Status of Tevatron CDF
&
Selected QCD Results

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Gauge Boson Production

- Z^0/Drell-Yan $\ell^+\ell^-$ Production
- $W^\pm$ Boson Production
- Prompt Photon Production

Heavy Quark Production

- Open b and c Quark Production
- Quarkonium Production

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 $\sqrt{s} = 1.8 - 2.0$ TeV. QCD is one of them.

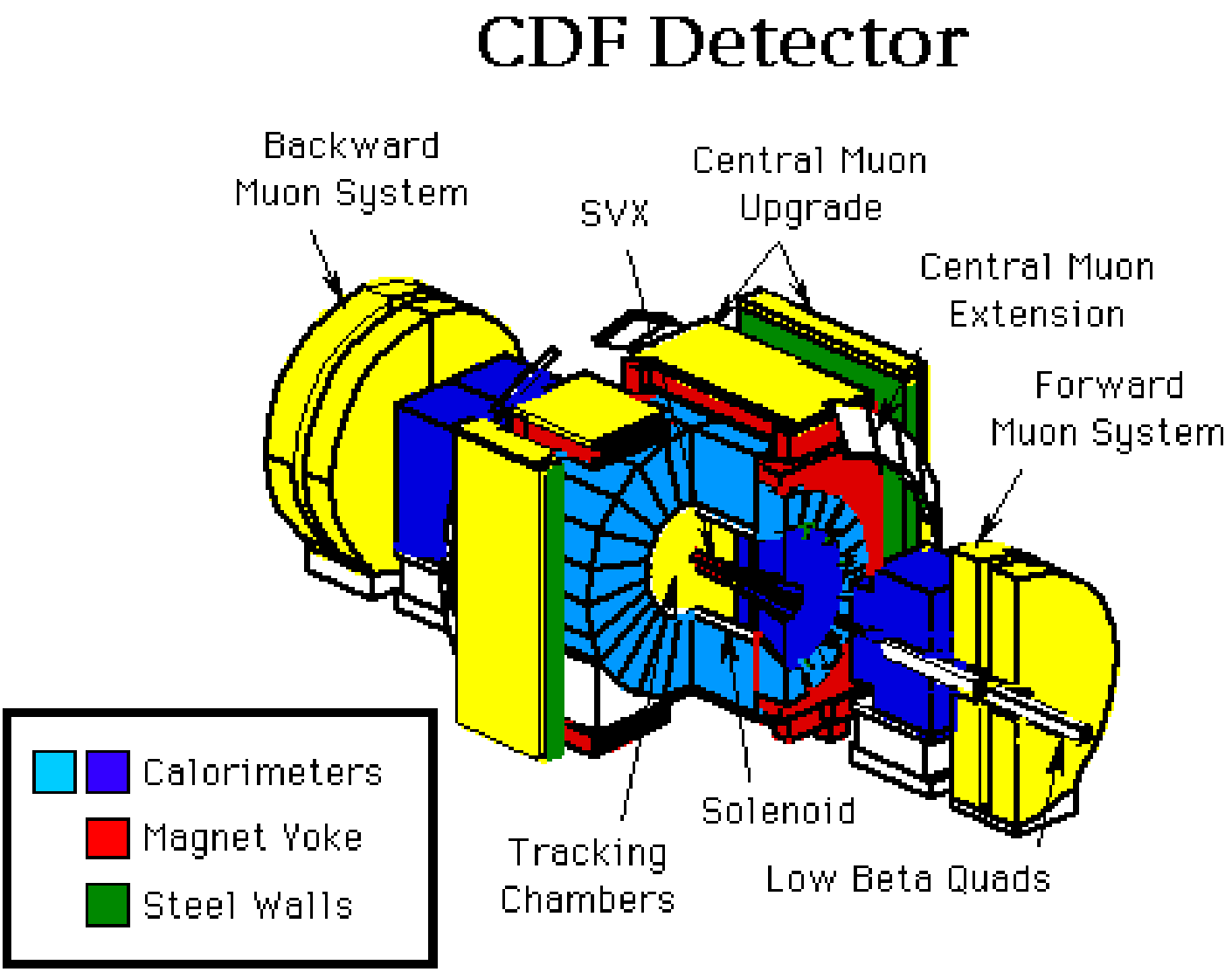
CDF detector is a general purpose, $\sim 4\pi$ detector.

Brief History

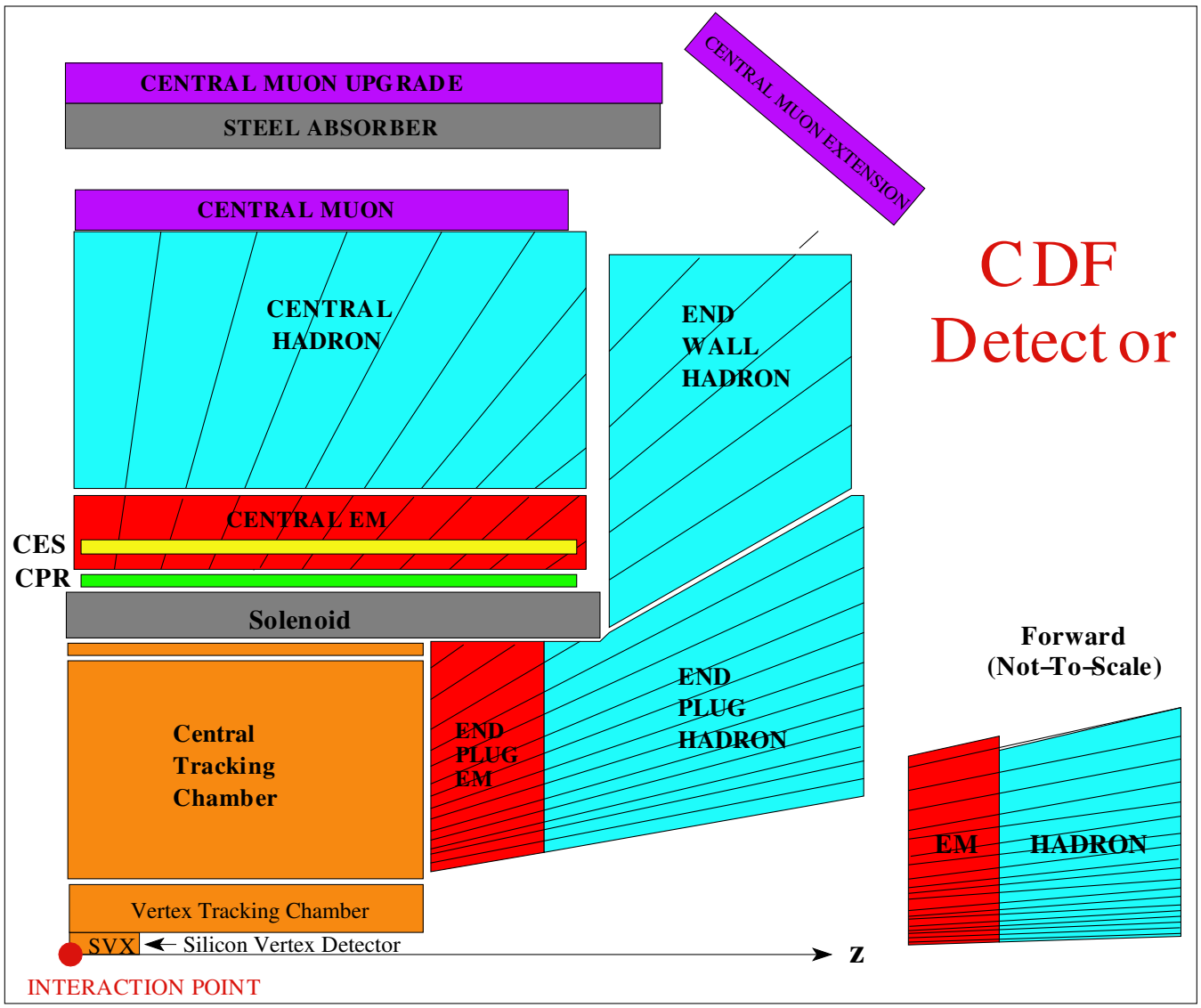
- 1985: First collisions. ~20 events.
- 1987: 25 nb^{-1}. First physics results.
- 1988 - 1989: 4 pb^{-1}. Some intersting measurements.
- 1992 - 1996: 100 pb^{-1}. Top quark discovered.
- 2001 - 2004: 2.0 TeV. 2 fb^{-1}. Ongoing.
- 2005 - 2008(?): +13 fb^{-1}. Higgs?

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

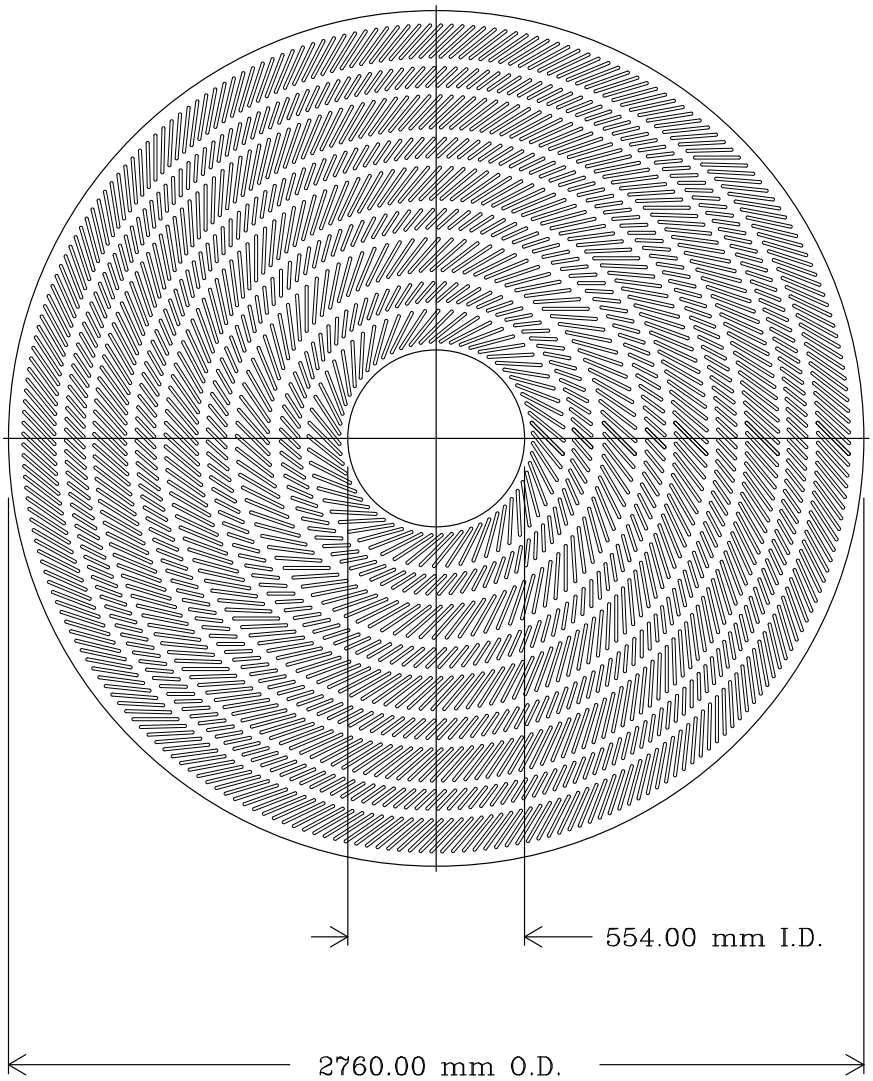


CDF detector, sliced in the plane with the beam axis. Only one quadrant is shown.



- 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 :

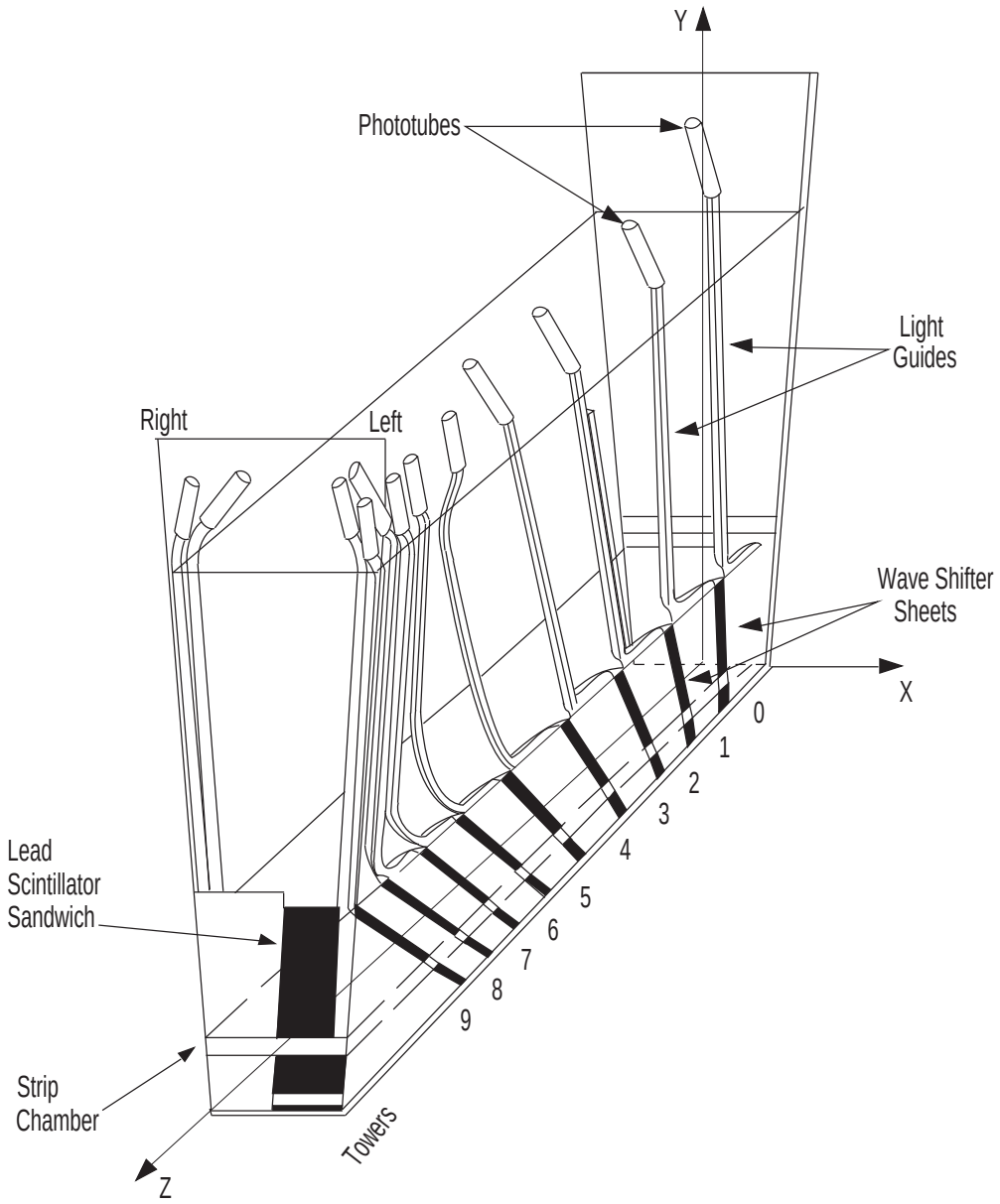


- Drift chamber inside 1.5 T B field.
- 1.4 m in radius, 3 m long.
- 84 measurement layers, grouped into 9 "superlayers".
- 12×5 axial layers, 6×4 stereo (3°) layers.
- Momentum resolution

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

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

Central Electromagnetic Calorimeter CEM :



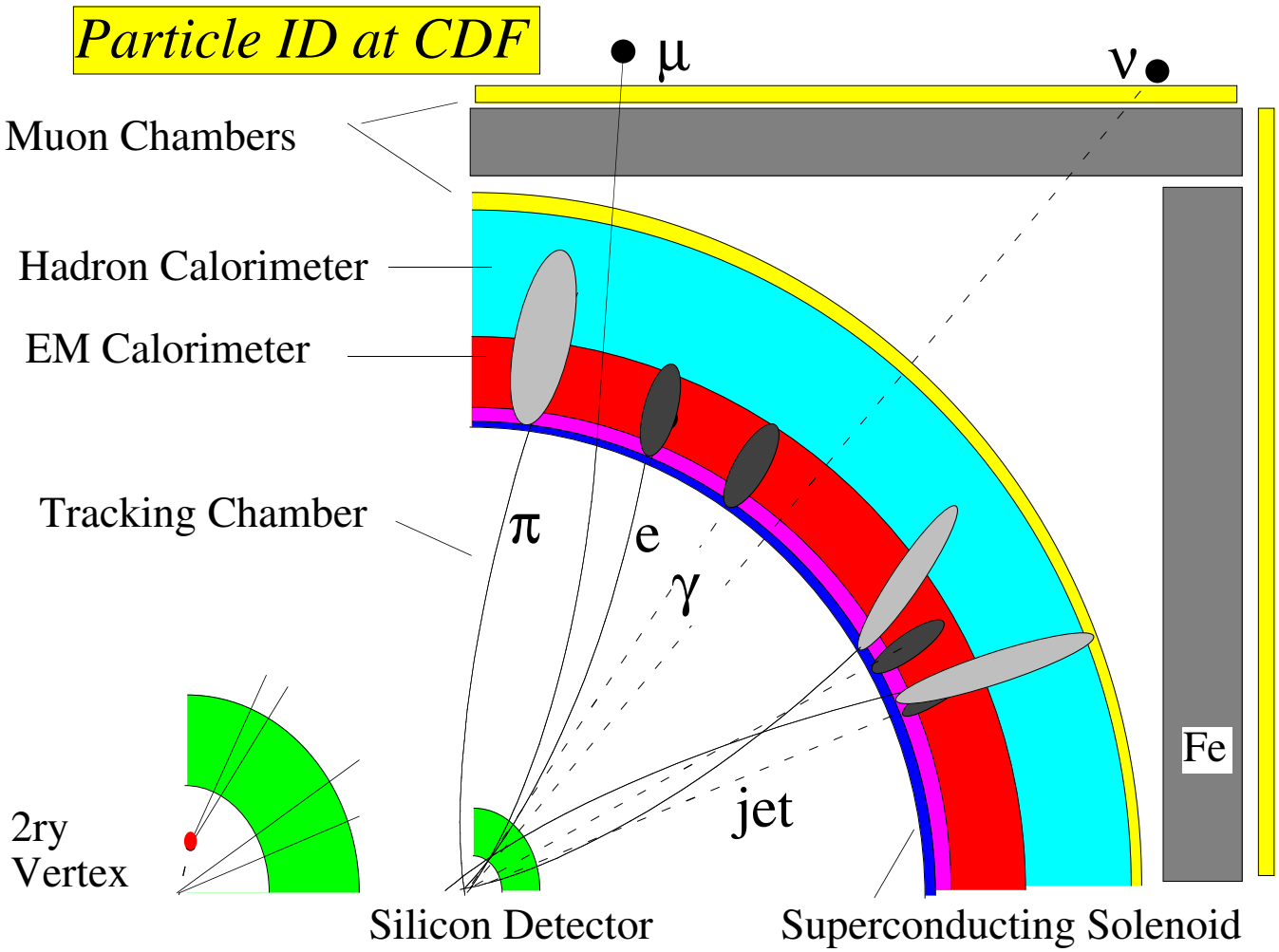
- Covers $\Delta\phi = 15°$, $|\eta| < 1.1$. 10 towers per wedge.
- 3-mm lead, 5-mm plastic scintillator, 31 layers. Total thickness $\simeq 18\, X_0$.

  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.

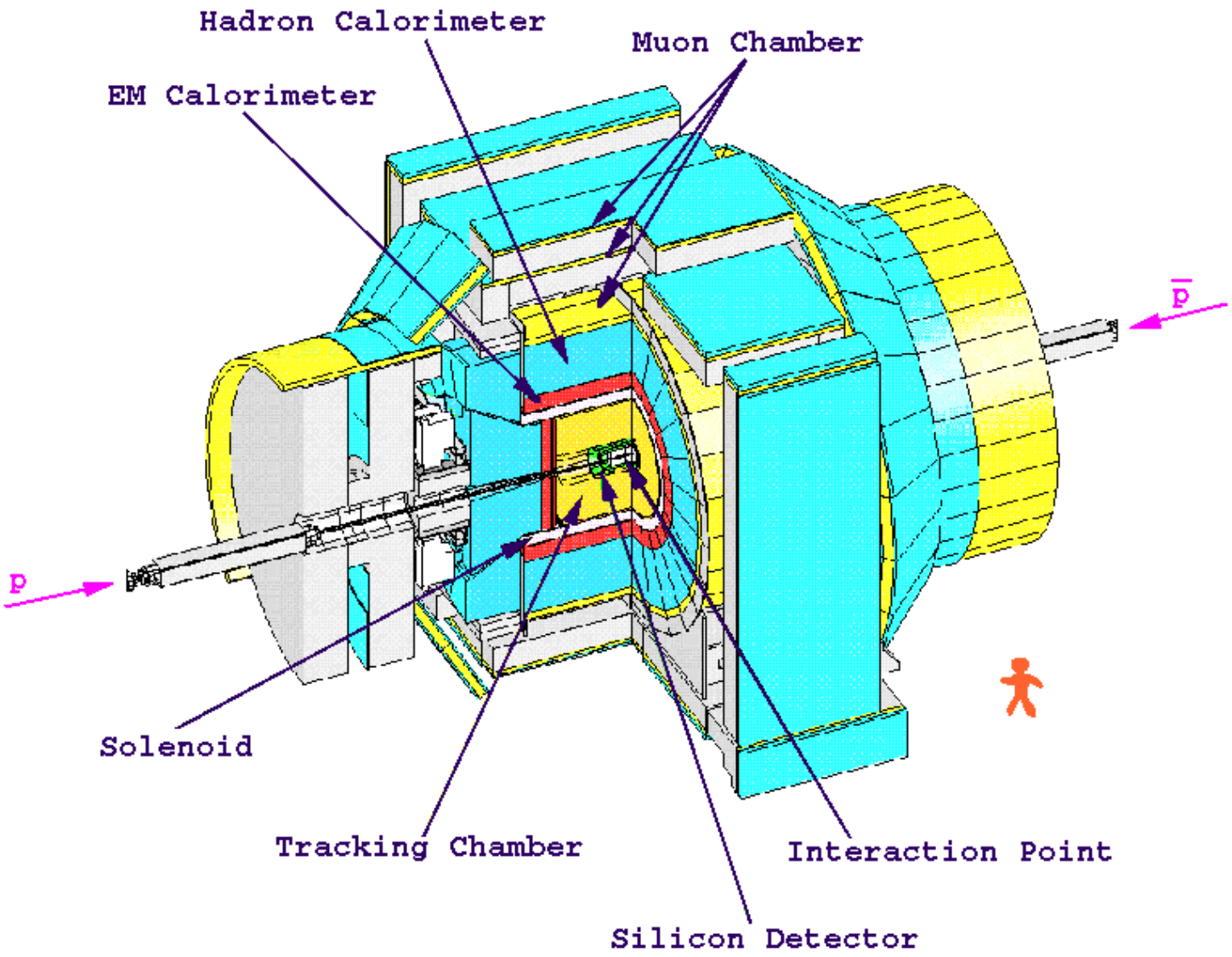
We measure

- 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).

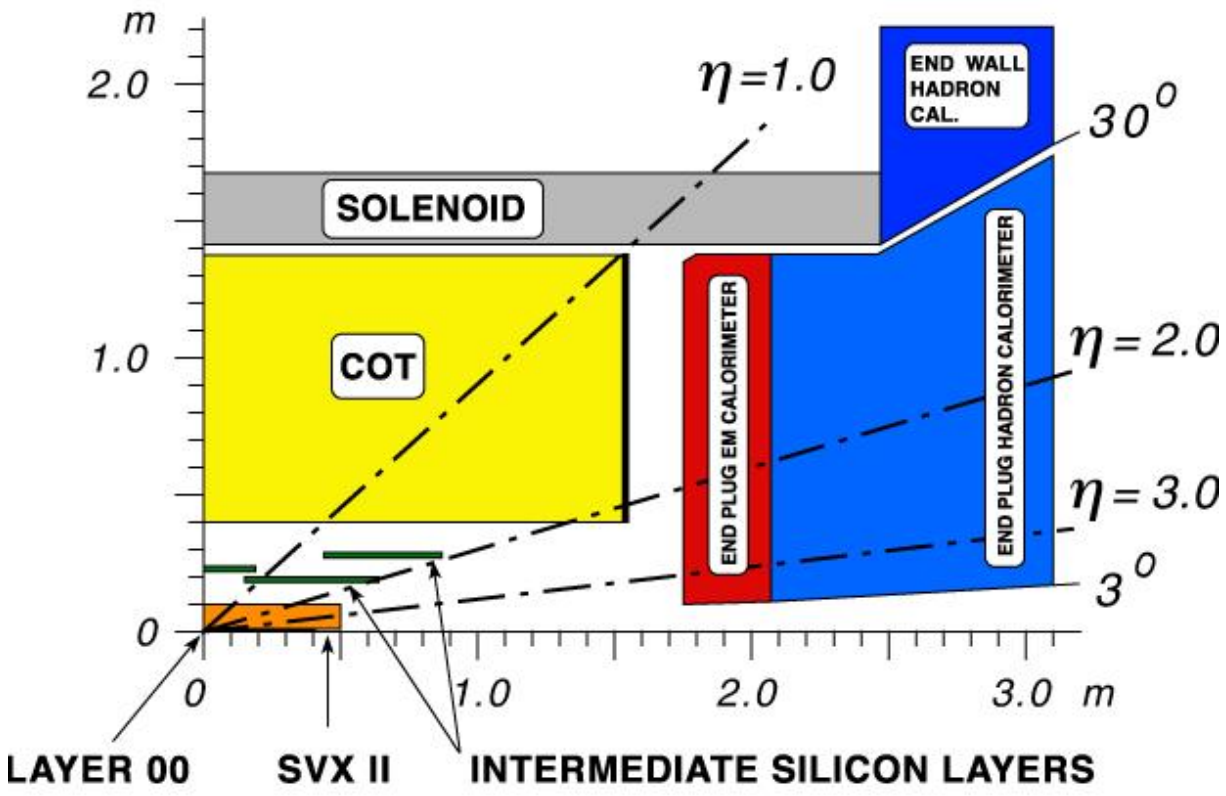
How Different Particles Look Like at CDF



Run-II CDF Detector



CDF-II Detector



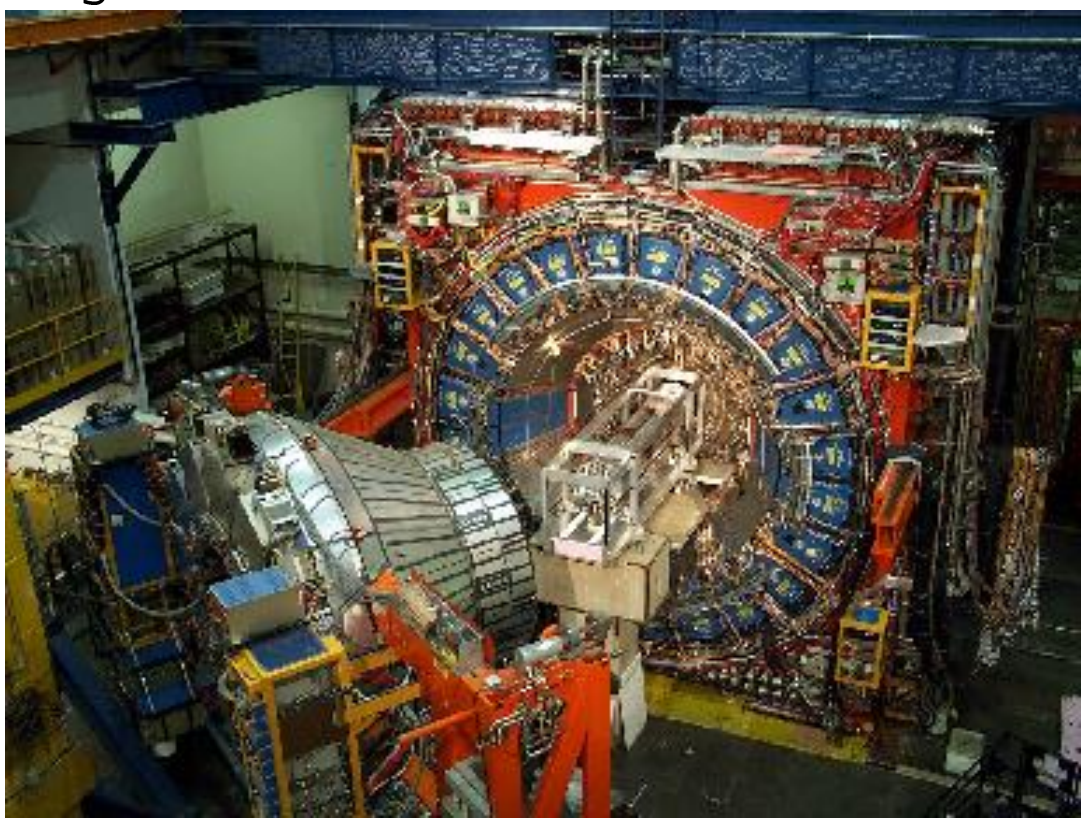
Everything inside the solenoid is new.

- Charged particle tracking

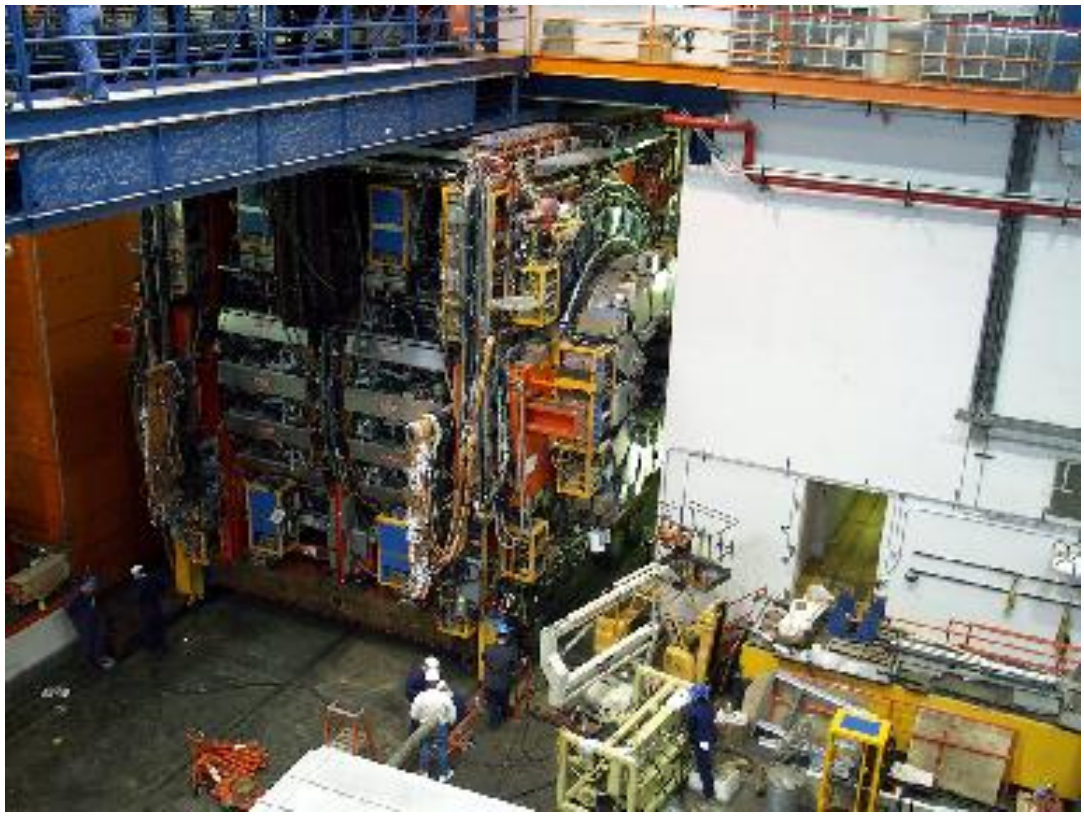
  Central Outer Tracker : 30 k sense wires.
  - $\sigma(p_T)/p_T = 0.0008\, p_T$ for $|\eta| < 1$.
  - Relativistic rise dE/dx.

  SVX : 700 k channels (r-φ-z), 15 readouts per track.
  - $\sigma(P_T)/p_T = 0.004\, p_T$ for $1 < |\eta| < 2$.
- New scintillating plug calorimeter to $|\eta| < 3.6$.
  - electron ID.
- TOF particle ID, $|\eta| < 1$.
- Muon coverage increased by $\times 1.7$.
  - $p_T > 1.4$ GeV/c, $|\eta| < 1.5$.

Installing the silicon detectors.



Rolling into the collision hall.



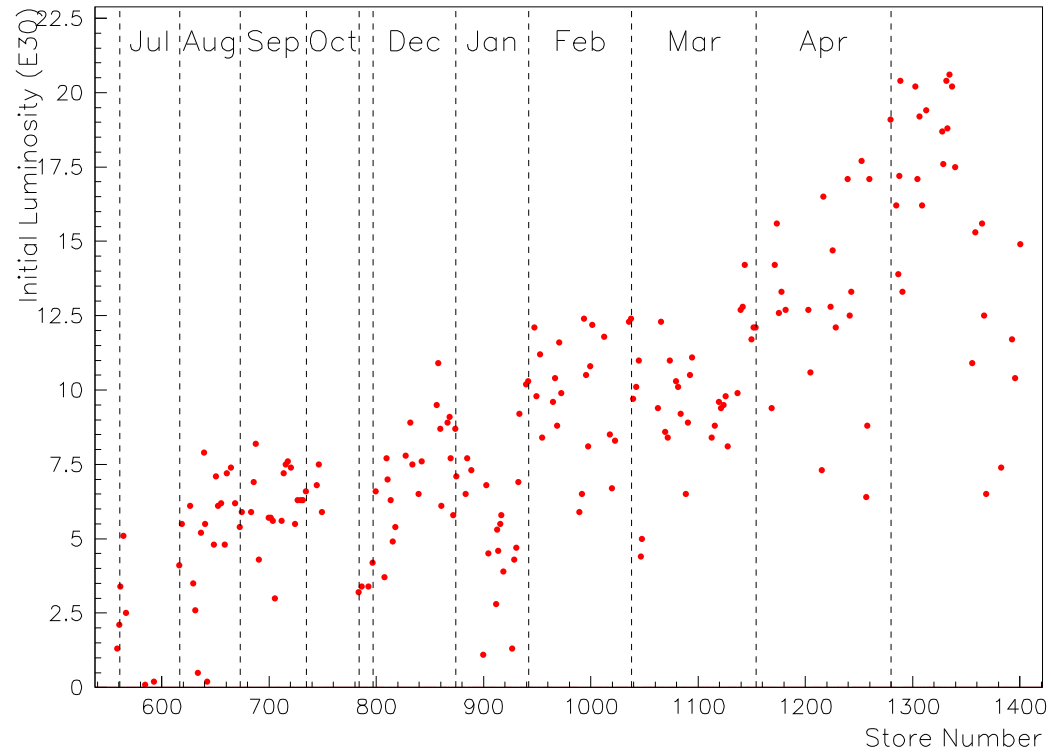
Tevatron Status

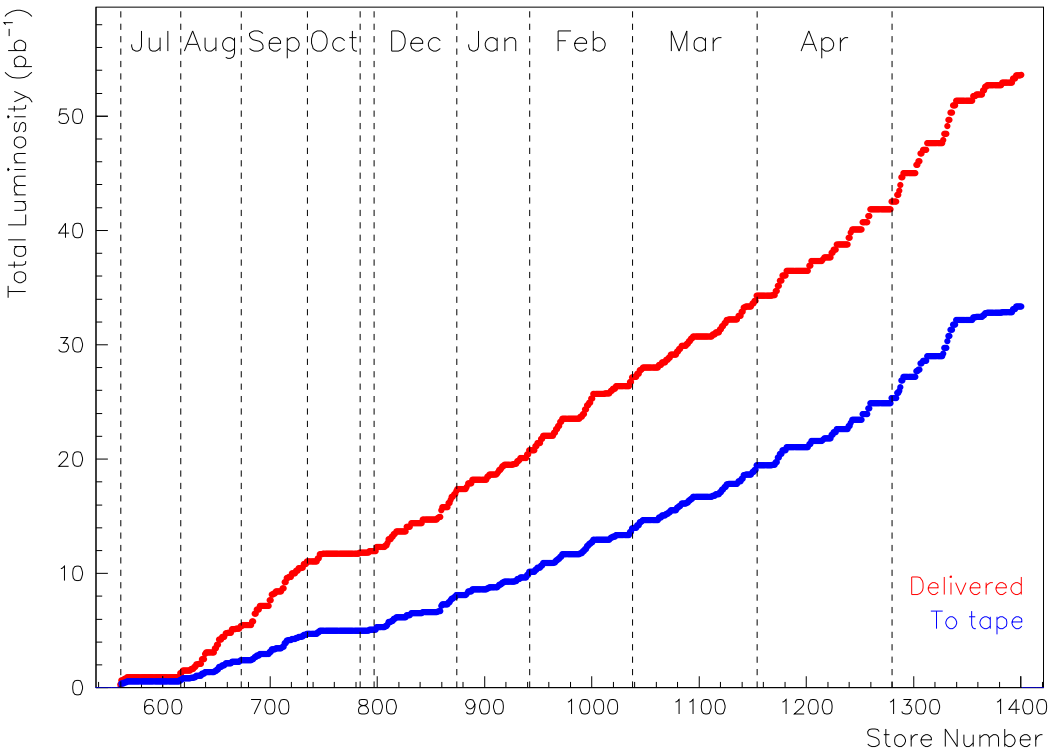
Run II Started in March 2001

36 $\times$ 36 bunches of p's and $\bar{p}$'s
$\Rightarrow$ Beam crossing every 400 ns.

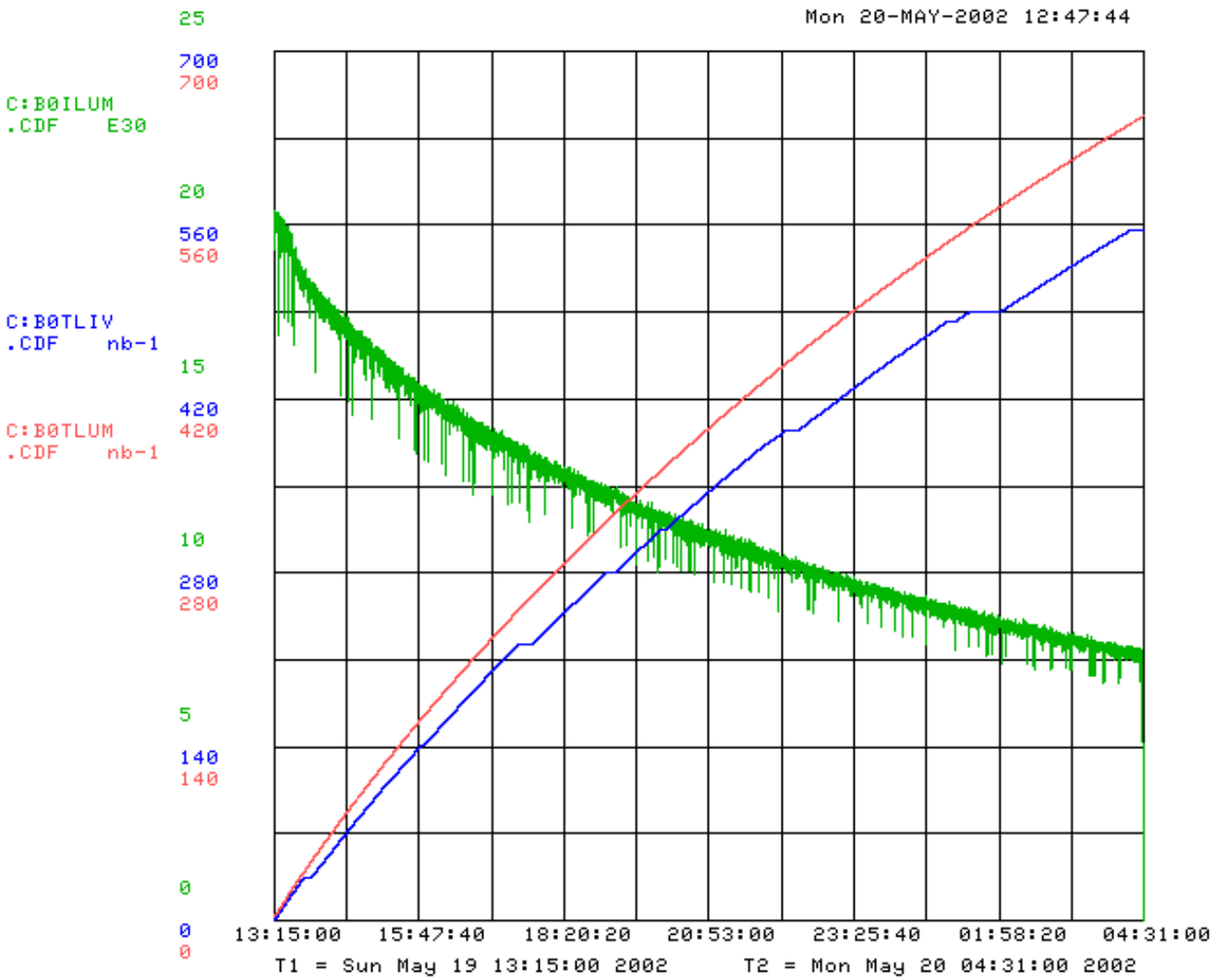
New 150 GeV Main Injector
$\Rightarrow$ Higher $\bar{p}$ production rate. More p's and $\bar{p}$'s to Tevatron.

- Peak lum of 0.5×10^{31} cm^{-2} s^{-1} achieved in June 2001.
- Now typically 2×10^{31} cm^{-2} s^{-1}, $\sim$ best in Run I.





The Best Store : #1335



Initial luminosity : 20.6×10^{31} cm^{-2} s^{-1}.

Duration : 14.9 hours.

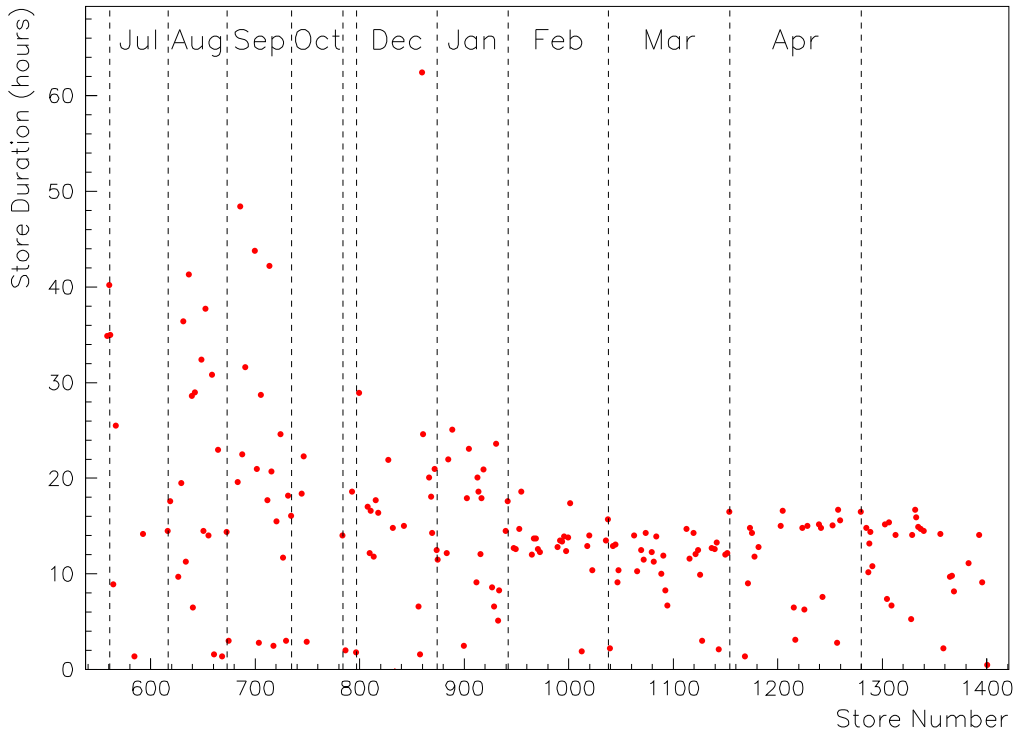
Integrated luminosity delivered : 648 nb^{-1}.

Integrated luminosity recorded : 556 nb^{-1}.

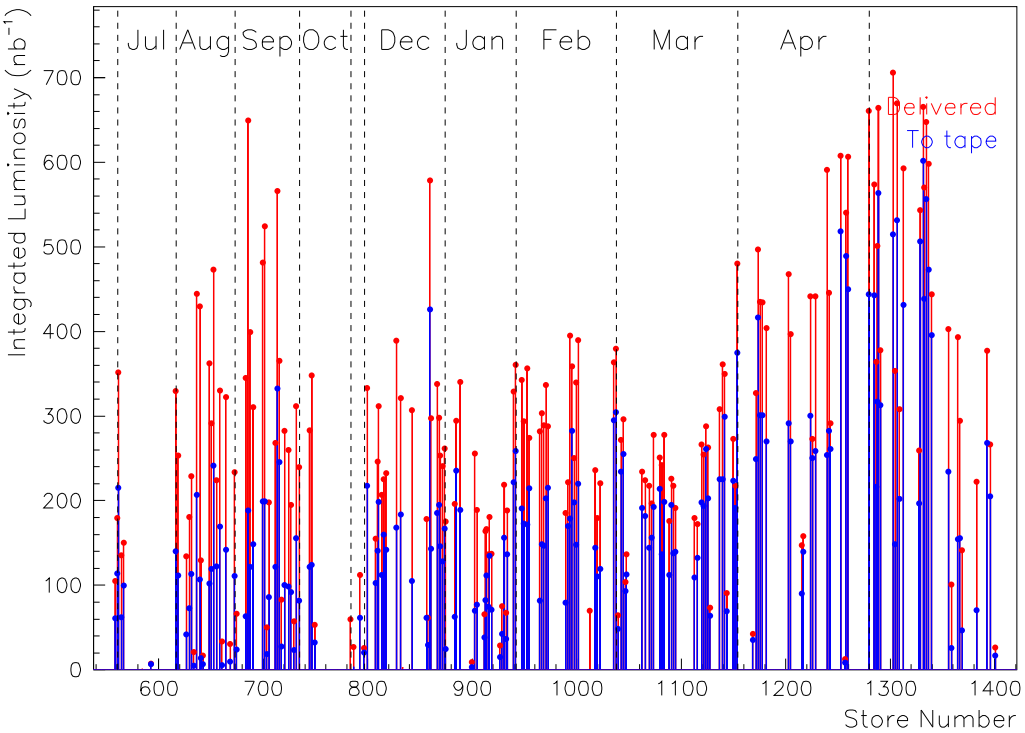
Shot Summary, store 1359, Sun May 26 01:07:01
CDT 2002, Initial Stack Size =
107.78750000000001 E10

	Proton Intensity E9	**Step Efficiency %**	**Cumulative Efficiency %**	**Pbar Intensity E9**	**Step Efficiency %**	**Cumulative Efficiency %**
Accumulator				948.00		
AP3				874.06	92.20	92.20
AP1				845.36	96.72	89.17
P2				801.79	94.85	84.58
P1				860.83	107.36	90.80
MI Inj				948.07	110.13	100.01
MI 8Gev				816.22	86.09	86.10
MI 150Gev				845.50	103.59	89.19
Coalescing	10679.89			615.63	72.81	64.94
Inject Protons	8759.53	82.02	82.02			
Pbar Injection porch	8797.78	100.44	82.38			
Inject Pbars	7210.40	81.96	67.51	502.69	81.65	53.03
Before Ramp	7189.64	99.71	67.32	404.64	80.50	42.68
Flattop	6748.72	93.87	63.19	350.91	86.72	37.02
Squeeze	6738.70	99.85	63.10	338.75	96.53	35.73
Initiate Collisions	6731.23	99.89	63.03	340.96	100.65	35.97
Remove Halo	6593.03	97.95	61.73	327.60	96.08	34.56
HEP	6599.60	100.10	61.79	331.79	101.28	35.00
Initial Luminosity	15.25	CDF		14.11	DZero	
Shot Setup Time	143.28	min				

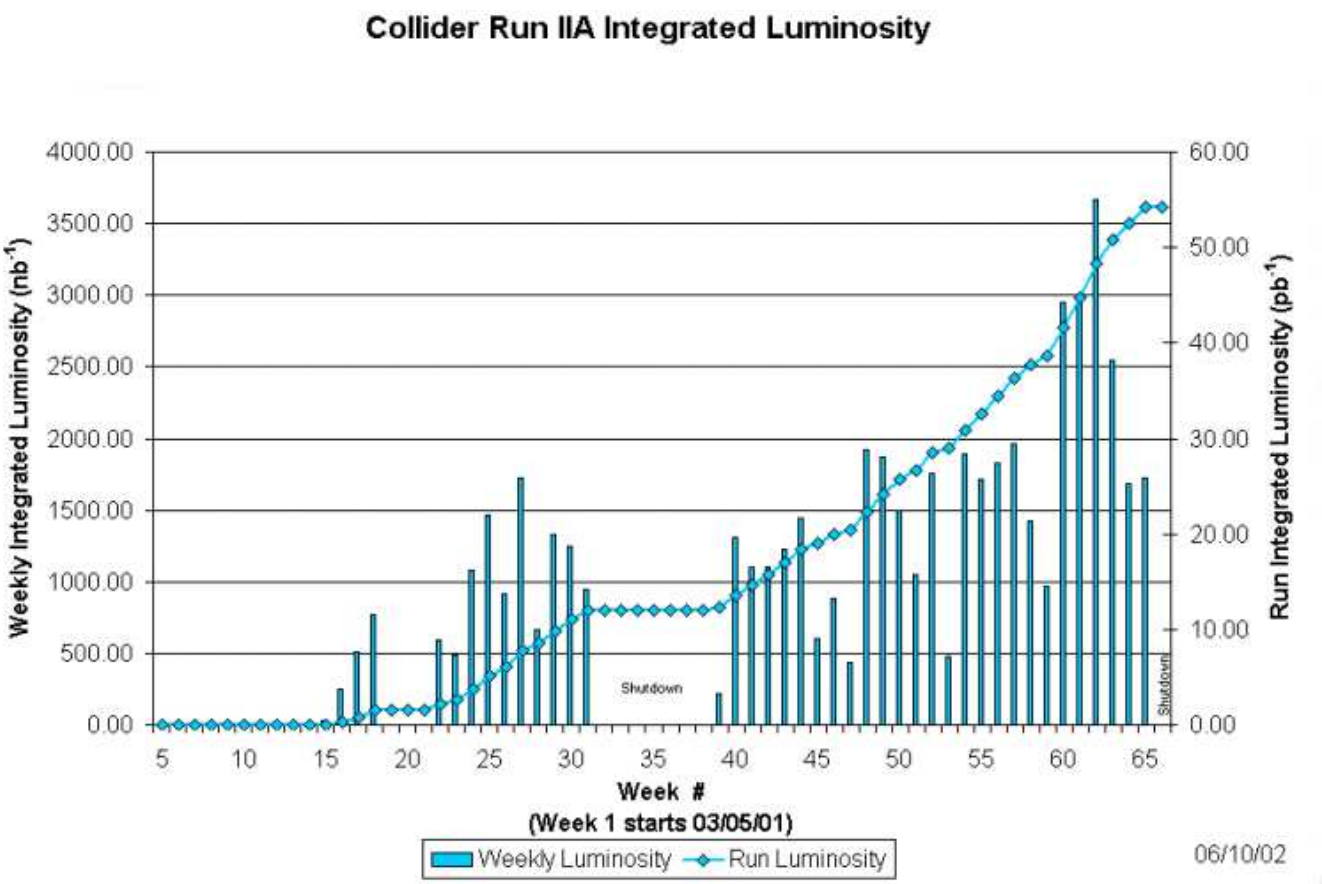
Store duration



Integrated luminosity per store



Integrated luminosity (delivered) by week



Luminosity not as high as we hoped for :

- $\bar{p}$ transfer efficiency (MI to TeV) low.
  Emittance large.

  Just finished 2-week shutdown to improve stochastic cooling (Accumulator).

  Hope to get a factor of two in lum.

- 6-week shutdown planned for Oct - Nov,
  to work on Recycler and others.

  Hope to get another factor of two then.

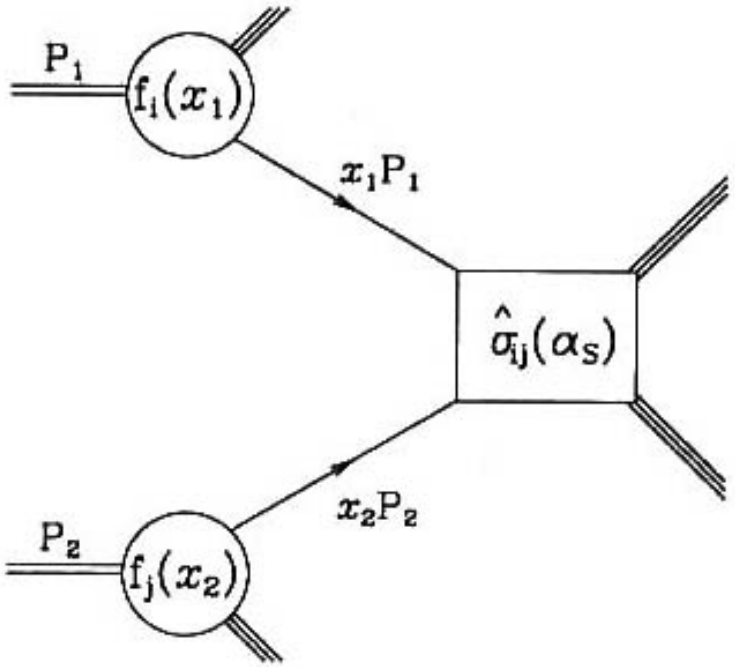
  $\Rightarrow 8 \times 10^{31}$ cm^{-2} s^{-1} $\sim$ Run-IIa goal.

Plans :

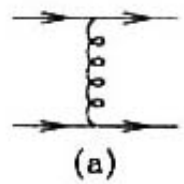
- 300 pb^{-1} by end of 2002.
- 1200 pb^{-1} by end of 2003.
- 2500 pb^{-1} in Run-IIa total (end of 2004).
- 2005 : 6-month shutdown to replace silicon.
- After that, Run IIb continues thru 2008, 15 fb^{-1}.

Jet Production

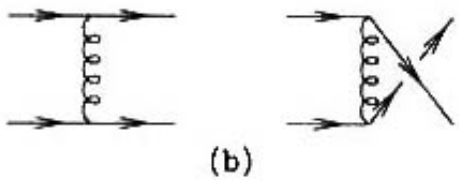
Jets are the most common events in hard hadron-hadron collisions.



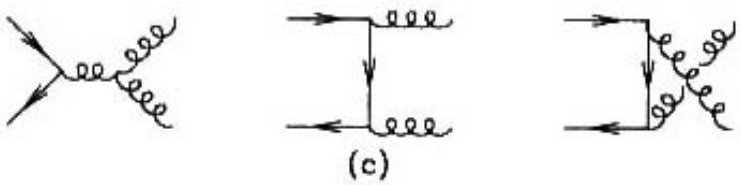
Lowest order sub-processes for jet production:


(a)

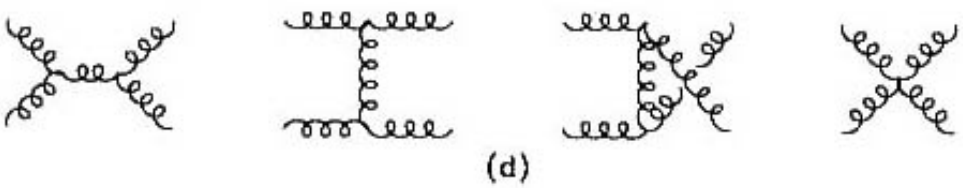
$qq' \to qq'$


(b)

$qq \to qq$


(c)

$q\bar{q} \to gg$


(d)

$gg \to gg$

Initial parton composition vs. final state jet E_T

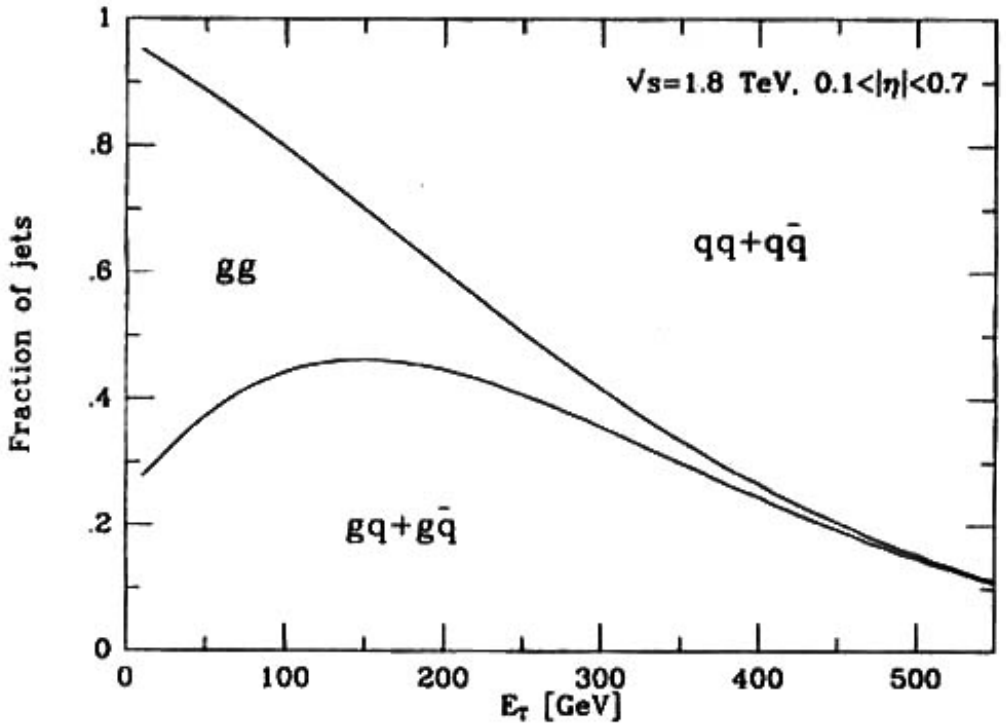
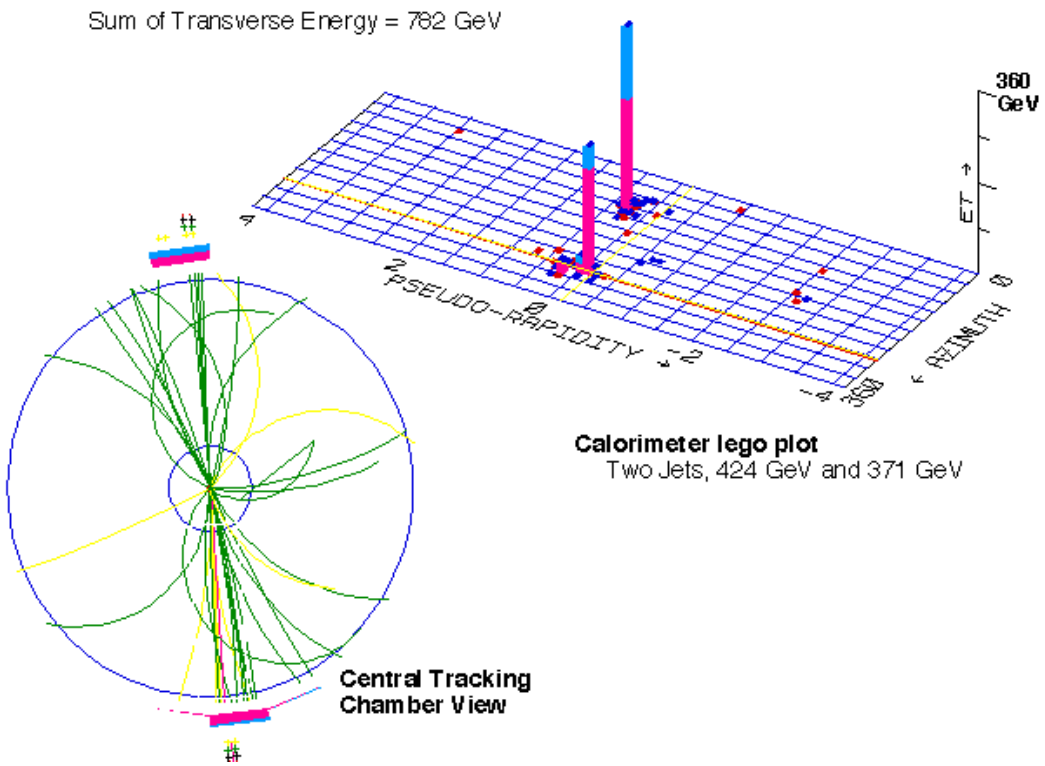


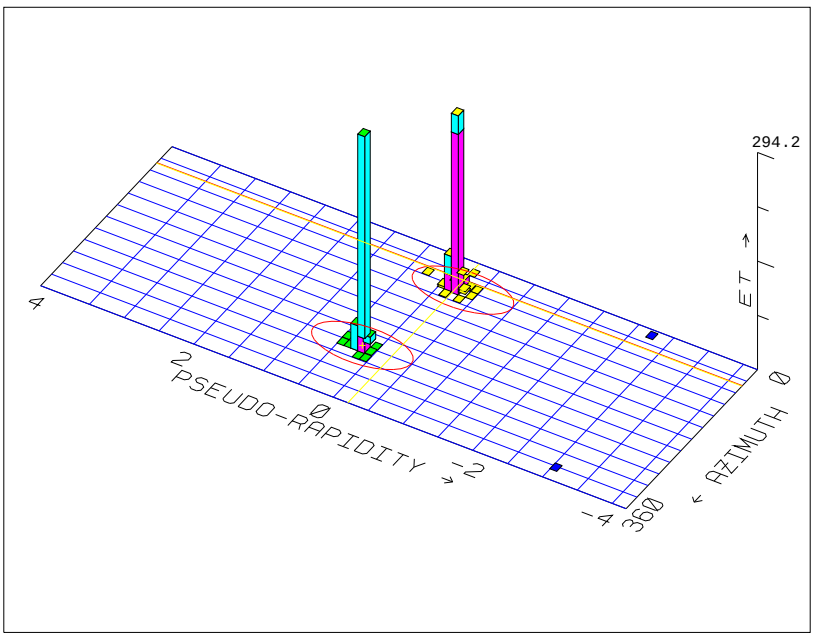
Fig. 7.8. Plot showing the fraction of the jet E_T distribution initiated by different parton combinations.

CDF: Highest Transverse Energy Event from the 1988-89 Collider Run

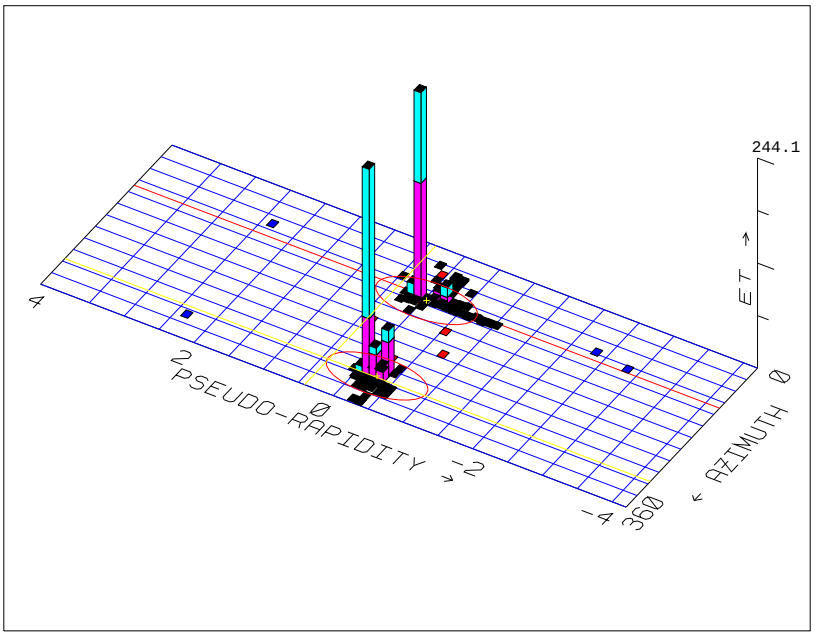


How you define jets?

CDF has used cone algorithm.
Cone in η-ϕ space, radius $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.
Add all calorimeter tower energies inside the cone.
Cone size : $R =$ 0.7 usual, sometimes 0.4, 1.0.

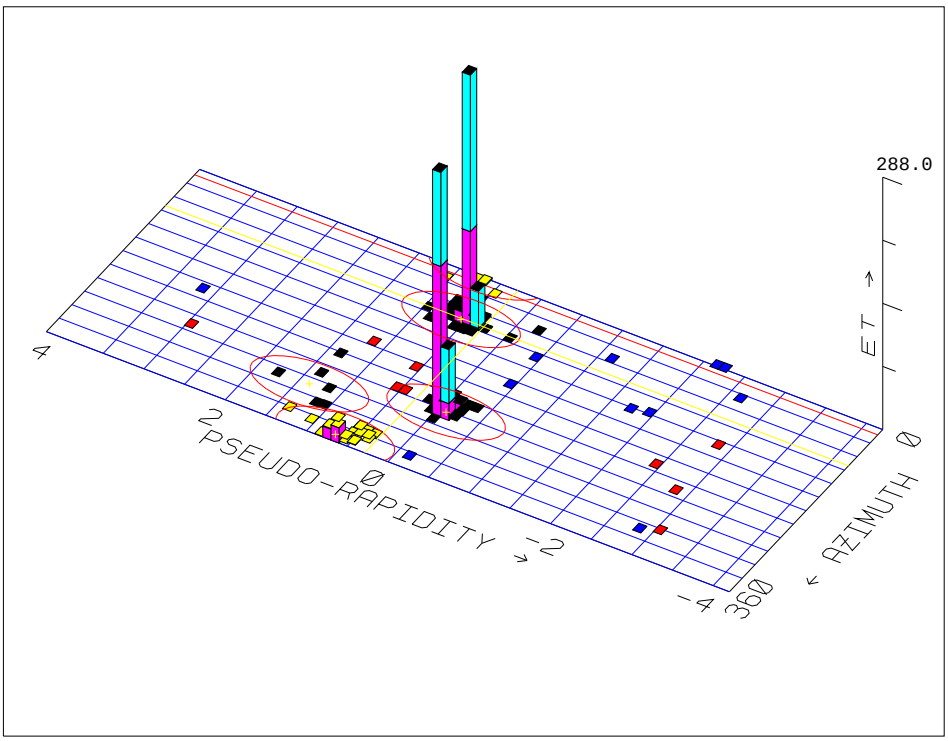


Two jets

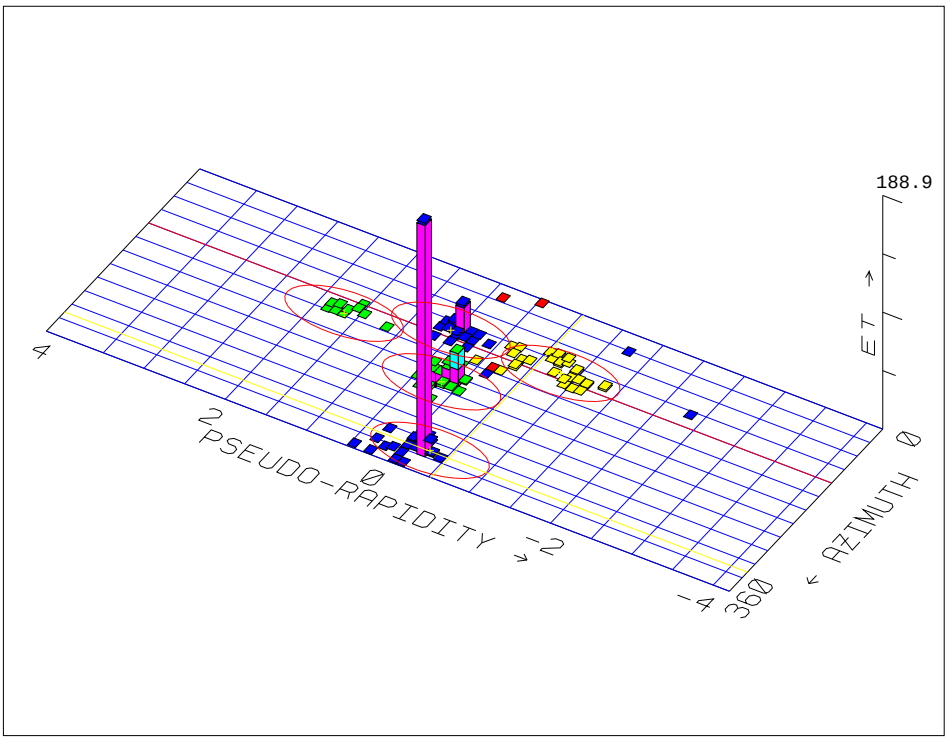


Two jets

Four jets



Five jets

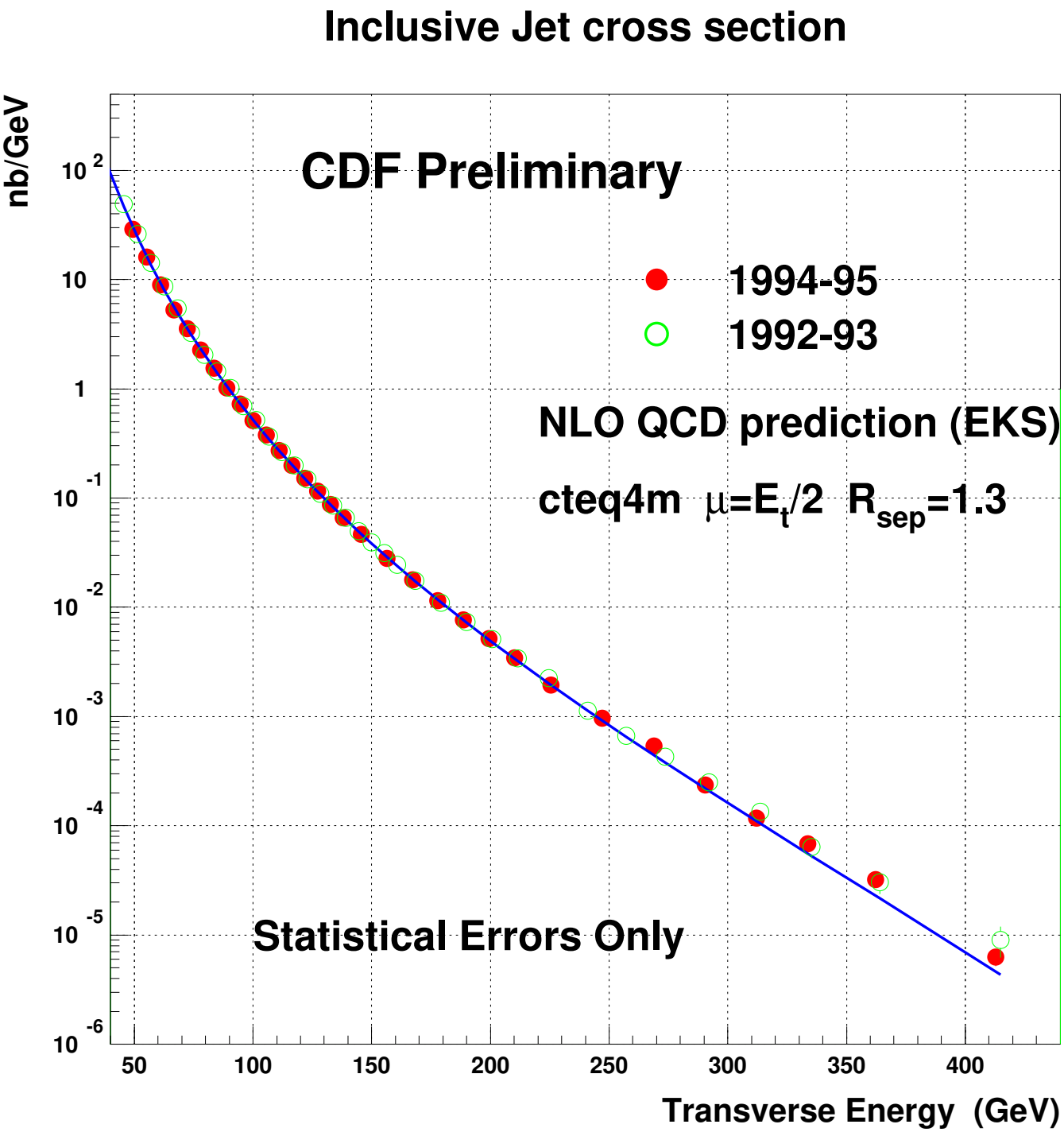


Red : EM cal energy

Blue : Hadron cal energy

Inclusive Jet Cross Section

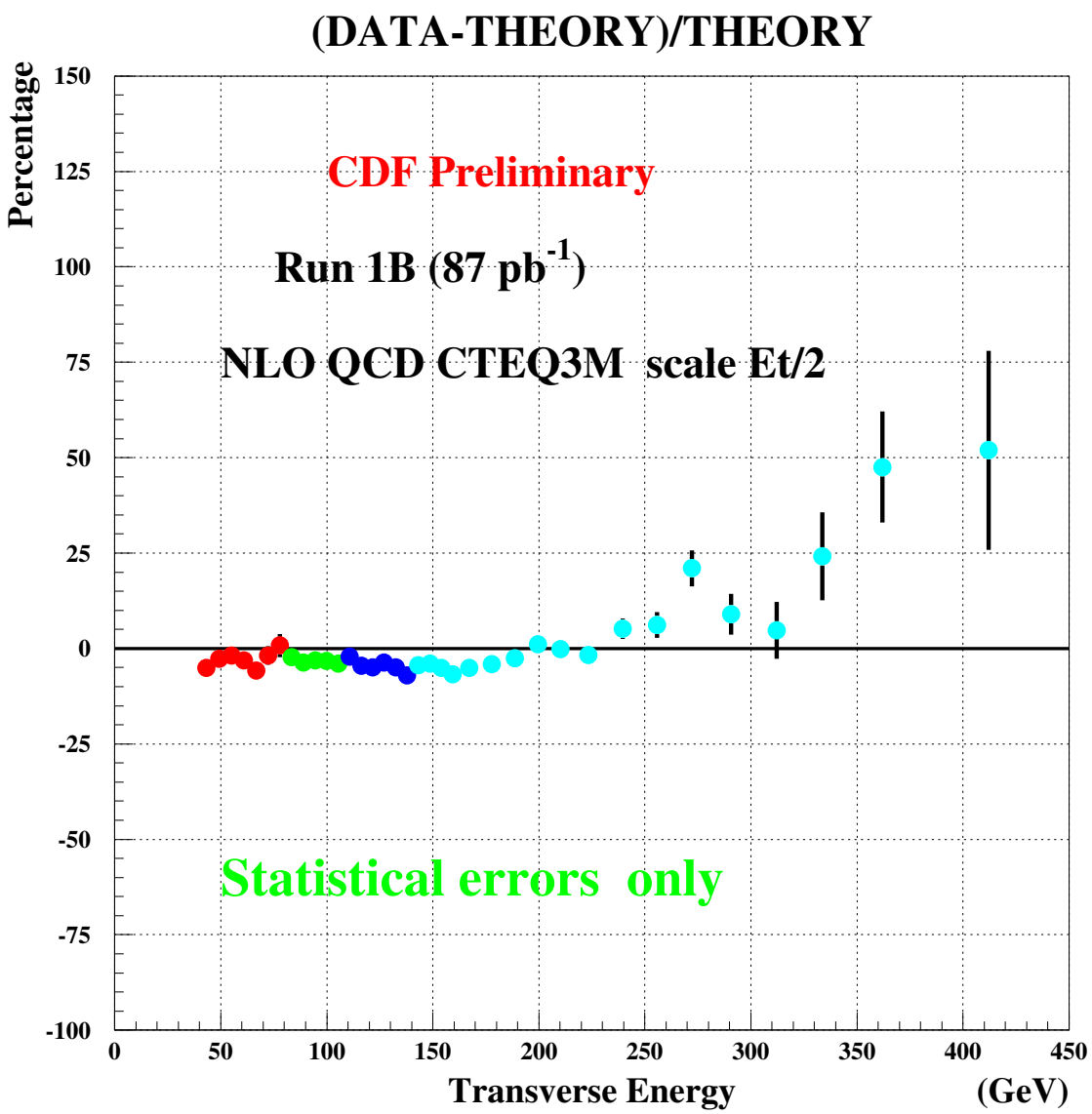
PRD 64, 032001 (2001)



Covers seven orders of magnitudes.

Overall, impressive agreement with theory.

Data-Theory Comparison

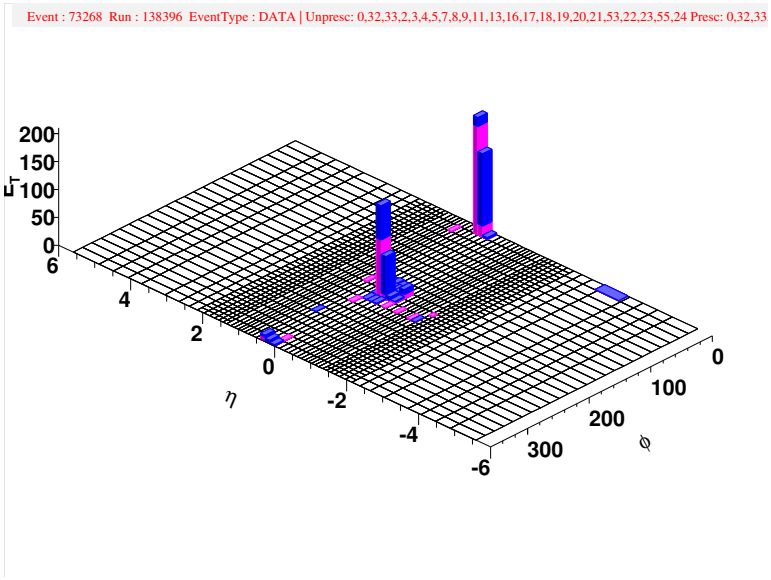


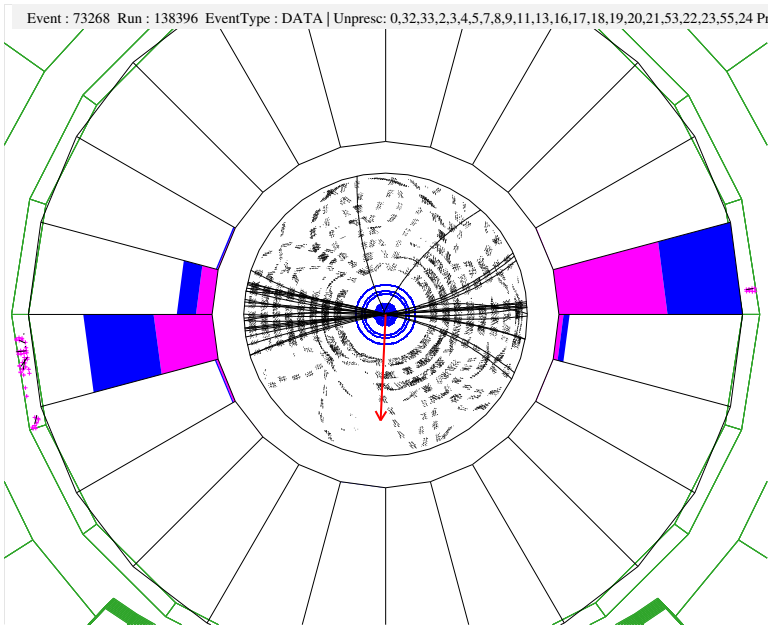
Excess at the high end? Need more stat.

Run-II examples :

CDF Highest E_T Dijet Event

- Jet E_{T1} = 403.3 GeV, η_1 = 0.037 (uncorrected)
- Jet E_{T2} = 322.0 GeV, η_2 = -0.364 (uncorrected)
- Vertex z = 39.0 cm
- Missing E_T Significance = 1.93

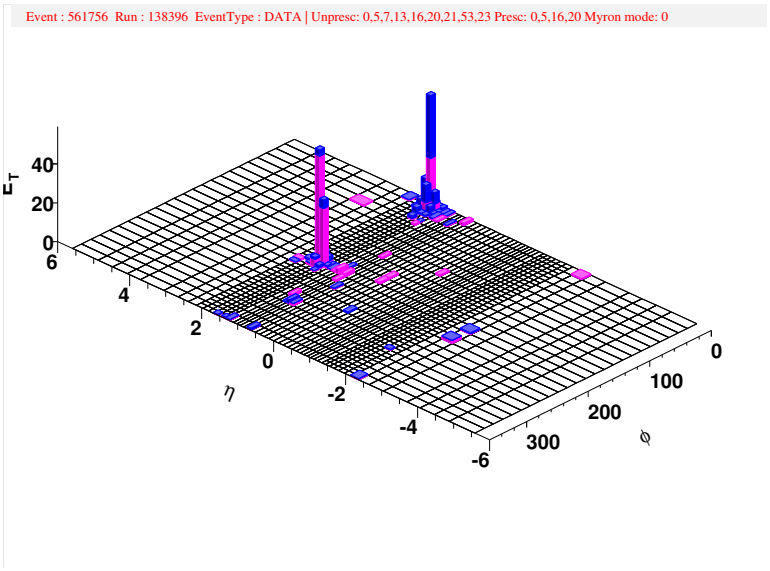


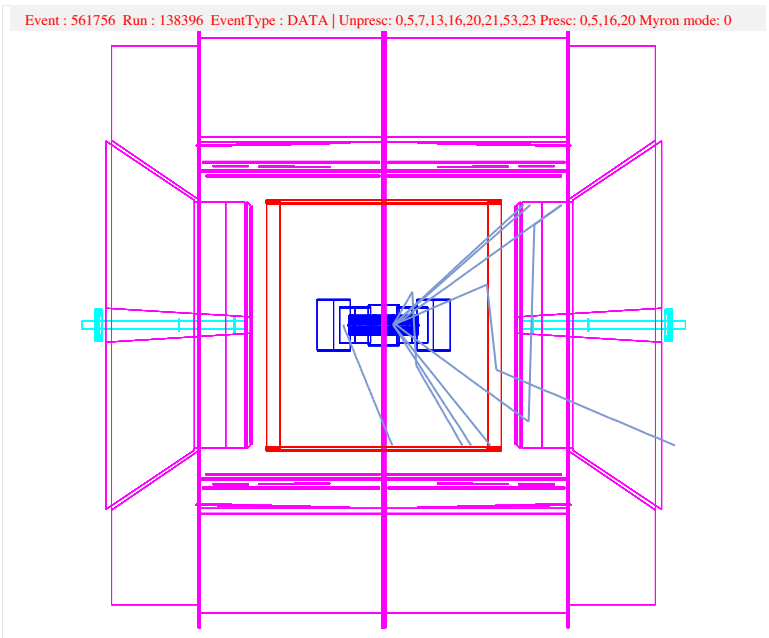


Run-II forward jets :

CDF Forward Dijet Event

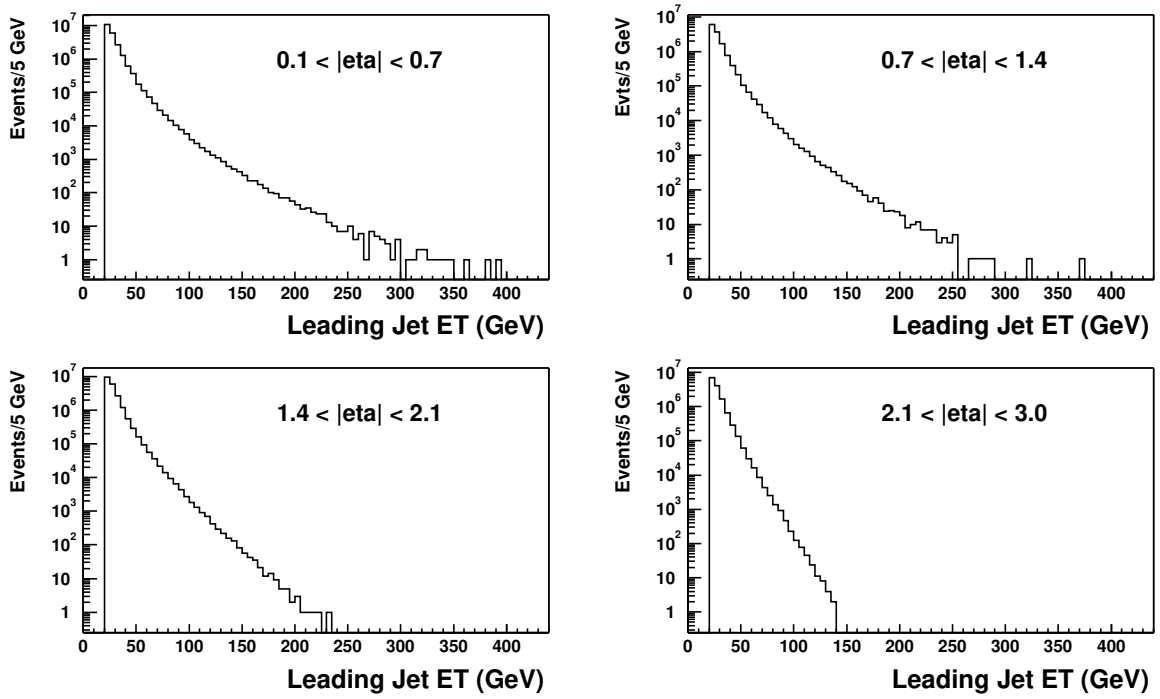
- Jet E_{T1} = 153.9 GeV, η_1 = 1.48 (uncorrected)
- Jet E_{T2} = 146.8 GeV, η_2 = 1.45 (uncorrected)
- Vertex z = 14.1 cm
- Missing E_T Significance = 0.08





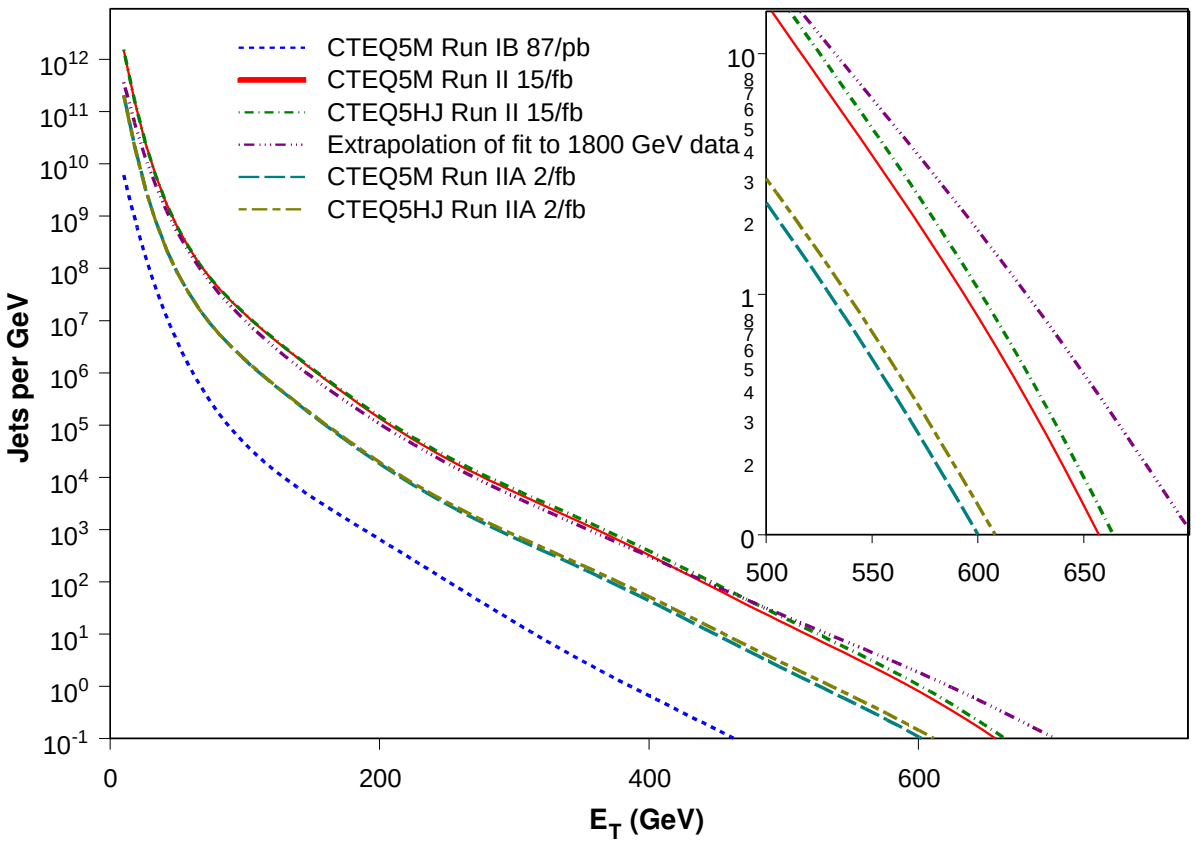
Leading Jet ET in CDF Jet Events

CDF Run 2 Preliminary (12/14/2001 - 2/18/2002) 4.4 pb-1



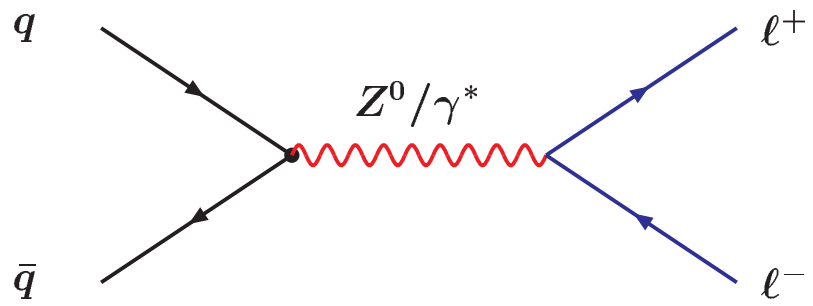
Run-II reach

Jet Yields Bin 1 - 0.1 < |y| < 0.7



Up to 550 GeV with 2 fb^{-1}, 600 GeV with 15 fb^{-1}.

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



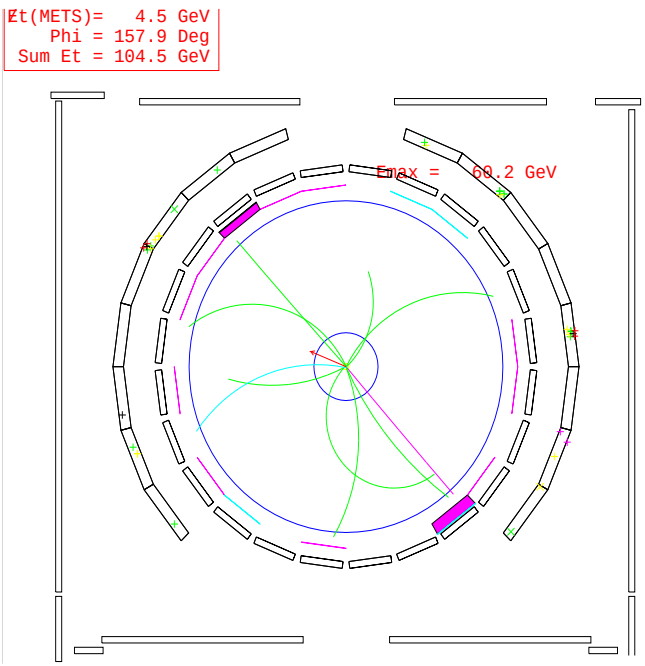
Z^0

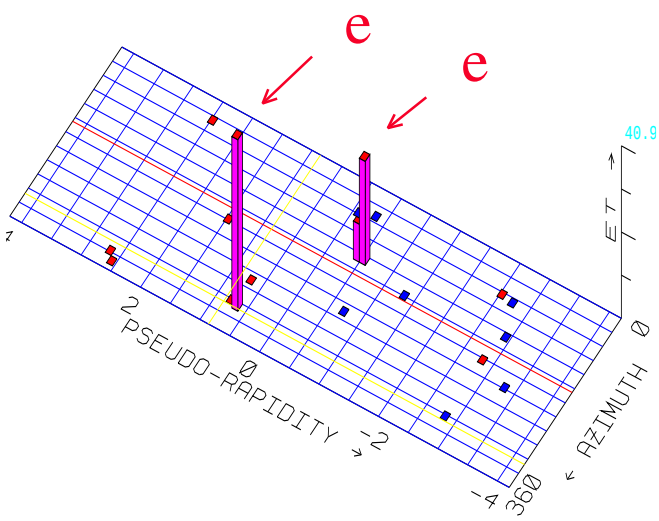
- $M_{Z^0} = 90$ GeV/c^2, thus $\sqrt{x_1 x_2} = M_Z^0/\sqrt{s} \simeq 0.05 \rightarrow$ quarks at small x.
- Z^0 decays to $\ell^+\ell^-$, $q\bar{q}$, $\nu\bar{\nu}$.
  $\ell^+\ell^-$ final states very distinctive. $\mathcal{B} \simeq 3\%$.
- Require two high p_T leptons. $\ell = e$ or μ.
  Electrons :
  - 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.

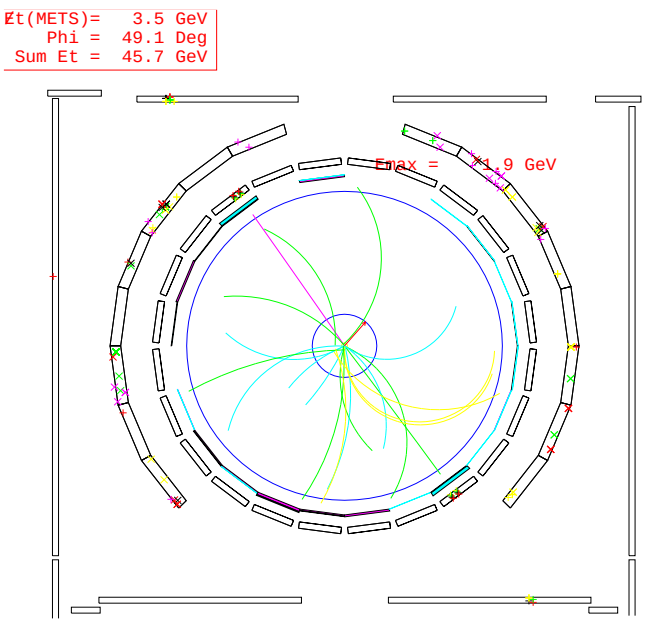
CDF

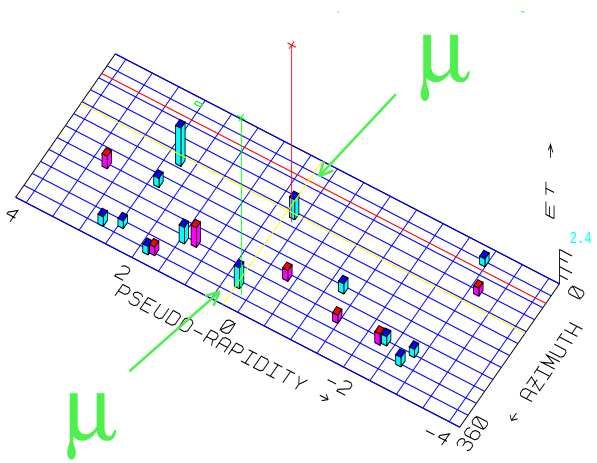
$Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ Events





$E_T \cong 44$ and 36 GeV



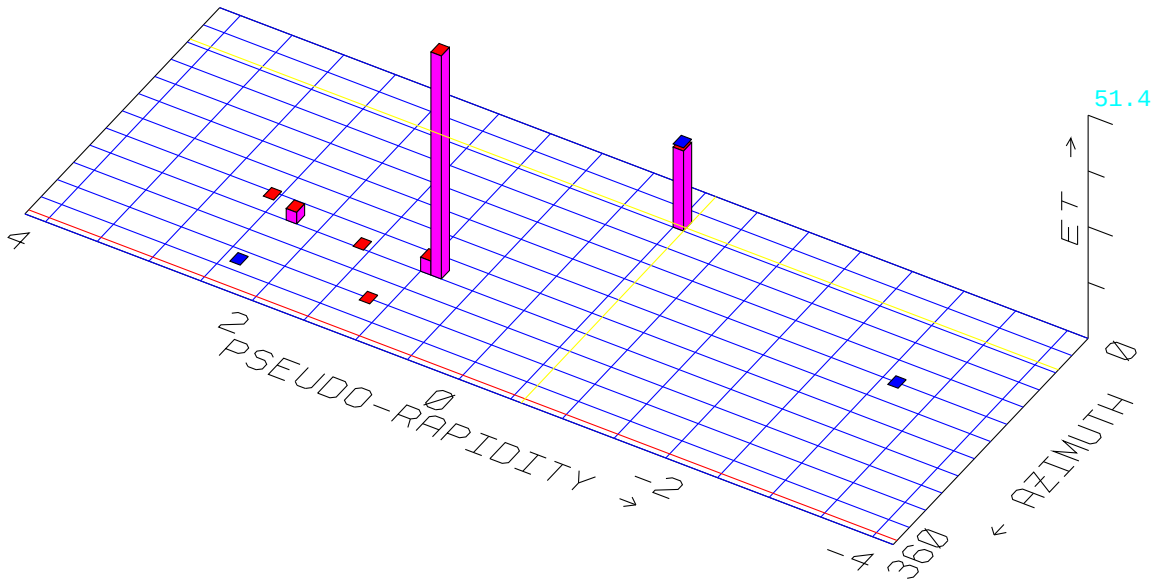


$P_T \cong 50$ and 32 GeV

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

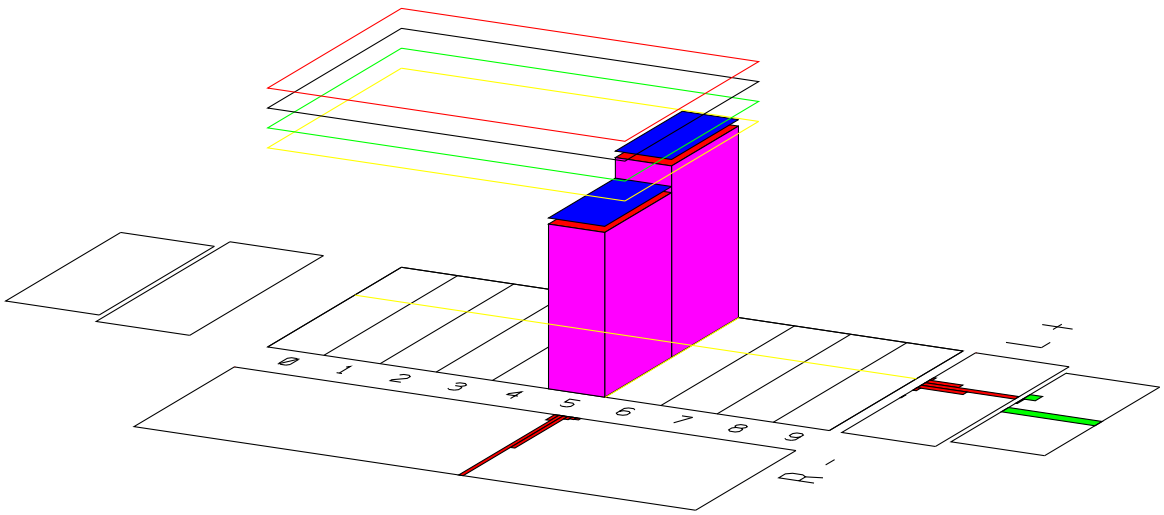
0	0	0	0	1279	65535	1477	1057	0	0
0	0	0	0	1018	6986	1036	0	0	0

* CHAD * AMP x16, x1 LEFT towers 0 - 7

0	0	0	0	1000	1000	1000	1000
0	0	0	0	1020	1237	0	0

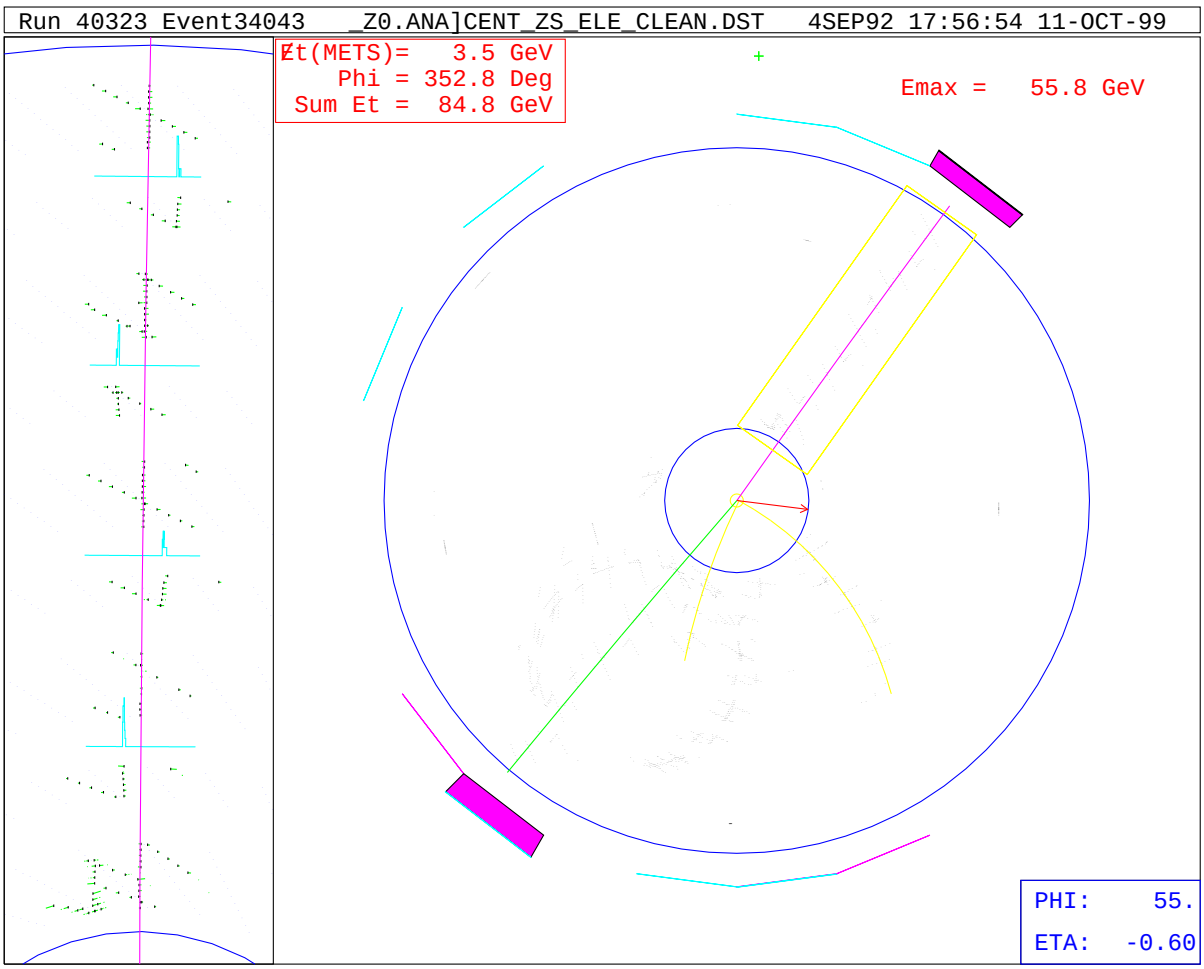
* CHAD * AMP x16, x1 RIGHT towers 0 - 7

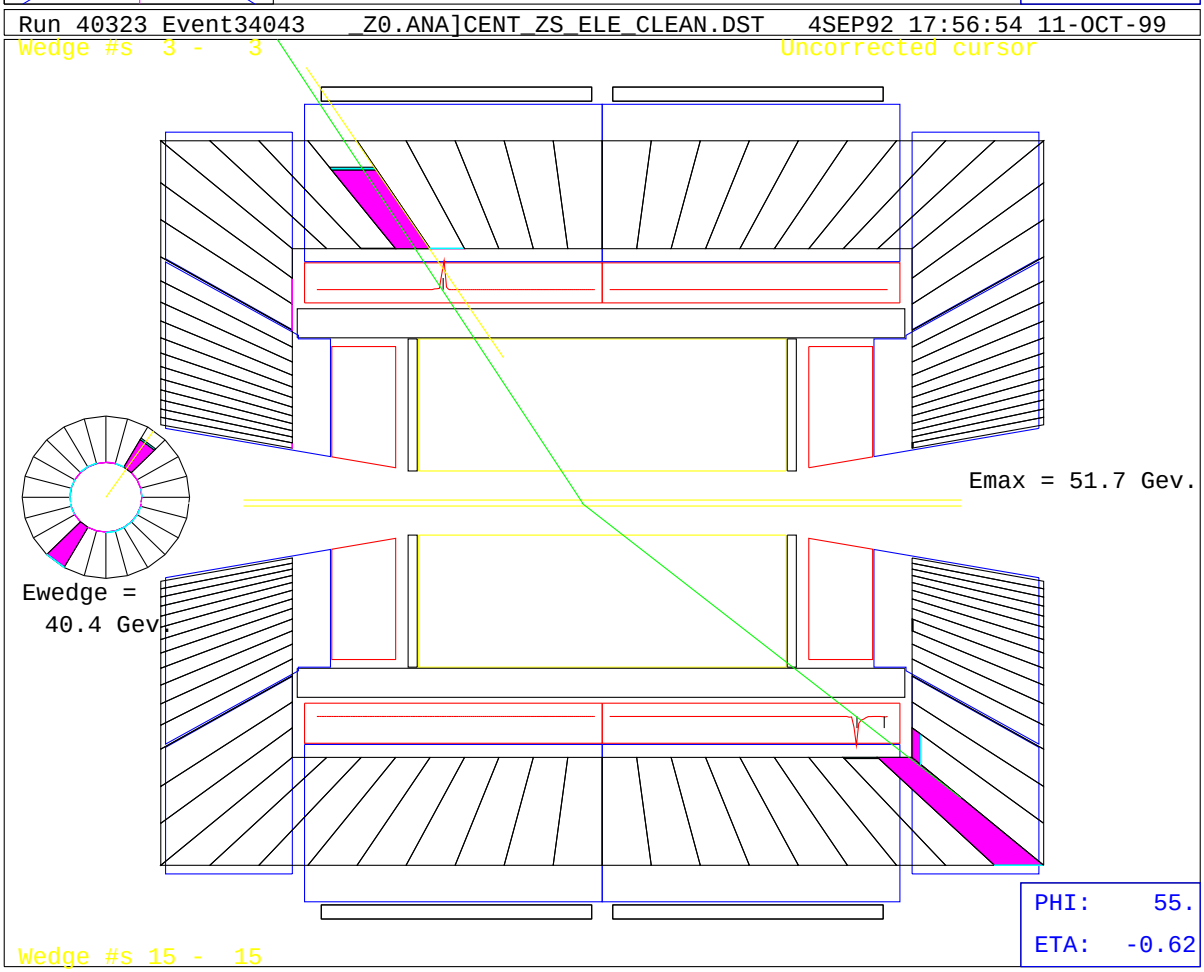
0	0	0	0	0	1000	0	0	
0	0	0	0	0	1224	0	0	
0	0	0	0	0	13263	0	0	CHA TDC



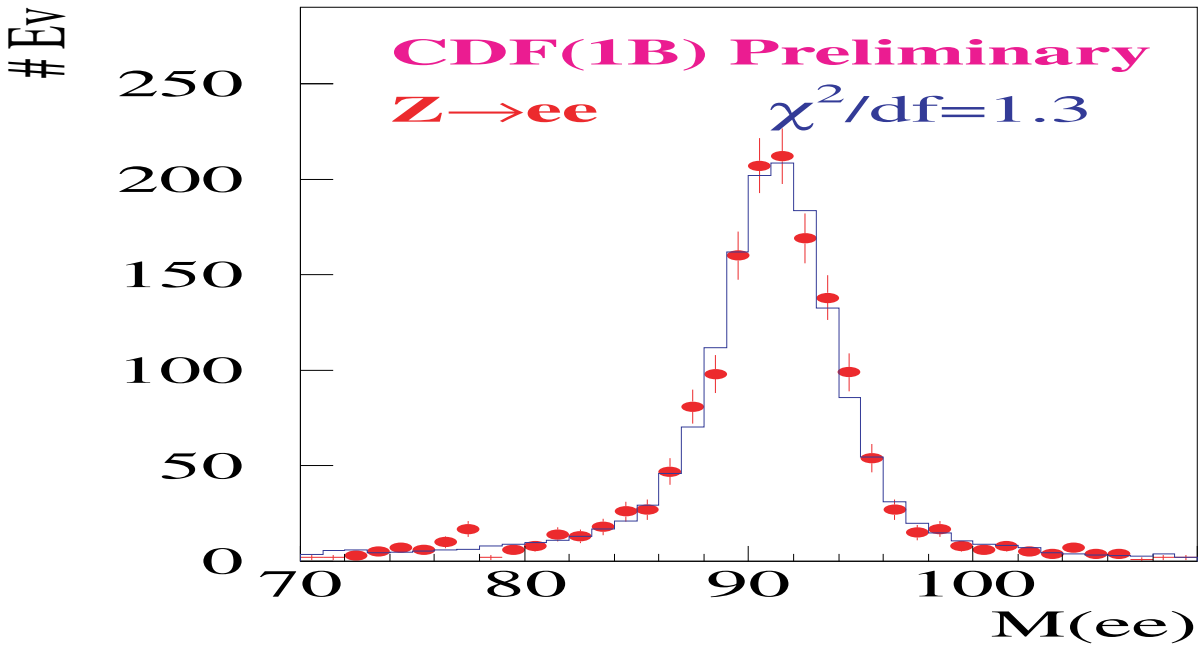
Min and Max(Channel = 74) Str GeV 0.000 9.562
Min and Max(Channel = 51) Wir GeV 0.000 10.049
Min and Max(Channel = 24) Pre fC 0.00 4393.51(= 8 MIPS)

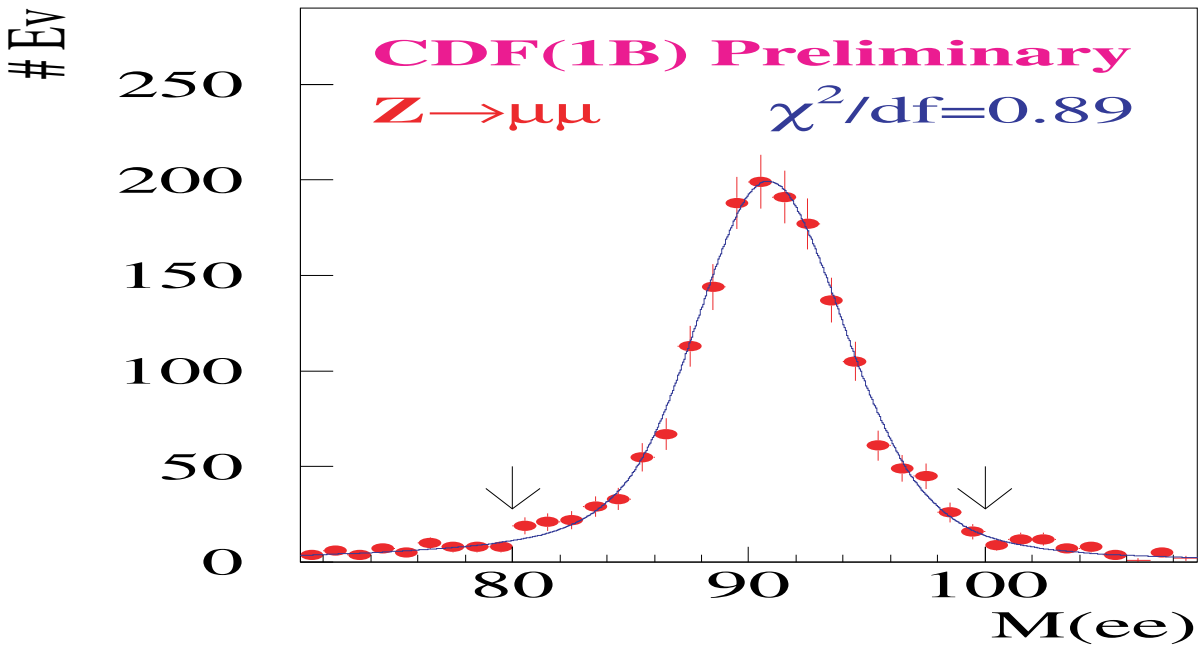
PHI: 55.
ETA: -0.60


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

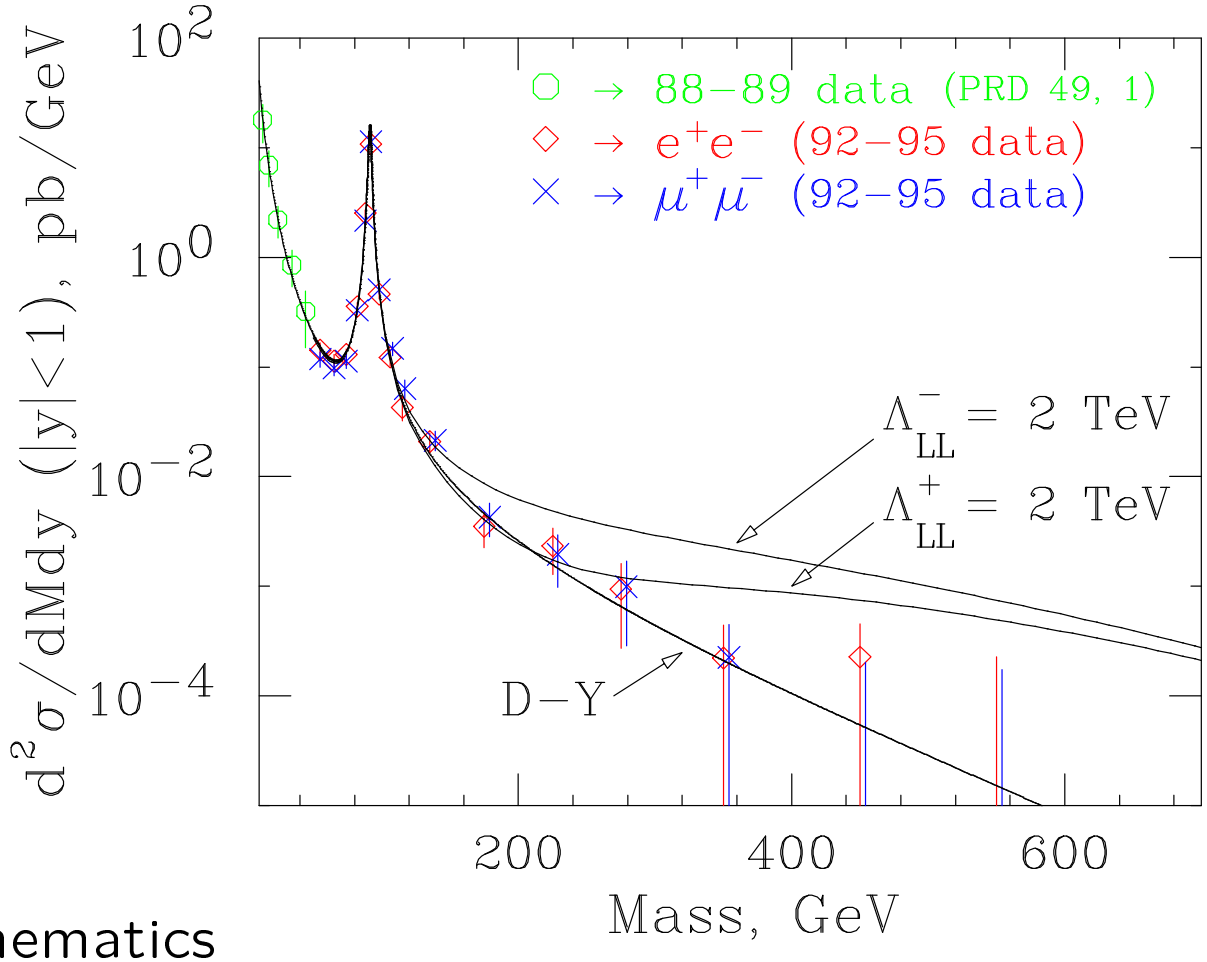

Run 40323 Event34043 _Z0.ANA]CENT_ZS_ELE_CLEAN.DST 4SEP92 17:56:54 11-OCT-99
Wedge #s 3 - 3
Uncorrected cursor
Emax = 51.7 Gev.
Ewedge =
40.4 Gev
PHI: 55.
ETA: -0.62
Wedge #s 15 - 15

Dilepton mass spectra near Z^0





Mass Distribution in a wider range :



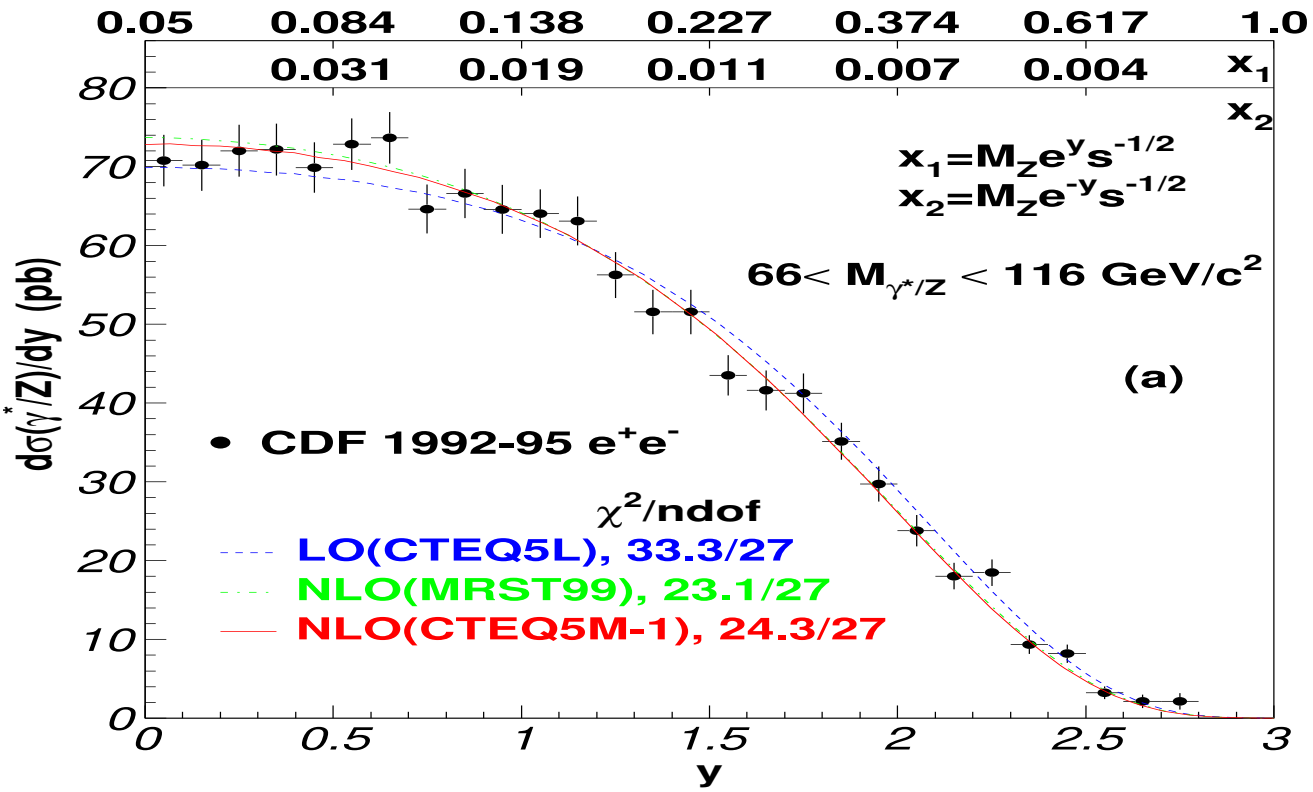
Kinematics

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

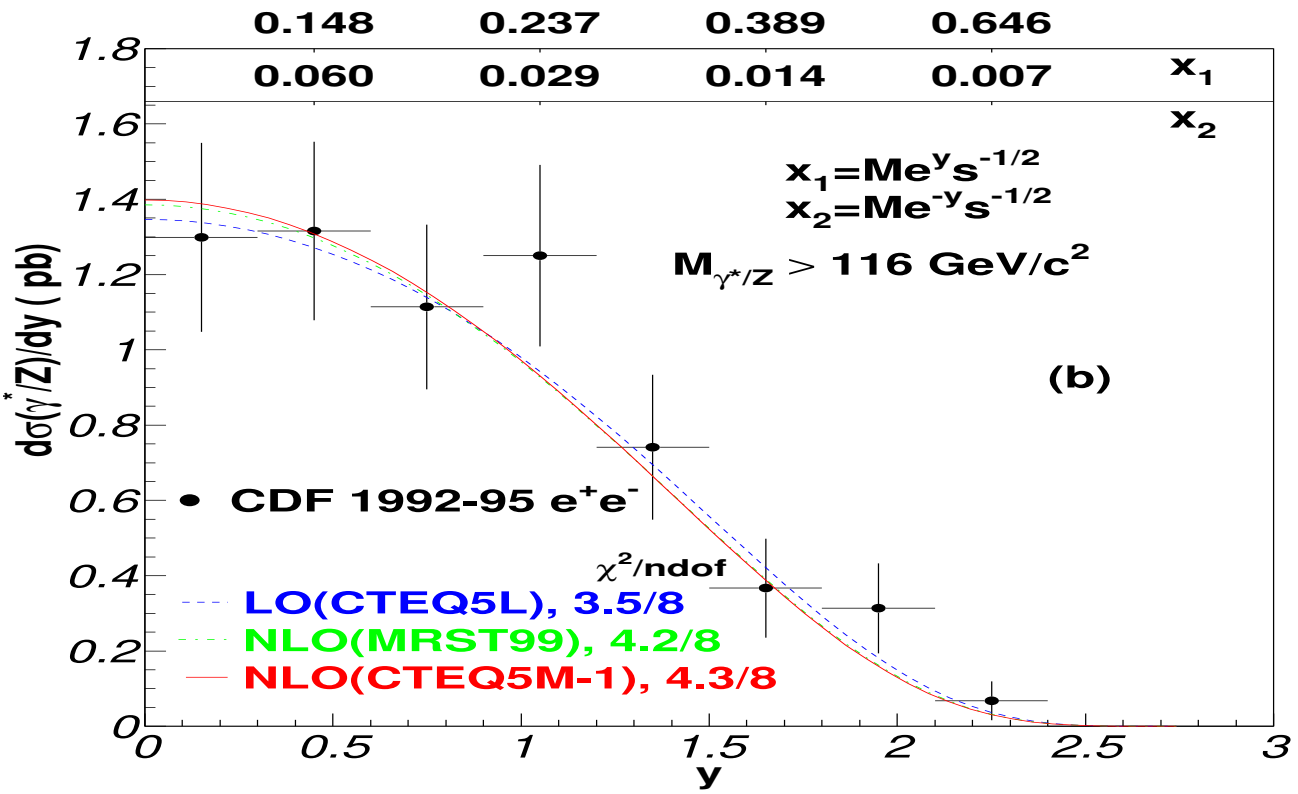
For $M = 90$ GeV/c^2,

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

$Z^0/\gamma^* \to \ell^+\ell^-$ Rapidity Distributions



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

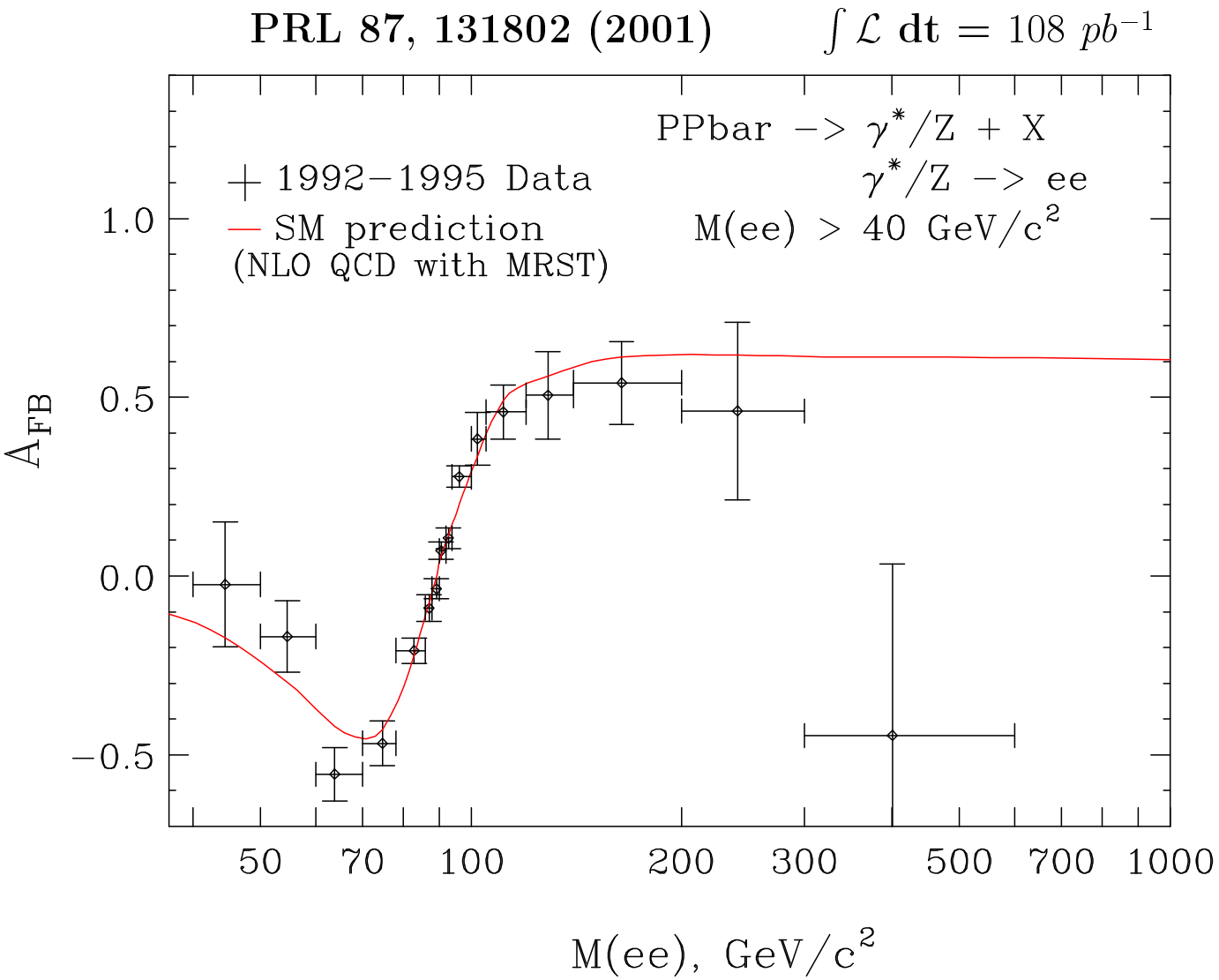


Forward-backward Lepton Charge Asymmetry

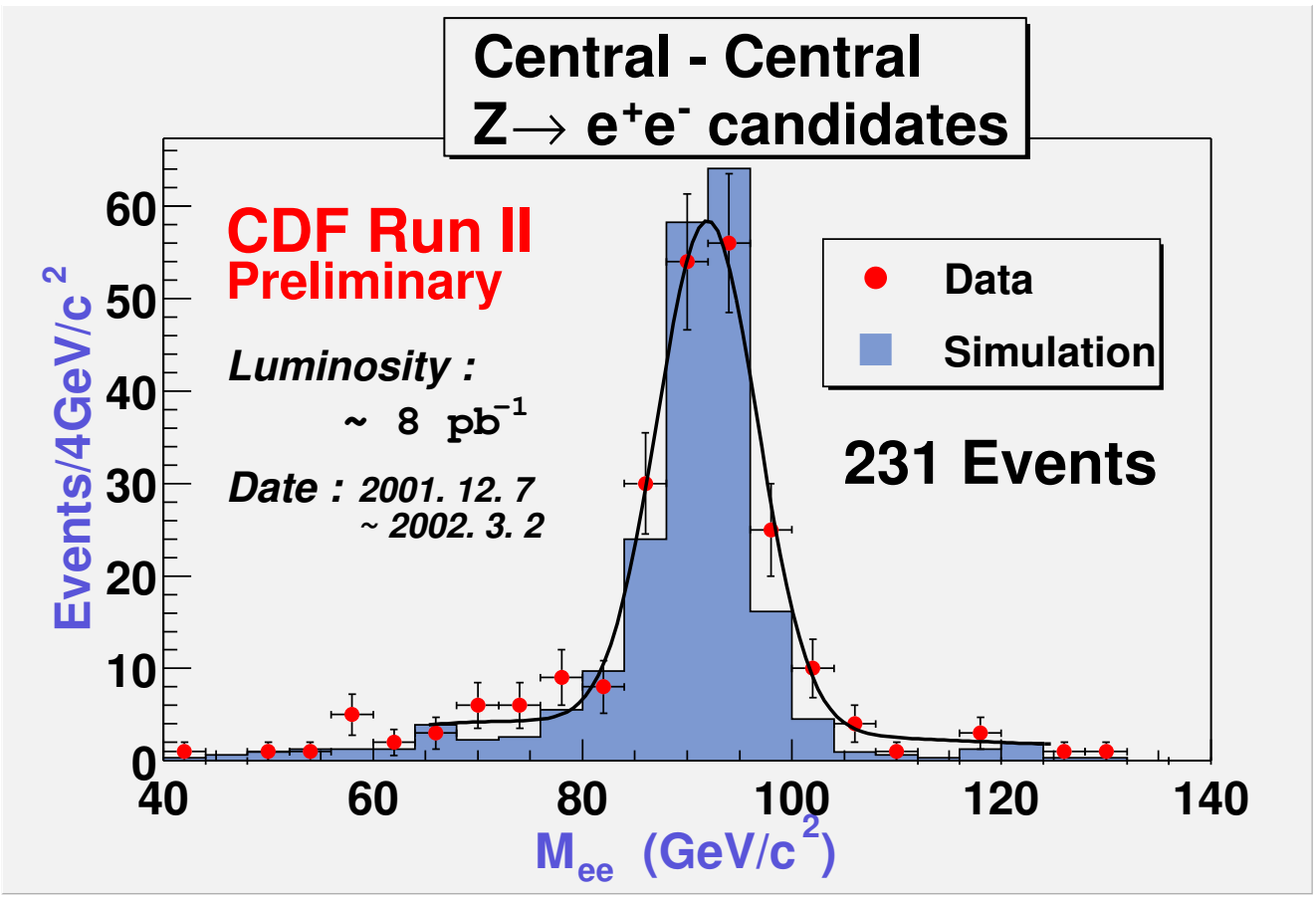
Both vector (γ/Z^0) and axial-vector (Z^0) couplings exist $\Rightarrow$ interference creates asymmetry.

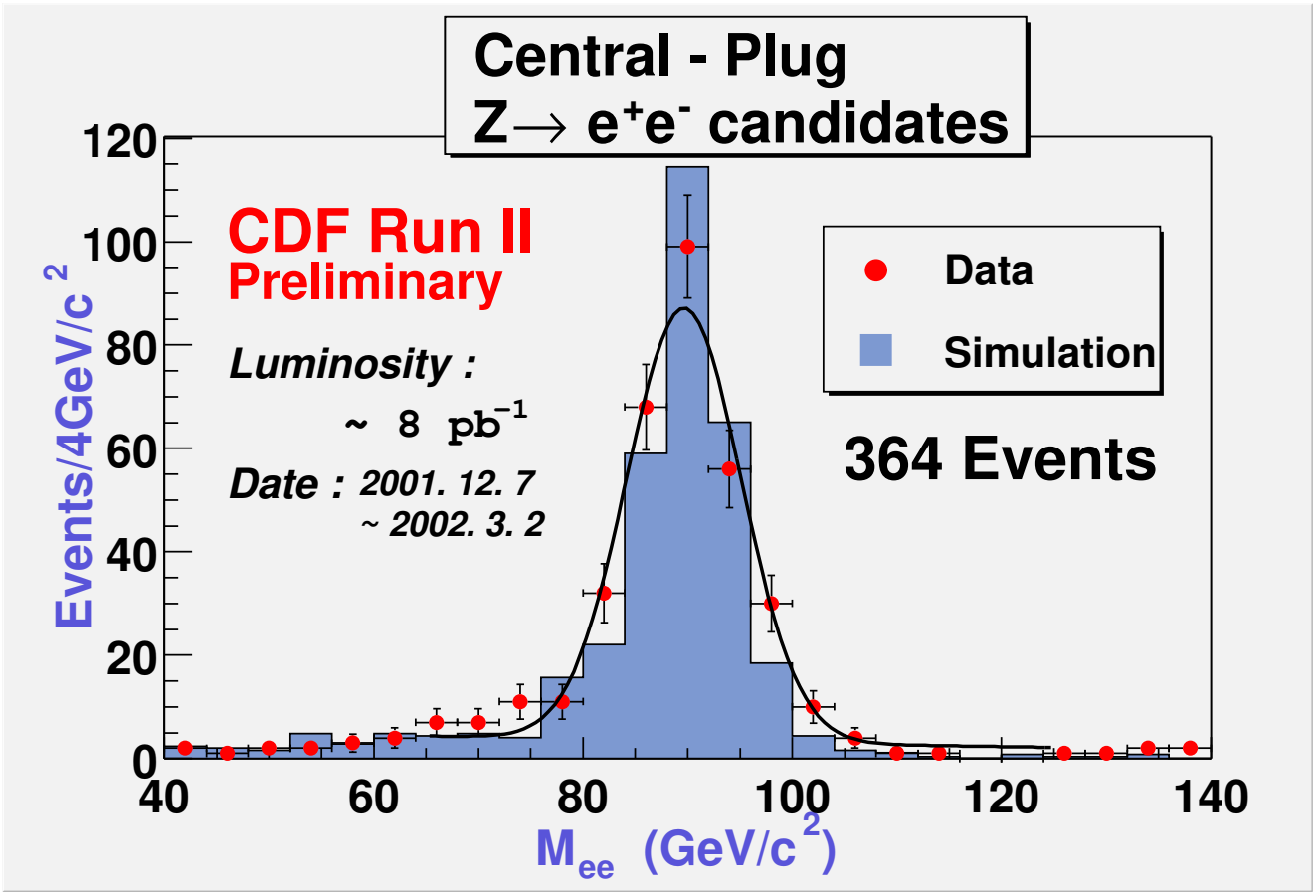
Definite prediction by SM, so sensitive to new bosons.

Asymmetry large, $\sim +0.6$ for $M_{\ell+\ell-} > Z^0$.



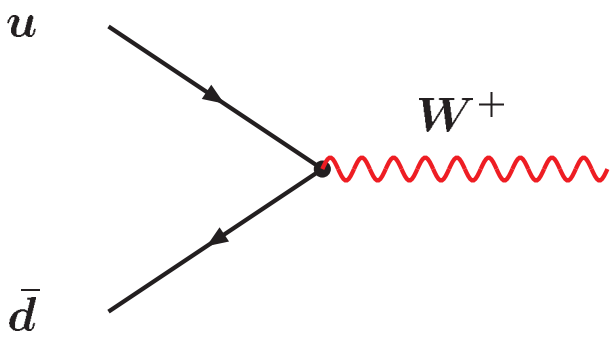
Run-II $Z^0 \rightarrow e^+e^-$ candidates :



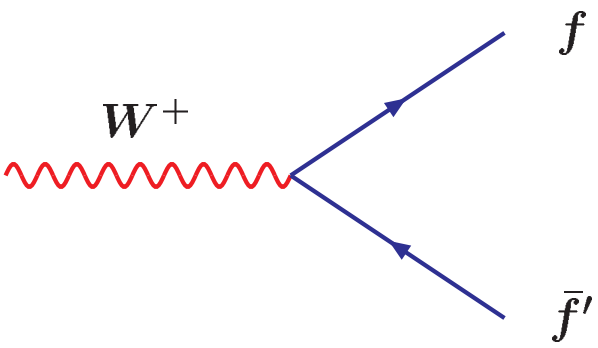


$W^{\pm}$ Boson Production

LO :



- $M_W = 80$ GeV/c^2, thus $\sqrt{x_1 x_2} = M_W/\sqrt{s} \simeq 0.04 \rightarrow$ 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.
  $\rightarrow$ missing transverse energy.

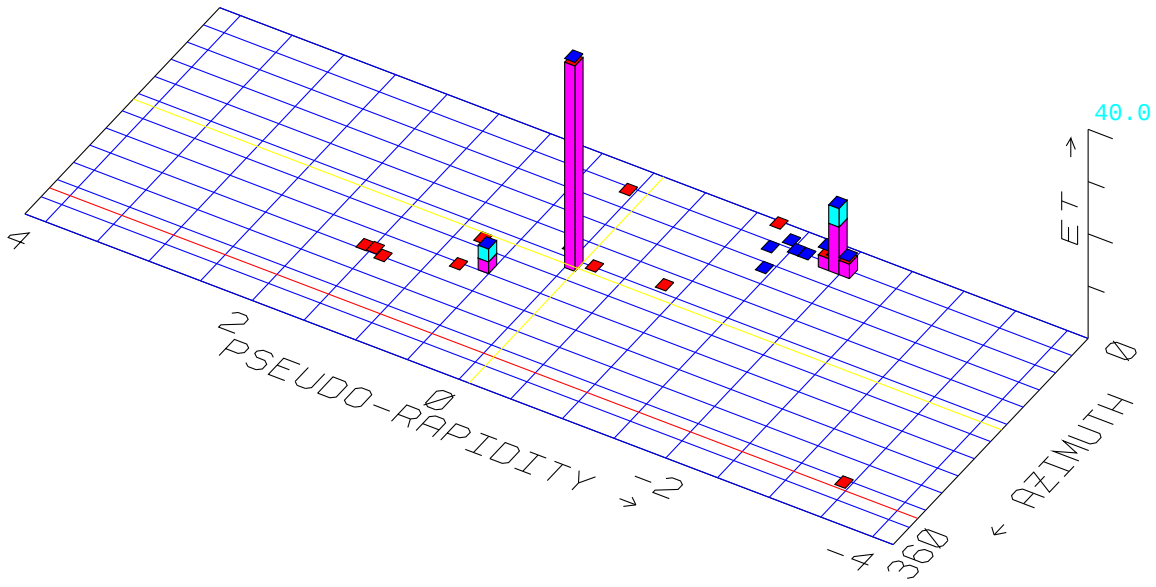
$$\vec{p}_T^{\,\nu} \equiv \vec{\not{E}}_T \equiv -\sum_i \vec{E}_T^{\,i}$$

  Sum is over all calorimeter towers i.
- 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.



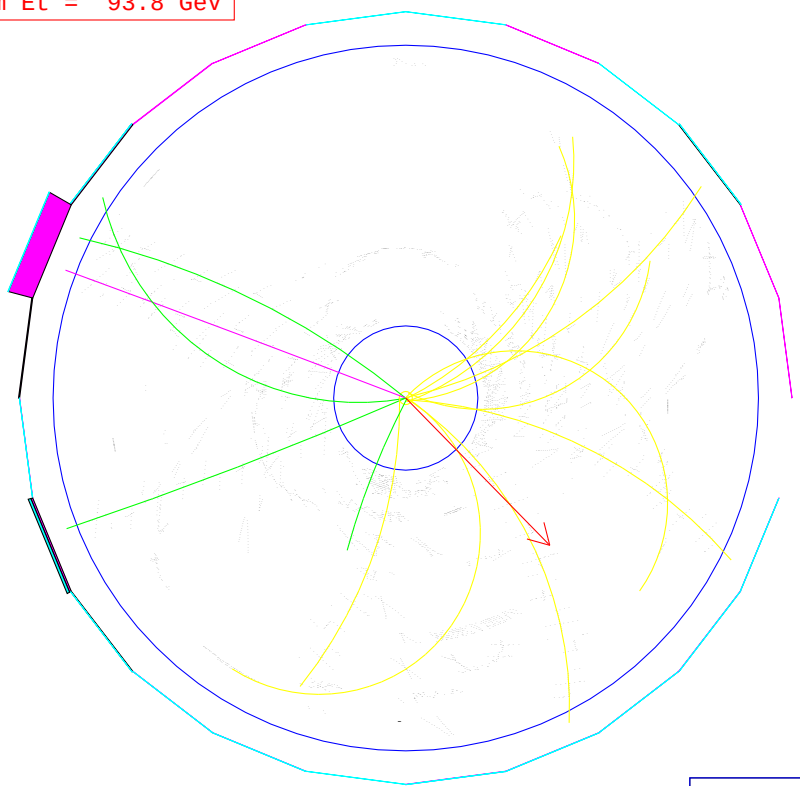
PHI: 160.
ETA: -0.10

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	

Et(METS)= 37.7 GeV
Phi = 314.4 Deg
Sum Et = 93.8 GeV

Emax = 42.8 GeV



Hit & to refresh

PHI: 159.
ETA: 0.12

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

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

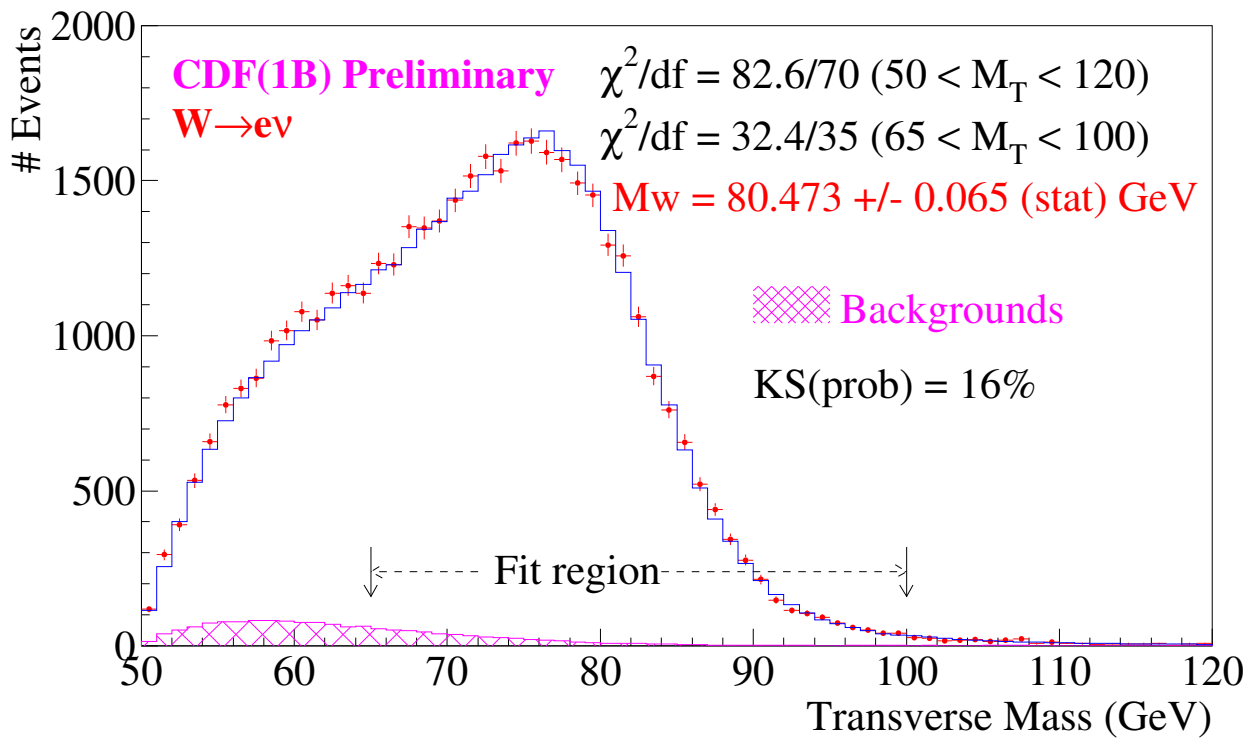
dN/dp_T^ℓ, dN/dp_T^ν show characteristic peak at $\sim M_W/2$ (Jacobian peak), and M_T at $\sim M_W$.

Require:

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

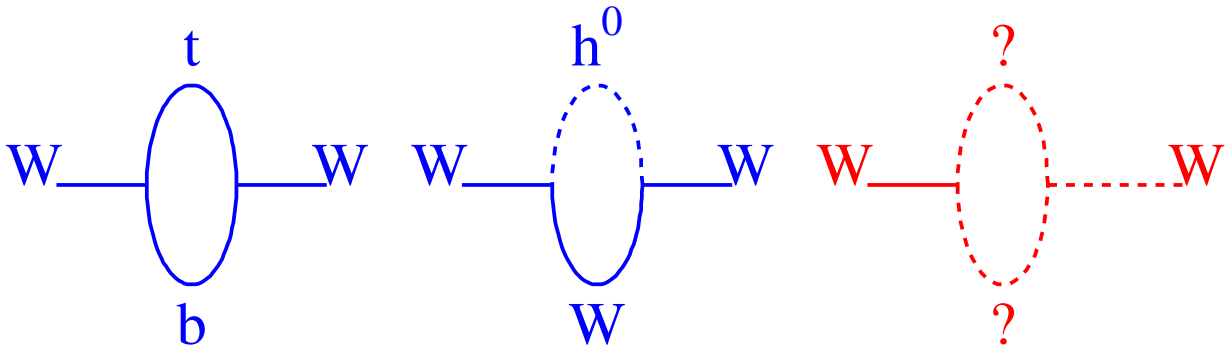
This is usually enough to separate W's from BG.

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

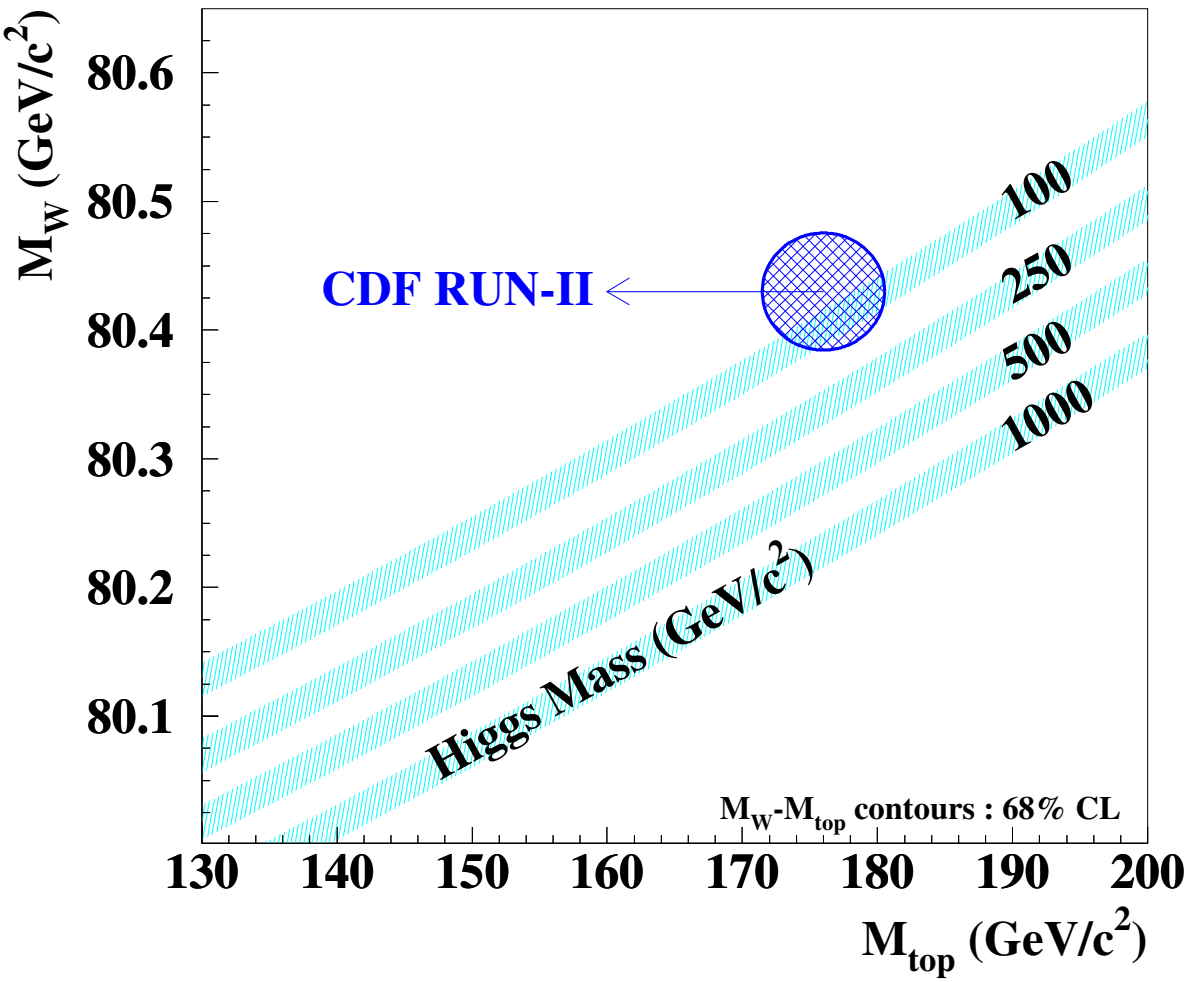


$\Rightarrow M_W = 80.443 \pm 0.079$ GeV/c^2 (CDF combined).

Somewhat sensitive to the Higgs mass thru radiative corrections.

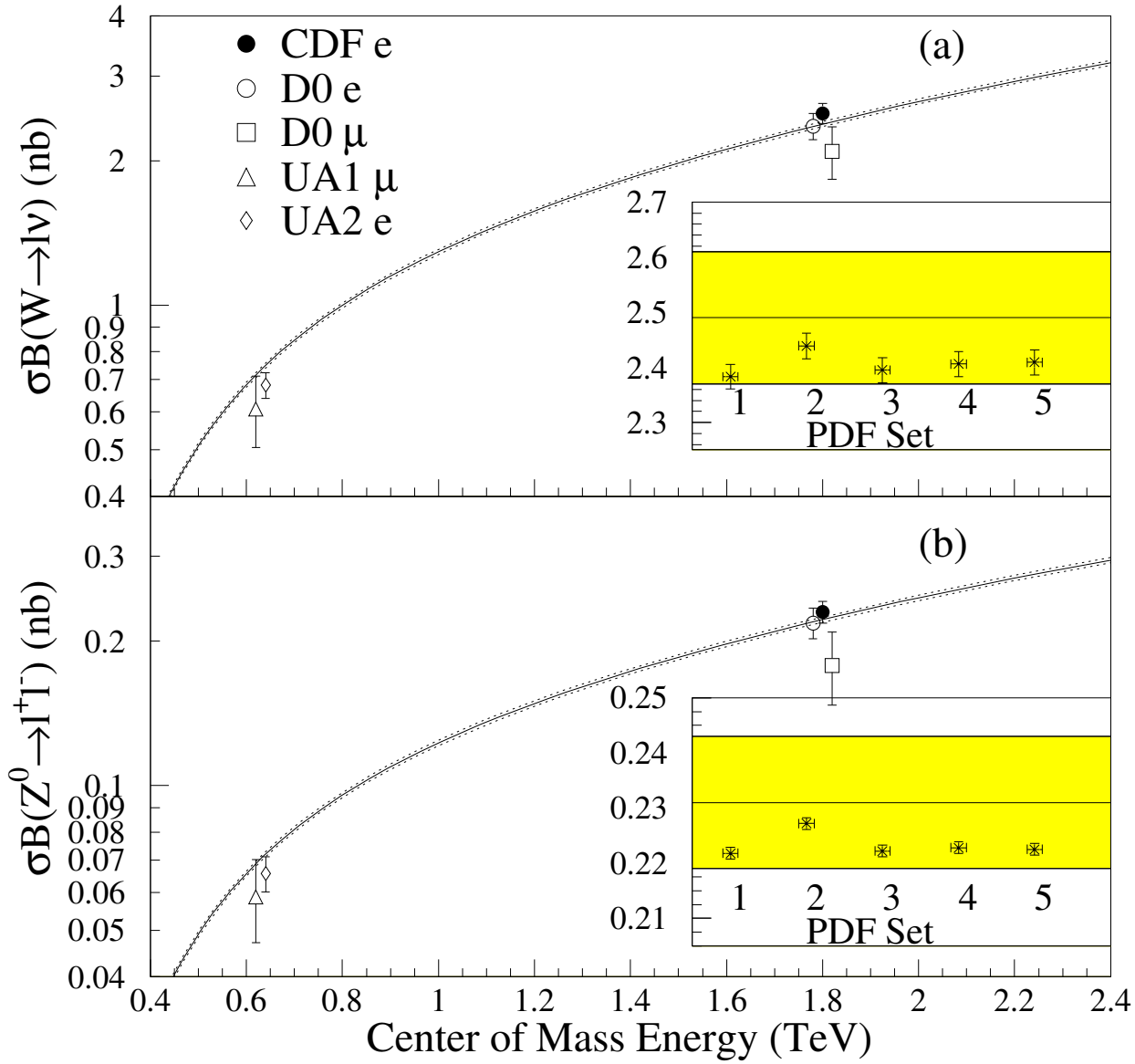


Constraints on the Higgs mass :
CDF Run-II projecctions.



Measured Production Cross Section

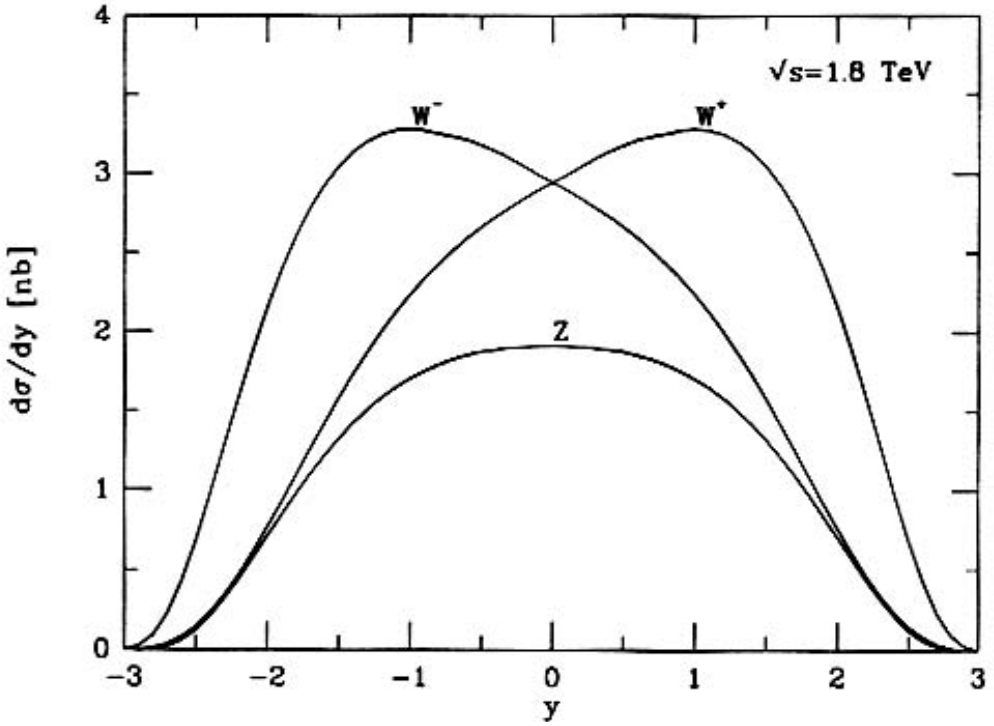
$$\begin{aligned} & \sigma(\bar{p}p \to W^+X) \cdot \mathcal{B}(W^+ \to \ell^+\nu) \\ + \; & \sigma(\bar{p}p \to W^-X) \cdot \mathcal{B}(W^- \to \ell^-\bar{\nu}) \\ = \; & 2.47 \pm 0.07\,(\text{stat} + \text{syst}) \pm 0.08\,(\text{lum})\ \text{nb} \end{aligned}$$

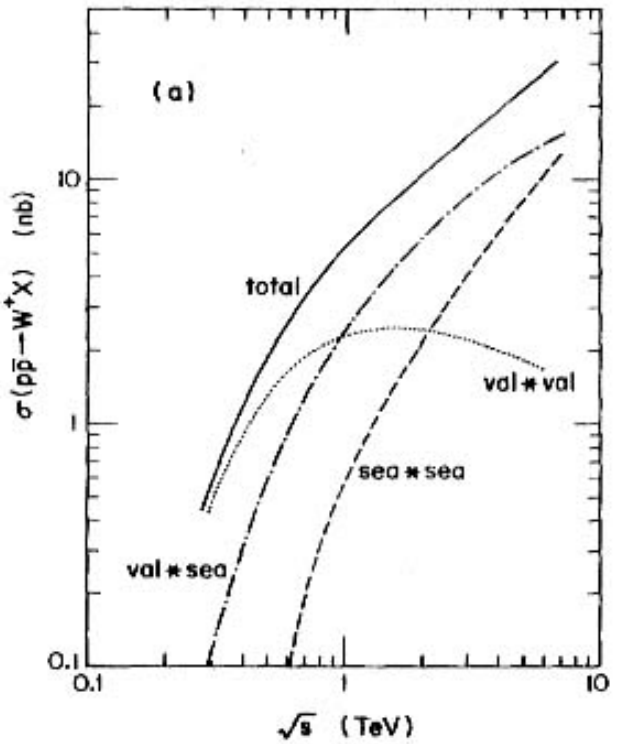


W Rapidity Distributions

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.

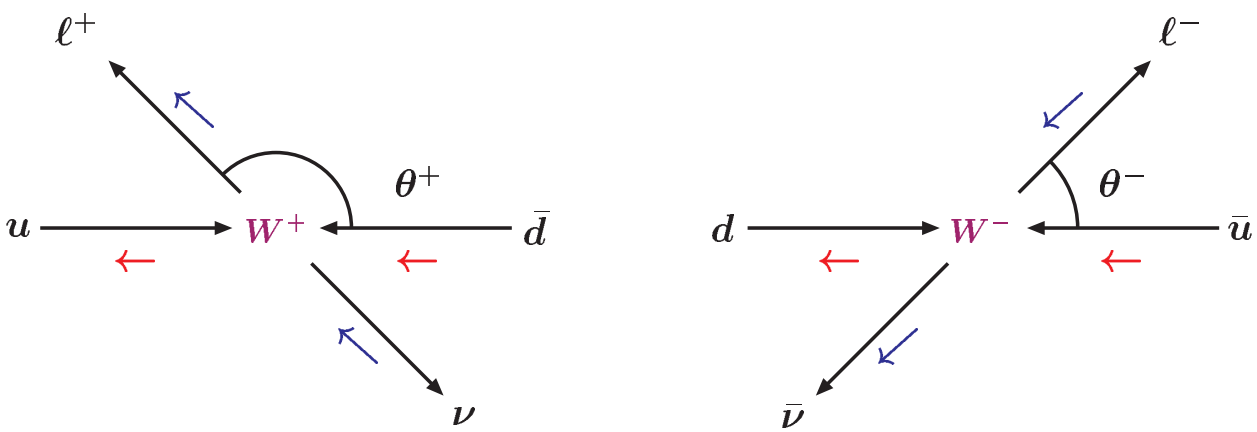
Define asymmetry as

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

y^{ℓ} : lepton rapidity.

Complication : $W^{\pm}$ is polarized $(V - A)$.

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

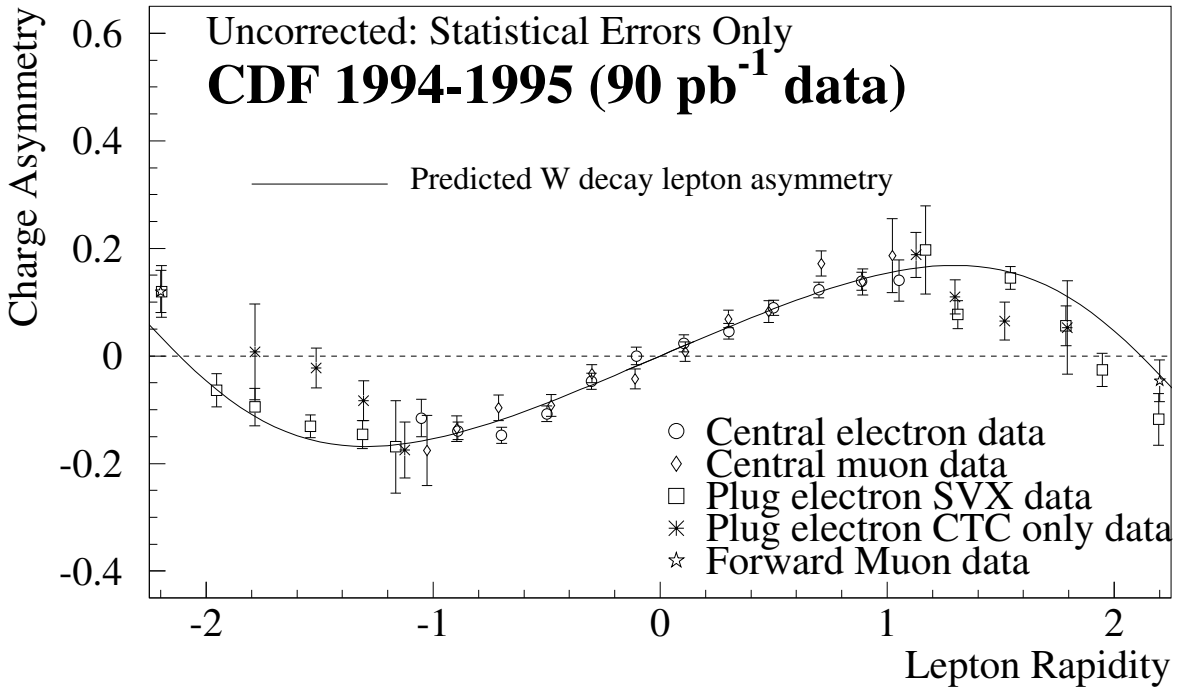


$$\frac{dN^{+}}{d\cos\theta} = |d^{1}_{1,-1}|^{2} \propto (1 - \cos\theta)^{2} \Rightarrow \bar{d}\,(\bar{p}) \text{ direction}$$

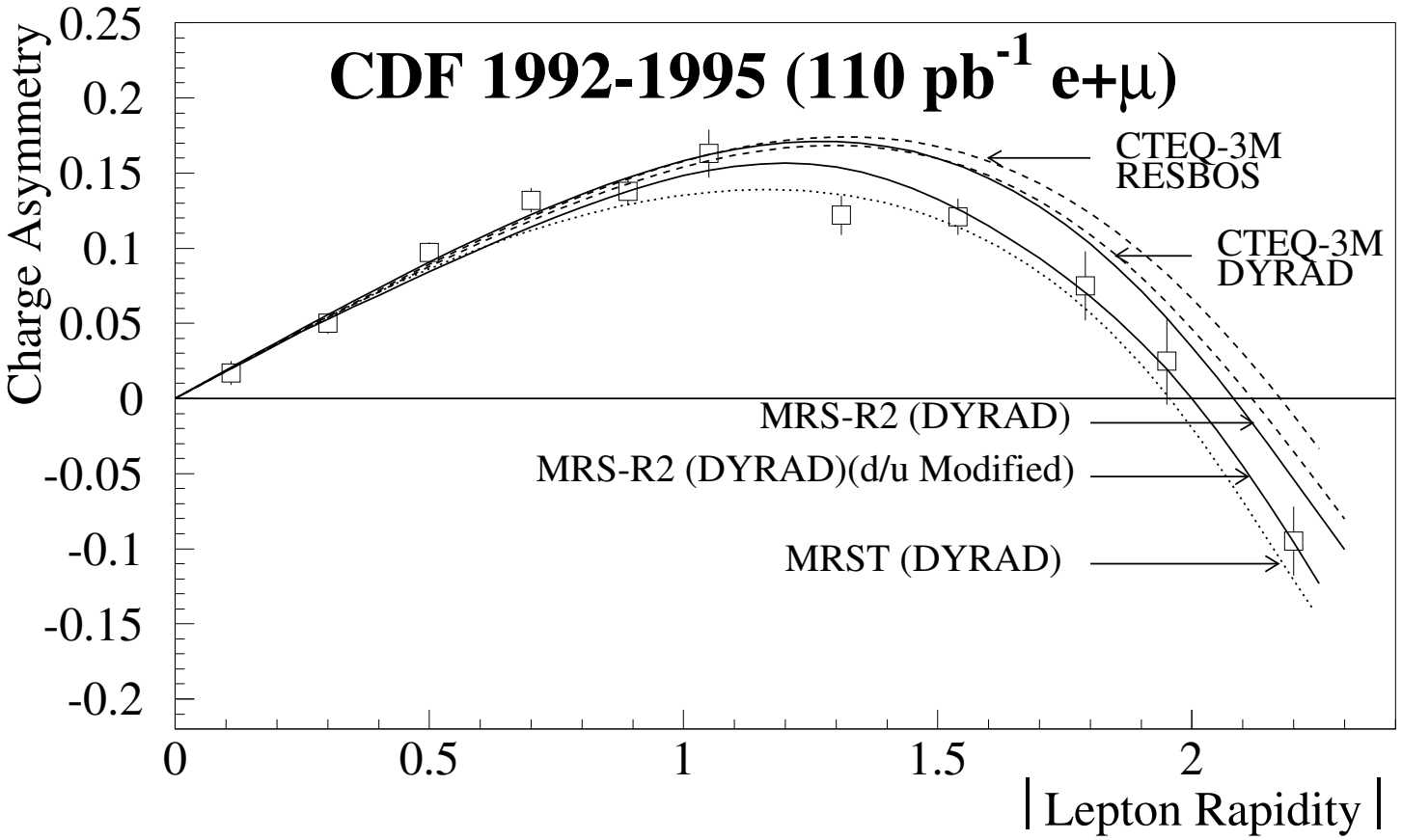
$$\frac{dN^{-}}{d\cos\theta} = |d^{1}_{-1,-1}|^{2} \propto (1 + \cos\theta)^{2} \Rightarrow d\,(p) \text{ direction}$$

The two effects above are in opposite directions:
Stronger one wins, structure function for $|y^{\ell}| \leq 2$.
$\Rightarrow W^{+} > W^{-}$ for $y^{\ell} > 0$,
$W^{+} < W^{-}$ for $y^{\ell} < 0$.

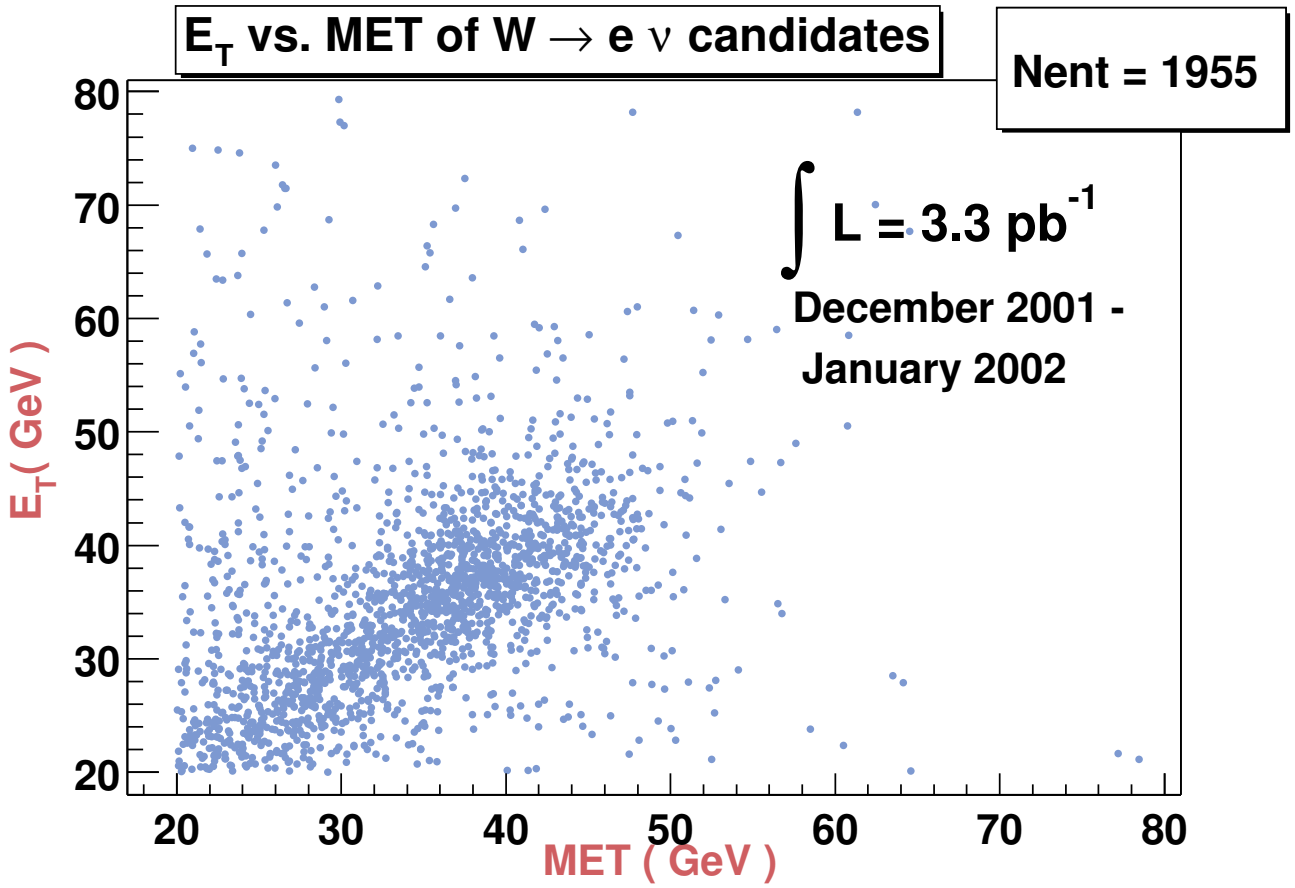
Raw lepton asymmetry distribution

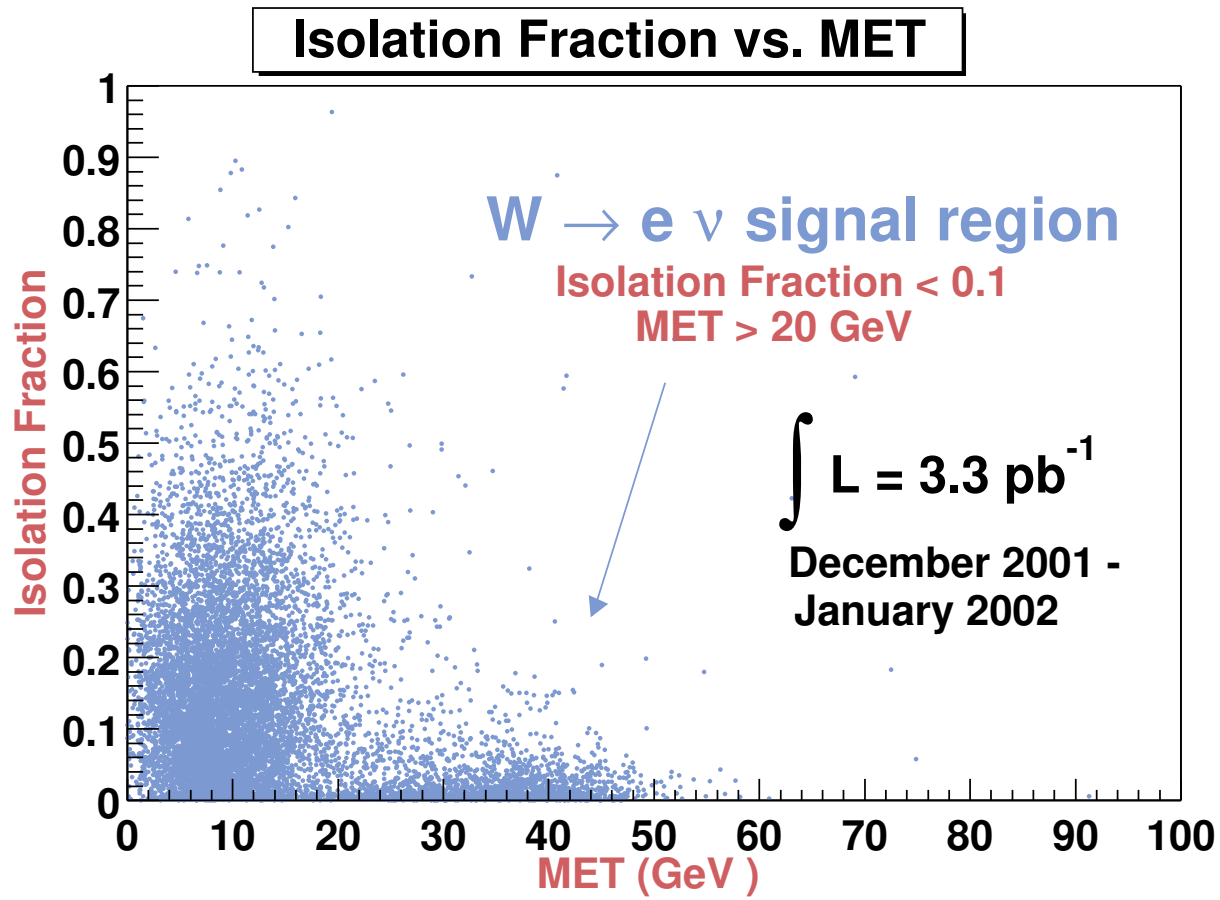


Corrected, and folded

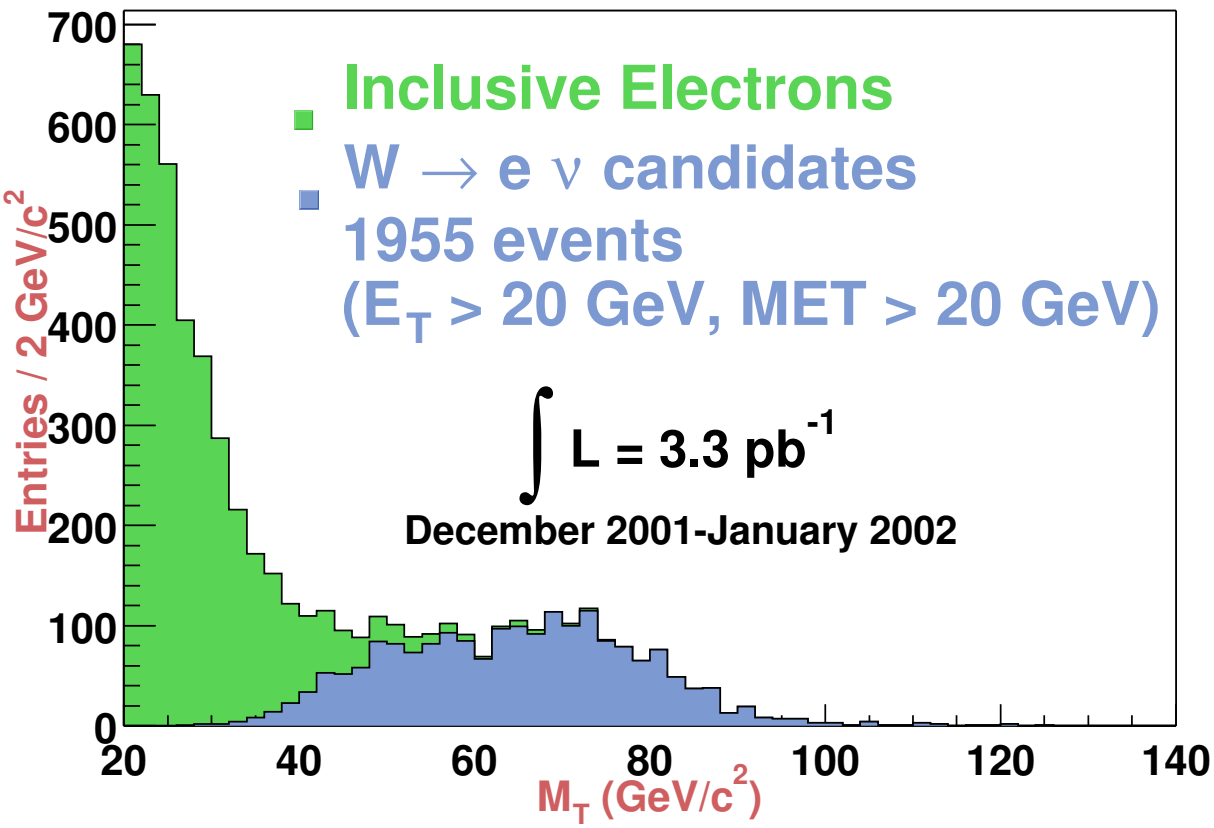


Run-II $W \to e\nu$ candidates



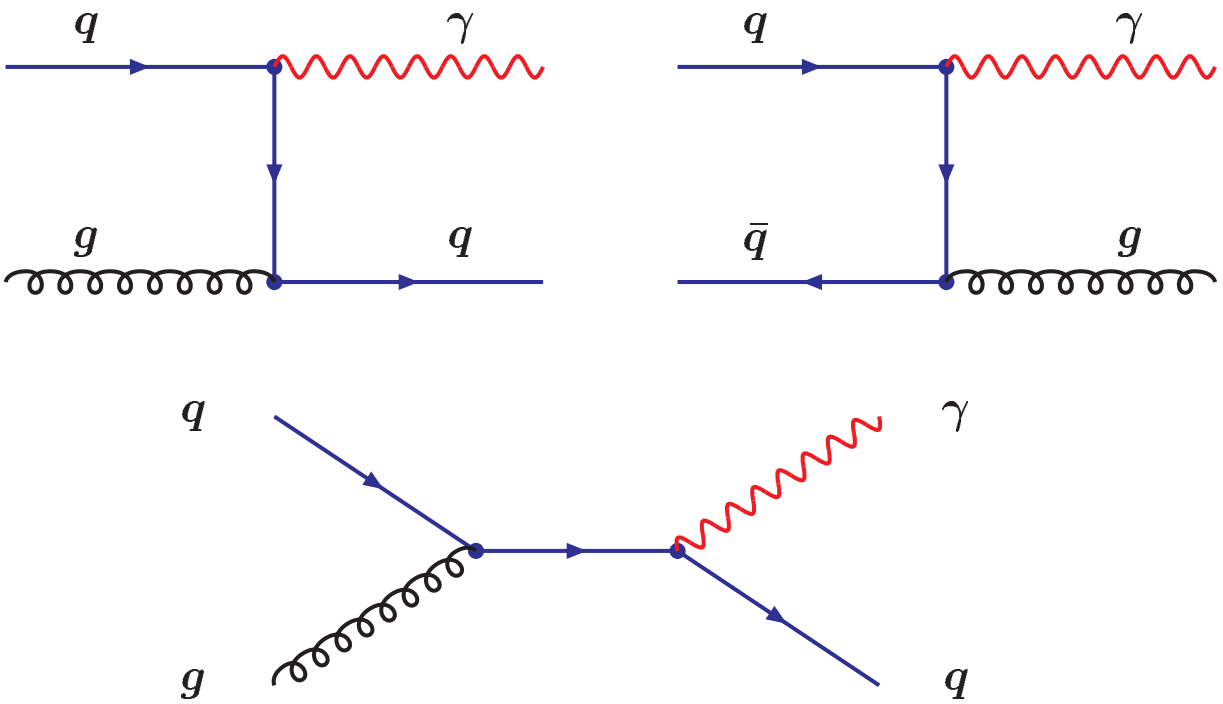


$W \to e\nu$ transverse mass distribution

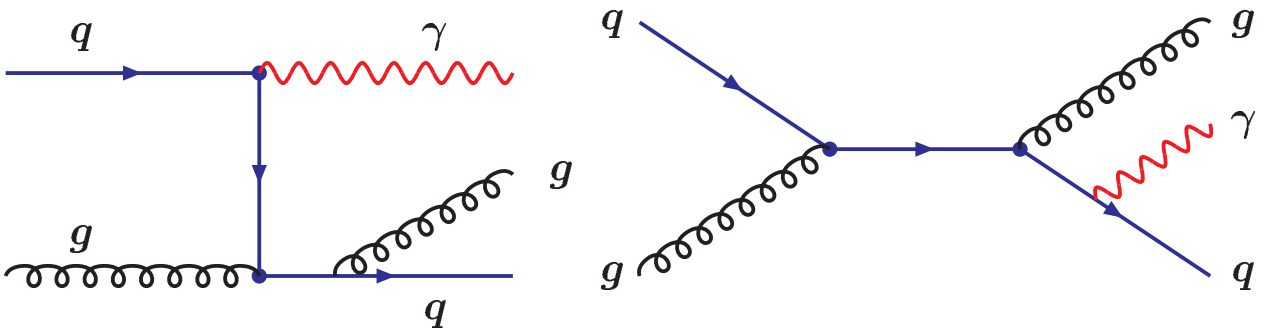


Prompt Photon Production

- 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.
- $\alpha_s \to \alpha$: cross section smaller than jets.

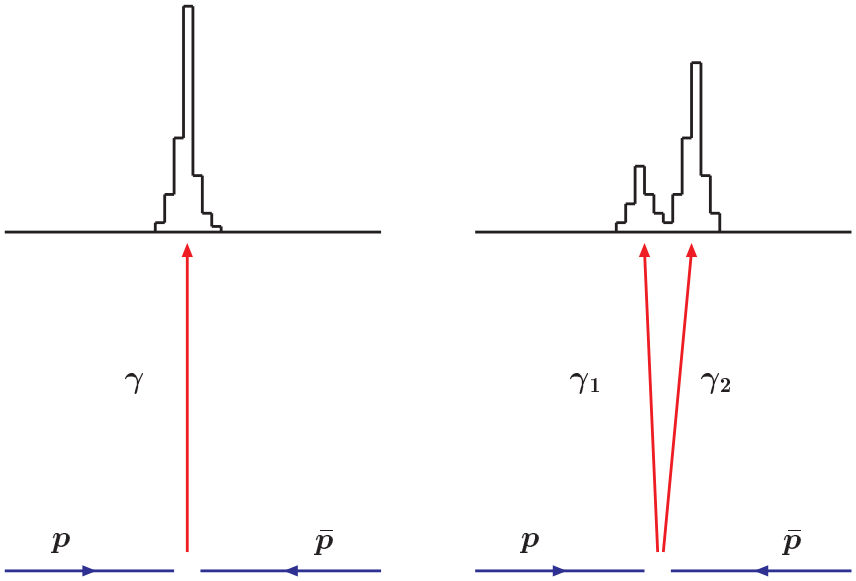
How to identify the photon?
Main BG: jets $\to$ leading $\pi^0 \to \gamma\gamma$,
energy deposit in electromagnetic calorimeter.

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.

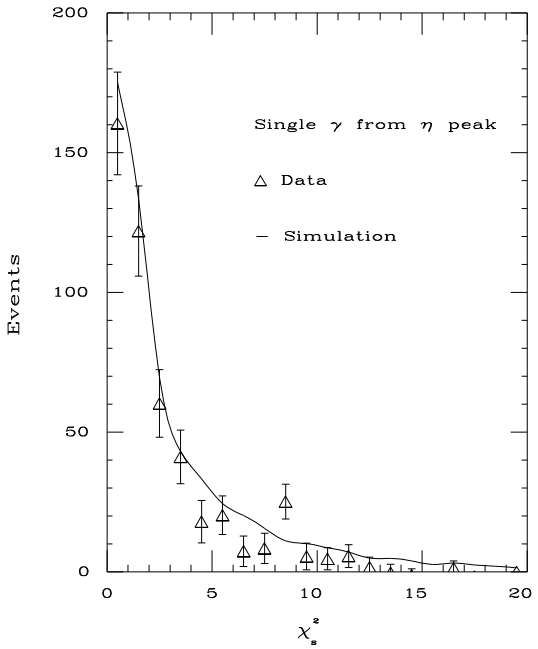
I: Profile method

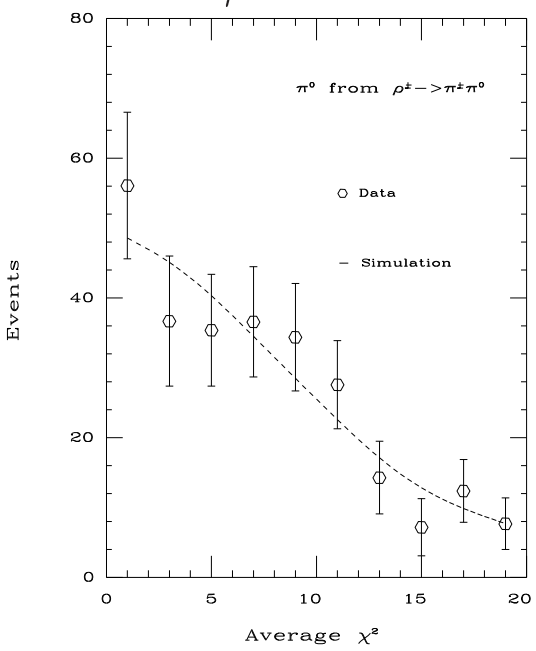


CES at $R = 181$ cm. Channel spacing ~ 1.5 cm.

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

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

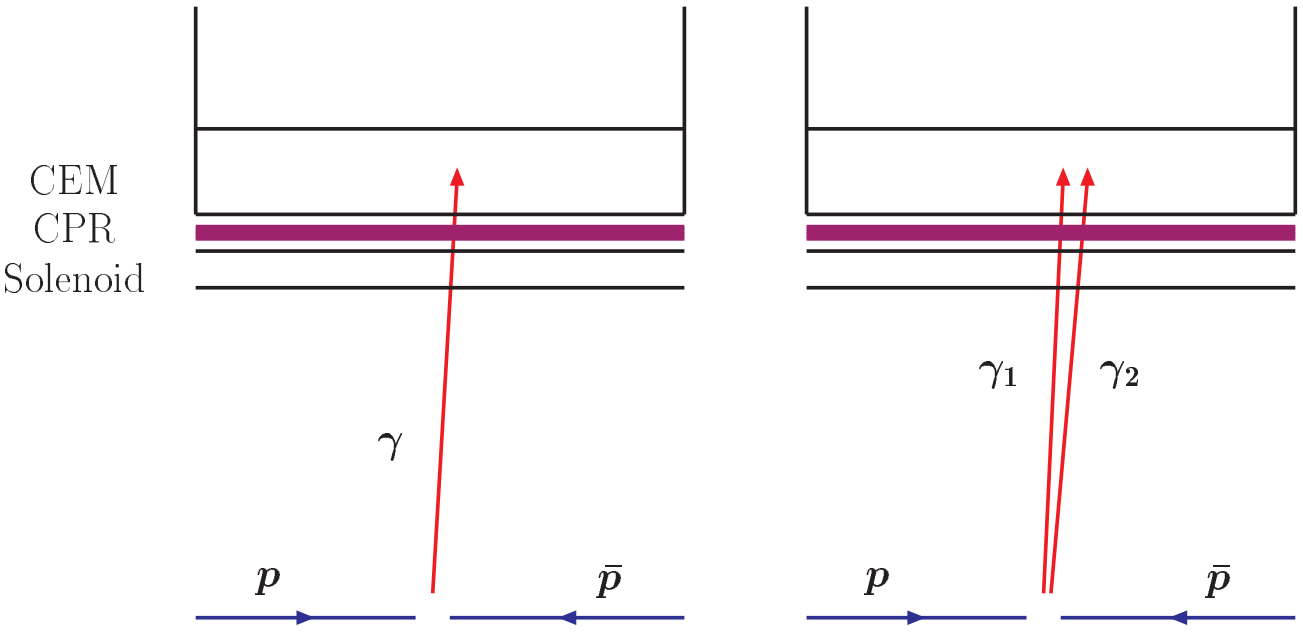
$$P_\gamma(t) = 1 - \exp\left[-\frac{7t}{9X_0}\right].$$

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 $P_\gamma = 0.5$ or thickness $t \sim 1.0\, X_0$.

CDF solienoid is $1.075\, X_0$ thick. Use it as a radiator, and detect converted photons just behind it. $\to$ CPR (proportional chamber).



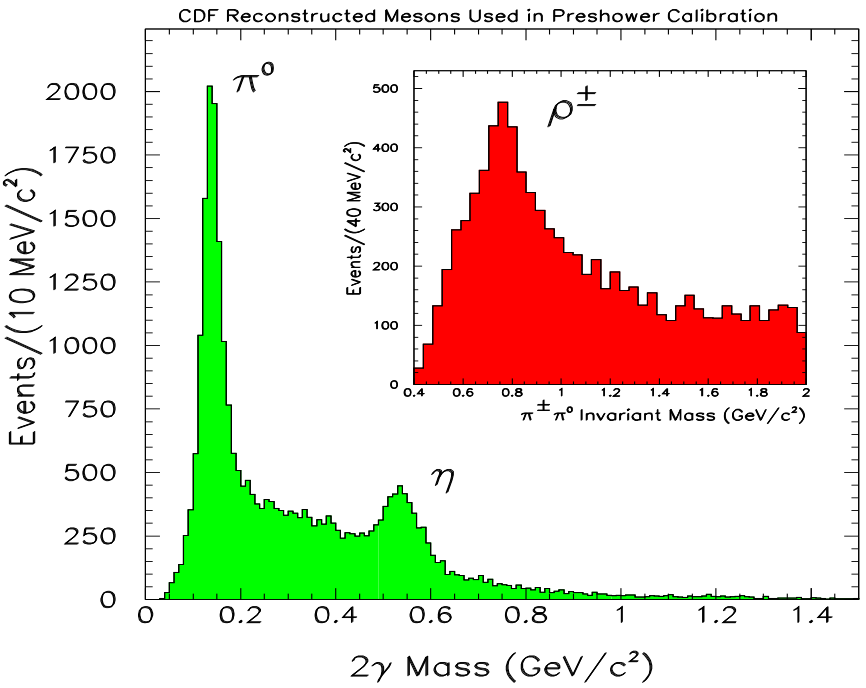
Measure the conversion probability P_{CPR} at CPR for photon candidates:

If $P_{\mathrm{CPR}} = P_\gamma$, all signal, if $P_{\mathrm{CPR}} = P_{\pi^0}$, all BG. Somewhere in between $\to$ photon fraction.

Measure CES/CPR efficiencies in data :

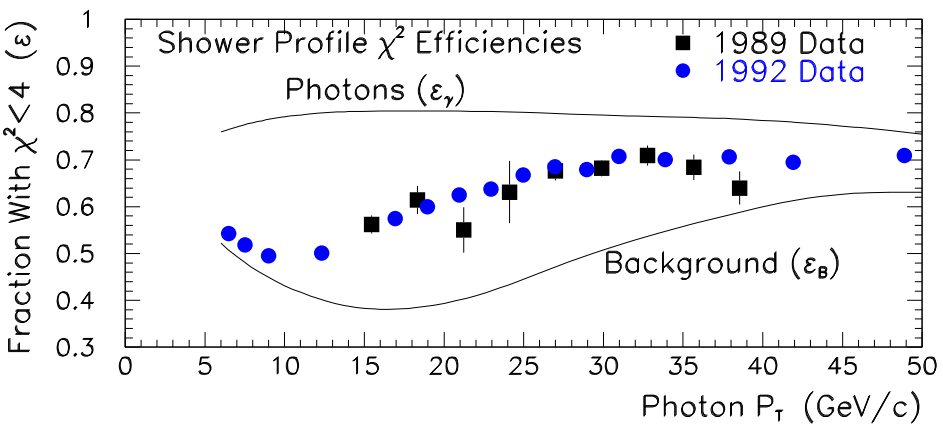
ϵ for single γ's from $\pi^0/\eta \to \gamma\gamma$

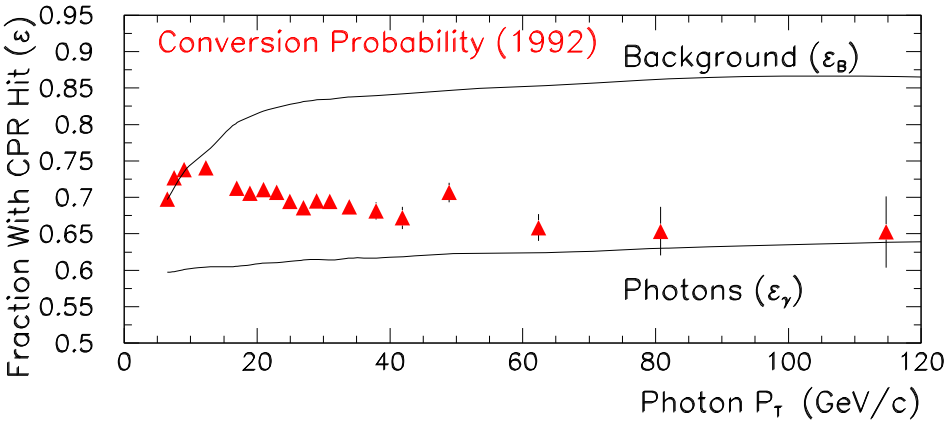
ϵ for π^0 from $\rho^{\pm} \to \pi^{+}\pi^{0}$



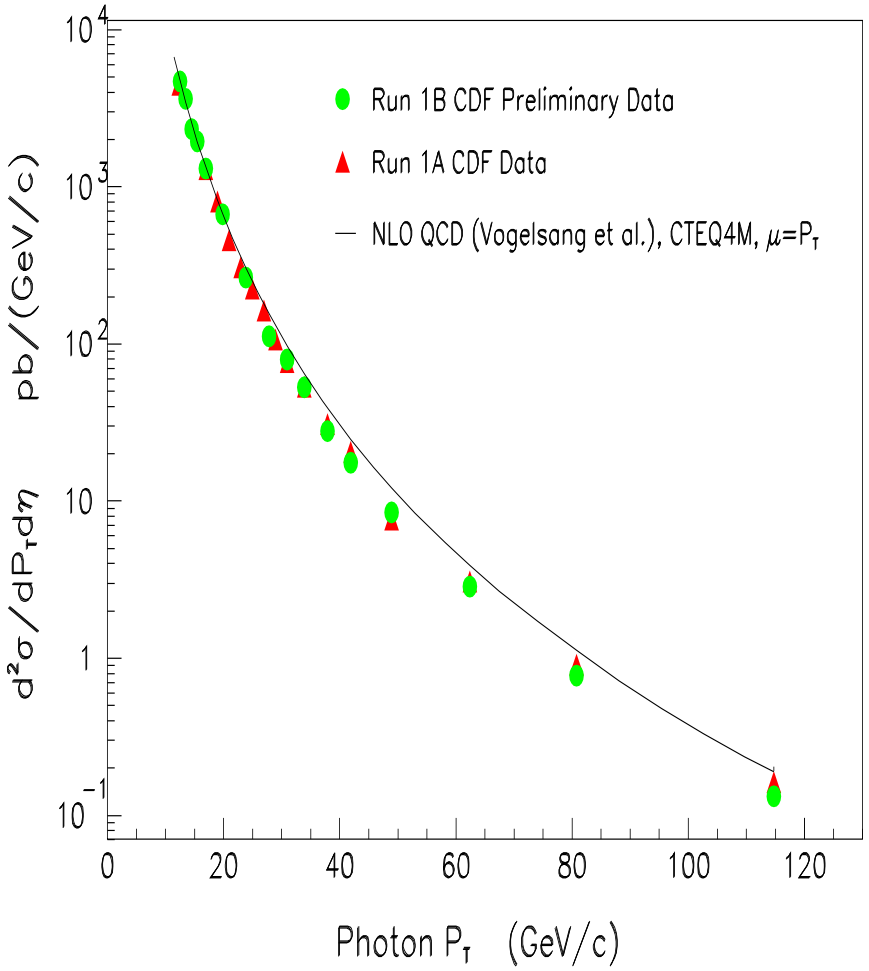
CDF Background Subtraction Methods

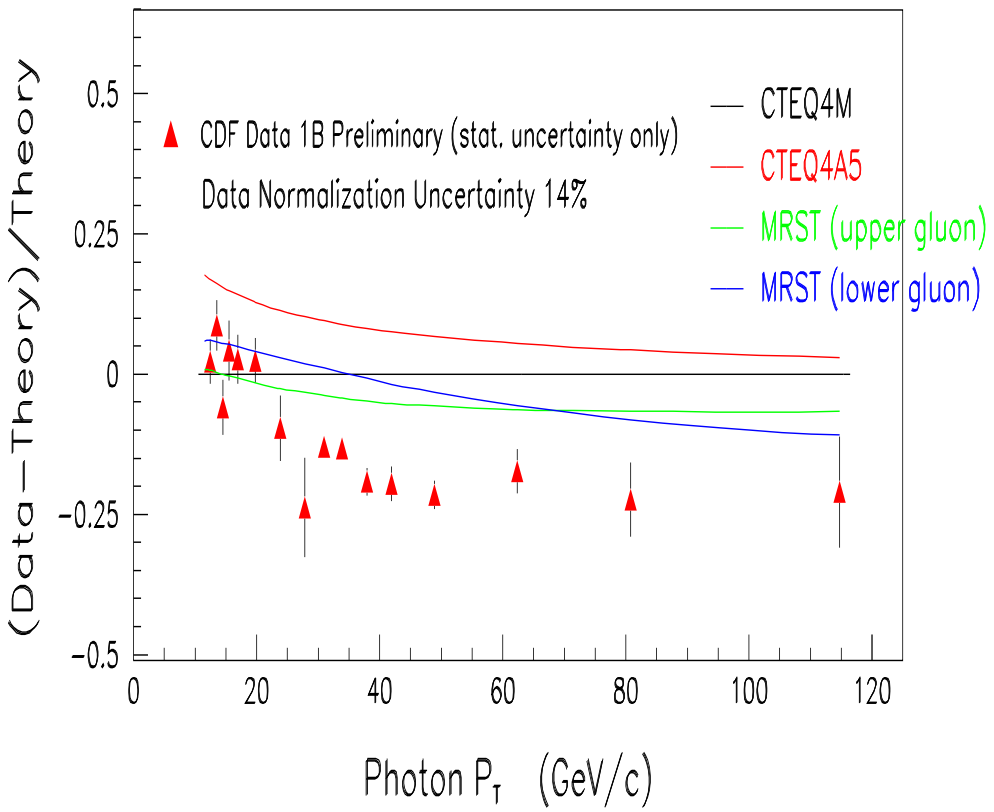
Fraction of Photons = $(\varepsilon_B-\varepsilon)/(\varepsilon_B-\varepsilon_\gamma)$





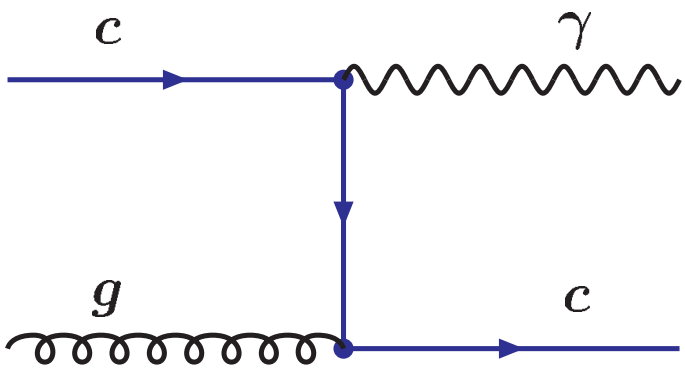
Single γ inclusive cross section (110 pb^{-1}).



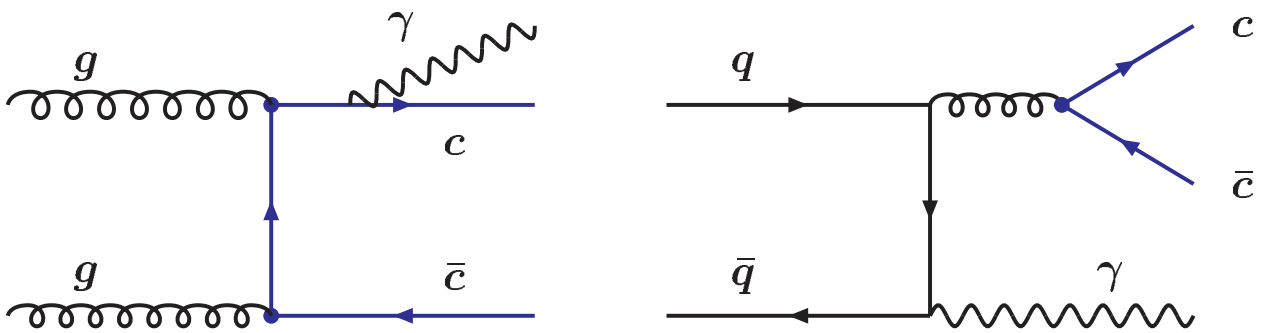


Photon + Charm Production

- 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.

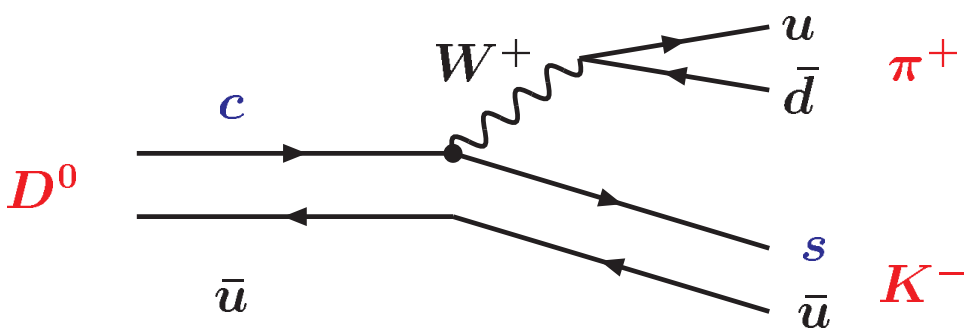
Charm Mesons

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	$\to D_s^+\gamma$

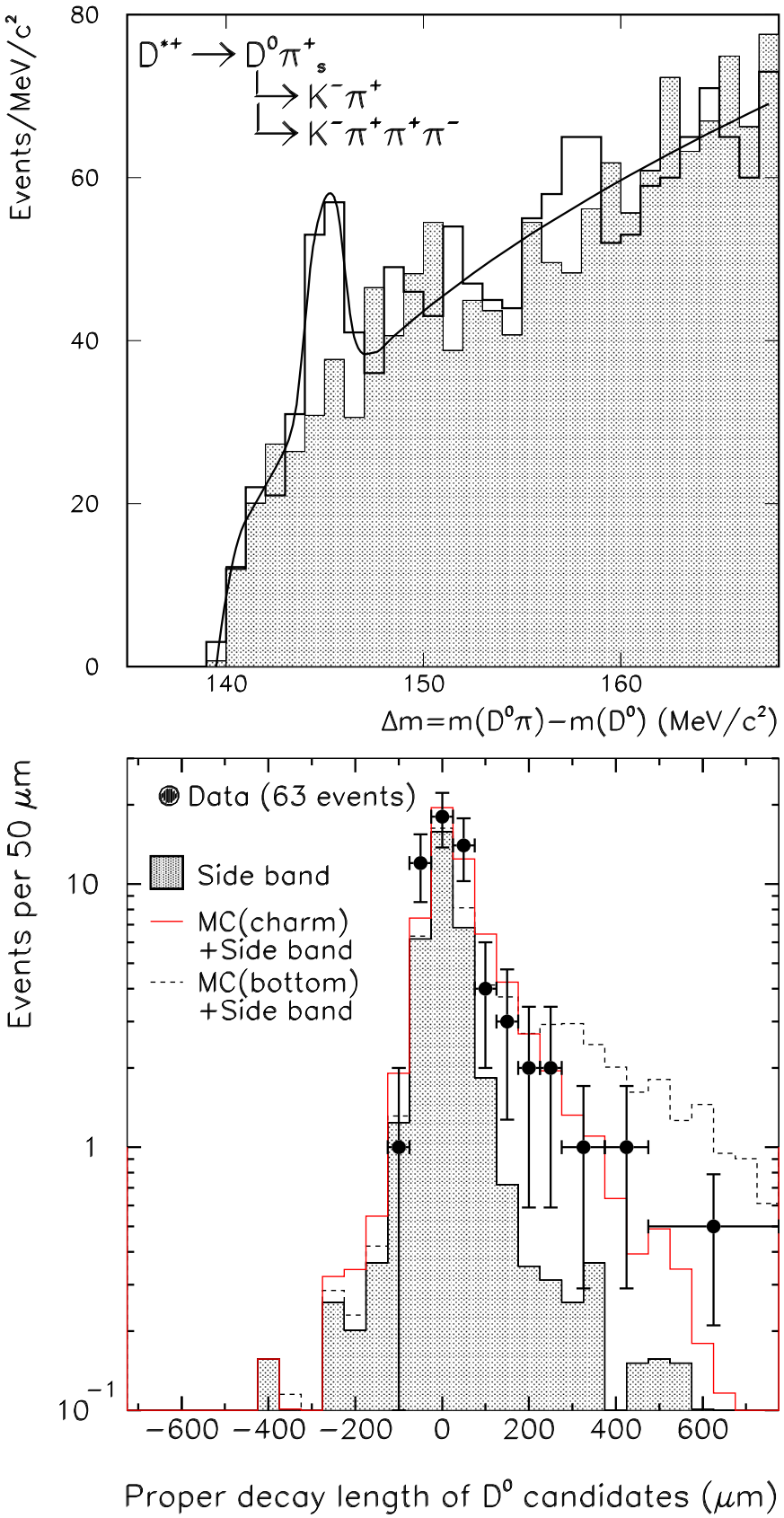
$D^{*+} \to D^0\pi^+$ attractive,
because of the small Q value in the decay:

- 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
$D^0 \to K^-\pi^+\pi^+\pi^-$ ($BF = 7.5\%$).



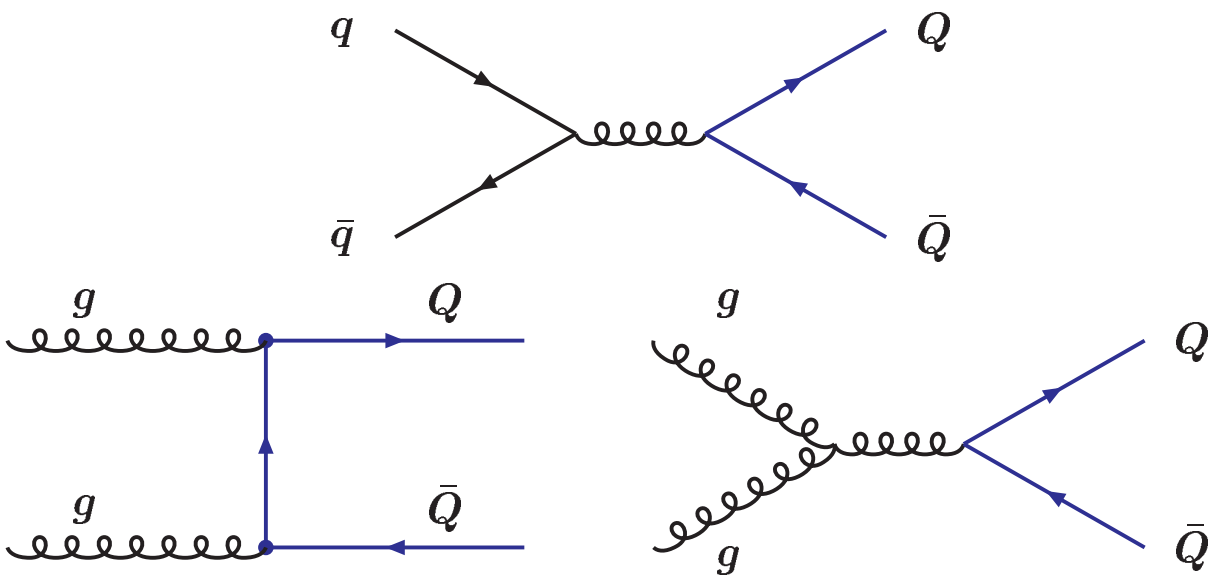
$\gamma + D^{*+}$ Production



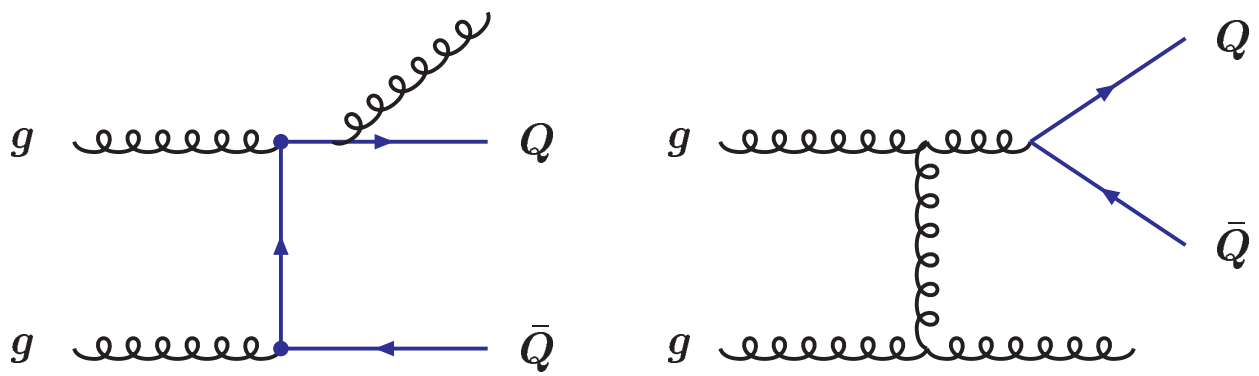
PRL 77, 5005 (1996).

Heavy Quark Production

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

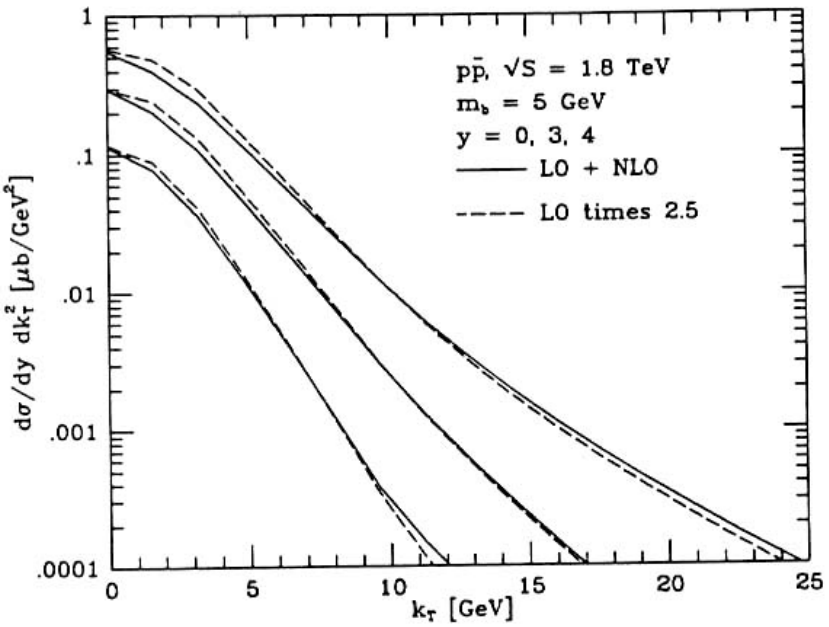


- NLO calculations available for
  - total cross sections
  - one-particle inclusive cross sections
  - two-particle correlations

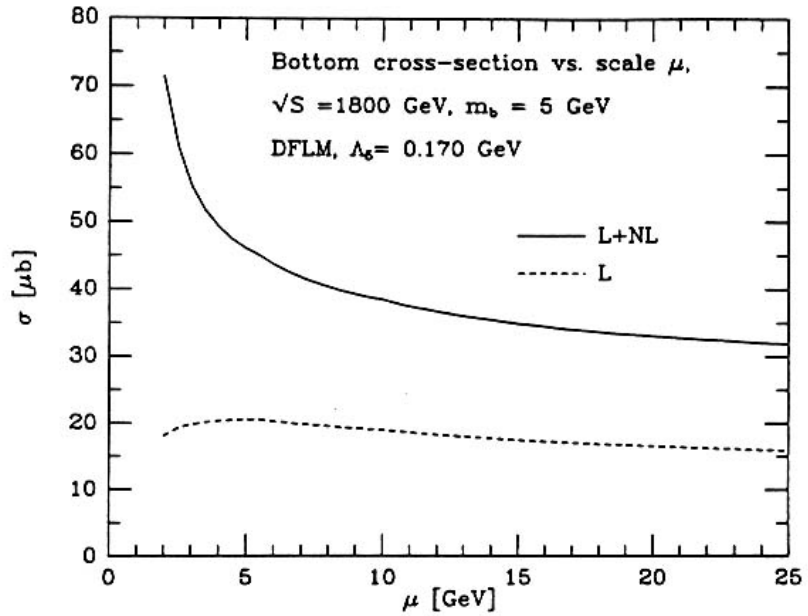


Bottom Quark Production

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

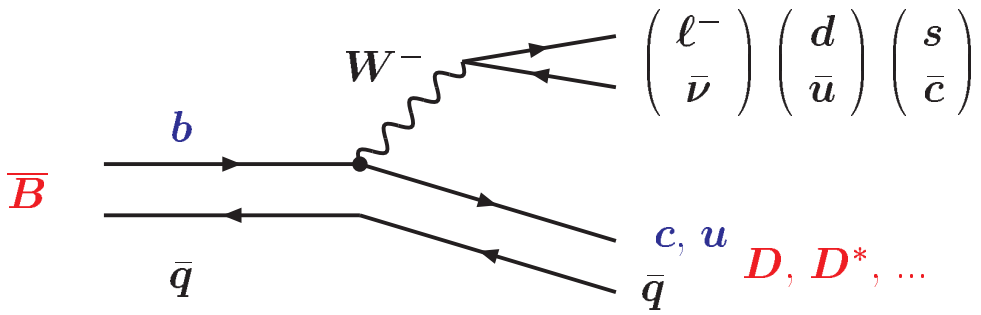


Dependence on renormalization scale μ not reduced in NLO.
A bit worrisome.

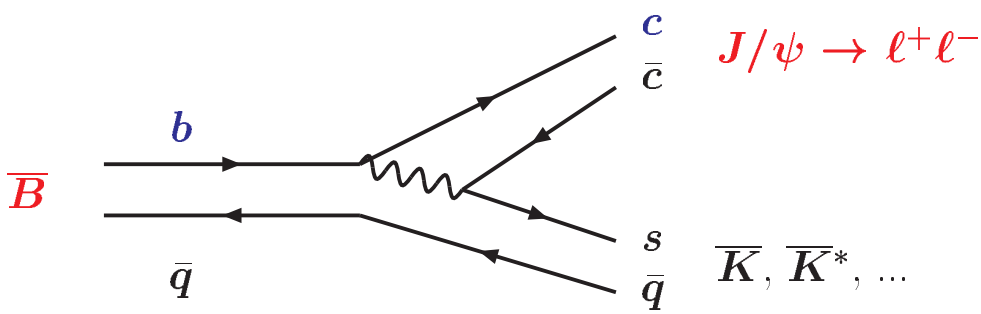


How to detect the b quark?

Have to identify its decay.

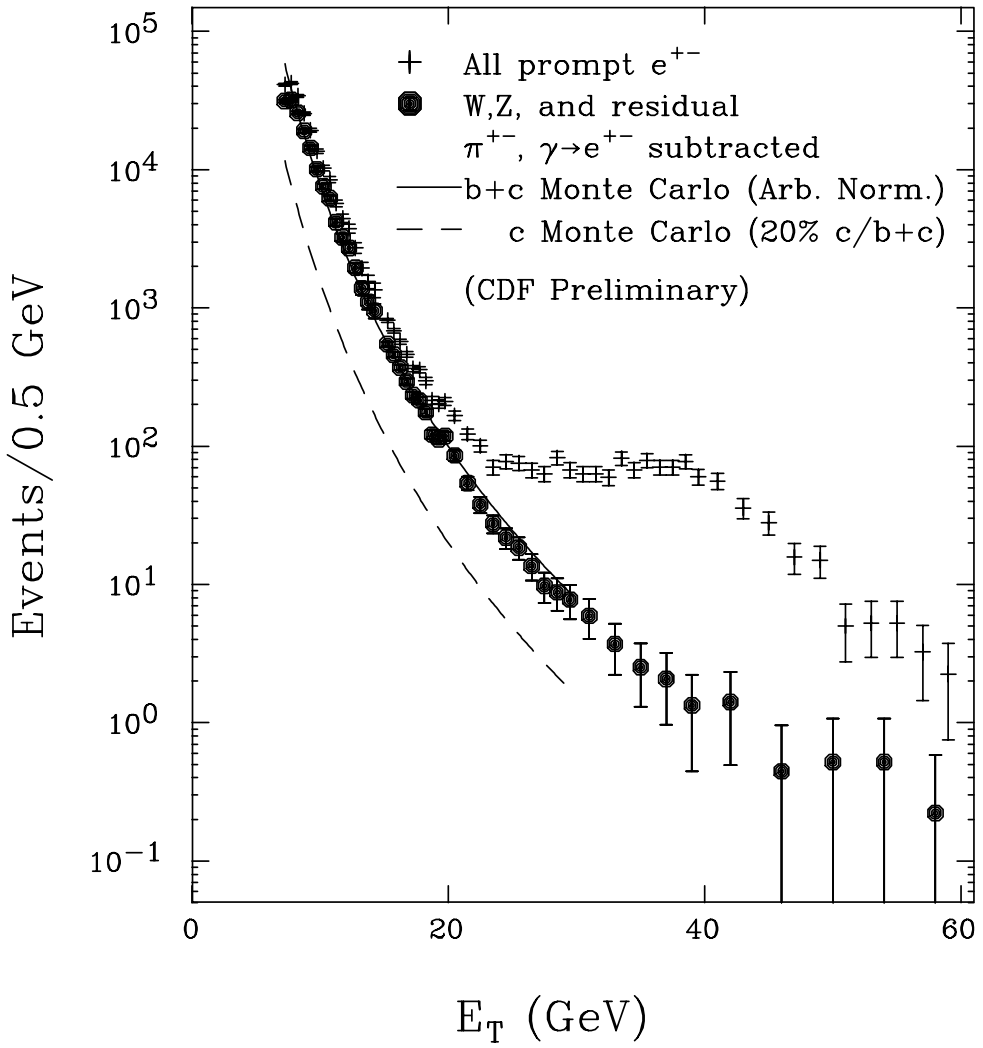


- 0-th order approximation :
  Decay of a heavy hadron $H_Q(\equiv Q\bar{q})$ is the decay of the heavy quark Q.
- b quark decays to c or u quark.
  $b \to c$ decay dominant, because $|V_{cb}| \gg |V_{ub}|$.
- Have to isolate among BG of q and g jets.
  $\Rightarrow$ use semileptonic decay and the lepton.
  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).



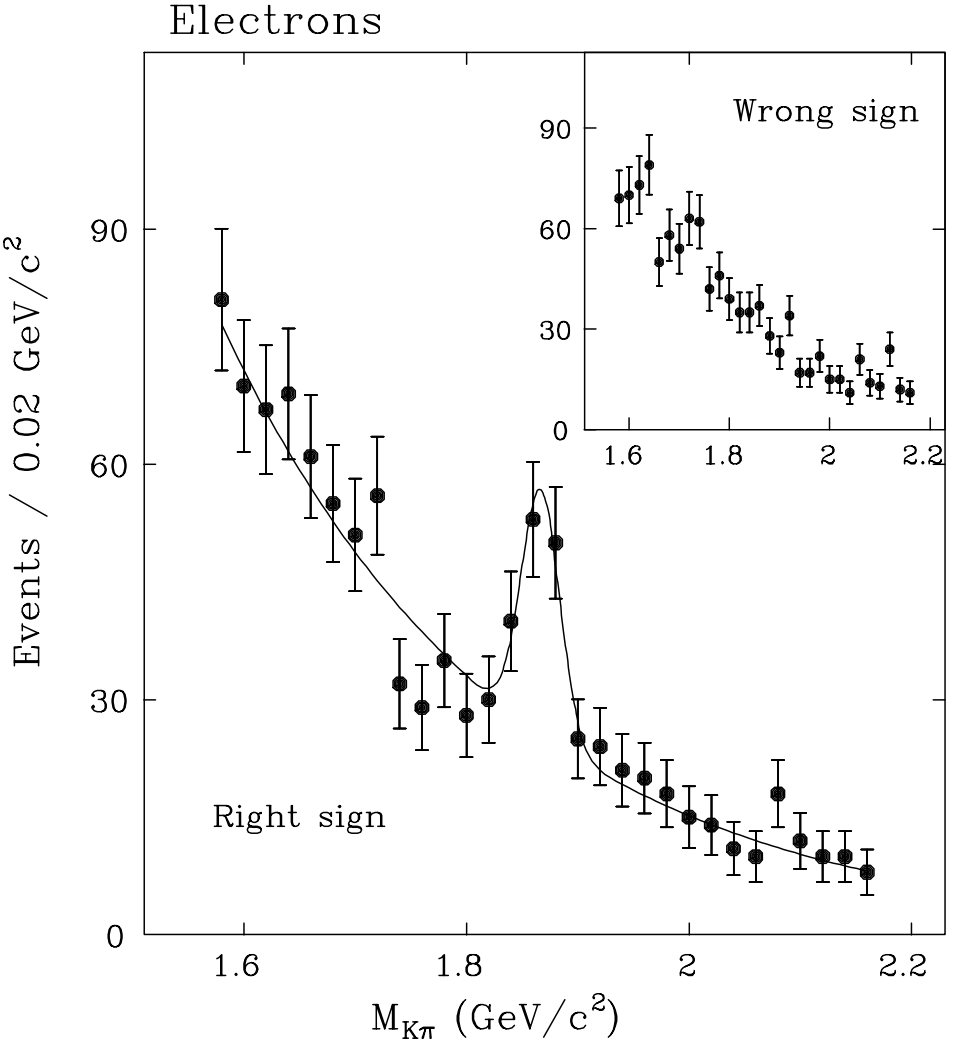
"Shoulder" above ~ 25 GeV from $W^{\pm} \to e^{\pm}\nu$ and $Z^0 \to e^+e^-$.

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

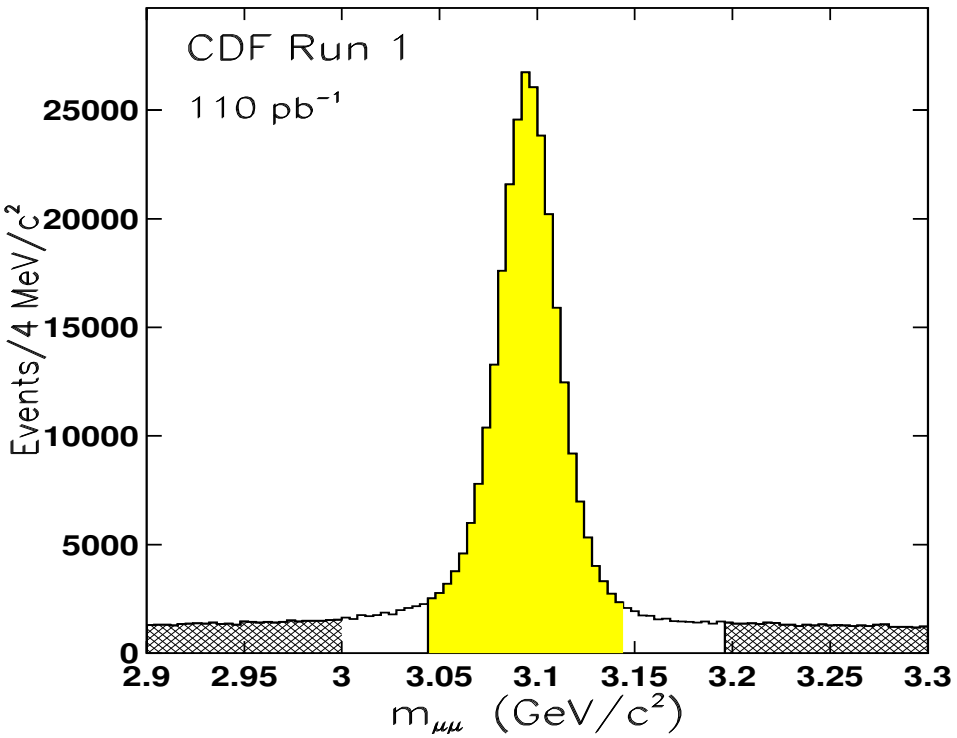
$b \to \overline{B}$ fragmentation harder than $c \to D$.
Lepton momentum in the B rest frame larger than in the D.
$\Rightarrow$ bottom leptons enhanced over charm leptons.

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

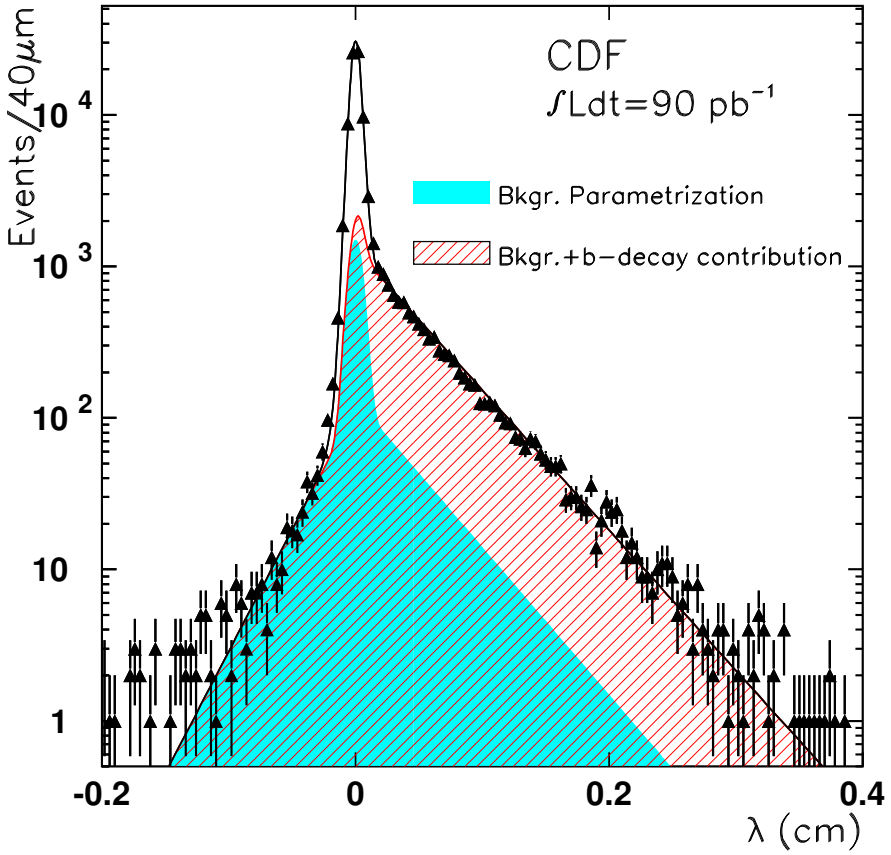
Reconstruct charm meson $D^0 \to K^- \pi^+$ near e^-.



$J/\psi \to \mu^+\mu^-$ and B decays

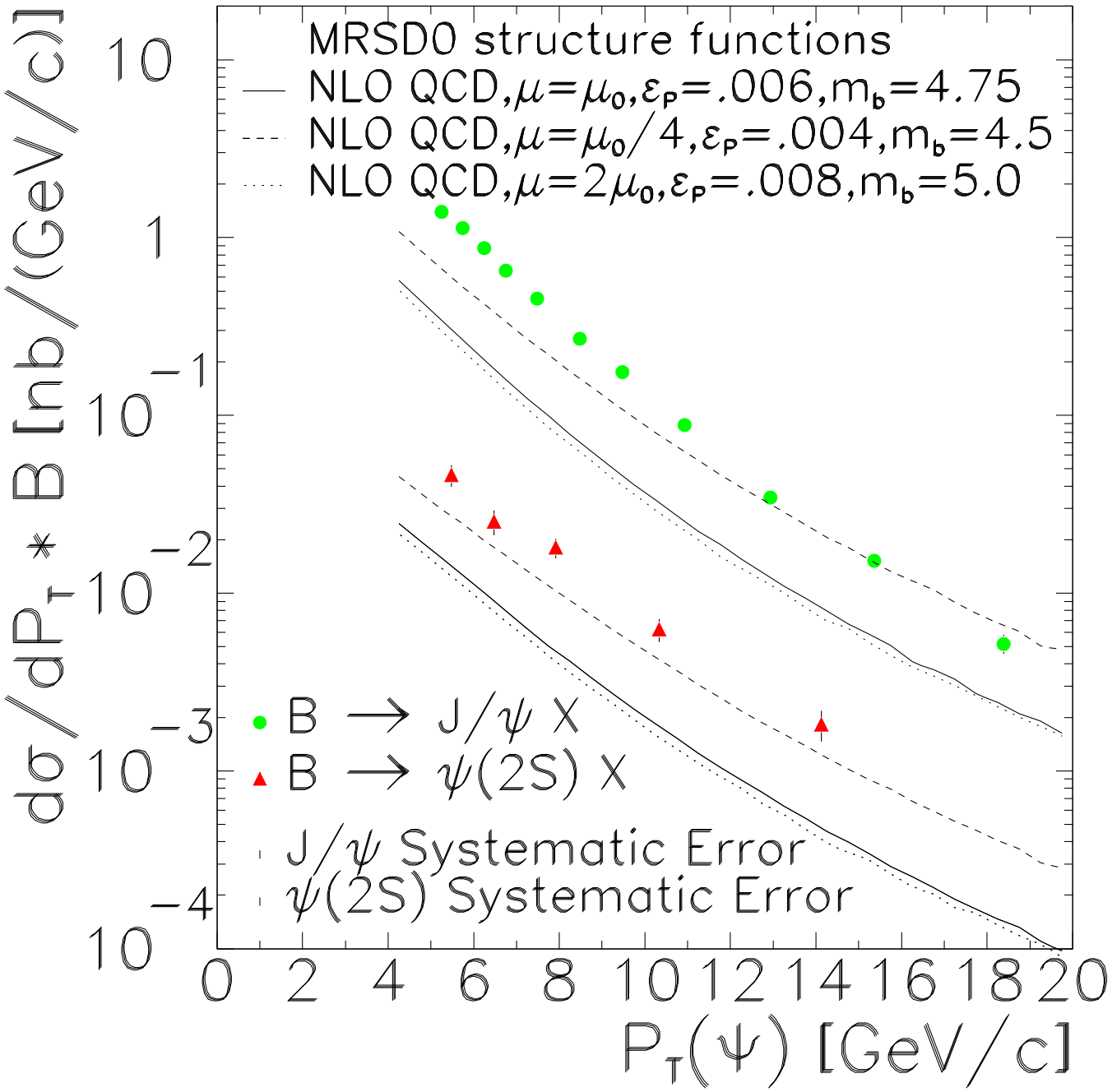


Decay length distribution



$\sim$ 20% of J/ψ's from B decays.

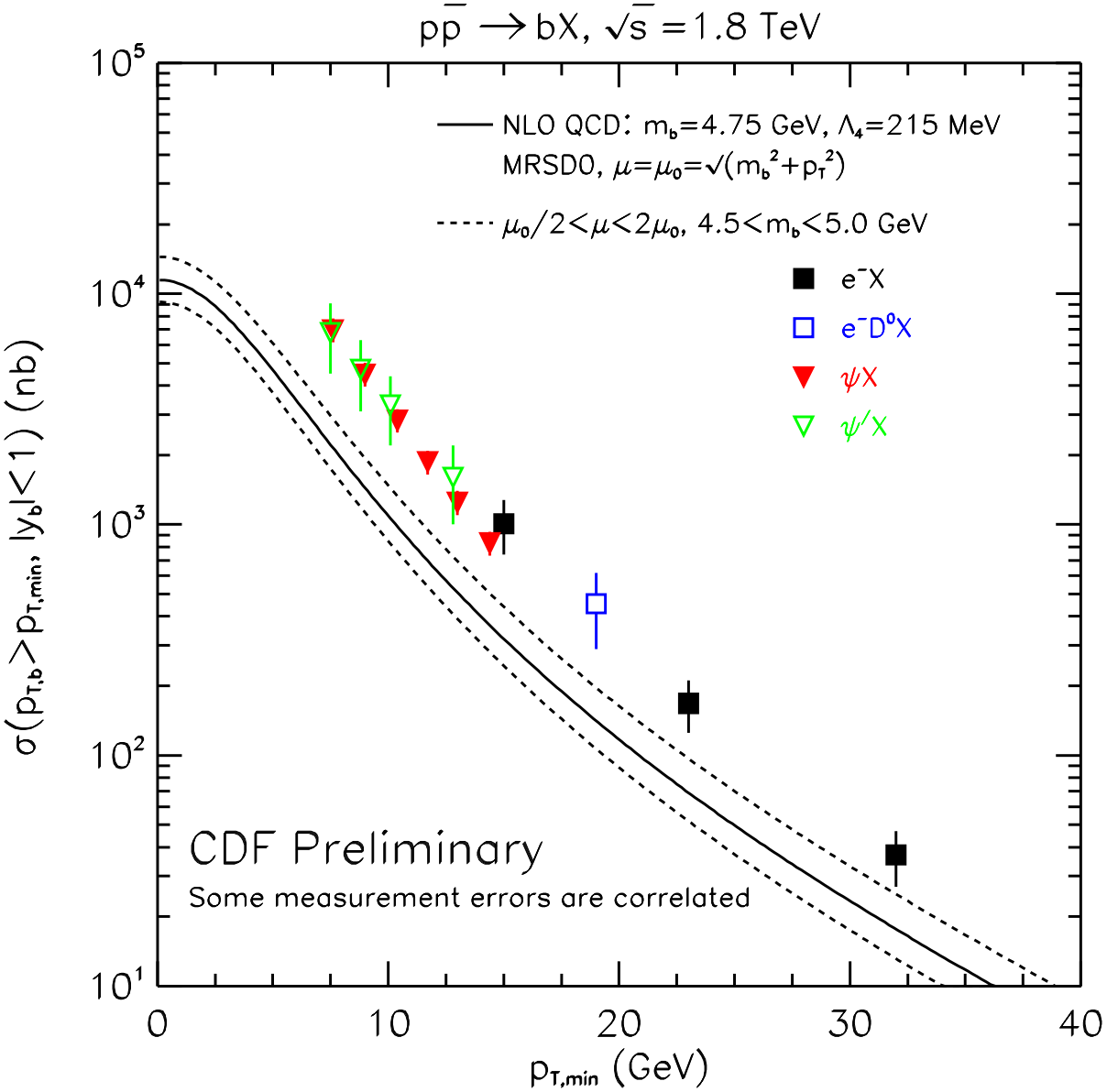
Production of J/ψ and $\psi(2S)$ from B decays



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

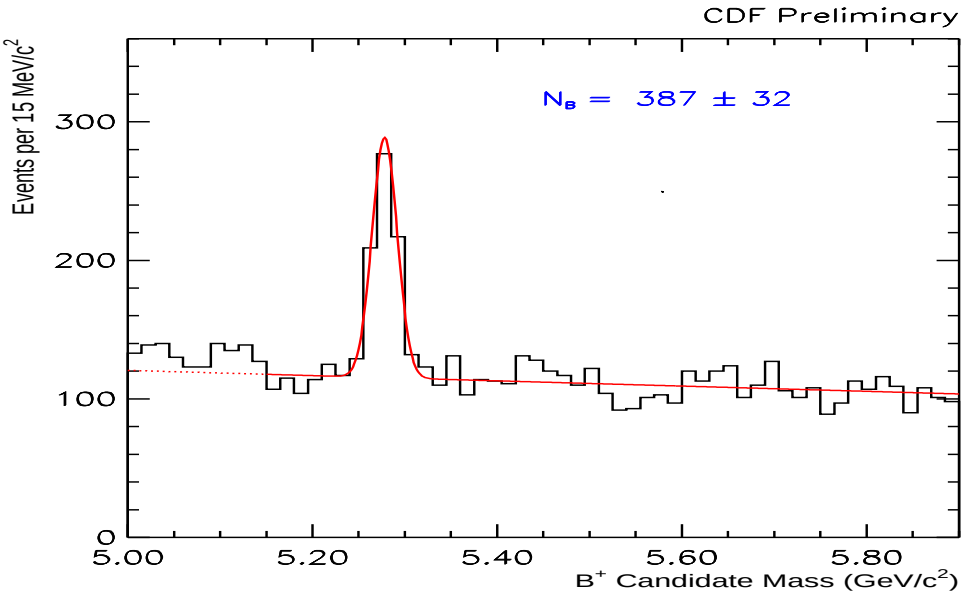
PRL 79, 572 (1997).

b-quark Production Cross Section above $p_T^{\rm min}$, with ψ's and semileptonic decays.

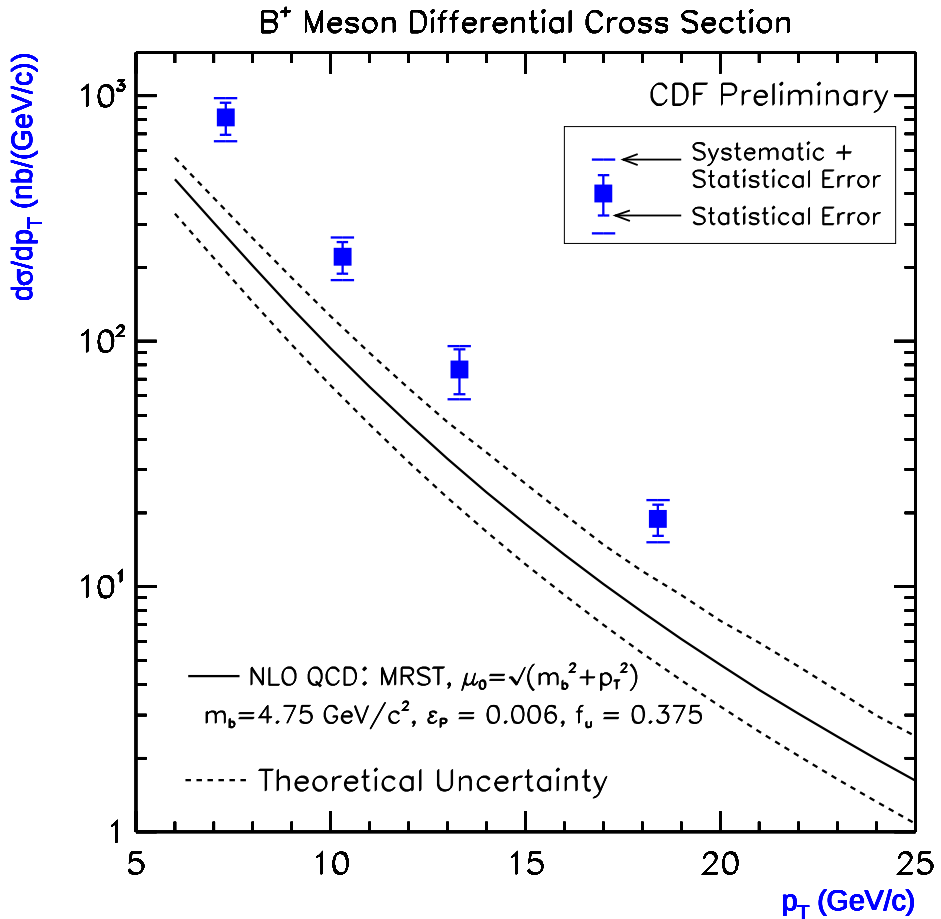


Data $\sim 2 \times$ Theory

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



B^+ meson production cross section



$\sigma(\bar{p}p \to B^+X) = 3.51 \pm 0.42 \pm 0.53$ μb
for $p_T > 6$ GeV/c and $|y| < 1.0$.
PRD 65, 052005 (2002).

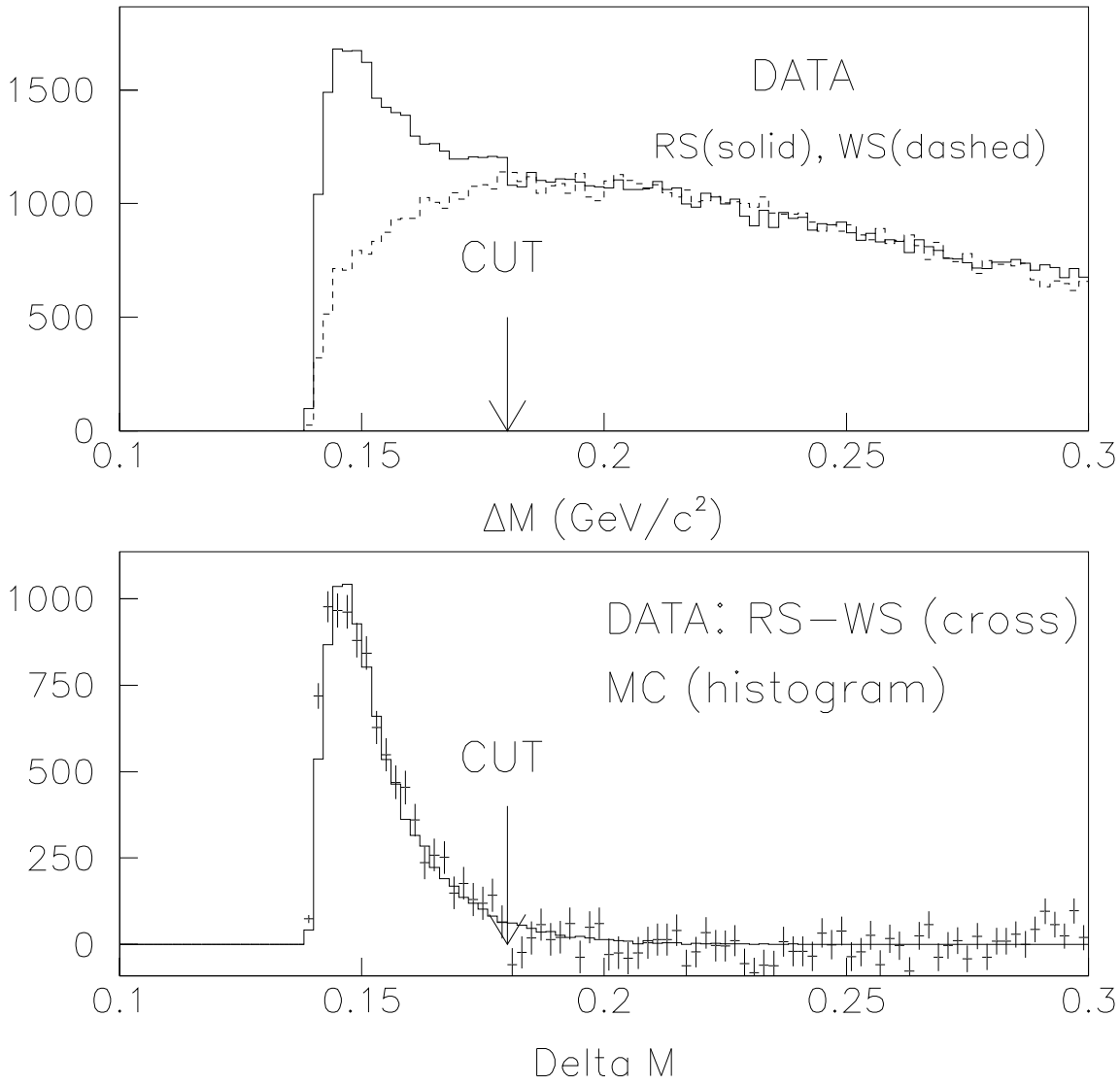
Open Charm Production

Is charm heavy enough?

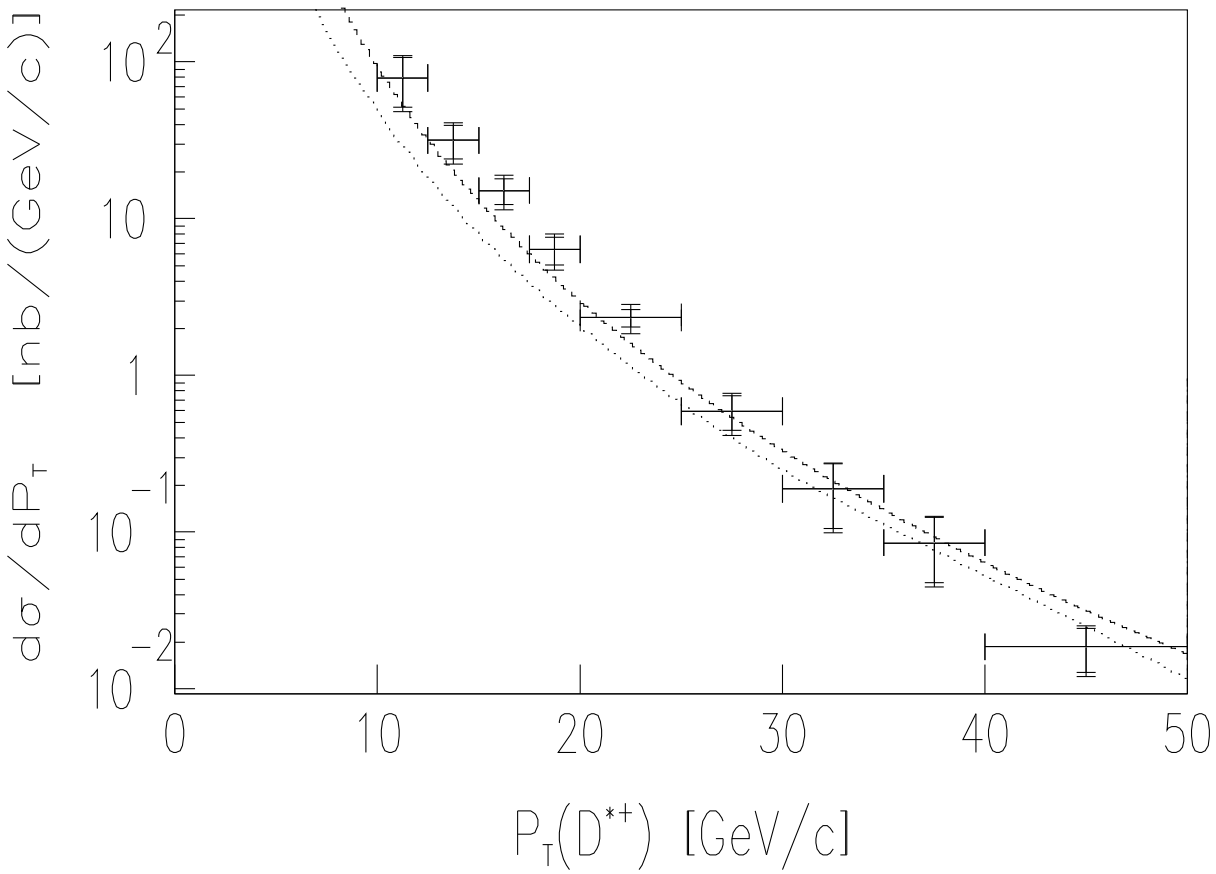
Otherwise similar to bottom.

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

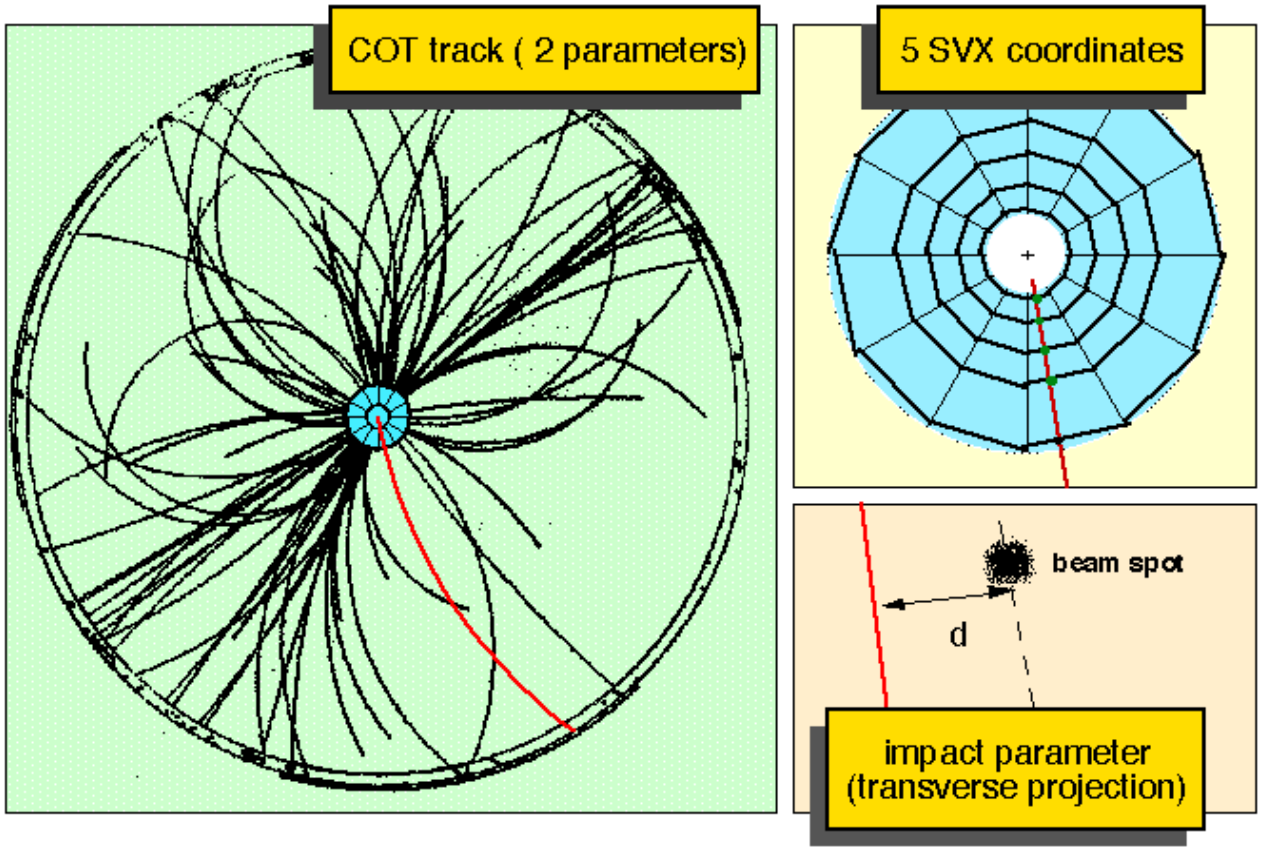


$\sigma(\bar{p}p \to D^{*+}X) = 347 \pm 65 \pm 58$ nb
for $p_T > 10$ GeV/c and $|\eta| < 1.0$.

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

Run-II Silicon Vertex Trigger : SVT

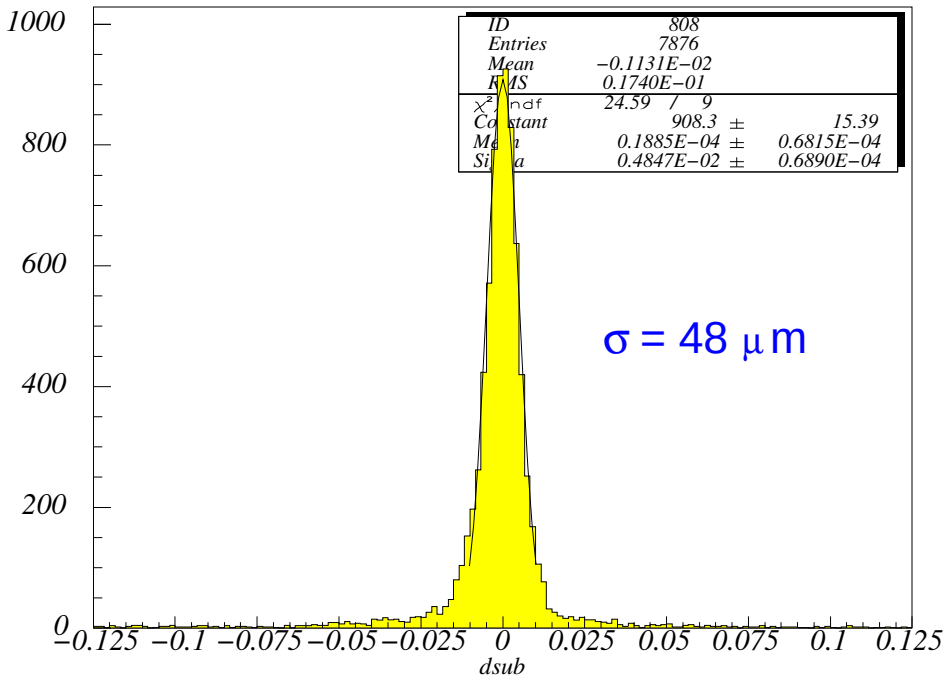
Use silicon information at 2nd level of trigger.



- Find a track in the main tracker COT.
- Extrapolate inwards.
- Find silicon hits along the road.
- Calculate impacct parameter d with respect to the primary vertex (beam spot).

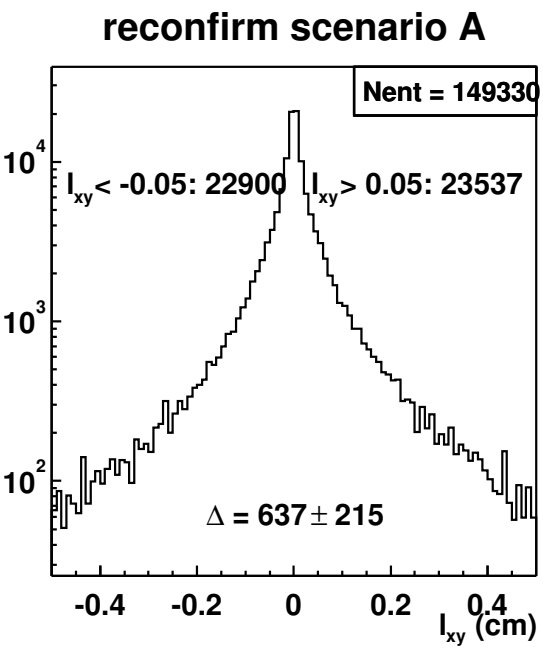
Resolution $\sigma_d \sim 50$ μm for $p_T > 2$ GeV/c.

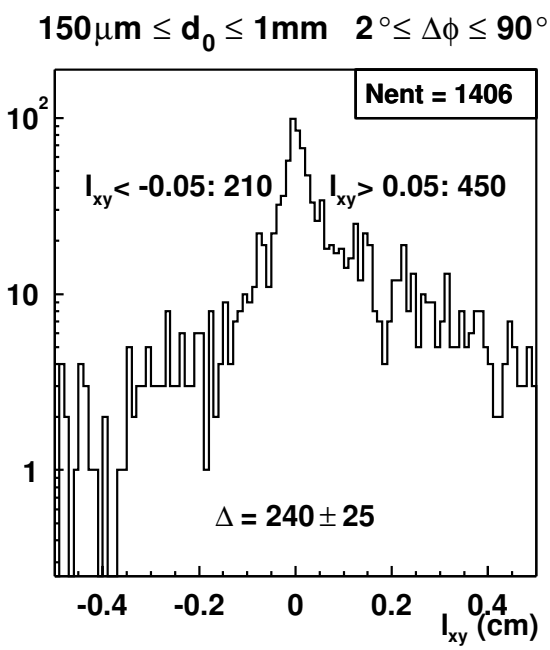
SVT Performance



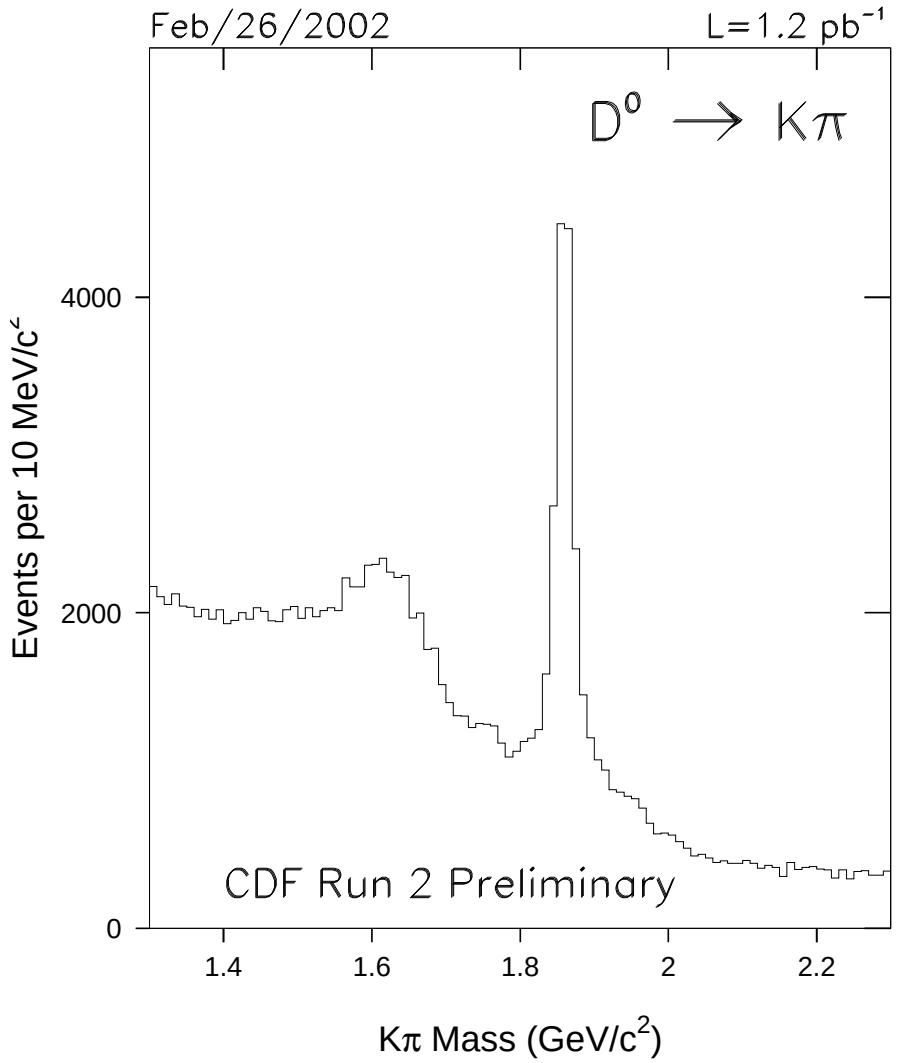
Trigger on tracks ($p_T > 2$ GeV/c) with
100 μm $< |d| <$ 1000 μm.

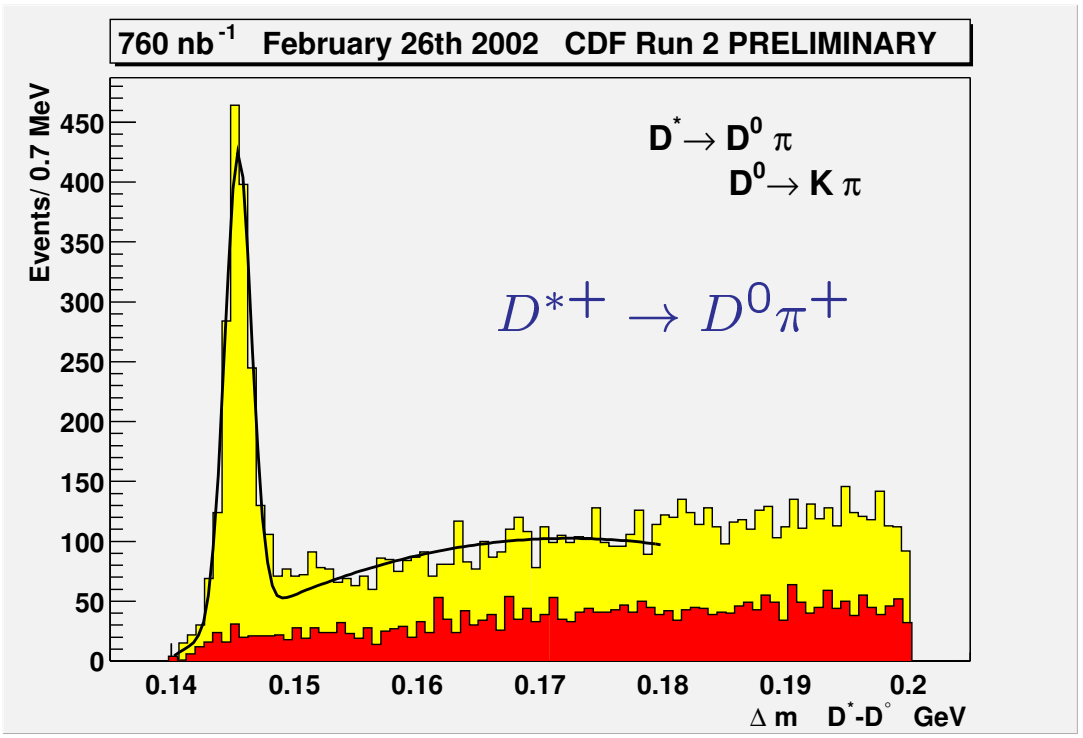
Calculate decay length L_{xy}, require $L_{xy} > 500$ μm.



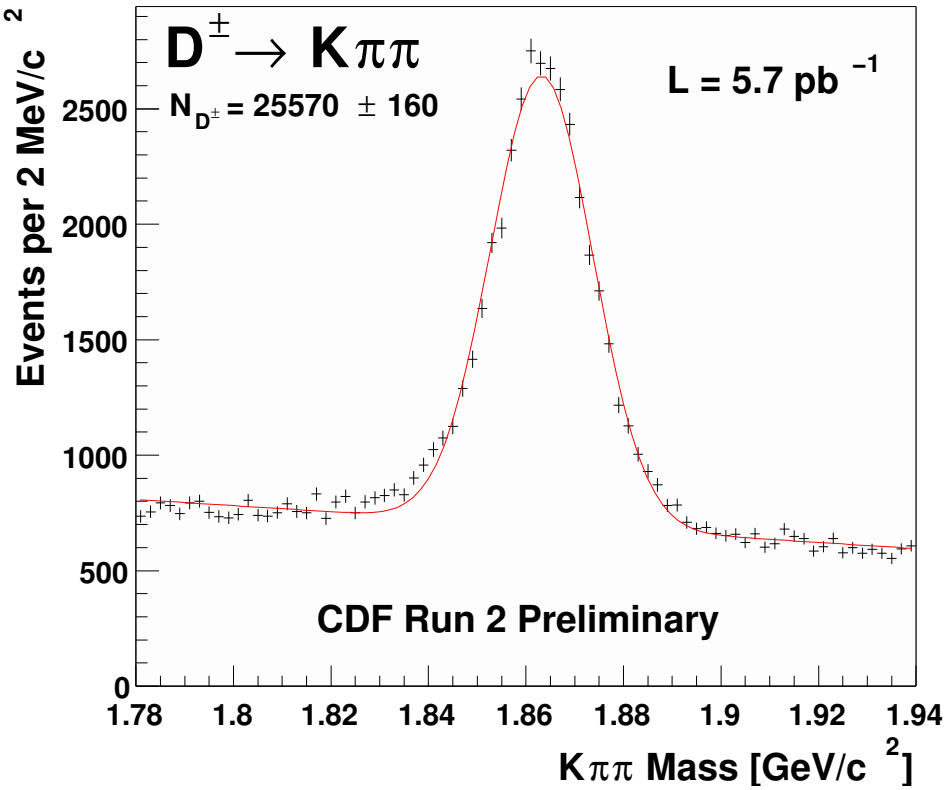


Run-II $D^0 \to K^-\pi^+$ from SVT trigger

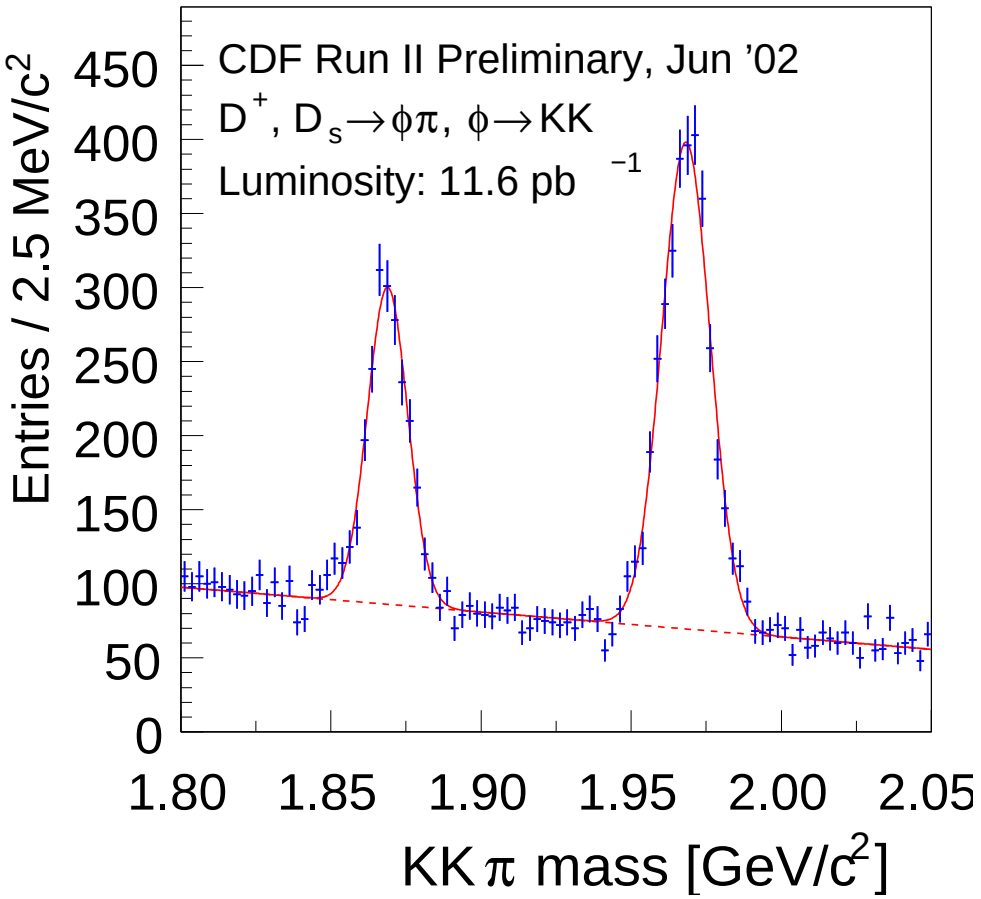




More charm : $D^+ \to K^-\pi^+\pi^+$



$D^+,\ D_s^+ \to \phi\pi^+,\ \phi \to K^+K^-$



Onium Production

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

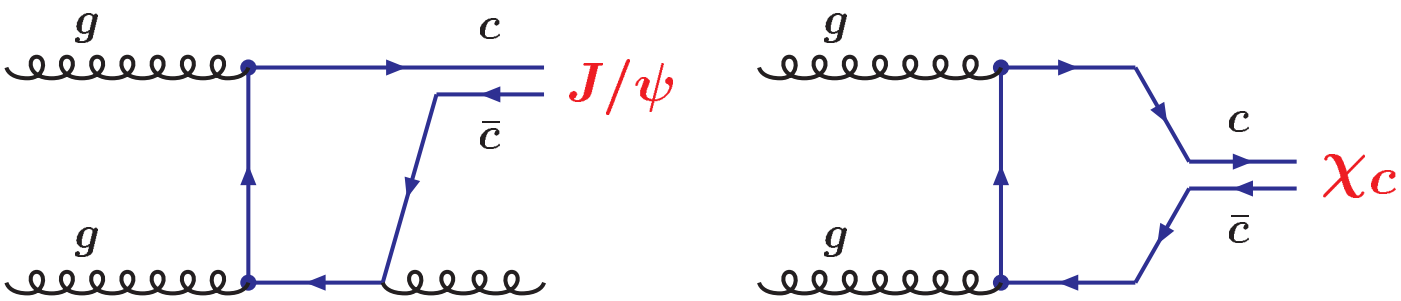
$c\bar{c}$ states :

$L = 0,\ S = 0,\ J^P = 0^-$: η_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 $b\bar{b}$:

$L = 0,\ S = 0,\ J^P = 0^-$: η_b
$L = 0,\ S = 1,\ J^P = 1^-$: Υ
$L = 1,\ S = 1,\ J^P = 0^+,\ 1^+,\ 2^+$: $\chi_{b0},\ \chi_{b1},\ \chi_{b2}$

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



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

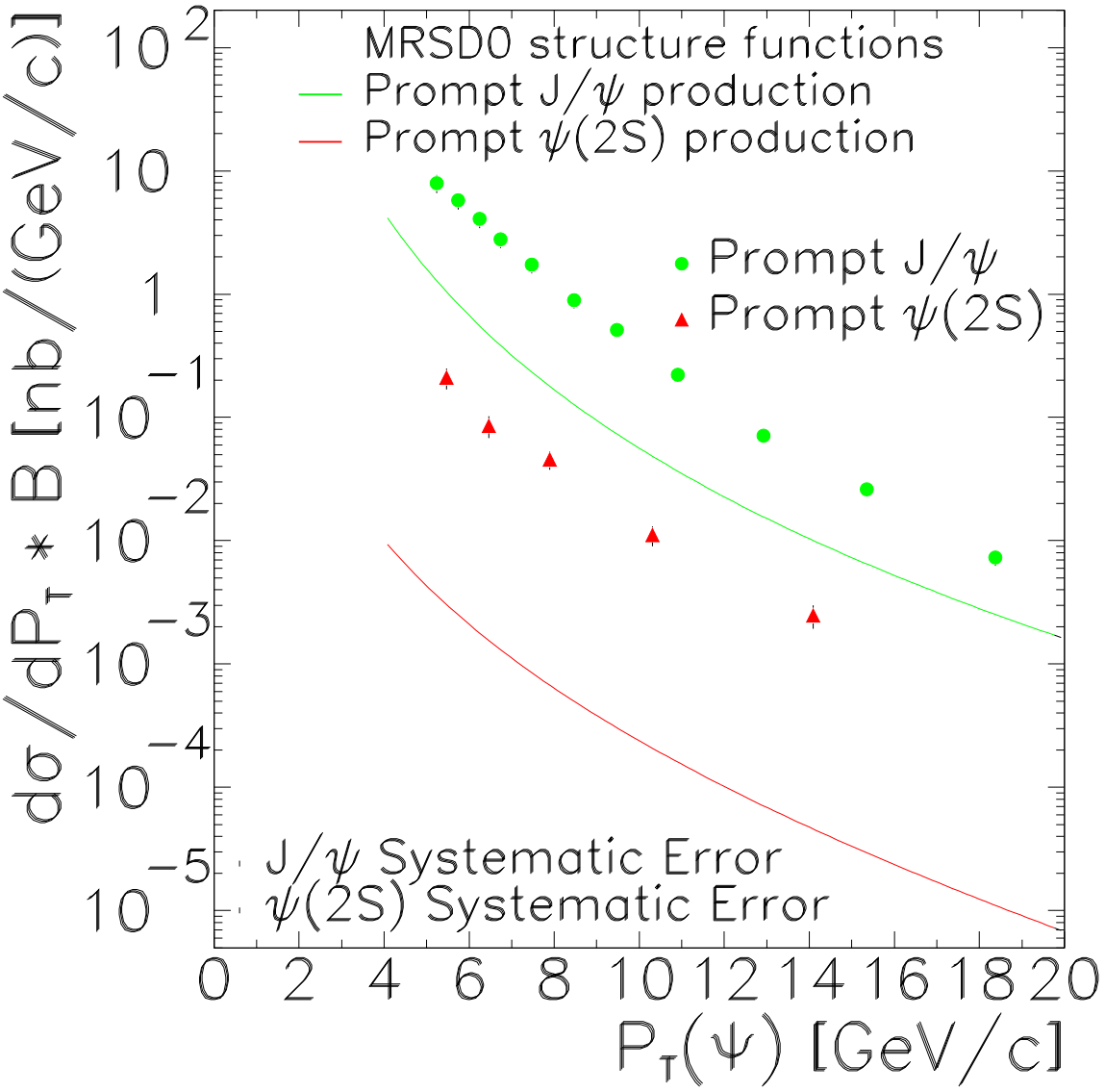
CDF has found $\times 50$ direct J/ψ and $\psi(2S)$ yields above "color singlet model".

J/ψ and $\psi(2S)$ Production

Sources:

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

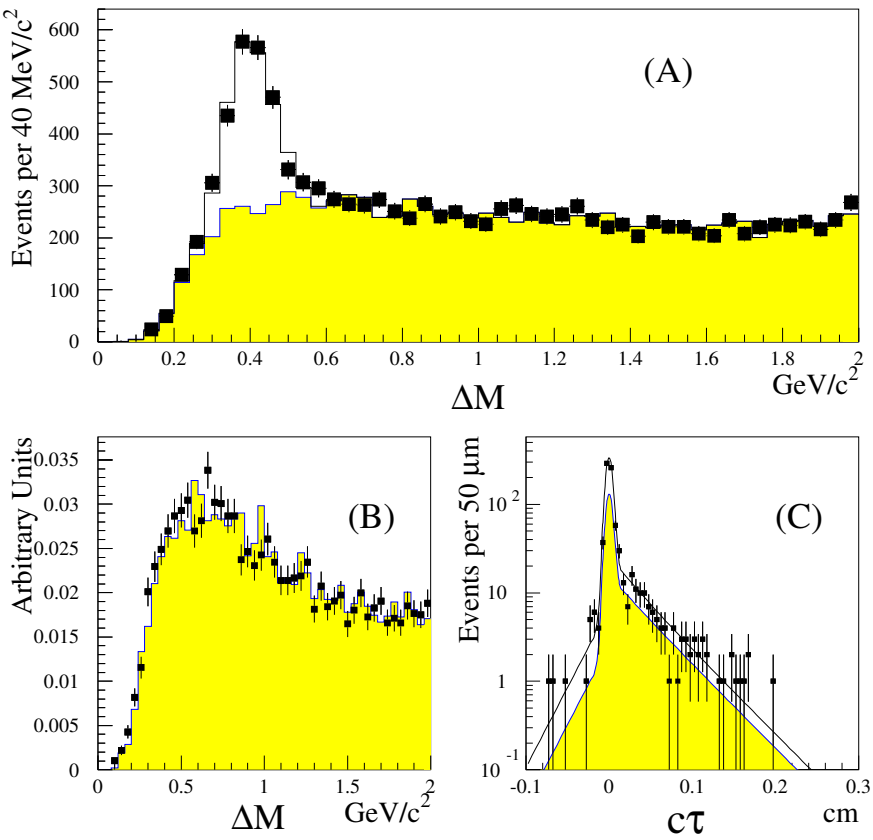
The latter two have zero lifetime : "prompt"



PRL 79, 572 (1997).

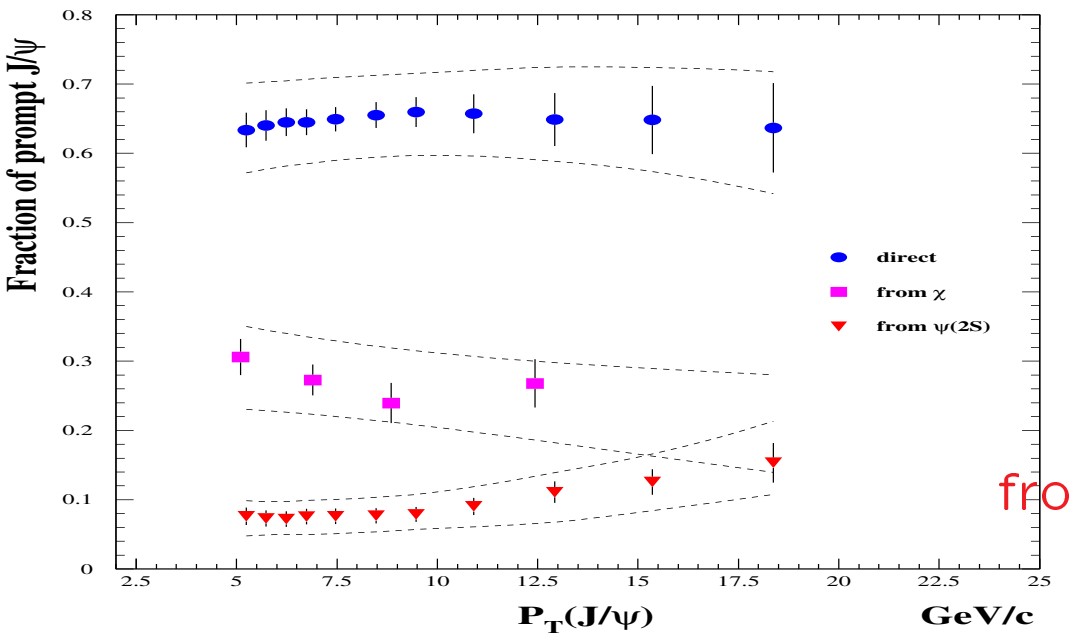
J/ψ from χ_c : $\chi_c \to J/\psi\,\gamma$

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.



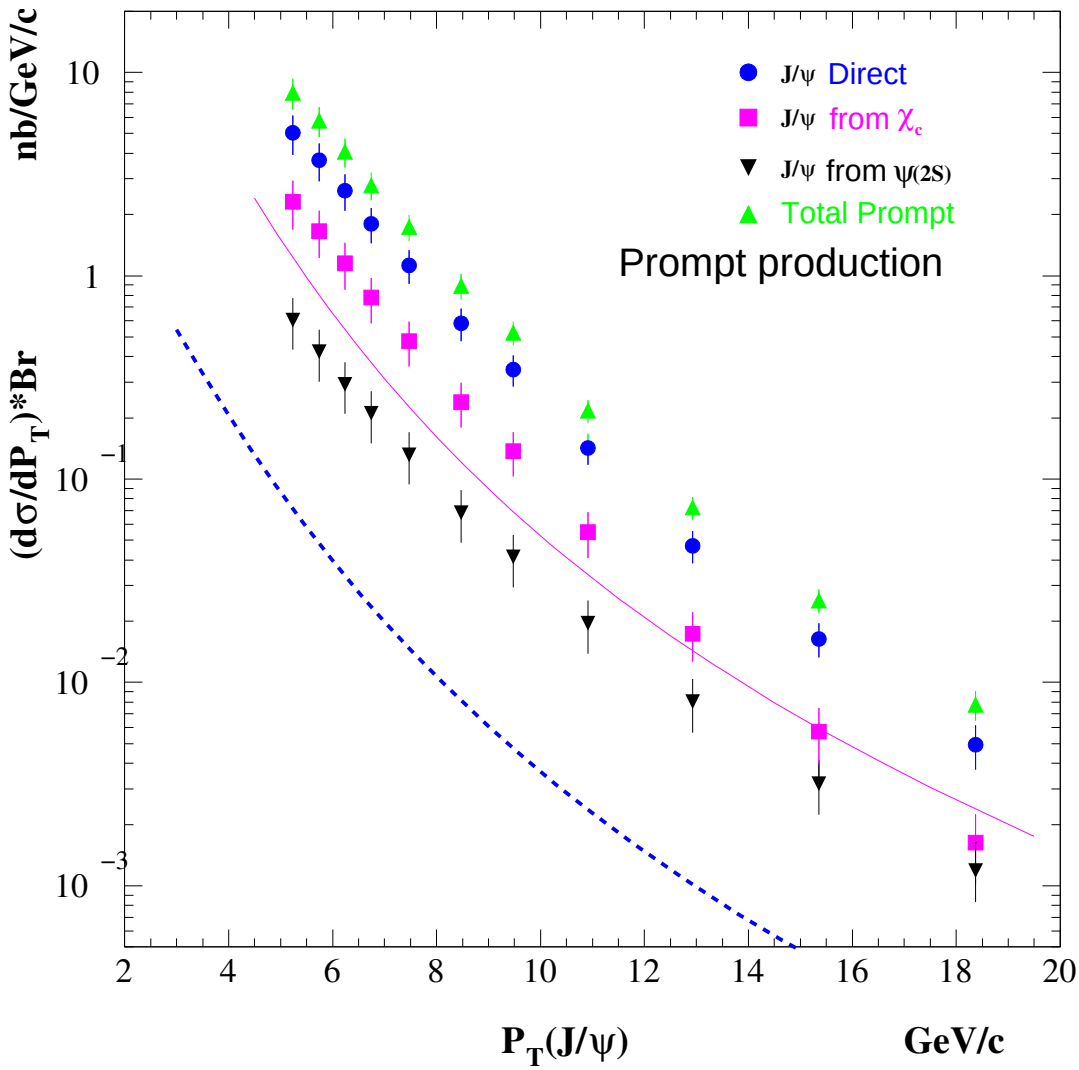
direct

from χ_c

from $\psi(2S)$

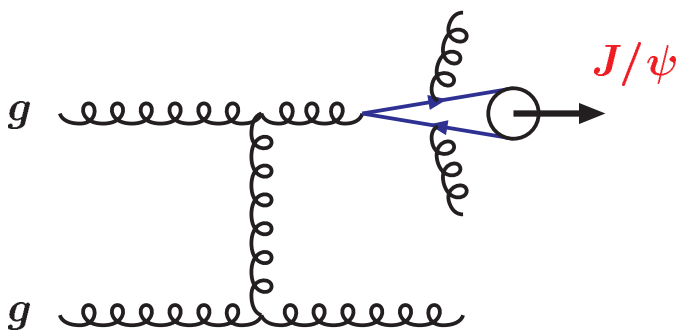
Prompt J/ψ Production Breakdown

PRL 79, 578 (1997)



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

Other mechanisms must exist.
Gluon fragmentation? Color octet?

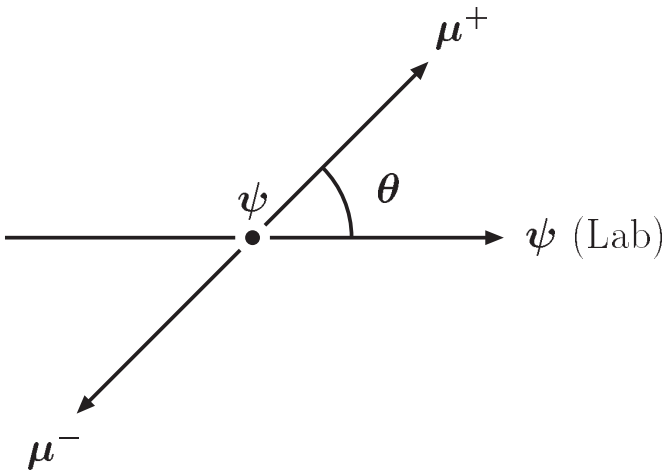


J/ψ and $\psi(2S)$ Polarization

Gluon fragmentation into ψ :

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

Helicity angle θ :



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

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

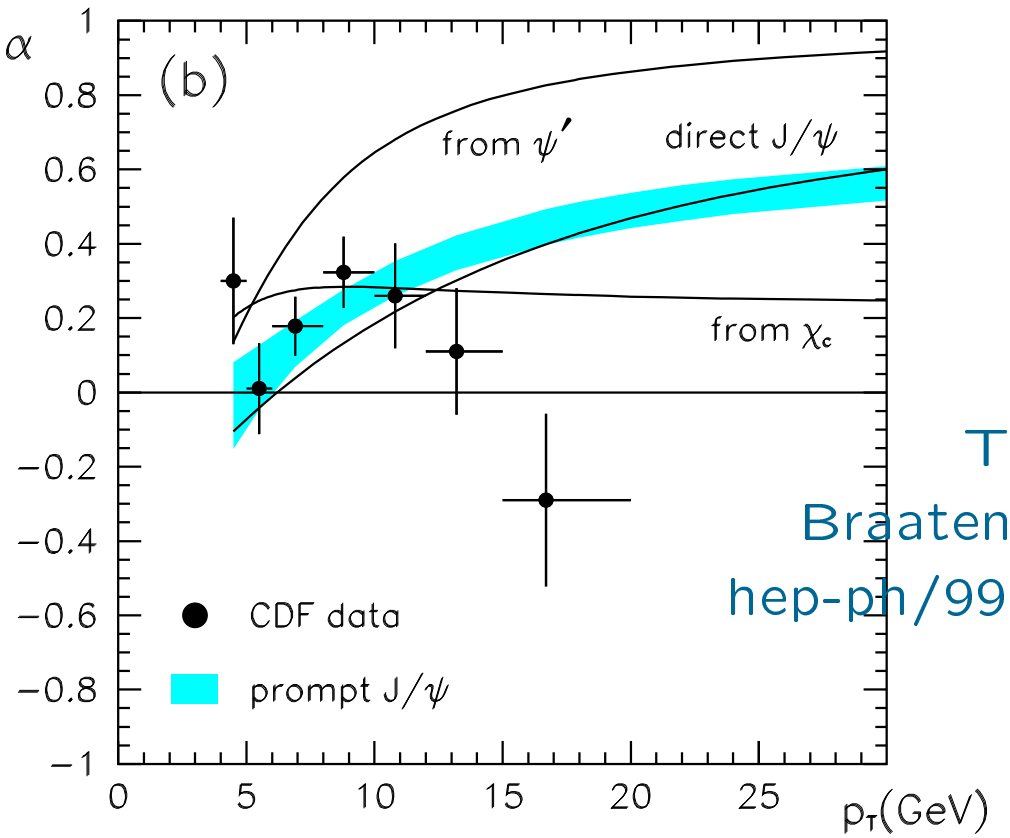
Prediction for direct production :

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

at $p_T = 20$ GeV/c.

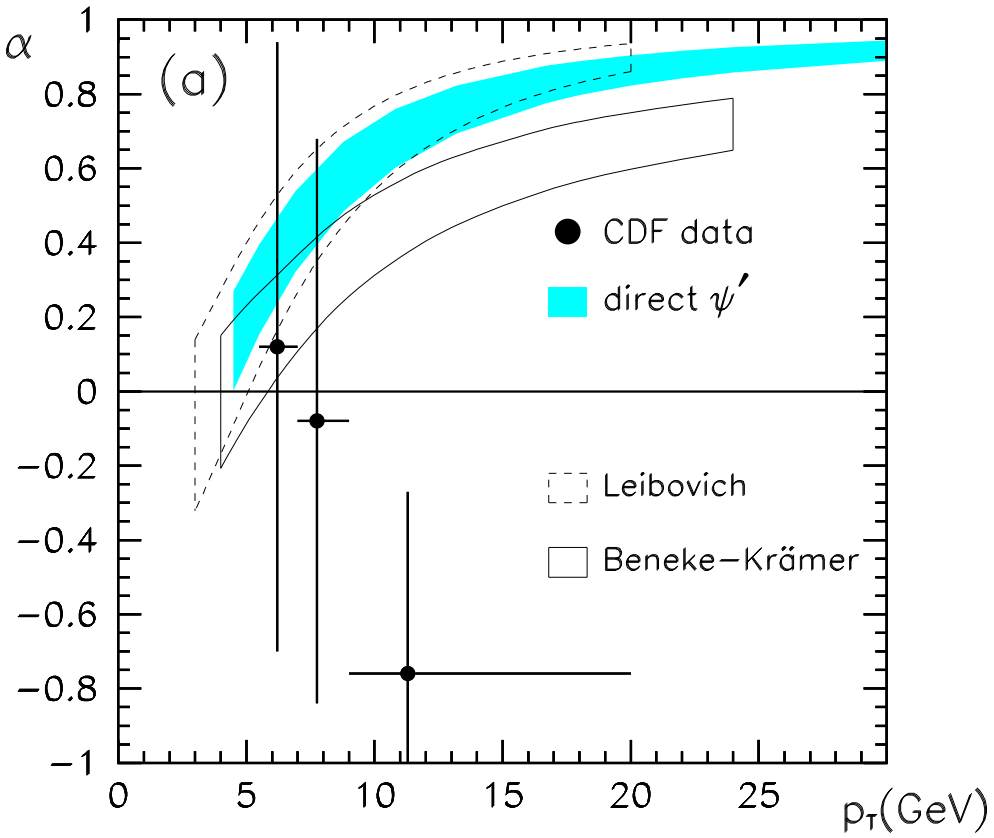
J/ψ and $\psi(2S)$ Polarization

J/ψ



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

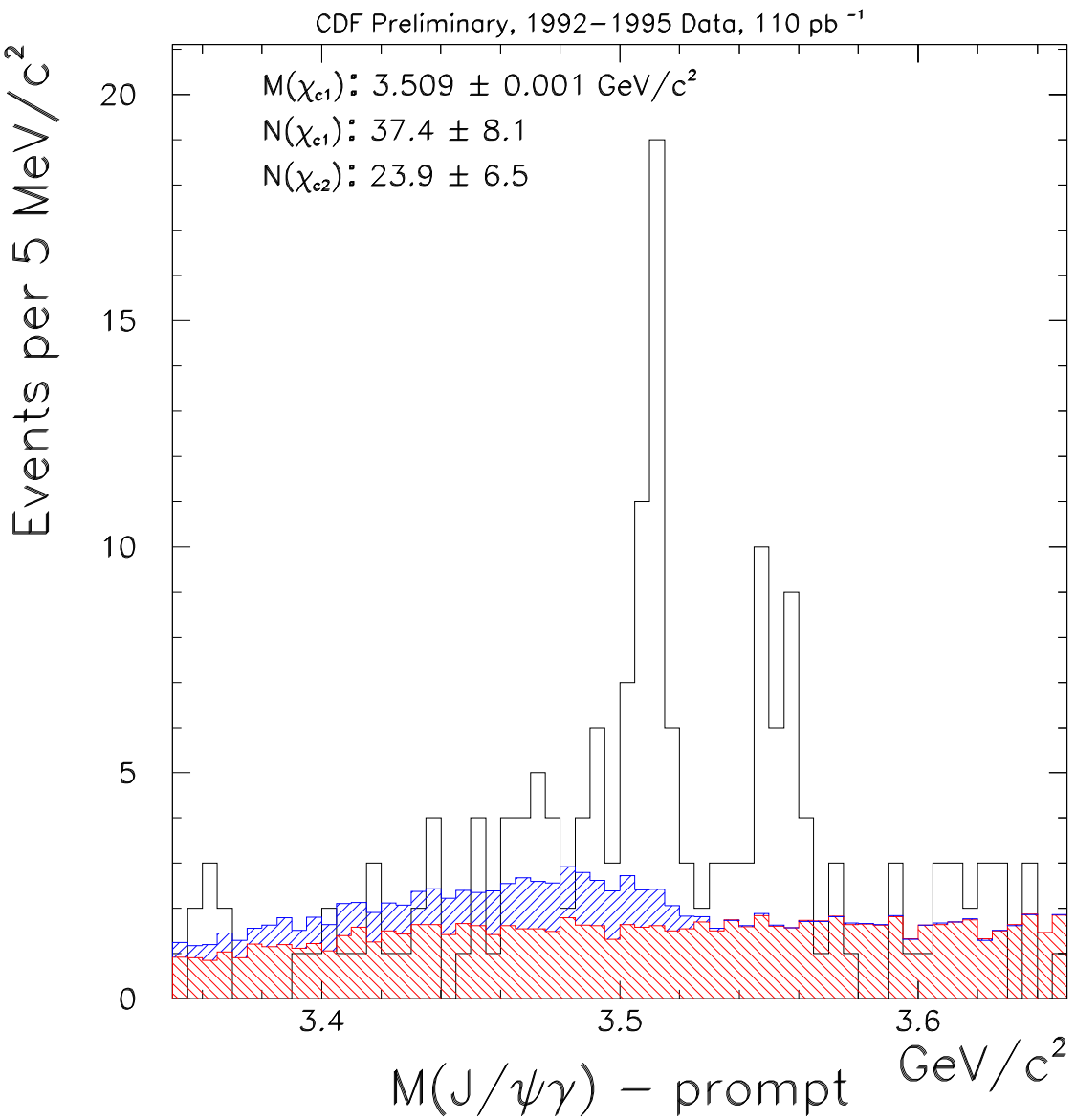
$\psi(2S)$



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)

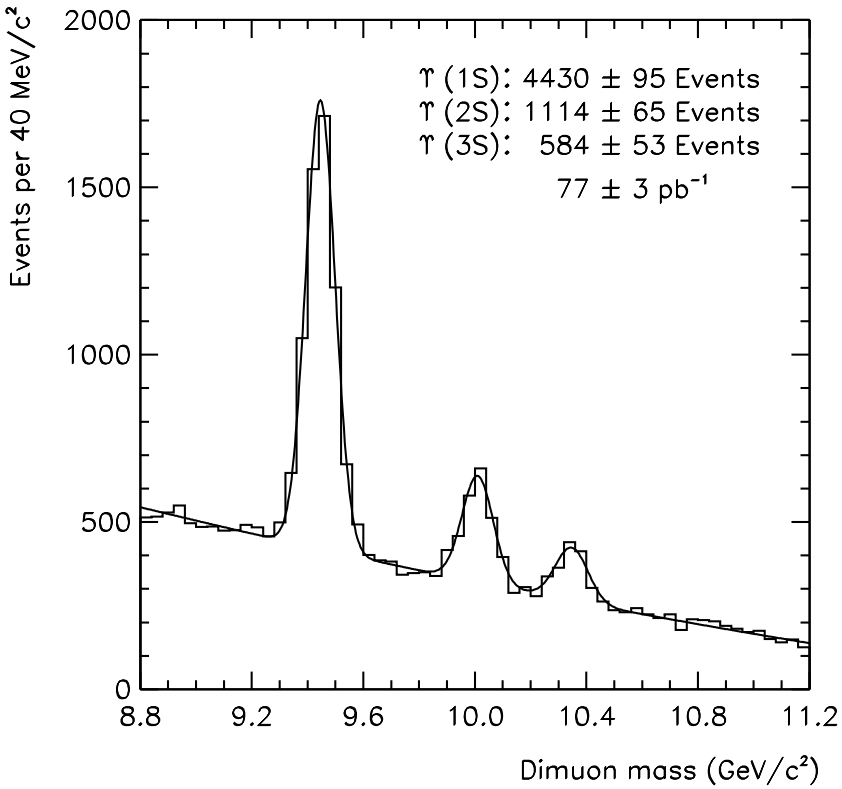


$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.89 \pm 0.33 \,^{+0.13}_{-0.10}$$

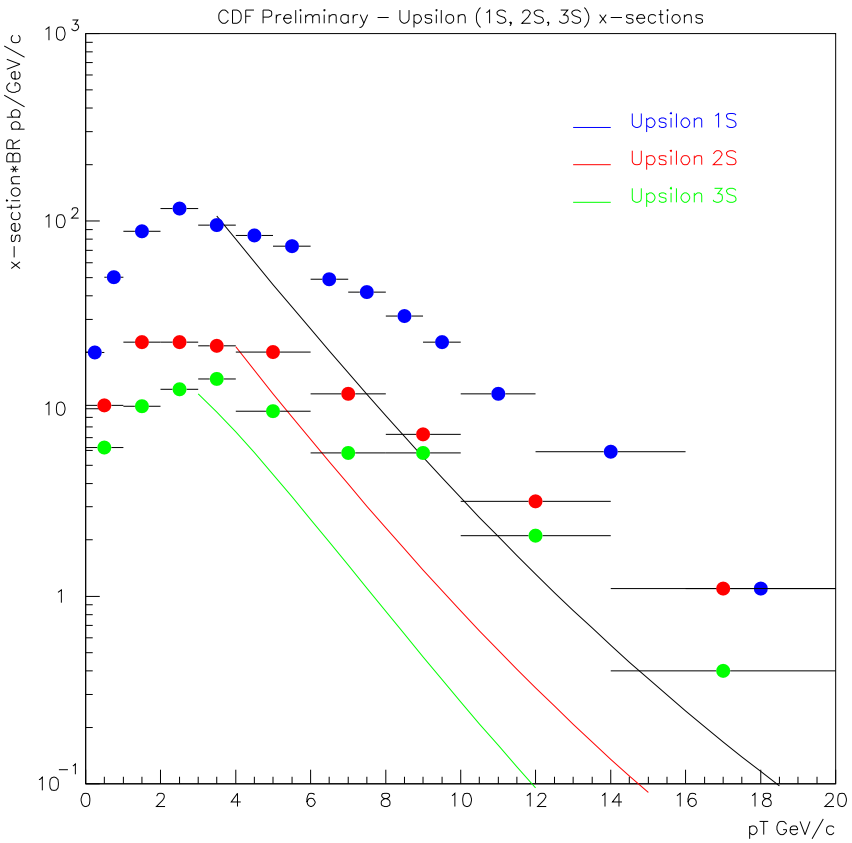
PRL 86, 3963 (2001)

Υ Production

Mass peaks

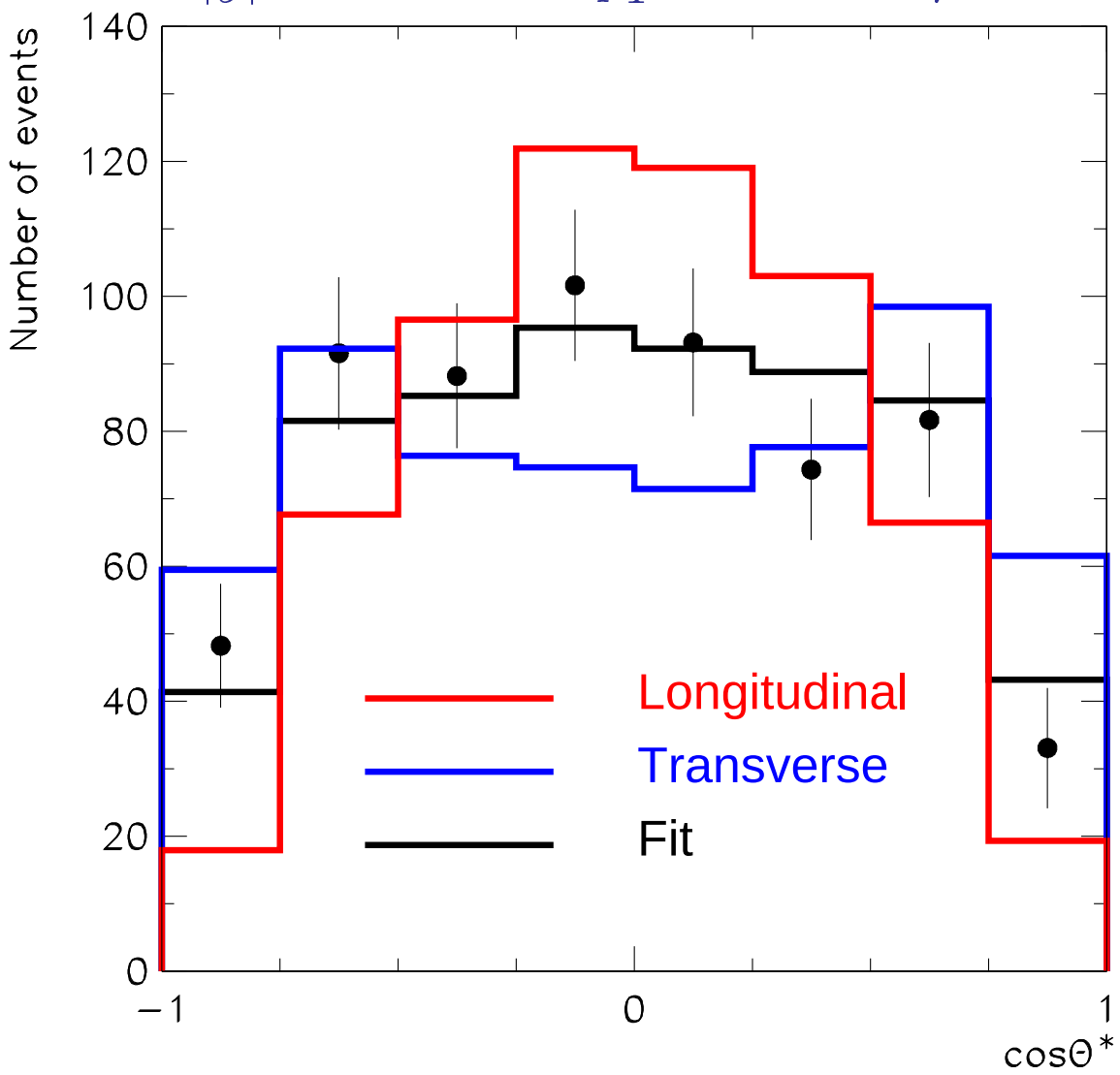


Cross section vs. p_T



$\Upsilon(1S)$ Polarization

$|y| < 0.4, \quad 8 < p_T < 20$ GeV/c

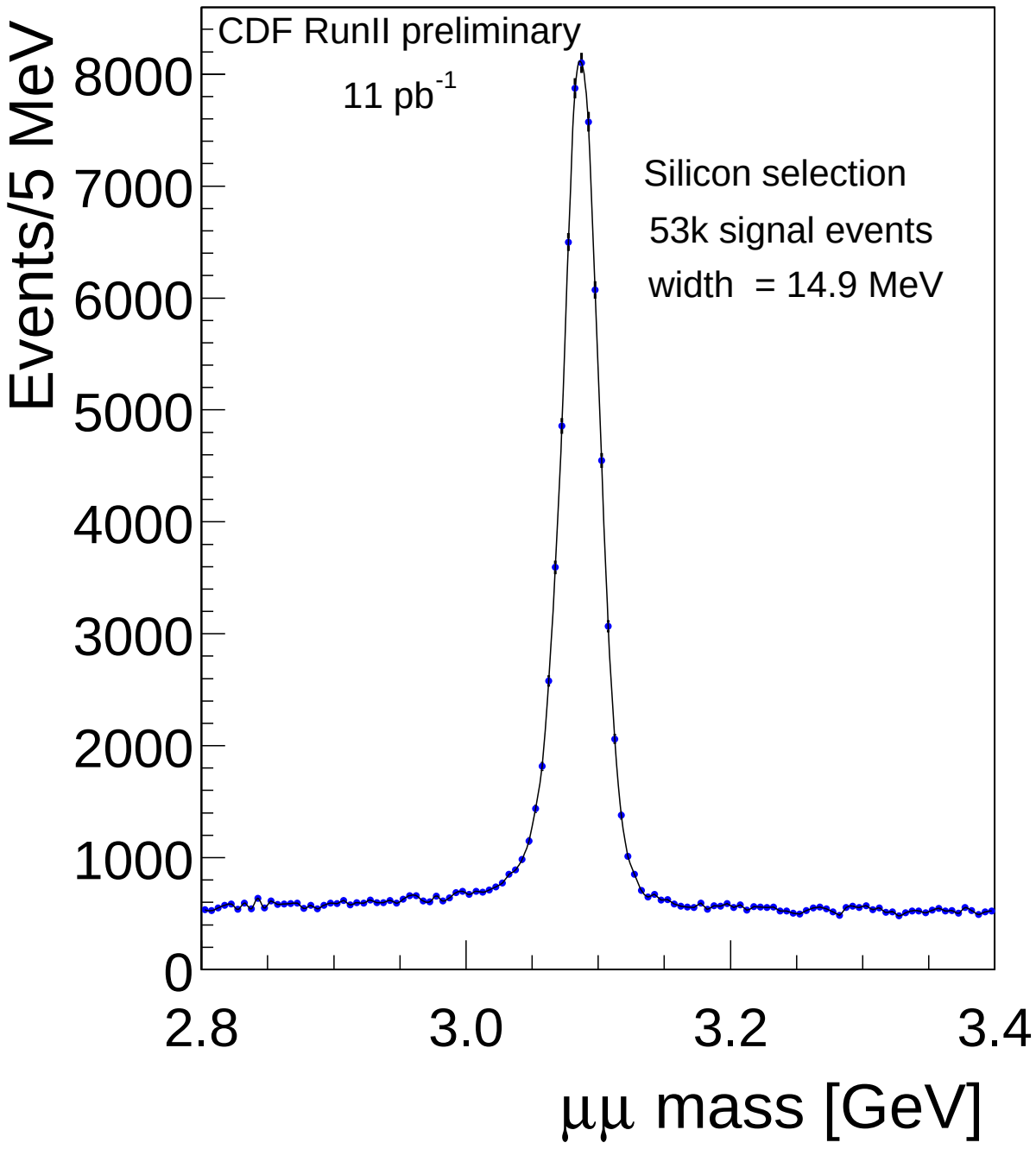


$\Gamma_L/\Gamma = 0.39 \pm 0.11$

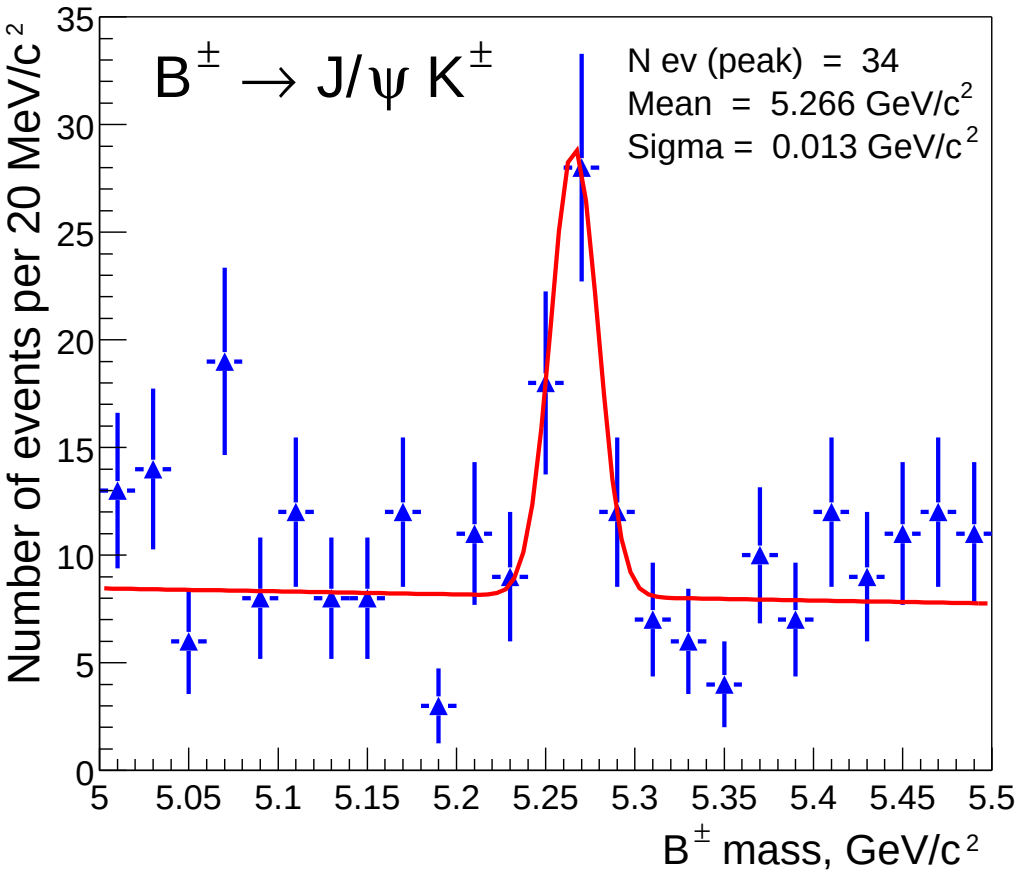
$(\alpha = -0.12 \pm 0.22)$

PRL 88, 071801 (2002)

Run-II Dimuon Data



Run-II $B^+ \to J/\psi K^+$



Summary

- Tevatron upgraded.
  New 150-GeV Main Injector.
  36 bunches now, 108 eventually.
  Increaed center-of-mass energy, 2 TeV.
  Higher luminosity (expected).
- CDF detector underwent a vast upgrade as well.
- Run-II started about a year ago.
  Detector commissioned successfully.

  CDF is now ready for serious data taking.
  Waiting for higher Tevatron luminosity.
- Some preliminary physics results expected this summer.
- 2 fb^{-1} by the end of 2004, 20-fold increase from previous run.
  Many improved measurements expected.
- Tevatron/CDF continues thru 2008, 15 fb^{-1}.
  Hope to find a Higgs and others.