Physics of Proton-antiproton Collisions at Tevatron CDF (Mostly QCD)

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Contents

CDF Experiment

CDF is an experiment at the Tevatron $p\bar{p}$ collider at Fermilab.

CDF studies various aspects of elementary particle physics using $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV.
QCD is one of them.

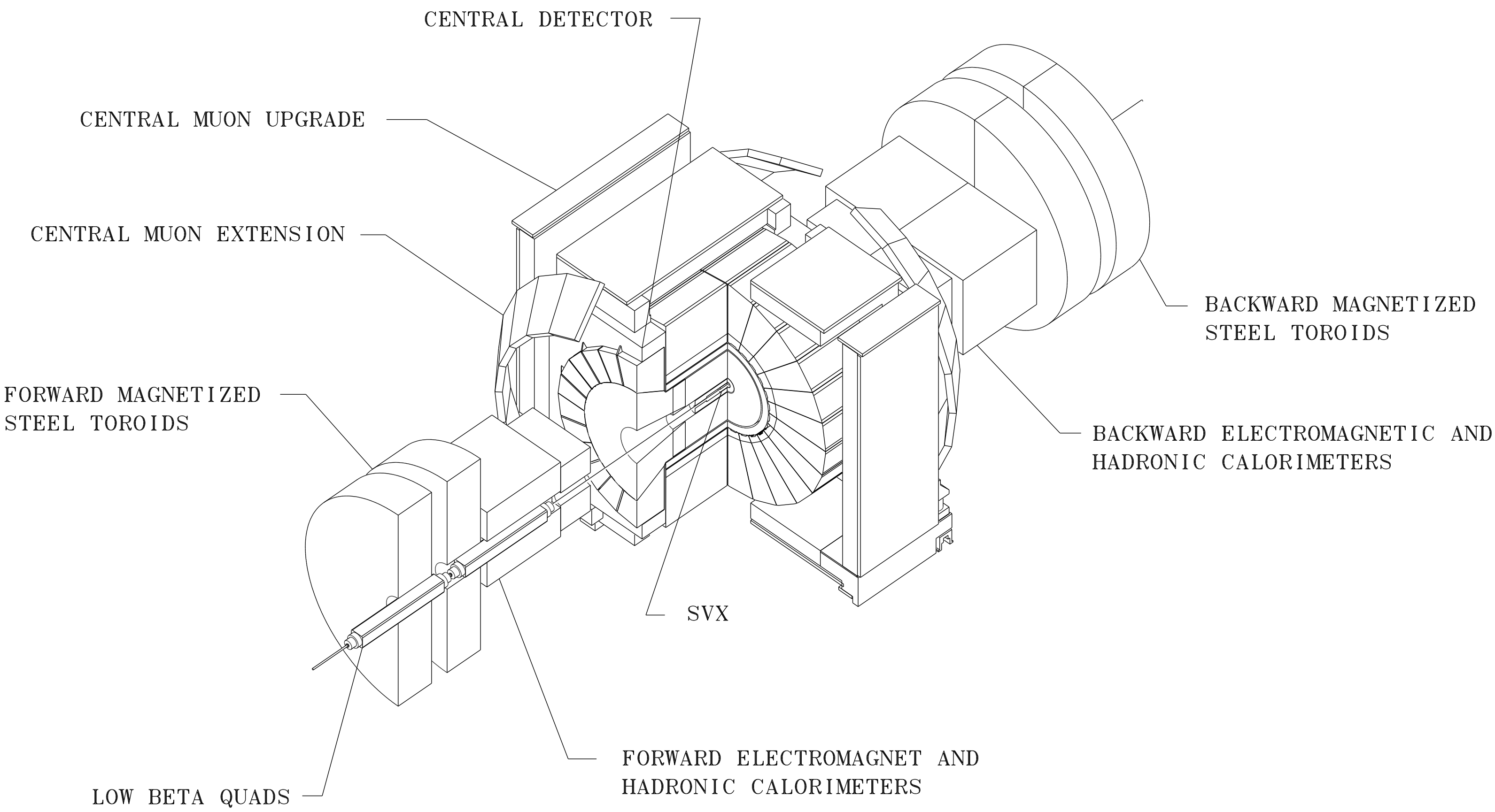
CDF detector is a general purpose, $\sim 4\pi$ detector.

Brief History

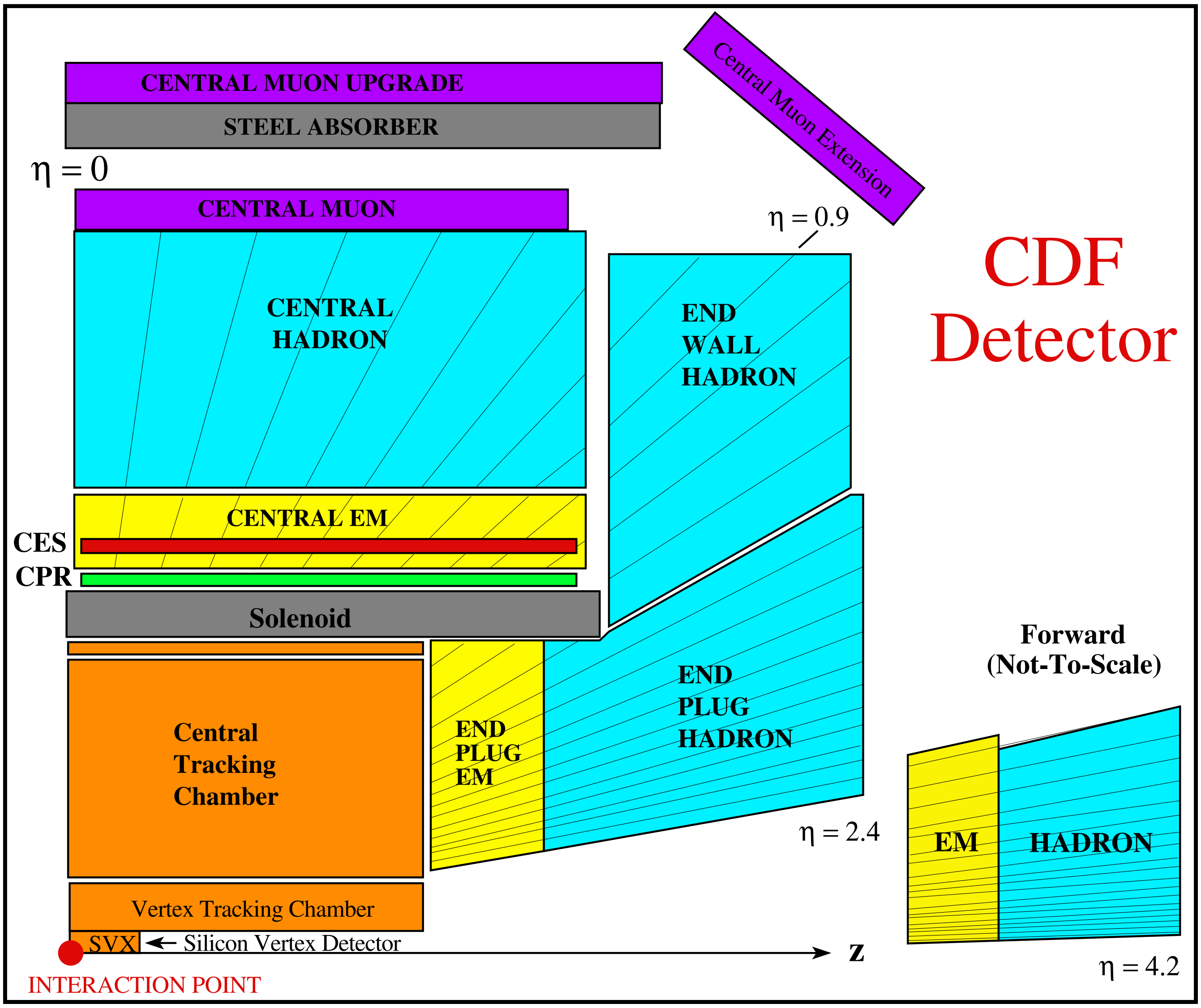
- 1985: First collisions. ~20 events.
- 1987: 25 nb^{-1}. First physics results.
- 1988 - 1989: 4 pb^{-1}. Some intersting measurements.
- 1992 - 1996: 100 pb^{-1}. Top quark discovered.
- 2001 - 2007(?): 15 fb^{-1}. Higgs?

CDF Detector

- CDF : a general purpose detector with almost 4π coverage.
- Consists of
  - tracking chambers inside the 1.4 T solenoid
  - electromagnetic and hadron calorimeters
  - muon chambers

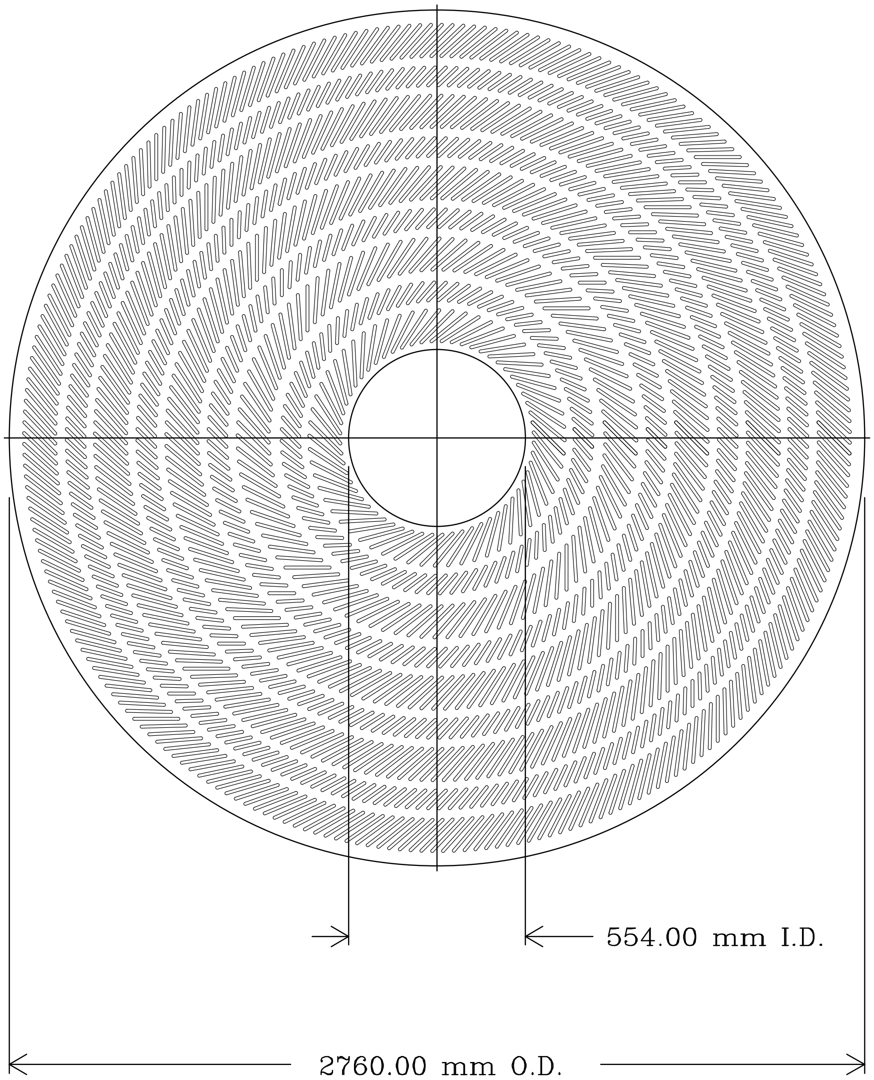


CDF detector, sliced in the plane with the beam axis. Only one quadrant is shown.



- **SVX: silicon vertex detector**
  VTX: vertex tracking chamber (TPC)
  CTC: central tracking chamber
- **Electromagnetic calorimeters with preshower detector and shower max detector**
- **Hadron calorimeters**
- **Muon chambers**

Central Tracking Chamber CTC :

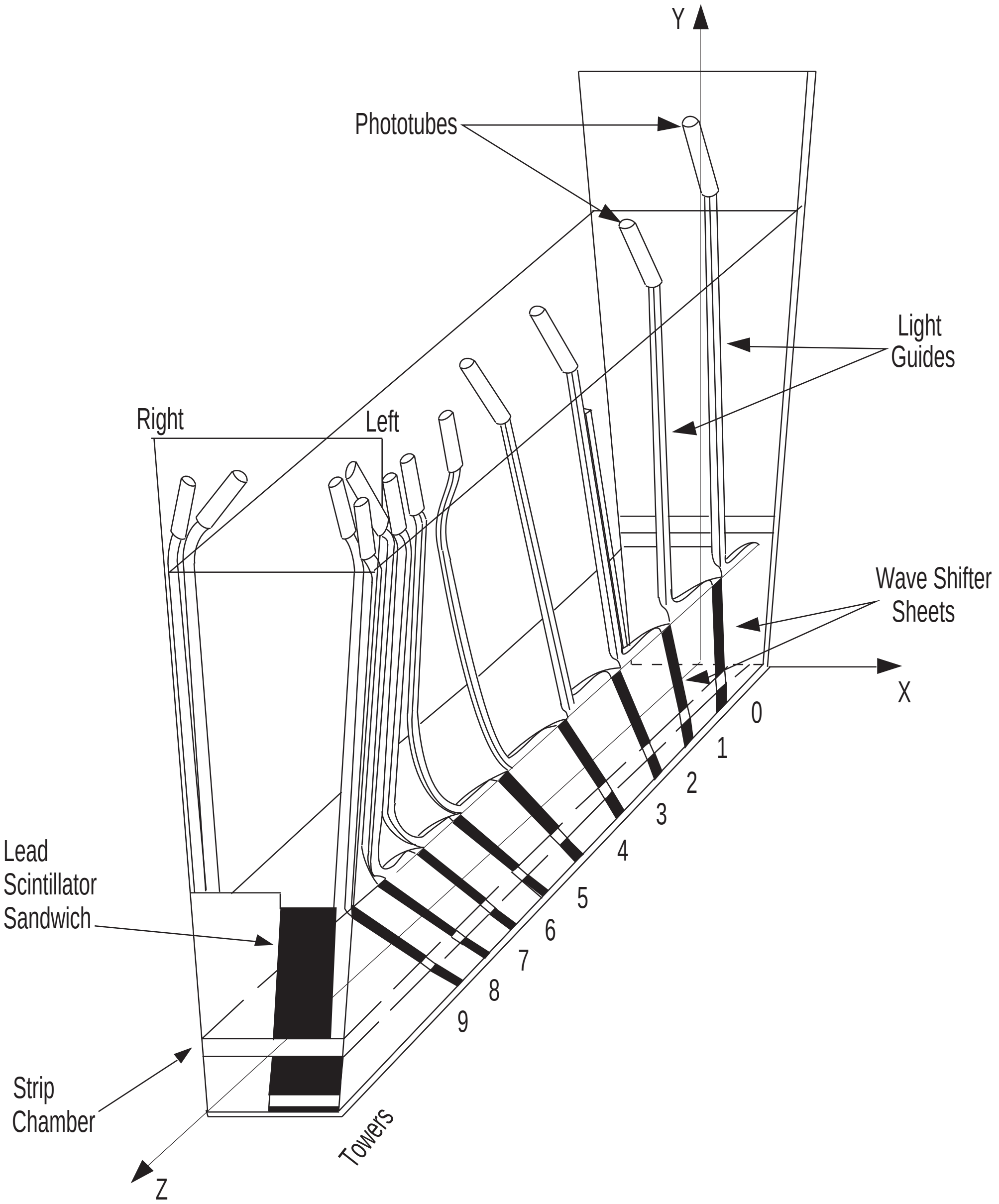


- **Drift chamber inside 1.5 T B field.**
- **1.4 m in radius, 3 m long.**
- **84 measurement layers, grouped into 9 "super-layers".**
- **12×5 axial layers, 6×4 stereo (3°) layers.**
- **Momentum resolution**

$$\sigma / p_T \simeq 0.001\ p_T$$

with $p_T \equiv p \sin\theta$ in GeV/c.

Central Electromagnetic Calorimeter CEM :

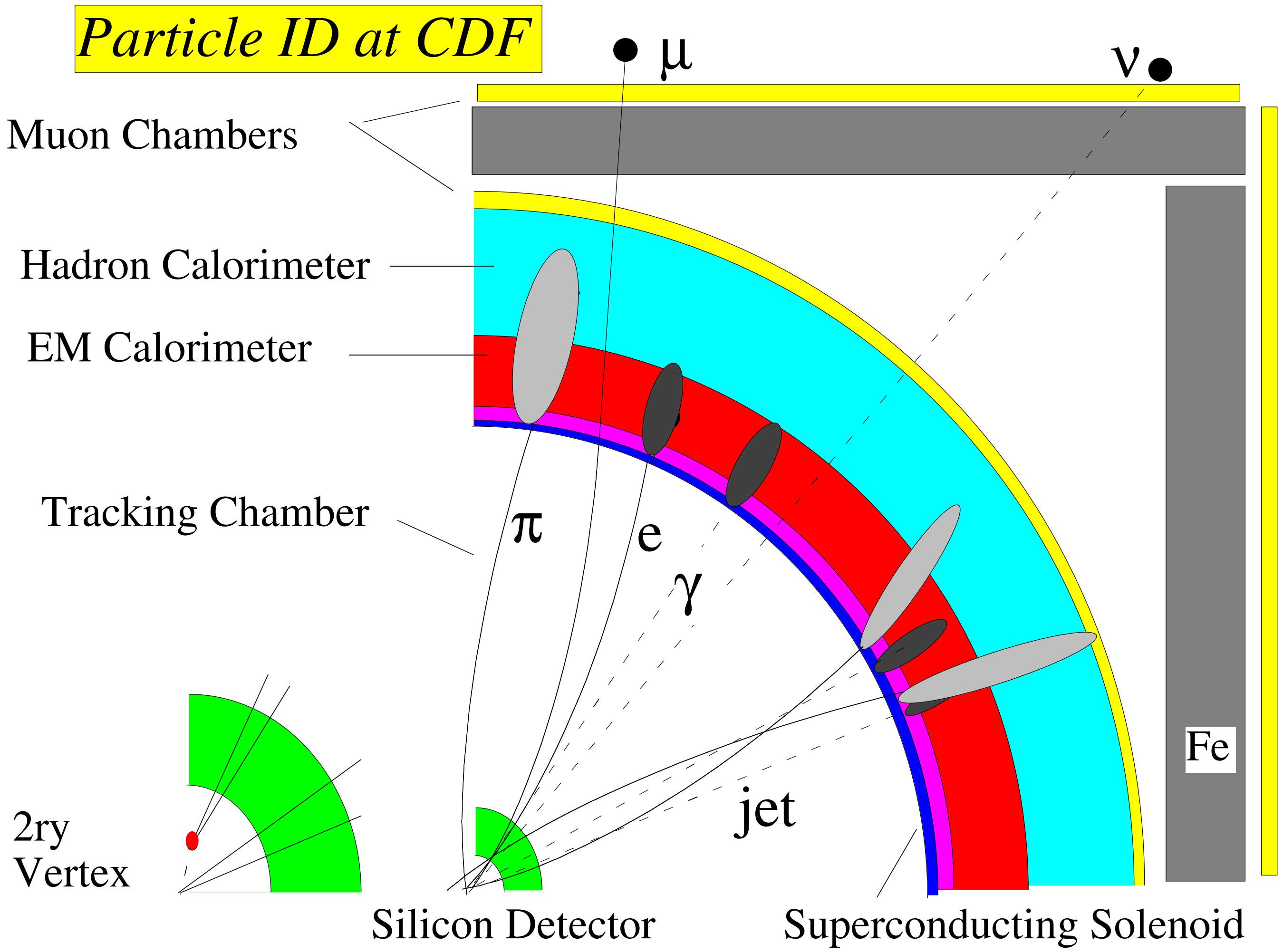


- **Covers $\Delta\phi = 15^\circ$, $|\eta| < 1.1$. 10 towers per wedge.**
- **3-mm lead, 5-mm plastic scintillator, 31 layers. Total thickness $\simeq 18\, X_0$.**
  Resolution $\sigma_E/E = 13.5\%/\sqrt{E\sin\theta}$.
- **A layer of proportional chambers (CES) near shower maximum ($5.9\, X_0$).**
  $\Delta(r\varphi) = 1.5$ cm, $\Delta z = 1.7, 2.0$ cm.

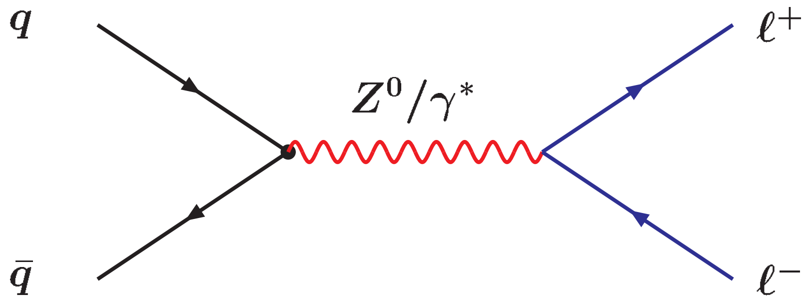
We measure

- **Charged particle momenta with CTC.**
- **Electromagnetic and hadronic energies with calorimeters. ($e^{\pm}$, γ, hadrons)**
- **Detect/identify muons with muon chambers.**
- **Decay vertices of long-lived particles (e.g. B's) with silicon microstrip detector (SVX).**

How Different Particles Look Like at CDF



Z^0 and Drell-Yan $\ell^+\ell^-$ Production



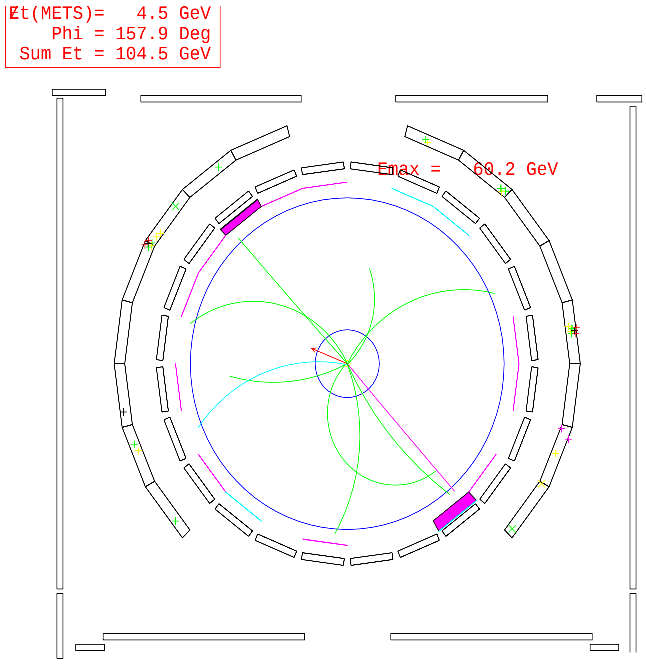
Z^0

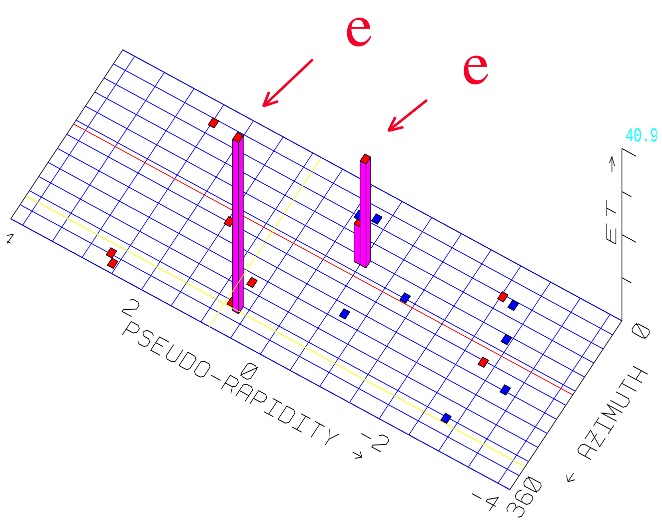
- $M_{Z^0} = 90$ GeV$/c^2$, thus $\sqrt{x_1 x_2} = M_Z^0/\sqrt{s} \simeq 0.05 \rightarrow$ quarks at small x.
- Z^0 decays to $\ell^+\ell^-$, $q\bar{q}$.
  $\ell^+\ell^-$ final states very distinctive. $\mathcal{B} \simeq 3\%$.
- Require two high p_T leptons. $\ell = e$ or μ.
  Electrons :
  - Electromagnetic cluster in the calorimeter.
  - Longitidinal and transverse shower profiles consistent with electrons.
  - High p_T CTC track matched in positions and in E/p.

  Muons :
  - Track segments in the muon chambers.
  - High p_T CTC track matched in positions.
  - Energy deposit in calorimeters consistent with MIP.

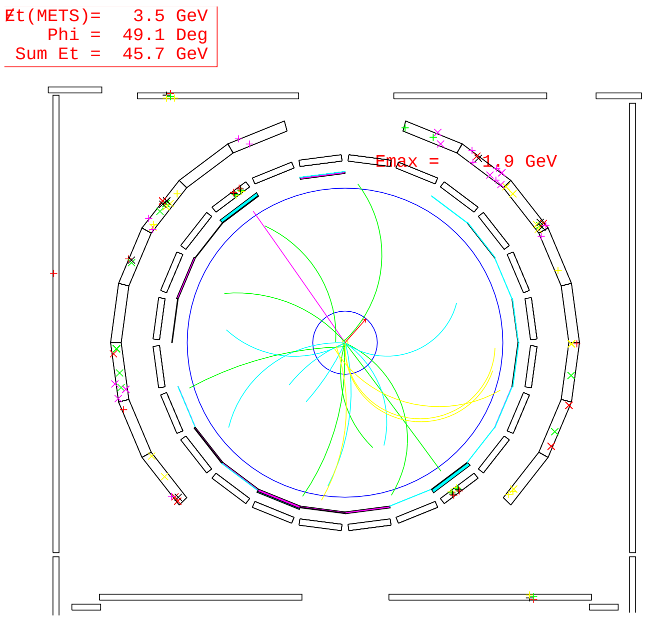
CDF

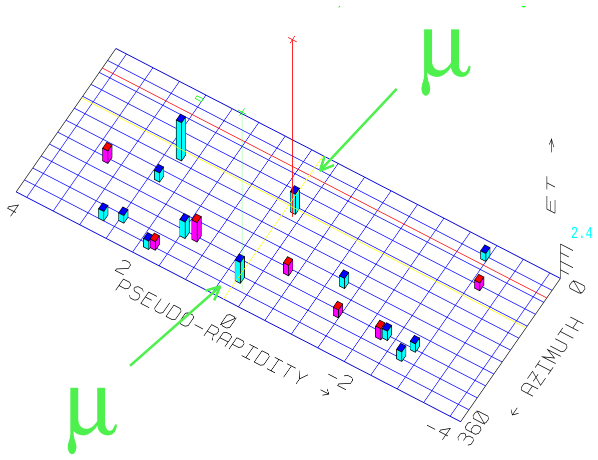
$Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ Events





$E_T \cong 44$ and 36 GeV





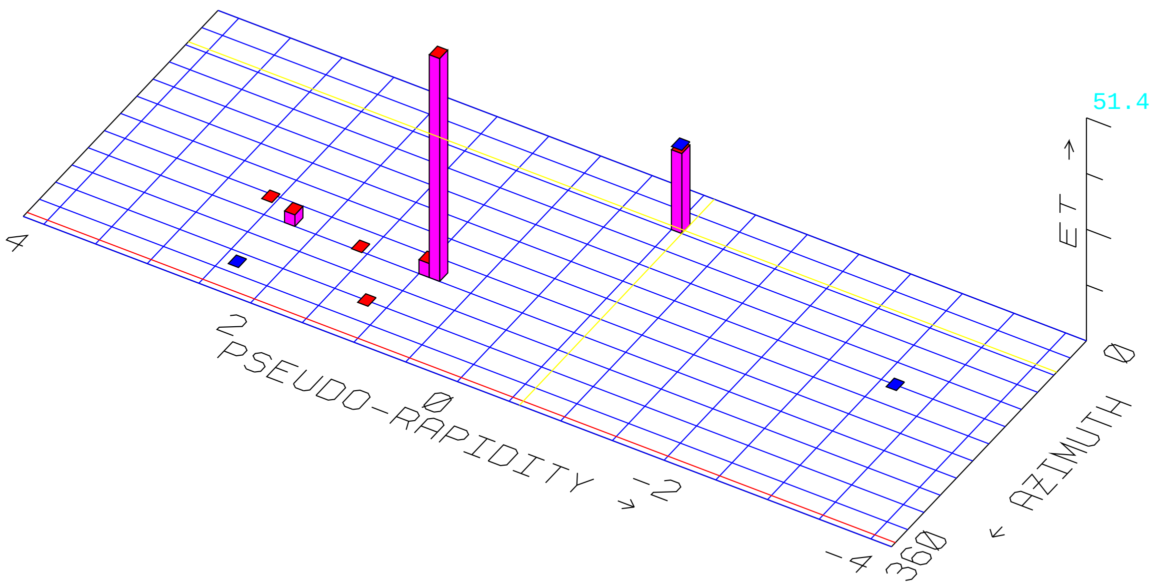
$P_T \cong 50$ and 32 GeV

Run 40323 Event34043 _Z0.ANA]CENT_ZS_ELE_CLEAN.DST 4SEP92 17:56:54 11-OCT-99

DAIS E transverse Eta-Phi LEGO Plot

Max tower E= 51.4 Min tower E= 0.50 N clusters=

METS: Etotal = 281.5 GeV, Et(scalar)= 84.8 Ge
Et(miss)= 3.5 at Phi= 352.8 Deg.

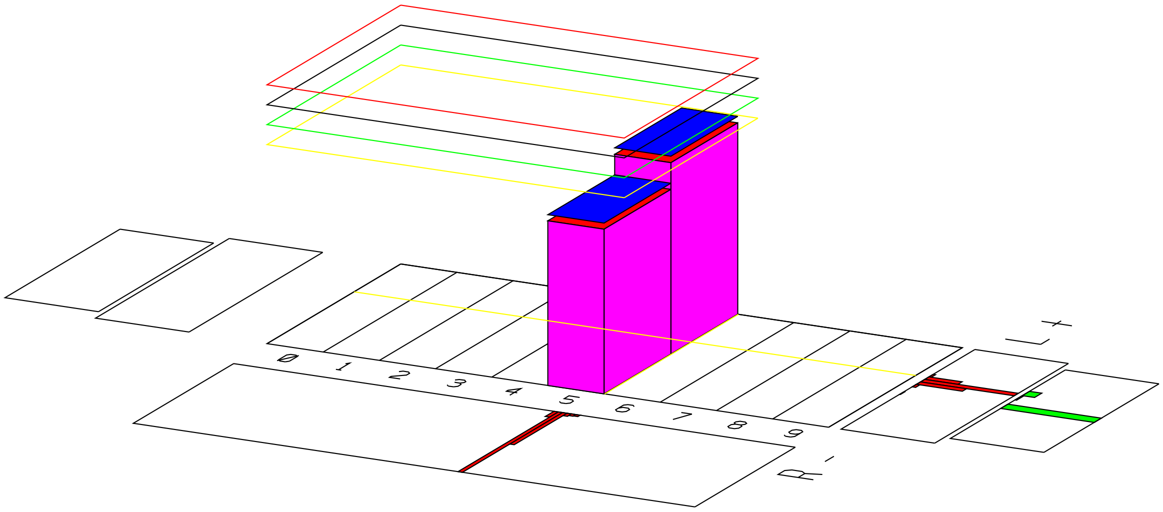


PHI: 55.
ETA: -0.60

Run 40323 Event34043 _Z0.ANA]CENT_ZS_ELE_CLEAN.DST 4SEP92 17:56:54 11-OCT-99

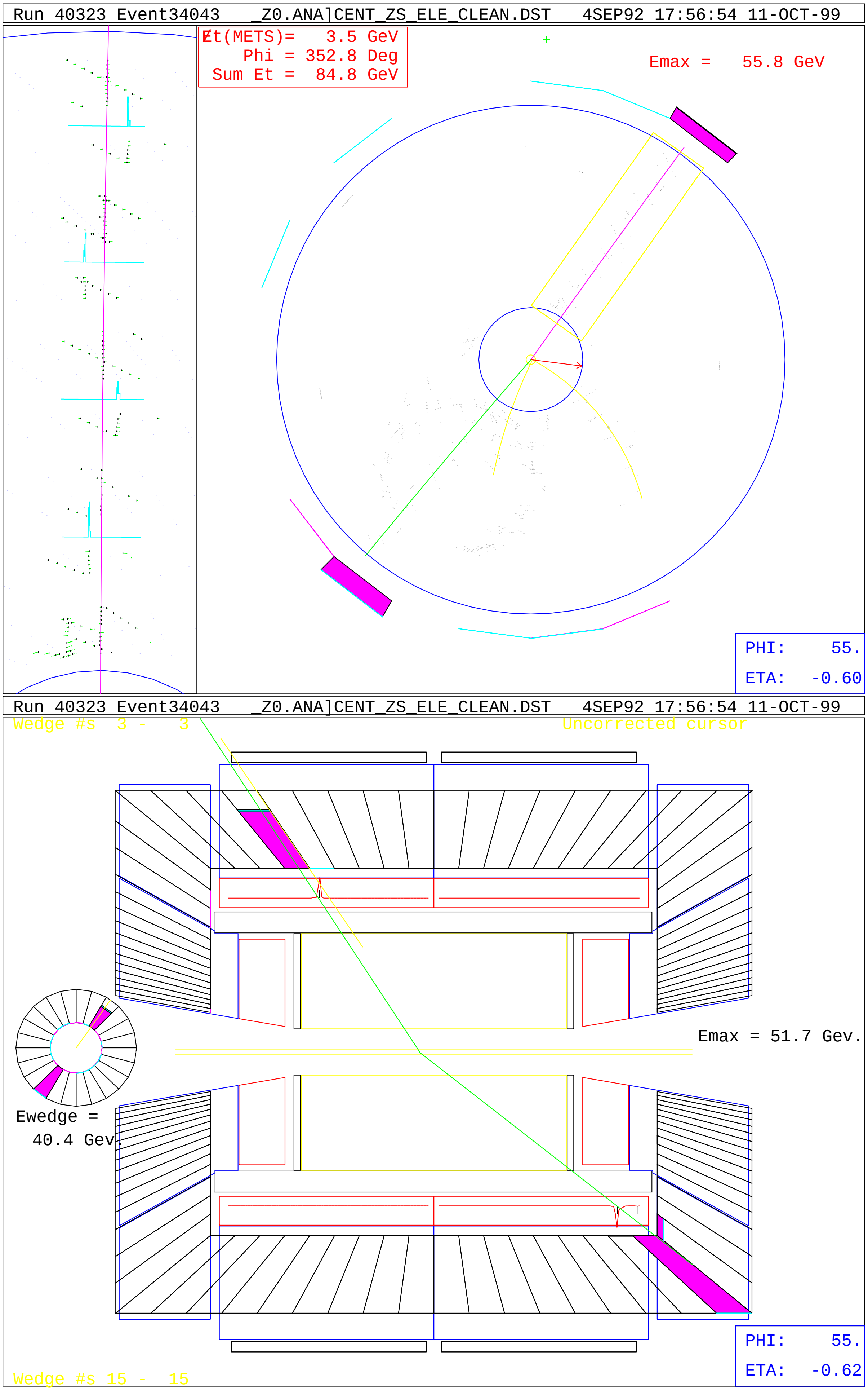
* WEST Wedge 3 Max Tower = 39.0392 GeV *

```
* CEMD * AMP x16, x1 LEFT  towers 0 - 9
  0     0     0     0  1469 65535  1582     0     0     0
  0     0     0     0  1030  7957  1042     0     0     0
* CEMD * AMP x16, x1 RIGHT towers 0 - 9
  0     0     0     0  1279 65535  1477  1057     0     0
  0     0     0     0  1018  6986  1036     0     0     0
* CHAD * AMP x16, x1 LEFT  towers 0 - 7
  0     0     0     0  1000  1000  1000  1000
  0     0     0     0  1020  1237     0     0
* CHAD * AMP x16, x1 RIGHT towers 0 - 7
  0     0     0     0     0  1000     0     0
  0     0     0     0     0  1224     0     0
  0     0     0     0     0 13263     0     0 CHA TDC
```

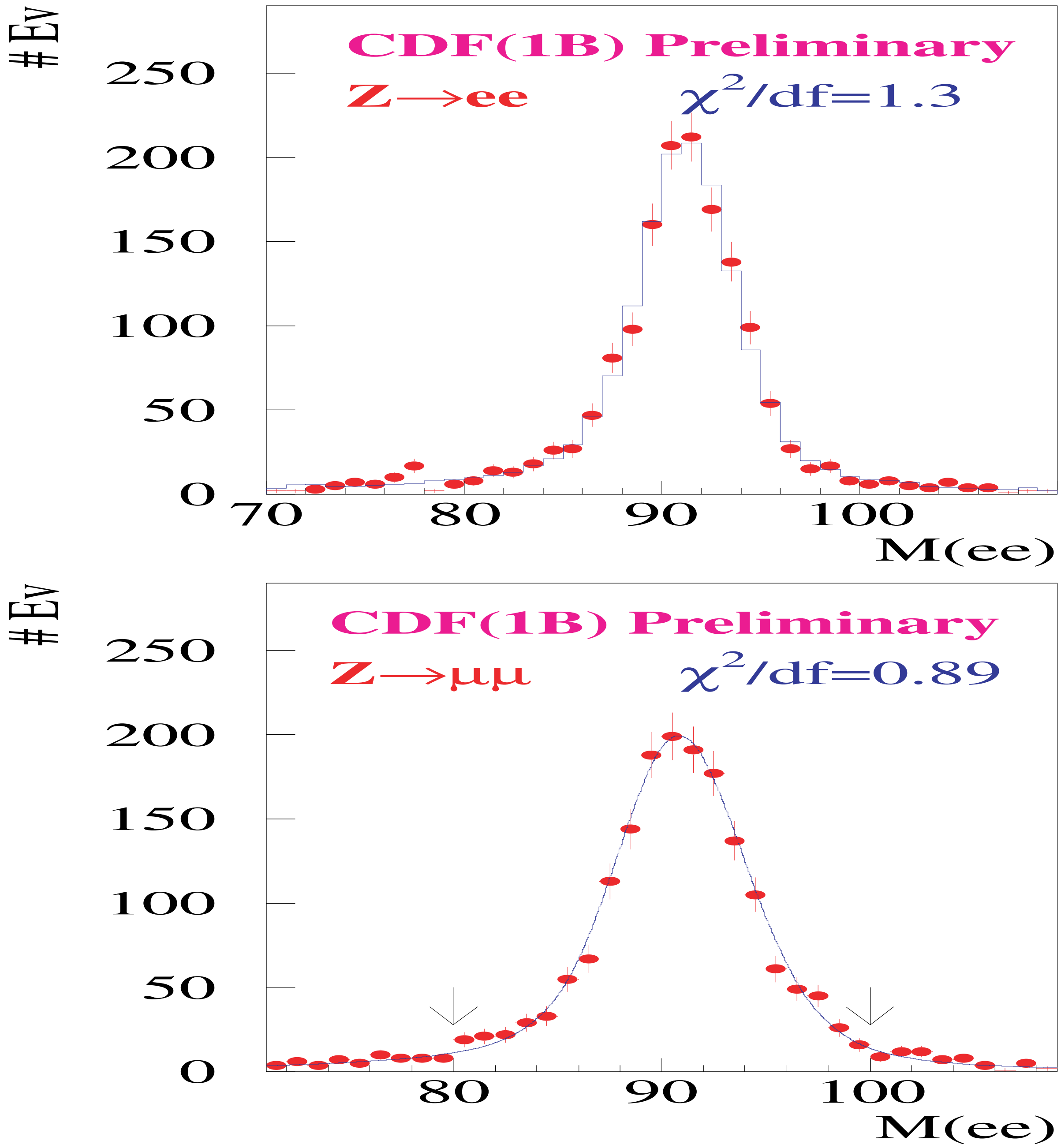


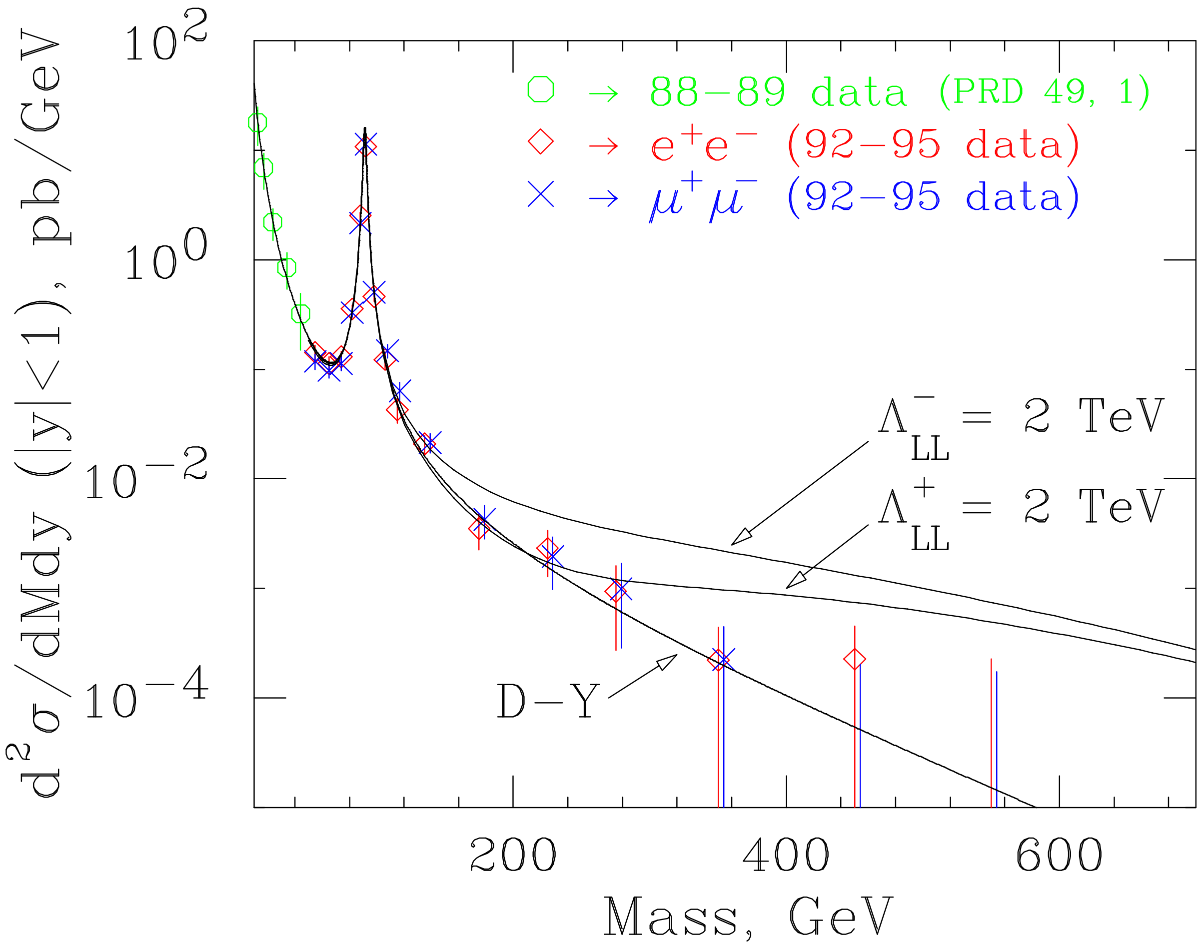
Min and Max(Channel = 74) Str GeV 0.000 9.562
Min and Max(Channel = 51) Wir GeV 0.000 10.049
Min and Max(Channel = 24) Pre fC 0.00 4393.51(= 8 MIPS)

PHI: 55.
ETA: -0.60


Run 40323 Event34043 _Z0.ANA]CENT_ZS_ELE_CLEAN.DST 4SEP92 17:56:54 11-OCT-99
Et(METS)= 3.5 GeV
Phi = 352.8 Deg
Sum Et = 84.8 GeV
Emax = 55.8 GeV
PHI: 55.
ETA: -0.60
Run 40323 Event34043 _Z0.ANA]CENT_ZS_ELE_CLEAN.DST 4SEP92 17:56:54 11-OCT-99
Wedge #s 3 - 3
Uncorrected cursor
Emax = 51.7 Gev.
Ewedge =
40.4 Gev.
PHI: 55.
ETA: -0.62
Wedge #s 15 - 15

Dilepton mass spectra near Z^0





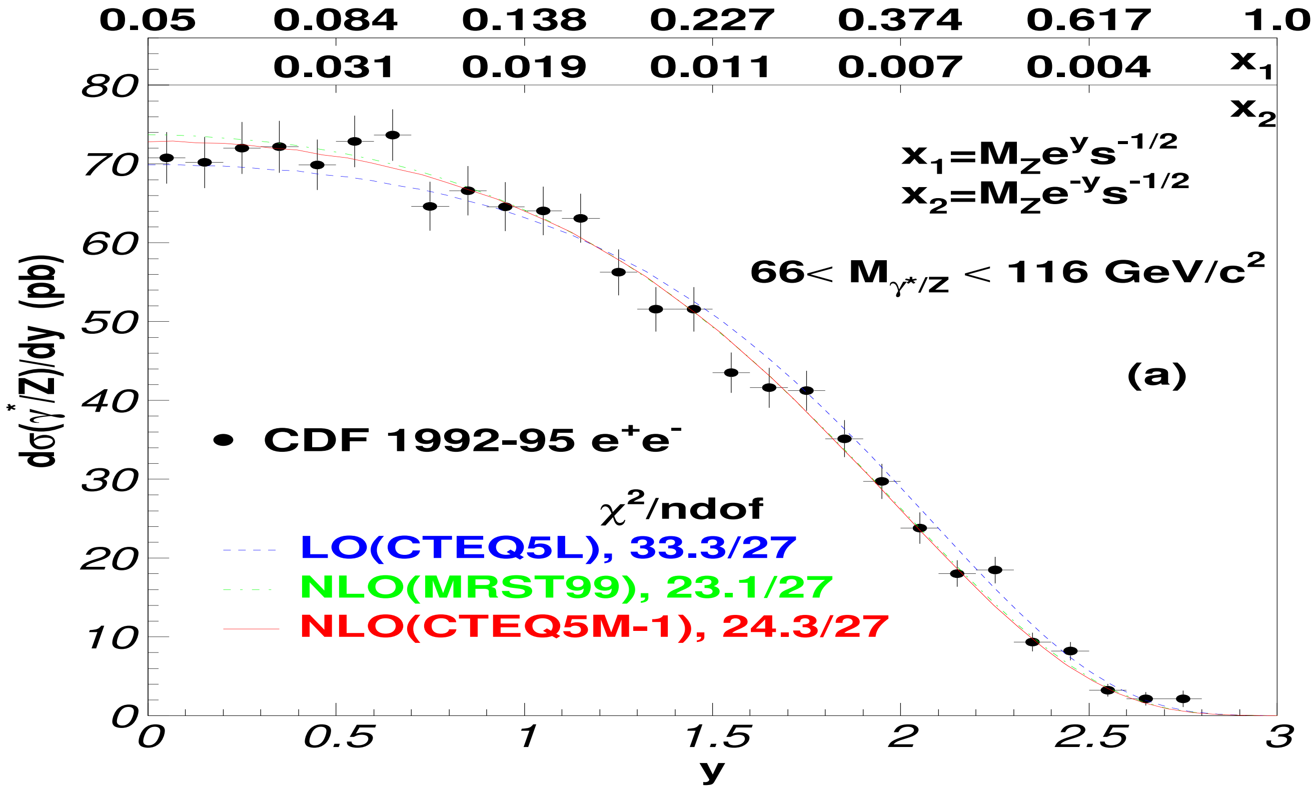
Kinematics

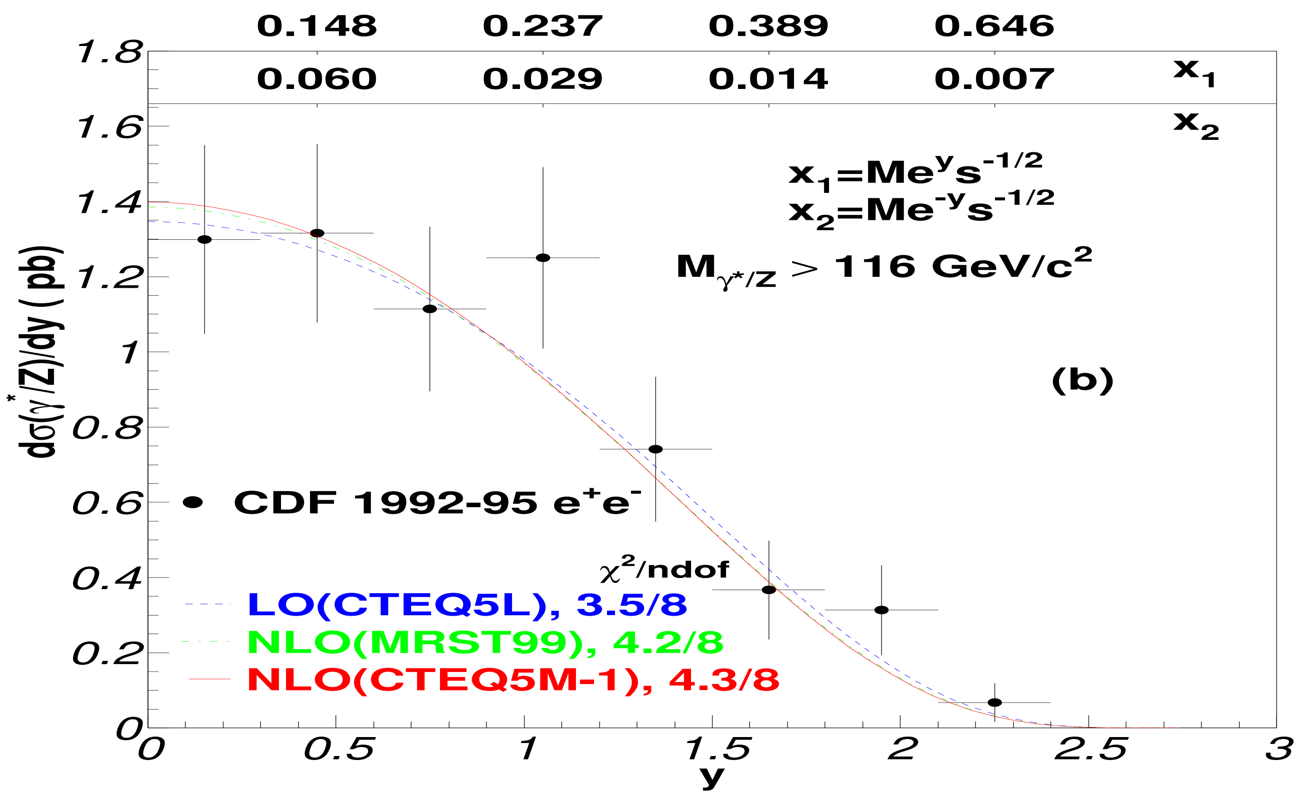
$$
\begin{aligned}
p_1 &= \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1) \\
p_2 &= \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2) \\
\tau &\equiv M^2/s = p_1 \cdot p_2/s = x_1 x_2 \\
y_{\ell^+\ell^-} &= \frac{1}{2}\ln\left[\frac{E+p_z}{E-p_z}\right] = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right) \\
&\rightarrow x_1 = \sqrt{\tau}\exp(y), \;\; x_2 = \sqrt{\tau}\exp(-y)
\end{aligned}
$$

For $M = 90$ GeV$/c^2$,

$$
\begin{aligned}
x_{\min} &= M^2/s = 0.0025 \\
y_{\max} &= \frac{1}{2}\ln(s/M^2) \simeq 3.0
\end{aligned}
$$

Z^0/DY Rapidity Distributions

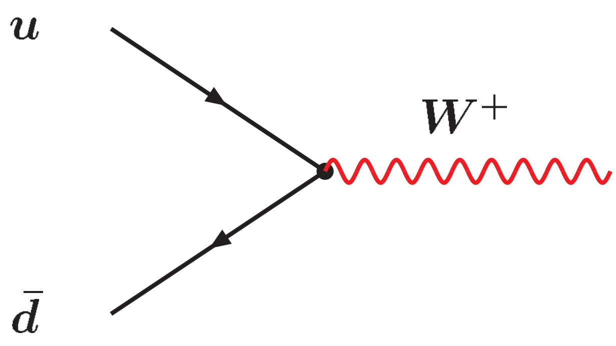




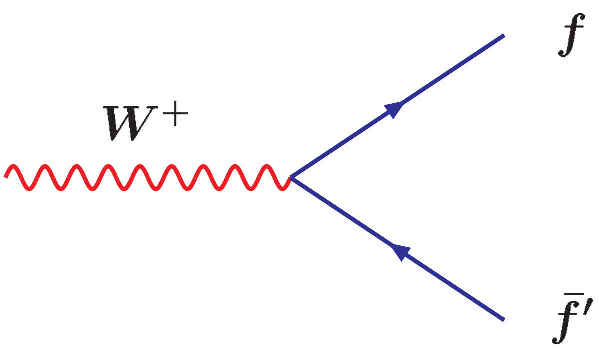
$$\int \left(\frac{d\sigma}{dy}\right) dy = 253 \pm 4 \pm 10 \text{ pb for } Z^0 \to \ell^+\ell^-.$$

W Boson Production

LO:



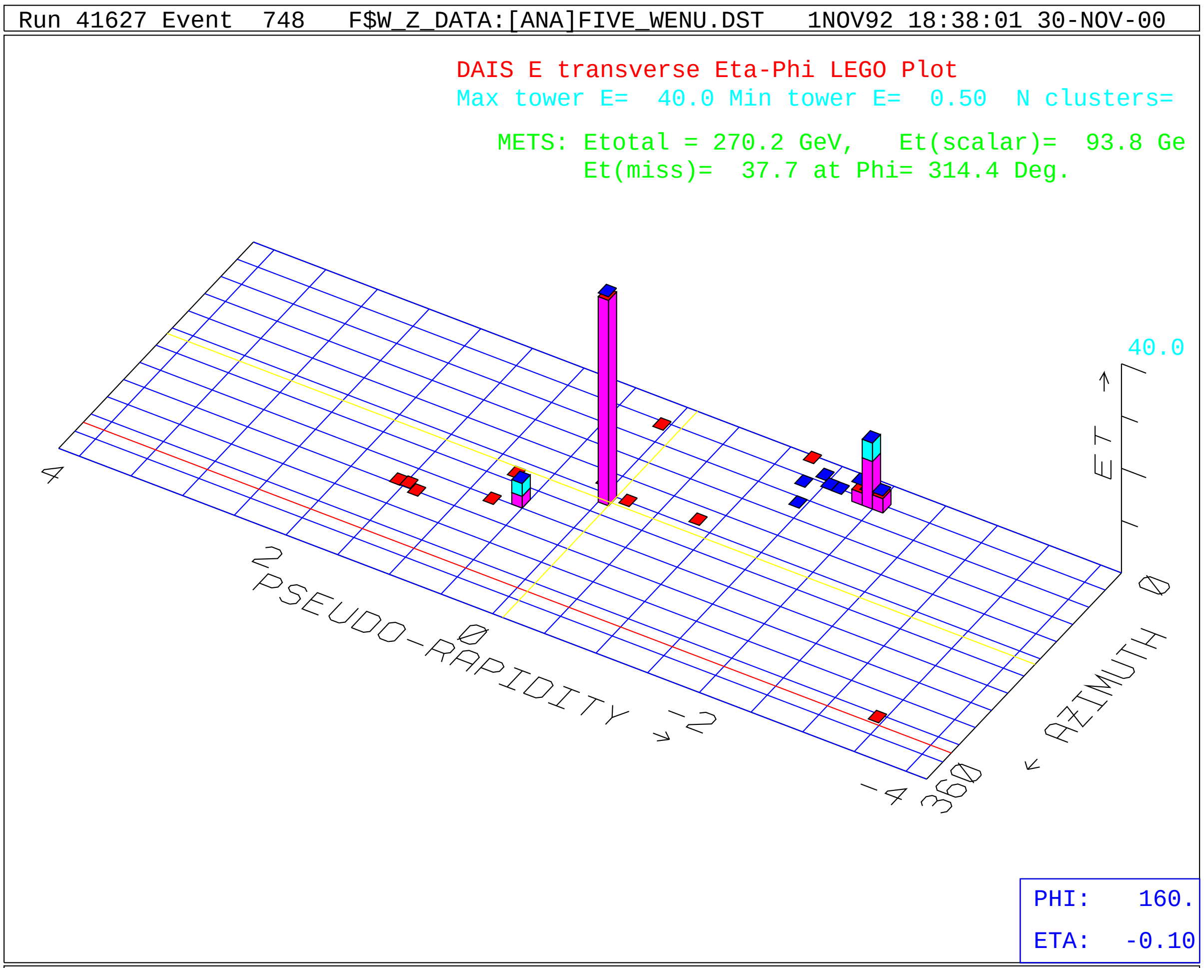
- $M_W = 80$ GeV/c^2, thus $\sqrt{x_1 x_2} = M_W/\sqrt{s} \simeq 0.04 \to$ quarks at small x.
- W^+ decays to $e^+\nu$, $\mu^+\nu$, $\tau^+\nu$, $u\bar{d}$, $c\bar{s}$.

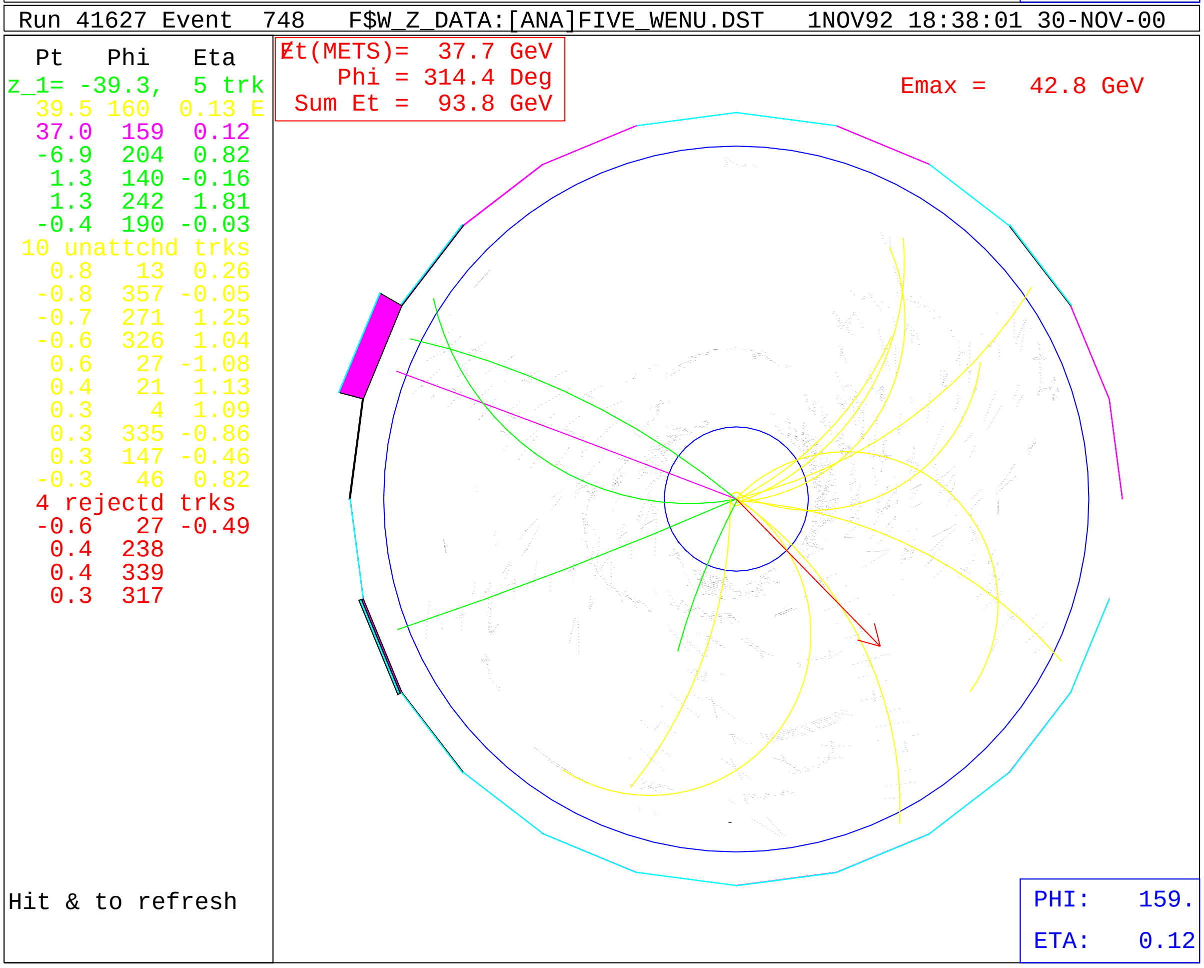


- $\ell^+\nu$ final states clean. $\mathcal{B} = 1/9$.
- How to detect the neutrino? We don't. $\to$ missing transverse energy.

$$\vec{p}_T^{\,\nu} \equiv \vec{\not{E}}_T \equiv -\sum_i \vec{E}_T^{\,i}$$

Sum is over all calorimeter towers.
- In LO, $\vec{p}_T^{\,W} \simeq 0$. Then $\vec{p}_T^{\,\ell} \simeq -\vec{p}_T^{\,\nu}$.


Run 41627 Event 748 F$W_Z_DATA:[ANA]FIVE_WENU.DST 1NOV92 18:38:01 30-NOV-00
DAIS E transverse Eta-Phi LEGO Plot
Max tower E= 40.0 Min tower E= 0.50 N clusters=
METS: Etotal = 270.2 GeV, Et(scalar)= 93.8 Ge
Et(miss)= 37.7 at Phi= 314.4 Deg.
40.0
ET
4
2
PSEUDO-RAPIDITY
0
-2
-4
360
AZIMUTH
0
PHI: 160.
ETA: -0.10


Run 41627 Event 748 F$W_Z_DATA:[ANA]FIVE_WENU.DST 1NOV92 18:38:01 30-NOV-00
Pt Phi Eta
z_1= -39.3, 5 trk
39.5 160 0.13 E
37.0 159 0.12
-6.9 204 0.82
1.3 140 -0.16
1.3 242 1.81
-0.4 190 -0.03
10 unattchd trks
0.8 13 0.26
-0.8 357 -0.05
-0.7 271 1.25
-0.6 326 1.04
0.6 27 -1.08
0.4 21 1.13
0.3 4 1.09
0.3 335 -0.86
0.3 147 -0.46
-0.3 46 0.82
4 rejectd trks
-0.6 27 -0.49
0.4 238
0.4 339
0.3 317
Hit & to refresh
Et(METS)= 37.7 GeV
Phi = 314.4 Deg
Sum Et = 93.8 GeV
Emax = 42.8 GeV
PHI: 159.
ETA: 0.12

How to reconstruct W?
Neutrino longitudinal momentum not known, so cannot form invariant mass.
$\rightarrow$ Transverse mass:

$$M_T^2 \equiv 2\, p_T^\ell\, p_T^\nu\, (1 - \cos\Delta\phi)$$

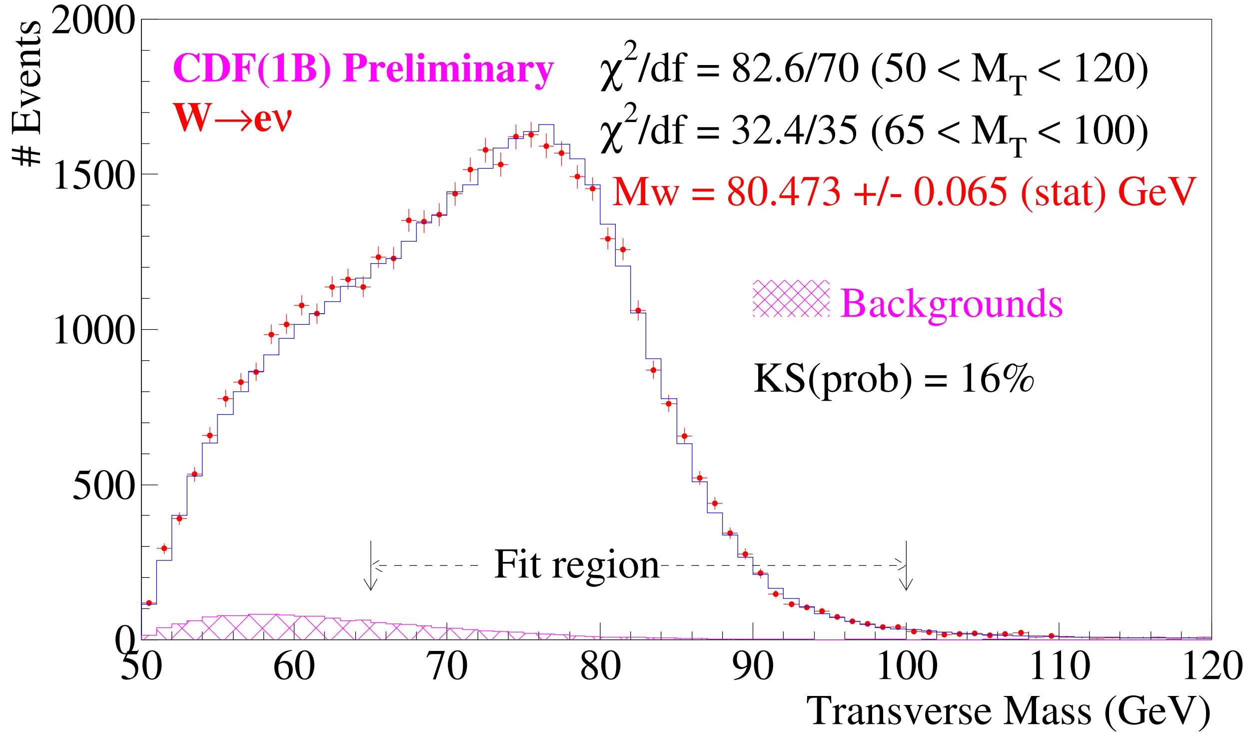
dN/dp_T^ℓ, dN/dp_T^ν show characteristic peak at $\sim M_W/2$ (Jacobian peak), and M_T at $\sim M_W$.

Require:

- **high p_T lepton (> 25 GeV$/c$).**
- **large missing E_T (> 25 GeV$/c$).**

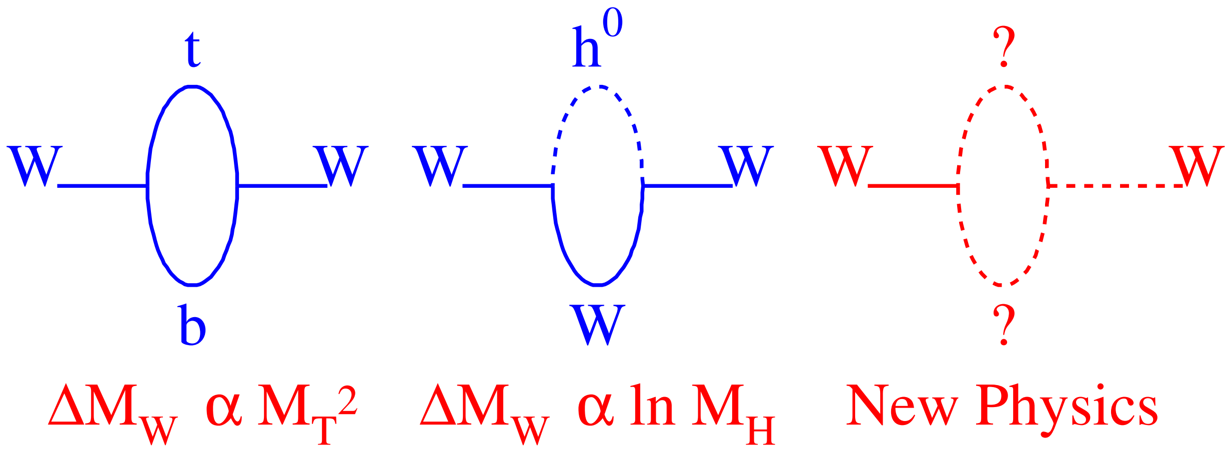
This is usually enough to separate W's from BG.

Run Ib (90 pb^{-1}), electron channel.

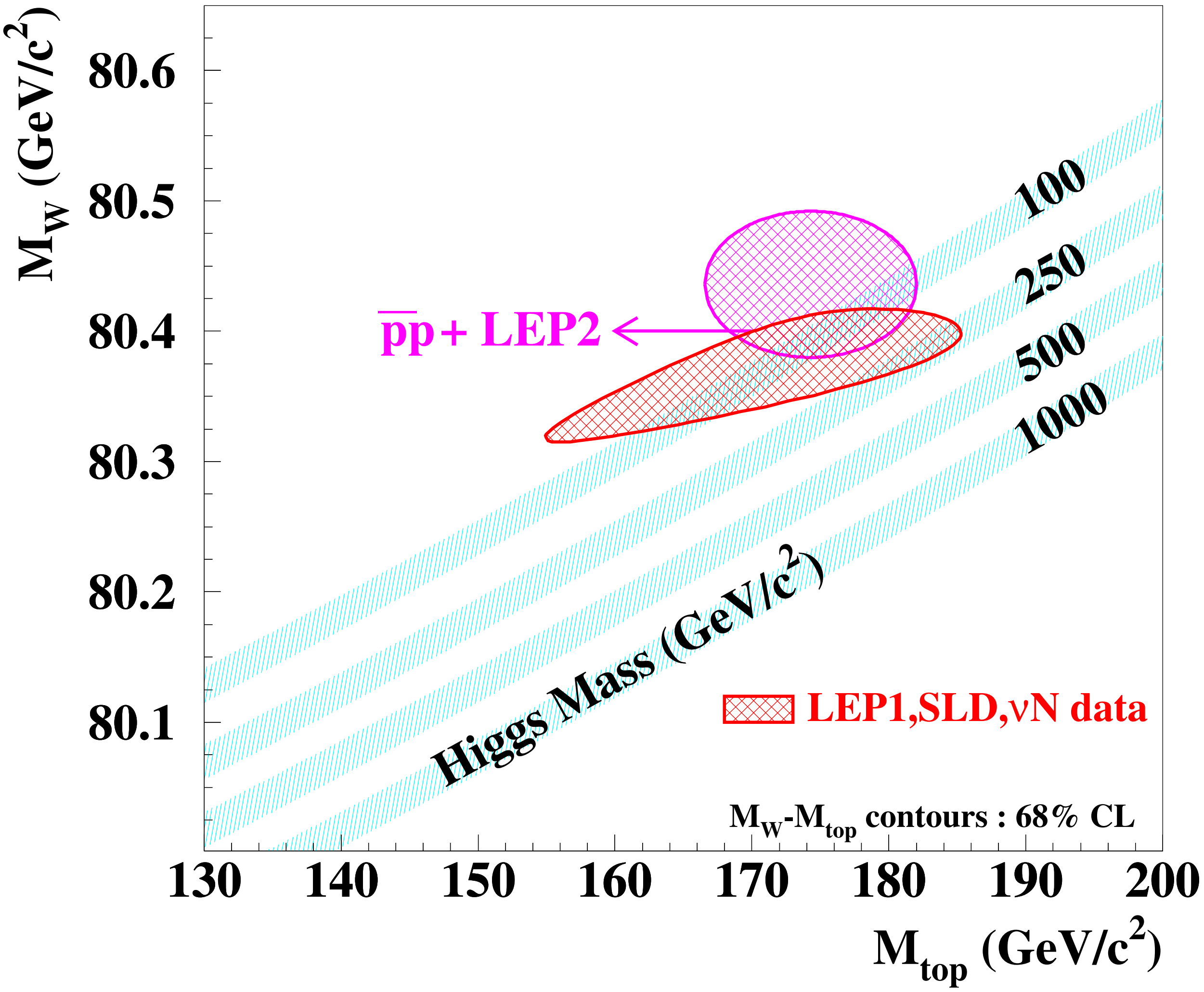


$\Rightarrow M_W = 80.443 \pm 0.079$ GeV$/c^2$ (CDF combined).

Somewhat sensitive to the Higgs mass thru radiative corrections.

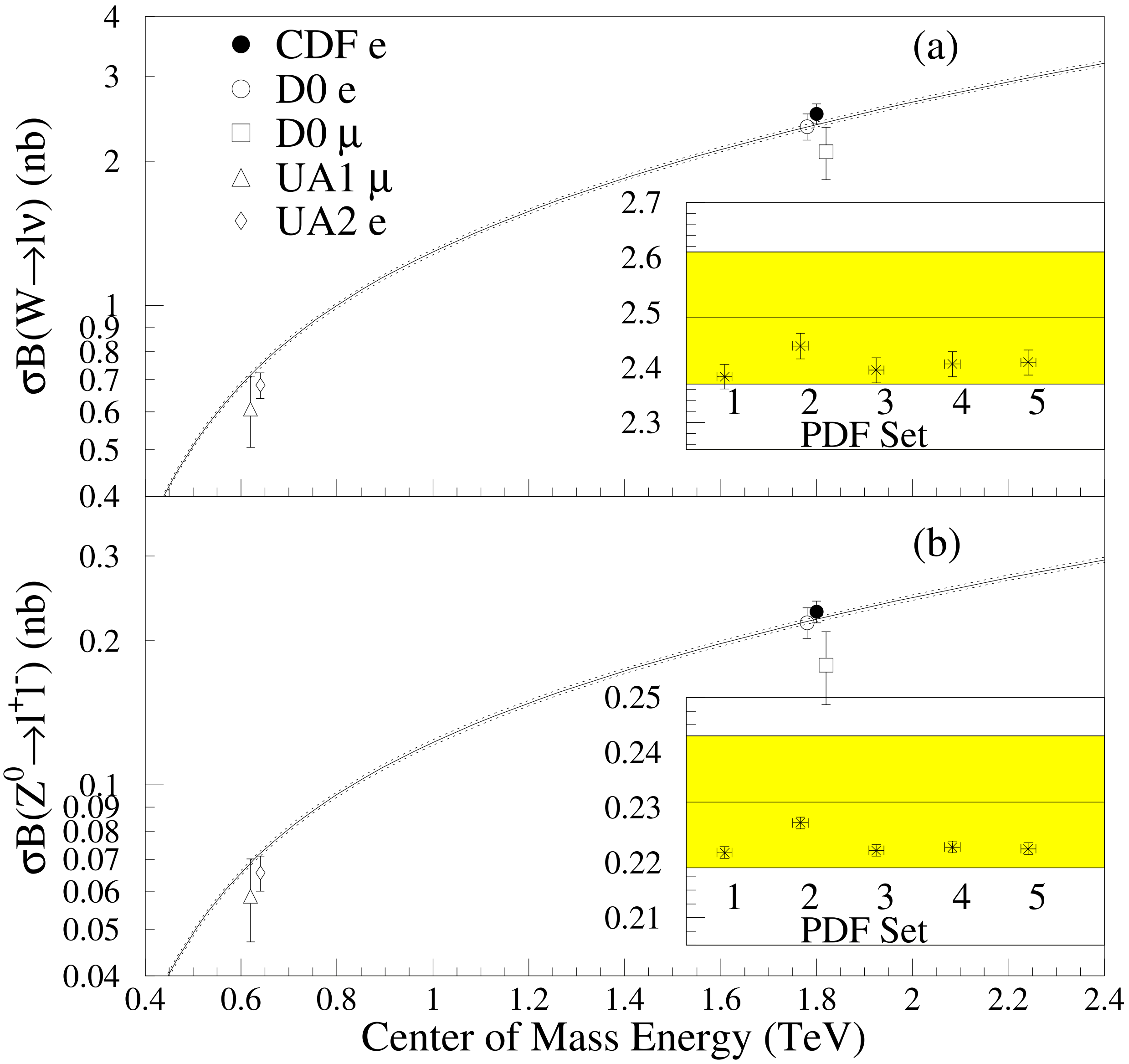


Constraints on the Higgs mass



Measured Production Cross Section

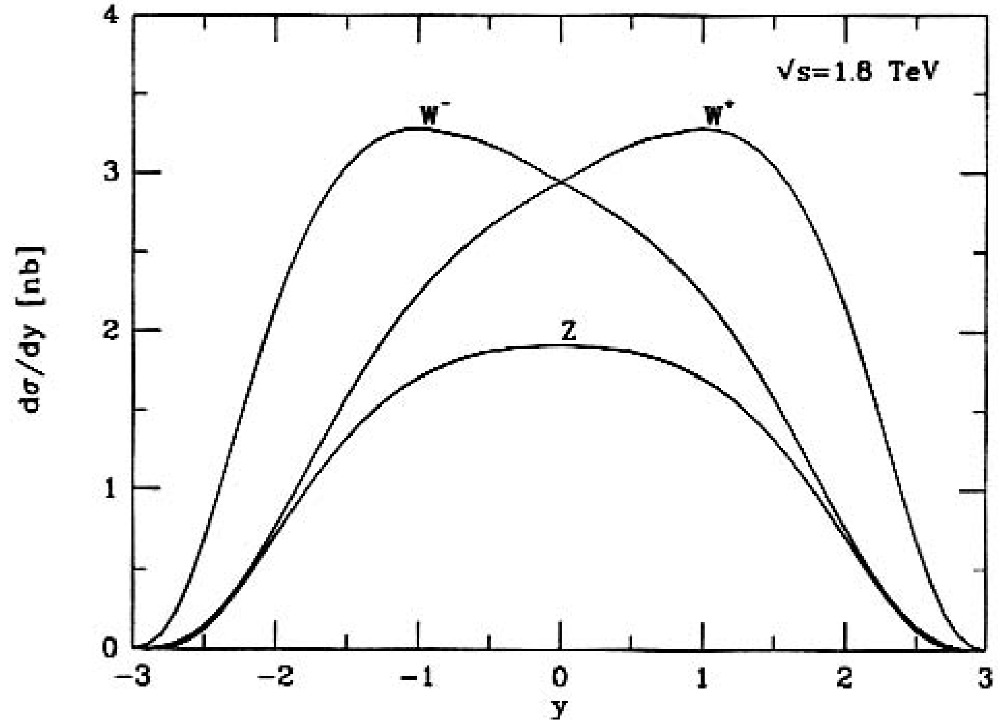
$$\sigma(\bar{p}p \to W^+X) \cdot \mathcal{B}(W^+ \to \ell^+\nu) + \sigma(\bar{p}p \to W^-X) \cdot \mathcal{B}(W^- \to \ell^-\bar{\nu}) = 2.49 \pm 0.12 \text{ nb}$$

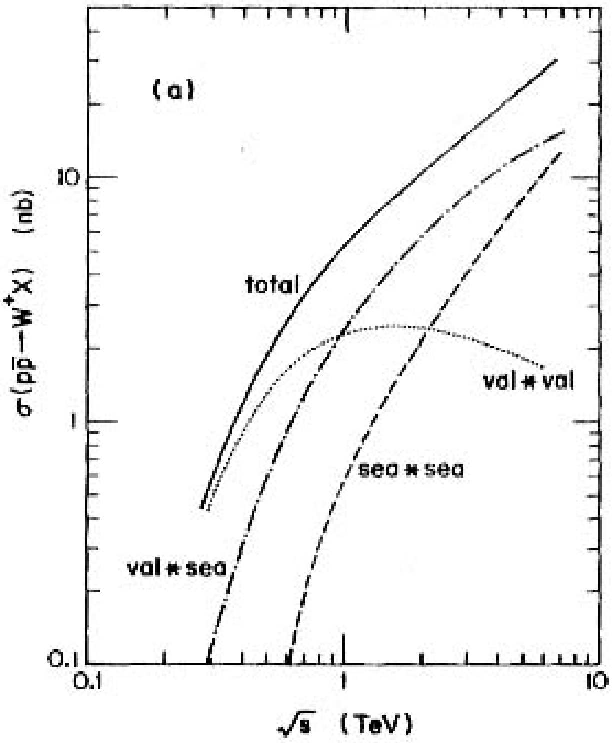


W Rapidity Distributions

Not symmetric around $y = 0$ even for $\bar{p}p$ collisions with valence dominance, because $u(x)$ is harder than $d(x)$.

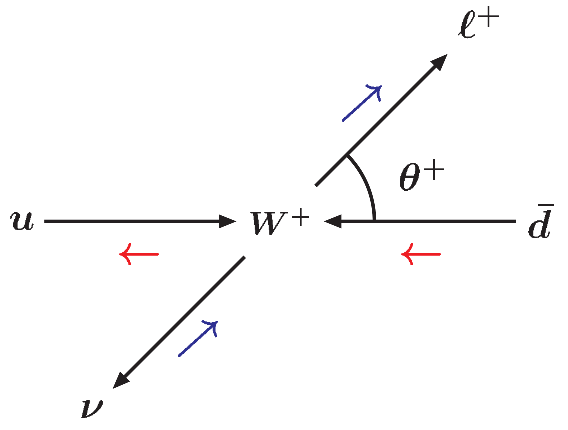
W^+ tends to follow the u (p) direction ($y > 0$),
W^- tends to follow the $\bar{u}$ ($\bar{p}$) direction ($y < 0$).

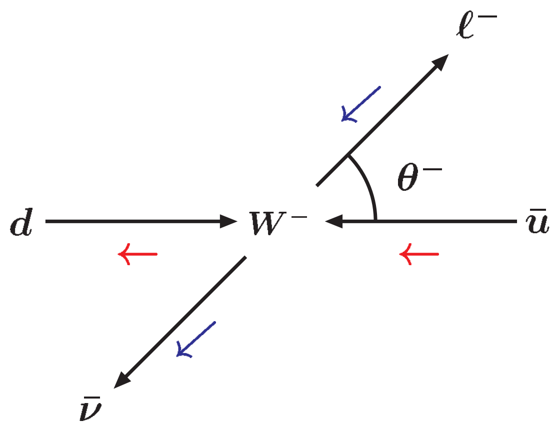




$W^\pm$ longitudinal momentum not measured:
$\rightarrow$ measure the lepton rapidity distribution.
Complication arises because $W^\pm$ is polarized.

$$u\bar{d} \rightarrow W^+ \rightarrow \ell^+\nu \qquad d\bar{u} \rightarrow W^- \rightarrow \ell^-\bar{\nu}$$





$$\frac{dN}{d\cos\theta^+} = |d^1_{1,-1}|^2 \propto (1-\cos\theta)^2 \;\Rightarrow\; \bar{p} \text{ direction}$$

$$\frac{dN}{d\cos\theta^-} = |d^1_{-1,-1}|^2 \propto (1+\cos\theta)^2 \;\Rightarrow\; p \text{ direction}$$

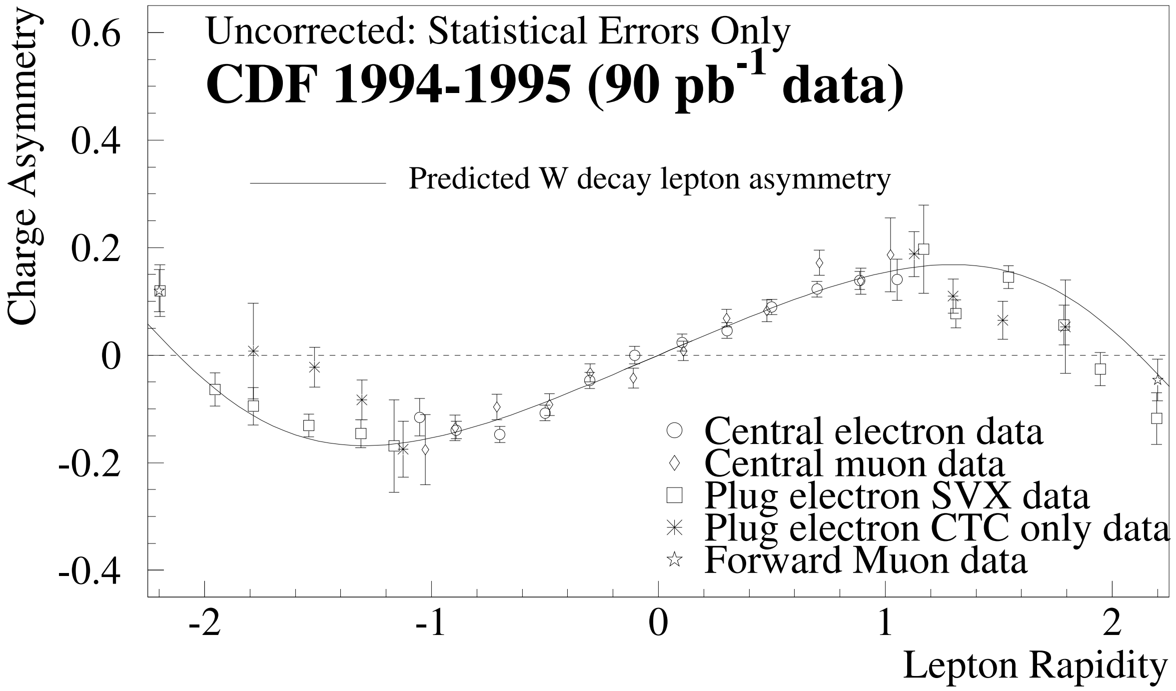
The two effects above are in opposite directions: stronger one (structure function) wins.

Define asymmetry as

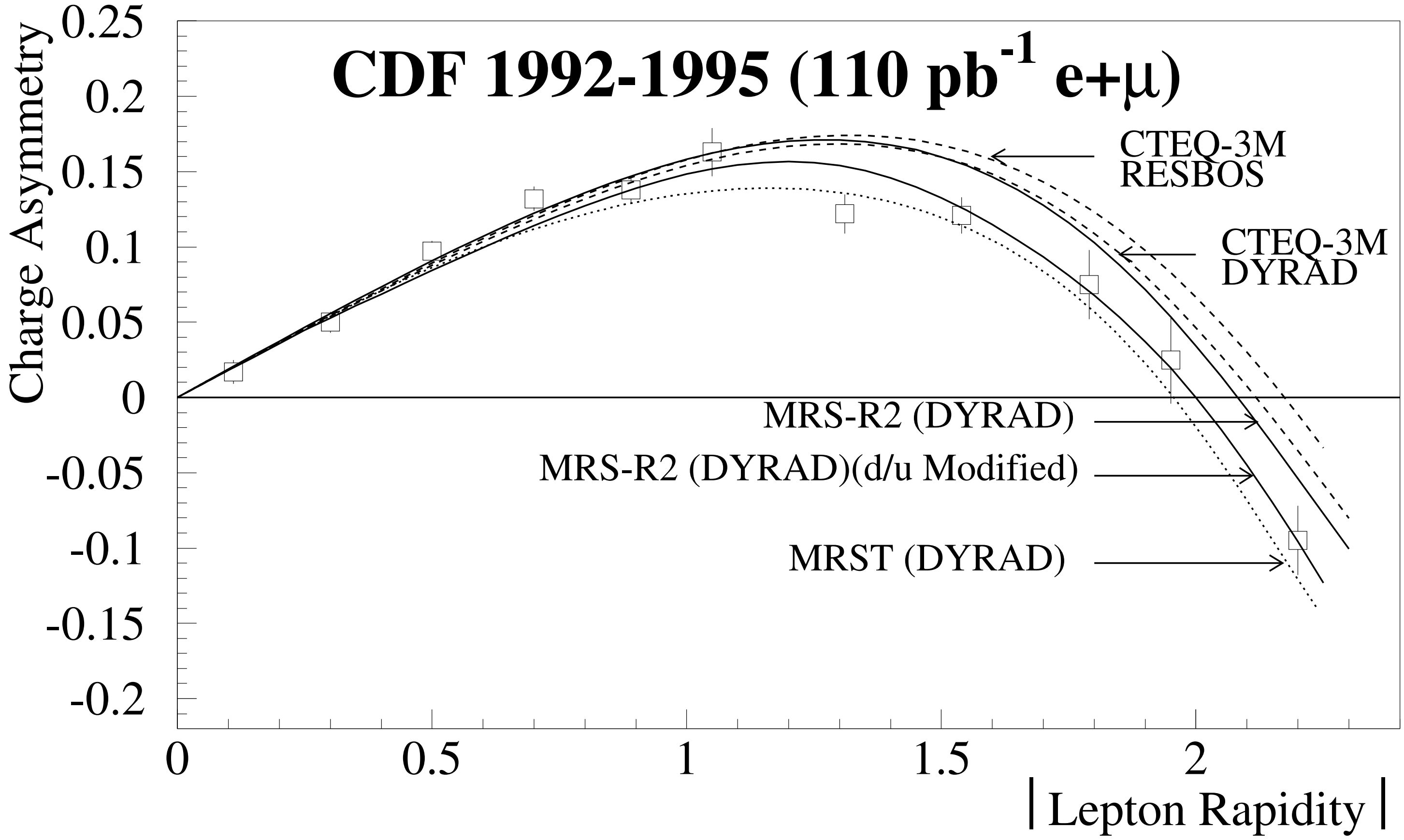
$$A(y) \equiv \frac{(d\sigma^+/dy) - (d\sigma^-/dy)}{(d\sigma^+/dy) + (d\sigma^-/dy)}$$

y: lepton rapidity.

Raw distribution

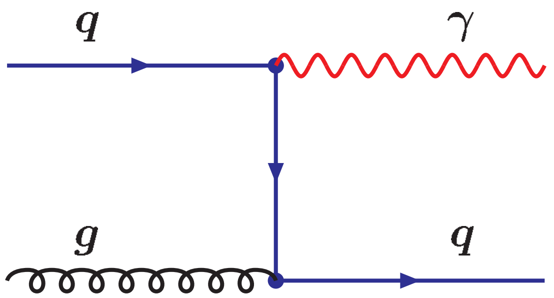


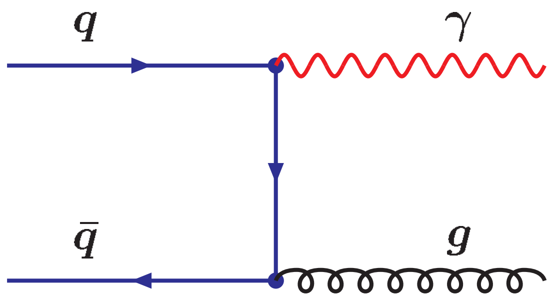
Corrected, and folded

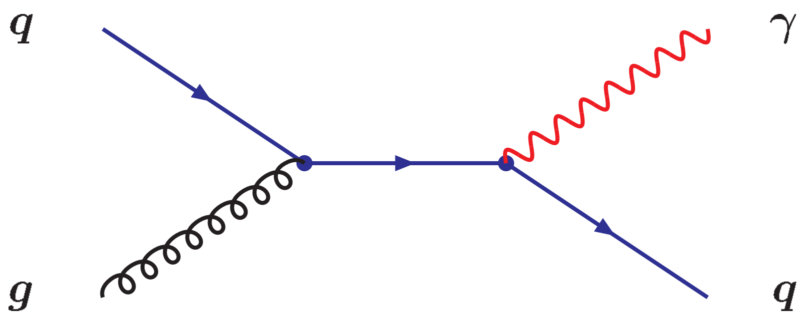


Prompt Photon Production

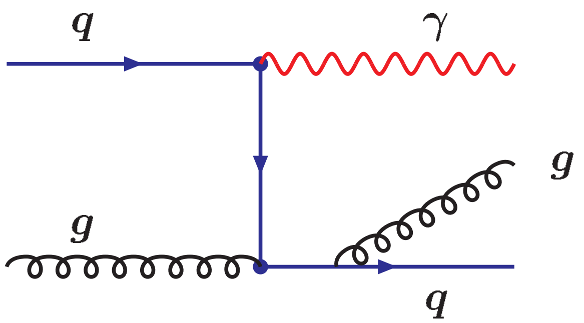
- **LO:**

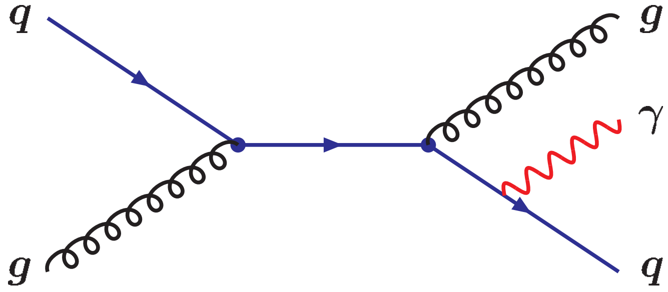






- **NLO: (examples)**





- **Sensitive to the quarks, as opposed to the gluons in case of jets.**

- **Parton = photon. Energy-momentum well defined.**
- **Photon energy measured with calorimeter. Resolution better than for hadrons/jets.**
- $\alpha_s \rightarrow \alpha$ **: cross section smaller than jets.**

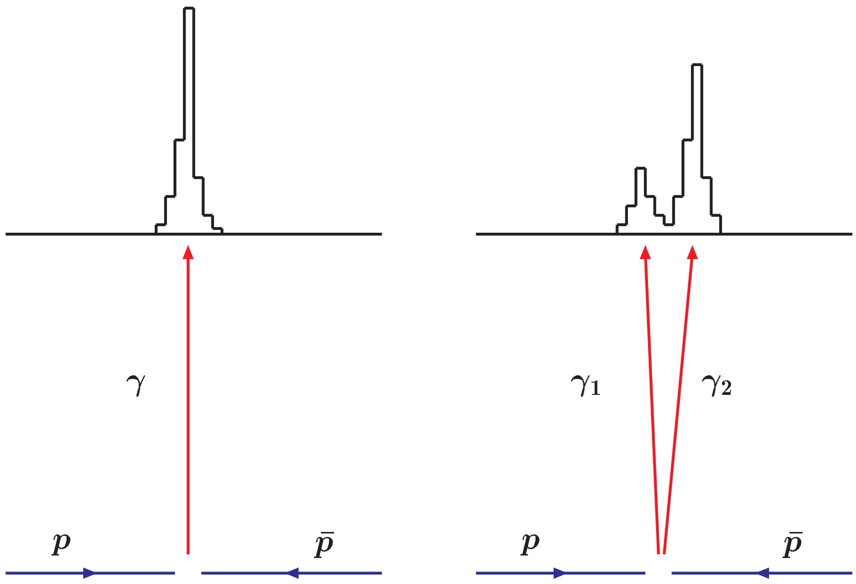
How to identify the photon?
Main BG: jets $\rightarrow$ leading $\pi^0 \rightarrow \gamma\gamma$,
energy deposit in electromagnetic calorimeter.

In principle separable, one photon vs. two photons.

Method I: Lateral shower profile using shower max detector CES.

Method II: Detect converted photon signal at preshower detector CPR.

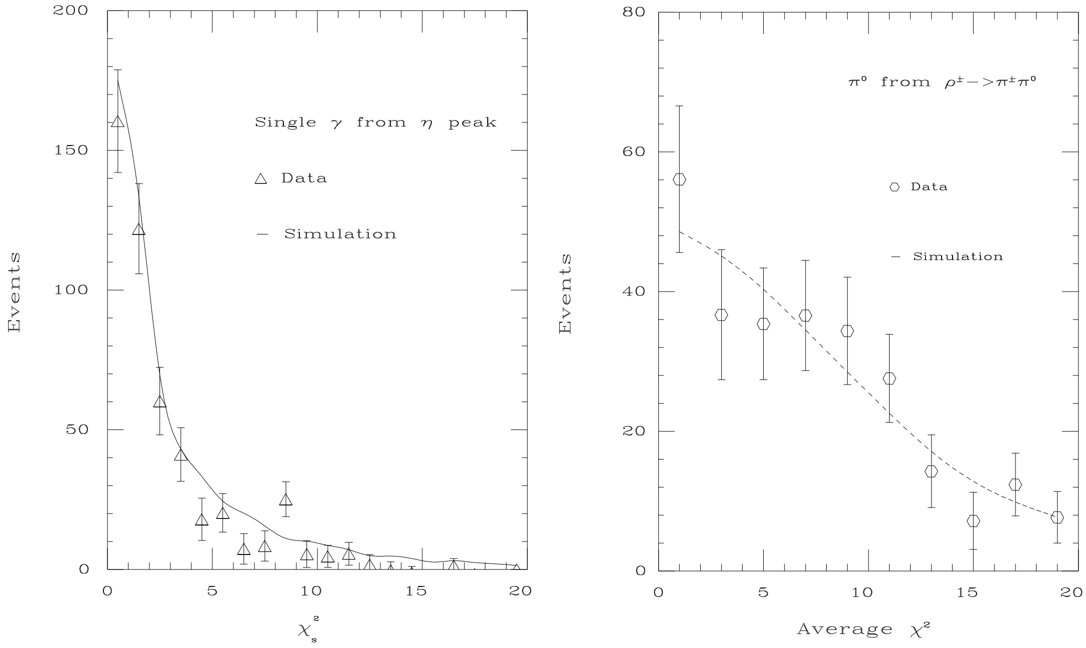
I: Profile method



CES at $R = 181$ cm. Channel spacing ~ 1.5 cm.

$$d_{\min} = \frac{49}{p_T(\pi^0)} \text{ cm} \quad \text{with } p_T \text{ in GeV}/c.$$

Fit CES profile with single shower hypothesis.
Templates from electrons in real data and test beam.
χ^2 of the fit $\rightarrow$ larger for π^0, smaller for γ.



Count the fraction with $\chi^2 < 4.0 \Rightarrow$ photon fraction.

Provides γ/π^0 separation up to ~ 30 GeV/c.

II: Conversion method

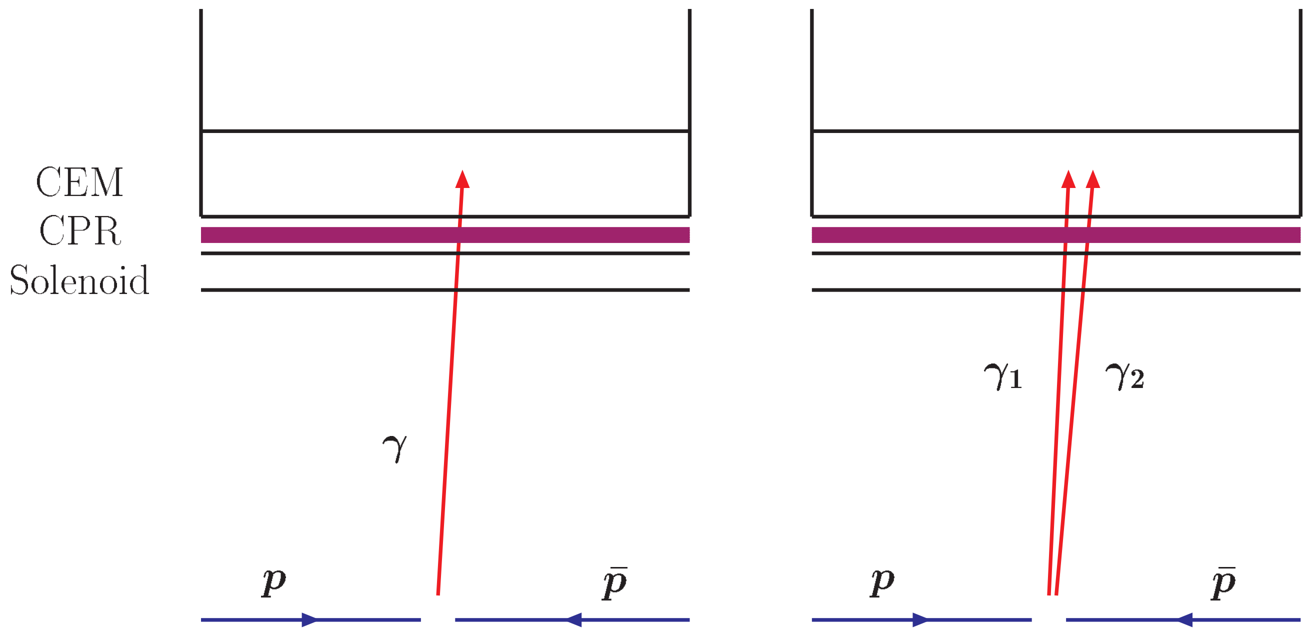
Photon conversion probability thru material thickness t is

$$P_\gamma(t) = 1 - \exp\left[-\frac{7t}{9X_0}\right].$$

For $\pi^0 \to 2\gamma$, the probability that at least one photon converts is

$$P_{\pi^0} = 1 - (1 - P_\gamma)^2 > P_\gamma.$$

Separation $P_{\pi^0} - P_\gamma$ is maximal for $P = 0.5$ or $t \sim 1.0\,X_0$.
CDF solienoid is $1.075\,X_0$ thick. Use it as the radiator, and detect converted photons just behind it. $\to$ CPR (proportional chamber).

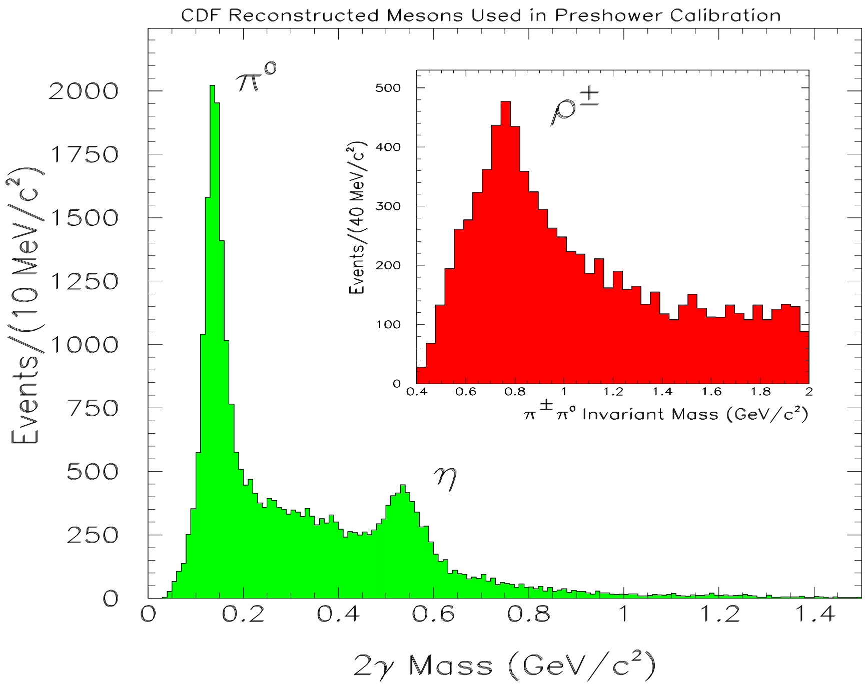


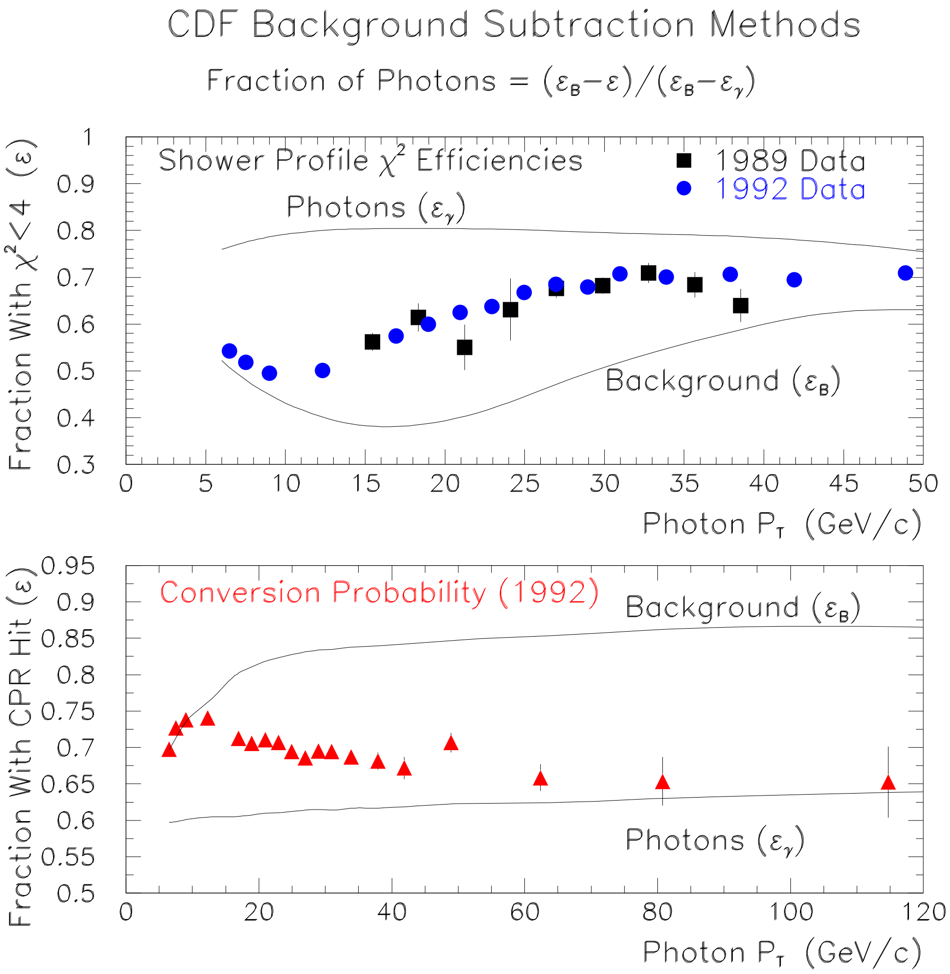
Measure the conversion probability $P_{\rm CPR}$ at CPR for photon candidates:
If $P_{\rm CPR} = P_\gamma$, all signal, if $P_{\rm CPR} = P_{\pi^0}$, all BG.
Somewhere in between $\to$ photon fraction.

Measure CES/CPR efficiencies in data :

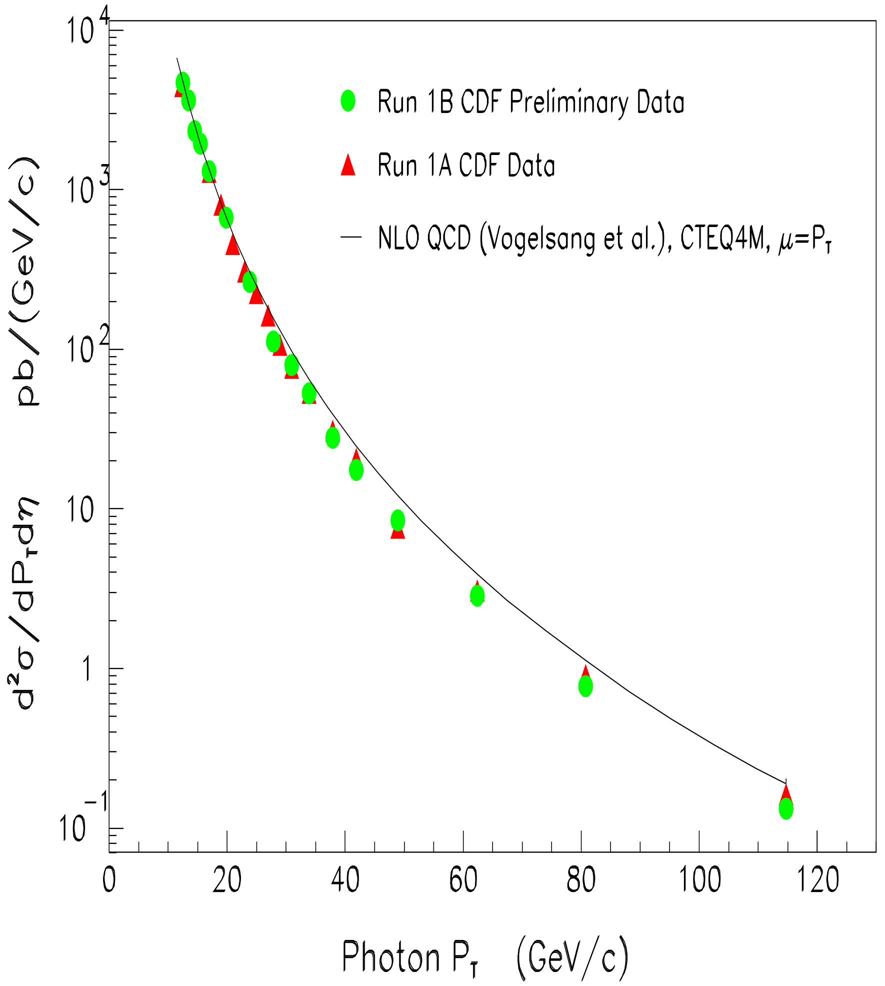
ϵ for single γ's from $\pi^0/\eta \rightarrow \gamma\gamma$

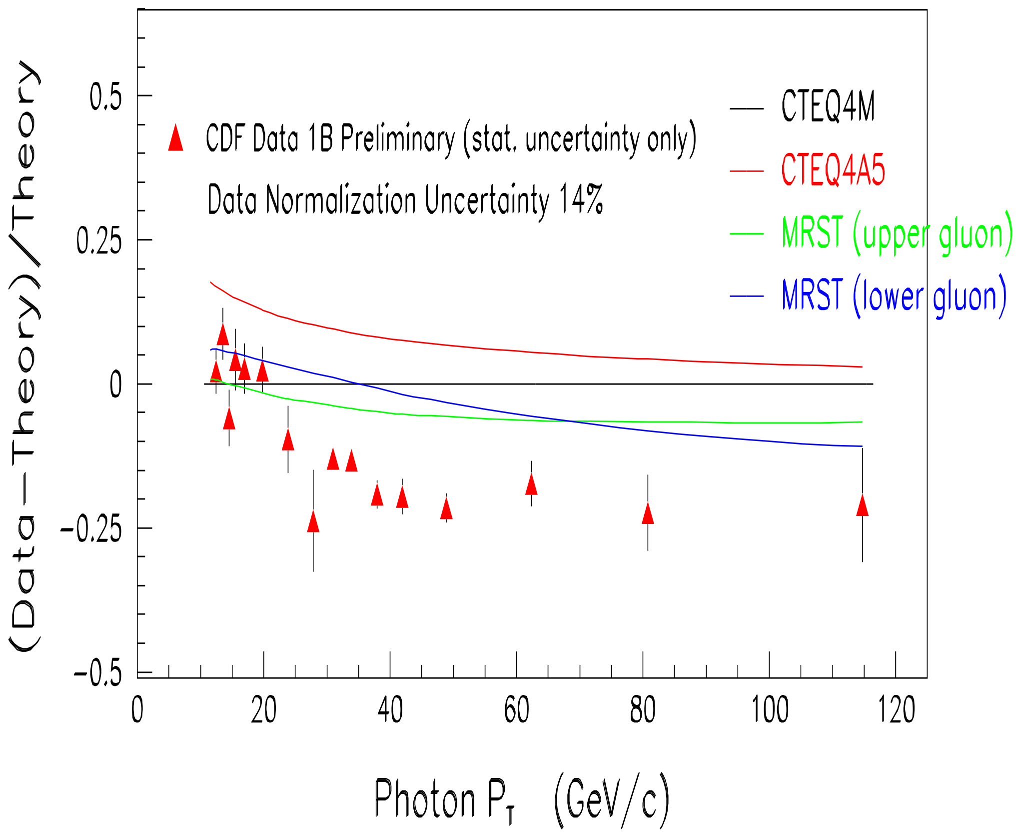
ϵ for π^0 from $\rho^\pm \rightarrow \pi^+\pi^0$





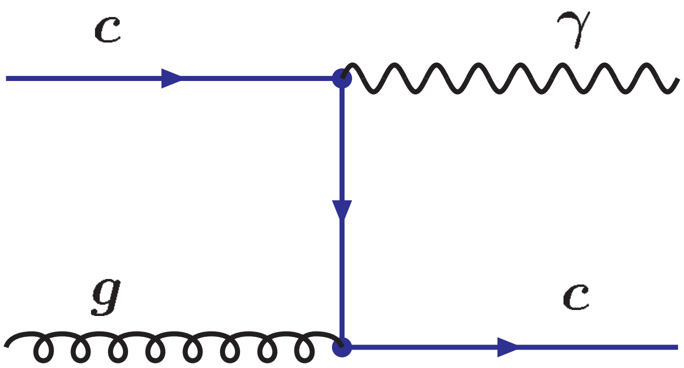
Single γ inclusive cross section (110 pb^{-1}).



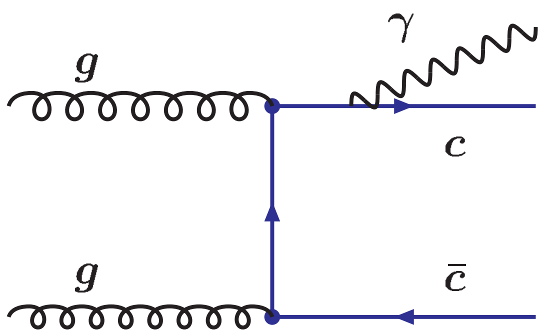


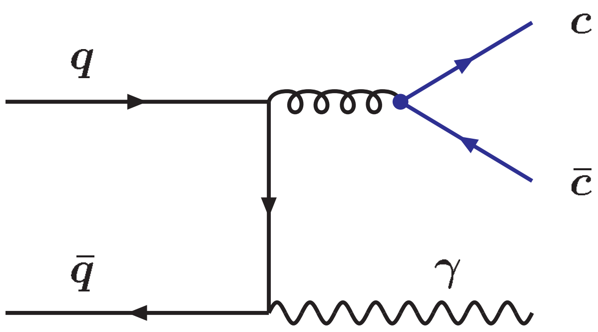
Photon + Charm Production

- **Ideally Compton process probes the charm quark in proton.**



- **However, other diagrams contribute, too.**





- **In any case, measure $\gamma + c$ production cross section.**

How to identify the charm quark?
Best if charm hadrons are fully reconstructed.

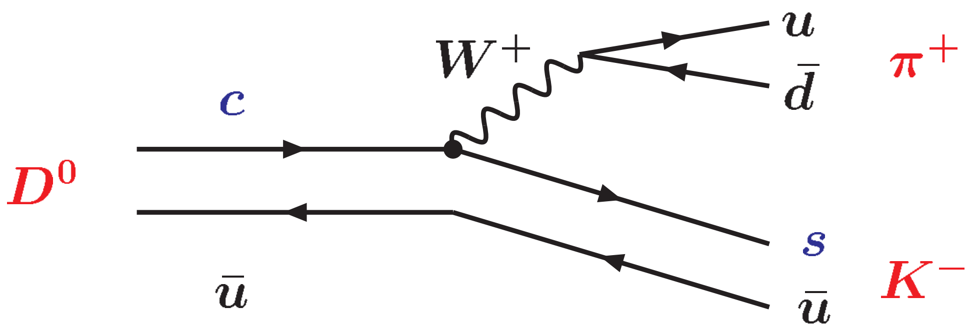
Charm Mesons

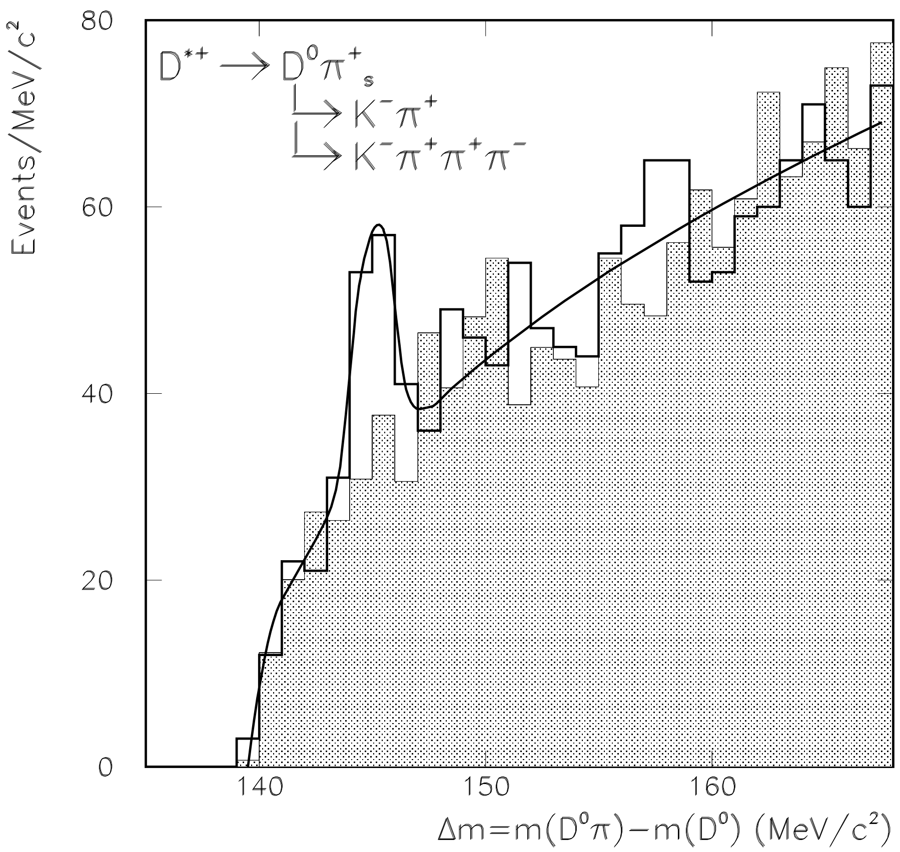
Quark comp.	J^P 0^-	Mass (MeV)	J^P 1^-	Mass (MeV)	Decay modes
$c\bar{u}$	D^0	1860	D^{*0}	2007	$\to D^0\pi^0$
$c\bar{d}$	D^+	1865	D^{*+}	2010	$\to D^0\pi^+$, $D^+\pi^0$
$c\bar{s}$	D_s^+	1970	D_s^{*+}	2112	$\to D_s^+\gamma$

$D^{*+} \to D^0\pi^+$ attractive,
because of the small Q value in the decay:

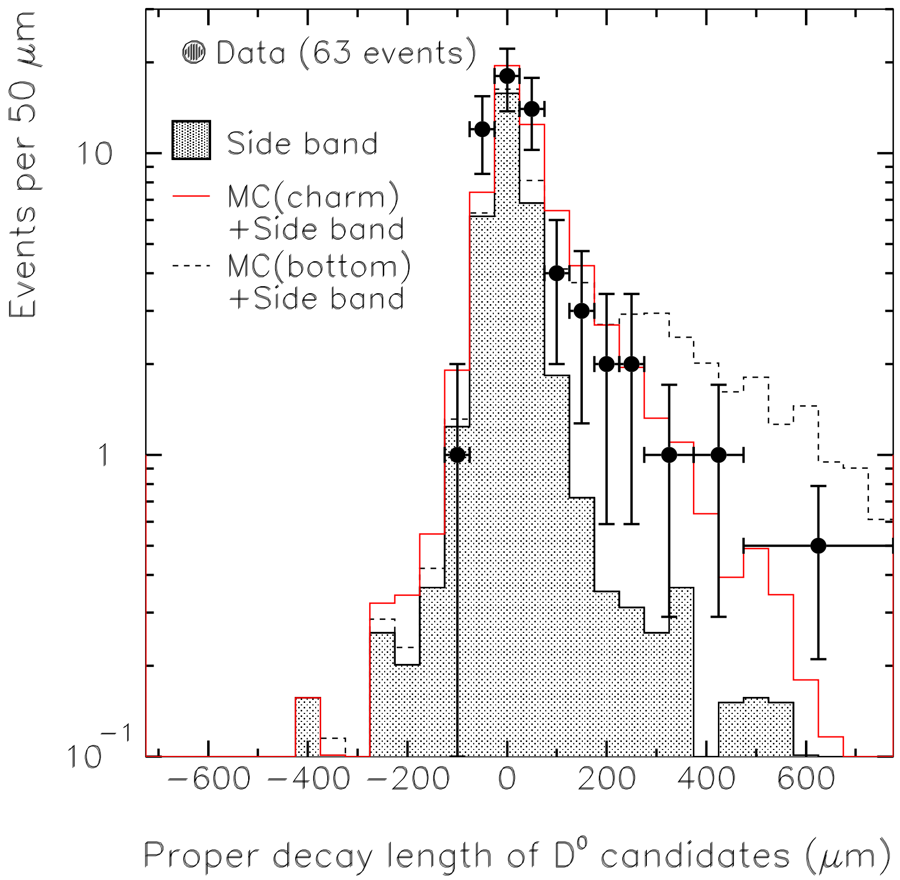
- Small background
- Good mass resolution in $\Delta M \equiv m(D^0\pi^+) - m(D^0)$.

Reconstruct D^0, usually use the decay modes
$D^0 \to K^-\pi^+$ ($BF = 3.8\%$) and
$D^0 \to K^-\pi^+\pi^+\pi^-$ ($BF = 7.5\%$).





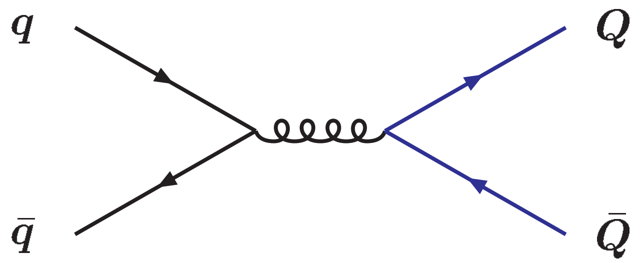
$D^{*+} \rightarrow D^0\pi^+_s$
$\rightarrow K^-\pi^+$
$\rightarrow K^-\pi^+\pi^+\pi^-$
Events/MeV/c^2
80
60
40
20
0
140
150
160
$\Delta m = m(D^0\pi) - m(D^0)$ (MeV/c^2)

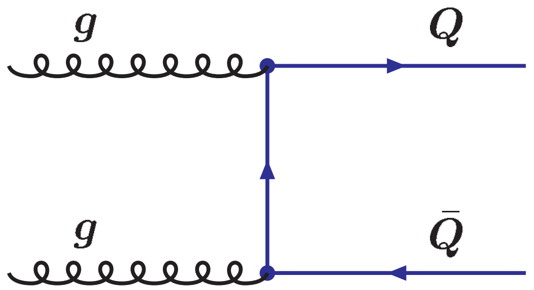


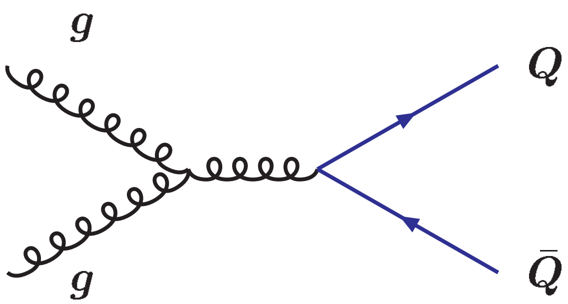
Data (63 events)
Side band
MC(charm) +Side band
MC(bottom) +Side band
Events per 50 μm
10
1
10^{-1}
−600
−400
−200
0
200
400
600
Proper decay length of D^0 candidates (μm)

Heavy Quark Production

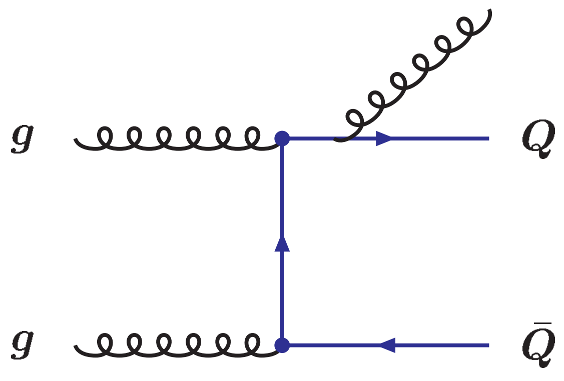
- Heavy quark mass $M_Q \gg \Lambda_{\mathrm{QCD}} \Rightarrow$ always a hard process.
  Perturbative QCD applicable for all momenta.
  LO:

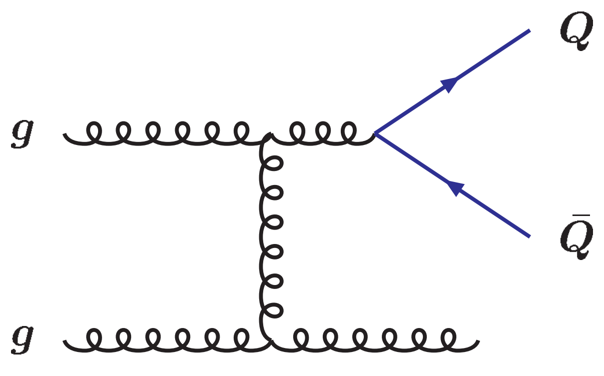






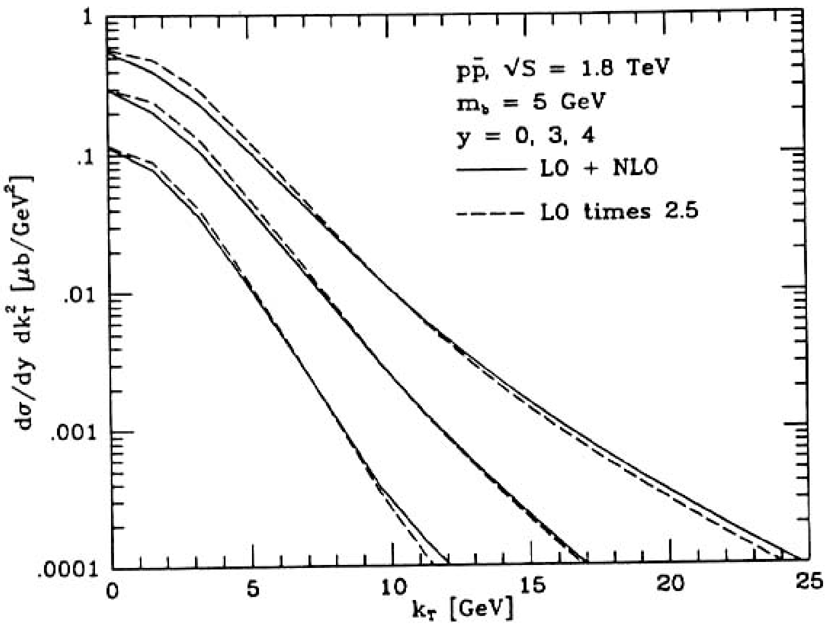
- NLO calculations available for
  – total cross sections
  – one-particle inclusive cross sections
  – two-particle correlations



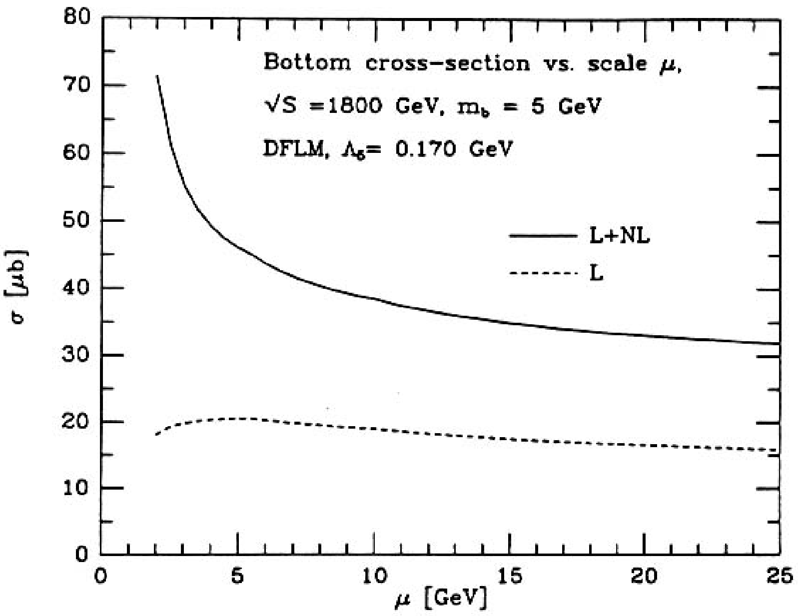


Bottom Quark Production

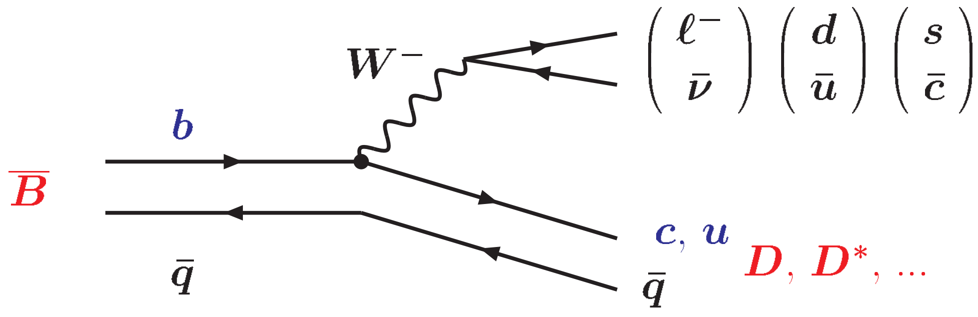
Correction to LO large, $\times 2.5$.
But p_T and rapidity distributions virtually unchanged.



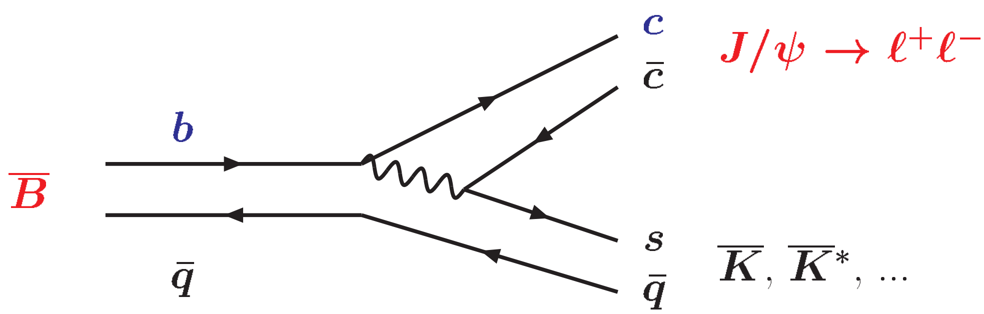
Dependence on renormalization scale μ not reduced in NLO.
Somewhat worrisome.



How to detect the b quark?
Have to identify its decay.

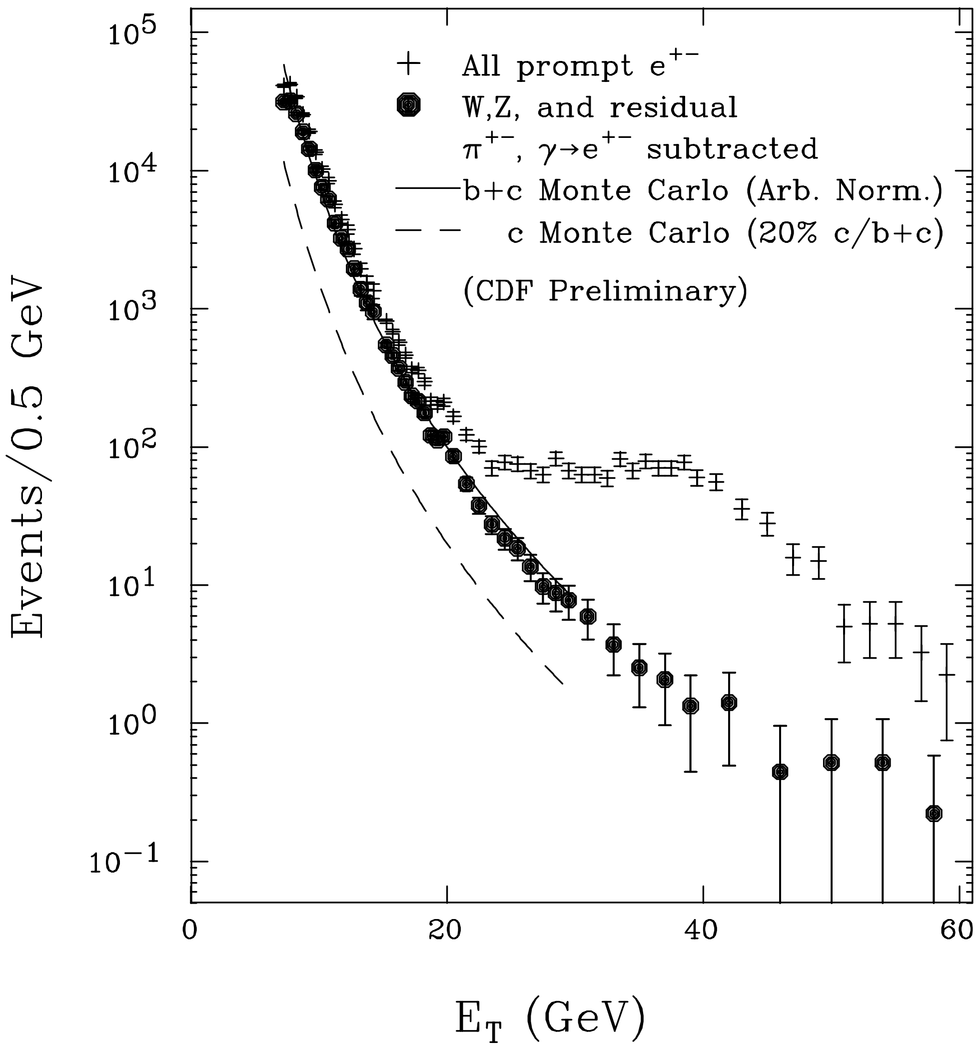


- 0-th order approximation :
  Decay of a heavy hadron $H_Q(\equiv Q\bar q)$ is the decay of the heavy quark Q.
- b quark decays to c or u quark.
  $b \to c$ decay dominant, because $|V_{cb}| \gg |V_{ub}|$.
- Have to isolate among BG of q and g jets.
  $\Rightarrow$ use semileptonic decay and the lepton.
  Rate sizable : $\mathcal{B}(\overline{B} \to \ell^- \bar\nu X) = 10\%$.
  Main source of single leptons at low p_T (below $W^\pm$ and Z^0).
- B decays can also produce two leptons :
  - Sequential decays : $b \to \ell^- \bar\nu c$, $c \to \ell^+ \nu s$.
  - $\overline{B} \to J/\psi\, X$ via $b \to c\,\bar c s$, and $J/\psi \to \ell^+\ell^-$.



$\mathcal{B}(\overline{B} \to J/\psi\, X) \simeq 1\%$, $\mathcal{B}(J/\psi \to \ell^+\ell^-) = 7\%$.

Inclusive electron spectrum : 1988-89, PRL 71, 500 (1993).



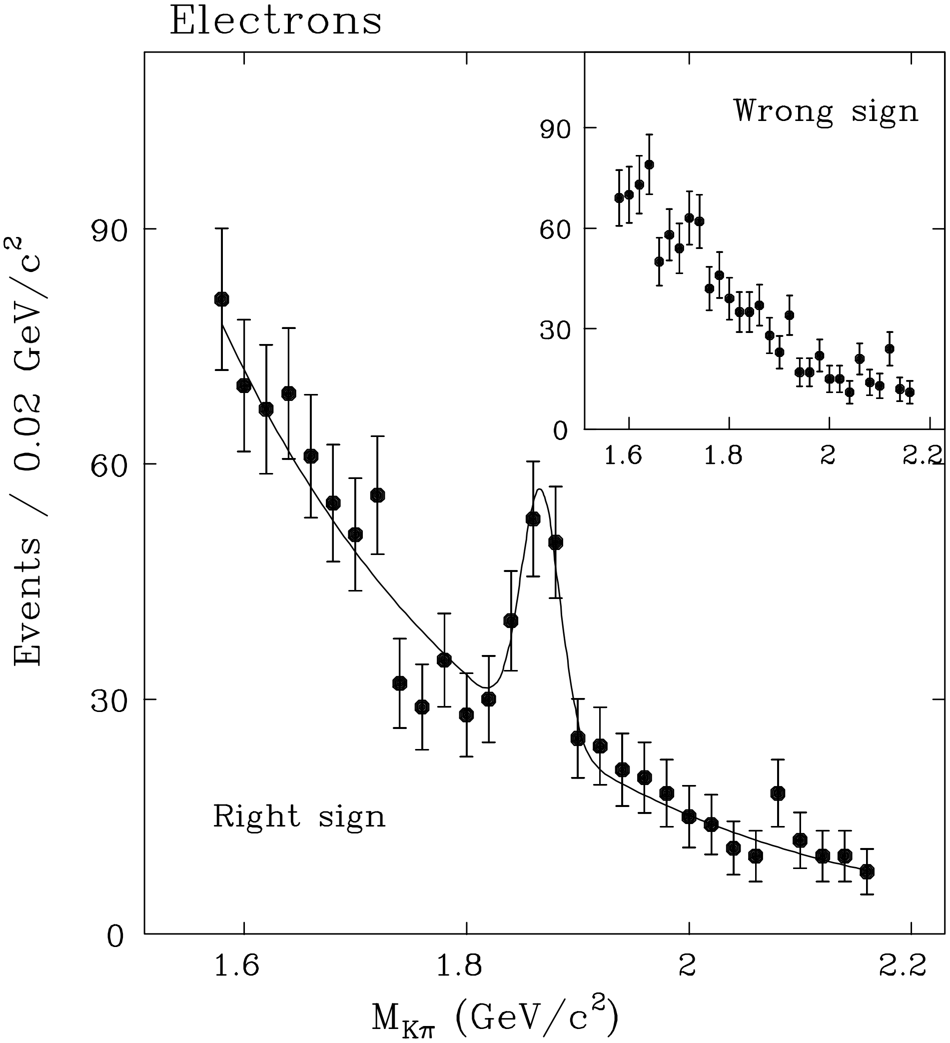
"Shoulder" above $\sim$ 25 GeV from $W^{\pm} \to e^{\pm}\nu$ and $Z^0 \to e^+e^-$.

Rest: $b \to e^-\bar{\nu}X$, $\bar{c} \to e^-\bar{\nu}X'$, hadron fakes.

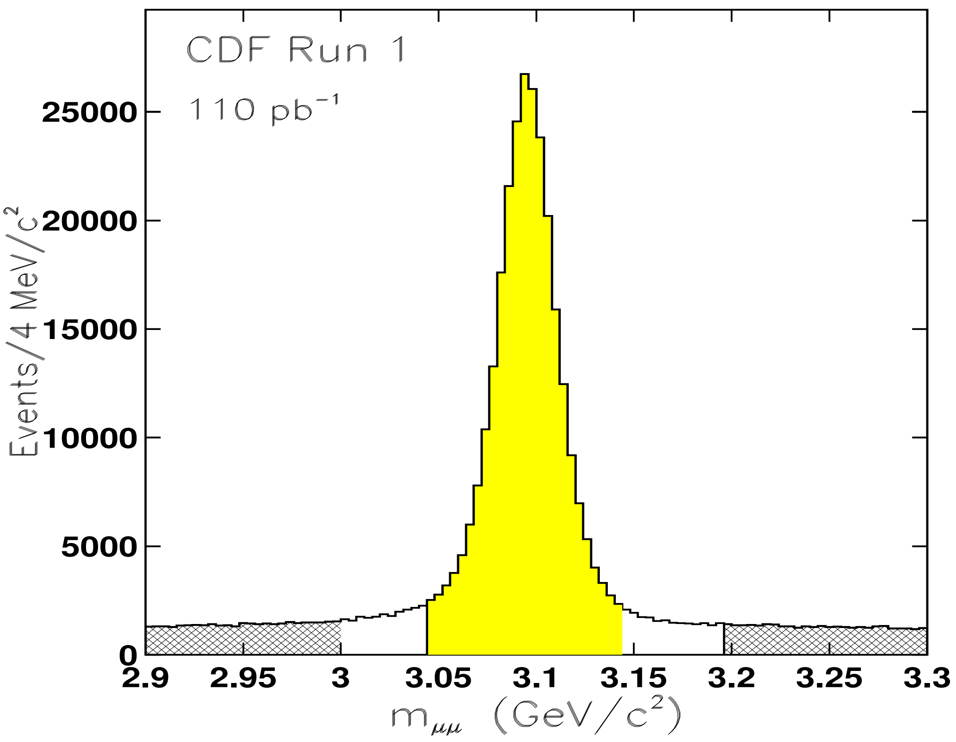
$b \to \overline{B}$ fragmentation harder than $c \to D$.
Lepton momentum in the B rest frame larger than in the D.
$\Rightarrow$ bottom leptons enhanced over charm leptons.

$\overline{B} \to \ell^- \bar{\nu} D$, D^*, ... Should see the charm hadron associated with ℓ^-.

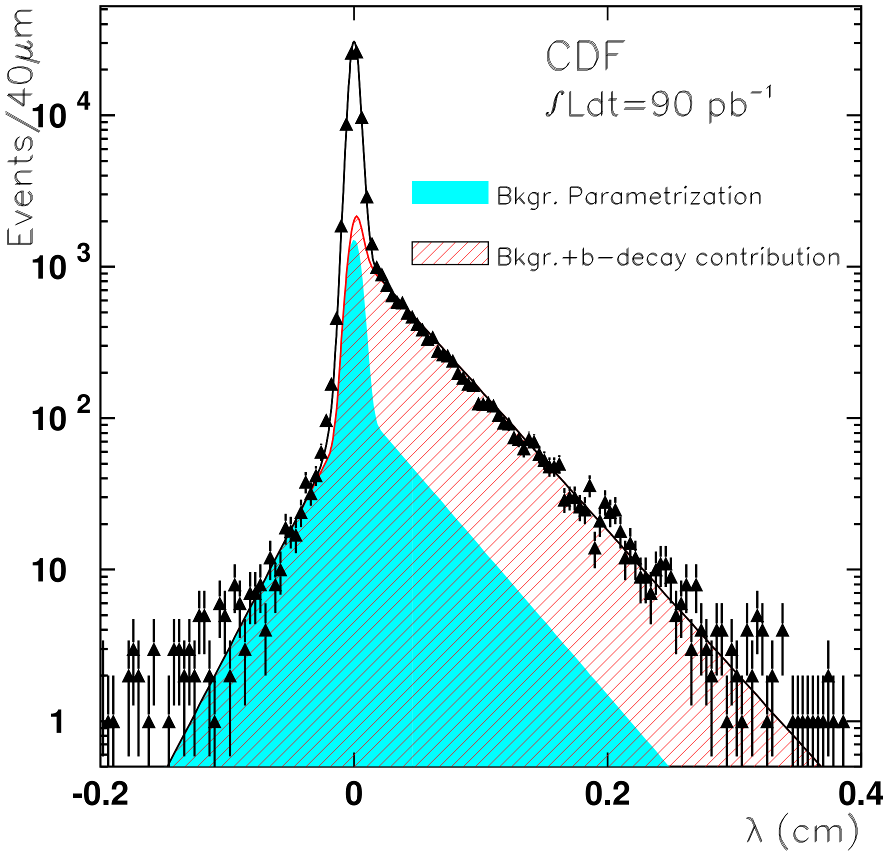
Reconstruct charm meson $D^0 \to K^-\pi^+$ near e^-.



J/ψ and B decays

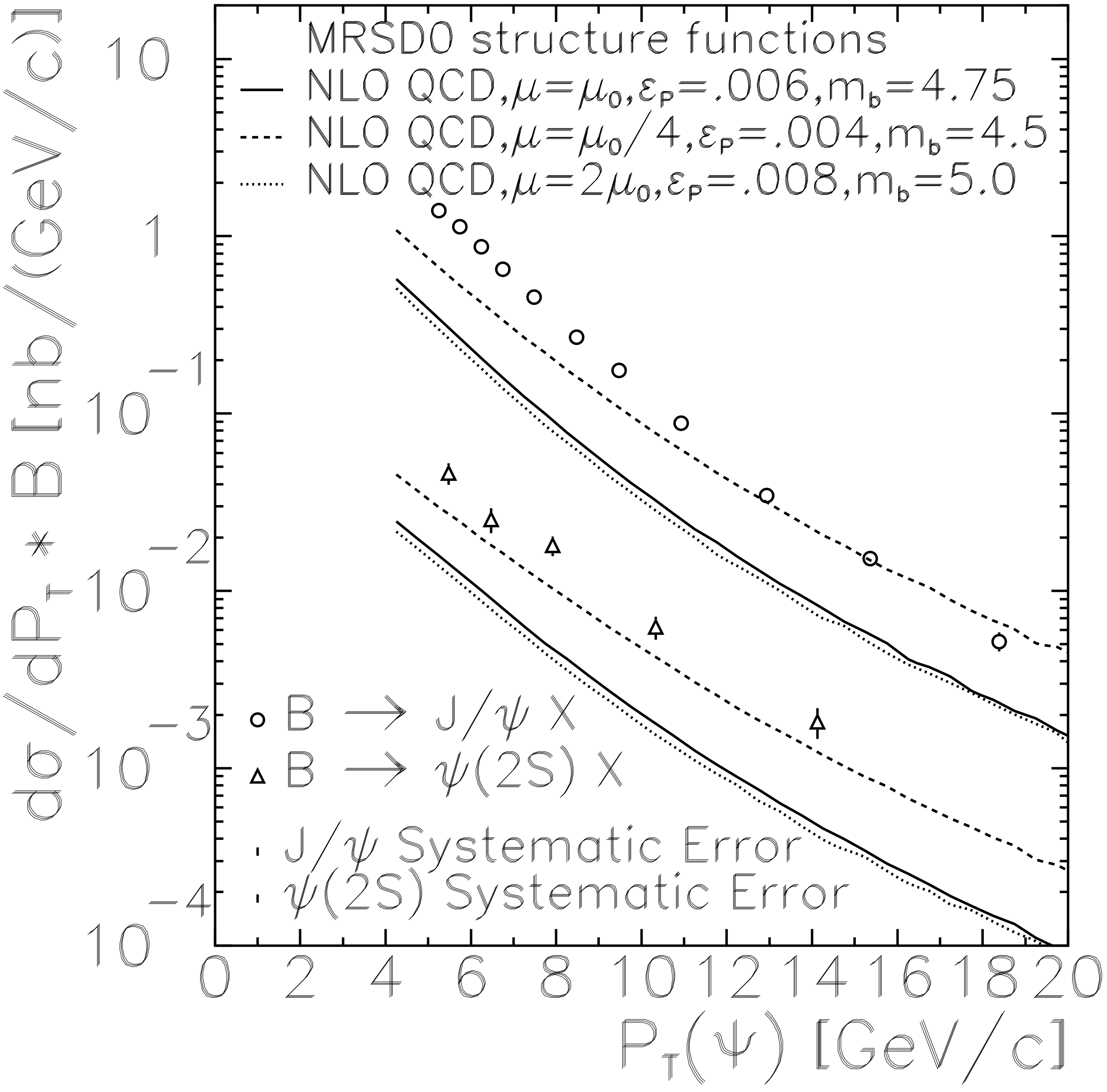


Decay length distribution



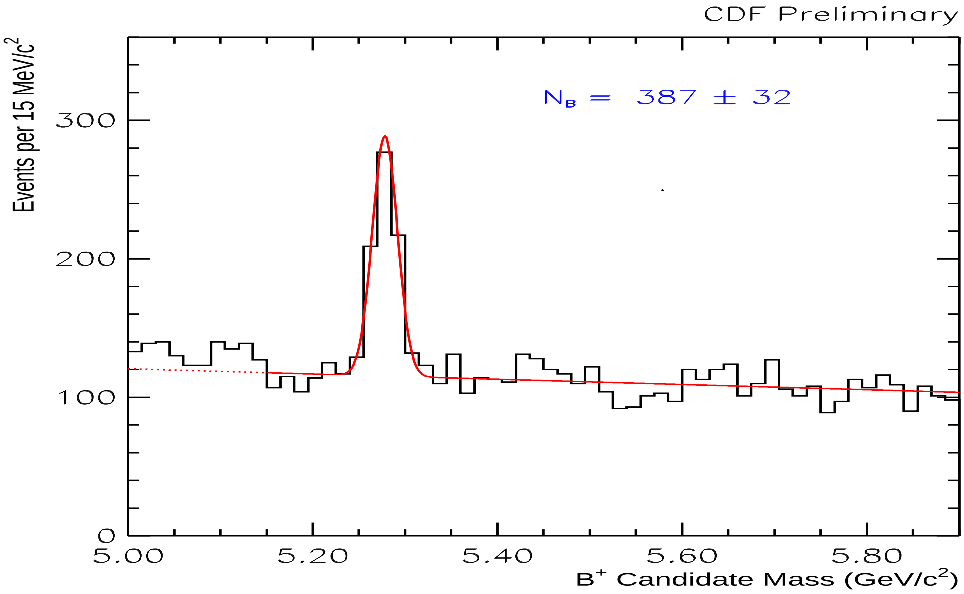
$\sim$ 20% of J/ψ's from B decays.

Production of J/ψ and $\psi(2S)$ from B decays

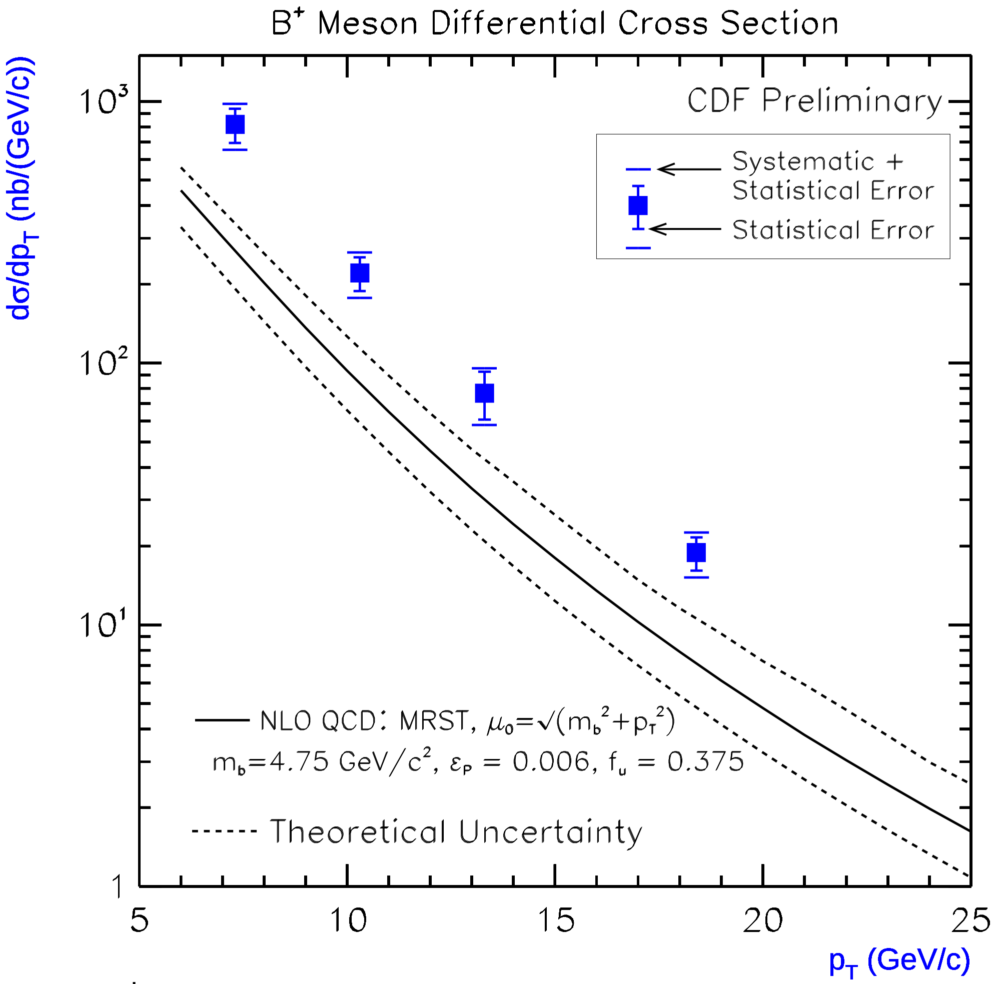


Higher than NLO QCD calculation with "normal" choices of scale μ, $\Lambda_{\rm QCD}$ and m_b.

Fully reconstructed $B^+ \to J/\psi K^+$ decays



B^+ meson production cross section



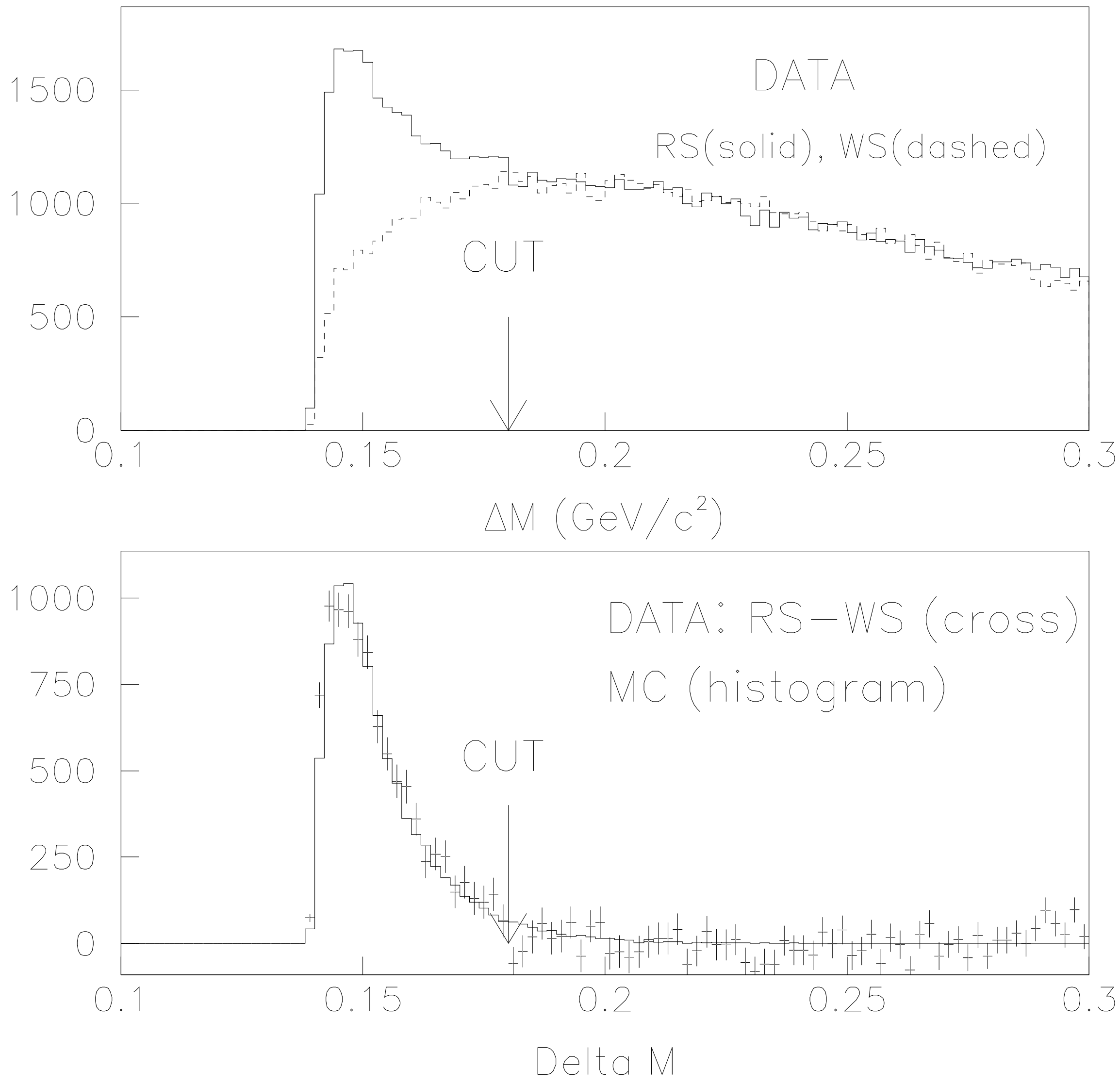
$\sigma(\bar{p}p \to B^+X) = 3.51 \pm 0.42 \pm 0.53\ \mu\text{b}$ for $p_T > 6\ \text{GeV}/c$ and $|y| < 1.0$.

Open Charm Production

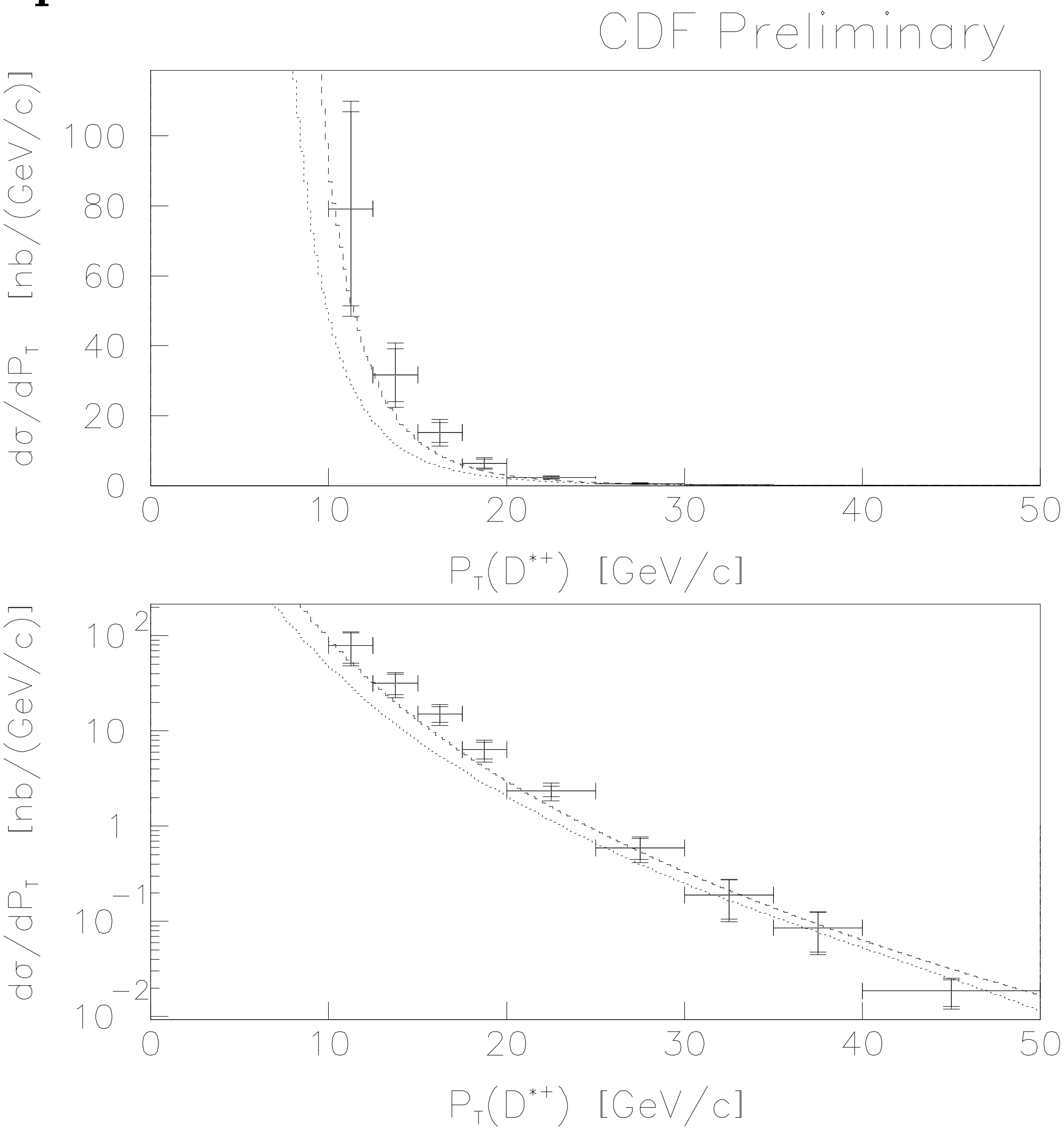
Is charm heavy enough?
Otherwise similar to bottom.

Measure D^{*+} production.

Start with single μ sample ($p_T > 8$ GeV$/c$).
Use $D^{*+} \to D^0\pi^+$, $D^0 \to \mu^+\nu K^- X$.
Form $\Delta m \equiv m(\mu^+K^-\pi^+) - m(\mu^+K^-)$.



D^{*+} production



$\sigma(\bar{p}p \to D^{*+}X) = 347 \pm 65 \pm 58$ nb for $p_T > 10$ GeV/c and $|\eta| < 1.0$.

Theory : 240 nb, M. Cacciari (1998).

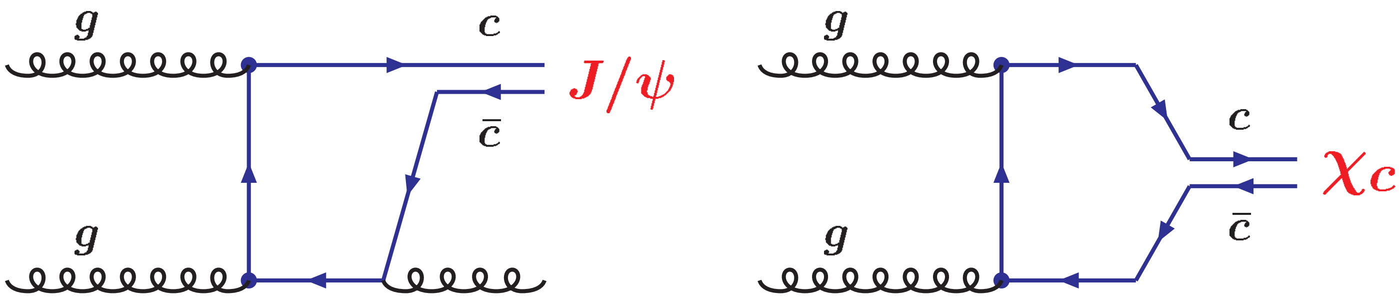
Onium Production

Quarkonia: bound states of heavy quark Q and its antiquark $\bar{Q}$.

$c\bar{c}$ states :
$L=0,\ S=0,\ J^P=0^-\ :\ \eta_c$
$L=0,\ S=1,\ J^P=1^-\ :\ J/\psi,\ \psi(2S),\ \ldots$
$L=1,\ S=1,\ J^P=0^+,\ 1^+,\ 2^+\ :\ \chi_{c0},\ \chi_{c1},\ \chi_{c2}$

Similarly for $b\bar{b}$:
$L=0,\ S=0,\ J^P=0^-\ :\ \eta_b$
$L=0,\ S=1,\ J^P=1^-\ :\ \Upsilon$
$L=1,\ S=1,\ J^P=0^+,\ 1^+,\ 2^+\ :\ \chi_{b0},\ \chi_{b1},\ \chi_{b2}$

$J/\psi \to 3g,\ \chi_{c(0,2)} \to 2g.$



"Old" theory had predicted :
$\sigma(\psi(2S), \text{direct } J/\psi) \gg \sigma(\chi_c)$.

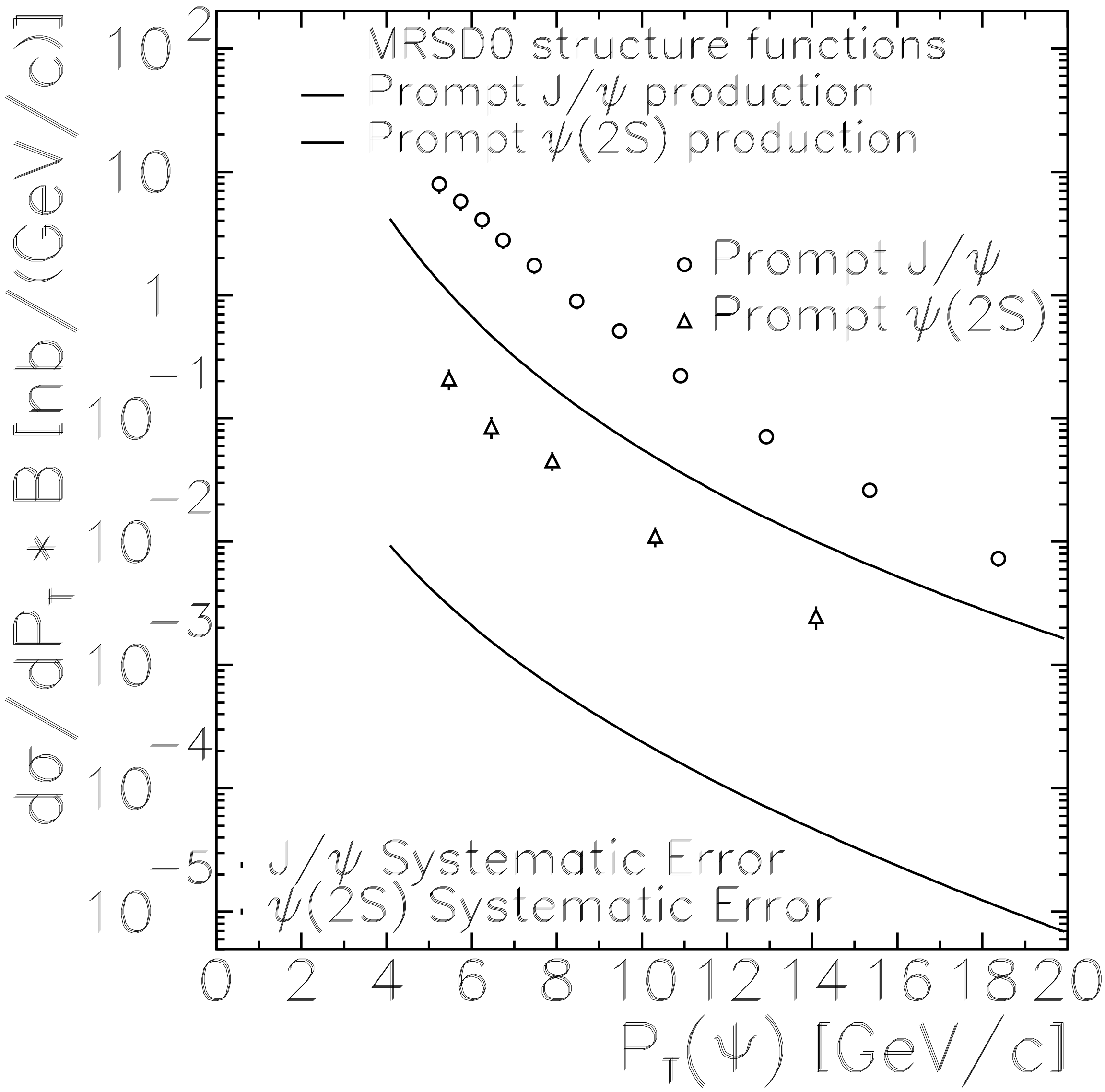
CDF has found $\times 50$ direct J/ψ and $\psi(2S)$ yields than "color singlet model".

J/ψ and $\psi(2S)$ Production

Sources:

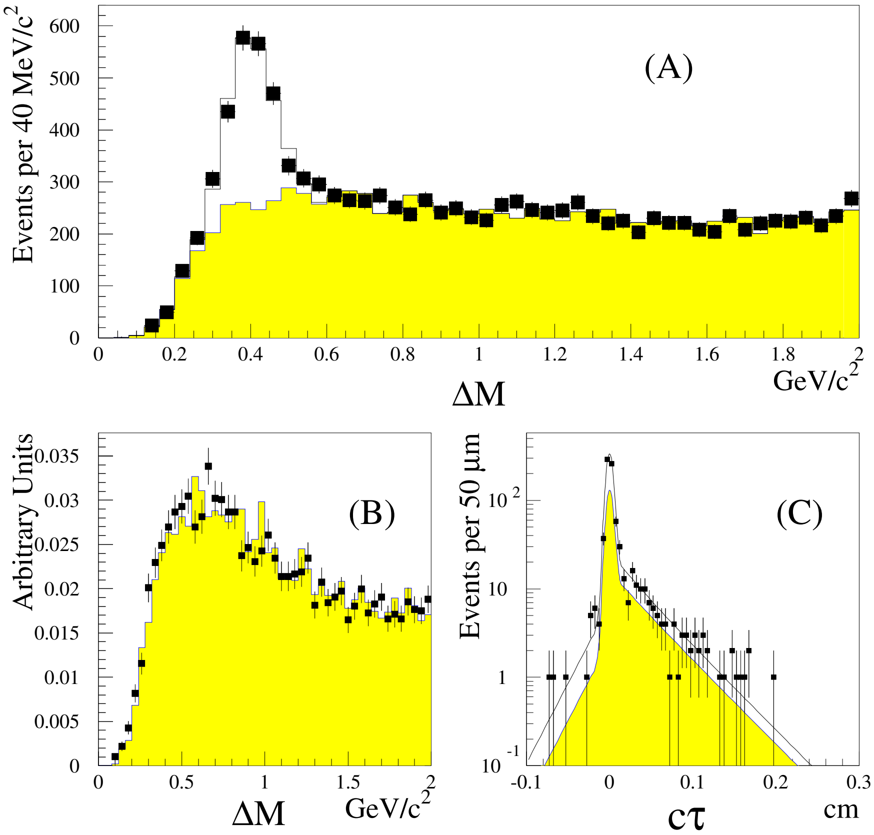
- $B \to J/\psi X$ **(lifetime,** $\sim$ **20% of all)**
- **Direct** J/ψ
- **Direct** $\chi_c \to J/\psi\,\gamma$ **(not the case for** $\psi(2S)$**)**

The latter two have zero lifetime ("prompt") :

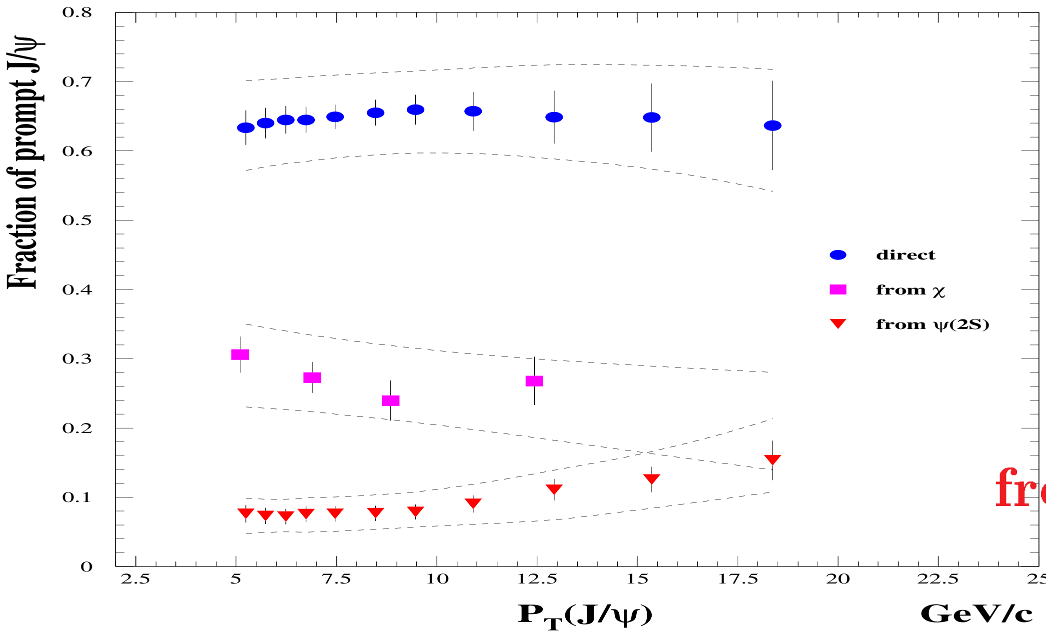


J/ψ from χ_c : $\chi_c \to J/\psi\,\gamma$

Identify γ with CEM/CES, combine it with J/ψ, calculate $\Delta M \equiv M(J/\psi\,\gamma) - M(J/\psi)$.



Use lifetime to subtract $B \to \chi_c X$.
Then extract sources of prompt J/ψ's.

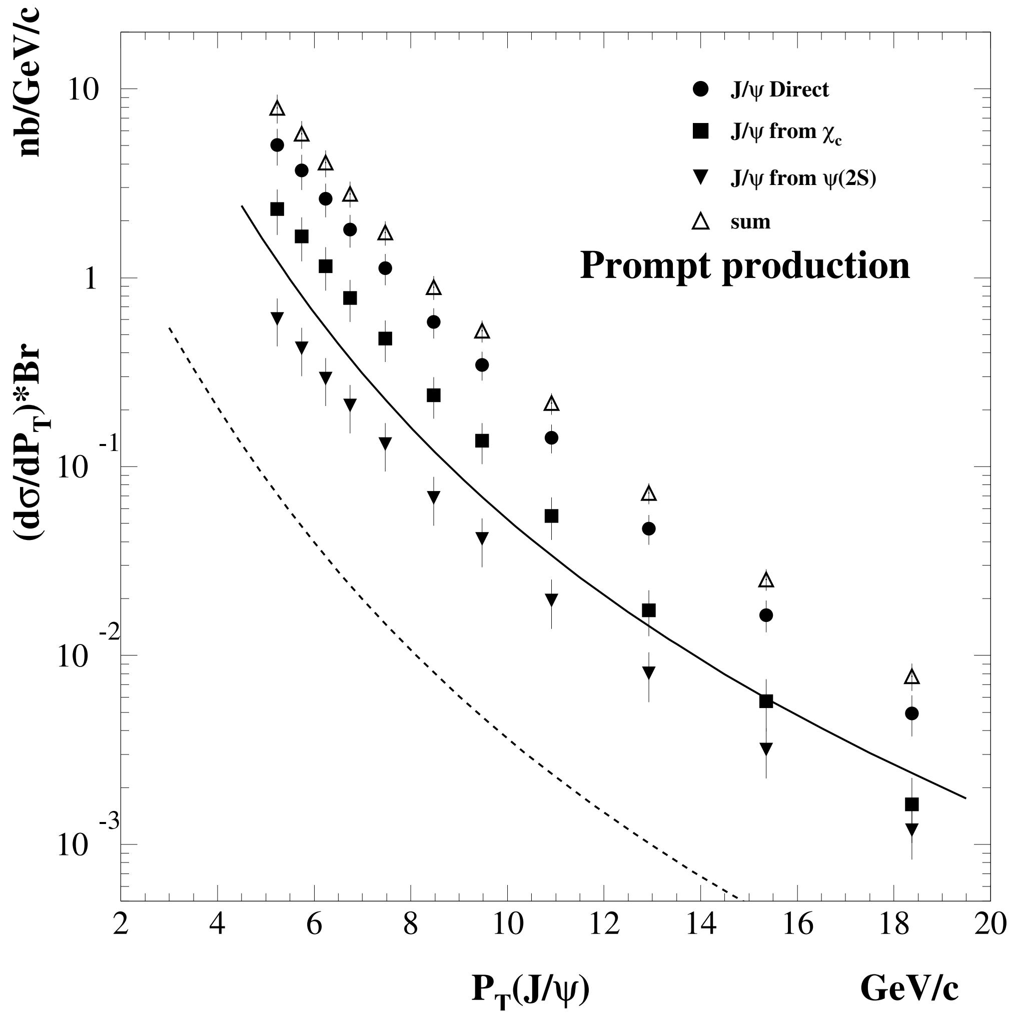


direct

from χ_c

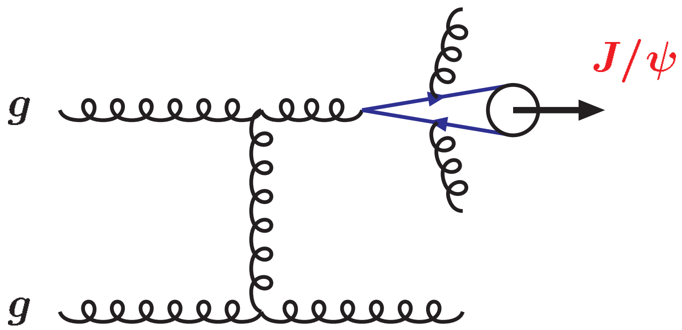
from $\psi(2S)$

Prompt J/ψ Production Breakdown



Direct production: both J/ψ and $\psi(2S)$ higher than prediction by a factor of ~ 50.

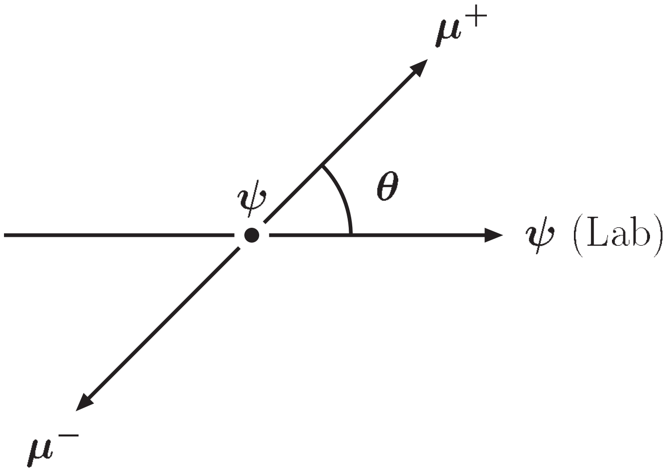
Other mechanisms must exist.
Gluon fragmentation?
Color octet?



J/ψ and $\psi(2S)$ Polarization

Gluon fragmentation into ψ :

Gluons are massless ($p_T \gg m_\psi$) and thus transversely polarized.
ψ should inherit the gluon polarization.
Helicity angle:



$$\frac{dN}{d\cos\theta} = 1 + \alpha \cos^2\theta$$

$\alpha = +1 \Rightarrow$ 100% transverse.
$\alpha = -1 \Rightarrow$ 100% longitudinal.

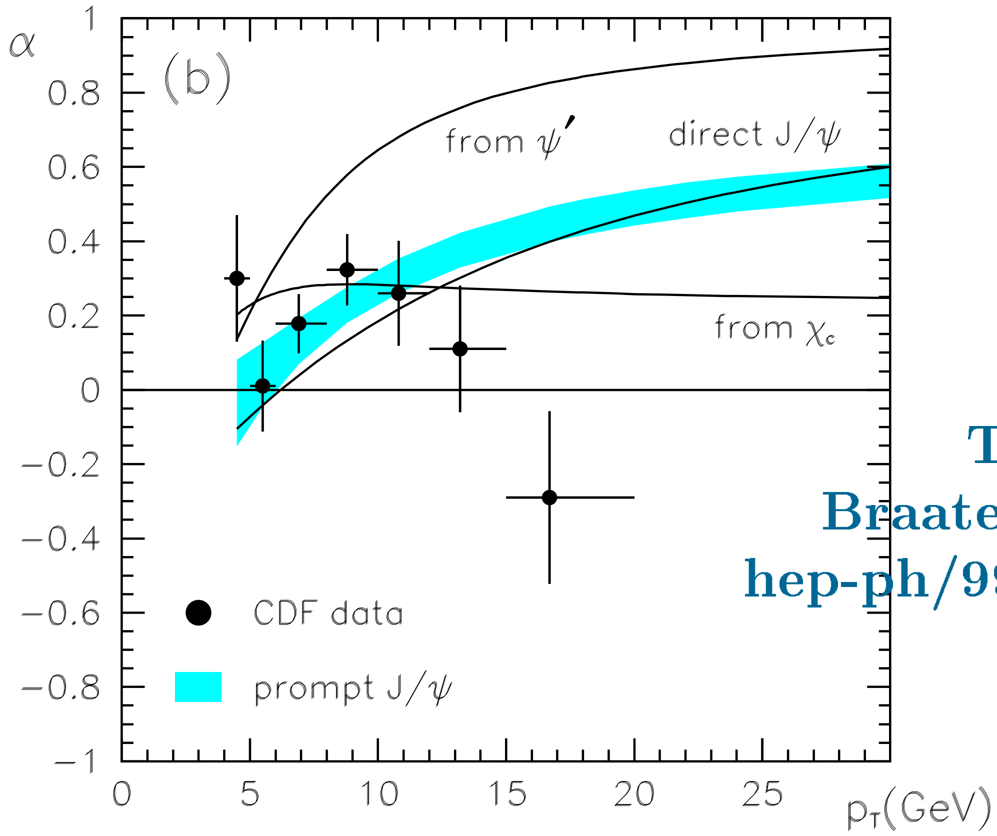
Prediction for direct production

Beneke and Krämer	$\alpha = 0.77 \pm 0.08$
Leibovich	$\alpha = 0.90 \pm 0.04$

at $p_T = 20$ GeV/c.

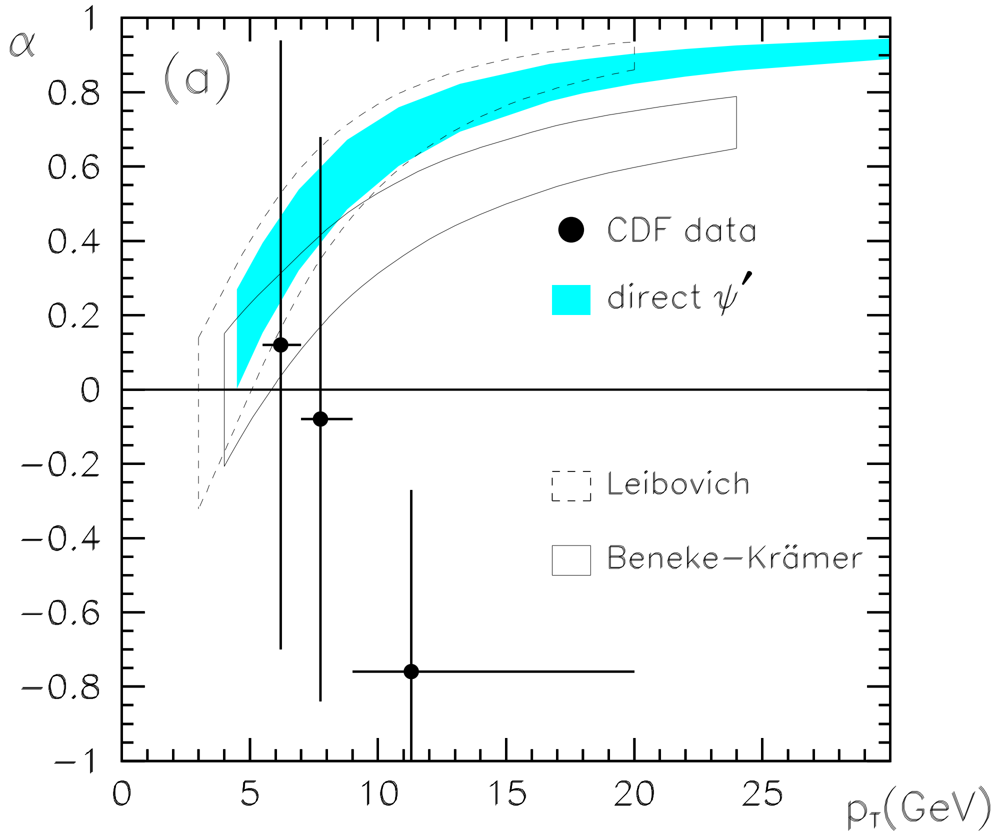
J/ψ and $\psi(2S)$ Polarization

J/ψ



Theory:
Braaten *et al.*
hep-ph/9911436

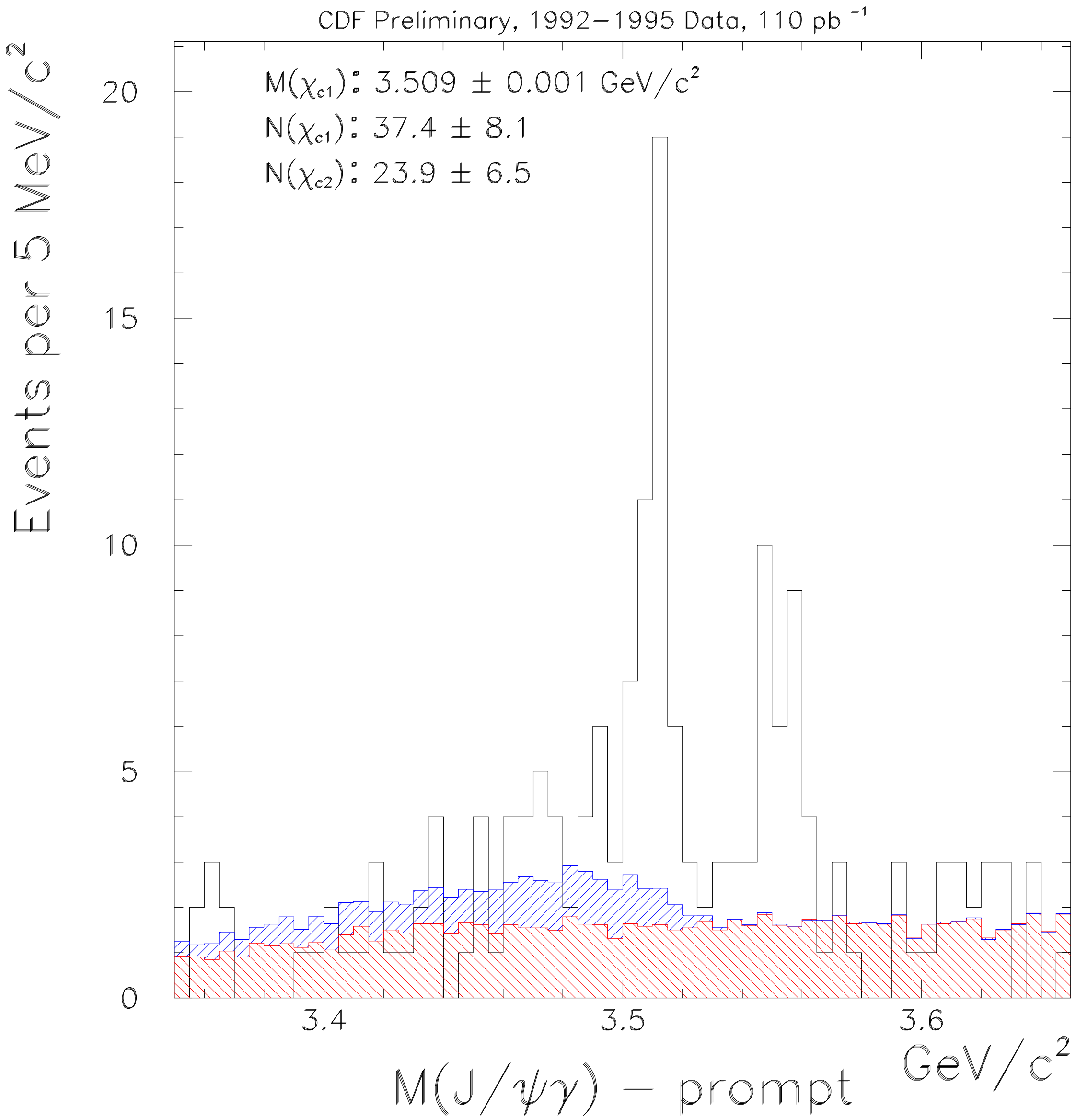
$\psi(2S)$



Phys. Rev. Lett. 85, 2886 (2000).

χ_c **Production : separate** χ_{c1} **and** χ_{c2}**.**

Need good energy resolution for photon :
$\Rightarrow$ **use converted** $\gamma \to e^+e^-$ **(tracking momentum resolution better than calorimeter)**



$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.89 \pm 0.33\,^{+0.13}_{-0.10}$$

Υ Production