Latest Physics Results from the Tevatron

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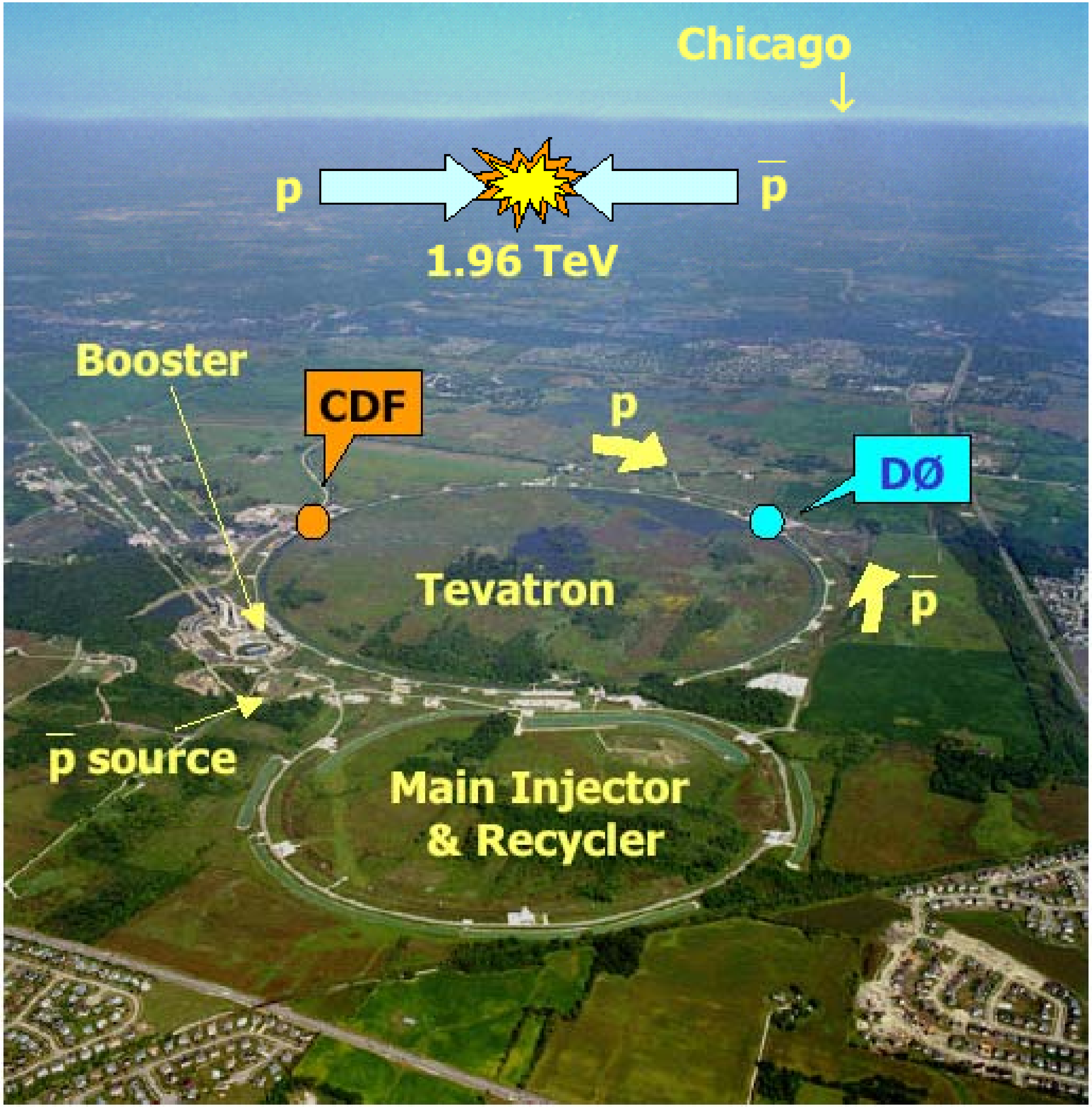
International Conference on Particle Physics
In Memoriam
Professor Engin Arik and colleagues

October 27, 2008

Tevatron at Fermilab

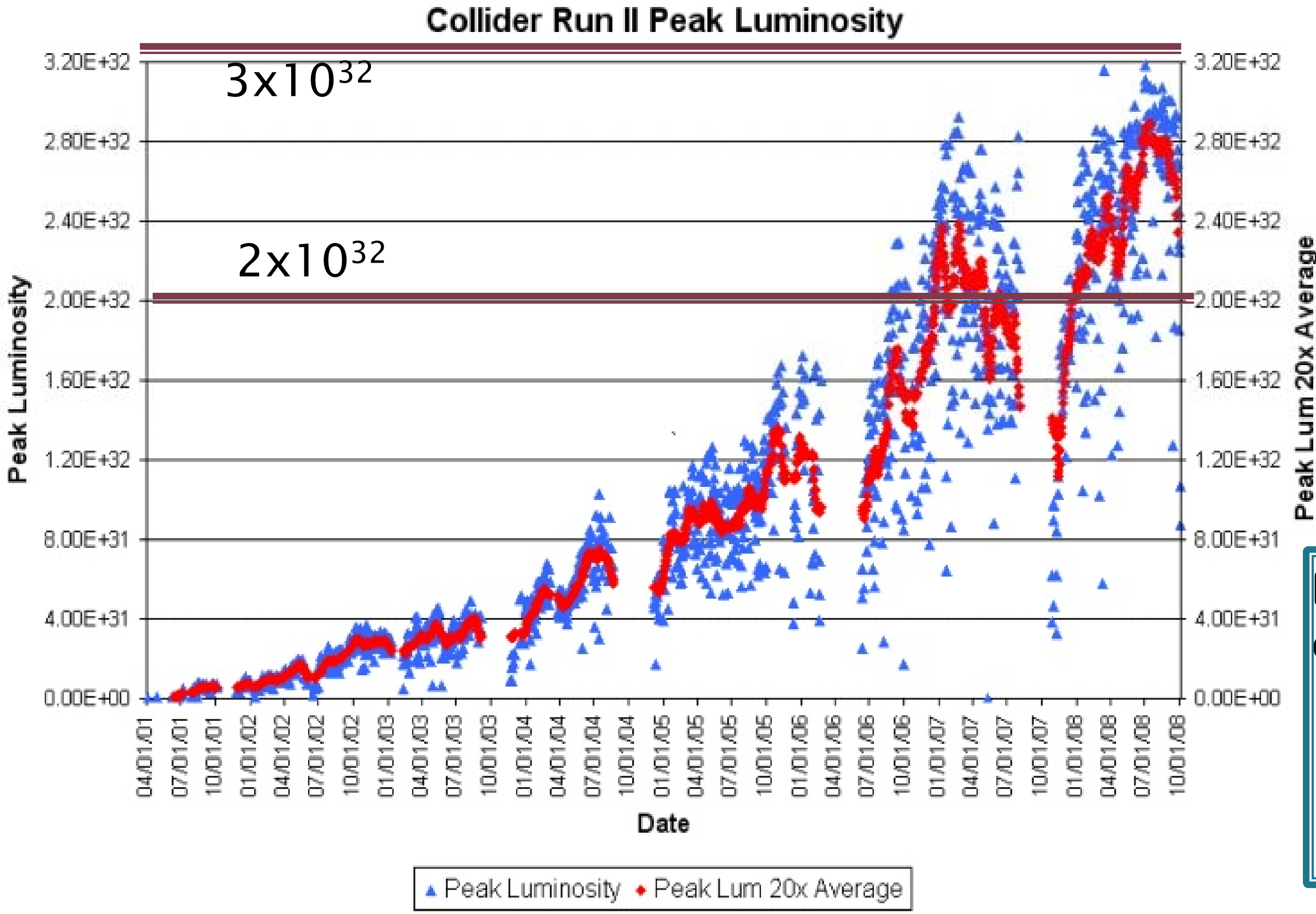


Tevatron Run 2

Record-setting performance!

Highest instantaneous lum store: 3.15×10^{32}

Integrated lum over 1 week: 57.4 pb^{-1} [June 30-Jul 7]



Each experiment:

Integrating ~ 200 pb-1/month

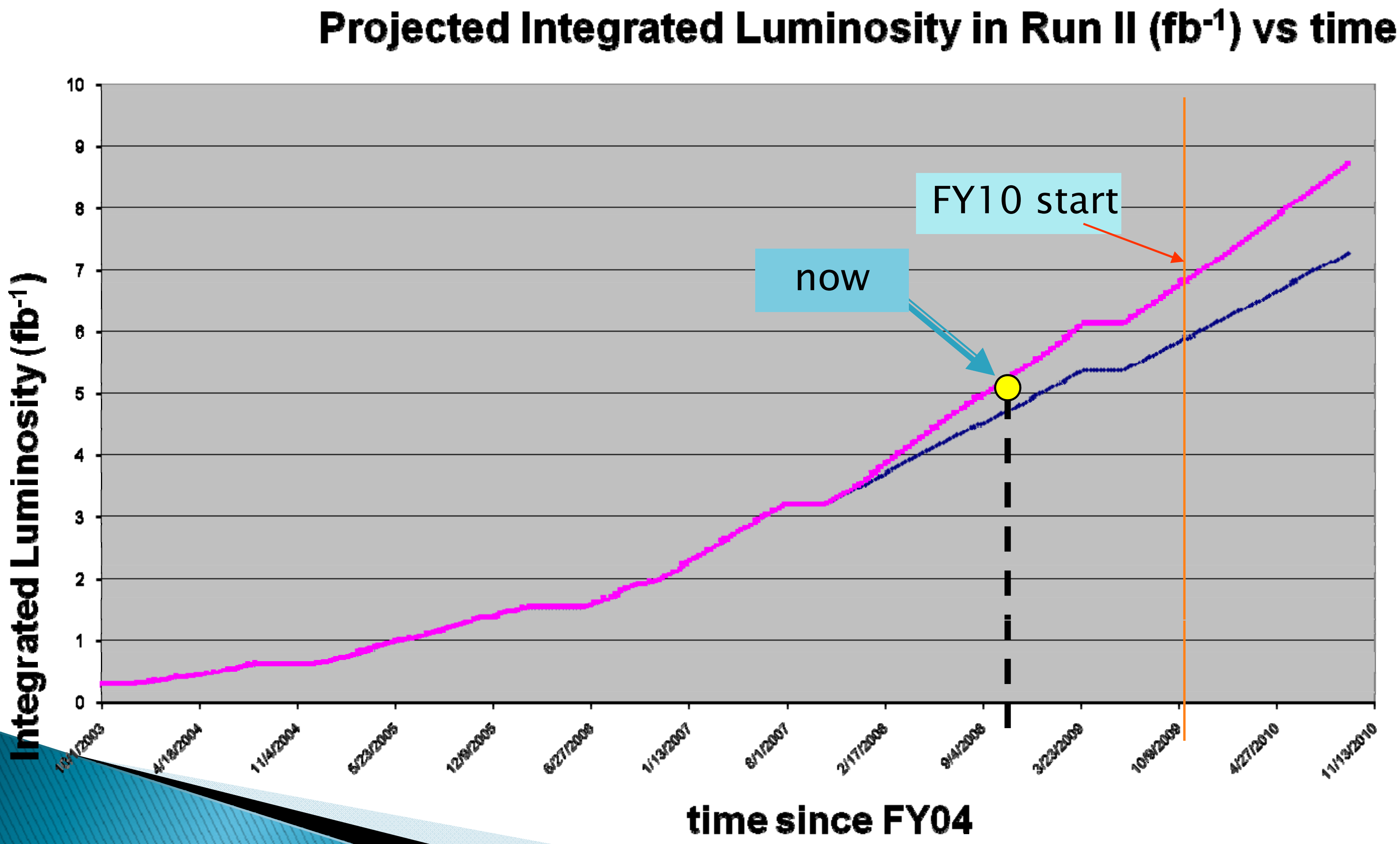
Over 1.8/fb delivered in FY08

Luminosity for each experiment:

~5 fb^{-1} delivered

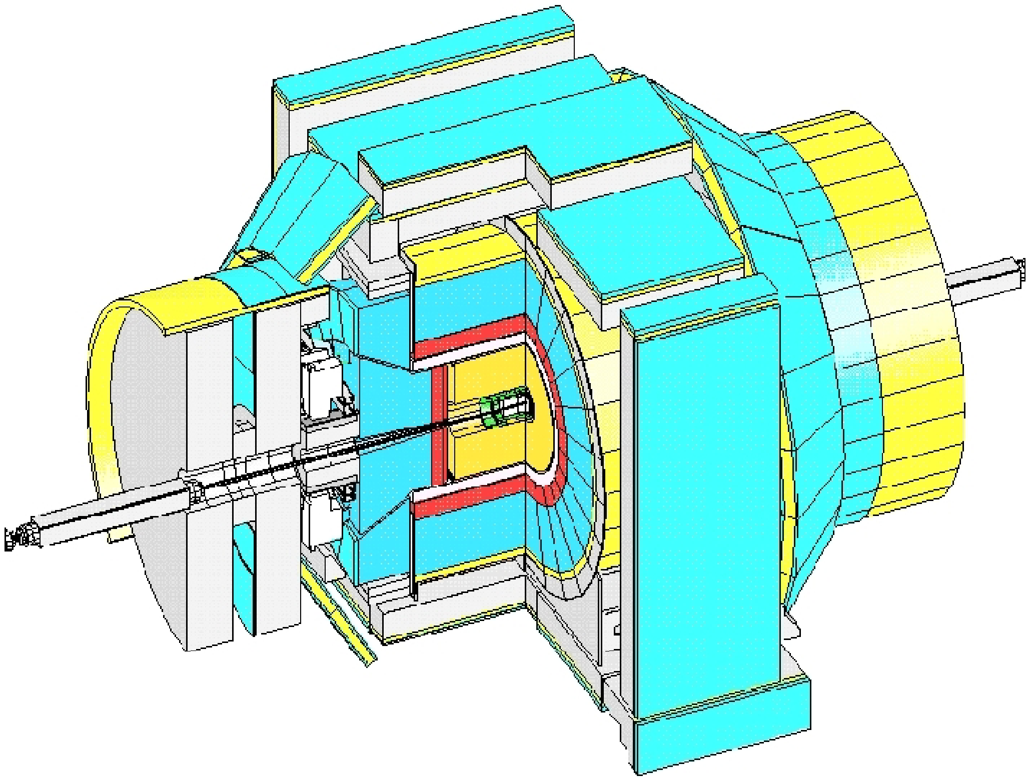
~4 fb^{-1} to tape !

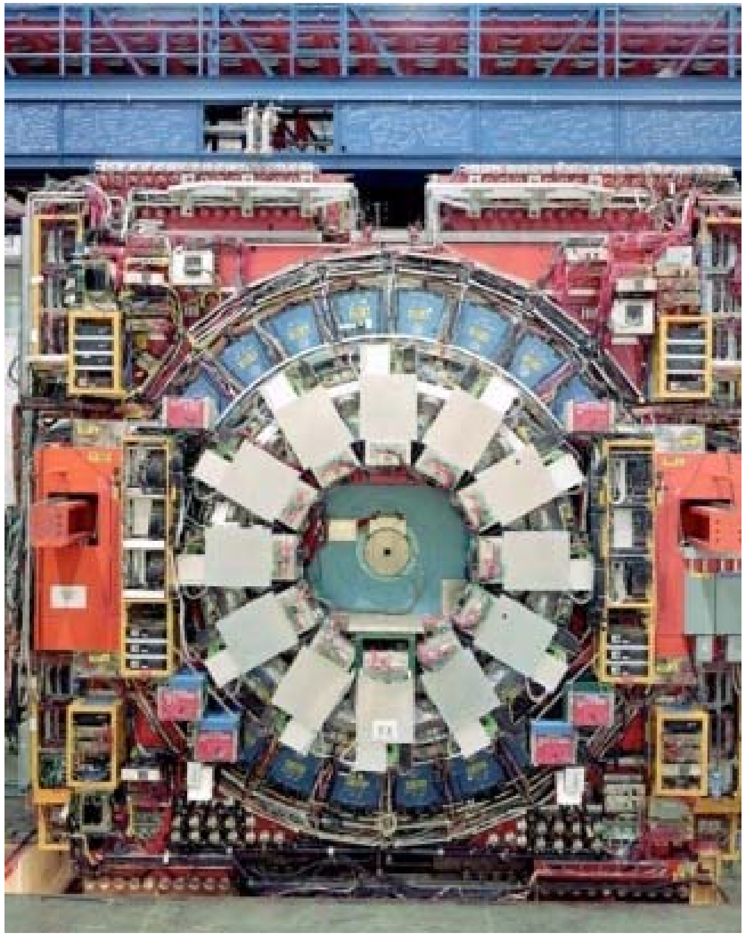
More to come



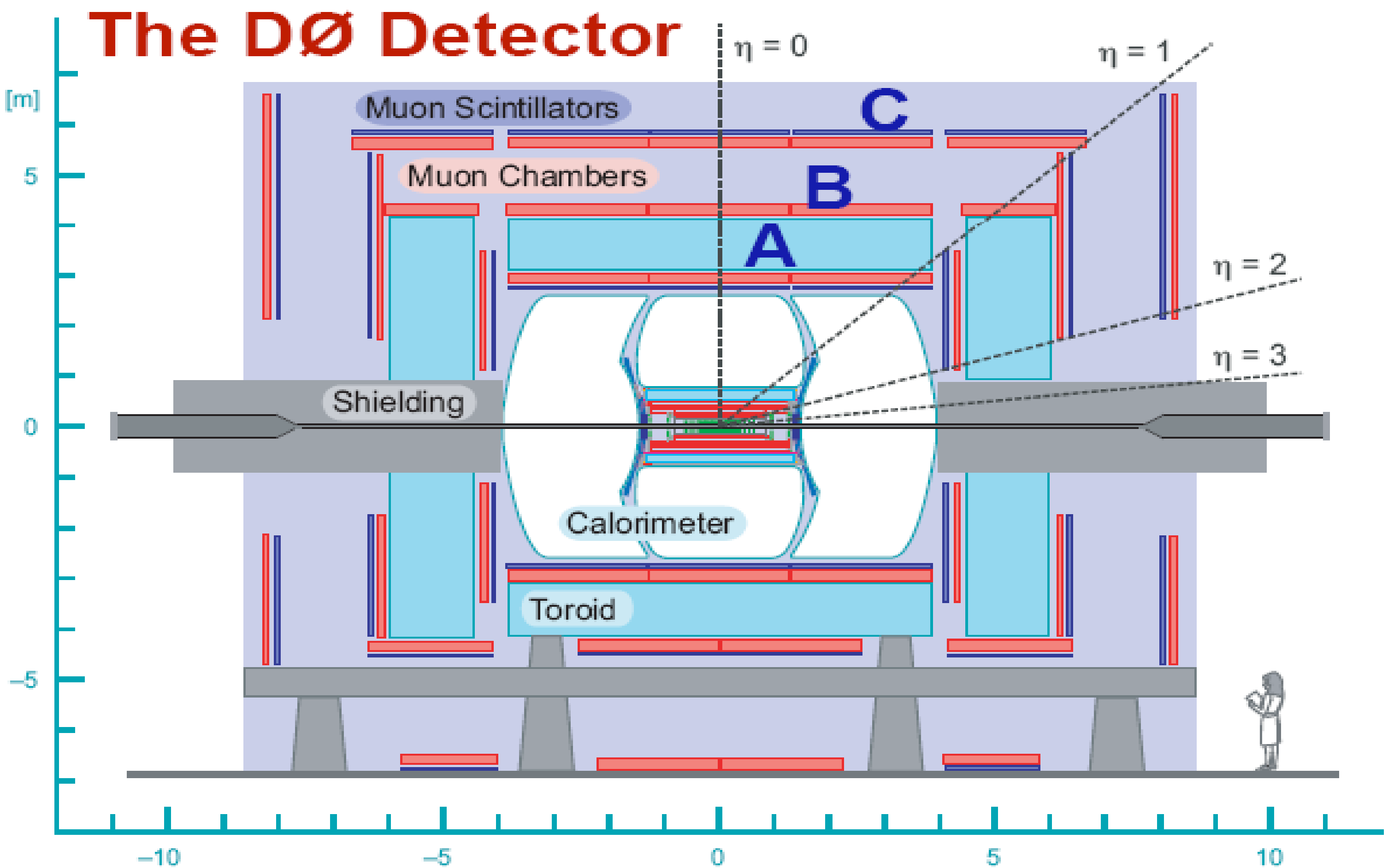
Projected Integrated Luminosity in Run II (fb-1) vs time
Integrated Luminosity (fb-1)
10
9
8
7
6
5
4
3
2
1
0
4/18/2004
11/4/2004
5/23/2005
12/9/2005
6/27/2006
1/13/2007
8/1/2007
2/17/2008
9/4/2008
3/23/2009
10/9/2009
4/27/2010
11/13/2010
time since FY04
FY10 start
now

CDF Detector





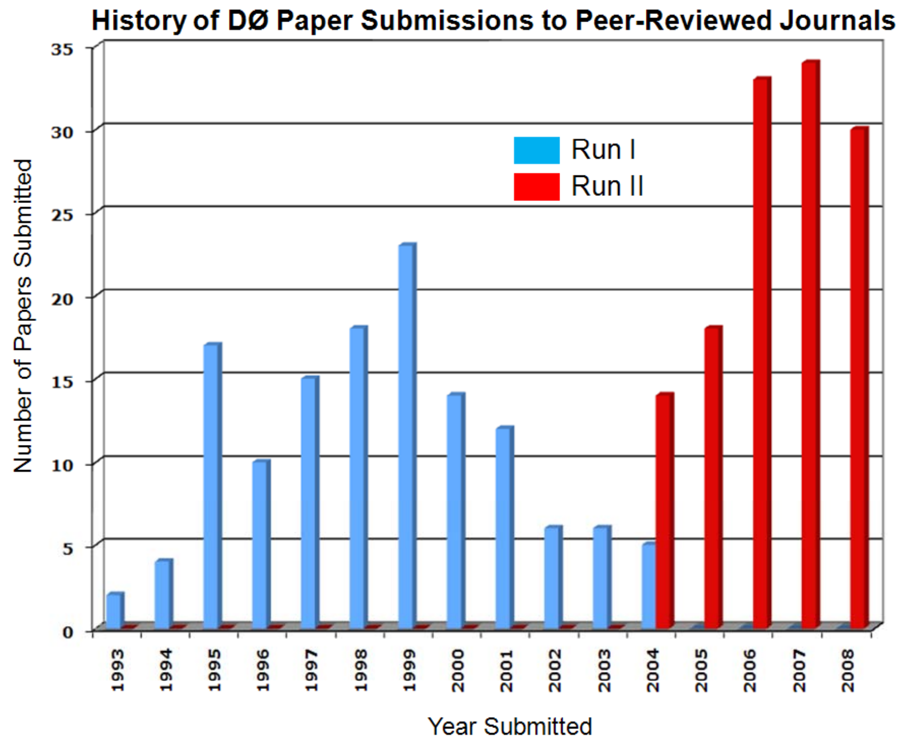
D0 Detector

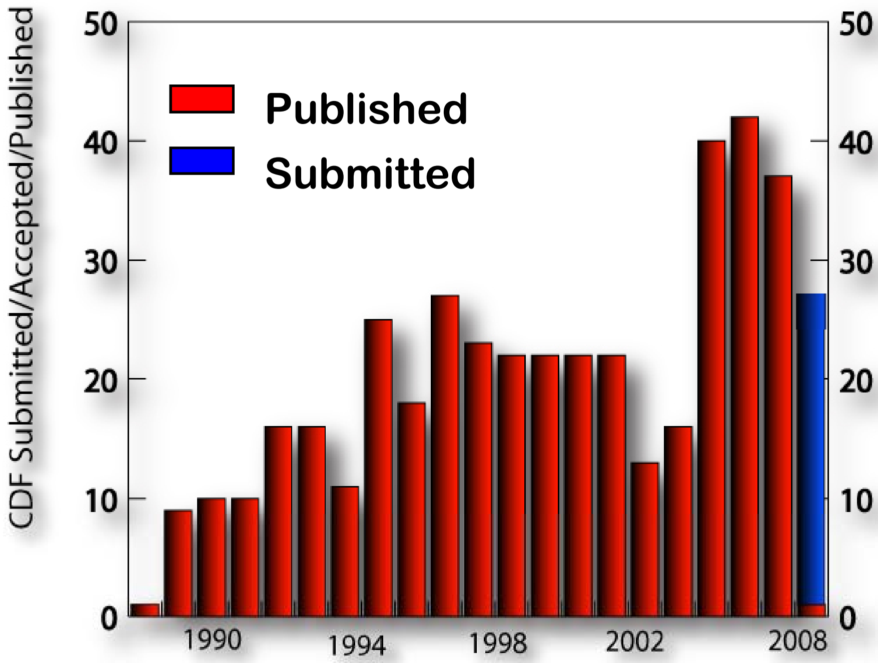


The DØ Detector
η = 0
η = 1
η = 2
η = 3
[m]
Muon Scintillators
C
Muon Chambers
B
A
Shielding
Calorimeter
Toroid
5
0
–5
–10
–5
0
5
10

Tevatron experiments producing physics results

So far in 2008, D0 has
- 37 preliminary results,
- 30 publications (~1/week).
  [34 submitted in CY 2007]





CDF has
- 51 papers submitted in 2008
  (32 published so far)

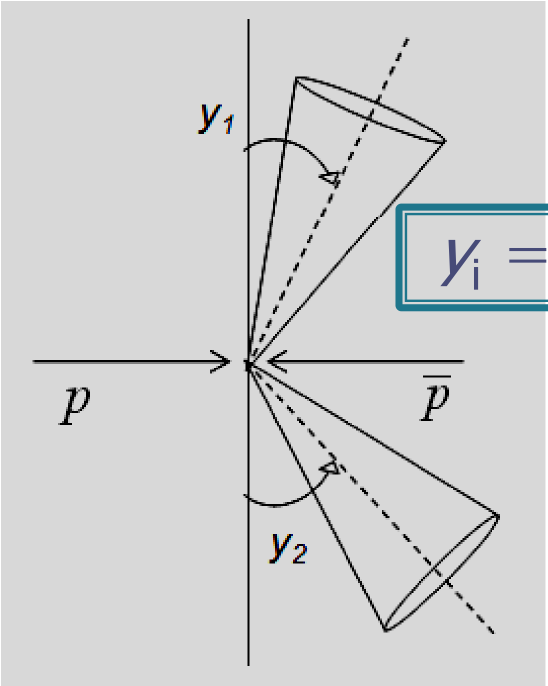
Tevatron Physics

- Mature program, characterized by
  - Depth
    - Precision electroweak measurements
    - sophisticated techniques
  - Breadth
    - Discovery of B baryons, ZZ production
    - Cross sections for top, jets, bosons
    - Global searches for new physics
  - Collaboration
    - CDF and D0 combine Higgs, top mass results
- Valuable lessons from Tevatron for LHC!

Topics covered today

- Many new results – too many to cover here -- will show selected new results
- Testing the Standard Model
  - QCD – angular distributions, diffractive W,Z
  - Electroweak – W mass, ZZ observation
  - Top – precise top mass measurement, single top, t'
  - Higgs – combined CDF/D0 result
- Breaking the Standard Model – searches for New Phenomena
  - SUSY, resonances, Extra Dimensions, global searches
- Apologies for results that I don't have time to discuss…
  - B physics – baryon discovery, βs – not covered today

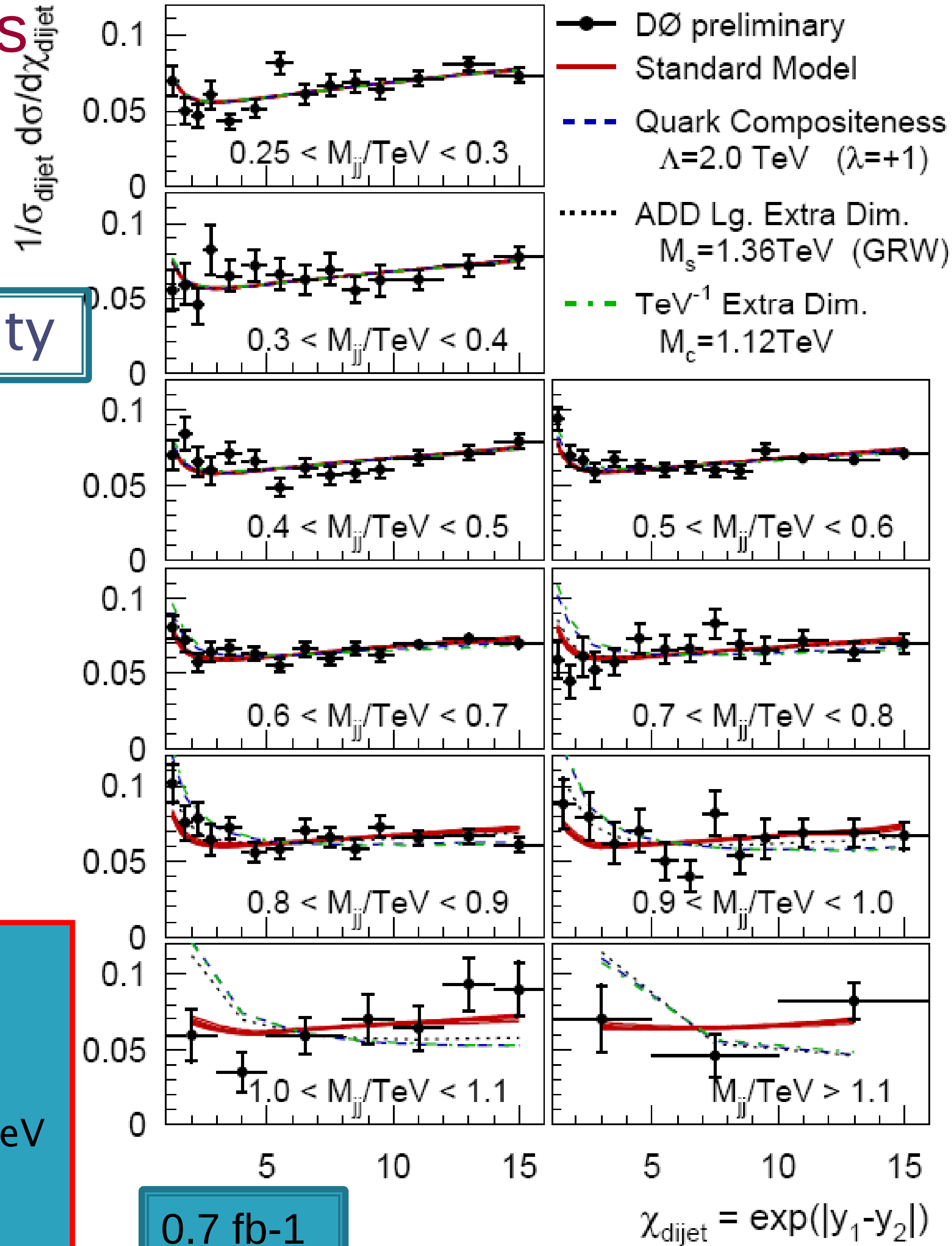
Dijet Angular Distributions



y_i = jet rapidity

Bin in dijet mass
yjet<2.4

$$\chi_{dijet} = \exp(|y_1 - y_2|) \approx \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



0.7 fb-1

<u>Sensitivity to New Physics (95% CL)</u>

Compositeness ($\lambda=+1$): $\Lambda>2.6$ TeV

ADD extra-dimensions (n=4): $M_s>1.6$ TeV

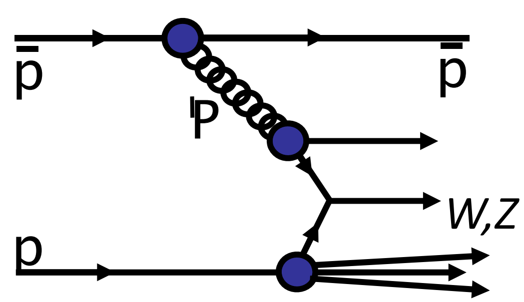
TeV^{-1} extra-dimensions: $M_c>1.4$ TeV

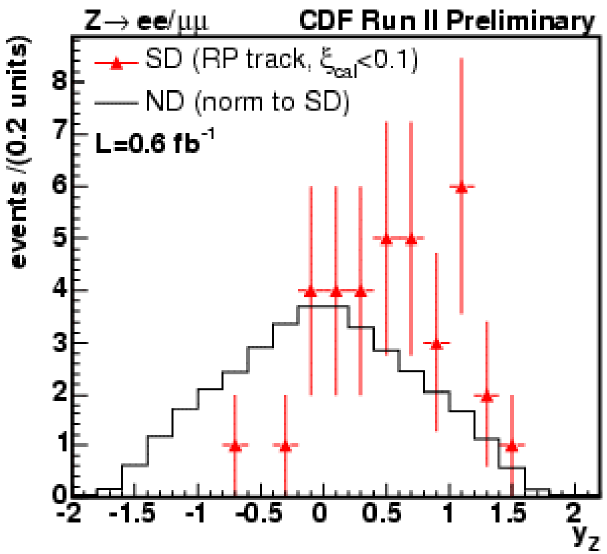
Diffractive *W* and *Z* Production

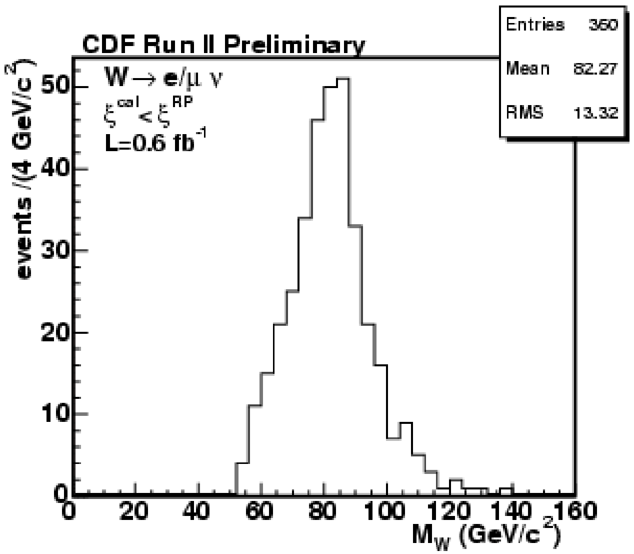
Study pomeron radiation from antiproton – use W,Z as probes of structure function

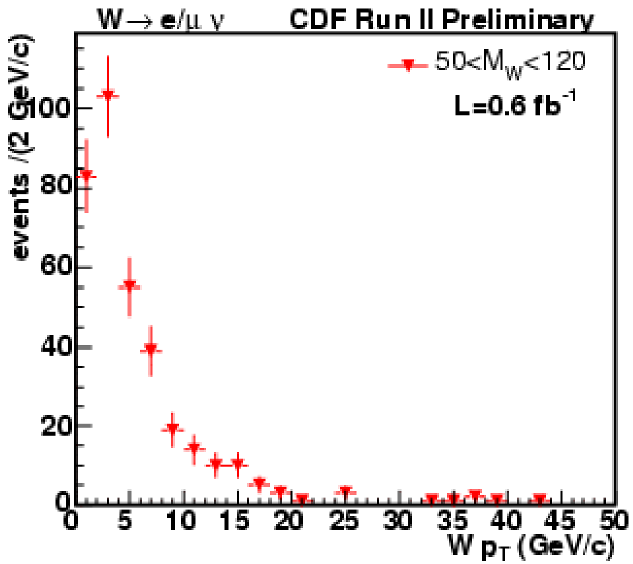
-- outgoing antiproton momentum measured with downstream beam detectors

--difference between pbar track and cal electron gives neutrino momentum →W mass









Single diffraction cross section / total cross section:

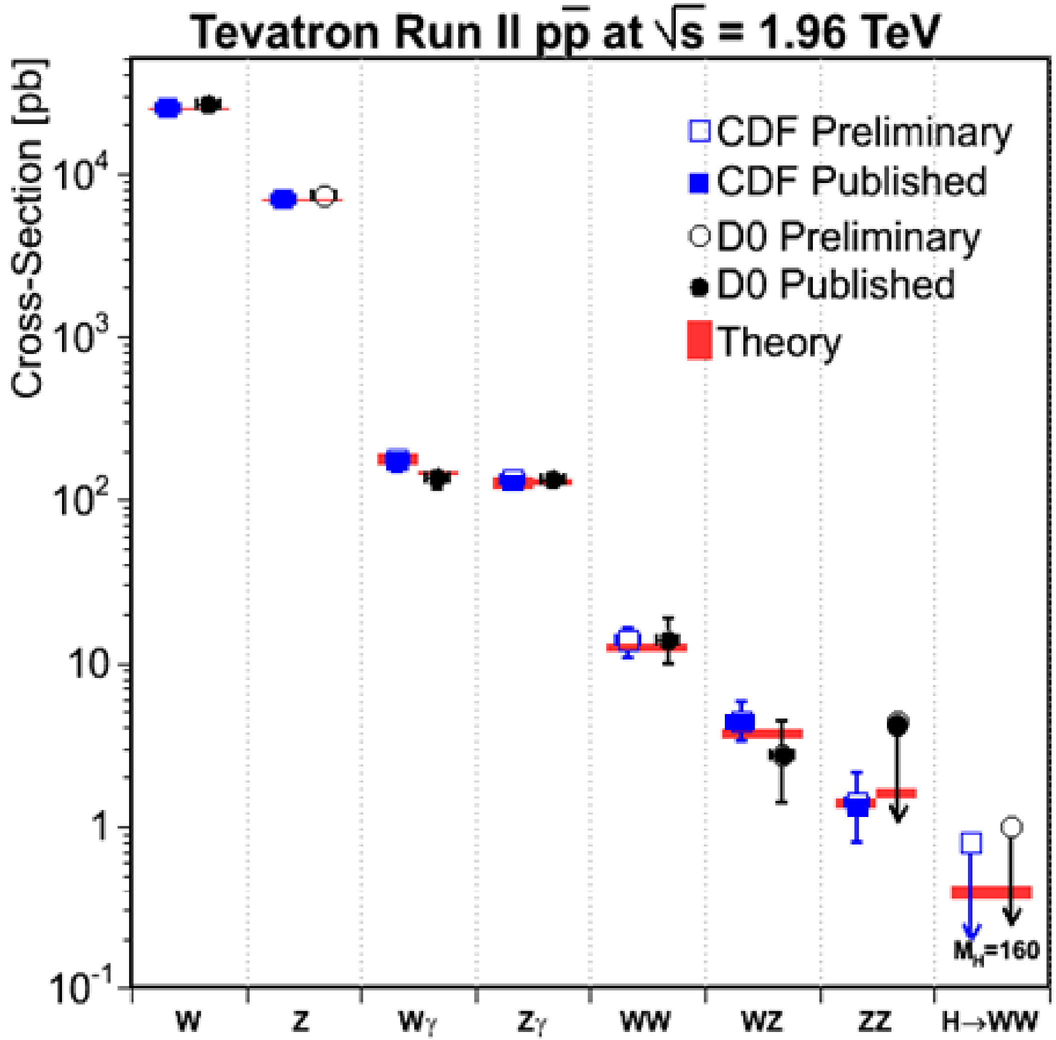
*W*s: 0.95 ± 0.05 ± 0.11%

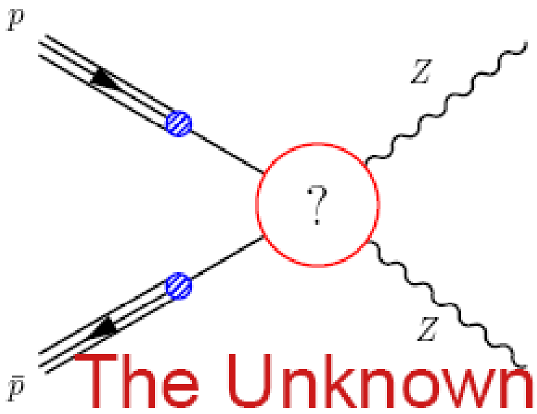
*Z*s: 0.85 ± 0.20 ± 0.11%

0.6 fb^{-1}

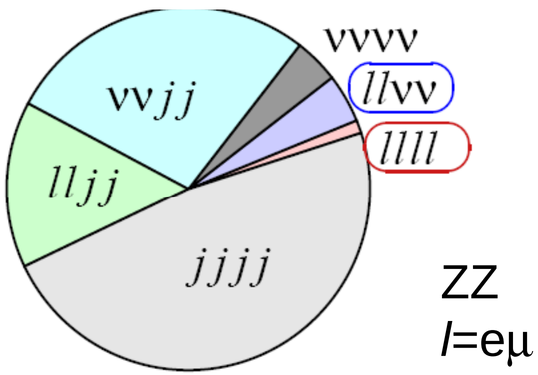
Dibosons

- Tevatron datasets now large enough to observe rare processes – WZ, ZZ
  - Prerequisite for a Higgs discovery!
  - Sensitivity to new physics





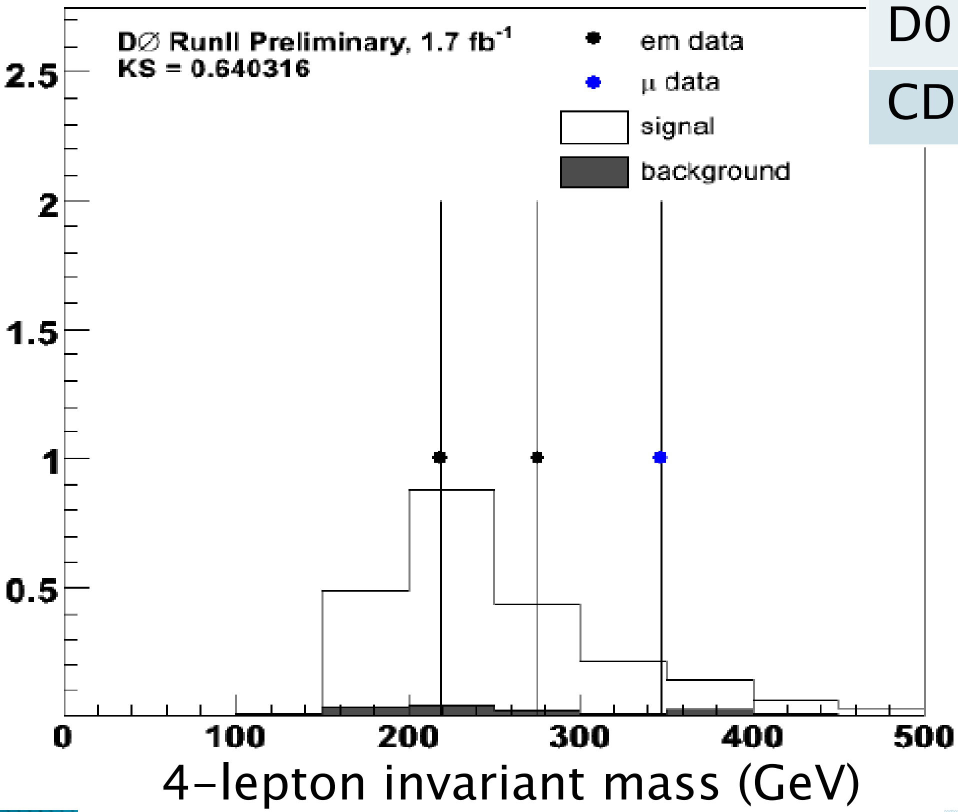
Lepton/neutrino channels have low branching ratio but cleanest signature



Diboson observation

Result	Cross section	Sign.
D0 WZ+WW	20.2 +/− 4.5 pb	4.4s
CDF WZ	5.0 +/− 1.7 pb	6σ
D0 ZZ (llnn)	1.9 +/− 1.1 pb	2.3σ
D0 ZZ (4l)	$1.75^{+1.28}_{-0.87}$ pb	4.2σ
CDF ZZ (4l)	1.4 +0.7 − 0.6 pb	4.4σ

ZZ→llll



W and Z Boson Mass

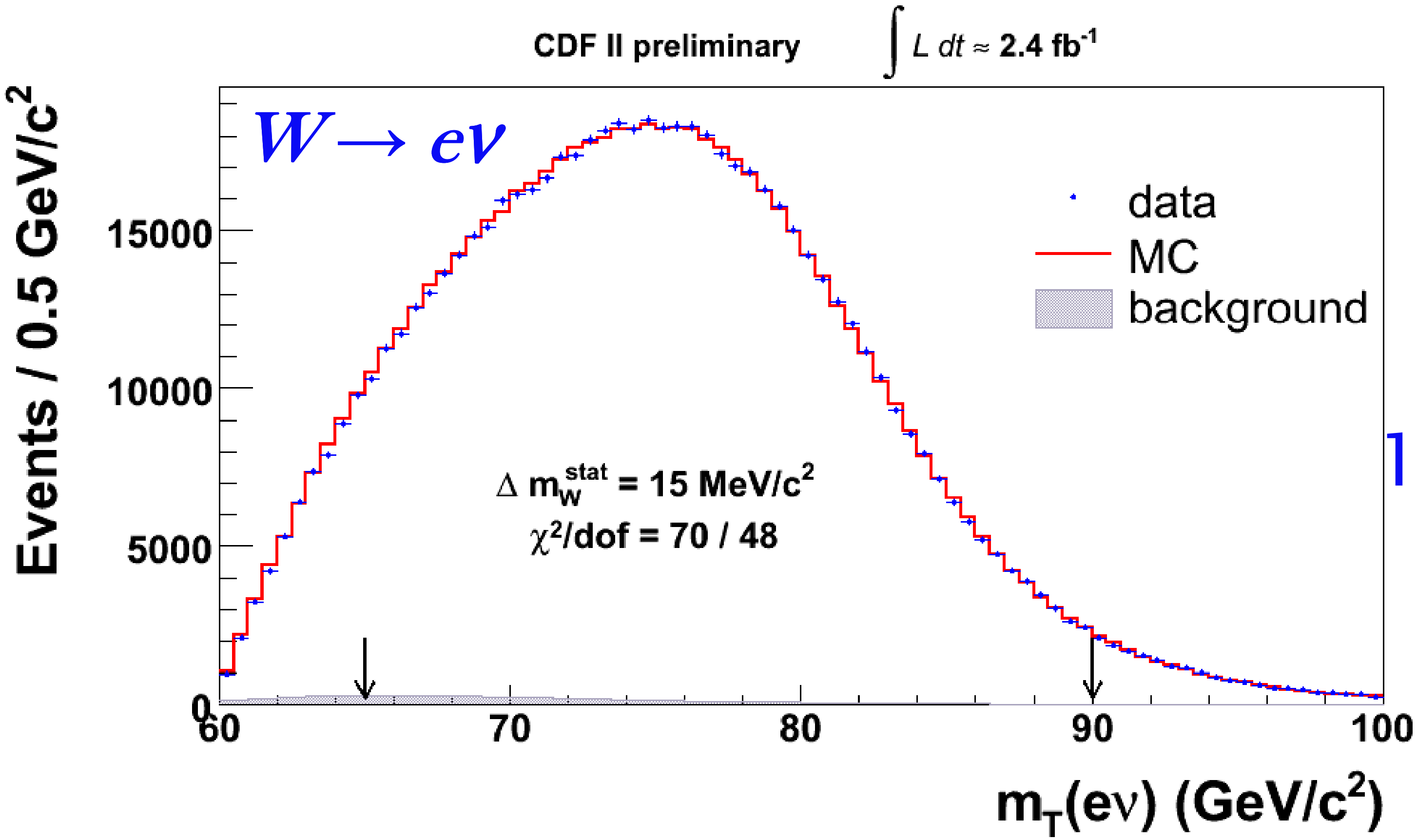
W mass provides input to indirect Higgs mass constraint

-- *W* precision is primary limitation

PRL 99, 151801
PRD 77, 112001

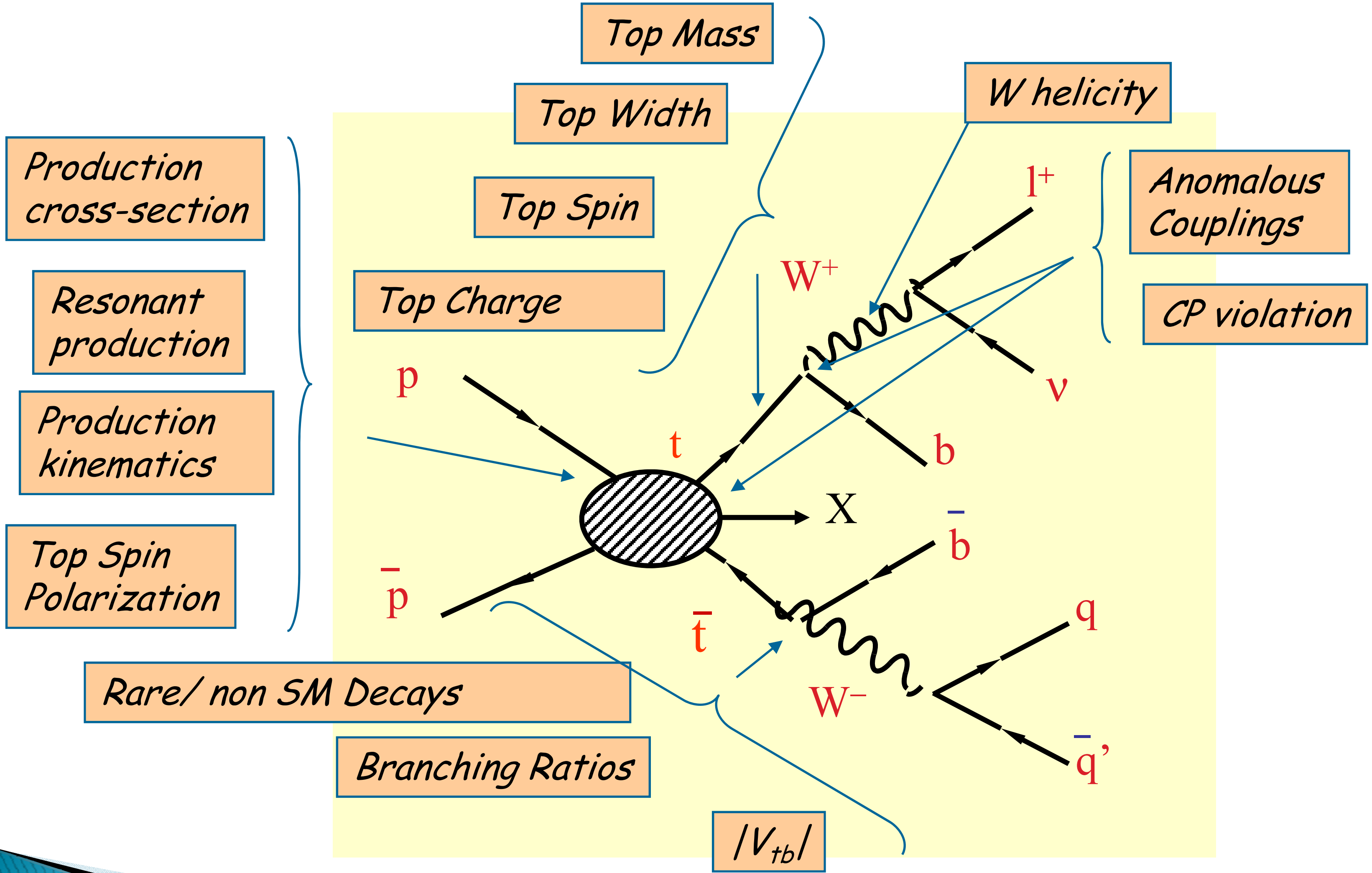
CDF Published measurement -- 200 pb^{-1} → 48 MeV/c2 uncertainty

Now analyzing 2.4 fb-1 → expected uncertainty < 25 MeV/c2



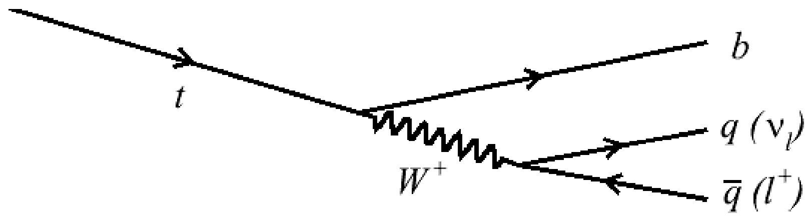
1.4M $W \rightarrow l\nu$ events

Top physics

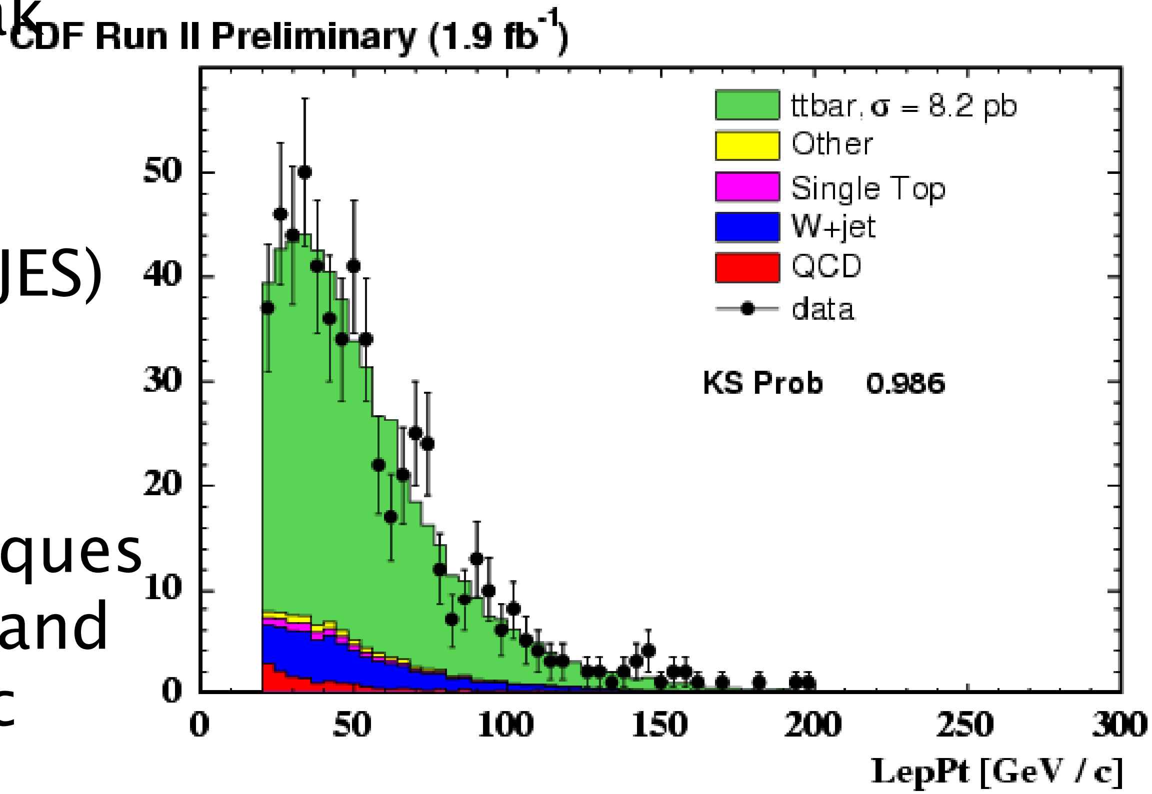


From Aurelio Juste, Fermilab Wine and Cheese, 7-25-08

Top Quark Mass

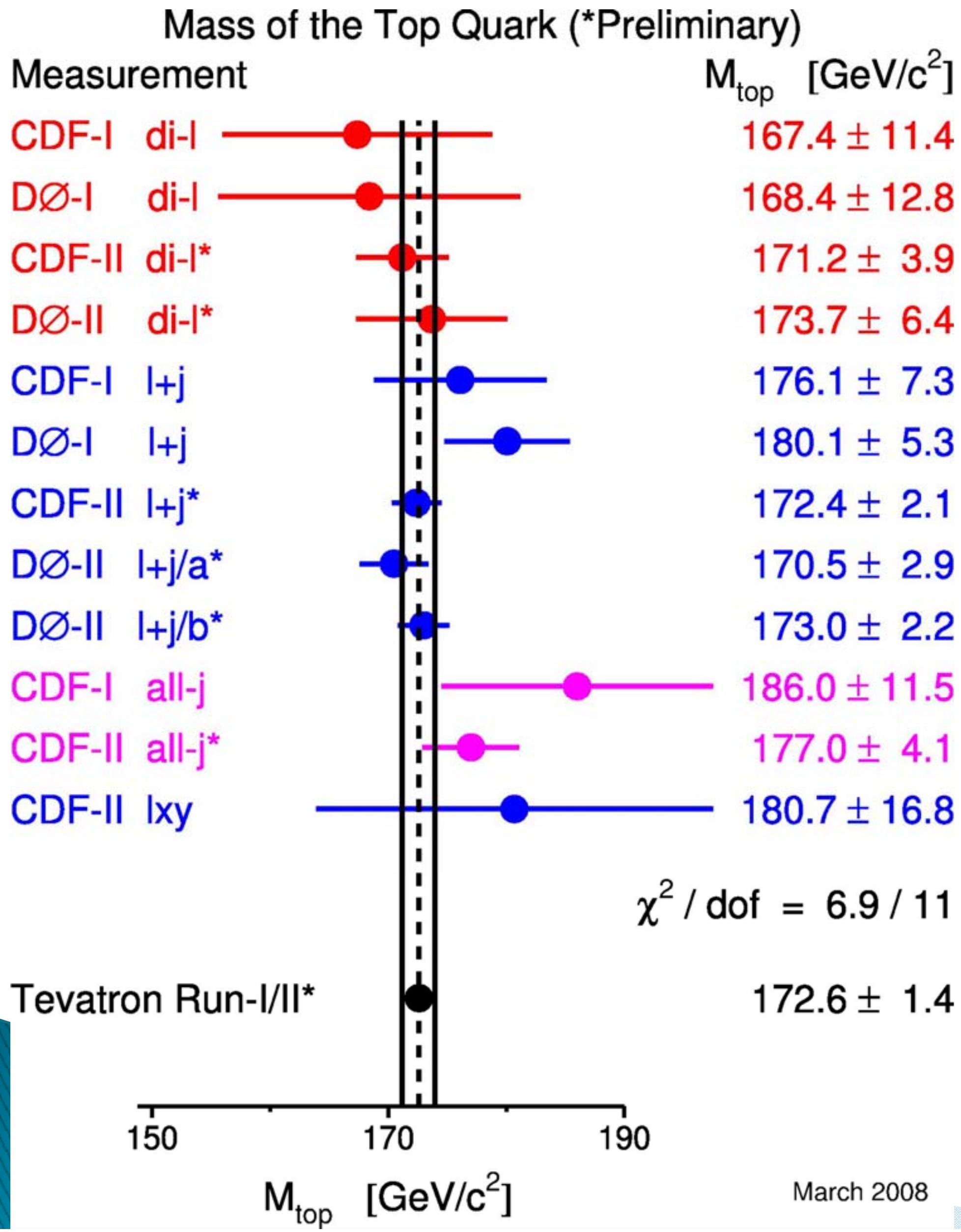


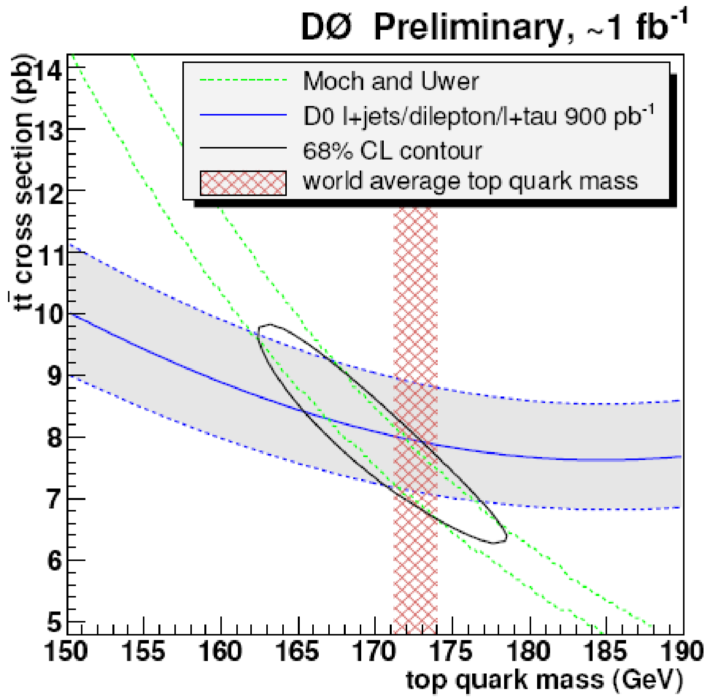
- Important parameter in precision electroweak analyses.
- Challenges:
  - Jet energy scale (JES)
  - Signal modeling
  - Combinatorics
- Sophisticated techniques minimize statistical and dominant systematic uncertainties
- JES dominant
  - Develop alternate measurements with less reliance on JES



→ For example, use lepton pT (depends on W pT more than JES)

Top Quark Mass





Good agreement between mass from direct reconstruction and cross section measurement.

$$m_{top} = 169.6 \pm 5.5\,\text{GeV}$$

(Different systematic uncertainties)

Constraints on new physics from top cross section measurement

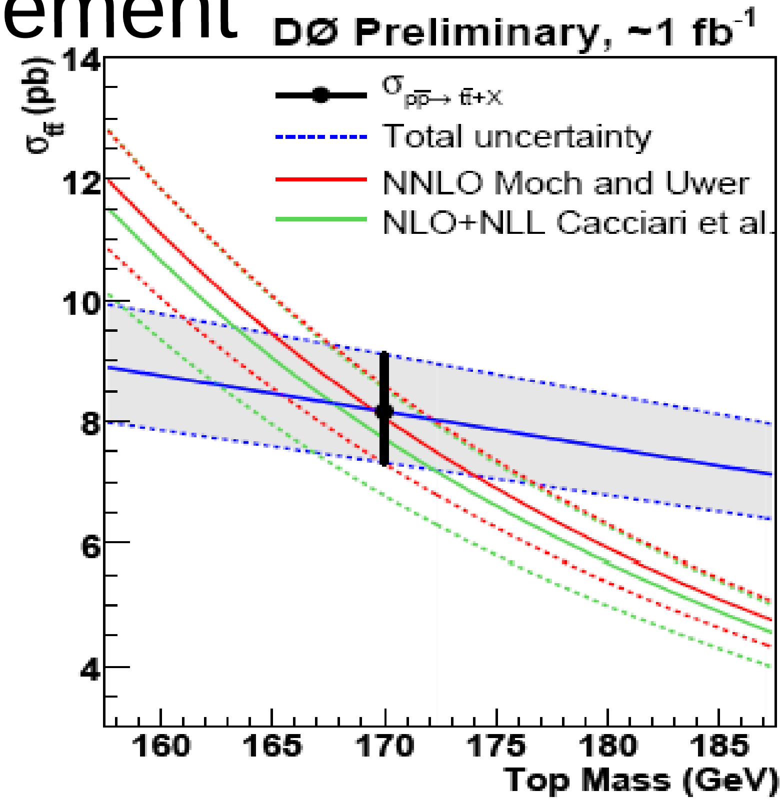
- ttbar cross section measured in many channels (combination of W decays + b-jet)
- Top is heavy – if it were decaying into some other heavy object, could modify observed cross-section channels
- Eg, **$t \to H^+ b$** : final states depend on H^+ decay modes.

  Tauonic: **$B(H^+ \to \tau\nu)=1$**

  - Observe **fewer** l+jets, dilepton
  - Observe **more** l+τ

  Leptophobic: **$B(H^+ \to cs)=1$**

  - **Fewer** l+jets, dilepton and l+τ
  - **More** hadronic

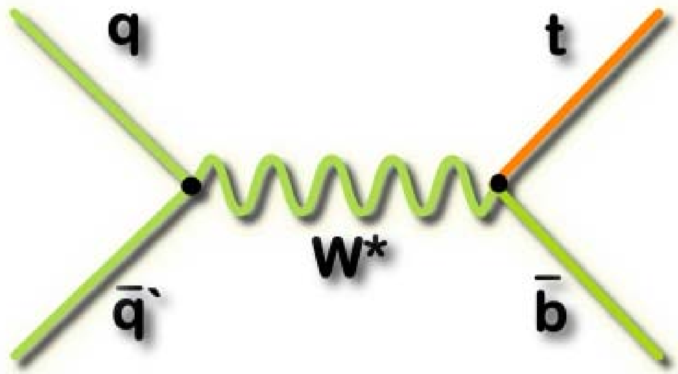


From D0, for m_t=170 GeV:

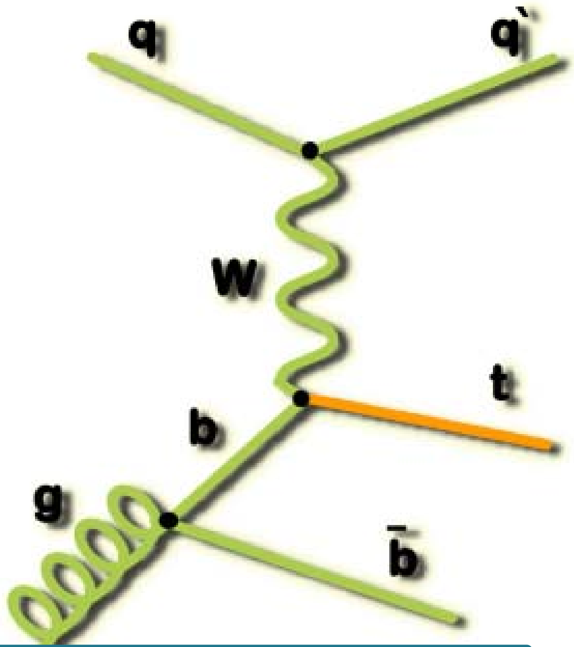
$$\sigma(t\bar{t}) \ = \ 8.16^{+0.95}_{-0.84} \ (\text{stat+syst}) \ \text{pb}$$

Good agreement with the SM prediction -- CDF and D0 use to constrain H+

Single Top Production

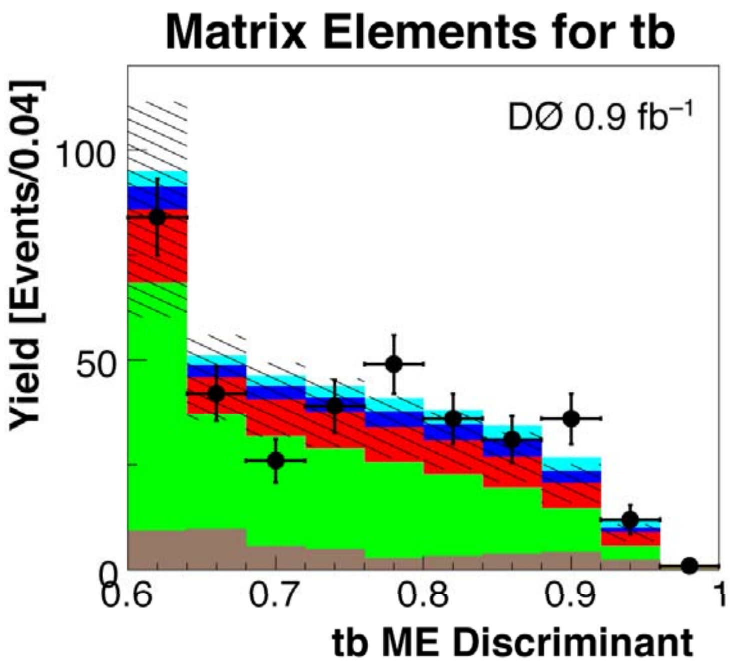


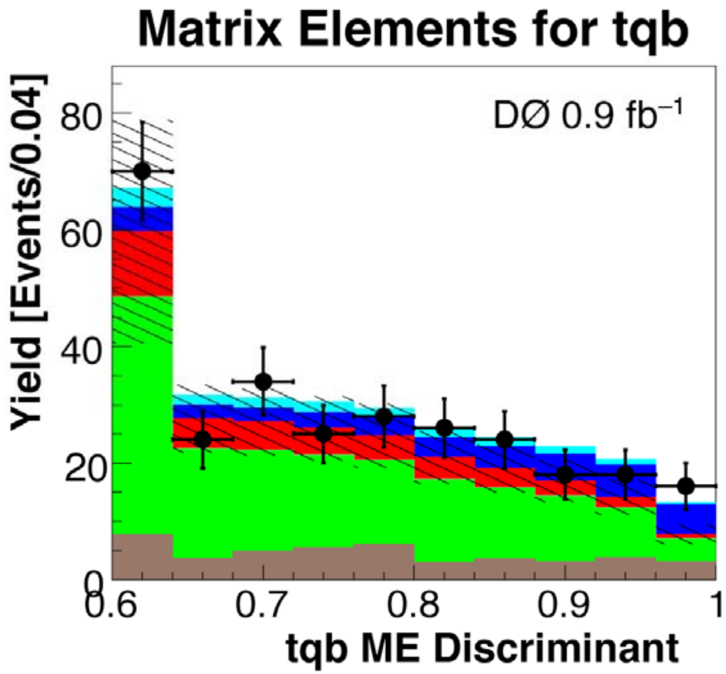
- Top produced weakly in s-channel (σtb = 0.9 pb) or t-channel (σtq = 2.0 pb)
- Cross section directly measures Vtb magnitude

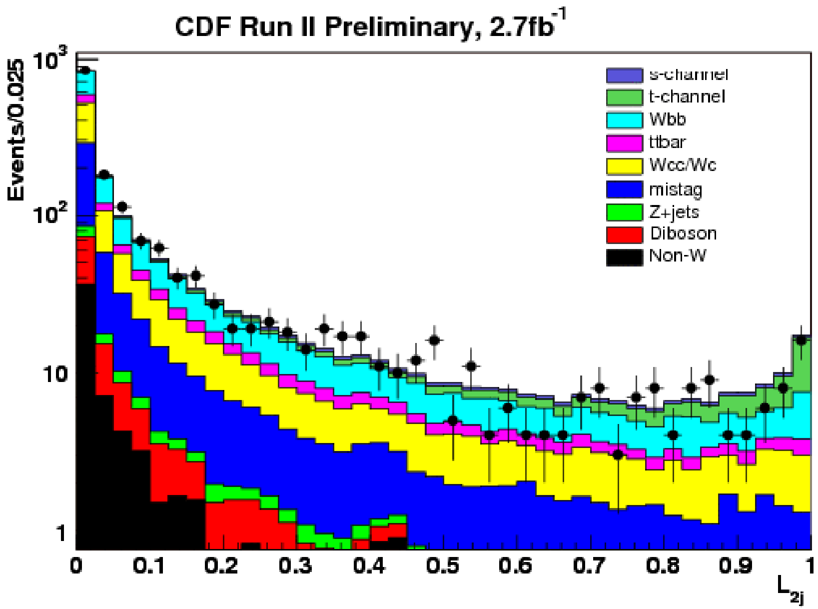


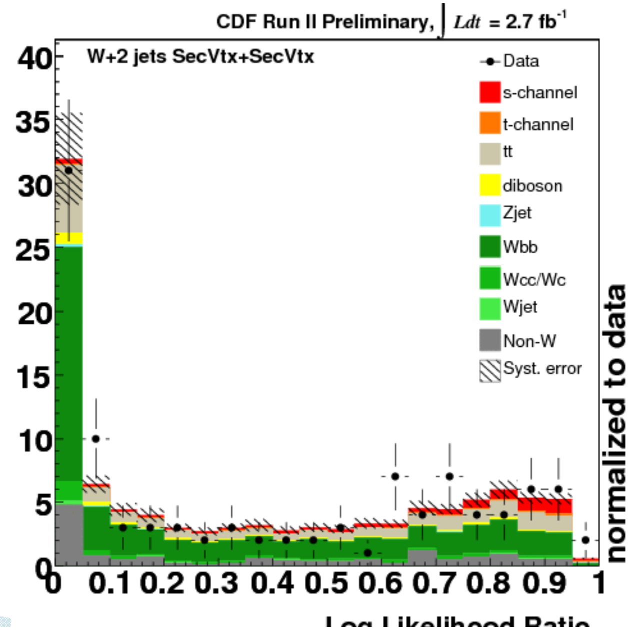
Single top cross section overwhelmed by $W+$ jets background
Advanced techniques required to separate signal from background

Single top – analysis methods

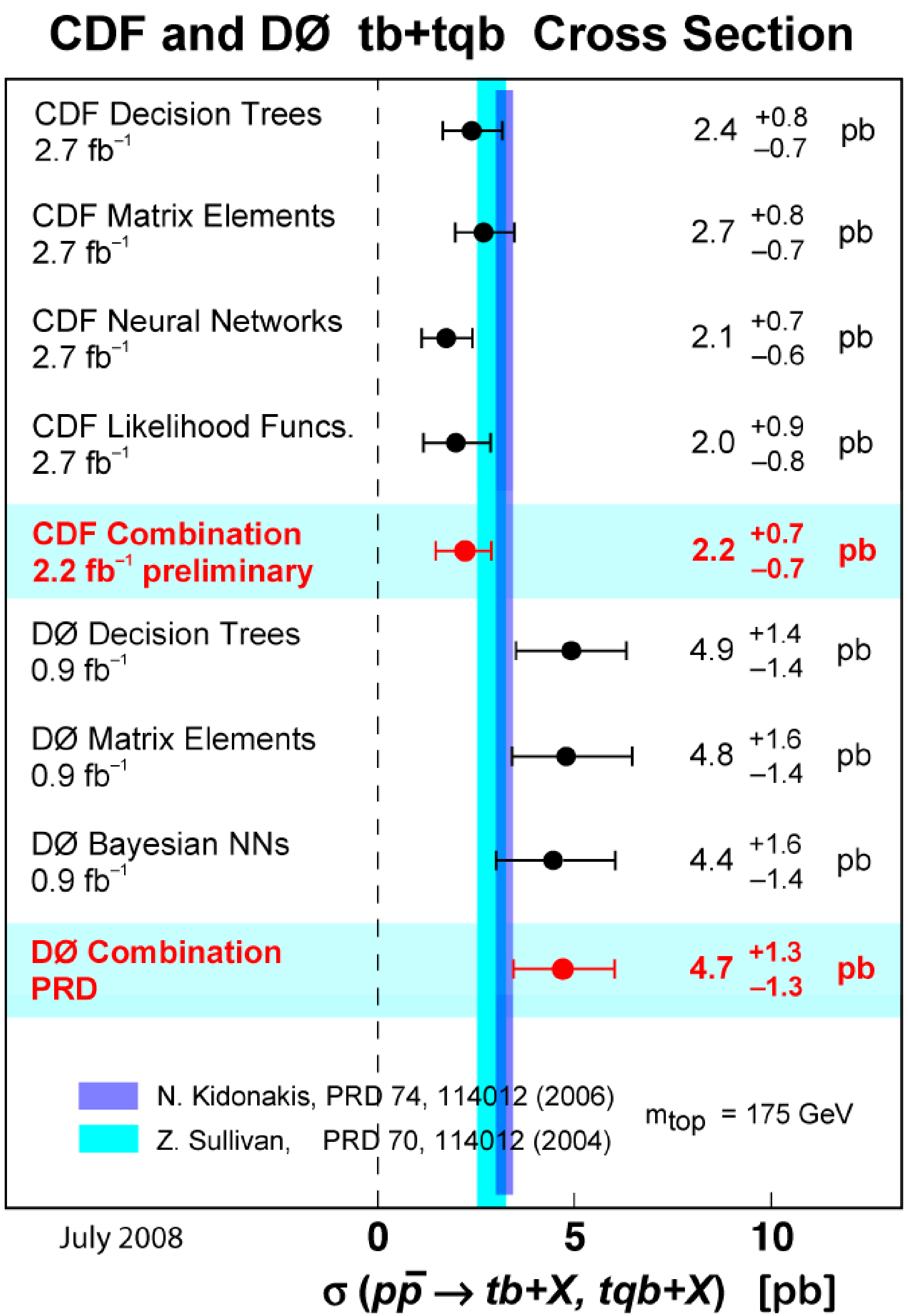








Single Top Production cross section summary

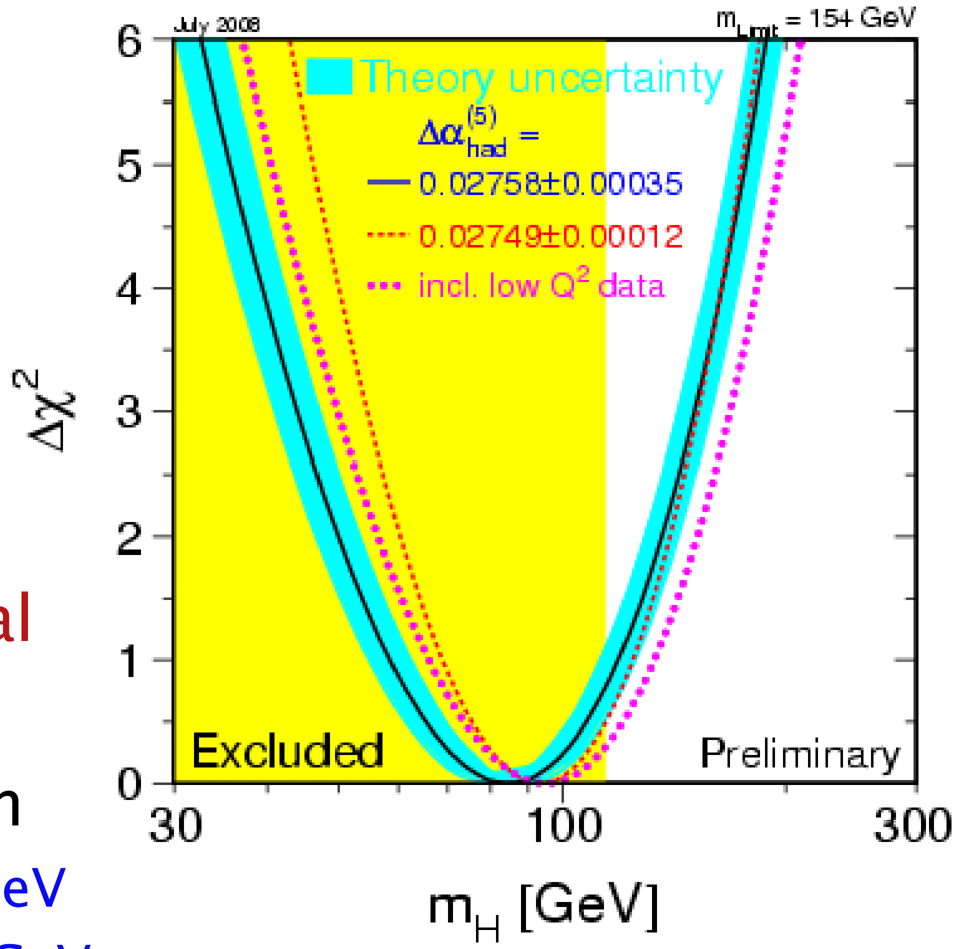


The Higgs Boson

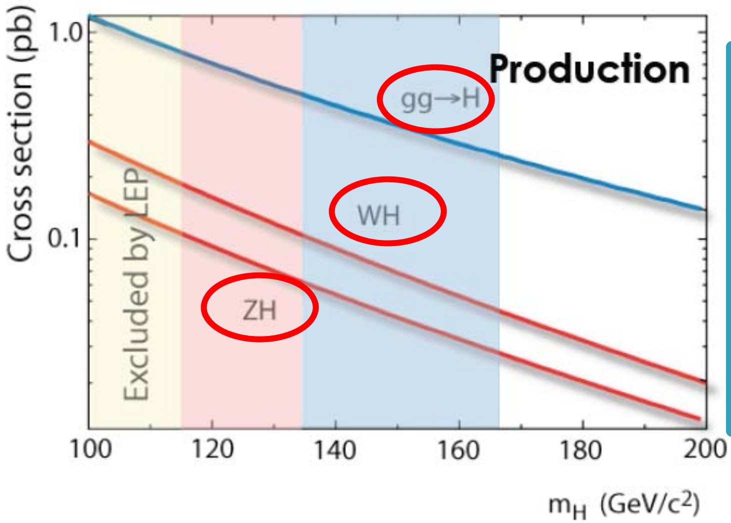
- The last unobserved particle in the Standard Model
- Only fundamental scalar
- Gives fermions and weak bosons their masses
- Responsible for generational mixing
- Narrow allowed mass region

Direct 95% CL limit : mH > 114 GeV

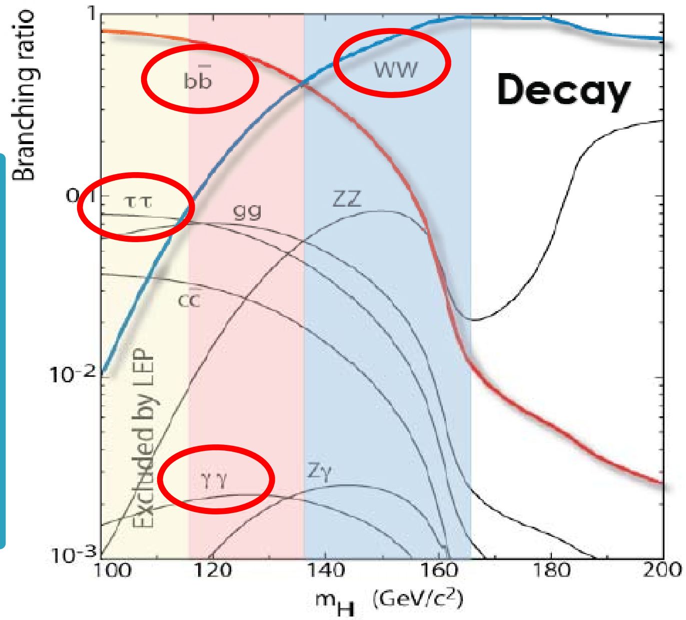
Indirect 95% CL limit: mH < 154 GeV



Higgs at the Tevatron

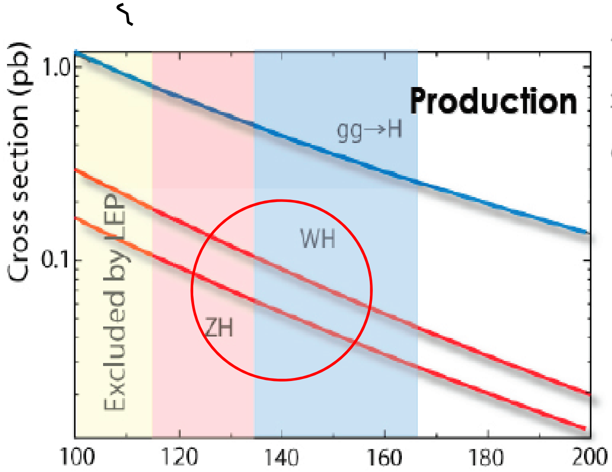


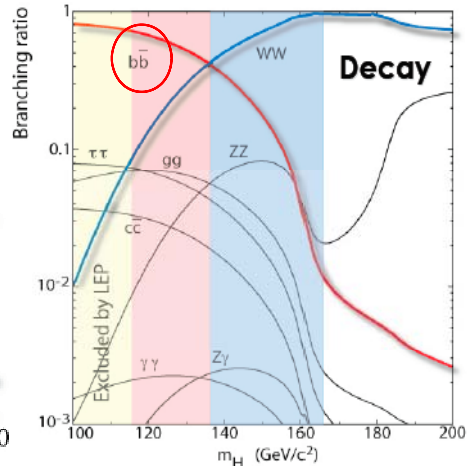
Analyses tailored to Higgs mass region



- Finding the Higgs at the Tevatron is possible!
- Higgs program explores many possible channels
- Major effort from both CDF and D0 to continue to improve sensitivity:
  - Addchannels
  - Optimize object identification/resolution
  - Optimize selections, sophisticated techniques
  - Adding more luminosity (combine CDF – D0 doubles dataset)

Higgs Searches ($m_H \lesssim 130$ GeV)



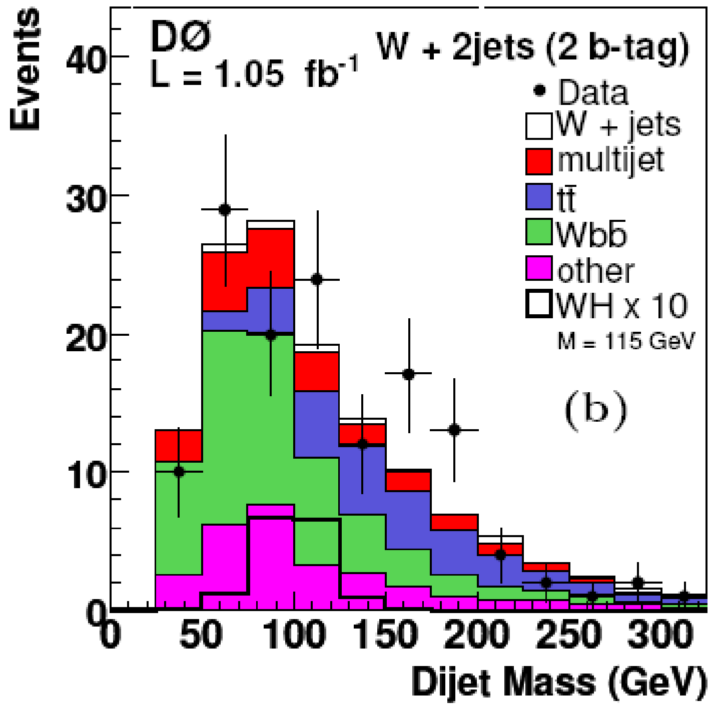


Use W/Z + H at low mass

- Significantly suppresses background
- Leptonic boson decays for further suppression
- Large H → bb BR

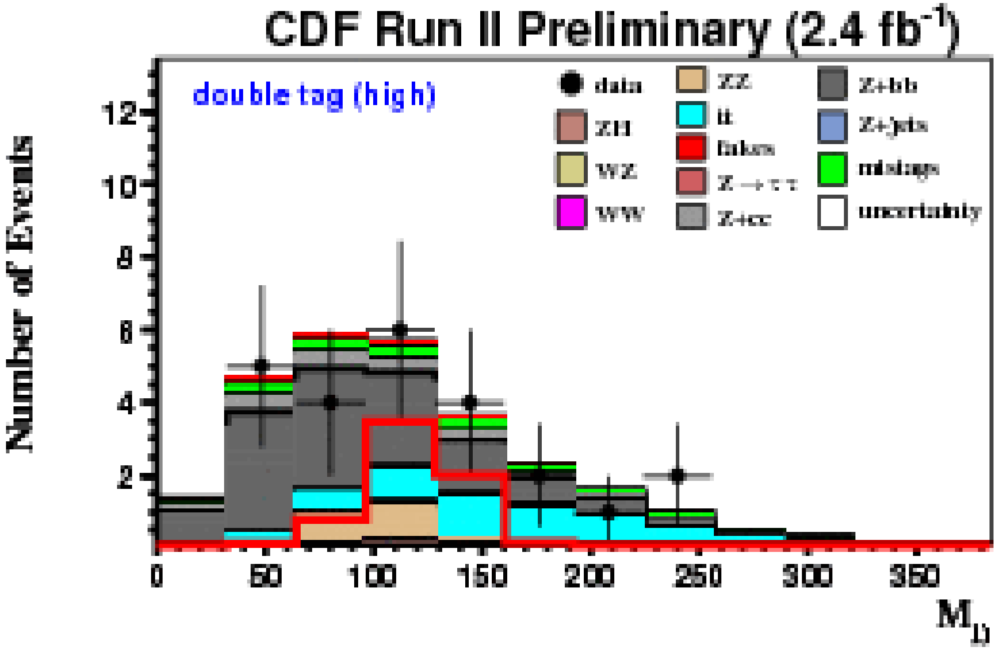
WH → lνbb analysis

- Independent channels for combinations:
  - e+jets, μ+jets
  - 2, 3 jets
  - 1, 2 b-tags (NN-based)
- Main background: W+ b-jets, tt
- Dijet mass ➔ multivariate discriminants

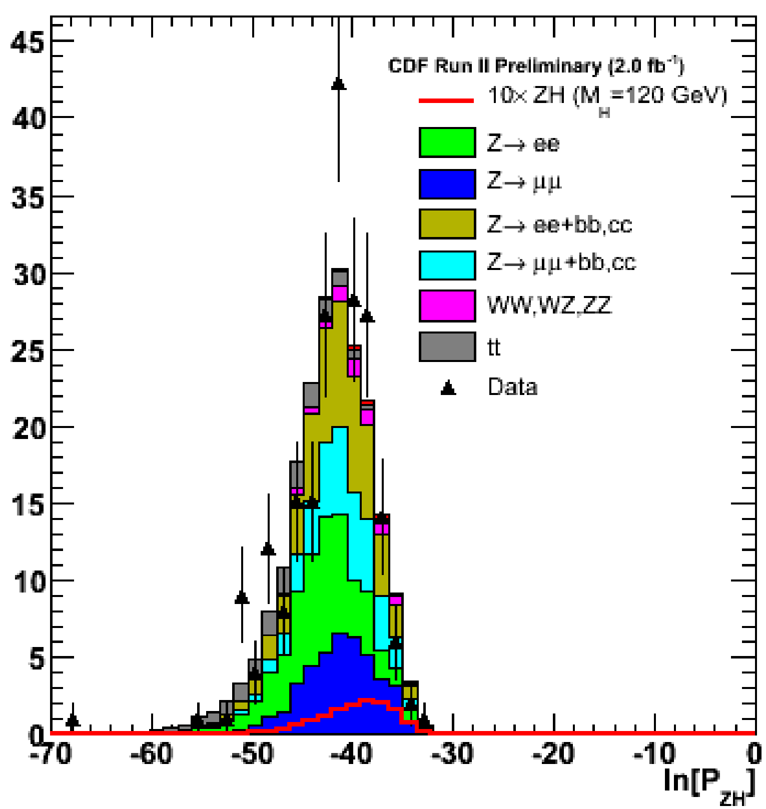


ZH →llbb (m_H ≤130 GeV)

- 2-dimensional neural network:
- 13 input variables separate *ZH* from *tt* and *Z*+jets

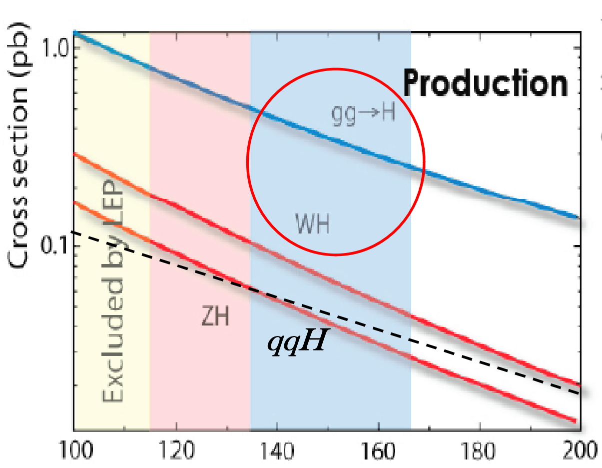


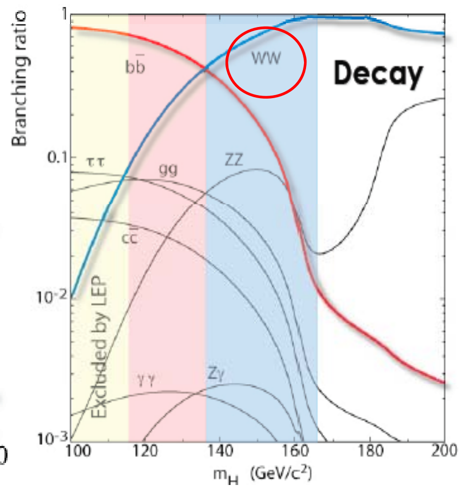
- Matrix element probability:
- Less data and lepton coverage
- Better sensitivity for overlap sample

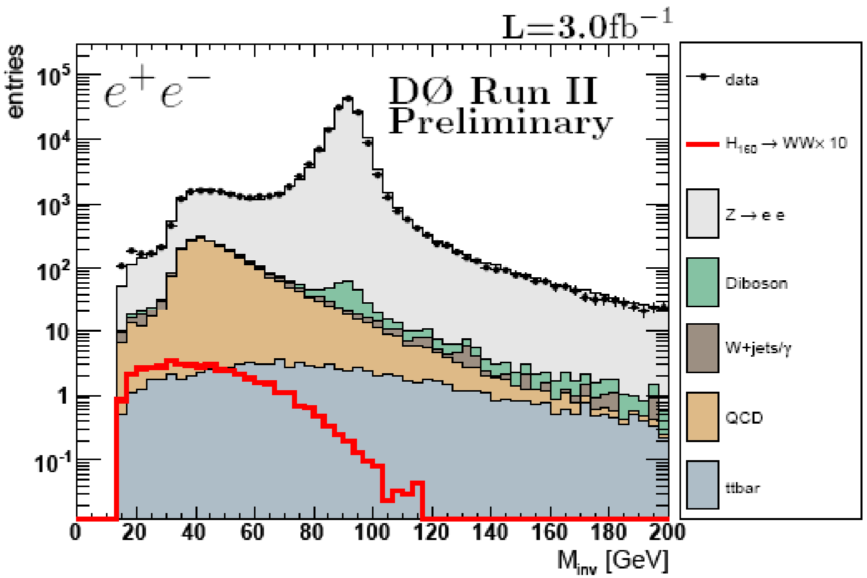


Also, analyses optimized for WH + ZH

Higgs Searches ($m_H \geq 130$ GeV)



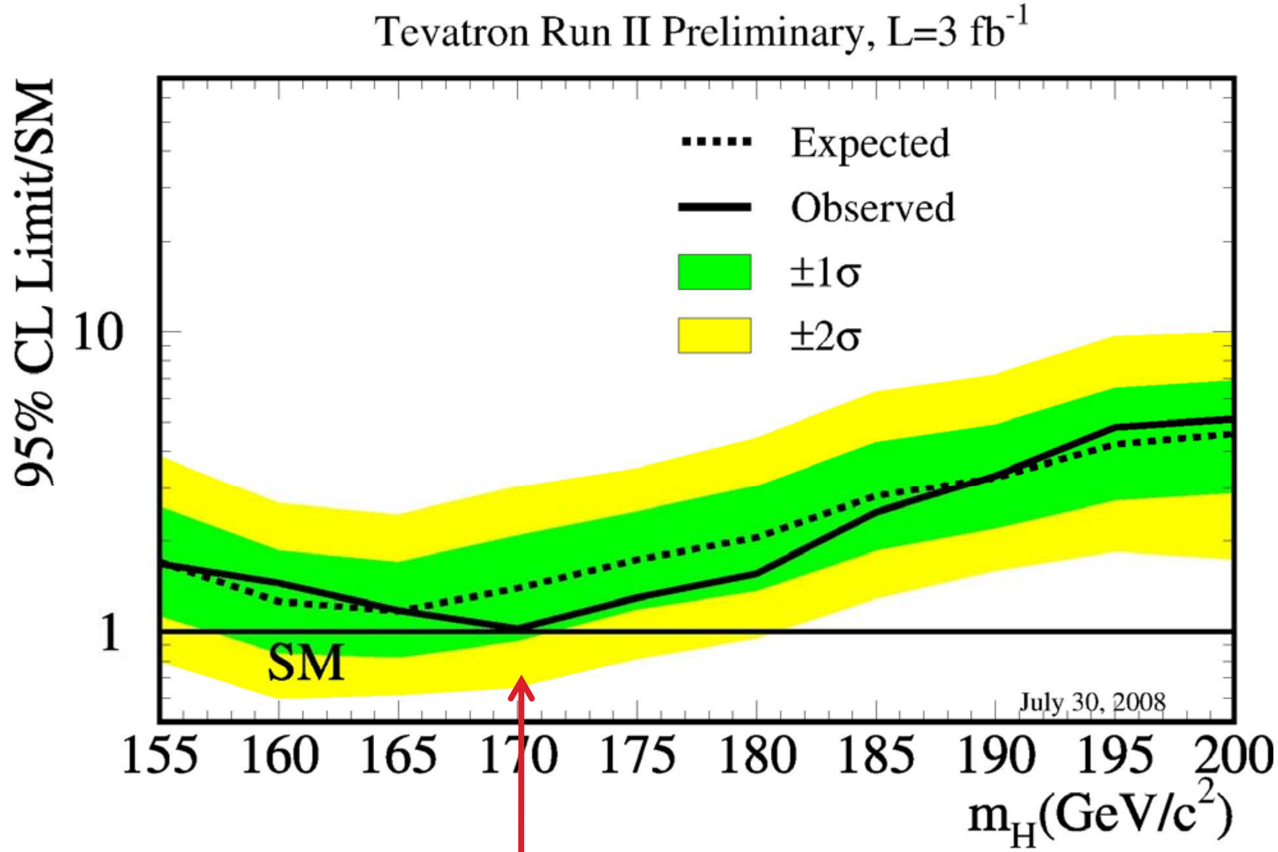




- H→ WW most sensitive at high mass
  - W→lν low background
  - Main background
    - mH~160: WW
    - mH~130: W+jets
  - More modes
    - WH + ZH + qqH →qqWW
- Also at high mass
  - WH→WWW→lνlνlν
- use neural nets, matrix element techniques

Higgs exclusion at the Tevatron

- CDF and D0 combine results of all searches for Standard Model Higgs



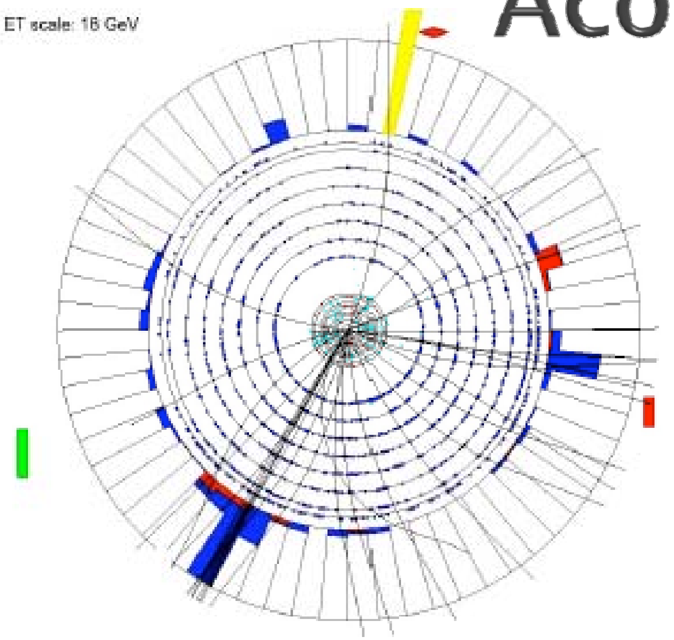
Beginning to reach SM sensitivity!

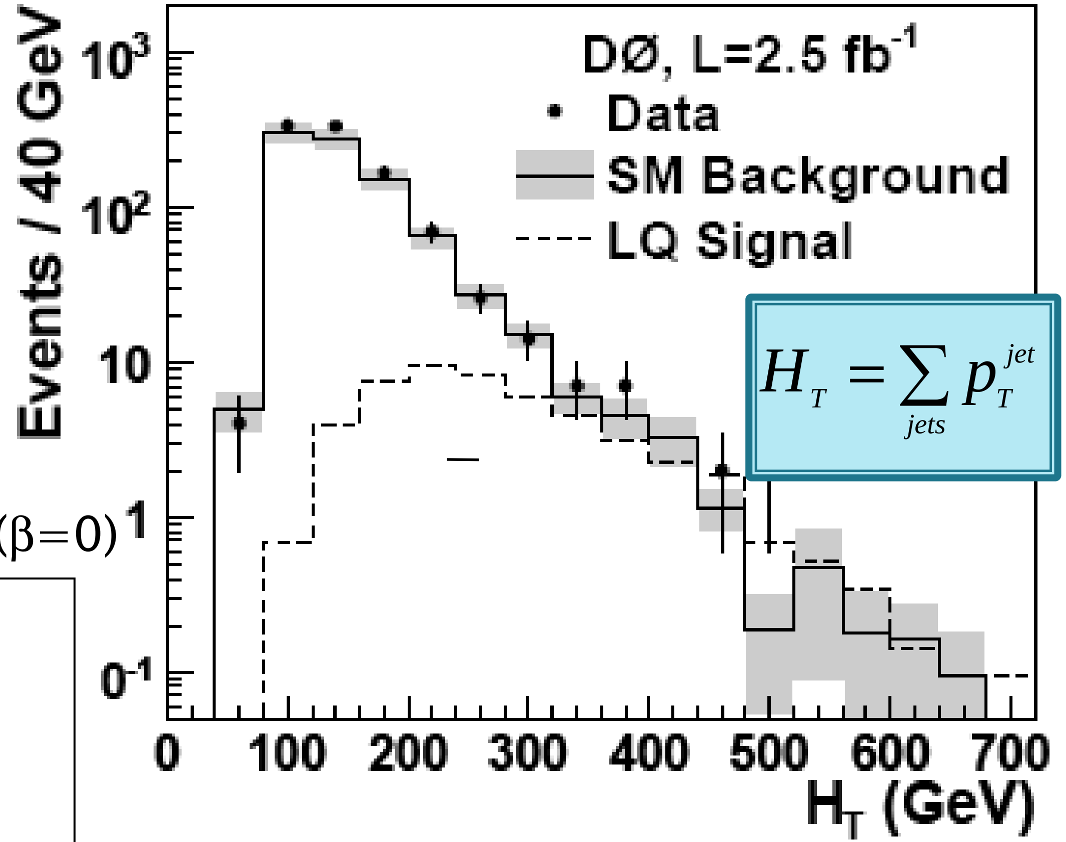
Searches for New Phenomena

- Several approaches for broad search program
  - Indirect -- use Standard Model analyses (eg, top cross section) to constrain
  - Direct search, re-using analysis techniques from Standard Model Analyses (eg, resonance in t-tbar mass)
  - By topology (eg, acoplanar jets), then apply to model
  - Unusual objects that would not normally appear in our detectors (eg, stable heavy particles)
  - Following a model (eg, Supersymmetry)
  - Model-independent – search by topology
    - Global search analysis – attempt to look "everywhere"

Tevatron searches cover a range of possibilities!

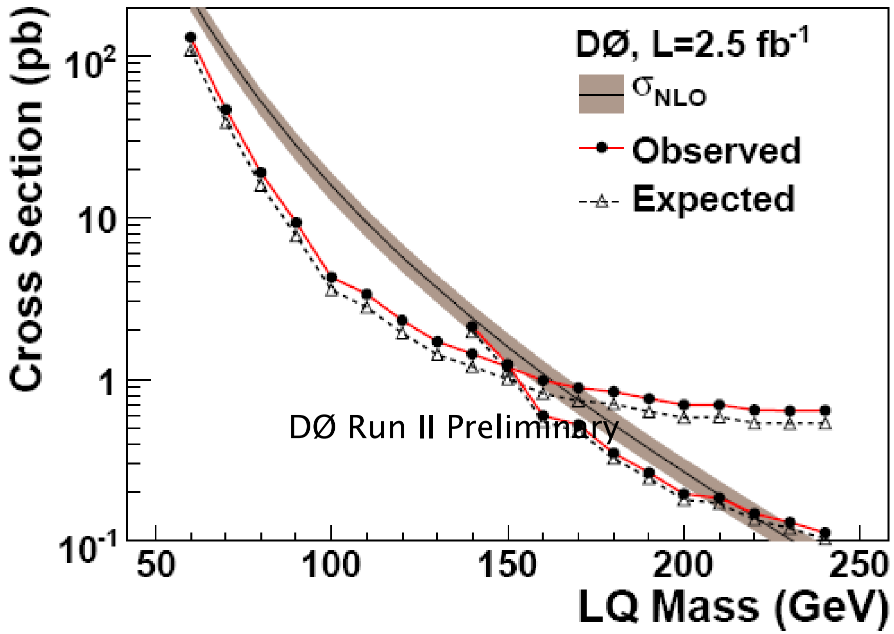
Acoplanar Jets + Missing E_T





$$H_T = \sum_{jets} p_T^{jet}$$

1st Generation Leptoquarks (β=0)



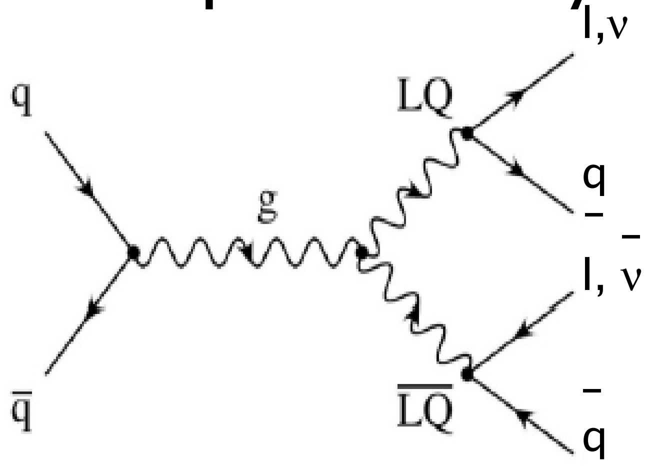
Apply to Leptoquark model

$$LQLQ \rightarrow \nu q \overline{\nu q}$$

$1-\beta = B(LQ \rightarrow \nu q)$

Scalar Leptoquarks (3rd Generation)

- Predicted by a variety of New Physics models (GUTs, Compositeness, etc).
- Couple directly to a quark and a lepton:

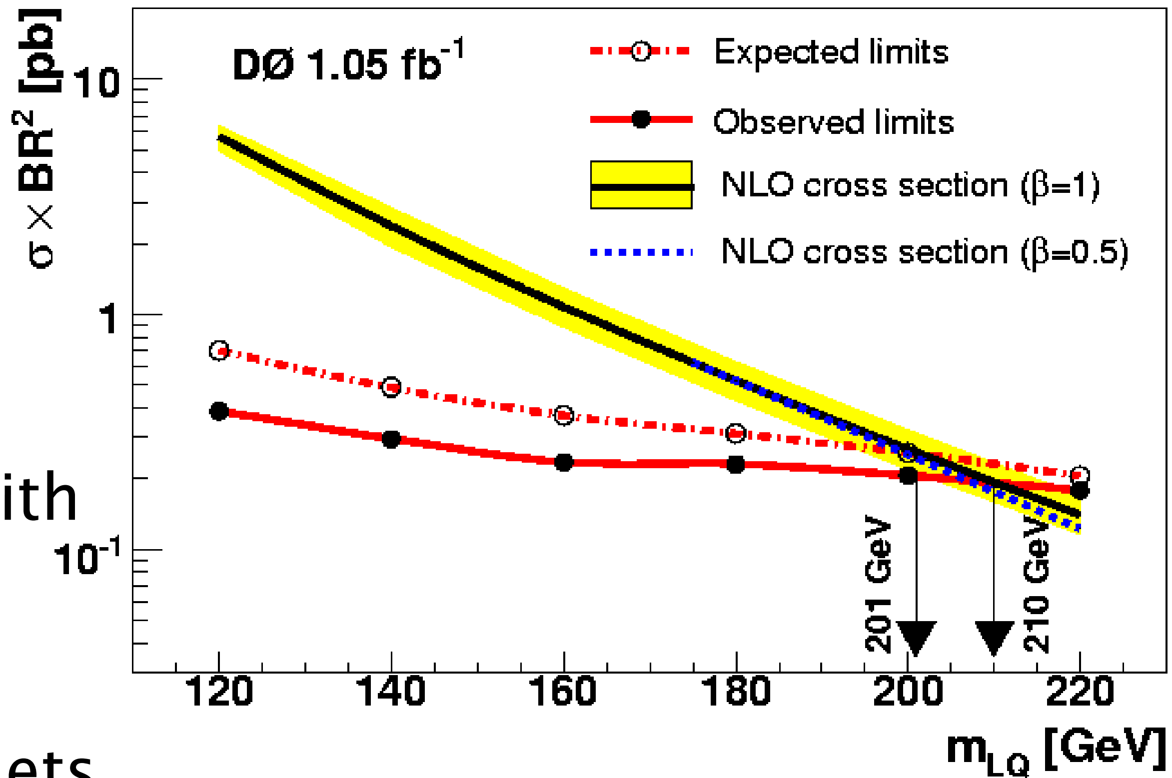


$$LQ_3 \overline{LQ}_3 \rightarrow \tau^- b \tau^+ \bar{b}$$

$$\tau_1 \rightarrow \mu \bar{\nu} \nu, \tau_2 \rightarrow \nu + hadrons$$

For 3rd gen scalar LQ with charge 2/3 or 4/3: **LQ→τ+b**

β ~ B(LQ→l+q)



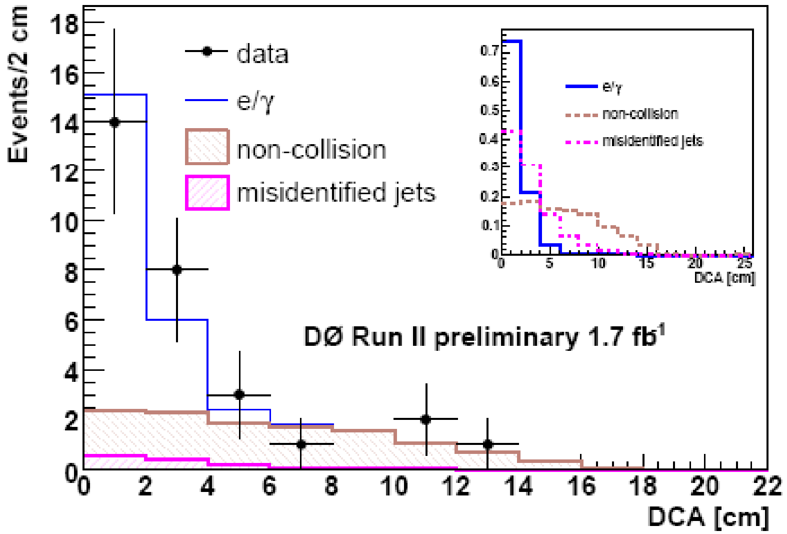
- Look for μ, τ ,b-tag jets

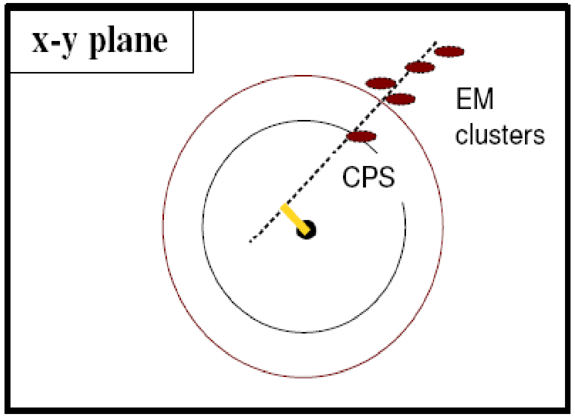
Extra Dimensions

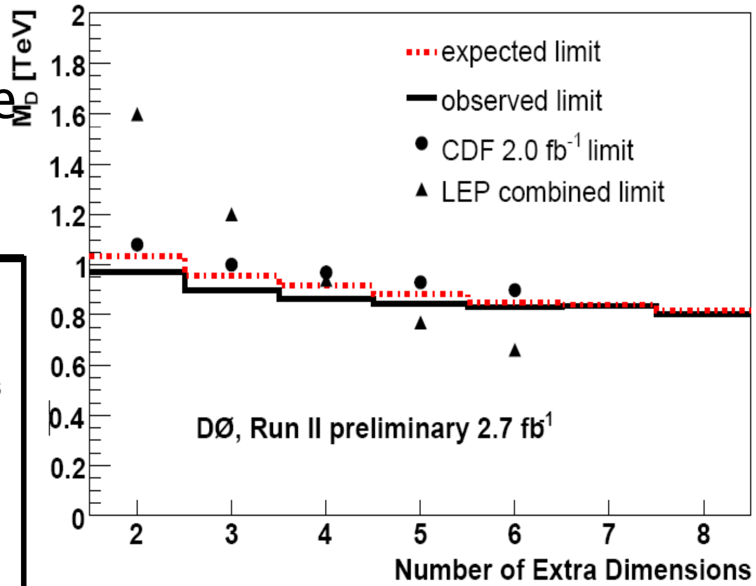
- May be more than four dimensions of space-time
  - "extra" dimensions confined
- Large Extra Dimension models predict ED ~10μm
  - eg, ADD models
  - Experimentally, continuous energy spectrum – recoil from Kaluza-Klein towers (don't interact)
- Small Extra Dimension models
  - eg, Randall-Sundrum
  - Predict towers of KK modes → mass resonances with spacing O(TeV)
- Tevatron can search data for various scenarios (few examples today)

Large Extra-Dimensions: mono-photon

- $qq \rightarrow \gamma + G_{KK}$ ➔ monophoton signal
- Require energetic photon, missing ET
- Backgrounds:
  - $Z(\rightarrow \nu\nu)\gamma$,..
  - Non-collision (cosmics, beam-halo)
- Exploit fine granularity of the D0 detector to do “photon pointing”.



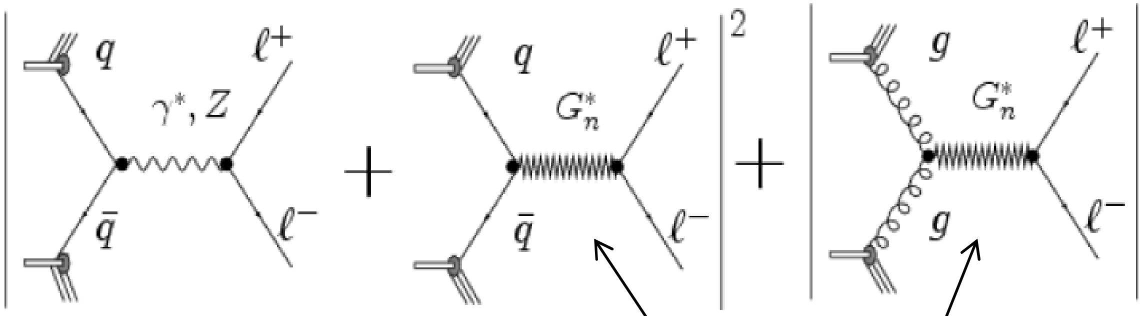




Improve upon LEP limits for $n_d > 4$

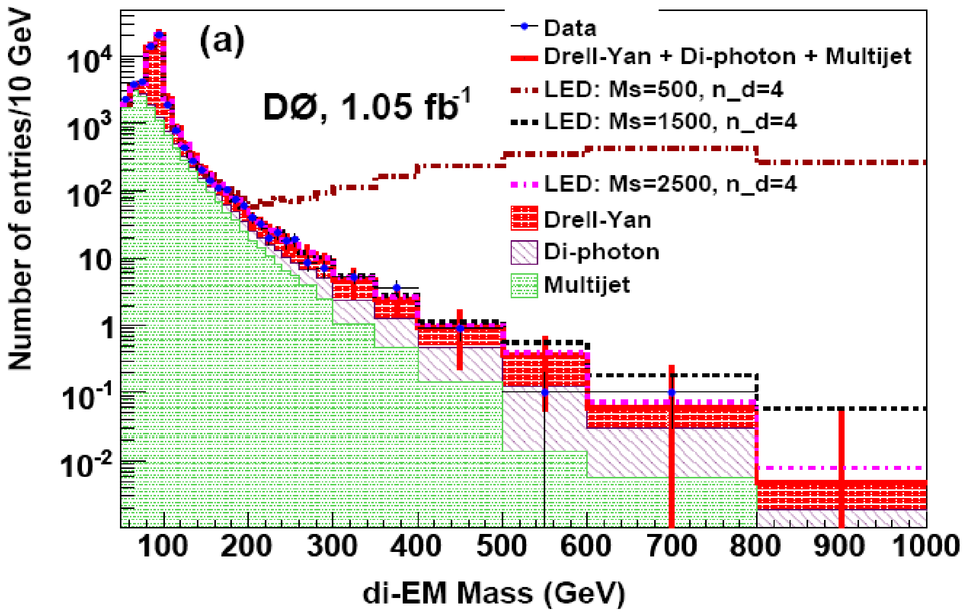
Large Extra-Dimensions: ee, γγ

- Gravity diluted in large compactified extra spatia dimensions.
- Tower of Kaluza-Klein gravitons G_{KK} (massive, stable, non-interacting).

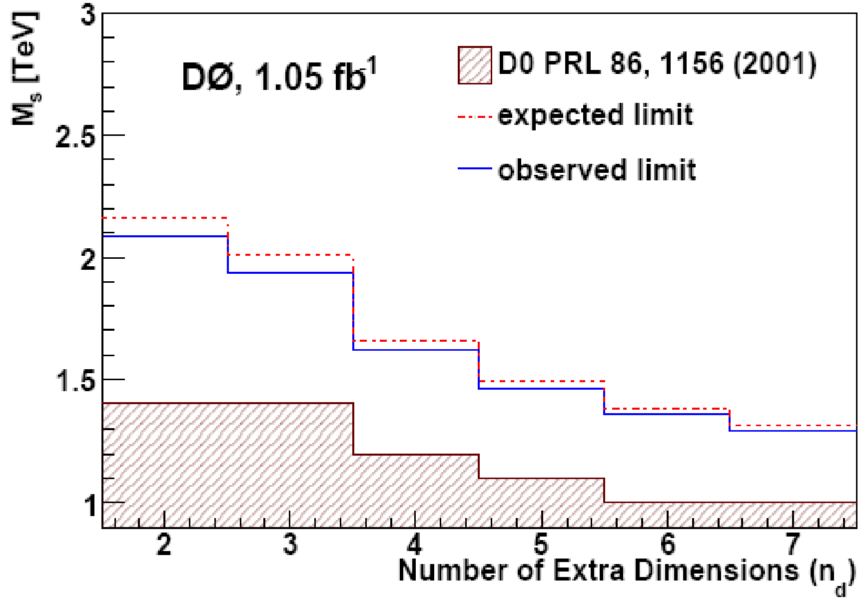


- Di-EM (ee,γγ) final state signature.

DØ Run II Preliminary



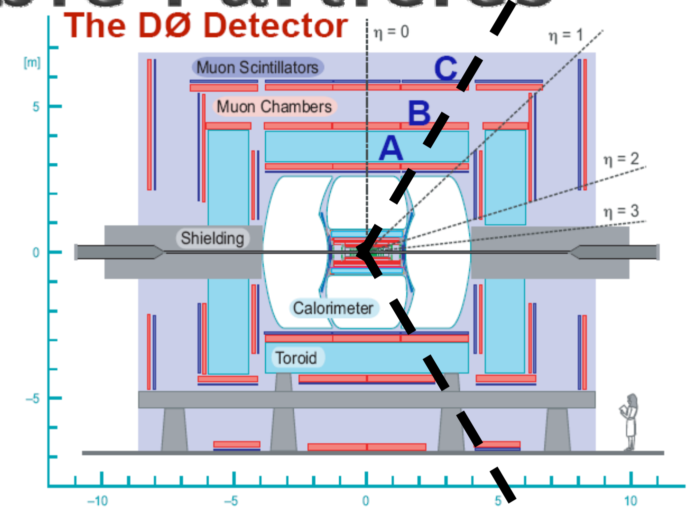
DØ Run II Preliminary

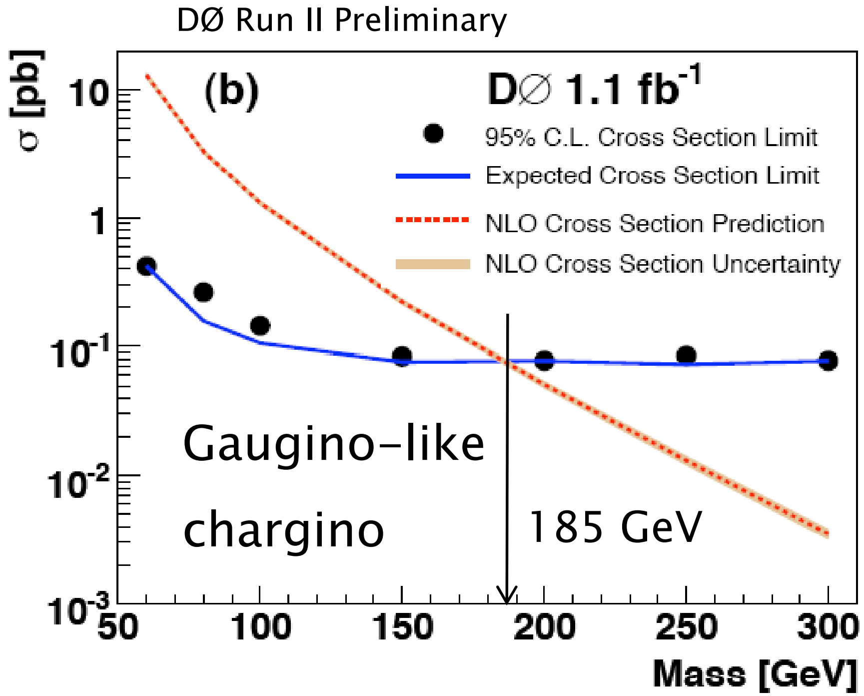


Charged Massive Stable Particles

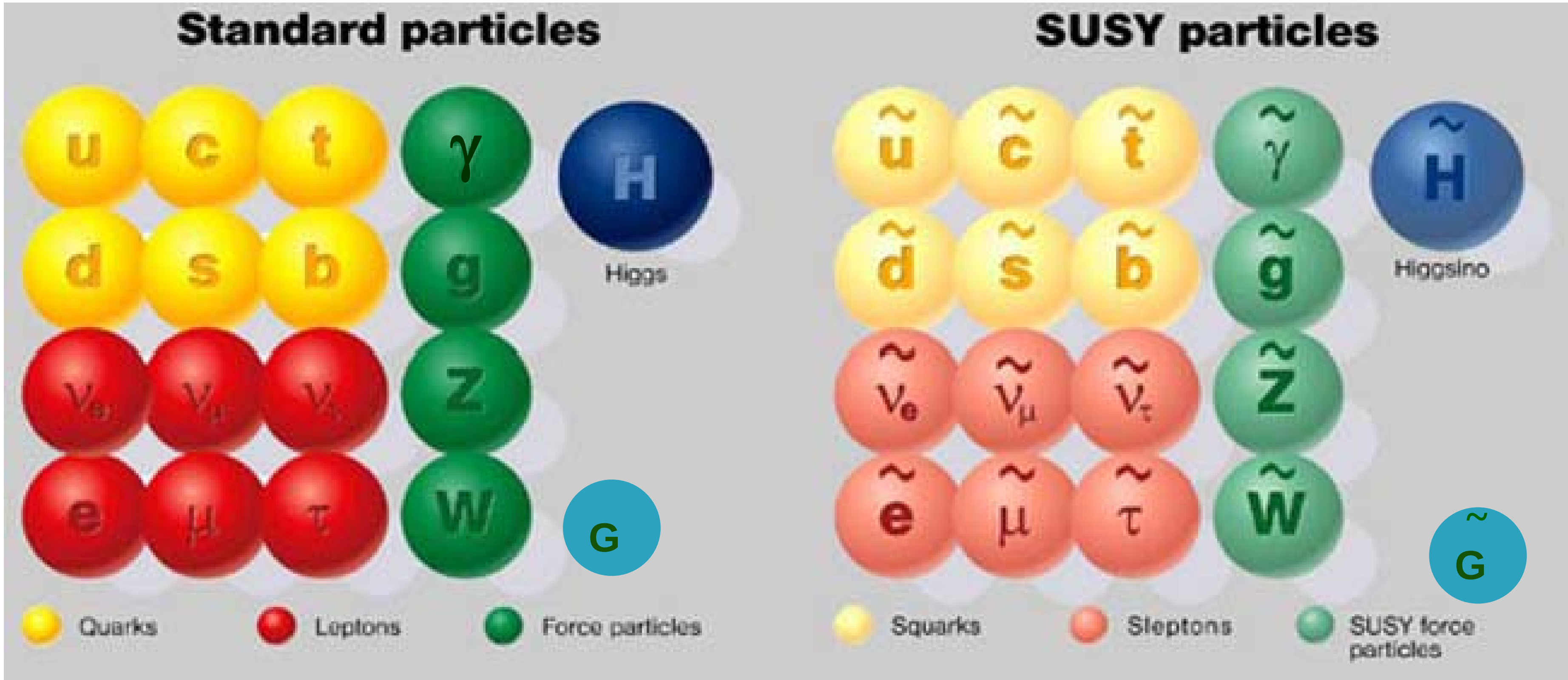
- Charged: leaves track in detector
- Massive: long time-of-flight, heavily ionizing
- "Stable" = long-lived ➔ signal in muon system

- Search for dimuon-like signature with long time-of-flight. Exploit timing information from muon scintillator system





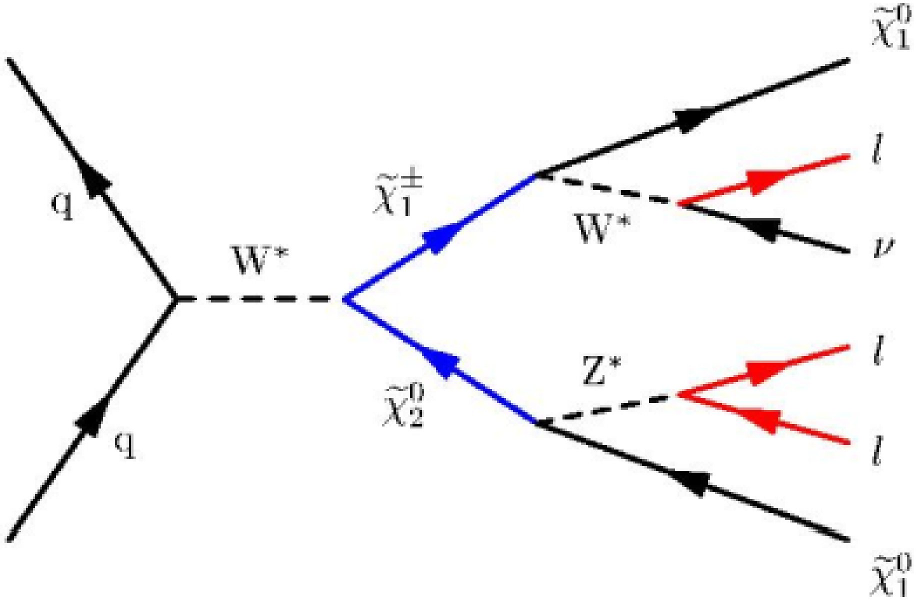
Supersymmetric extension of the Standard Model

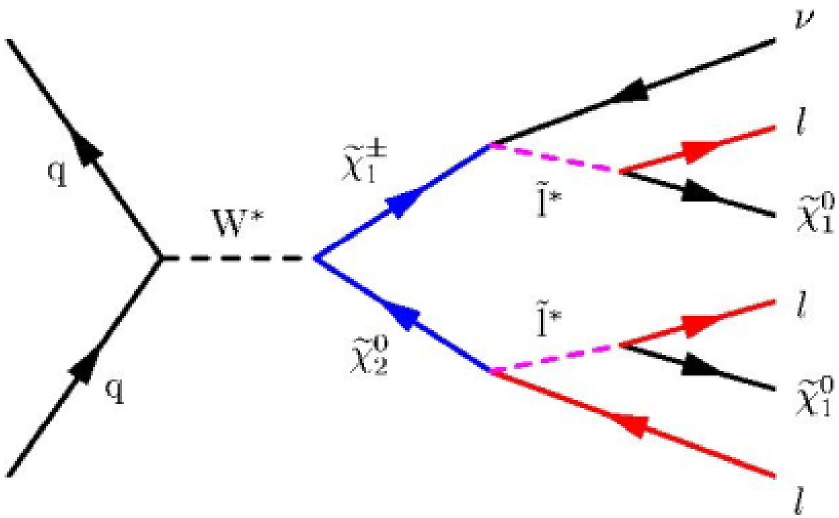


- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - Sfermions (squarks, selectron, smuon ...): spin 0
    - gauginos (chargino, neutralino, gluino,...): spin 1/2
- No SUSY particles found yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in “minimal” models!

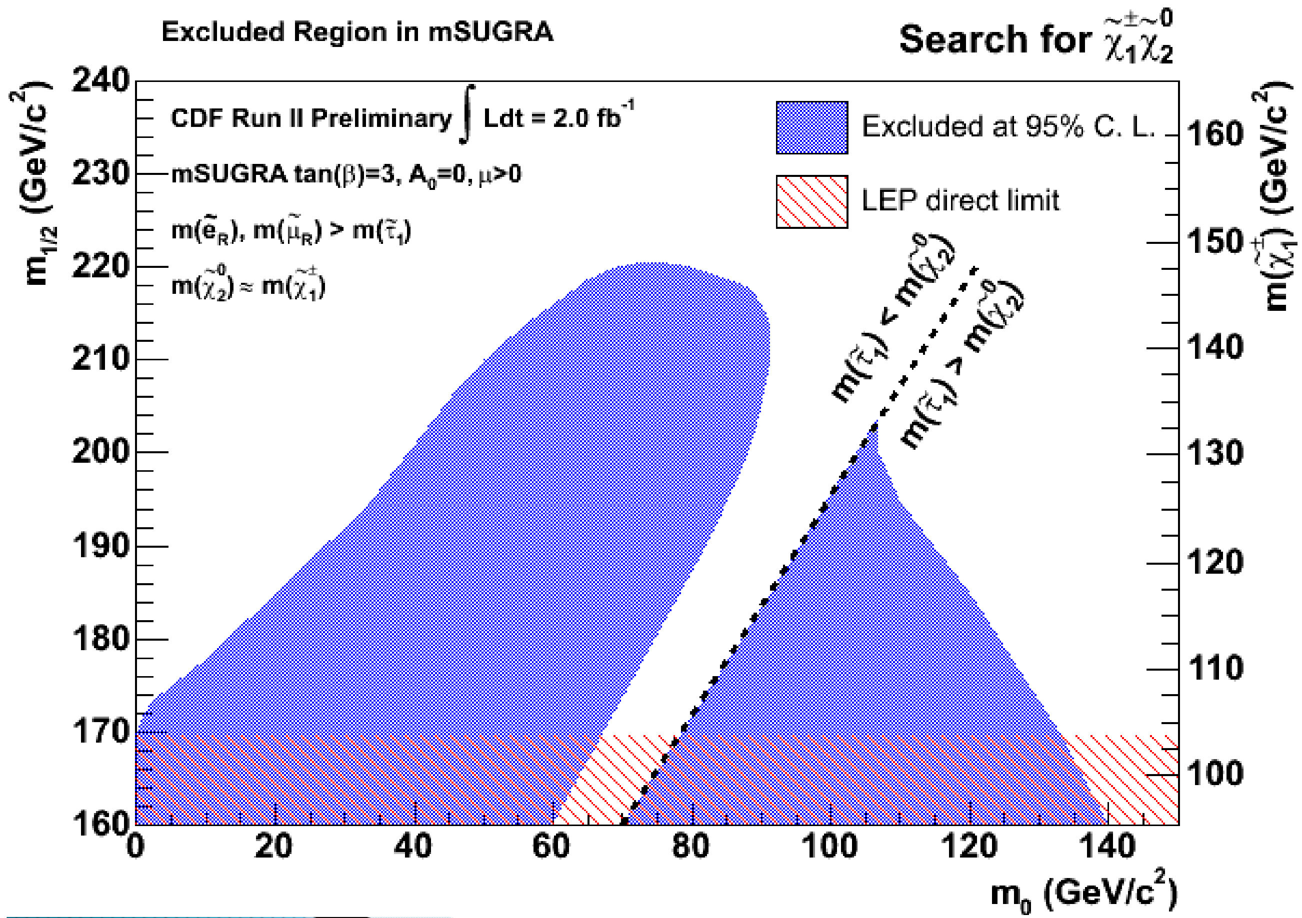
Search for Chargino-Neutralino Production

- Trileptons from chargino-neutralino: flagship analysis for discovery of SUSY at the Tevatron
- Clear signature – 3 isolated leptons, missing energy





CDF and D0 Trilepton Searches

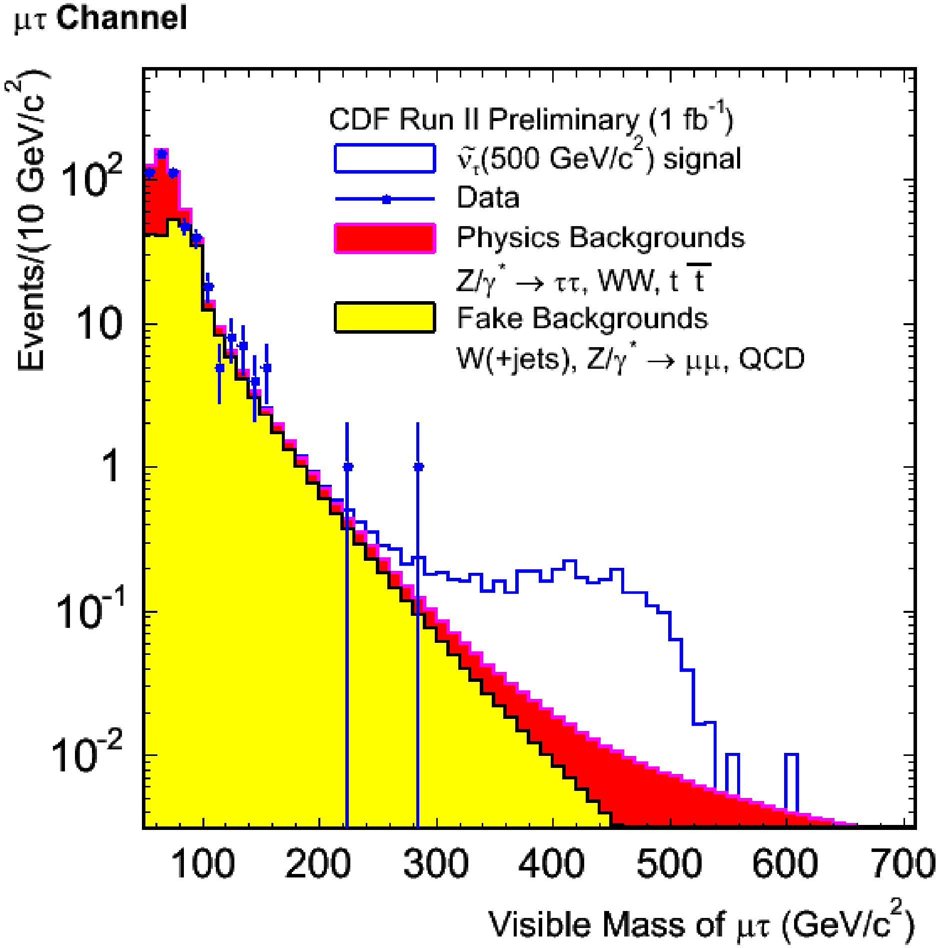


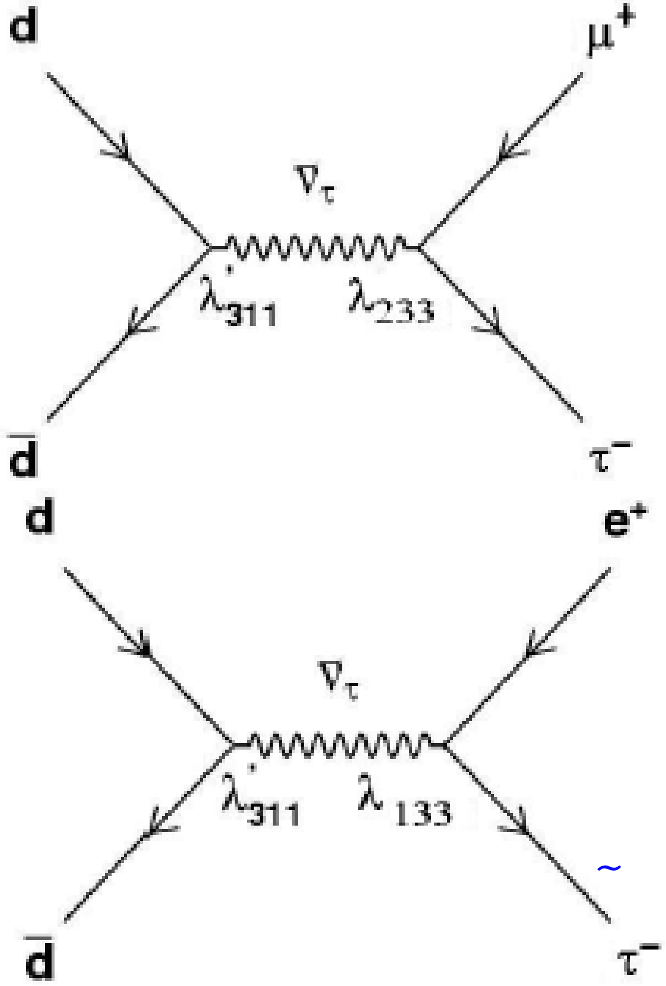
- CDF and D0 have a suite of searches for trileptons – combinations of electrons, muons, tracks (for 3rd lepton)
- Exclusion in terms of SUSY model parameters

Sneutrino Search

Resonant production if *R*–parity violated

$e\mu$, $e\tau$, $\mu\tau$ final states

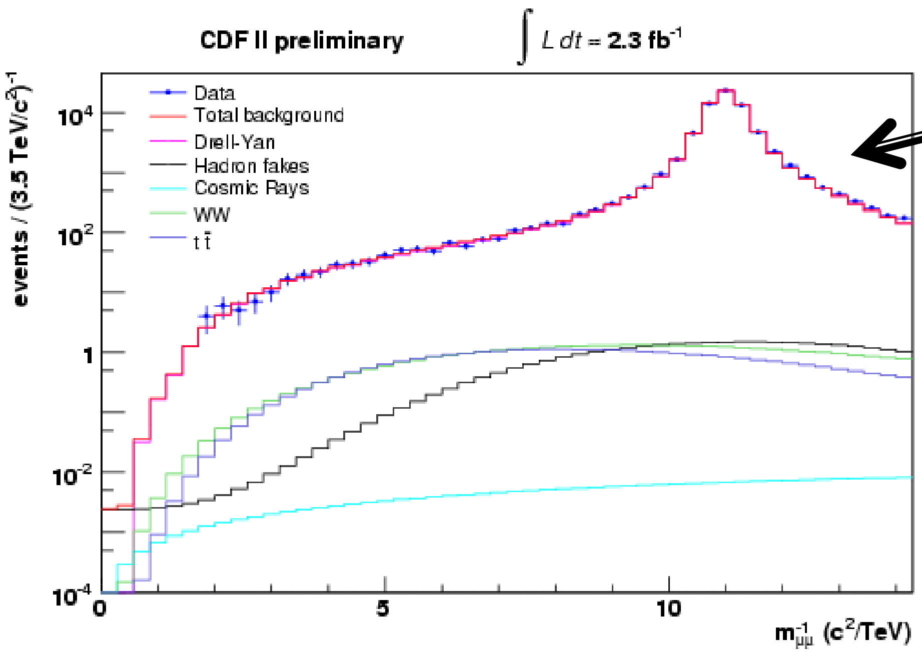




$m\tilde{\nu}$ >
586 GeV ($e\mu$)
487 GeV ($e\tau$)
484 GeV ($\mu\tau$)
for couplings 0.05–0.1

Resonance Decays to Dileptons

- Many models predict neutral resonances, Z', at electroweak scale
  - Supersymmetry, extra dimensions
- New search in dimuon channel
  - Result in dielectrons – excess at M=240 GeV (0.6% probability to be a background fluctuation)
    - Dimuon search has similar sensitivity at this mass



Use 1/m spectrum -- resolution constant vs 1/m (c^2/TeV)

Most significant excess at 103 GeV
6.6% probability to be due to background

Set mass limits on *Z'* and gravitons

Limits on Z', gravitons from dimuon resonance search

CDF II preliminary $L = 2.3\ fb^{-1}$

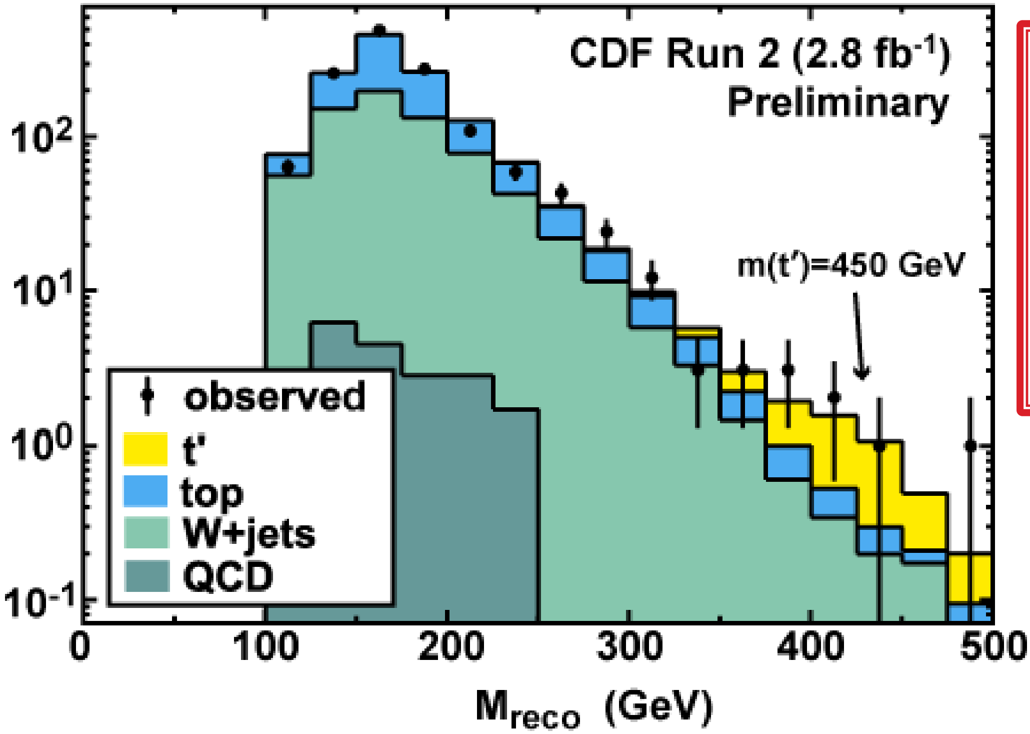
Model	Mass Limits, 95% CL (GeV/c^2)
Z' (SM)	1030
Z' (η)	975
Z' (χ)	892
Z' (ψ)	878
Z' (N)	861
Z' (I)	789
Z' (sq)	754

CDF II preliminary $L = 2.3\ fb^{-1}$

Graviton k/M_{Pl}	Mass Limit, 95% CL (GeV/c^2)
0.1	921
0.07	824
0.05	746
0.035	651
0.025	493
0.015	409
0.01	293

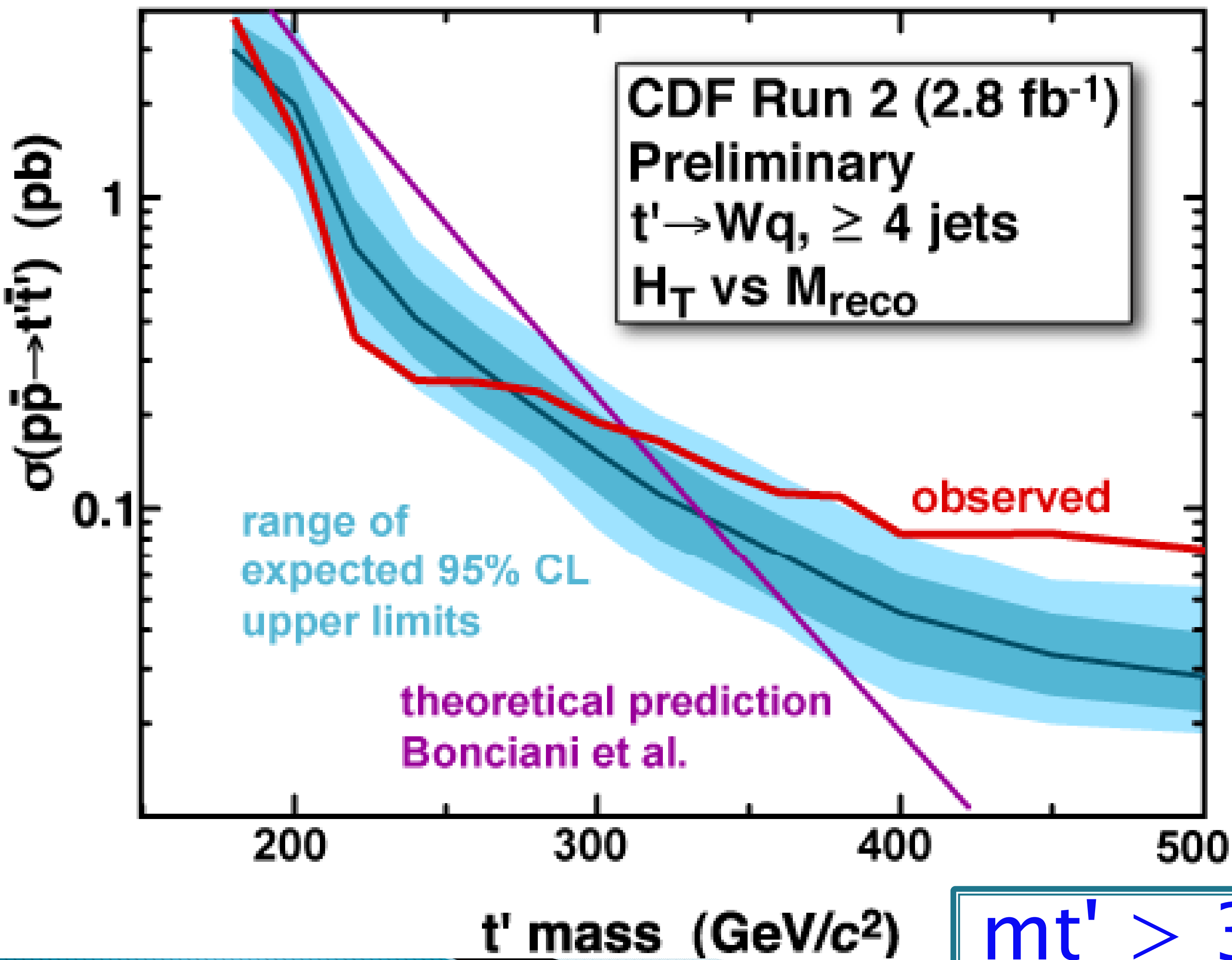
Fourth Generation Top Quark

- Search for fourth generation top, t' ,in lepton + jets final state, using tools from top analysis
- Reconstruct hypothesized t' mass and search in plane of mass vs total transverse energy



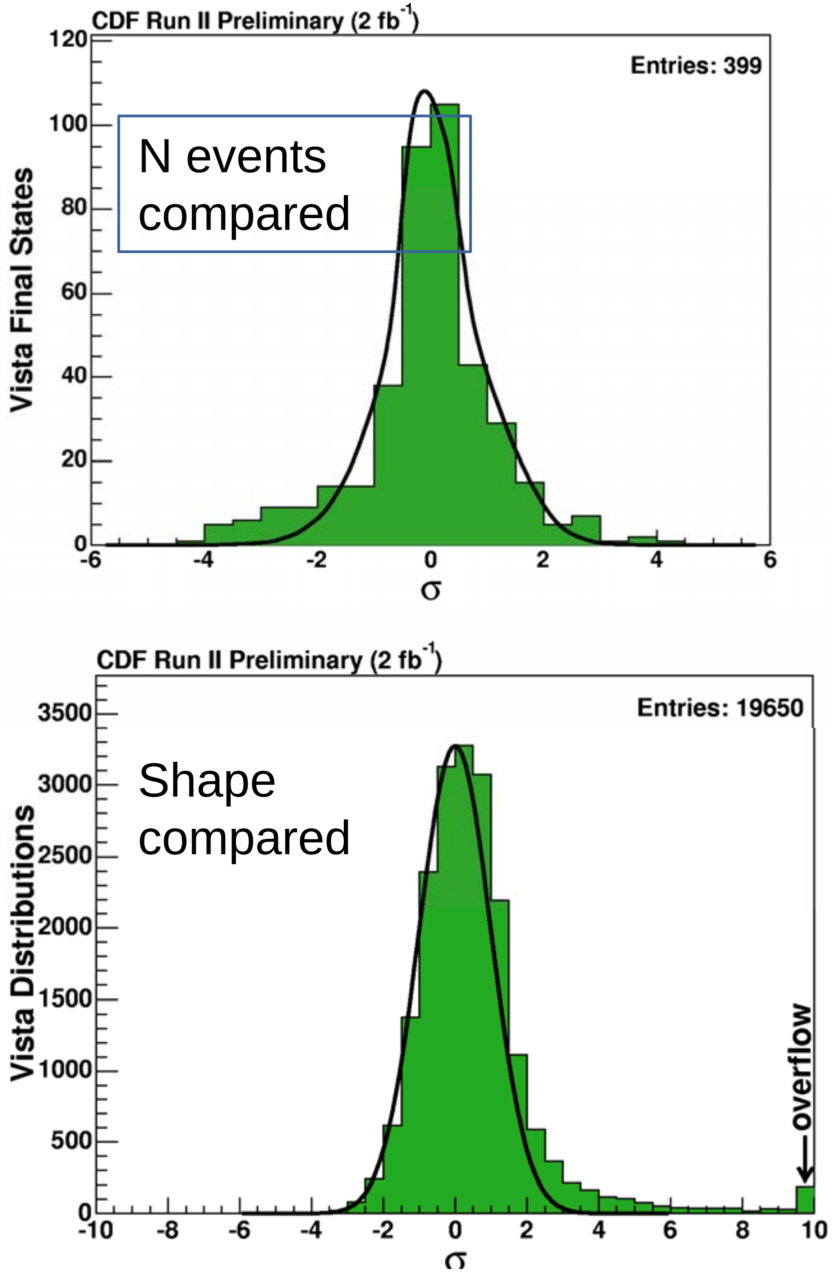
1% consistency between data and SM at M(t') = 450

Set limits on t' production



mt' > 311 GeV

Global Search at CDF -- Vista

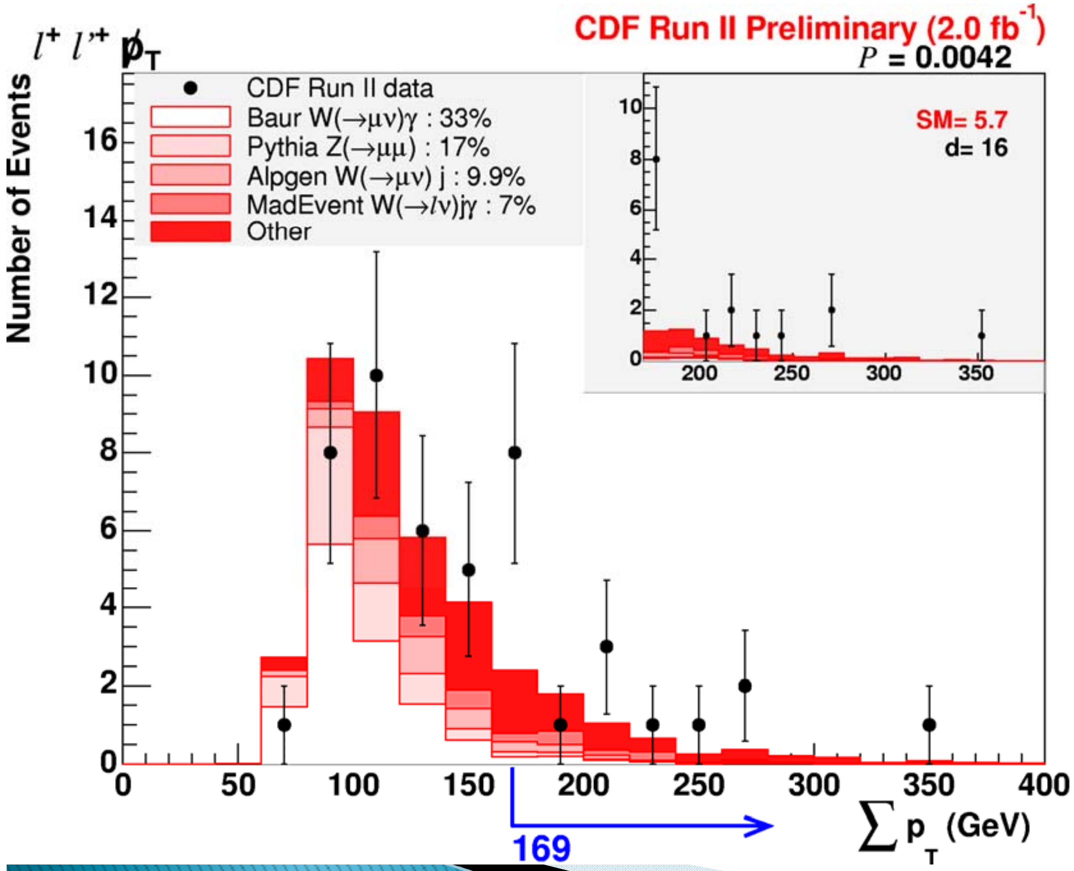


- Vista – search bulk features of high-pT data, model-independent
- Objects: e, μ, τ, γ, jet, b-jet, missing energy
- Combinations of objects -- exclusive final states
- Global comparison to develop correction model for background (take into account known deficiencies in simulation, NLO/LO calc, etc)
- Compare data to background model in 19650 kinematic distributions, 399 final states
  - Account for trials factor

Global Search at CDF -- Sleuth

Interesting final state found by Sleuth

Like-sign dilepton events



- Sleuth – "quasi-model-independent" search of high ΣpT tails
  - Look for the unexpected!
- Find most interesting deviation from prediction in ΣpT tail
  - With trials factor
- Look for everything – sacrifice sensitivity to a specific signal for breadth of search
- Probability of observing largest discrepancy (or larger) = 8%

Conclusion

- CDF and D0 are reaching the peak of the Tevatron's physics potential
- Broad programs – many new results and many more to come
  - Precision measurements
  - Observation of rare processes
  - Some interesting excesses in searches

- Many thanks to the organizers!