Recent Results on Standard Model Physics and Beyond at the Fermilab TeVatron

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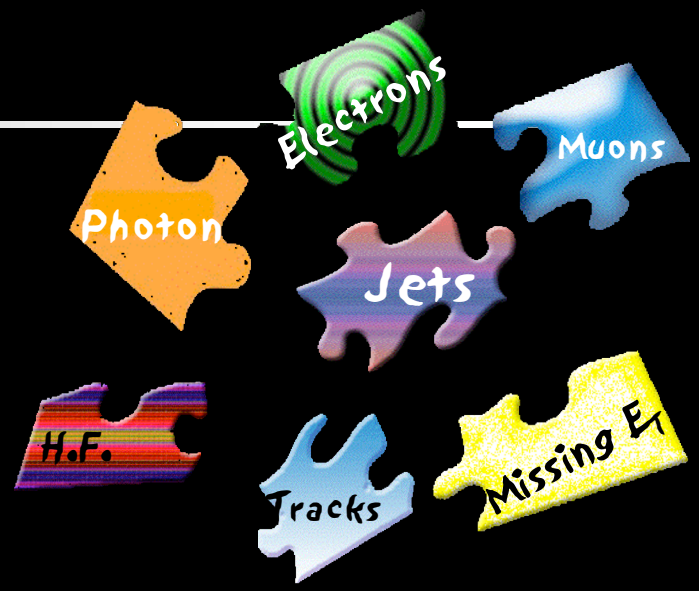
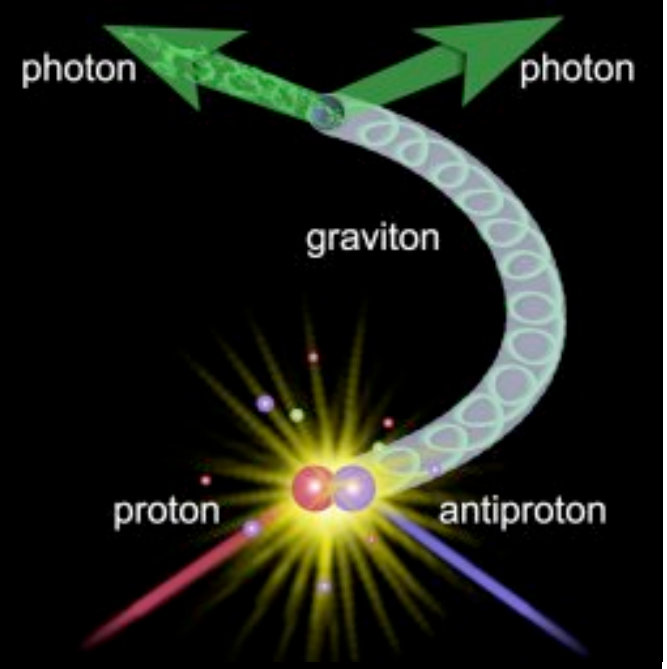
Outline of the talk

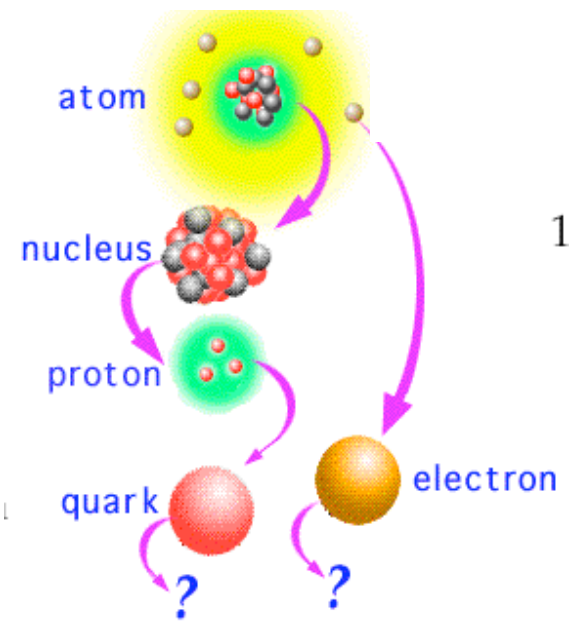


- **What is the Universe made of ?**
  - **The Standard Model of particle physics**
- **The Experimental Apparatus**
  - **The Fermilab TeVatron**
  - **The CDF detector**
- **The thrill of discovery**
- **Physics Processes and their Signatures**
  - From W/Z to the Top quark and Beyond
  - **Leptons-only final states (and isolated tracks)**
  - **… + Missing Energy and Photons**
  - **… + Jets and heavy flavors**
- **The puzzle of Nature….**



What is the Universe made of?

- Everything we see is made of molecules or chains of atoms
- Atoms contain a nucleus surrounded by electrons
- In the nucleus there are protons and neutrons
- Proton and neutrons are bound states of quarks and gluons
- When we look closer we find an amazing world of particles and interactions and we travel back in time…..



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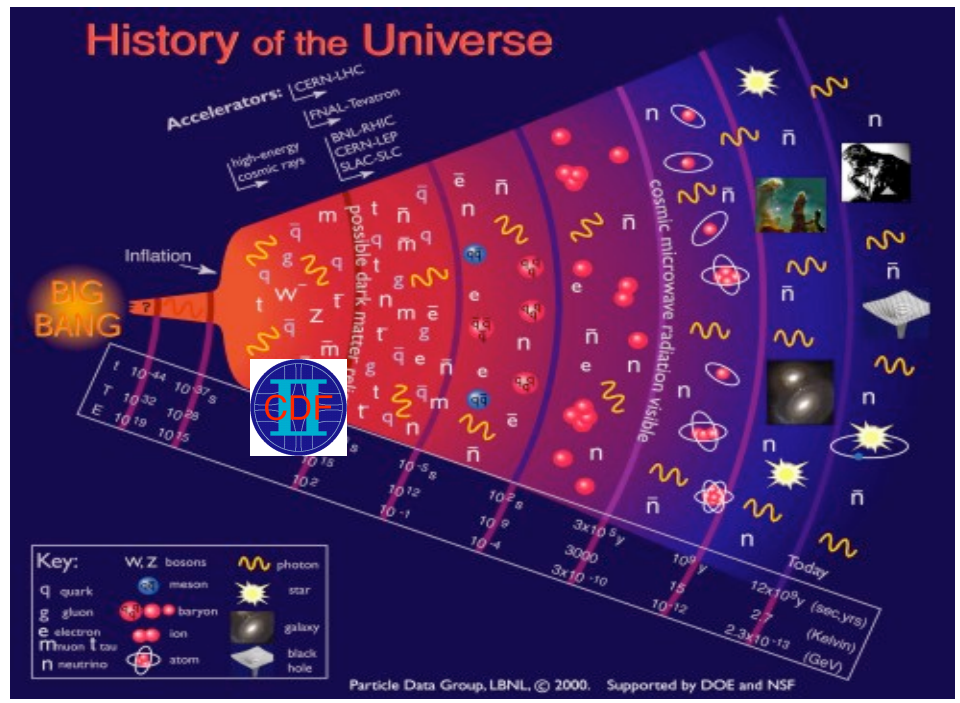
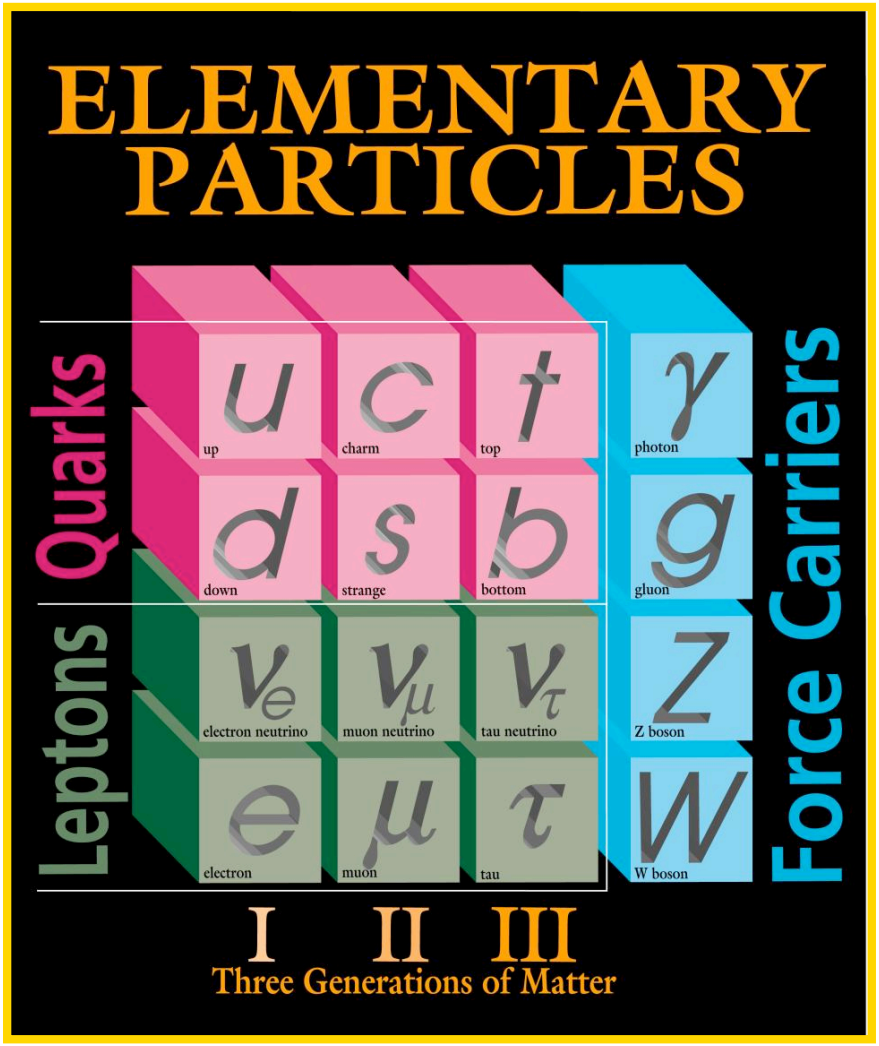


The Standard Model of Particle Physics

- The Standard Model describes the fundamental particles and the interactions between them;
- Leptons like electrons are believed to be fundamental
- Hadrons are composite states of quarks and gluons;
  - Baryons (three quarks like protons and neutrons)
  - Mesons (a quark and one anti-quark)
- Force carriers are particles responsible for the interactions



The Standard Model Properties

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Collider Experiments can Identify all types of particles

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

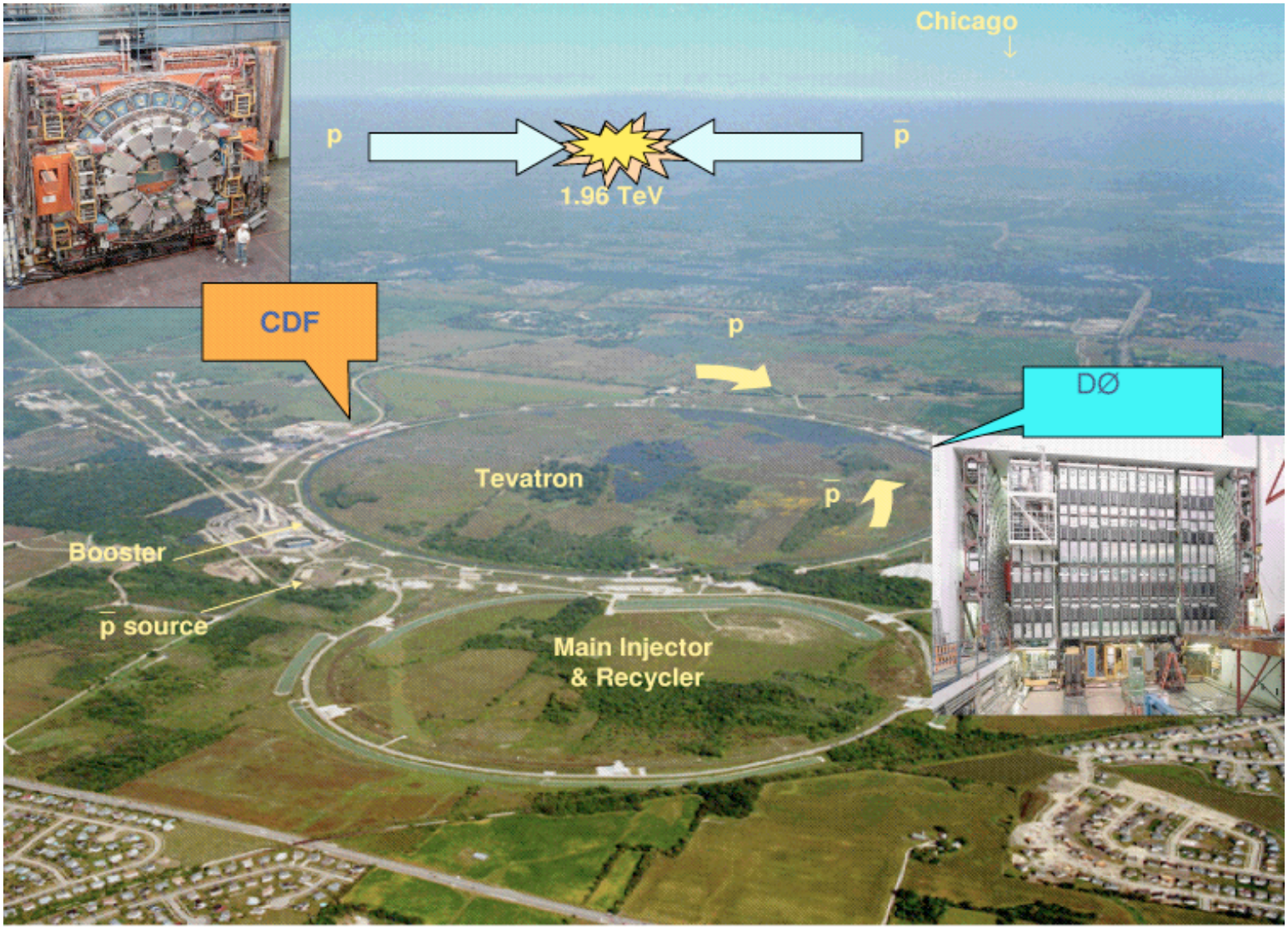
The Thrill of Discovery: A Brief History of CDF

- 1985: First collisions with partial detector
- 1987: Core detector in place. Jet Physics
- 1988-89: "Run 0" 4x the expected data, seen lots of W/Z's
- 1992-1995 : "Run I" -added silicon detector. Top quark discovered!

- 2001-present: Run II era begins with essentially a new detector, higher collisions energy and more data.
- 2004: First Run II physics papers published

12 countries, 59 institutions
706 physicists

The Experimental Apparatus



The Accelerator Chain

An **electronvolt** (symbol: eV) is the amount of energy gained by a single unbound electron when it falls through an electrostatic potential difference of one volt. Very small amount of energy: 1 eV ≈ 1.602×10^{-19} J.

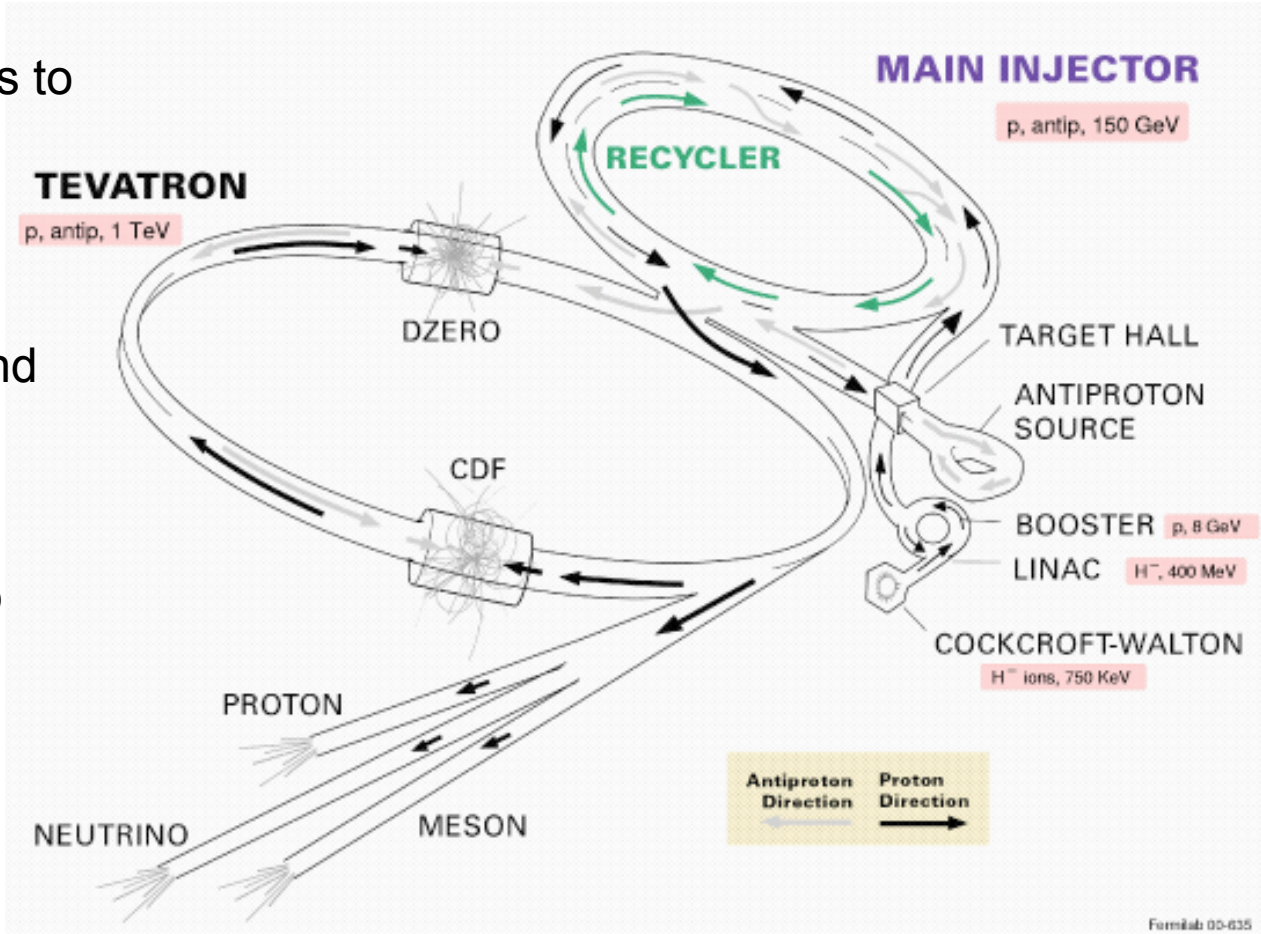
Start by accelerating protons

Some protons hit targets to make antiprotons

Store antiprotons

Use main injector to send p's and antiprotons into the TeVatron

The TeVatron ramps up the beam energy



A small digression on Luminosity

The event rate $\mathcal{R}$ in a collider is proportional to the interaction cross section σ_{int} and the factor of proportionality is called Luminosity $\mathcal{L}$

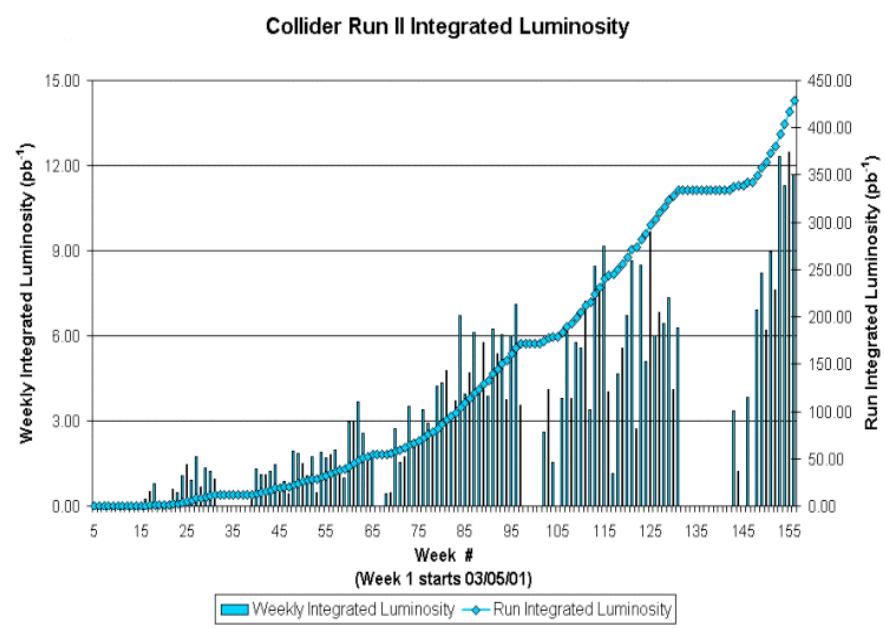
$$\mathcal{R} = \sigma \, \mathcal{L}$$

Luminosity is dependent on the number of bunches n_1 and n_2 of particles colliding, their frequency f and the gaussian beam profiles $\sigma_x \sigma_y$

$$\mathcal{L} = f \, n_1 n_2 / 4\pi\sigma_x\sigma_y$$

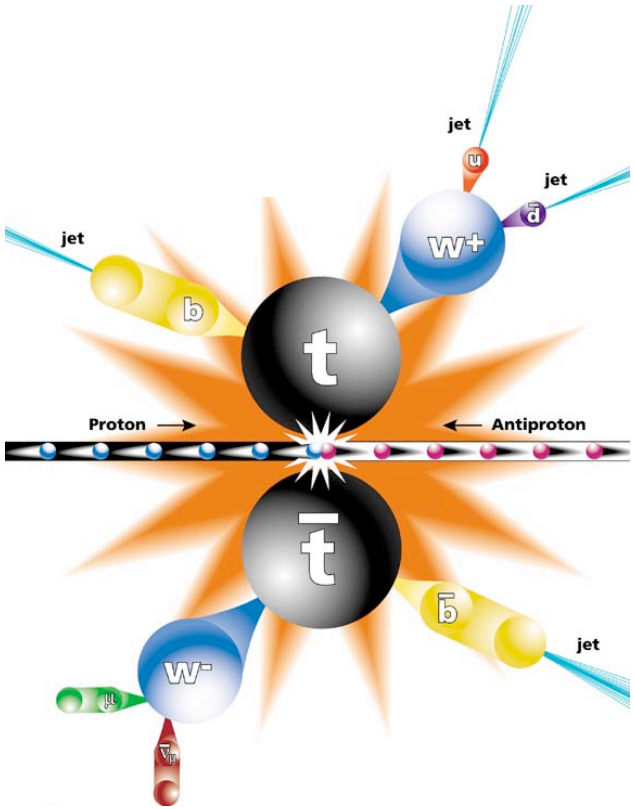
$(cm^{-2}\ s^{-1})$

The real important quantity is the integrated Luminosity, expressed in units inverse to the cross section, pb^{-1}, fb^{-1}.
It tells us the number of events we can see during the duration of the experiment!



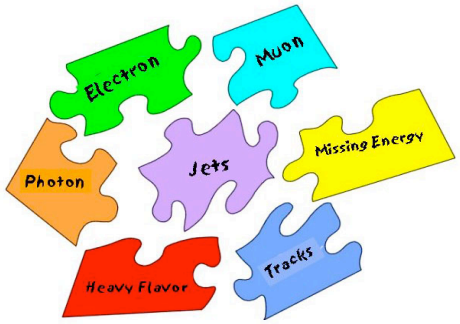
Proton-Antiproton Collisions

- Collisions:
  - At high energies we go inside the protons and antiprotons where we collide the internal quarks and gluons
- $E = mc^2$
  - Energy and mass are equivalent. With lots of energy we can produce lots of particles
- Production
  - In the collision process we can produce several types of particles and study their properties
- Decay
  - Some particles decay and the study of their daughters gives us insight on the nature of the interactions

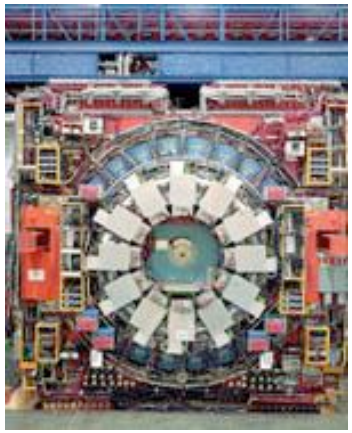


Physics Processes and their Signatures

- Physics Objects
  - Tracks
  - Jets
  - Electron
  - Photons
  - Neutrinos
  - Muons

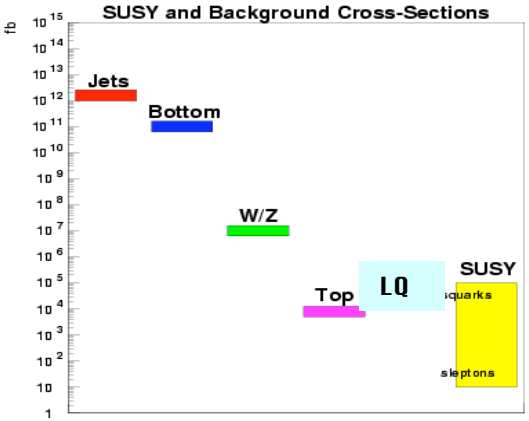


- Detector Components
  - Tracking system
    - COT
    - Silicon detector
  - Calorimeters
  - Muon Chambers



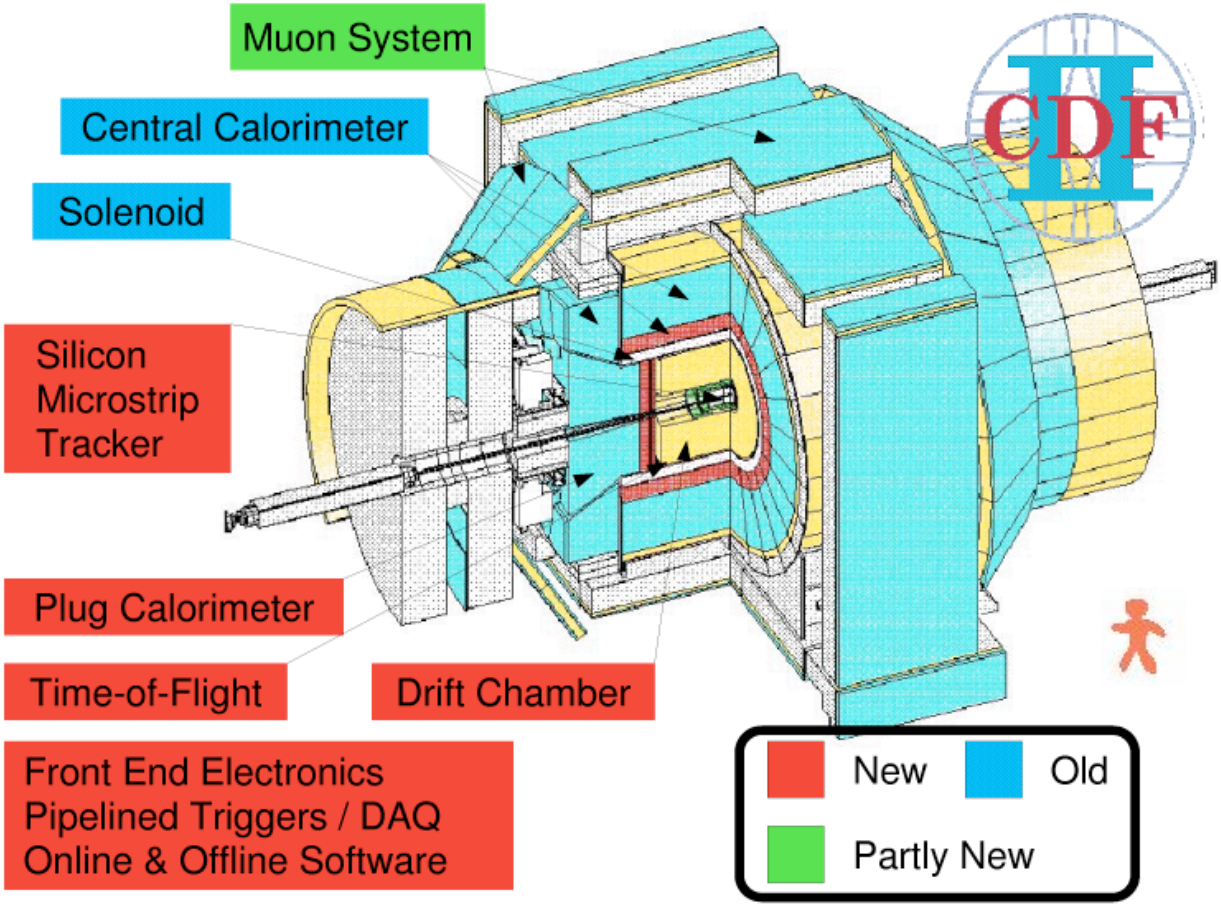
An Overview of Results (incomplete)

- Leptons-only final states
  - Z production
  - Drell-Yan studies
  - dilepton searches
- ... + Missing Energy and Photons
  - W production
  - Multibosons
- ... + Jets and heavy flavors
  - Jet Physics
  - Leptoquarks
  - Top quark
  - Higgs boson



The CDF Detector

The Experiment studies interesting collisions between protons and antiprotons



Transparent tracking in a magnetic field

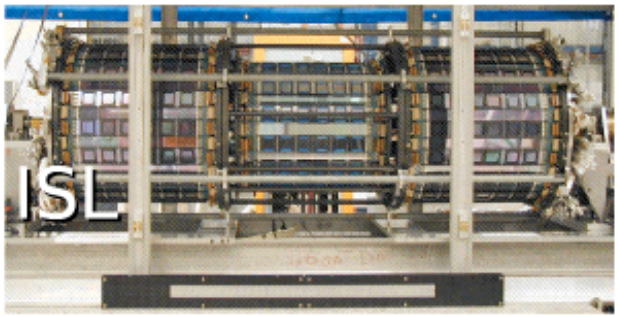
Absorb most particles with calorimeters

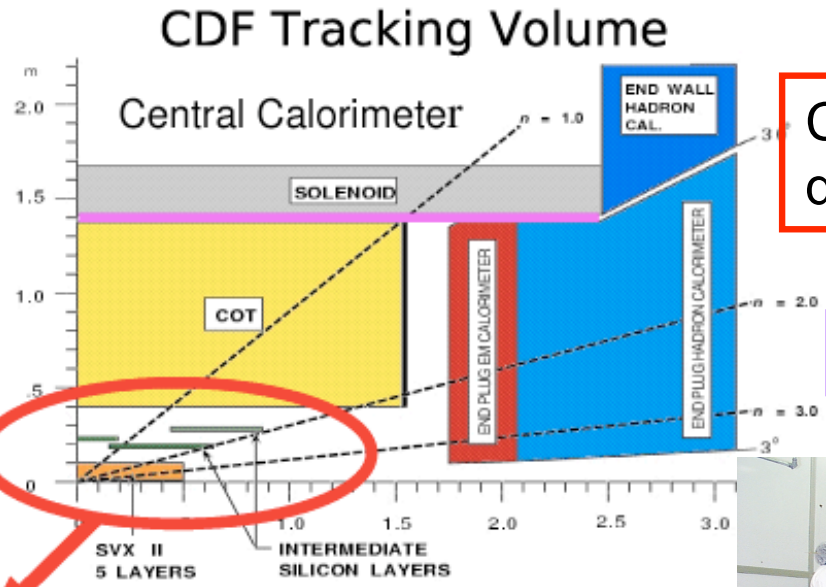
Surround the outside with muon chambers

Electronics to read out each subsystem

Computers to record and analyze data

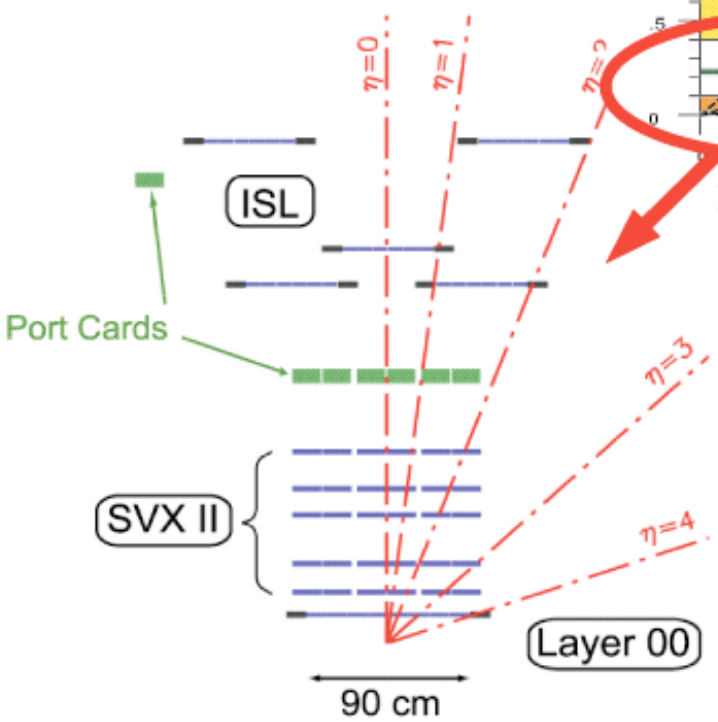
Tracking

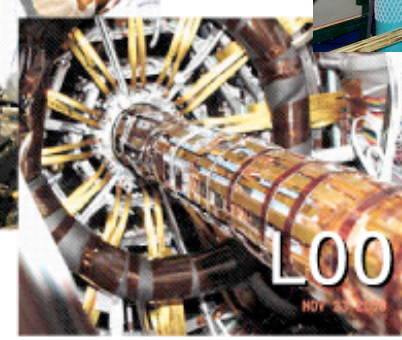




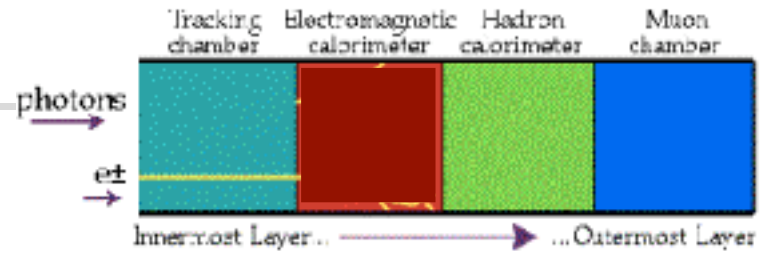
COT: open cell drift chamber

$\eta = -\log(\mathrm{tg}\,\theta)$

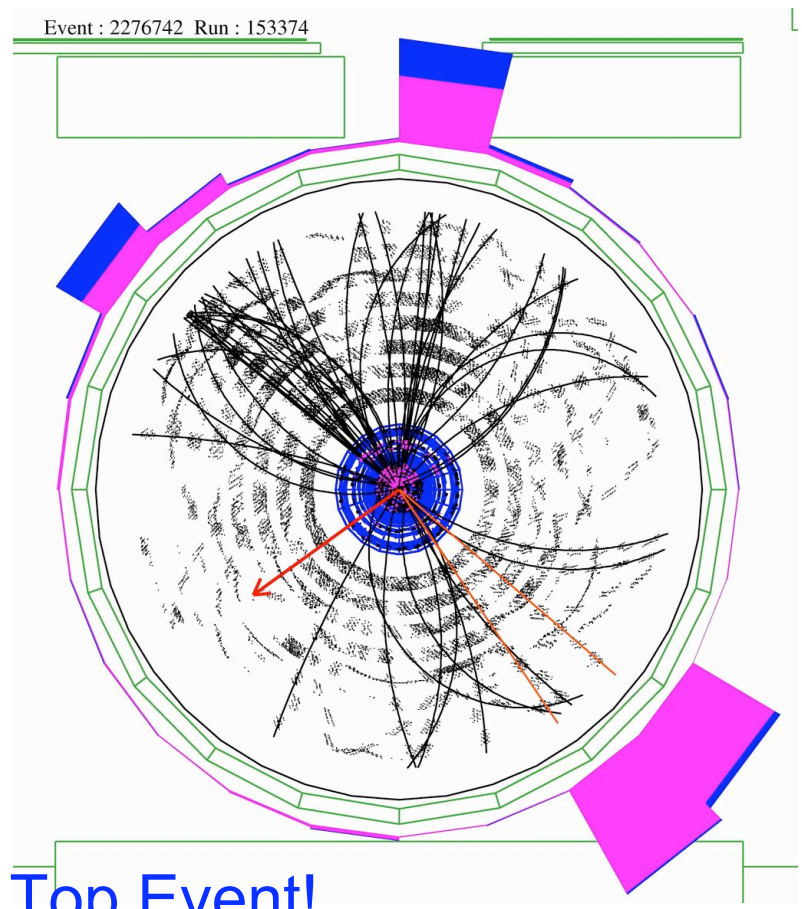




Seeing Tracks



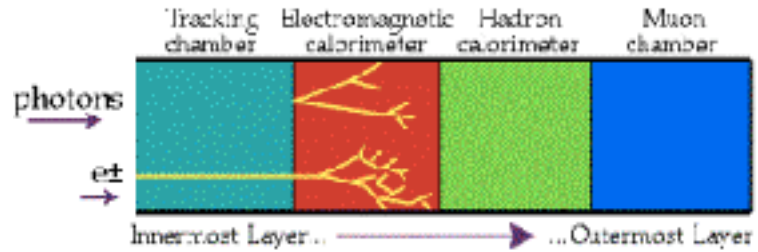
- Charged particles bend in the magnetic field
- Ions (e's) knocked off gas molecules drift to the wires giving electronic signals (drift chambers)
- Hit patterns can be recognized as tracks
- The higher the energy (momentum) the straighter is the track
- Beside momentum, tracks give information about the collision point

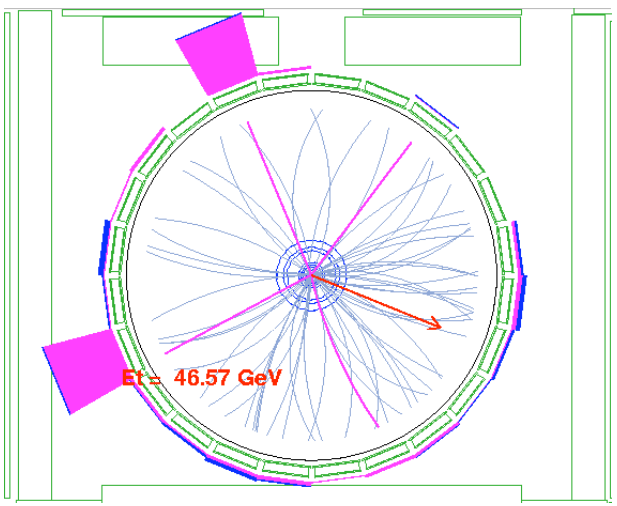


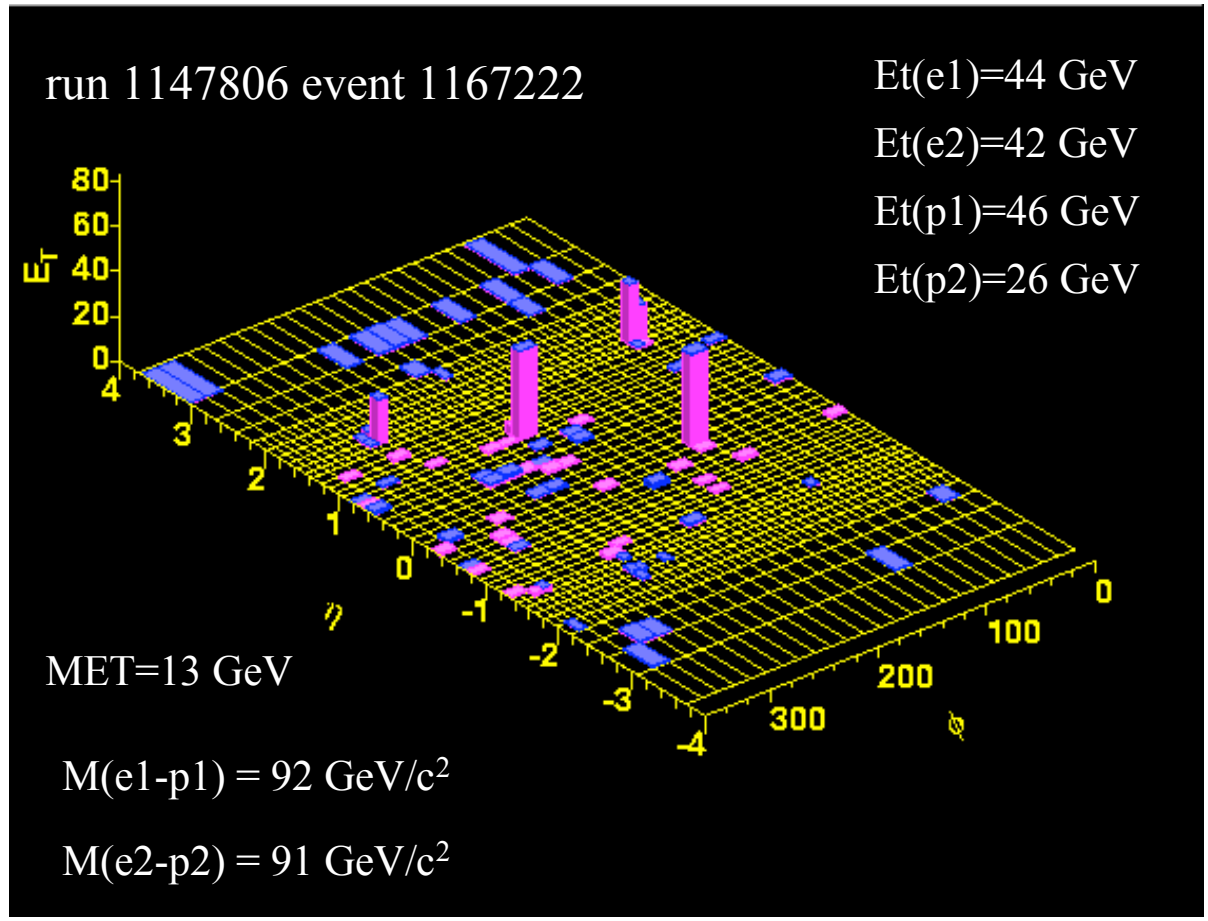
A Top Event!

Electrons and Photons

- Electrons and Photons get easily absorbed by the calorimeter
- Tracking association gives the ability to identify a charge particle, the electron.

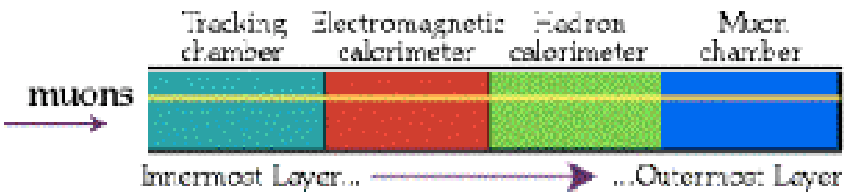


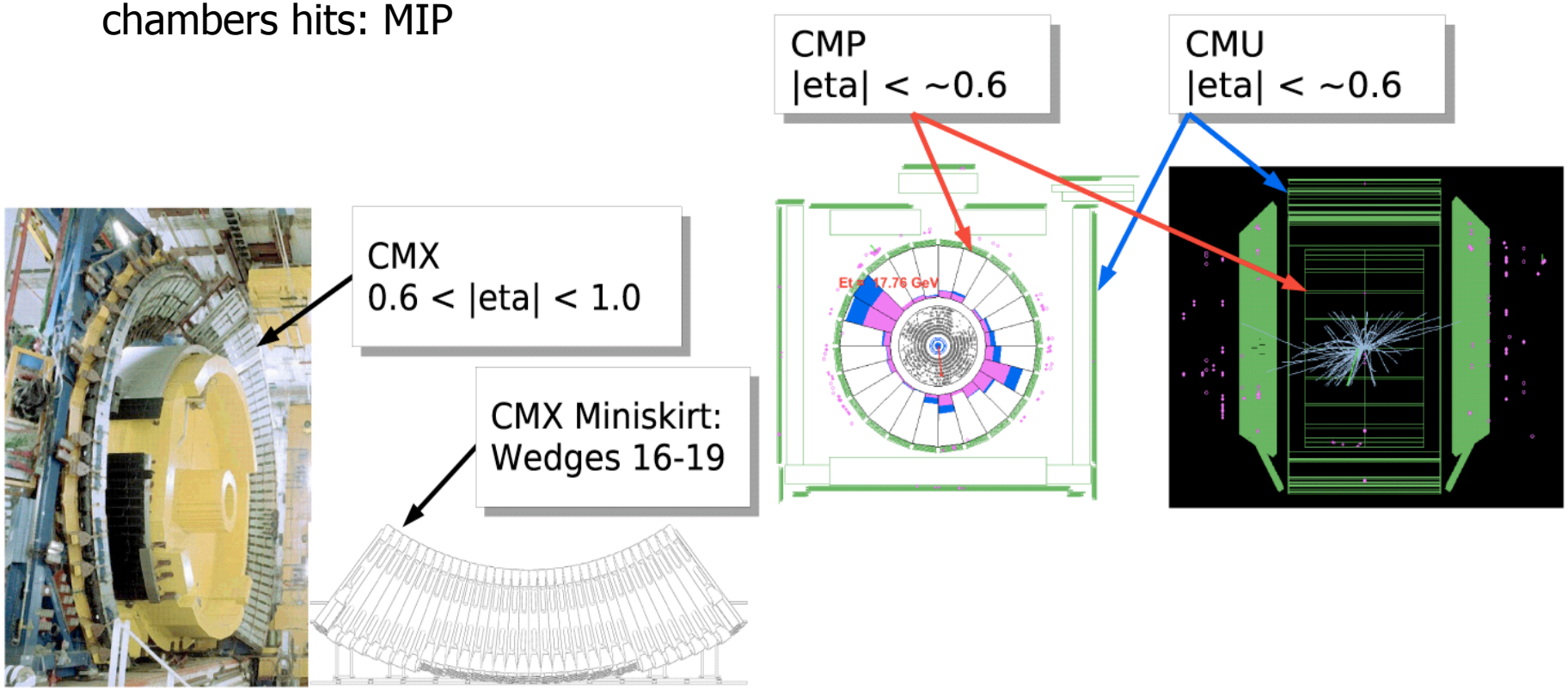




Muons

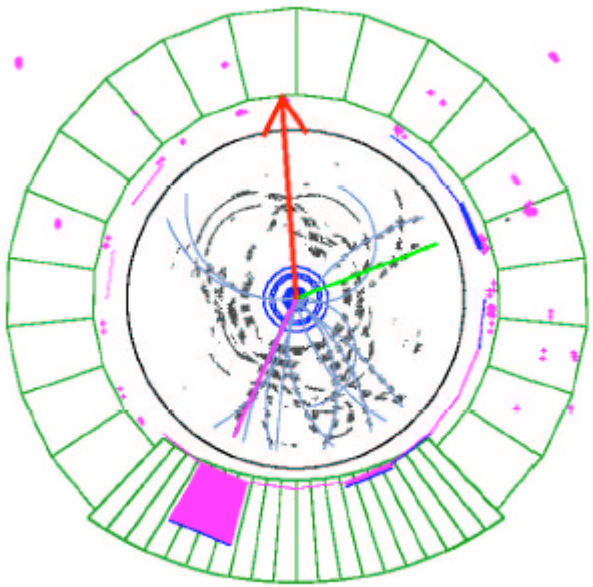
- Muon can penetrate lots of material before getting absorbed.
- Easily identified as coincidence between tracks and muon chambers hits: MIP



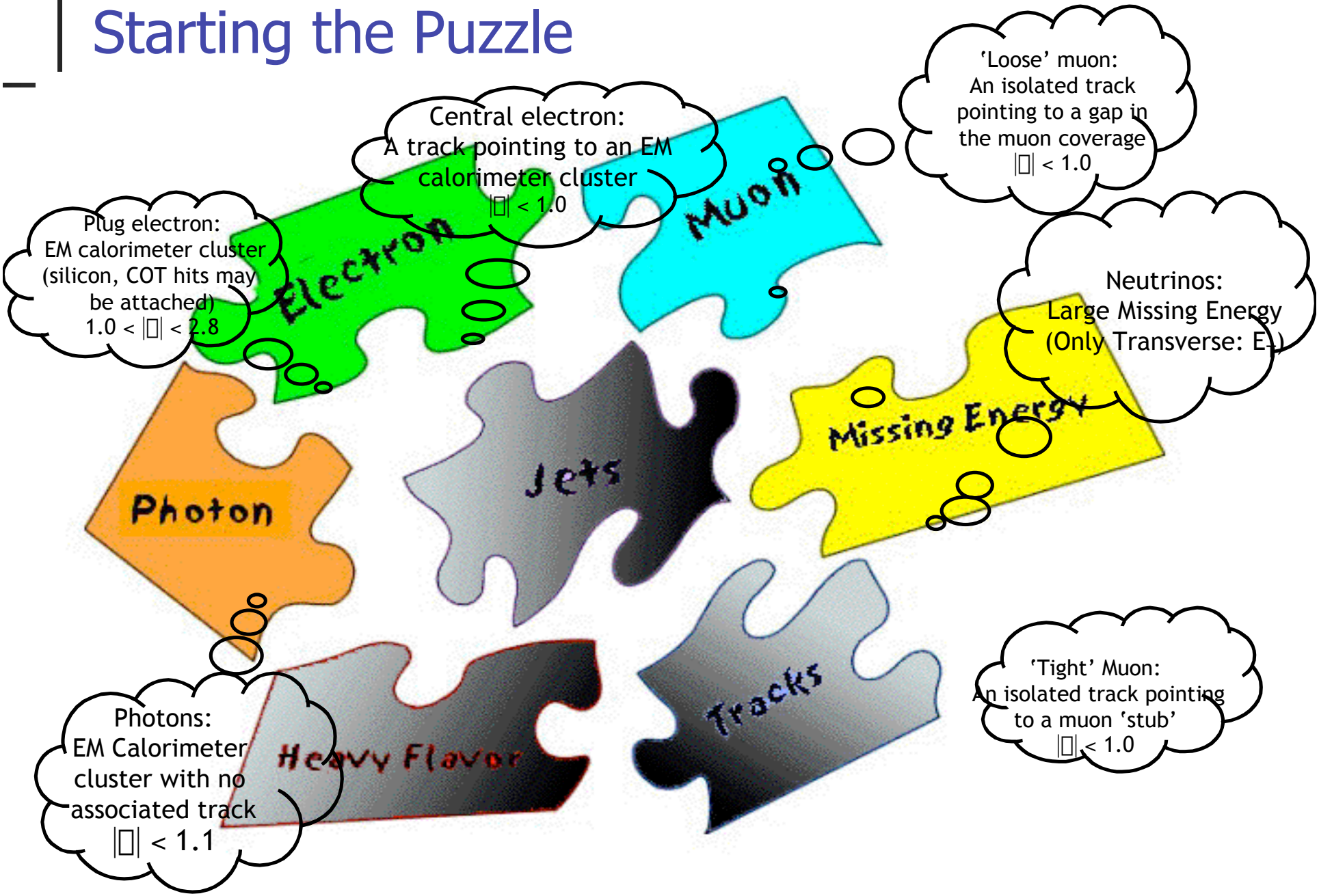


Neutrinos

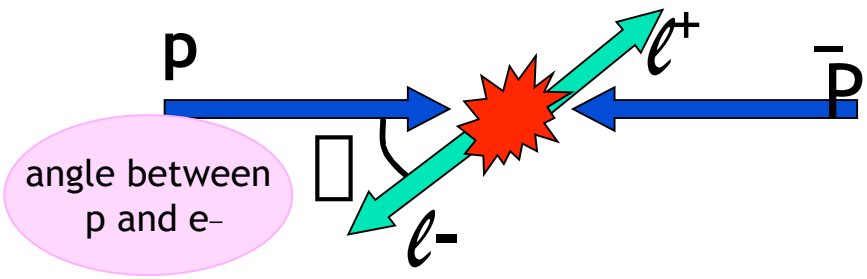
- Neutrinos rarely interact at all.
  - Since they have no charge, there is no track associated to them.
  - They don't leave energy in the calorimeter
  - They leave the detector undisturbed…
- <u>The presence of the neutrino is inferred by its absence!</u>
- We deduce the presence of neutrinos by calculating the missing energy to the total energy of the event.



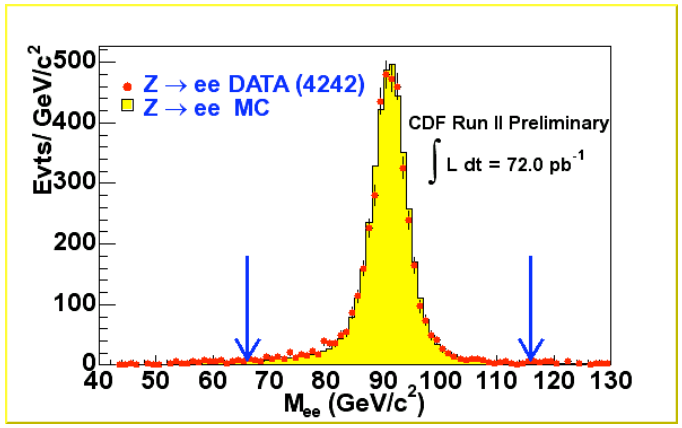
Starting the Puzzle

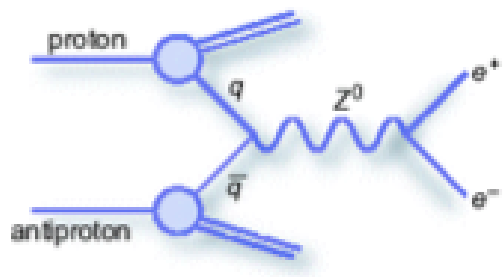


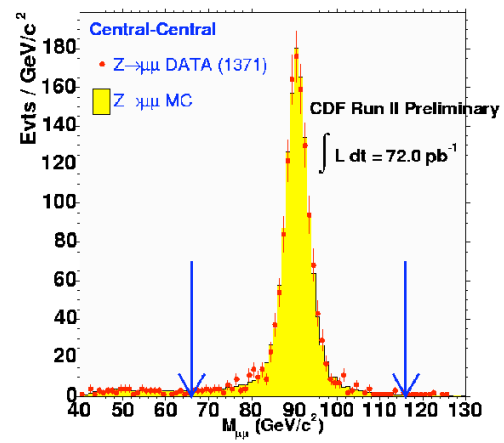
Z^0 Vector Boson Production



Very low backgrounds (QCD, $Z \rightarrow \tau\tau$, cosmics) : < 1%
Important systematics : PDF's, Material Descriptions



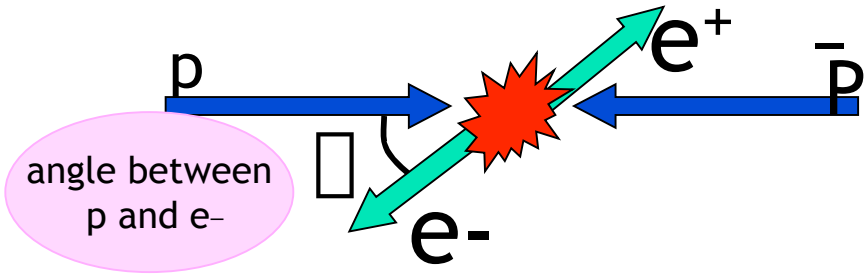




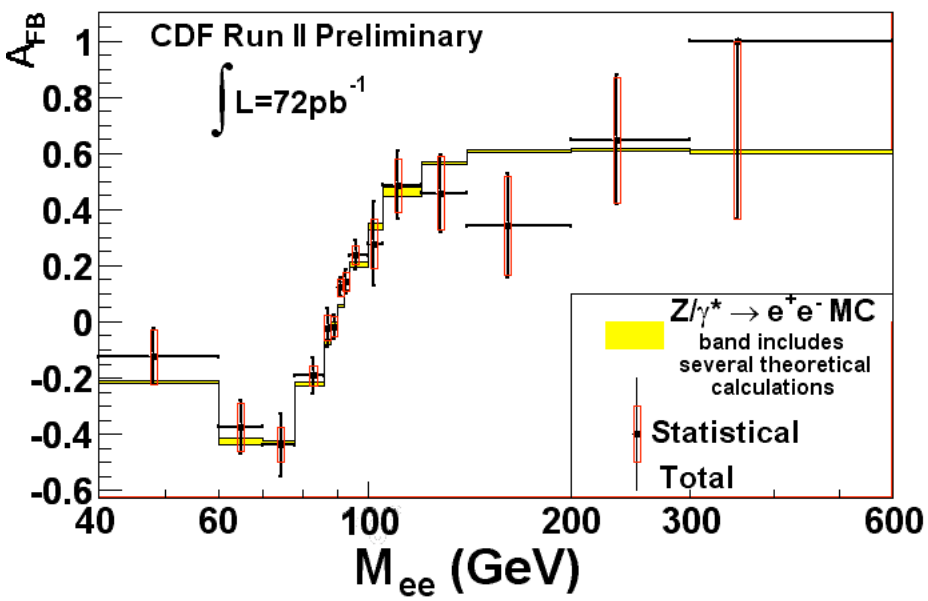
□□BR(Z□ ee) = 255.2 ±3.9(stat) ± 5.5 (sys) ± 15.3(lum) pb
□□BR(Z□ □□) = 248.9 ±5.9(stat) $^{+7.0}_{-6.2}$ (sys) ± 14.9(lum) pb

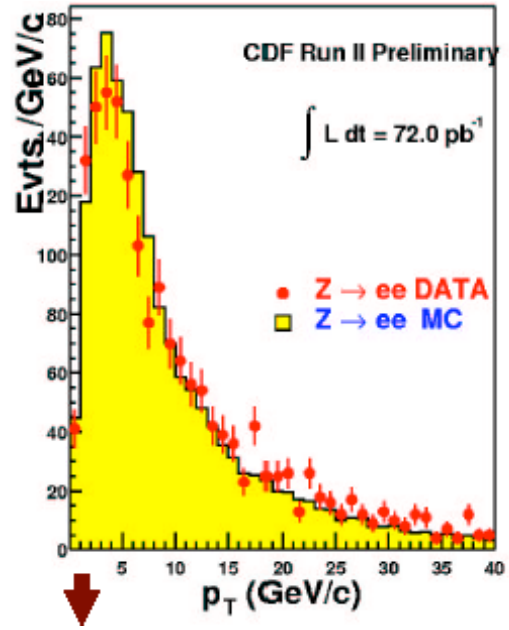
→ Extended measurements of cross section are well advanced

Drell-Yan Measurements



$$A_{fb} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

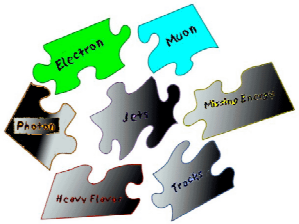




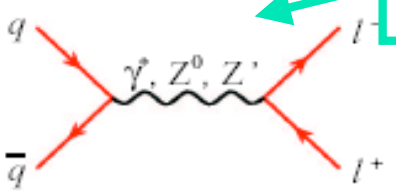
- Production properties : eventually feed into precision measurements (M_W)

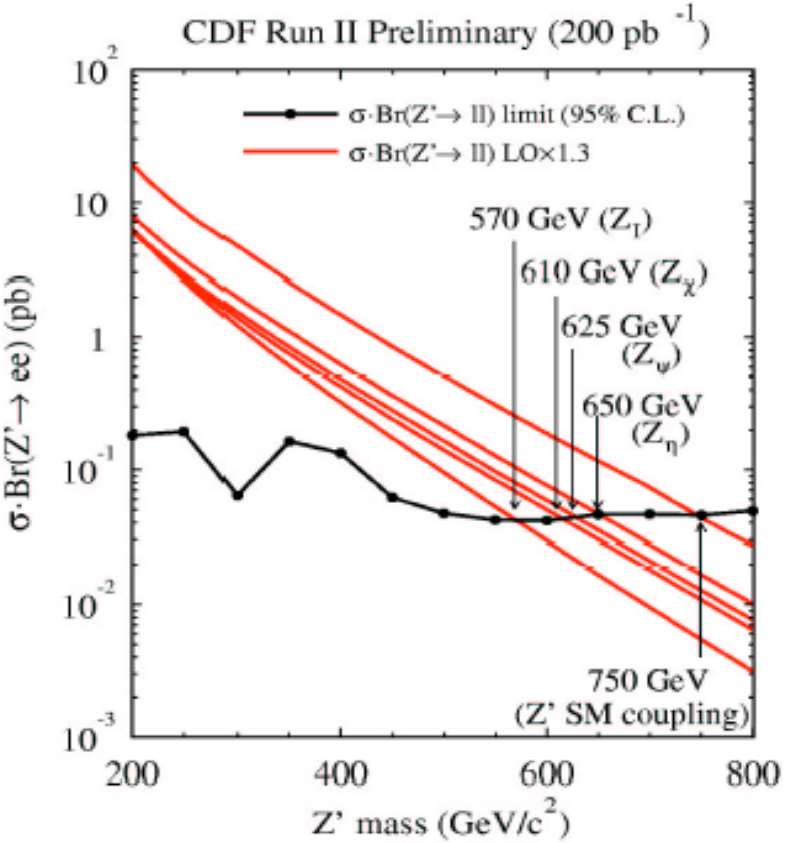
- $|\eta^e|<3.0$: using full detector coverage
- extract quark, lepton couplings & $\sin^2\vartheta_W$
- sensitive to new physics

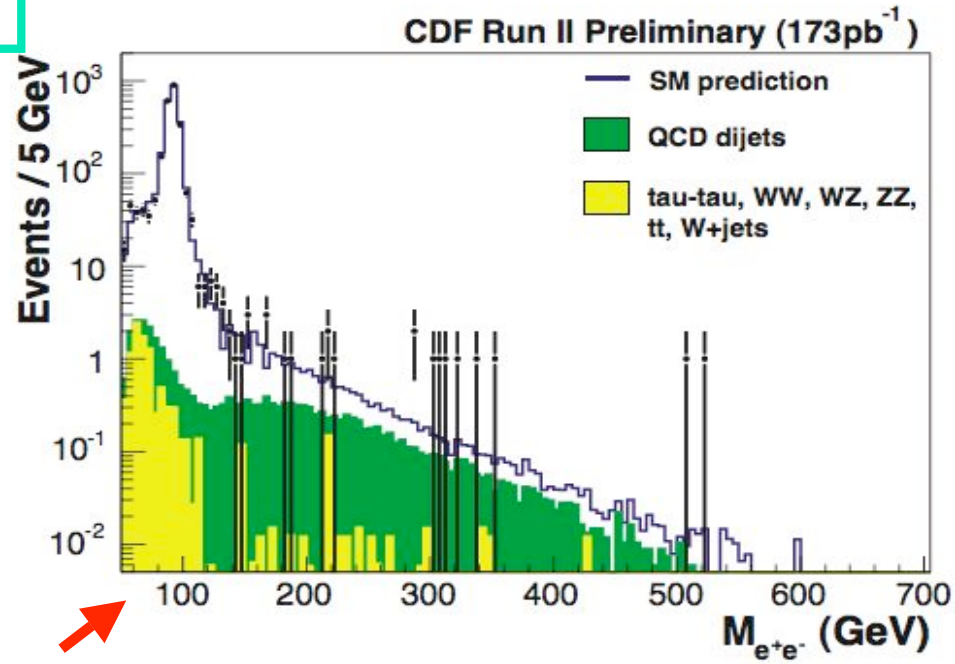
Searches in dileptons



Non SM!

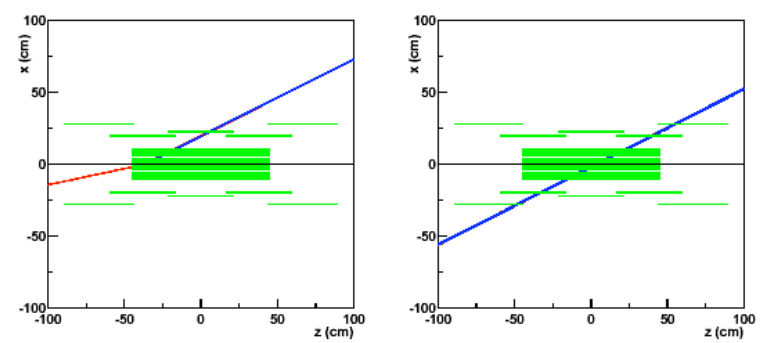






Forward electrons : $1.2 < |\eta| < 2.5$

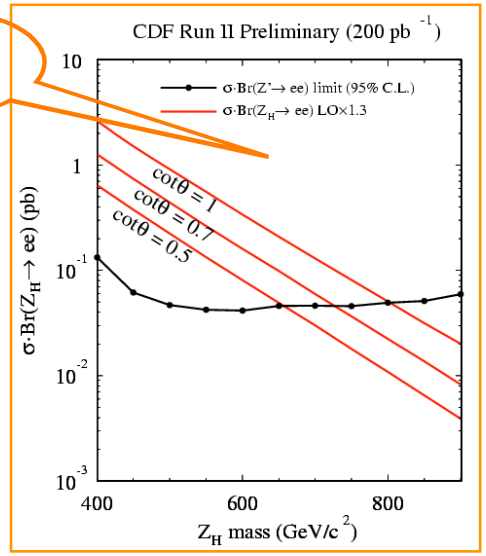
Calorimeter seeded Si tracking

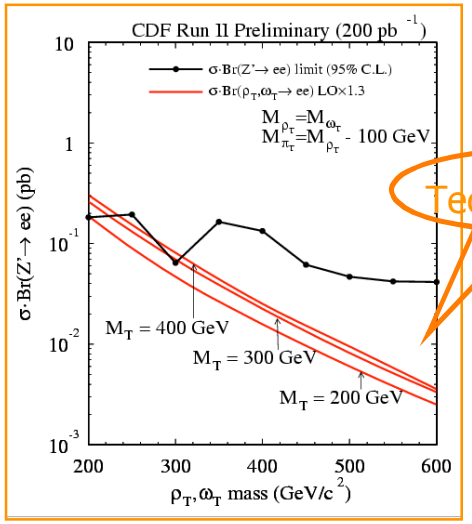


Searches in dileptons (cont'd)

Calculate the acceptances for resonant states for 3 different spin assumption (0,1,2)

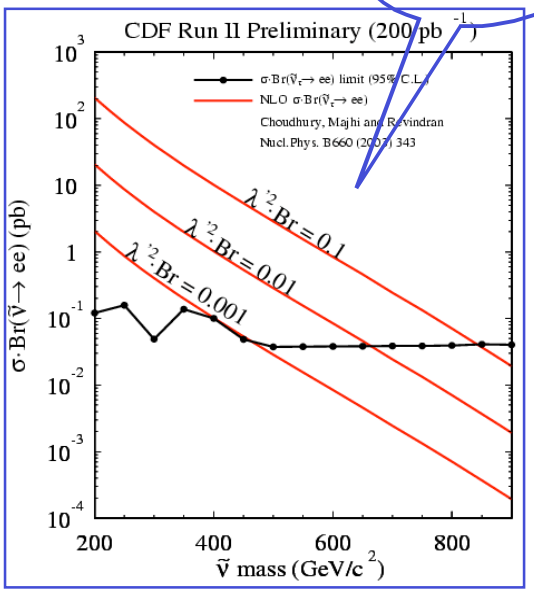
Little Higgs

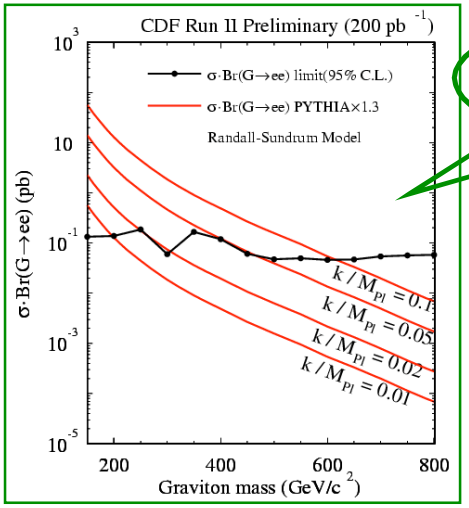




Technicolor

SUSY



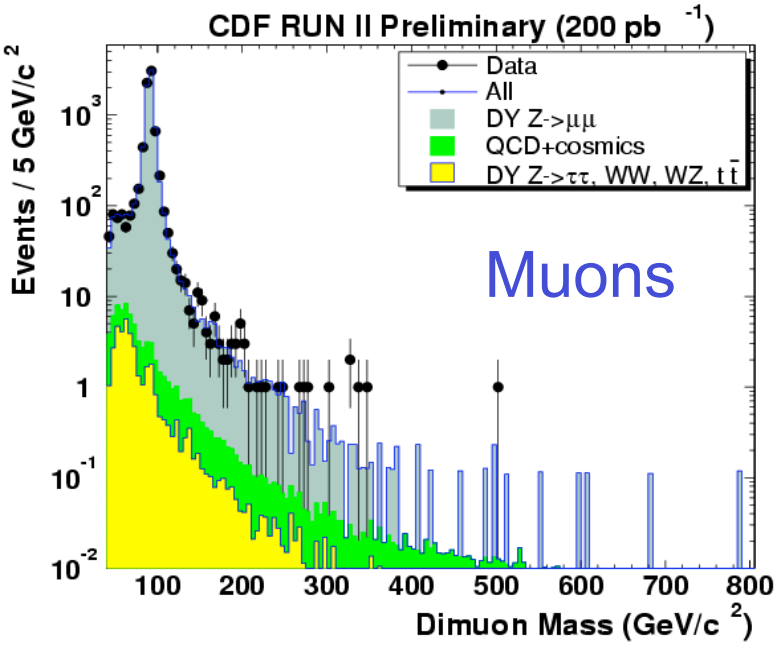


Extra-Dimensions

- Randall-Sundrum graviton model
  4-dimensional metric multiplied by *warp* factor exponentially changing with the additional dimension
  Generating a large hierarchy does not require a large r_c

The coupling of individual KK states to matter is set by the weak scale (parameters : M_G and $k/M_{P\ lanck}$)
KK states can be observed as spin 2 resonances

Searches in dileptons (cont'd)



- Z' gauge bosons: $M_{Z'} > 735 GeV/c^2$ (SM-Like)

CDF Run II Preliminary

CDF Run	Luminosity (pb^{-1})	$M_{Z',95\%C.L}$ (GeV/c^2)
IA	18.8	440
IB	88.6	575
IIA (summer '02)	16	275
IIA (winter '03)	72.0 (56.0 for CMX)	455
IIA (summer '03)	126 (110 for CMX)	585
IIA (winter '04)	200 (180 for CMX)	735

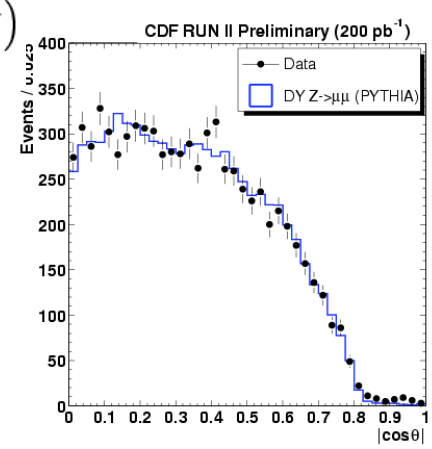
- E_6 Z' Limits:

CDF Run II Preliminary

Model	Mass Limit at 95%C.L (GeV/c^2)		
	Run I	Run II (summer '03)	Run II (winter '04)
Z'_{SM}	590	585	735
Z'_{ψ}	495	465	600
Z'_{χ}	500	455	580
Z'_{η}	520	495	635
Z'_{I}	480	425	530

- Littlest Higgs Z': $M_{Z_H} > 755 GeV/c^2$ (cosθ =0.9)

$$\cos\theta = \frac{2}{M\sqrt{M^2 + P_T^2}}\left(\ell_1^+\ell_2^- - \ell_1^-\ell_2^+\right)$$



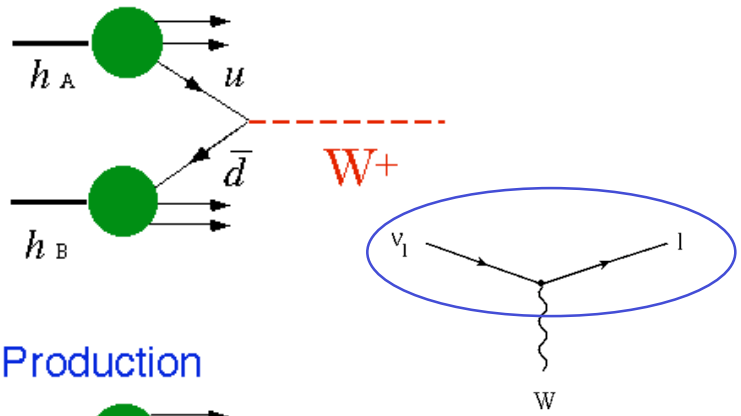
- RS Graviton of extra dimensions: $M_G > 605 GeV/c^2$ (k/M_{Pl} =0.1)

CDF Run II Preliminary

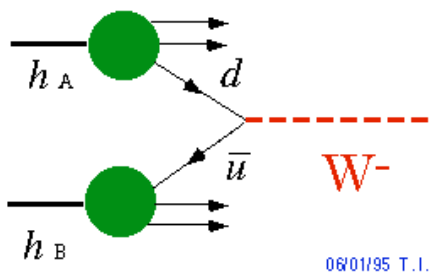
CDF Run	Luminosity (pb^{-1})	$M_{G,95\%C.L}$ (GeV/c^2) (k/Mpl = 0.1)
IA	–	–
IB	–	–
IIA (summer '02)	16	255
IIA (winter '03)	72.0 (56.0 for CMX)	370
(summer '03)	126 (110 for CMX)	475
IIA (winter '04)	200 (180 for CMX)	605

$W^{\pm}$ vector boson production

W^+ Production

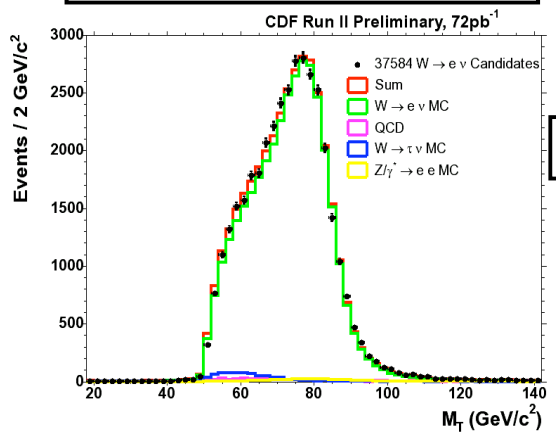


W^- Production

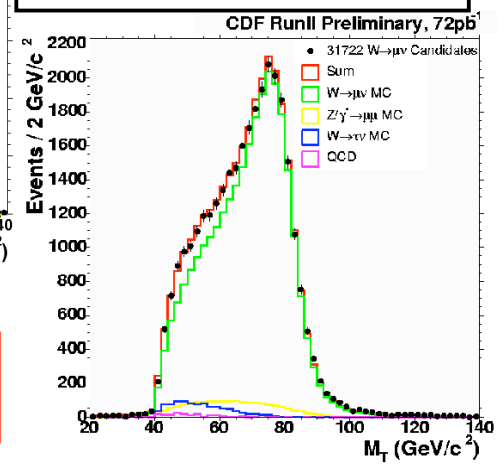


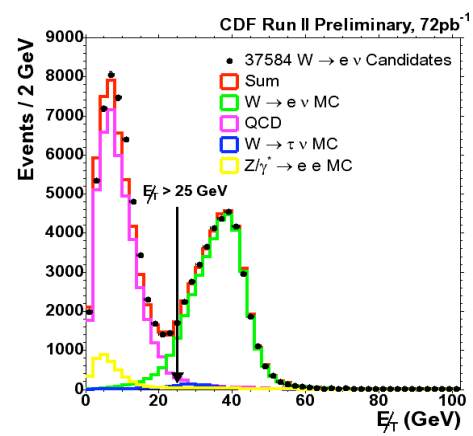
Backgrounds (QCD, W→τν, Z, cosmics) : 6% (e), 11% (μ).
Important systematics : PDF's, Energy Scales, Material Description

Transverse Mass - W→ e



Transverse Mass - W→ μμ





$$\sigma \cdot \mathrm{BR}(p\bar{p} \to W \to e\nu) = 2782 \pm 14(stat)^{+61}_{-56}(syst) \pm 167(lum)\,\mathrm{pb}$$

$$\sigma \cdot \mathrm{BR}(p\bar{p} \to W \to \mu\nu) = 2772 \pm 16(stat)^{+64}_{-60}(syst) \pm 166(lum)\,\mathrm{pb}$$

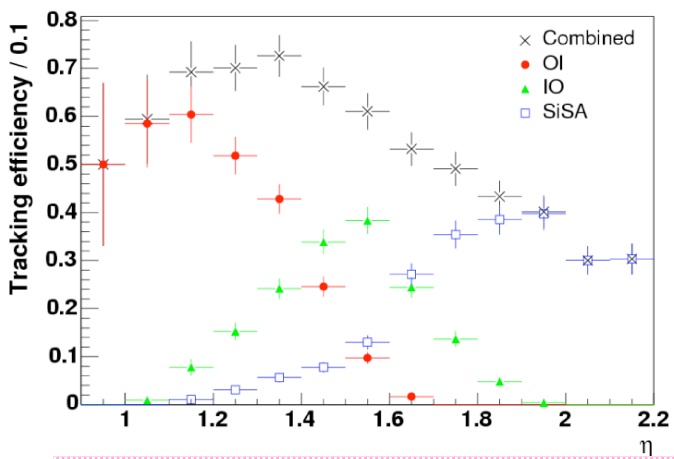
Inclusive W cross section (cont'd)

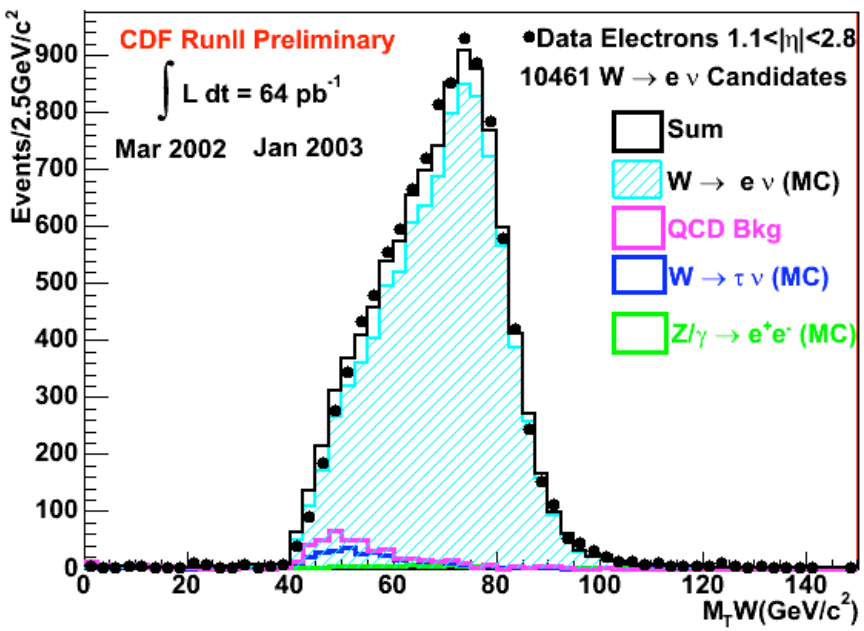
Following the same strategy pursued in the |□| <1 region, full tracking is used in the forward region

EM cluster is matched to a 3D track reconstructed using the Silicon detector only in the region 1 < |□| < 2.8

- Two 3-D hits & vertex seed silicon track (SISA)
- OI seeded by COT hits
- IO attaches COT hits to SISA

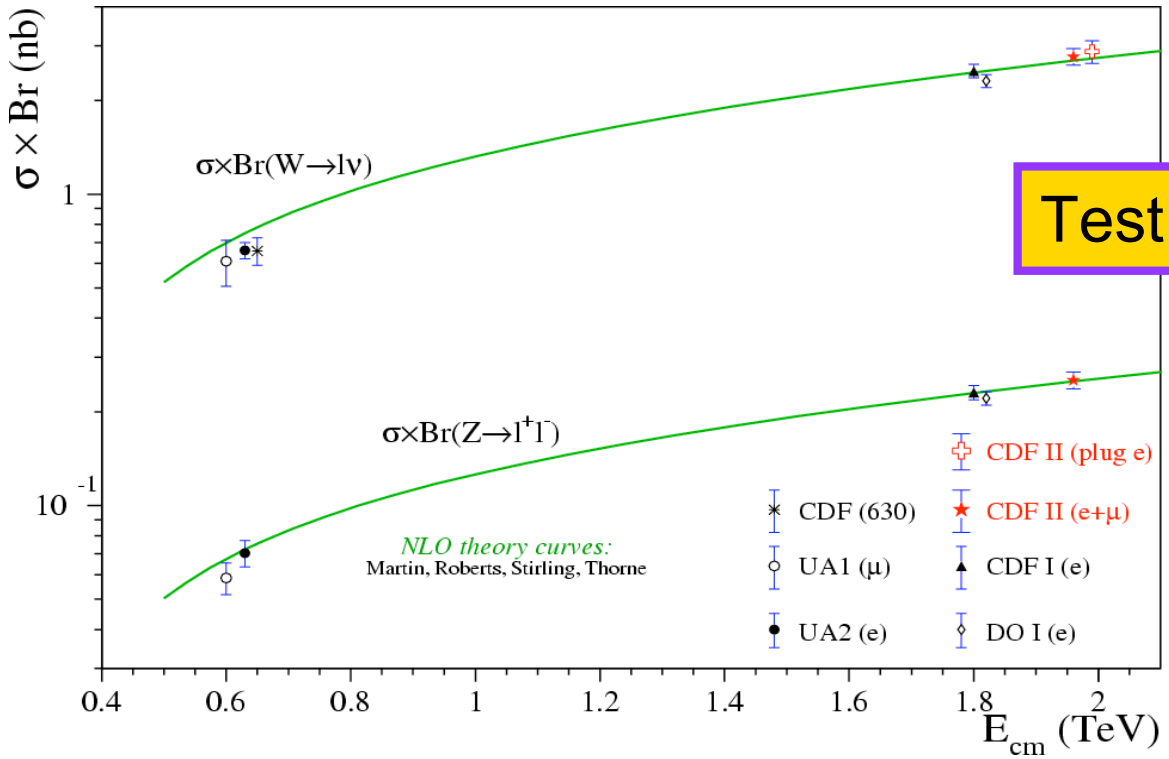
Tracking Efficiency





□ □ BR(W□ e□) = 2874 ± 34 (stat) ± 167 (sys) ± 172 (lumi) pb

Summary and X-Sections Ratio



Test of SM!

$$R = \frac{\sigma \cdot Br(p\bar{p} \to W \to \ell\nu)}{\sigma \cdot Br(p\bar{p} \to Z \to \ell^+\ell^-)} = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \times \frac{\Gamma_Z}{\Gamma_Z(\ell^+\ell^-)} \times \frac{\Gamma_W(\ell\nu)}{\Gamma_W}$$

The combined ratio is precise at 1.8% independent on the luminosity

$$R_e = 10.86 \pm 0.18_{(stat)} \pm 0.16_{(syst)}$$

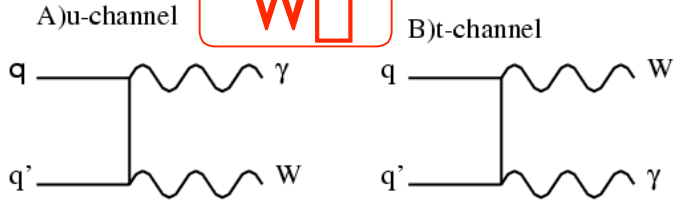
$$R_\mu = 11.10 \pm 0.27_{(stat)} \pm 0.17_{(syst)}$$

$$R = 10.94 \pm 0.15_{(stat)} \pm 0.13_{(syst)}$$

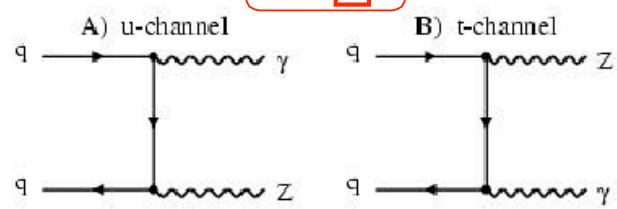
Di-boson Signals

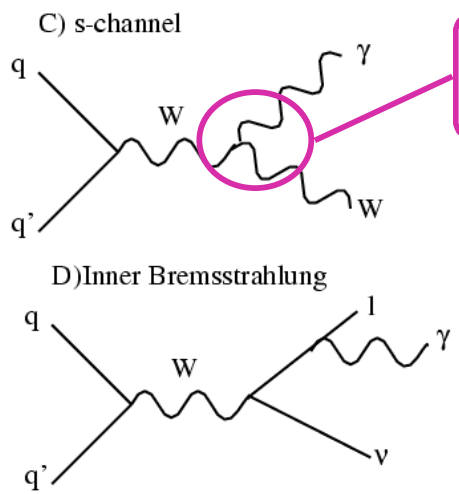
Test of gauge couplings (as predicted by the SM) and a window on new physics

W

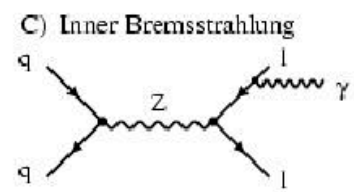


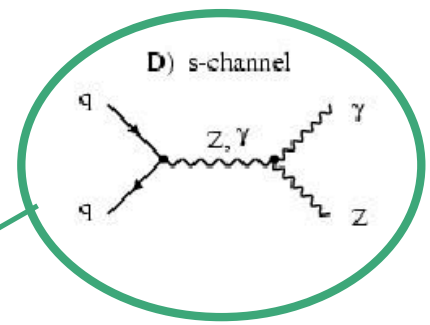
Z





Triple Boson Coupling





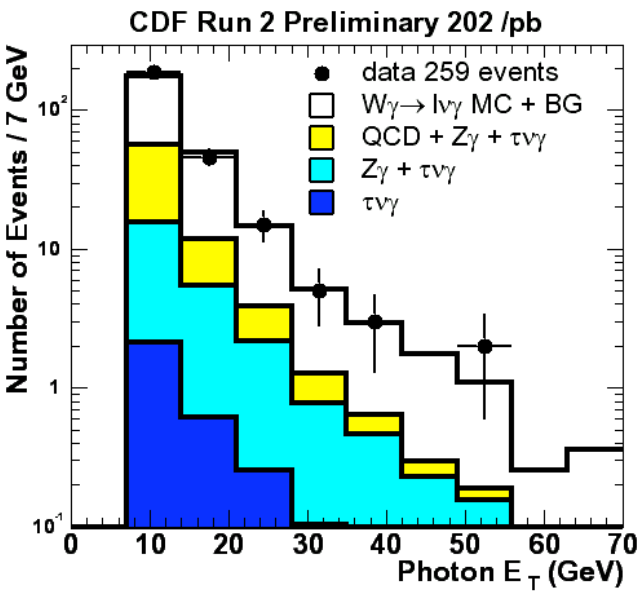
Non SM!

W□

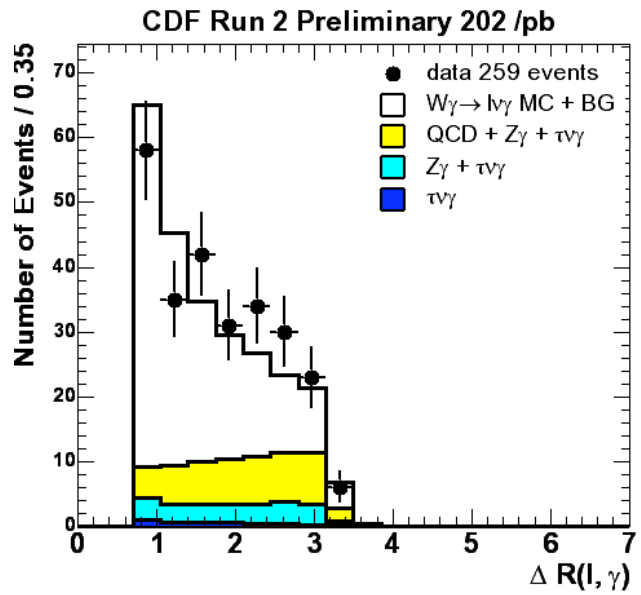
- First select $W \rightarrow l\nu$ events :
  - Electrons : E_T>25 GeV; missing−E_T>25 GeV
  - Muons : E_T>20 GeV; missing−E_T>20 GeV
- Then look for additional photons :
  - E_T(photon) > 7 GeV
  - $|\eta^{\gamma}| < 1.1$
  - $\Delta R(l,\gamma) > 0.7$

□(W□)□BR(W□ l□) = 19.7
± 1.7 (stat) ± 2.0 (sys)
± 1.1 (lumi) pb

For E_T(□) > 7 GeV and □R(l, □) > 0.7:
□(W□)□BR(W□ l□) (Theory) = 19.3 ± 1.4



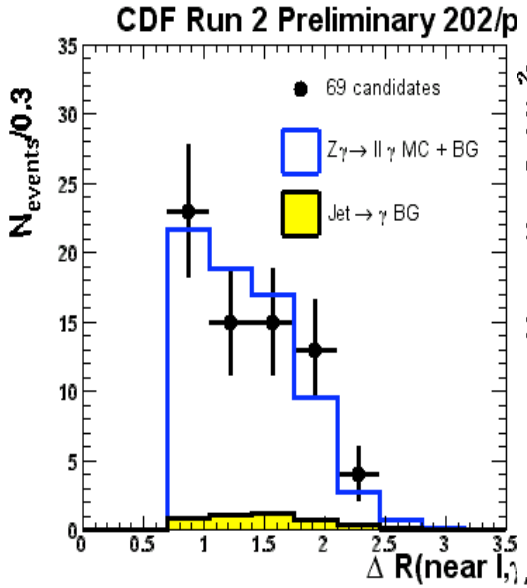
data well described over all photon E_T's and separations

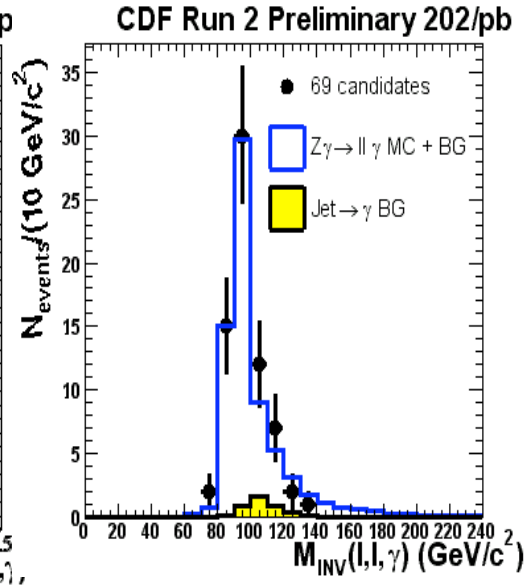


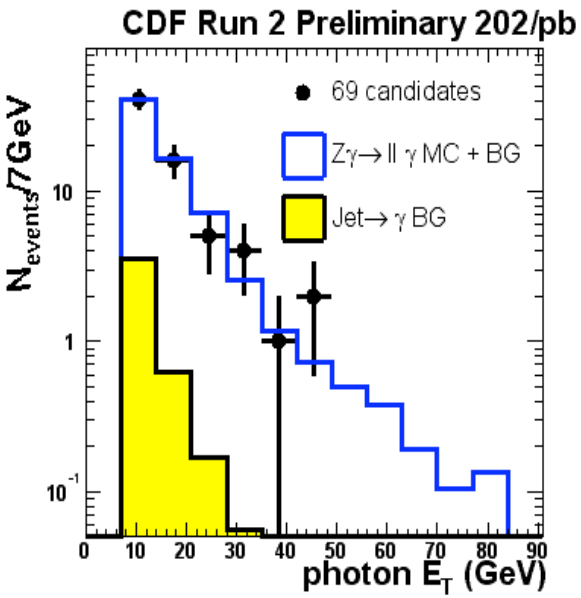
Z□

□(Z□)□BR(Z□ ll) =5.3
± 0.6 (stat) ± 0.4 (sys)
± 0.3 (lumi) pb

For E_T(□) > 7 GeV and □R(l, □) > 0.7:
□(Z□)□BR(Z□ ll) (Theory) = 5.4 ± 0.4

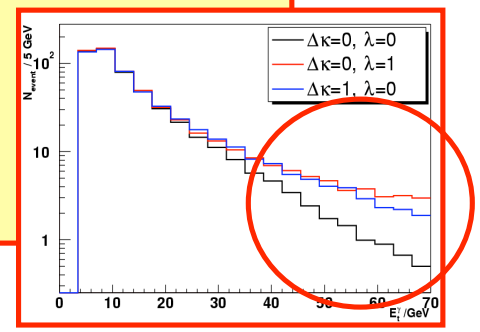






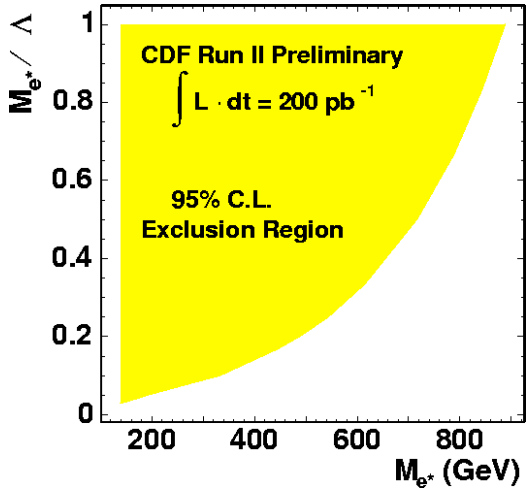
Now V+□cross-sections well established, we are:

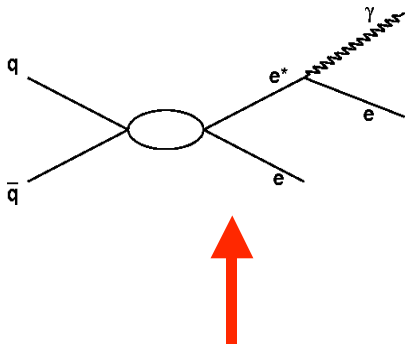
- optimizing sensitivity to anomalous coupling and new physics
- testing the Standard Model in ways unique to the TeVatron (e.g. observing RAZ in W □production)



Excited electrons

Observation of excited states of quarks and leptons might confirm the hypothesis that they are not elementary particles , but composite states



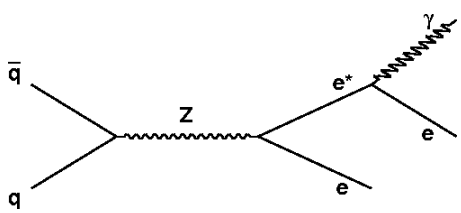


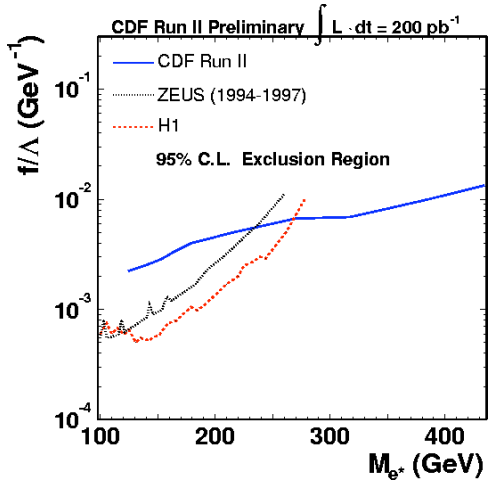
CDF searched for excited electron (e^*) using high pt electron data (L=200 pb^{-1})

At Tevatron, e^* can be produced via contact interactions or gauge mediated interactions

- an excited electron would decay into e□
  - Select events with ee□in the final state
  - Look for resonance in M(e□)
  - SM backgrounds :

    Z □+ DY , Z+jets, WZ, Multi-jets, □□+jets, …

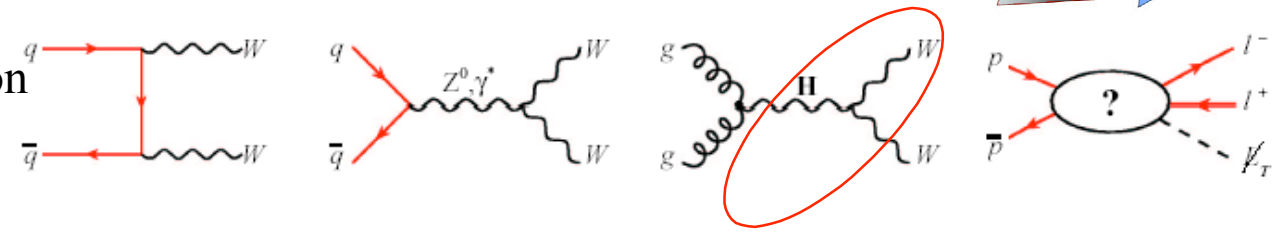




Expect 3 events, observe 3 events

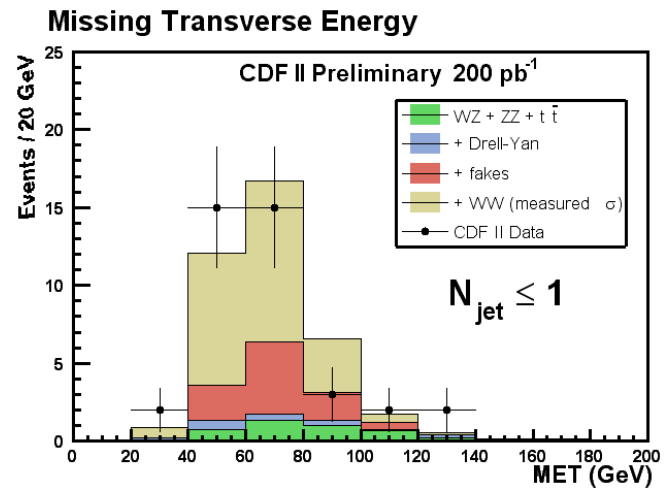
WW Production

Further step towards limits on anomalous WWZ, WW□ coupling

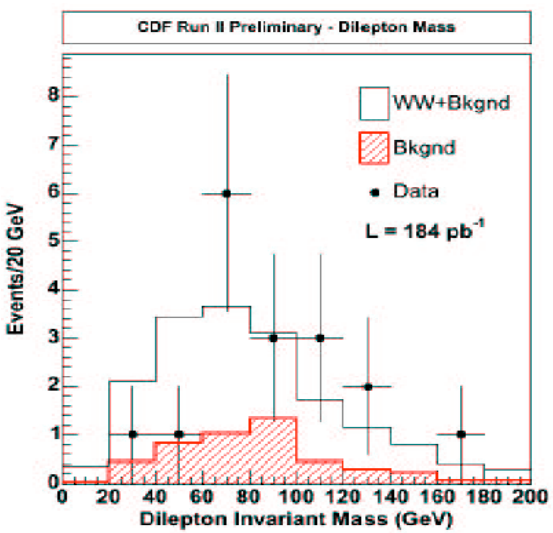


- Two isolated E_T>20 GeV leptons (e or μ) .
- Missing−E_T > 25 GeV.
- Remove events consistent with Z decay.
- Remove top background by requiring no additional jets.
- Remove fakes by requiring opposite sign.

Tight lepton selection complemented by lepton + tracks selection



Larger fakes contamination and uncertainty

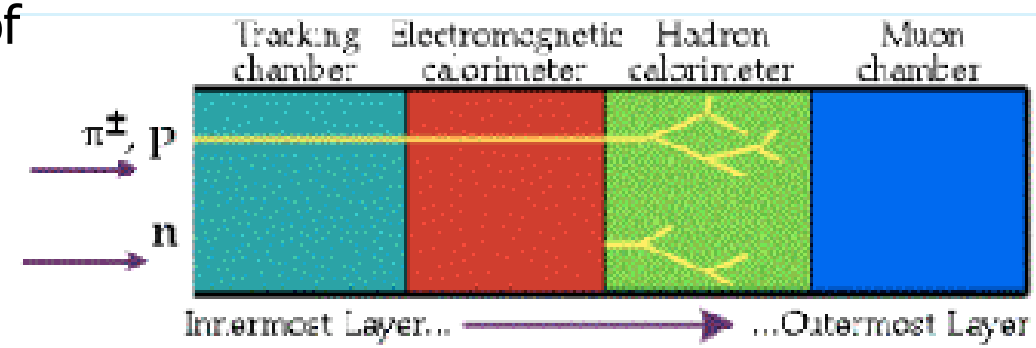


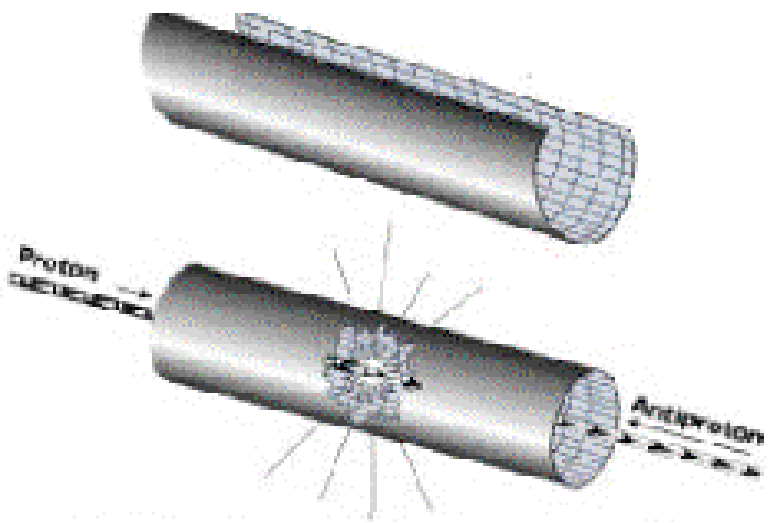
□$_{WW}$ = 19.4 ± 5.1 (stat) ± 3.5 (sys) ± 1.2 (lumi)

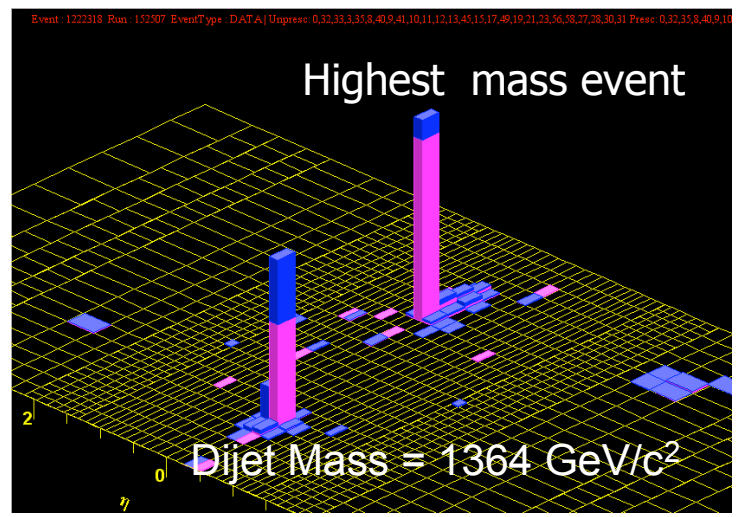
$$\sigma_{meas}^{WW} = 14.3^{+5.6}_{-4.9}\ (\text{stat}) \pm 1.6\ (\text{syst}) \pm 0.9\ (\text{lum})\ \text{pb}$$

Jets

- A quark or gluon flying out of the interaction point will generate lots of hadrons moving in the same general direction: a jet.







QCD and Jet Physics

The Tevatron is a Jet Factory

All production processes are "QCD realated"

Optimal understanding is basic for all analyses:

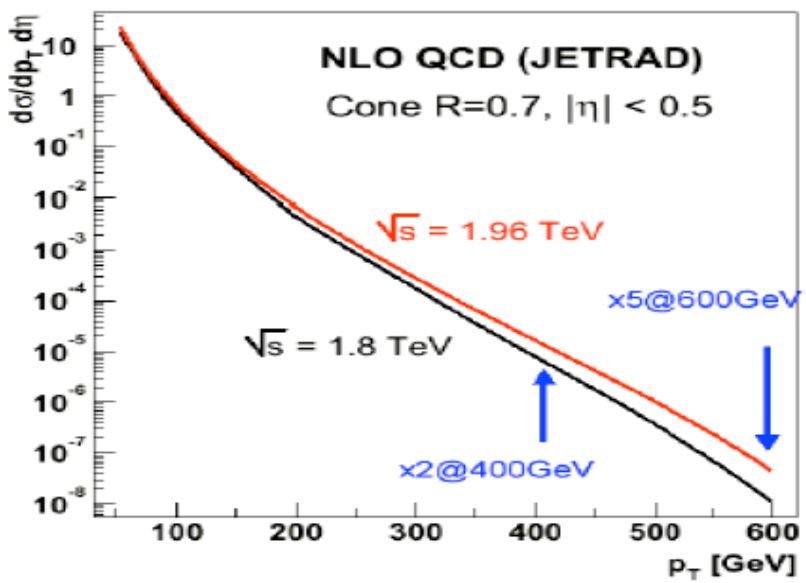
- Main parameters (ex: gluon PDFs in high x)
- Non perturbative regime (ex: underlying event studies)
- Studies of specific processes where QCD is important

Probing higher energy scales:

Precise test of perturbative QCD at NLO

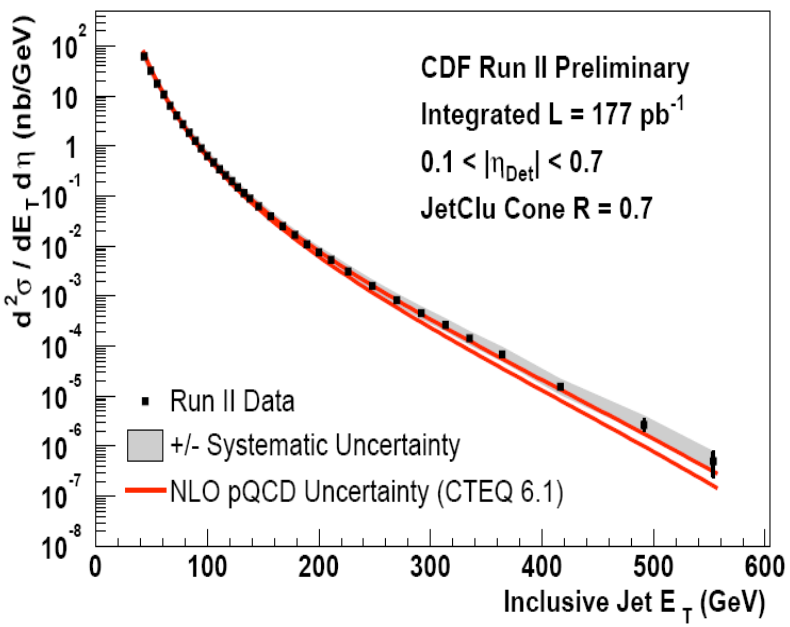
Look for deviations from SM predictions as a sign of new physics

The increase in the center of mass energy and the large integrated luminosity expected of RunII will dramatically increase the kinematic range of measuring jet production and the potential for discovery new physics.

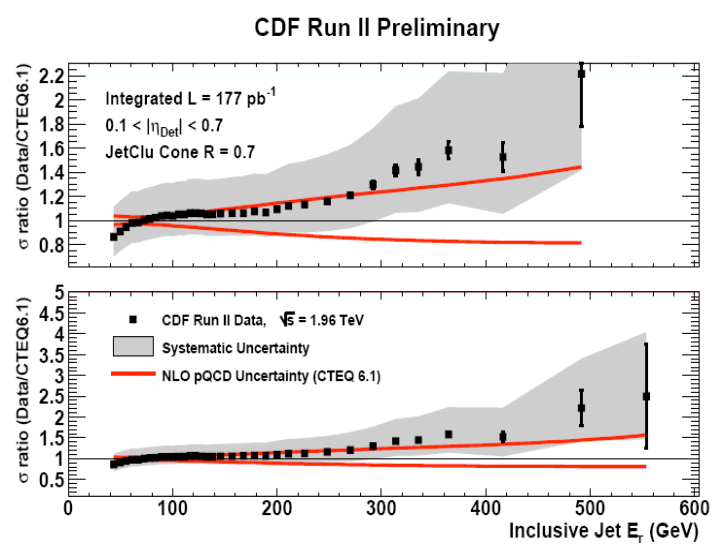


Inclusive Jet Cross Section

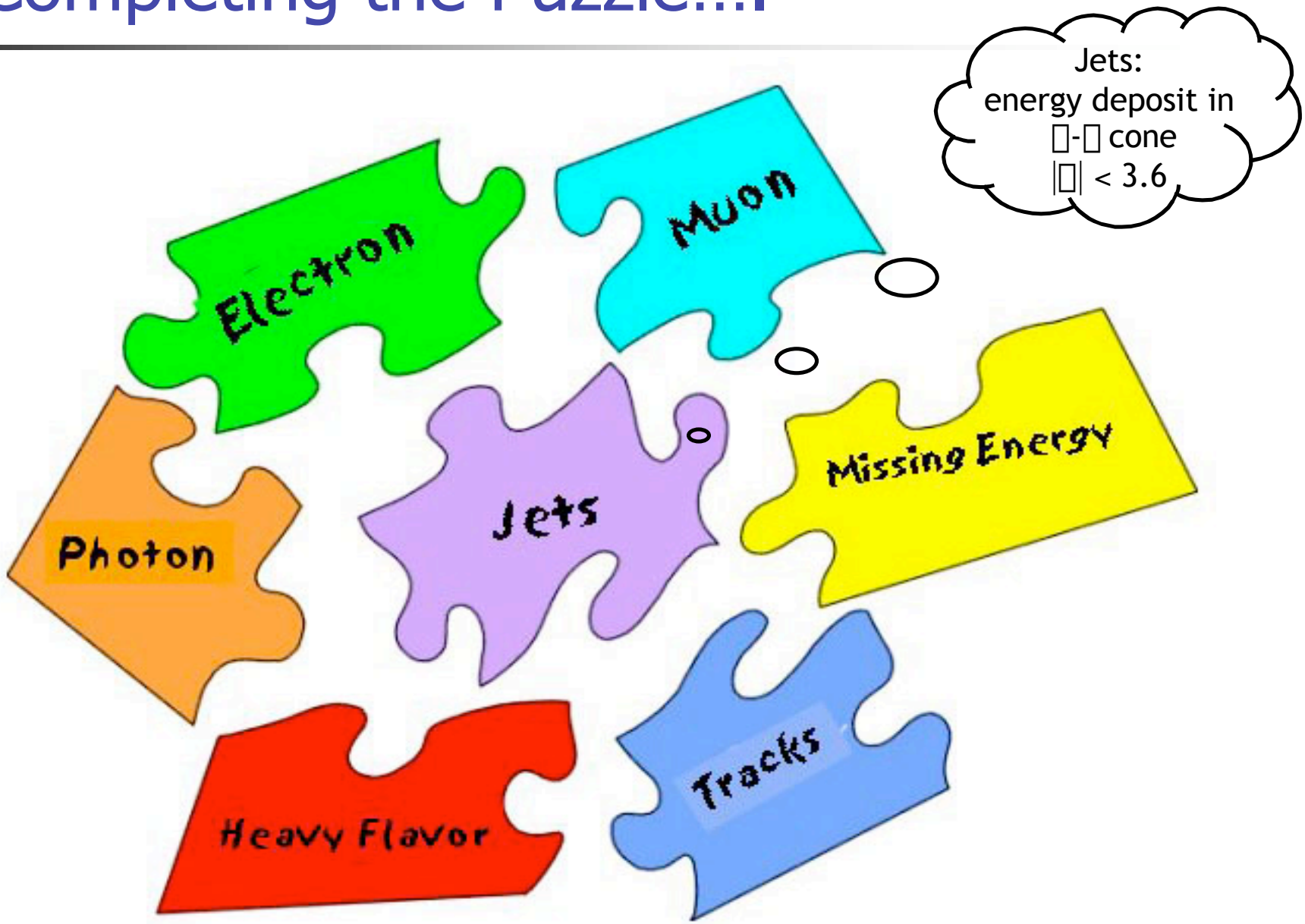
- In RunI the inclusive cross section exhibited an excess at high jet E_T.
- Global PDF analyses by CTEQ have shown that one explanation is a larger than expected gluon distribution at high x.
- The gluon distribution at high x has indeed increased in recent PDF fits (CTEQ6, CTEQ6.1) leading to better agreement with the CDF inclusive jet cross section measurements.



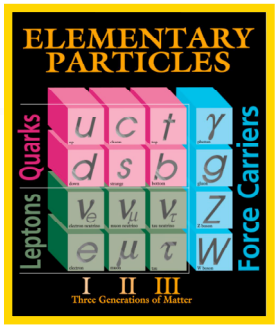
The error band shows the change in the cross section due to the 5% energy scale uncertainty



Completing the Puzzle….



Leptoquarks



- **Leptoquarks (LQ)** are hypothetical particles which appear in many SM extensions to explain **symmetry between leptons and quarks**
  - SU(5) GUT model
  - superstring-inspired models
  - 'colour' SU(4) Pati-Salam model
  - composite models
  - technicolor

•LQs can have:

–spin 0 (scalar)

•couplings fixed, i.e., no free parameters

•Isotropic decay

–spin 1 (vector)

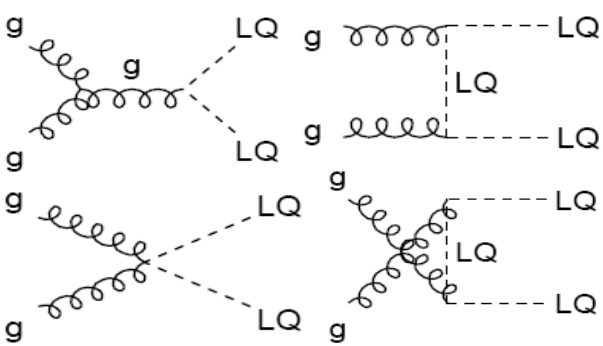
•anomalous magnetic (k_G) and electric quadrupole (λ_G) model-dependent couplings

–Yang-Mills coupling: $k_G = \lambda_G = 0$

–Minimal coupling: $K_G = 1$, $\lambda_G = 0$

–Decay amplitude proportional to $(1 + \cos\theta^*)^2$

•LQs are coupled to both leptons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) numbers



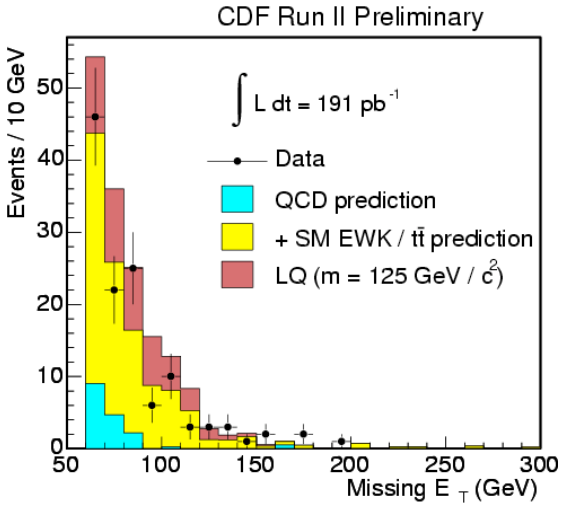
- **Experimental evidence searched:**
  - indirectly: LQ-induced 4-fermion interactions
  - directly: production cross sections at collider experiments

LQ search in □□jj

Signature: Large MET and 2 jets

□′ =BR(LQ□ □q) = 1

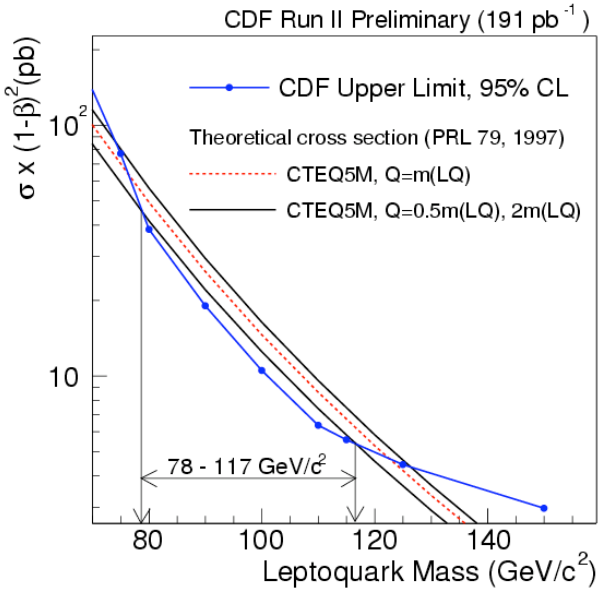
Flavor independent



Sample Composition:
- W/Z + jets
- top
- QCD fakes

Expected =118±14

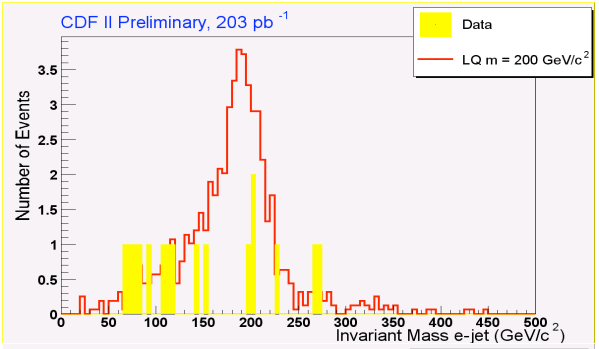
124 events seen after analysis cuts

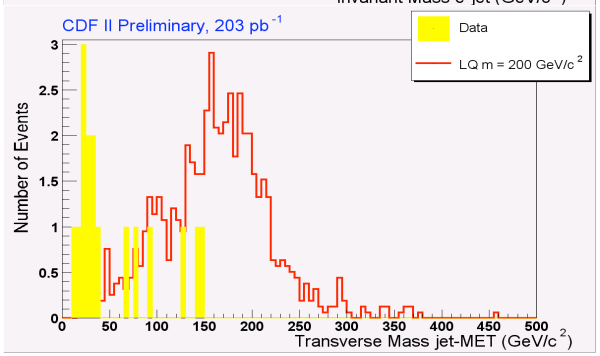


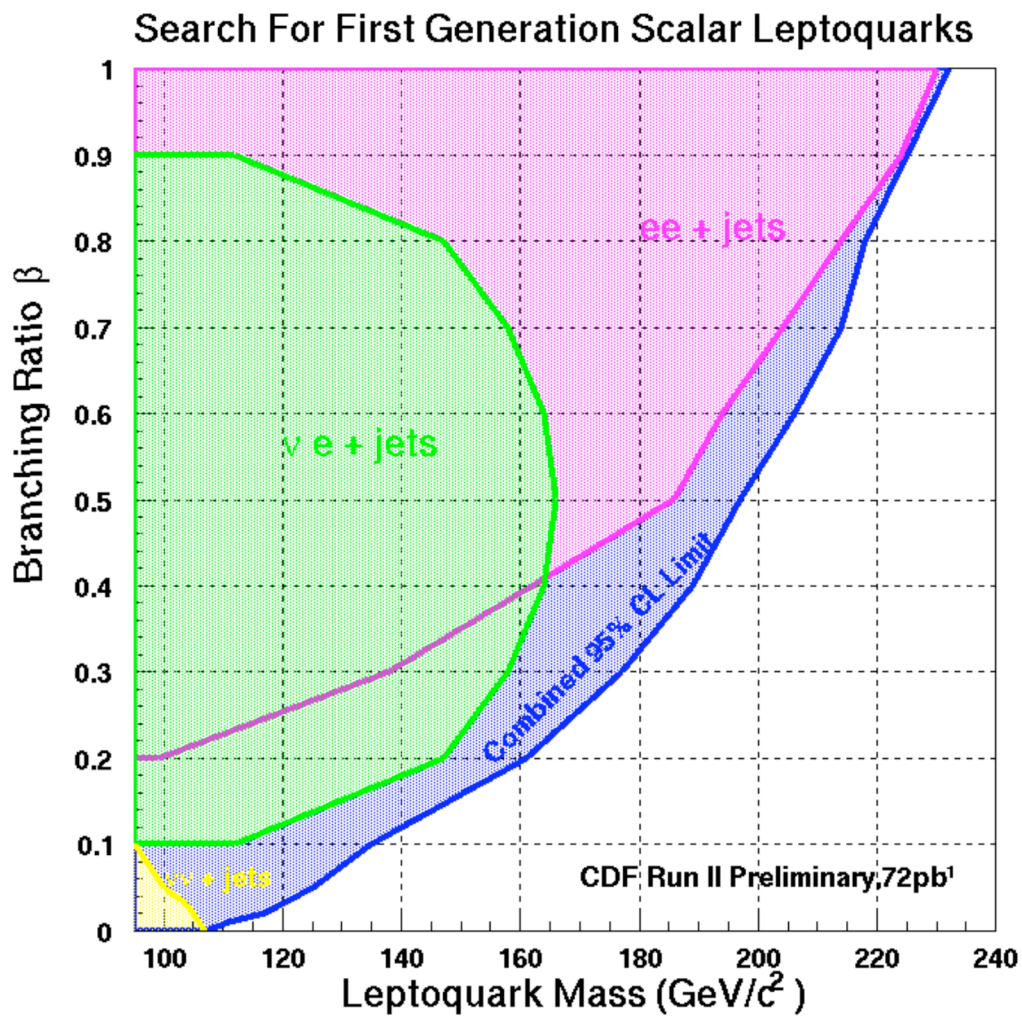
M(LQ) > 117 GeV/c² @ 95 % C.L.

1st generation LQ

Signature:
2 electrons and 2 jets
electron, $\not{E}_T$ and 2 jets
$\not{E}_T$ and 2 jets







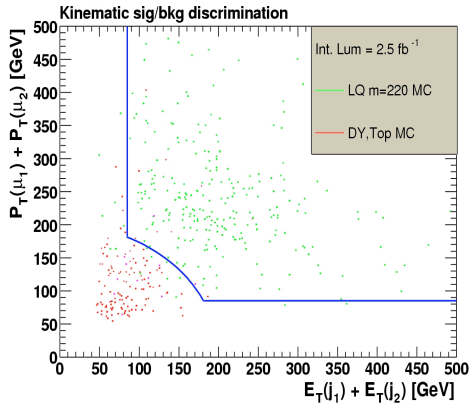
2nd generation LQ at CDF

Signature: 2 muons and 2 jets

□ =BR(LQ□ □q) = 1

Tight □'s selection complemented by □ + track selection

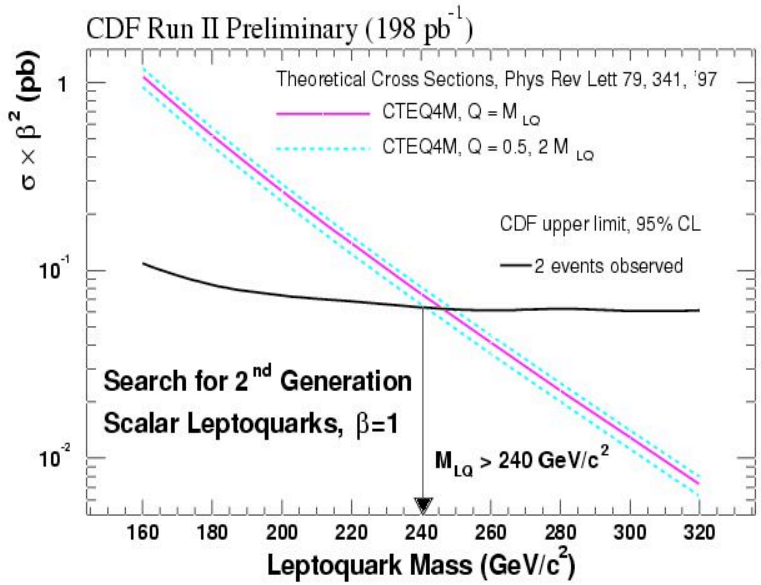
Background:
- Z + 2 jets
- top
- QCD fakes

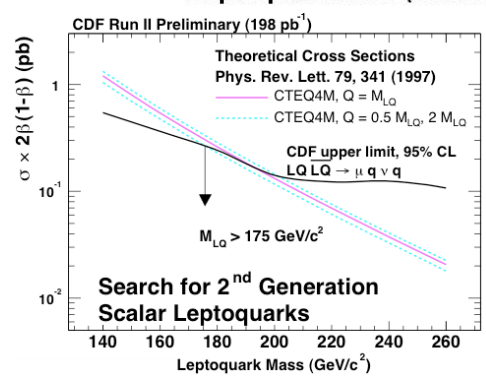


expected 3.15 ± 1.17

2 events seen after analysis cuts

M(LQ) > 240 GeV/c² @ 95% C.L.

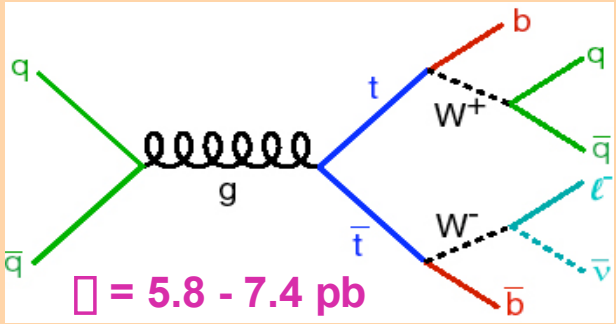


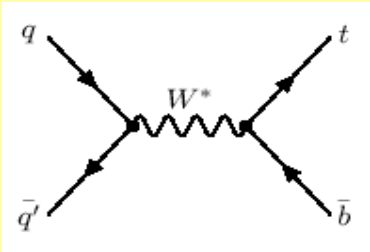


□ = 0.5

Top Quark

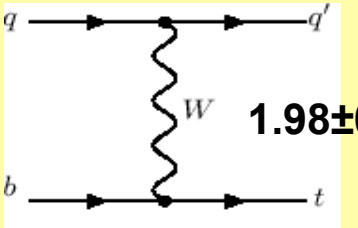
Pair production via strong interactions
- Central, spherical events
- Large transverse energy
- High P_T isolated leptons (tracks)
- Heavy-Flavored Jets



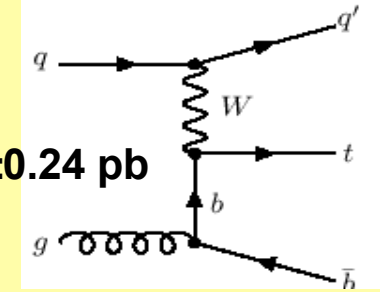


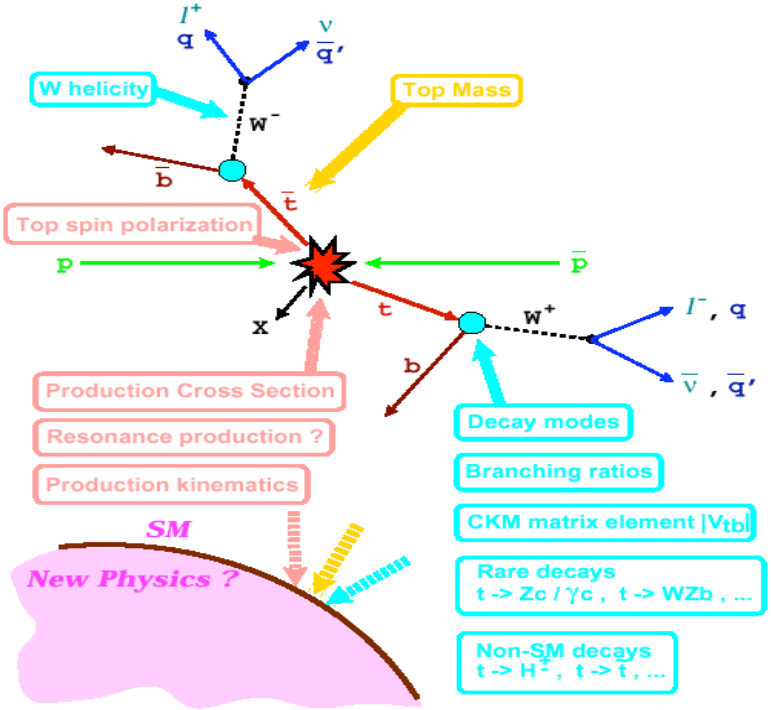
0.88±0.11 pb

EW single-top production,
x2 smaller rate, not (yet) seen



1.98±0.24 pb

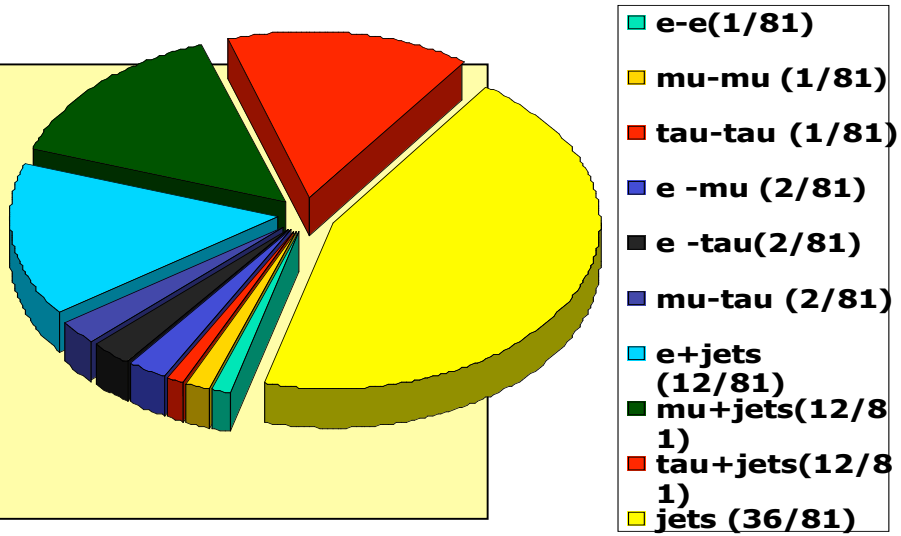


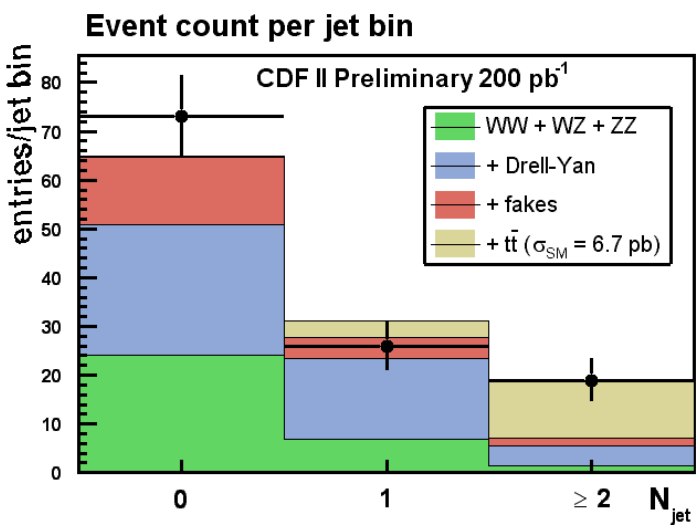


Top Data Samples

W's decay modes used
to classify the final states:
dileptons, lepton + jets, all-hadronic

B(t→ Wb) = 100%





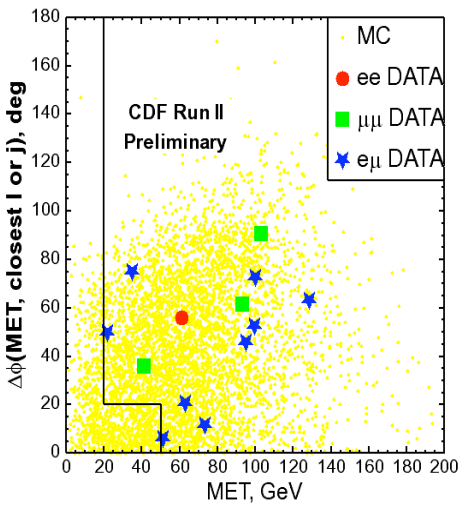
Samples are defined by counting leptons and jets

Cross section results validate
top-enriched samples

can also point toward new physics

Top Dilepton Cross Section

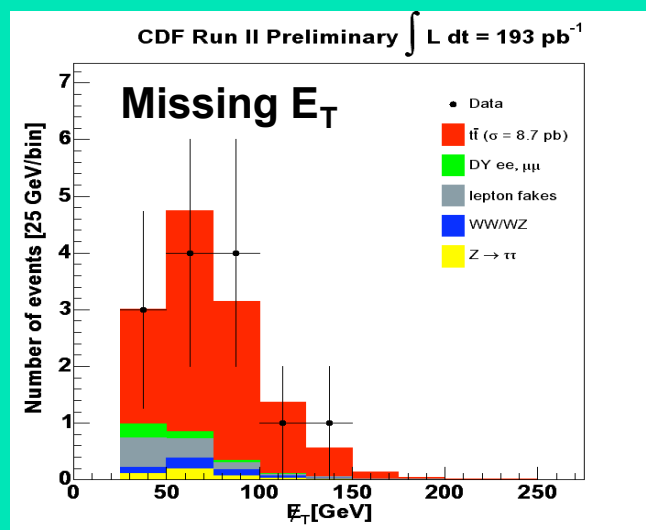
Small sample but very clean for top signal: 2 leptons, 2 jets and $\not{E}_T$

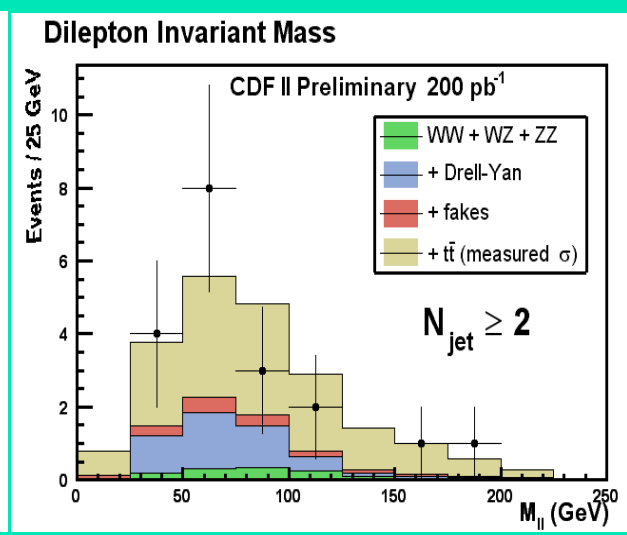


Tight e/μ selection complemented by e/μ + track selection

Lepton + track sample has looser ID requirements for second lepton
It is sensitive to μlepton final state

Interesting place to follow up on Run I anomalies



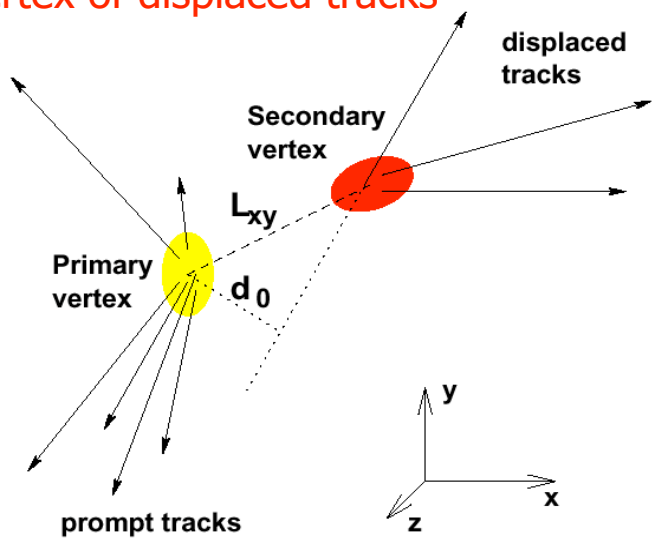


Heavy Flavor jets: tagging tools

B hadrons in top signal events

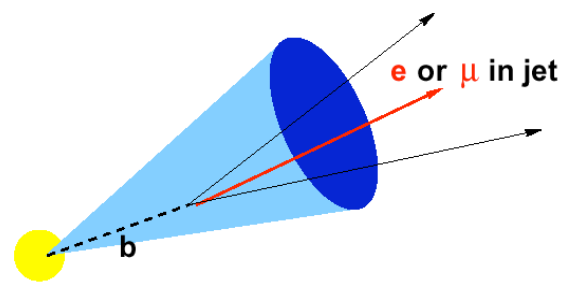
are long-lived and massive

Vertex of displaced tracks



may decay semileptonically

Identify low-pt muon from decay

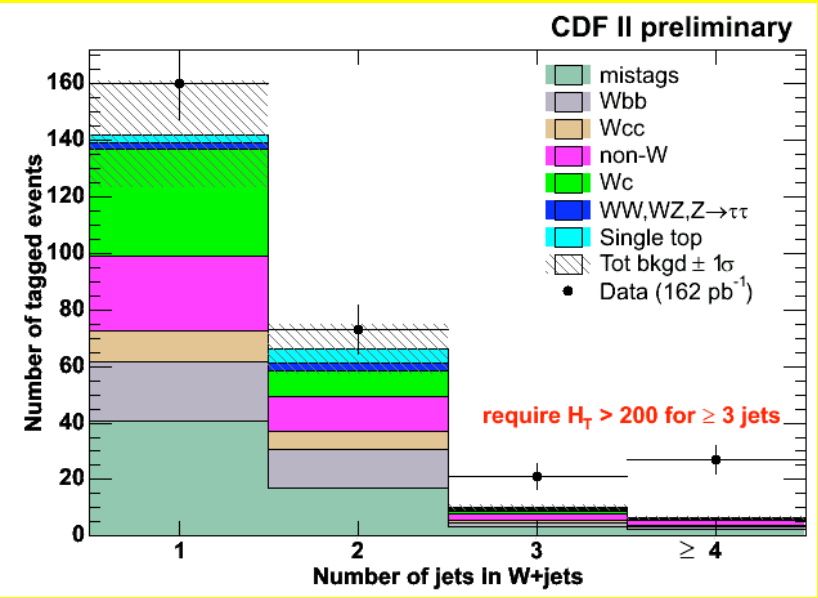


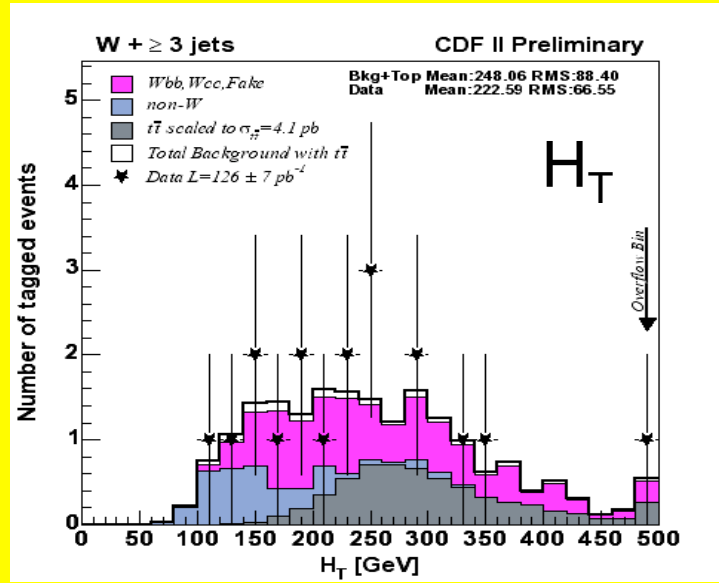
- $b \to \ell\nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell\nu s$ (BR $\sim$ 20%)

55%	Top Event Tag Efficiency	15%
0.5%	False Tag Rate (QCD jets)	3.6%

Cross Section Results using Tagging

Counting experiments with vertex tag and soft muon tag in 3,4-jet bins





Backgrounds estimate in the lepton + jets sample carried on:

- using data as much as possible (non-W QCD, fake tags)
- using MC calculations for diboson and W + heavy flavor

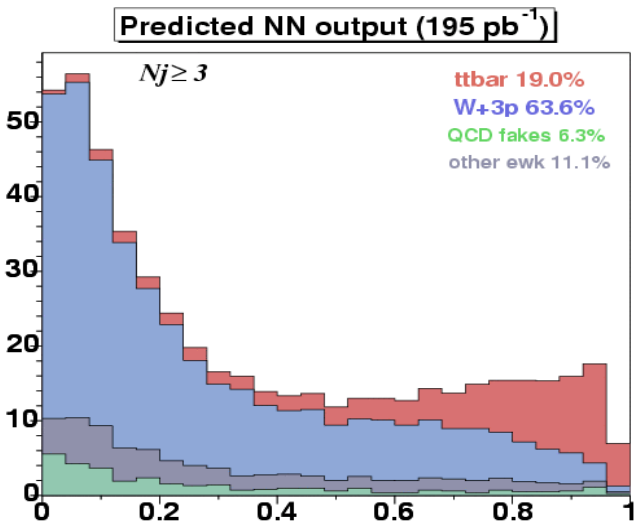
Lepton + jets: NN results

ttbar and W+jets kinematics differ modestly, but do so in several different variables.

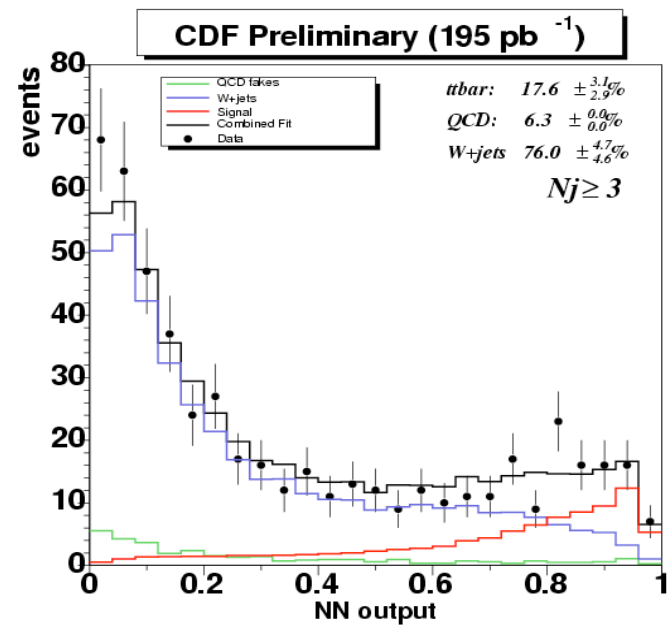
Develop a neural net to use this information optimally.

Statistical and systematic uncertainties improved compared to single-variable fit.

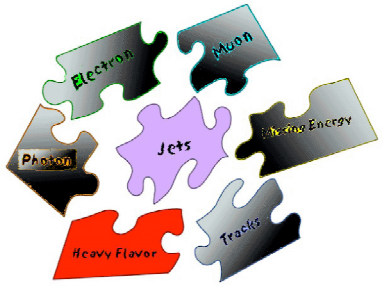
No b tagging information is used



Good separation between signal and background



Hadronic top



Signature: six jets, 2 tagged
Large QCD background

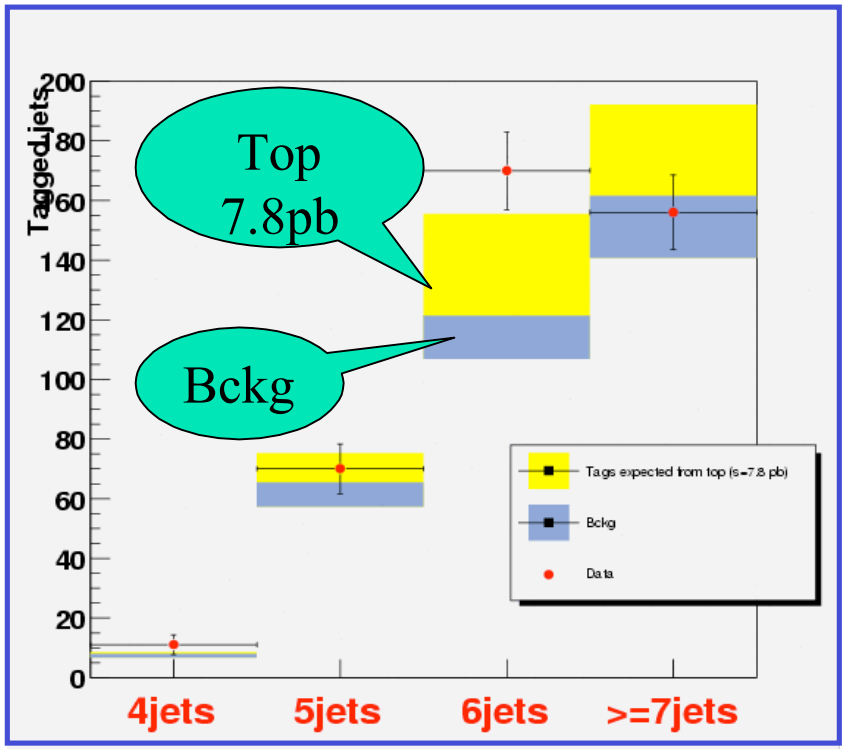
Kinematical selection of the sample complemented by b-tagging of at least one jet

Cross Section is a function of the number of observed tagged jets

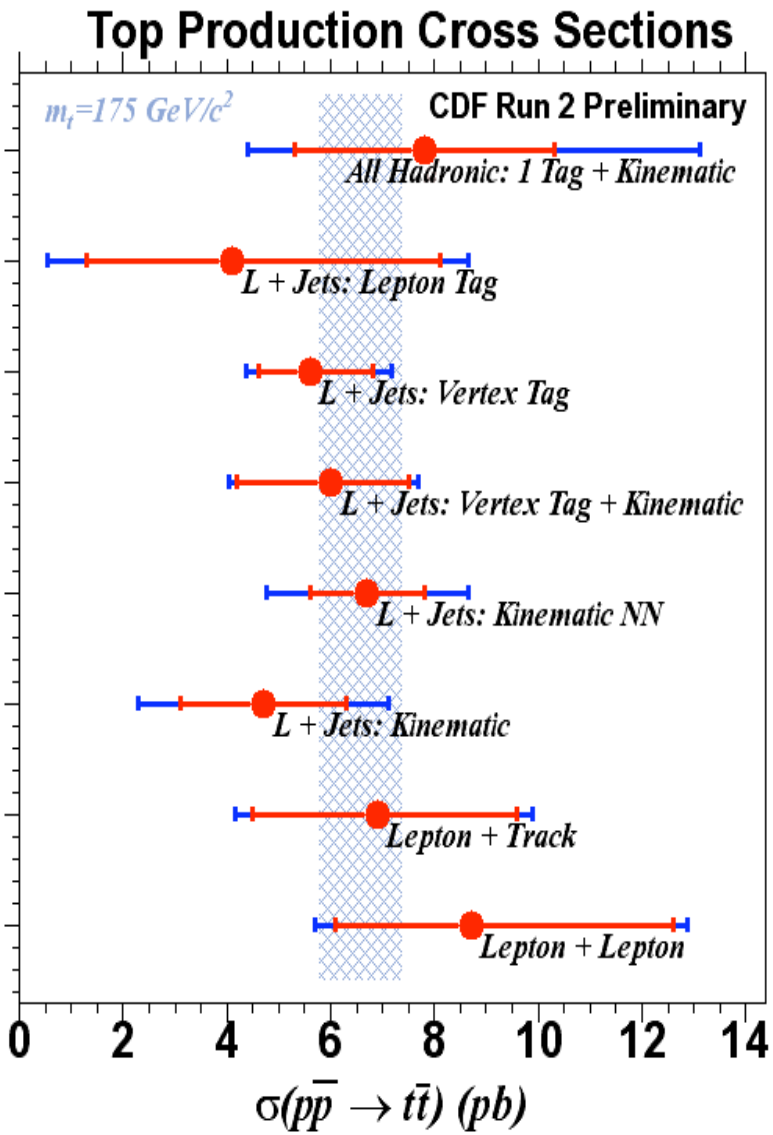
$$\sigma_{t\bar{t}} = \frac{ObservedTags - ExpectedTags}{\varepsilon_k \varepsilon_{tag}^{ave} L} \pm \delta$$

Kinematics

b-tag



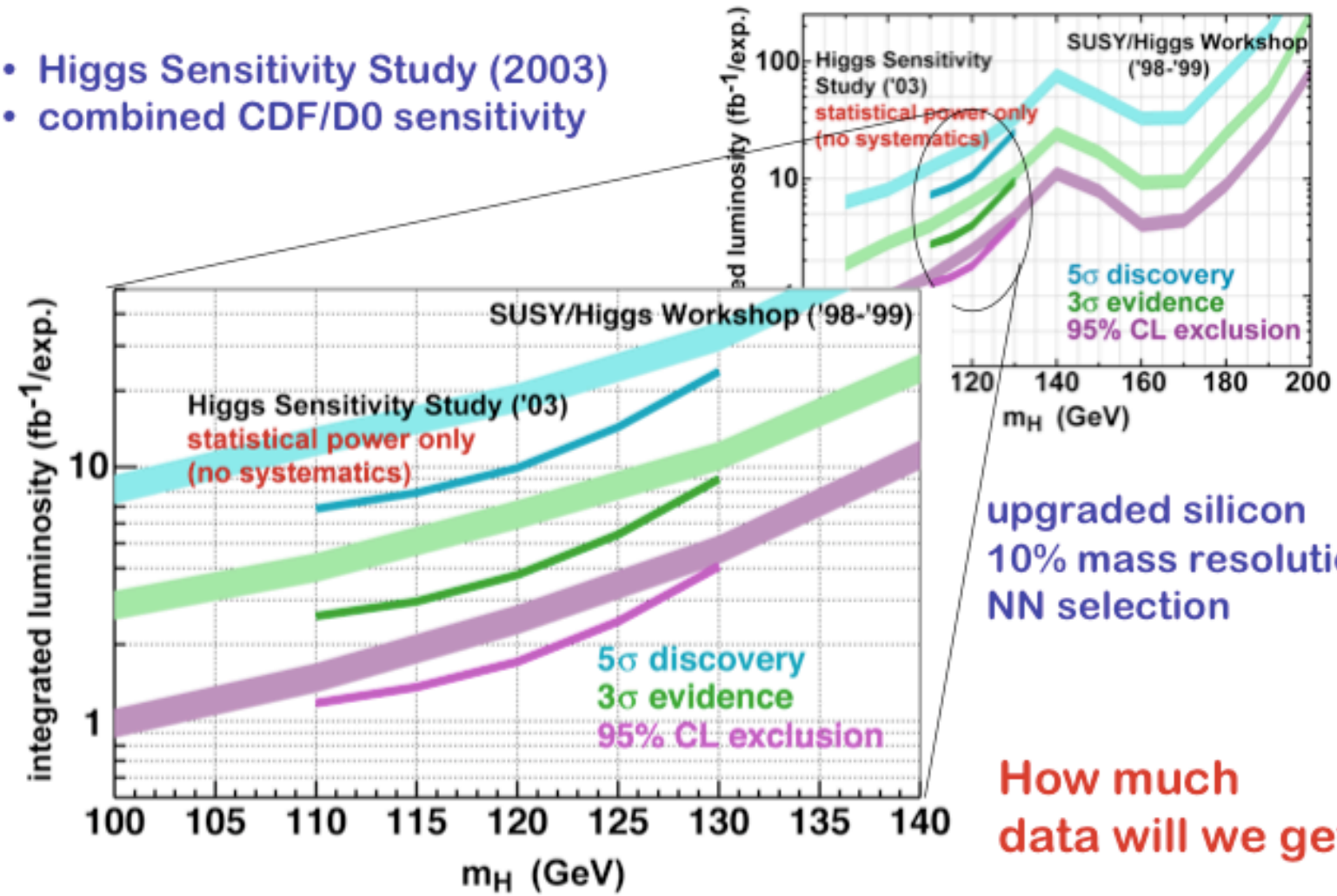
CDF Top Cross Section Summary



165 pb^{-1}	$7.8 \pm 2.5(\text{stat})\ ^{+4.7}_{-2.3}(\text{sys})$
126 pb^{-1}	$4.1^{+4.0}_{-2.8}(\text{stat.}) \pm 1.9\ (\text{syst.})$
162 pb^{-1}	$5.6^{+1.2}_{-1.0}(\text{stat.})\ ^{+1.0}_{-0.7}(\text{syst.})$
162 pb^{-1}	$6.0^{+1.5}_{-1.8}(\text{stat.}) \pm 0.8\ (\text{syst.})$
195 pb^{-1}	$6.7 \pm 1.1(\text{stat}) \pm 1.6(\text{sys})$
195 pb^{-1}	$4.7 \pm 1.6(\text{stat.}) \pm 1.8\ (\text{syst.})$
202 pb^{-1}	$6.9^{+2.7}_{-2.4}(\text{stat.}) \pm 1.3\ (\text{syst.})$
193 pb^{-1}	$8.7^{+3.9}_{-2.6}(\text{stat.}) \pm 1.5\ (\text{syst.})$

The Search for the Higgs Boson

- Higgs Sensitivity Study (2003)
- combined CDF/D0 sensitivity

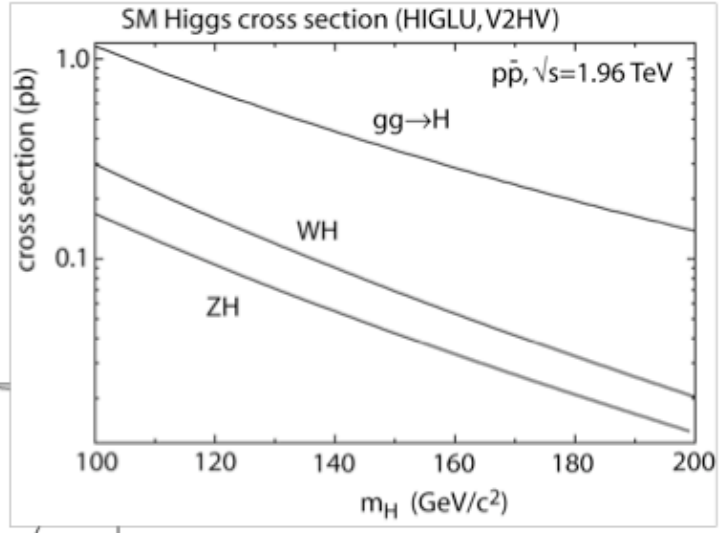


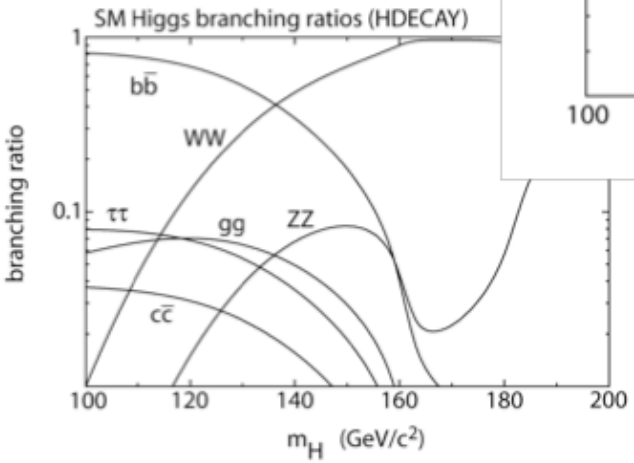
upgraded silicon
10% mass resolution
NN selection

How much data will we get?

The Search for the Higgs Boson

- gg→H dominates but dijet background too big…
- bb and WW decay modes are best!



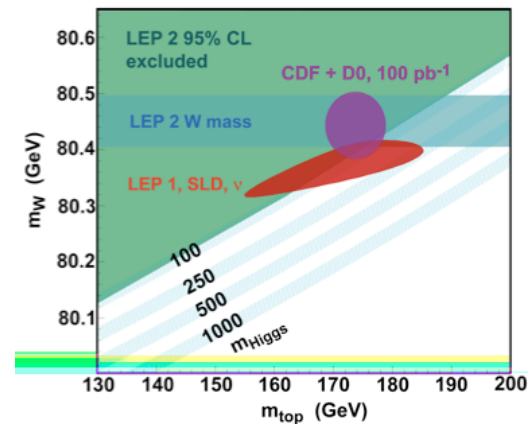


WH+ZH ~300 fb at 115 GeV

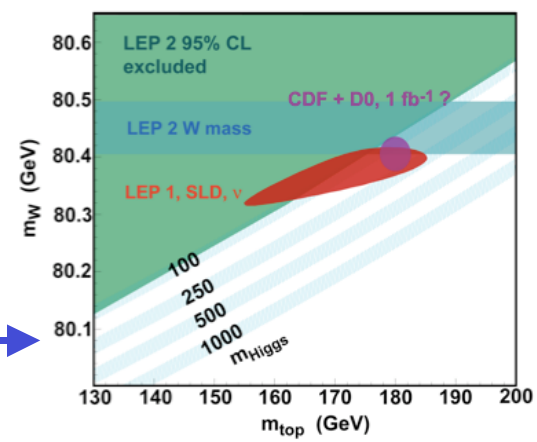
typical efficiencies ~ 2%

A daunting proposition!

Indirect Searches

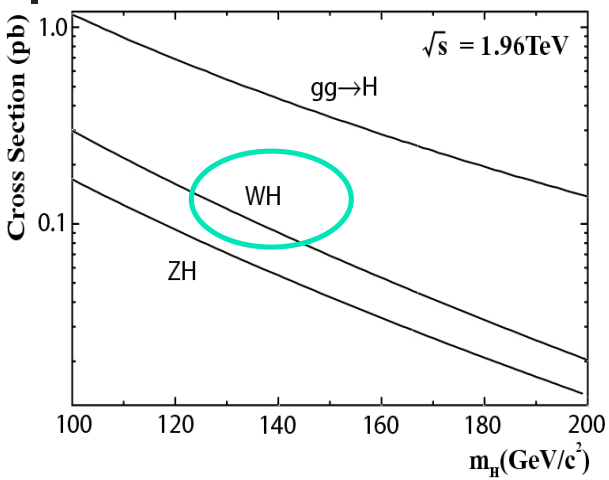


?



Evidence for New Physics!

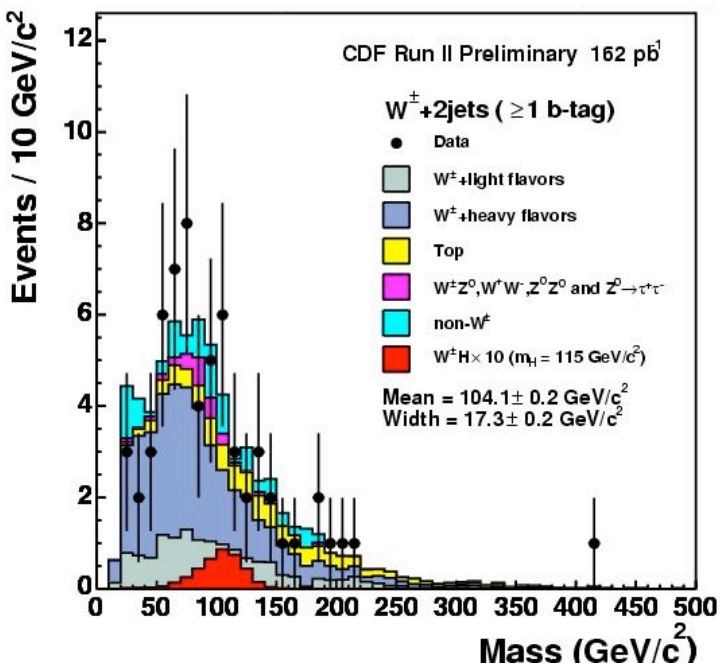
Higgs Search -Results



$p\bar{p} \to WH \to l\nu b\bar{b}$

Selection:

- High pt lepton data
- One high pt central *e* or μ, large MET (MET>20 GeV)
- 2 jets (at least one is tagged as b-jet)
- Veto events with >1 lepton (suppress ttbar)

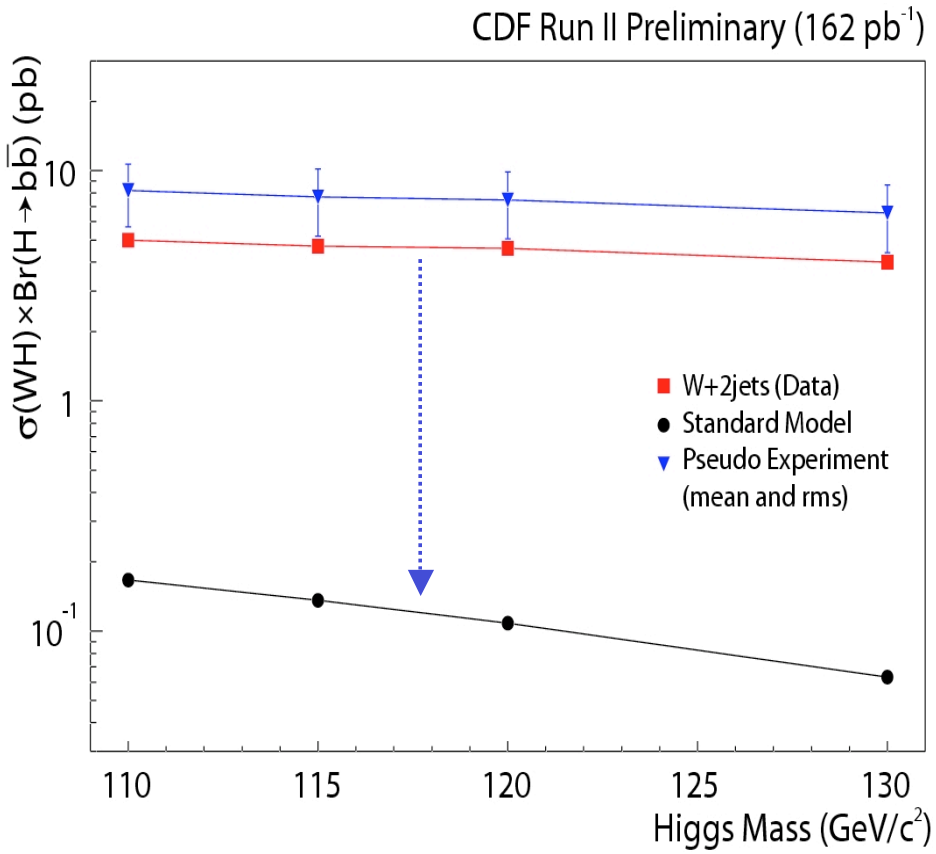


Backgrounds:

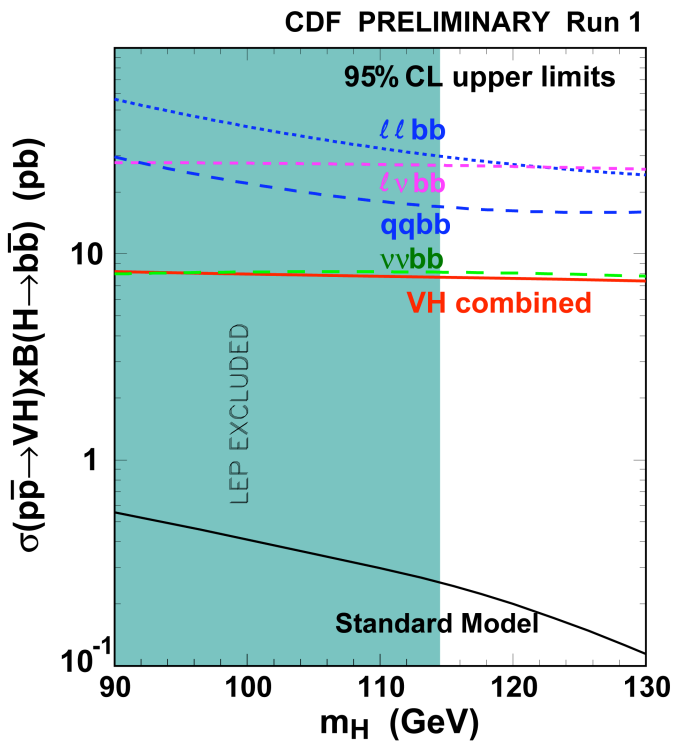
- Mistags
- Wbb, Wcc, Wc
- QCD
- tt, single t, di-boson, Z(→ tt)

S/ B = 0.054

Higgs Search (cont'd)



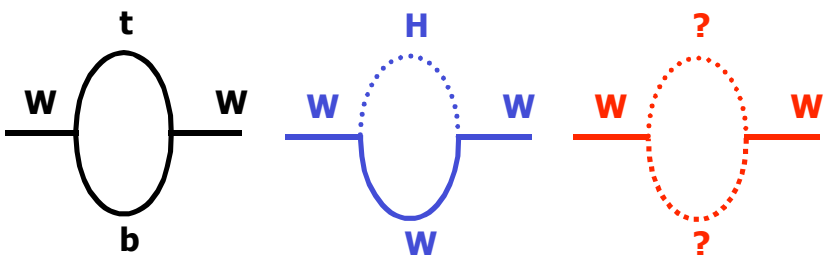
Future improvements :
Include forward electron
Improvement jet energy resolution
Improve b-tagging
Combine with other channels



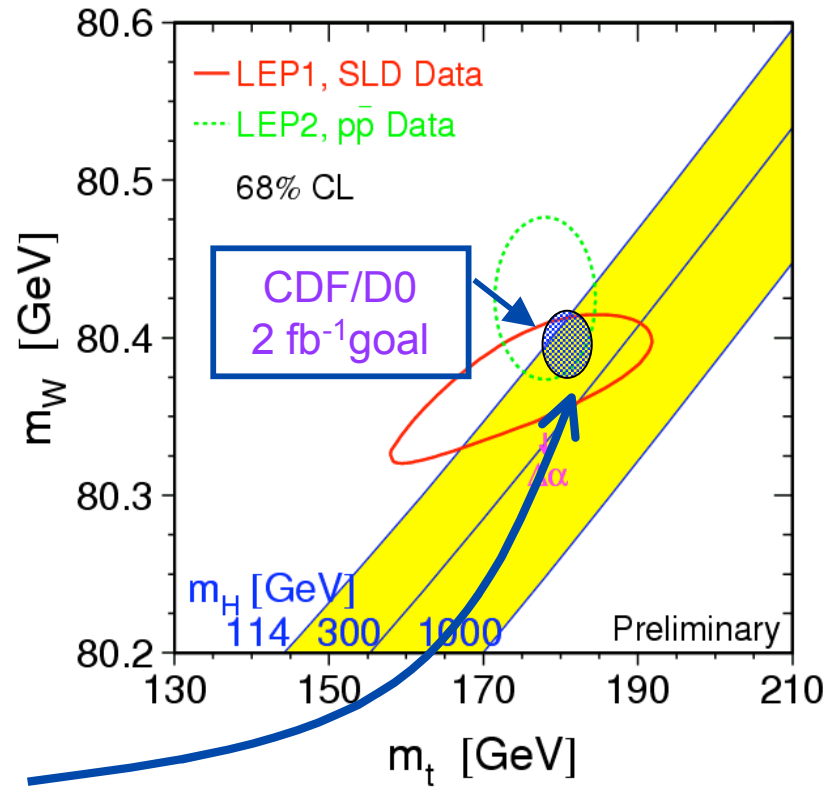
Improved limit over Run1, but sensitivity of current search is limited by statistics

Top Quark Mass Measurement

- The Top Quark Mass is a fundamental parameter of the Standard Model
  - Only fermion with mass near electroweak scale
- Correlated to other SM parameters via electroweak corrections

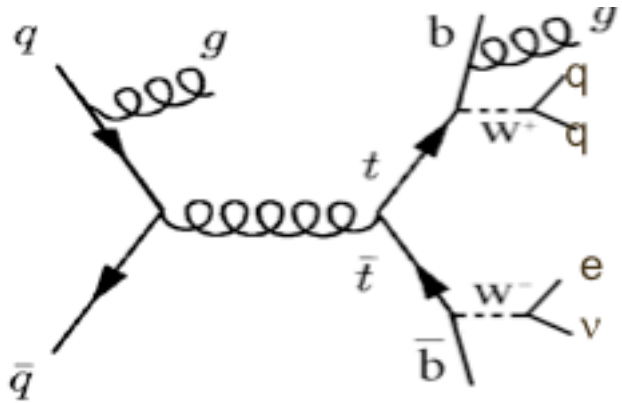


$\Delta M_W \propto M_T^2$ $\Delta M_W \propto \ln M_H$ New Physics



- **Precise measurement provides stringent SM test**
  - **Constrains the mass of the Higgs Boson**

Top Mass Measurement Challenges



- Why so challenging?
  not just a calculation of M(W+b) !!!
  - missing neutrino
  - confusion in ID (additional jet from ISR/FSR, b-tag: not 100%)
  - jet energy scale

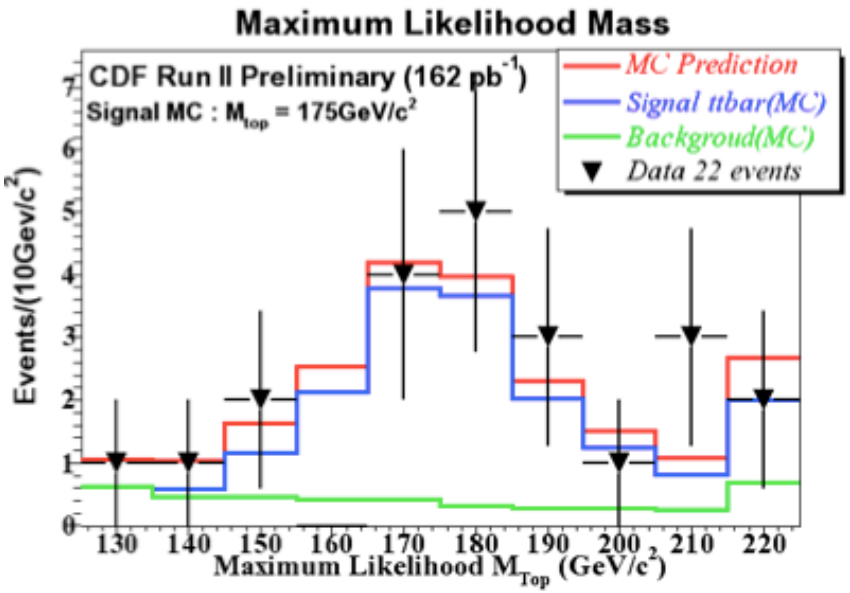
Link observables to parton-level energies
- Accurate detector simulation vital to precision physics measurements
- Large systematic uncertainty from energy scale

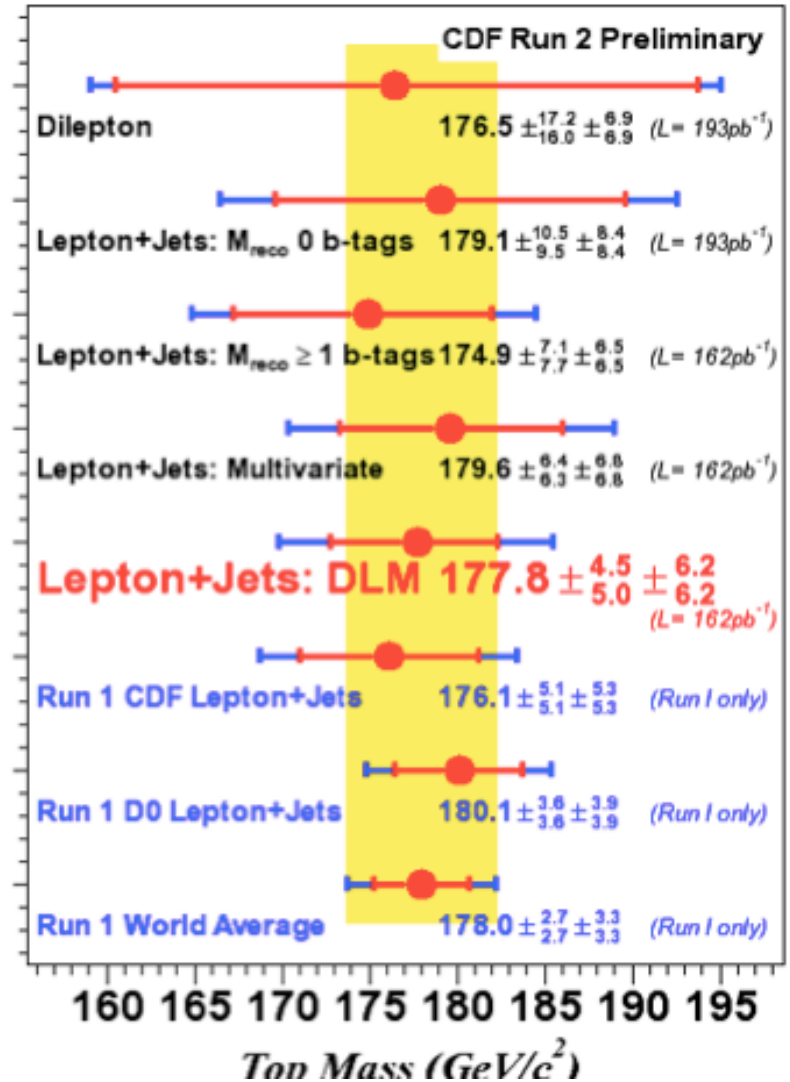
Method: reconstruct Mtop with 2 constraints, $M(W^+)=M(W^-)$, $M(t)=M(\bar{t})$

- Take the best combination over all 12 combinations
- Use all combinations(12) weighted by the diff. cross section (full kinematic info): dependence on tt event kinematics?

data is fitted to most likely mass template from Top MC

Top Mass Measurements





- Prospect: $\delta m_{top} \approx$ 2-3 GeV with 2fb^{-1}
  improved jet energy scale
  - Accurate detector simulation (jets)
  - γ+jet Et, Z+jet balance, W mass from top
  - Z→bb mass for b-jets

Combined Run I Top mass

Old DØ top mass average: 172.1 ± 5.2(stat.) ± 4.9(sys.) GeV

New DØ top mass average: 179.0 ± 3.5(stat.) ± 3.8(sys.) GeV

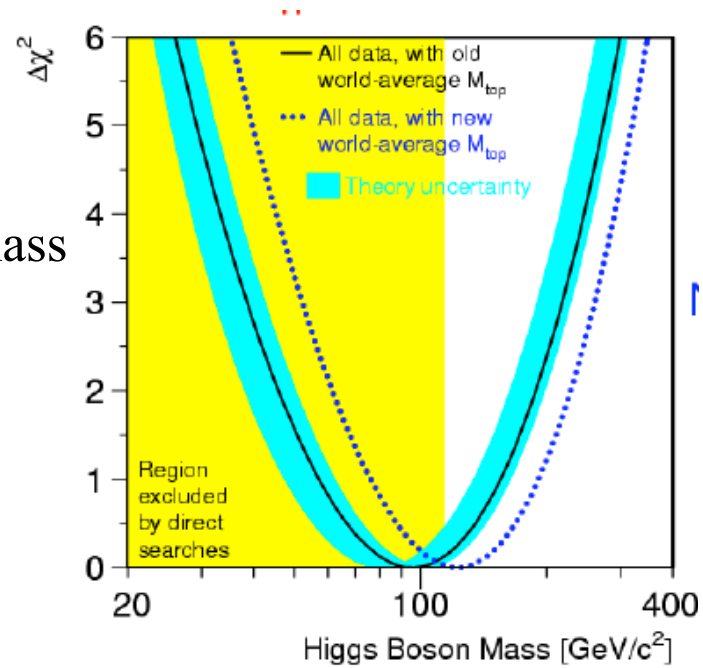
Combination Method:
weighted mean of un-correlated measurements
numerical minimization of χ^2 for correlated measurements

χ^2_{min} = 2.6 for 4 degrees of freedom: 63.2% probability.

Experiment	Measurement	Pull#	Weight [%]
CDF	leptons+jets	−0.32	22.2
	di-leptons	−1.01	7.1
	all-hadronic	+0.75	6.9
DØ	leptons+jets	+0.66	57.8
	di-leptons	−0.80	6.0

#Pull: $(x_i - \overline{x})/\sqrt{\sigma_i^2 - \sigma^2}$

New Higgs mass constraint



M_{top} = 178.0 ± 4.3 GeV

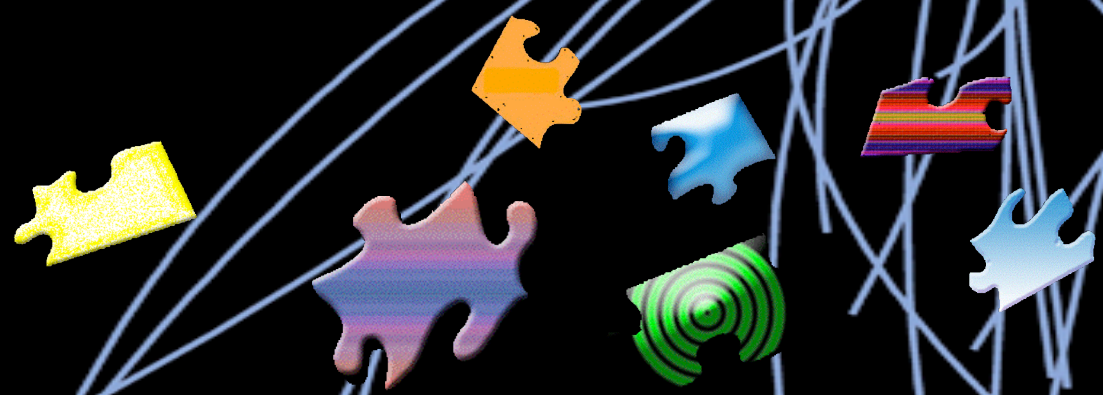
$\log M_H = 2.07^{+0.20}_{-0.21}$

$M_H = 117^{+67}_{-45}$ GeV

or < 251 GeV (95% CL)

Conclusions

Many exciting results are currently produced at CDF!

Many of our results interplay nicely :
From testing the SM processes to searches for Exotica
same signature, different physics

The Puzzle is becoming more and more interesting!