The DØ Detector and Physics Program

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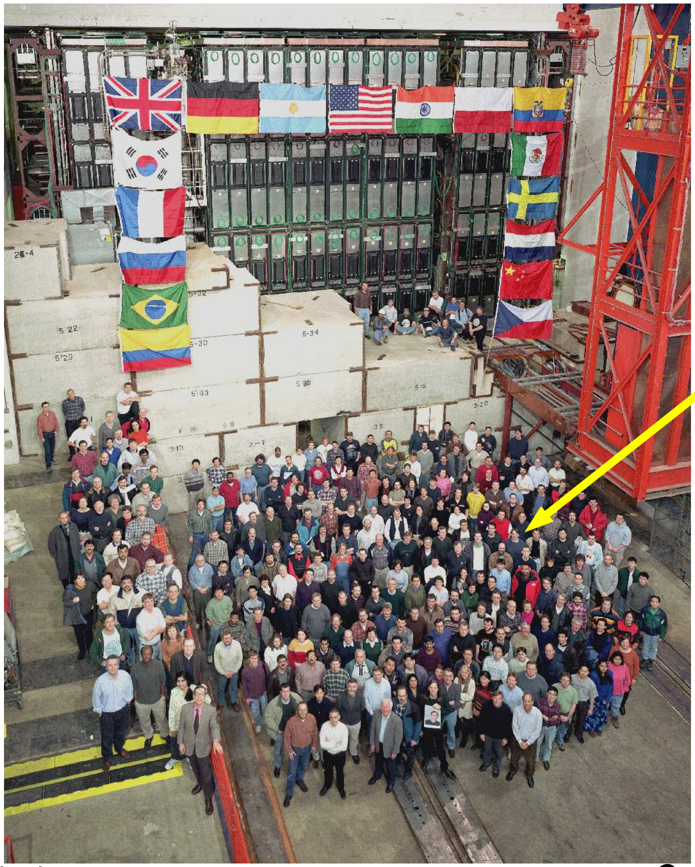
DØ

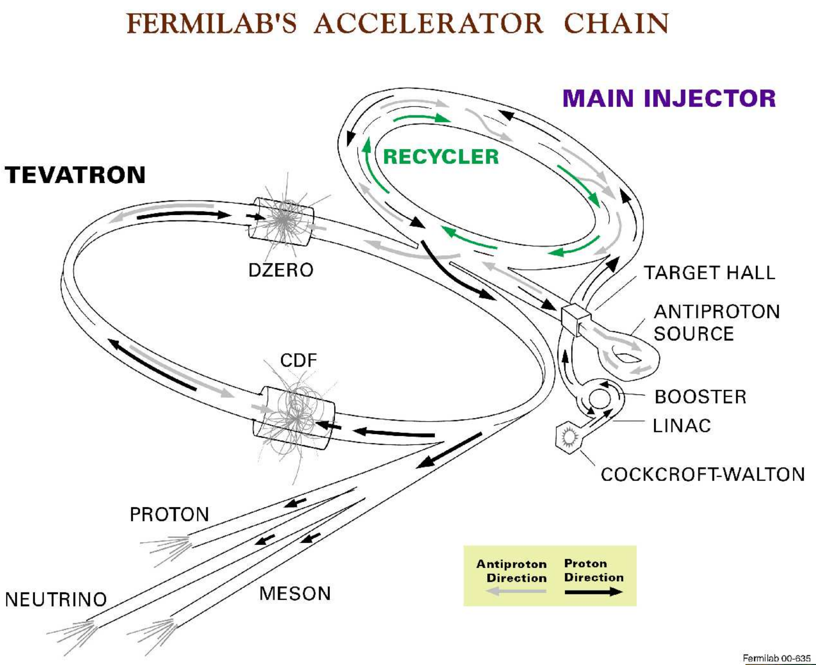
- DØ is a large (5,000 tons) experiment on the Tevatron proton/anti-proton collider at Fermilab
- Run by a Collaboration of ~550 physicists
  - ~75 institutions, 18 countries

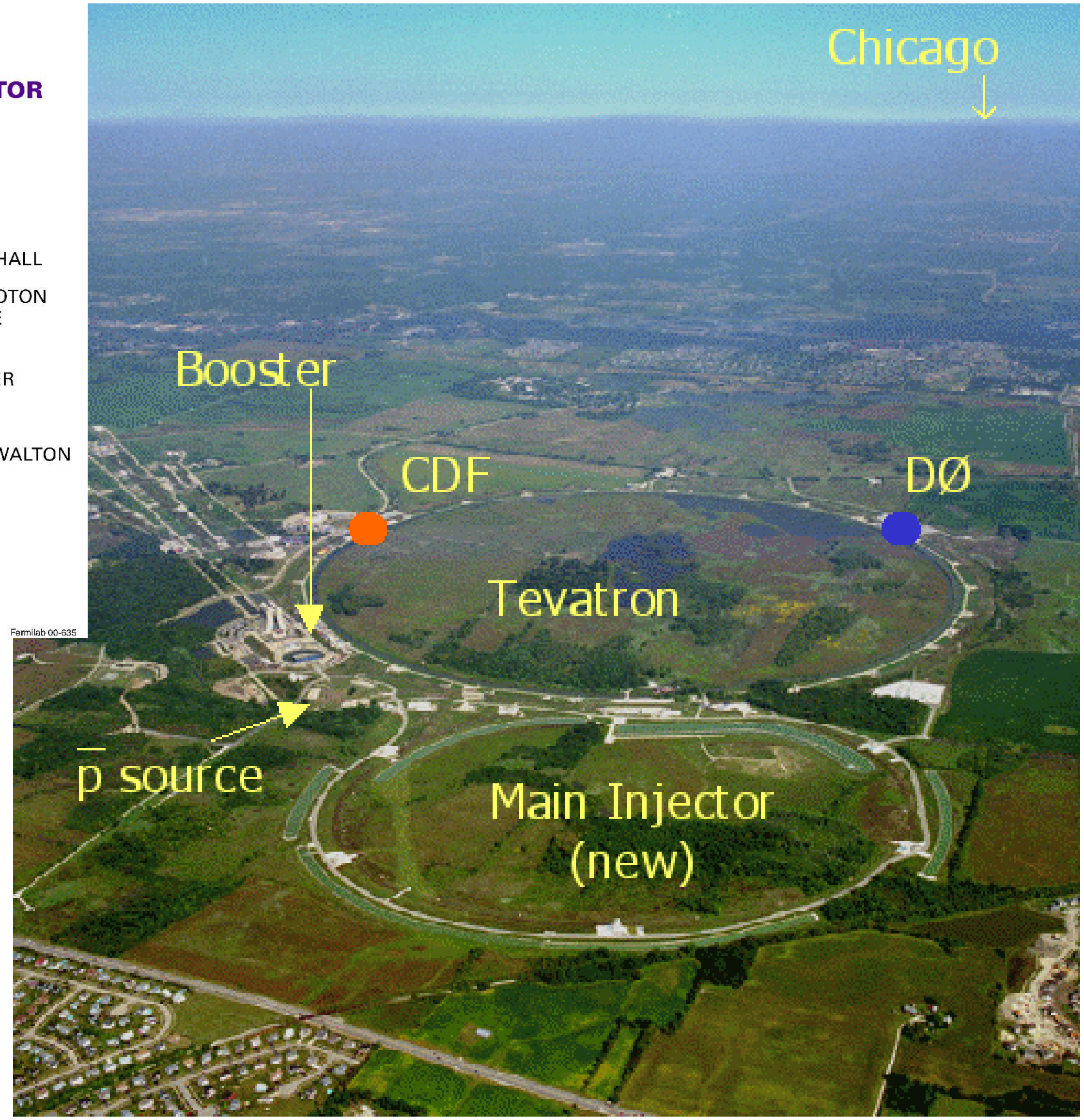


The Tevatron Collider

- Currently world's highest energy collider
- Recently upgraded for Run II (pre-upgrade Run I)
- Collides bunches protons and anti-protons
  - Centre-of mass energy 1.96TeV=10^{12}eV eV=electron volt
  - 6.2km circumference
  - Design luminosity 5×10^{32}cm^{-2}s^{-1} (Run I: 10^{31}cm^{-2}s^{-1})
  - Bunch spacing 396ns -> 132ns? (Run I: 3.5μs)
- Superconducting magnets
  - Energy limited by magnetic field strength
  - Larger ring means less powerful magnets needed
- Protons are composite particles (quarks/gluons)
  - Collisions occur over a range of energies ~1 GeV - 1 TeV

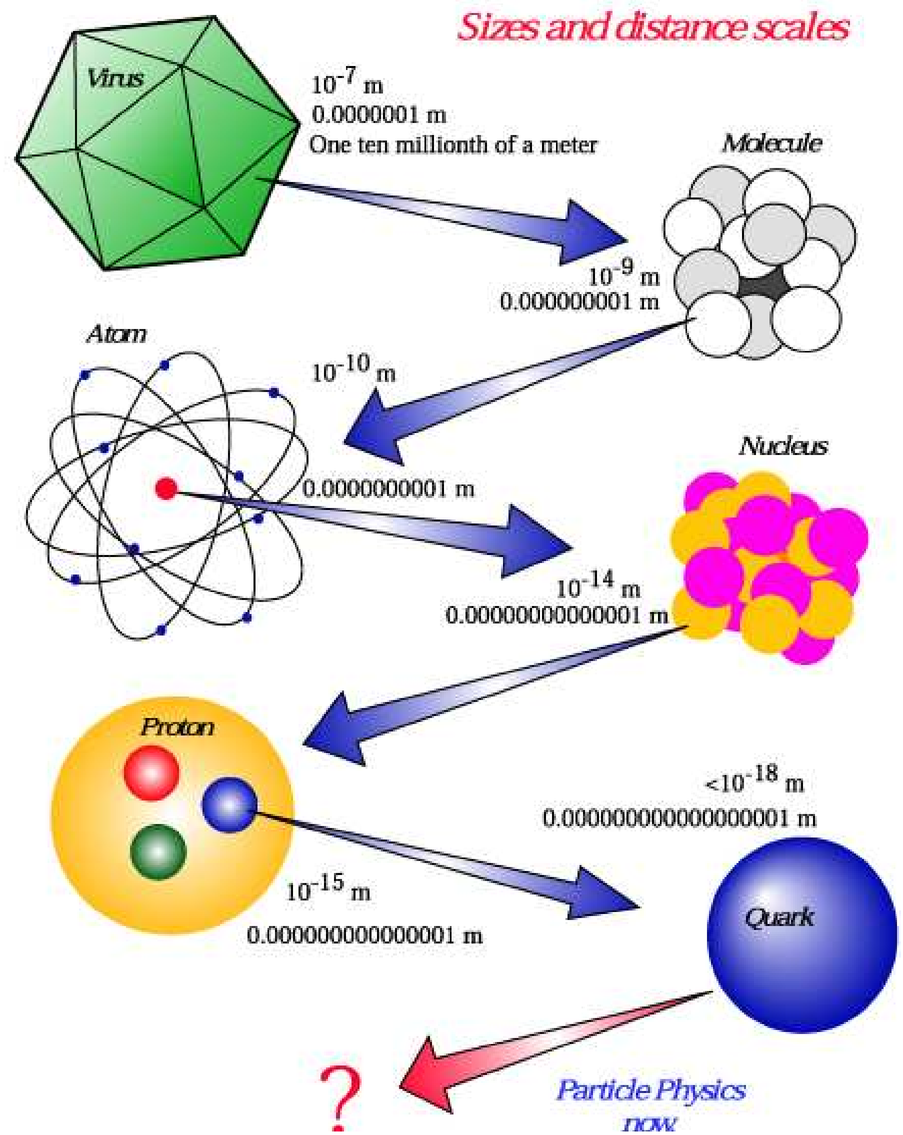
The Tevatron Collider



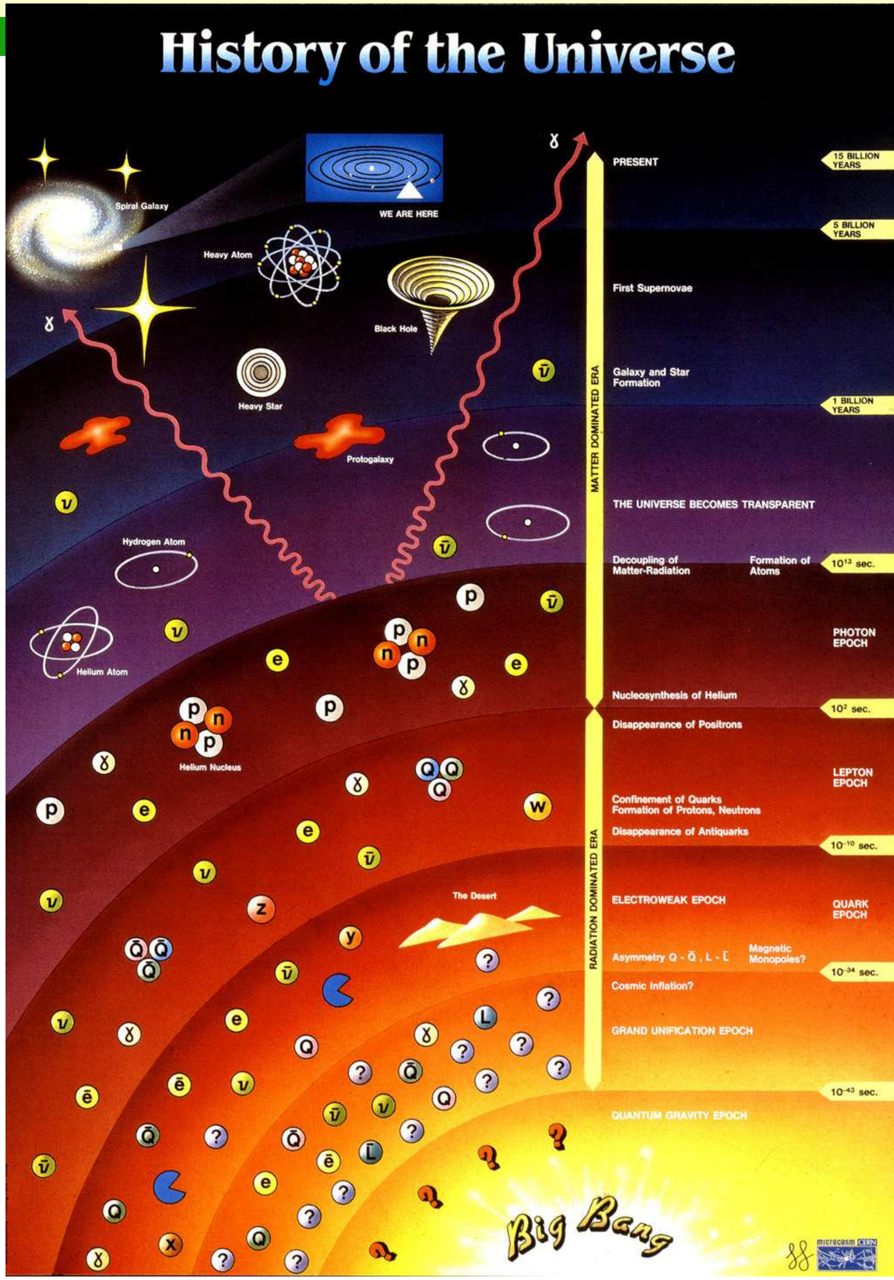


Scales

- Colliders force high energy interactions between particles
- The higher the energy the smaller the scale probed
- Recreate very high temperatures last observed in the early Universe
    - Understand processes occurring just after the Big Bang



Big Bang



Now (13.7 billion years) [WMAP]

Stars form (1 billion years)

Atoms form (380k yrs) [WMAP]

Nuclei form (180s)

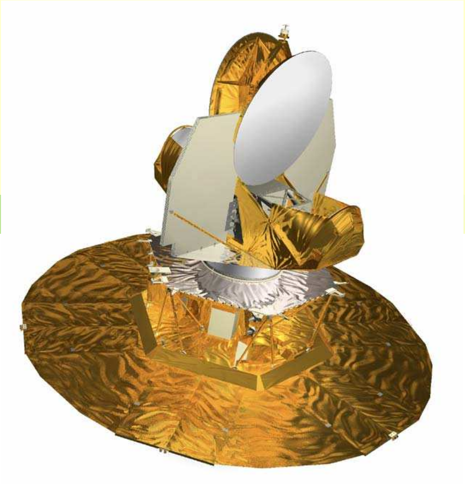
Protons/Neutrons form (10^{-10}s)

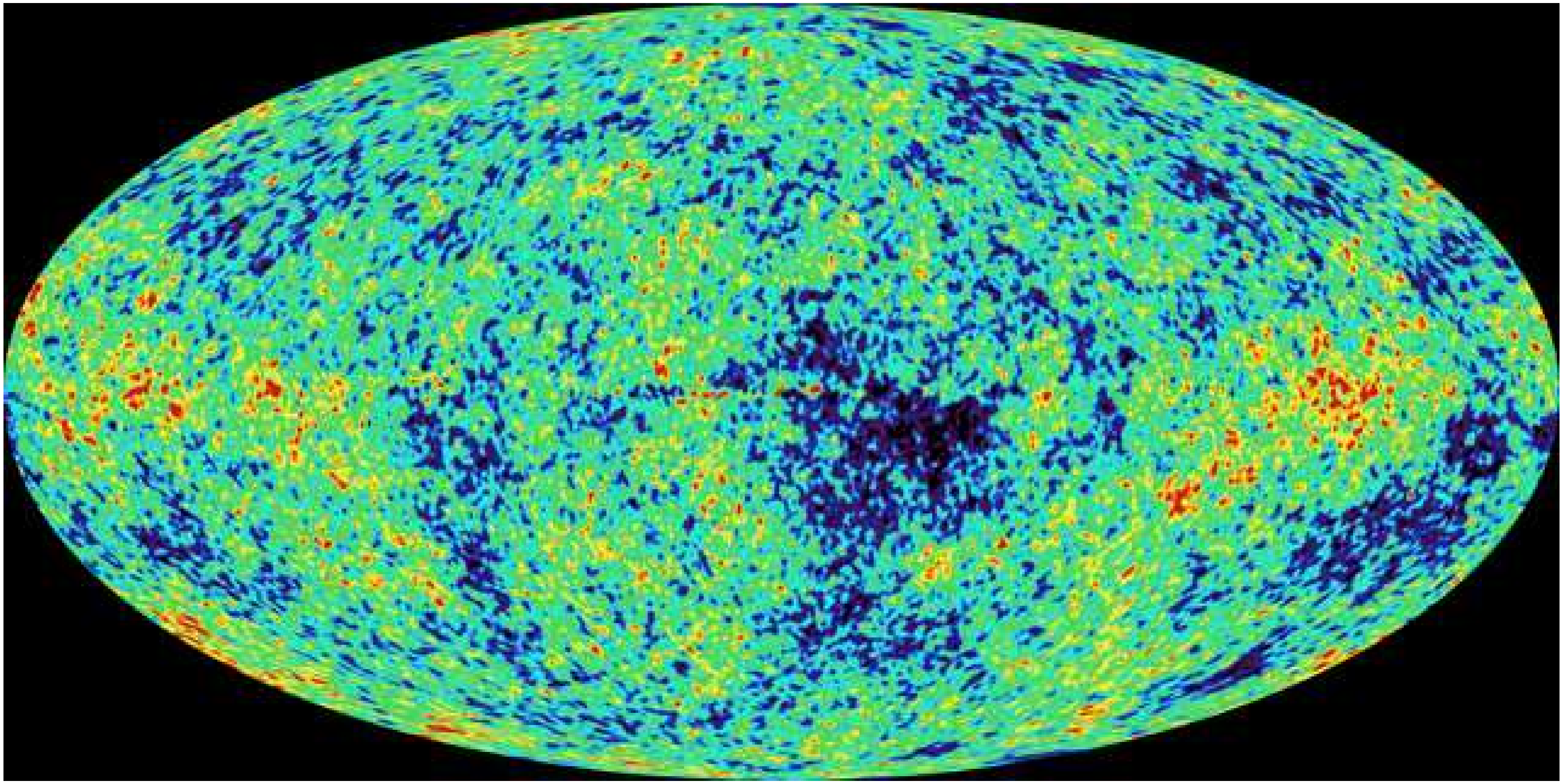
Fermilab: $4x10^{-12}$s
LHC: 10^{-13}s

Strong CP Violation?

??? Quantum gravity?

Early Universe



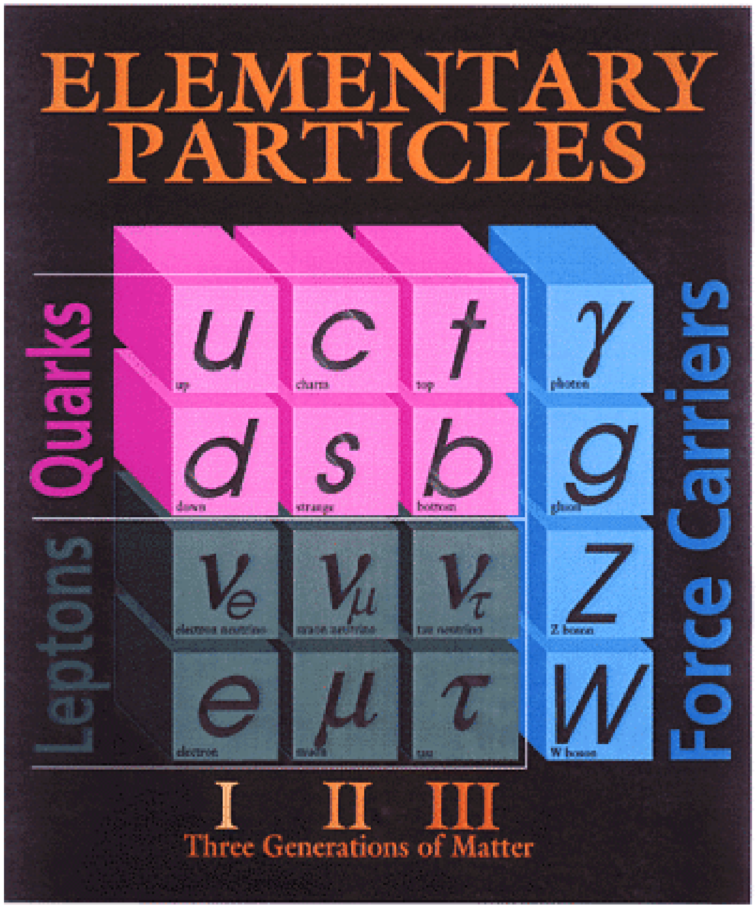


The Standard Model

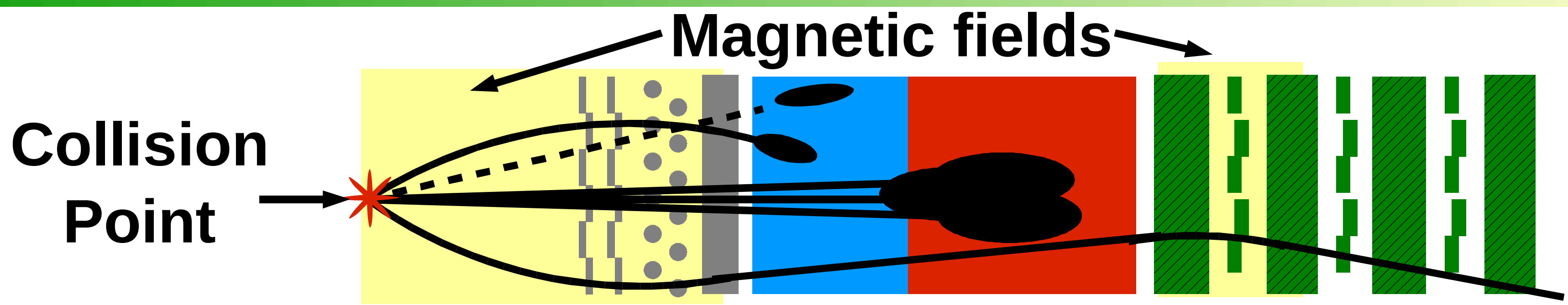
- Describes the fundamental (as far as we know) building blocks of matter and how they interact
- All matter consists of quarks and leptons (fermions)
  - 6 quarks, 6 leptons each divided into 3 generations
- Interact by exchanging force carriers (bosons)
  - gluon: strong force, binds nuclei
  - W/Z: weak force, β decay
  - photon: electromagnetic force
- EM and weak forces unified above ~100GeV
  - Single Electroweak force

The Standard Model

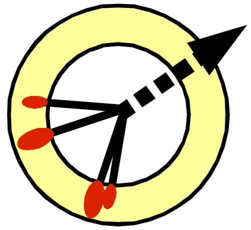
- Annoyingly persistent: survived for > 20 years
  - but cracks (finally!) starting to appear....
    - neutrino oscillations
- We know it isn't complete
  - Four forces: Gravity?
  - Higgs boson (or something else) needed to give particles mass
  - Dark matter
- Many theories (SM included) expect new physics between EW and TeV (100GeV-1TeV)
  - DØ pushing at boundaries, LHC will cover them



Particle Detectors



- Tracking detectors, inside magnetic field
  - Measure momentum and charge of charged particles
- Calorimeters: EM + Hadronic
  - Measure particle energies from showers
- Muons: penetrate entire detector, charged
- Neutrinos: penetrate light years of material
  - neutral, missing transverse momentum



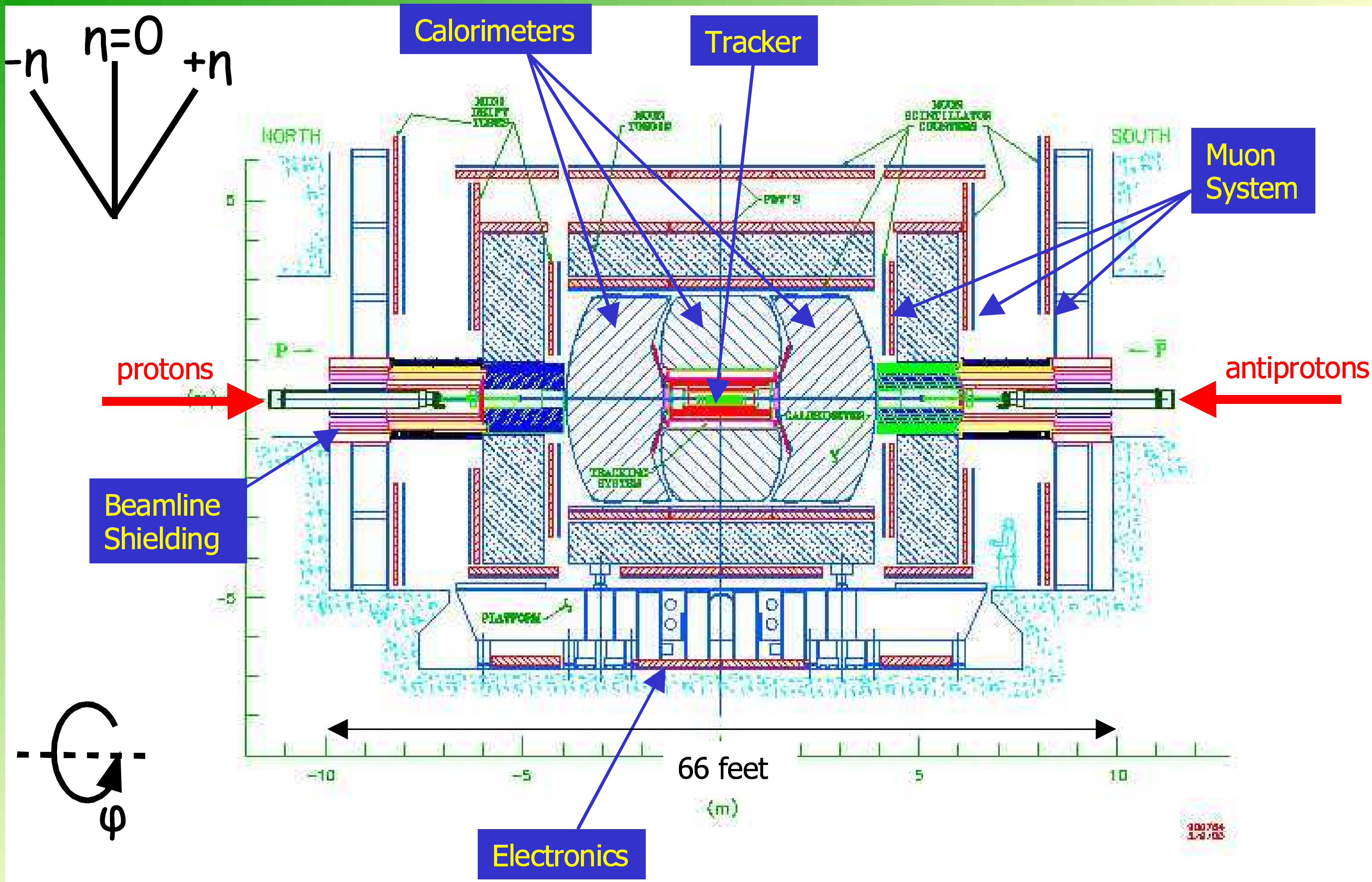
The DØ Detector

- DØ detector recently heavily upgraded for the newly upgraded Tevatron
  - Bunch crossing down to 132/396ns from 3.5μs
- Practically a new detector!
  - Only Calorimeter remains mainly unchanged
- Central tracking system completely replaced
  - Magnetic field added (no field in Run I!)
- Trigger and DAQ system completely replaced
  - Higher trigger rate due to increased luminosity
  - Need to make decision once every bunch crossing

The DØ Timeline

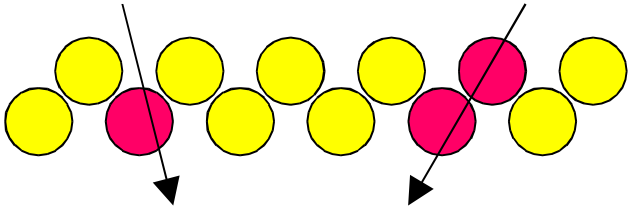
1983	First meeting at Stonybrook
1984	Approval from U.S. DoE
1985-1987	Detector R&D
1988-1991	Construction
1992-1996	Data taking for Run I
1993	First Paper published
1995	Discovery of Top Quark
1996-2000	Ugrade for Run II
2000	100^{th} Paper Published
2001	Run II starts...

The DØ Detector

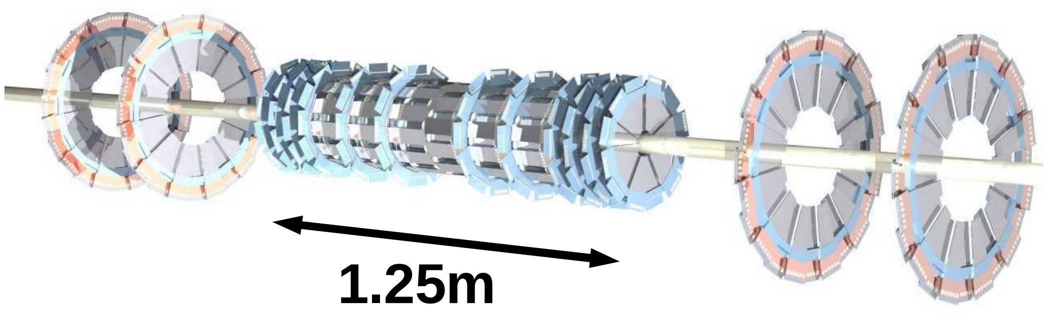


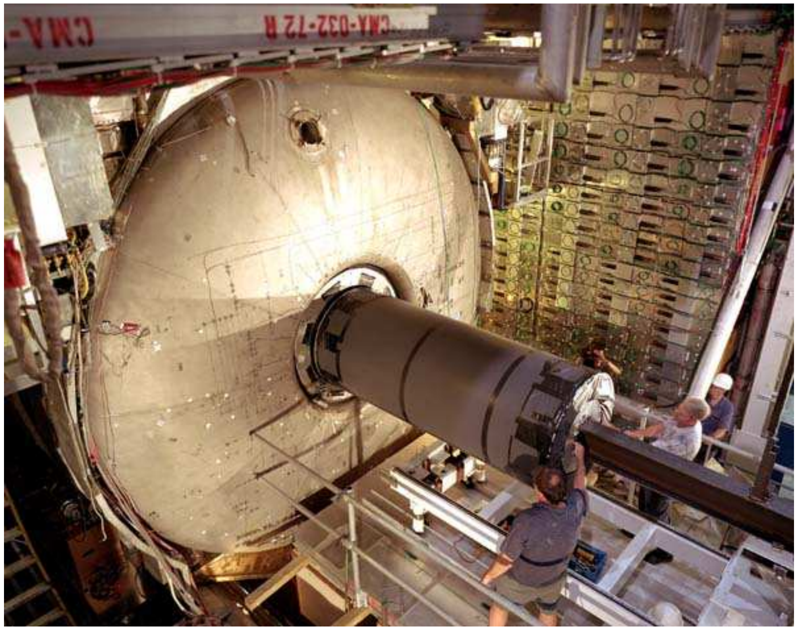
The DØ Tracking Detectors

- Two types of tracking detector
  - Silicon: 800,000 channels
  - Scintillating fibre



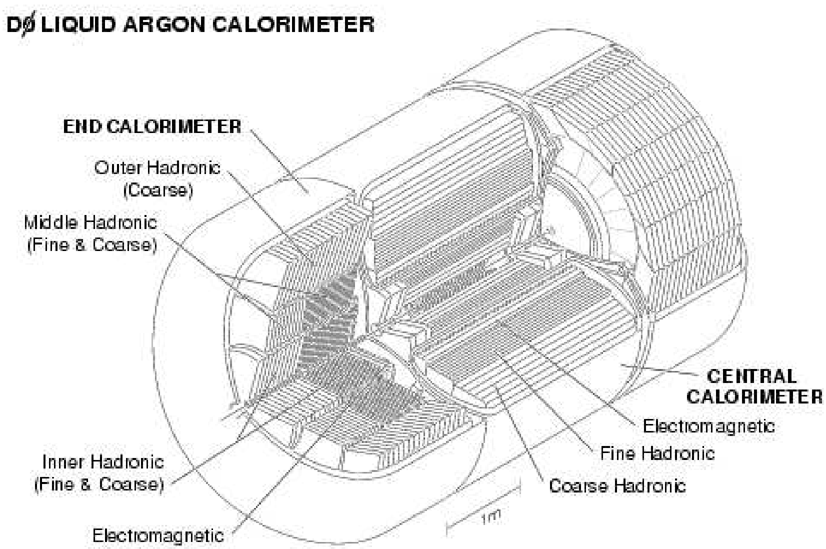
- Inside super-conducting solenoid which provides 2T magnetic field





The DØ Calorimeter

- Liquid Argon/Uranium - first time used
  - Both EM and hadronic regions: EM, FH, CH
  - Nearly compensating: e/h = 1.04-1.11
- Granularity 0.05x0.05 - 0.10x0.10 in η, φ



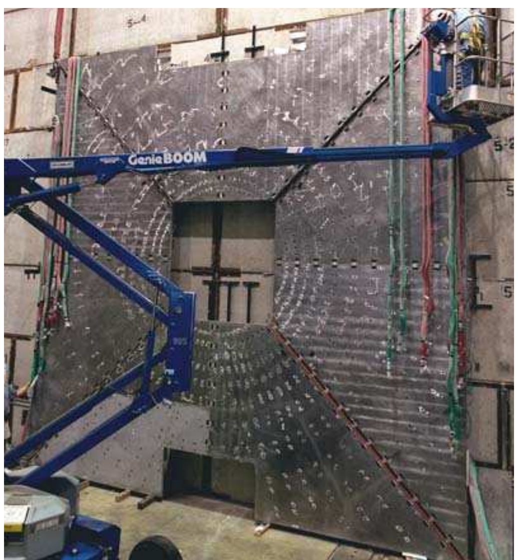
$$\textbf{Electrons}: \frac{\sigma}{E} = \frac{16\%}{\sqrt{E}} \oplus \frac{0.14}{E} \oplus 0.003$$

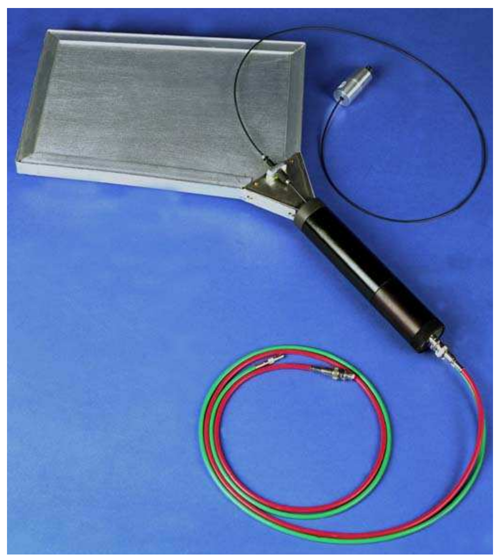
$$\textbf{Pions}: \frac{\sigma}{E} = \frac{41\%}{\sqrt{E}} \oplus \frac{1.28}{E} \oplus 0.03$$

$$\textbf{Jets}: \frac{\sigma}{E} \approx \frac{80\%}{\sqrt{E}}$$

The DØ Muon Detector

- DØ muon system has three planes: A,B and C
- Surrounds detector, fewer planes underneath
- Combination of technologies
  - Wire chambers for position
  - 2-3 scintillator planes for timing
  - Toroid magnet between A and B



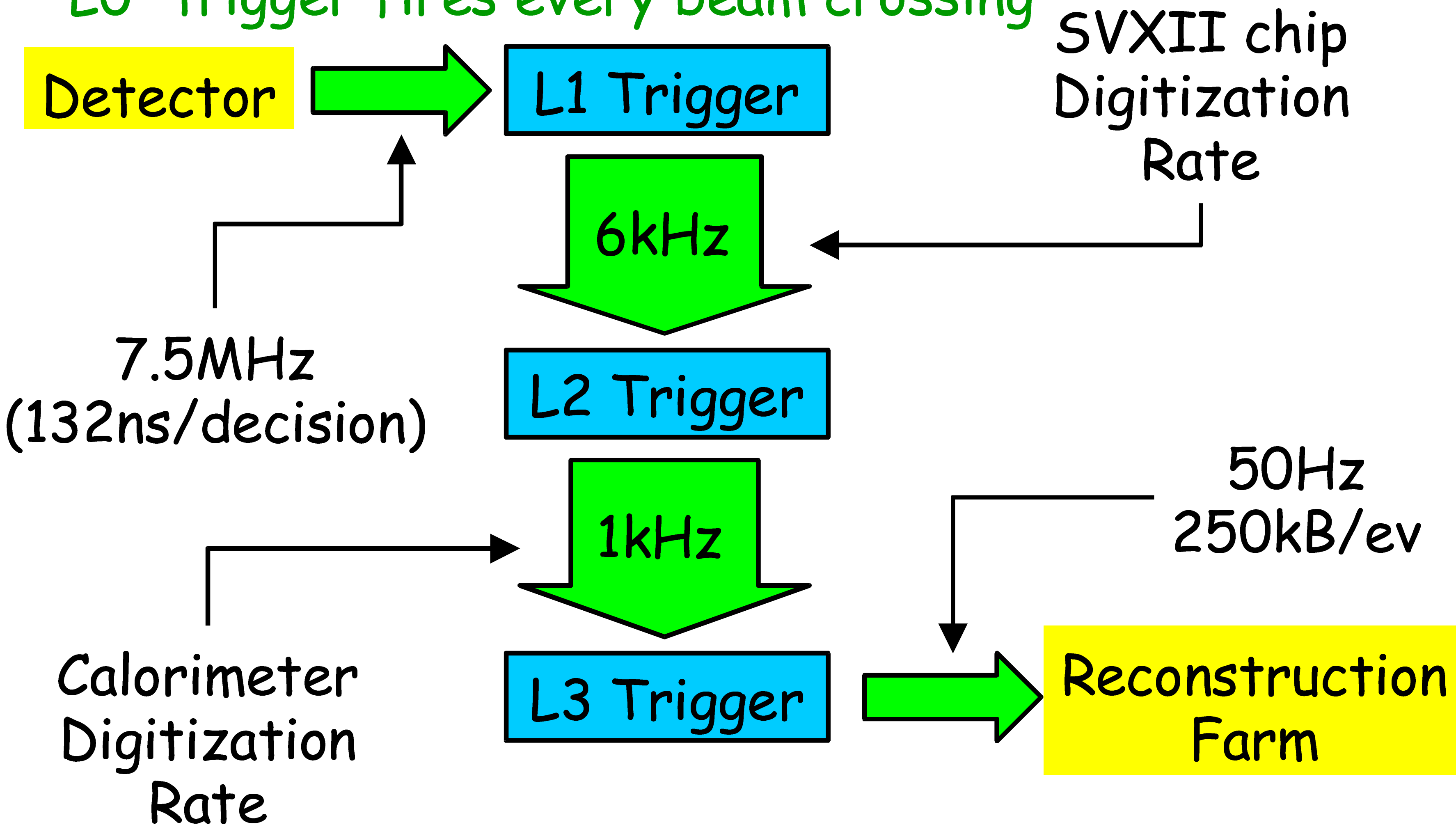


The DØ Trigger

- Tevatron beams cross every 396ns
- Why not just readout on every crossing?
  - Need to digitize all channels at 7.5MHz (expensive)
  - Enormous output data rate
    - 7.5MHz x 0.25MB = 1.9TB/s!
  - Most of what we readout will be very uninteresting
- Need to decide if it is worth reading out for a given beam crossing...need a Trigger!
- Must be a lot faster than the full readout
  - Use fraction of full readout data
  - Run simple algorithms - not a full reconstruction
- Must cope with a large variety of physics signatures

The DØ Trigger

- DØ Trigger split into 3 levels
  - "L0" trigger fires every beam crossing

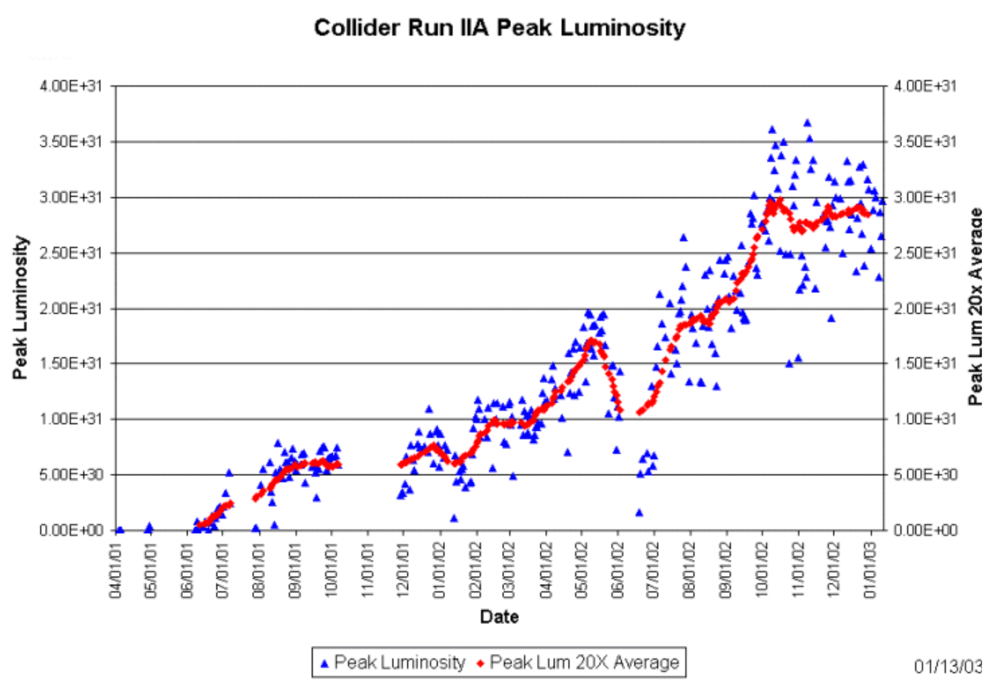


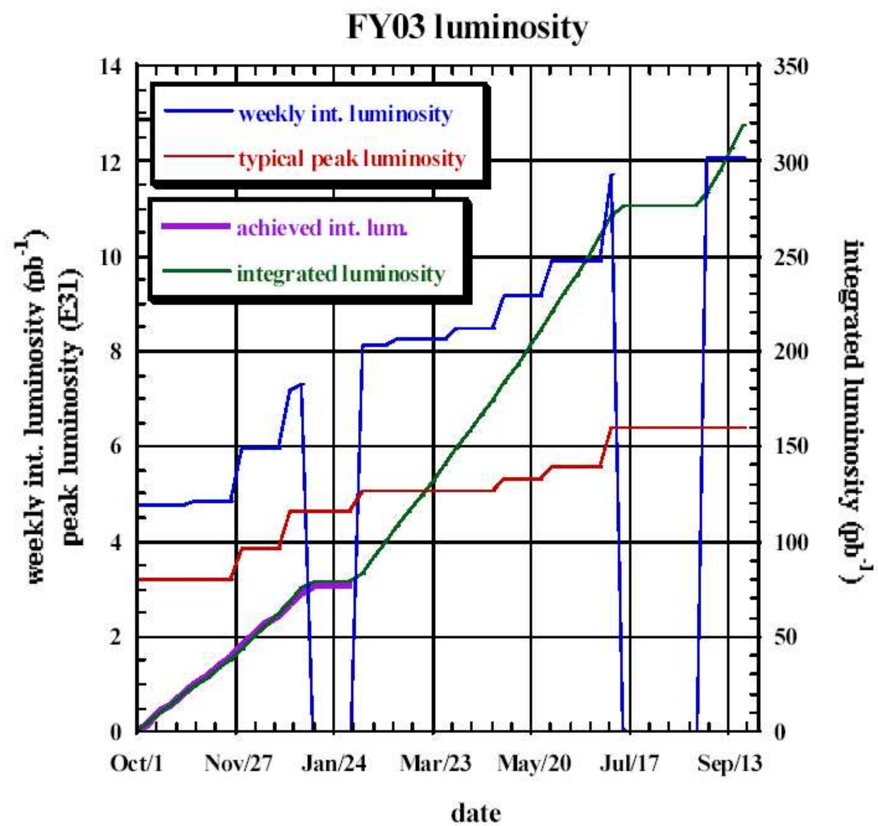
DØ Detector Status

- Commissioning complete
  - Tracking trigger mostly in place but not yet certified
- Accelerator luminosity currently ~15% design
  - Run II peak luminosity $4.1 \times 10^{31} cm^{-2} s^{-1}$ (4.1 x Run I)
  - Just returned from a shutdown when material was removed from the beam pipe
- $80 pb^{-1}$ Integrated luminosity delivered to date
  - Current data taking efficiency ~85%
- Predicted luminosity by the summer conferences will be ~$200 pb^{-1}$ or 2 x Run I
  - $200 pb^{-1}$ means a process with σ=1 pb will happen 200 times

DØ Luminosity

- Moriond 2002: 1 pb^{-1} data, Summer: > 5 pb^{-1} data
- Moriond 2003: > 50 pb^{-1} data
- Summer 2003: > 200 pb^{-1} data





DØ Physics Program

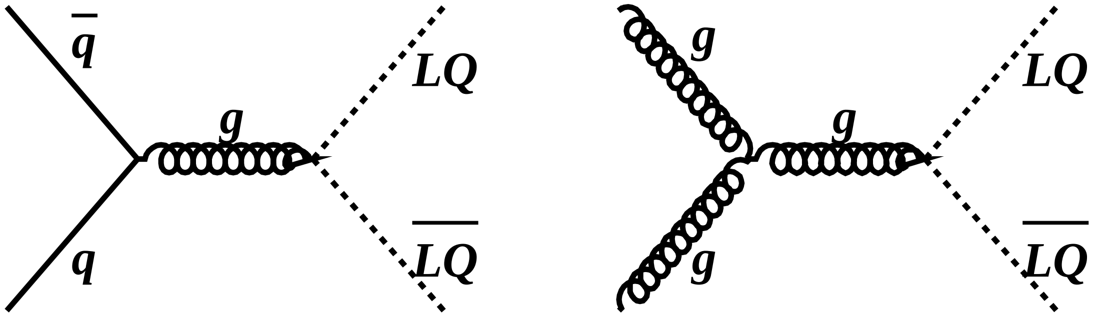
- Large variety of physics being studied in Run II at D0
  - Search for New Phenomena
  - Search for the Higgs Boson
  - Top physics
  - B Physics
  - Electro-weak physics
  - QCD

Search for New Phenomena

- Currently Tevatron is the highest energy accelerator in the world
  - Good place to look for new things
- Many candidate theories being looked for:
  - Supersymmetry (see tomorrow's seminar)
  - Lepto-quarks
    - Symmetry between quark and lepton sectors
  - Large extra dimensions
    - Possibility of > 3 spatial dimensions
  - Generic searches
    - Sleuth and Quaero (web based access to DØ data)

Leptoquarks

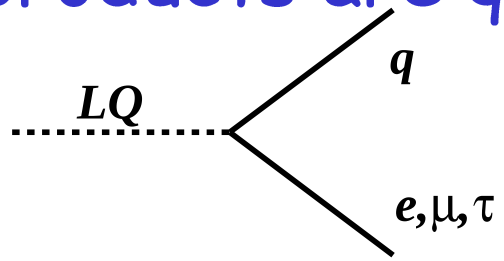
- Lepton and quark sectors of the Standard Model appear very similar
  - 6 of each divided into 3 generations
- Theories suggesting a symmetry between the two give rise to new particles called Leptoquarks
  - Couple to the strong and weak forces
- Produced in pairs
  - Scalar and vector
    - Consider scalar

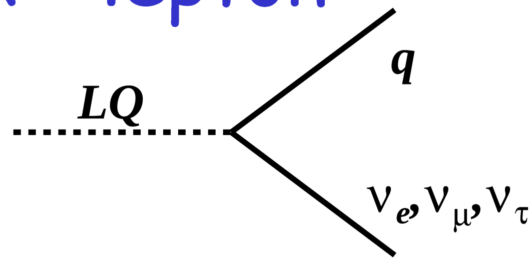


- Three generations of Leptoquark: LQ_1, LQ_2, LQ_3
  - Decays to same generation of quarks/leptons
  - Prevents processes like: e→μ,u→c (Flavour Changing NC)

Leptoquarks

- Decay products are quark + lepton





Branching Ratio = β **Branching Ratio = (1-β)**

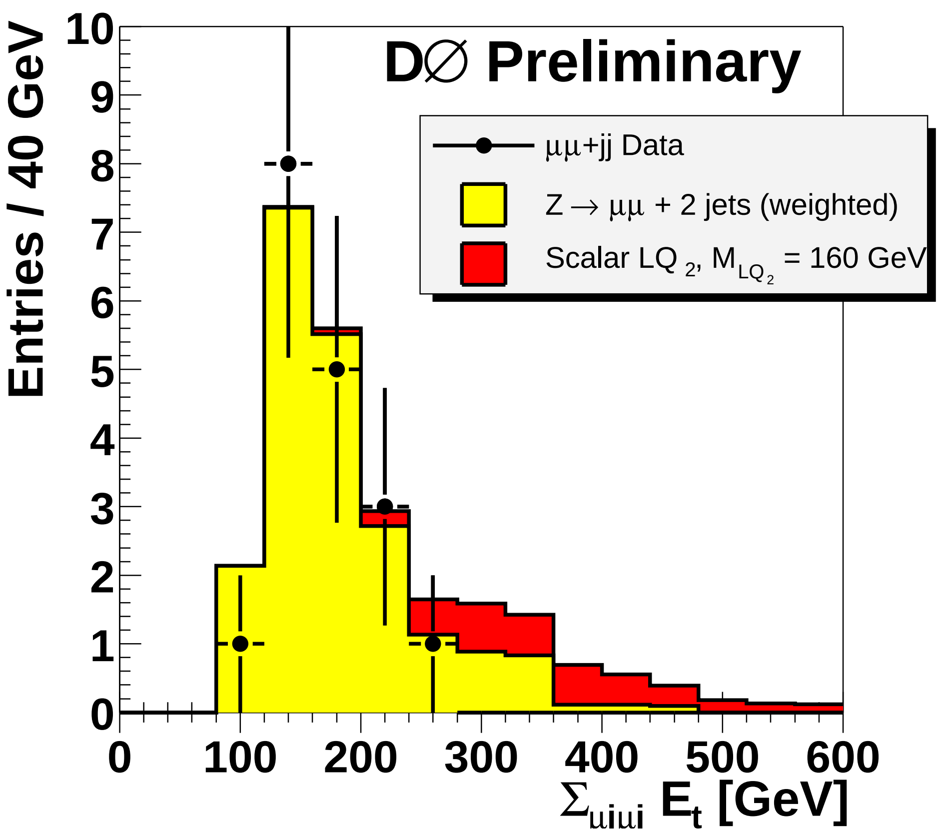
- Final states looked for are 2 jets + 2 leptons
  - 2 jets + 2 e, 2 jets + 2μ, 2 jets + missing ET
- Preliminary RunII analysis looks for second generation scalar Leptoquarks
  - i.e. 2 jets + 2 muons [assume β=1]
  - Scalar LQs have model independent cross-section
- Backgrounds from standard model processes
  - Z+jets (Z→μμ), ttbar→μμ+2jets+MET,WW+jets (W→μν)

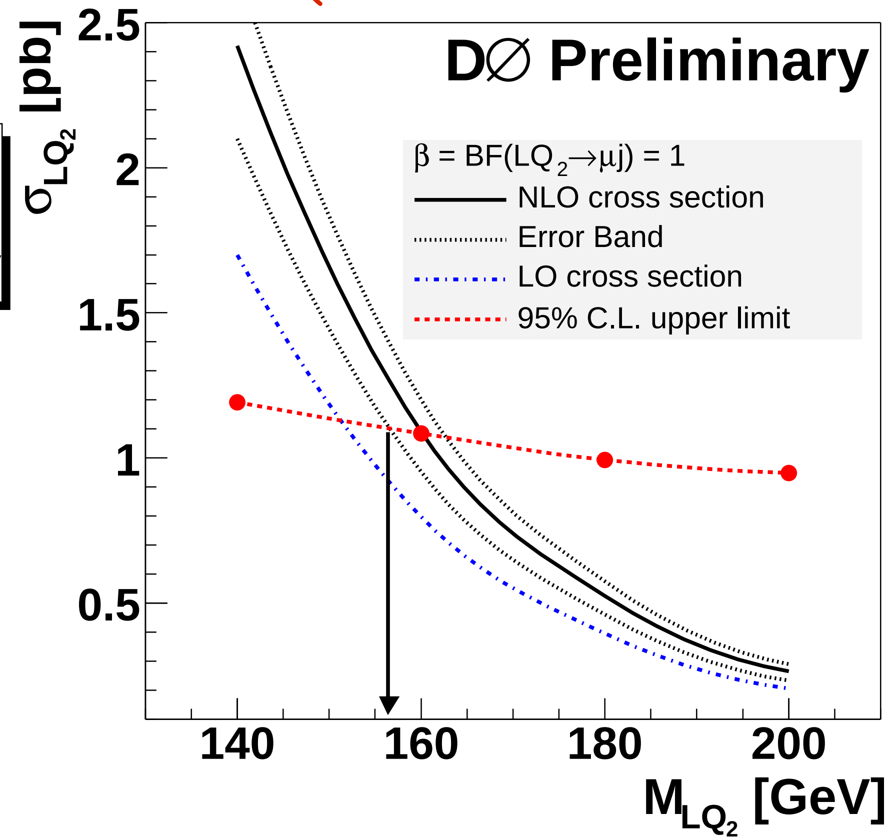
Leptoquark Event Selection

- 2 muons each with
  - Transverse momentum, $p_T > 15$ GeV/c
  - $|\eta| < 2.0$ after excluding the region where $|\eta| < 1.0$ and $-1.96 < \varphi < -1.17$ (detector supports)
- Cosmic ray muons removed (timing cut)
- Invariant muon mass, $M_{\mu\mu} > 60 GeV/c^2$
- Muon isolation requirements
  - Calorimeter halo < 2.5 GeV (0.4 cone-0.15 cone)
  - Track Halo < 2.5 GeV/c (track momenta in 0.5 cone)
- At least 2 jets (0.5 cone algorithm) with transverse energy, $E_T > 20$ GeV and $|\eta| < 2.4$

Preliminary LQ_2 Results

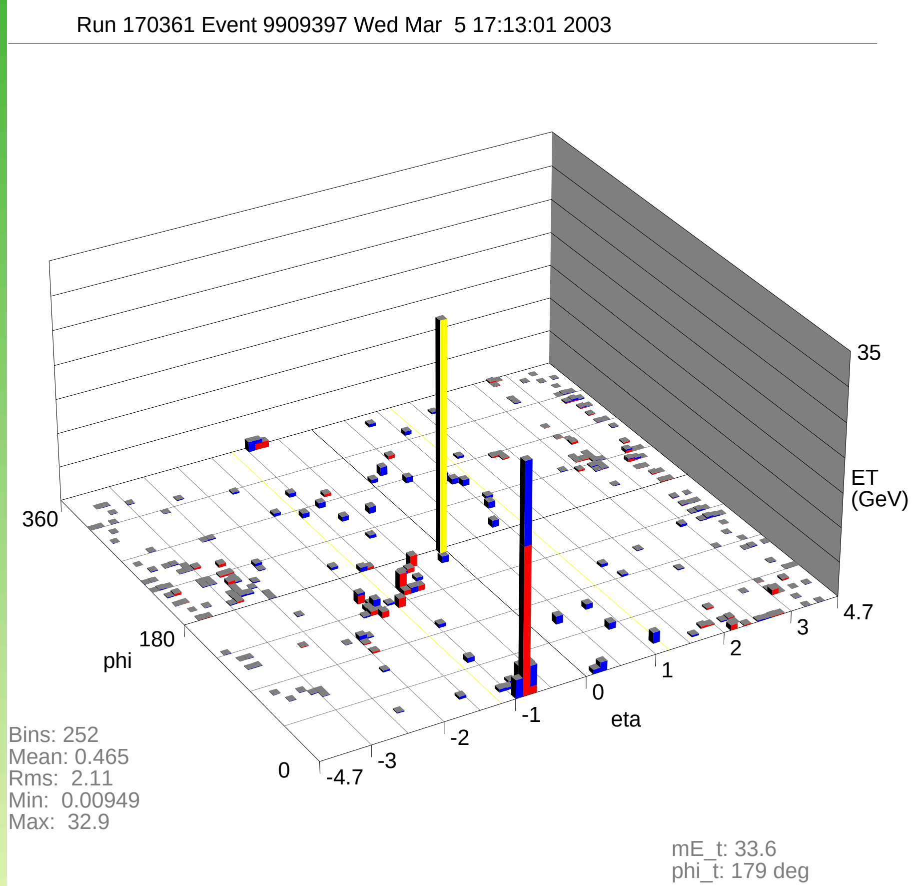
- Final cut: $M_{\mu\mu} > 110 GeV/c^2$ (removes $Z \rightarrow \mu\mu$)
- Zero events observed (SM ~4±0.6 [stat.])
  - $M_{LQ2} > 157 GeV/c^2$ for $\beta=1$ [Run I $M_{LQ2} > 200 GeV/c^2$]

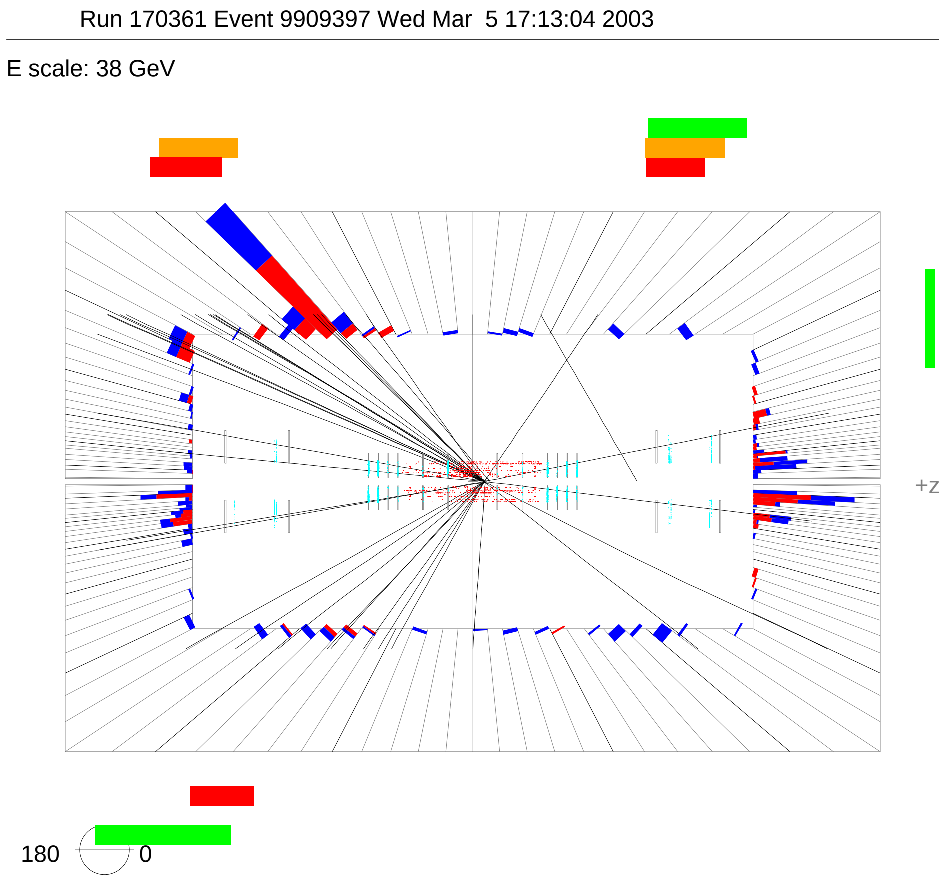




Leptoquark Events

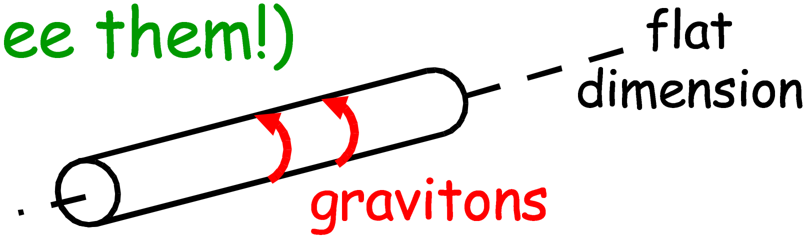
- Event with highest $M_{\mu\mu}$=108GeV/c^2 and 2 jets



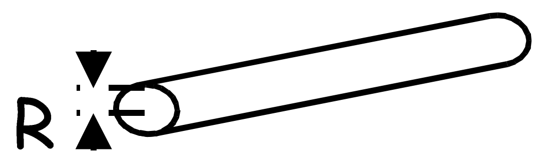


Extra Dimensions

- Possibly > 3 spatial dimensions
  - "Extra" dimensions compactified to a small scale (otherwise we would already see them!)



- Extra dimensions only accessed by gravity
  - Relative weakness of gravity at large distances is because it is "diluted" by volume of extra space
- Theories have 3 free parameters:
  - Fundamental mass scale, M_S (M_D)
  - Compact dimension's radius, R
  - Number of compact, extra dimensions, n

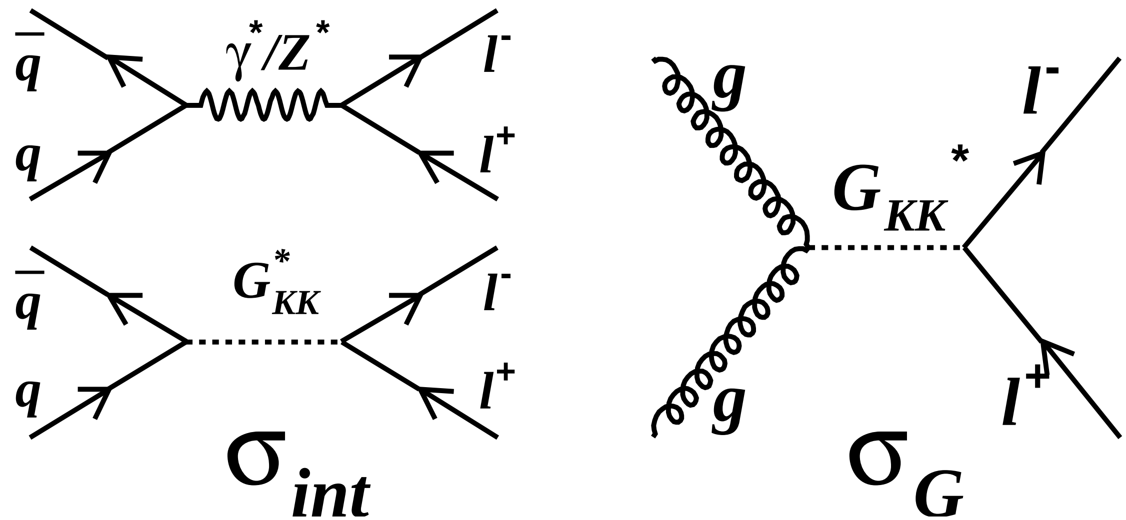


Other Experimental Limits

- Limits on R come from measurements of the gravitational potential, assuming $M_S \sim 1 TeV/c^2$
  - n=1 excluded by solar system
  - R< 0.19 mm for n=2 (Eöt-wash)
- Cooling of SN1987A by graviton emission (preventing the neutrino flux) limits M_S:
  - M_S> ~30 TeV/c^2, n=2; M_S> ~2 TeV/c^2, n=3
- Smoothness of the cosmic diffuse gamma radiation (CDG) due to graviton decay, $G_{KK} \rightarrow \gamma\gamma$
  - M_S> ~100 TeV/c^2, n=2; M_S> ~5 TeV/c^2, n=3

Extra Dimensions Signature

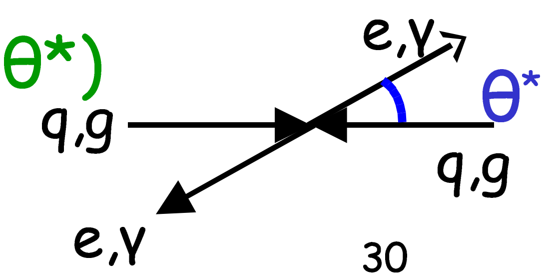
- Look fermion or boson pair production by virtual graviton exchange
  - Two additions to SM cross-section
    - Interference term
    - Gluon term



- Cross section given by:

$$\frac{d^2\sigma}{dM\,d\cos\theta^*} = f_{SM} + f_{int}\eta_G + f_{KK}\eta_G^2$$

- f_{SM}, f_{int} amd f_{KK} are functions of (M,cosθ*)
- $\eta_G = F/M_S^4$ F is model dependent ≈1

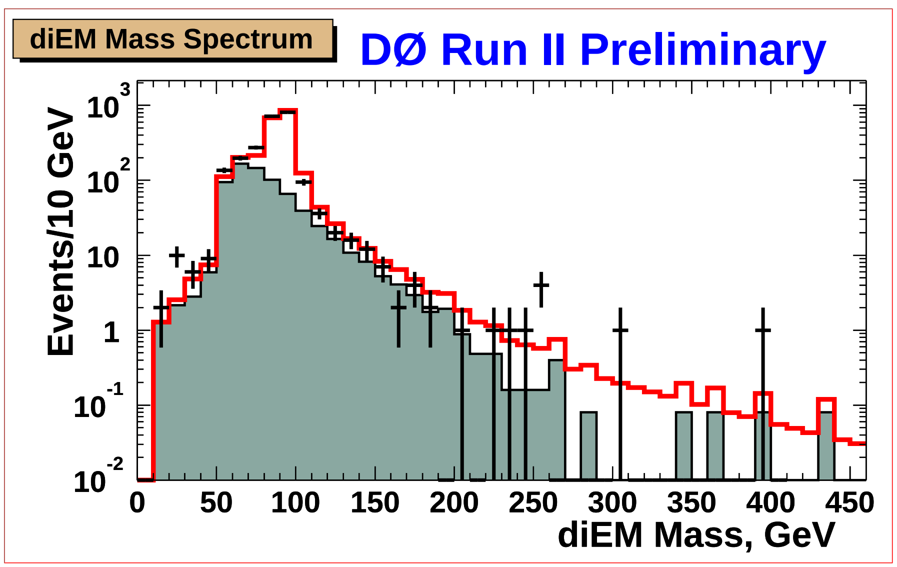


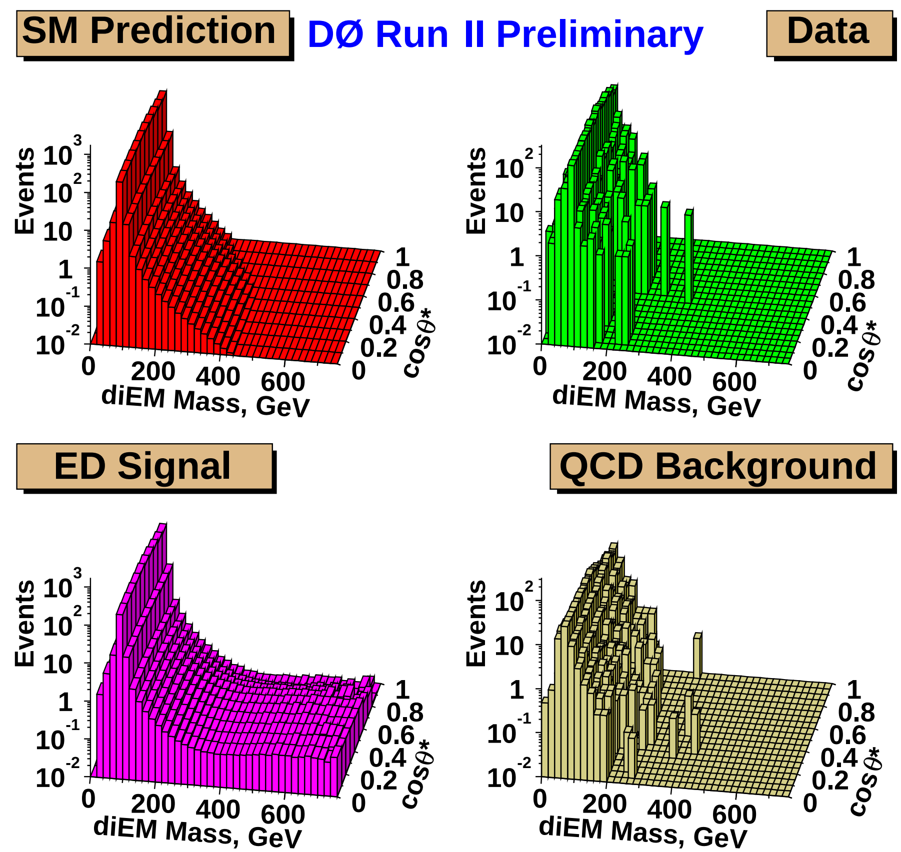
Extra Dimensions Signature

- Gravity enhanced by phase space
  - Kaluza-Klein excitations
    - Winding of graviton about the compactified dimensions
    - Interaction as $1/M_S^2$, not $1/M_{planck}^2$
- Two analyses using Run II data at DØ:
  - $G_{KK} \rightarrow e^+e^-/\gamma\gamma$ and $G_{KK} \rightarrow \mu\mu$
- $G_{KK} \rightarrow e^+e^-/\gamma\gamma$ uses 50 pb^{-1} data
  - 2 EM objects with E_T > 20 GeV, EM fraction > 0.9
  - Within good fiducial region of the calorimeter
    - $|\eta|<1.1$ or $1.5 < |\eta| < 2.4$ (gap between cryotstats)
  - Cut events with > 2 EM objects with E_T > 5 GeV and with > 25 GeV of missing E_T

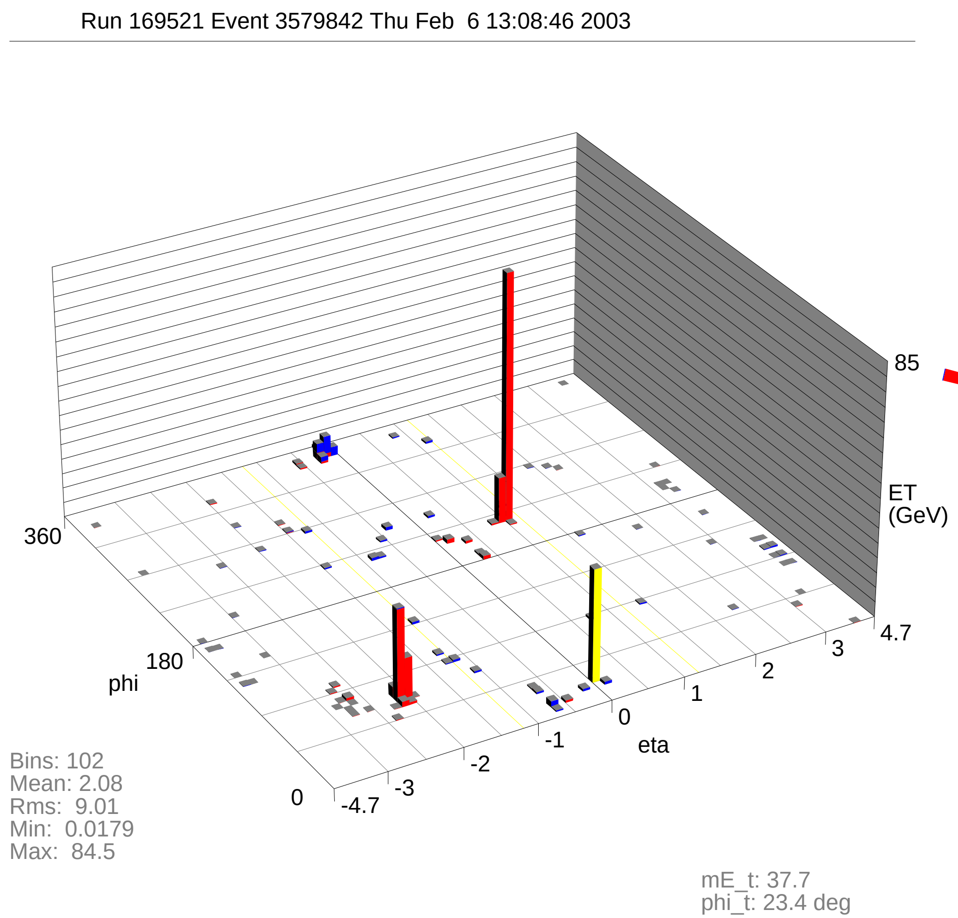
Extra Dimensions Di-EM

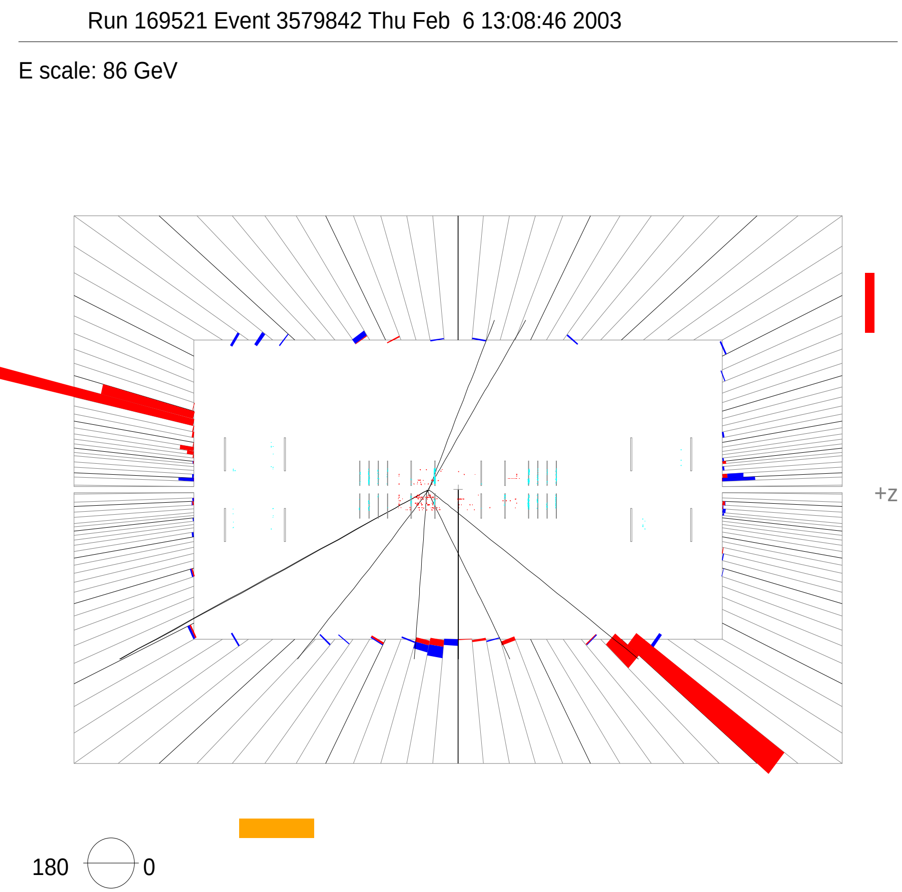
- Compare SM+instrumental backgrounds to data
  - Drell-Yan + direct photon events
  - Jets faking electrons
- Measure: $\eta_G < 2.1\ \mathrm{TeV}^{-4}$ 95% CL
  - $M_S > 1.12\ \mathrm{TeV}/c^2$ [F=1]
  - Run I limit: $> 1.2\ \mathrm{TeV}/c^2$





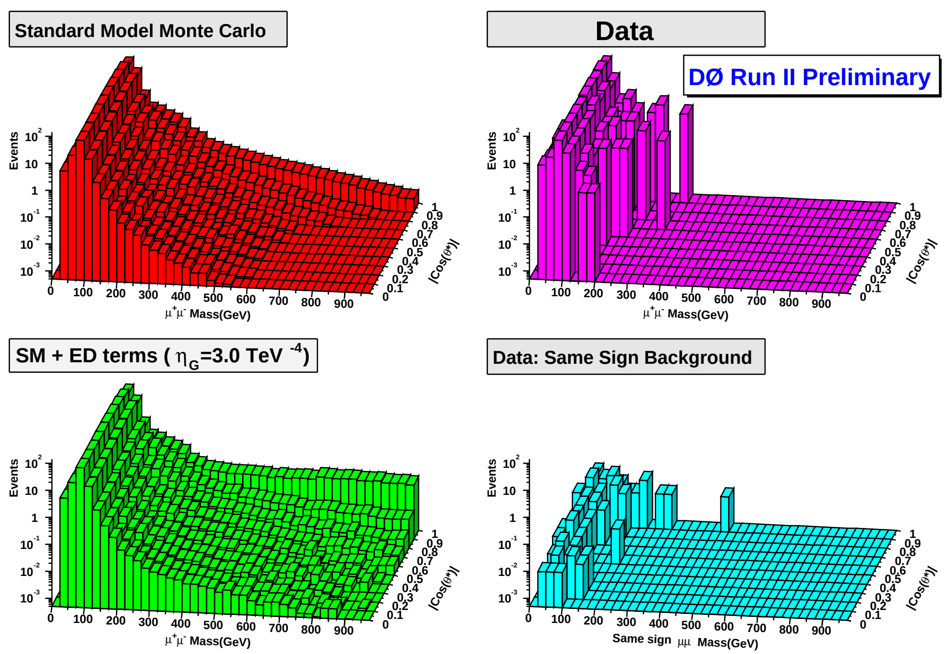
LED Di-EM Candidate





LED Di-Muon Analysis

- Look for the same physics but with $G_{KK} \rightarrow \mu\mu$
  - $30 pb^{-1}$ data used
- Events similar to LQ analysis:
  - Transverse momentum, $p_T > 15$ GeV/c, (η,φ) acceptance...
  - Isolation cuts: E-Halo < 2.5GeV and Track-Halo< 2.5 GeV/c
  - $\mu\mu$ mass > 40 GeV/c^2
- Data consistent with SM background
  - $\eta_G < 2.5$ TeV^{-4} 95% CL
  - $M_S < 0.79$ TeV/c^2 [F=1]



Sleuth

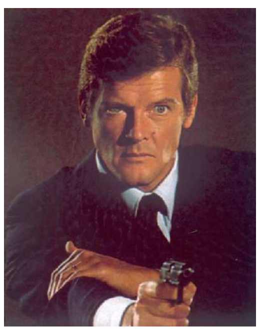
- Search for new physics in a model independent way
  - Divide data up into regions about sets of data points
  - Choose the region which is most "interesting"
    - Defined as: "disagrees with SM background the most"
  - Determine # hypothetically similar experiments which would produce even more interesting data
- Result for Run I in several channels
  - 89% of similar experiments would be more interesting!
- Tested with Top
  - 1.9σ excess in eμ+MET+2jets vs. 4.6σ for top analysis
  - Not as good as targeted search…but model independent

Search for the Higgs

- The Standard Model needs the Higgs boson to give particles their mass
- Upper limit for Higgs mass from W^+W^- unitarity limit: $M_{Higgs} < 1$ TeV/c^2
  - Above this >100% chance of interaction!
- Current best limits on the Higgs mass come from LEP II at CERN (electron-positron collider)
  - LEP II limit: $M_{Higgs} > 116$ GeV/c^2
- Only missing SM parameter is Higgs mass
  - Plug in other parameters and calculate the Higgs mass
  - Current best fit of SM favours M_{Higgs} < LEP II limit

Higgs Mass Mechanism

- Higgs field "slows" particles down = mass
  - Particle mass depends on coupling strength



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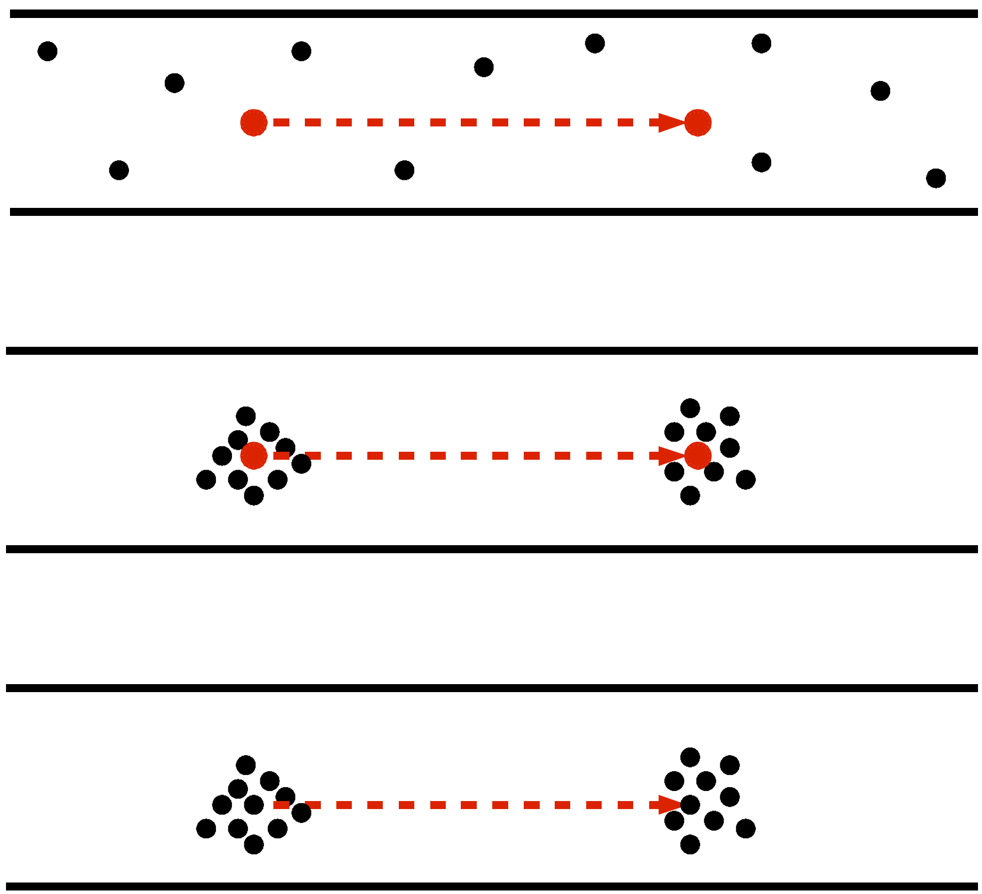
Rumour



<u>Low mass case:</u>

small coupling,

easy to move

<u>High mass case:</u>

strong coupling,

crowd to move

<u>Higgs boson case:</u>

no real person,

self-coupling

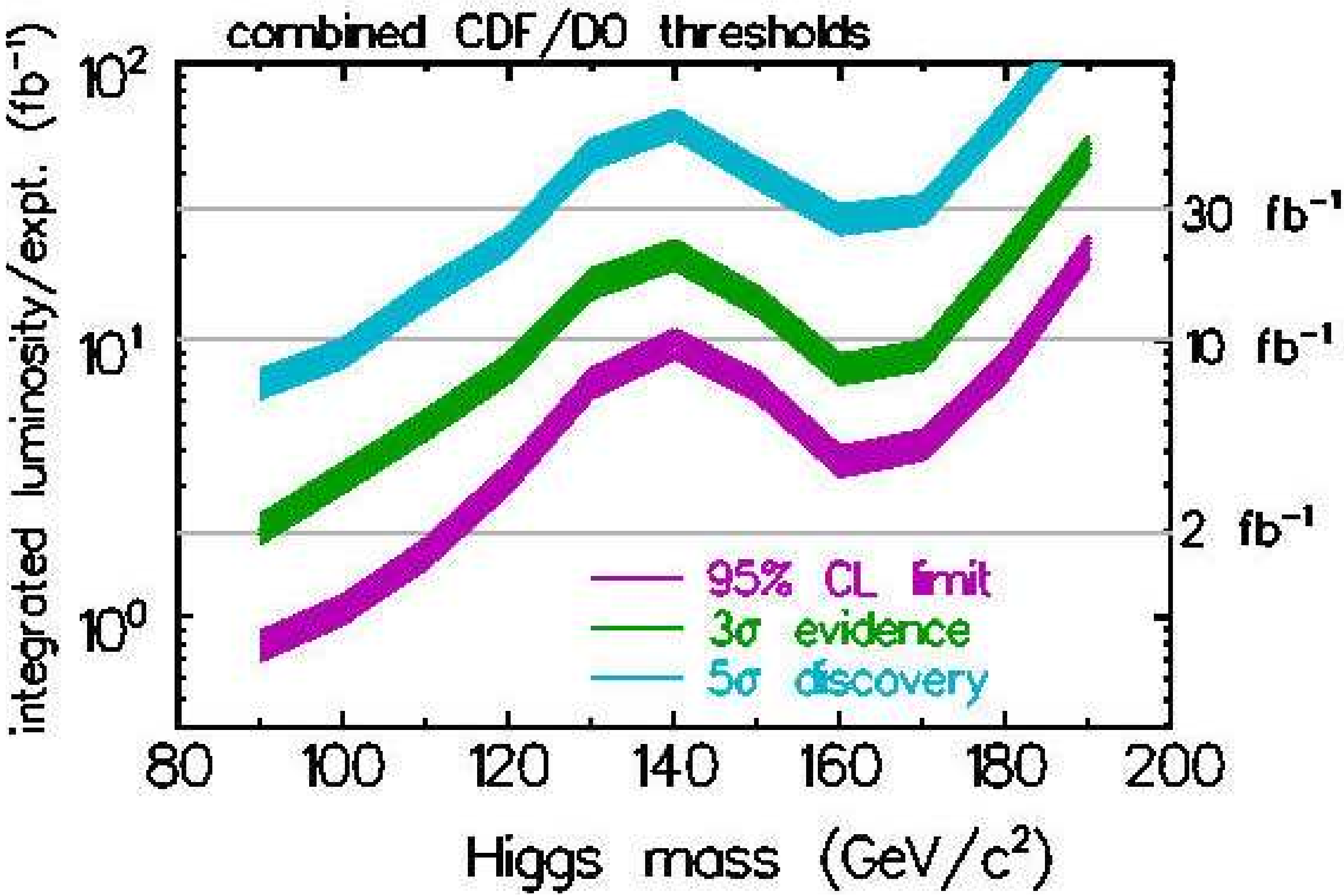
Tevatron Higgs Signal

- Higgs hunting is hard at the Tevatron
  - Low cross-section, lots of background
- Search for Higgs uses associated production

$$p\bar{p} \rightarrow WH + X, \quad p\bar{p} \rightarrow ZH + X$$

  - Decay H→bbbar: dominant for M_{Higgs}< 130GeV/c^2
  - Decay H→$WW^{(*)}$ dominant for M_{Higgs} >130GeV/c^2
- Run IIa ~2 fb^{-1} integrated luminosity
  - Limit ~ LEP II, then the silicon detector dies!
- Run IIb total of 6-11 fb^{-1} integrated luminosity
  - ...but Run IIb very close to LHC turn on (1- 2 years?)

Search for the Higgs

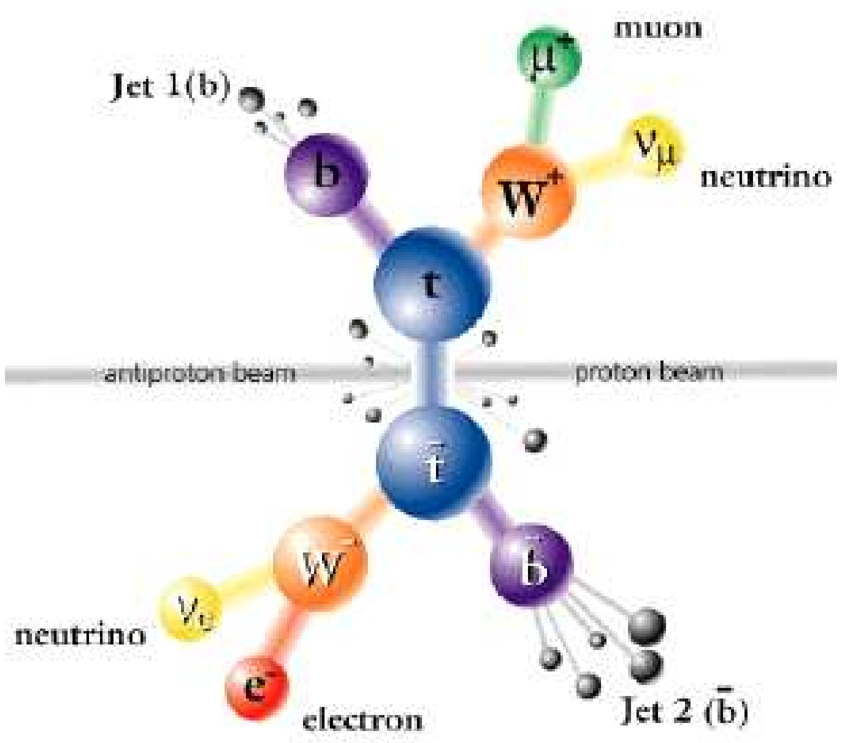


Top Physics at DØ

- Top quark physics
  - Top quark discovered in Run I
  - Tevatron is the only place in the world where you can study the Top quark until the LHC starts up
- Far more top in Run II than in Run I (10's→100's)
  - Increase in energy from 1.8 to 1.96 TeV increases ttbar cross section by ~30%
  - Luminosity will give factor ~20 more ttbar in Run IIa
- Lots of interesting, new physics to study
  - Improve top mass and cross-section mesasurements
  - Search for single top production
  - Unconfined quark physics since top decays very quickly

t-tbar Cross-section

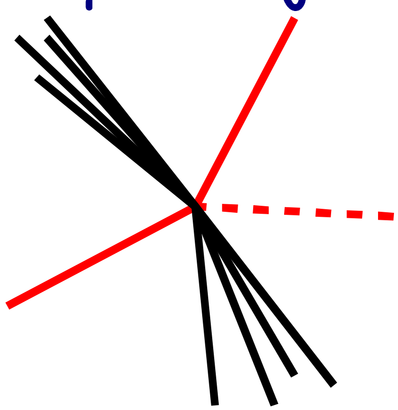
- Preliminary measurement of cross-section from RunII data at 1.96TeV
  - Run I measured cross-section at 1.8TeV
- Top decays too fast to observe directly
  - look for decay products
- Predominant decay: $t \rightarrow Wb$
  - W decays to quarks (jets) or [e,μ,τ]+neutrino
  - b quark produces a jet
- Several different sets of decay products to look for



Decay Channels

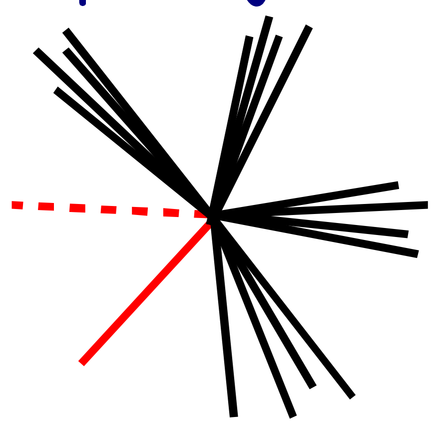
- 6 decay channels considered (all jets in progress)
  - Only use states with one or more e,μ
    - τ heavy enough to decay to hadrons: looks like a jet
- Tagged b jets: b→Wc and W→μν
  - look for jets with an associated muon

2 leptons+jets



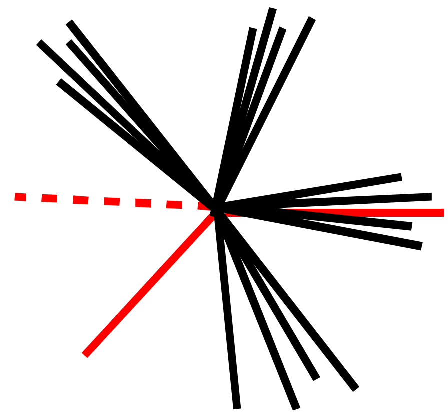
Pure and efficient, low branching ratio

lepton+jets



Efficient but not pure

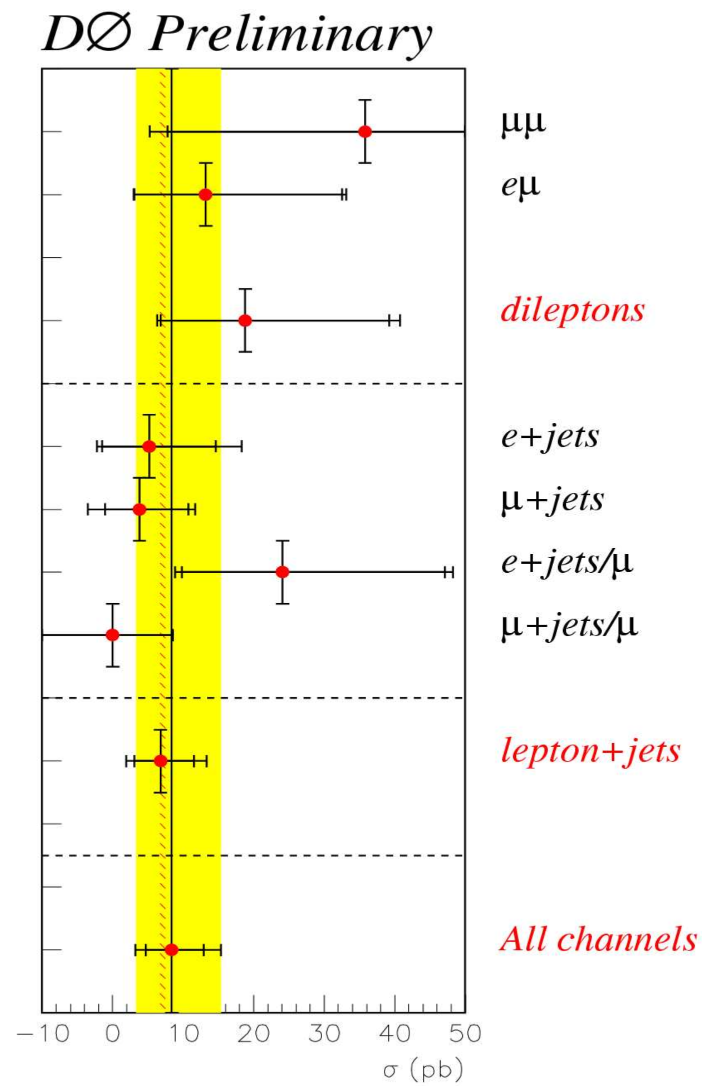
lepton+tagged jet



Pure, but not efficient

Analysis

- Data sample: 30-50 pb^{-1} depending on channel
  - 12pb^{-1} without μ data
  - 8pb^{-1} with low tracking efficiency (recoverable)
- Trigger: calorimeter and muon detectors
  - Conditions applied at all three levels: L1,L2,L3
- Selection criteria similar to those for NP analyses



Results

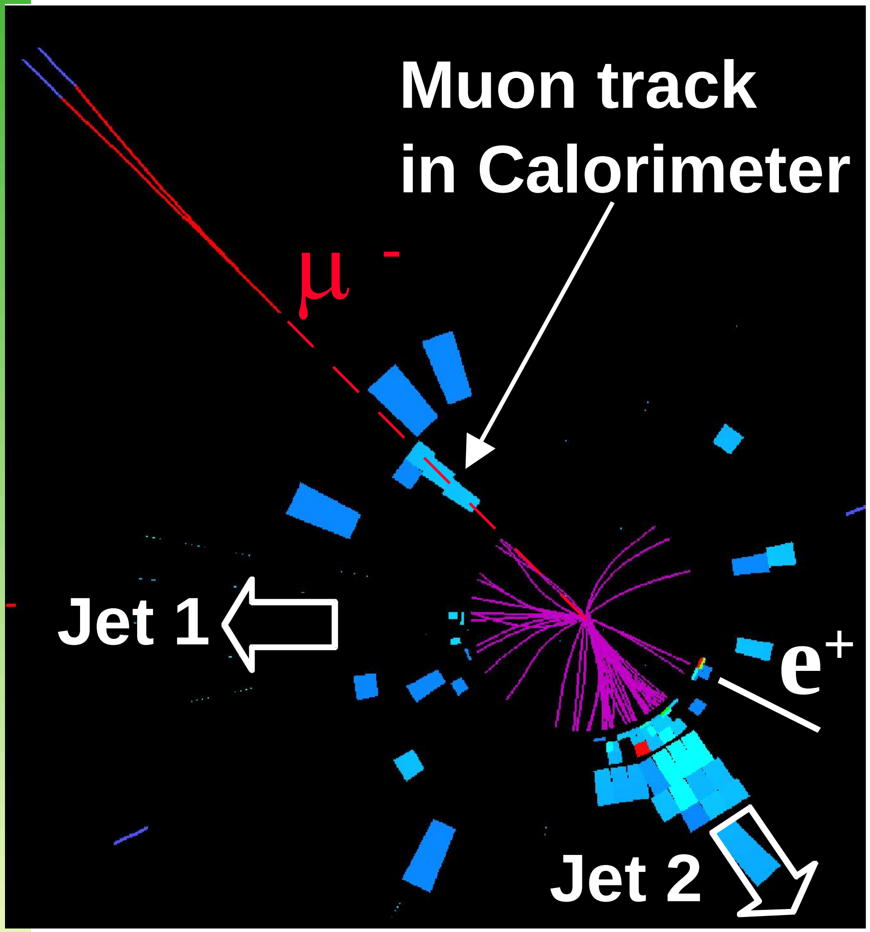
- Theory expects cross-section to be ~30% higher at 1.96TeV vs. 1.8TeV (Run I)
  - 6.7-7.5pb Next to Leading Order (NLO) calculations
  - 8.8pb NNLO estimate
- Run II preliminary result with all channels combined

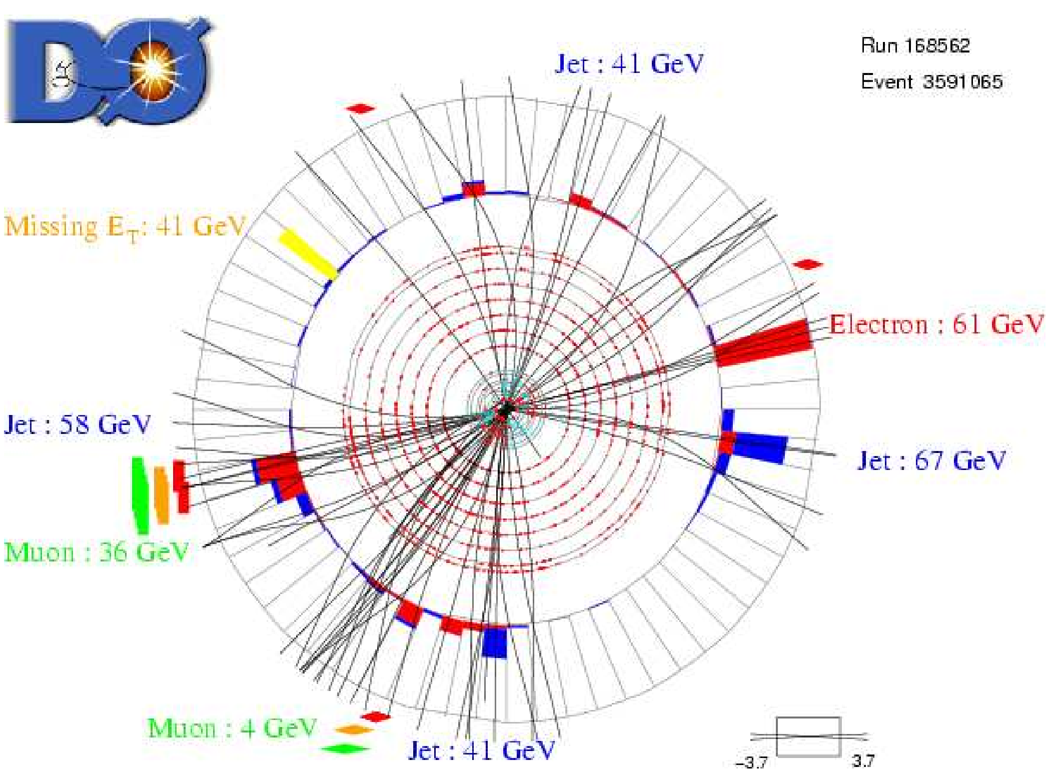
$$\sigma_{\mathrm{t\bar{t}}} = 8.4^{+4.5}_{-3.7}(stat)^{+5.3}_{-3.5}(sys) \pm 0.8(lum)\ \ \mathrm{pb}$$

- Observe 3σ excess of combined signal over background
  - Top quark is still there!
- New top results in the pipeline...

Two leptons + jets

- Candidates from eμ+jets and e+jets channels





Conclusions

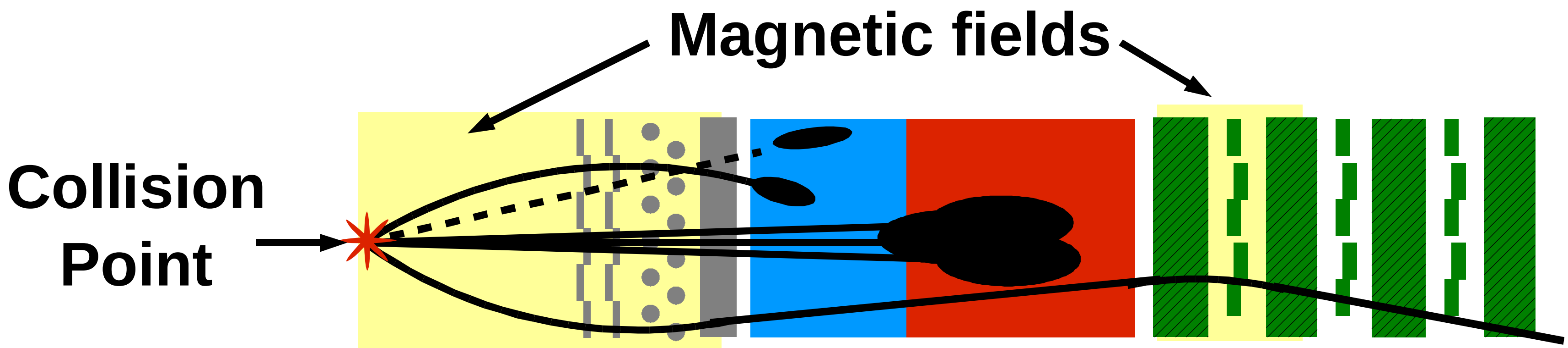
- DØ starting to probe a very interesting range of energies...will be continued by LHC
  - Something new between 100-1,000 GeV
  - Could be the Higgs: more exciting if it isn't!
- Even if we find the Higgs why it is so light compared to the Planck scale (10^{19} GeV)?
  - Heirarchy problem...see tomorrow's seminar
  - Large extra dimensions and Supersymmetry
- Lots of hints for other new physics (but not necessarily in reach of DØ or even LHC)
  - WMAP non-baryonic matter fraction of the Universe
  - Neutrino oscillations: lepton flavour violation

Conclusions

- Currently a very busy, and very exciting, time on DØ!
  - Detector and trigger now complete and working well
  - Working hard on understanding the data
    - Tracking algorithms and alignment
    - Calorimeter noise
- A lot more data is coming very soon
  - ~200pb^{-1} by summer conferences
  - Will exceed Run I luminosity in next few months
- Physics results starting to come...

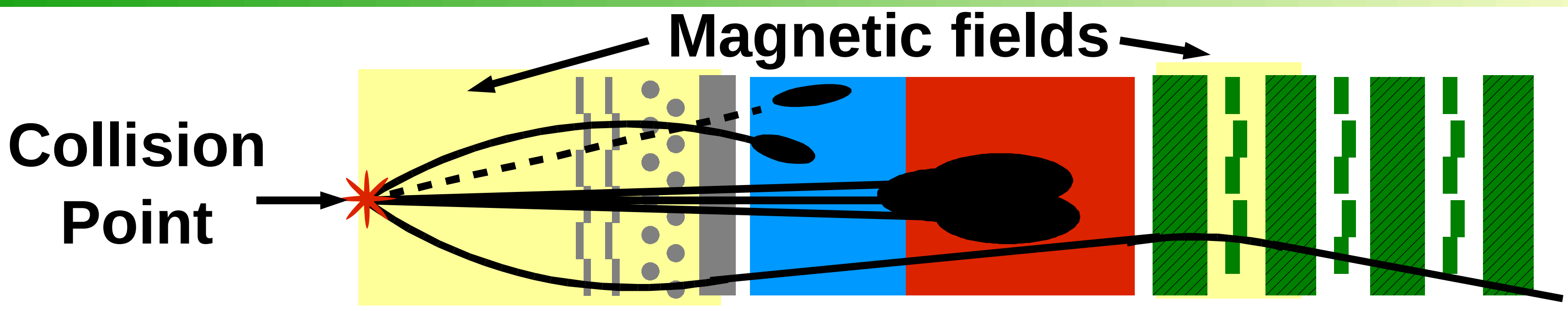
Particle Detectors

- Particle physics detectors split into components
  - Each optimized for a specific purpose



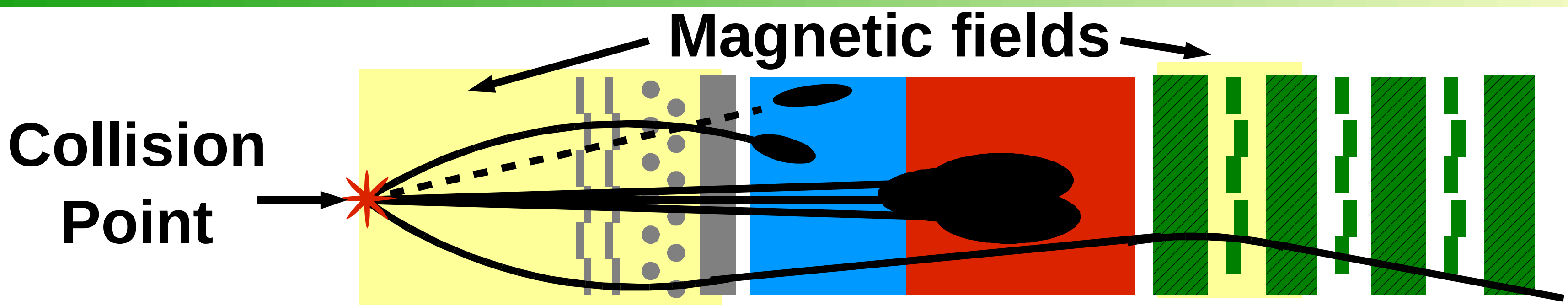
- <u>Tracking detectors</u>, inside magnetic field
  - Measure position accurately at points, join to get track
  - Curvature of track gives momentum and charge
  - Don't detect neutral particles (no ionization energy)

Particle Detectors



- <u>Electro-Magnetic Calorimeter</u>
  - e+/e- and photons create EM showers in matter
  - Showers narrow and not penetrating
  - Finely divided calorimeter
- <u>Hadron Calorimeter</u>
  - Jets or hadrons create hadronic showers (strong int.)
  - Broader and more penetrating than EM
  - Bigger cells than EM and more material

Particle Detectors



- **Muons**
  - Too heavy to bremstrahlung like electrons, do not interact via strong force and have a long lifetime
  - Penetrate entire detector, detected by counters which ring the outside of the experiment
- **Neutrinos**
  - weakly interacting, neutral and stable
    - penetrate light years of material!
  - Carry away momentum: signature missing transverse p