# GTeV: Gluon Physics at the Tevatron

- A possible future experiment at the Tevatron
- 2009: CDF & D0 complete data taking
  - BTeV to run 2009 to ~ 2013 (?)
- Primary Goal of GTeV: QCD (perturbative & non-perturbative)
- Uses CDF or D0 detector as "core"
- Add precision forward and very forward tracking

# *Primary Goal: Understand Strong Interactions*

**Foci:**

**Gluon density g(x, Q2) at very low x**

saturation, unitarity, gluodynamics, non-perturbative frontier

**Pure Gluon jets**

profiles, content, color connection, gg compared to q-qbar jets

**Determine glueball spectrum**

Relates to pomeron trajectories, strings, lattice ...

**Measure exclusive** $\chi_c^0, \chi_b^0$

Relates to SM Higgs study at LHC

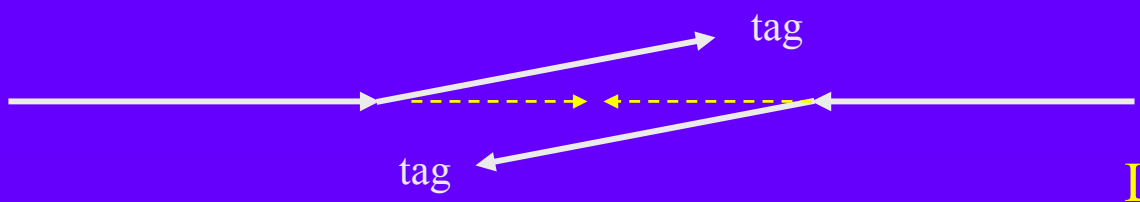
**Discover new exotic hadrons**

Hybrids, 4-quark, pentaquarks, ...

**Search for the really exotic**

CP-odd H, Radions, gluinoballs $gg(^{0^{++}}_{0^{-+}})$, White pomeron, ...

# Use Tevatron as Tagged Gluon-Gluon Collider




Like γγ collider in LC

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

$$\sigma_{\sqrt{s}} \sim 100\,\text{MeV} \longleftarrow \text{(Stretch Goal)}$$

Glueballs and Hybrids

New Exotic Hadrons

chi_c and chi_b states

Hunting strange exotic animals (radions, ...?

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

# The REAL Strong Interaction

extended, strong coupling
non-perturbative

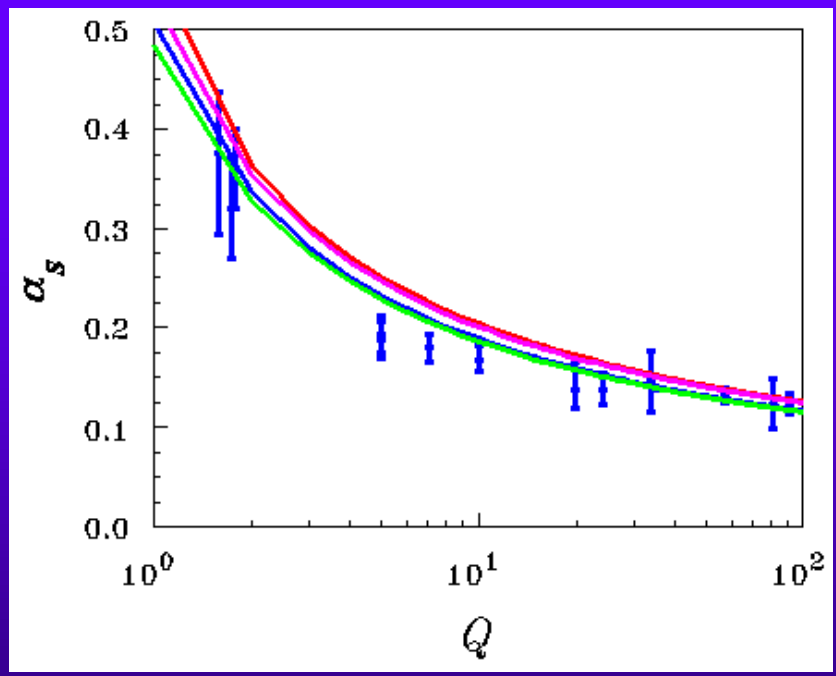
point-like, weak coupling
perturbative

Many approaches, none complete:

→ Lattice Gauge Theory
Small volume, hadron size

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

→ String models




**Want a complete understanding of S.I.** $Q^2 = 0 \rightarrow \infty$

**Non-perturbative – perturbative transition**

Some of proposed program could be done now, except:

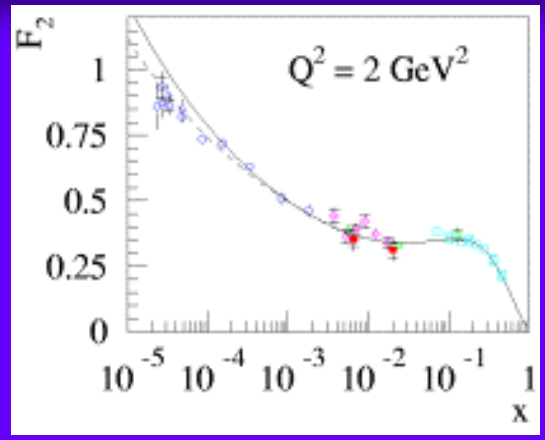
1) Do not have 2-arm forward p-taggers (dipole spectrometer)
2) Small angle ( < 3 deg) region trackless
3) Limit on number of triggers
4) Bandwidth allocated small

**60 Hz → 250 Hz → > 1 KHz for 2009 [ $10^{10}$ /year]**

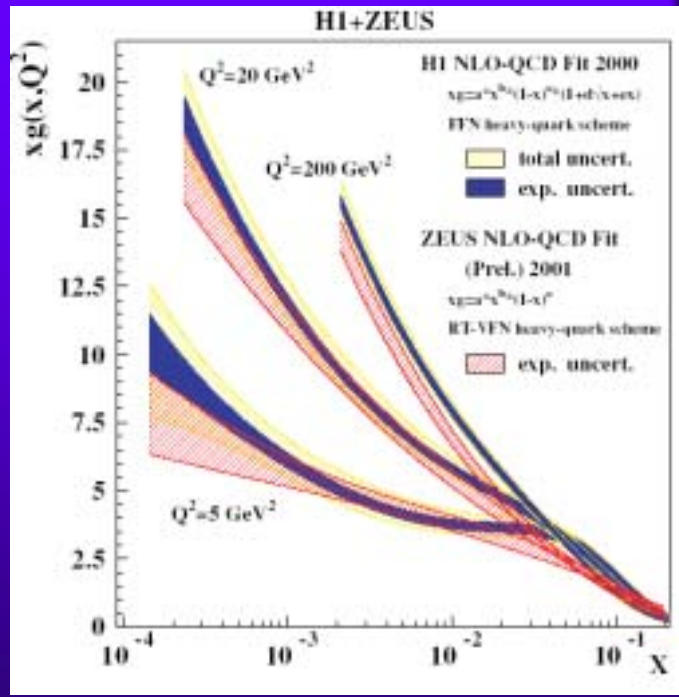
CDF, D0: NP QCD <~ 10%, other ~ 90%
**GTeV: NP QCD ~ 90%, other(?) <~ 10%**

& upgrade of forward and very forward detectors

# 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$^0$)

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

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

# Gluon Jets

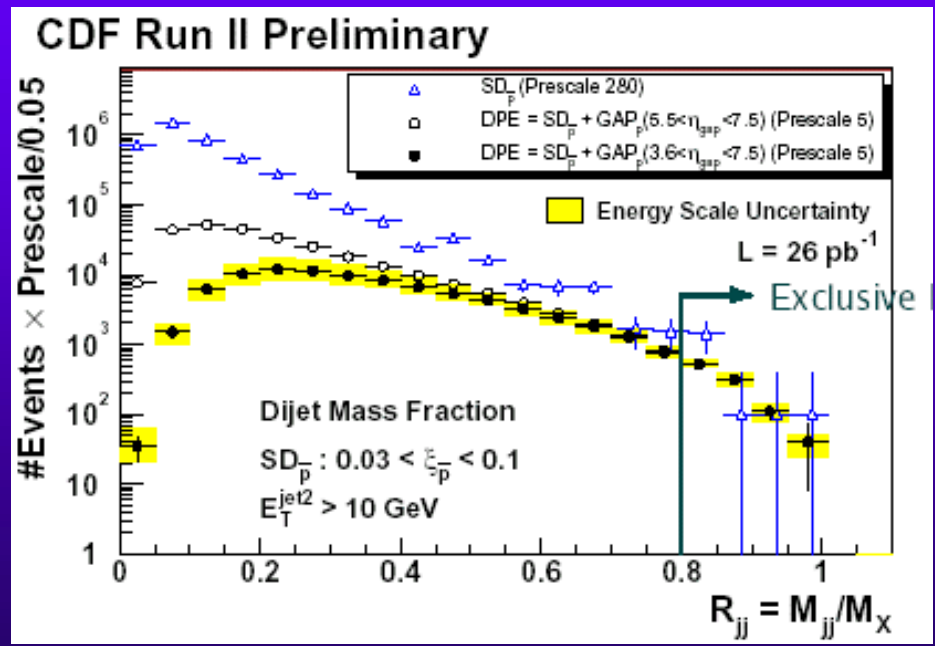
LEP(Z) ... ~ 10^7 q-jets, detailed studies
"Pure" g-jet sample: 439 events (OPAL), Delphi more but 80% "pure"

$e^+e^- \rightarrow Z \rightarrow b\,\bar{b}\,g$ g-jet contaminated at low-x

In $pp \rightarrow p$ JJ $\bar{p}$ with $M_{MM} \approx M_{JJ}$

(2 jets and ~ nothing else)
> ~ 99% pure g-jets
q-jets suppressed by Jz = 0 rule

$10^4$ - $10^5$ pure g-jets




Fragmentation, scaling
color singlet back-to-back gg jets: DPE unique

# 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 $0^0$ |
| $0^+$ | $1^{-+}$ | |
| $0^+$ | $1^{++}$ | |
| $0^+$ | $2^{++}$ | ← |

# 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:

This one →

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

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

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

$gg \rightarrow G, GG, G+anything$

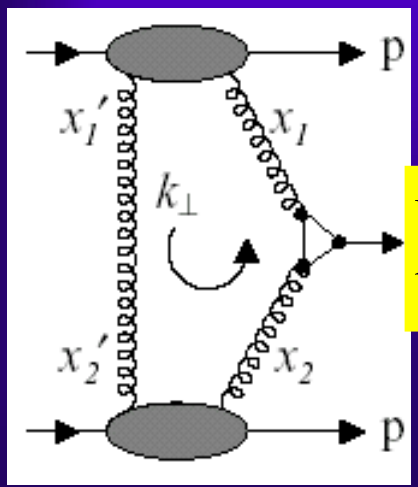
# Central Exclusive Production

gg fusion: main channel for H production.

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

p p → p + H + p

Theoretical uncertainties in cross section, involving skewed gluon distributions, gluon k_T, gluon radiation, Sudakov form factors →Probably $\sigma(SMH) \sim 0.2$ fb at Tevatron, not detectable, but may be possible at LHC (higher L and $\sigma \sim 3$ fb?)




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

b-loop : $\chi_b^0$ t-loop: H

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

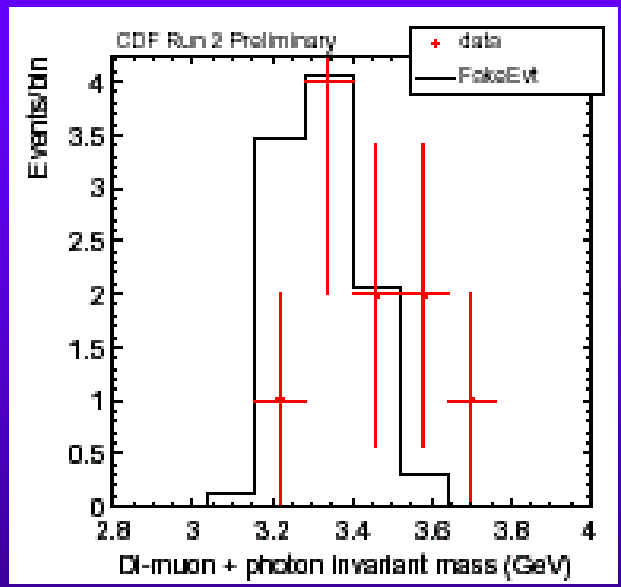
# Exclusive $\chi_c$ search in CDF : $p\,\bar{p} \rightarrow p \quad \chi_c \quad \bar{p}$

Predictions for Tevatron: Khoze, Martin, Ryskin ~ 600 nb
Feng Yuan ~ 735 nb (20 Hz at Tevatron!)

In reality: $BR(\chi_c^o \rightarrow J/\psi\,\gamma) \sim 10^{-2}$; $BR(J/\psi \rightarrow \mu^+\mu^-) \sim 6.10^{-2}$

No other interaction ~ 0.25; acceptance(trig) ~ $10^{-2}$

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




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

$\times(BR \rightarrow \Upsilon\gamma) \times (BR \rightarrow \mu\mu\gamma) \Rightarrow \sim 500/fb^{-1}$

Measuring forward p → central quantum numbers

$J^P = 0^+$ ; 2++ suppressed at t=0 for $q\bar{q}$ state

If MM resolution <~ 100 MeV, exclusive test, resolve states

# Beyond the Standard Model

**CP-odd Higgs** : allowed $20 < M < 60$ GeV

Don't couple to W,Z ... produced by gg → t-loop → h

But b-bbar b/g large too ... Mass resolution critical

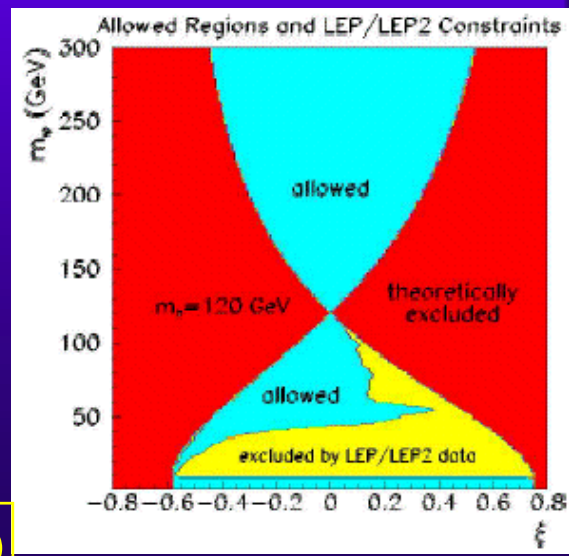
Low $\beta \Rightarrow$ Medium $\beta$ $\quad \sigma_{MM} \approx 100$ MeV

(z,t) correction $\approx$ ?

**Radions** : Quantum fluctuations in 5th dimension: tensor + scalar

20 GeV and up allowed if parameters right. Like h but gg coupling high

Width ~ keV, Decay → b bbar




## Light Gluinos and Gluinoballs

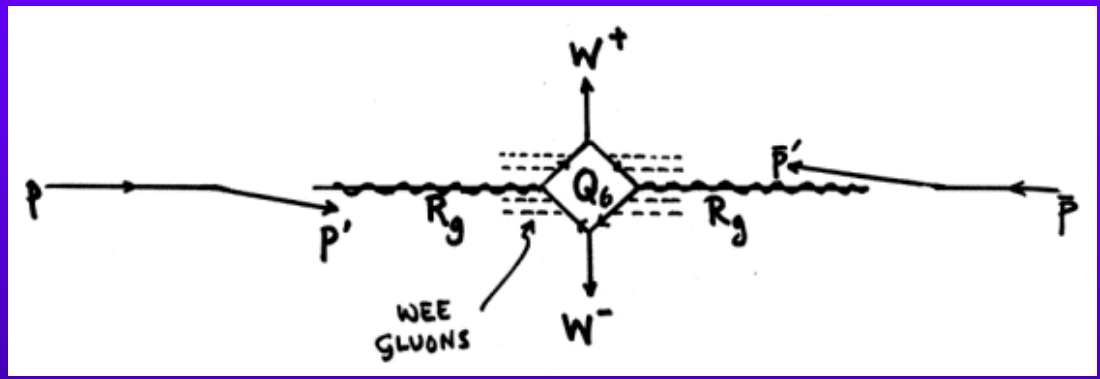
Gluino $\tilde{g}$ could be lightest SUSY particle LSP

Does not decay in detector --- forms heavy hadrons. Can form $\tilde{g}g$ bound states "gluinoballs"

$$\sigma(p\bar{p} \to p + \tilde{G}(60\text{GeV}) + \bar{p}) \approx 20\text{fb (Tevatron)}$$

# The White Pomeron

Alan White: **Pomeron = reggeized gluon + cloud of wee gluons.**
Six color triplet quarks not enough: **additional heavy color sextet U,D**
Pomeron couples especially strongly to sextet quarks
"Supermesons" e.g. $\eta_6 = U\bar{U}+D\bar{D}$ → EW symmetry breaking




**No need for Higgs boson**, maybe not there, but:

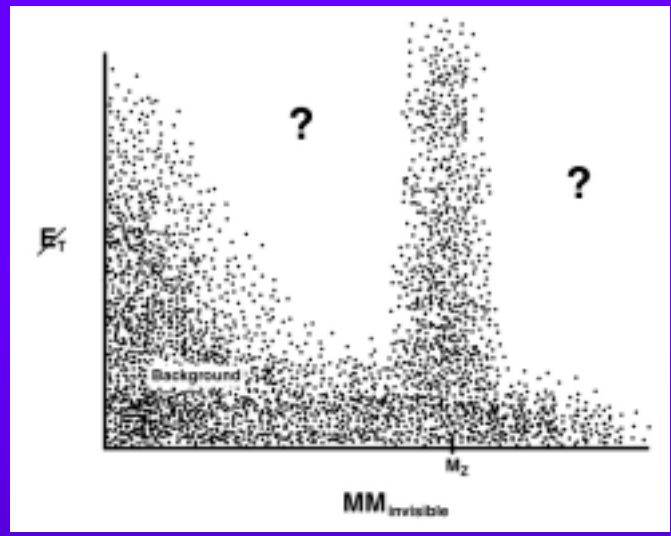
Abnormally **strong DPE → WW** (possibly SDE → WW also)
Interesting life at LHC! Perhaps can be glimpsed at Tevatron??

# Missing Mass!

$$MM^2_{central} = (p_1 + p_2 - p_3 - p_4)^2 \quad (4-vectors)$$

$$MM^2_{invisible} = (p_1 + p_2 - p_3 - p_4 - \Sigma_{rest} p_i)^2$$

Peak at $M_Z$ for $Z \rightarrow \nu\bar{\nu}$

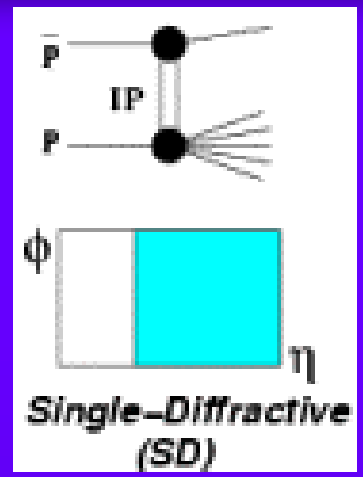



Extreme case of rest of detector completely empty
No MM peaks "expected"
But threshold bump → pair production of e.g. LSPs
Needs measurement of "all" forward particles

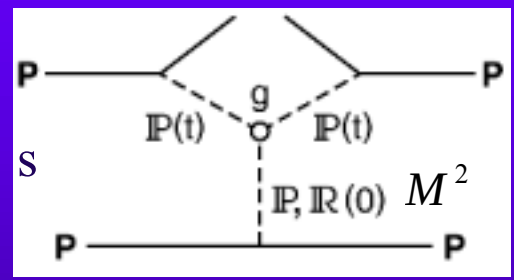
# Single Diffractive Excitation

$$\sigma_{inv} = \frac{m_0^2}{16\pi^2}\frac{1}{s}\sum_{iij} G_{iij}(t)\left(\frac{s}{M^2}\right)^{2\alpha_i(t)}\left(\frac{M^2}{m_0^2}\right)^{\alpha_j(0)} + \ldots$$

s-dependence at various fixed t, $M^2 \Rightarrow \alpha_i(t)$




System X can be soft (all low pT)
or hard (jets, W, Z).



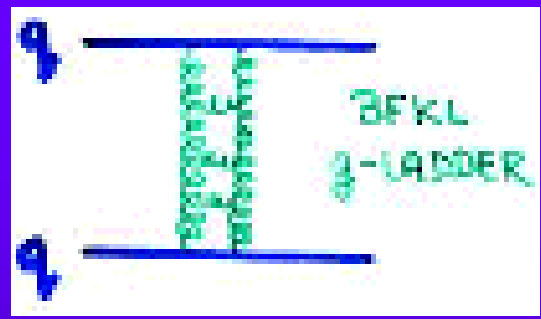

Pomeron trajectory probably different for
hard and soft systems. Similar seen at HERA in

$\gamma^* p \rightarrow \rho \quad p$ (soft) and $\gamma^* p \rightarrow \psi/\Upsilon \quad p$ (hard)

Systematic study of trajectories, needs s-dependence
→short runs at sqrt{s} = 630, 900, 1300, 1960 GeV
(in CDF & D0 ~ 2009?)

# BFKL and Mueller-Navelet Jets

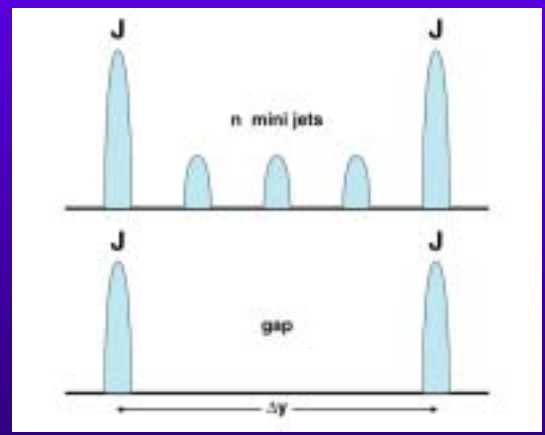
Color singlet (IP) exchange between quarks
Enhancement over 1g exchange – multiRegge gluon ladder
Jets with large y separation
n minijets in between (inelastic case)
large gap in between (elastic case)




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

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

# Hadron Spectroscopy: an example

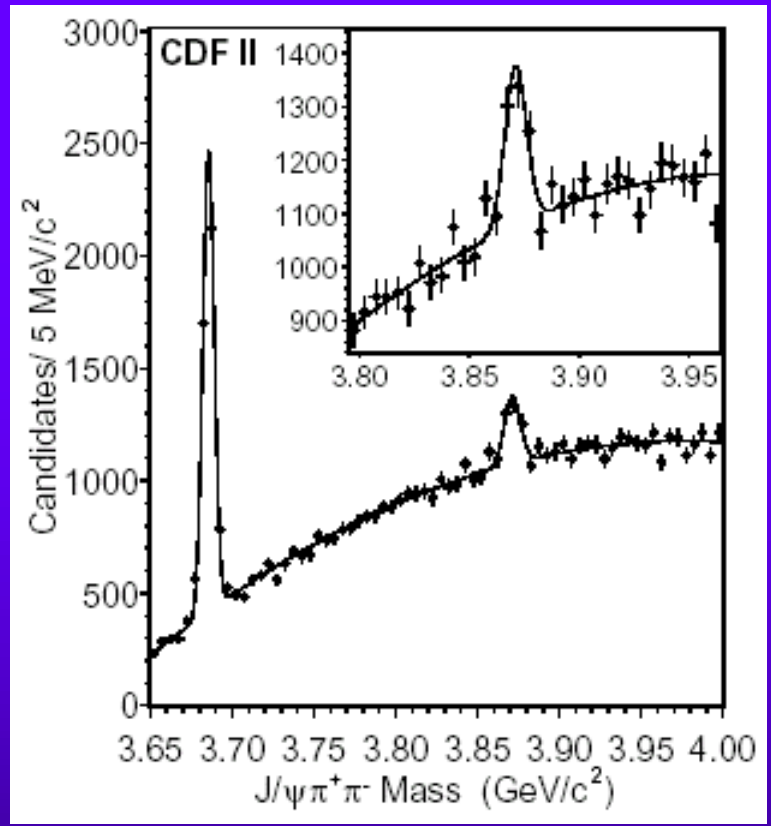
X(3872) discovered by Belle (2003)
Seen soon after by CDF
Surprisingly narrow

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

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

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

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




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.

# ***Bjorken: Low pT is the frontier of QCD***

High density, temperature in extended volume is another!

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

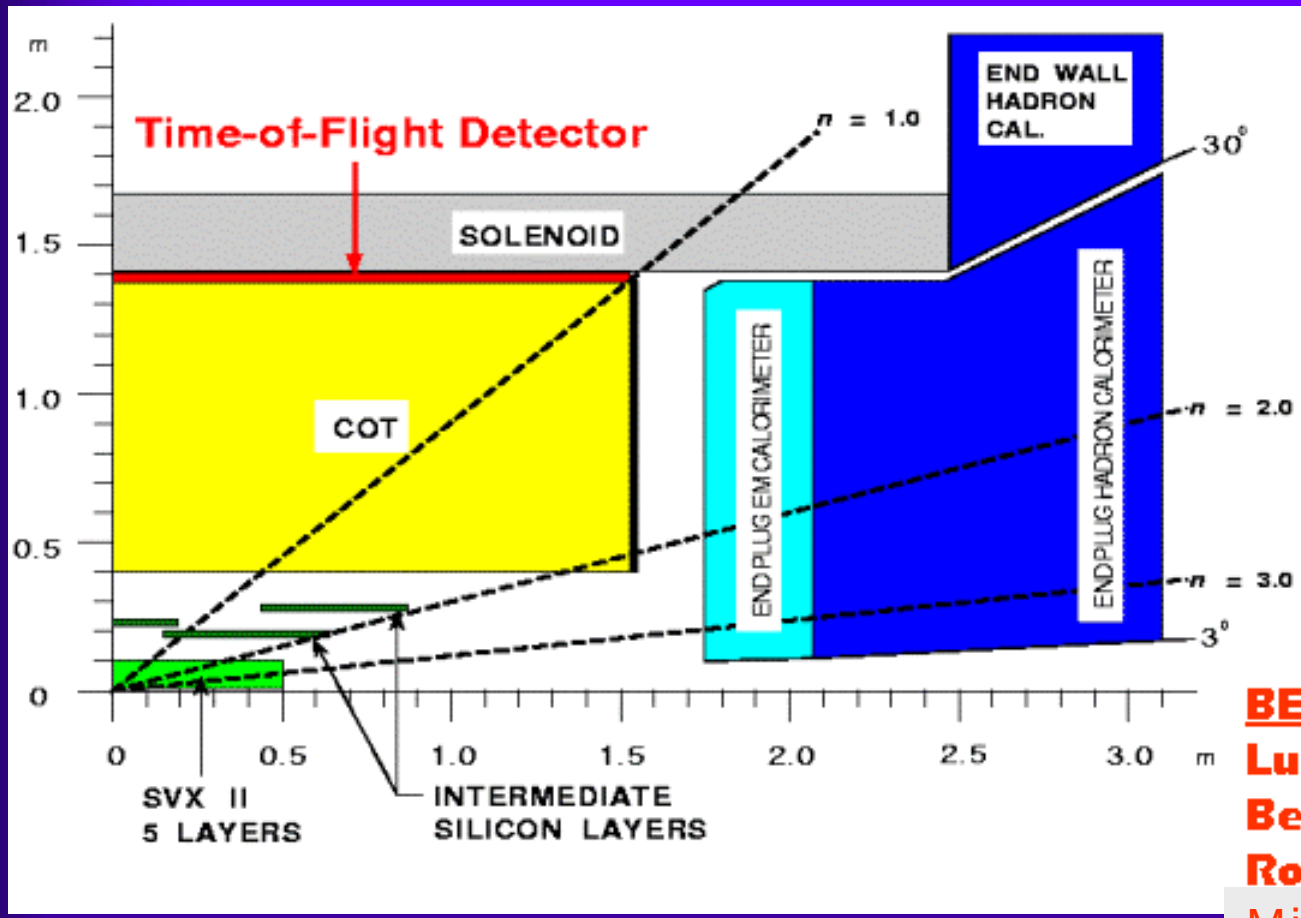
Multiplicity distributions of very low pT particles, correlations, ...
Low-pT cloud in special events

[Runs with reduced field, Si-only tracking, etc
.....absorption and multiple scattering is limit]

Large impact parameter, b, collisions

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

# Detectors

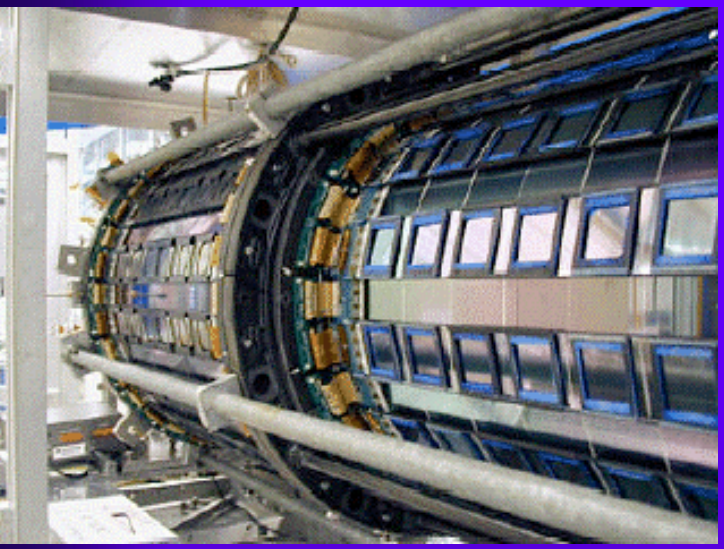


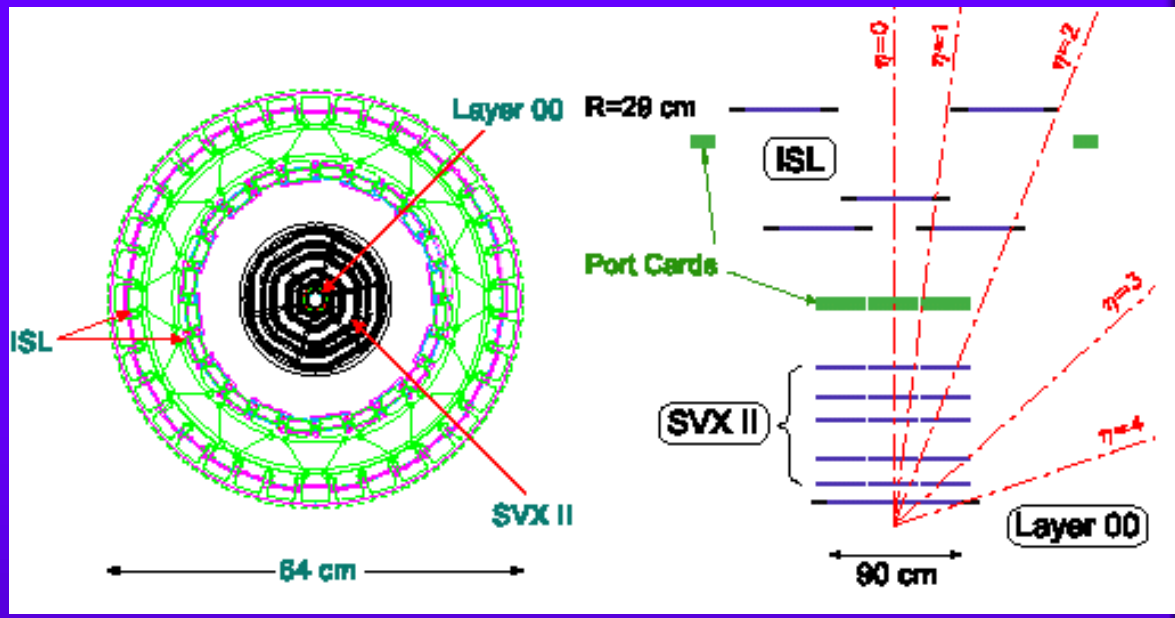

D0 an option.
I focus on CDF
(tracking, hadron ID
dE/dx, TOF)

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

Add:
New pots very forward E&W: through quadrupoles + near (55m) + far (165m)
Other forward detectors (tracking, upgrade calorimetry e.g.) → **"Cone Spectrometers"**
Upgrade DAQ → kHz, new triggers.

# CDF Silicon VerteX Detector SVX



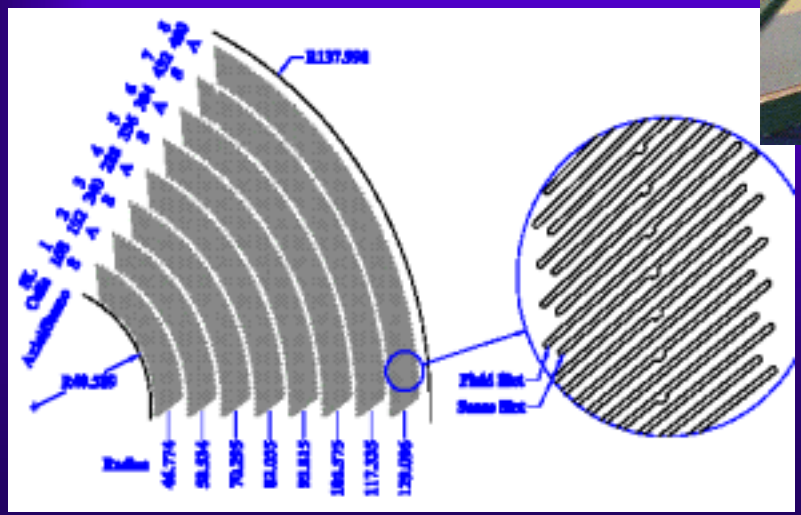



For beauty, charm, tau identification and measurement.
~ 720,000 strips, 25um with 50um readout
L00 : ~ 1.5 cm from x, R-phi view
SVXII: 3 double 90 deg layers + 2 double 1.2 deg layers
ISL : 1 or 2 double 1.2 deg layers.
Impact parameter resolution ~ 30 um @ 1 GeV/c

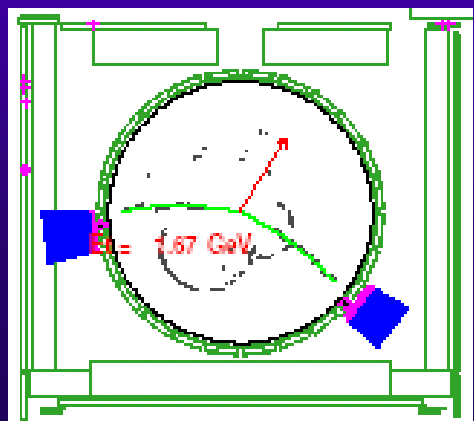
# CDF Central Outer Tracker (COT)

Drift chamber
3.1m in z, 0.34-1.32m in R
96 layers → 30,240 s.wires
40 um gold-plated tungsten
ADC & TDC each end
6 um Au-mylar field sheets

Resolution ~ 150 um/wire

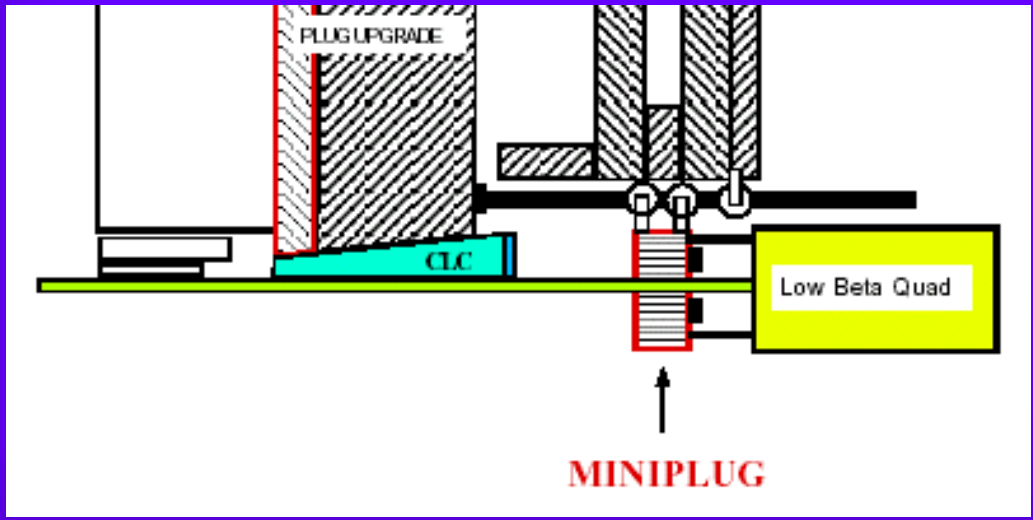


$J/\psi\ \gamma$
(*probably* $\chi_c$)



# New Forward Region (0.5-3.0 deg): Cone Spectrometer?

Now: 48 CLC counters + MiniPlugs




Can (remove Q1 and) push back ~ 2 m low-beta quads
Tracking e.g. GEM layers (50 um, 15 ns) over large area
Deeper Calorimeter (~6 int. lengths) high granularity, em/had

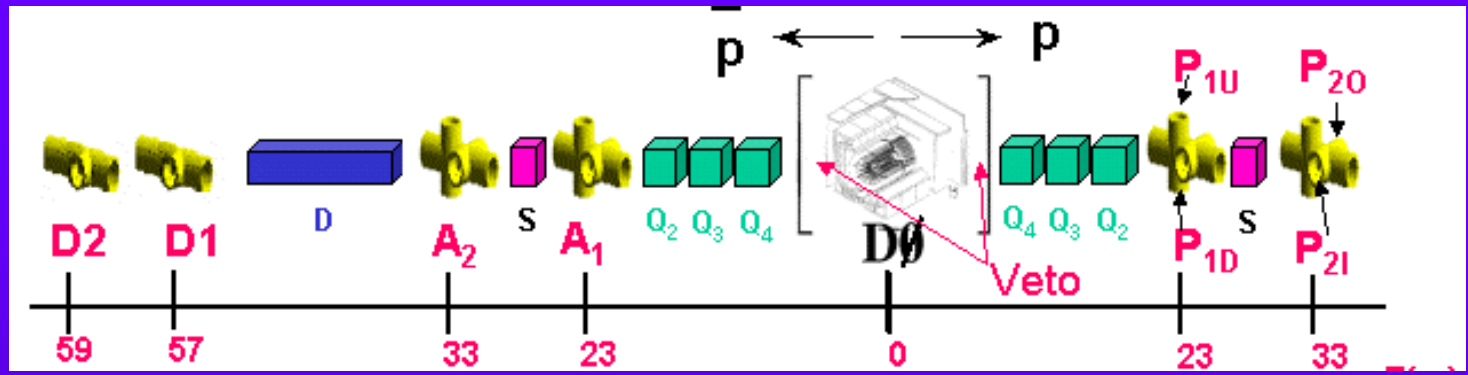
Physics motivation: Low-x with v.forward jets, J/psi
(BFKL) J - minijets - J, J – gap – J and J + X + J ... etc

"Cone Spectrometers"

Jets, μ, e, J/ψ, γ ?

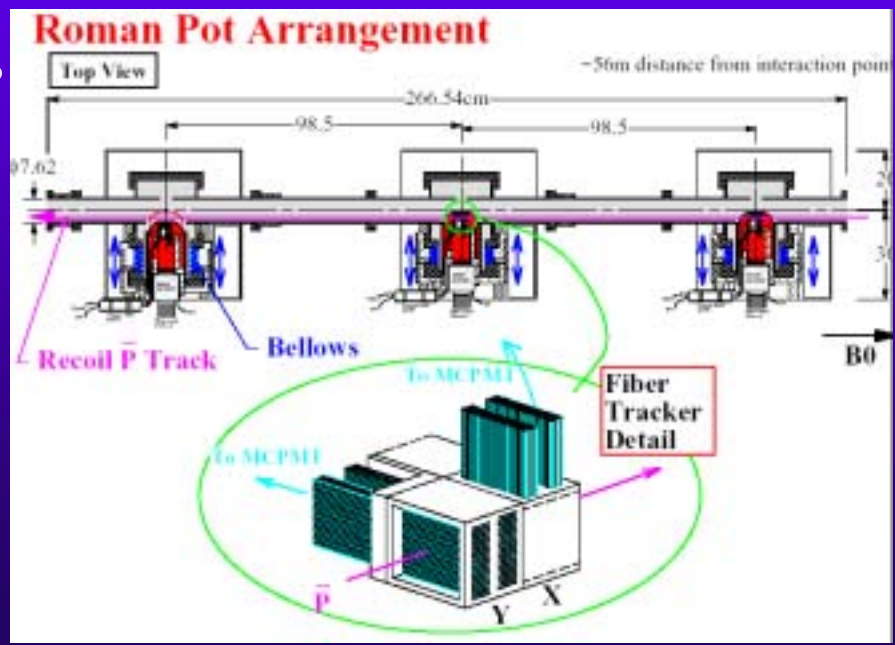
# Very Forward: Roman Pots

D0 has 8+8 quadrupole spectrometer pots + 2 dipole spectrometer pots
Scintillating fiber hodoscopes (~ 1mm)

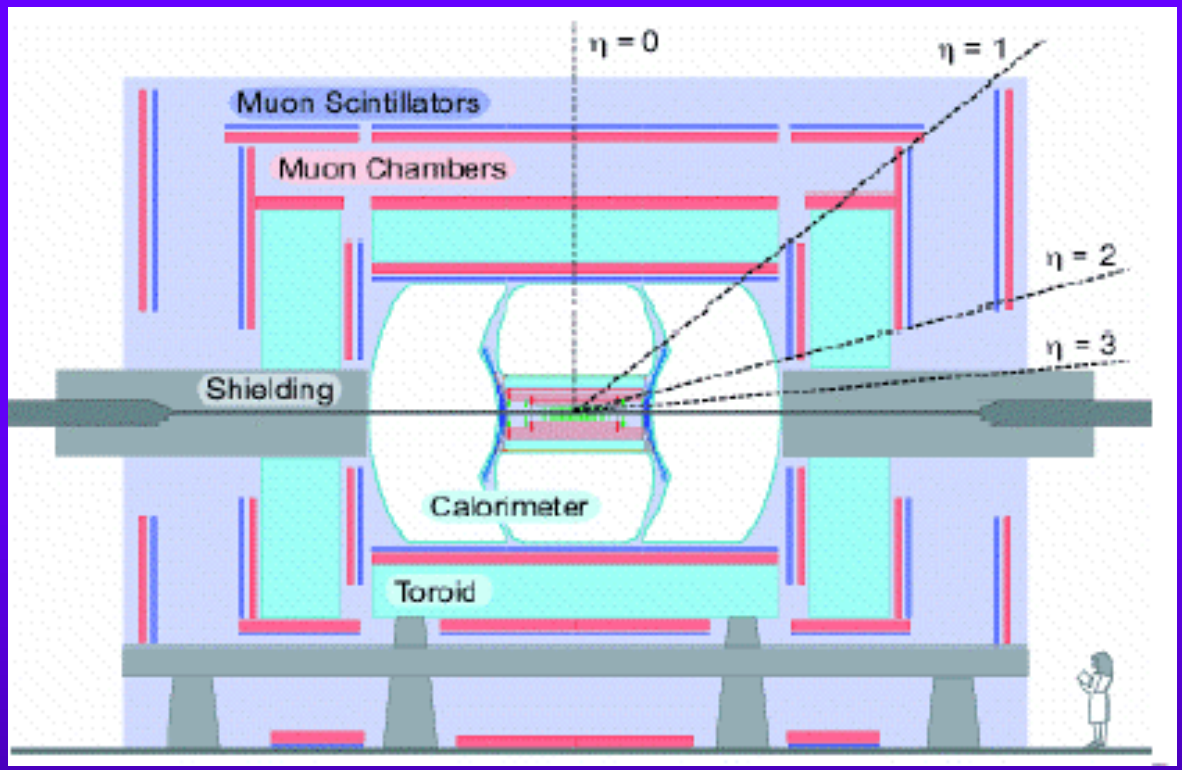



CDF has 3 dipole spectrometer pots
0.8 mm x-y fibers

GTeV: Near + far dipoles
Silicon ustrips.
Quartz Cerenkov for ~ 30 ps TOF



# Re-using D0 detector?




Add :
New/upgrade pots very forward E&W: quad + near (55 m) + far (165 m)

Forward ("cone") region not instrumentable
Less central hadron ID

# Tevatron Issues

Spaces for new pots

**Replace 3 dipoles with 2 High Field dipole(s)** → ~ 3 m spaces

~ 6.5 Tesla, same current, temperature! (Tech.Div or outside)

→ critical path, ~ 4 years

Momentum and Missing mass resolution Limits? Medium-beta?

p-z correlation? stability, drifts

Instrumentation: precision (~ 10 um?) BPMs at pots

Co-existence with BTeV: Luminosity (~2-4 E31),

Beam-beam tune shift, Long-range tune shift,

Electrostatic separators, Luminosity lifetime.

# *Many Subjects not Covered*

**Just a few:**

**The cosmic ray connection:** very forward particle production data needed

**Jet – gap - X – gap - Jet ( low mass X)** different from p—X---p ?

**Very soft photons** < 100 MeV, via conversions

**p → 3 jet fragmentation:** 3 very forward jets, with & without gaps

**Bose-Einstein correlations:** directional, event type, high statistics

**Many other studies will be done,** as happens in CDF & D0 now.

# ***Plan***

Workshop May 20-22nd: **The Future of QCD at the Tevatron**

Work up **Physics Case** → Report
Maximize **QCD physics in CDF/D0**:
Modest additions, s-scans, higher data rates, more triggers, etc.
Some **special running in 2008/2009** ?

Understand **differential physics case**.

Does it convince **enough people** to make a serious **proposal**, full or partial?

# *Concluding Remarks*

We must **maximize the physics** output of **CDF** and **D0** before 2009
There will probably be **much QCD physics still to be done**.
**Physics case** still needs to be quantified (with simulations)
Here I have only scratched the surface.
Unknown territory: **discoveries likely**.

The **CDF and D0 detectors** are great central detectors for this program, suitably upgraded at modest cost:
DAQ, trigger, forward (few deg) and very forward (pots)
Not all ~1500 physicists on CDF and D0 will want to go to LHC
Perhaps physicists will come from DESY and elsewhere.

**Tevatron running anyway for BTeV, so it's great value.**