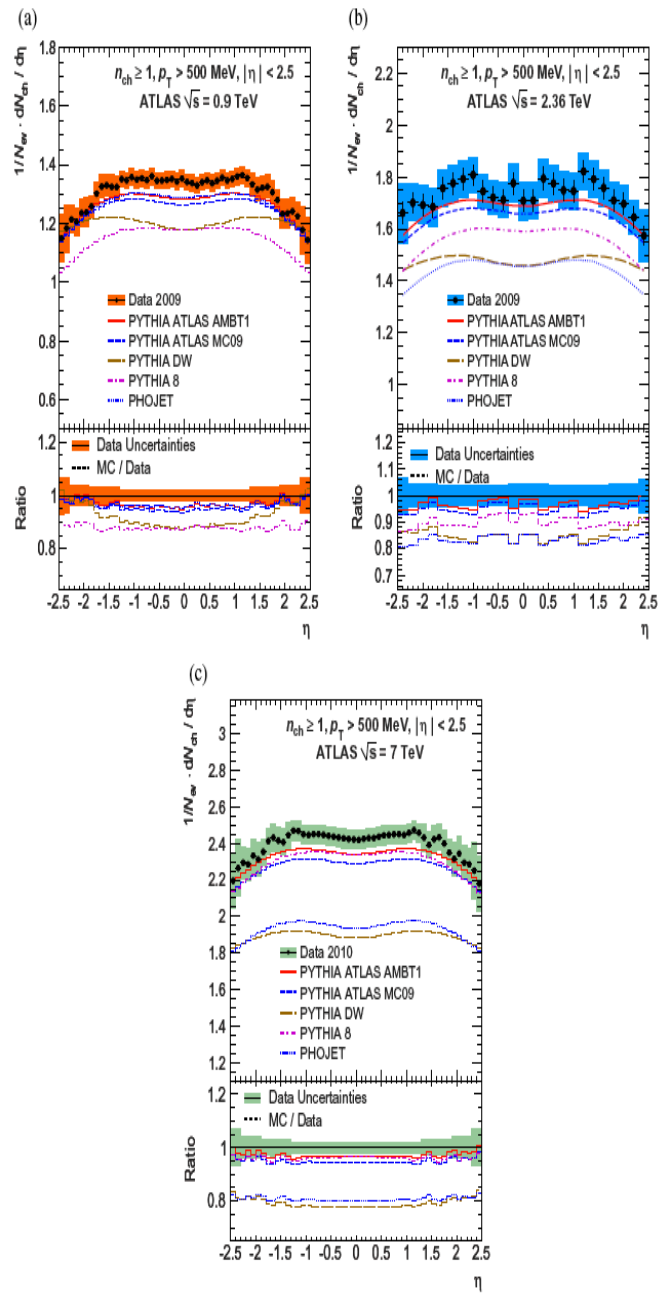


# Charged Particle @ LHC

7TeV ATLAS New Journal of Physics 13 (2011)

053033

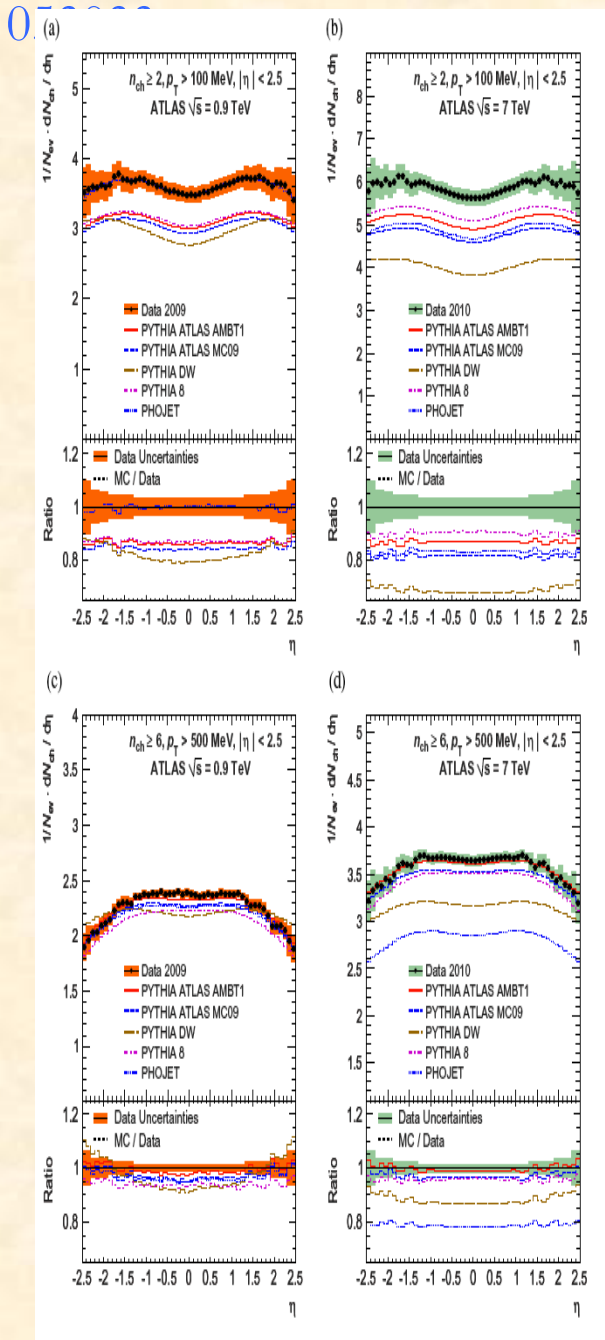
- Phojet, Pythia8, Pythia DW, MC09 tutti tuning basati su SppS e Tevatron
- AMBT1 unico tuning su dati LHC → produzione 2010 dei MC in Atlas



# Charged Particle @ LHC

## 7TeV

ATLAS New Journal of Physics 13 (2011)

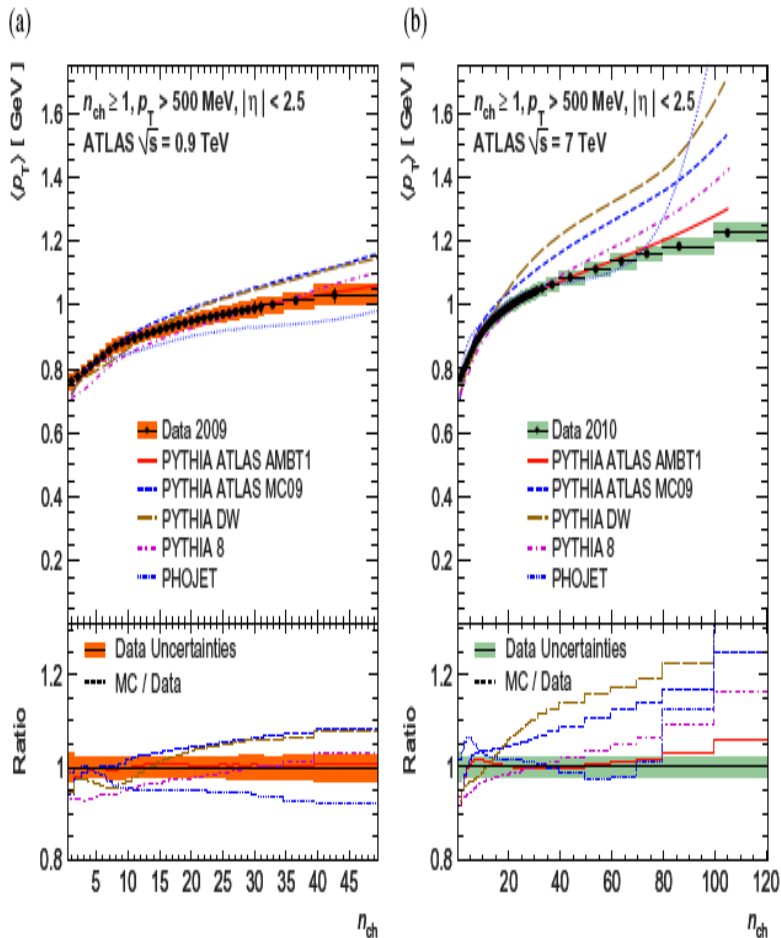


- Accordo peggiora a basso impulso
- (diffractive enhanced)
- Accordo nella regione diffractive limited
- Pre LHC tunes OK a 900 GeV, discrepanze emergono con l'extrapolazione di  $\sqrt{s}$

# Charged Particle @ LHC

7TeV ATLAS New Journal of Physics 13 (2011)

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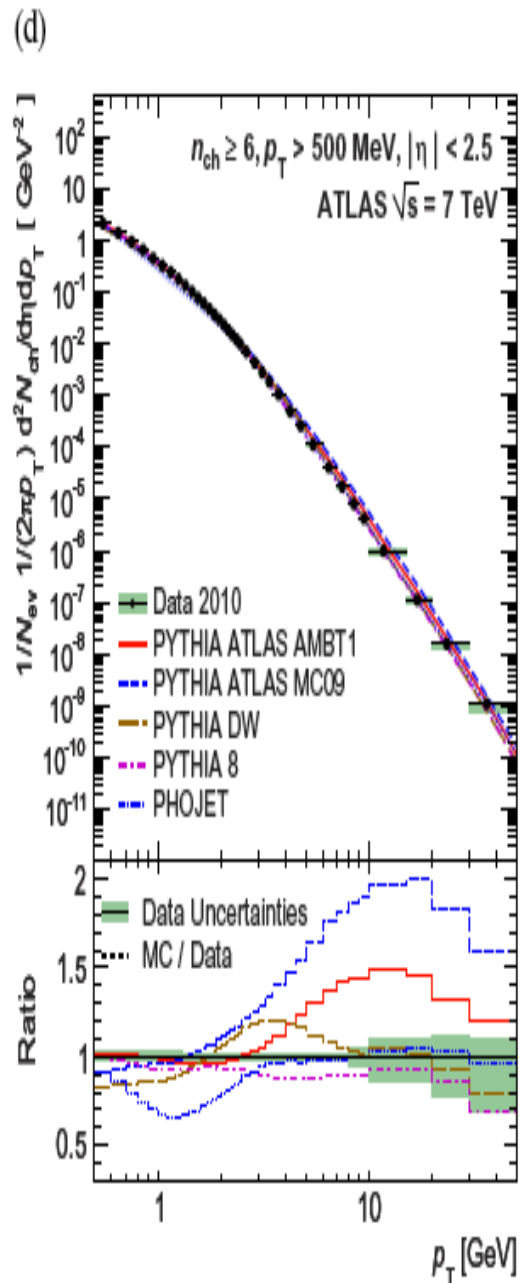
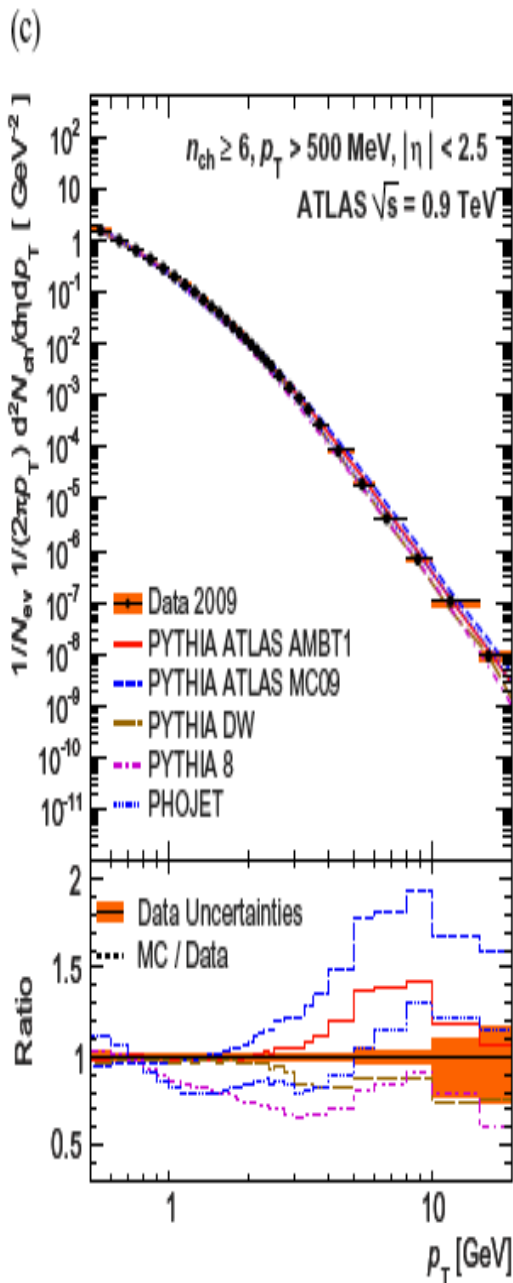


**Figure 11.** Average transverse momentum as a function of the number of charged particles in the event for events with  $n_{ch} \geq 1$ ,  $p_T > 500$  MeV and  $|\eta| < 2.5$  at  $\sqrt{s} = 0.9$  TeV (a) and  $\sqrt{s} = 7$  TeV (b). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom insets show the ratio of the MC to the data. The values of the ratio histograms refer to the bin centroids.

# Charged Particle @ LHC

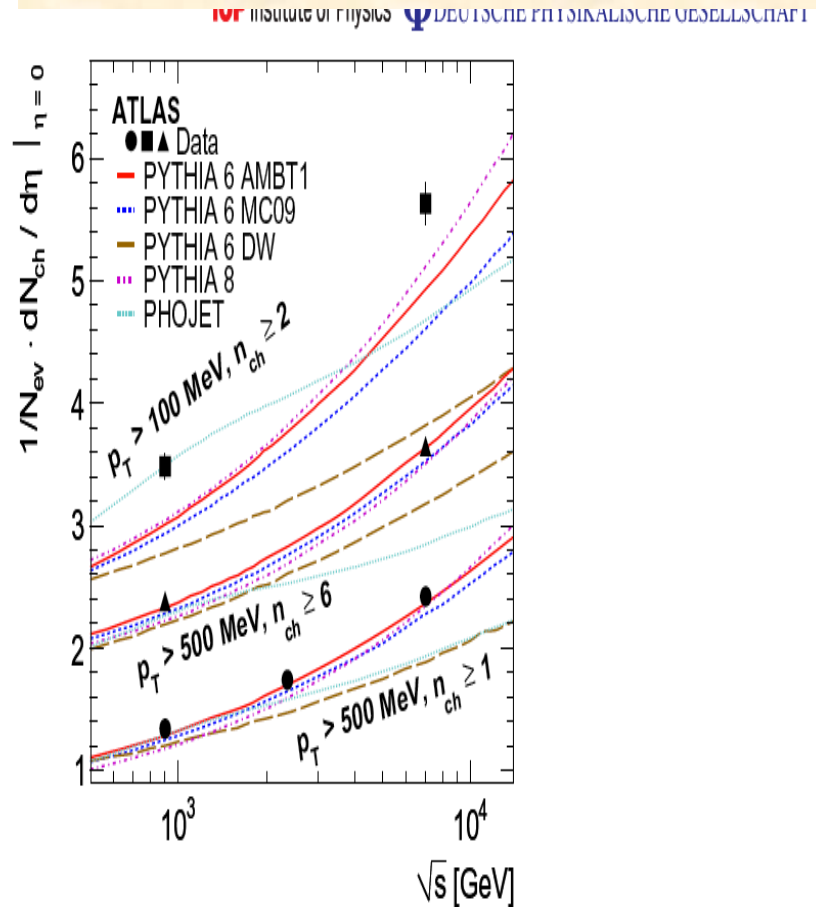
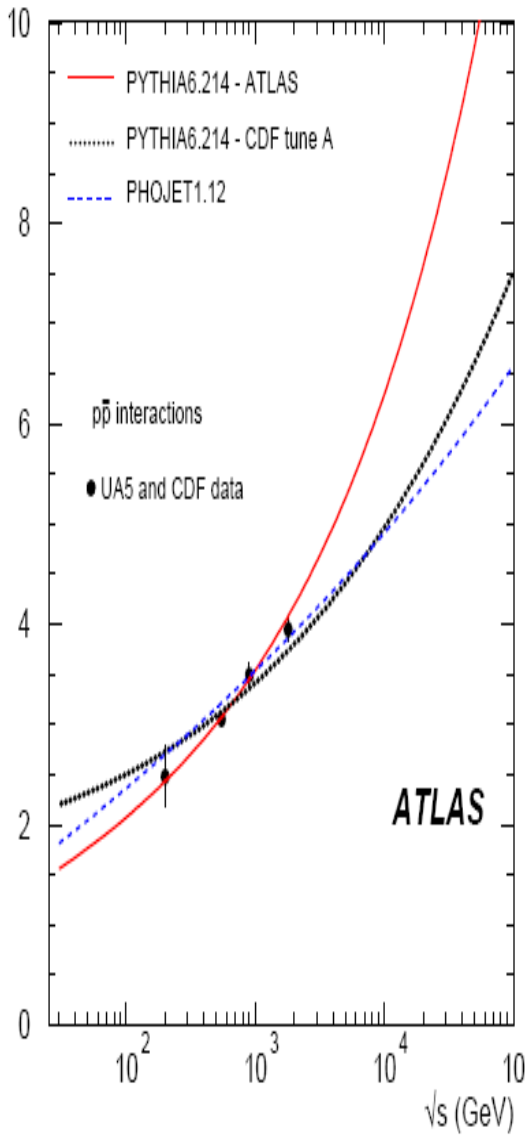
7TeV ATLAS New Journal of Physics 13 (2011)

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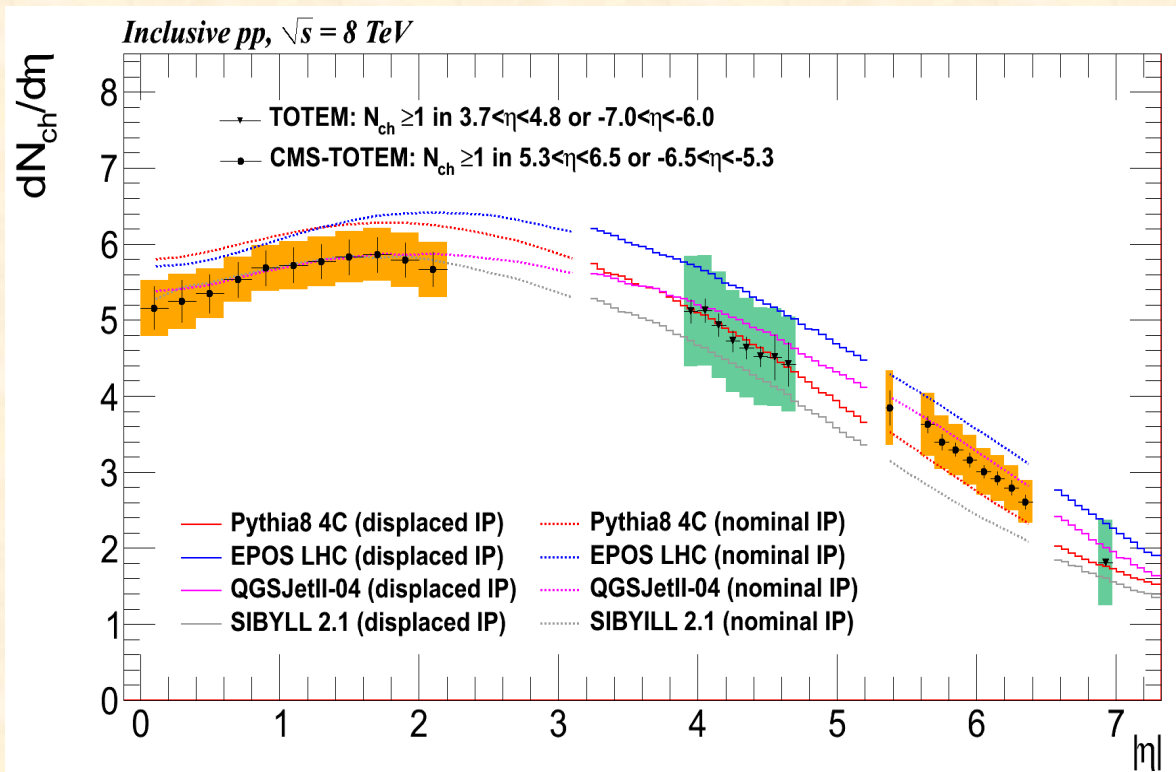
# Estrapolazione/Misura a differenti $\sqrt{s}$



**Figure 13.** The average charged-particle multiplicity per unit of rapidity for  $\eta = 0$  as a function of the centre-of-mass energy. The results with  $n_{ch} \geq 2$  within the kinematic range  $p_T > 100 \text{ MeV}$  and  $|\eta| < 2.5$  are shown alongside the results with  $n_{ch} \geq 1$  within the kinematic range  $p_T > 500 \text{ MeV}$  and  $|\eta| < 2.5$  at 0.9, 2.36 and 7 TeV. The data are compared to various particle-level MC predictions. The vertical error bars on the data represent the total uncertainty.

ed particle density for non-single diffractive ...

# Misura nella regione forward con CMS + TOTEM



**Fig. 5** Charged particle pseudorapidity distributions obtained in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$  for inelastic events. The coloured bands show the combined systematic and statistical uncertainties and the error bars represent the  $\eta$ -uncorrelated uncertainties. The results obtained in this work based on collisions at  $z = 11.25 \text{ m}$  (displaced IP) are shown under the green band, while the distributions under the orange band are taken from [7], where collisions occurred at  $z = 0 \text{ m}$  (nominal IP). The measurements are compared in each  $\eta$  region to the corresponding prediction from PYTHIA8 (tune 4C), SIBYLL 2.1, EPOS (tune LHC), and QGSJETII-04.

# Charged Particle @ LHC

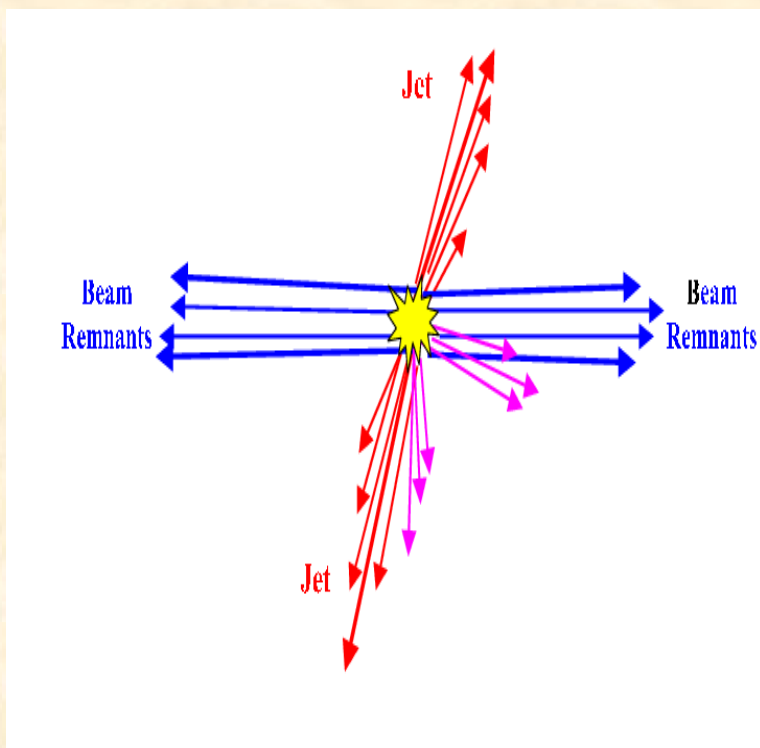
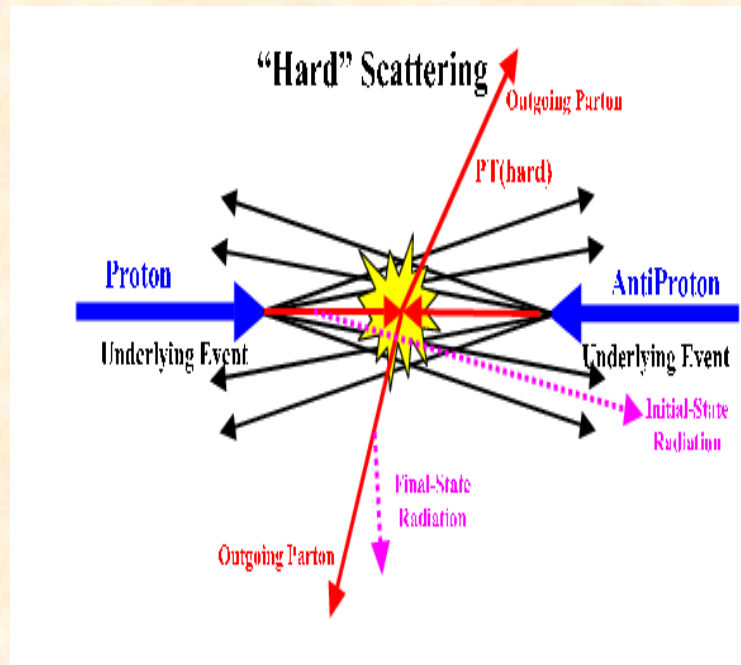
## 7TeV

- Conclusioni (dopo il primo run di LHC)
- I primi dati a bassa luminosita' sono stati utilissimi per studiare sia il detector sia le caratteristiche delle collisioni anelastici a 7 TeV/8 TeV
- Difficile trovare un accordo per molteplicita' e spettri in tutto il range di  $p_t$
- Ad LHC si ripetera' l'esercizio questa estate a 13 TeV



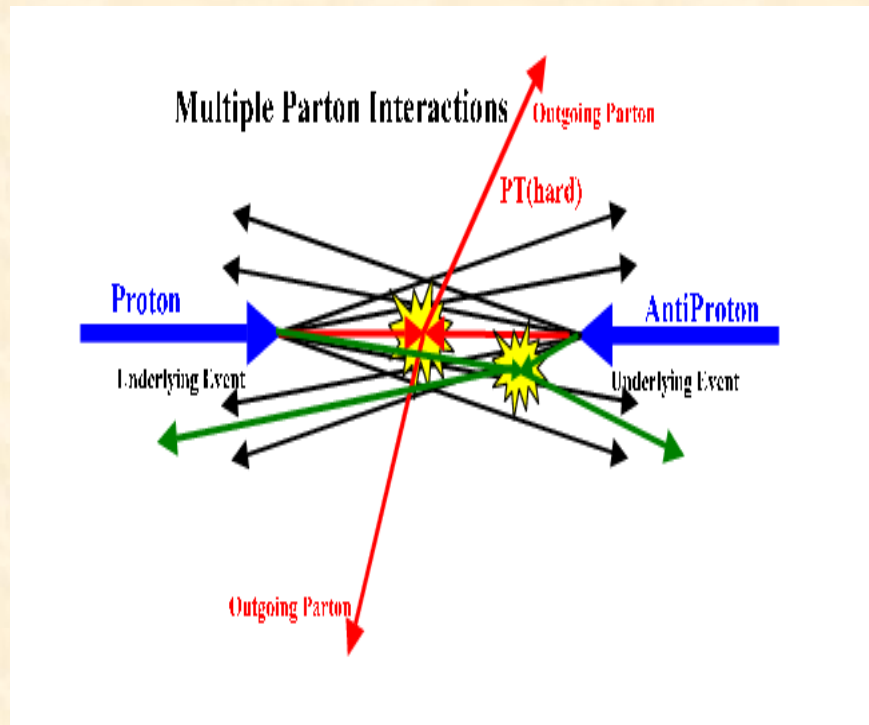
# Produzione di Jet in interazioni p-(anti)p

- Produzione di jet adronici nelle collisioni p-p
- Oltre ai jet prodotti nello scattering duro dobbiamo considerare il così-detto “underlying event” composto da
  - Beam Remnants (a differenza che per particelle collidenti puntiformi)
  - Radiazione di QCD da stato iniziale e finale (ISR,FSR)
  - ...



# Produzione di Jet in interazioni p-(anti)p

- E talvolta da ulteriori interazioni soffici in una singola collisione protone-protone dette: Multiple Parton Interactions (MPI)

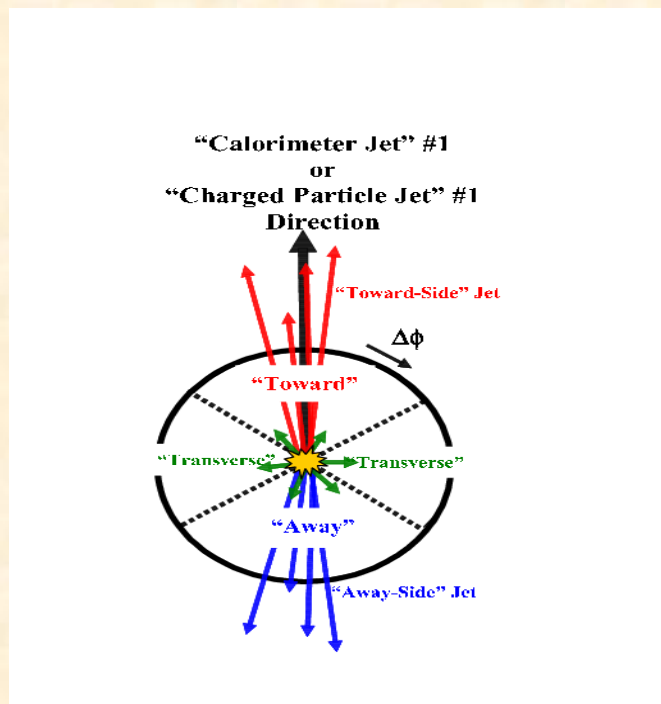


- Questi fenomeni non-perturbativi vengono modellati fenomenologicamente ed opportunamente codificati nei normali generatori di eventi Monte Carlo

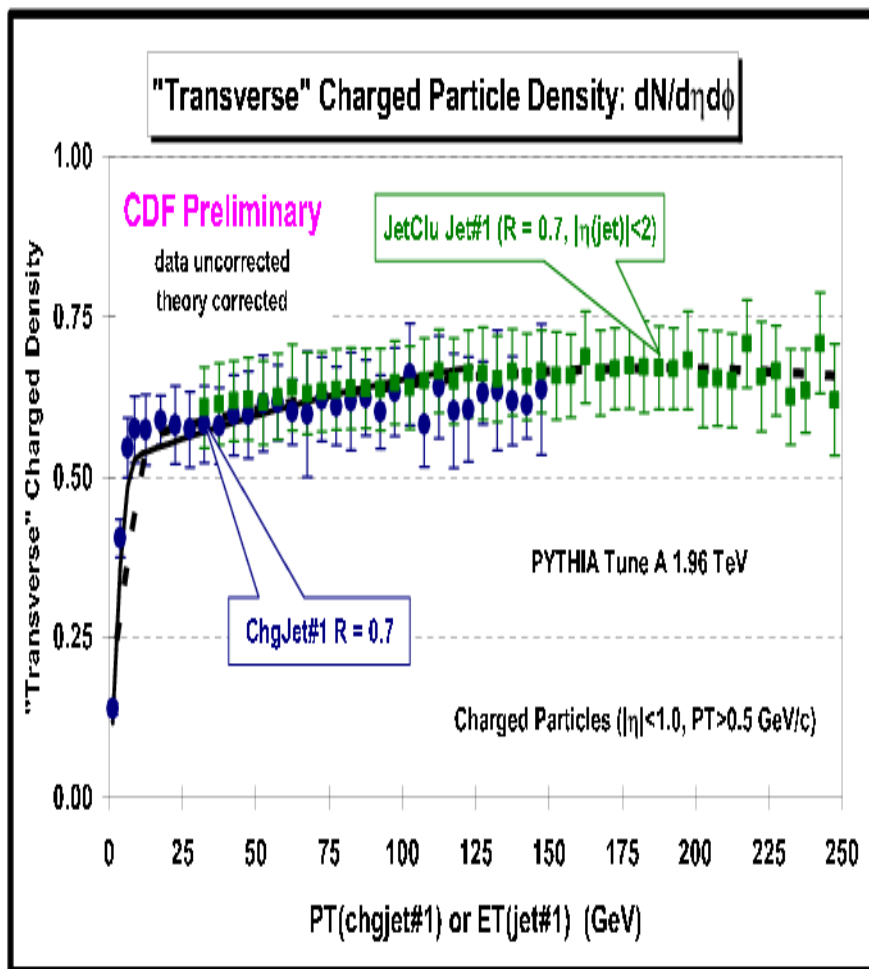
# Studio dello “underlying event”

- I modelli fenomenologici sono stati adattati ai dati di Tevatron
- In particolare attraverso lo studio degli eventi a due jet e del flusso di particelle cariche e della densita' di impulso nelle regioni “Transverse” :

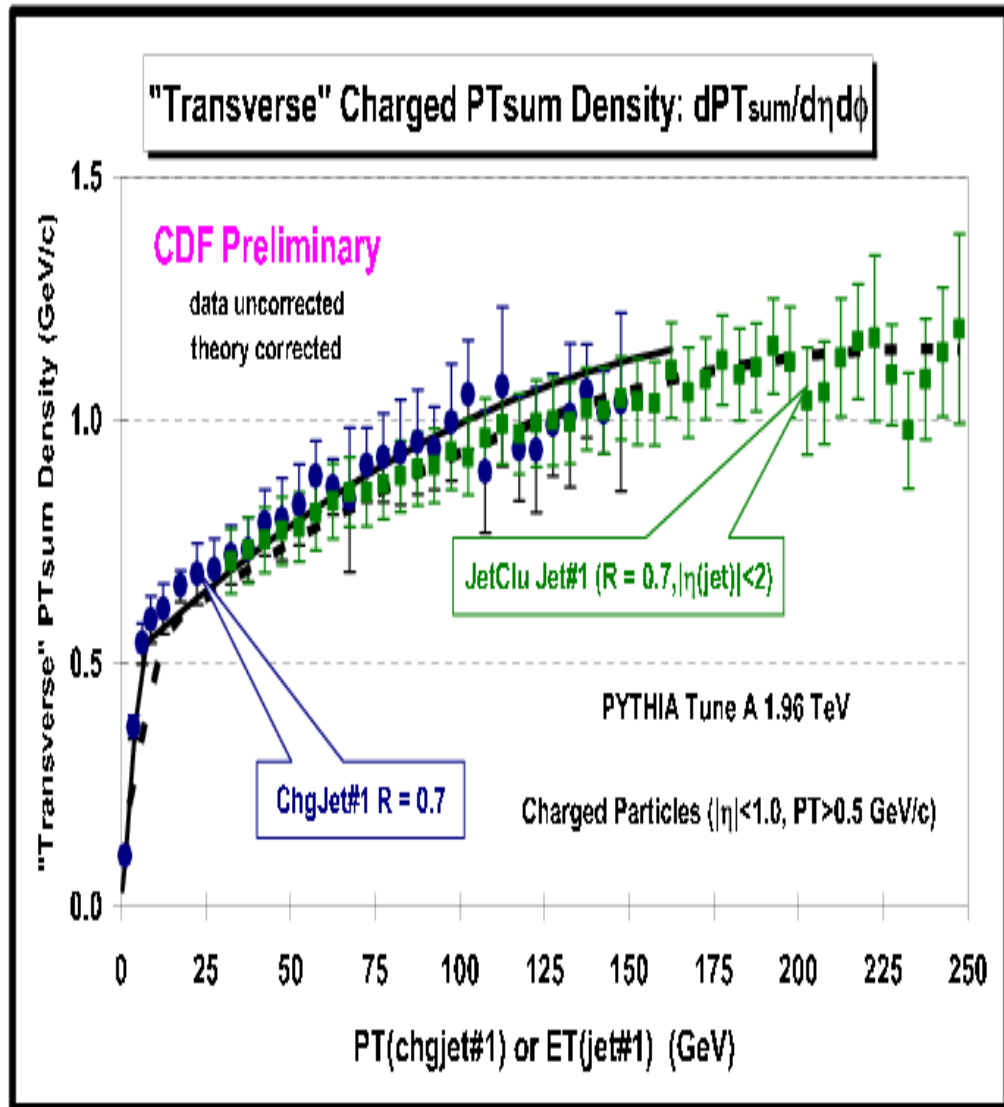
$$60^\circ < |\Delta\Phi| < 120^\circ$$



# Charged particle density

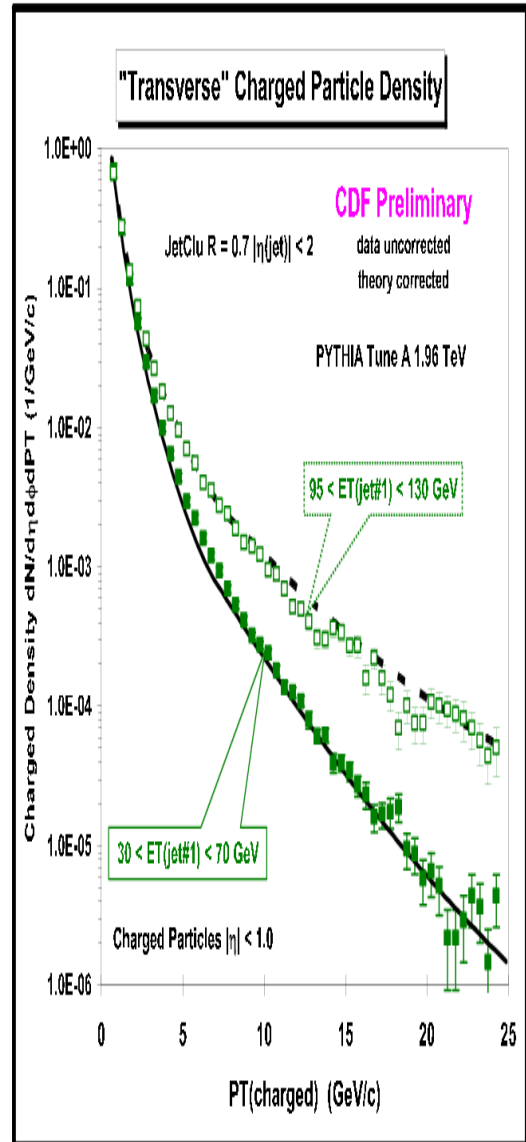


# Transverse Momentum Density

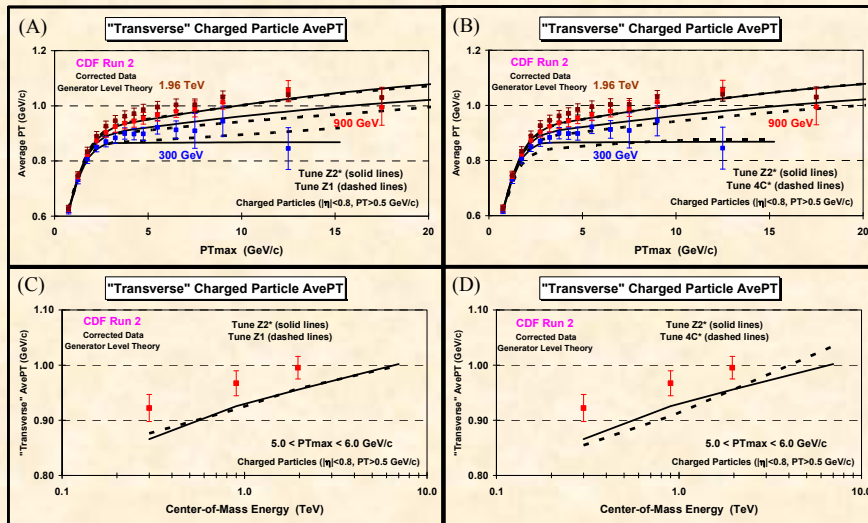


# Pt spectra of underlying event particles

- A crescente energia del jet principale corrisponde uno spettro dell'underlying event sempre piu' duro (code piu' elevate della distribuzione) dovuto all'aumentare della probabilita' di emettere gluoni hard a grande angolo
- Andamento ben riprodotto dal tuning di CDF



# Studio in funzione di $\sqrt{s}$



**Figure 19.** (A,B) Data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle average  $p_T$  ( $p_T > 0.5$  GeV,  $|\eta| < 0.8$ ) in the transverse region as defined by the leading charged particle,  $PT_{max}$ , as a function of  $PT_{max}$ . (C,D) Data on the transverse charged particle average  $p_T$  as defined by the leading charged particle,  $PT_{max}$ , for  $5.0 < PT_{max} < 6.0$  GeV/c plotted versus the center-of-mass energy (on a log scale) for charged particles with  $p_T > 0.5$  GeV and  $|\eta| < 0.8$ . The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty, and are compared with PYTHIA Tune Z1 and Z2\* (A,C) and PYTHIA Tune Z2\* and 4C\* (B,D).

# Sezioni d'urto per collisioni tra adroni

- Prendiamo ad esempio la produzione Drell-Yan di di-leptoni ( $\mu^+\mu^-$  o  $e^+e^-$ )
- Nel modello a partoni:

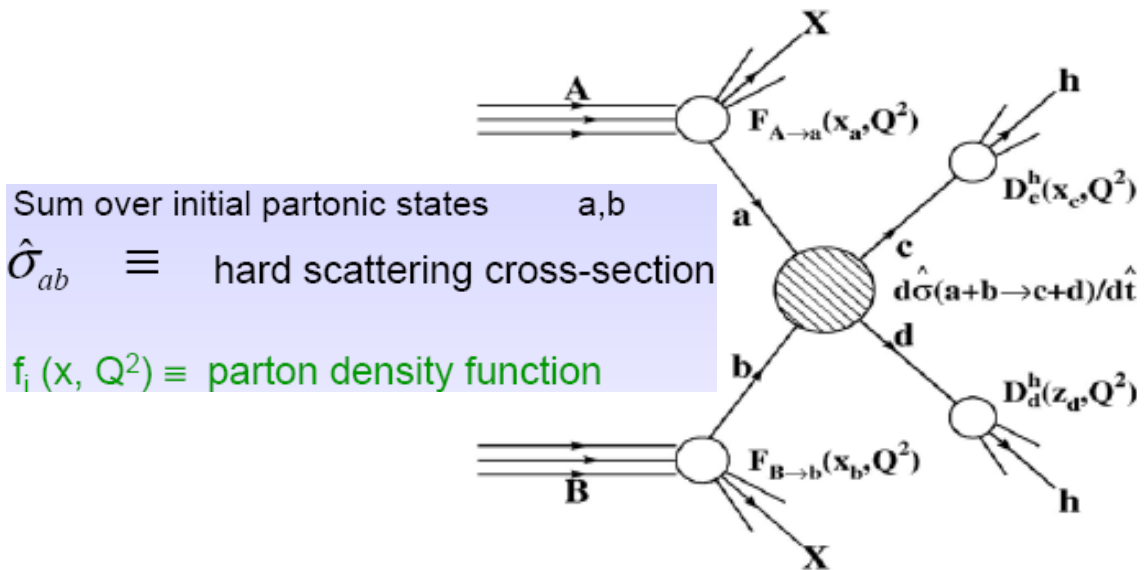
$$d^2\sigma(h_1 h_2 \rightarrow l^+ l^- X) = \frac{1}{3} \frac{4\pi\alpha^2}{3M^2} \sum_i e_{q_i}^2 [q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)] dx_1 dx_2.$$

- Tenendo conto anche dell'evoluzione con  $Q^2$  delle pdf (eq. altarelli parisi)

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{3N_c M^2} \int_0^1 dx_1 dx_2 \delta(x_1 x_2 s - M^2) \times \left\{ \sum_i e_{q_i}^2 [q_i(x_1, Q)\bar{q}_i(x_2, Q) + \bar{q}_i(x_1, Q)q_i(x_2, Q)] \right\}.$$



## Calculation of cross sections



$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$

- effective centre-of-mass energy  $\sqrt{\hat{s}}$  smaller than  $\sqrt{s}$  of colliding beams:

$$\left. \begin{array}{l} \vec{p}_a = x_a \vec{p}_A \\ \vec{p}_b = x_b \vec{p}_B \end{array} \right\} p_A = p_B = 7 \text{ TeV} \quad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x \sqrt{s}$$

if  $x_a \approx x_b$

- to produce  $m \approx 100 \text{ GeV}$   $x \sim 0.01$
- to produce  $m \approx 5 \text{ TeV}$   $x \sim 0.35$

# Cross Sections a SppS

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e, \mu^+ + \nu_\mu$$

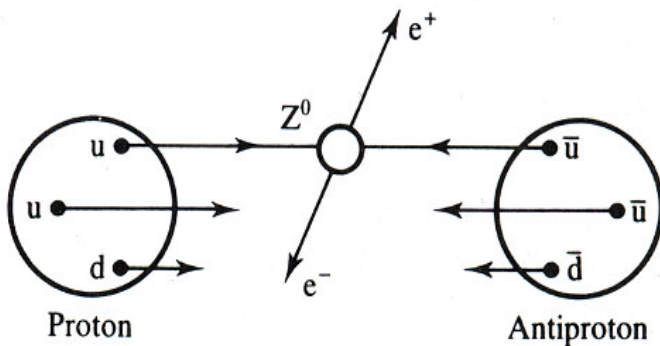
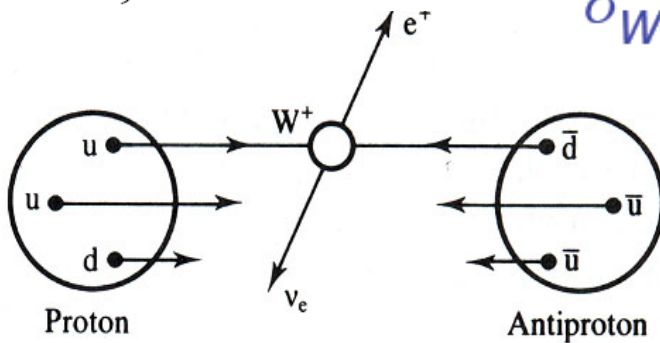
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}_e, \mu^- + \bar{\nu}_\mu$$

$$\left. \begin{array}{l} u + \bar{u} \\ d + \bar{d} \end{array} \right\} \rightarrow Z^0 \rightarrow e^+e^-, \mu^+\mu^-$$

$$\sigma(q\bar{q}' \rightarrow W) = 2\pi |V_{qq'}|^2 \frac{G}{\sqrt{2}} M_W^2 \delta(\hat{s} - M_W^2)$$

$$\sigma(q\bar{q} \rightarrow Z) = 8\pi \frac{G}{\sqrt{2}} [(c_q^Z)^2 + (c_q^Z)^2] M_Z^2 \delta(\hat{s} - M_Z^2)$$

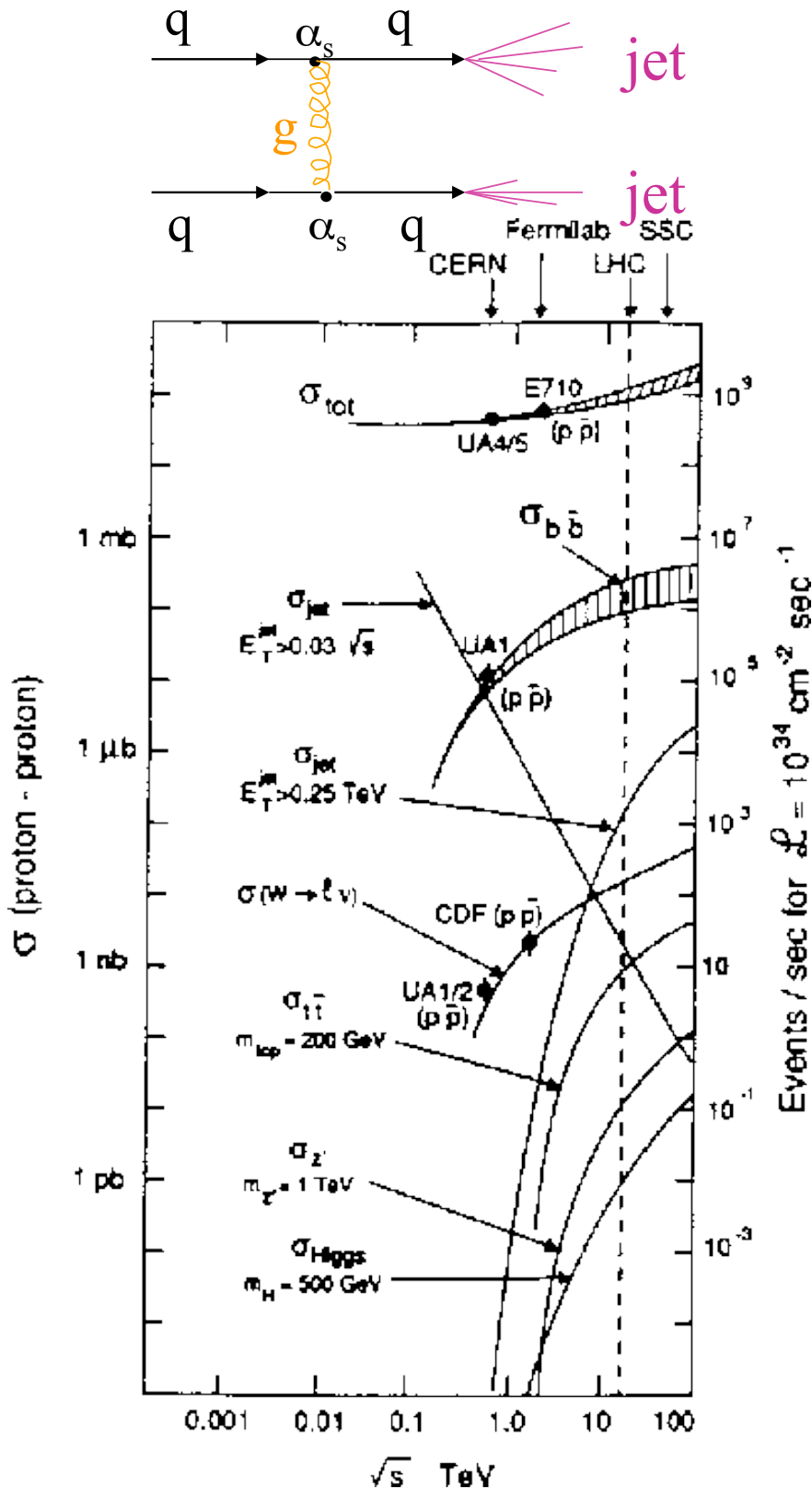
$$\sigma_{W^\pm} \approx 4 \text{ nb} \quad ; \quad \sigma_Z \approx 2 \text{ nb}$$



- Notare la minore sezione d'urto per la produzione di Z

# Canali osservabili

- Ad alto  $p_T$  il processo con sezione d'urto più alta è la produzione di jet ( $\sigma_{jet}$ )
- Per poter osservare il processo inclusivo  $pp \rightarrow W+X$  ( $pp \rightarrow Z+X$ ) al collider ci si limita ai decadimenti leptonici di W e Z
- I decadimenti in coppie di quark non sono osservabili in generale a causa della sezione d'urto di produzione di jet molto più grande di  $\sigma_W$  e  $\sigma_Z$



# Decadimenti di W e Z

**Decadimenti:** I bosoni W e Z decadono nel 70% dei casi in adroni che alle energie di 540 GeV non si possono identificare dagli altri adroni creati nelle collisioni protone-antiprotone. Si cerca invece di identificarli dai loro decadimenti leptonici.

$$\bar{p} + p \rightarrow W^+ + X$$
$$\quad \quad \quad \searrow \rightarrow q' + \bar{q}$$

$$\bar{p} + p \rightarrow W^+ + X$$
$$\quad \quad \quad \searrow \rightarrow l^+ + \nu_l$$

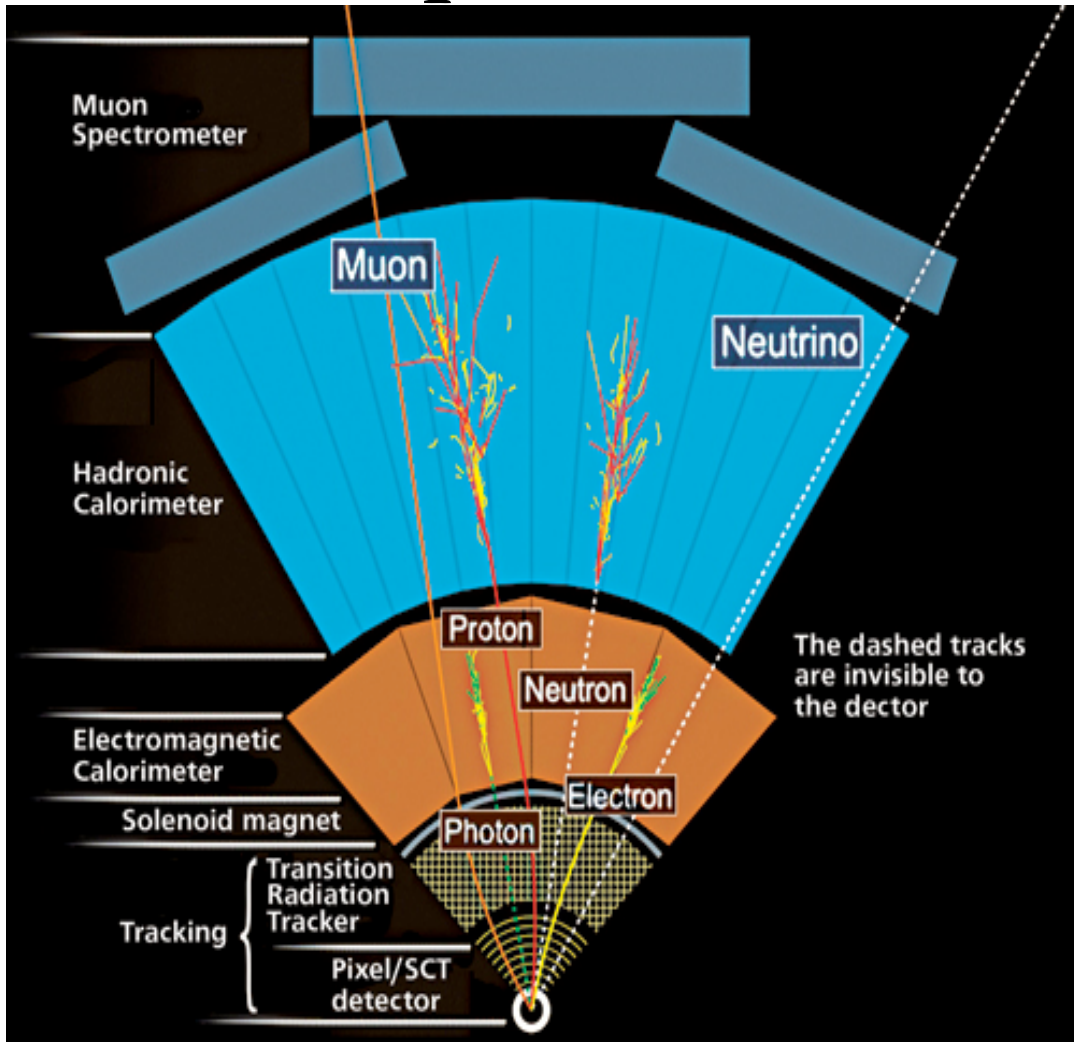
$$\bar{p} + p \rightarrow W^- + X$$
$$\quad \quad \quad \searrow \rightarrow q' + \bar{q}$$

$$\bar{p} + p \rightarrow W^- + X$$
$$\quad \quad \quad \searrow \rightarrow l^- + \bar{\nu}_l$$

$$\bar{p} + p \rightarrow Z^0 + X$$
$$\quad \quad \quad \searrow \rightarrow q + \bar{q}$$

$$\bar{p} + p \rightarrow Z^0 + X$$
$$\quad \quad \quad \searrow \rightarrow l^+ + l^-$$

# Identificazione di particelle in un tipico rivelatore



- Parte piu' interna del rivelatore – Spettrometri magnetici per particelle cariche + rivelatori di vertici secondari

# Cause di mis- identificazione di leptoni

- Elettroni:
  - $\pi^0$  isolati con traccia carica overlapping
  - $\pi$  carichi isolati con reazione di scambio carica nel calorimetro (e.g.  $\pi^+ + n \rightarrow \pi^0 p$ )
  - $\gamma$  conversion su beam pipe, inner tracker
  - Heavy Flavor decays
- Muoni
  - Punch through
  - Pion and Kaon decay in flight (DIF)
  - Heavy Flavor decays
  - Cosmici, accidentali
- In ogni caso si tratta di effetti non sempre facilmente simulabili... (se non altro per il costo in termini di CPU!)

# Missing Transverse Energy

- Momentum conservation in the transverse plane is the basis for neutrino detection

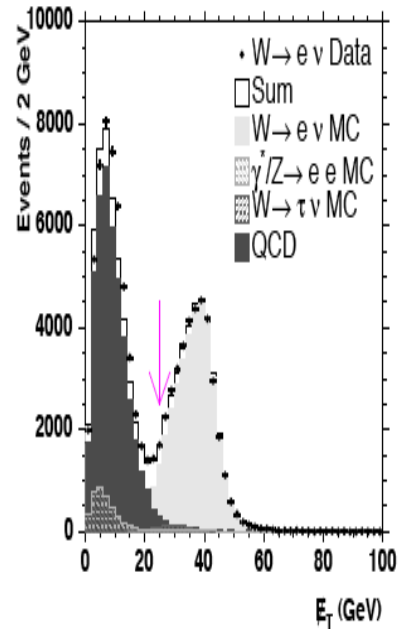
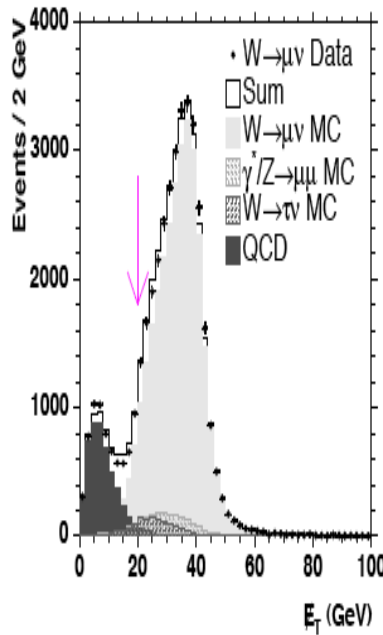
$$E_x^{\text{miss,calo}} = - \sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i \cos \phi_i, \quad E_y^{\text{miss,calo}} = - \sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i \sin \phi_i$$

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad \phi^{\text{miss}} = \arctan(E_y^{\text{miss}} / E_x^{\text{miss}})$$

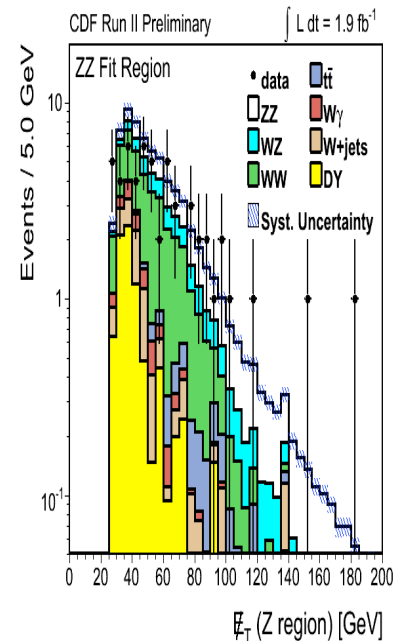
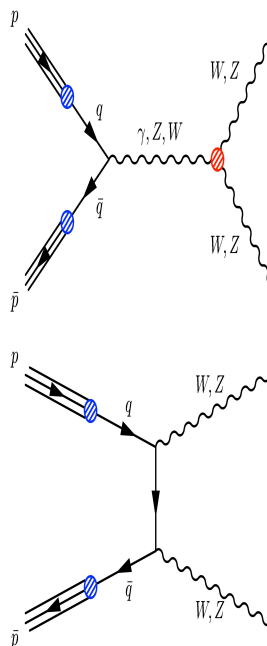
- Various correction needed to account for e.g. muons (which only leave a few GeV by dE/dX in the calorimeters)
- Improve resolution by applying correction based on identified jet
- Key detector point: coverage (no holes), hadronic calibration, linearity

# Neutrini e missing energy

- Segnatura distintiva nel decadimento  $W \rightarrow l\nu$



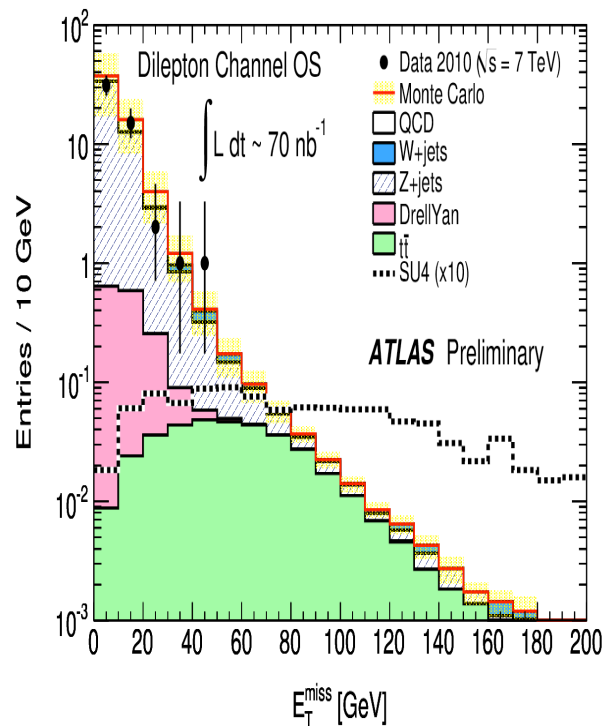
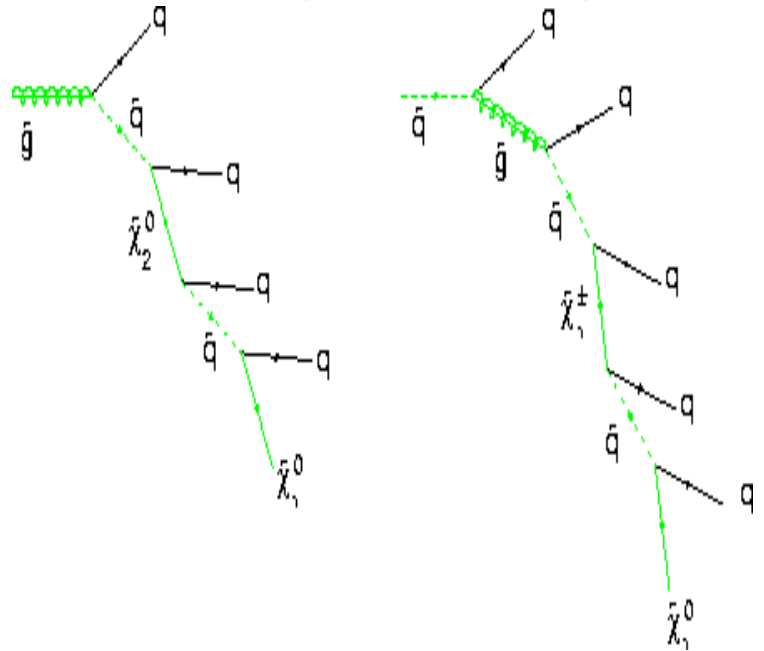
- Anche  $Z \rightarrow \nu\nu$ , per esempio in  $pp \rightarrow ZZ \rightarrow ll\nu\nu$





# Neutrini e missing energy

- Segnatura distintiva di modelli di nuova fisica che prevedono particelle stabili non interagenti (candidati dark matter)



# Missing energy Materia Oscura

- Processo elementare ricercato molto semplice:

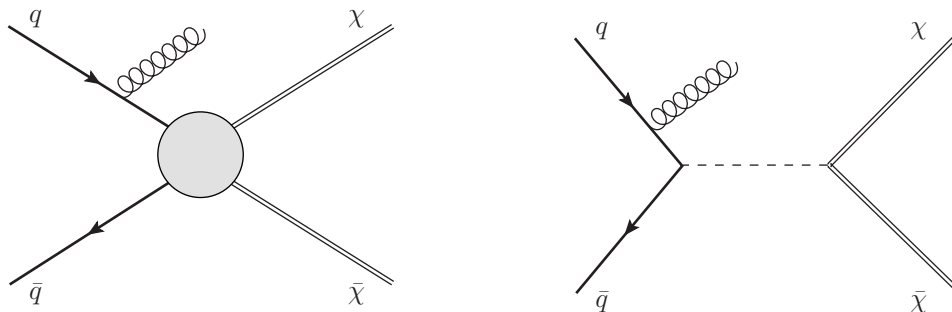
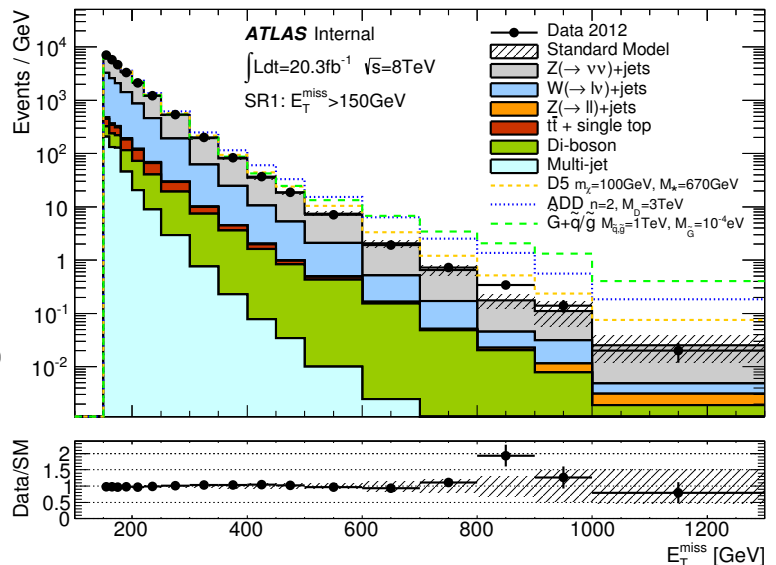


Figure 1: Feynman diagrams for the production of WIMP pairs considered here. The contact interaction described with effective operators is shown on the left, the simplified model with a  $Z'$  as new mediator particle is shown on the right.

- Background dominato da processi con neutrini nello stato finale



# Missing energy resolution from Z event

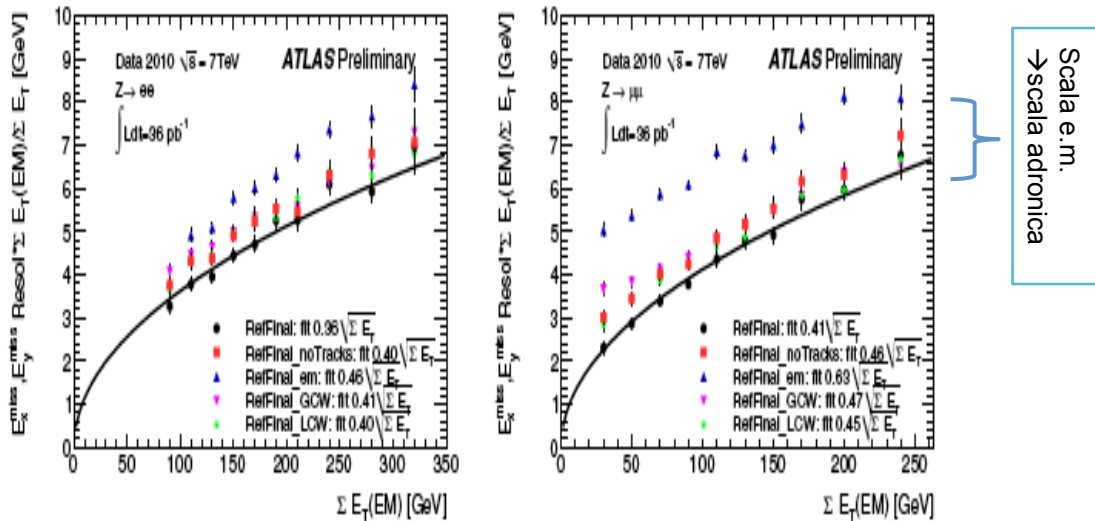


Figure 4:  $E_x^{\text{miss}}$  and  $E_y^{\text{miss}}$  resolution as a function of the total transverse energy in calorimeters for  $Z \rightarrow ee$  (left) and  $Z \rightarrow \mu\mu$  (right) events in data. The  $\Sigma E_T$  is at the EM scale and  $E_x^{\text{miss}}, E_y^{\text{miss}}$  are scaled by the ratio  $\Sigma E_T(\text{EM})/\Sigma E_T$ . Different calibrations of  $E_T^{\text{miss}}$  are compared. The curve is the fit to the resolution of RefFinal  $E_T^{\text{miss}}$ , and fit values are indicated for all  $E_T^{\text{miss}}$  calibration schemes used.

- The measured Z momentum can be compared with missing energy obtained removing the Z decay products
- Resolution is a function of total measured energy:

$$\Sigma E_T = \sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i$$

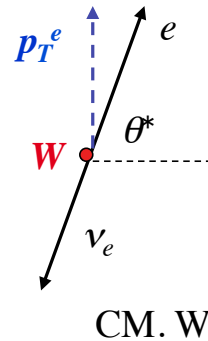
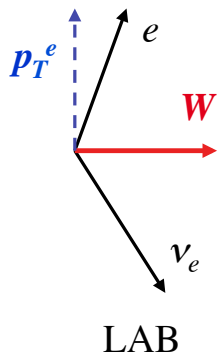
- Stochastic term fluctuate as :  $\text{sqrt}(\Sigma E_T)$

# Picco Jacobiano

$$W \rightarrow l \nu_l$$

trascurando il moto trasversale della  $W$  (piccolo)

$$p^e = m_W/2$$



$p_T^e$  è il medesimo nei due riferimenti =  $(m_W/2) \sin \theta^*$

Distribuzione angolare di decadimento nel CM nota

$$\frac{dn}{d\theta^*} \xrightarrow{\text{trasf. coordinate}} \frac{dn}{dp_T} = \frac{dn}{d\theta^*} \frac{d\theta^*}{dp_T}$$

$$\frac{dp_T^e}{d\theta^*} = \frac{m_W}{2} \cos(\theta^*)$$

$$\frac{d\theta^*}{dp_T^e} = \frac{1}{\frac{m_W}{2} \cdot \sqrt{1 - \sin^2(\theta^*)}}$$

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

**Picco "Jacobiano" per  $p_T^e = m_W/2$**

**Picco "Jacobiano" per  $p_T^{\text{missing}} = m_W/2$**

Il moto trasversale della  $W$  ( $p_T^W \neq 0$ ) sbrodola il picco, ma non lo cancella. La misura della  $m_W$  si basa sulla misura dell'energia del picco o del suo fronte di discesa

# $W \rightarrow e \bar{\nu}$ event UA1

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

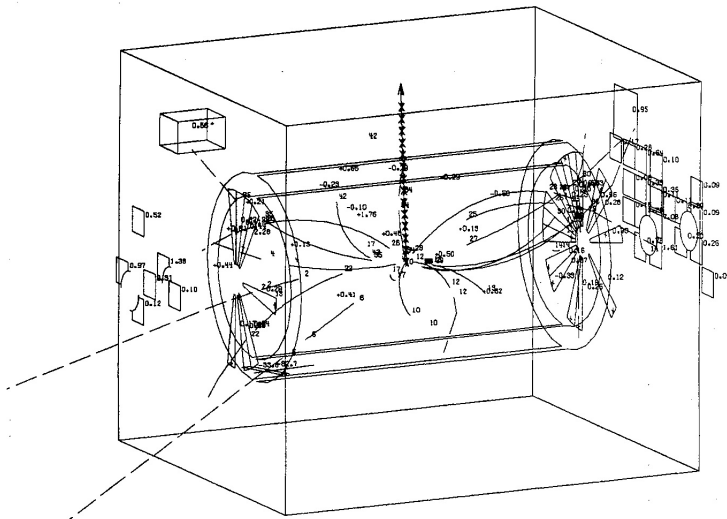


Fig. 16a. Event of the type  $W^- \rightarrow e^- + \bar{\nu}_e$ . All tracks and calorimeter cells are displayed.

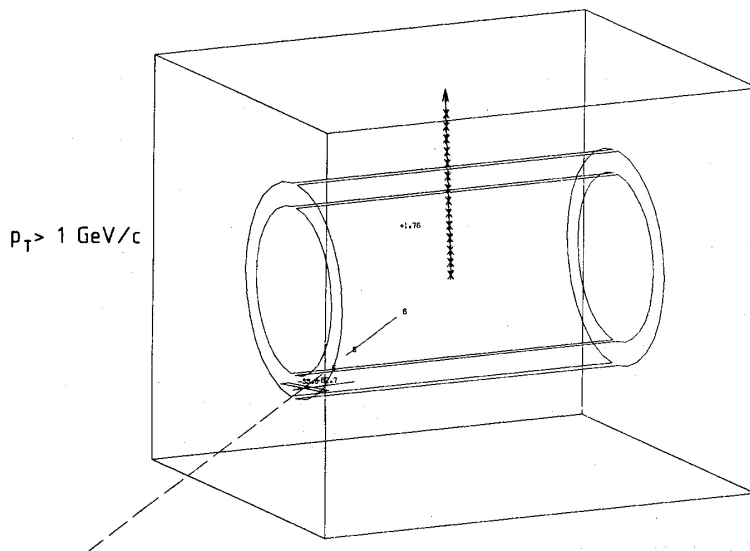
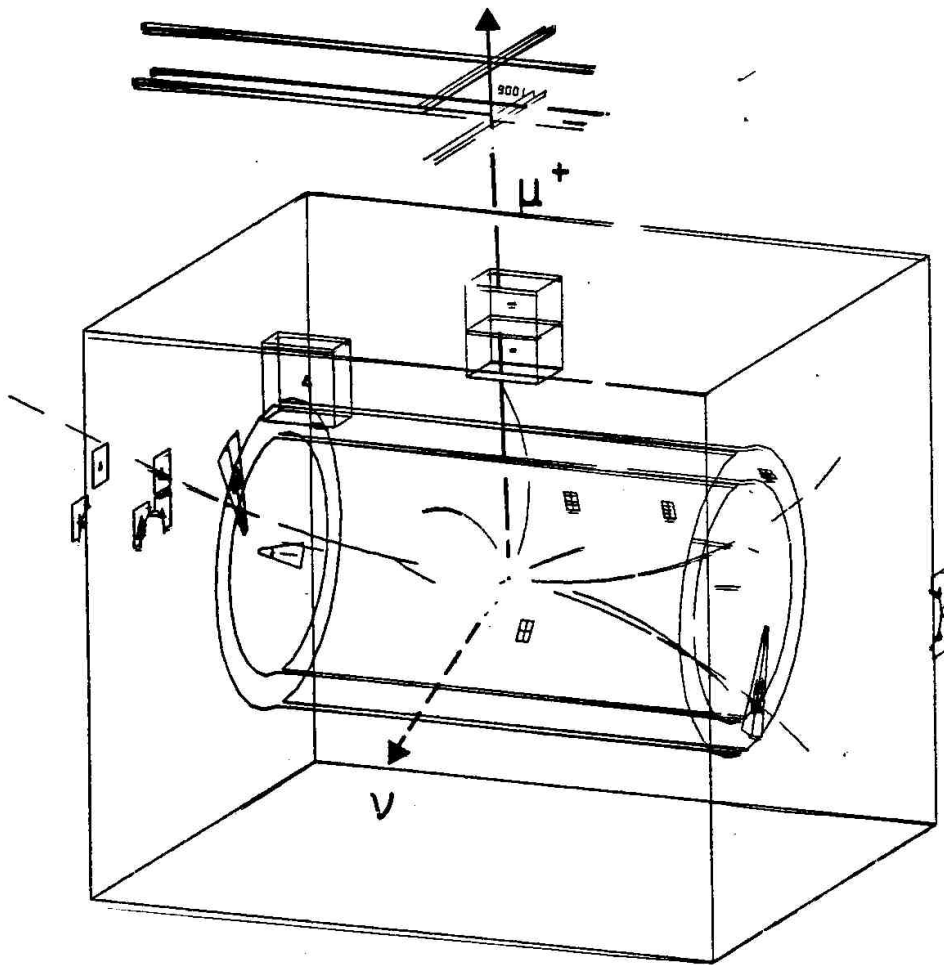
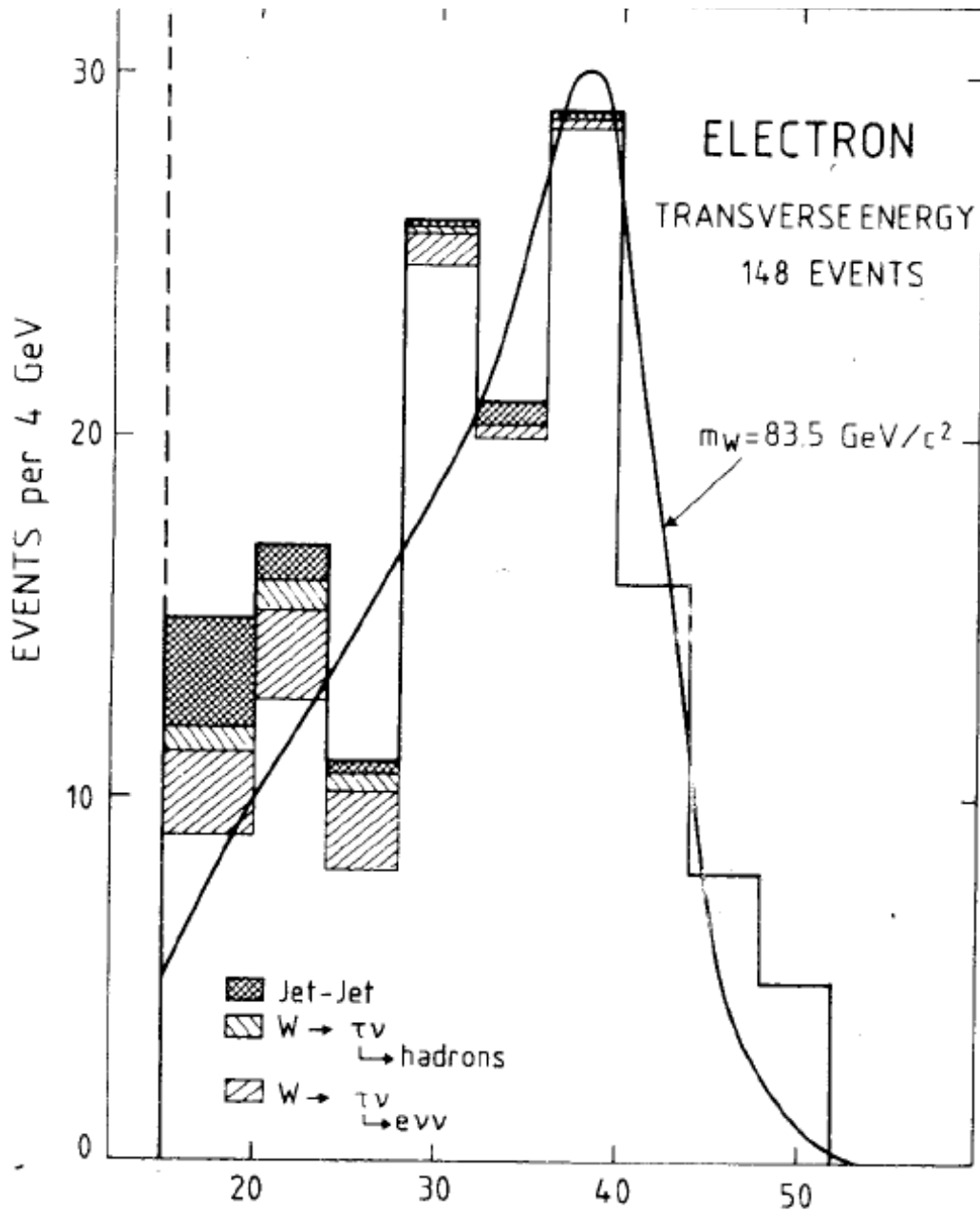


Fig. 16b. The same as picture (a), except that now only particles with  $p_T > 1 \text{ GeV}/c$  and calorimeters with  $E_T > 1 \text{ GeV}$  are shown.

$W \rightarrow \mu\nu$  event UA1



# Picco Jacobiano

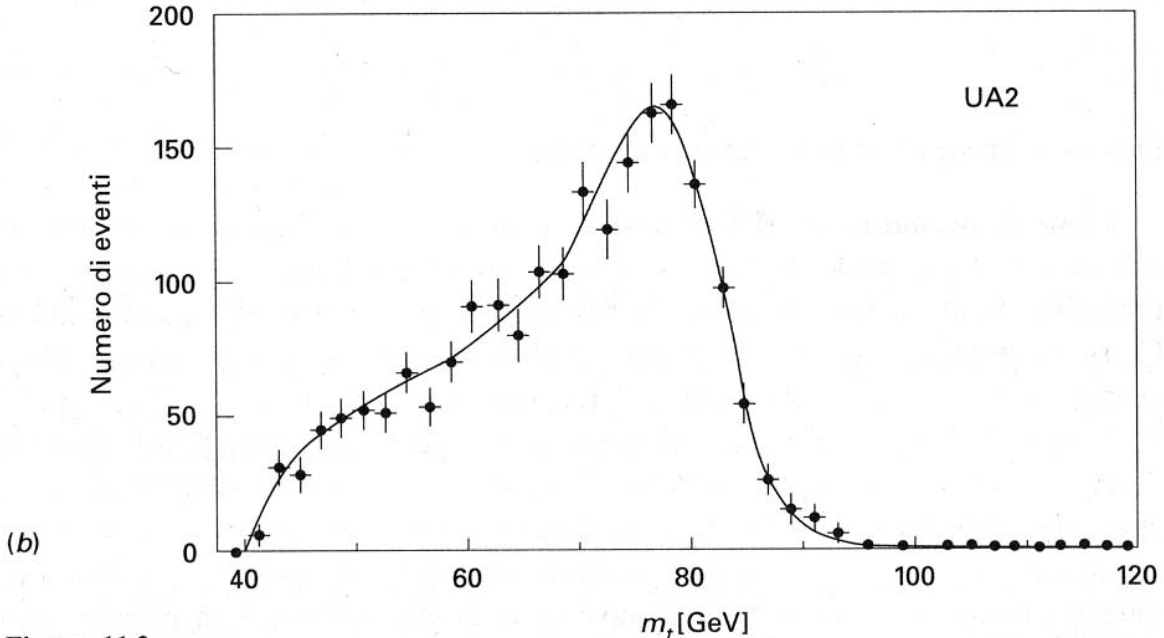
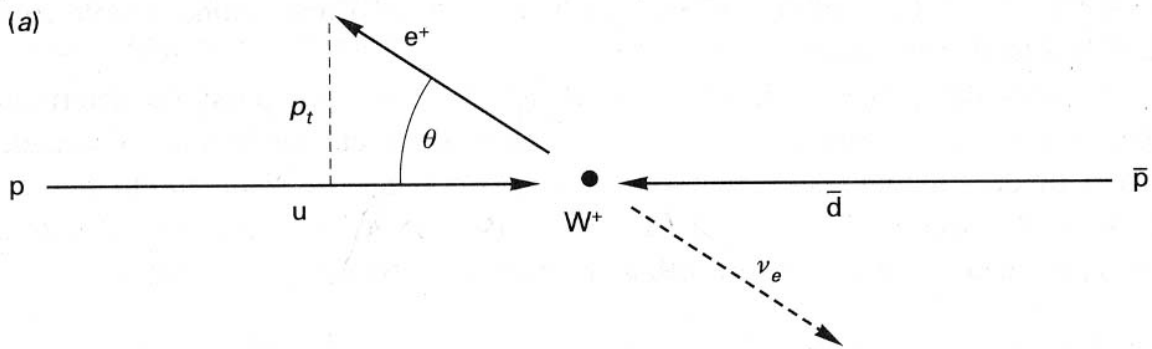


# Transverse Mass

$$M_T^2 = m_1^2 + m_2^2 + 2(E_{T,1}E_{T,2} - \vec{p}_{T,1} \cdot \vec{p}_{T,2})$$

For massless part.

$$M_T^2 \rightarrow 2E_{T,1}E_{T,2}(1 - \cos\phi)$$



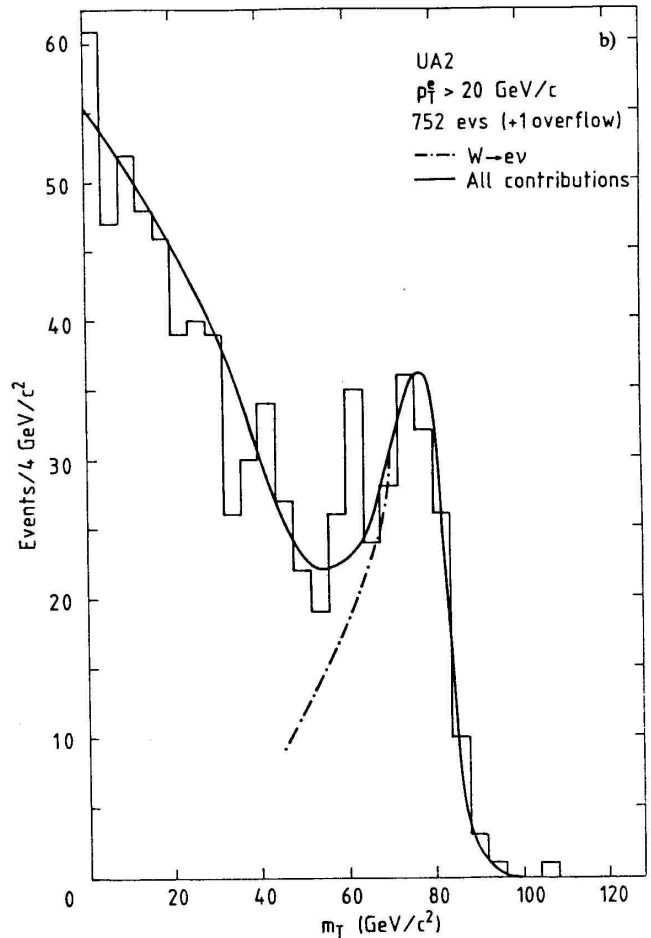
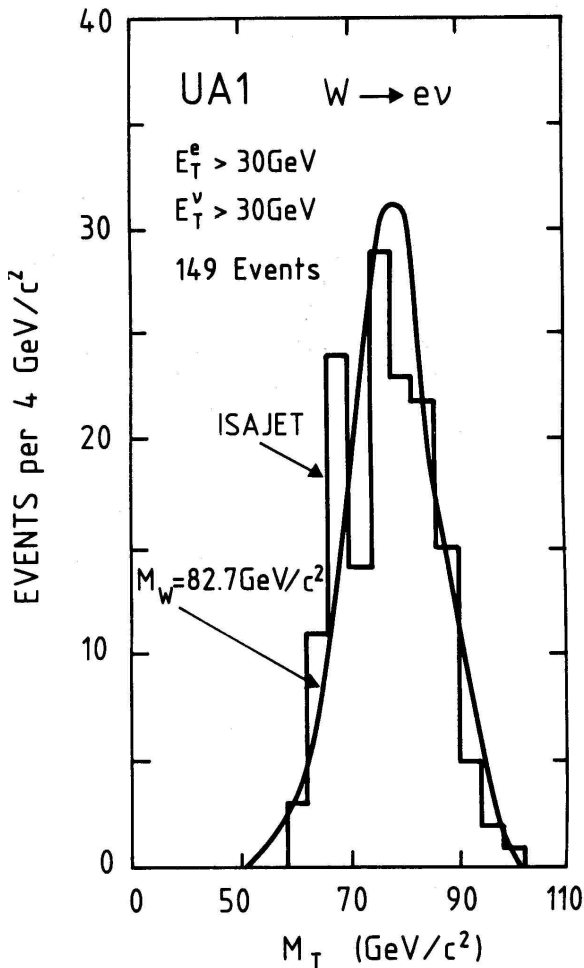
**Figura 11.2**

(a) Cinematica del decadimento  $W^+ \rightarrow e^+ + \nu_e$ . Il valore massimo possibile per l'impulso trasverso  $p_t$  del  $e^+$  è  $M_W c/2$ . (b) Distribuzione della "massa trasversa"  $m_t = 2p_t/c$  di  $e^+$  ed  $e^-$ , nel processo  $q_1 + \bar{q}_2 \rightarrow e^\pm + \text{"nulla"}$ , dall'esperimento UA2 al CERN [A192b]. (La

Anche in  $M_T$  si verifica la presenza di un picco jacobiano. Cosa sono gli eventi con  $M_T > m_W$ ?



# Massa e Larghezza W



**UA1**

**$M_W = 82.7 \pm 1.0(\text{stat}) \pm 2.7(\text{syst})\text{ GeV}$**

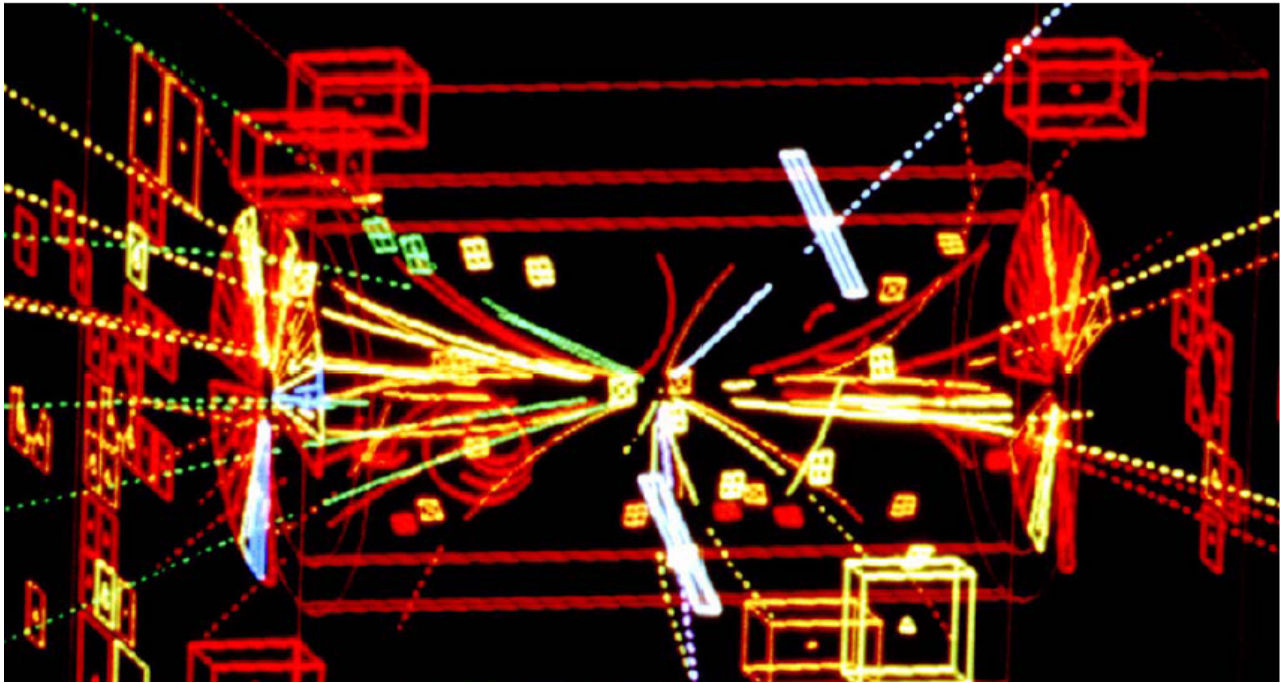
**$\Gamma_W < 5.4\text{ GeV}$**

**UA2**

**$M_W = 80.2 \pm 0.8(\text{stat}) \pm 1.3(\text{syst})\text{ GeV}$**

**$\Gamma_W < 7\text{ GeV}$**

# DISCOVERY OF THE Z BOSON



→ The signature of a  $Z^0$  boson created in  $p\bar{p}$  collision is a **pair of leptons** with large transverse momenta.

→ The mass of the  $Z^0$  is given by the invariant mass of the leptons:

$$Z \rightarrow \begin{matrix} E_l \\ E_{\bar{l}} \end{matrix} \quad M_Z^2 = \begin{matrix} \text{if } m_l=0 \\ 2 E_l E_{\bar{l}} (1 - \cos \varphi) \end{matrix}$$

# Il picco $Z \rightarrow e^+e^-$ a UA1

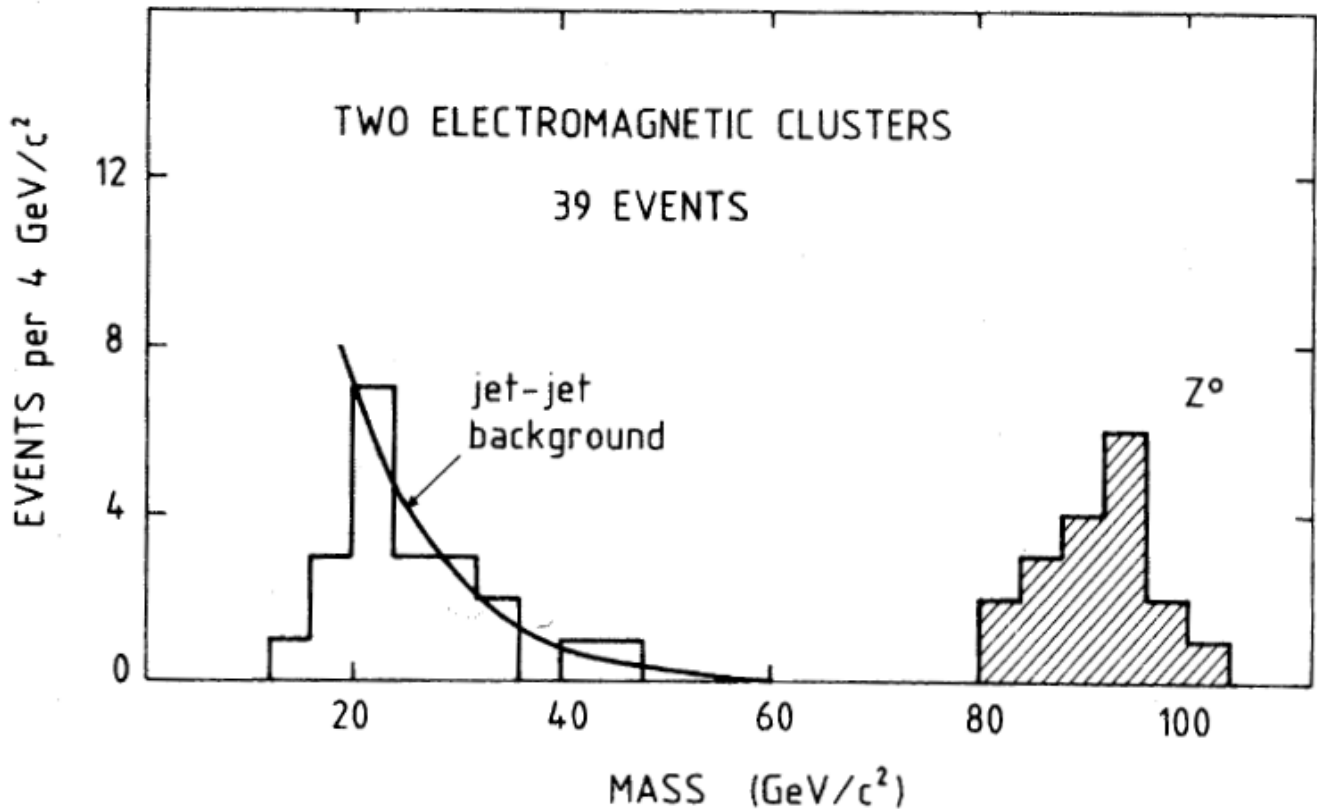


Figure 88: The UA1 mass distribution of pairs of electrons  
 → From the first 18 electron and 10 muon events recorded by the UA1 it was estimated that

$$M_Z = 93,0 \pm 1,4 \text{ GeV}$$

$$\Gamma_Z \leq 8,1 \text{ GeV}$$

$$m^2 \cong 4E_1E_2 \sin^2 \theta/2$$

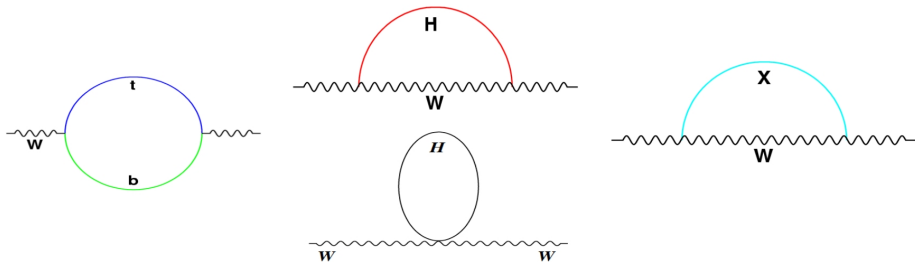
$$\frac{\sigma_m}{m} = \sqrt{\left(\frac{\sigma(E_1)}{E_1}\right)^2 + \left(\frac{\sigma(E_2)}{E_2}\right)^2 + \left(\frac{\sigma(\theta)}{\tan \theta/2}\right)^2}$$

Domina  
 risoluzione  
 su Energie

# Misura di precisione di

$$m_W$$

- In tempi piu' recenti la misura di  $m_W$  è diventata sempre più precisa. Due strade a LEP2 e a Tevatron (e, in futuro, LHC)
- La motivazione è essenzialmente quella di verificare le correzioni radiative dello SM al propagatore del W



$$M_W^2 = \frac{\rho M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{4A_0^2}{\rho M_Z^2} \left( \frac{1}{1 - \Delta\alpha} + \dots \right)} \right)$$

$$A_0 = \left( \frac{\pi\alpha}{\sqrt{2}G_\mu} \right)^{1/2} = 37.2802(3)$$

Precision fine structure constant

$$\Delta\alpha \simeq 0.06$$

Photon vacuum polarization ( $\alpha_{e.m.}$  running)

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

- A livello albero ==1, sensibile a correzioni radiative o effetti di nuova fisica

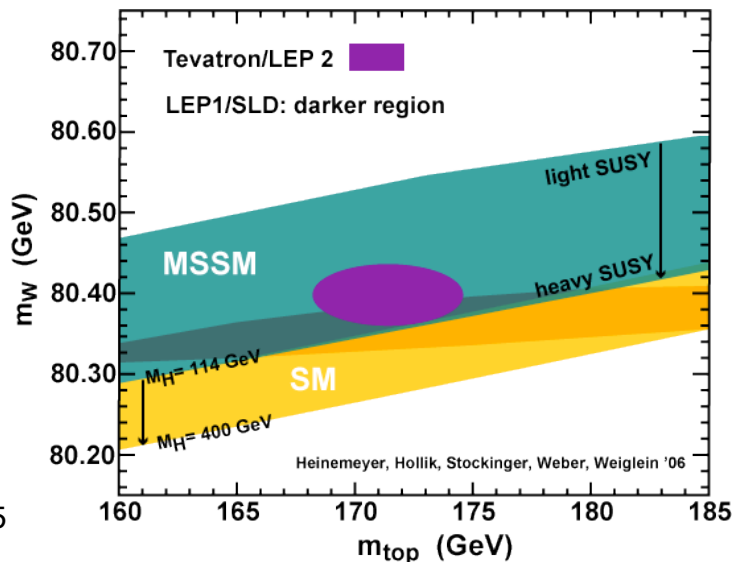
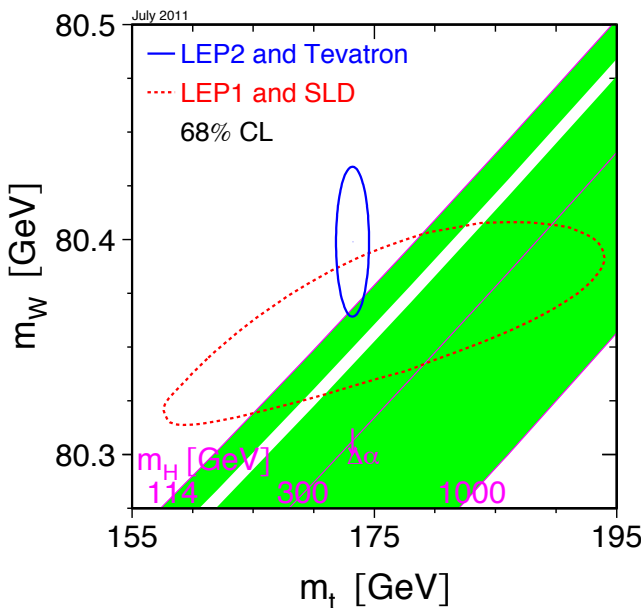
# Misura di precisione di

$$m_W$$

- Una parametrizzazione dell'effetto delle correzioni radiative:

$$M_W = 80.3827 - 0.0579 \ln \left( \frac{m_h}{100 \text{ GeV}} \right) - 0.008 \ln^2 \left( \frac{m_h}{100 \text{ GeV}} \right) - 0.517 \left( \frac{\Delta\alpha_{had}^{(5)}(M_Z)}{0.0280} - 1 \right) + 0.543 \left( \left( \frac{m_t}{175 \text{ GeV}} \right)^2 - 1 \right) - 0.085 \left( \frac{\alpha_s(M_Z)}{0.118} - 1 \right).$$

- Dipendenza quadratica dalla massa del top
- Dipendenza "solo" logaritmica da massa Higgs
- Dopo la scoperta del quark top (e la misura precisa della sua massa) consente di determinare indirettamente la massa del bosone di Higgs (assieme alle altre osservabili di precisione di LEP) e/o di evidenziare nuova fisica



# Misura di precisione di $m_W$ (LEP2)

- Due metodi possibili con sistematiche essenzialmente differenti:
  1. Metodo della soglia basato sulla misura della sezione d'urto di produzione  $e^+e^- \rightarrow W^+W^-$  (con soglia  $\sqrt{s}=2M_W$ )

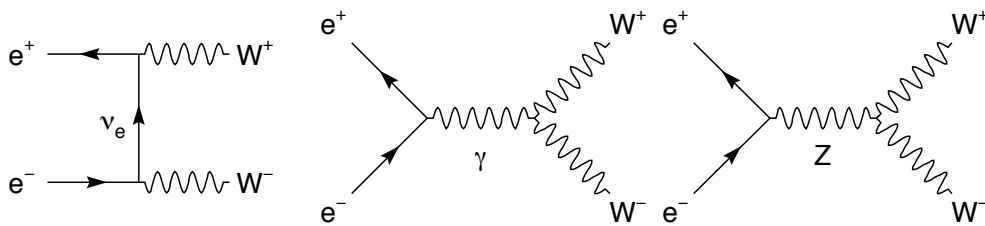


Figure 3.19: Feynman diagrams in  $W$ -pair production in  $e^+e^-$  interactions.

2. Metodo della ricostruzione diretta della massa invariante degli eventi
- Nel primo caso massima sensibilità vicino alla soglia
    - Penalizzante in termini di sezione d'urto per altri studi
    - Sistematiche relative alla conoscenza dell'energia dei fasci diventano potenzialmente rilevanti
  - Nel secondo caso possibili decadimenti in 4 getti adronici, decadimenti semi-leptonici ( $2\text{jet} + l\nu$ ), completamente leptonici:
    - Possibile applicare fit cinematici alla ricostruzione per ottimizzare la risoluzione (ad esempio  $m_{W_1}=m_{W_2}$ , conservazione momento-energia)
    - Sistematiche dominanti sono teoriche

# Misura di precisione di $m_W$ (LEP2)

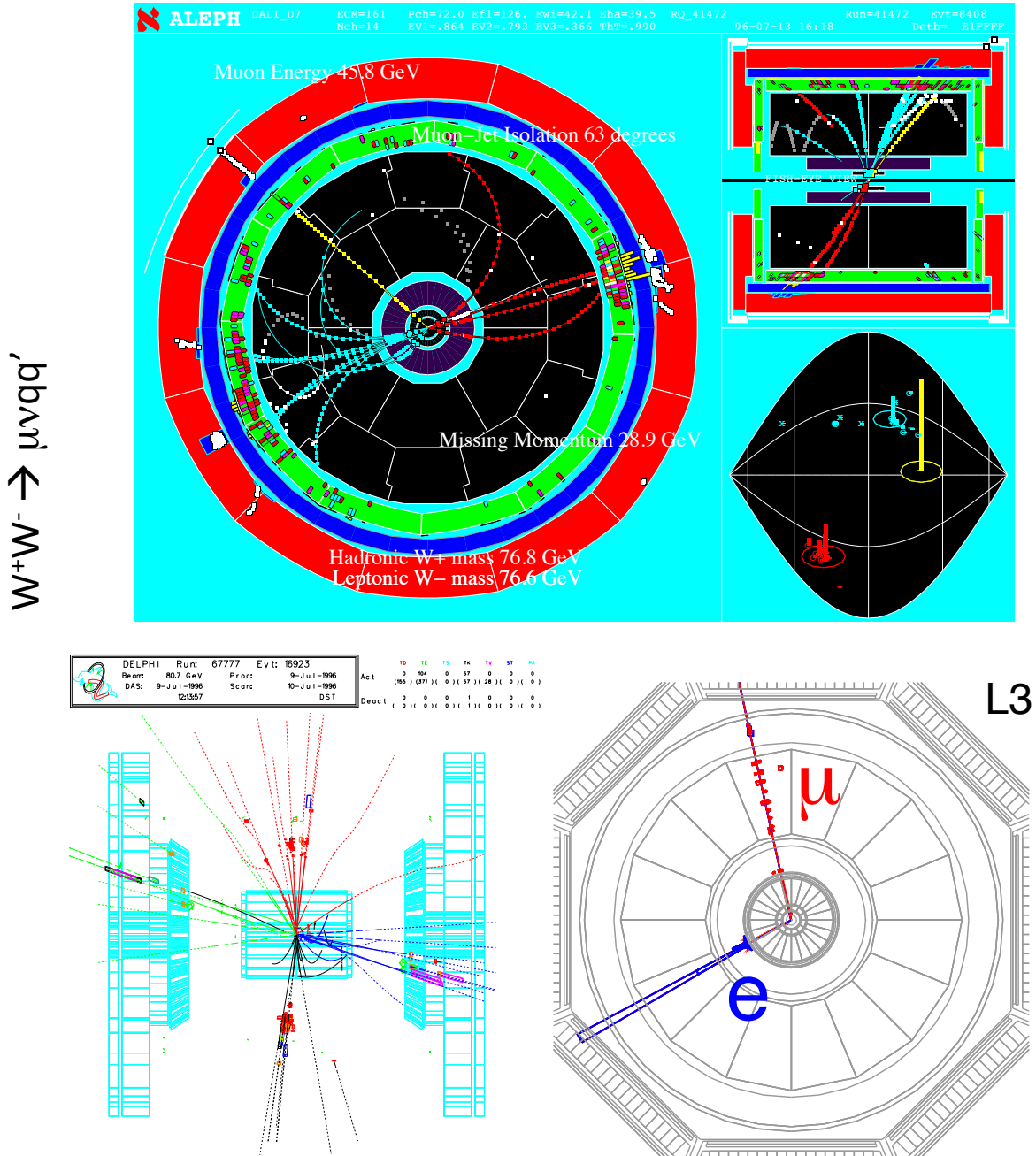


Figure 5.48: W-pair events selected at LEP-II. Left:  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  event observed in the DELPHI detector, showing four well separated jets. Right:  $W^+W^- \rightarrow e\nu\mu\nu$  event observed in the L3 detector showing apparent lepton flavour violation.

# Misura di precisione di $m_W$ (metodo della soglia)

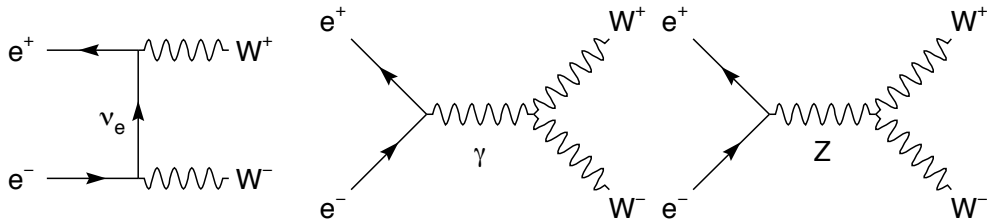


Figure 3.19: Feynman diagrams in  $W$ -pair production in  $e^+e^-$  interactions.

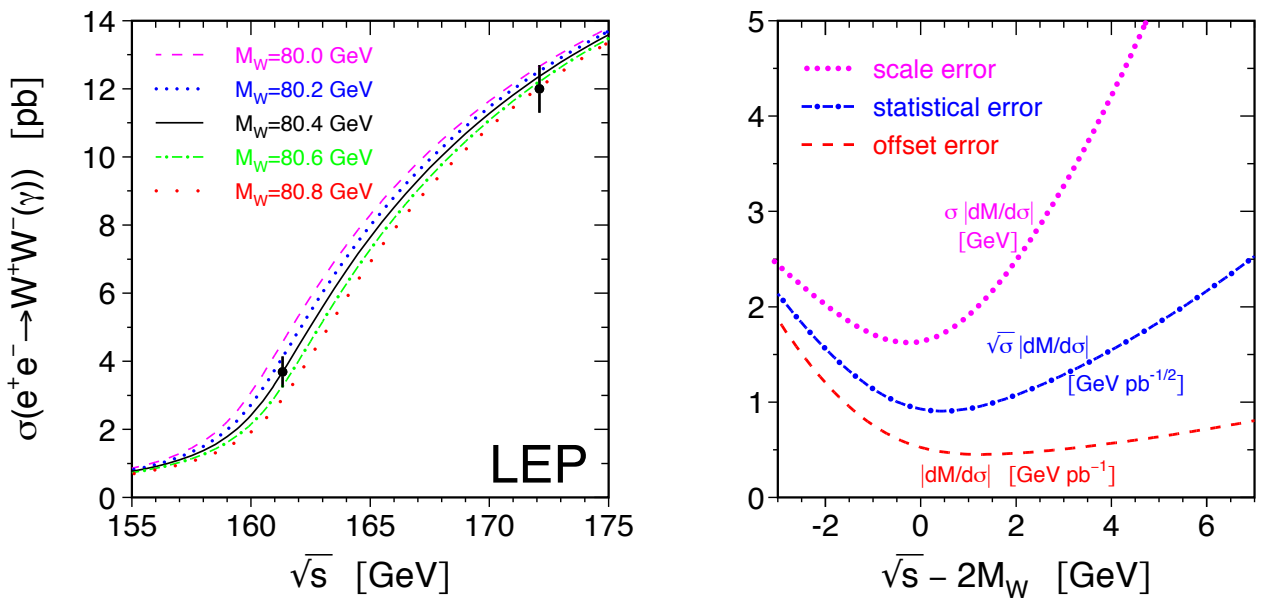
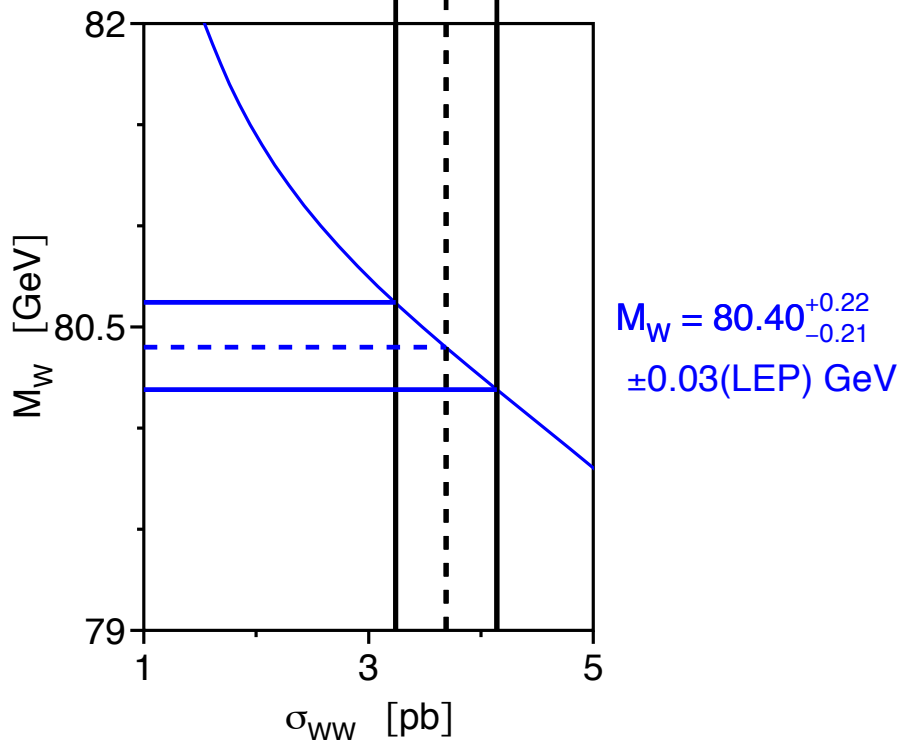
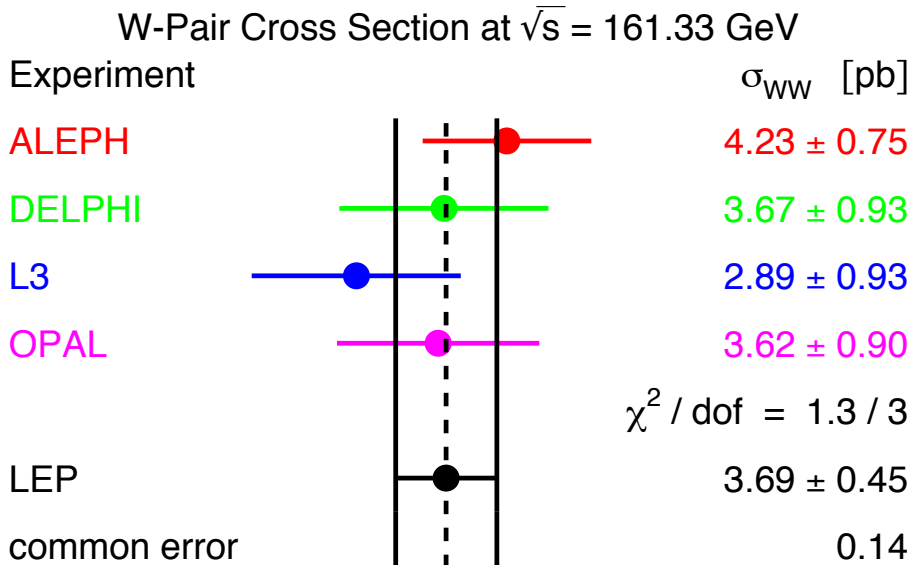


Figure 5.52:  $W$ -mass measurement at threshold. Left: Cross section for  $W$ -pair production as a function of  $\sqrt{s}$  in the vicinity of the kinematic threshold for different values of  $M_W$ . Right: Error components of  $M_W$  error arising from the statistical error and systematic scale and offset errors on the cross section measurement at threshold. All contributions show a minimum around zero to 2 GeV above the nominal threshold of  $\sqrt{s} = 2M_W$ .



# Misura di precisione di $m_W$ (metodo della soglia)



# Misura di precisione di $m_W$ (ricostruzione diretta)

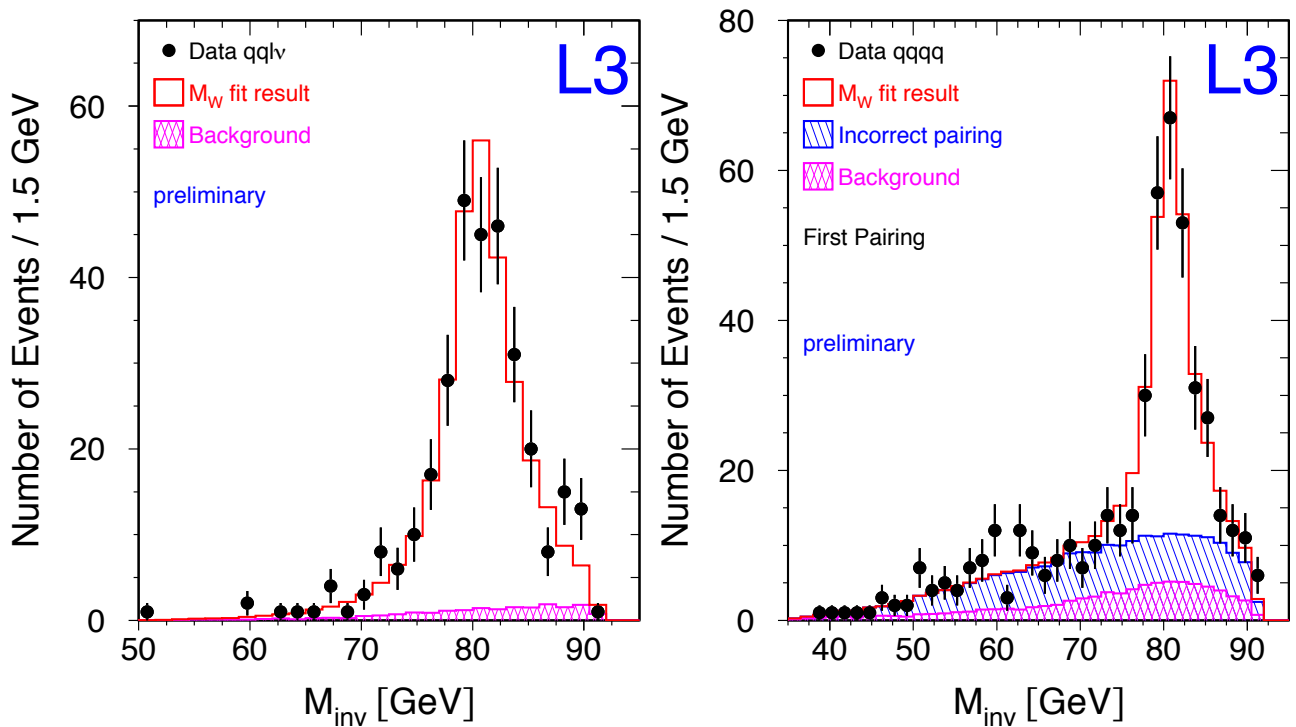


Figure 5.54: Distribution of invariant masses reconstructed in W-pair events selected by L3 at  $\sqrt{s} = 183$  GeV [218]. Left: semileptonic events; right: hadronic events.

- Utilizzati eventi semileptonici e completamente adronici unicamente, eventi dileptonici non sensibili a causa della presenza di due neutrini
- Statistica superiore nei 4 jet, ma sistematiche ridotte nel canale semileptonico

# Misura di precisione di $m_W$ (ricostruzione diretta)

Modelli di adronizzazione: il processo che trasforma quark colorati in getti di particelle adroniche neutre di colore

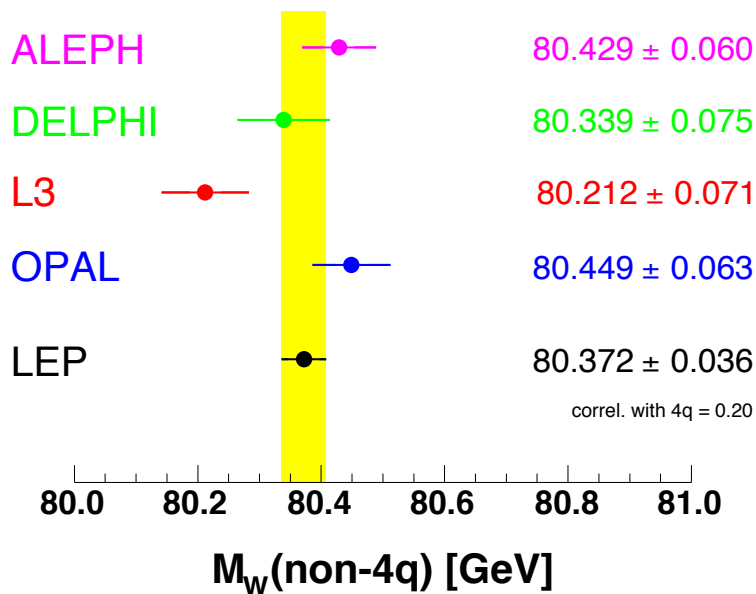
Sistematiche teoriche relative allo scambio di gluoni tra i 4 quark dello stato finale (solo nel canale completamente adronico)

Source	Systematic Uncertainty in MeV			
	on $m_W$			on $\Gamma_W$
	$q\bar{q}l\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	—	35	8	27
Bose-Einstein Correlations	—	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

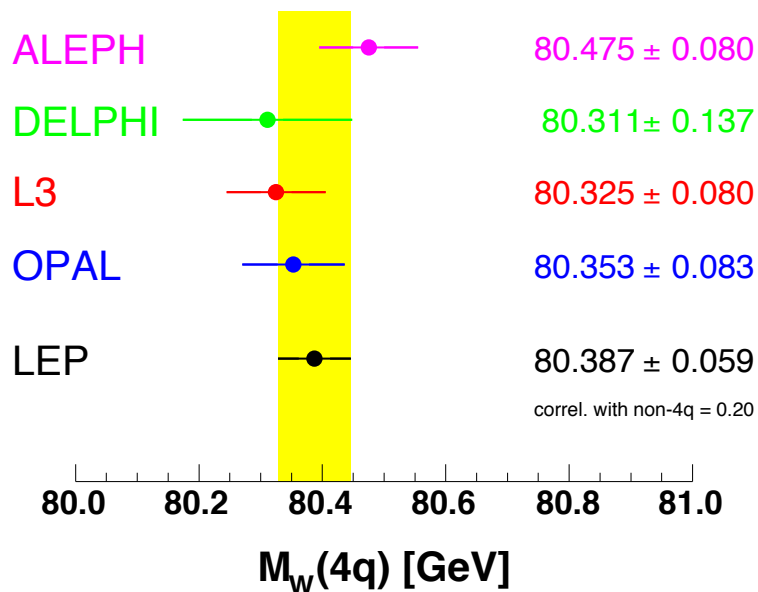
Table 7.3: Error decomposition for the combined LEP  $W$  mass and width results using the direct reconstruction method. Information from cross-section measurements at the  $W$ -pair production threshold are not included in the  $W$ -mass uncertainties. Detector effects include uncertainties in the jet and lepton energy scales and resolution. The ‘Other’ category refers to errors, all of which are uncorrelated between experiments, arising from: simulation statistics, background estimation, four-fermion treatment, fitting method and event selection. The error decomposition in the  $q\bar{q}l\nu_\ell$  and  $q\bar{q}q\bar{q}$  channels refers to the independent fits to the results from the two channels separately. Large correlated uncertainties, mainly from FSI, lead to a reduced weight of measurements contributing to the average result and thus an increased statistical uncertainty both in the  $q\bar{q}q\bar{q}$  channel and for the LEP combination.

# Misura di precisione di $m_W$ (ricostruzione diretta)

## LEP W-Boson Mass



## LEP W-Boson Mass



# Misura di precisione di $m_W$ (ricostruzione diretta)

## LEP W-Boson Mass

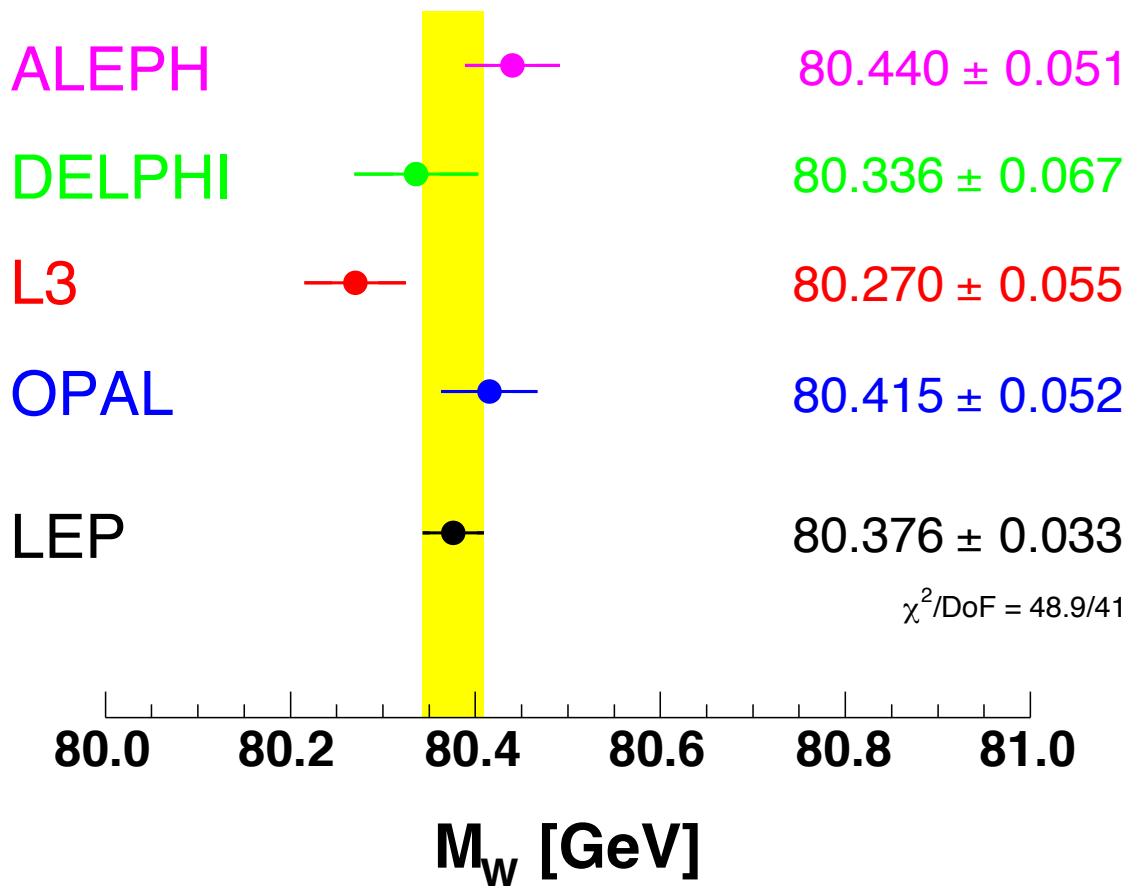


Figure 7.1: The measurements of the W-boson mass obtained by the four LEP collaborations (as published) together with the LEP combined result. The combined value includes correlations between experiments, between different energy points, and between the  $q\bar{q}\ell\nu_\ell$  and  $q\bar{q}q\bar{q}$  channels. A revised estimation of systematic uncertainties due to colour reconnection and Bose-Einstein correlations is applied to the input of the individual measurements to the LEP combined results in order to take the direct determination of FSI parameters into account.

# Misura di precisione di $m_W$ (collider)

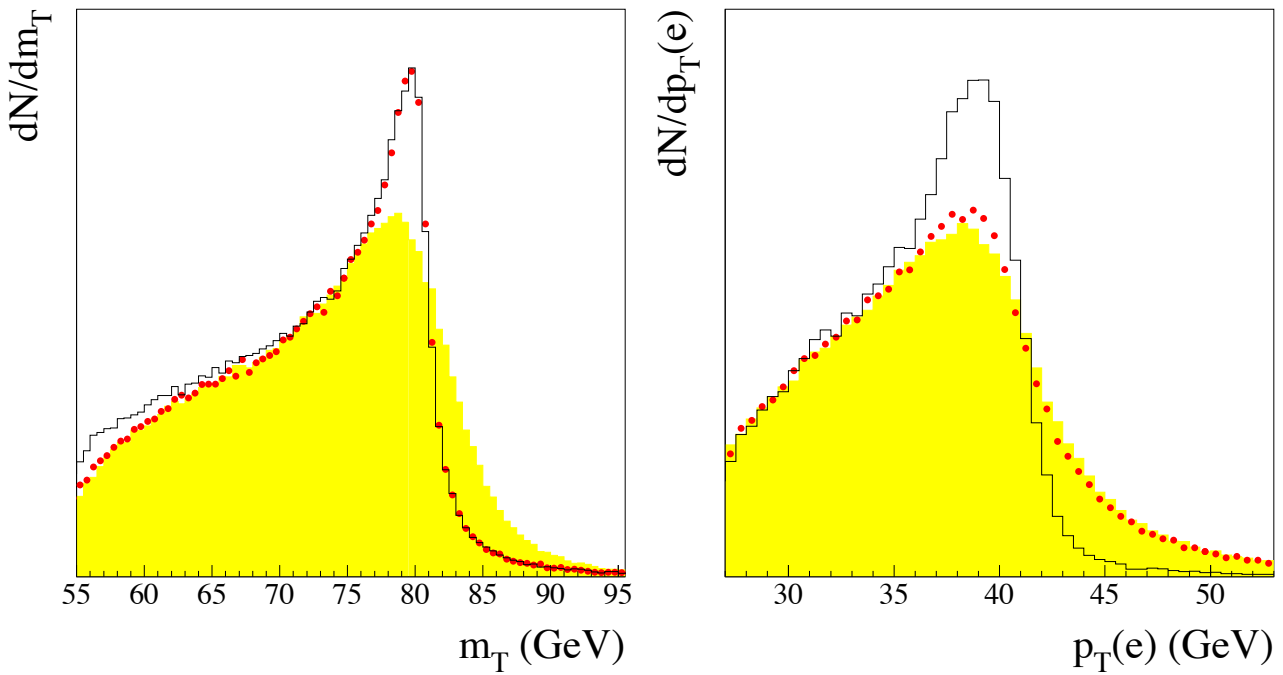
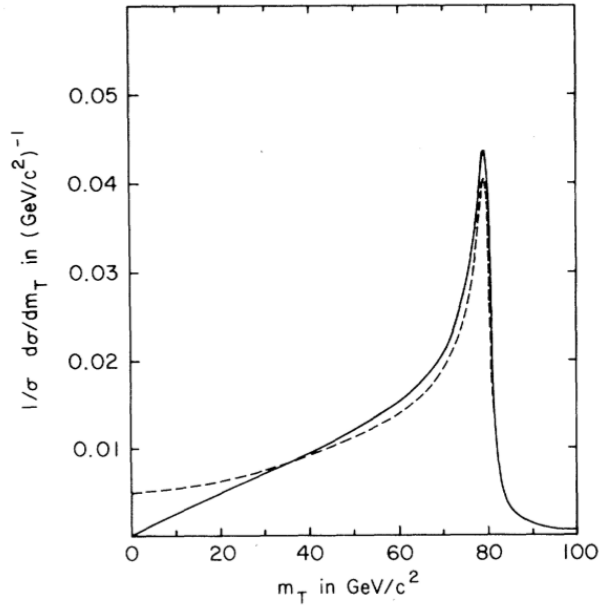


Figure 5.45: Monte Carlo simulation of the transverse lepton-neutrino mass (left) and the transverse lepton energy (right) for  $D\bar{O}$  [213]. The solid lines show the distributions at generator level with the transverse  $W$  momentum set to zero. The dots show the distributions when the transverse  $W$  momentum is included according to the  $W$  production model, modifying the transverse lepton energy but not the transverse lepton-neutrino mass. The shaded area show the spectra when the resolution of the detector, here  $D\bar{O}$ , is included, visibly affecting the transverse lepton-neutrino mass but not the transverse lepton energy.

- La variabile  $m_T$  e' molto meno sensibile a  $p_T(W)$  diverso da 0 rispetto all'impulso trasverso del leptone  $p_T(e)$  (il boost dovuto al moto del  $W$  sull'impulso trasverso del leptone compensa quello in verso opposto del neutrino: decadimento in due corpi)
- La risoluzione su  $m_T$  dipende da quella sulla missing energy (neutrino), che a sua volta dipende dai dettagli dell'emissione di adroni soffici (underlying event) che accompagnano il  $W$ , al contrario del caso della misura di  $p_T(e)$
- La migliore misura sperimentale e' attualmente ottenuta dal fit di  $m_T$

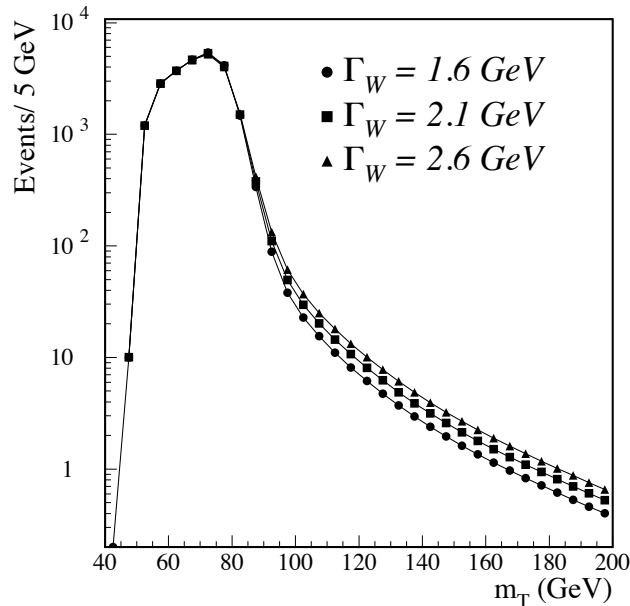
# Misura di precisione di

$$m_W$$



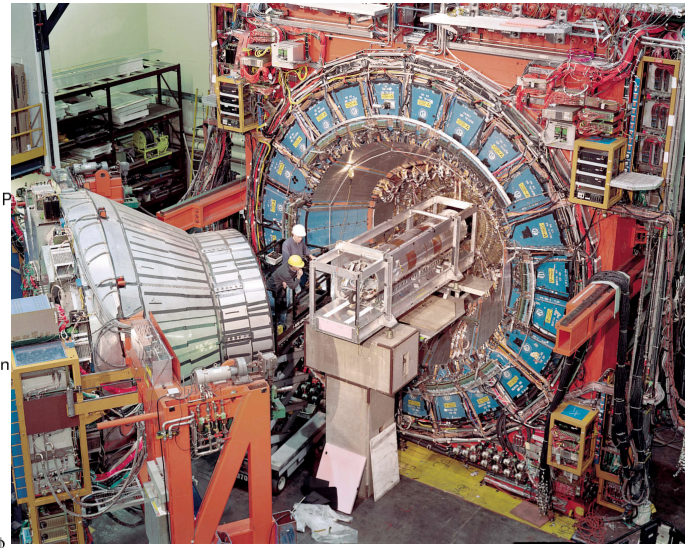
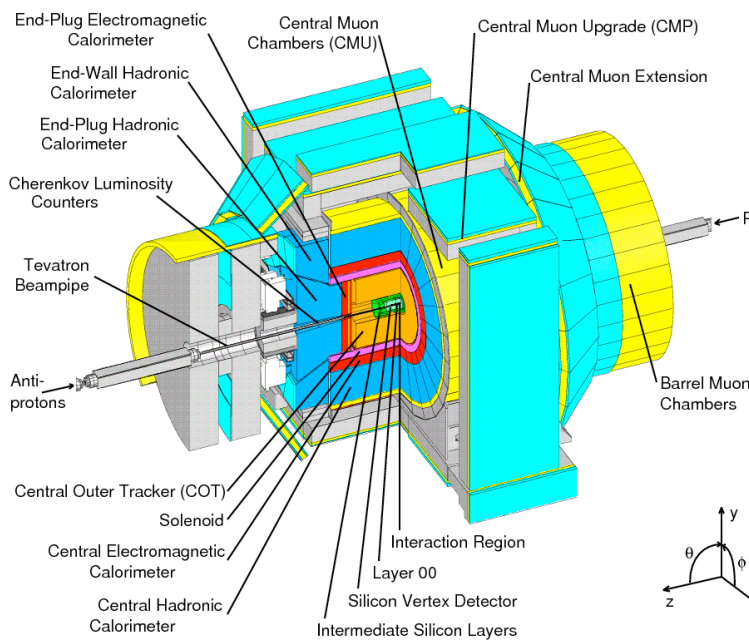
Calcolo teorico della distribuzione differenziale di  $m_T$  in assenza e in presenza di impulso trasverso del bosone W

FIG. 1.  $\sigma^{-1}d\sigma/dm_T$  for  $M = 80 \text{ GeV}/c^2$  and  $\Gamma = 2.5 \text{ GeV}/c^2$ . The solid line is for  $p_T^W = 0 \text{ GeV}/c$ , while the dashed line is for  $p_T^W = 50 \text{ GeV}/c$ .



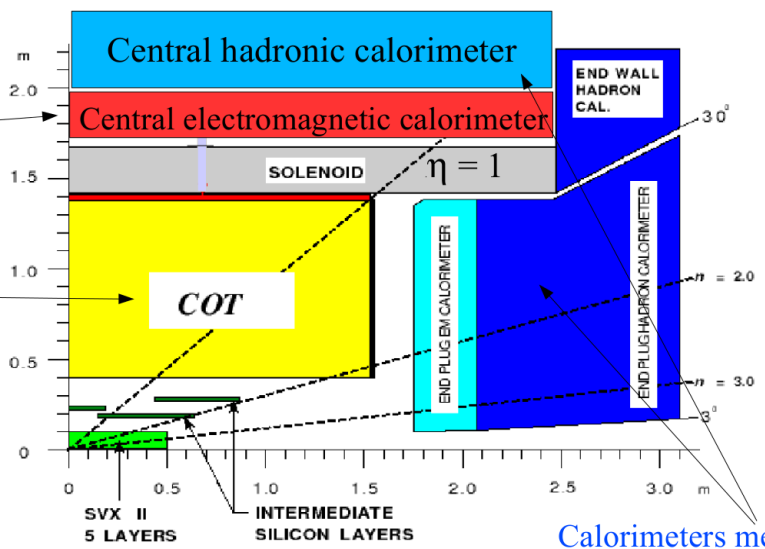
Principio di base per la misura di precisione di  $\Gamma_W$  ai collider

# Misura di precisione di $m_W$ a CDF



EM calorimeter provides precise electron energy measurement

COT provides precise lepton track momentum measurement

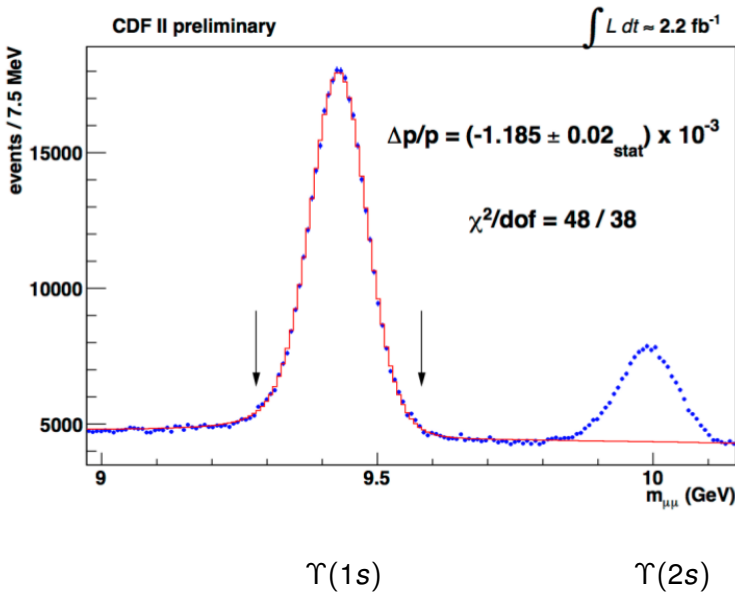


Calorimeters measure hadronic recoil particles

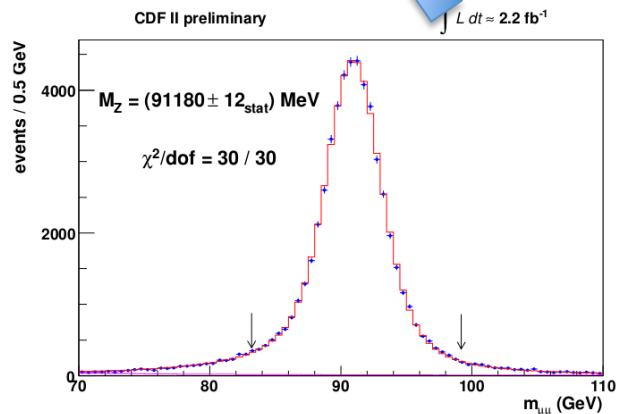
Inner silicon tracker, outer tracking drift chamber, COT, 1.4 T m. f. inside trackers, EM and Had calorimeters, muon system (CMU, CMP, CMX)



# Misura di precisione di $m_W$ a CDF



Accurata misura della calibrazione della misura del momento trasverso dei muoni utilizzando campioni di controllo:  $J/\psi \rightarrow \mu\mu$   
 $\Upsilon(1s) \rightarrow \mu\mu + Z \rightarrow \mu\mu$



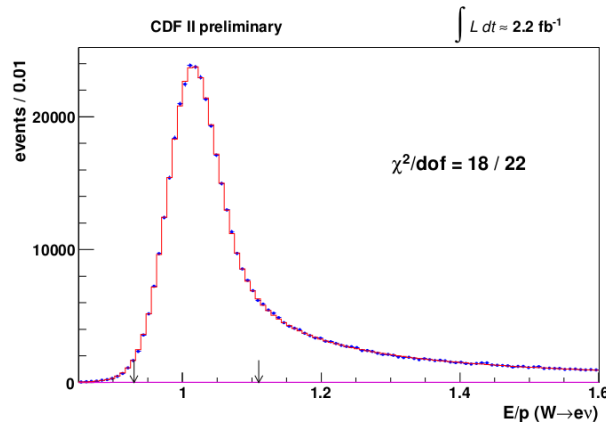
$\delta M_W = 7 \text{ MeV}$

consistent with world average  $m_Z = 91188 \pm 2 \text{ MeV}$

Overall momentum scale  $\Delta p/p = (-129 \pm 9) 10^{-5}$

# Misura di precisione di $m_W$ a CDF

EM calorimeter energy scale is set using  $E/p$  electron distribution



$$\delta M_W = 13 \text{ MeV}$$

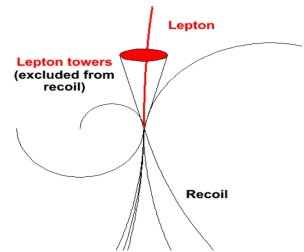
Confronto tra l'energia dell'elettrone vista nel tracciatore con l'energia misurata nel calorimetro. Sensibili ad effetti diversi: tracciatore non vede fotoni di bremsstrahlung ( $E/p > 1$ ), risoluzione del calorimetro + tracciatore domina ad  $E/p < 1$

L'accuratezza con cui si riesce a simulare gli effetti di risoluzione e di bremsstrahlung corrisponde ad una variazione di soli 13 MeV (0.016 %) della massa del W

# Misura di precisione di $m_W$ a CDF

## Recoil calibration

**Recoil**  $\vec{u}$ : vector sum of transverse energy over all EM and Had towers for  $|\eta| < 2.4$ , explicitly removing lepton towers.



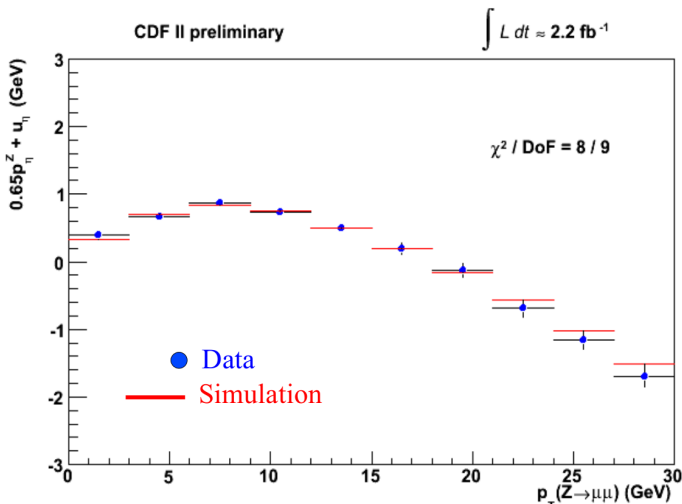
Two components

- soft “spectator interaction” component, randomly oriented  $\implies$  minimum bias event with tunable magnitude
- hard jet component, opposite to  $p_T(W) \implies p_T$  dependent, logarithmically increasing in  $p_T$ , following Z data

Z  $\rightarrow$   $ll$  because we need to reveal both decay products

$\eta$  axis defined as the geometric bisector of two leptons,  $\xi$  axis  $\perp \eta$

Mean and rms of recoil projection as a function of  $p_T(ll)$

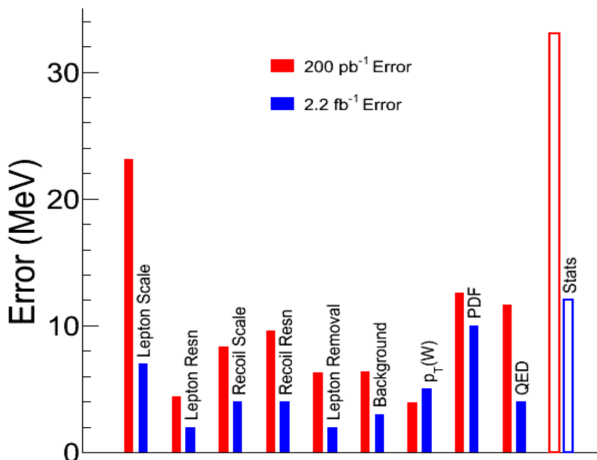
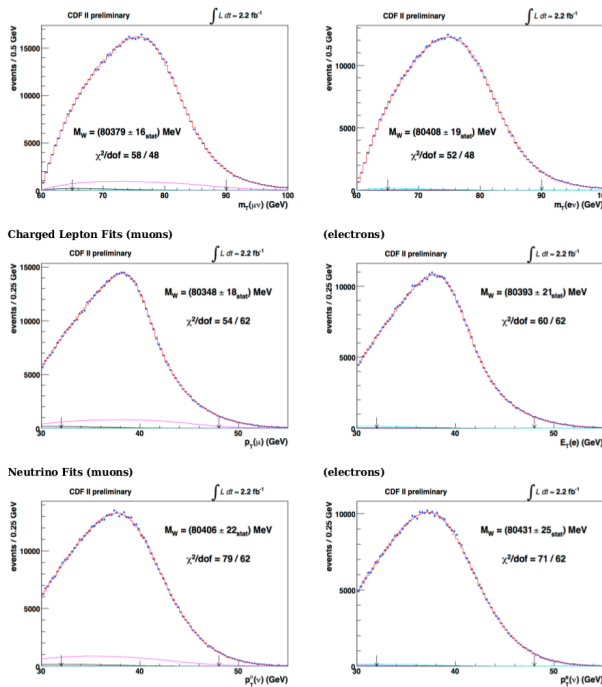


$\delta M_W = 7 \text{ MeV}$

# Misura di precisione di $m_W$ a CDF

## Mass fits

Binned maximum-likelihood fit to  $p_T(l)$ ,  $p_T(\nu)$ ,  $m_T$  for each lepton channel



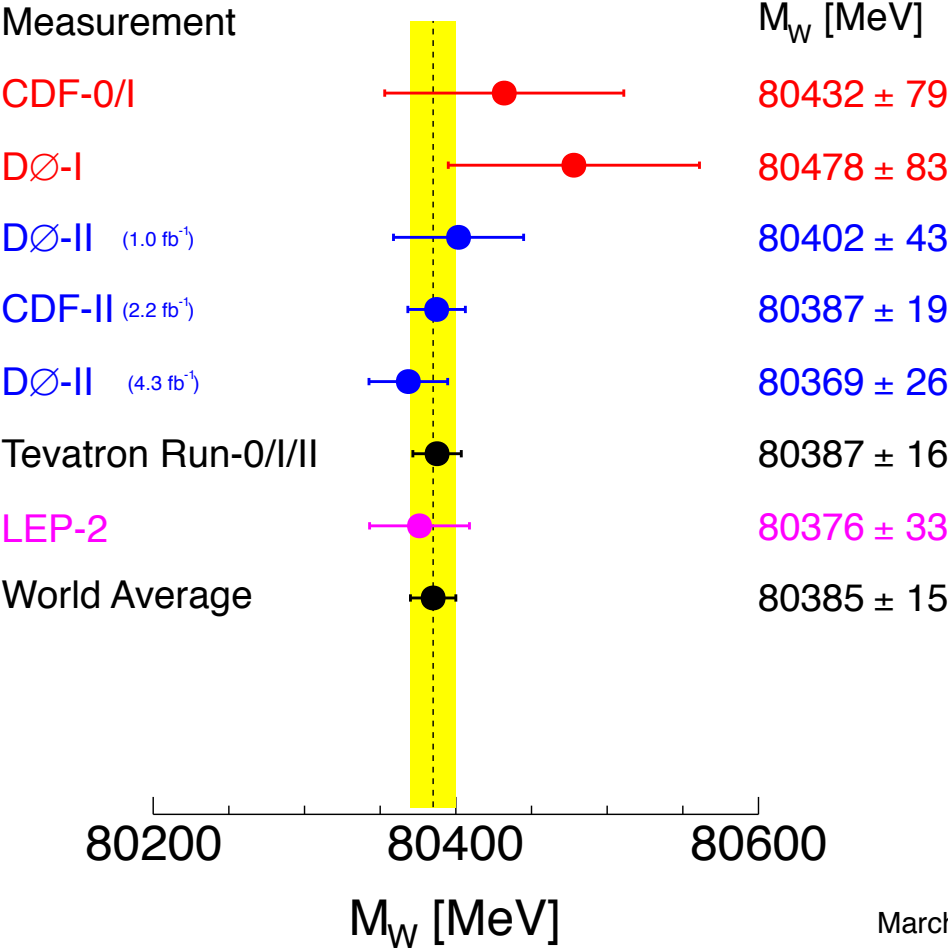
Errore Teorico importante:

1. PDF  $\rightarrow$  cambiano le distribuzioni dei prodotti di decadimento nel lab frame
2. QED  $\rightarrow$  c'è bisogno di implementare correzioni  $\alpha_{e.m.}^3$  per migliorare

# Misura di precisione di

$$m_W$$

Mass of the W Boson



March 2012

# Misura di precisione di $m_W$

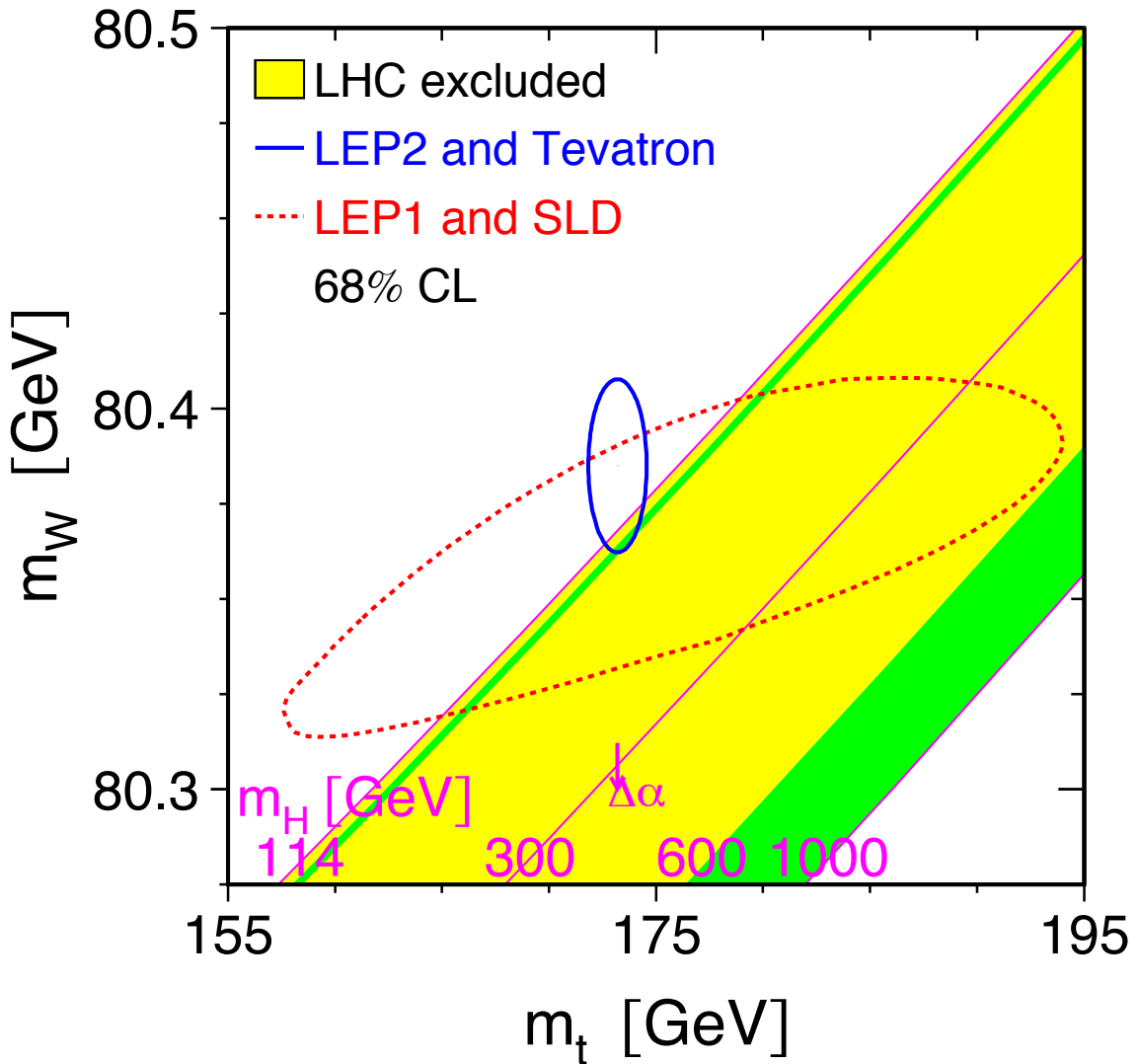
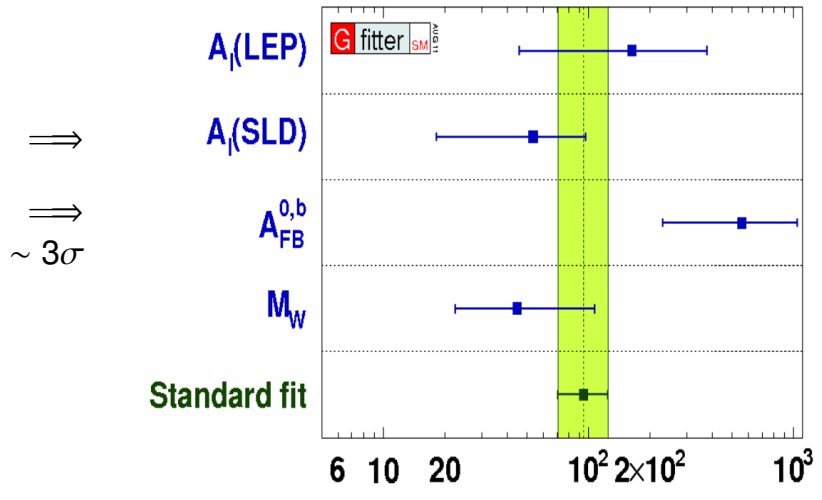


Figure F.1: The comparison of the indirect constraints on  $m_W$  and  $m_t$  based on LEP-I/SLD data (dashed contour) and the direct measurements from the LEP-II/Tevatron experiments (solid contour). In both cases the 68% CL contours are plotted. Also shown is the SM relationship for the masses as a function of the Higgs mass in the region favoured by theory ( $< 1000$  GeV) and allowed by direct searches (dark green bands). The arrow labelled  $\Delta\alpha$  shows the variation of this relation if  $\alpha(m_Z^2)$  is changed by plus/minus one standard deviation. This variation gives an additional uncertainty to the SM band shown in the figure.

# Misura di precisione di

$$m_W$$



Precisione comparabile alle misure di LEP nel fornire un constraint indiretto alla massa del bosone di Higgs

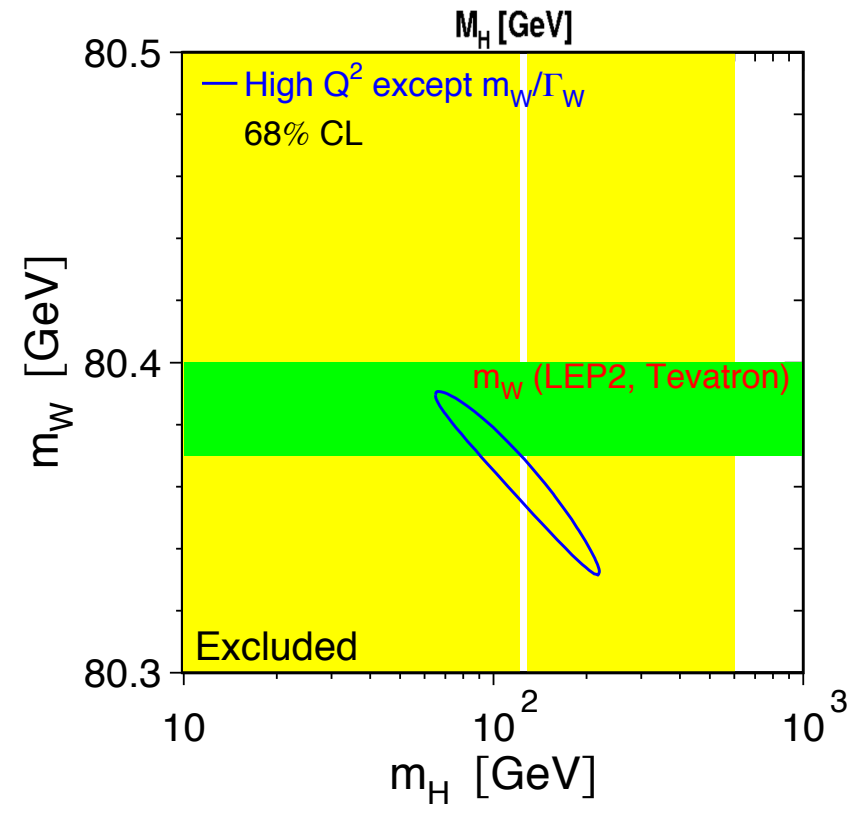


Figure F.2: The 68% confidence level contour in  $m_W$  and  $m_H$  for the fit to all data except the direct measurement of  $m_W$ , indicated by the shaded horizontal band of  $\pm 1$  sigma width. The vertical bands show the 95% CL exclusion ranges on  $m_H$  from the direct searches.

# Misura di precisione EWK vs $m_H$

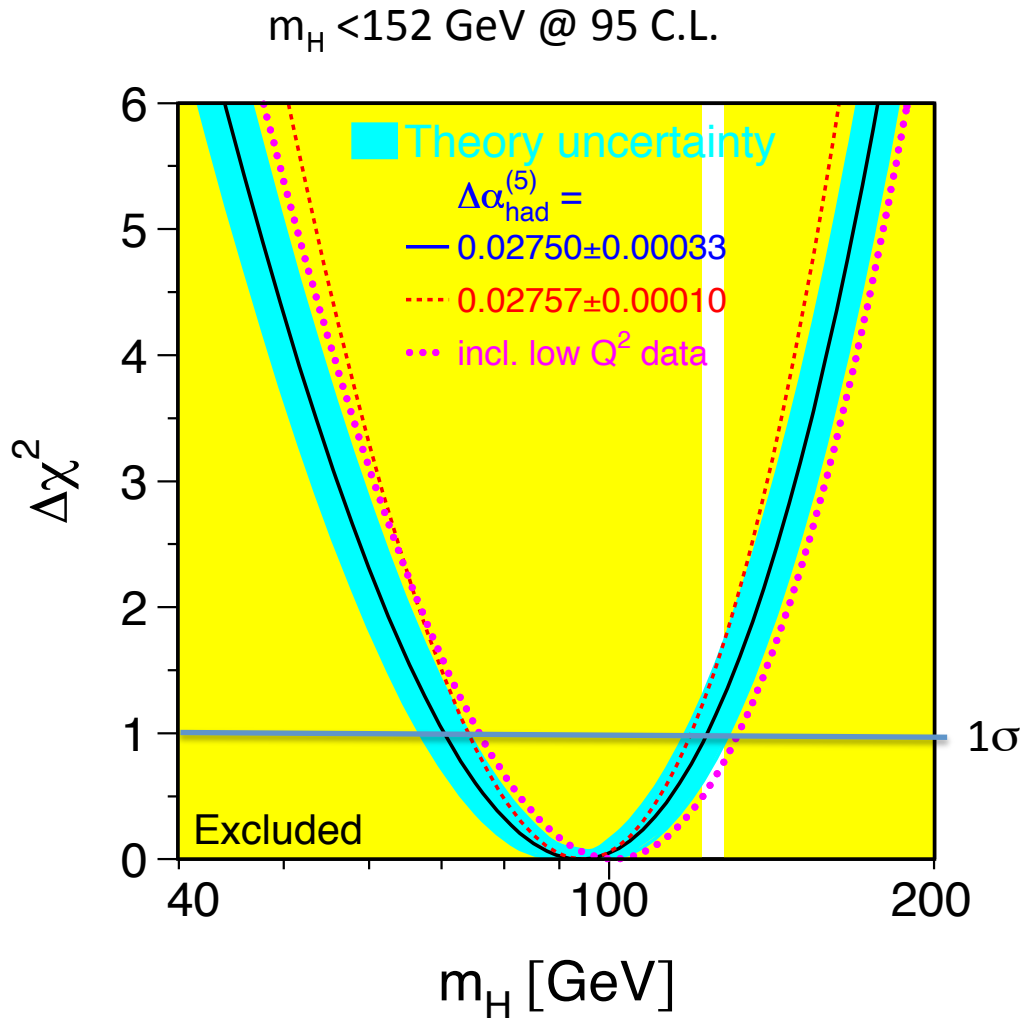
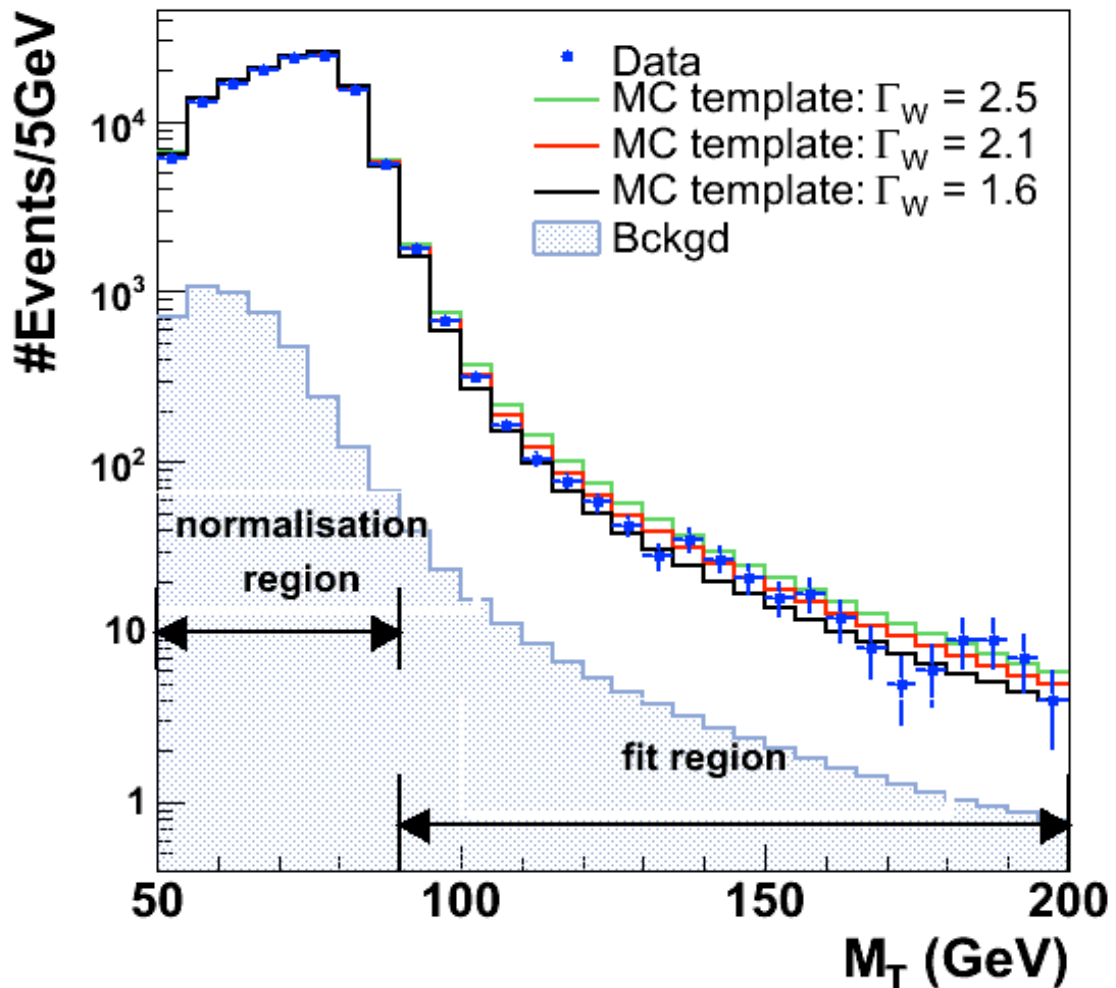


Figure F.4:  $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2$  vs.  $m_H$  curve. The line is the result of the fit using all high- $Q^2$  data (last column of Table F.2); the band represents an estimate of the theoretical error due to missing higher order corrections. The vertical bands show the 95% CL exclusion ranges on  $m_H$  from the direct searches. The dashed curve is the result obtained using the evaluation of  $\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$  from Reference [194]. The dotted curve corresponds to a fit including also the low- $Q^2$  data from Table F.3.



# Misura di precisione di $\Gamma_W$



$$\Gamma_W = 2.033 \pm 0.039 \text{ (stat)} \pm 0.061 \text{ (syst)}$$

Source	$\Delta\Gamma_W$ (MeV)
Electron response model	33
Electron resolution model	10
Hadronic recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson $p_T$	1
$M_W$	5
Total Systematic	61

# Misura di precisione di $\Gamma_W$

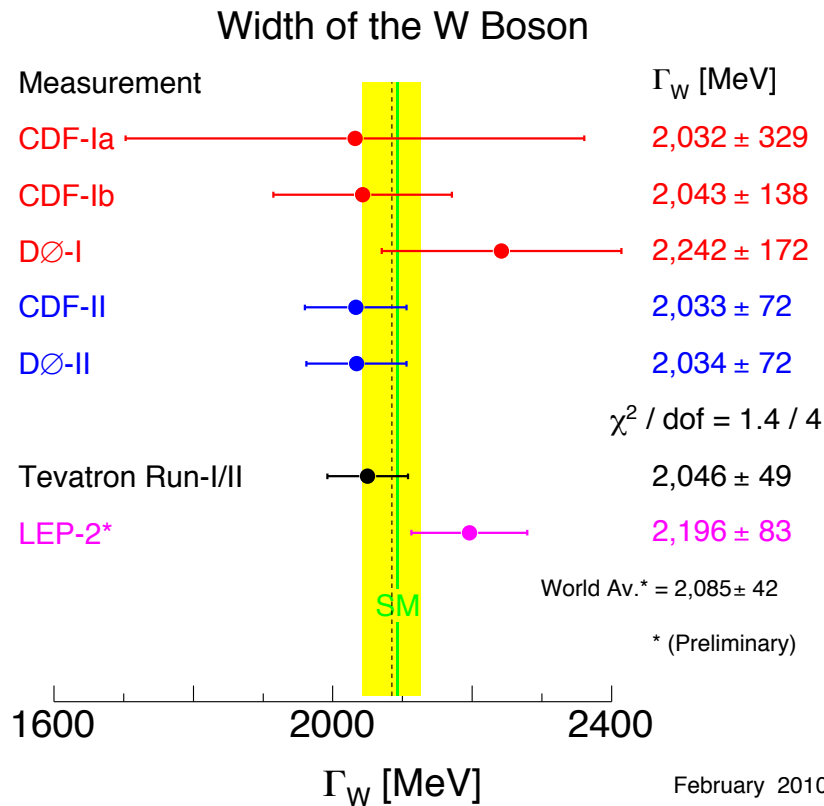


Figure 1: Comparison of measurements of the width of the  $W$ -boson and their average. The most recent preliminary result from LEP-2 [20] and the Standard Model prediction are also shown. The Tevatron values are corrected for small inconsistencies in theoretical assumptions among the original publications .

3 famiglie di leptoni

2 famiglie di quark (ud+cs) ;  
tb non permesso per  
conservazione energia

$$\Gamma_W = (3 + 2f_{QCD}) \frac{G_F M_W^3}{6\sqrt{2}\pi} (1 + \delta) = 2.093 \pm 0.002 \text{ (SM)}$$

Fattore di colore  
\*QCD correction

$$f_{QCD} = 3(1 + \alpha_s(M_W^2)/\pi)$$

$\delta$  corr. radiative  $\sim 2\%$

# Misura di precisione di $m_W$

## Uno sguardo al futuro

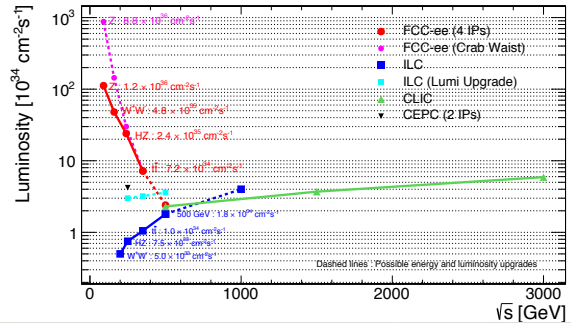
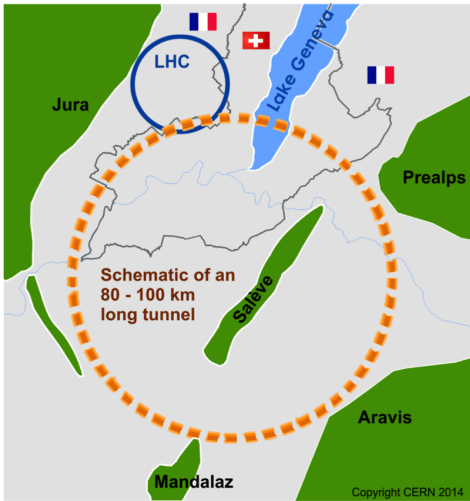
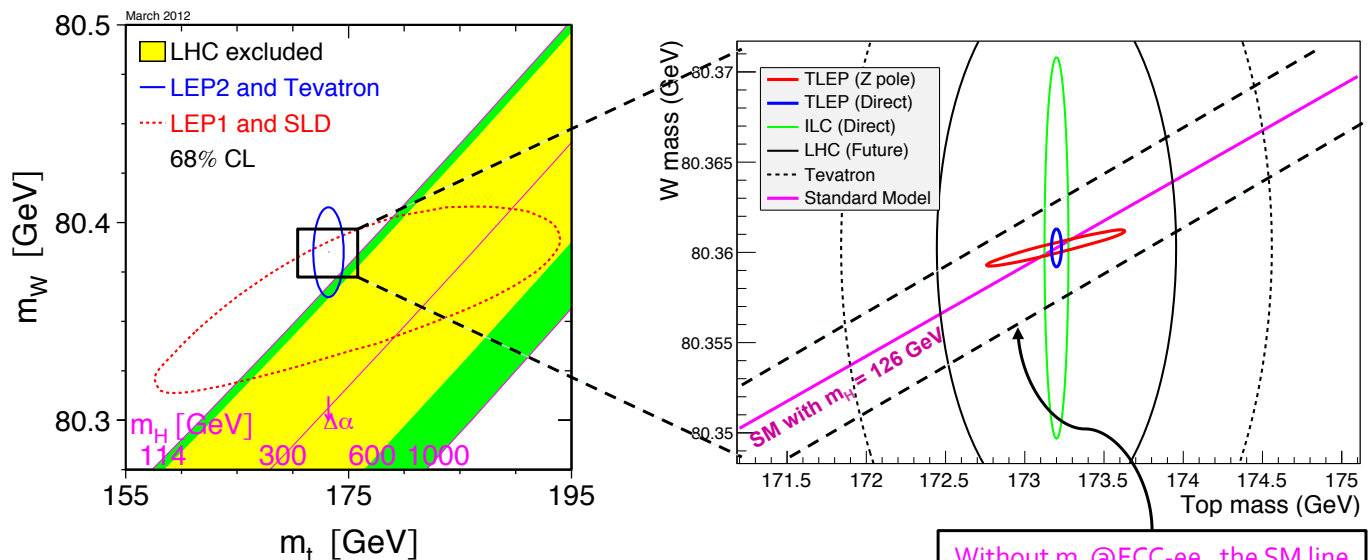


Figure 1: A possible location of the Future Circular Collider in the Geneva area.

- ❖ Intermediate step in the FCC global project
- ❖ Very high luminosity + up to 4 Interaction Points
- ❖ Beam energy from 45 to 175(250) GeV



◆ Constraints on new physics ?

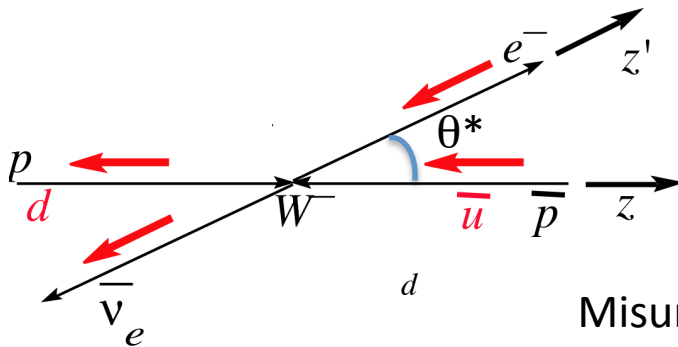
Without  $m_Z$ @FCC-ee, the SM line would have a 2.2 MeV width

# W polarization

Nel riferimento del c.m. della  $W$  :

l'energia dell'elettrone  $\gg m_e$ . chiralità  $\approx$  elicità

$V-A \Rightarrow W$  si accoppia solo a fermioni con elicità -  
antifermioni con elicità +



Misuriamo  $\theta^*$  rispetto al fascio di protoni che corre lungo  $z$

Mom. ang. tot.  $J=S_W=1$

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

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

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

N.B. Se fosse stato  $V+A$   $\frac{d\sigma}{d\Omega} \propto [d_{1,1}^1]^2 = \left[ -\frac{1}{2} (1 + \cos \theta^*) \right]^2$

L'asimmetria avanti-indietro è conseguenza della violazione di P

Per distinguere  $V-A$  da  $V+A$  sono necessarie misure di polarizzazione dell'elettrone

N.N.B: nel caso di  $W^+$  l'elicità del leptone e del neutrino è invertita e sarà favorita l'emissione lungo l'asse dell'antiprotone  $J_{z'}(\text{fin.})=+1$   $\frac{d\sigma}{d\Omega} \propto [d_{-1,+1}^1]^2 = \left[ \frac{1}{2} (1 - \cos \theta^*) \right]^2$

# Verifica spin e massima violazione di parita'

Occorre determinare la componente longitudinale del momento del neutrino imponendo la massa del W al valore misurato

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

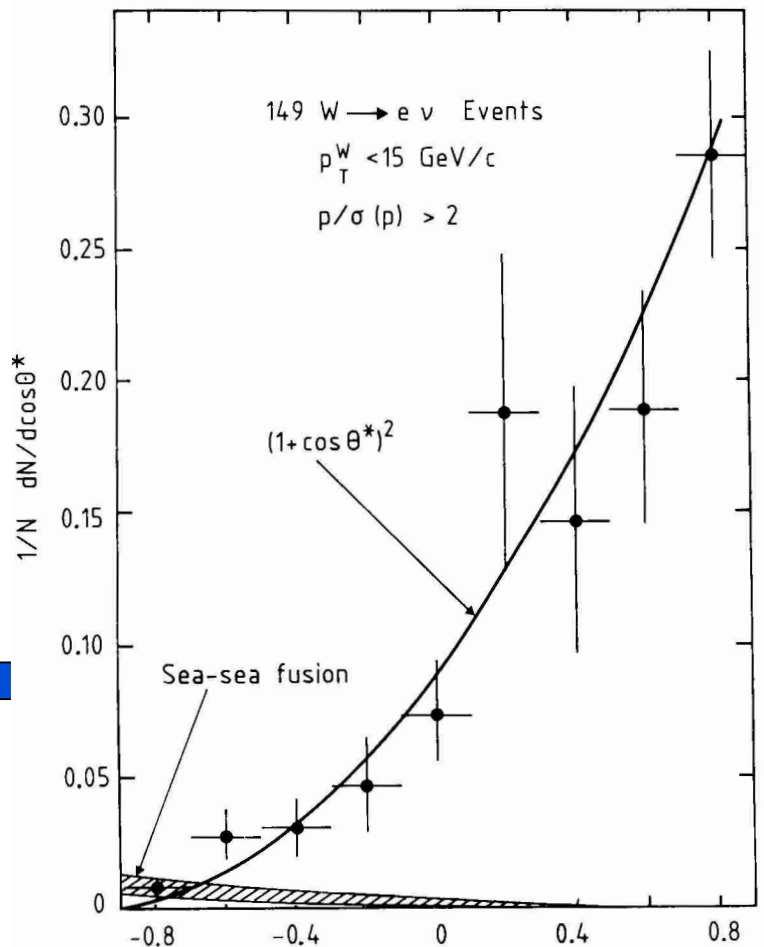
$$\langle \cos\theta^* \rangle = \frac{\langle \lambda \rangle \langle \lambda' \rangle}{J(J+1)}$$

$$J=1 \quad \langle \cos\theta^* \rangle = \frac{1}{2}$$

$$J=0 \quad \langle \cos\theta^* \rangle = 0$$

$$J>1 \quad \langle \cos\theta^* \rangle \leq \frac{1}{6}$$

$$\langle \cos\theta^* \rangle = 0.43 \pm 0.07$$



cioè  $J=1$  e elicità massima ( $\lambda, \lambda' = \pm 1$ )

N.B. nell'articolo originale di UA1  $\theta^*$  misurato a partire dalla direzione del fascio di anti-protoni  $\cos(\theta^*) \rightarrow -\cos(\theta_{UA1}^*)$

# Asimmetria $W^+/W^-$ a Tevatron e LHC

Passiamo ora alla misura dell'asimmetria nella produzione di  $W^+$  e  $W^-$ :

$$u + \bar{d} \longrightarrow W^+ \longrightarrow e^+ + \nu_e, \mu^+ + \nu_\mu$$

$$\bar{u} + d \longrightarrow W^- \longrightarrow e^- + \bar{\nu}_e, \mu^- + \bar{\nu}_\mu$$



$$A(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \simeq \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

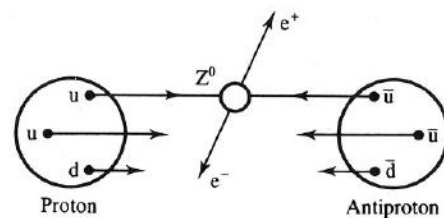
Una misura di quest' asimmetria e' molto sensibile alle differenze fra le pdf  $u$  e  $d$  nella regione  $Q^2 \simeq M_W^2$ ; possiamo percio' sfruttarla per ottenere informazioni sull'andamento del loro rapporto  $\frac{u}{d}$  in funzione di  $x$ .

## Un po' di cinematica...

$$q(x_1) + \bar{q}(x_2) \rightarrow Z/\gamma^* \rightarrow e^+ e^-$$

$$x_1 = \frac{M_Z}{\sqrt{s}} e^y \quad x_2 = \frac{M_Z}{\sqrt{s}} e^{-y}$$

$$\sqrt{s} = 1.96 \text{ TeV}$$



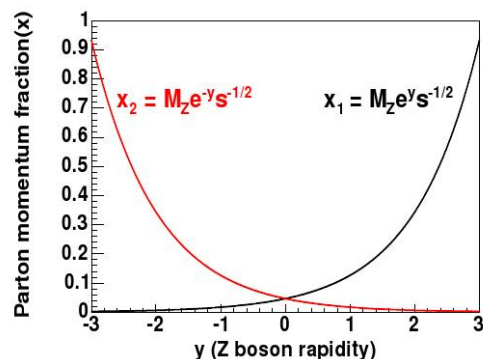
Rapidita':

$$y = \frac{1}{2} \log\left(\frac{E+p_z}{E-p_z}\right)$$

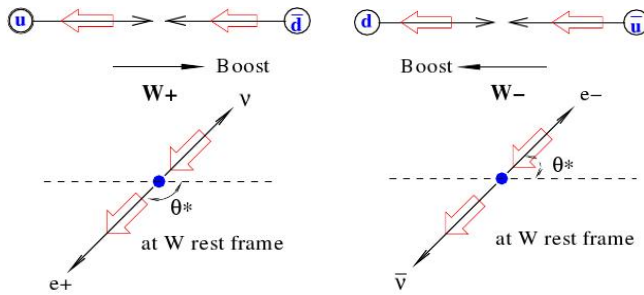
⇓ se  $m \simeq 0$

Pseudorapidita':

$$\eta = -\log\left(\tan\left(\frac{\theta}{2}\right)\right)$$



# Cinematica di $p\bar{p} \rightarrow W \rightarrow e\nu$

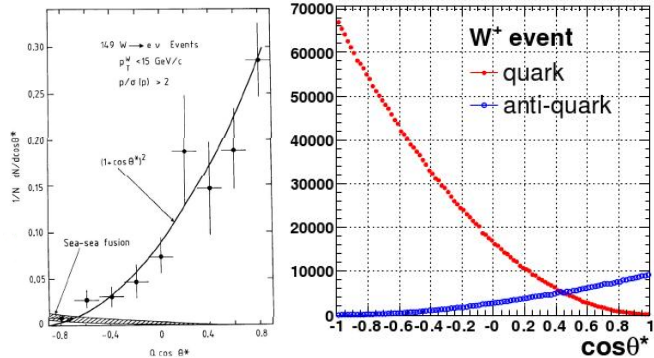


Analogamente a prima:

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}$$

$$x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

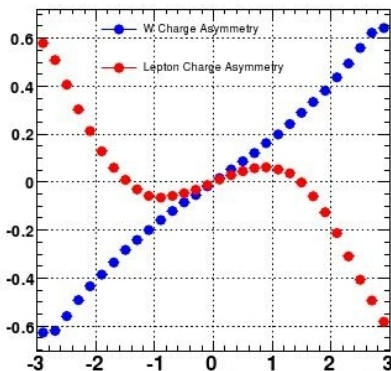
Se ci limitiamo a vedere il bosone  $W^+$ , l'accoppiamento  $V - A$  fa si' che il numero degli eventi in funzione dell'angolo di decadimento sia  $(1 - \cos\theta^*)^2$ ; se, pero', teniamo conto del contributo dei quark del mare, ci sara' anche una componente con l'andamento  $(1 + \cos\theta^*)^2$ :



# Asimmetria $e^+/e^-$

Nell'effettuare la misura possiamo servirci solo delle particelle che osserviamo; definiamo percio' l'asimmetria elettrone-positrone in funzione della loro pseudorapidita':

$$A(\eta_e) = \frac{d\sigma(e^+)/d\eta_e - d\sigma(e^-)/d\eta_e}{d\sigma(e^+)/d\eta_e + d\sigma(e^-)/d\eta_e}$$

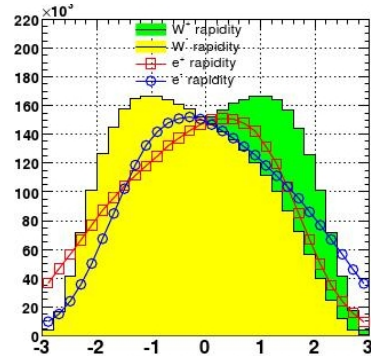


Come si puo' notare dalla figura gli andamenti delle due asimmetrie sono differenti; in particolare e' da notare il cambiamento di segno nell'asimmetria elettrone-positrone.

## Distribuzioni *bosone – leptone*

Se andiamo ad osservare le distribuzioni dei  $W^\pm$  e dei corrispettivi leptoni di decadimento, notiamo quale sia il motivo del cambio di segno:

In base ad alcune considerazioni di spin possiamo capire il perche' le distribuzioni abbiano questa forma:



Il caso dell'altro bosone carico e' del tutto analogo e quello che si nota e' che, in entrambi i casi, il leptone di decadimento tende ad andare nella direzione opposta rispetto a quella del  $W$ ; questo fa si' che le distribuzioni per  $e^+ - e^-$  risultino leggermente spostate verso rapidita' minori in modulo.

## Come risolvere il problema?

Quello che possiamo fare e' imporre il valore della massa del bosone  $W$ ; a questo punto l'impulso del neutrino (o dell'antineutrino), puo' essere dedotto a meno del segno, informazione che pero' possiamo ricostruire parzialmente dalla conoscenza della distribuzione angolare del decadimento prevista dall'accoppiamento  $V - A$ .

Parametriamo la distribuzione in questo modo:

$$P_{\pm}(\cos\theta^*, y_W, P_T^W) = (1 \mp \cos\theta^*)^2 + Q(y_W, P_T^W)(1 \pm \cos\theta^*)^2$$

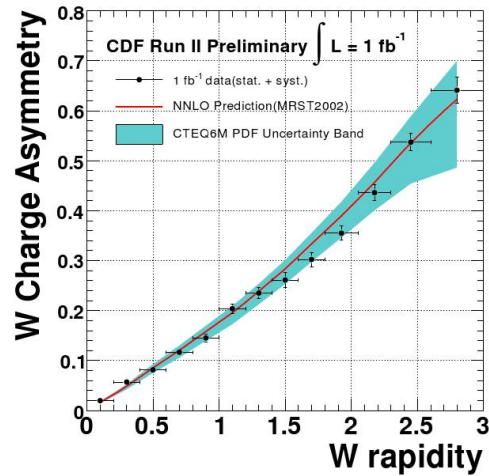
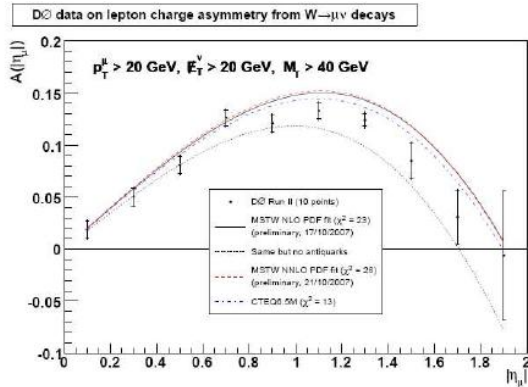
Notiamo che  $Q(y_W, P_T^W)$  e' il termine che deve tenere in conto del contributo alla produzione dei  $W$  dei quark del mare; inoltre, in generale, dobbiamo utilizzare quanto trovato per pesare opportunamente le varie soluzioni:

$$wt_{1,2}^{\pm} = \frac{P_{\pm}(\cos\theta_{1,2}^*, y_{1,2}, P_T^W) \sigma_{\pm}(y_{1,2})}{P_{\pm}(\cos\theta_1^*, y_1, P_T^W) \sigma_{\pm}(y_1) + P_{\pm}(\cos\theta_2^*, y_2, P_T^W) \sigma_{\pm}(y_2)}$$

Come si puo' vedere, questo e' un processo iterativo, in quanto i pesi sono funzioni delle sezioni d'urto che intendiamo misurare.



# Risultati

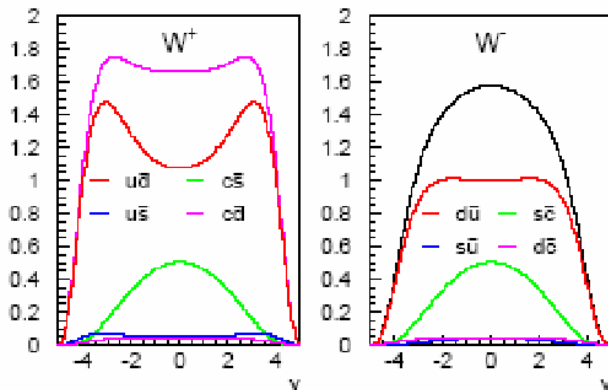


Come si puo' vedere nella prima figura, il Run I e' riuscito ad arrivare ad  $|\eta| = 2$  mentre con il Run II e l'esperimento presentato, il cui risultato e' presentato nella seconda figura, si e' potuti arrivare ad  $|\eta| = 2.8$ , riuscendo percio' a ricavare informazione in una regione in cui le pdf non sono mai state misurate.

## Cosa si puo' fare ad LHC?

Tevatron  $\rightarrow p - \bar{p}$  (l'asimmetria di produzione dipende dalla forma delle pdf)

LHC  $\rightarrow p - p$  (l'asimmetria dipende dall'integrale di quark ed antiquark)



In un collider protone-protone non sarebbe possibile, tramite una misura di questo tipo, stabilire la forma del rapporto  $\frac{u}{d}$ ; se non altro perche' la produzione di  $W^+$  sarebbe sicuramente maggiore di quella dei  $W^-$  data la presenza di due quark  $u$  nel protone (contro un solo quark  $u$ ).

# W asymmetry LHC

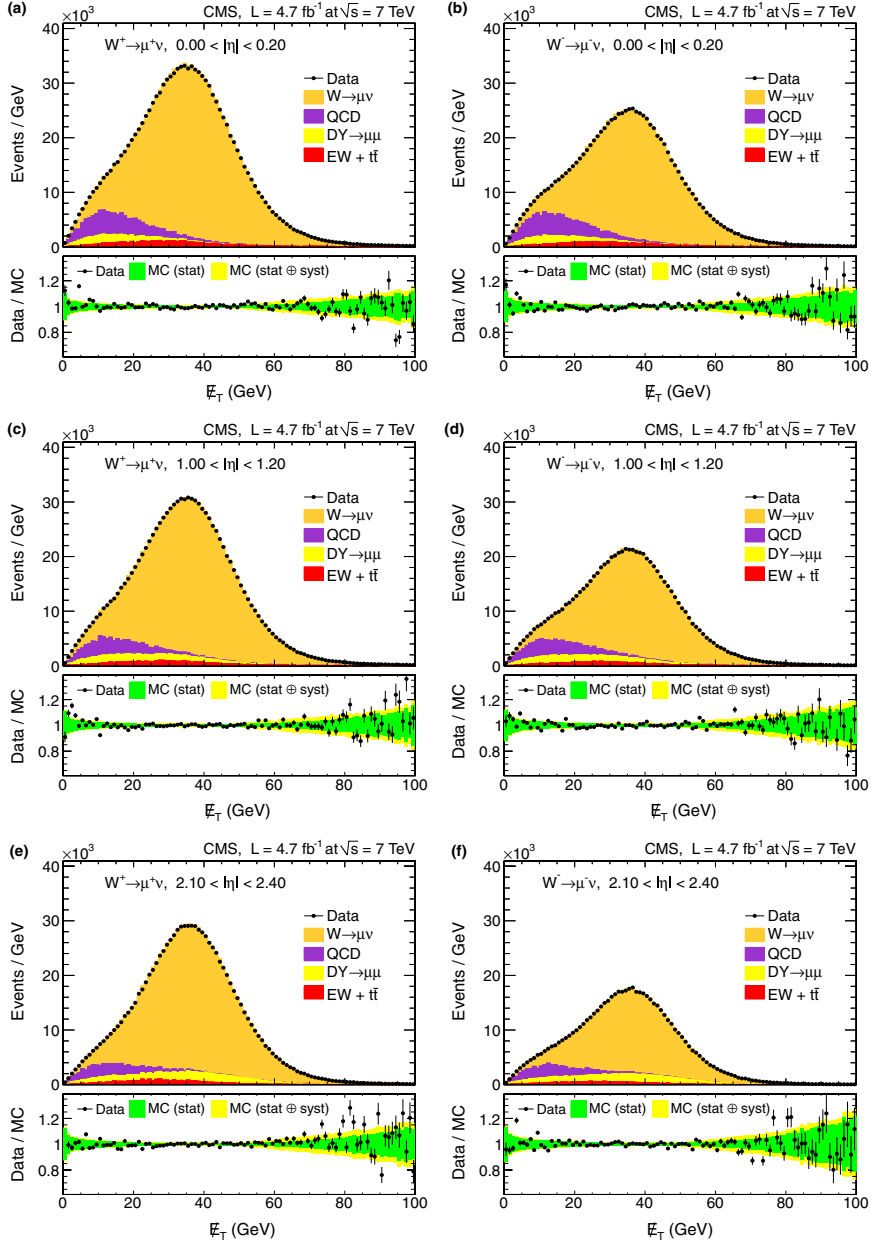


FIG. 5 (color online). Muon  $p_T > 25$  GeV data sample. Examples of the extraction of the  $W \rightarrow \mu\nu$  signal from fits to  $E_T$  distributions of  $W \rightarrow \mu\nu$  candidates in data:  $0.0 \leq |\eta| < 0.2$  (a), (b),  $1.0 \leq |\eta| < 1.2$  (c), (d), and  $2.1 \leq |\eta| < 2.4$  (e), (f). The fits to  $W^+ \rightarrow \mu^+\nu$  and  $W^- \rightarrow \mu^-\bar{\nu}$  candidates are in panels (a), (c), (e) and (b), (d), (f), respectively. The ratios between the data points and the final fits are shown at the bottom of each panel. The dark shaded band in each ratio plot shows the statistical uncertainty in the shape of the MC  $E_T$  distribution, and the light shaded band shows the total uncertainty, including all systematic uncertainties as discussed in Sec. VI.

# W asymmetry LHC

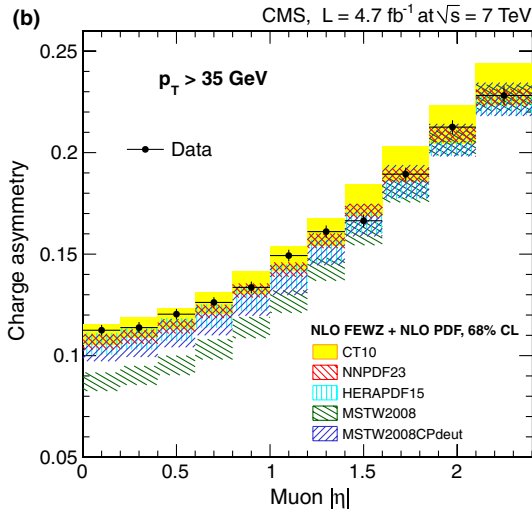
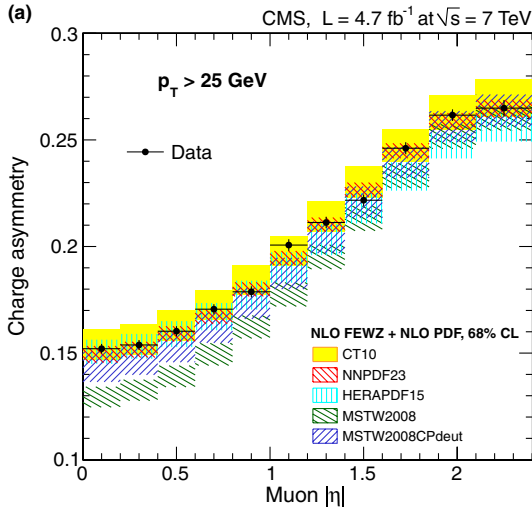


FIG. 7 (color online). Comparison of the measured muon charge asymmetries to the NLO predictions calculated using the FEWZ 3.1 [38] MC tool interfaced with the NLO CT10 [3], NNPDF2.3 [45], HERAPDF1.5 [46], MSTW2008 [2], and MSTW2008CPdeut [15] PDF sets. No EW corrections have been considered in these predictions. Results for muon  $p_T > 25$  and  $> 35 \text{ GeV}$  are shown in panels (a) and (b), respectively. The vertical error bars on data points include both statistical and systematic uncertainties. The data points are shown at the center of each  $|\eta|$  bin. The theoretical predictions are calculated using the FEWZ 3.1 [38] MC tool. The PDF uncertainty for each PDF set is shown by the shaded (or hatched) band and corresponds to 68% CL.

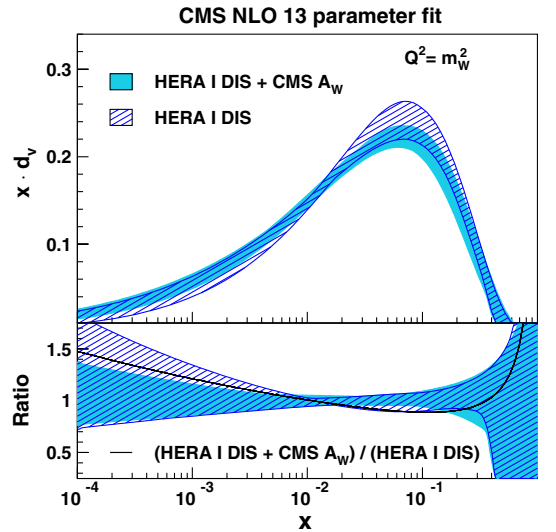
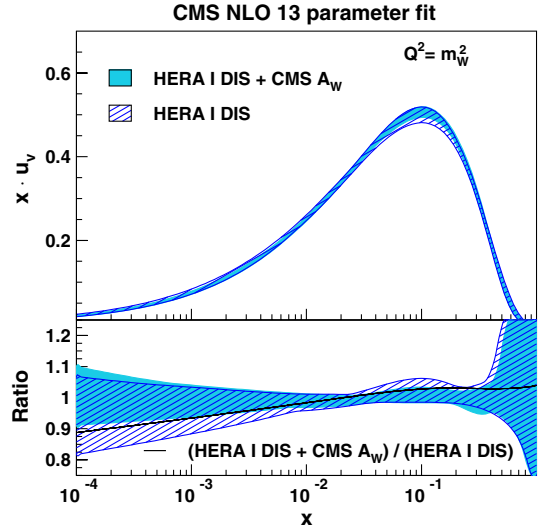
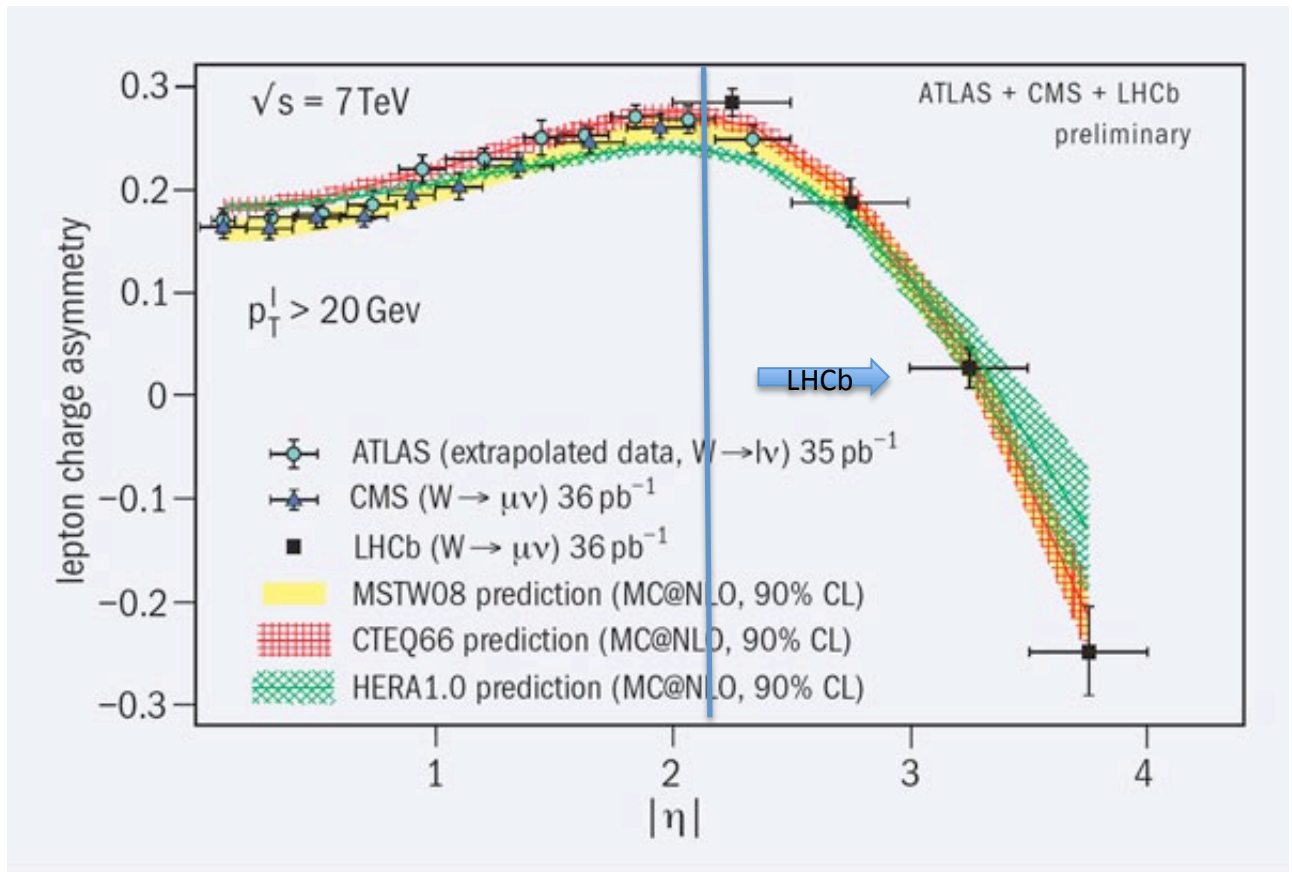


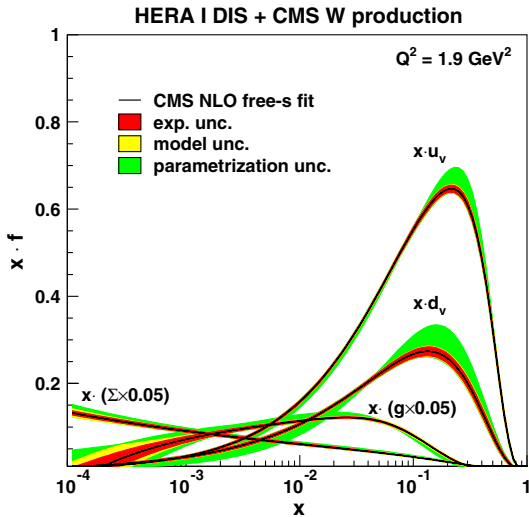
FIG. 11 (color online). Distributions of  $u$  valence (top) and  $d$  valence (bottom) quarks as functions of  $x$  at the scale  $Q^2 = m_W^2$ . The results of the 13-parameter fixed- $s$  fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The total PDF uncertainties are shown. In the bottom panels the distributions are normalized to one for a direct comparison of the uncertainties. The change of the PDFs with respect to the HERA-only fit is represented by a solid line.

# W asymmetry CMS +ATLAS + LHCb



- L'esperimento LHCb dedicato allo studio della fisica del beauty e del charm copre la regione tra 2.5 e 4 in pseudo-rapidita' e consente la misura dell'asimmetria su un range piu' esteso di valori di  $\eta$

# W asymmetry + W+charm



Uno sguardo ad una versione aggiornata delle pdf !

Include anche la determinazione indipendente del “mare strano” basata sulla reazione  $pp \rightarrow W + \text{charm}$

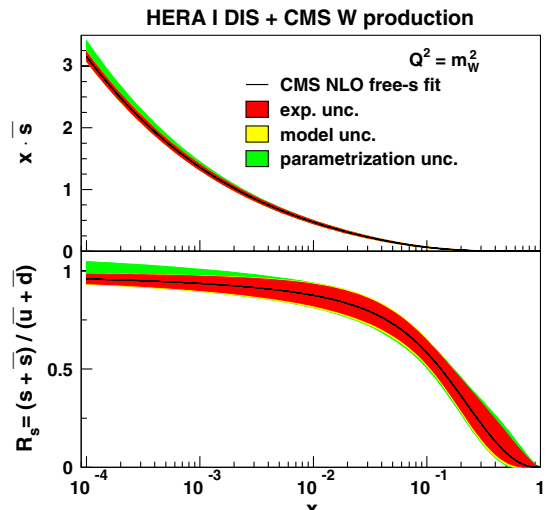
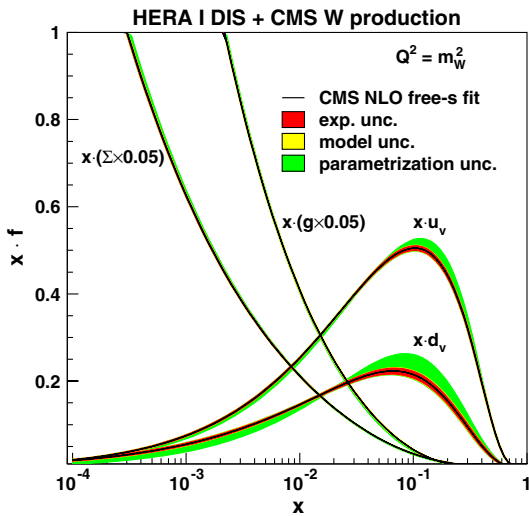


FIG. 12 (color online). Parton distribution functions, shown as functions of  $x$ , obtained by using HERA DIS data and CMS measurements of  $W$ -boson production in the free- $s$  NLO QCD analysis. Gluon, valence, and sea distributions are presented at the starting scale  $Q_0^2 = 1.9 \text{ GeV}^2$  of the PDF evolution (top) and the mass squared of the  $W$  boson (bottom). The sea distribution is defined as  $\Sigma = 2 \cdot (\bar{u} + \bar{d} + \bar{s})$ . The full band represents the total uncertainty. The individual contributions from the experimental, model, and parametrization uncertainties are represented by the bands of different shades. The gluon and sea distributions are scaled down by a factor of 20.

