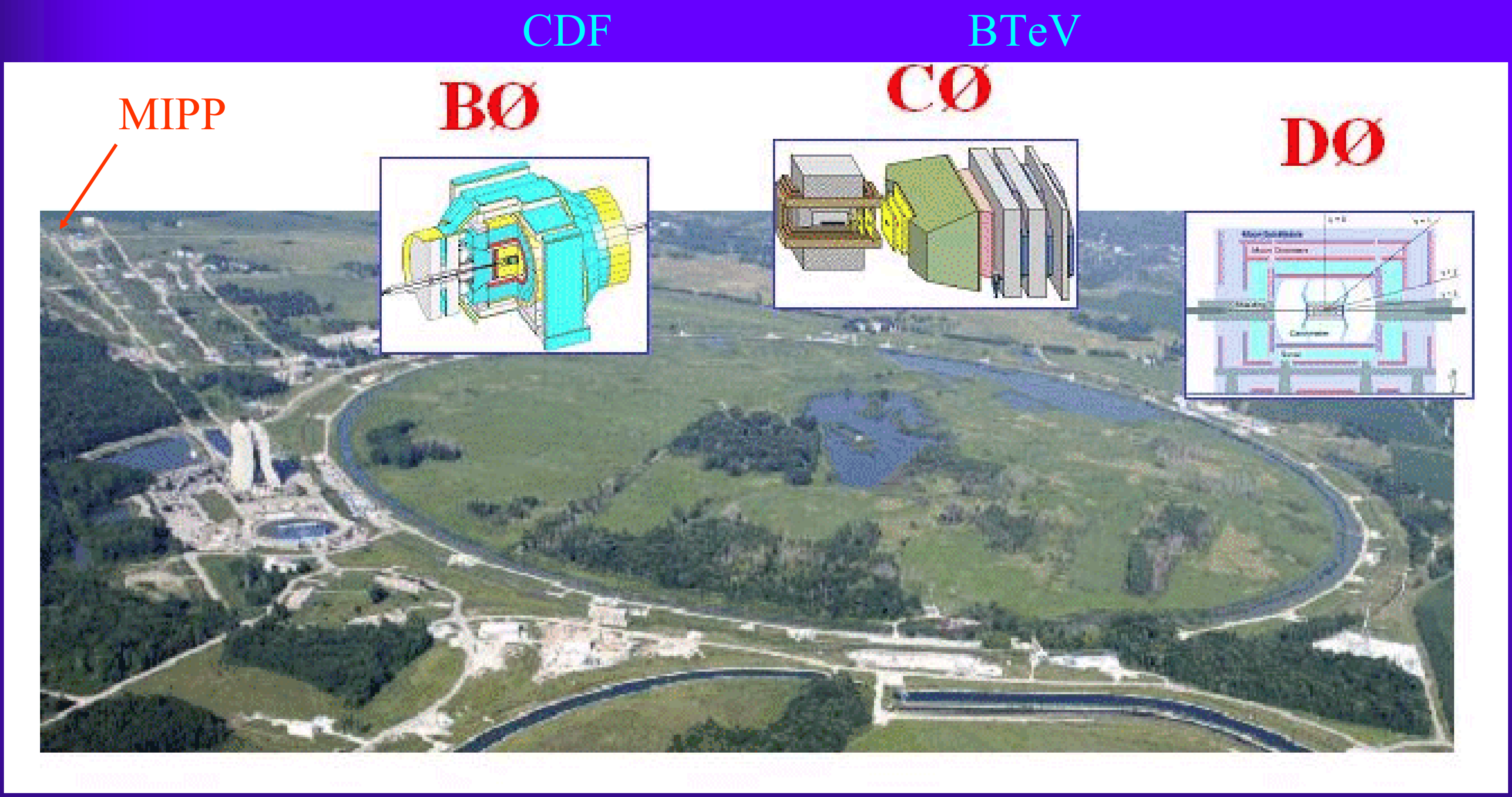
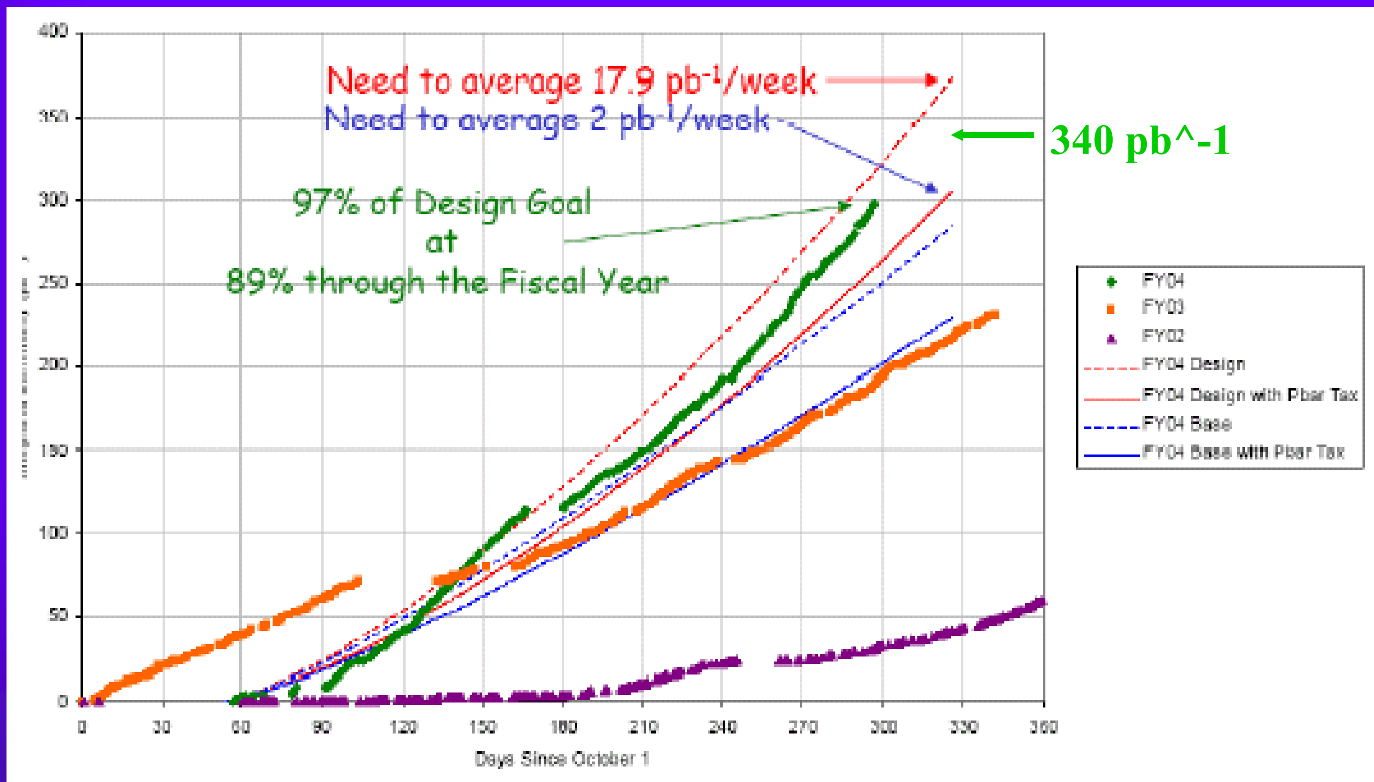
Perspectives of QCD at Fermilab

- **Fermilab:** Tevatron, **CDF, D0, MIPP, BTeV**
- Comments on **QCD in Hadron Collisions**
- **Run II Results**: CDF and D0 (from hard to soft)
- The **Future** of QCD at the Tevatron


CDF
BTeV
MIPP
BØ
CØ
DØ

Tevatron Run II Performance



340 pb^-1

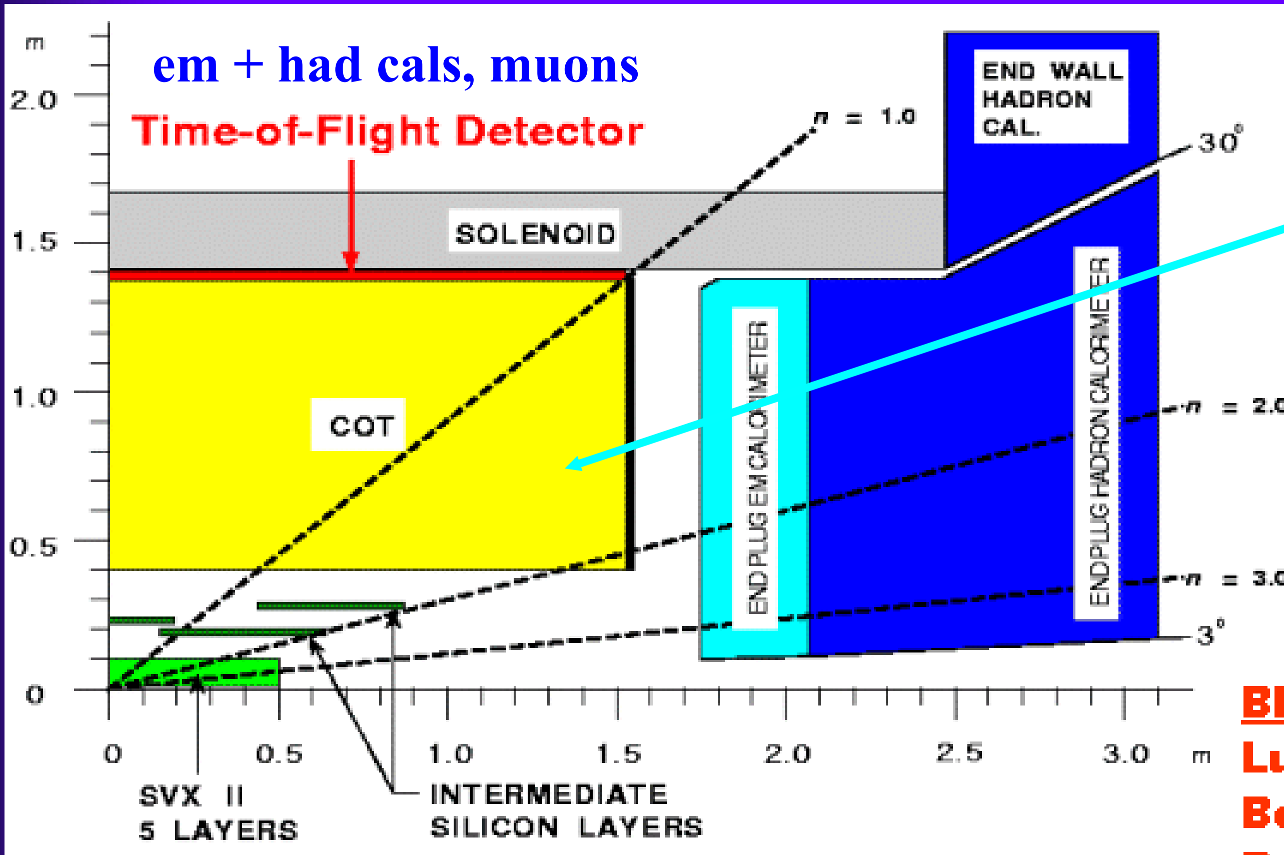
Total Run II ~ 440 pb^-1 on tape per experiment so far

Best peak luminosity = 1.03×10^{32} $cm^{-2}s^{-1}$

Expect at least $4fb^{-1}$ by Summer 2009

$8fb^{-1}$ appears possible

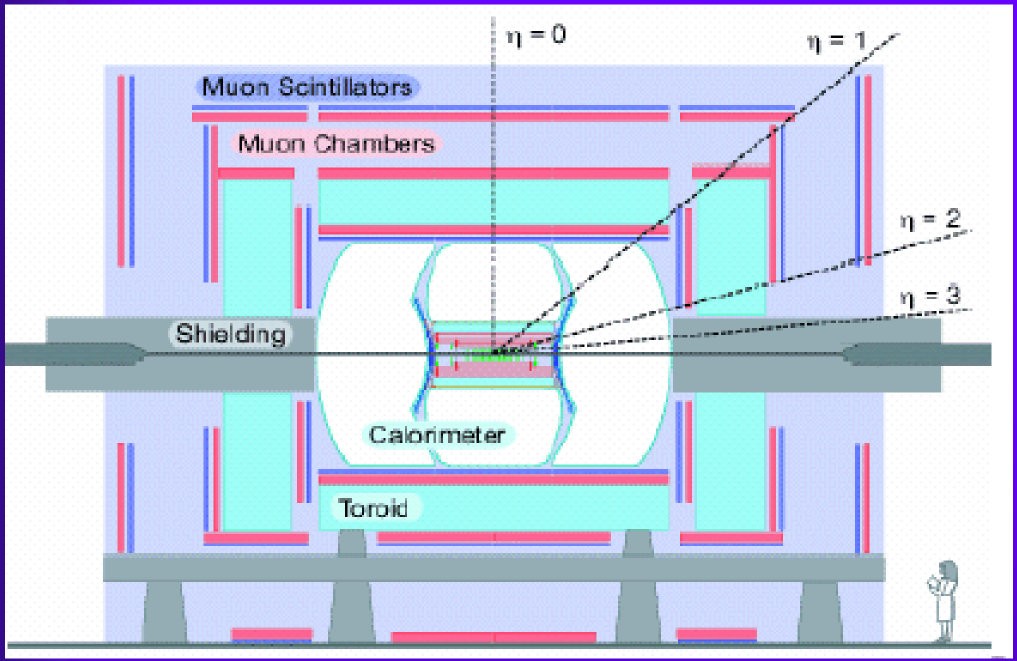
CDF Detectors



BEYOND 3 deg :
Luminosity Counters
Beam Shower Counters
Roman Pots
MiniPlugs

Possible mini-upgrades for diffractive physics:
Precision roman pots on both beams
Fully instrument very forward region (< 3 deg)

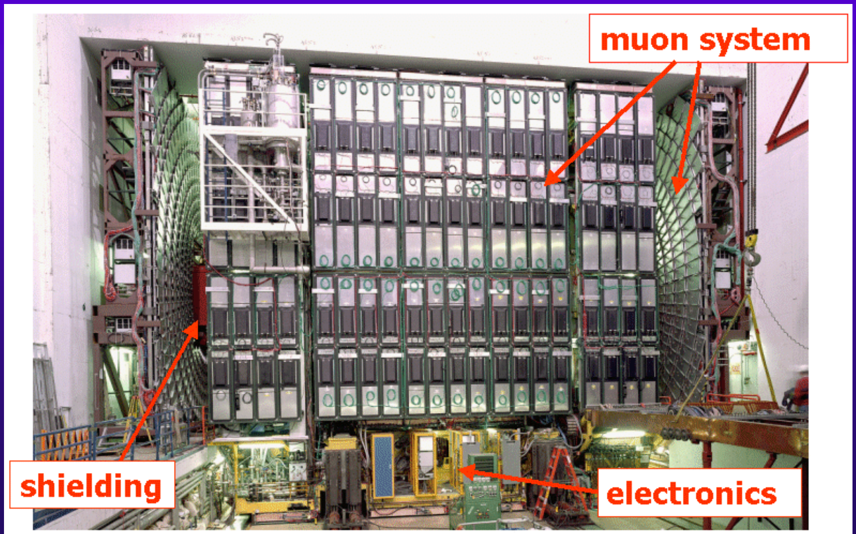
D0 Detector



Tracking (incl. muons)
+ L.A. Calorimeter

For Run II added:

Solenoidal field
Silicon tracking
Scintillating fiber tracking
Roman pots with fibers



Possible mini-upgrade:
Roman pots beyond dipoles
on both beams

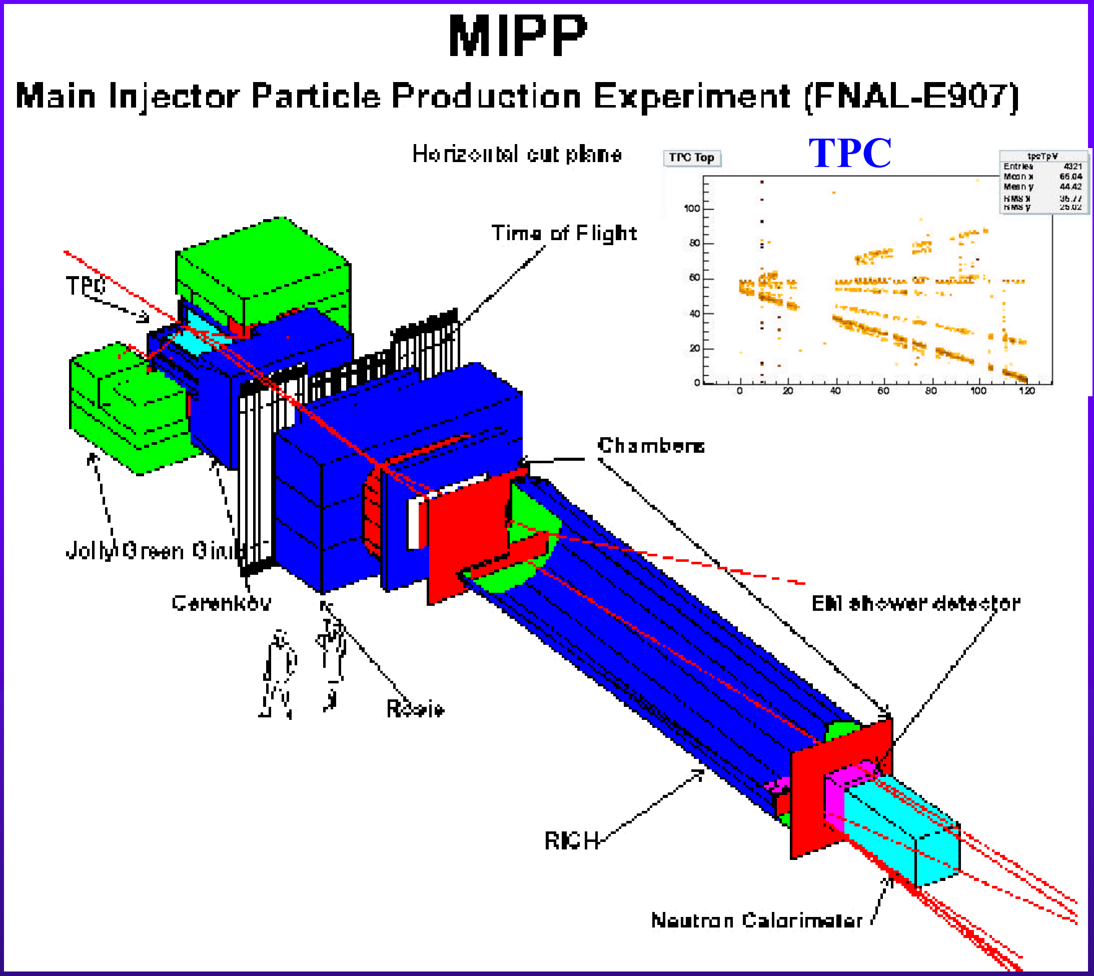
MIPP: Main Injector Particle Production

π, K, p beams
5 GeV → 120 GeV
H, Be, .. Ag targets

Particle production
Scaling Laws
Non-perturbative QCD

Multi-particle Spectrometer:

Drift Chambers, TPC, Magnet,
TOF, Cerenkov, RICH
Neutral Calorimeter



... starting now

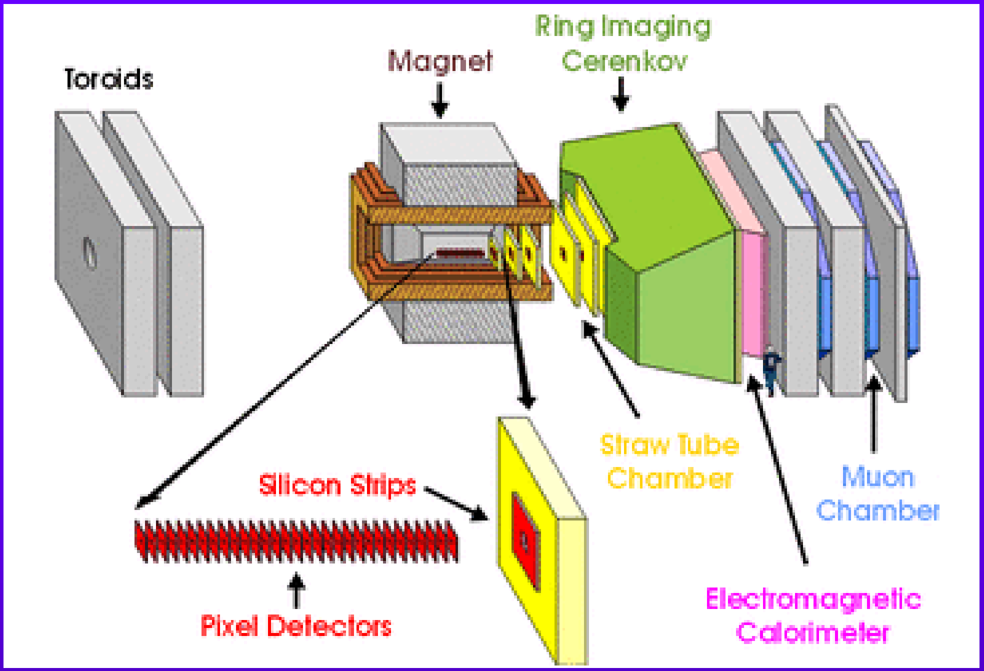
BTeV: B Physics at the Tevatron

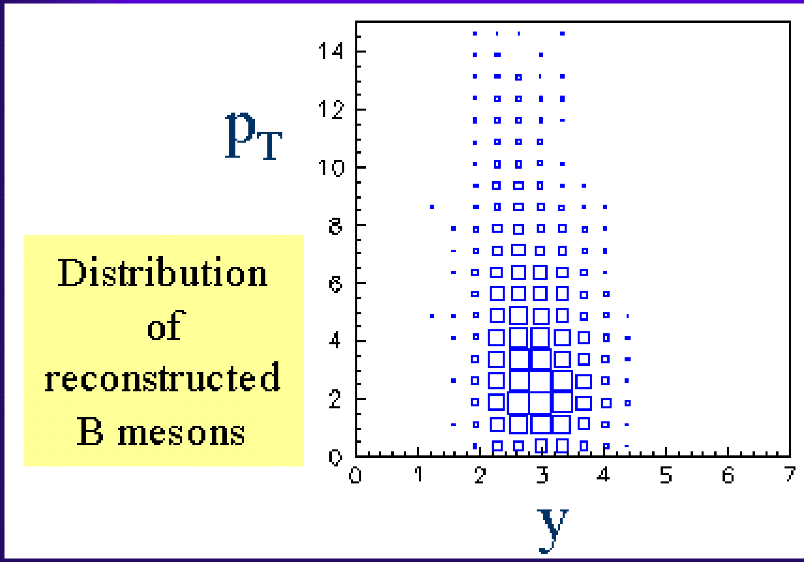
2009 →

Primary motivation:
CP-violation and mixing in
b- and c-sectors

But good QCD capability.

Excellent tracking, vertexing,
particle ID, e, γ, μ





Could add: hadron calorimeter for jets,
veto counters for gaps,
roman pots for diffraction ...

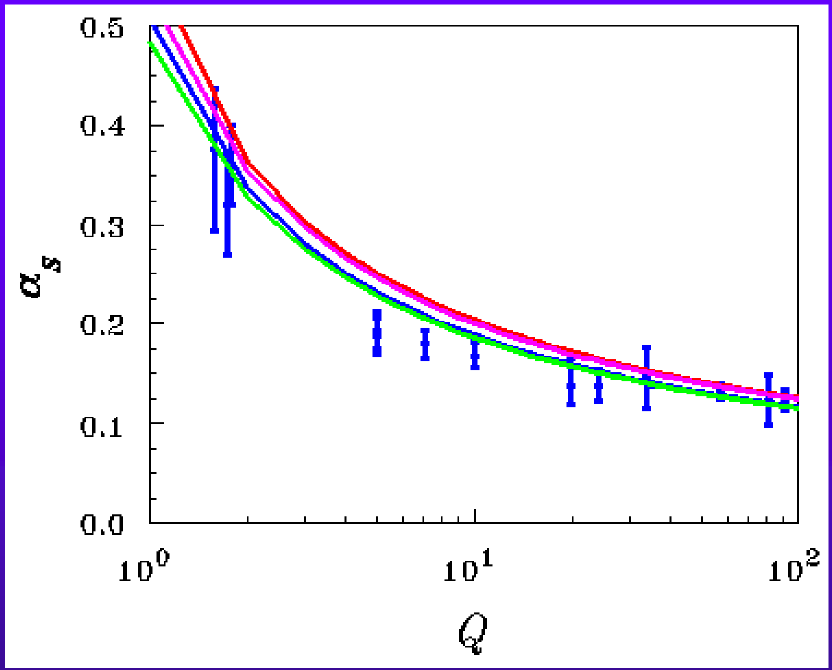
Beam is at 7.5

The REAL Strong Interaction

extended, strong coupling
non-perturbative

point-like, weak coupling
perturbative

Many approaches, none complete:



→ Lattice Gauge Theory
Small volume, hadron size

→ Regge Theory: Analyticity + Unitarity + Crossing Symmetry + Complex angular momenta

→ String models, etc.

Want a complete understanding of S.I.

$Q^2 = 0 \rightarrow \infty$

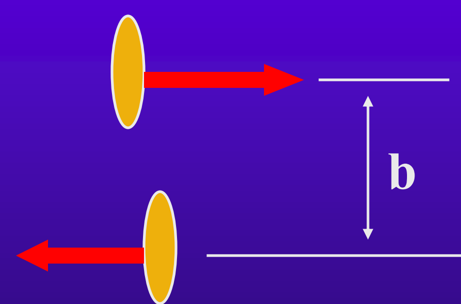
Non-perturbative – perturbative transition

Bjorken: Low pT is the frontier of QCD

As pT drops from **200 → 100 → 50 MeV** what happens?
Larger distances: 1 f → 4 fm
How do gluon fields in protons "cut off" ?

Multiplicity distributions of very low pT particles, correlations, ...
Low-pT cloud in special events, new phenomena …

Run with reduced field, Si-only tracking, etc



Large impact parameter, b, collisions

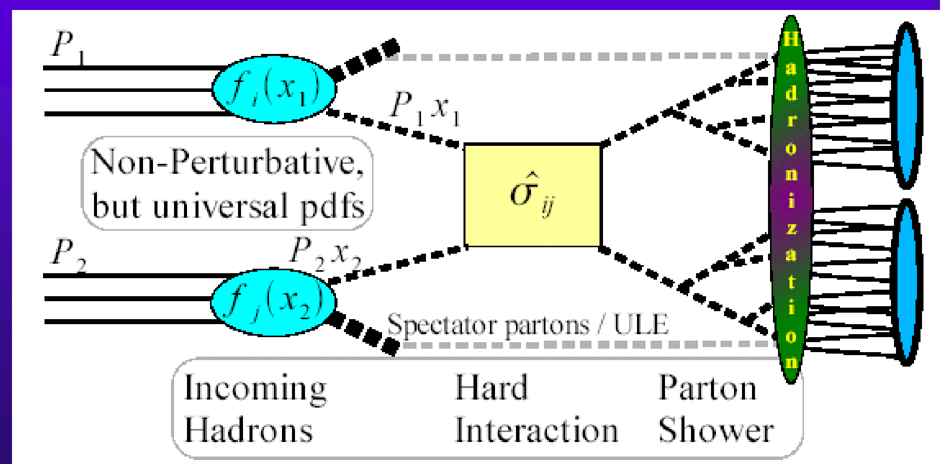
RHIC AA can measure b, how can we?   Diffraction at small t, n_ass?

QCD Event Generators (Monte Carlo) : example PYTHIA

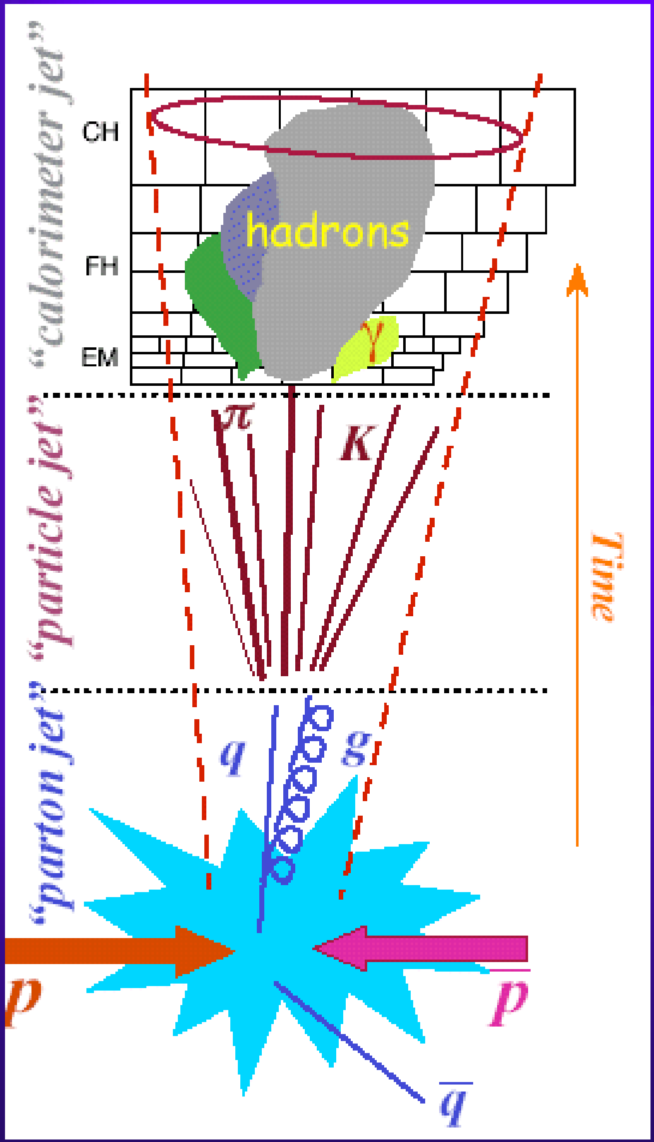
Torbjorn Sjostrand et al. hep-ph/0308153
http://www.thep.lu.se/~torbjorn/Pythia.html

Collisions producing hadrons all involve non-perturbative phenomena and cannot be accurately calculated. Resort to "QCD-based" models where necessary, analytic where possible. (e+e-, e p, p p)

→ Parton distributions in beam particles with scaling violations
→ Initial and final state parton showers
→ Hard sub-processes
→ Beam remnants and "underlying event"
→ Parton fragmentation and hadron decays



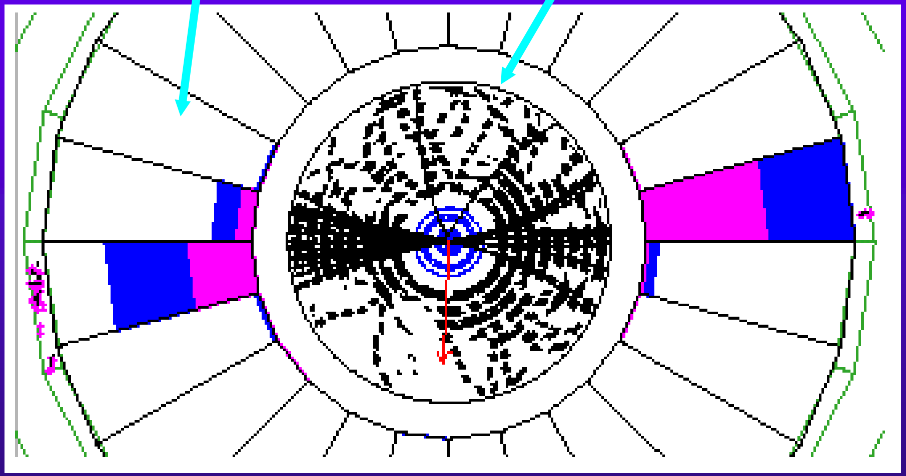
High E_T Jets



gg, gq and qq hard scattering

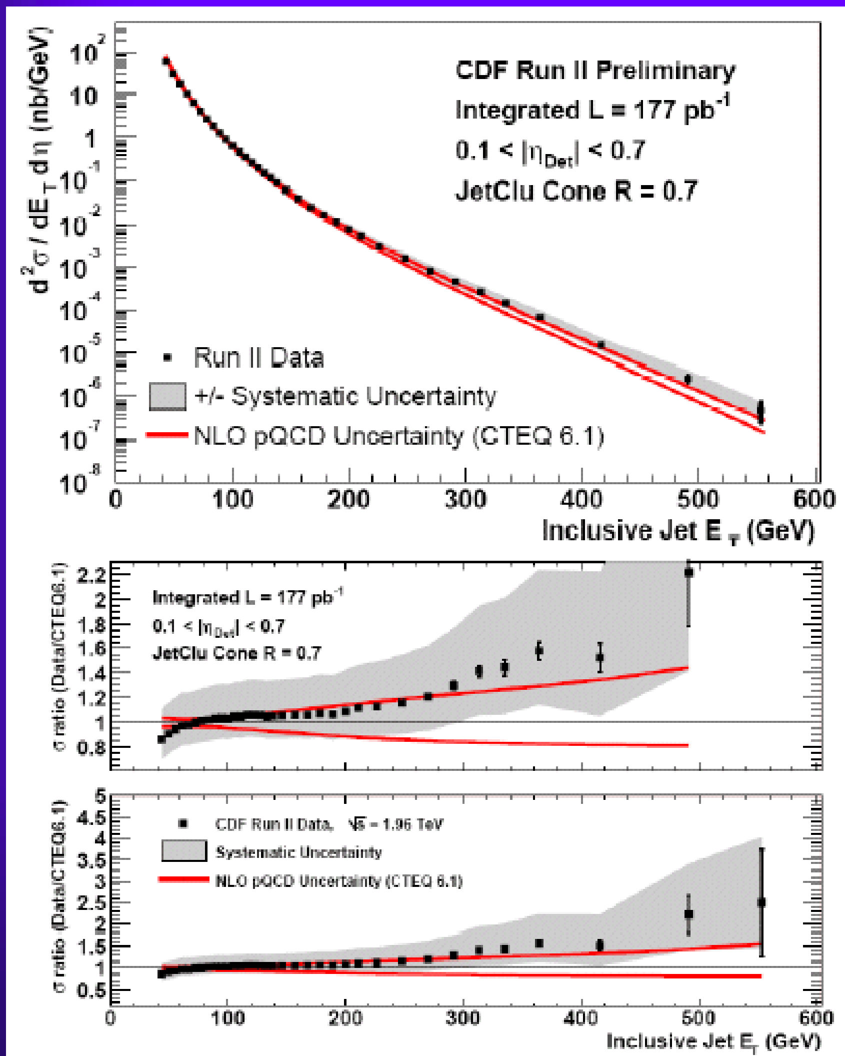
CDF event display

em + had calorimeter   drift chamber tracks

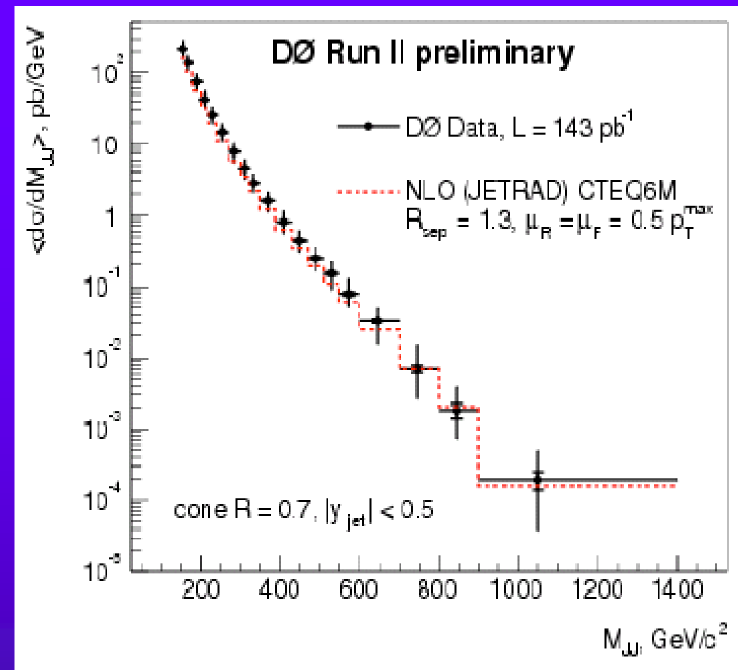


Jet ET and Di-Jet Mass Spectra

CDF



D0



$$M_{JJ} = 1000 \text{ GeV} \equiv Q^2 = 10^6 \text{ GeV}^2$$

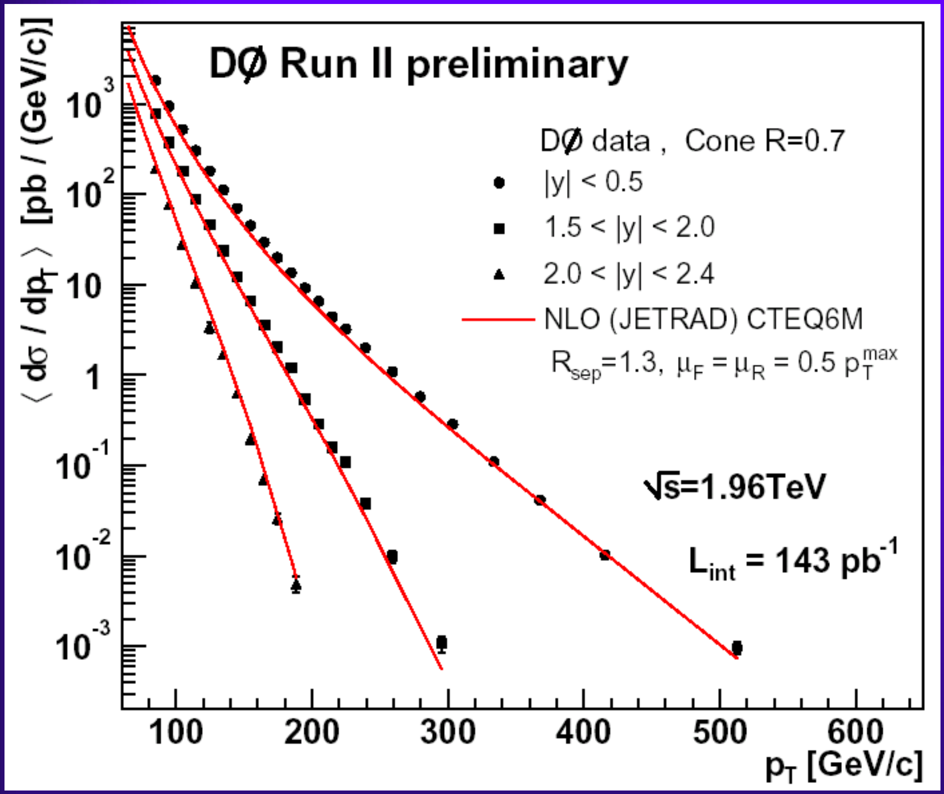
$$\Rightarrow d = 2.10^{-17} \text{ cm}$$

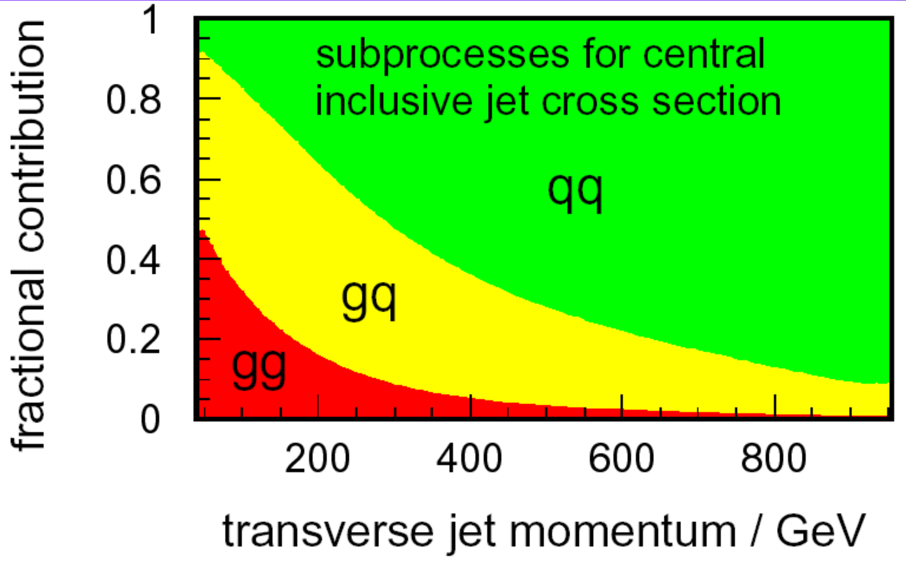
More on Jets ...

Angular (or y) distributions
well fit (log scale!) ... but
y = 2.4 still "central"

Below 50 GeV mostly gg (at y=0)
Above 400 GeV mostly q-qbar

Can study g and q fragmentation

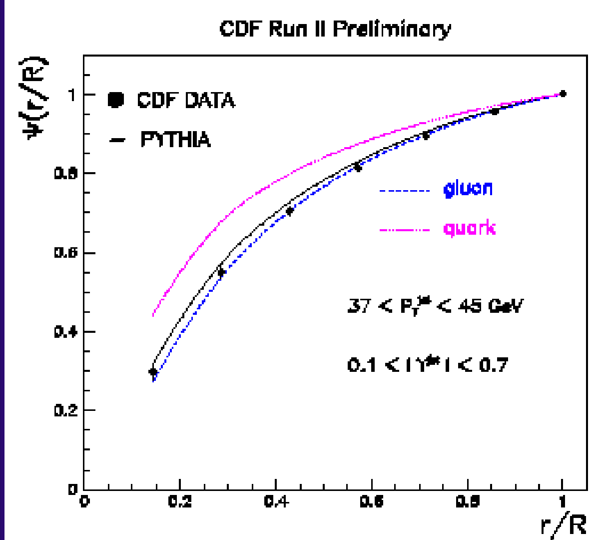




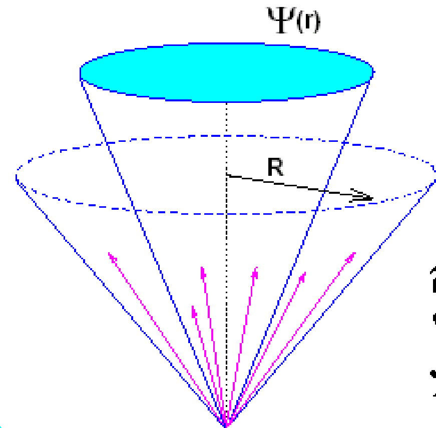
Differences between Quark and Gluon Jets

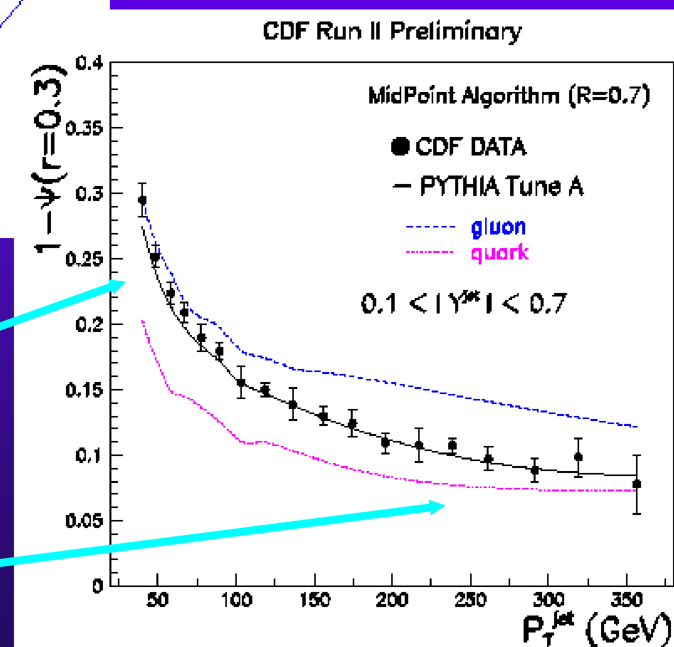
CDF: Integrate pT in cone, fraction out to r of max R = 0.7
Gluon jets are wider than quark jets

Integrated Jet shape



$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$



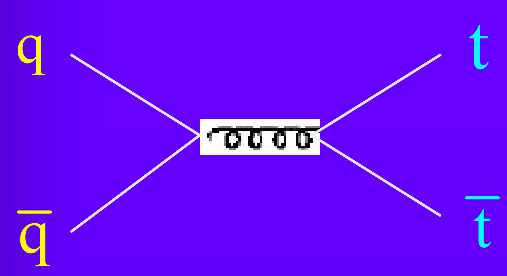


At "low" ET (~ 40 GeV)
mostly gluon jets (PYTHIA)

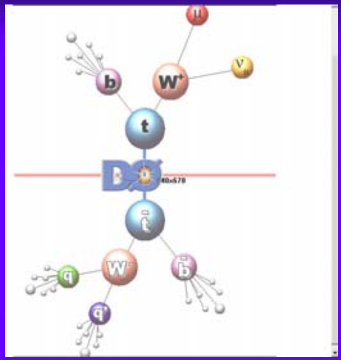
At high ET mostly quark jets

Top Quark Pair Production

(Single top (t+b) production not yet observed – background)



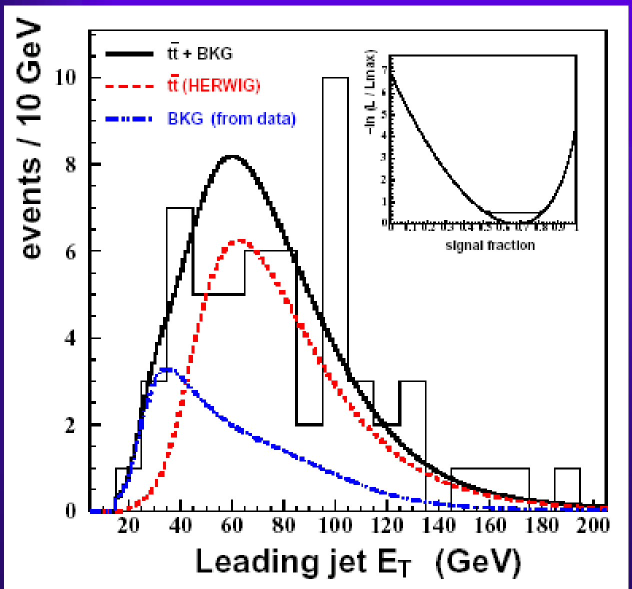
V_{tb}

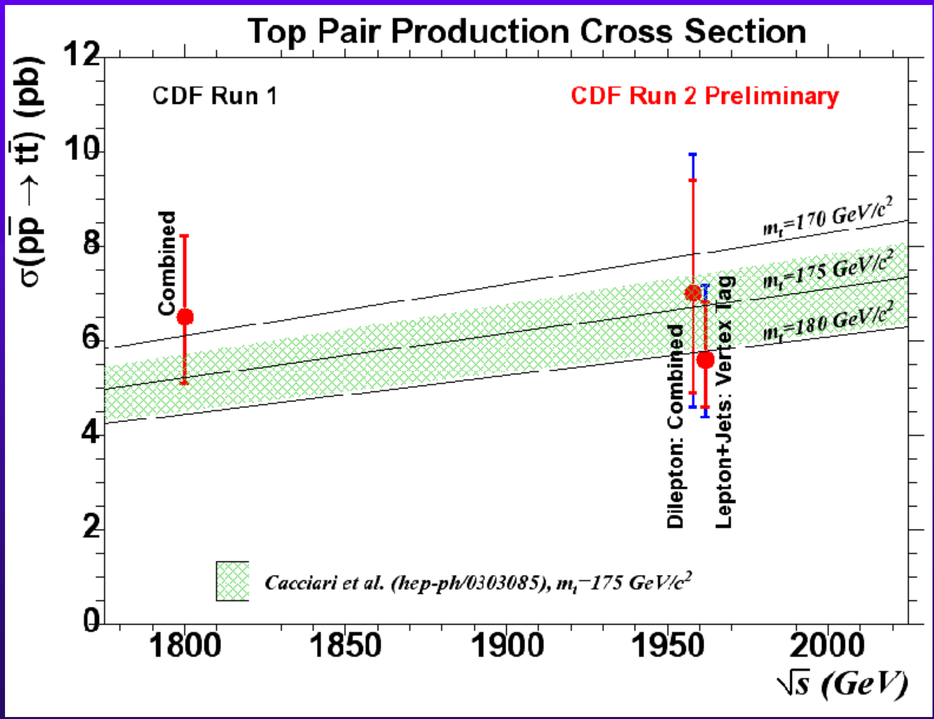


Good test of pQCD at short distances
Sensitive to new phenomena.
Statistics still limiting – much more to come

lepton + jets +MET + b-tag
163 pb-1

CDF

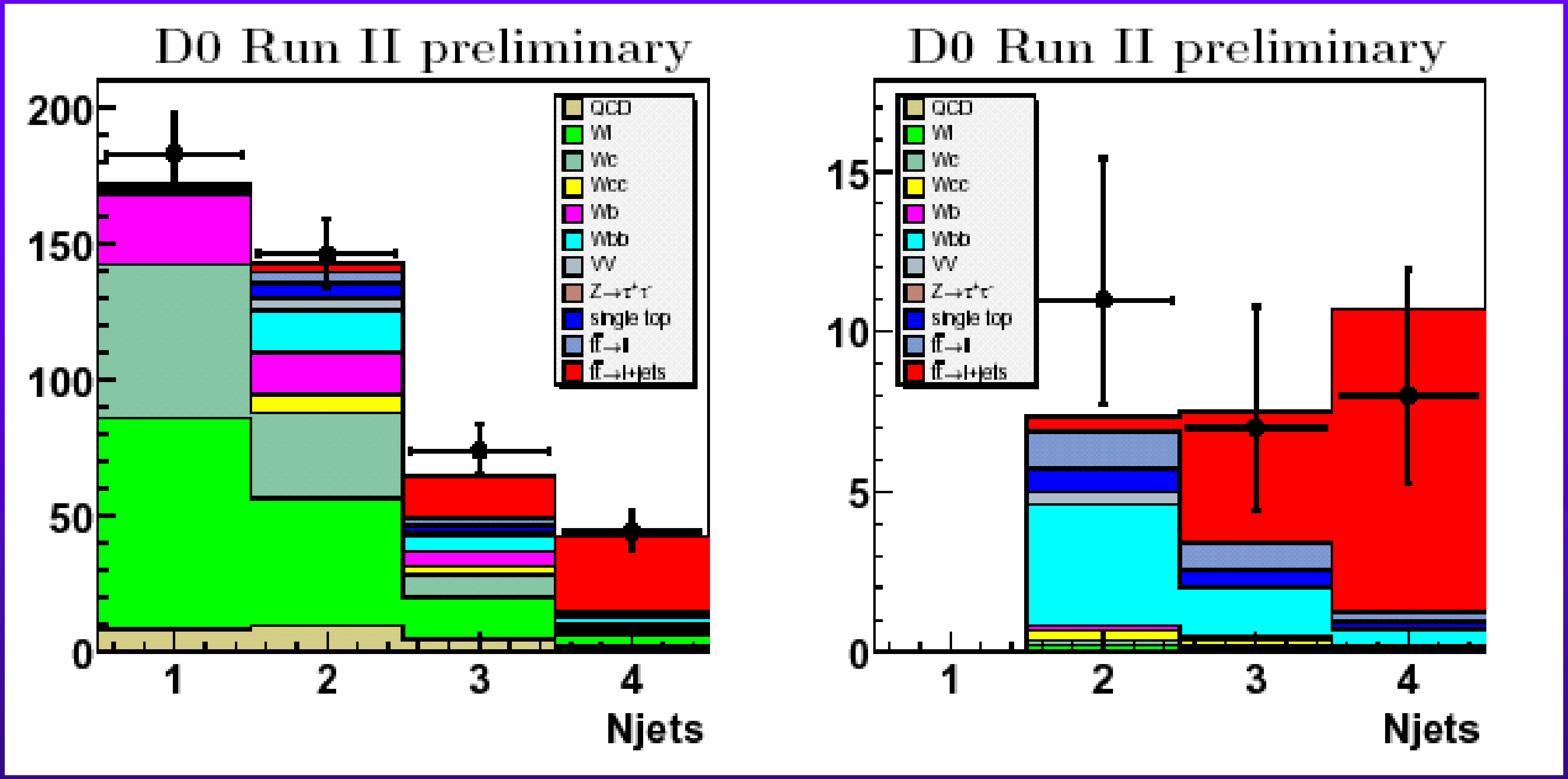




Top Backgrounds in D0 (lepton + MET + jets)

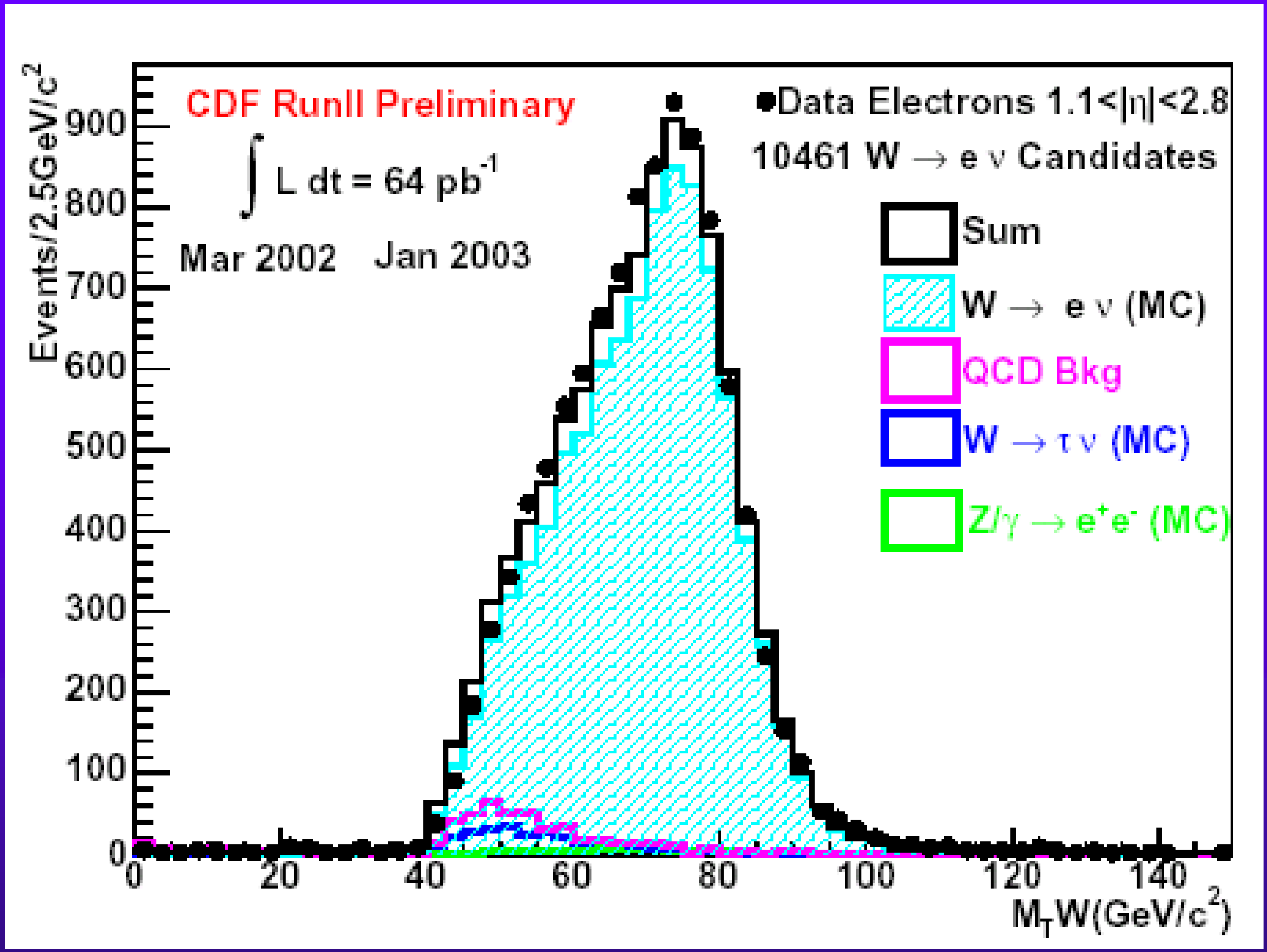
1 b-tagged jet 2 b-tagged jets

EVENTS
Per BIN



lepton + MET + 4 jets is clean with 1 or 2 b-tagged jets

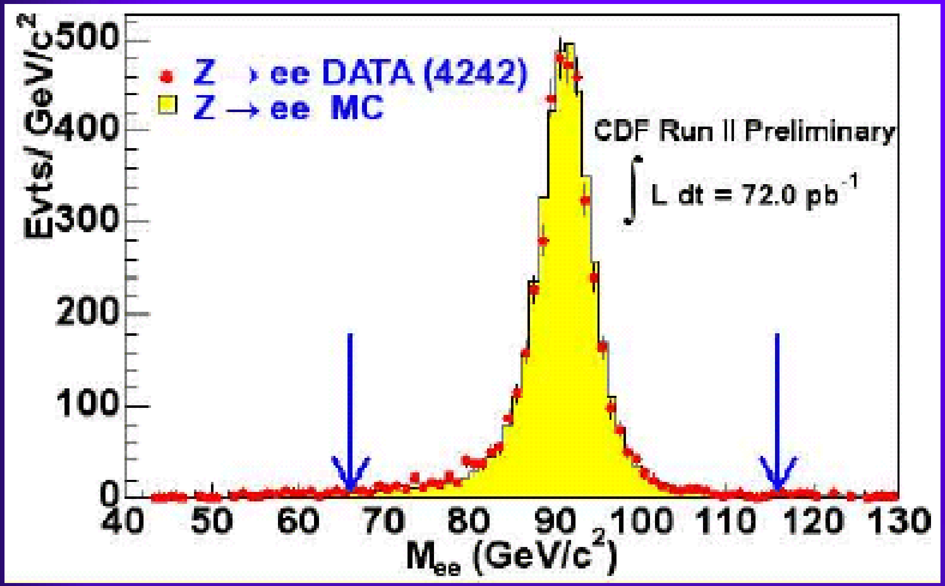
W are very clean at the Tevatron



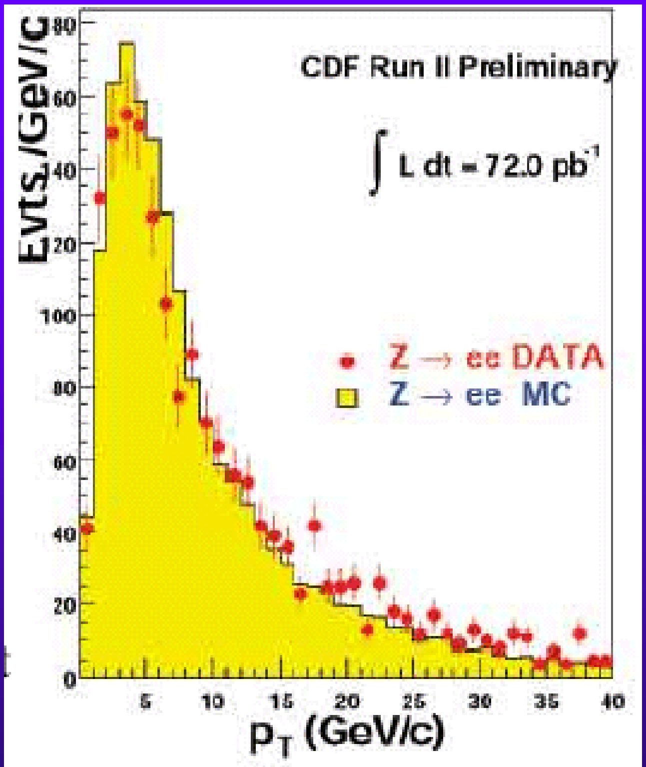
M_T = Invariant mass of lepton + $\not{E}_T$

Z are very clean at the Tevatron

2 “isolated” em showers > 25 GeV
with matching tracks
(central-central & central-plug)



pT(Z) agrees with MC



$\sigma B(Z \rightarrow e^+e^-)$ = [256.3 ± 3.9 (stat) ± 5.3 (sys) ± 15.3 (lum)] pb

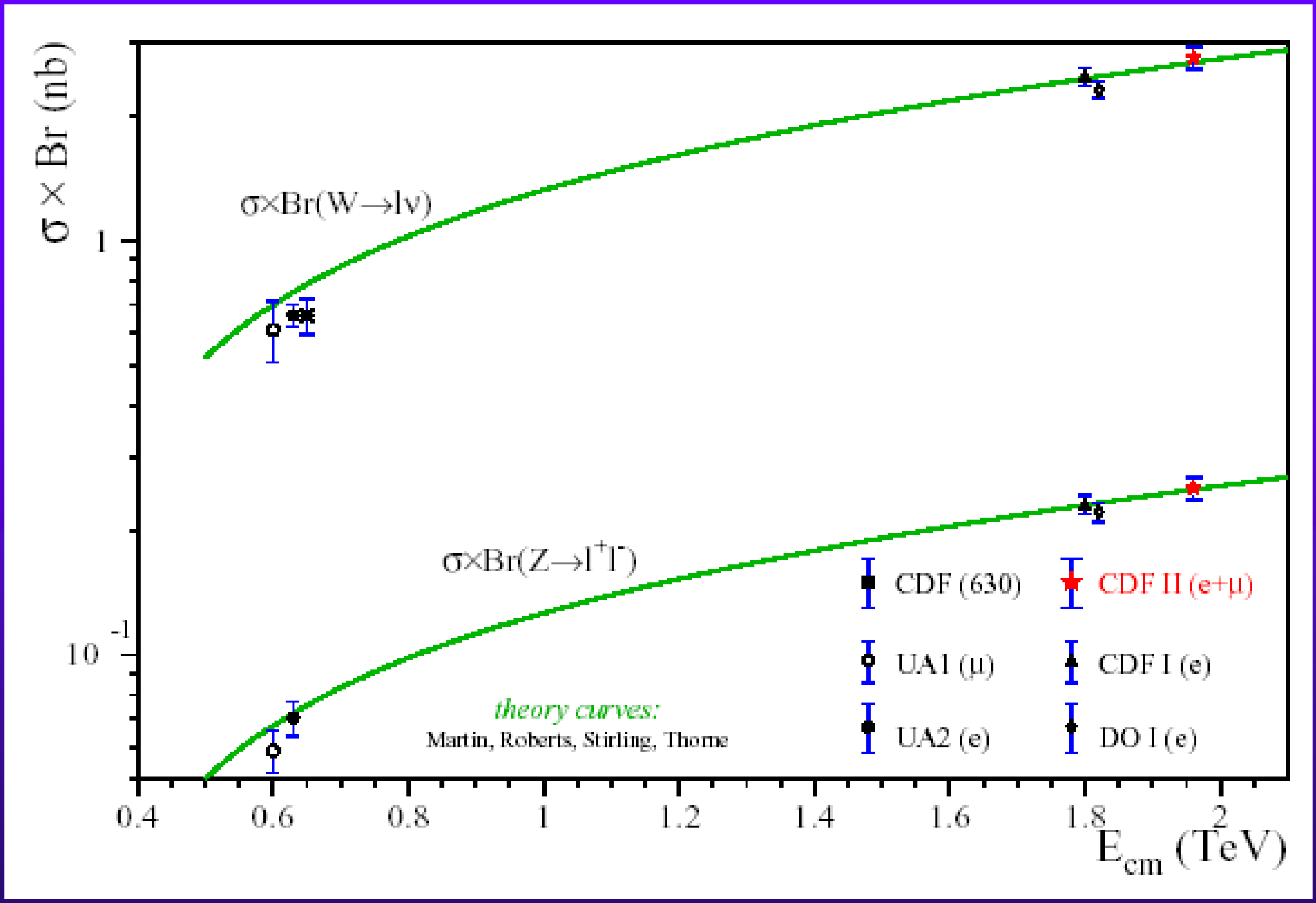
$\Rightarrow \sigma(Z) = 7.6 \pm 0.5$ nb $\Rightarrow \sim 1\ s^{-1}$

Theory (e.g.W.J.Stirling et al.) [250.5 ± 3.8] pb

Uncertainty mostly from pdf's

W and Z Cross Sections

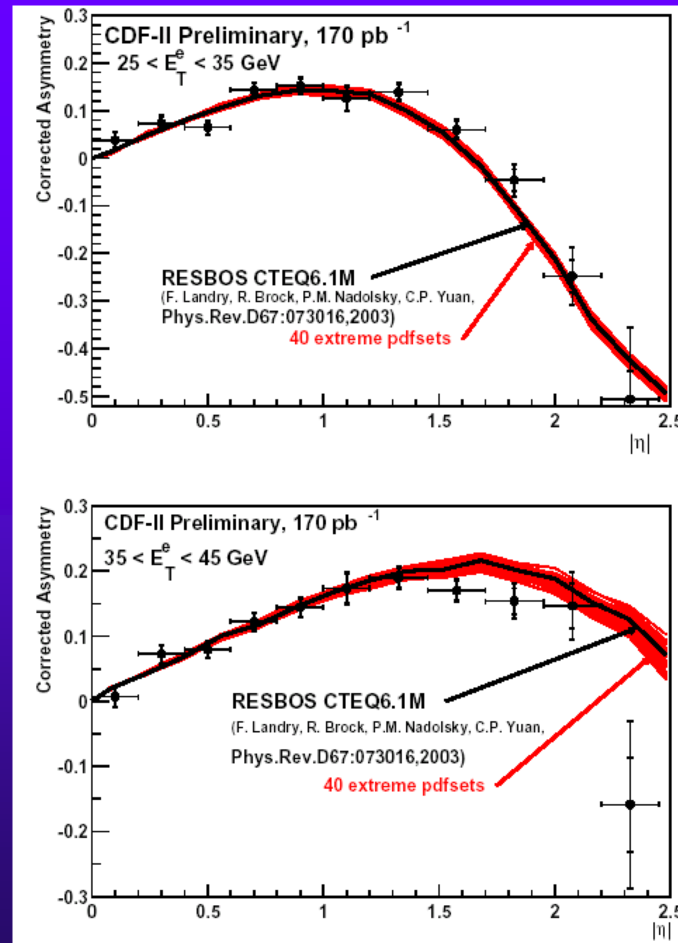
s-dependence well fit by theory
(NLO production diagrams, pdf's and their evolution)

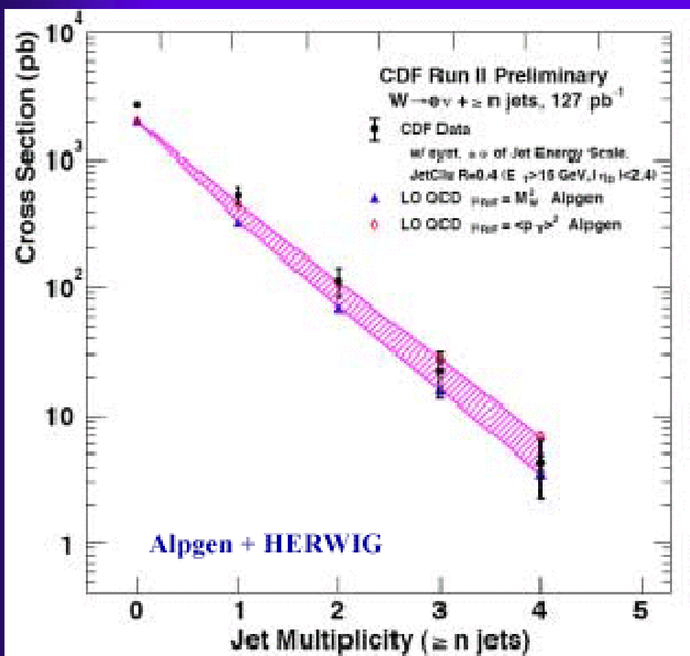


W-Production and Decay

Angular (rapidity) distribution of (charge tagged) lepton is sensitive to pdf's and u,d quark differences

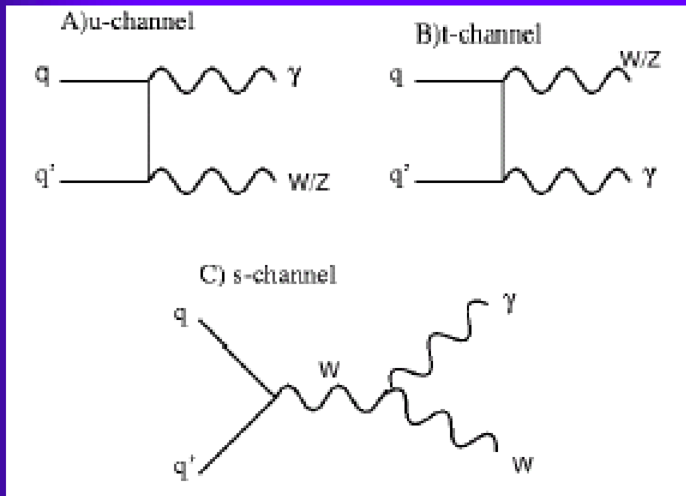
CDF now able to tag some forward (~12 deg) electrons using vertex, silicon and shower position.





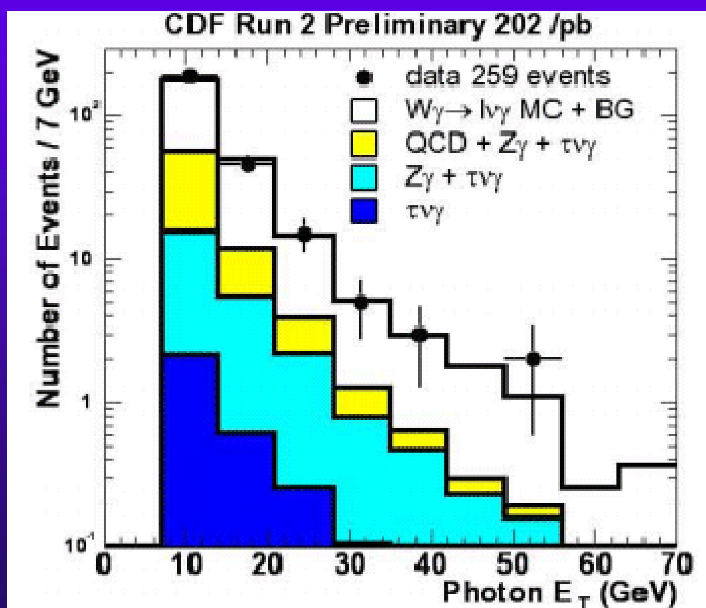
Number of jets with W agrees with MC (Alpgen)

W,Z + high pT photon

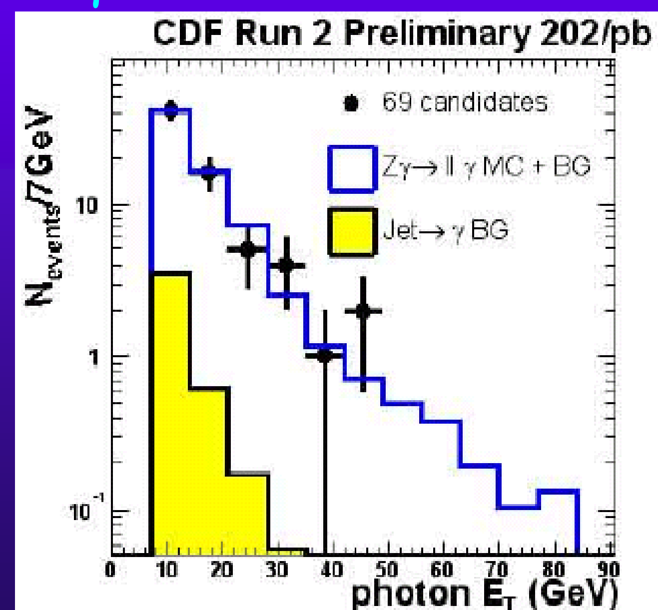


+ inner brems

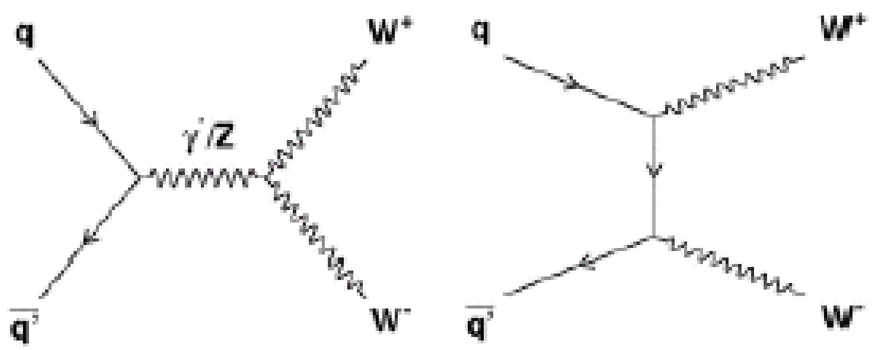
Wγ

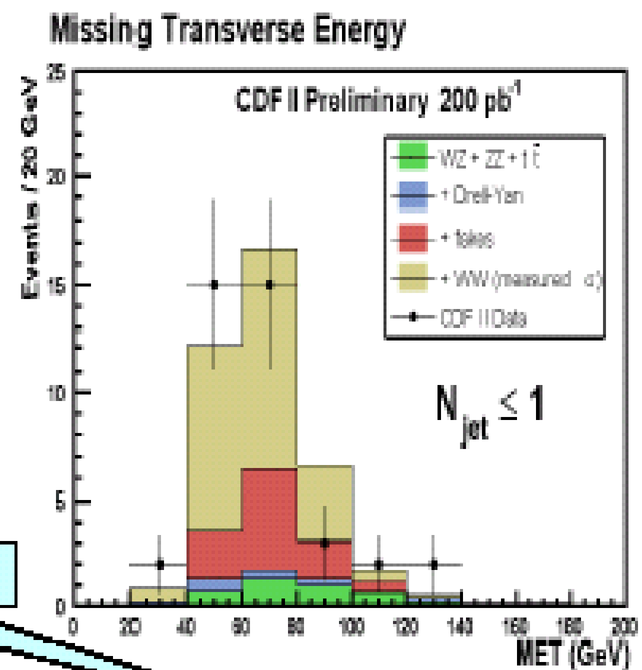


Zγ



WW Production (also WZ, ZZ)



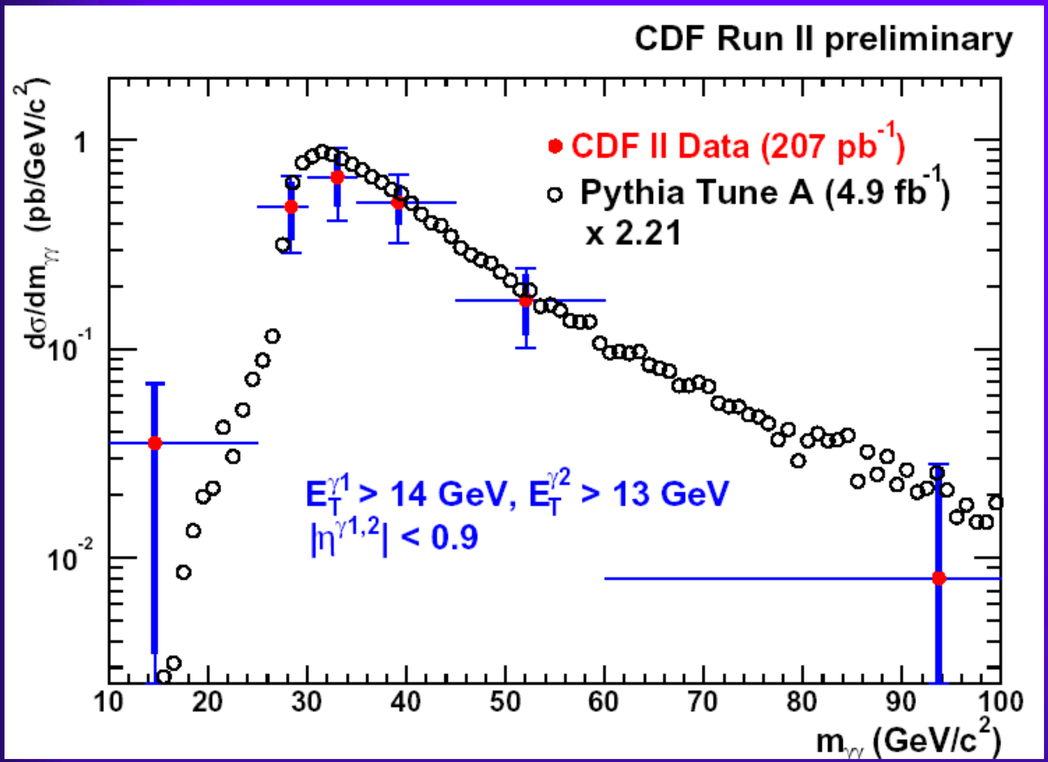


Campbell & Ellis 1999

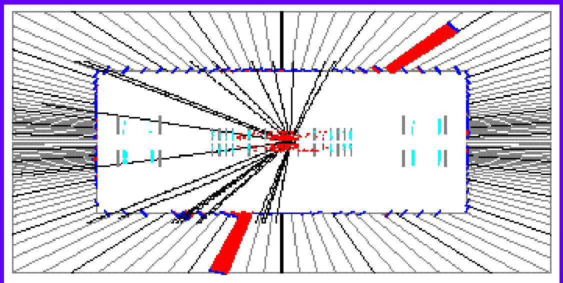
	CDF (pb)	NLO (pb)
σ(WW) (e,μ)	14.3+5.6(stat)-4.9(stat)±1.6(sys)±0.9(lum)	12.5±0.8
σ(WW) (l+track)	19.4±5.1(stat)±3.5(sys)±1.2(lum)	12.5±0.8

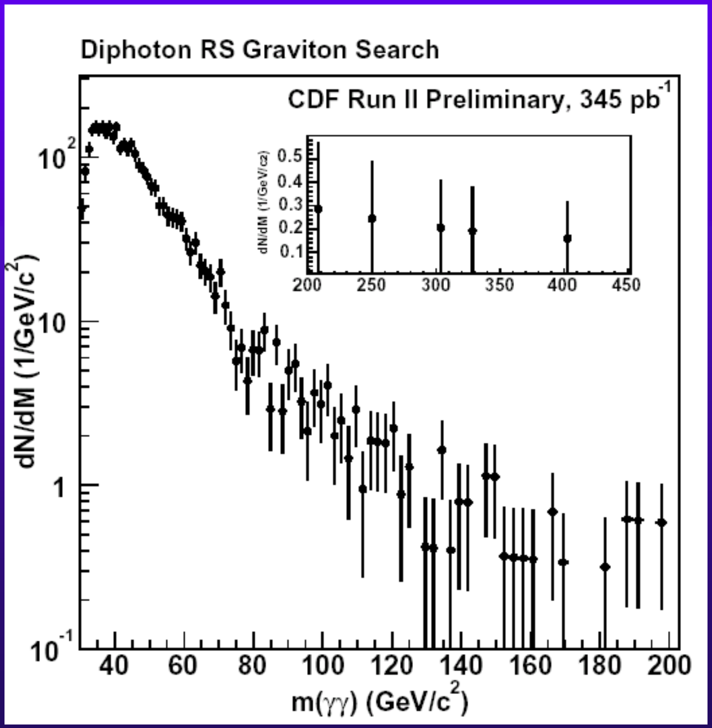
Photon-Photon Mass Spectrum

$q\bar{q}$ (X?) $\rightarrow \gamma\gamma$



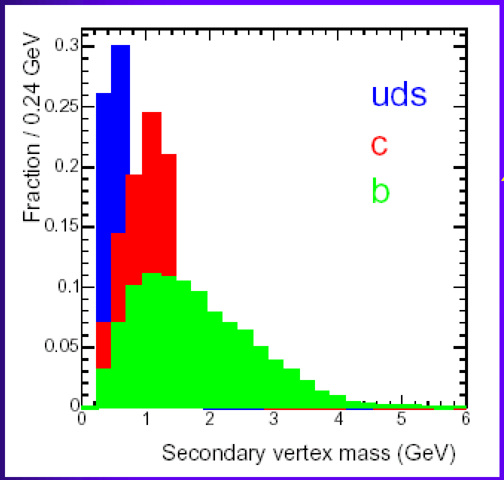
D0: highest $M_{\gamma\gamma}$ = 436 GeV!





Looser cuts to search for "bumps"

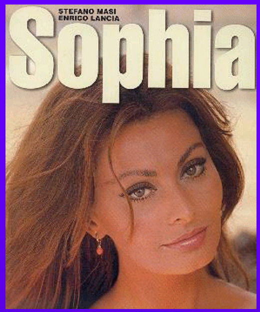
Photon + Heavy Flavor Production

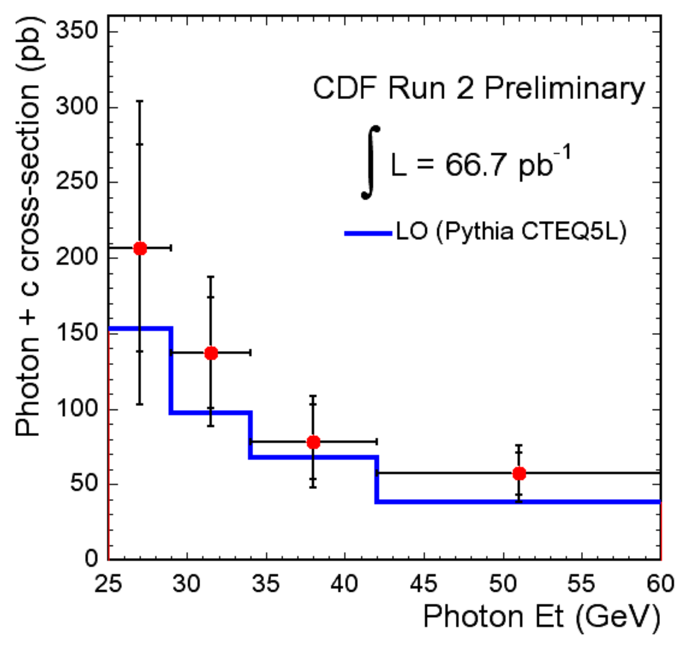


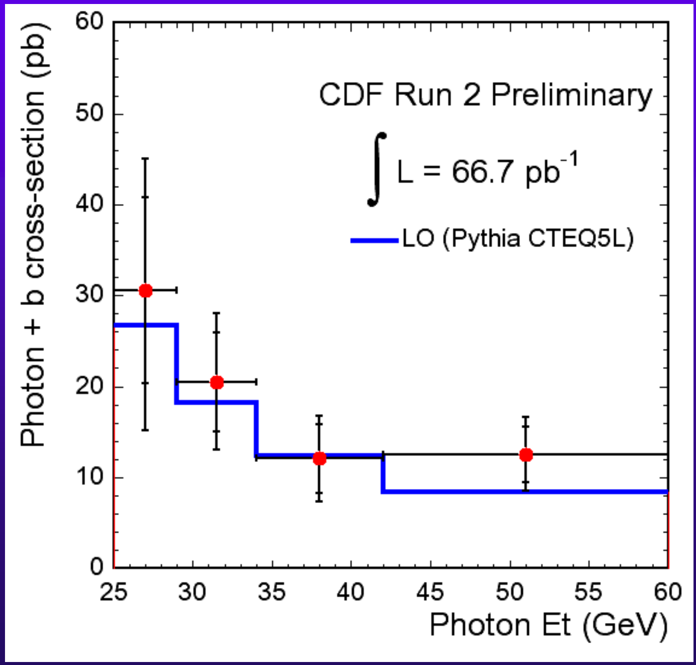
Mass of particles on 2ry vertex

Marcello

Charm and Beauty



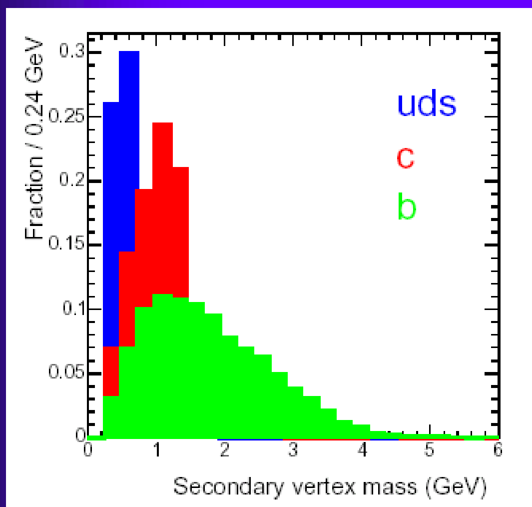




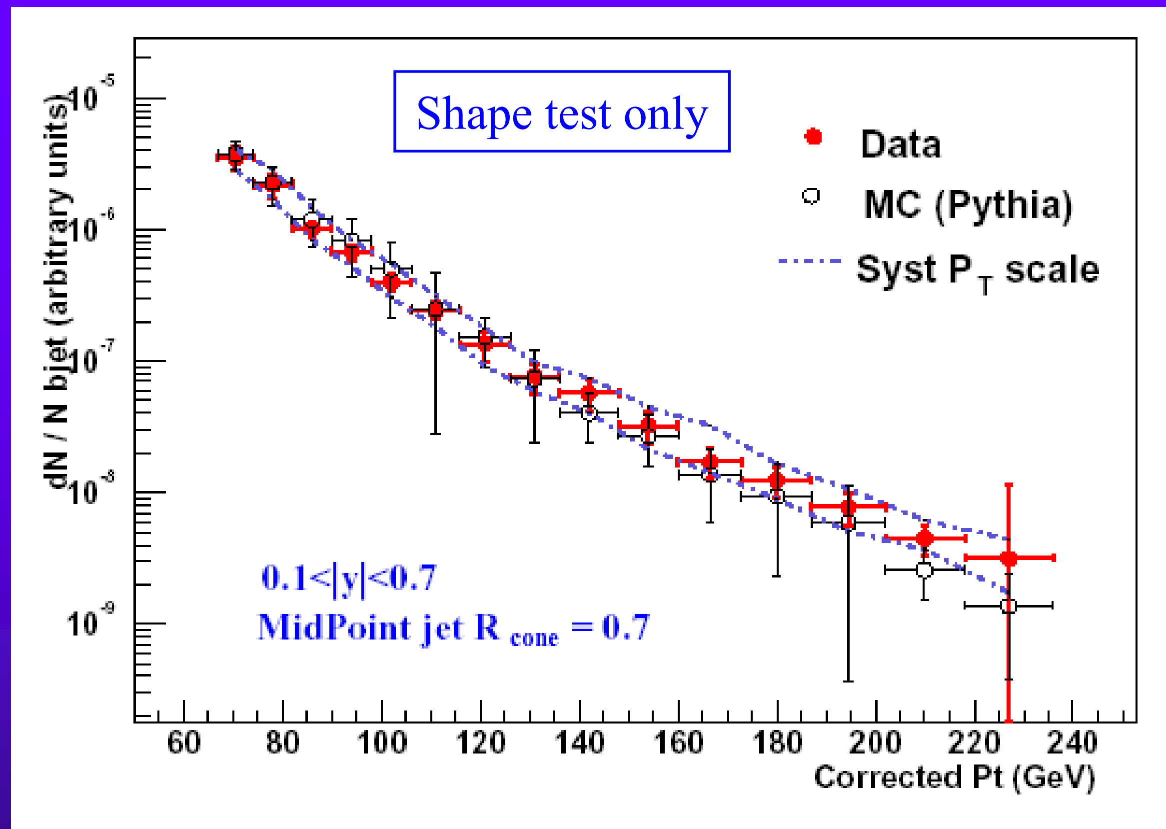
B-hadron Production at High pT

b-jets

$c\tau(B) \approx 0.5\,\mathrm{mm}$



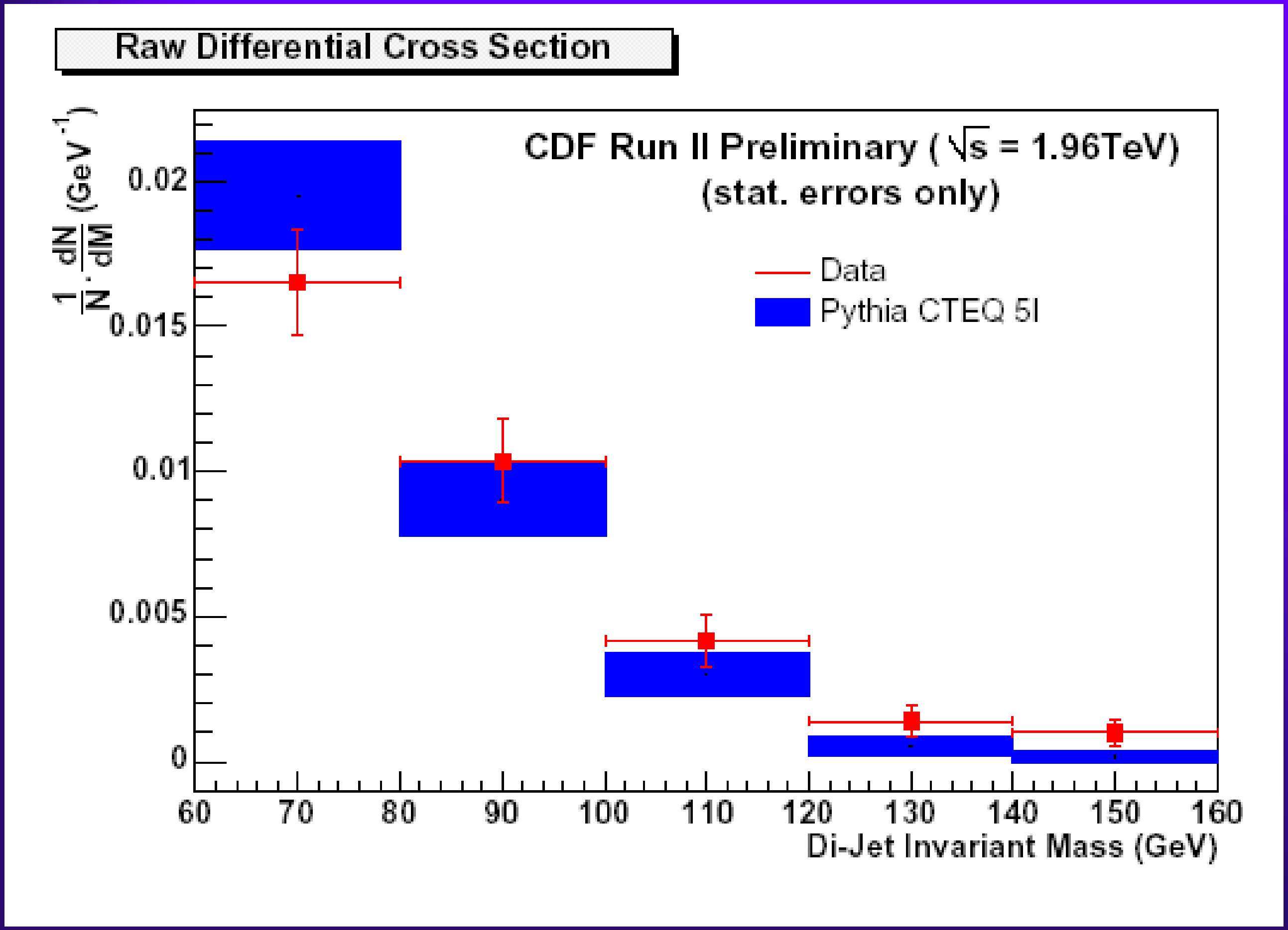
Secondary vertex, mass of s.v. tracks



B-Bbar Dijet Mass Distribution

Two secondary vertex tagged jets
Tagging efficiency ~ 20%/jet
251 events in 32 pb^-1

$H(130) \rightarrow b\bar{b} \sim 0.05$ events!



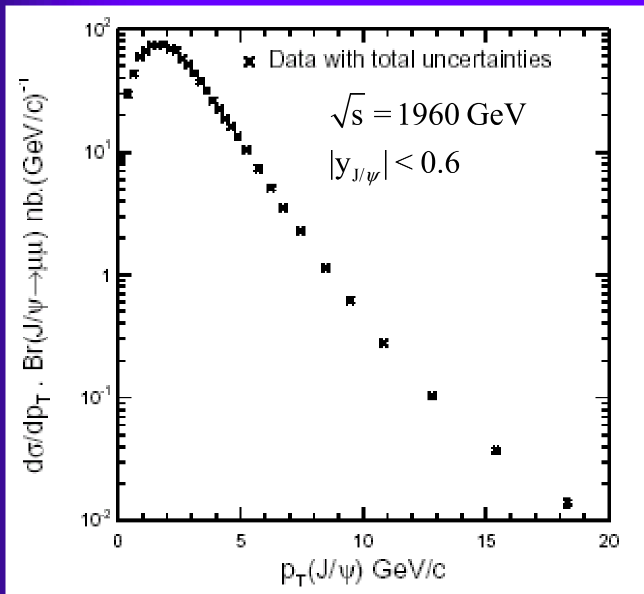
CP-odd h(40) ?

$\sigma(h_{40})\, BR(b\bar{b}) \sim 14$ fb
But S/B ~ 0.01(?)

J/psi and B-hadron Production

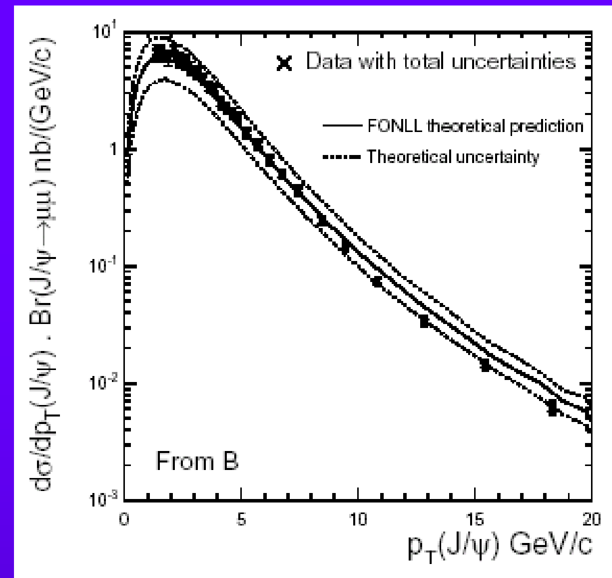
40 pb^{-1} !

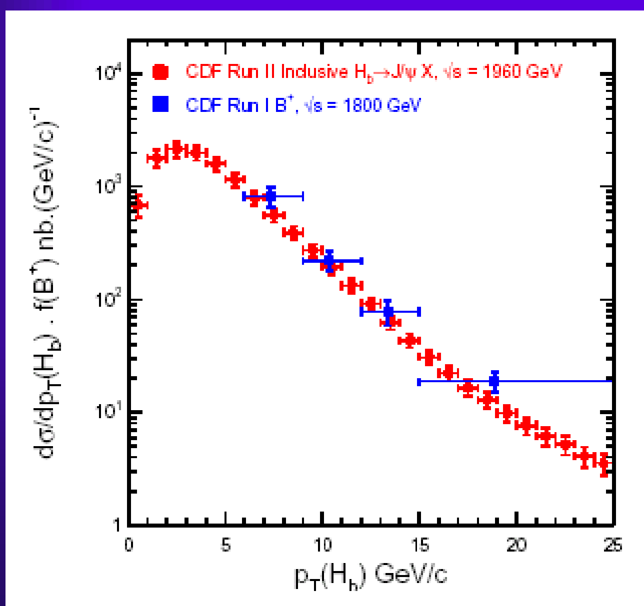
CDF-7037



J/ψ

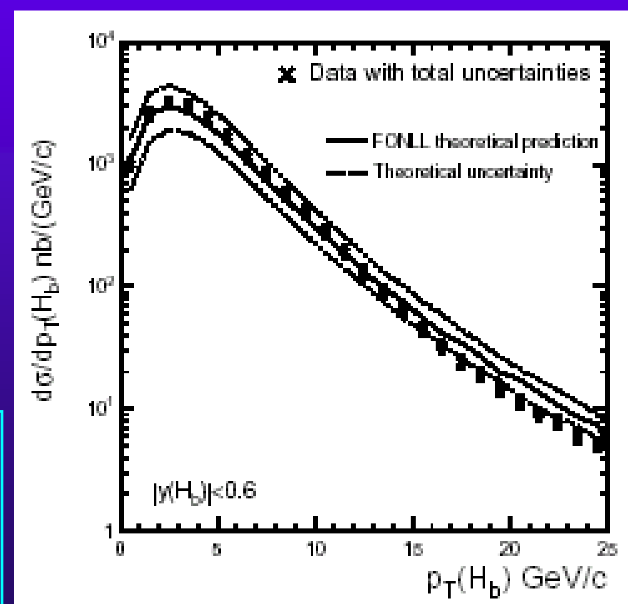
J/ψ from B



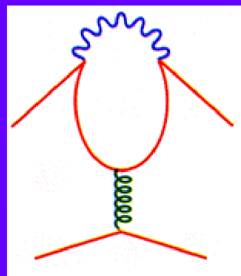


B-hadrons
Run II vs I
(trigger!)

FO-NLL
Cacciari et al
hep/ph-0312132

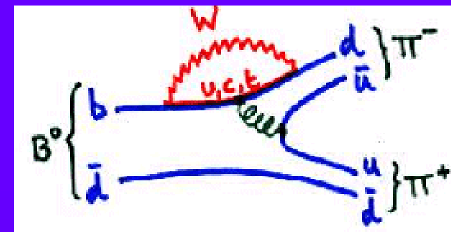


Rare Charmless B decays

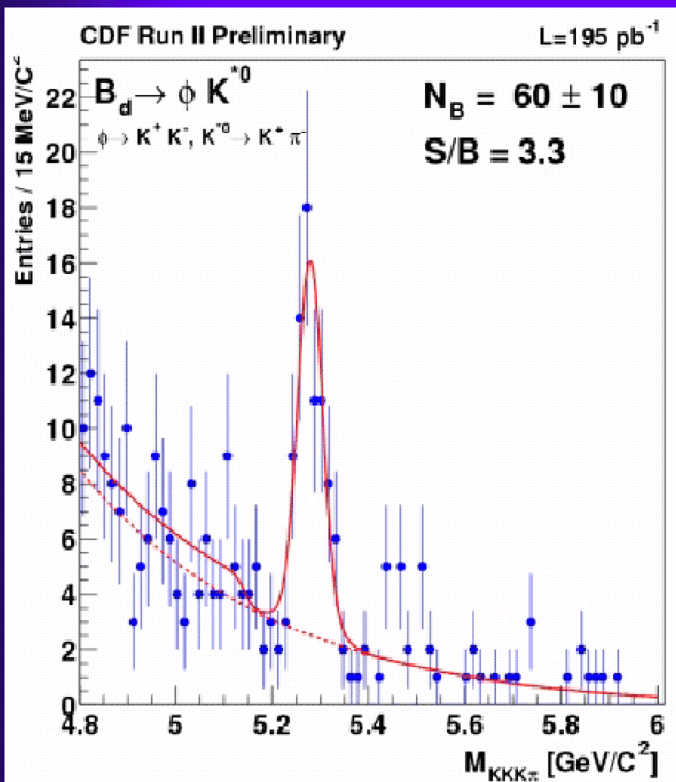


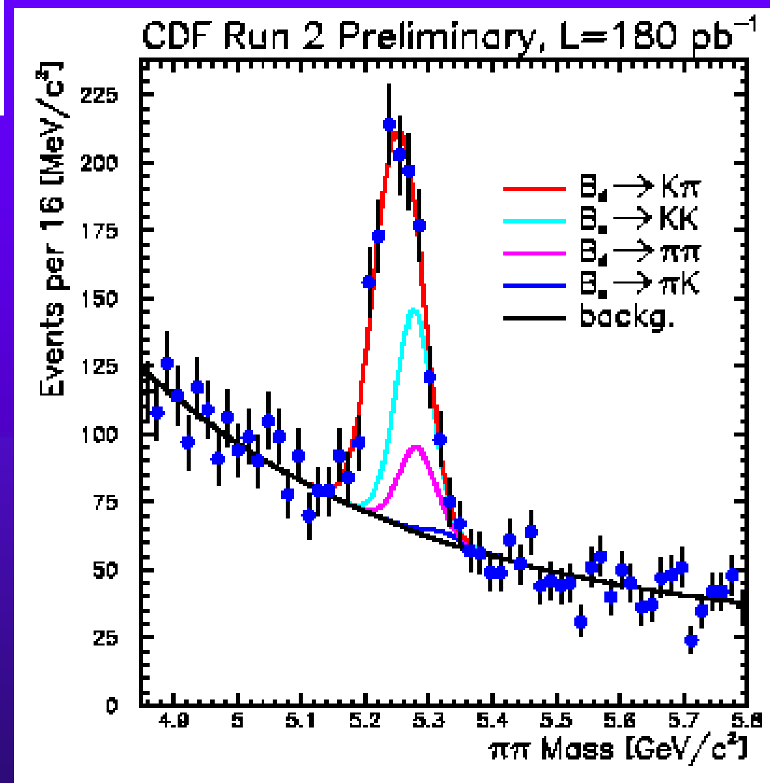
Penguin diagram

$B^0_d \to \pi^+\pi^-$



CDF-7142



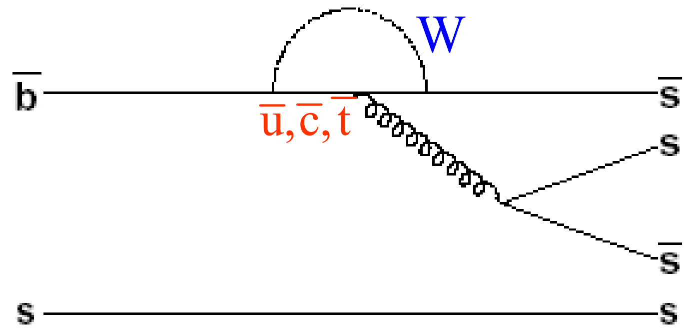


$BR(B^0_d \to K^{0*}\phi) = 1.1\times10^{-5}$

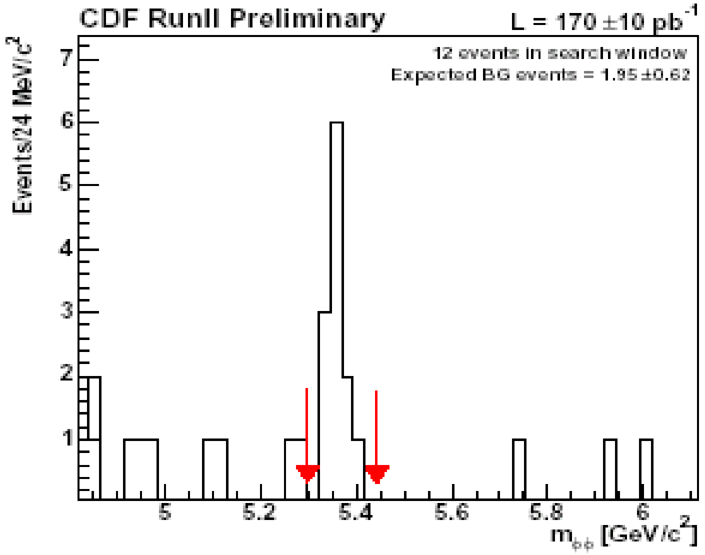
$BR(B^0_d \to \pi^+\pi^-) = 5\times10^{-6}$

First Observation $B_s \to \phi\phi$

Another ...

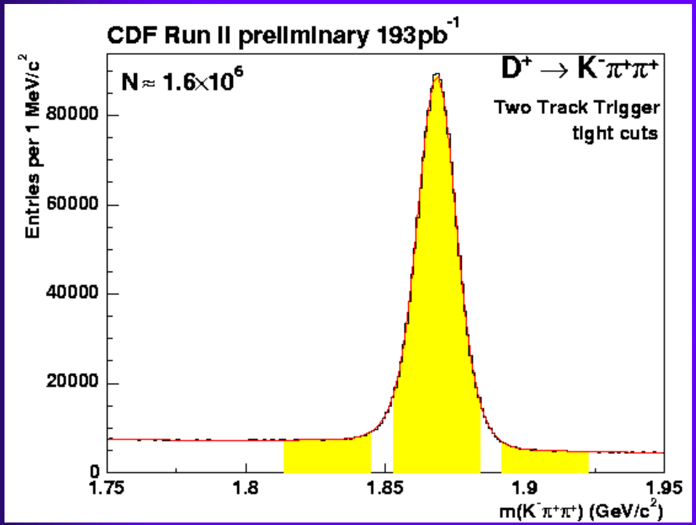


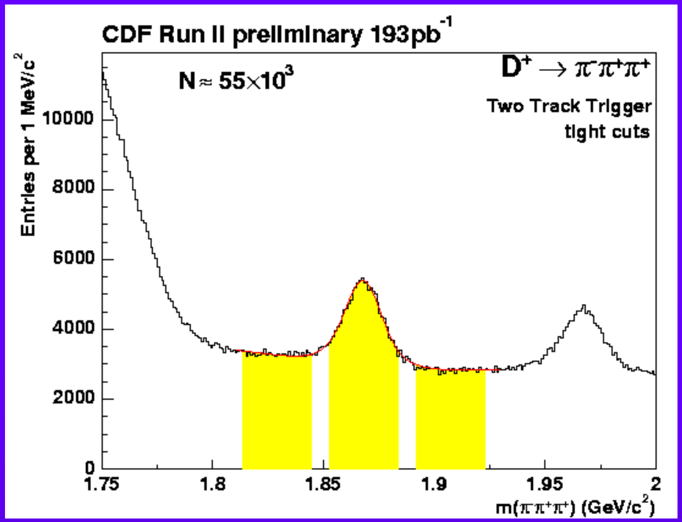
W



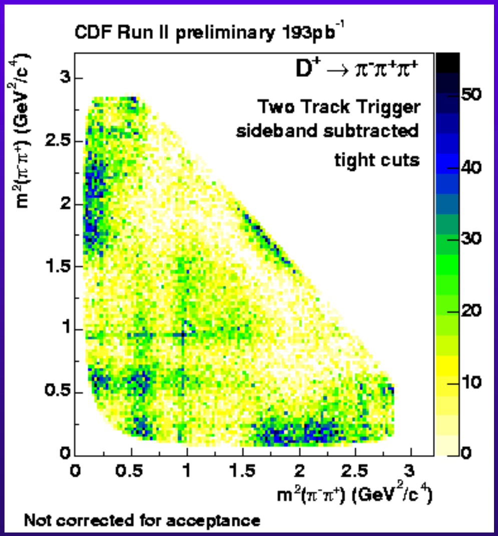
$$BR(B_S \to \phi\phi) = [1.4 \pm 0.6(stat) \pm 0.2(syst) \pm 0.5(BRs)] \times 10^{-5}$$

Charmed Hadrons





90,000 per MeV at peak!



QCD:
Charm spectroscopy
Production mechanisms
(correlations)

http://www-cdf.fnal.gov/physics/new/bottom/040422.dplus/

Central Exclusive Production

... or, diffractive excitation of the vacuum

> "It is contrary to reason to say that there is a vacuum
> or a space in which there is absolutely nothing."
>
> Descartes

→ Virtual states in the vacuum can be promoted to real states
by the glancing passage of two particles.

Charged lepton (or q) pairs : 2-photon exchange
Hadronic states : 2-pomeron exchange (DPE) dominates

Vacuum quantum number exchange.
Central states' quantum numbers restricted.
Measure forward p,pbar → missing mass, Q-nos.

Ideal for Glueball, Hybrid spectroscopy

I^G	J^{PC} (DPE)	
0^+	0^{++}	←
0^+	0^{-+}	Not at 0^0
0^+	1^{-+}	Not at 0^0
0^+	1^{++}	Not at 0^0
0^+	2^{++}	←

Hadron Spectroscopy: an example

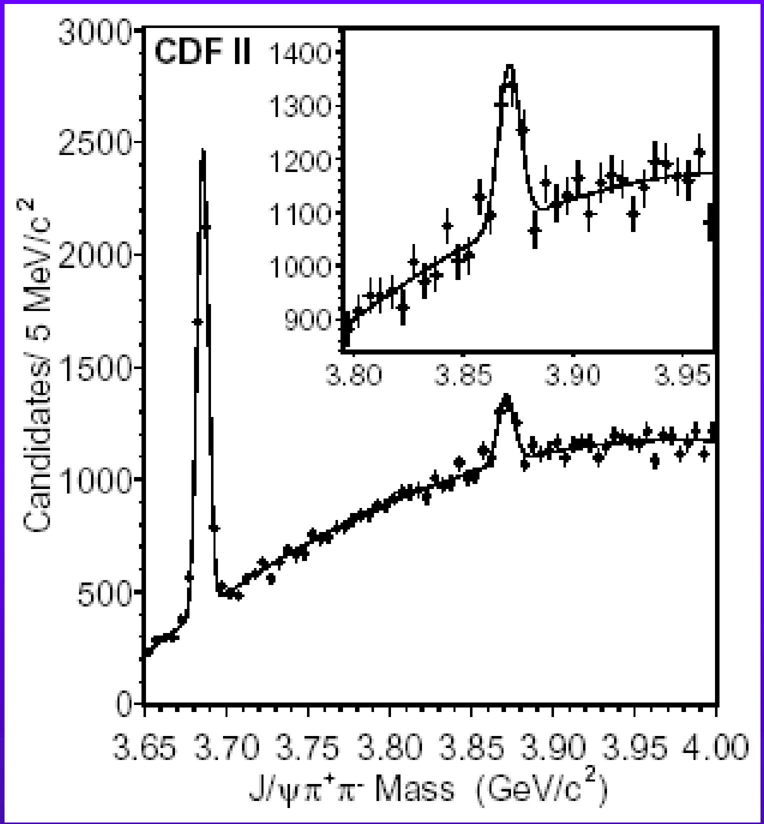
X(3872) discovered by Belle (2003)
Seen soon after by CDF
Relatively narrow

$$M_{X(3872)} - M_{J/\psi} - 2M_{\pi} = 495 \text{ MeV}$$

$$\Gamma < 3.5 \text{ MeV}$$

What are its quantum numbers?
Why so narrow? What is it?

$D\bar{D}^{*}$ "molecule" ? or $[\{cd\} \Leftrightarrow \{\bar{c}\bar{d}\}]$ state ?



PRL 93, 072001 (2004)

If we see in exclusive DPE:

$I^G J^{PC}$ (DPE)

$0^+0^{++} \Rightarrow$ favored

$0^+0^{-+}, 0^+1^{-+}, 0^+1^{++} \Rightarrow$ not at 0^o

$0^+2^{++} \Rightarrow$ not $q\bar{q}$

Also, cross-section depends on "size/structure" of state.

Gluonia and Glueballs

Hadrons G without valence quarks
Allowed in QCD – or, if not, why not ?
Some can mix with $q\bar{q}$ mesons
Some have exotic quantum numbers and cannot $J^{PC} = 0^{--}$, even^{+-}, odd^{-+}
Glue-glue collider ideal for production (allowed states singly, others in association GG', G + mesons.)
Forward $p\bar{p}$ selects exclusive state, kinematics filters Q.Nos :

Forward protons: $J^P = 2^+$ exclusive state cannot be non-relativistic $q\bar{q}$ (J_z=0 rule)

Exclusive central states e.g. $\phi\phi \rightarrow$ 4K, $\pi\pi$KK, $D\bar{D}^*$, $\Lambda\bar{\Lambda}$, etc

Other processes:

$\pi^- p \rightarrow [\phi\phi] + n$

$J/\psi \rightarrow \gamma + G$ $\quad e^+e^- \rightarrow J/\psi, \Upsilon + G$

$p\bar{p}$ (low $\sqrt{s}$) $\rightarrow$ G + anything

This one → $gg \rightarrow$ G, GG, G+anything

Use Tevatron as Tagged Glue-Glue Collider

$$\sqrt{s_{gg}} = \sim 1\ \mathrm{GeV} \Rightarrow \sim 100\ \mathrm{GeV}$$

$$\sigma_{\sqrt{s}} \sim 100\ \mathrm{MeV}$$ ← (Stretch Goal)

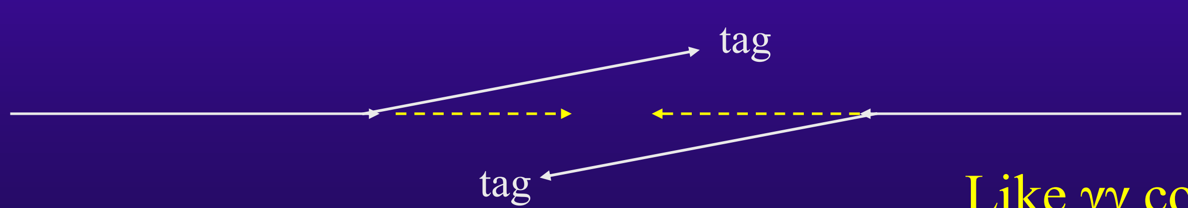
Glueballs and Hybrids

New Exotic Hadrons

chi_c and chi_b states

Hunting strange exotic animals (radions, ...?

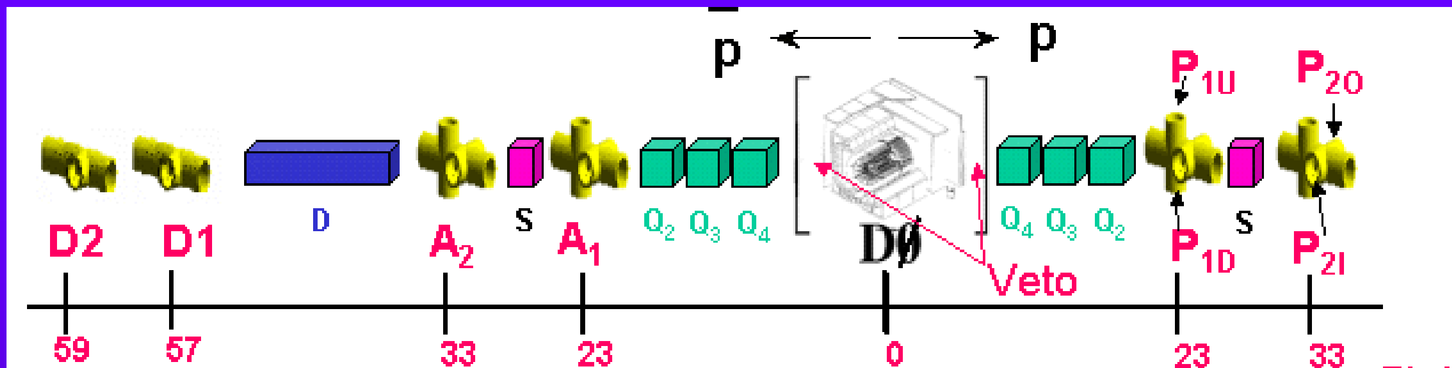
Everywhere: **Gluodynamics**, perturbative and non-perturbative issues



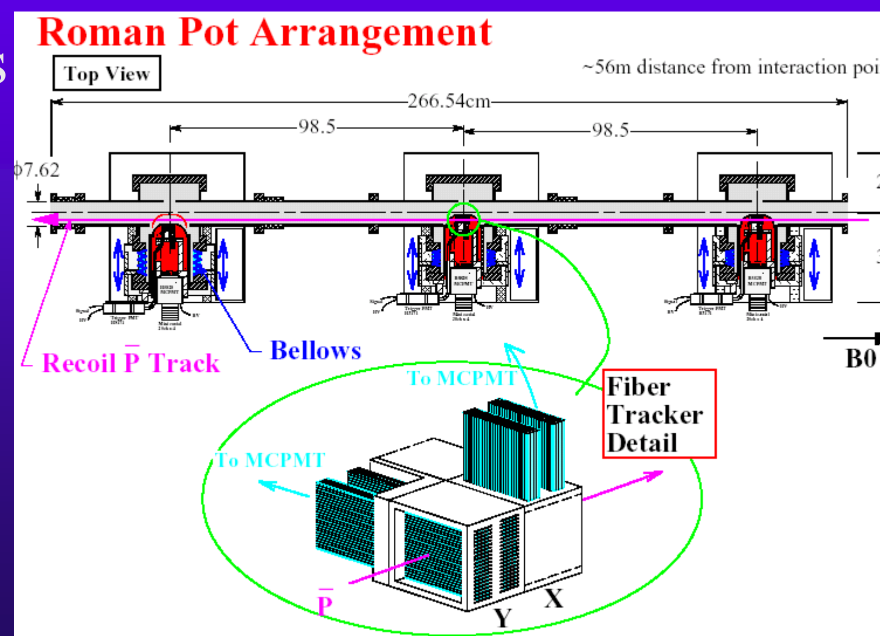
Like γγ collider in LC

Very Forward: Roman Pots

D0 has 8+8 quadrupole spectrometer pots + 2 dipole spectrometer pots
Scintillating fiber hodoscopes



CDF has 3 dipole spectrometer pots
0.8 mm x-y fibers



Possible: Quads + near + far dipoles
Silicon ustrips, pixels, trig scint
Quartz Cerenkov for ~ 30 ps TOF

Central Exclusive Production

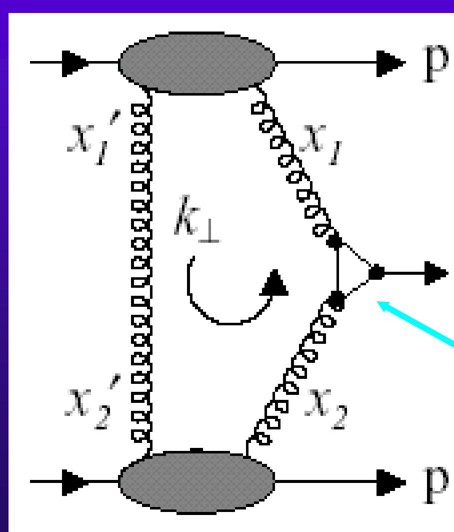
gg fusion: main channel for H production.

Another g-exchange can cancel color, even leave p intact.

$$p\,p \rightarrow p \quad + \quad H \quad + \quad p$$

Theoretical uncertainties in cross section, involving skewed gluon distributions, gluon k_T, gluon radiation, Sudakov ff etc.

→Probably $\sigma(SMH) \sim 1$ fb at Tevatron, not detectable, but may be possible at LHC (higher L and ~ 40 fb?)



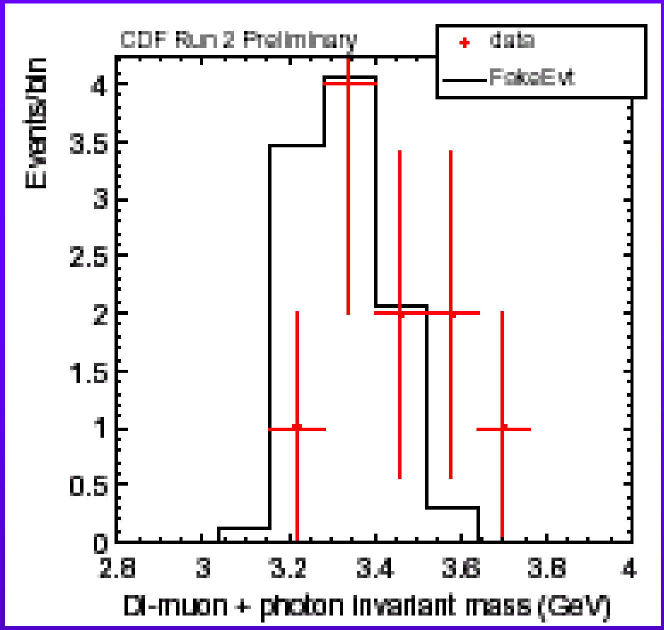
Theory can be tested, low x gluonic features of proton measured with exclusive $\gamma\gamma$, χ_c^0 and χ_b^0 production.

u-loop : $\gamma\gamma$ c-loop : χ_c^0

b-loop : χ_b^0 t-loop: H

Exclusive χ_c search: $p\,\bar{p} \rightarrow p \quad \chi_c \quad \bar{p}$

Predictions for Tevatron ~ 600 nb (~ 20 Hz!)



In reality: $BR(\chi_c^o \rightarrow J/\psi\,\gamma \rightarrow \mu^+\mu^-\gamma)$

$\times$ no other interaction $\times$ acceptance(trig)

$\Rightarrow$ few pb (1000's in 1 fb^{-1})

$\sigma(p\,p \rightarrow p \quad \chi_b \quad p) \sim 120$ pb (KMR)

$\times(BR \rightarrow \Upsilon\gamma)\times(BR \rightarrow \mu\mu\gamma) \Rightarrow$

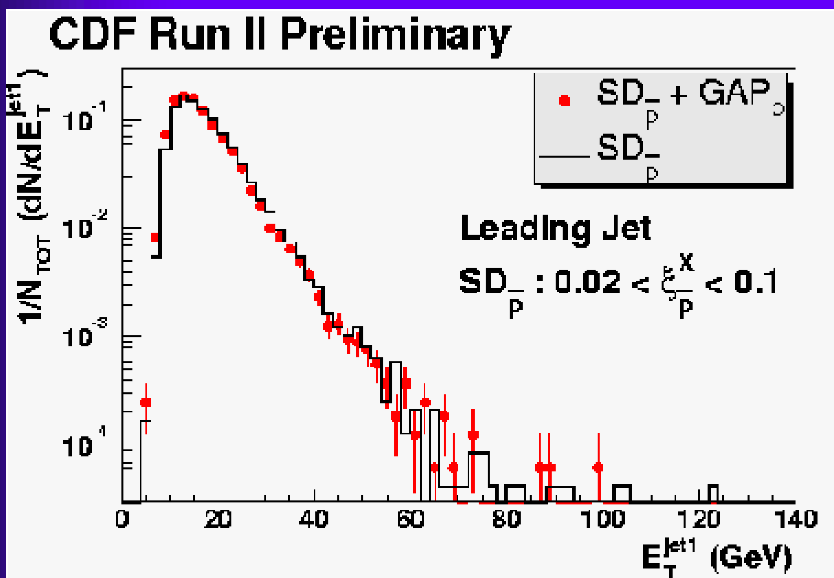
$> \sim 100 \times$ Acceptance / fb^{-1}

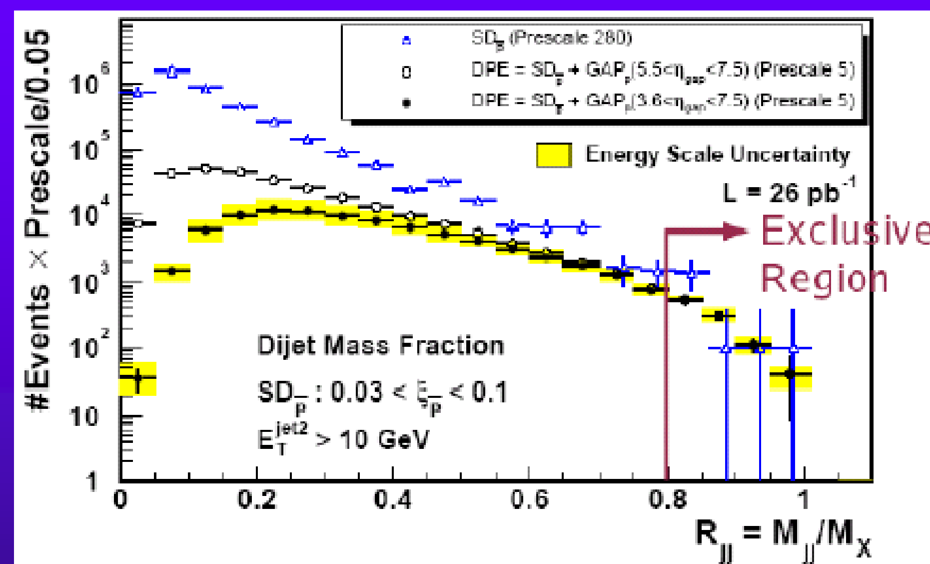
{Measuring forward p → central quantum numbers
2+ forbidden at t=0 for $q\bar{q}$ state}

$I^G J^P = 0^+ 0^+$

Exclusive Dijets?

Meaning p p → p JJ p and practically nothing else
See antiproton in roman pots, see rap gap on other side.
CDF Run I discovery {JJX} (130/~10 bg) ... Run II trigger:





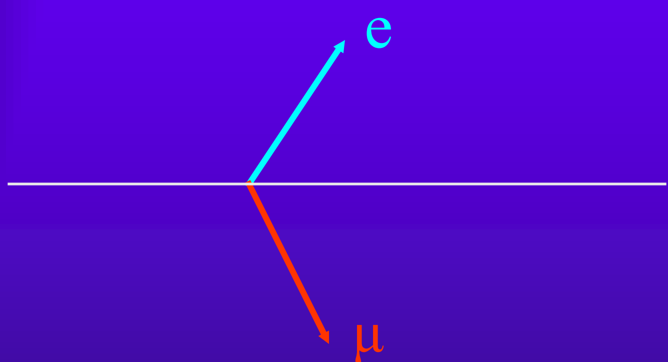
So far: upper limit ~ theoretical expectations
Expect enhancement rather than peak
They should all be gluon jets ! Unique sample

Central Exclusive Production at LHC

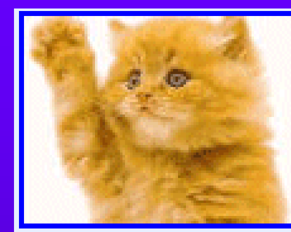
$$\mathrm{H(160)} \rightarrow \mathrm{W^+W^-} \rightarrow \mathrm{p}\;\; \mathrm{e^+\mu^-} \notin_T \;\; \mathrm{p}$$

$$\mathrm{MM}^2 = (p_1 + p_2 - p_3 - p_4)^2 = \mathrm{M_H^2}$$

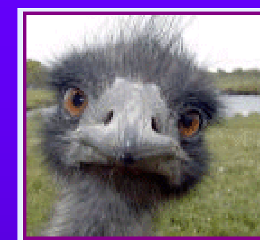
Nothing else on 2-lepton vertex!



ee



μμ



eμ

+ White Pomeron search

$$\text{Also H(120)} \rightarrow \tau^+\tau^-$$

The "White Pomeron"

e.g. A.R.White hep-ph/0405190
Sextet Quark Physics at the Tevatron?

Alan White: **Pomeron = reggeized gluon + cloud of wee gluons.**

Asymptotic freedom → 16 color triplet q's Only 6 known

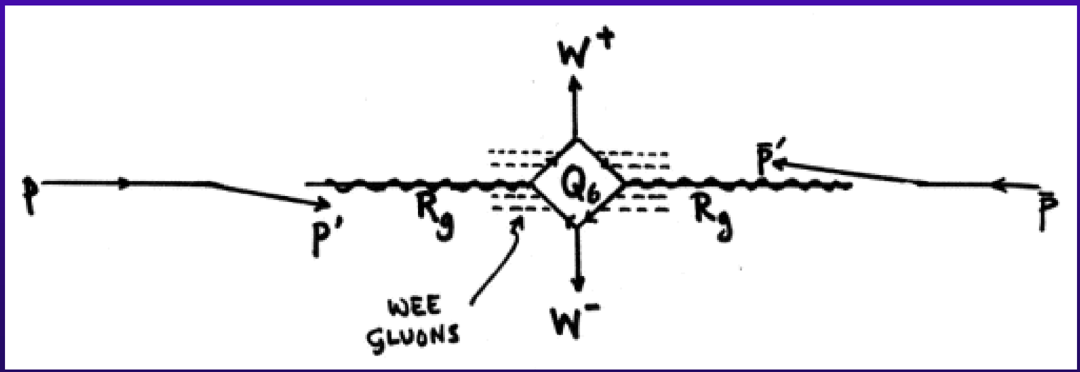
AHA! 1 color sextet Q counts 5 x 1 color triplet

{ud}+{cs}+{tb} + {UD} → AF

$\Pi = U\bar{D}$ etc, η_6 ....EWSB, role of Higgs

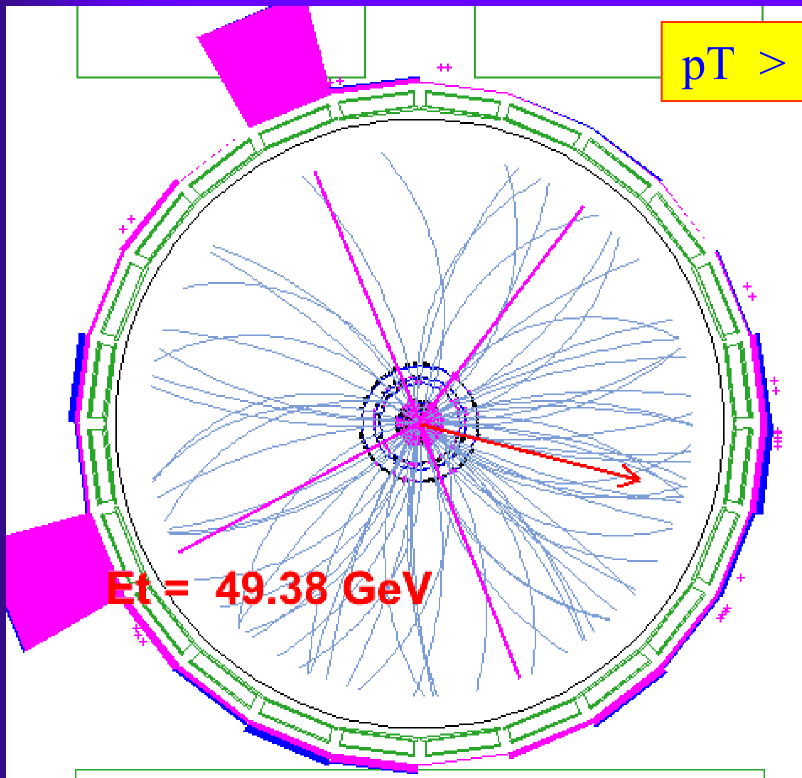
Can be dark matter (N = DDU ~ TeV)

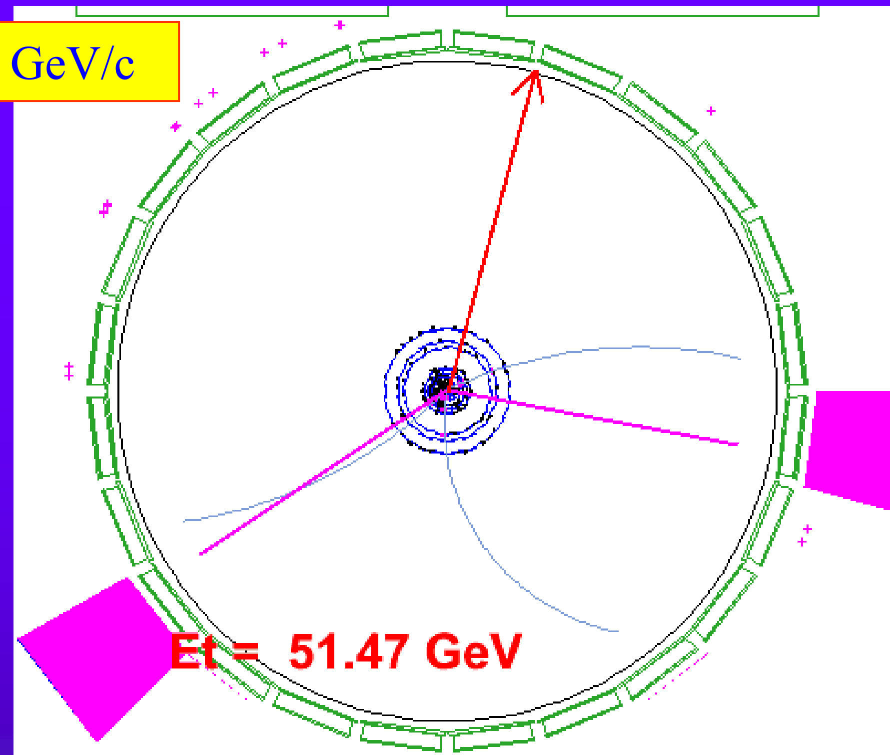
Pomeron couples strongly to WW through U,D loops



Two interesting Run II events

(2 / ~5)





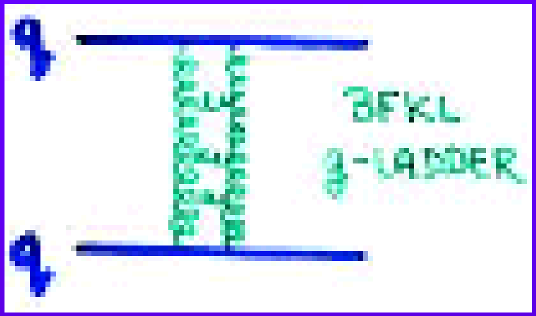
Probable ZZ
4e > 20 GeV.
~ 70 tracks & y < 1 : 34

ee MET (WW or ZZ)
2 tracks with y < 1
& very low forward activity

Fluctuation? High-b? Diffractive?
MC + more data

BFKL and Mueller-Navelet Jets

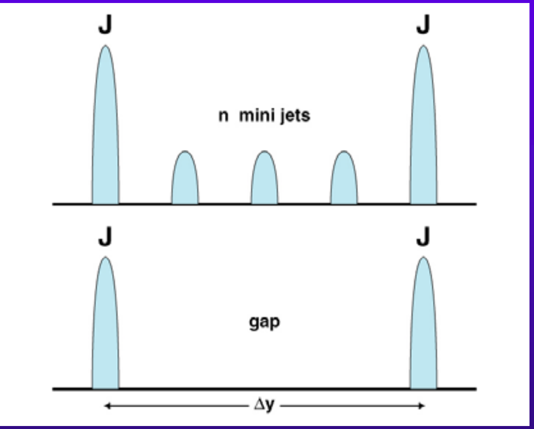
Color singlet (IP) exchange between quarks
Enhancement over 1g exchange – multiRegge gluon ladder
Jets with large y separation
n minijets in between (inelastic case)
large gap in between (elastic case)



Cross section enhanced $\left(\frac{s}{t}\right)^{\omega}$

$$\omega_{BFKL} = \frac{4N_c \ln 2}{\pi} \alpha_S \approx 0.5 \text{ for } \alpha_S = 0.19$$

$$\bar{n} \sim \omega \ln\left(\frac{s}{t}\right) \sim 3-4$$

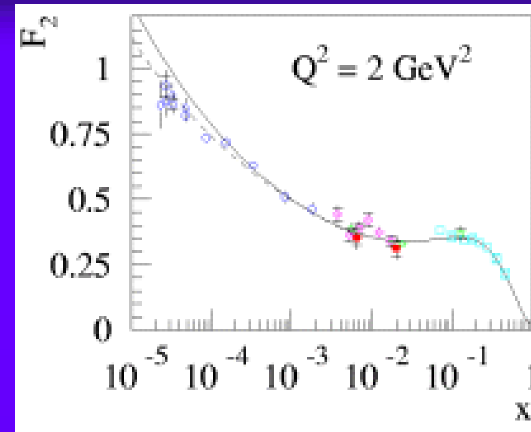


Measure fn(η, p_T, $\sqrt{s}$, $\Delta\eta$)

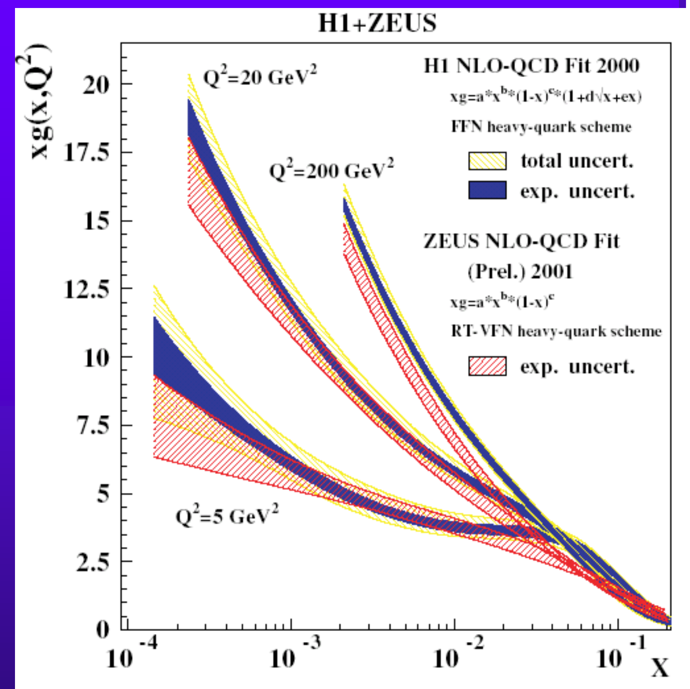
Fundamental empirical probe of new regime:
non-perturbative QCD at short distances.

Very forward calorimeters OS

Probing Very Small x Gluons



High parton densities
New phenomena (gluon saturation)
HERA measures q(x) to ~ 10^-5
g(x) by evolution, charm
GTeV : measure g(x) to ~ 10^-4
(also x >~ 0.5) more directly



$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{y_1} + e^{y_2}\right) \quad ; \quad x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-y_1} + e^{-y_2}\right)$$

e.g. $\sqrt{s}$=1960 GeV, p_T = 5 GeV, $y_1 = y_2$=4 (2.1^0)

$$\Rightarrow \quad x_1 = 0.56,\ x_2 = 10^{-4}$$

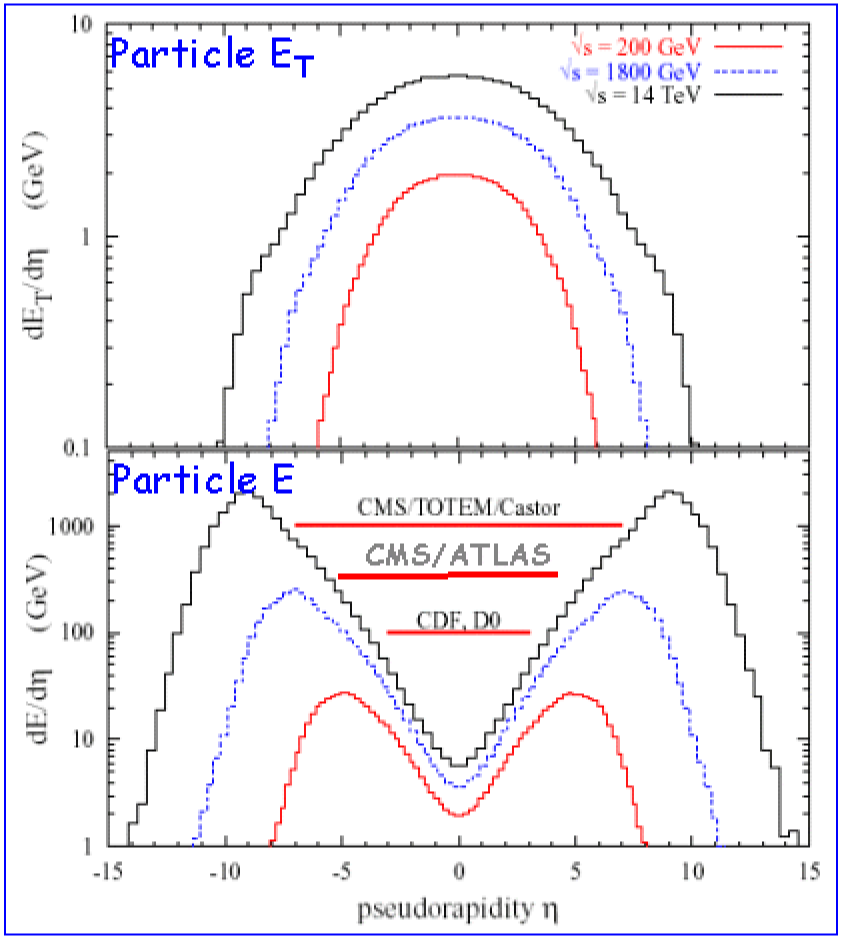
Instrument $0.5^0 < \theta < 3^0$ region with tracking, calorimetry (em+had), muons, J/ψ jets, photons ...

Very forward calorimeters SS

Colliders study (mostly) Central Region

Jim Pinfold

- Collider physics measurement emphasis:
  - High Transverse energy
    - Jets
    - Leptons
    - Leptonic secondaries
    - Missing energy
- Cosmic EAS measurements involve primarily:
  - Total/inelastic cross-section
  - Fraction of diffractive dissoc.
  - Energy flow
  - Particle multiplicity distributions
  - Hadronic secondaries



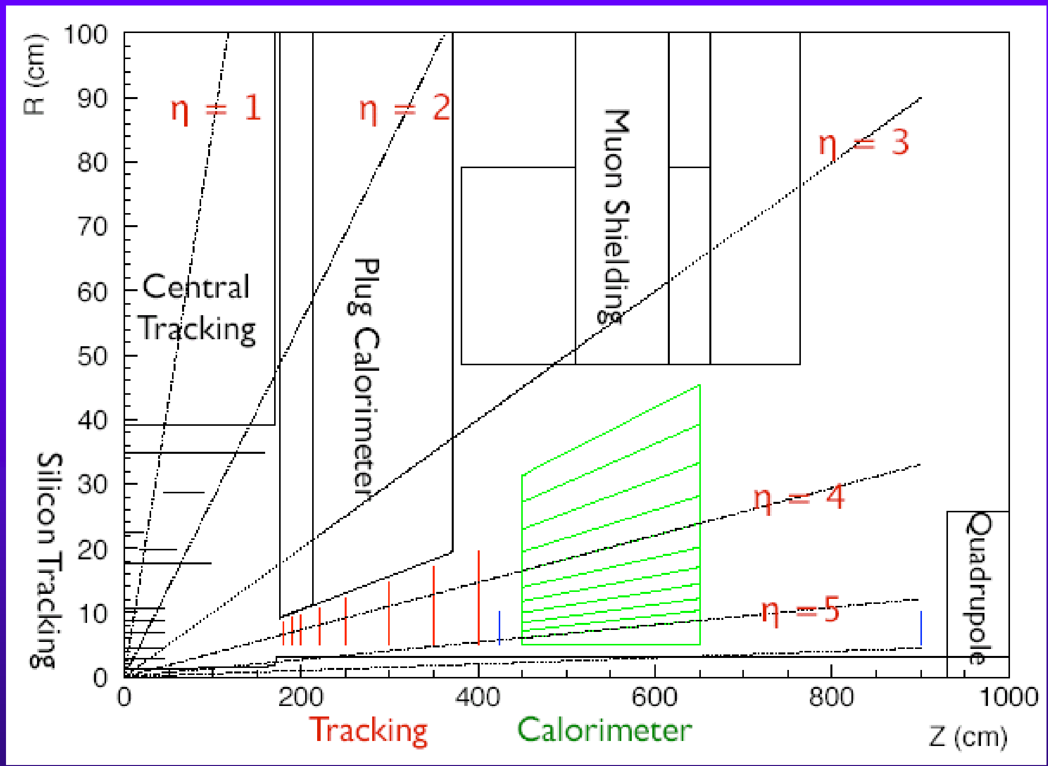
Forward "Cone" Spectrometer for CDF?

$$0.5^0 < \theta < 3^0 \;\Rightarrow\; 3.6 < \eta < 4.9$$

Now: luminosity counters + 1.1 interaction length calorimeter

Possible upgrade:

→ Tracking (in mag field)
→ electrons & photons
→ hadron calorimetry – jets
→ muons



Could be done if sufficiently motivated (and funded!)

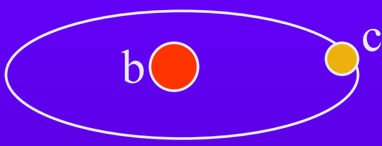
What do we need to do?

High E_T, M_{JJ} frontier — **Gain slow, LHC take-over**

Lower $p_T \Rightarrow$ large distances — **Low B runs, roman pots at small t**

More statistics - but *precision* tests limited

e.g. $B_c = b\bar{c} + \gamma$'s spectroscopy



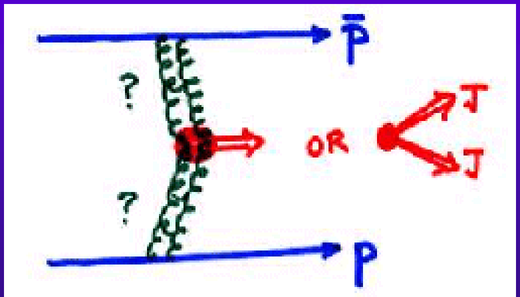
understand jets, for jet spectroscopy $\Rightarrow$ t, H

WW and ZZ pairs — **LHC take-over**

Diffractive sector, especially:

DPE (G, hybrids, hyperons, χ, jets, b-jets)

Very forward production



The Future of QCD at the Tevatron

Workshop May 2004: **http://conferences.fnal.gov/qcdws/**

Very active program will continue → > **10 x statistics**
CDF and **D0** detectors stop detecting in 2009 (probably)
Before:
Could add **precision (Si) roman pots** on both sides
Could upgrade CDF very forward (**cone spectrometers**)
Special running: root **s-scan** (630 – 1960), low **B-field** run

BTeV: Supplement B-physics program with more QCD studies:
+ roman pots, hadron calorimeter, veto (rap-gap) counters, + ?

Plan: **"Yellow Book"** on physics issues (cf **LHC, HERA** etc)

Fred Olness, Mark Strikman, MGA eds