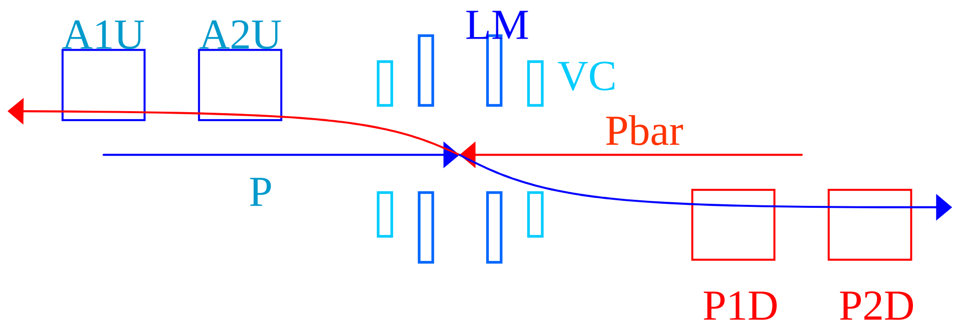
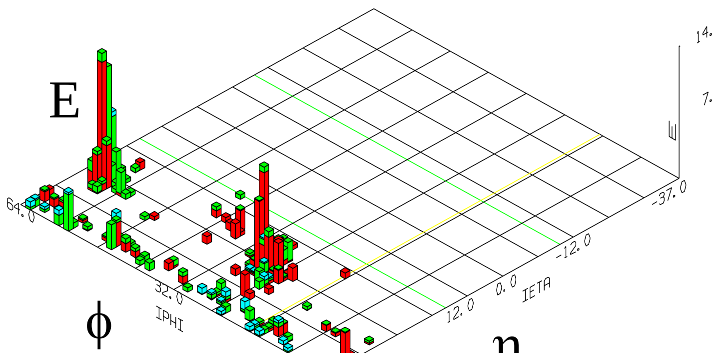
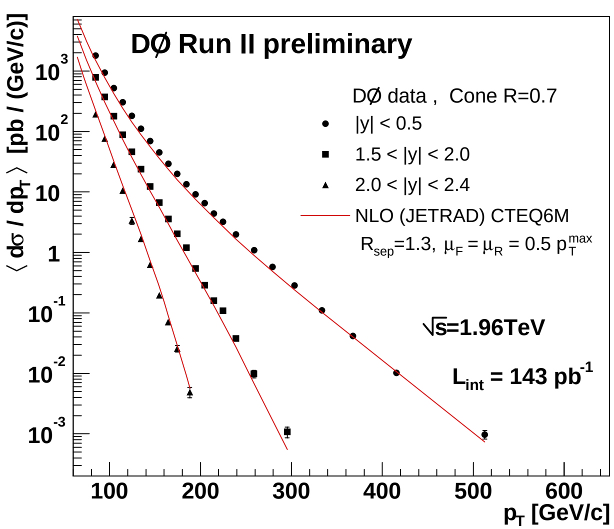
DØ QCD: Past, Present, and Future

Andrew Brandt, University of Texas at Arlington

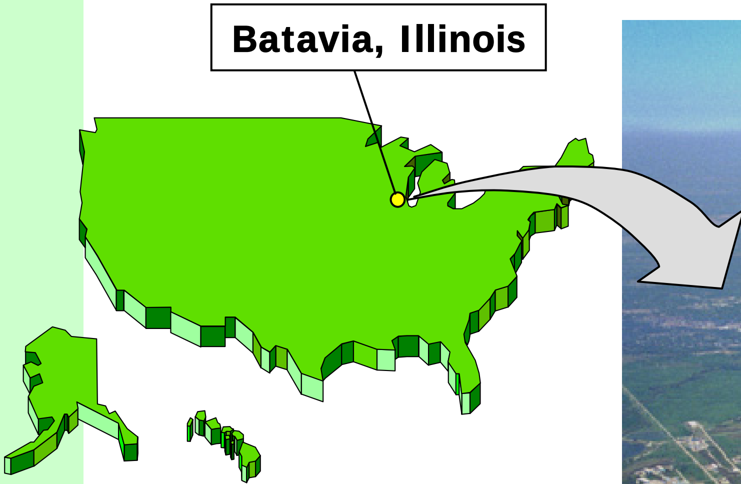


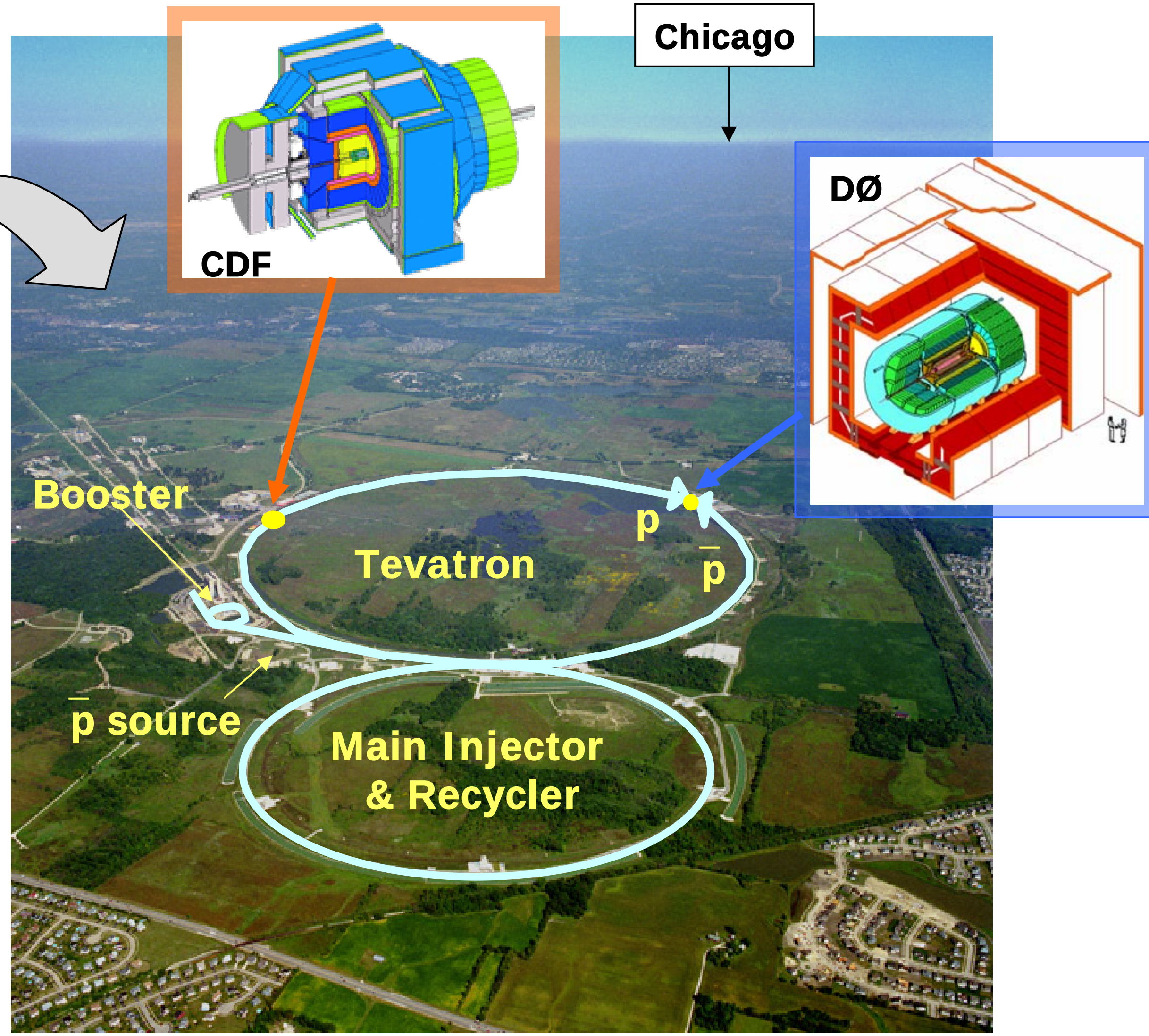


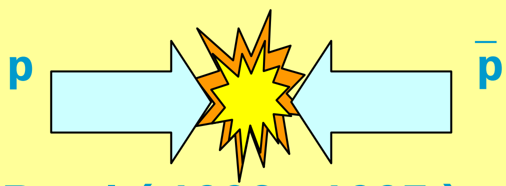


Physics Seminar
May 7, 2004
Jefferson Lab

Tevatron at Fermilab







Run I (1992 - 1997) :

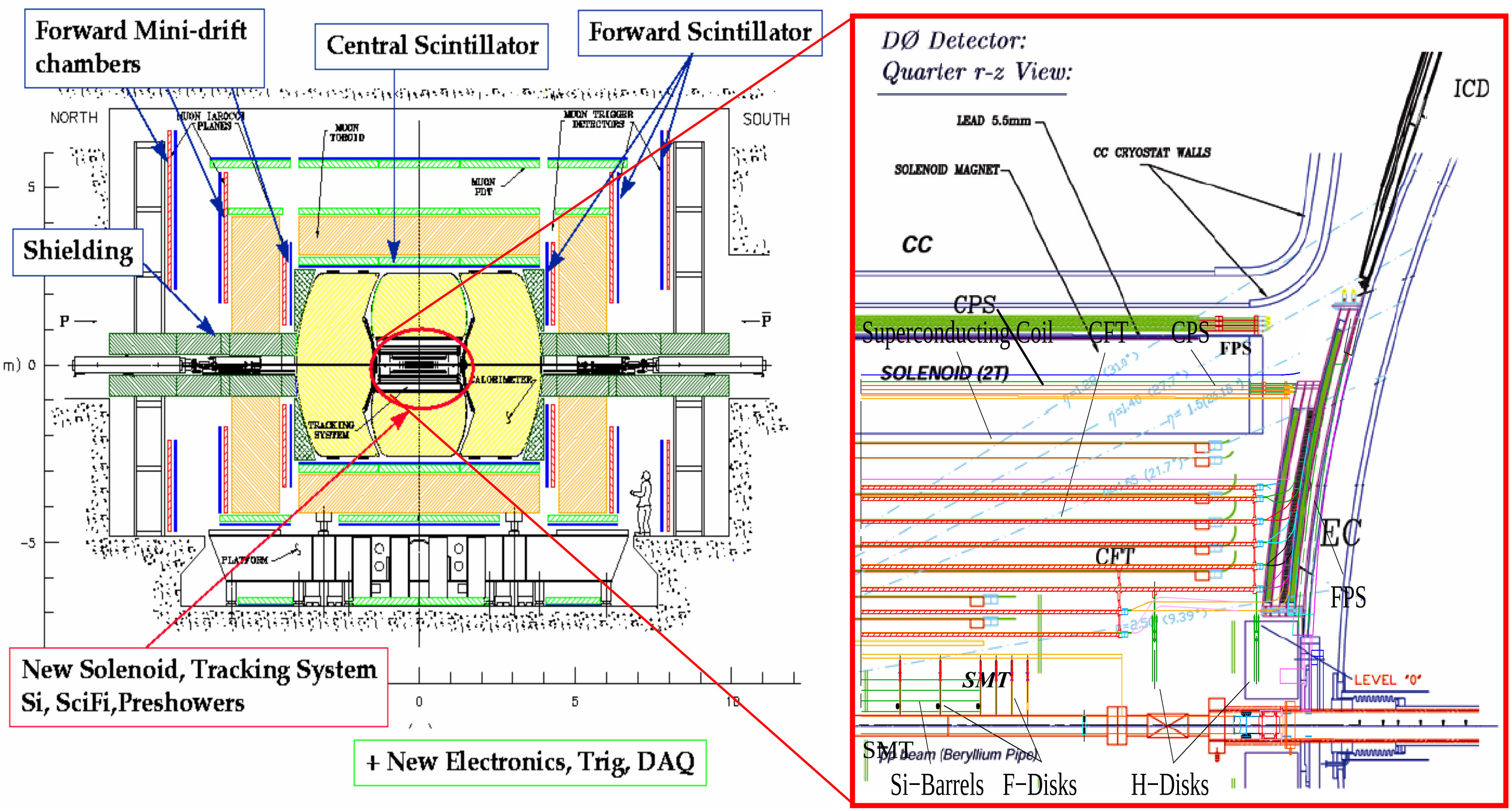
$\sqrt{s}$ =1.8 TeV

Run II (2001 - ?) :

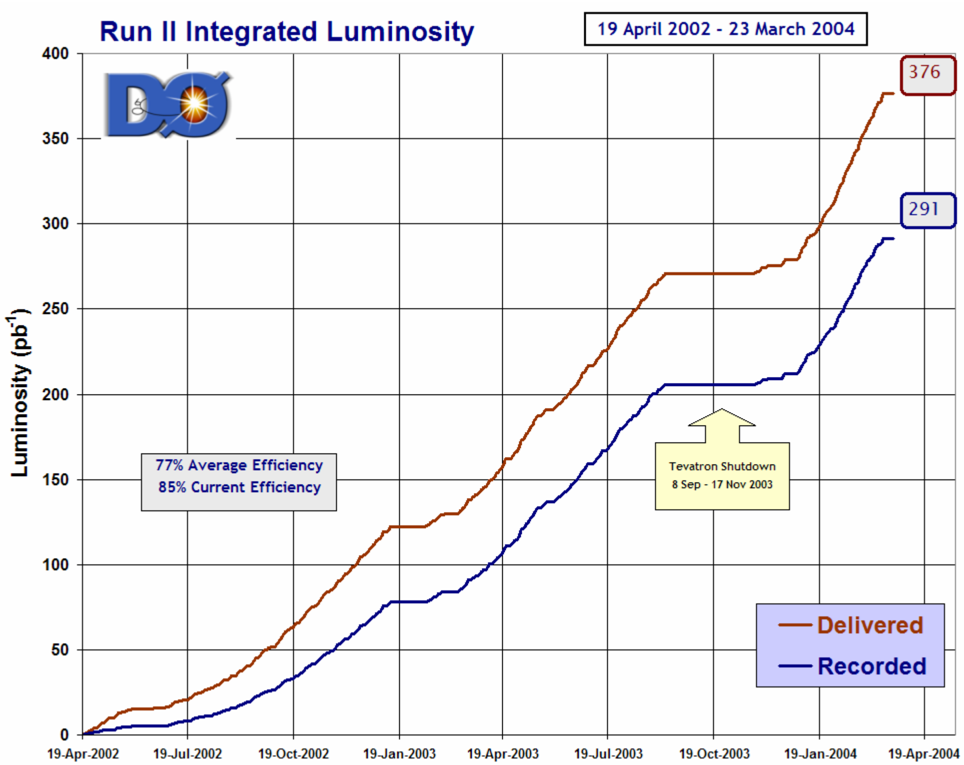
$\sqrt{s}$ =1.96 TeV

Upgraded Run II DØ Detector

- New Silicon and Fiber Trackers in 2 T magnetic field
- New forward muon system with |η|<2 and good shielding
- New trigger electronics to deal with 396 ns bunch spacing



DØ Status



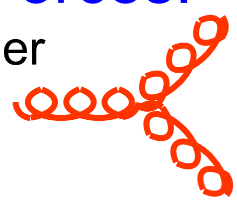
- Excellent performance of Accelerator Division in 2004
  - DØ recorded 70 pb^{-1} in 2004

- Important milestone : reprocessed full dataset in Fall 2003
  - Greatly improved tracking performance
  - Good fraction processed off-site
  - Current analyses use up to 250 pb^{-1}
  - Used primarily for Heavy flavor (t,b) physics, new particle searches (Higgs, SUSY, etc.), EW
  - But I'm not going to talk about that at all!

QCD

- Strong Nuclear Force:
  Quantum Chromodynamics
  Gluon Exchange, also holds the nucleus together.
  All quarks carry a color charge
  Gluons carry two color charges

- Different from other Forces:
  Gluons can interact with other gluons.



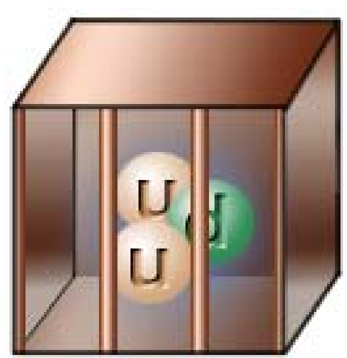
  Quarks and gluons are free at small distances (asymptotic freedom), but not at large distances (confinement) ⇒ cannot observe bare color

Always observe quarks in multiplets:
Baryons qqq (Proton neutron) and Mesons (quark antiquark pair)

Proton: uud
Also contains gluons and quark-antiquark pairs in a sea.

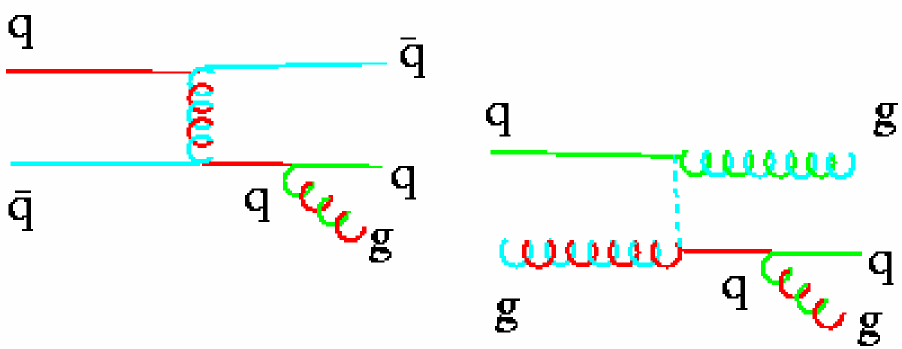
Neutron: udd

Pion: $u\bar{d}$

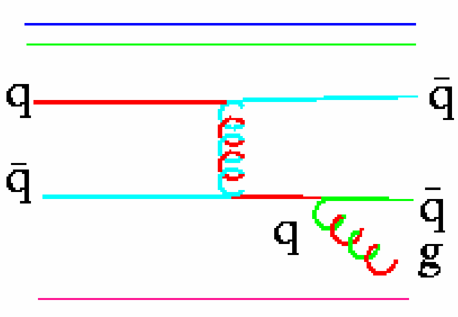


Typical QCD Event

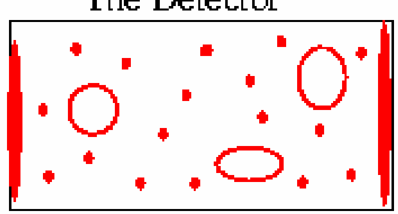
In a $p\bar{p}$ collision, a gluon or quark may be exchanged:



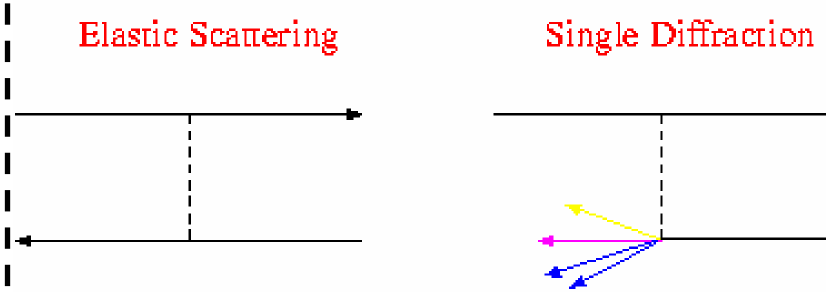
Due to the color flow in the event, particles are produced throughout phase space, and concentrated in regions around the struck partons (jets).



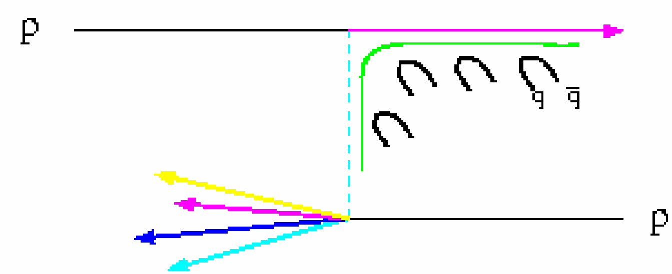
The Detector



Diffraction



If exchanged particle had color:



The event is no longer diffractive!

The exchanged particle must be colorless for diffractive event!

Lots of Run I QCD

1. "Rapidity Gaps between Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," S. Abachi *et al.* (DØ Collaboration), Phys. Rev. Lett. **72**, 2332 (1994).
2. "A Study of the Strong Coupling Constant using W+Jets processes" S. Abachi *et al.* (DØ Collaboration), Phys. Rev. Lett. **75**, 3226 (1995).
3. "Transverse Energy Distributions within Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," S. Abachi *et al.* (DØ Collaboration), Phys. Lett. B **357**, 500 (1995).
4. "Jet Production via Strongly-Interacting Color-Singlet Exchange in $p\bar{p}$ Collisions," S. Abachi *et al.* (DØ Collaboration), Phys. Rev. Lett. **76**, 734 (1996).
5. "The Azimuthal Decorrelation of Jets Widely Separated in Rapidity" S. Abachi *et al.* (DØ Collaboration), Phys. Rev. Lett. **77**, 595 (1996).
6. "Color Coherent Radiation in Multijet Events from $p\bar{p}$ Collisions at $\sqrt{s}$= 1.8 TeV," B. Abbott *et al.* (DØ Collaboration), Phys. Lett. B **414**, 419 (1997), Fermilab-Pub-97/201-E, hep-ex/9706012.
7. "Measurement of Dijet Angular Distributions and Search for Quark Compositeness," B. Abbott *et al.* (DØ Collaboration), Phys. Rev. Lett. **80**, 666 (1998), Fermilab-Pub-97/237-E, hep-ex/9707016.
8. "Probing Hard Color-Singlet Exchange in $p\bar{p}$ Collisions at $\sqrt{s} = 630$ GeV and 1800 GeV," B. Abbott *et al.* (DØ Collaboration), hep-ex/9809016, Phys. Lett. B **440**, 189 (1998).
9. "Determination of the Absolute Jet Energy Scale in the DØ Calorimeters.," B. Abbott *et al.*, Nucl. Instr. and Meth. A **424**, 352 (1999), Fermilab-Pub-97/330-E, hep-ex/9805009.
10. "The Inclusive Jet Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV.," B. Abbott *et al.*, Phys. Rev. Lett. **82**, 2451 (1999), Fermilab-Pub-98/207-E, hep-ex/9807018.
11. "The Dijet Mass Spectrum and a Search for Quark Compositeness in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV.," B. Abbott *et al.*, Phys. Rev. Lett. **82**, 2457 (1999), Fermilab-Pub-98/220-E, hep-ex/9807014.
12. "Evidence of color coherence effects in W+jets events from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV," B. Abbott *et al.*, Phys. Lett. B **464**, 145 (1999); Fermilab-Pub-99/224-E; hep-ex/9908017.
13. "The isolated photon cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV," B. Abbott *et al.*, Phys. Rev. Lett. **84**, 2786 (2000); Fermilab-Pub-99/354-E; hep-ex/9912017.
14. "Probing BFKL Dynamics in Dijet Cross Section at Large Rapidity Intervals in $p\bar{p}$ Collisions at $\sqrt{s} = 1800$ and 630 GeV," Phys. Rev. Lett. **84**, 5722 (2000); Fermilab-Pub-99/363-E; hep-ex/9912032.
15. "Hard Single Diffraction in $p\bar{p}$ Collisions at $\sqrt{s} = 630$ and 1800 GeV," B. Abbott *et al.*, Phys. Lett. B **531**, 52 (2002); FERMILAB-Pub-99/373-E; hep-ex/9912061.
16. "Limits on Quark Compositeness from High Energy Jets in $p\bar{p}$ Collisions at 630 and 1800 GeV," Phys. Rev. D Rapid Communication **62**, 031101 (2000); Fermilab-Pub-99/357-E; hep-ex/9912023.
17. "The ratio of jet cross sections at $\sqrt{s}$=630 and 1800 GeV," B. Abbott *et al.*, Phys. Rev. Lett. **86**, 2523 (2001); FERMILAB-Pub-00/213-E, hep-ex/0008072.
18. "Ratios of Multijet Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s}$=1800 GeV," B. Abbott *et al.*, Phys. Rev. Lett. **86**, 1955 (2001); FERMILAB-Pub-00/218-E, hep-ex/0009012.
19. "Inclusive jet production in $p\bar{p}$ collisions," B. Abbott *et al.*, Phys. Rev. Lett. **86**, 1707 (2001); FERMILAB-Pub-00/271-E, hep-ex/0011036.
20. "High-p_T Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 630$ and 1800 GeV," B. Abbott *et al.*, Phys. Rev. D **64**, 032003 (2001); FERMILAB-Pub-00/216-E, hep-ex/0012046.
21. "The ratio of isolated photon cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 630$ and 1800 GeV," V. M. Abazov *et al.*, Phys. Rev. Lett. **87**, 251805 (2001); FERMILAB-Pub-01/239-E, hep-ex/0106026.
22. "Subjet multiplicity of gluon and quark jets reconstructed using the k_T algorithm in $p\bar{p}$ collisions," V. M. Abazov *et al.*, Phys. Rev. D **65**, 052008 (2002); FERMILAB-Pub-01/248-E; hep-ex/010854.
23. "The inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the k_T algorithm," V. M. Abazov *et al.*, Phys. Lett. B **525**, 211 (2002); FERMILAB-Pub-01/290; hep-ex/019041.
24. "Multiple jet production at low transverse energies in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV", V. M. Abazov *et al.*, Phys. Rev. D **67**, 052001 (2003); FERMILAB-Pub-02/153-E, hep-ex/0207046.
25. "Observation of Diffractively Produced W and Z Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1800$ GeV," V. M. Abazov *et al.*, Phys. Lett. B **574**, 169 (2003); FERMILAB-Pub-03/233-E, hep-ex/0308032.

Jets+Subjets

Hard Diffraction

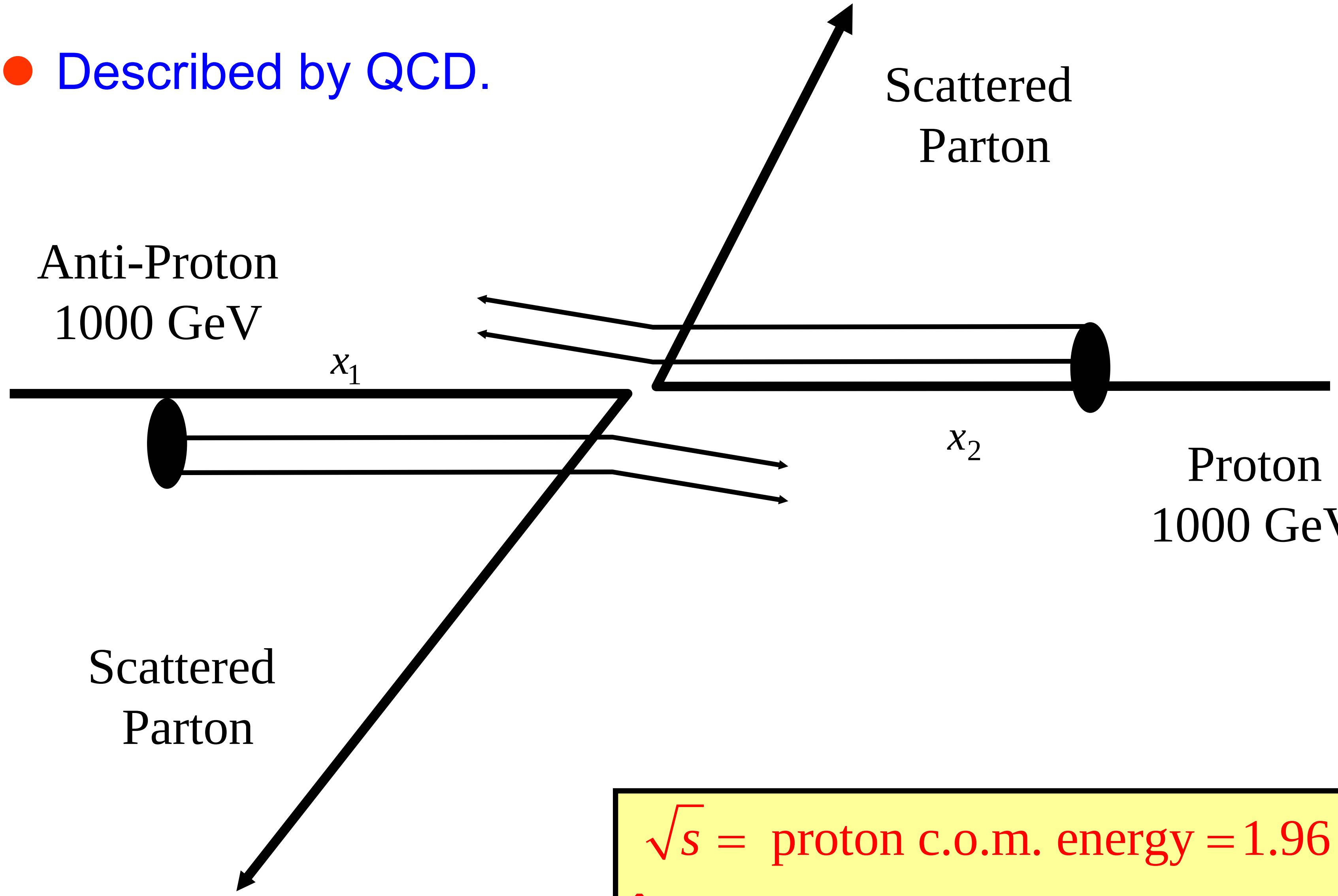
Color Coherence and Energy Flow

Photons

etc.

Parton-Parton Scattering

- Described by QCD.

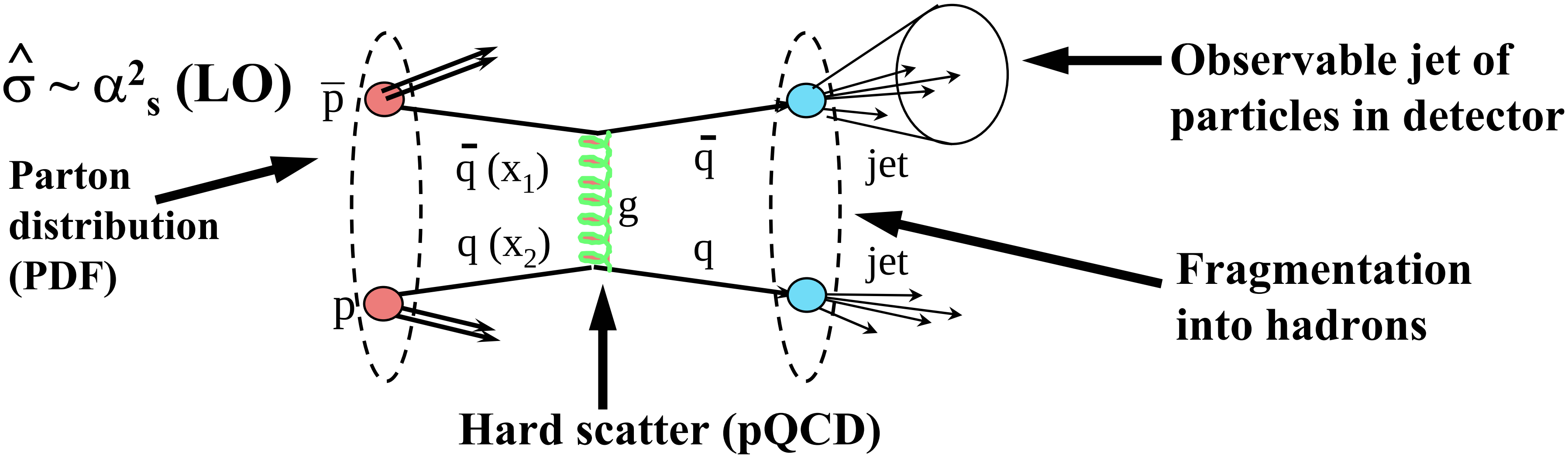


$\sqrt{s}$ = proton c.o.m. energy = 1.96 TeV

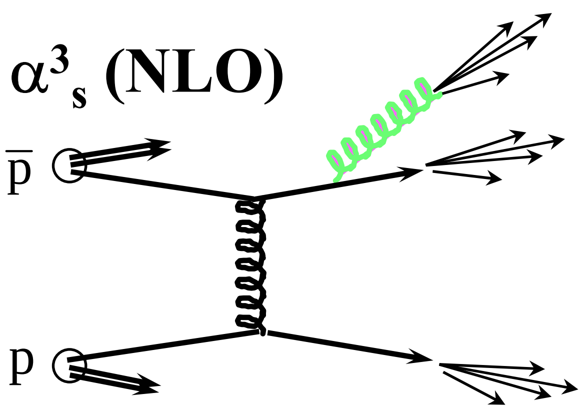
$\hat{s}$ = parton c.o.m. energy squared = $x_1 x_2 s$

Perturbative QCD and Jet Production

$\hat{\sigma} \sim \alpha_s^2$ (LO)



$\hat{\sigma} \sim \alpha_s^3$ (NLO)



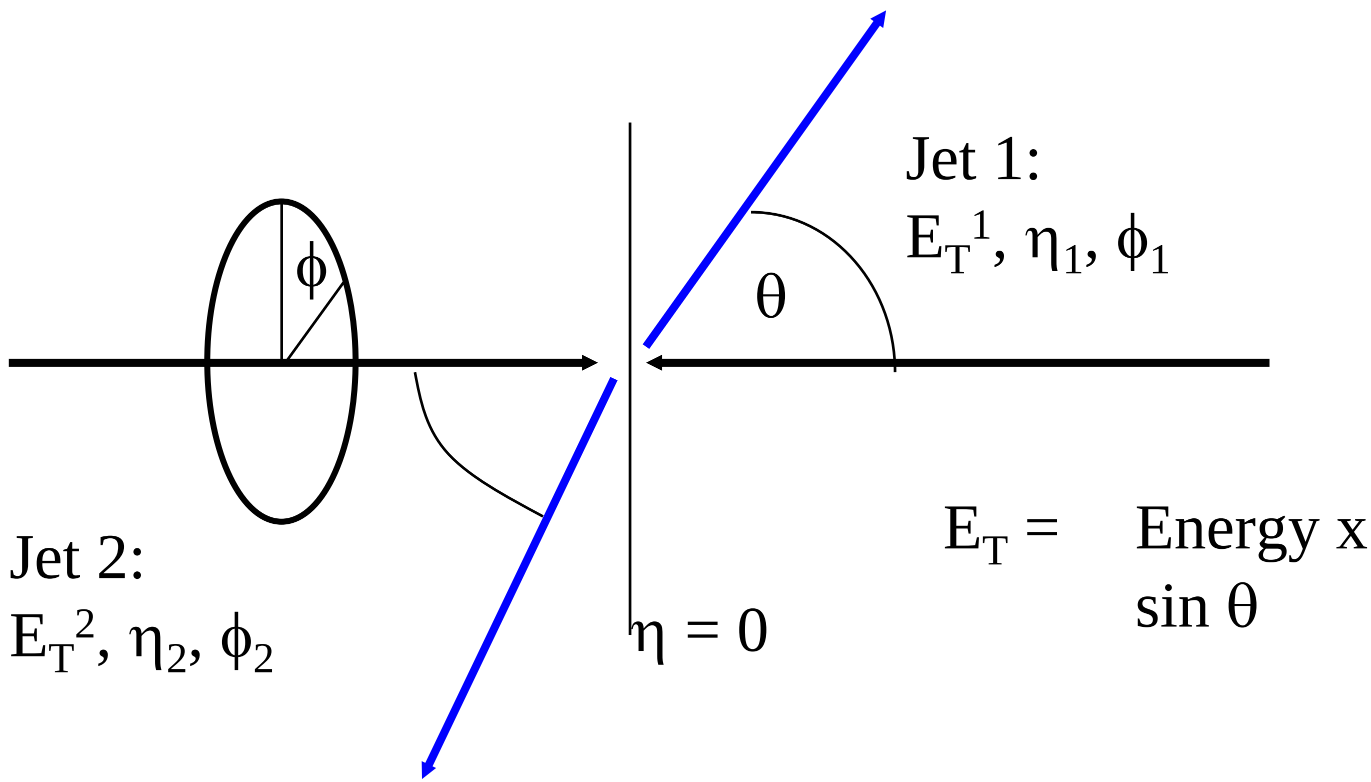
Includes radiative corrections and gluon emission - much of current QCD is a study of this additional radiation

Measured Event Variables

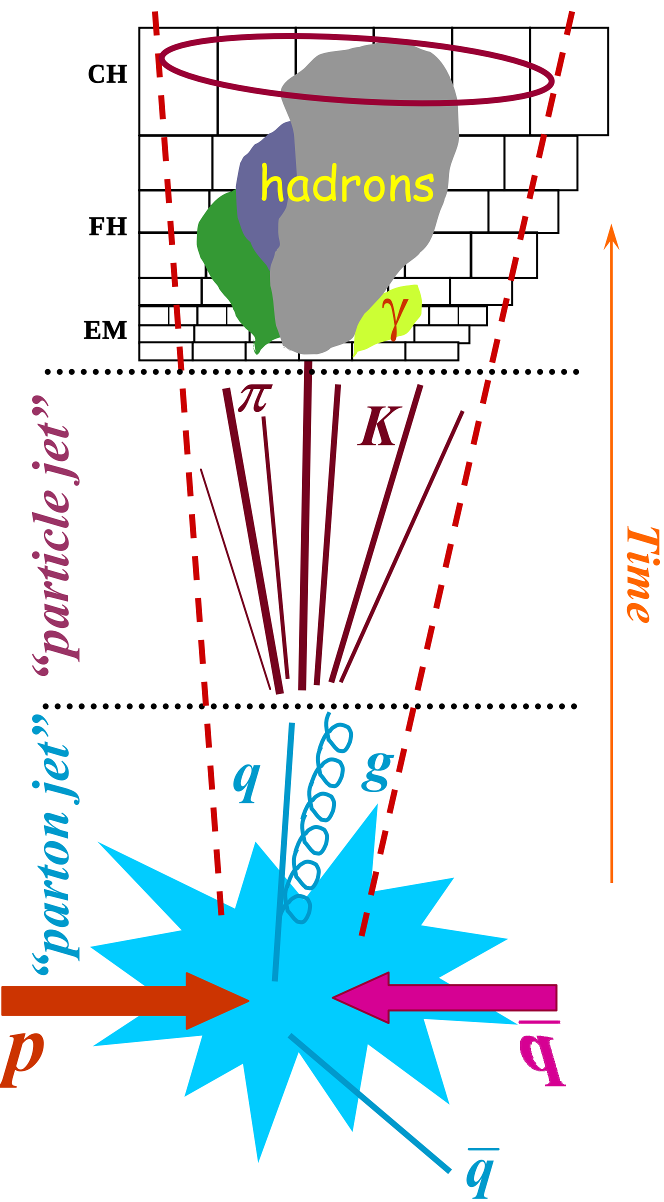
- In a Two Jet event the following is measured:

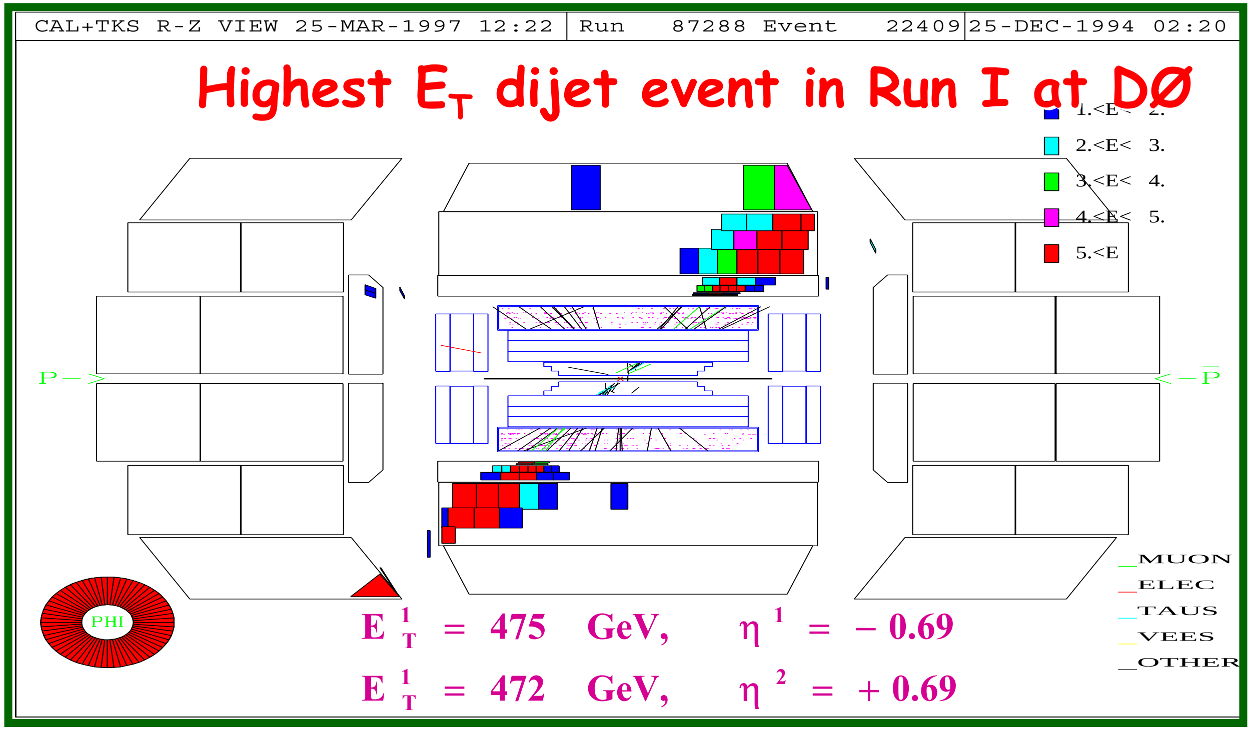
$$\text{Jet}: E_T, \eta, \phi \quad \left(\text{pseudorapidity } \eta = -\ln\left[\tan\theta/2\right]\right)$$

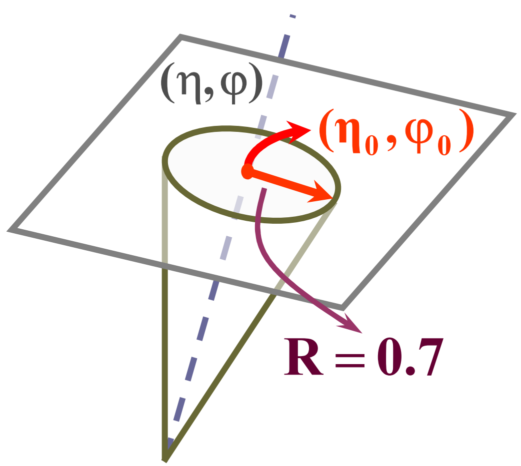
$$M^2 = 2E_{T,1}E_{T,2}\left[\cosh\left(\left|\eta_1 - \eta_2\right|\right) - \cos\left(\left|\phi_1 - \phi_2\right|\right)\right] (\text{massless})$$



Jet Production and Reconstruction







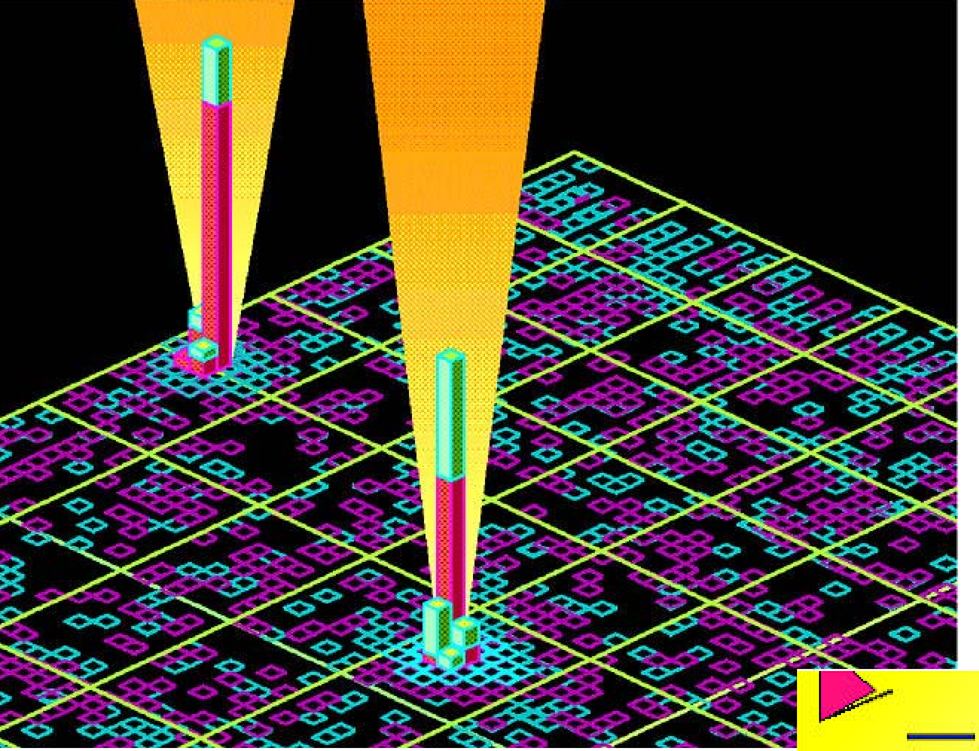
- Fixed cone-size jets
- Add up towers

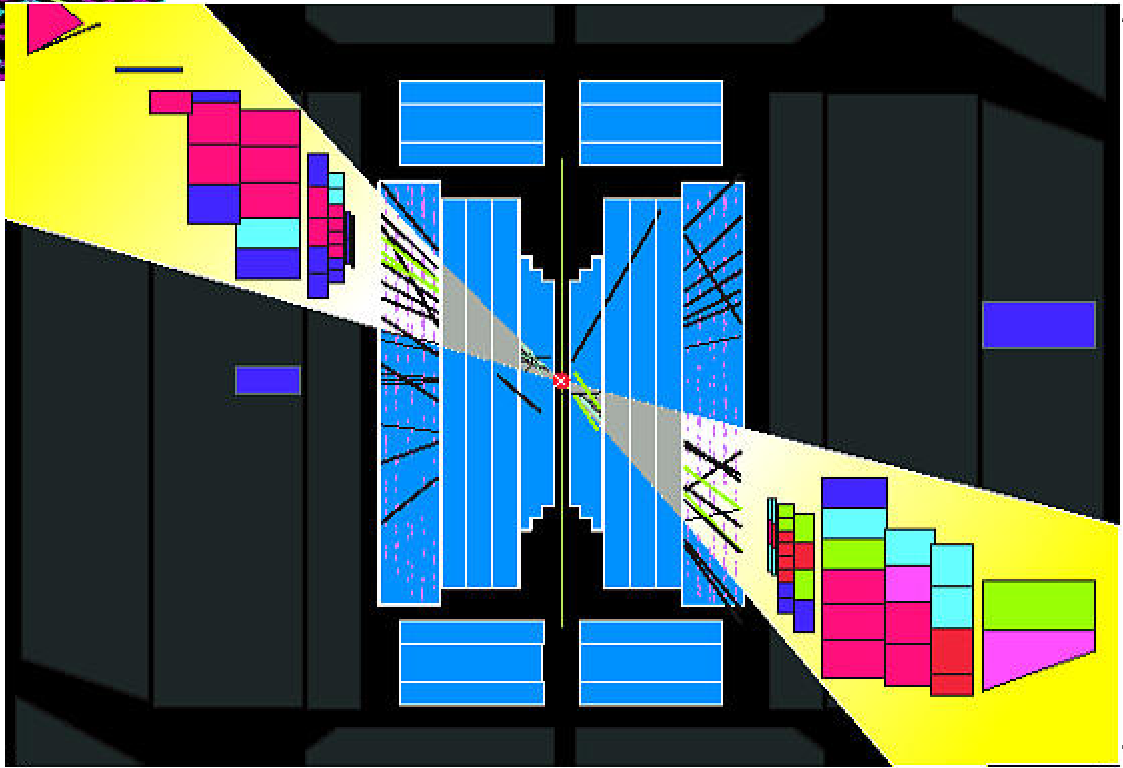
$$E_T^{jet} = \sum_{R_i \le 0.7} E_T^{tower}$$

- Iterative algorithm
- Jet quantities:

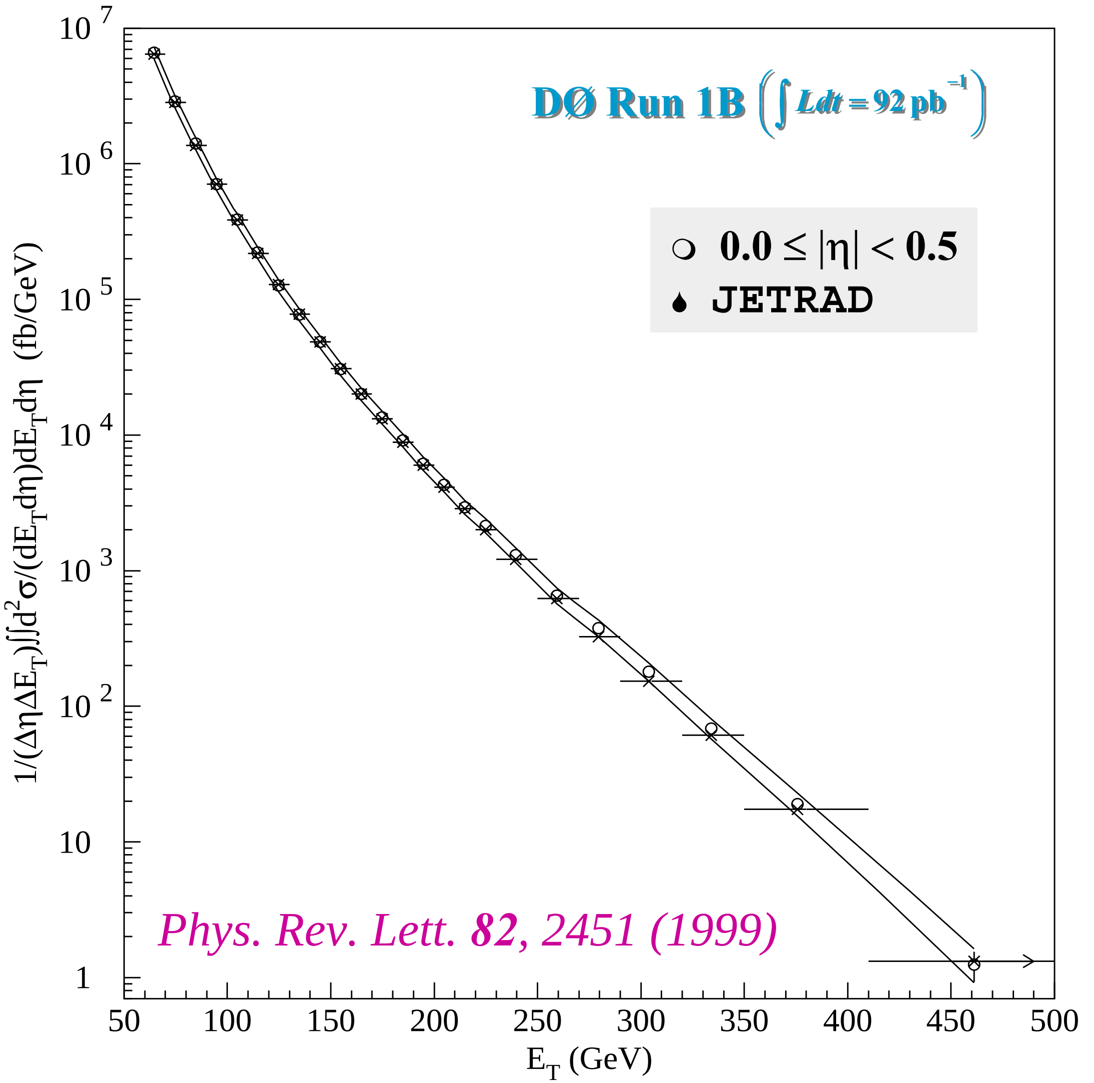
$$E_T, \eta, \varphi$$

High Energy Art

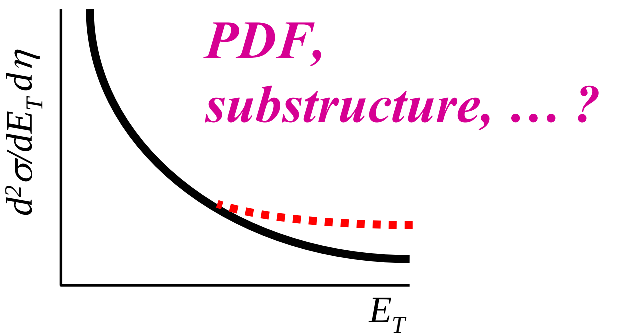




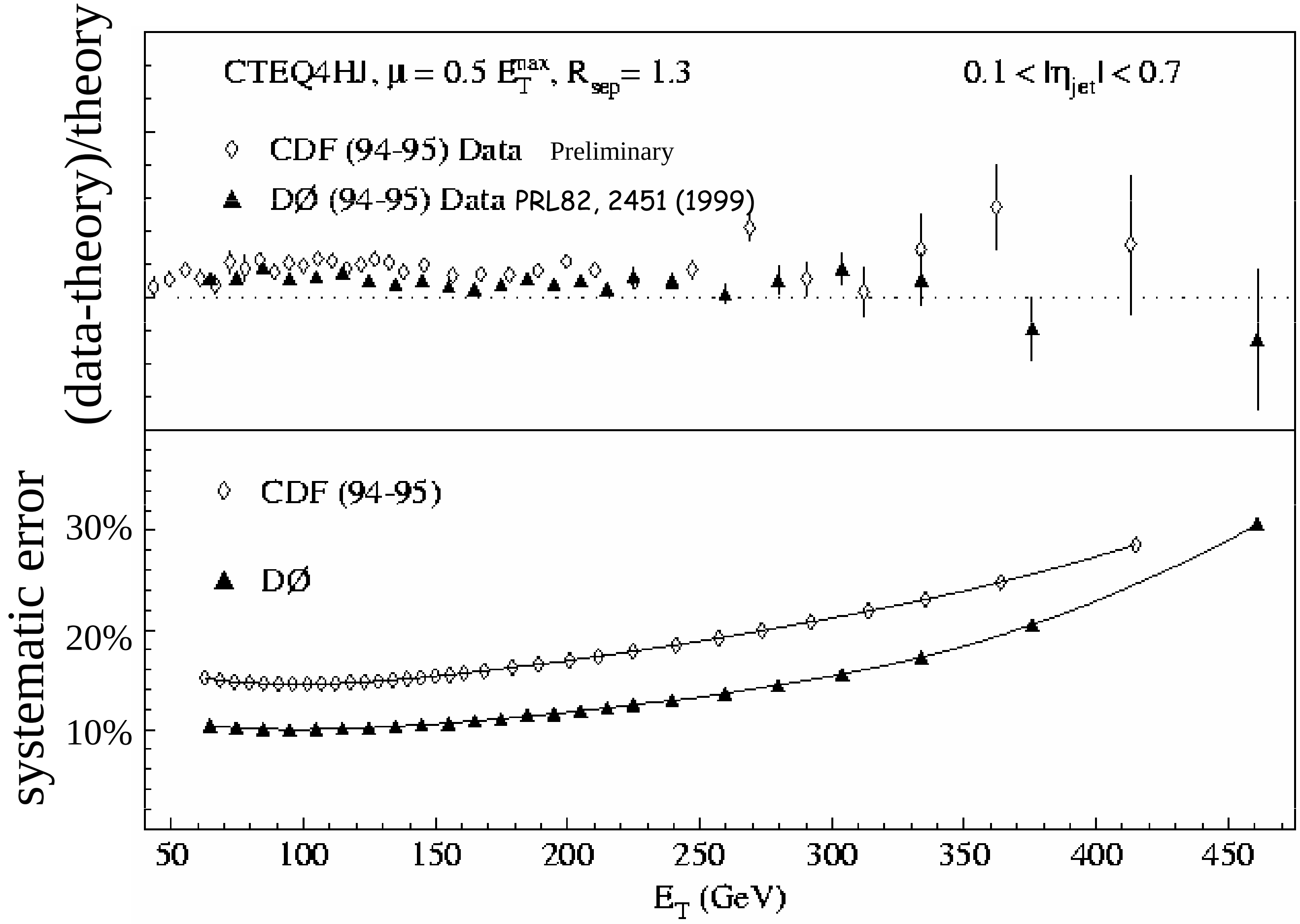
The Run I DØ Central Inclusive Jet Cross Section



- *How well do we know proton structure (PDF)?*
- *Is NLO (α_s^3) QCD "sufficient"?*
- *Are quarks composite (preons)?*



Inclusive Jet Cross Section at 1.8TeV

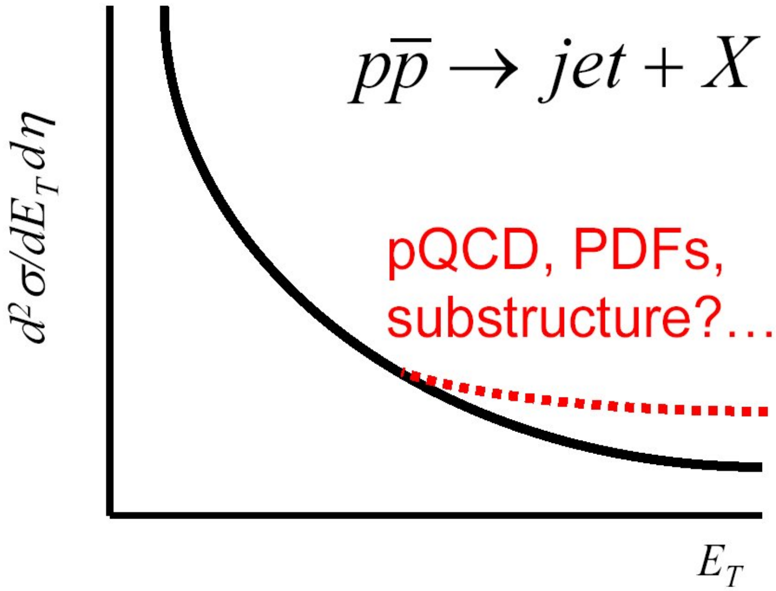


D0 and CDF data in good agreement.   NLO QCD describes the data well.

No evidence for compositeness (yet).

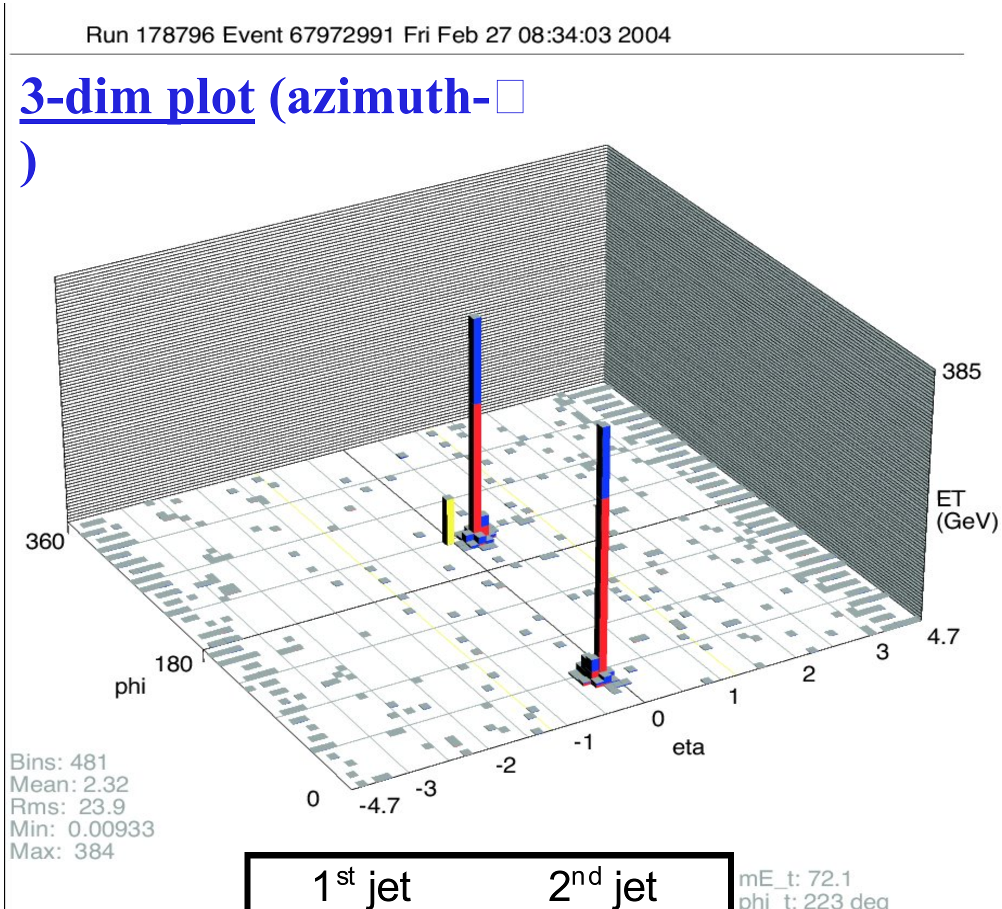
Run II Inclusive Jets

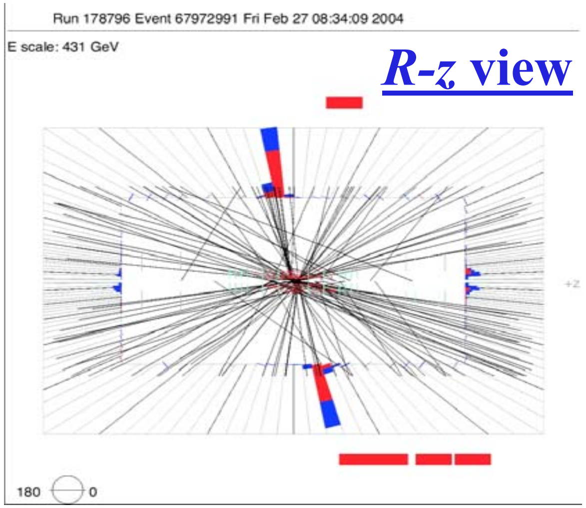
- Run II datasets have better discrimination of PDFs – for *gluons* at high x
- reliable test of accuracy of parton-level NLO calculation and pQCD matrix elements

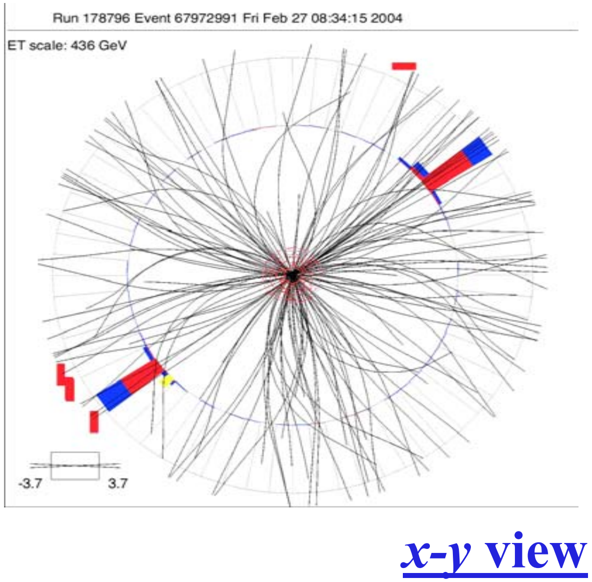


- place to search for new physics, traditionally
  - central region ⇨ the largest transverse energy ⇨ sensitive to PDFs and potential new physics
  - forward regions ⇨ still sensitive to PDFs but less "sensitive" to new physics

The highest p_T & di-jet mass



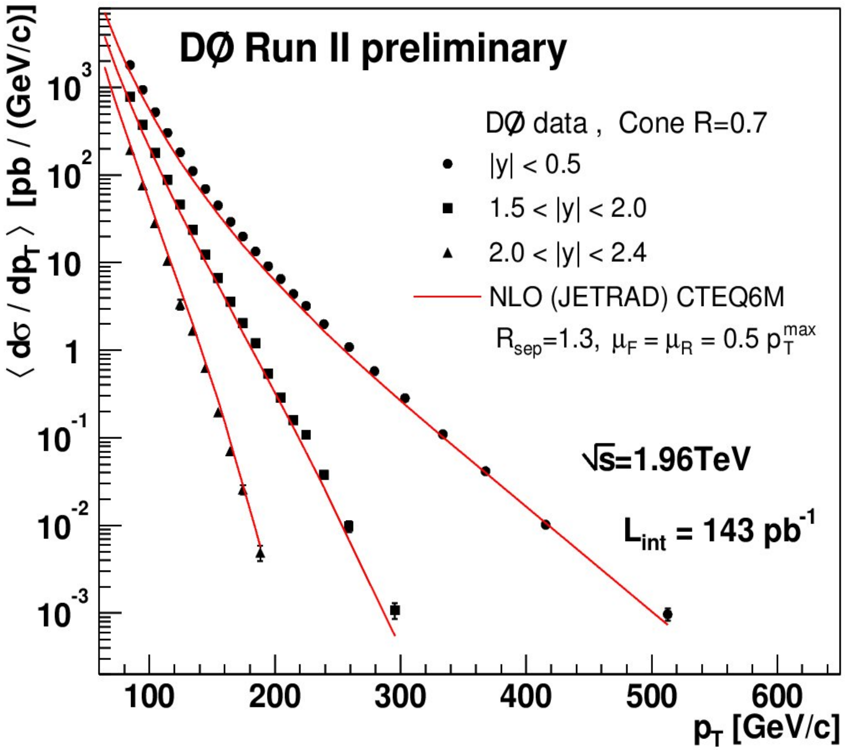




	1st jet	2nd jet
p_T [GeV/c]	616	557
η	-0.19	0.25
φ [rad]	0.65	3.78

Conclusions

- We measured inclusive cross section in the central and forward calorimeter regions.
- Run II – higher p_T than Run I (p_T~350 GeV)
- All presented results are preliminary – more luminosity is being collected.

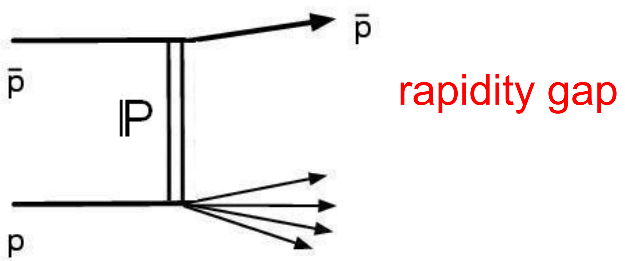


- Our measurement is well described by the next-to-leading order perturbative QCD throughout the whole kinematic region – theory is in good agreement with measured data, given the uncertainties.

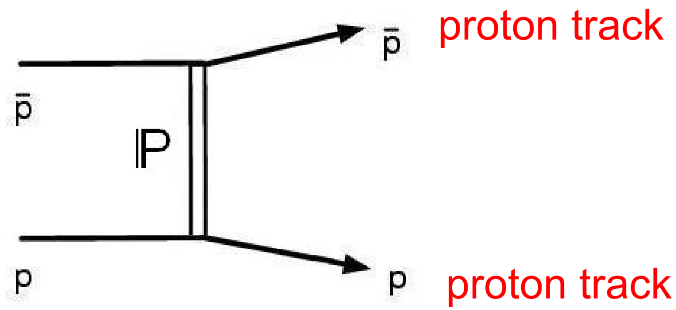
Diffraction/Color singlet exchange

- Exchange of quantum numbers of the vacuum (no charge or color), often referred to as **Pomeron** exchange
- Experimental signatures:
  - rapidity gap - absence of particles or energy above threshold in some region of rapidity in the detector
  - intact proton - p or $\bar{p}$ scattered at small angle from the beam

- Single Diffraction
  - either p or $\bar{p}$ intact
  - search for rapidity gap in forward regions of DØ
    - Luminosity Monitor
    - Calorimeter
  - Hard Diffraction (UA8), SD+high P_T



- Elastic Scattering
  - p and $\bar{p}$ intact, with no momentum loss
  - no other particles produced
  - search for intact protons in beam pipe
    - Forward Proton Detector



Learning about the Pomeron

- **QCD** is theory of strong interactions, but **40%** of total cross section is attributable to **Pomeron** exchange -- not calculable and poorly understood

- Does it have partonic structure? **Soft? Hard? Super-hard? Quark? Gluon?** Is it universal -- same in ***ep*** and $p\,\overline{p}$? Is it the same with and without **jet** production?

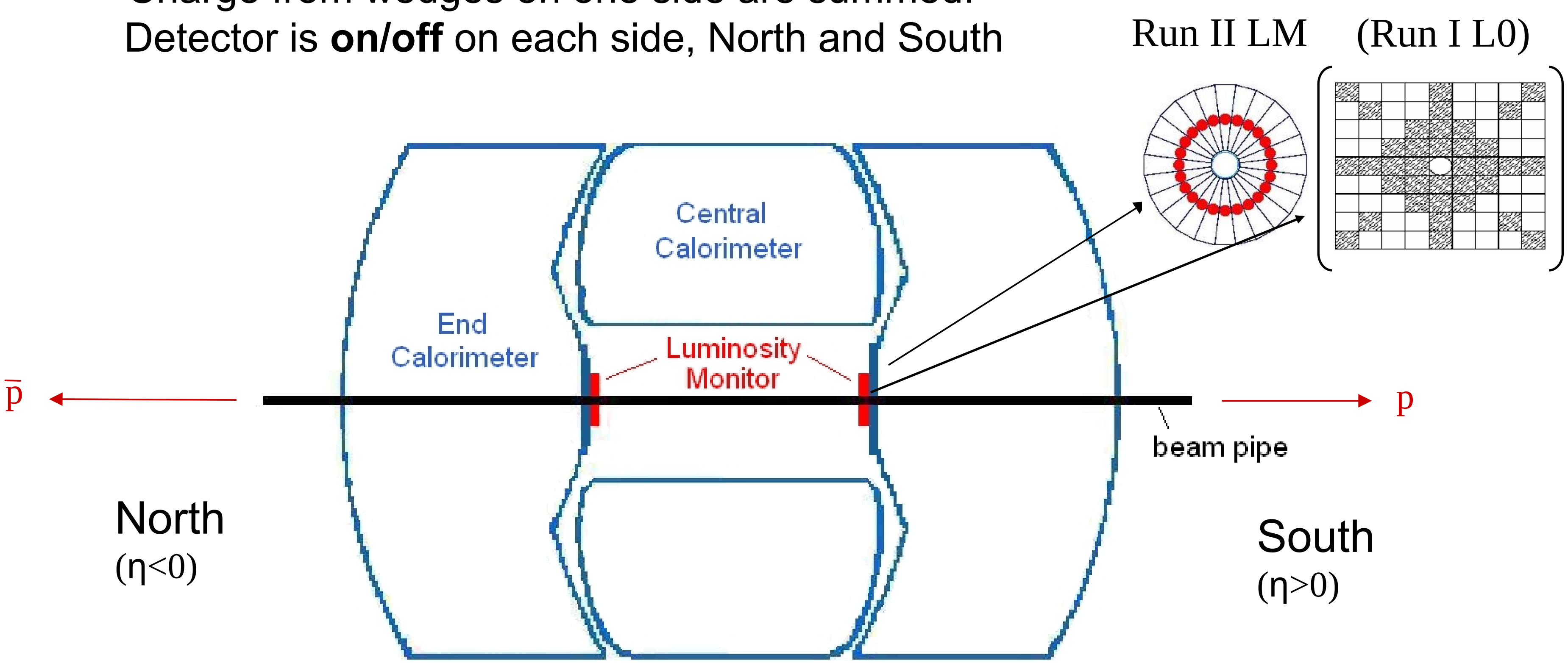
- Answer questions in HEP tradition -- collide it with something that you understand to learn its structure

- Note: variables of diffraction are ***t*** (momentum transfer) and $\xi \sim M^2$ (fractional momentum loss) with FPD measure $\frac{d^2\sigma}{dt\,d\xi}$ without FPD just measure σ

Luminosity Monitor

Luminosity Monitor (LM)

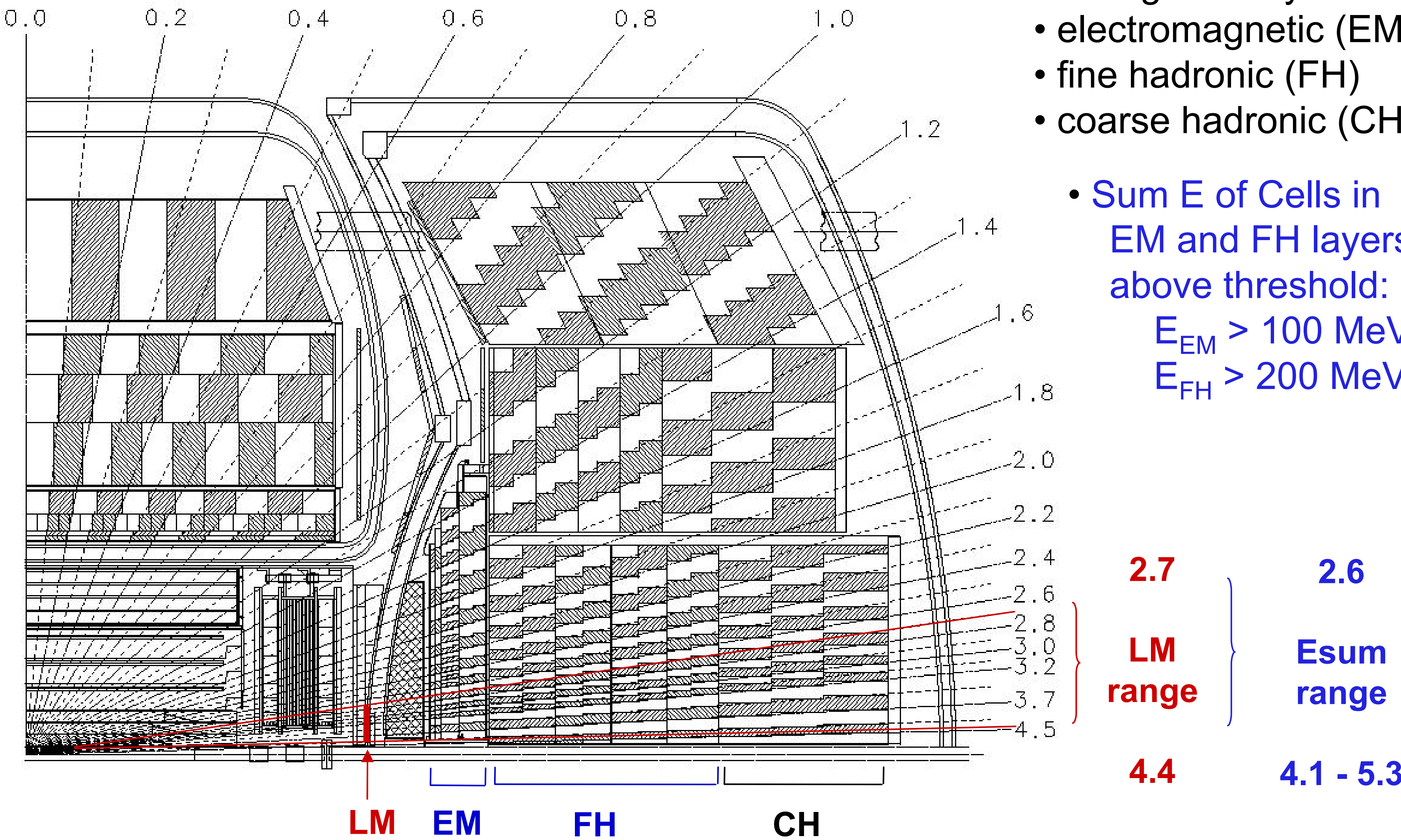
- Scintillating detector
- $2.7 < |\eta| < 4.4$
- Charge from wedges on one side are summed:
  Detector is **on/off** on each side, North and South



(*Run I:* n_{l0} = # tiles in L0 detector with signal $2.3 < |\eta| < 4.3$)

Calorimeter

Liquid argon/uranium calorimeter



Cells arranged in layers:

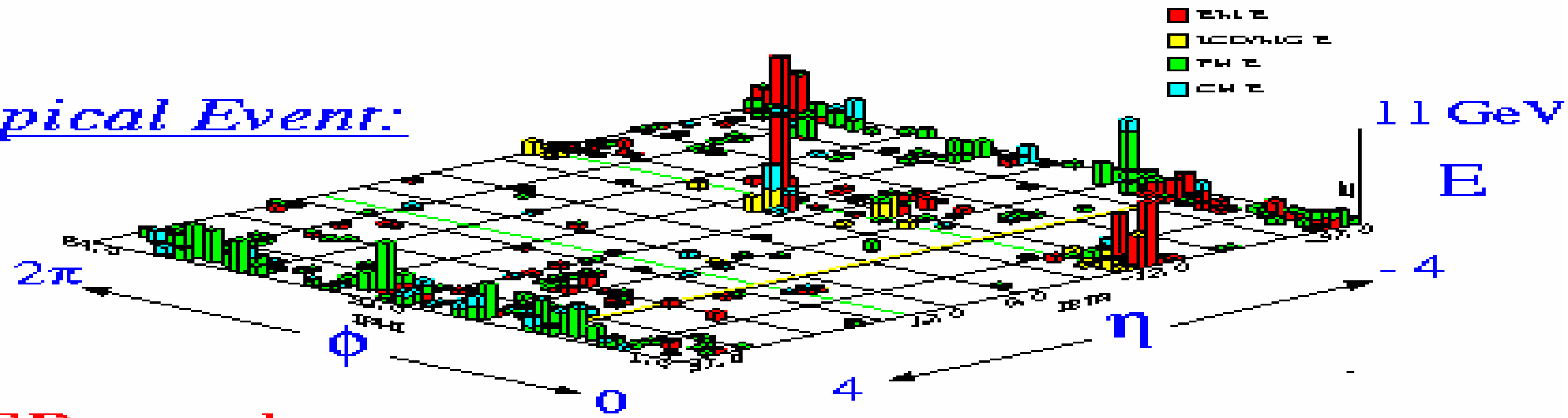
- electromagnetic (EM)
- fine hadronic (FH)
- coarse hadronic (CH)

- Sum E of Cells in EM and FH layers above threshold:
  E_{EM} > 100 MeV
  E_{FH} > 200 MeV

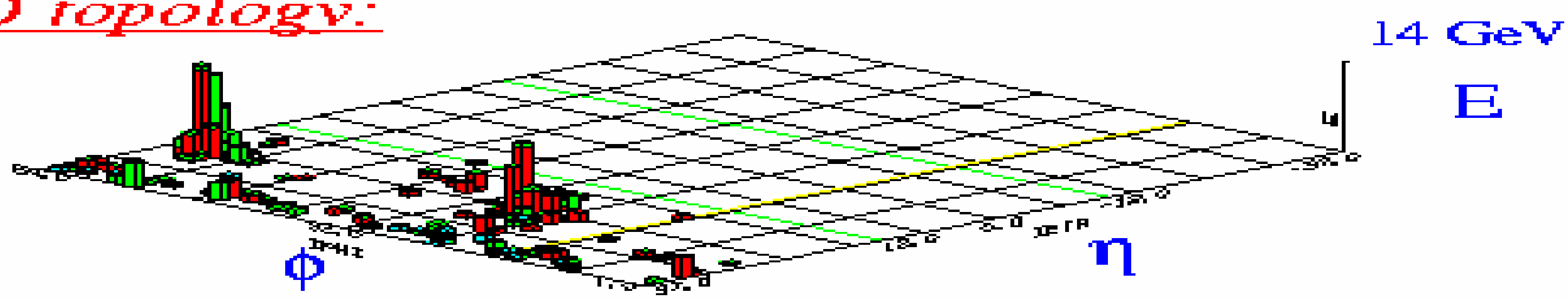
(*Run I:* n_{cal} = # cal towers with energy above threshold)

DØ Dijet Events: η–φ Legos

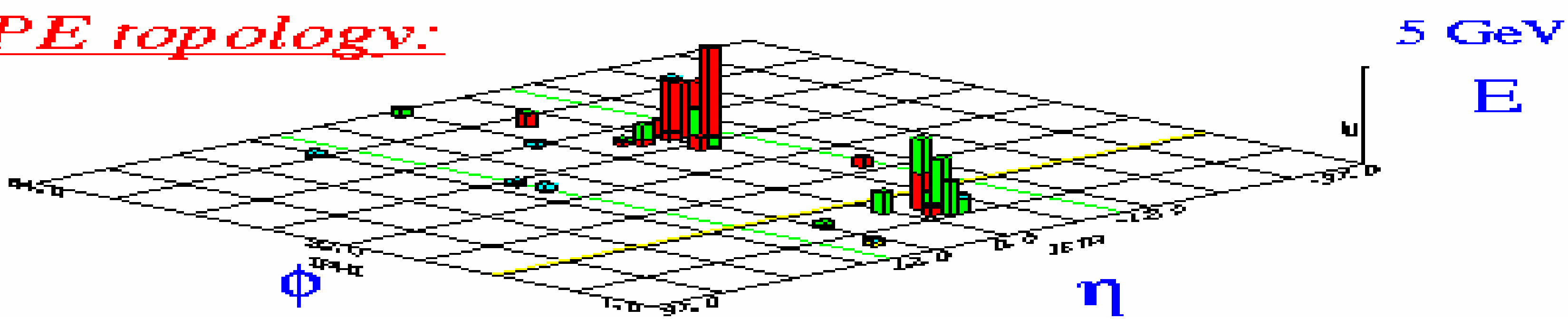
Typical Event:



HSD topology:

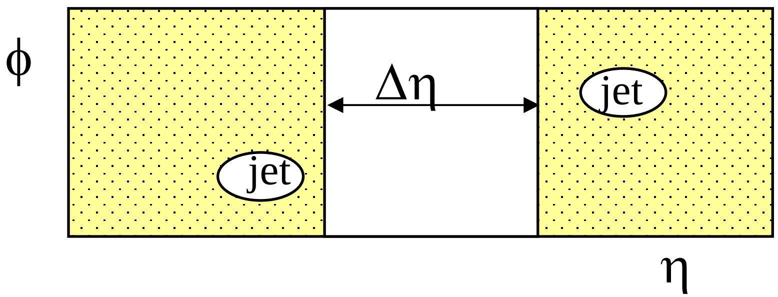


HDPE topology:

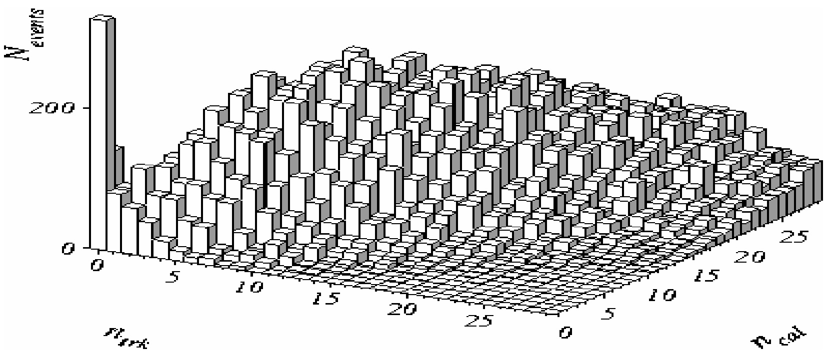


Hard Color-Singlet Exchange (central gap)

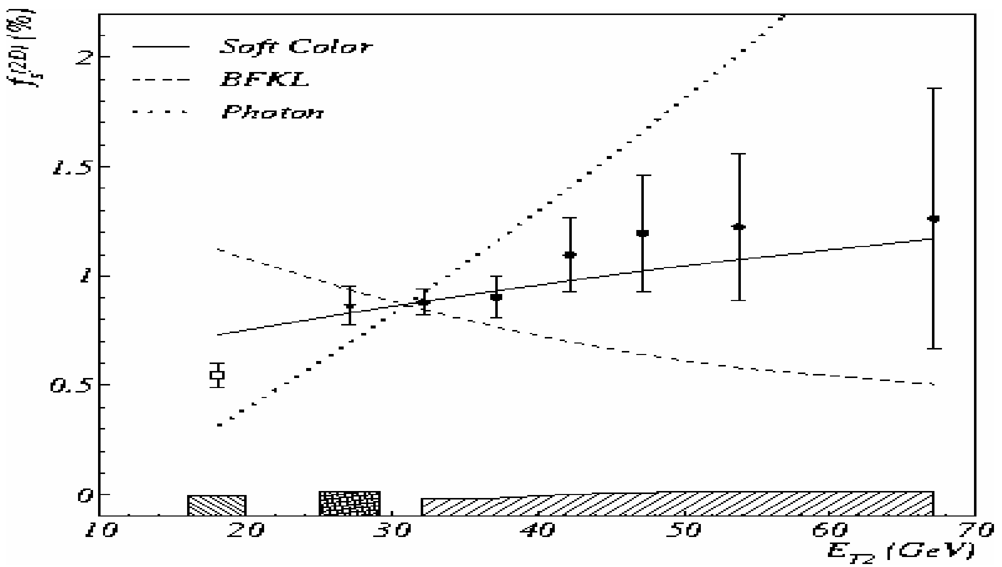
Count tracks and EM Calorimeter Towers in $|\eta| < 1.0$



(E_T > 30 GeV, $\sqrt{s}$ = 1800 GeV)



Measure fraction of events due to color-singlet exchange



Measured fraction (~1%) rises with initial quark content :

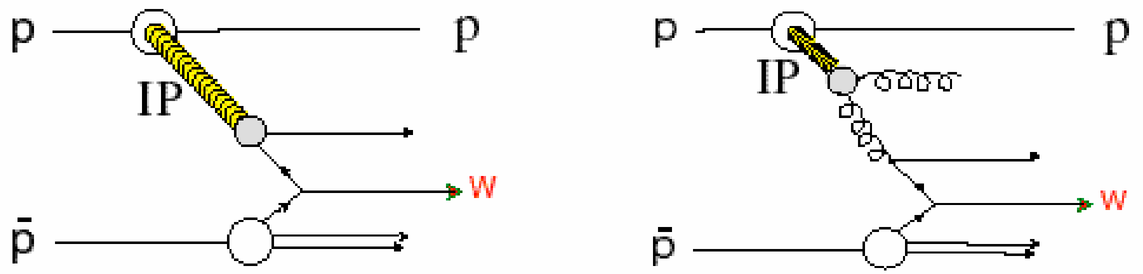
Consistent with a soft color rearrangement model preferring initial quark states

Inconsistent with two-gluon, photon, or U(1) models

Phys. Lett. B 440 189 (1998)

Why study Diffractive W Boson?

The pomeron ($I\!P$) structure is not yet understood which motivates a study that will better clarify the quark/gluon composition involved. This is found in the diffractive W, which to leading order can only happen based on a quark component in the pomeron.[1]



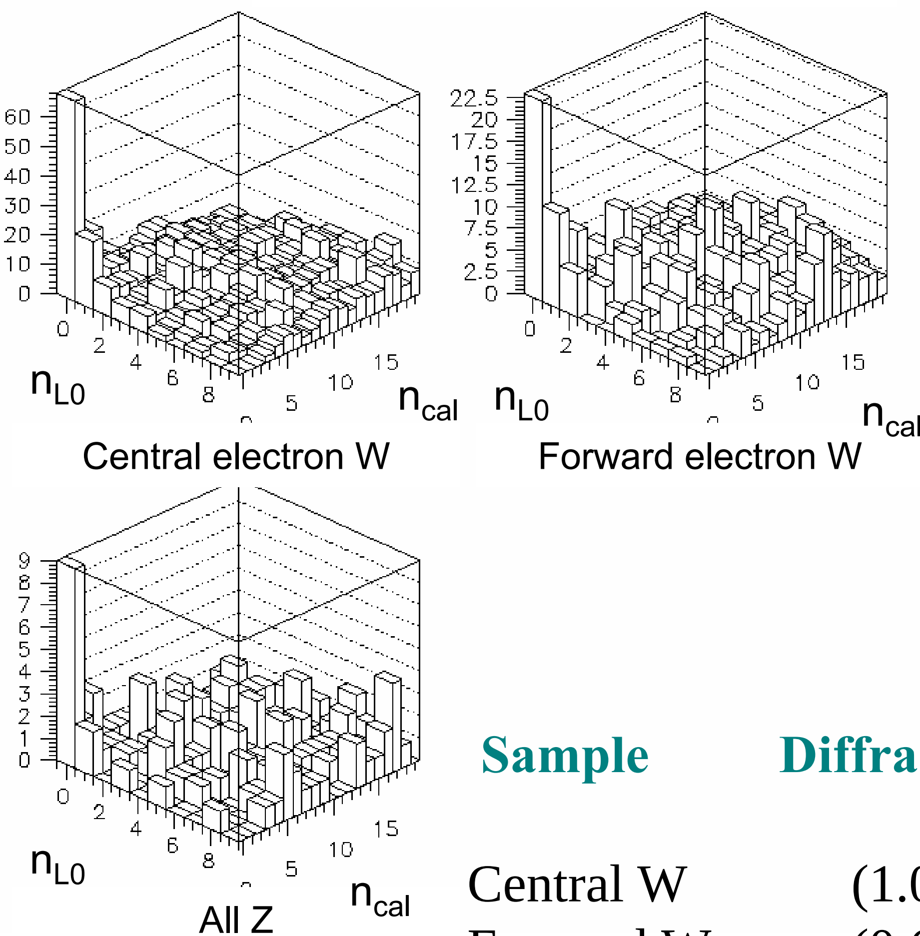
a) LO: $q\bar{q} \rightarrow W$ *b) NLO: $qg \rightarrow q + W$*

Diffractive process (a) probes the quark content of the pomeron.

[1] *(Bruni & Ingelman, Phys. Lett. B311(1993)318)*

Observation of Diffractive W/Z

Diffractive W and Z Boson Signals



•Phys. Lett. B 574, 169 (2003)

- Observed clear Diffractively produced W and Z boson signals
- Events have typical W/Z characteristics
- Background from fake W/Z gives negligible change in gap fractions

Sample	Diffractive / All	Probability Background Fluctuates to Data
Central W	(1.08 + 0.19 - 0.17)%	**7.7σ**
Forward W	(0.64 + 0.18 - 0.16)%	**5.3σ**
All W	**(0.89 + 0.19 – 0.17)%**	**7.5σ**
All Z	(1.44 + 0.61 - 0.52)%	**4.4σ**

Run II Improvements

- Larger luminosity allows search for rare processes
- Integrated FPD allows accumulation of large hard diffractive data samples
- Measure ξ, t over large kinematic range
- Higher E_T jets allow smaller systematic errors
- Comparing measurements of HSD with track tag vs. gap tag yields new insight into process

DØ Run II Diffractive Topics

Soft Diffraction and Elastic Scattering:

Inclusive Single Diffraction

Elastic scattering (t dependence)

Total Cross Section

Centauro Search

Inclusive double pomeron

Search for glueballs/exotics

Rapidity Gaps:

Central gaps+jets

Double pomeron with gaps

Gap tags vs. proton tags

Topics in **RED** were studied with gaps only in Run I

Hard Diffraction:

Diffractive jet

Diffractive b,c ,t , Higgs

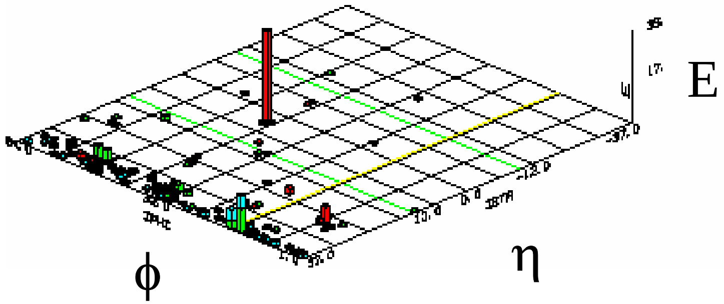
Diffractive W/Z →

Diffractive photon

Other hard diffractive topics

Double Pomeron + jets

Other Hard Double Pomeron topics

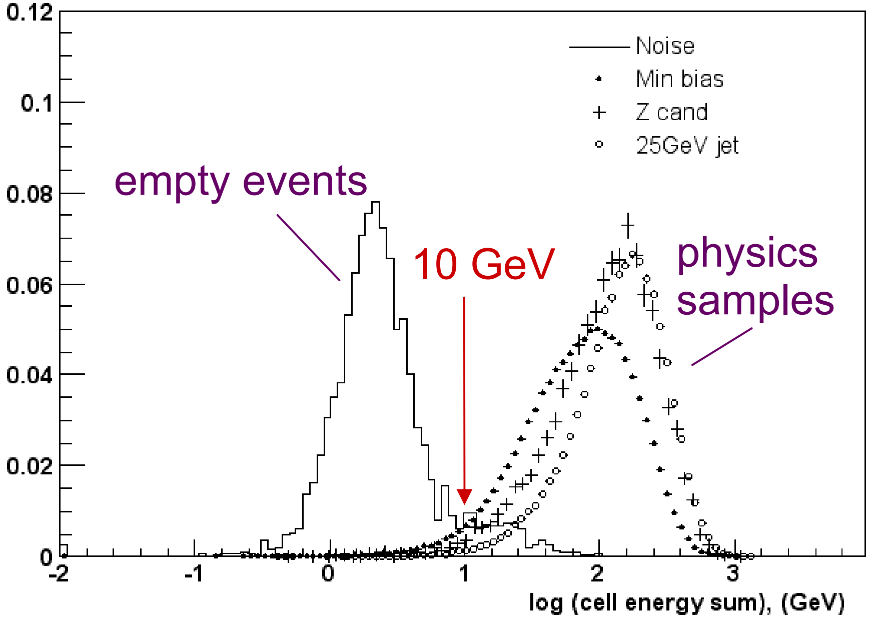


<100 W boson events in Run I, >1000 tagged events expected in Run II

Calorimeter Energy Sum

- Use energy sum to distinguish proton break-up from empty calorimeter:

Log(energy sum) on North side:



Areas are normalised to 1

- Esum cut of 10GeV was chosen for current study
- Final value will be optimised using full data sample

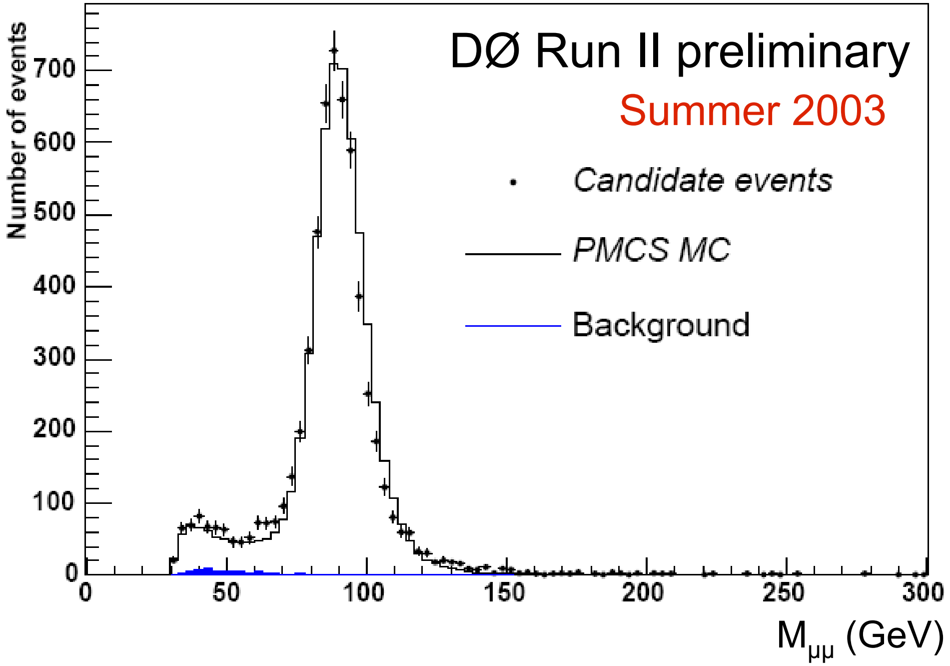
- Compare 'empty event' sample with physics samples:
  - Empty event sample: random trigger. Veto LM signals and primary vertex, i.e. mostly empty bunch crossings
  - Physics samples: minimum bias (coincidence in LM), jet and $Z \to \mu\mu$ events

Search for diffractive Z→μμ

- RunI publication "*Observation of diffractively produced W and Z bosons in $p\bar{p}$ Collisions at sqrt(s)=1.8 TeV*", Phys. Lett. B 574, 169 (2003)
  Nine single diffractive Z→e+e- events. No result in muon channel.

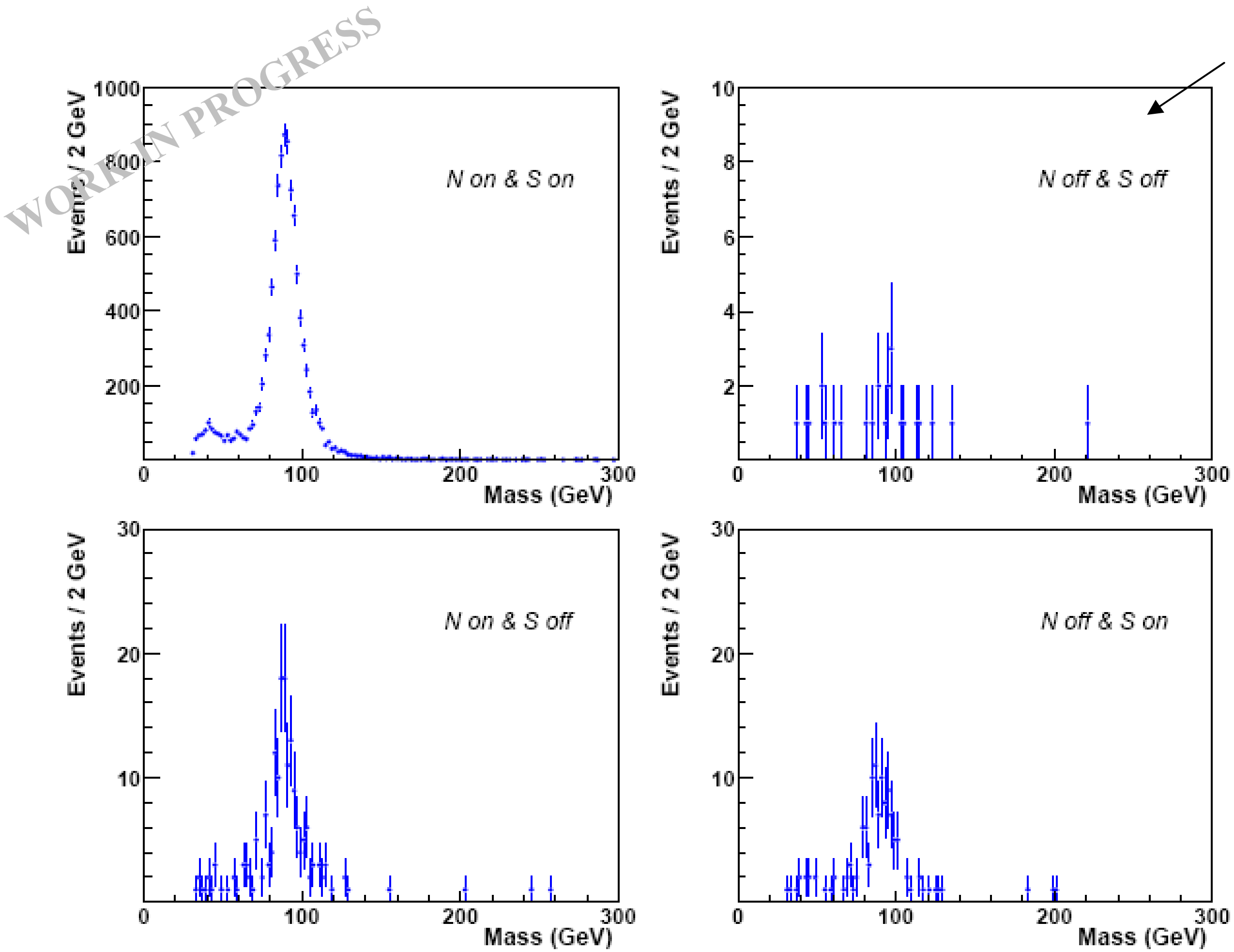
- RunII: first search for forward rapidity gaps in Z→μ+μ- events

- Inclusive Z→μμ sample well understood:
  - 2 muons, p_T > 15GeV, opposite charge
  - at least one muon isolated in tracker and calorimeter
  - anti-cosmics cuts based on tracks:
    - displacement wrt beam
    - acolinearity of two tracks

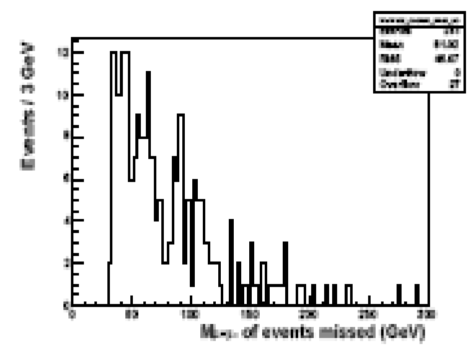


First step towards gap: LM only

- Separate the Z sample into four groups according to LM on/off:



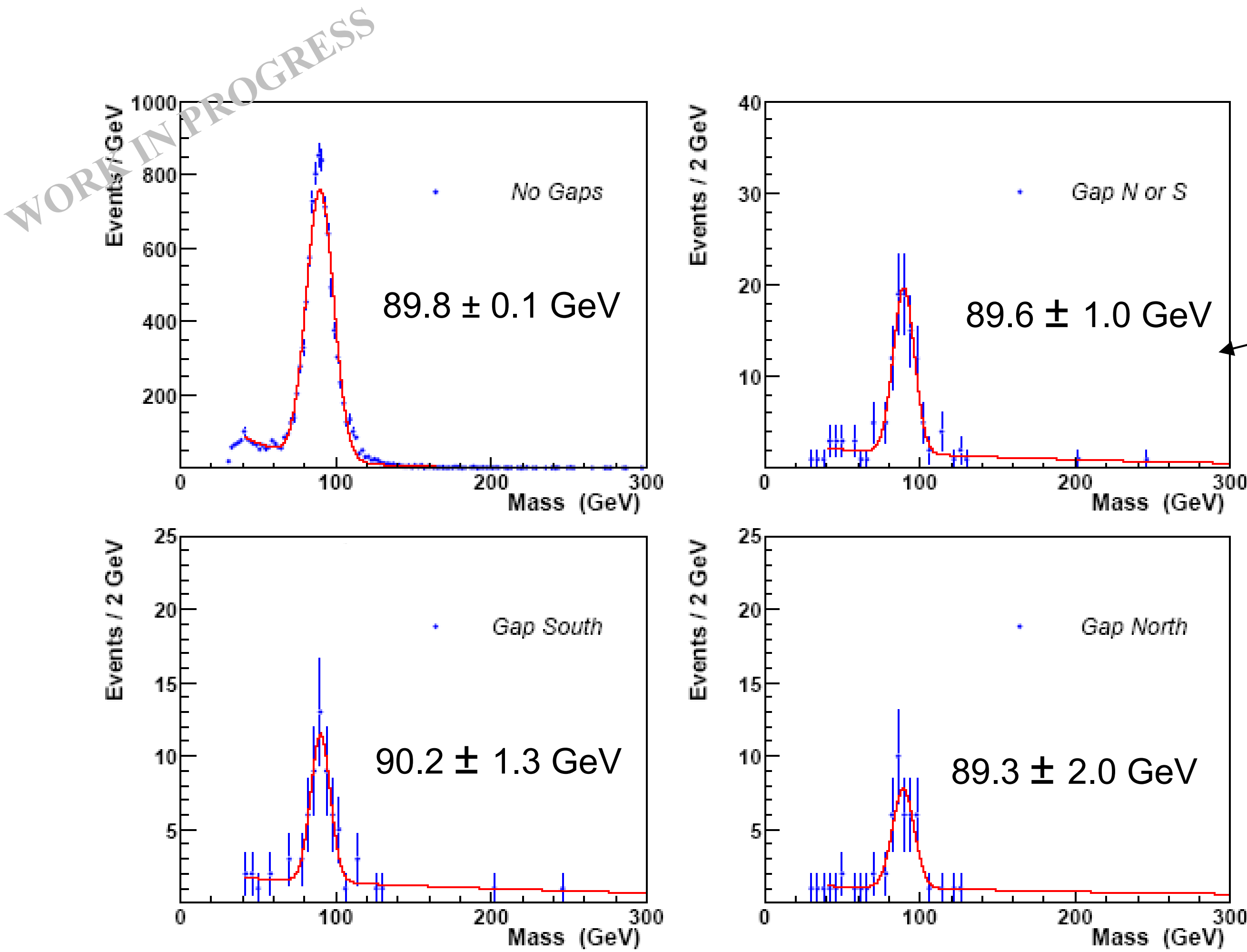
- Expect worst cosmic ray contamination in sample with both sides of LM off
- no evidence of overwhelming cosmics background in LM off samples



cosmics shape expected from inclusive sample

Z Mass of rapidity gap candidates

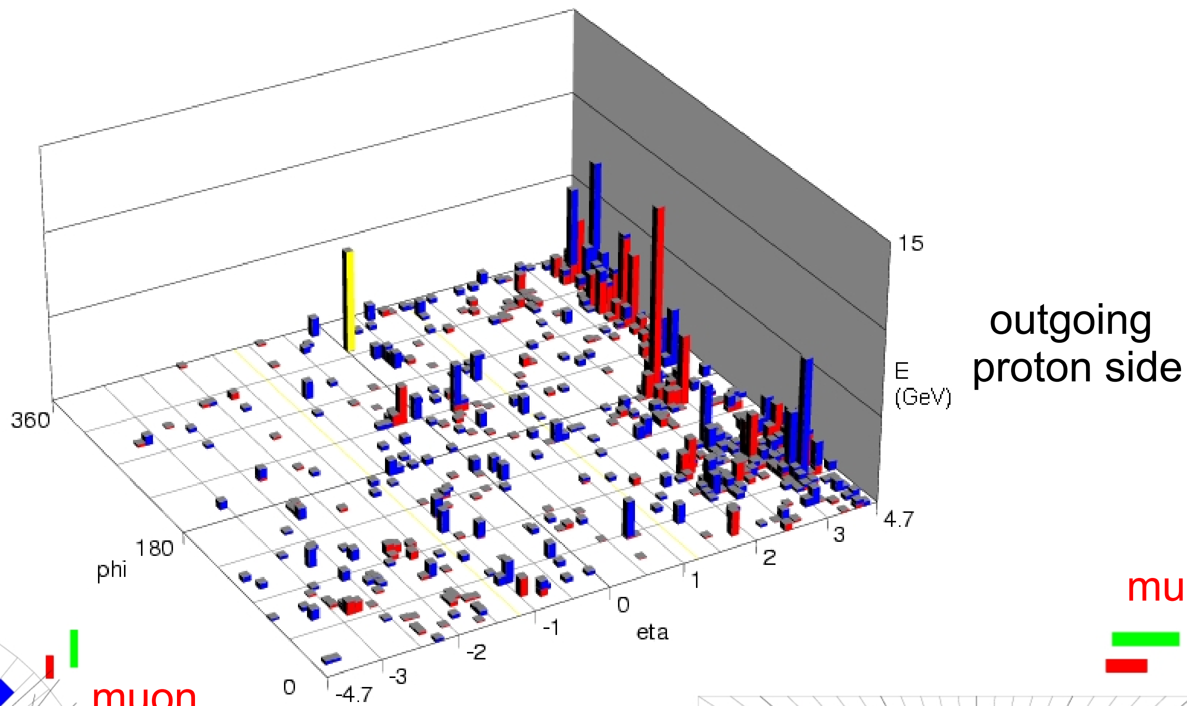
- Add Esum requirement:

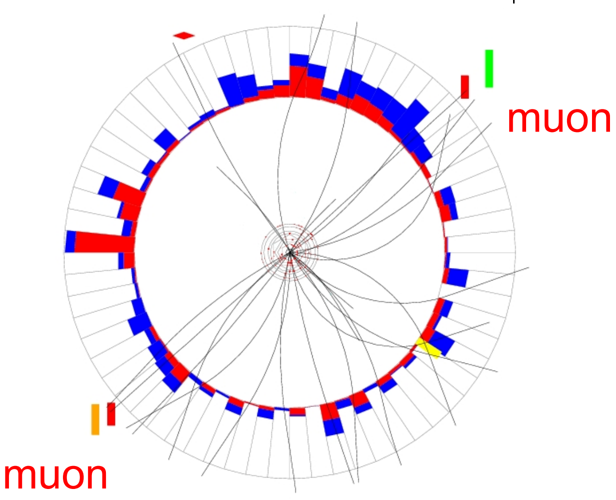


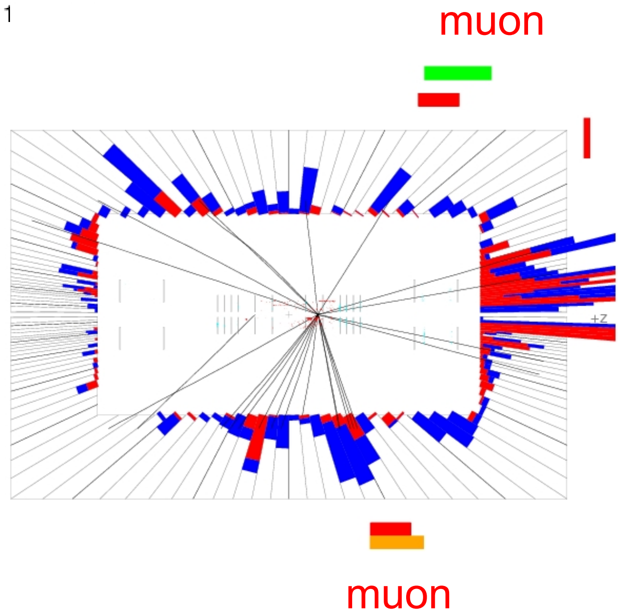
Gap North & Gap South combined

- Invariant mass confirms that these are all Drell-Yann/Z events
- Will be able to compare Z boson kinematics (p_T, p_z, rapidity)

Diffractive Z→μμ candidate







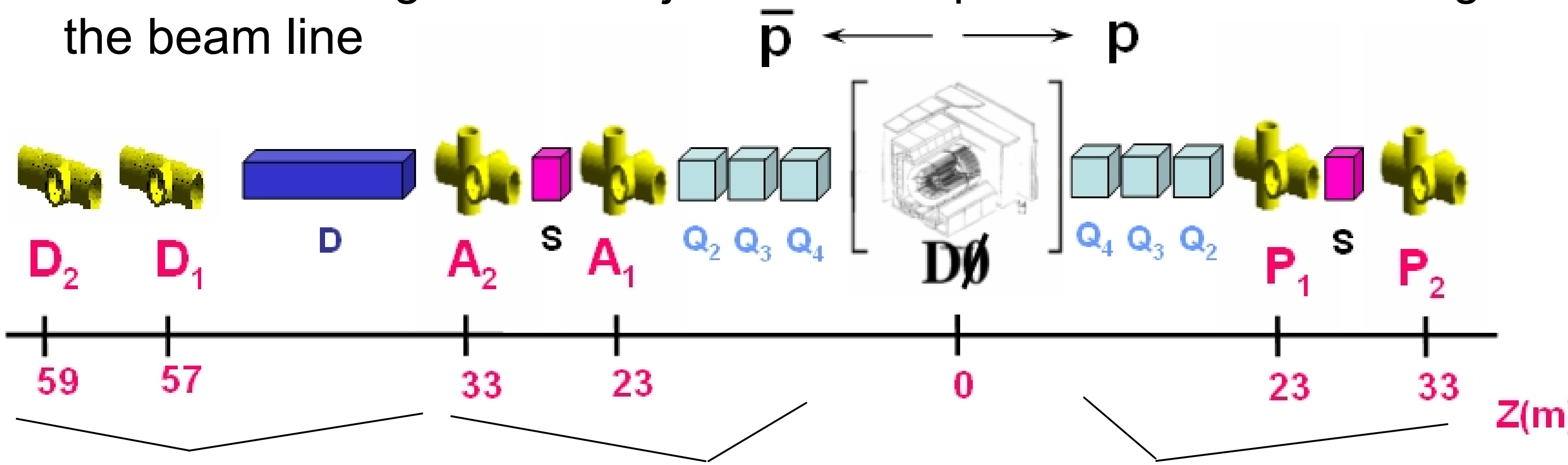
Z→μμ with rapidity gaps: Summary

- Preliminary definition of rapidity gap at DØ Run II
- Study of Z→μ+μ- events with a rapidity gap signature
  (little or no energy detected in the forward direction)
- Current status:
  - Evidence of Z events with a rapidity gap signature
  - Quantitative studies of gap definition, backgrounds, efficiency in progress
    (effects could be large)
  - No interpretation in terms of diffractive physics possible yet
- Plans:
  - Measurement of the fraction of diffractively produced Z events
  - Diffractive W→μν, W/Z→electrons, jets and other channels
  - Use tracks from Forward Proton Detector

Forward Proton Detector

Forward Proton Detector (FPD)

- a series of momentum spectrometers that make use of accelerator magnets in conjunction with position detectors along the beam line

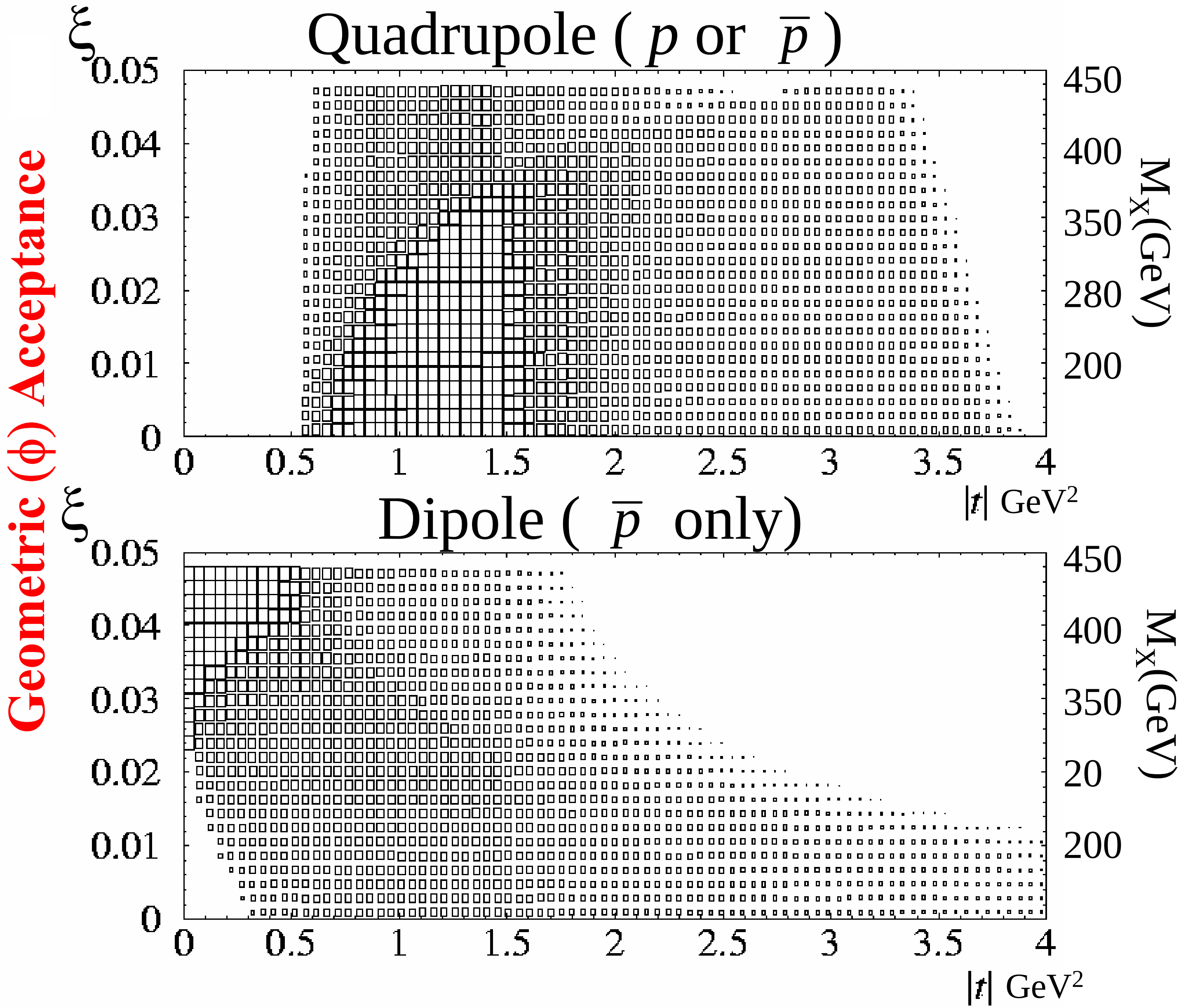


- **Dipole Spectrometer**
- inside the beam ring in the horizontal plane
- use dipole magnet (bends beam)

- **Quadrupole Spectrometers**
- surround the beam: up, down, in, out
- use quadrupole magnets (focus beam)
- also shown here: separators (bring beams together for collisions)

A total of 9 spectrometers composed of 18 Roman Pots

Acceptance



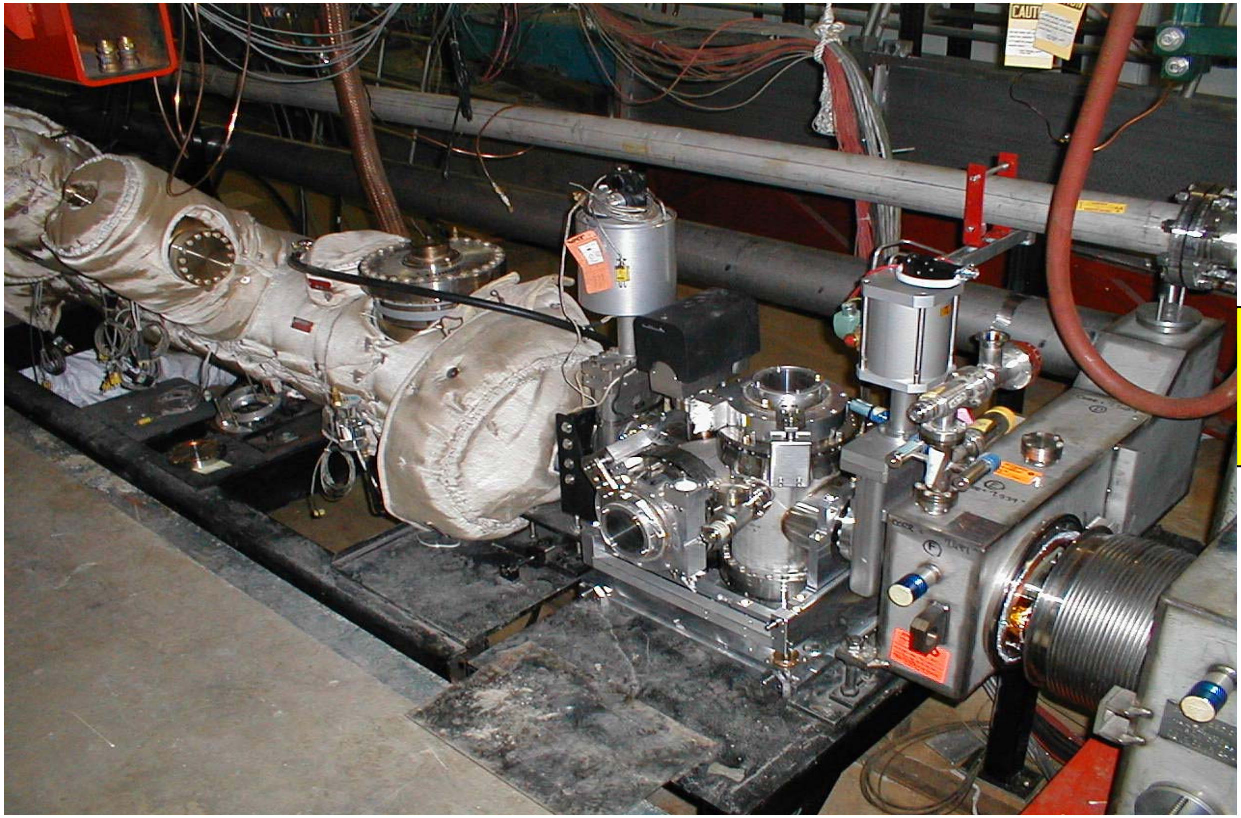
Dipole acceptance better at low |t|, large ξ

Cross section dominated by low |t|

Combination of Q+D gives double tagged events, elastics, better alignment, complementary acceptance

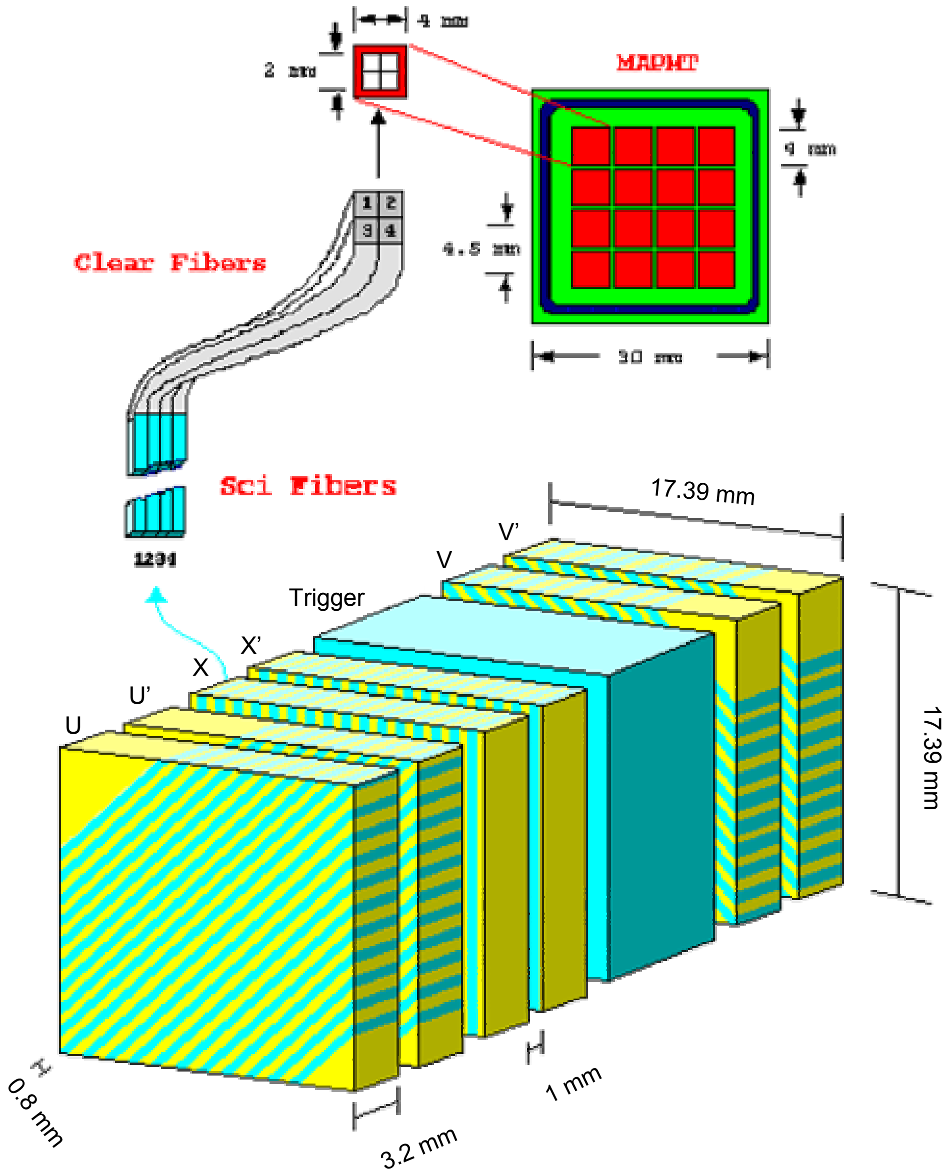
Castle Status

All 6 castles with 18 Roman pots comprising the FPD were constructed in Brazil, installed in the Tevatron in fall of 2000, and have been functioning as designed.



A2 Quadrupole castle installed in the beam line.

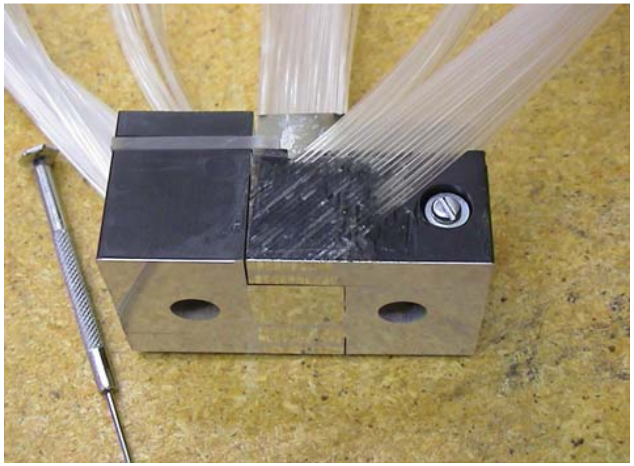
FPD Detector Design

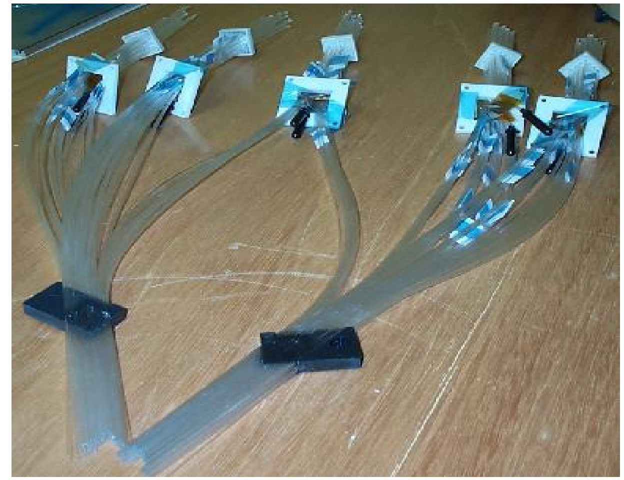


- 6 planes per detector in 3 frames and a trigger scintillator
- U and V at 45 degrees to X, 90 degrees to each other
- U and V planes have 20 fibers, X planes have 16 fibers
- Planes in a frame offset by ~2/3 fiber
- Each channel filled with four fibers
- 2 detectors in a spectrometer

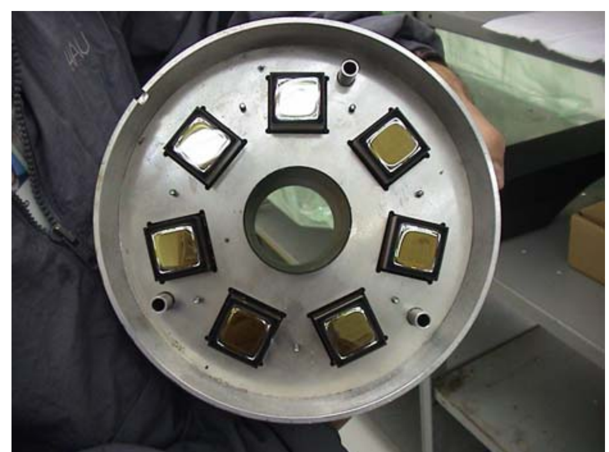
Detector Construction

At the University of Texas, Arlington (UTA), scintillating and optical fibers were spliced and inserted into the detector frames.





The cartridge bottom containing the detector is installed in the Roman pot and then the cartridge top with PMT's is attached.



Detector Status

- **20 detectors built over a 2+ year period at UTA.**

- **In 2001-2002, 10 of the 18 Roman pots were instrumented with detectors.**

- Funds to add detectors to the remainder of the pots have recently been obtained from NSF (should acknowledge funding from UTA REP, Texas ARP, DOE, and Fermilab as well).

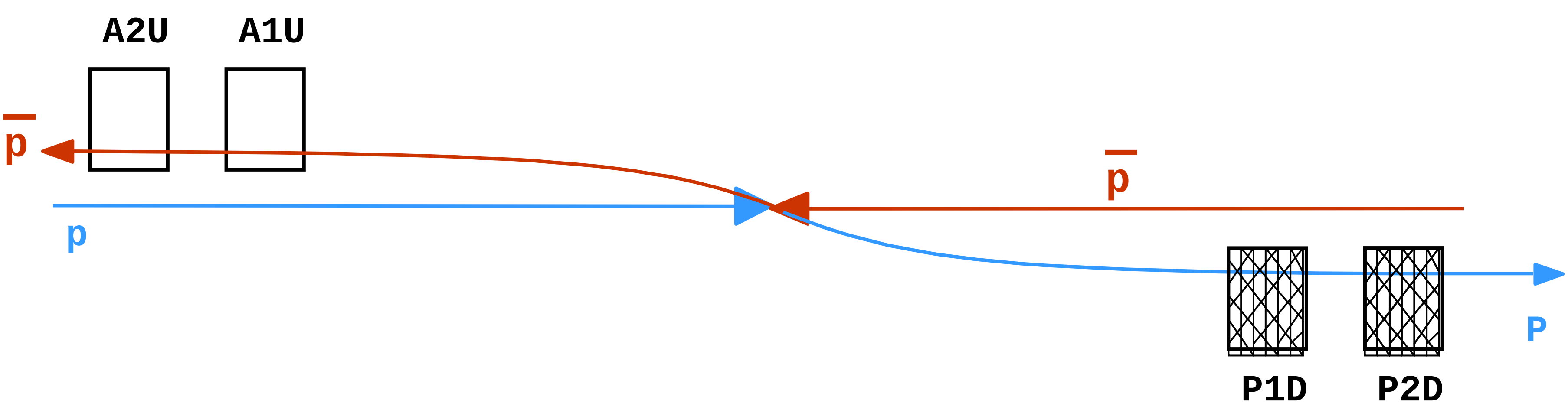
- **During the shutdown (Sep-Nov. 2003), the final eight detectors and associated readout electronics were installed. All 18 pots are routinely inserted near the beam.**

A2 Quadrupole castle with all four detectors installed

Elastic Scattering

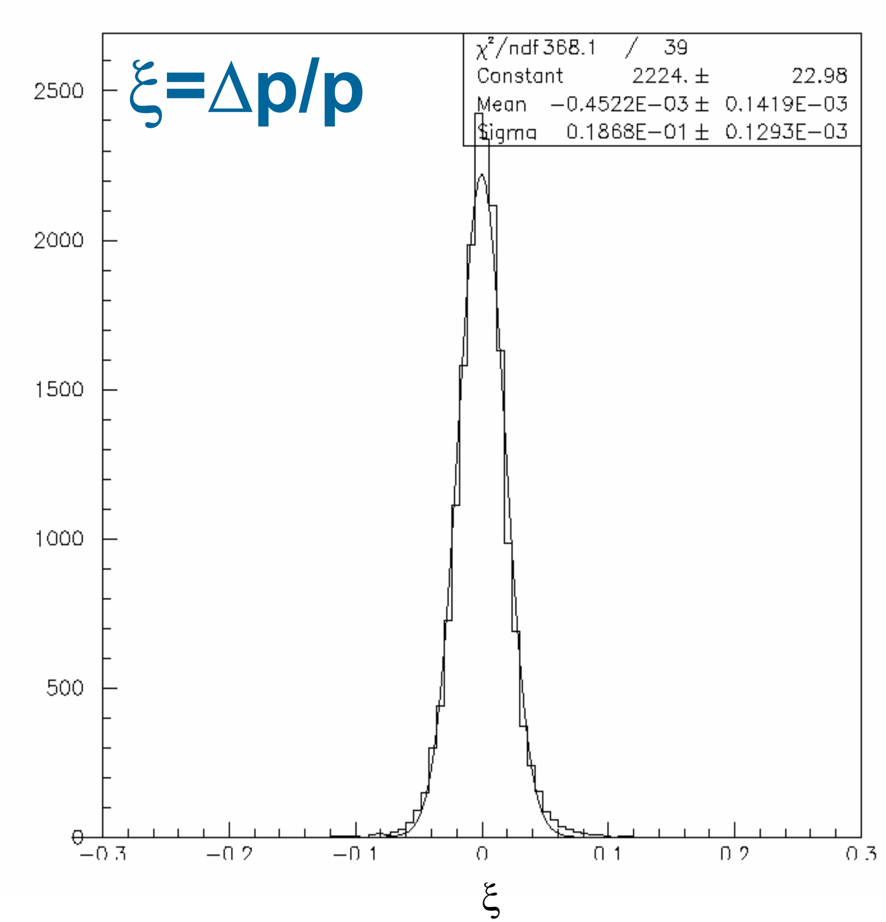
- Elastic scattering: ξ = 0
- Quadrupole acceptance:
  - $t > 0.8$ GeV^2 (requires sufficient scattering angle to leave beam)
  - all ξ (no longitudinal momentum loss necessary)
- Measure dN/dt for elastic scattering using incomplete FPD:

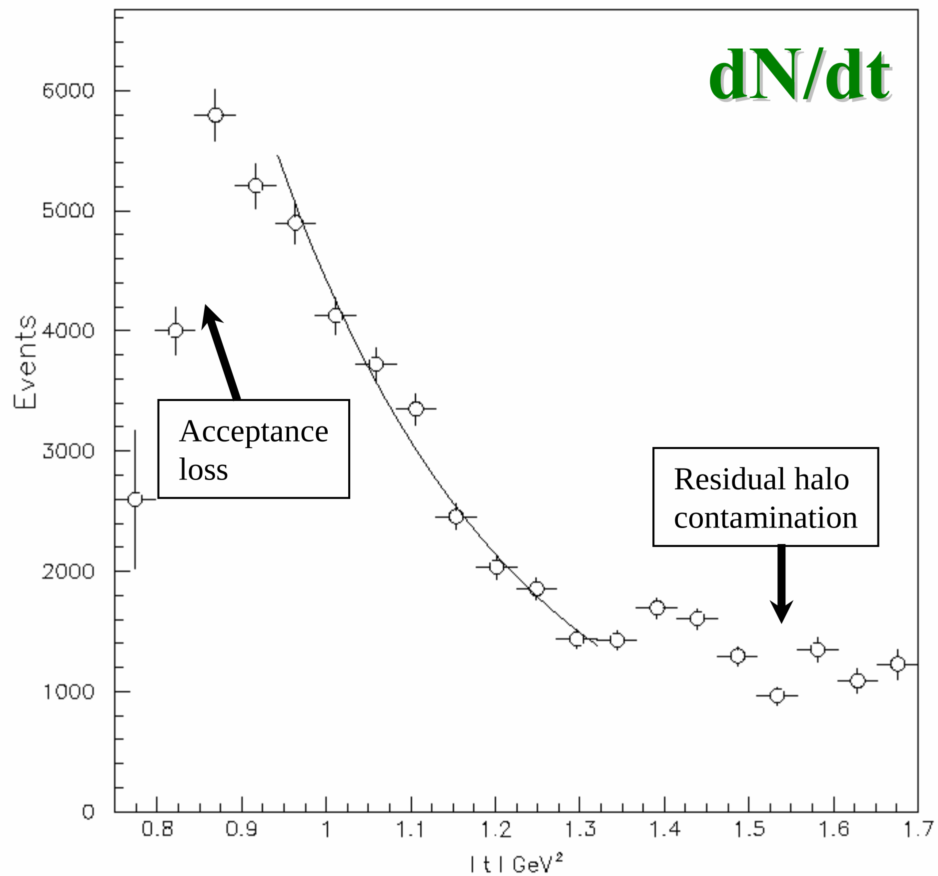
- antiproton side:
  - quadrupole ‘up’ spectrometer
  - trigger only
- proton side:
  - quadrupole ‘down’ spectrometer
  - full detector read-out



Elastic Data Distributions

After alignment and multiplicity cuts (to remove background from halo spray):



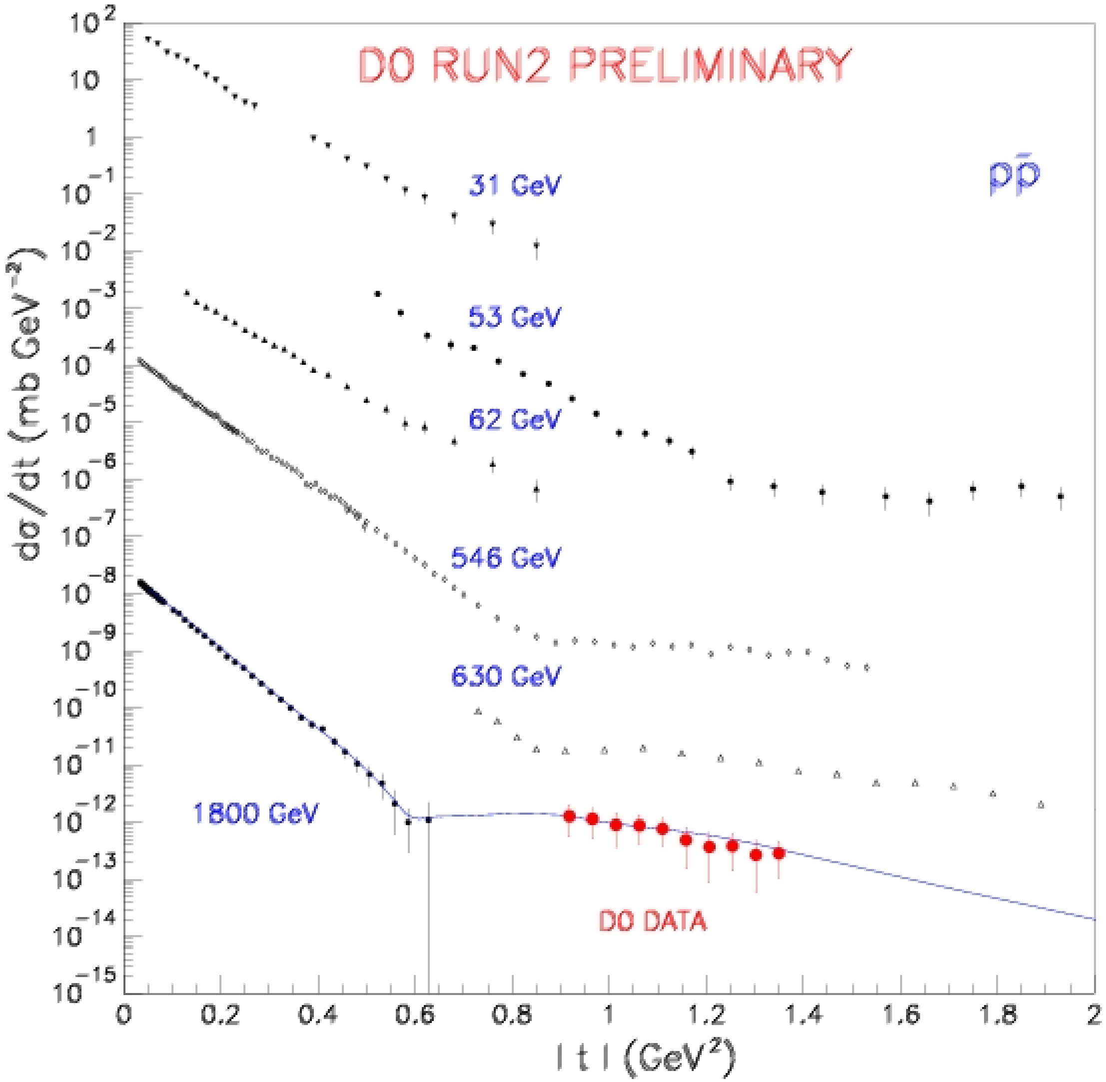


Events are peaked at zero, as expected, with a resolution of $\sigma_\xi = 0.019$

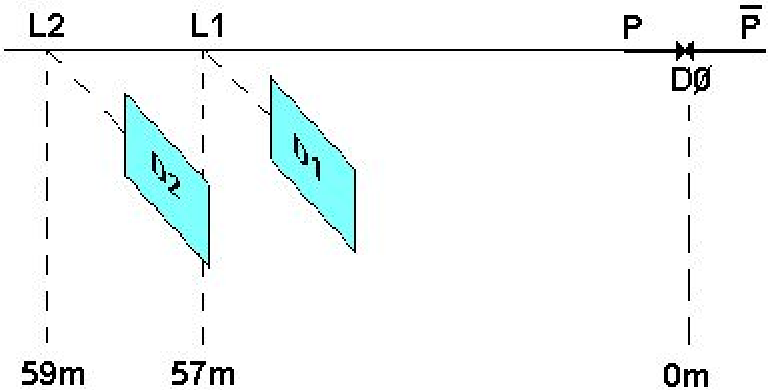
The fit shows the bins that will be considered for corrected dN/dt

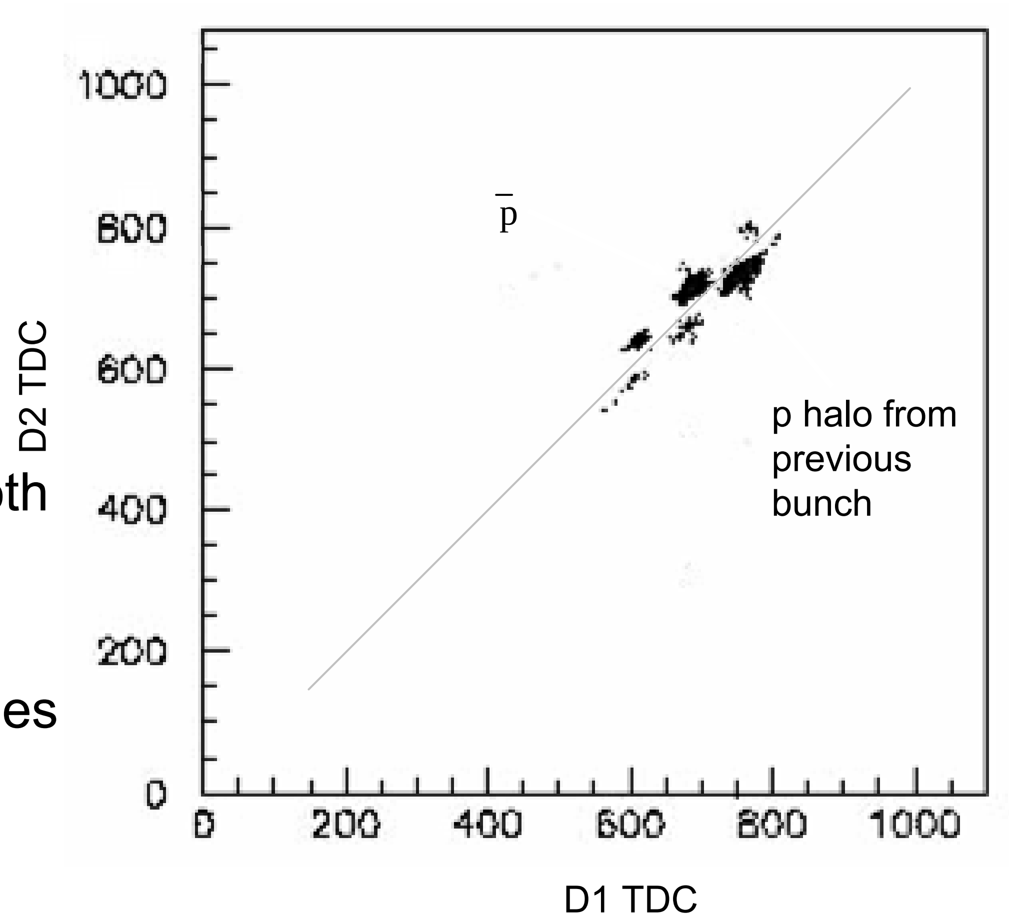
Preliminary Elastic Scattering Results

- The dσ/dt data collected by different experiments at different energies
- A factor of 10^{-2} must be applied to each curve
- New DØ dN/dt distribution has been normalized by E710 data
- Compare slope with model: Block *et al*, Phys. Rev. D41, pp 978, 1990.



Dipole TDC Resolution





- Can see bunch structure of both proton and antiproton beam
- Can reject proton halo at dipoles using TDC timing

Summary and Future Plans

- **Early FPD stand-alone analysis shows that detectors work, will result in elastic dN/dt publication (already 1 Ph.D.)**
- **FPD now integrated into DØ readout (detectors still work)**
- **Commissioning of FPD and trigger in progress**
- **Tune in next year for first integrated FPD physics results**

BUT Wait, There's More!

GTeV: Gluon Physics at the Tevatron

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

thanks to Mike Albrow for his slides

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 χ_c^0, χ_b^0

Relates to SM Higgs study at LHC

Discover new exotic hadrons

Hybrids, 4-quark, pentaquarks, ...

Search for exotic fundamentals

CP-odd H, Radions, gluinoballs ...

Use Tevatron as Tagged Gluon-Gluon Collider

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

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

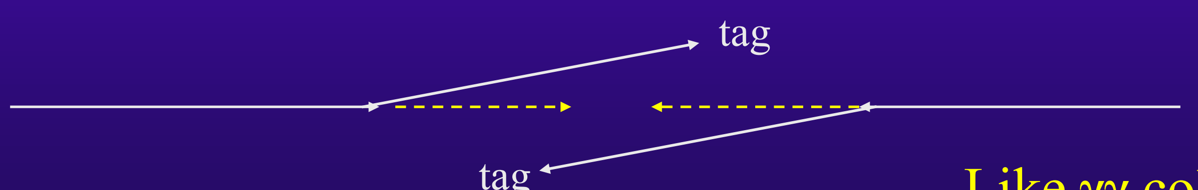
Glueballs and Hybrids

New Exotic Hadrons

chi_c and chi_b states

Hunting strange exotic animals (radions, ...?

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



Like $\gamma\gamma$ collider in LC

The REAL Strong Interaction

extended, strong coupling
non-perturbative

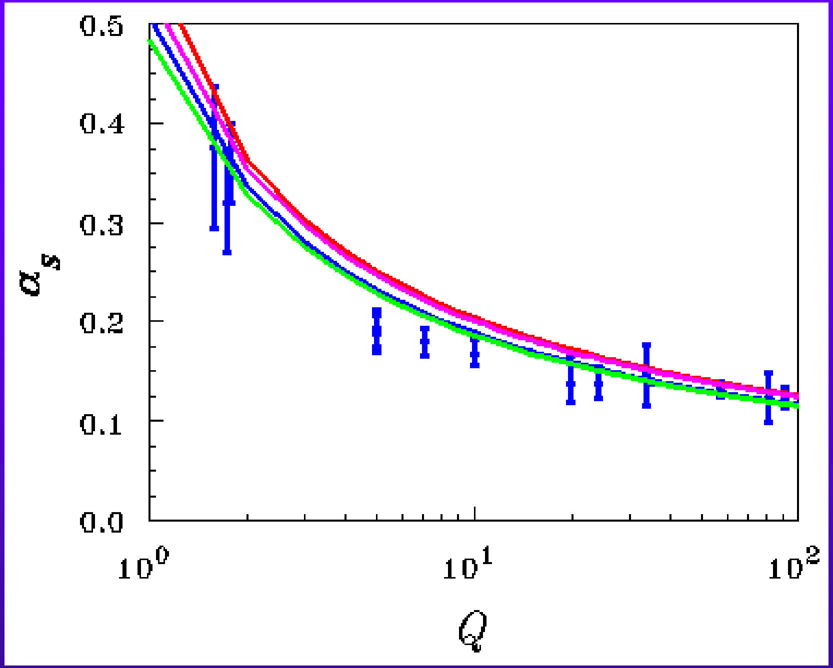
point-like, weak coupling
perturbative

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:

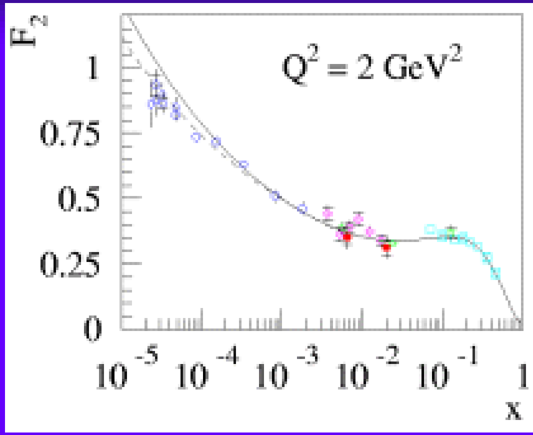
1) Do not have 2-arm forward p-taggers (dipole spectrometer)
2) Small angle (< 3 deg) region trackless
3) Limit on number of triggers
4) Bandwidth allocated small

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

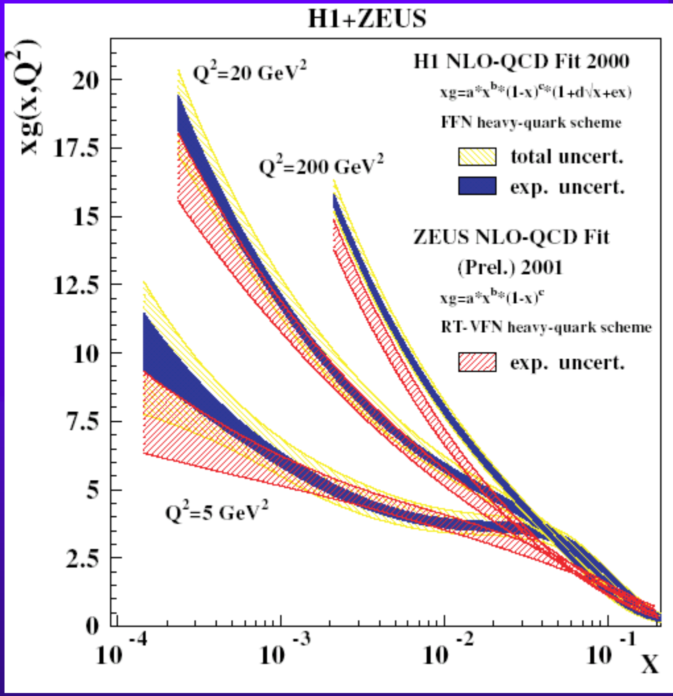
CDF, D0: NP QCD <~ 10%, other ~ 90%
GTeV: NP QCD ~ 90%, other <~ 10%

& 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/ψ jets, photons ...

& Q2 < ~ 2 GeV2 ? (HERA)

Gluon Jets

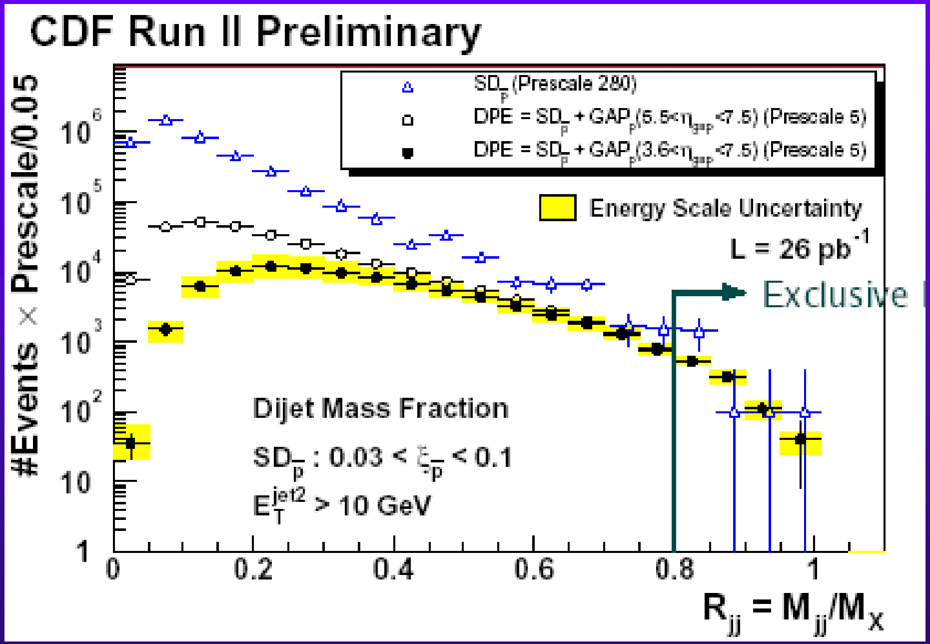
LEP(Z) ... ~ 10^7 q-jets, detailed studies
"Pure" g-jet sample: 439 events (OPAL), Delphi more but 80% "pure"

$e^+e^- \rightarrow Z \rightarrow b\,\bar{b}\,g$ 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

~ 10^5 pure g-jets



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

Gluonia and Glueballs

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^{++}	←

Glueballs (G) are hadrons 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

$$J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}$$

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. $\phi\phi \to 4K, \pi\pi KK, D\bar{D}^*, \Lambda\bar{\Lambda}$, etc

Other processes:

- $\pi^- p \to [\phi\phi] + n$
- $J/\psi \to \gamma + G$ $\quad$ $e^+e^- \to J/\psi, \Upsilon + G$
- $p\bar{p}$ (low $\sqrt{s}$) $\to G$ + anything
- $gg \to G$, GG, G+anything

This one →

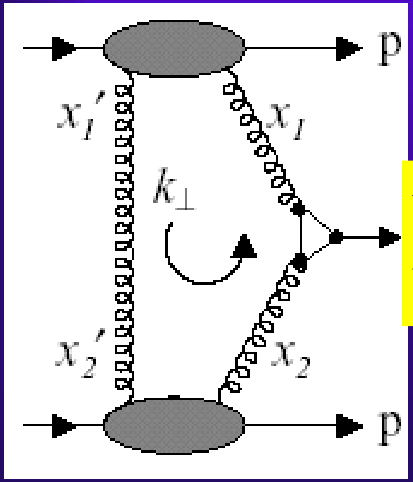
Central Exclusive Production

gg fusion: main channel for H production.

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

$$p\,p \rightarrow p \;+\; H \;+\; p$$

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 : χ_c^0
b-loop : χ_b^0 t-loop: H

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

Khoze,Martin,Ryskin hep-ph/0111078
Lonnblad & Sjodahl hep-ph/0311252
and many others

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

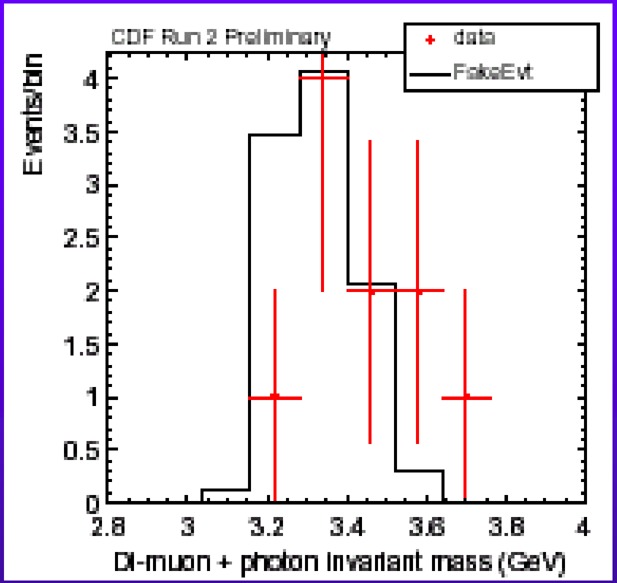
(Angela Wyatt)

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

(Khoze,Martin,Ryskin hep-ph/0011393; F.Yuan hep-ph/0103213)

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

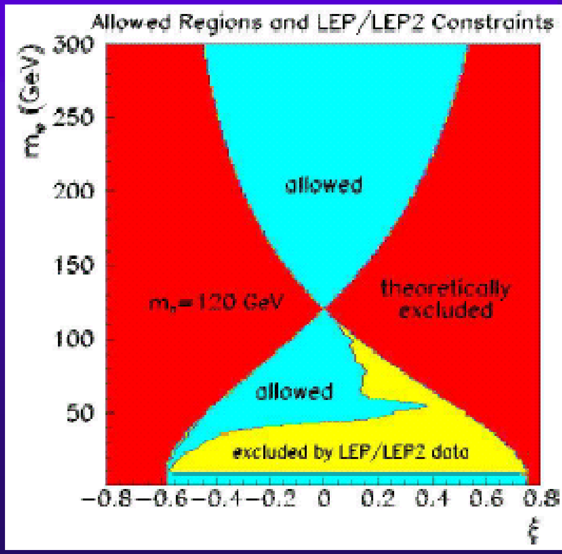
Beyond the Standard Model

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 β $\sigma_{MM} \approx 100$ 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



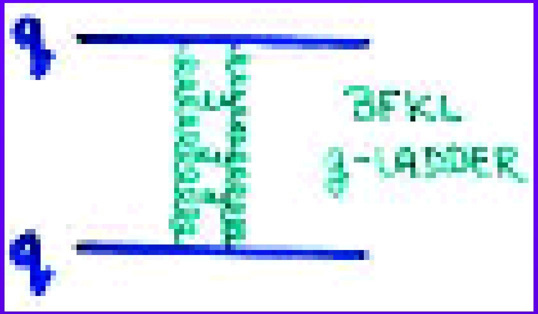
Light Gluinos and Gluinoballs

Gluino g~ could be lightest SUSY particle
LSP Does not decay in detector --- forms heavy hadrons. Can form bound states "gluinoballs"

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

BFKL and Mueller-Navelet Jets

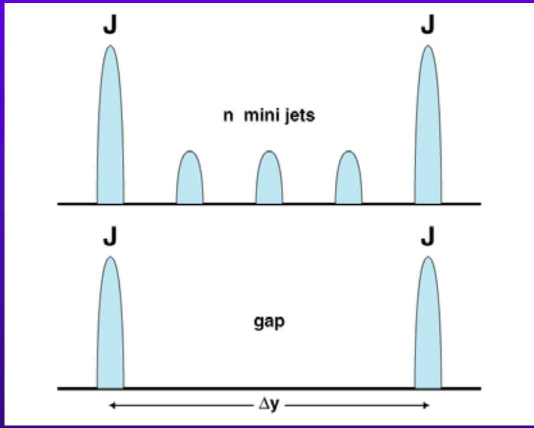
Color singlet (IP) exchange between quarks
Enhancement over 1g exchange – multiRegge gluon ladder
Jets with large y separation
n minijets in between (inelastic case)
large gap in between (elastic case)



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

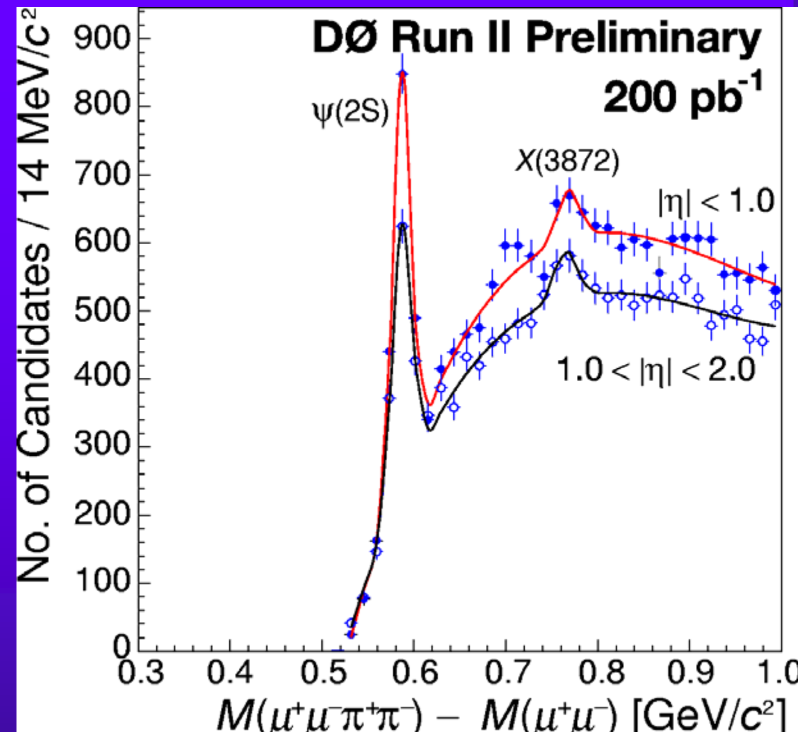
Fundamental empirical probe of new regime:
non-perturbative QCD at short distances.

Hadron Spectroscopy: an example

X(3872) discovered by Belle (2003)
Seen soon after by BaBar, CDF, and DØ
Relatively narrow

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

$\Gamma < 3.5$ 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)

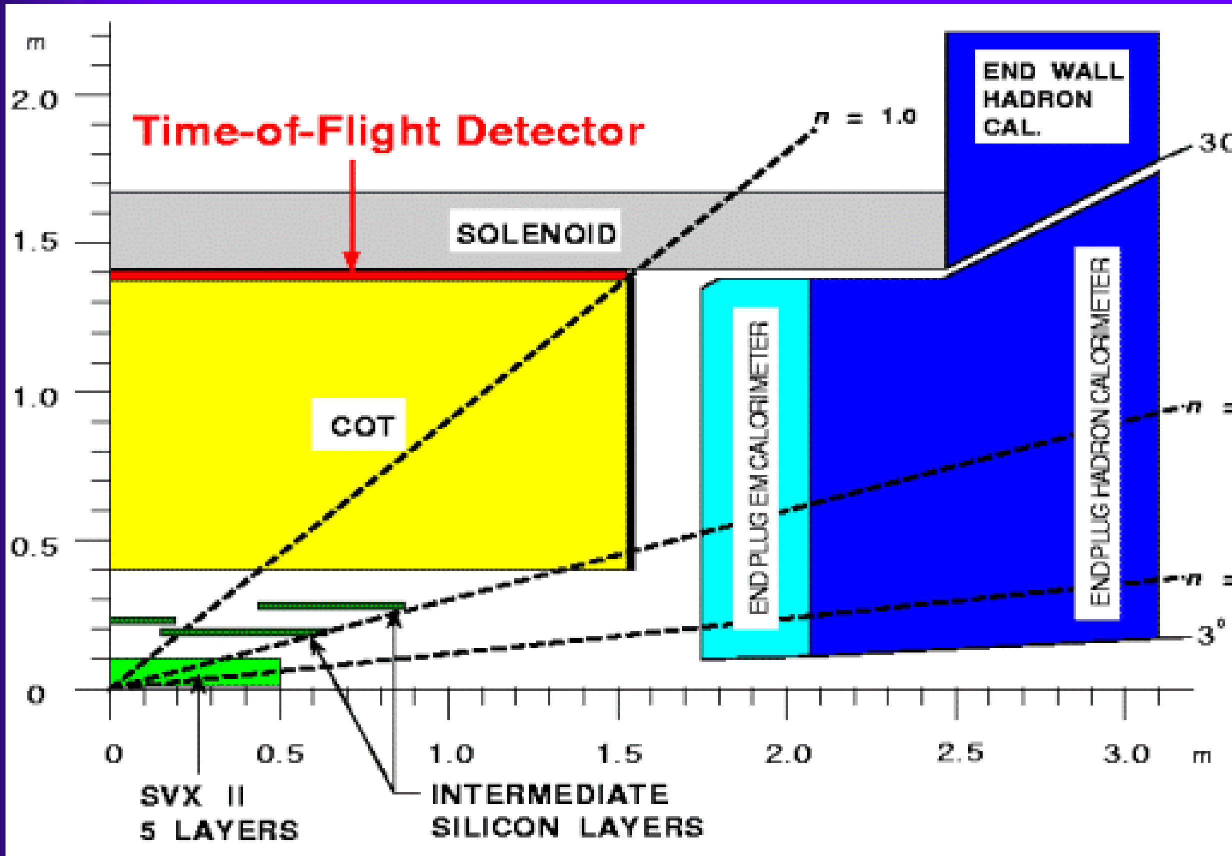
$0^+0^{++} \Rightarrow$ favored

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

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

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

Detectors

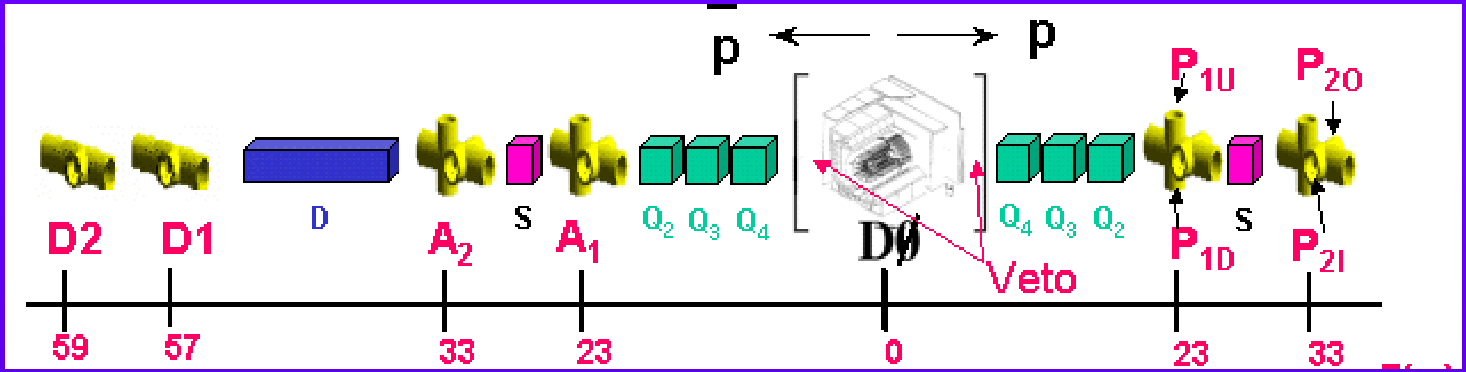


BEYOND 3 deg :
Luminosity Counters
Beam Shower Counters
Roman Pots
MiniPlugs

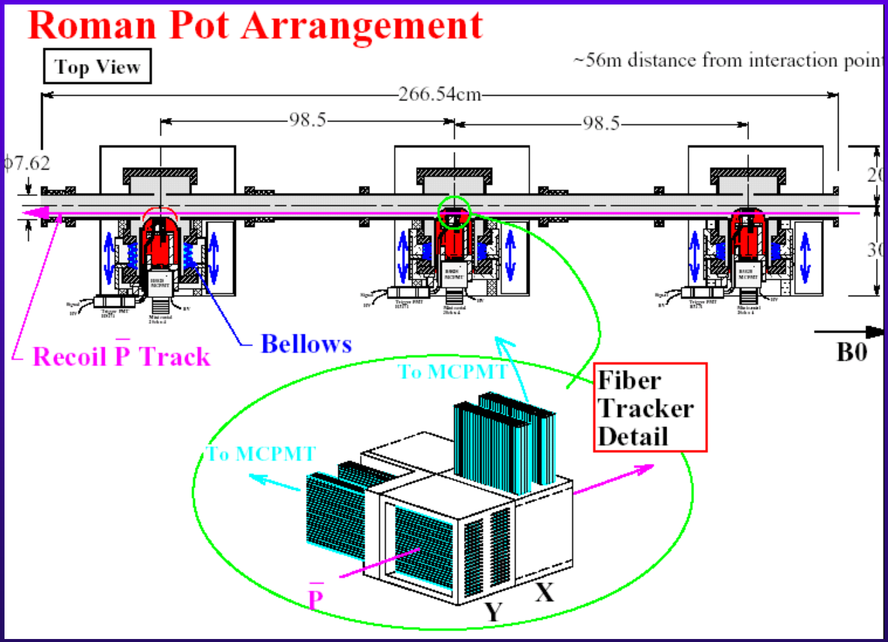
Add:
New pots very forward: through quadrupoles + near (55m) + far (~160m?)
Other forward detectors (tracking, upgrade calorimetry e.g.) → **"Cone Spectrometers"**
New DAQ and trigger system → kHz
Silicon (certainly want it) ... hope it's still good (COT also)

Very Forward: Roman Pots

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

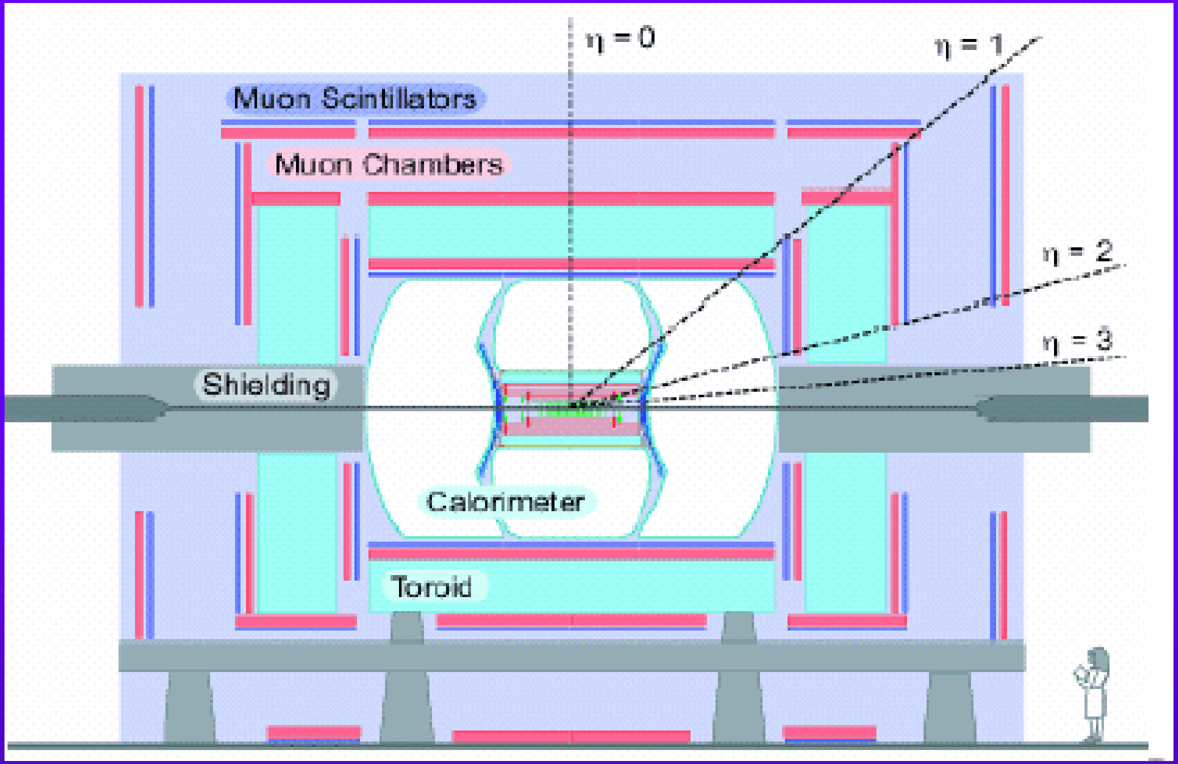


CDF has 3 dipole spectrometer pots
0.8 mm x-y fibers



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

Re-using D0 detector?



Add :
New/upgrade pots very forward: quad + near (55 m) + far (160 m?)

Forward ("cone") region probably not instrumentable

Tevatron Issues

Spaces for pots and their position: quad, near dipole, far dipole
Replace 3 dipoles with 2 High Field dipole(s) → ~ 4 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 also high?),
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

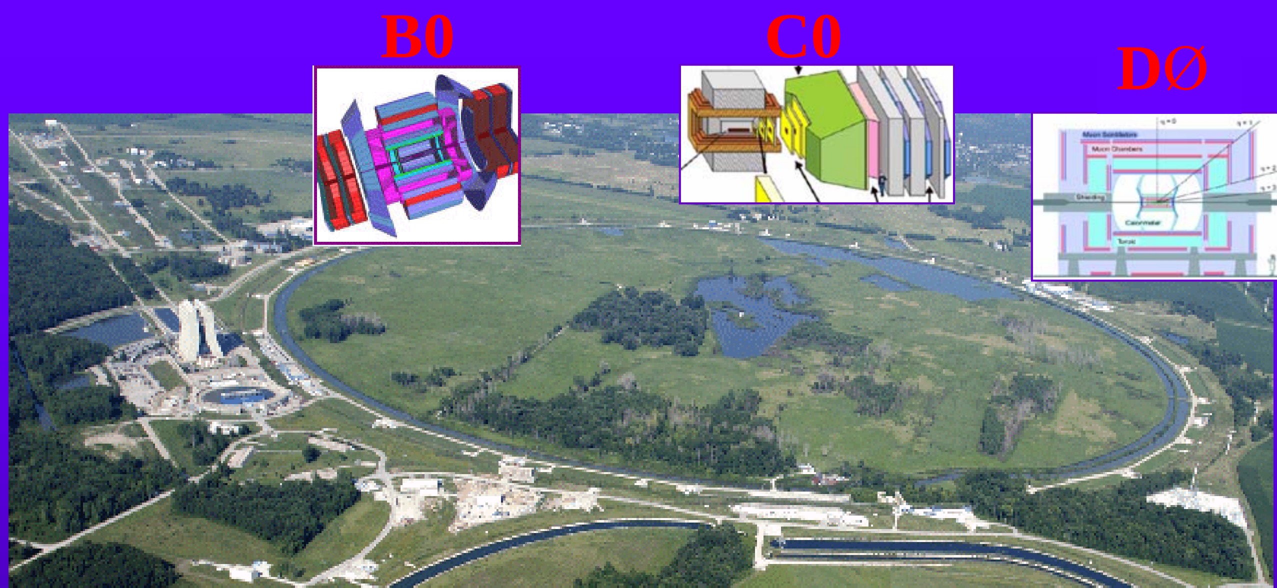
p → 3 jet fragmentation: 3 very forward jets, with & without gaps

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

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

The Future of QCD at the Tevatron

Workshop — May 20-22, 2004 — *at Fermilab*



> To present and discuss QCD issues that remain to be addressed by the CDF and DØ detectors at the Tevatron.
> To evaluate physics, especially non-perturbative QCD and the non-perturbative/perturbative interface, that may require upgrades to an existing detector and/or running beyond the present high-pT/high mass program.
> To review the QCD and other physics potential of the Tevatron beyond 2009 in the context of BTeV and the LHC.

http://conferences.fnal.gov/qcdws/

Contact: albrow@fnal.gov
brandta@uta.edu

Organizing Committee: M.G.Albrow(co-ch), Y.Alexahin, A.Brandt(co-ch), B.Cox, H.da Motta, M.Martens, F.Olness, R.Orava, C.Royon. M.Strikman, R.Tesarek

GTeV plans

- **LOI for Spring 2005 PAC**
- **Convenors:**

Physics: Fred Olness (SMU)+Mark Strikman (Penn St.)

MC: Brian Cox (Manchester)

Tevatron: Mike Martens (FNAL)+Yuri Alexahin (FNAL)

Forward Detectors: Rick Tesarek (FNAL) +Helio da Motta (CBPF) + Risto Orava (Helsinki)

Studying technical issues (critical path is high field dipole to create warm space) + can we build a collaboration?

My Opinion

- **Solid physics program, needs refinement**
- **Makes sense to have a second experiment**
- **Need U.S. HEP experimental alternatives to LHC**
- **Training of new GTeV experts will help offset LHC drain in 2007-2009**
- **Need 5-10% of CDF/ DØ + people from HERA, fixed target, Jlab, etc. to be viable**

Come to workshop, send me e-mail w/questions/commnts