Physics at the High-Energy Frontier: ...an introduction to the physics at D0

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Talk to Summer REU's
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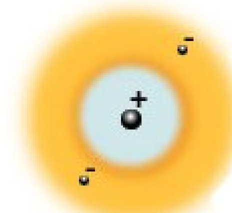
The Standard Model

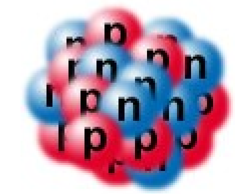
- The long quest to understand:

  "What is this stuff?"
  "What is it made of?"
  "What holds it together?"
  "What makes it move?"

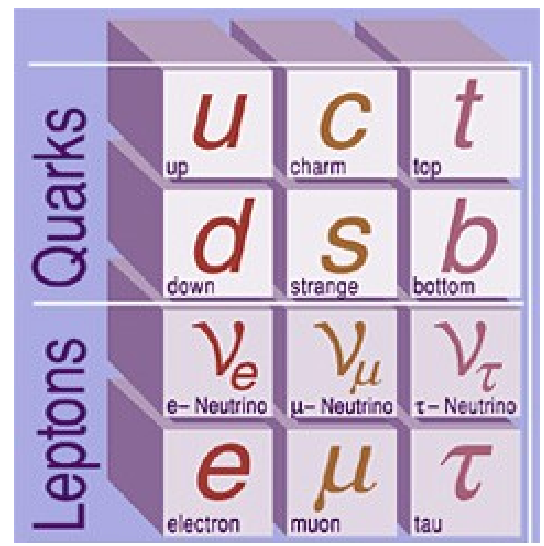
- We've come a long way... there are:
  - 6 quarks
  - 6 leptons
  - 3 forces
  - and gravity

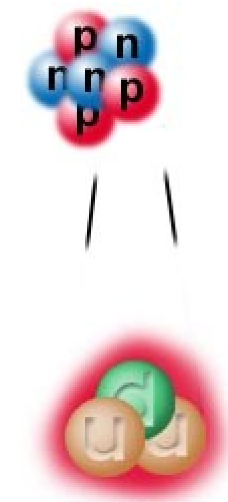


Atoms



Nuclei





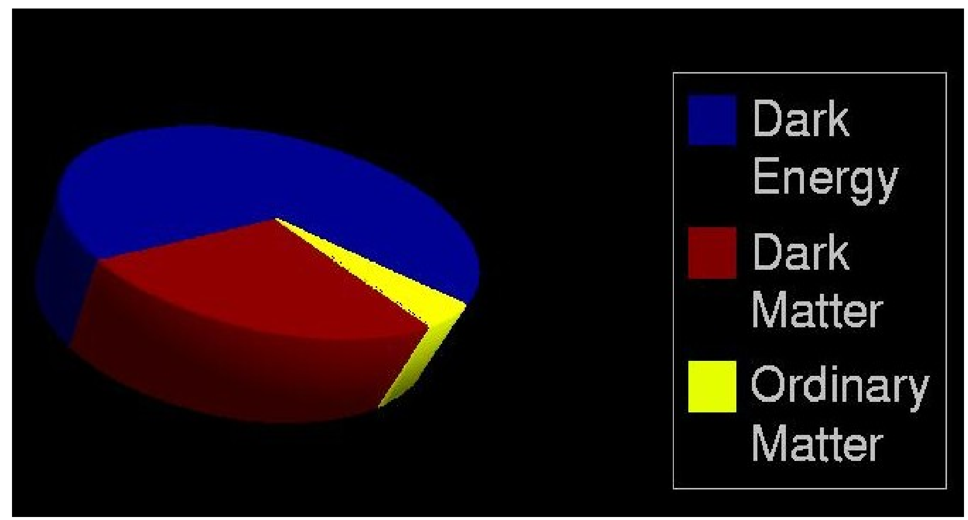
Quarks

Quarks, Leptons, and Forces

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

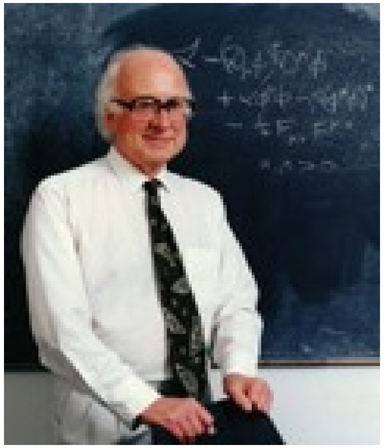
Big Questions

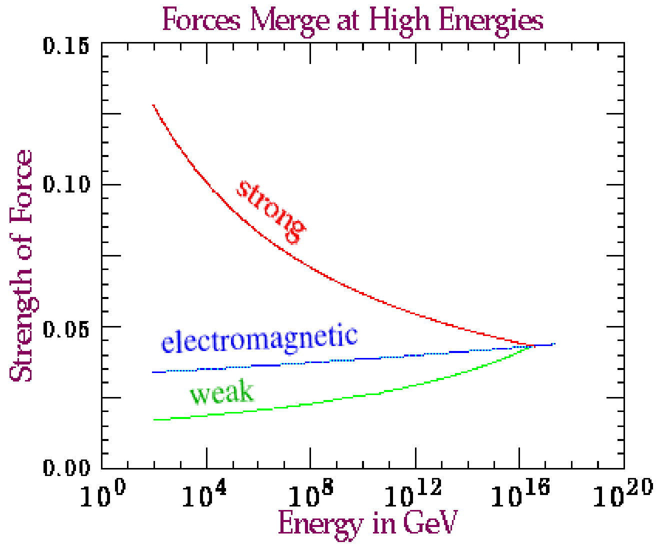
- Why 3 generations of particles?
- Why is there matter everywhere, and no anti-matter?
- Where do the particles get their mass?
- What is all this Dark Matter?

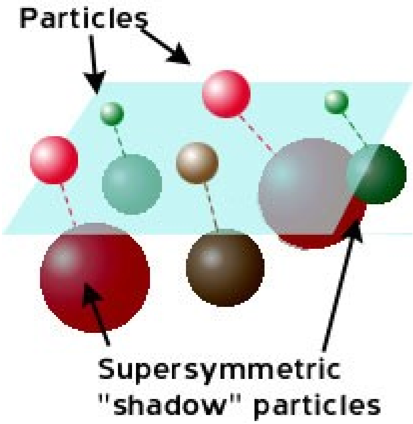


Big Answers ?

- Higgs Bosons?
- Grand Unification?
- Supersymmetry?
- Strings?





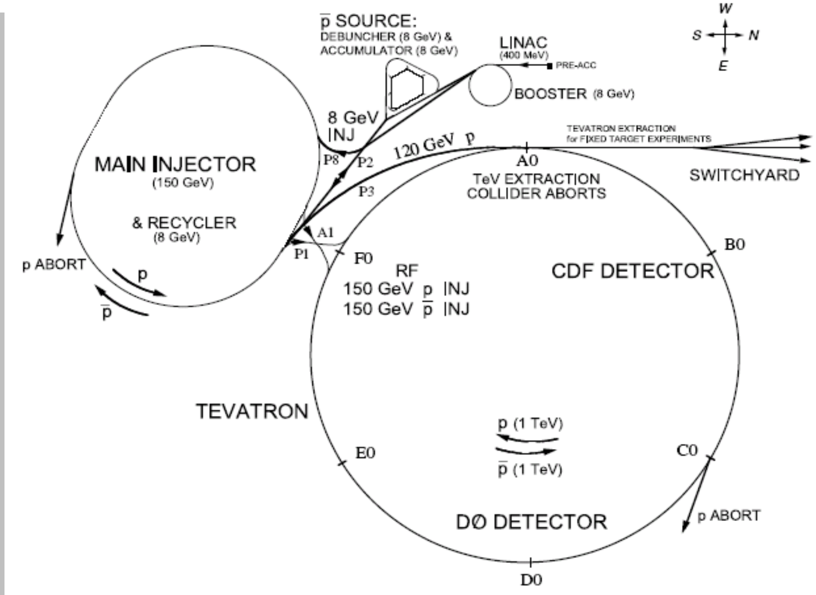


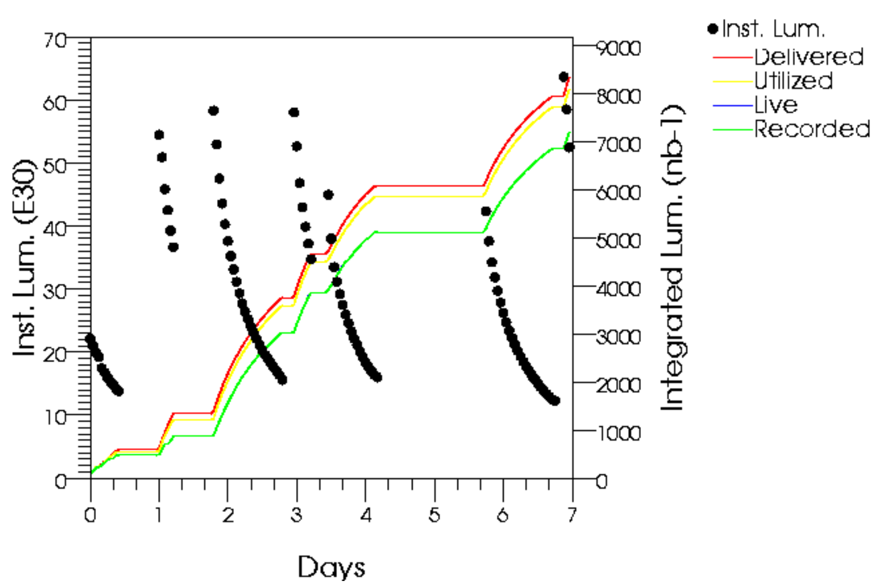
What we study

- Measure the properties and interactions of the particles we know about (with greater accuracy)
  - quarks and the strong interaction (QCD)
  - W and Z bosons
  - bottom quarks and hadrons
  - top quarks
- Search for new particles we think should exist
  - Higgs bosons
  - Supersymmetric particles
- Search for any new physics (particles and/or interactions) beyond the standard model

Fermilab Tevatron Accelerator – Run II

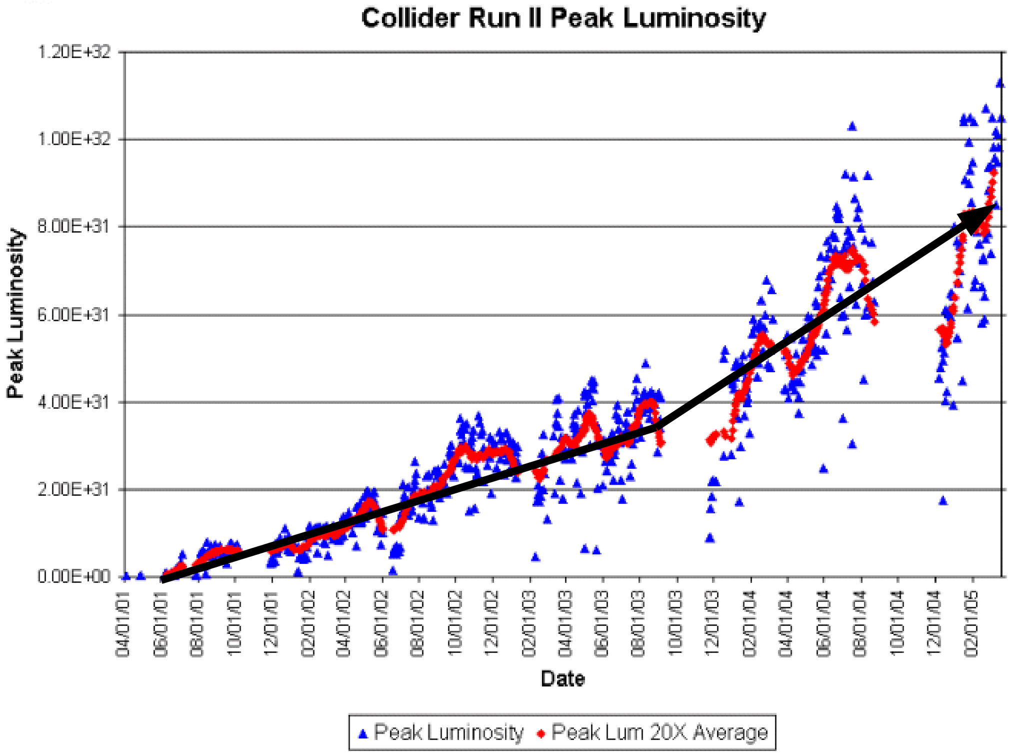
- 1 km radius p-pbar super-syncrotron
  - World's most powerful: 1.96 TeV
  - 36 bunches of p and pbar
  - 396 ns crossing period
  - 25 cm long interaction region
- One store every day or so...

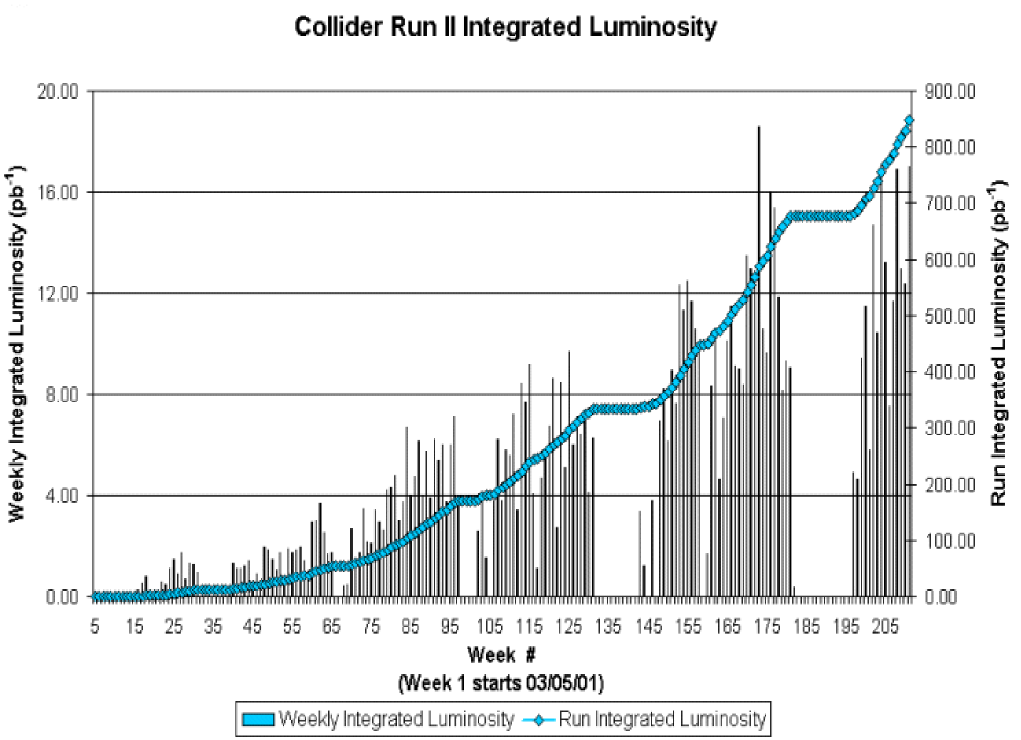




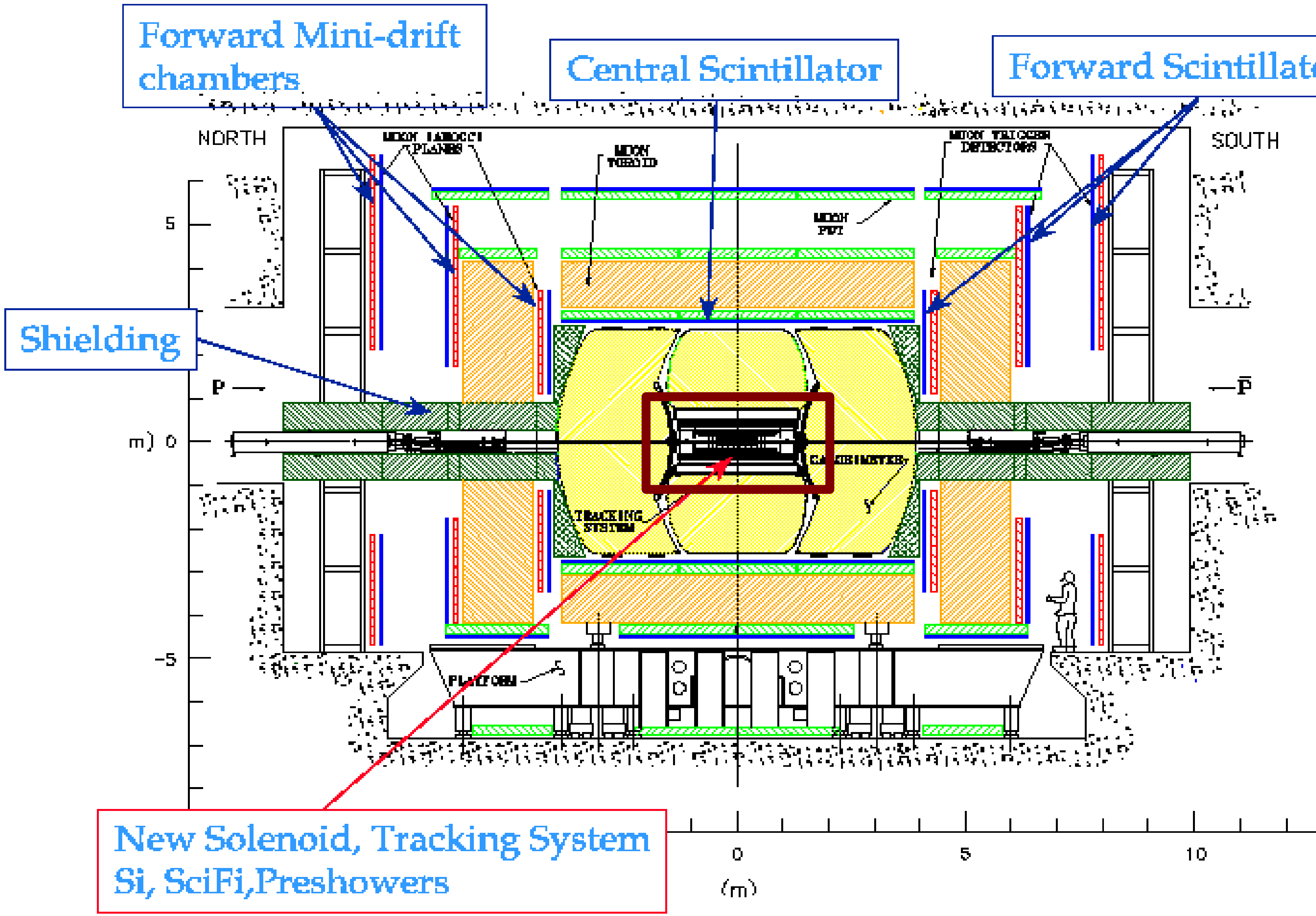
Tevatron Performance

- Run II began 5 years ago (2001)
- Instantaneous luminosity has steadily increased
- More than 1 fb^{-1} delivered so far
- Should collect 4-8 fb^{-1} in the next few years

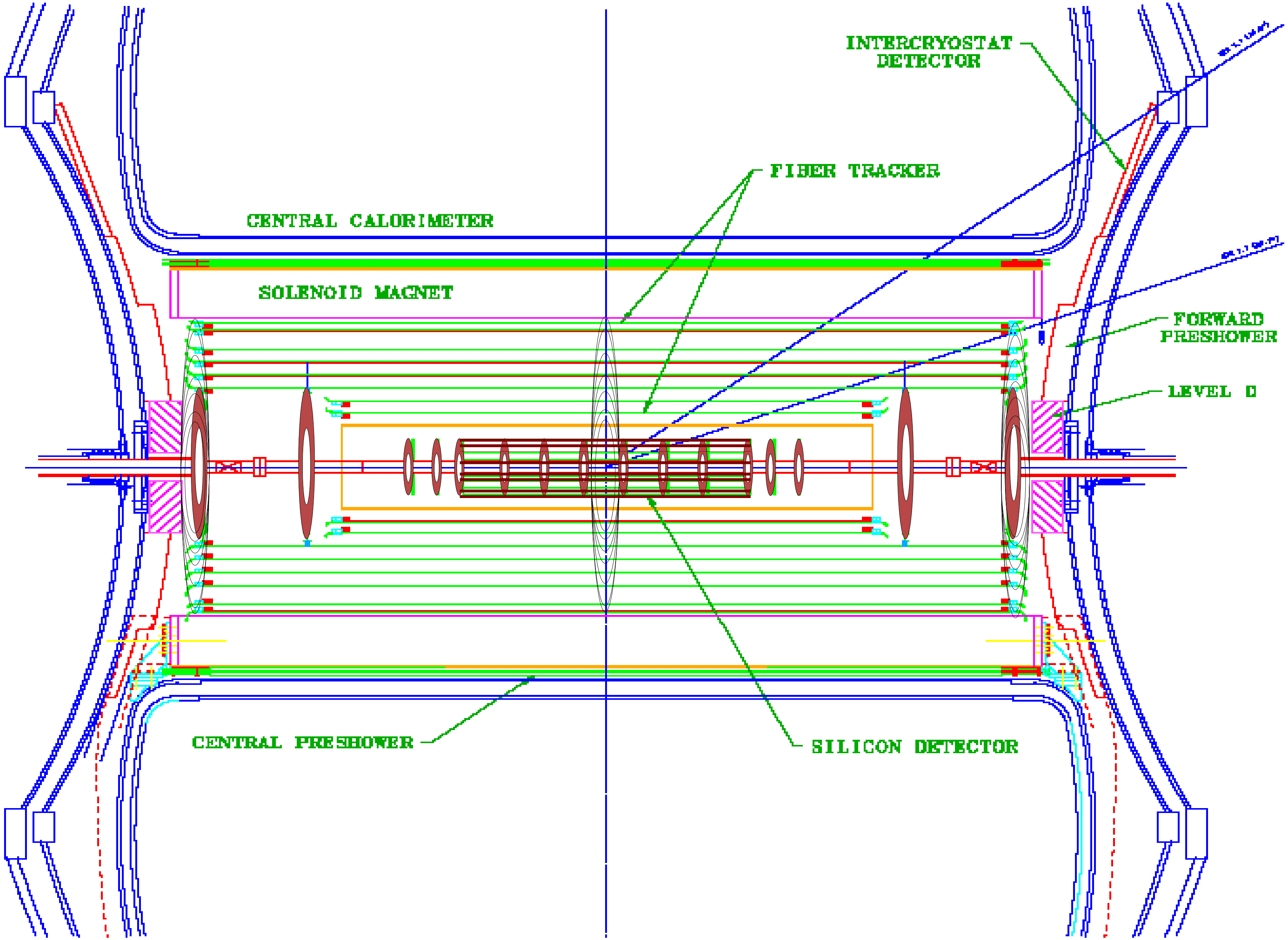




The DØ Detector for Run II

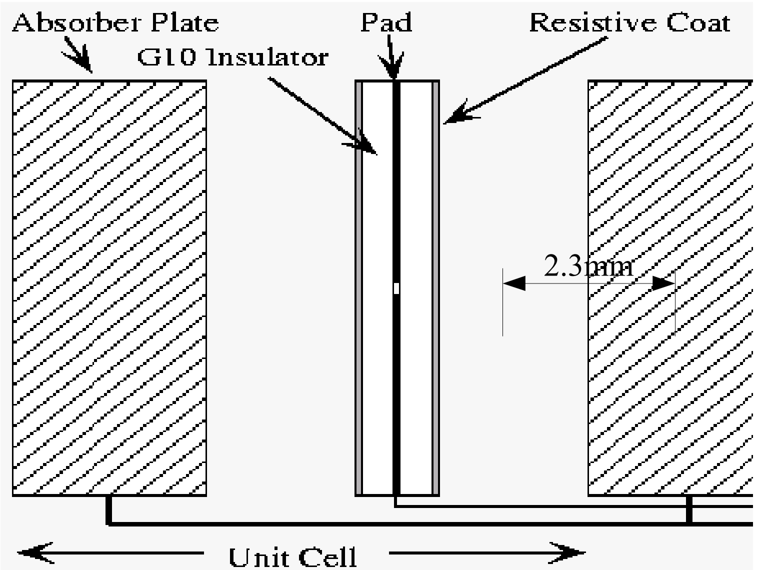


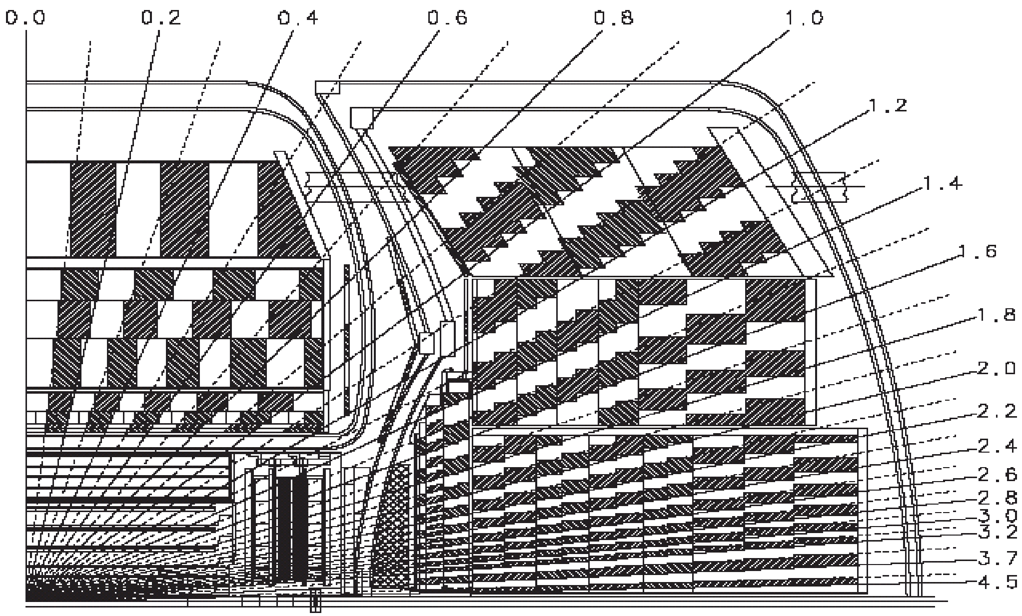
Tracking Systems



Calorimeters

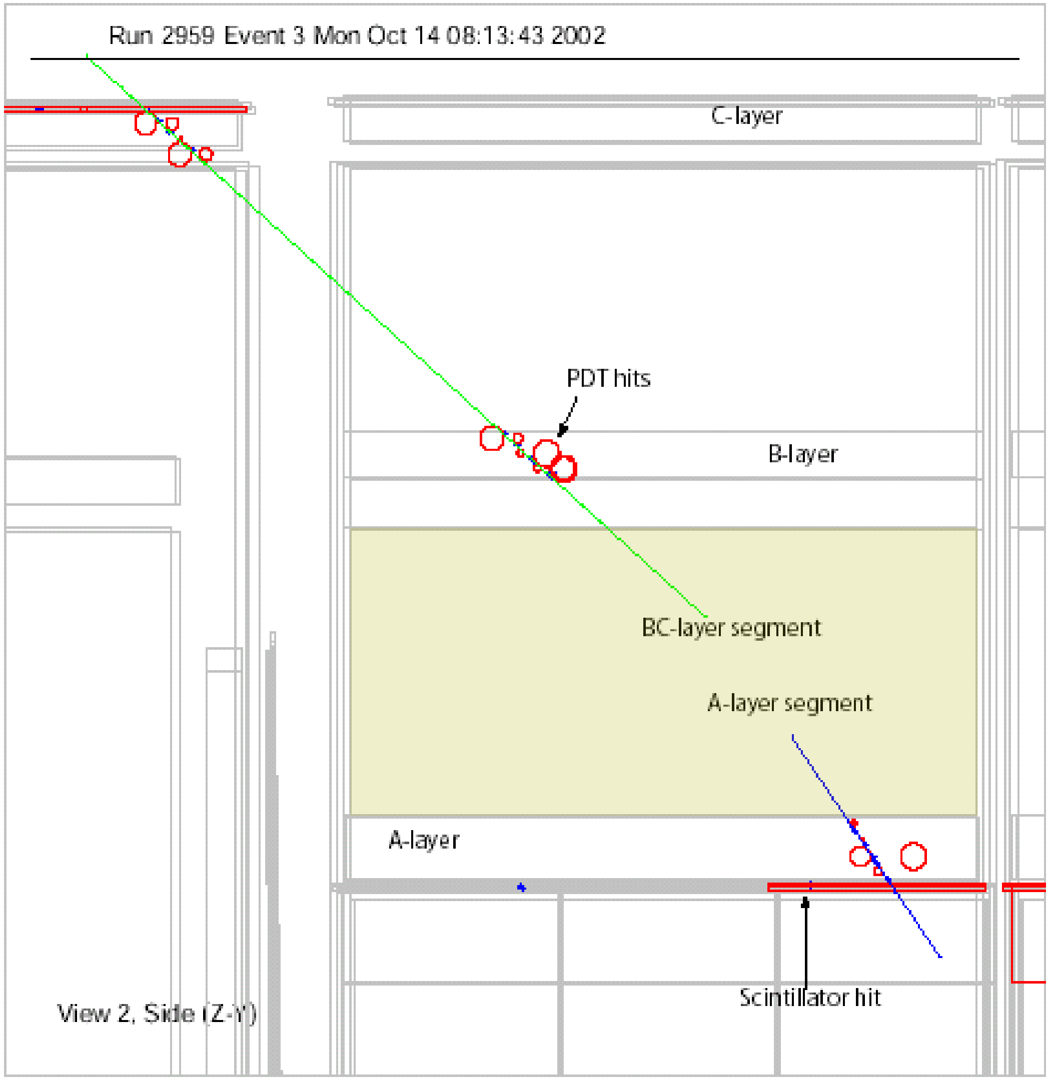
- Showers are induced by sheets of depleted Ur
- Cells measure the ionization in liquid Ar gaps
- Cells are arranged in a projective geometry
- Highly granular (.1x.1)(η-ϕ)
- Jets are almost completely contained: >20 hadronic interaction lengths





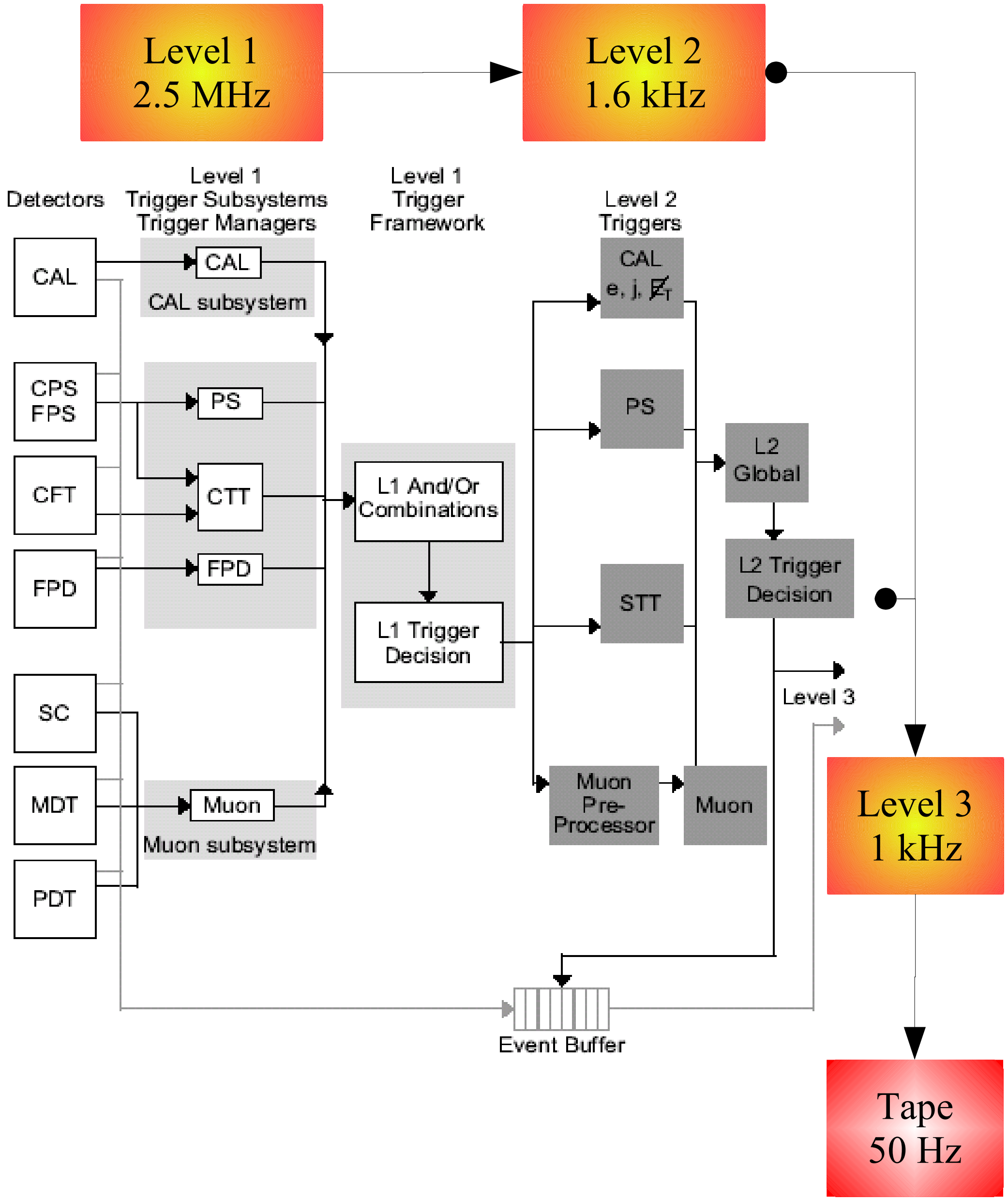
Muon System

- Used in this analysis for:
  - b-tagging studies…
  - jet energy corrections
- A big toroidal Iron magnet: ~2000 Ton and 1.9 Tesla
- Only muons with |p|>3 GeV penetrate the magnet
  - Very low background thanks to heavy shielding
- 3 drift-tube layers and scintillating panels determine the position and timing of muons
- Coverage out to |eta|<2.0
- A-layers and scintillators create the best muon trigger ever built



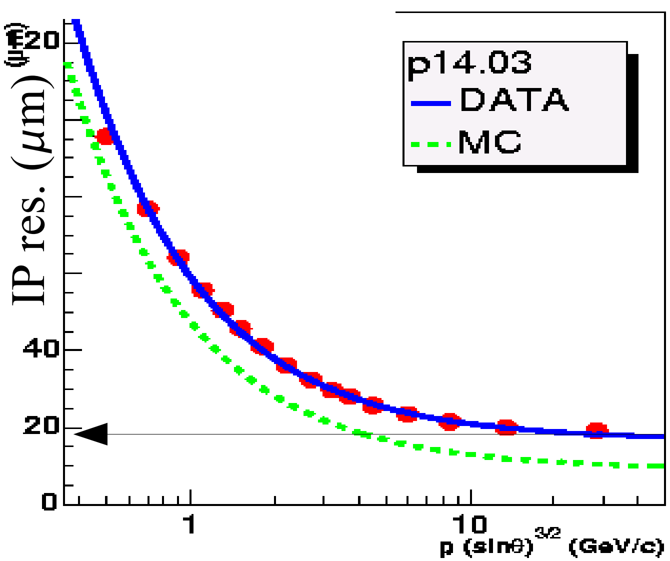
Trigger System

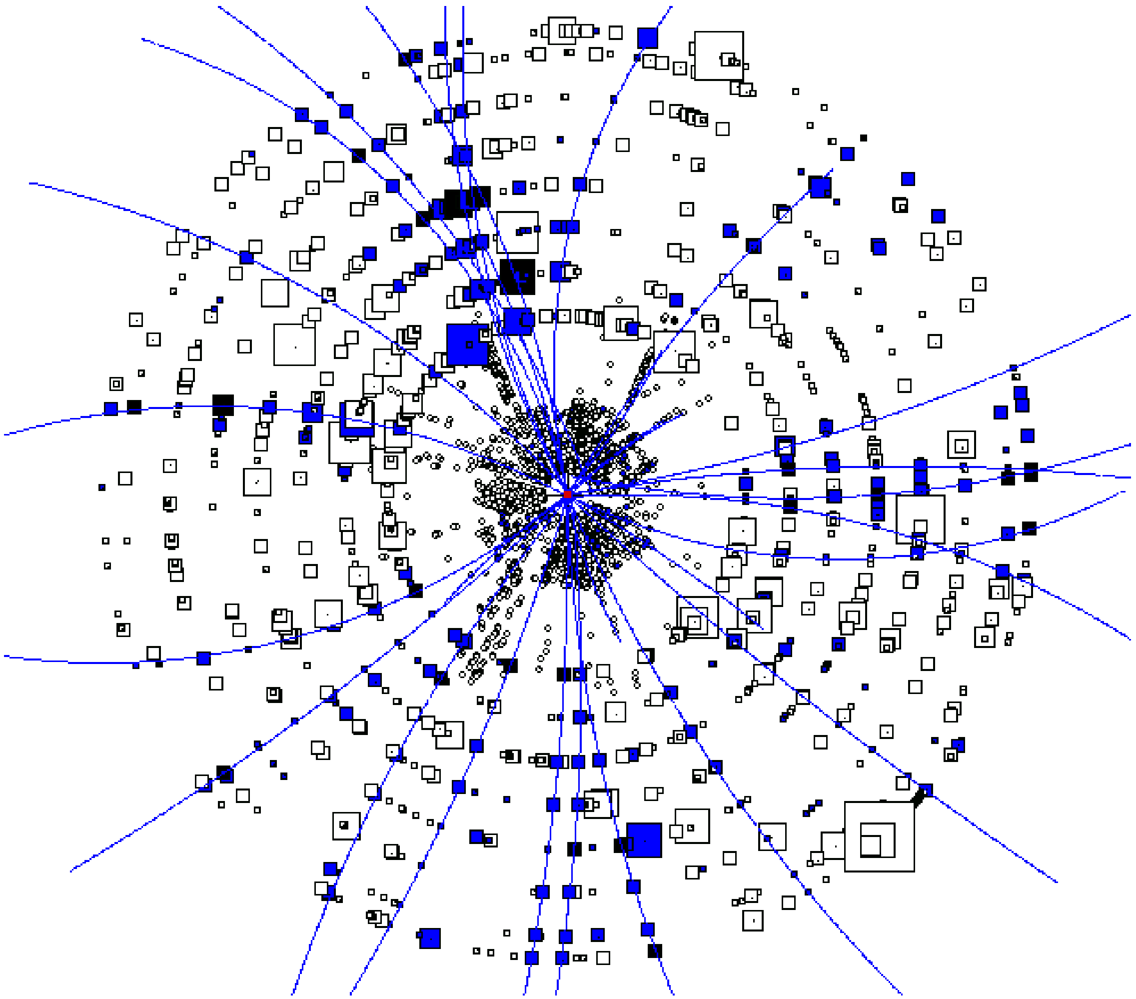
- Level 1
  - Calorimeter EM and TOT E_T (.2x.2)(η-ϕ)
  - Muon stubs
  - Central high-p_T axial tracks
- Level 2
  - Clustered calorimeter EM and TOT E_T
  - Missing transverse calorimeter E_T
  - Matched muon segments
  - Displaced high-p_T axial tracks
- Level 3 trigger algorithms:
  - Jets (no split/merge)
  - Central stereo tracks
  - Muons matched to central stereo tracks
  - Primary vertex
  - Jet lifetime b-tags



Track Reconstruction

- Reconstruct detector energy into clusters
- Pattern recognition combines clusters into tracks
- Efficiency for p_T>1GeV is about 95% in the central region, 85% for the forward
- Path resolution is ~20 microns

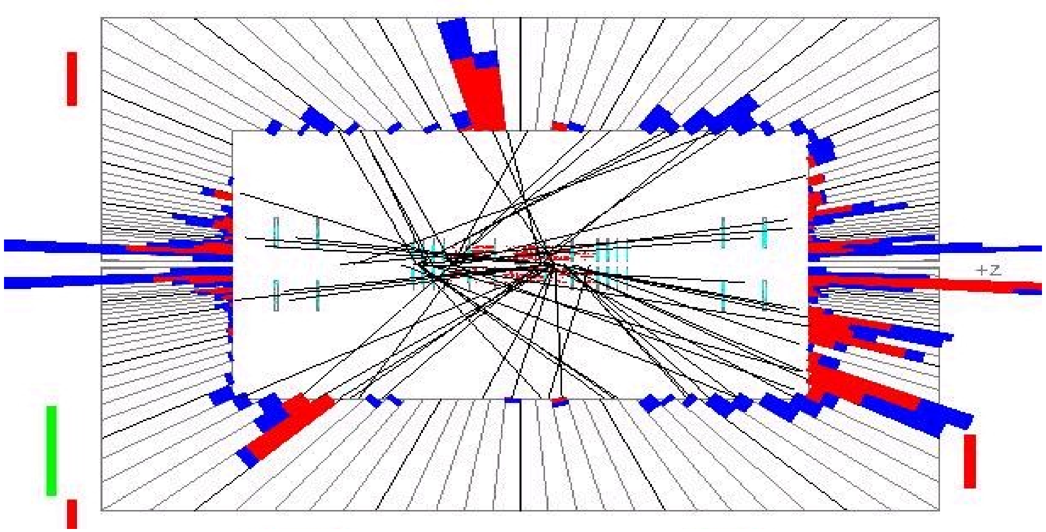


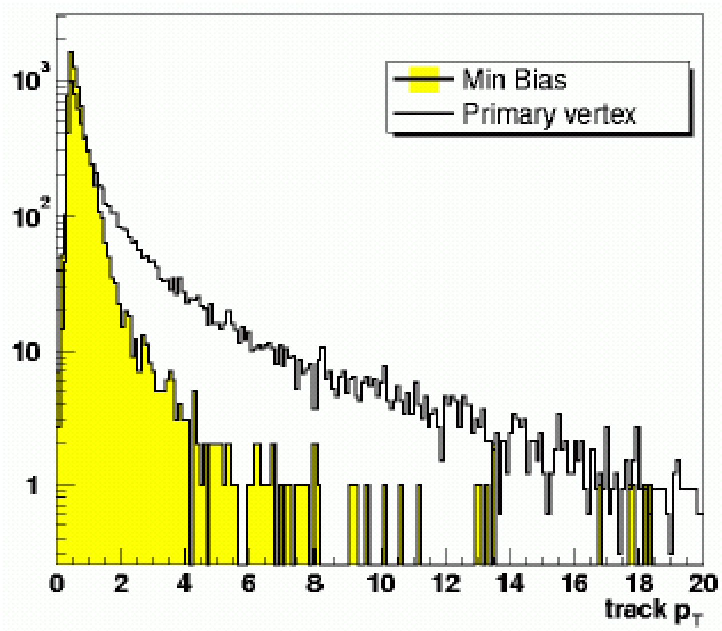


An axial view of a 3-jet event in data, with reconstructed clusters and tracks

Primary Vertex Reconstruction

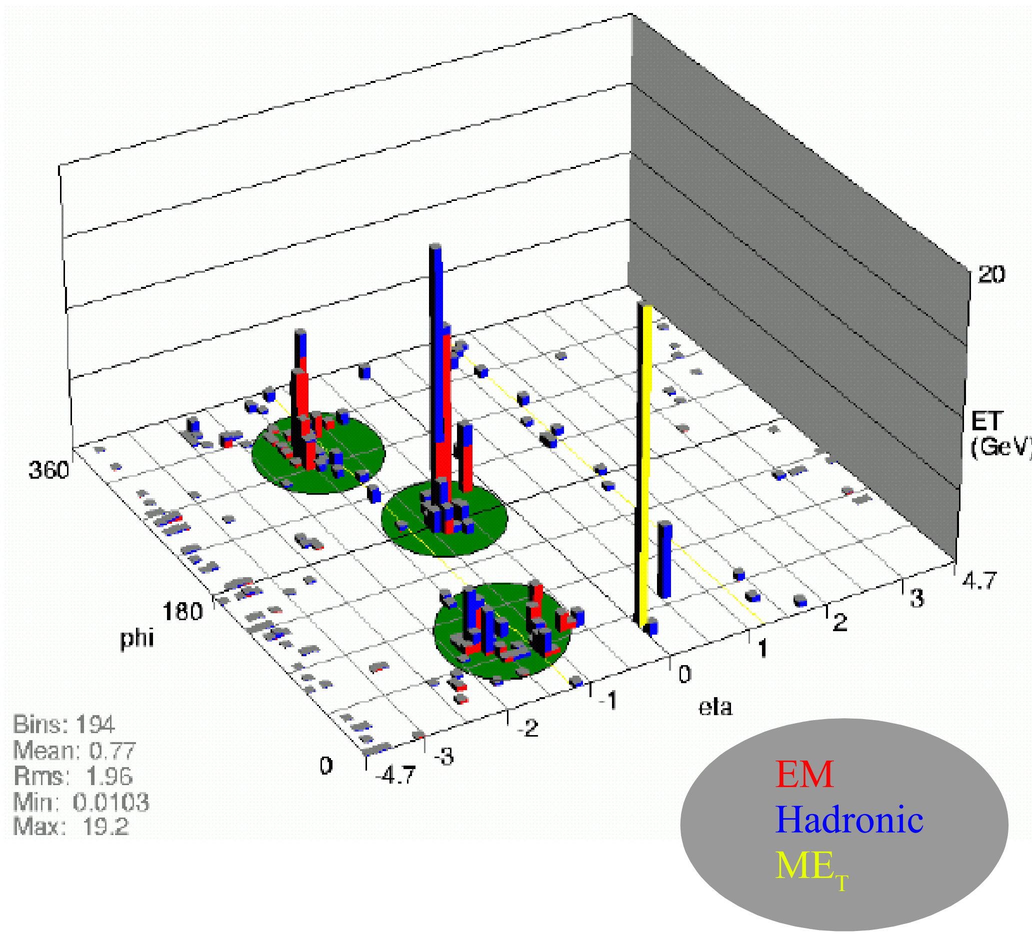
- Common locations of tracks along the beam-line are clustered into “primary vertices”
- There can be more than one interaction in a crossing
  - Very unlikely to have more than one interesting event in a single crossing
  - About 0.4 interactions per crossing on average for this data set - depends on instantaneous luminosity
- The interesting vertex is selected based on the momenta of the vertices' tracks
- This “hard-scatter” primary vertex is used to calculate jet E_T





Jet Reconstruction

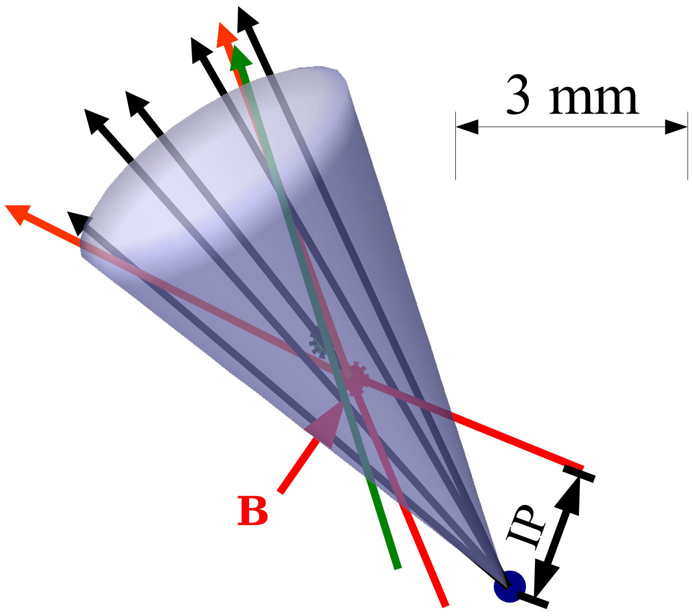
- The E_T in (0.1x0.1)(η-ϕ) towers is summed, and seeds are found
- Energy is clustered in cones of $\Delta R=\mathrm{sqrt}(\Delta\eta^2+\Delta\phi^2)=0.5$ around the seeds
- The midpoints (in η-ϕ) between stable cones are also used as seeds
- The unique cones with E_T>8 GeV are merged or split, depending on whether they share more or less than 50% of a jet's E_T
- Jets' E_T are calibrated, using the jet energy scale (JES)
  - accounts for out-of-cone showering and the underlying event, on average



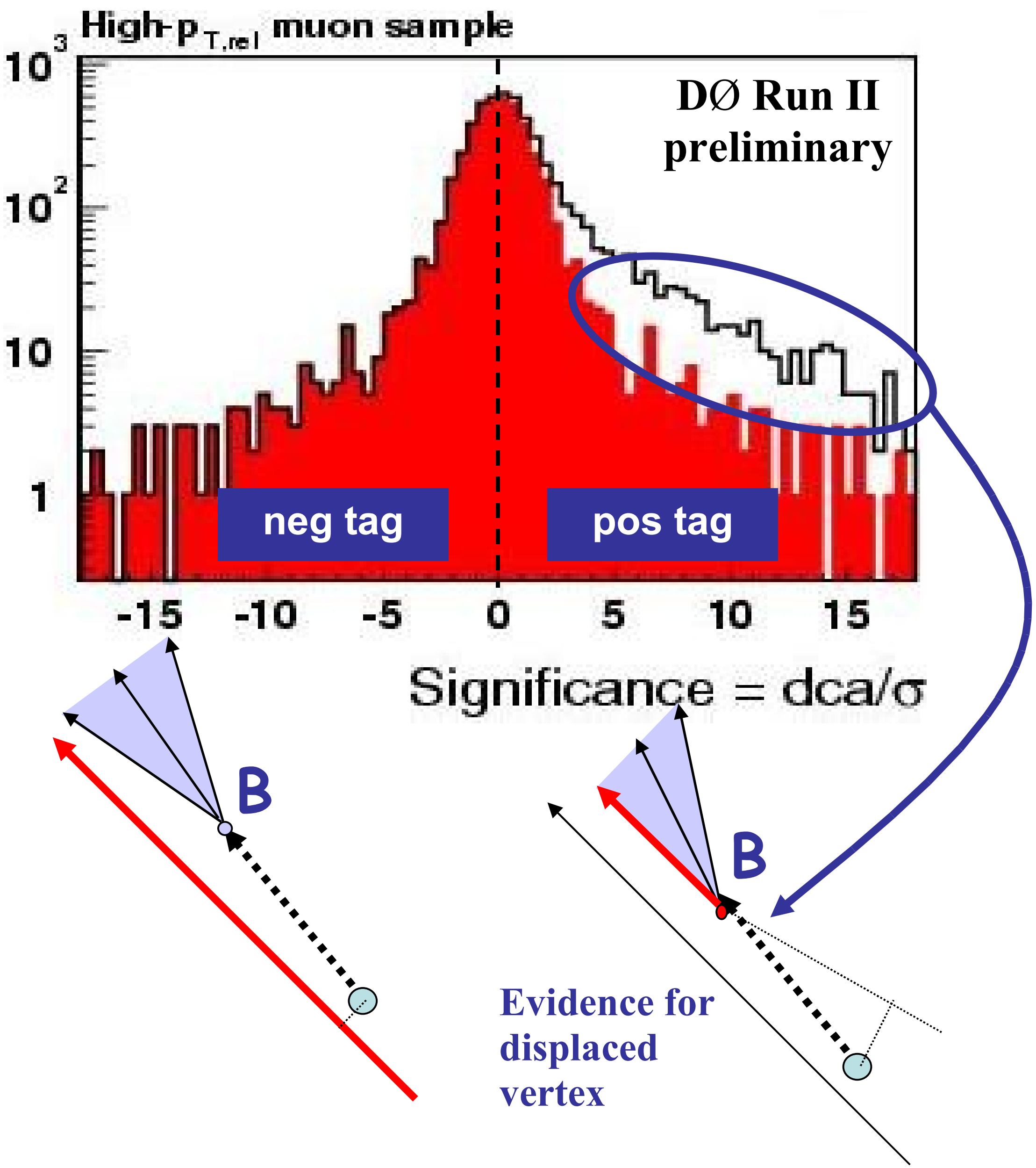
$$E_{jet}^{corrected} = \frac{E_{jet}^{colorimeter} - E_{offset}}{R_{jet} \cdot R_{cone}}$$

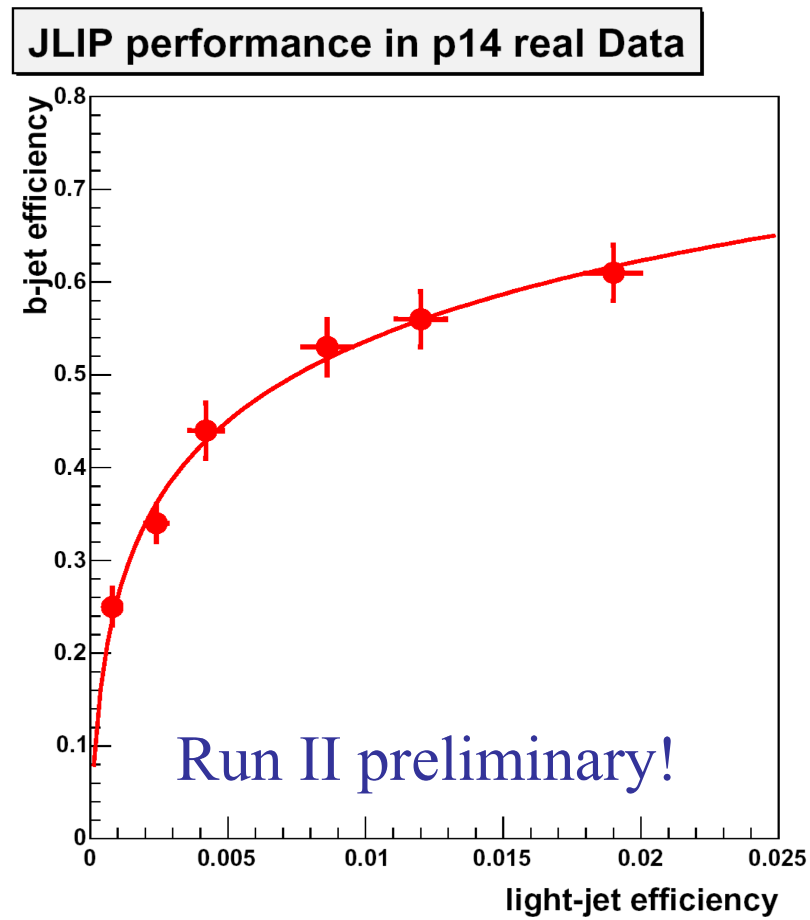
b-Jet Identification

- Identify jets containing bottom hadrons
  - main weapon again the huge QCD background
  - b-hadrons travel ~3 mm before decaying
  - Their mass leads to an opening angle between tracks --- large IP significances
  - Additional large IP significance tracks may arise from daughter decays (charms, tau)
- High-IP-significance tracks are used to find the secondary vertex(es)
  - Jets with a secondary vertex in $\Delta R<0.5$ are "tagged" as b-jets
- Backgrounds consist of:
  - mis-tags: poorly reconstructed tracks which randomly happen to form a vertex
  - long-lived strange / charm decays or photon to e^+e^- conversions
  - "gluon splitting" into nearly collinear charm or bottom pairs



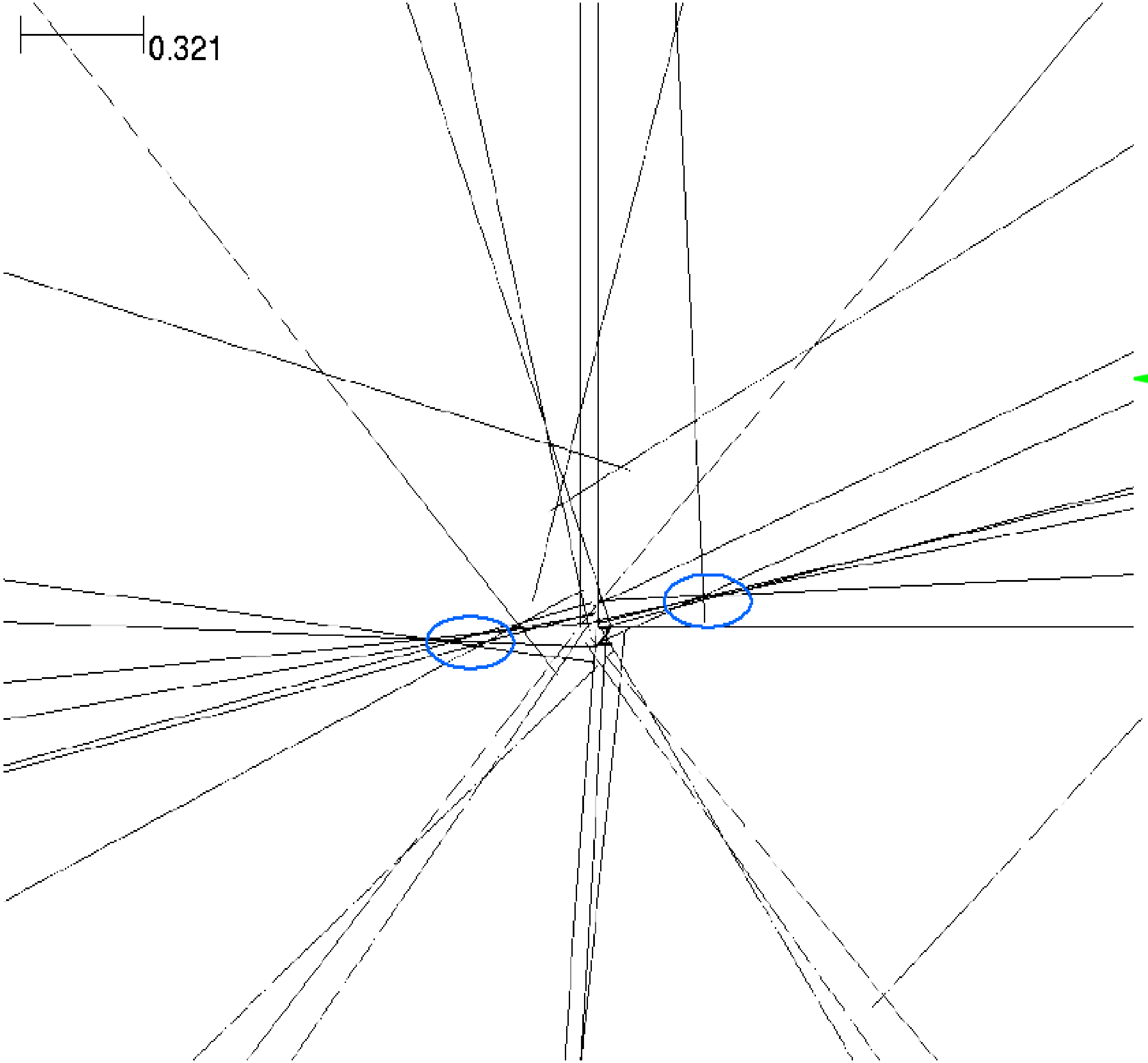
Lifetime *b*-tagging

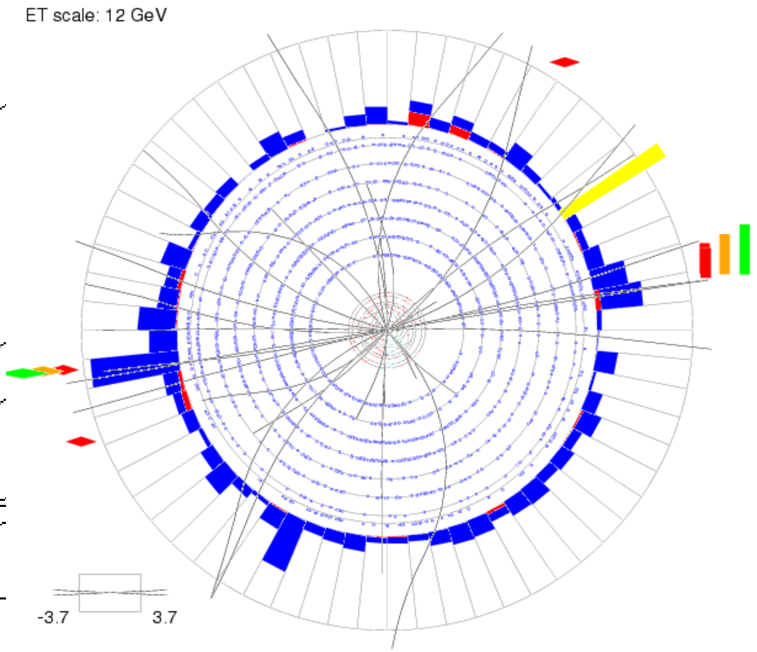




- Tracks with large IPs
- Secondary vertices

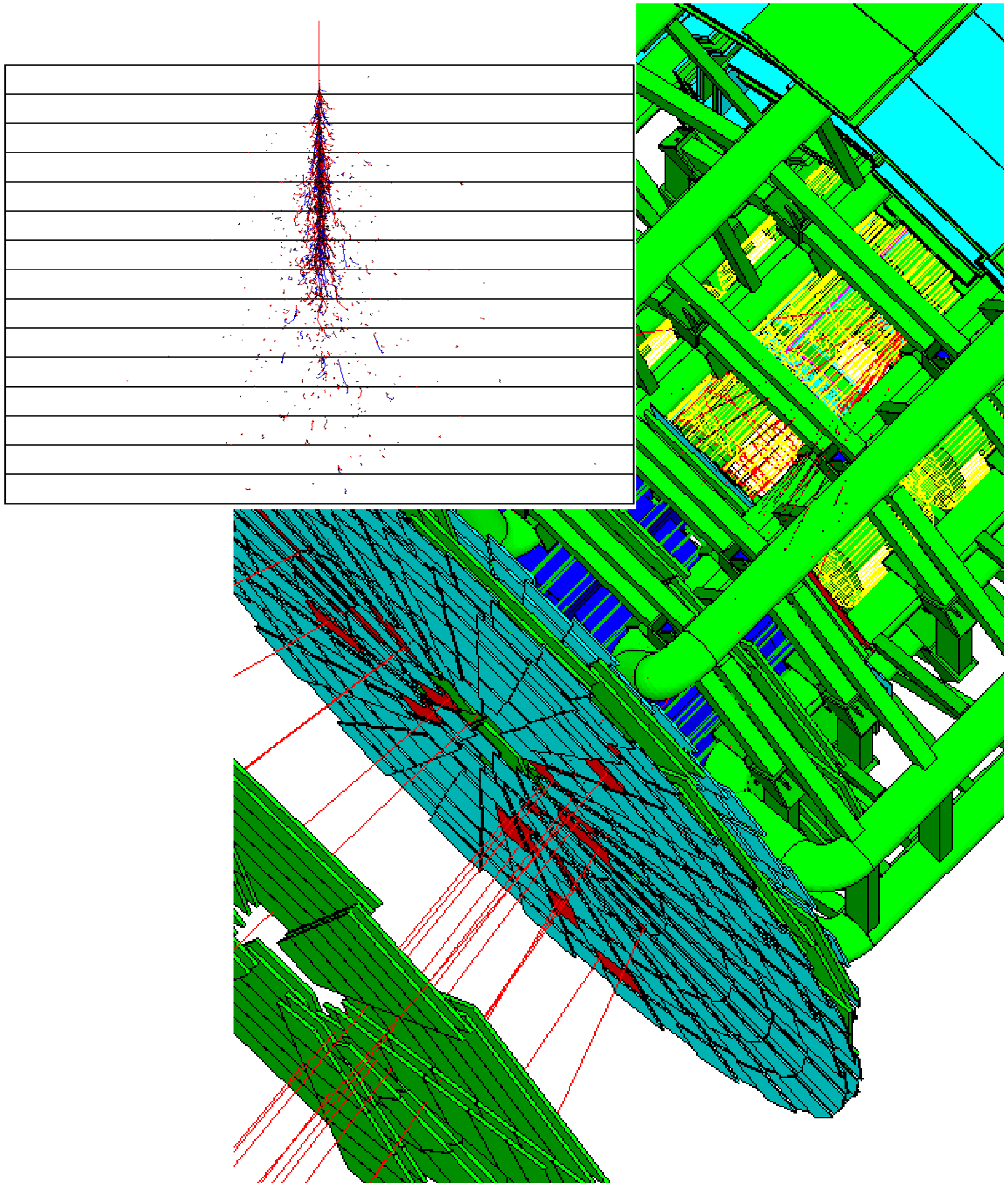
Secondary Vertices in Jets





Simulation

- To compare theory to data, the events from theory must be *simulated*
- Advanced methods used to simulate
  - particle creation (Monte Carlo)
  - particle interactions with matter and the detector elements (GEANT)
  - electronic responses of the detector



Ongoing analyses

QCD

Inclusive jet cross section, dijet mass and angular distributions, diffraction, …

Heavy flavor

Resonance reconstructions, masses, lifetimes, branching fractions, rare decays, B_s mixing, …

Electroweak

W/Z cross sections, dibosons and anomalous couplings, charge and rapidity asymmetry, …

Top Quark

Top quark pair production cross section measurements, top quark mass and decay properties, search for single top quark production, …

Higgs

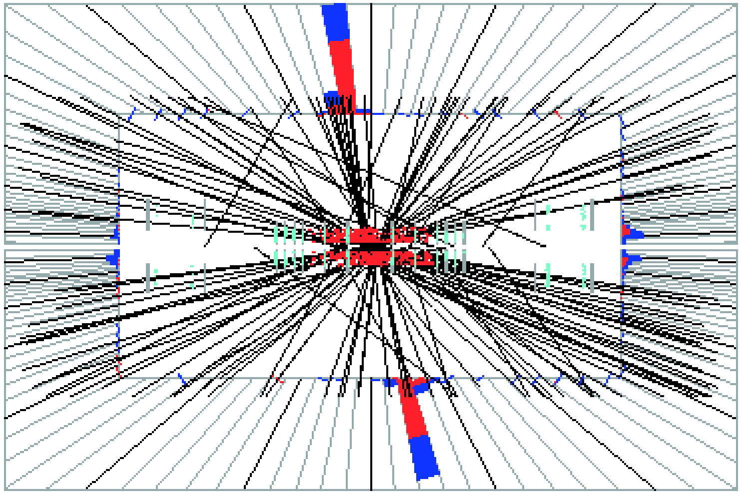
Searches within the standard model, searches in supersymmetic models, and other searches

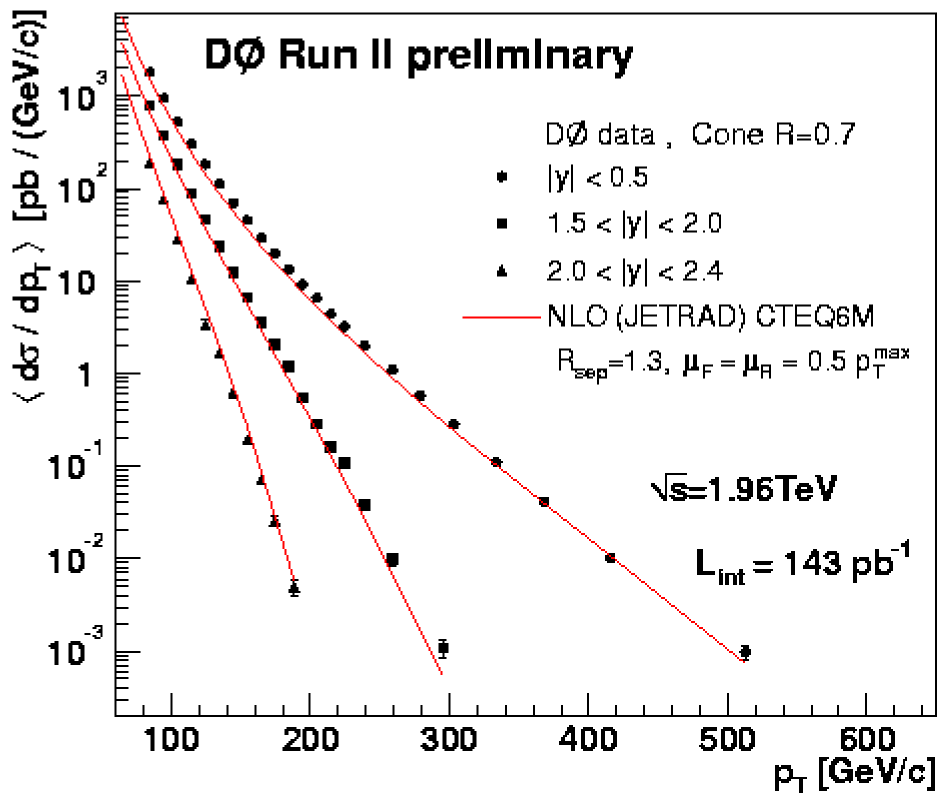
New phenomena searches

Higgs bosons, supersymmetry, leptoquarks, large extra dimensions, Z' ,…

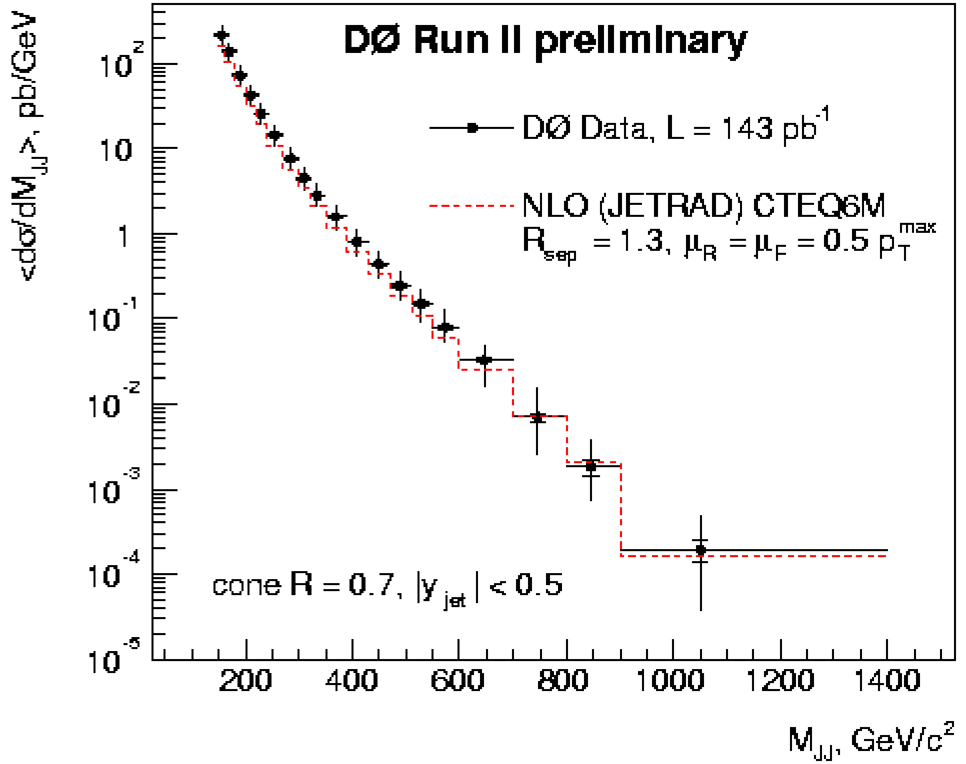
QCD

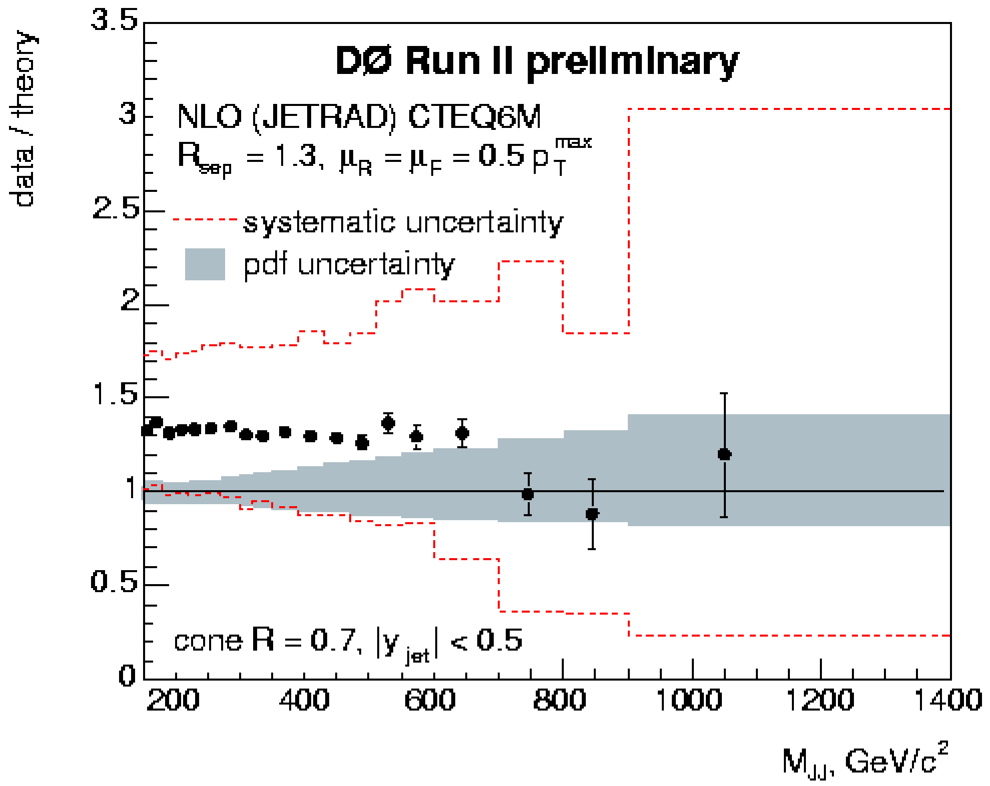
- In some ways, the simplest measurement at the Tevatron, but in practice, difficult.
- Tests our basic understanding of the proton, and QCD
- Measure the inclusive jet cross-section
  - vs. pT of the jet
  - 3 bins of |eta|





- Measure the di-jet invariant mass spectrum
  - Also compared to theory
  - Experimental errors are large still
- Can also measure the di-jet angular correlation... how back-to-back are the two leading jets?
  - Tests NLO in perturbation theory





b - Physics

$$\hat{V}_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

(u,c,t) quarks interact with (d,s,b) quarks with these probabilities:

(u,c,t)V(d,s,b) ...

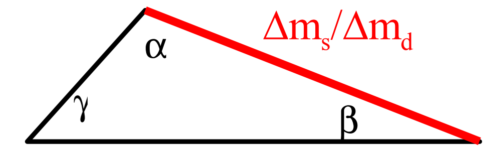
where V is the CKM matrix

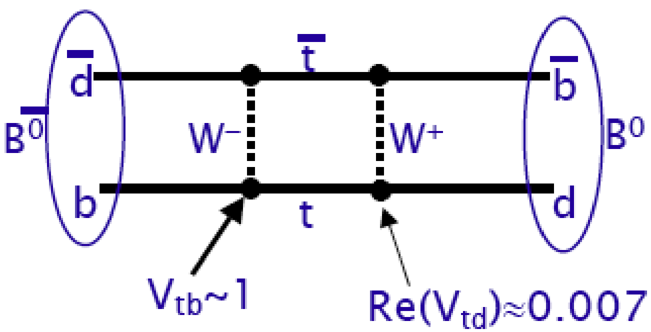
In the standard model, there are just four parameters...
... lamba, rho, A ... and eta... which is complex... CP violation!

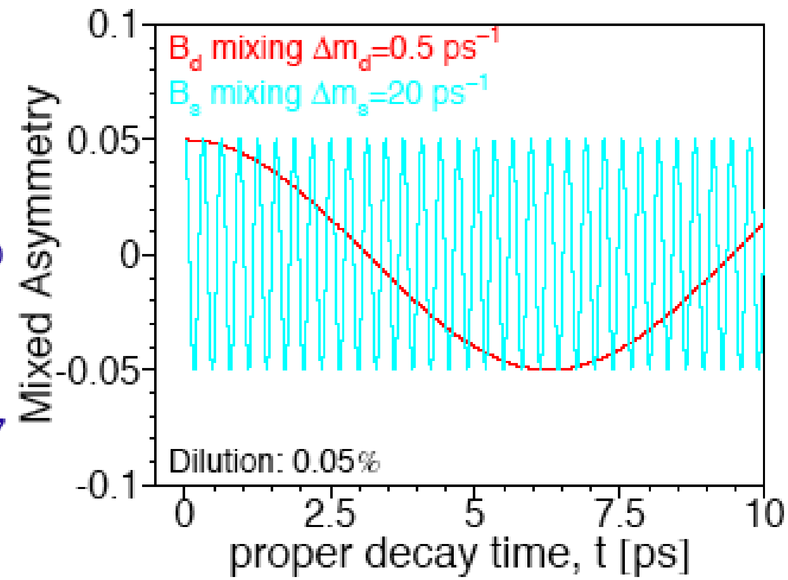
We want to know, is this really true? Is the standard model right?
Or are there other sources of CP violation?

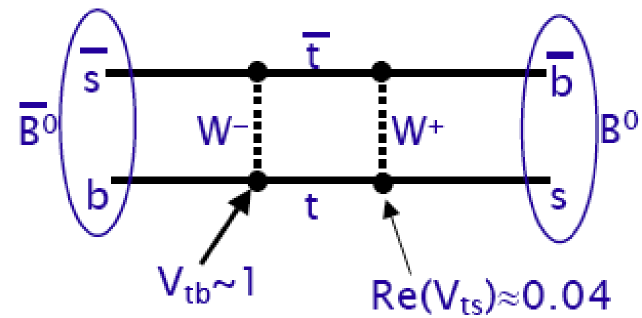
There are also hundreds of other properties of b-hadrons to measure!
Masses, lifetimes, branching ratios... which test QCD... very interesting for "heavy" quarks

B_s mixing









B_d fully mixes in about 4.1 lifetimes

$\Delta m_d = 0.502 \pm 0.006$ ps^{-1} (world comb.)

Measured with great precision by Belle & BaBar

B_s fully mixes in <0.15 lifetimes!!

Δm_s ~= 18 ps^{-1} (world comb.)

To measure B_s mixing, need:

- Tag initial state flavor (what was produced, a B or a Bbar?)
- Tag final state flavor (what decayed was a B or a Bbar?)
- Yield: as much decays as possible (flavor tagging is imperfect)
- Proper decay length: L_{xy} and $\beta\gamma = p_T/m_B$ (mix prob vs decay time)

D0 made the first measurement of this... this year!

Electroweak Physics

Why should you care?

Standard Candles!

W/Z cross-sections

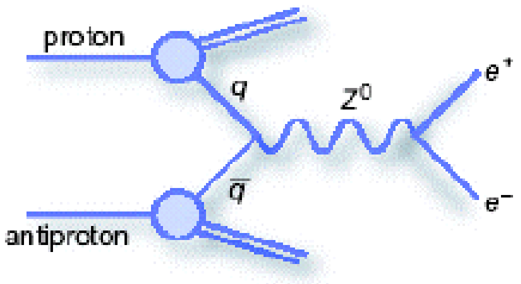
Ratio -> W width

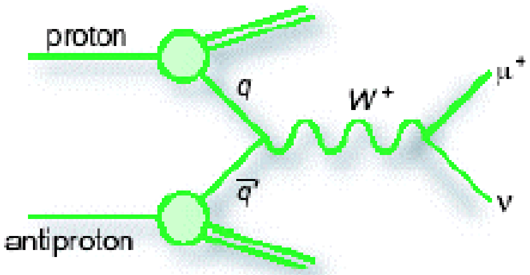
W mass

W charge Asymmetry

Z FB Asymmetry

WW, WZ, ZZ, Wγ, Zγ





Trigger on leptonic decays

Clean low bkg event signatures

W: 1 high p_T lepton + large MET

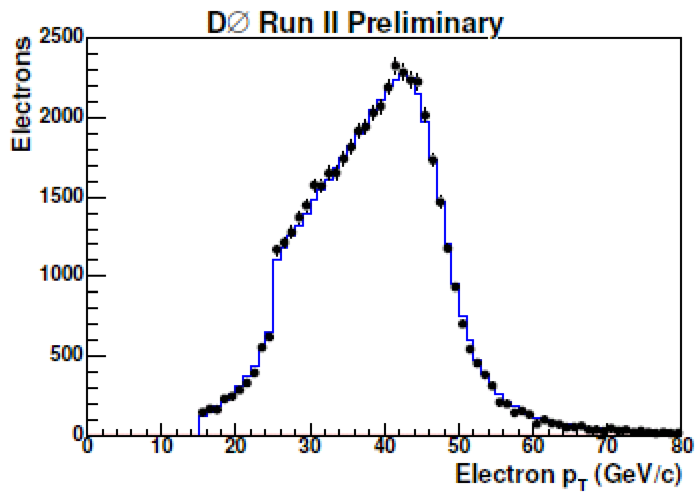
Z: 2 high p_T leptons

BR~11% per mode for $W \rightarrow \ell\,\nu$

BR~3% per mode for $Z \rightarrow \ell^+\ell^-$

Z (→ee)

also have mu, tau, and soon... b!



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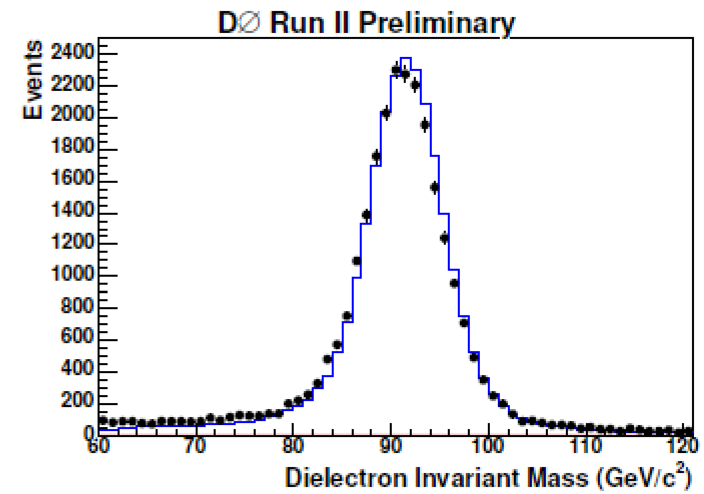
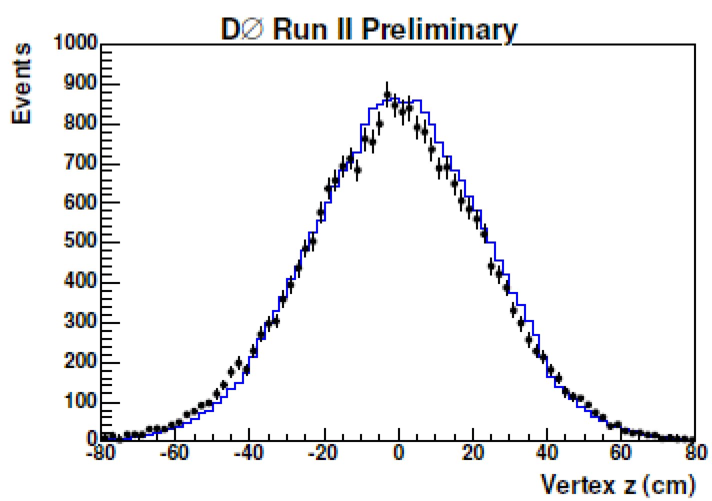


(d)



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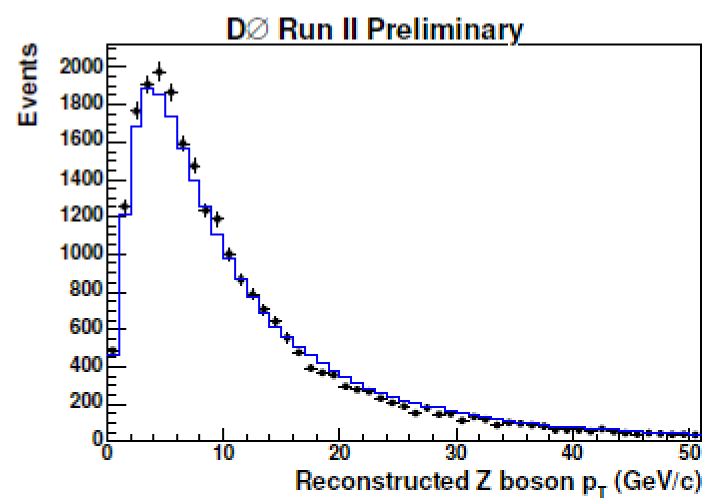
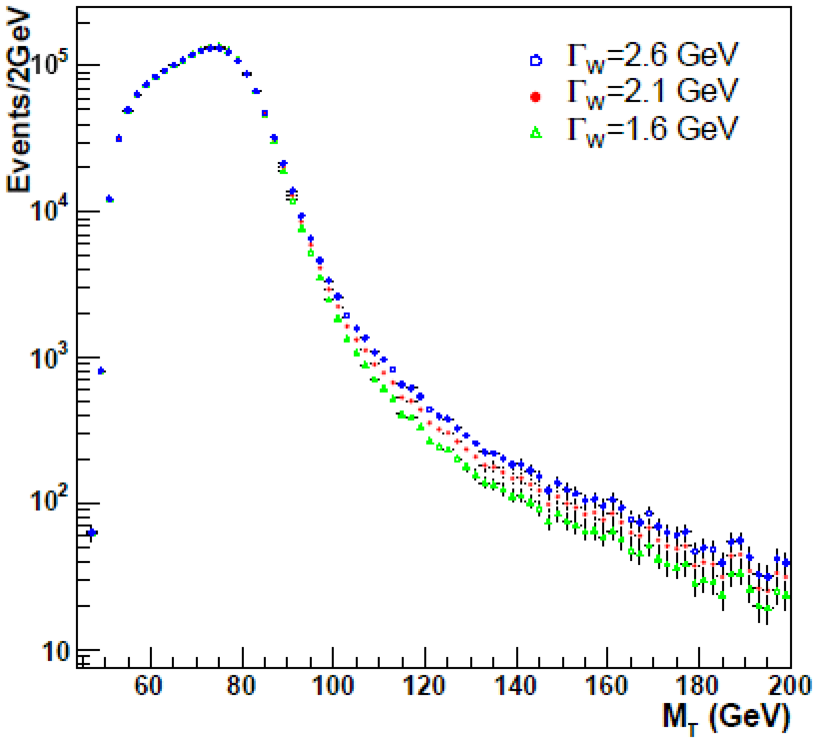
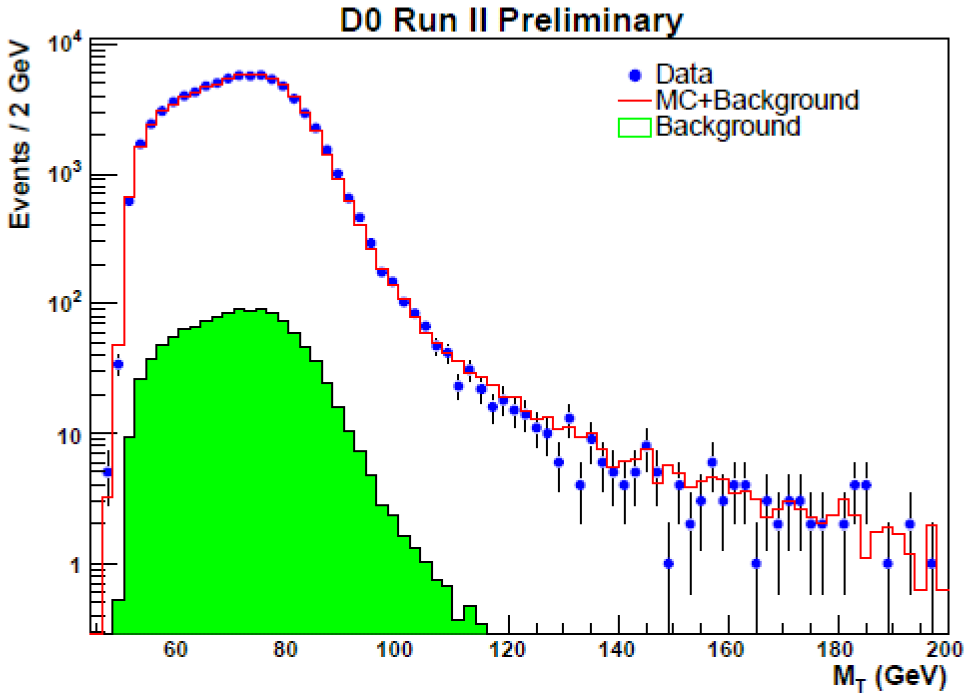


(f)

W (width)

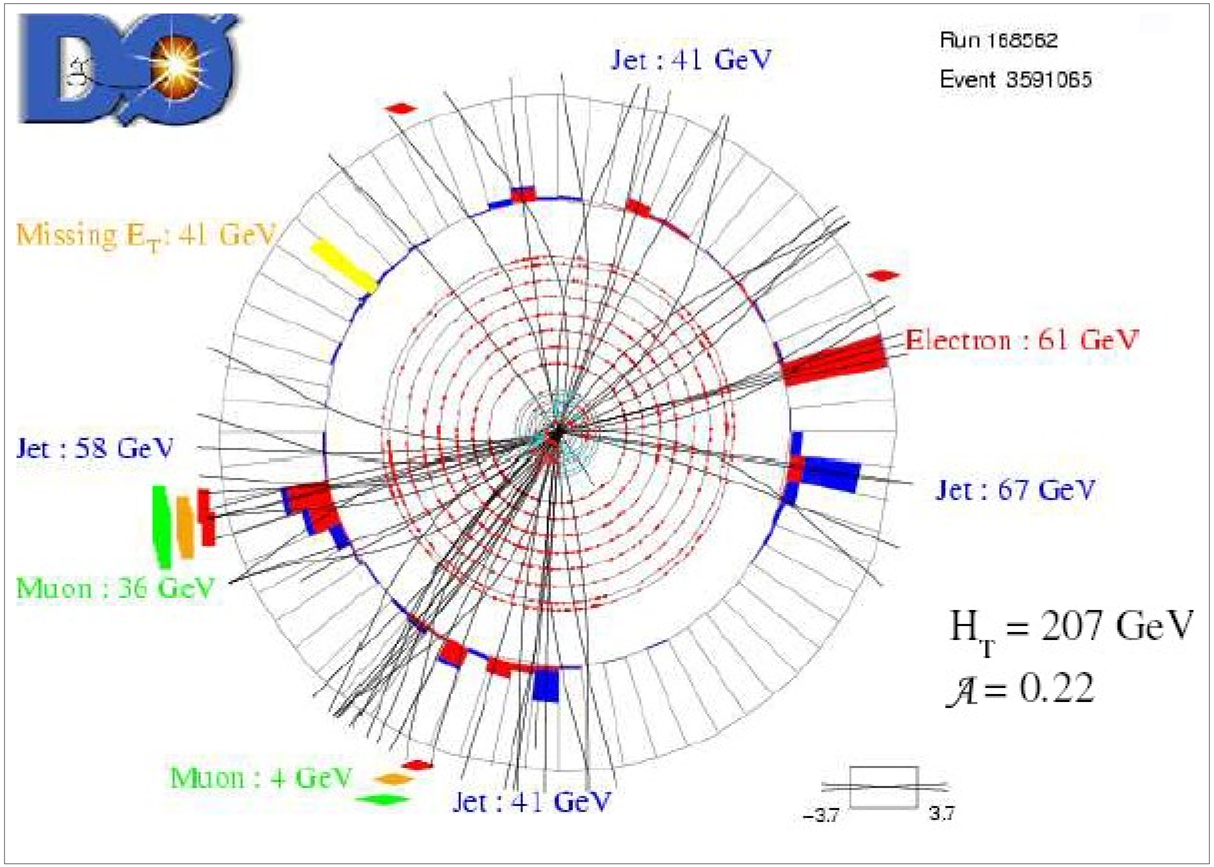




Next step... measure the W *mass*... very very important parameter!

A Needle in a Haystack

- 2.5 Million collisions each second
- ~1000 top quarks made each year
- A few Higgs bosons each year (perhaps!)
- Impossible to record every event... 2 TB/s
- Just keep the interesting events... ***trigger !***

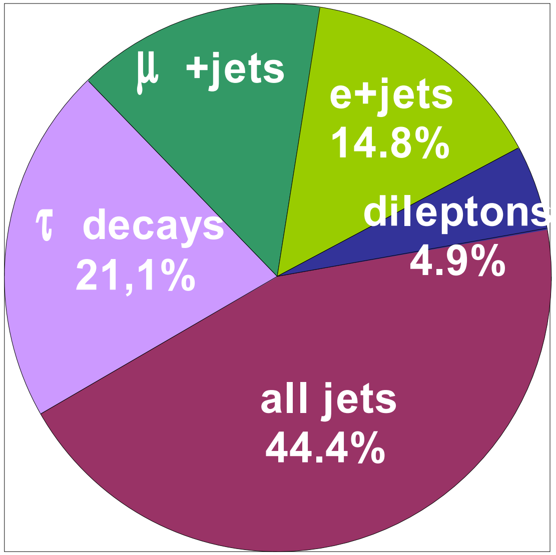


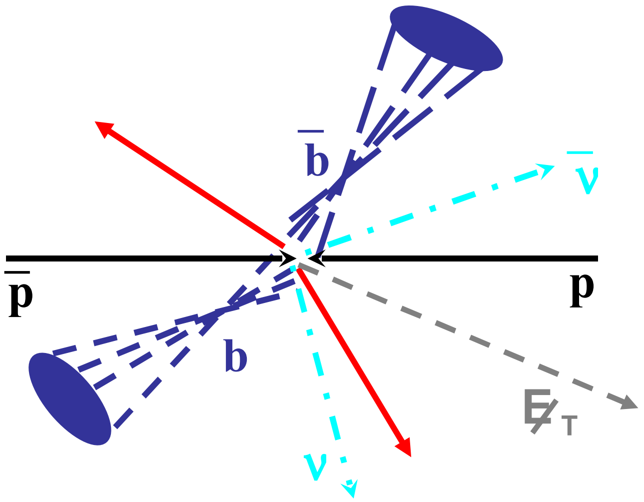
top quarks in action

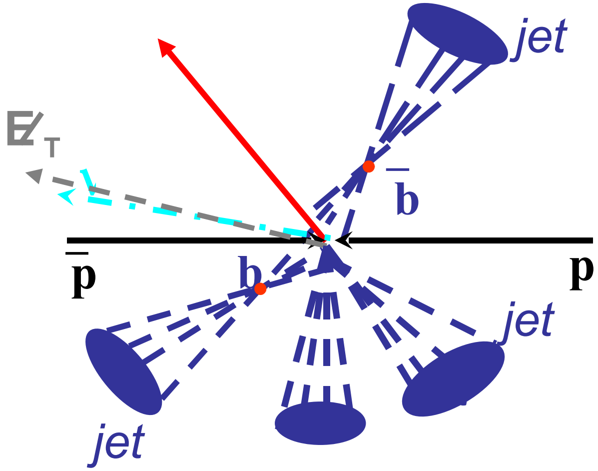
Top decays

In the SM: BR(t→Wb)~100%, classify topologies according to W decays from ttbar:

- **dilepton:** 2 high p_T leptons, 2 *b*-jets, large E_t^{mis}
  Small BR, but cleaner signal and small systematics. No *b*-tagging
- **lepton+jets:** 1 high p_T lepton, 4 jets (2 *b*'s), large E_t^{mis}
  Larger yield, larger bkg⇒Use event topology, *b*-tagging (and SLT)
- **all jets:** 6 jets (2 *b*'s)
  Swamped by bkg, very challenging, but impossible at LHC! Use NN





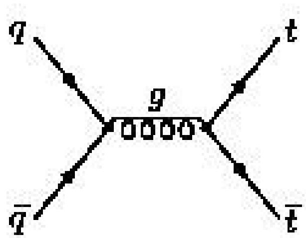


Top-quark Physics

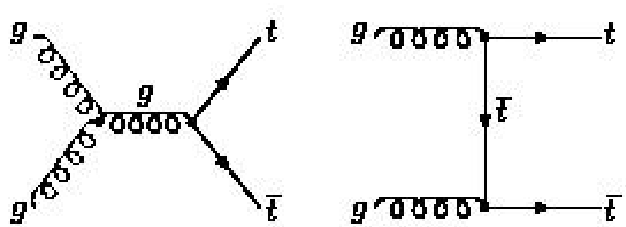
Pair production through strong interaction
σ(tt) ~ 7.5 pb at **1.96TeV**
M_t = 174.3±5.1 GeV

Measure cross-section more accurately
Measure the mass more accurately

Does it always decay the way the SM predicts it should?
Does it have any weird interactions???



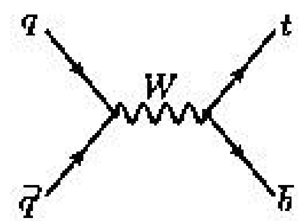
~90% of σ(tt)



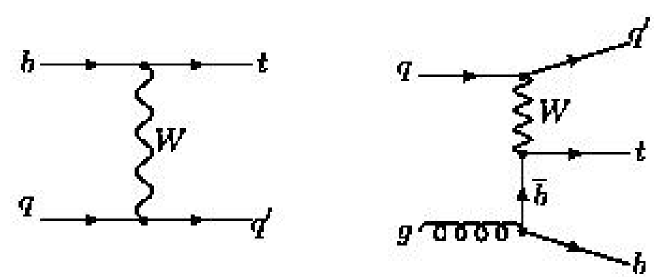
~10% of σ(tt)

Single top production via EW interaction
σ(t) ~ 2.86 pb at **1.96TeV**

Very difficult to observe because of large backgrounds
Would be a nice measurement: measure V_{tb} directly!

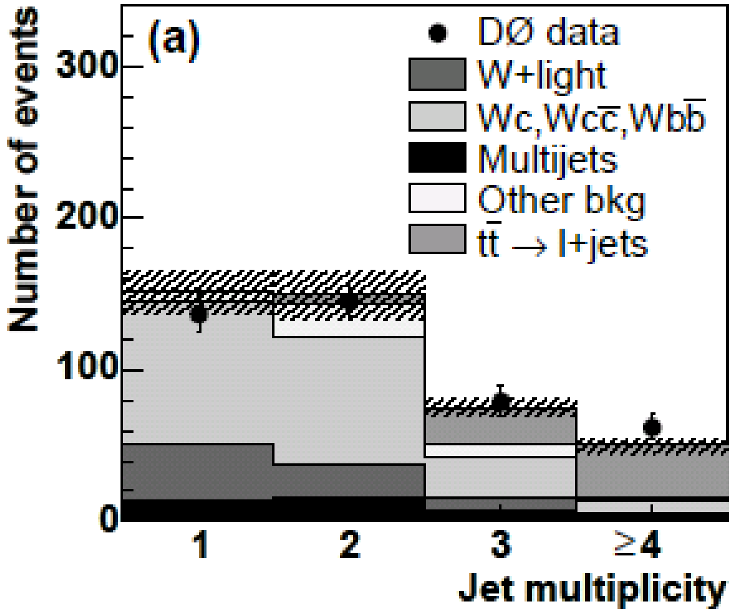


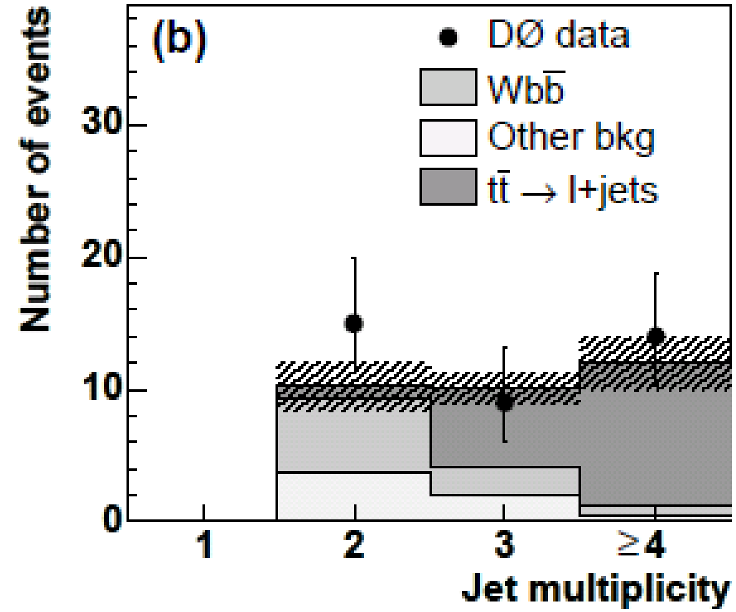
~30% of σ(t)

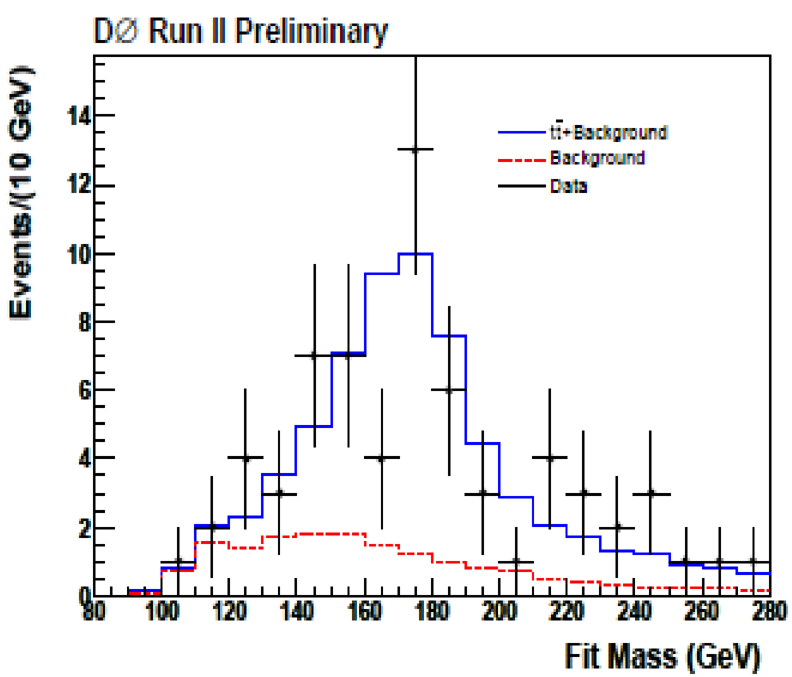


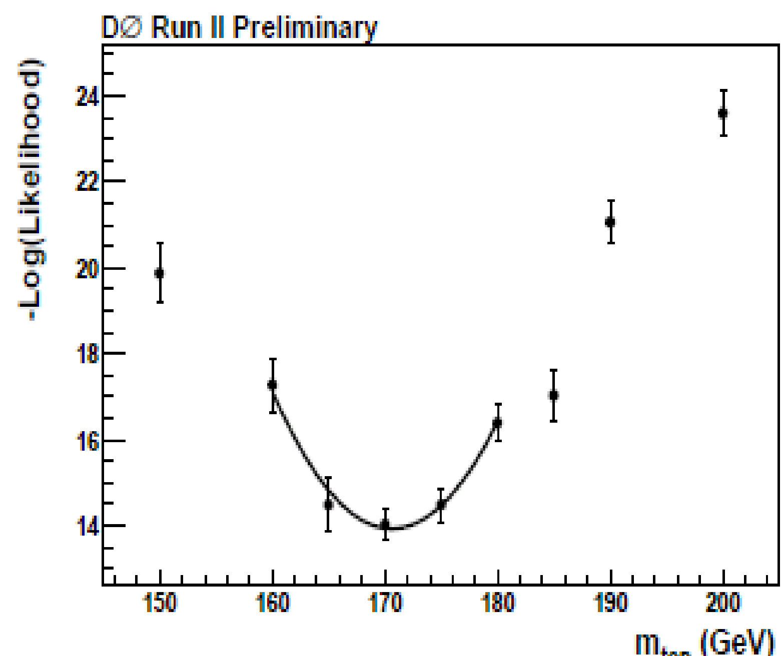
~70% of σ(t)

Top cross-section and mass : lepton +jets channel

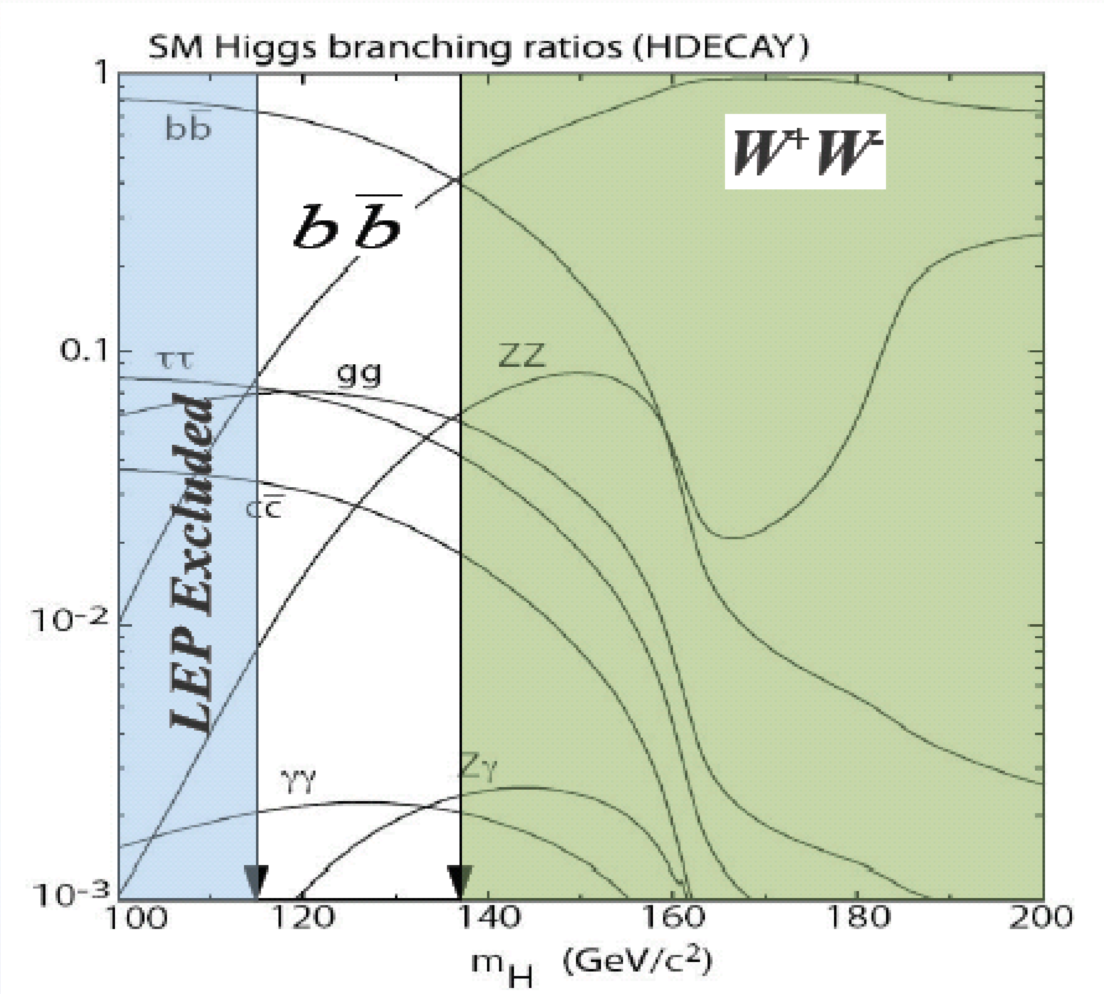


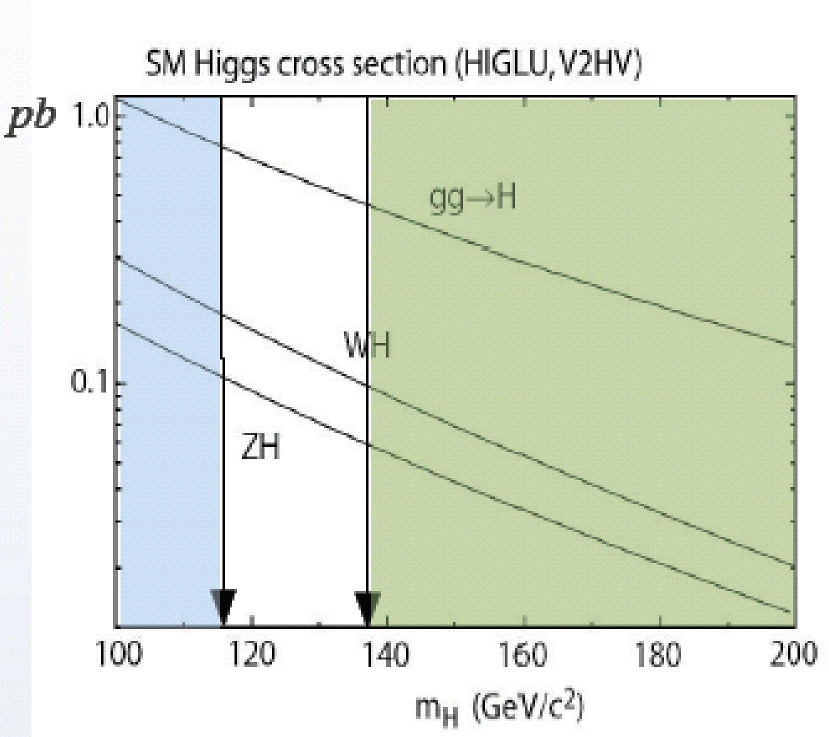






The Standard Model Higgs at the Tevatron



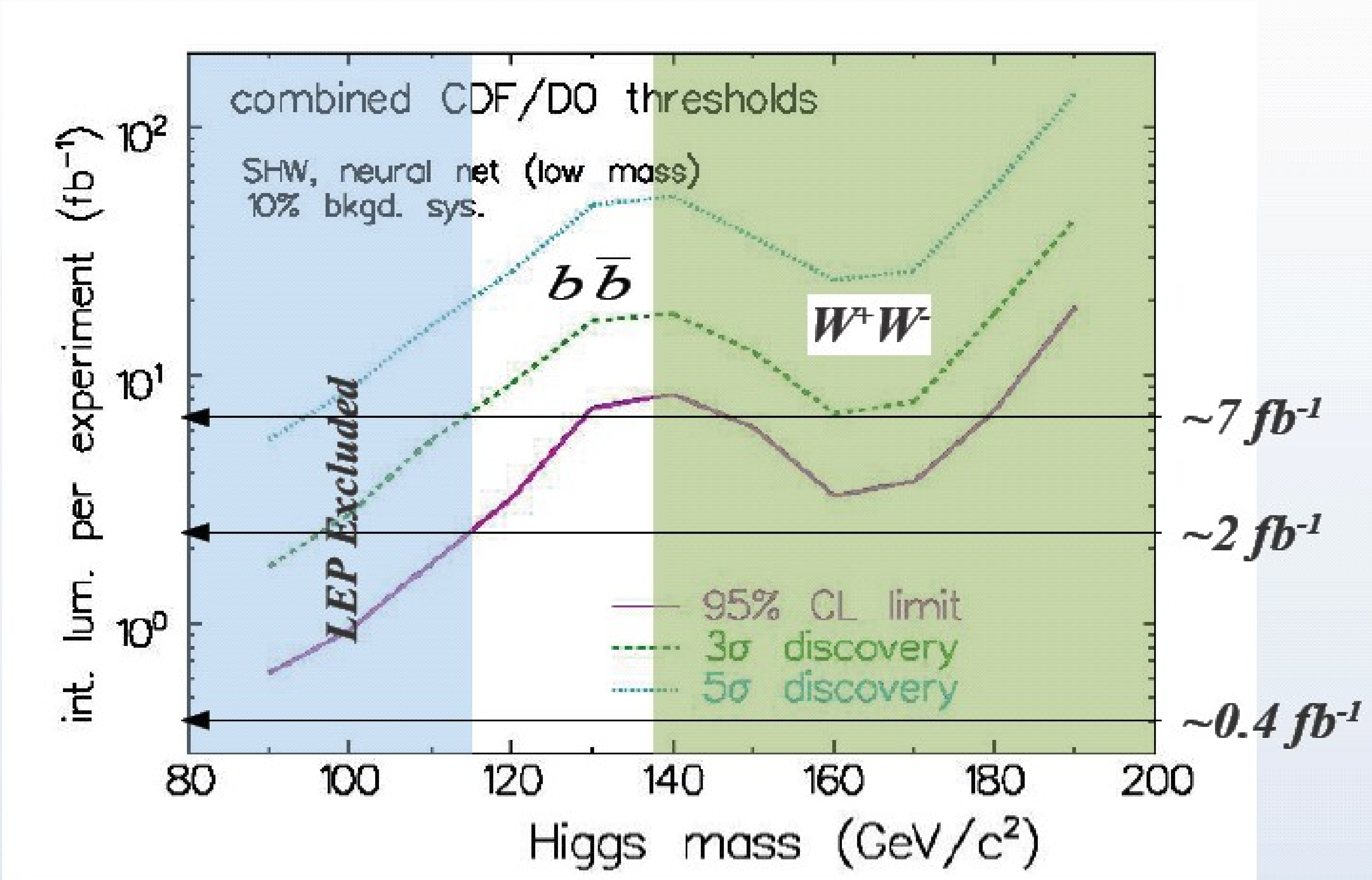


- The search method is different for the *high* and *low* mass regions

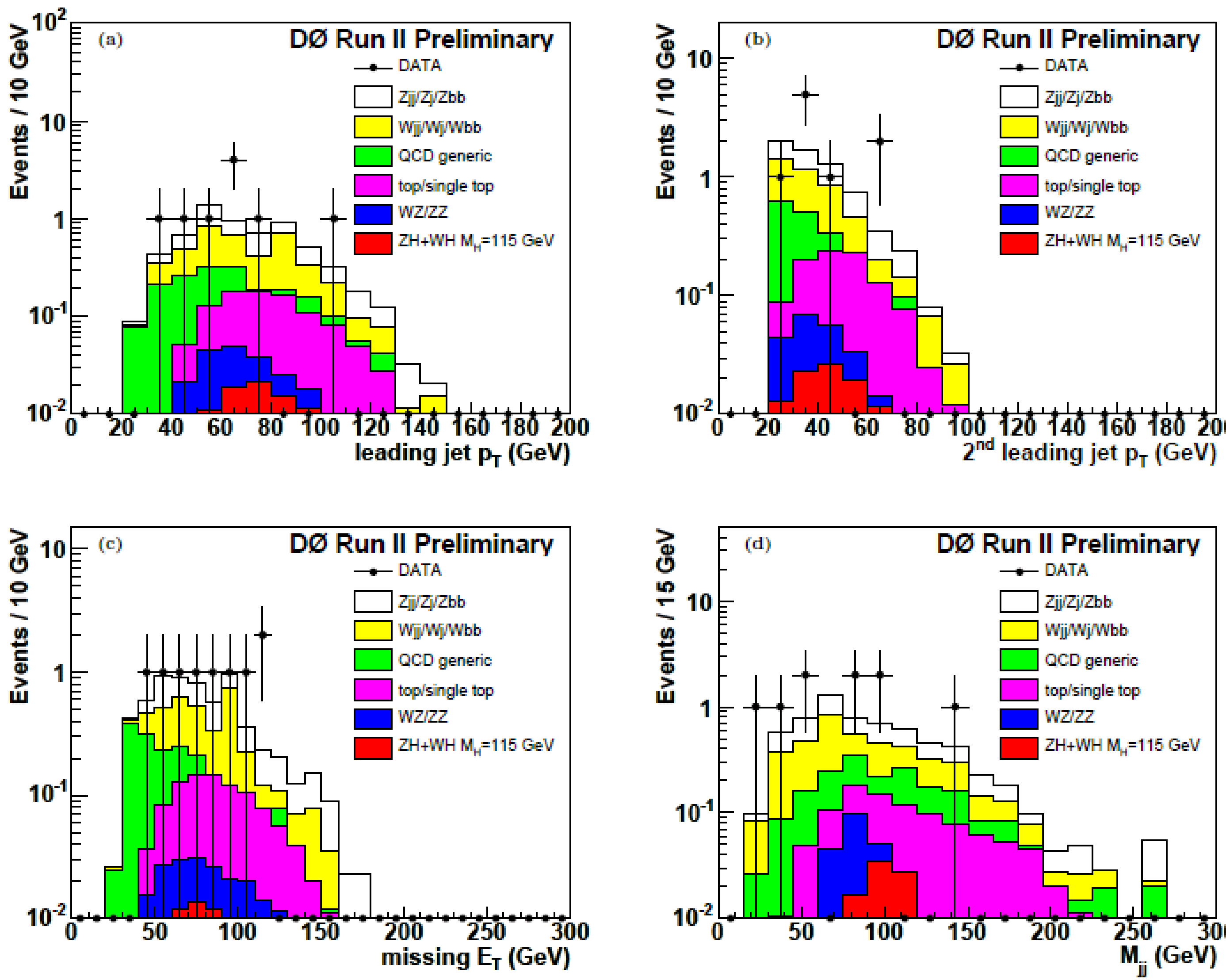
The couplings are proportional to mass...

The Higgs prefers to decay to the heaviest allowed final states.

Expected Higgs Sensitivity in the Standard Model

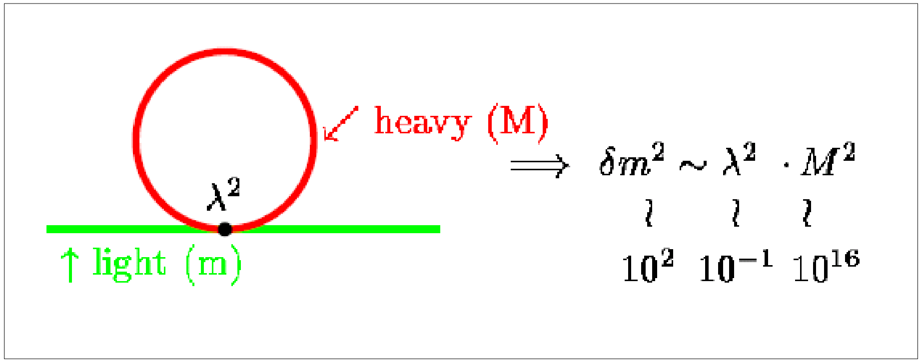


ZH (nu nu b b) Search

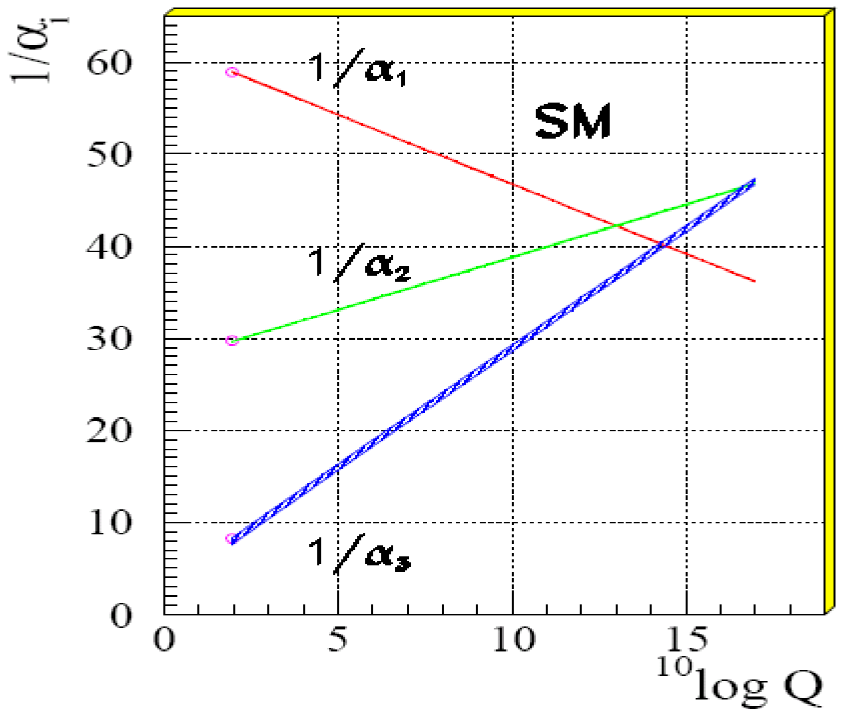


More to the Story?

- **Hierarchy problem:**
  - **Why is $m_h << m_{pl}$?**
- **Hierarchy stability problem:**
  - **QFT predicts *radiative corrections***
  - **How does m_h stay $<< m_{pl}$?**

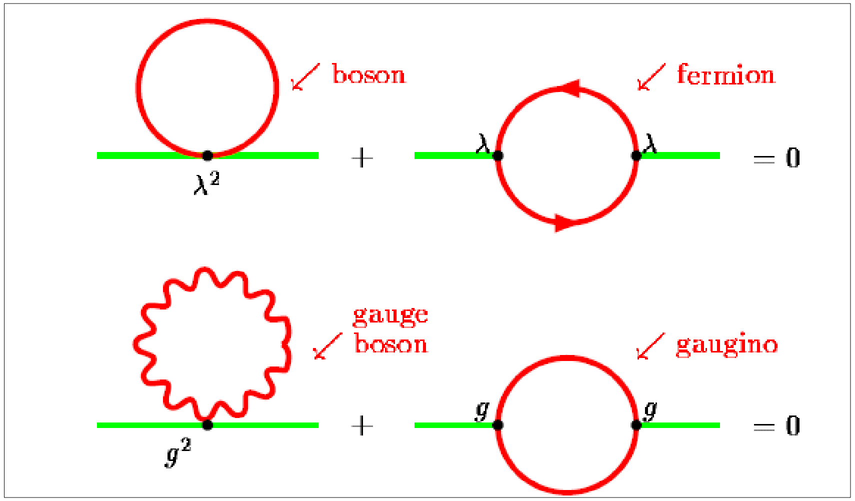


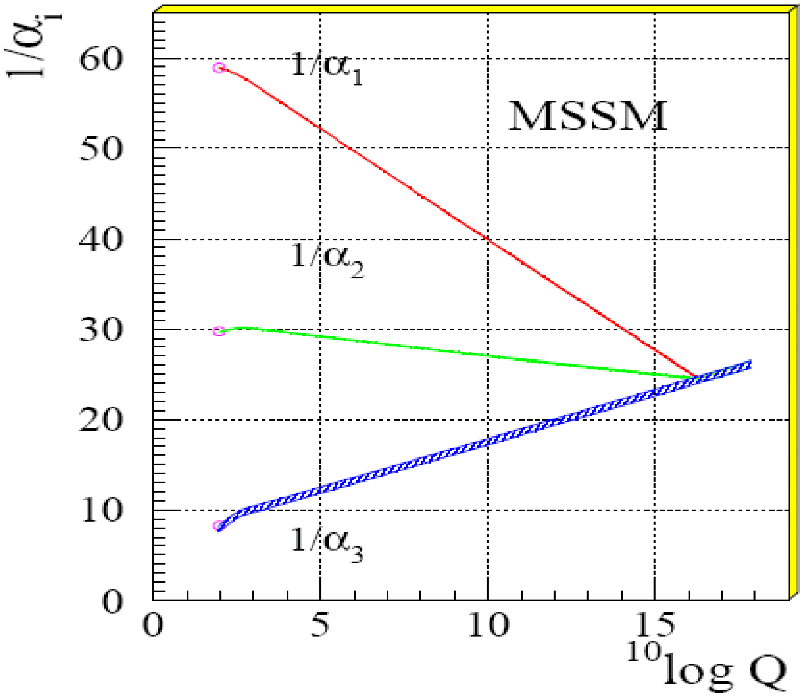
- **Can the gauge couplings unify?**
  - **Needed for Grand Unified Theories (GUT)**
  - **Ruled out in the SM !**



Supersymmetry to the Rescue?

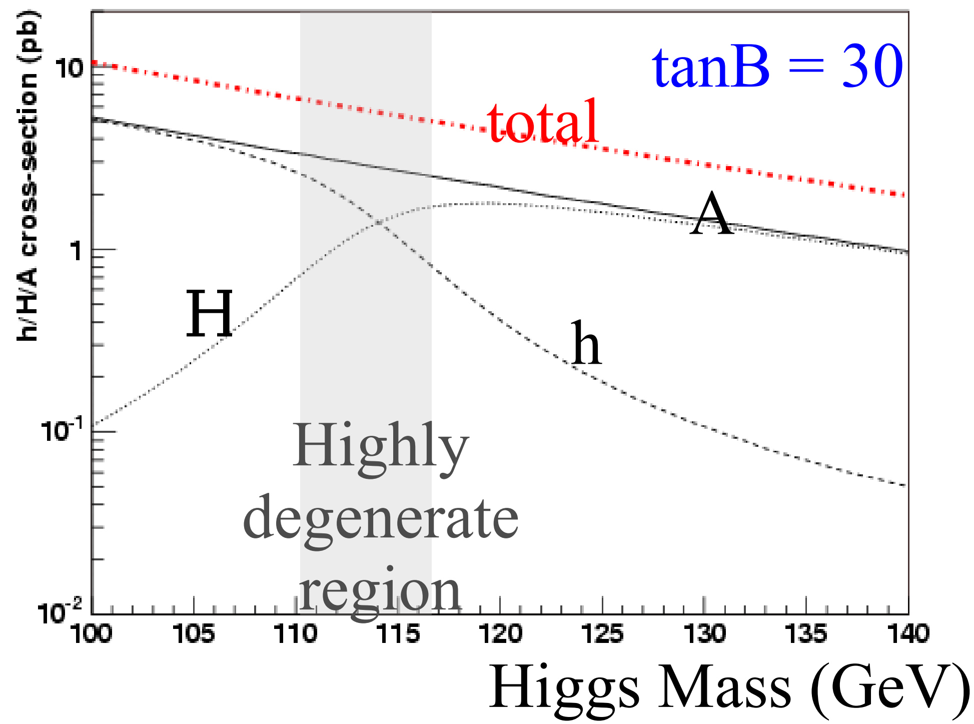
- Boson and fermion loop integral contributions differ by a factor of (-1)
  - A fermion for every boson: scalar field masses are stabilized
- Supersymmetry is *slightly* broken
- Supersymmetry demands an *even* number of Higgs doublets
  - A light higgs is predicted (m_h<m_Z at tree-level)
  - With 2 Higgs doublets, couplings unify at 10^{16} GeV
    - This is the MSSM

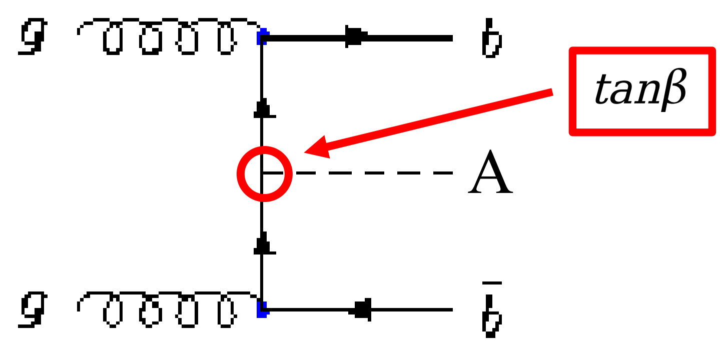




Higgses in Supersymmetry

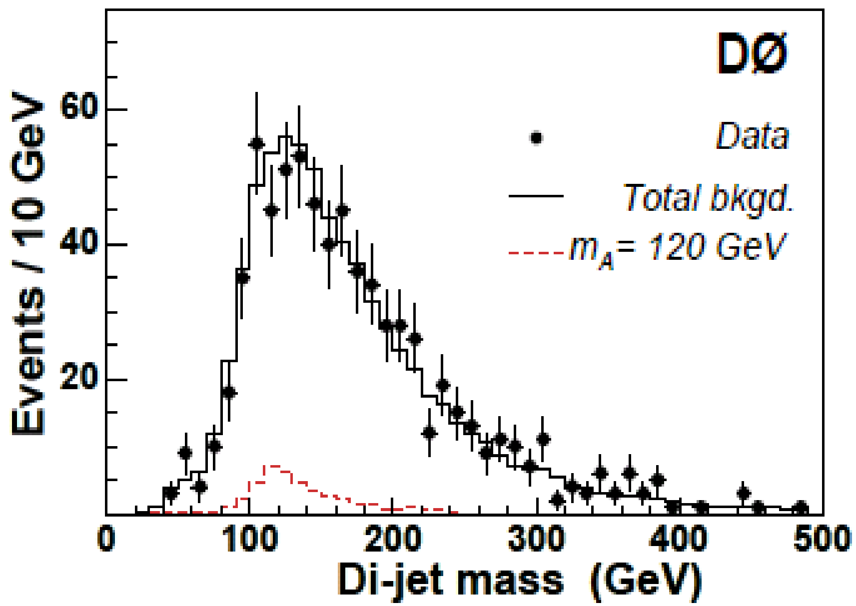
- Higgs fields come in pairs (H_u and H_d)
- 5 Higgs bosons : h, H, A, H+, H-
- $\tan\beta = H_u / H_d$
- Cross-sections for bbh grow like $\tan^2\beta$!



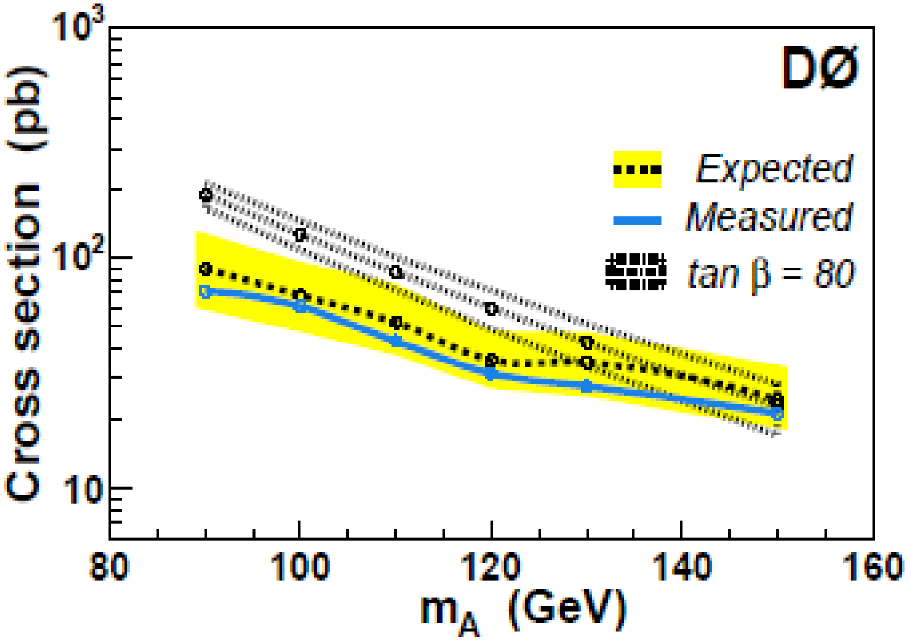


Search for Higgses in Supersymmetry (bh→bbb)

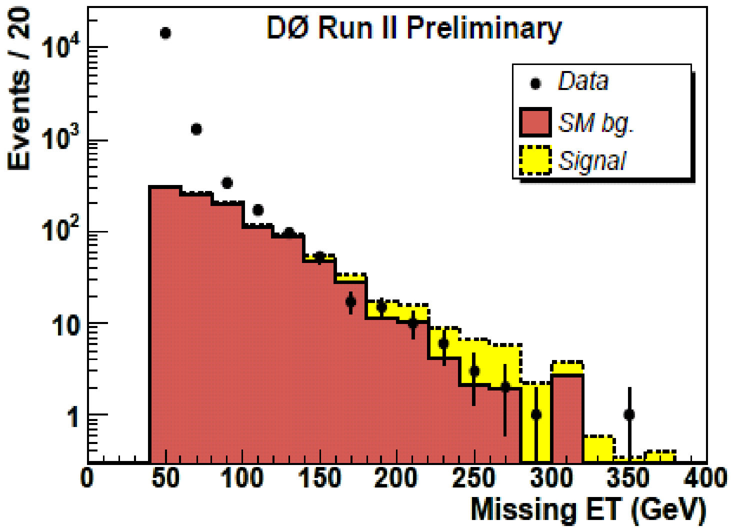
3 b-tagged jets



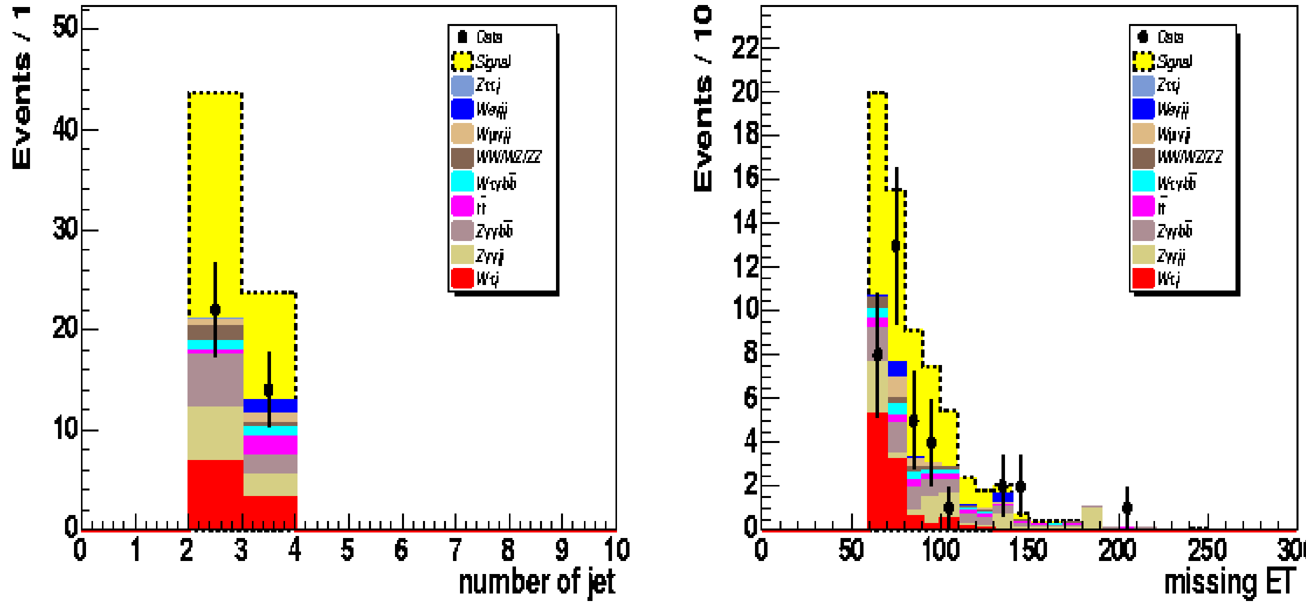
Set limits on bh→bbb



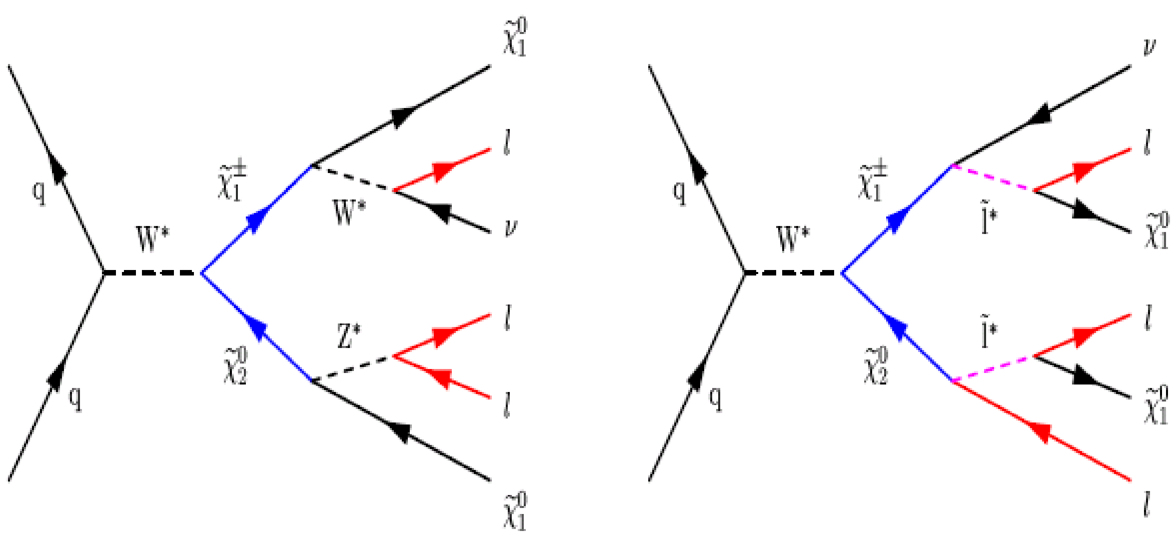
Searching for Supersymmetry...

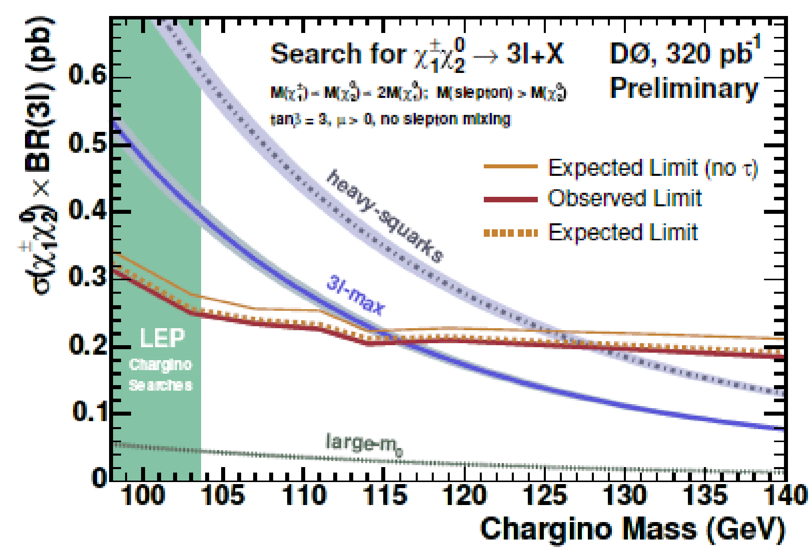


squarks/gluinos
(jets + MET)



sbottoms : (jets + btagging + MET)



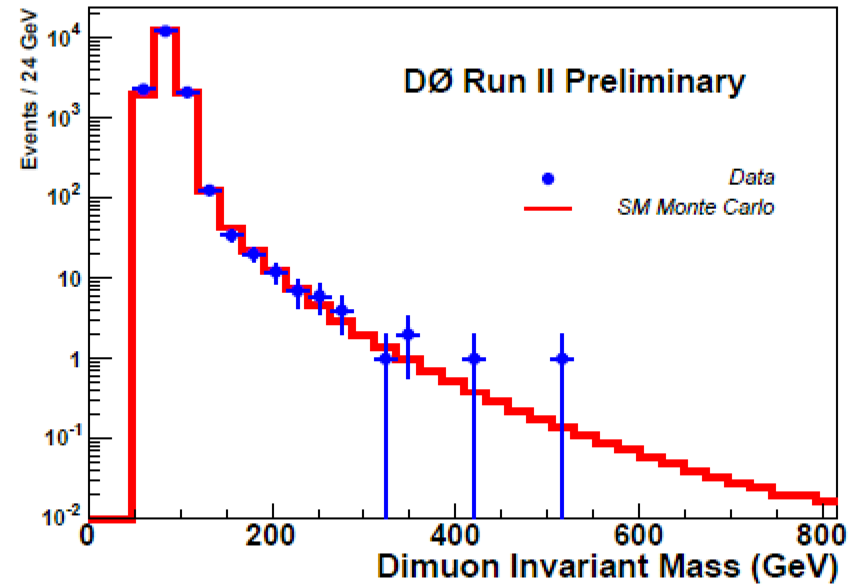


charginos / neutralinos (3 leptons + MET)

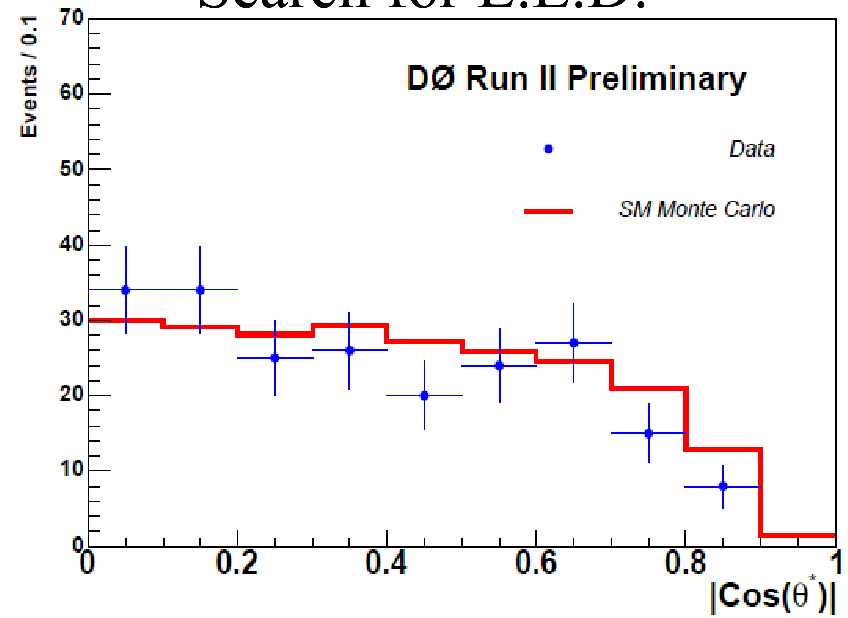
Other New Phenomena... have an open mind!

- Many other searches!
  - Large Extra Dimensions
  - Heavy Z' gauge bosons
  - R-parity violating Supersymmetry
  - Gauge-mediated Supersymmetry breaking: di-photon excesses
  - Lepto-quarks
  - Technicolor
  - Massive stable particles
  - ...

Search for Z' boson



Search for L.E.D.



Summary

- There's a huge amount of physics to study
- It takes a lot of people
- We have a lot of data on tape, more is coming in every day
- D0 and CDF are the only places currently capable of making these measurements and searches for new phyiscs
- We study the known particles and interactions
- We look for new particles and interactions we expect to exist
- We look for surprises!