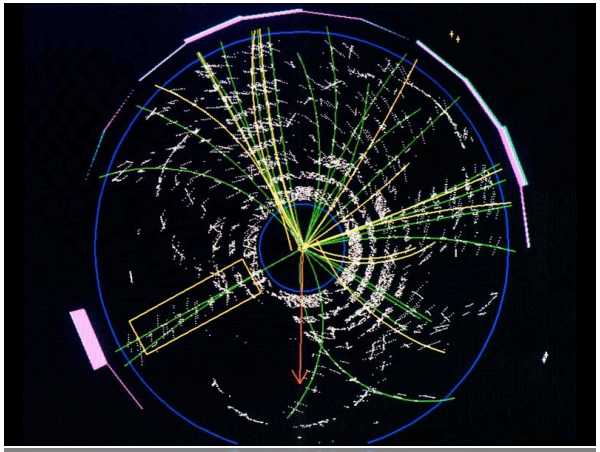
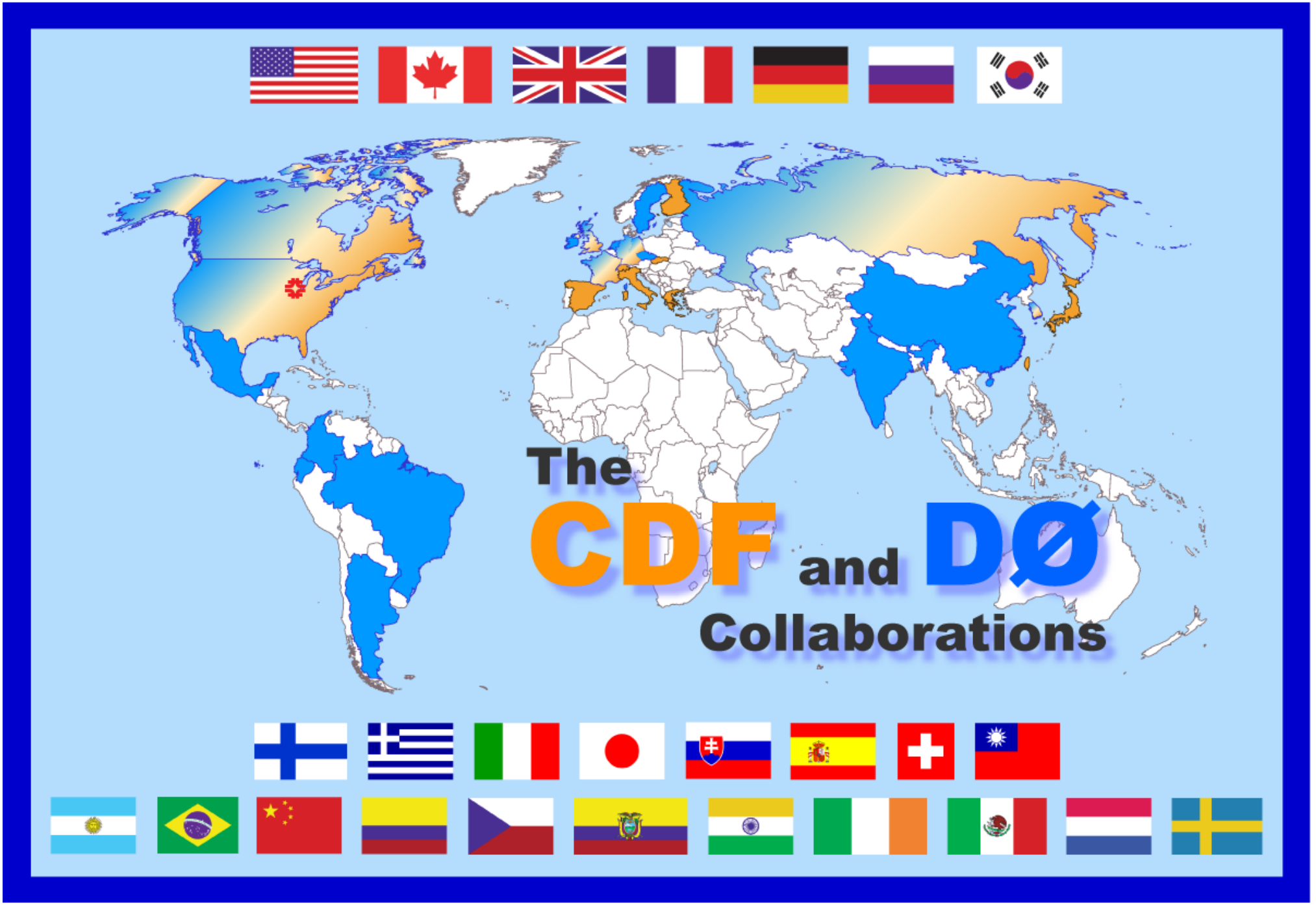
The Tevatron Experiments

Status and Perspectives



Prof. Robin D. Erbacher -- U.C. Davis

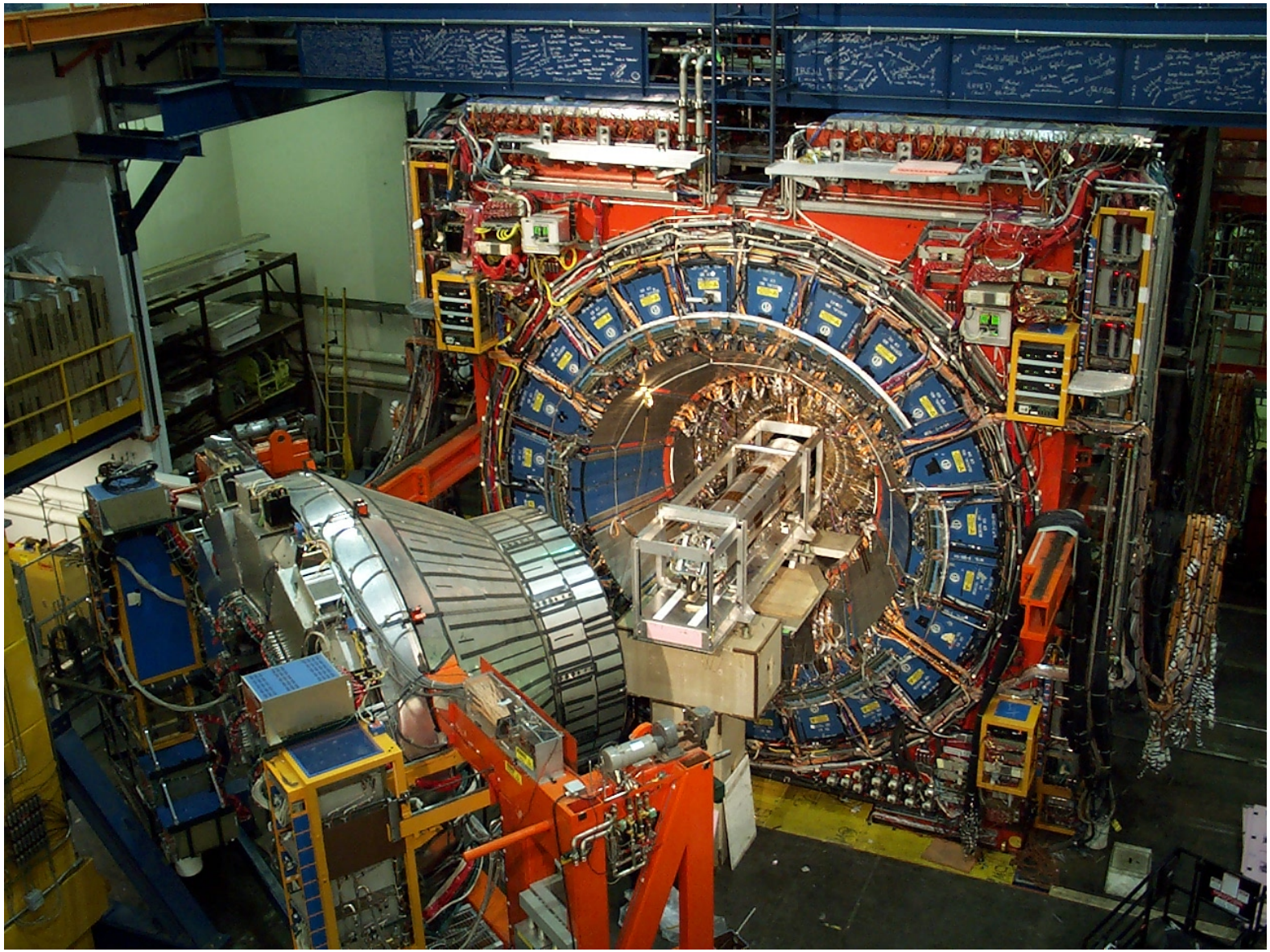
Top Quark 2010 -- Brugge, Belgium -- May 31, 2010


The
CDF and DØ
Collaborations

D0 Detector

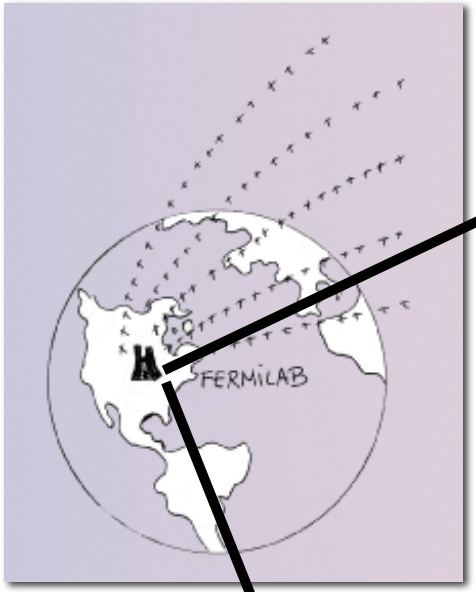
3

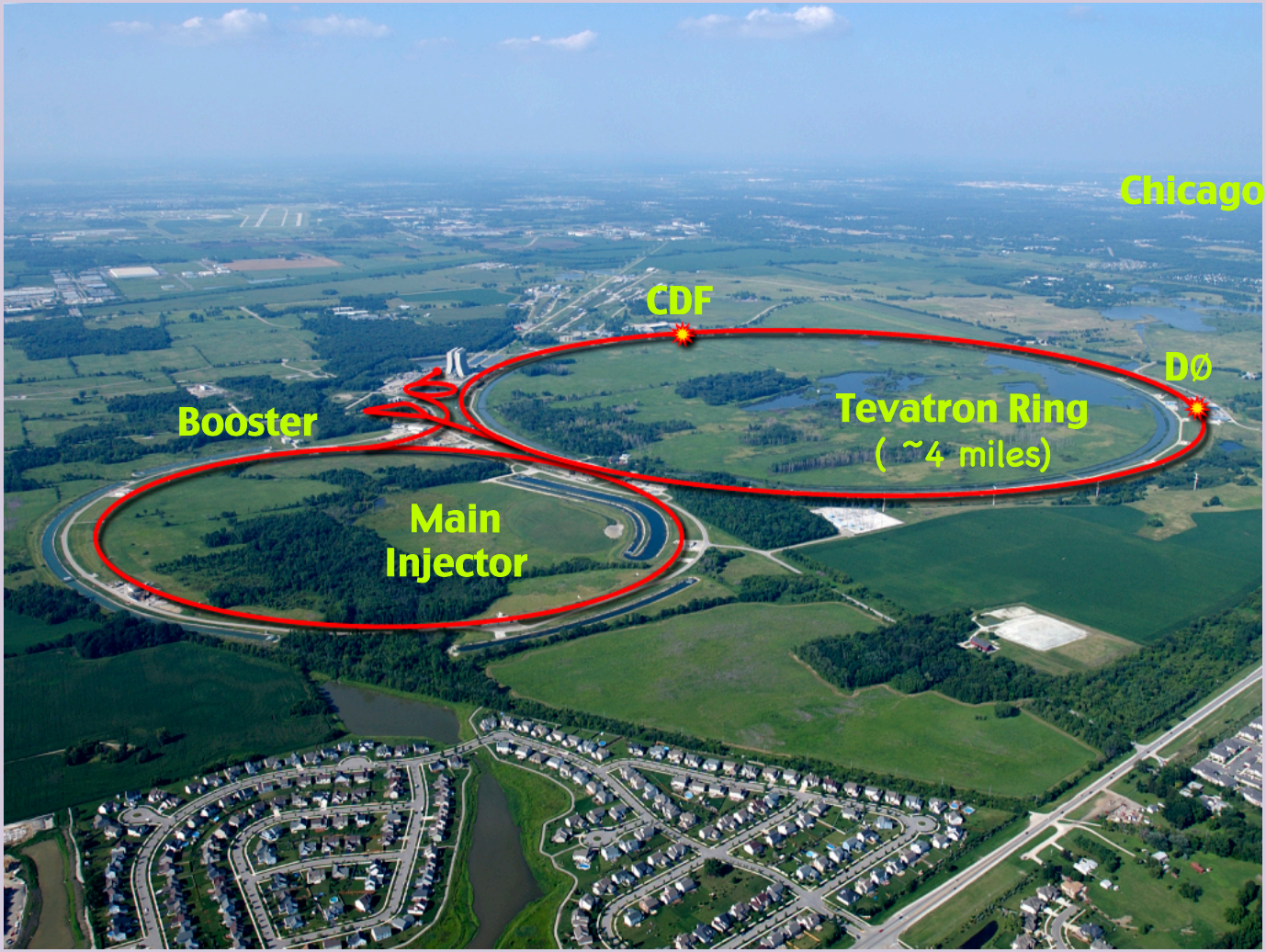
CDF Detector



4

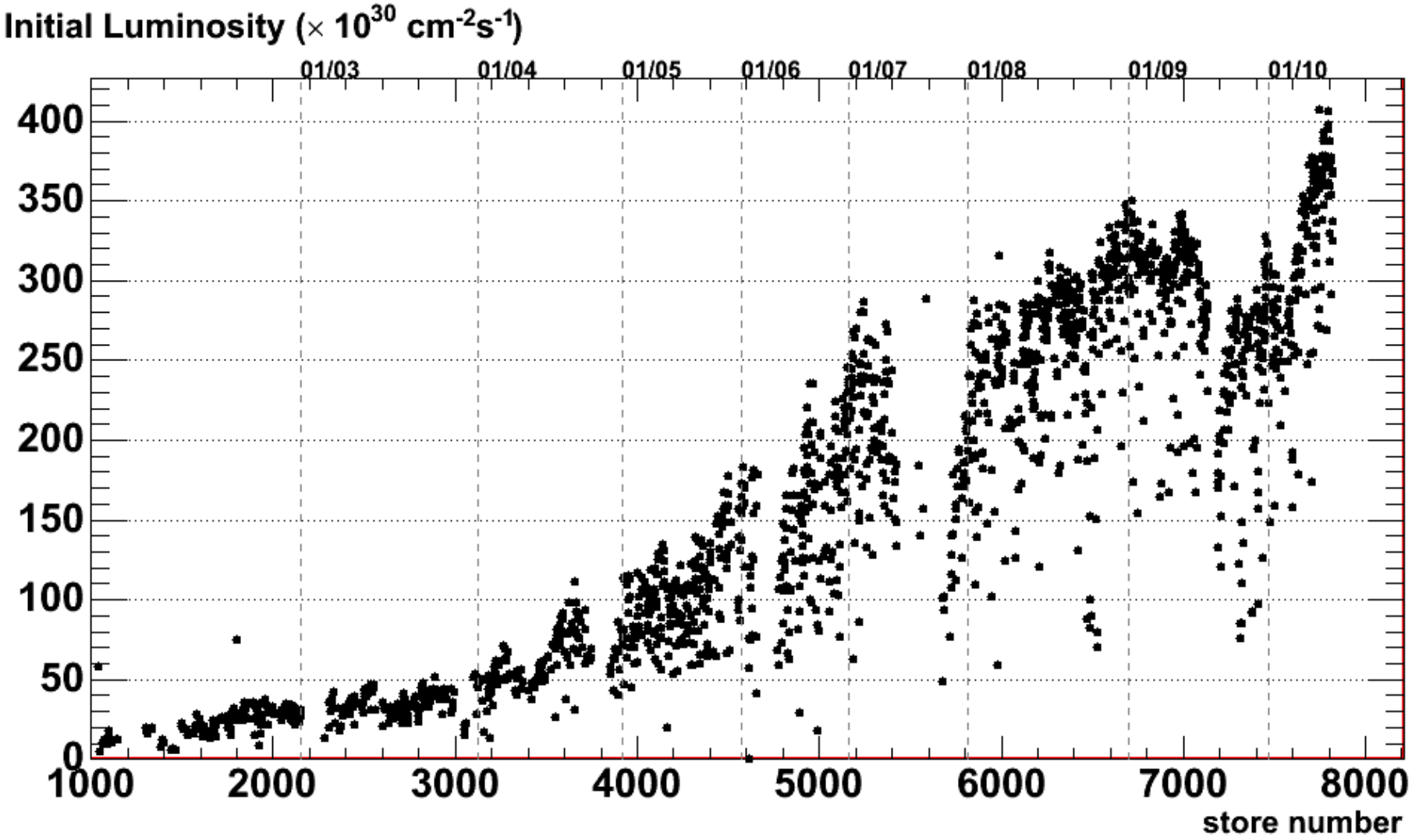
Fermilab's Tevatron





5

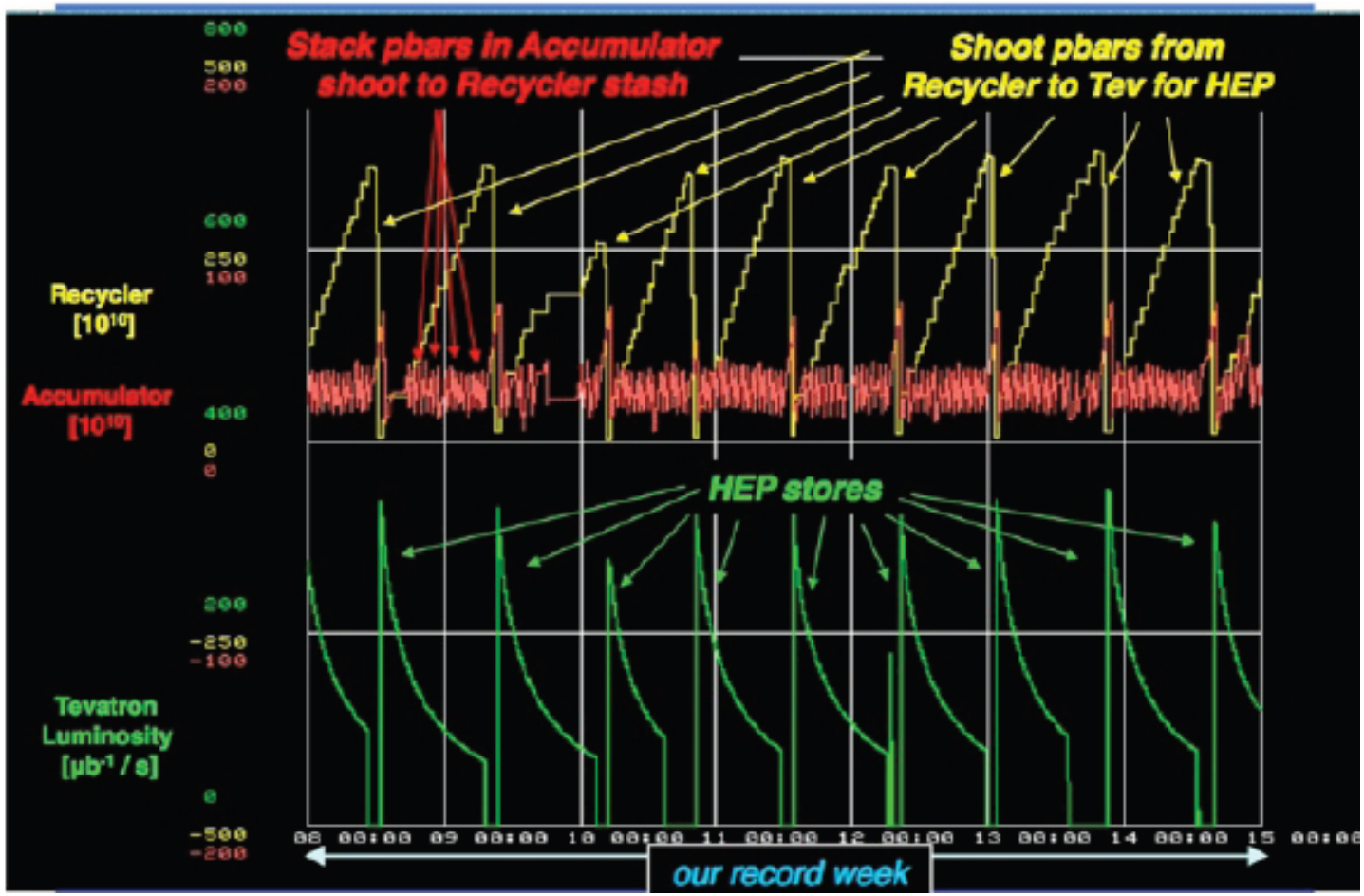
Tevatron


Initial Luminosity (× 10^30 cm^-2 s^-1)
01/03
01/04
01/05
01/06
01/07
01/08
01/09
01/10
400
350
300
250
200
150
100
50
0
1000
2000
3000
4000
5000
6000
7000
8000
store number

6

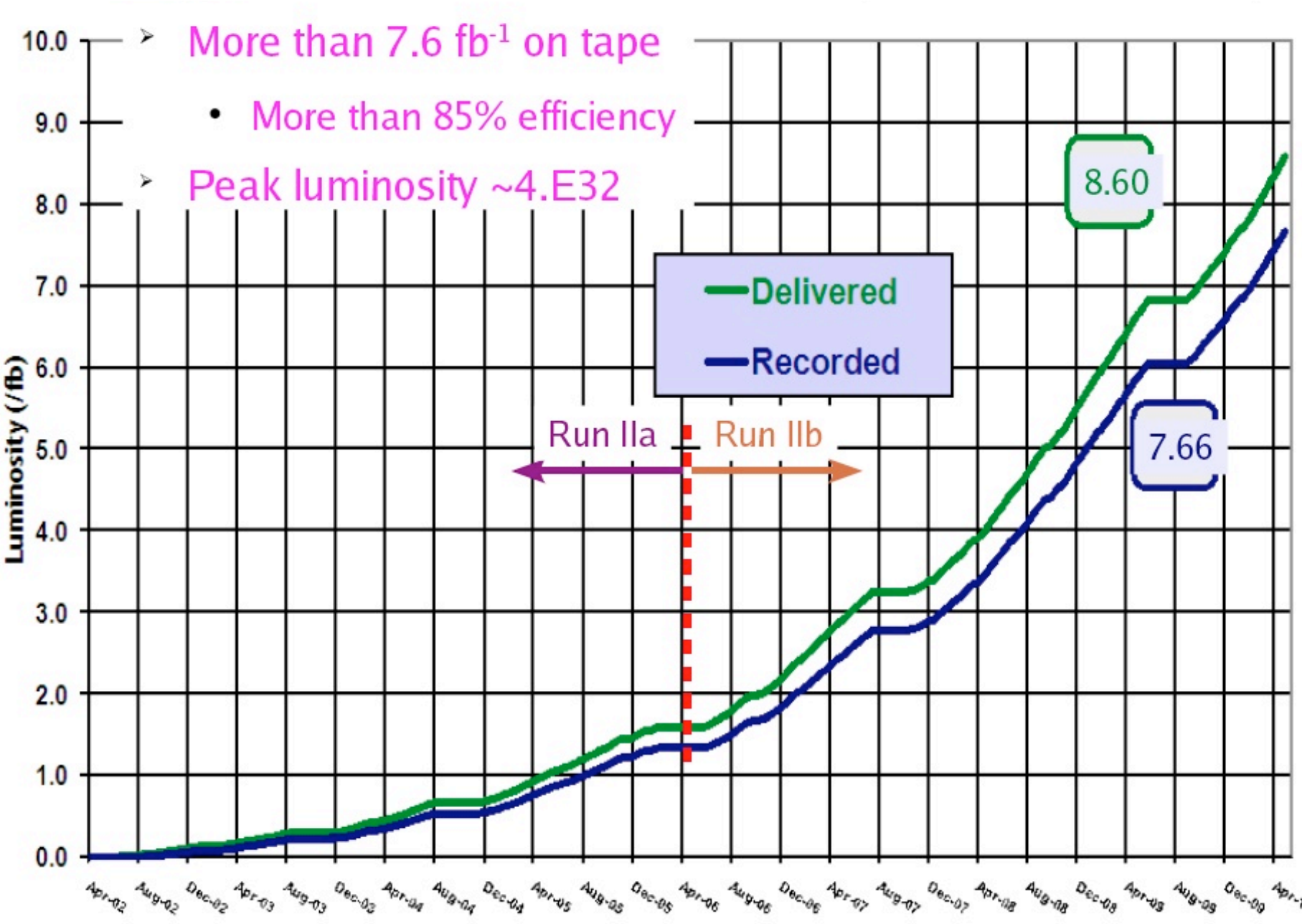
Tevatron Performance

- Stores routinely come in at > 3e32.
- 60 – 70 pb^{-1} delivered/week is typical.
- Expect >2fb/year.



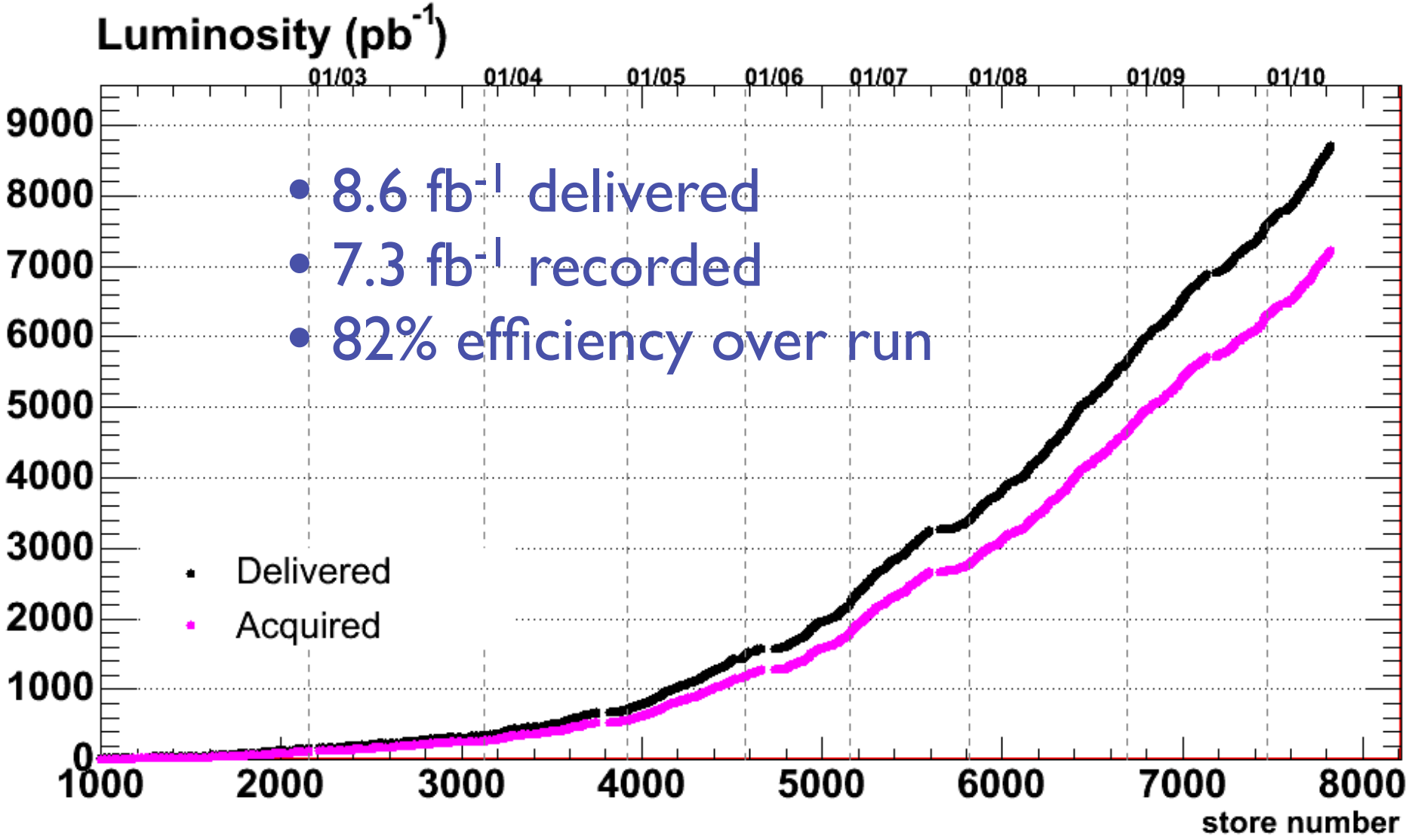
7

D0 Tevatron Profile



8

CDF Tevatron Profile



- 8.6 fb^{-1} delivered
- 7.3 fb^{-1} recorded
- 82% efficiency over run

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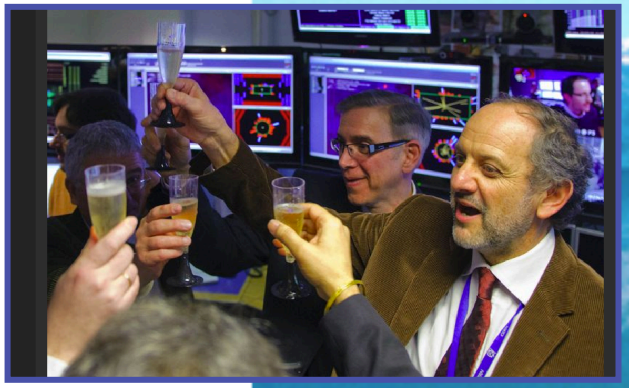
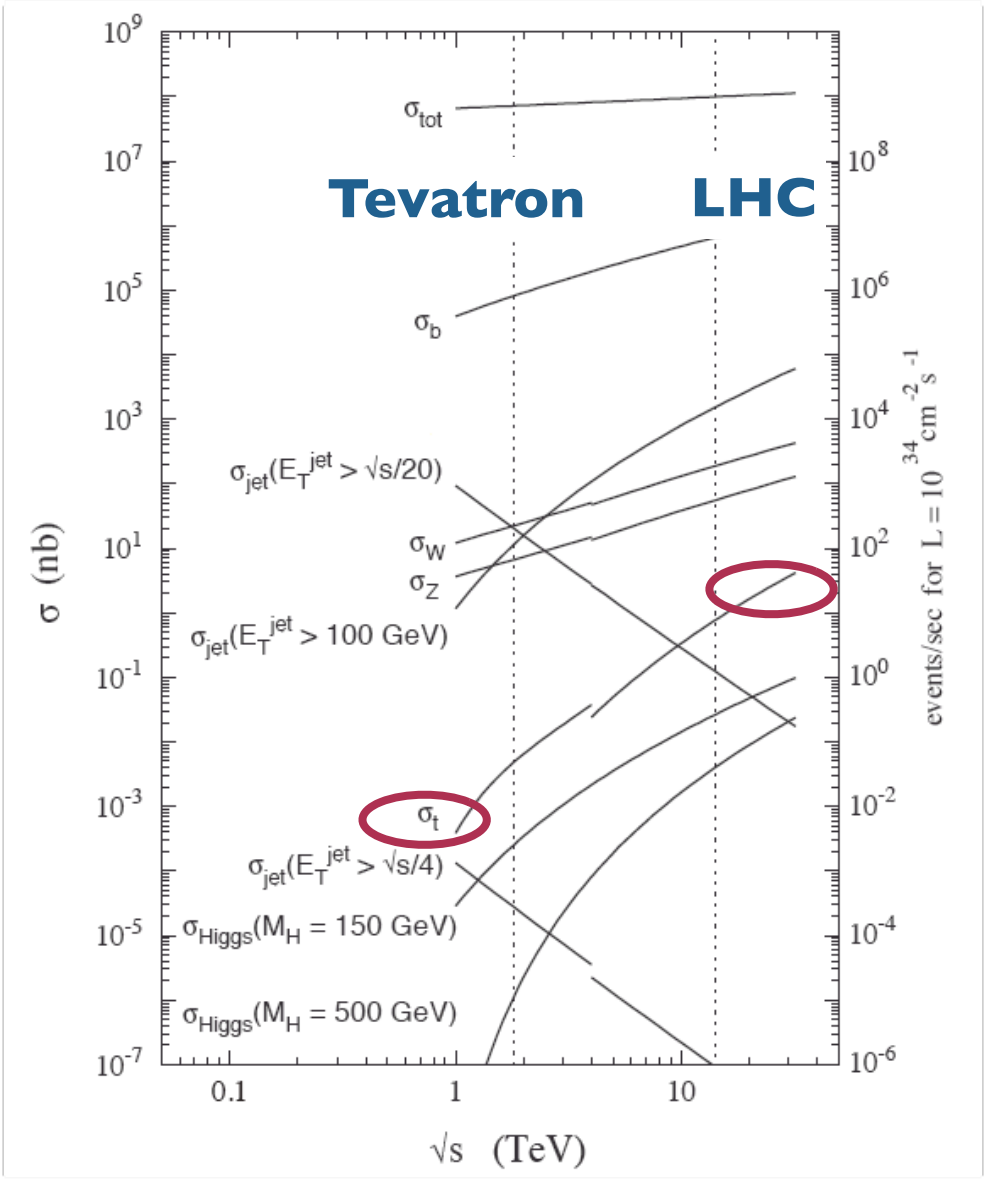
Meanwhile... enter the LHC!

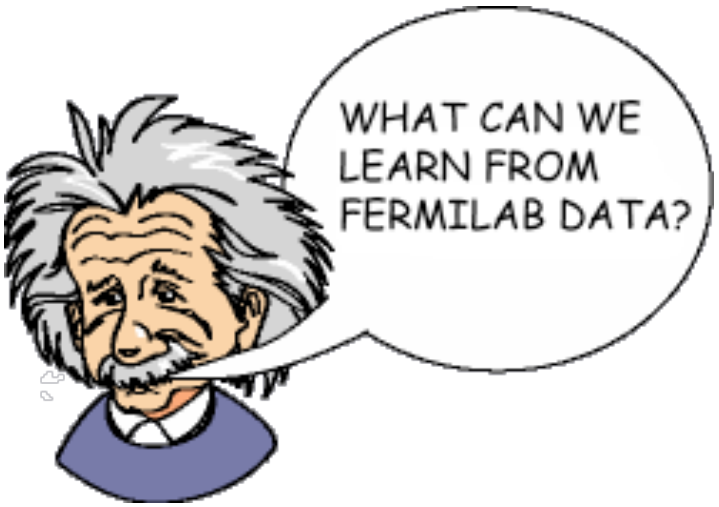


10

Cross section at LHC v. Tevatron

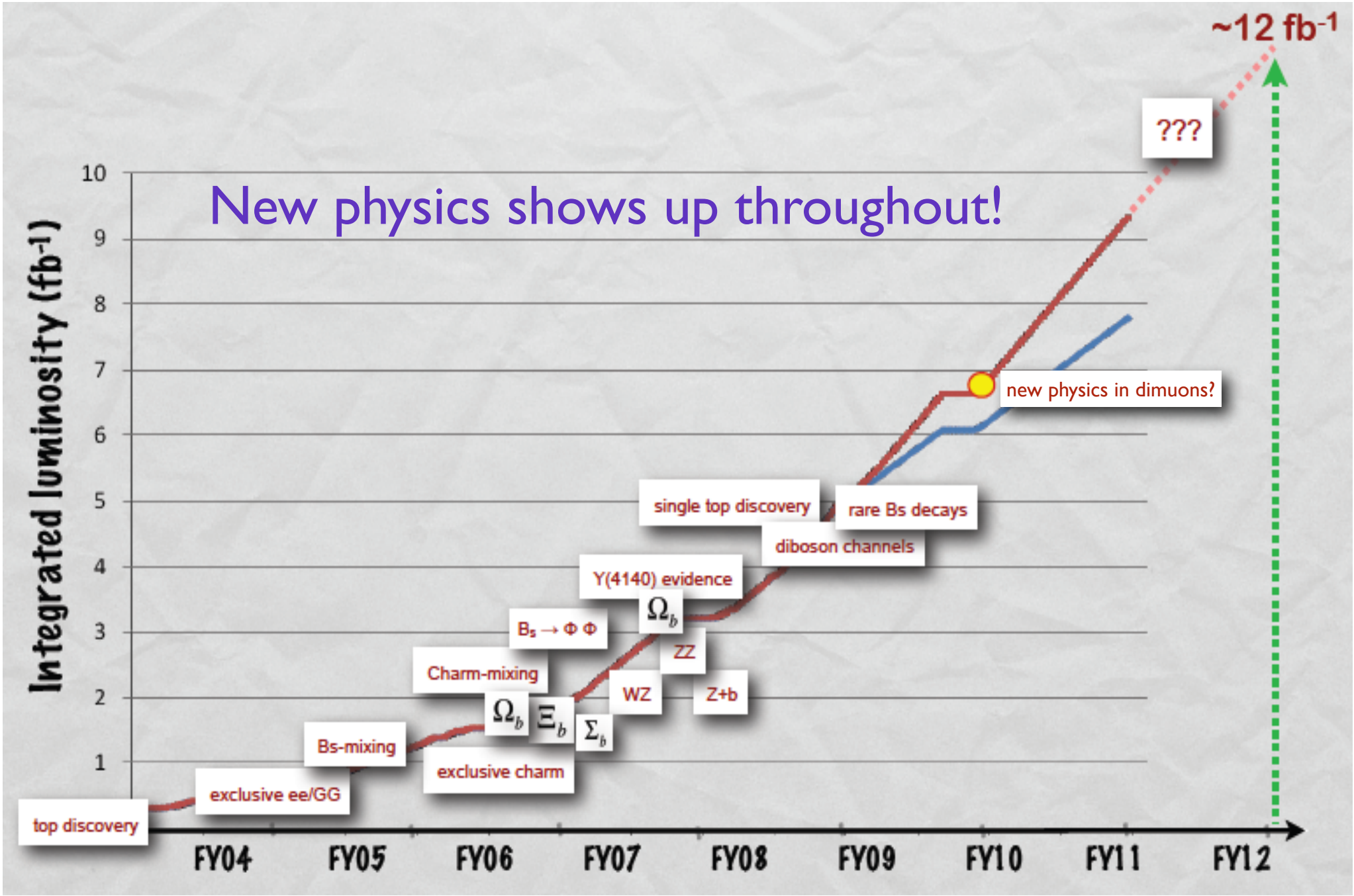


So then...



11

The great thing about hadron colliders



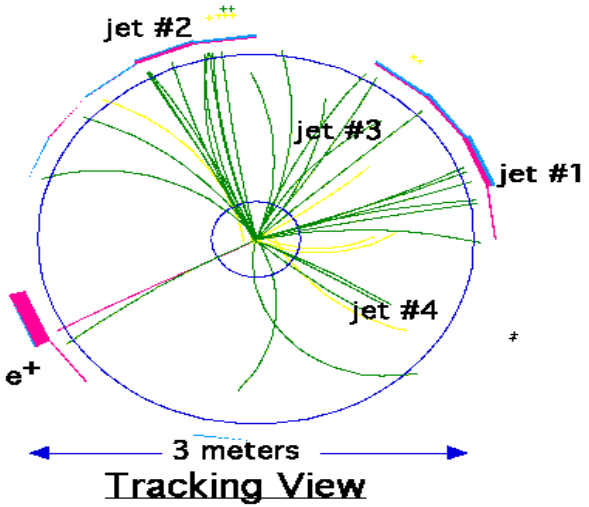
Top Discovery

Physicists Discover Top Quark

News Release - March 2, 1995

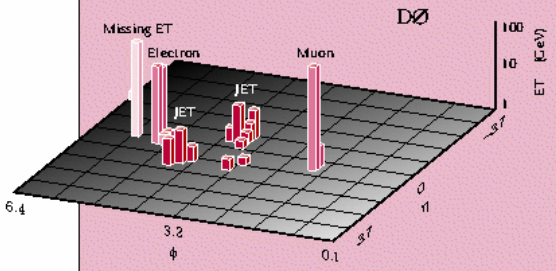
PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi Natic
subatomic particle called the top quark, the last undiscovered qua
sought the top quark since the discovery of the bottom quark at Fe
of the structure of matter.

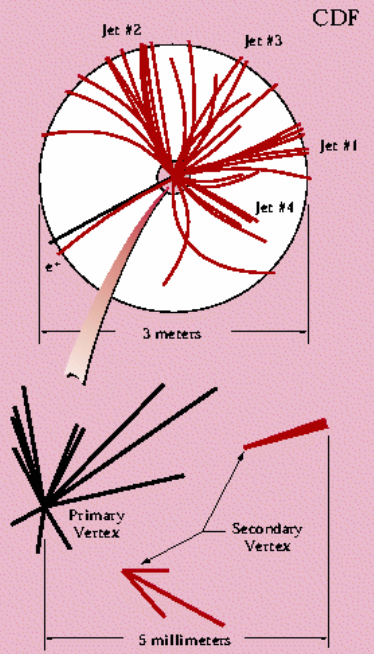


CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 6 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 6 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.



Additional studies helped to establish that the new signal



by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this

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Top Discovery

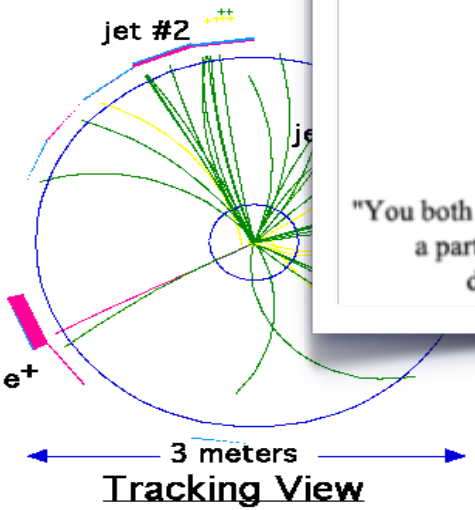
Physicists Discover Top Quark

News Release - M

PHYSICISTS DISCOVER TOP QU

Batavia, IL--Physicists at the Departm
subatomic particle called the top quark
sought the top quark since the discover
of the structure of matter.

"You both have something in common. Dr. Davis has discovered a particle which nobody has seen, and Prof. Higbe has discovered a galaxy which nobody has seen."



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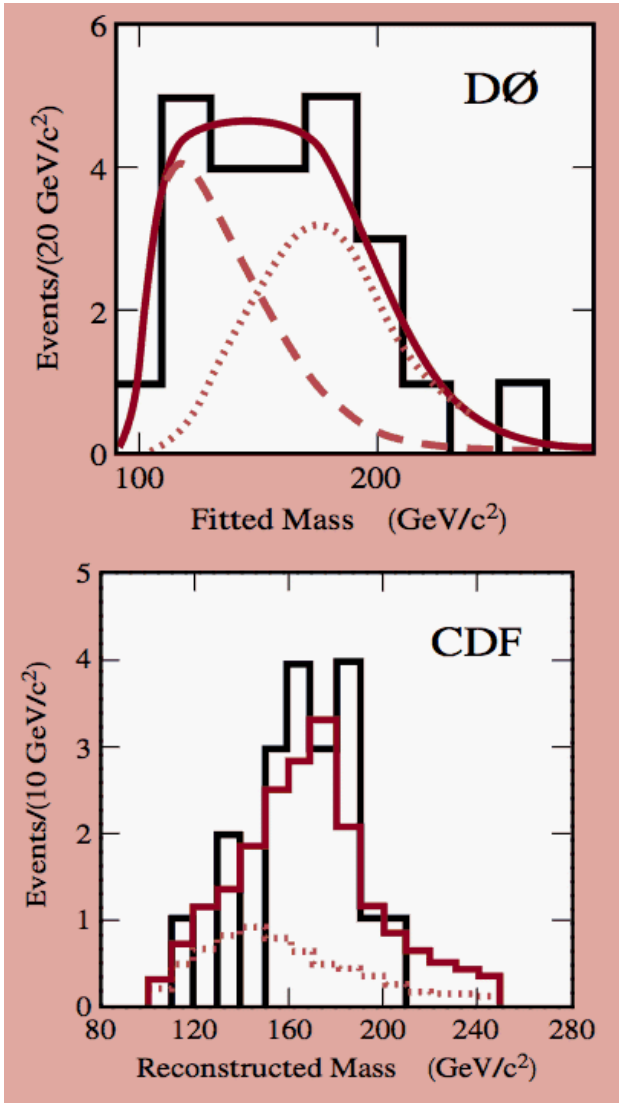
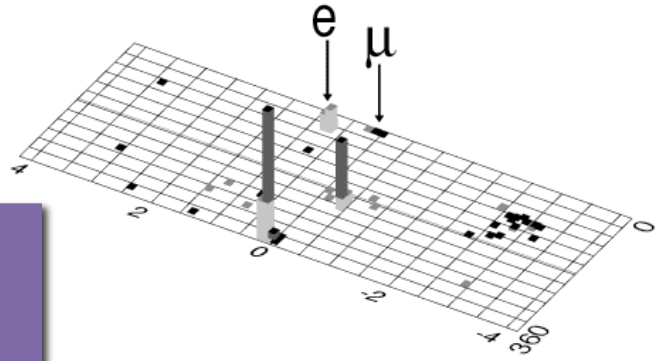
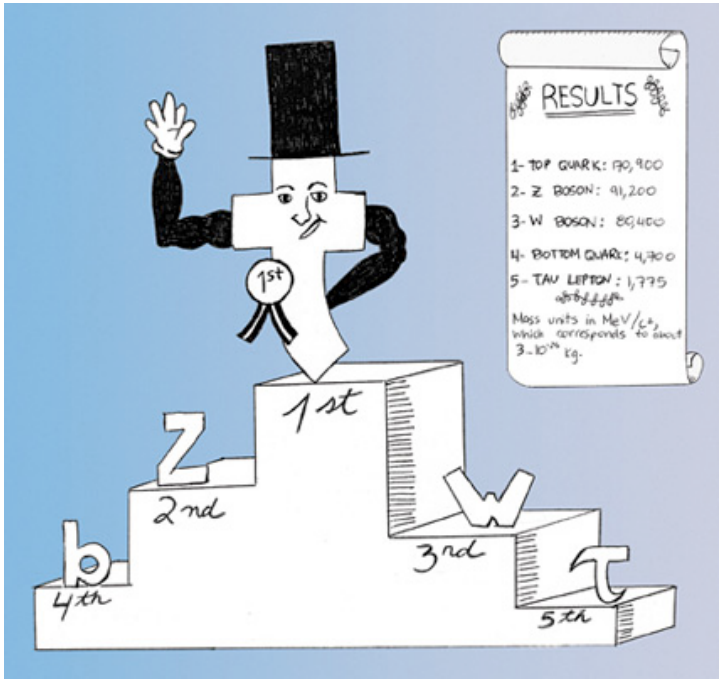
Top was surprising...



Top found at a peculiarly high mass





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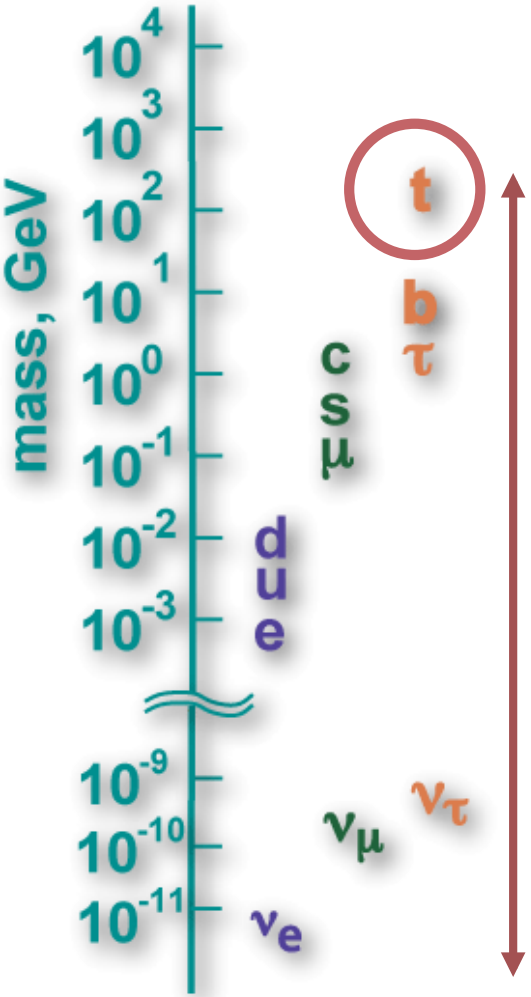
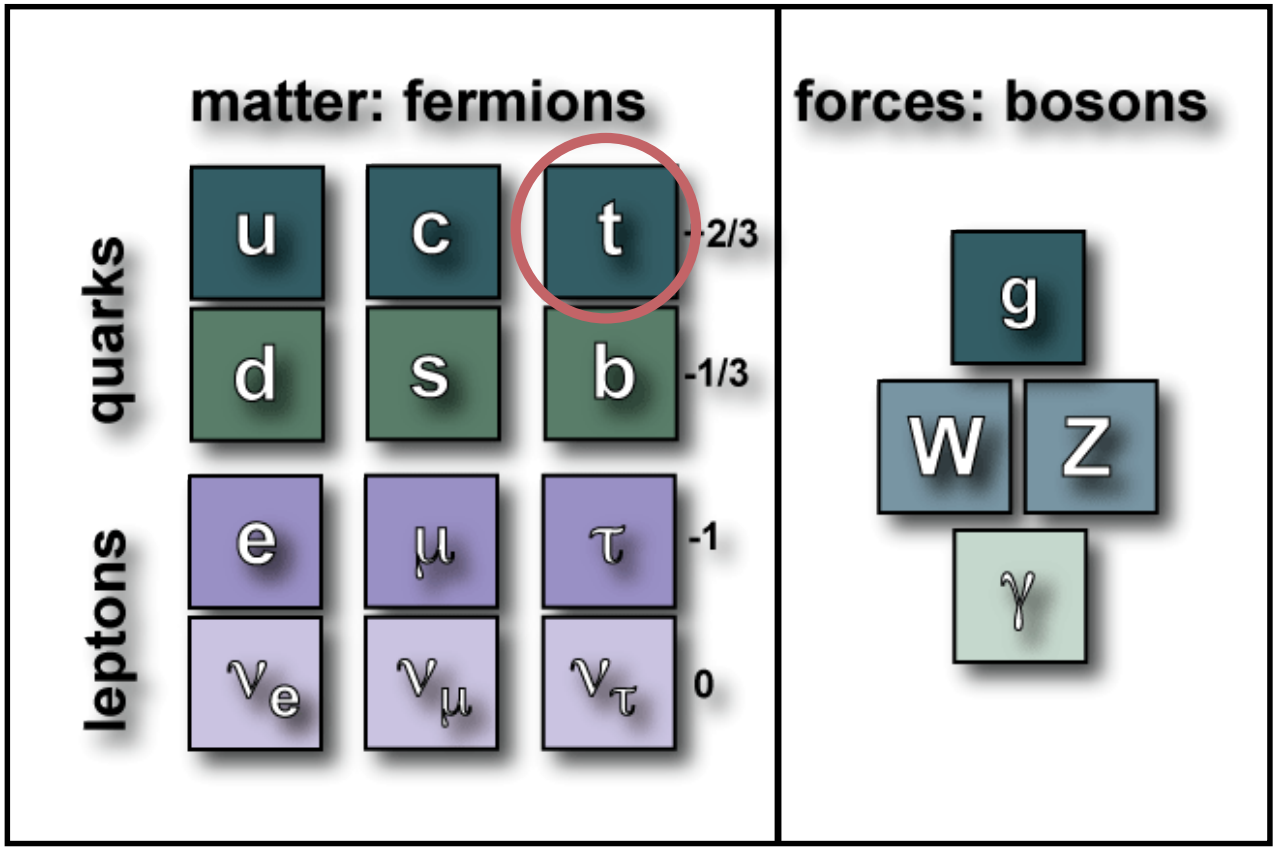
Periodic Table of the Particles





5 orders of magnitude!

Tevatron Research Program

Precision Measurements, New Reach for Discoveries

- Mixing, CKM Constraints and CP Violation
- Heavy Flavor Spectroscopy
- New Heavy Baryon States
- Tests of Quantum Chromodynamics
- Di-Boson production and SM Gauge Couplings
- New Exclusive/Diffractive Processes
- Precise measurement of Top-quark and W-boson Masses
- Top Quark Properties

Unique Window into the unknown

Searches for Supersymmetry, Extra Dimensions, Exotica

Still at the Energy Frontier... for now

Probing the Terascale with increased luminosity

The Standard Model Higgs Boson is almost within reach!

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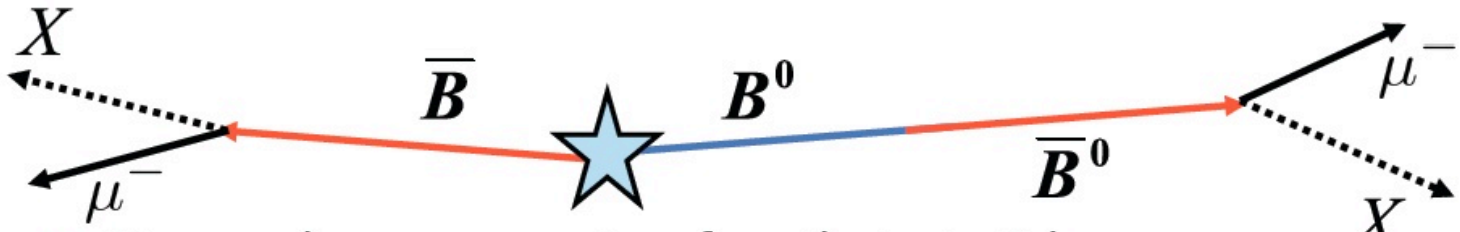
Anomalous Di-Muon Asymmetry



- Dimuon charge asymmetry of semileptonic *B* decays:

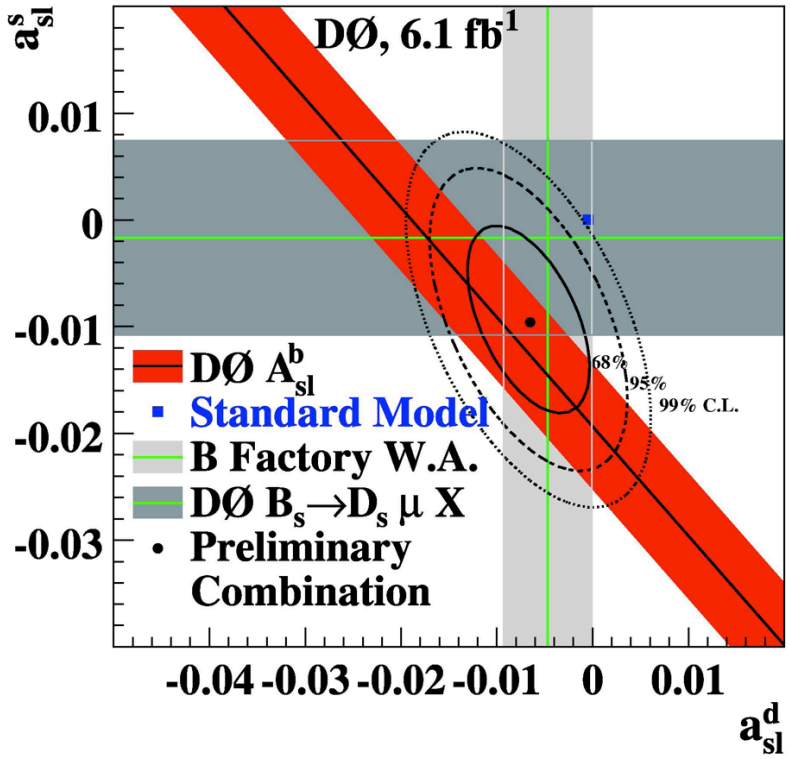
$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

- N_b^{++}, N_b^{--} are # events with 2 *b* hadrons decaying semileptonically to like-sign muons
- One muon comes directly from $b \rightarrow \mu X^-$
- Second μ comes from direct semileptonic decay after neutral B meson mixing: $B^0 \rightarrow \overline{B}^0 \rightarrow \mu^- X$
- A^b_{sl} is charge asymmetry from "wrong sign" semileptonic *b* decays from flavor oscillation in B_s and B_d

18

Anomalous Di-Muon Asymmetry

- Result discrepant from SM by 3.2σ (stat limited)
- Agrees with other measurements of $a_{sl}^{s,d}$ and previous version (unpublished)
- Translate to CPV parameter $\Delta\Gamma_s$: agrees with CDF/D0 combo



• CDF also did not publish early version: now redoing this study. Field reversal effect expected small due to solenoid.
• Will be interesting see how these results progress...

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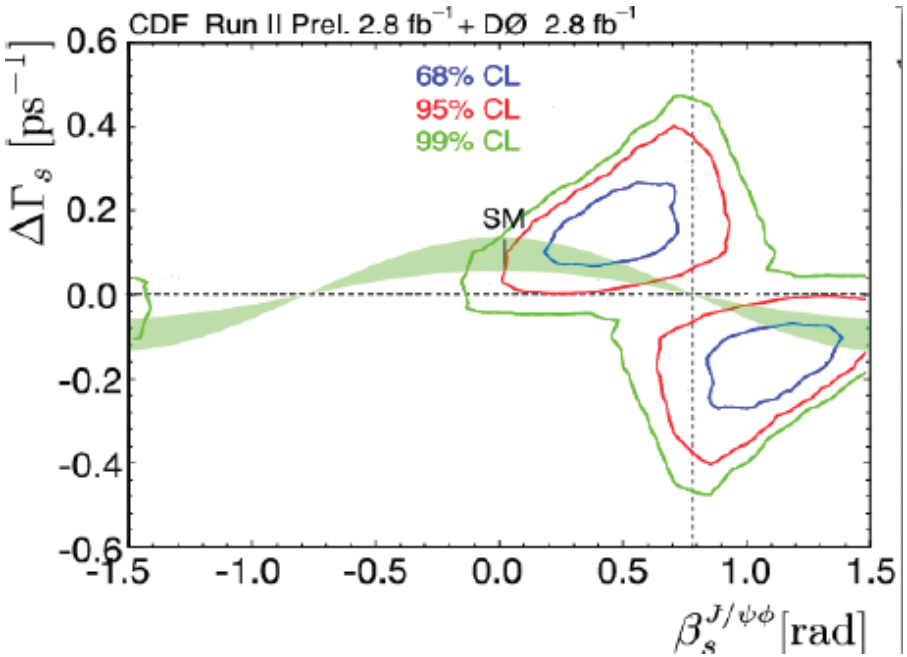
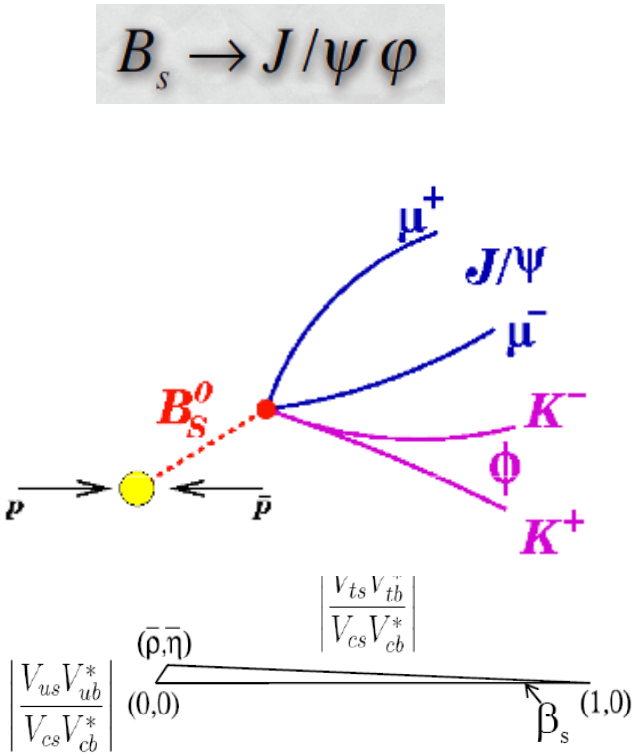
Precision: CP Violation

- Both CDF and D0 measure the CP Violating Parameter β_s in $B_s \rightarrow J/\psi\phi$ with 2.8/fb



Tevatron Combo at 2.8 fb^{-1}:
2.2σ from SM Prediction



- D0's Di-muon result is consistent with this discrepancy as translated in the mixing space.

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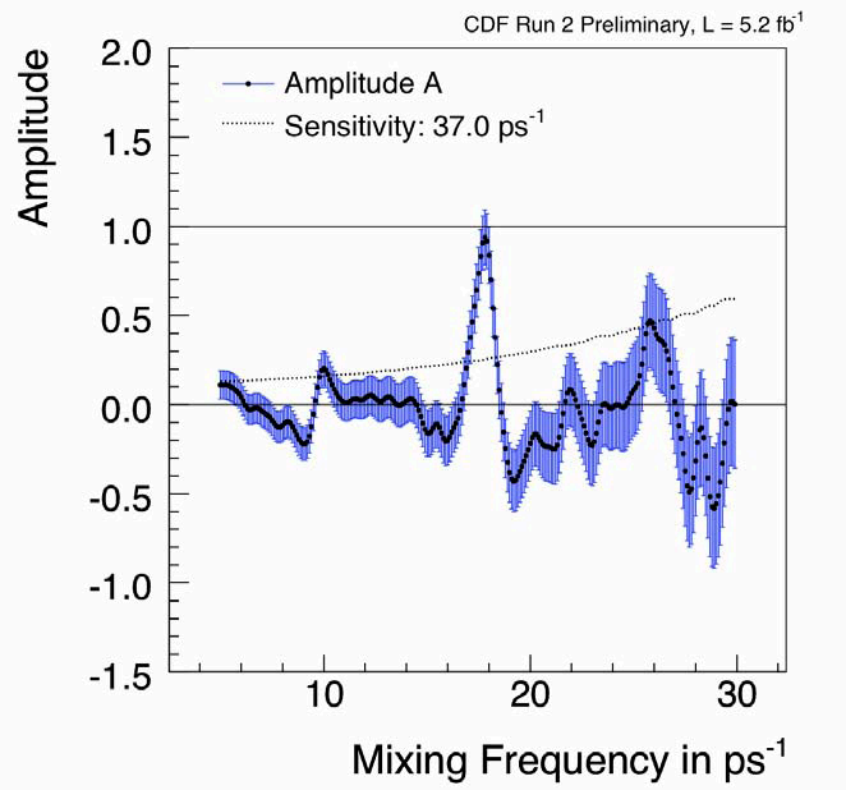
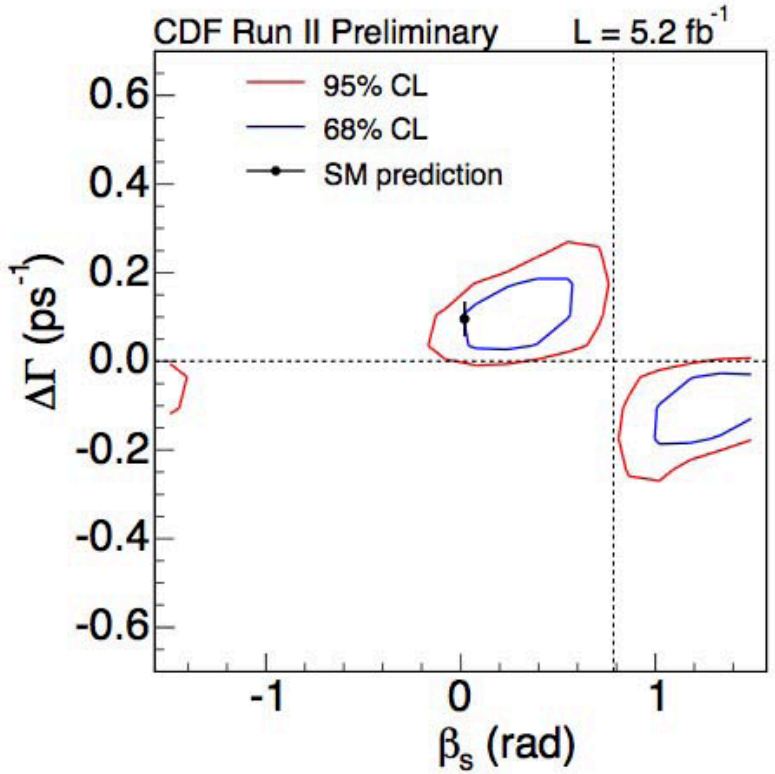
Updated Precision: CP Violation

- NEW: CDF last week has updated this result with 5.2 fb^{-1} (see FPCP talk, or Fermilab wine and cheese on June 11th)



$B_s \to J/\psi\,\varphi$



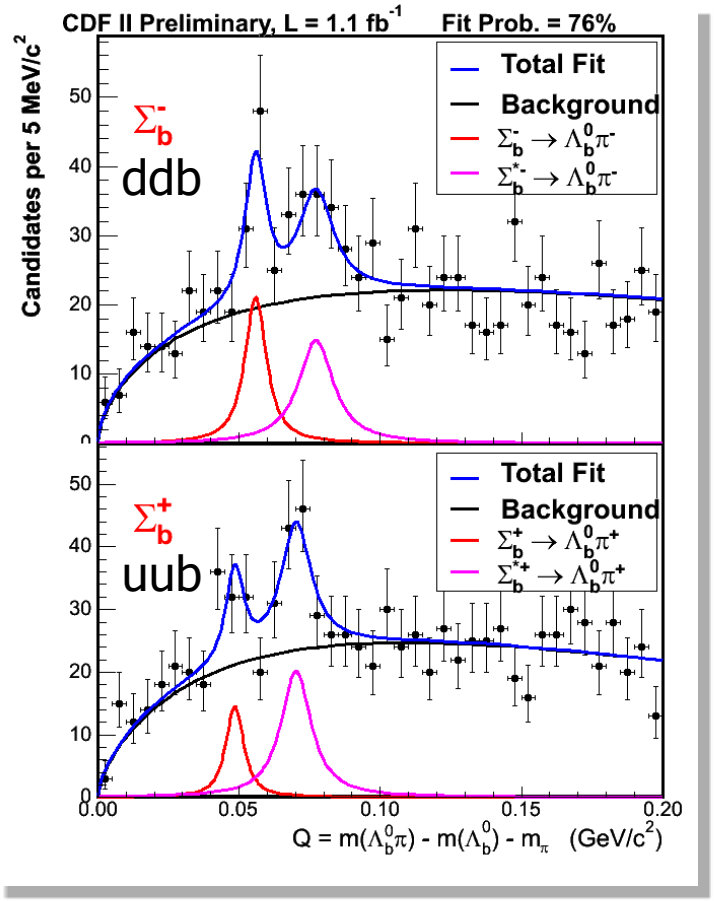
P-value 44% : 0.8σ from SM Prediction

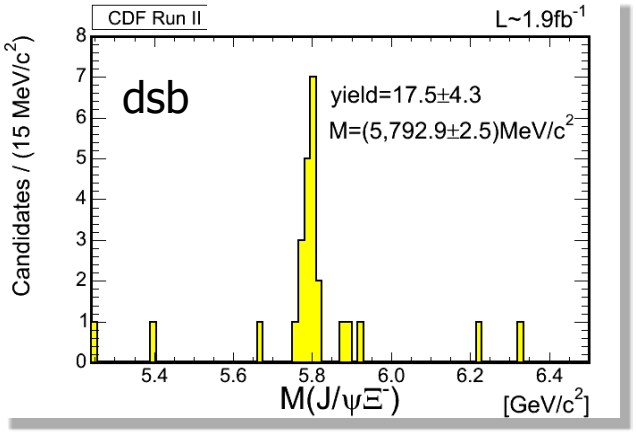
- But still consistent with D0's dimuon result.

21

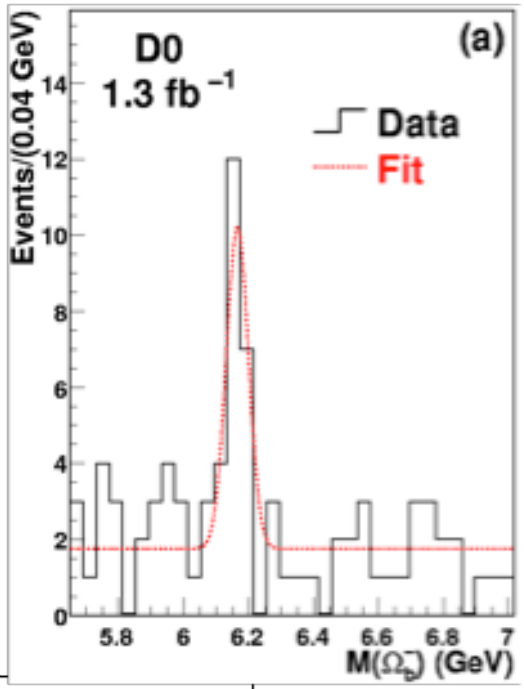
Observation of New Heavy Baryons

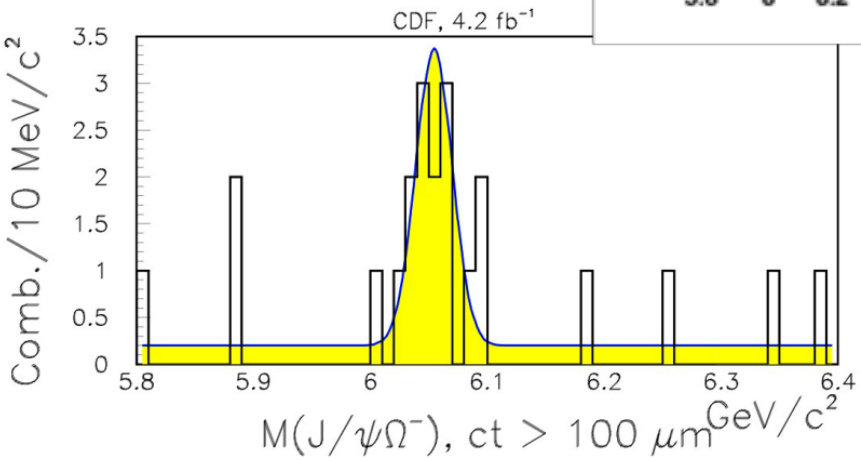
Σ_b





Ξ_b





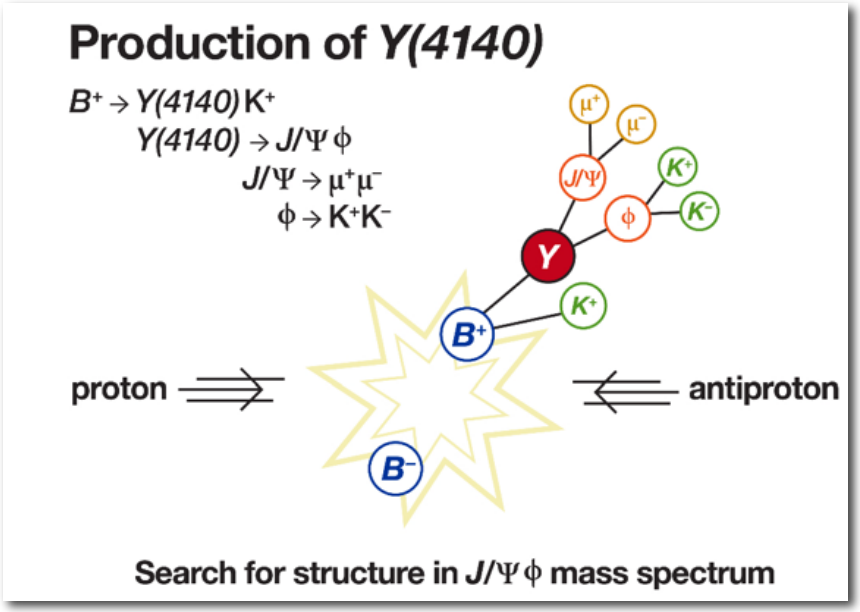
Ω_b

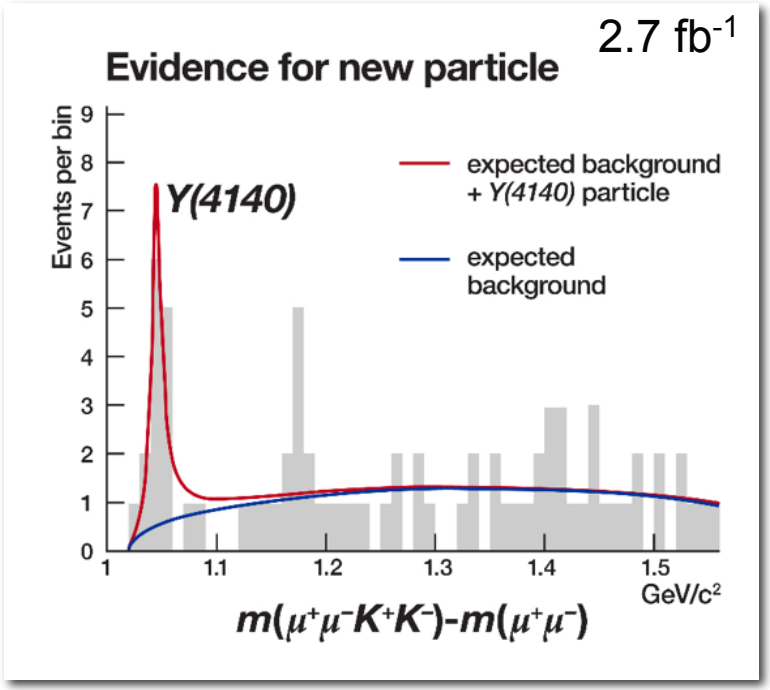
22

Emergence of a New Particle

Y(4140)

2009: unknown composition





These new discoveries yield a few events/fb^{-1}

==> new areas of research @ 10 fb^{-1}

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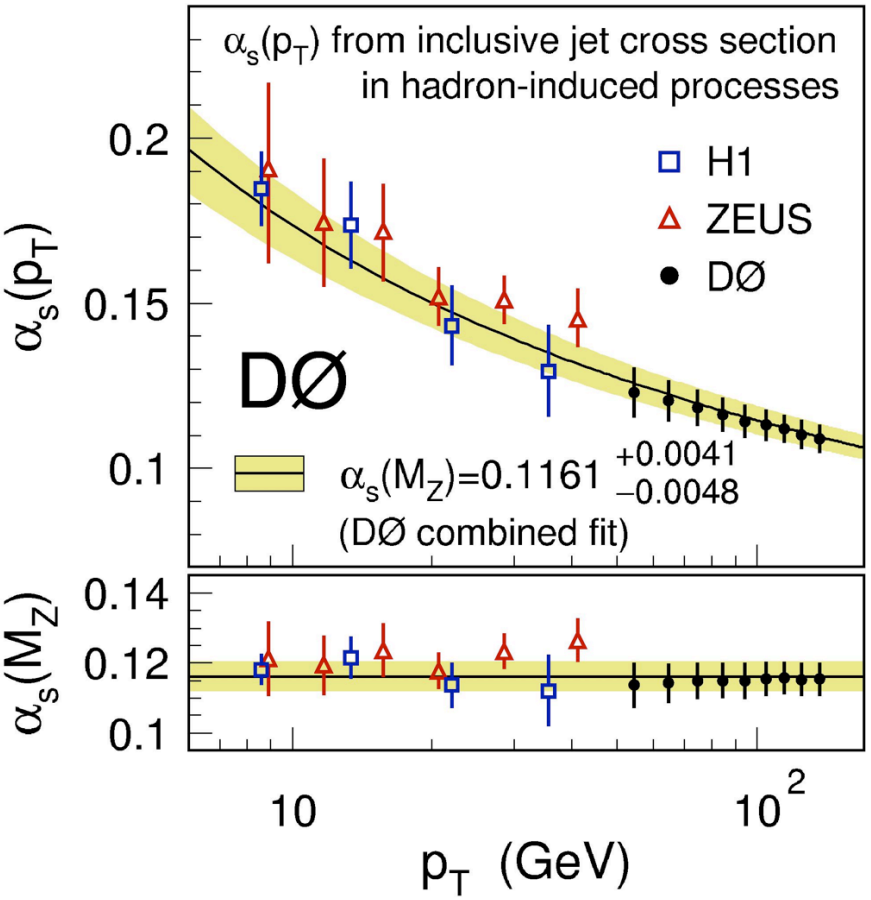
QCD works well...

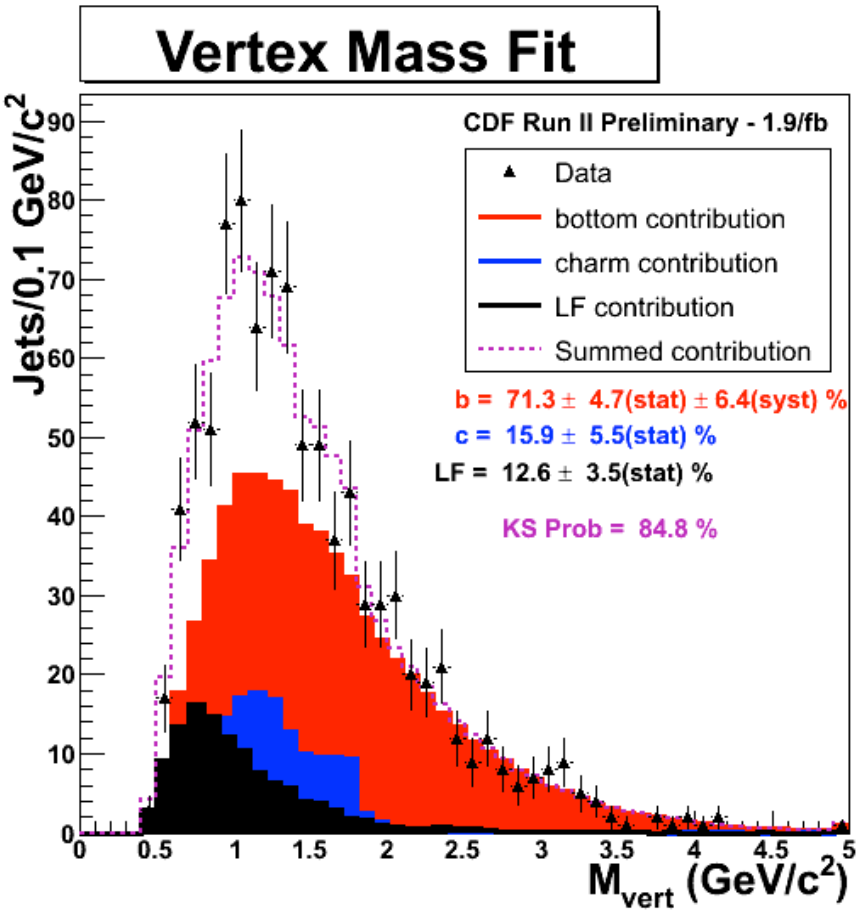


Inclusive jet cross section allows extraction of the strong coupling parameter, in good agreement with other measurements

24

QCD works well but...

CDF Measurement of Wb production



$\sigma\, b_{\text{-jets}}\,(W\text{+}b\text{-jets}) \cdot \mathrm{BR}(W \to l\,\nu) =$
$2.74 \pm 0.27\ (\text{stat}) \pm 0.42(\text{syst})\ \text{pb}$

Result is 2.5-3.5 times the theory prediction from AlpGen, and much higher than recent NLO as well

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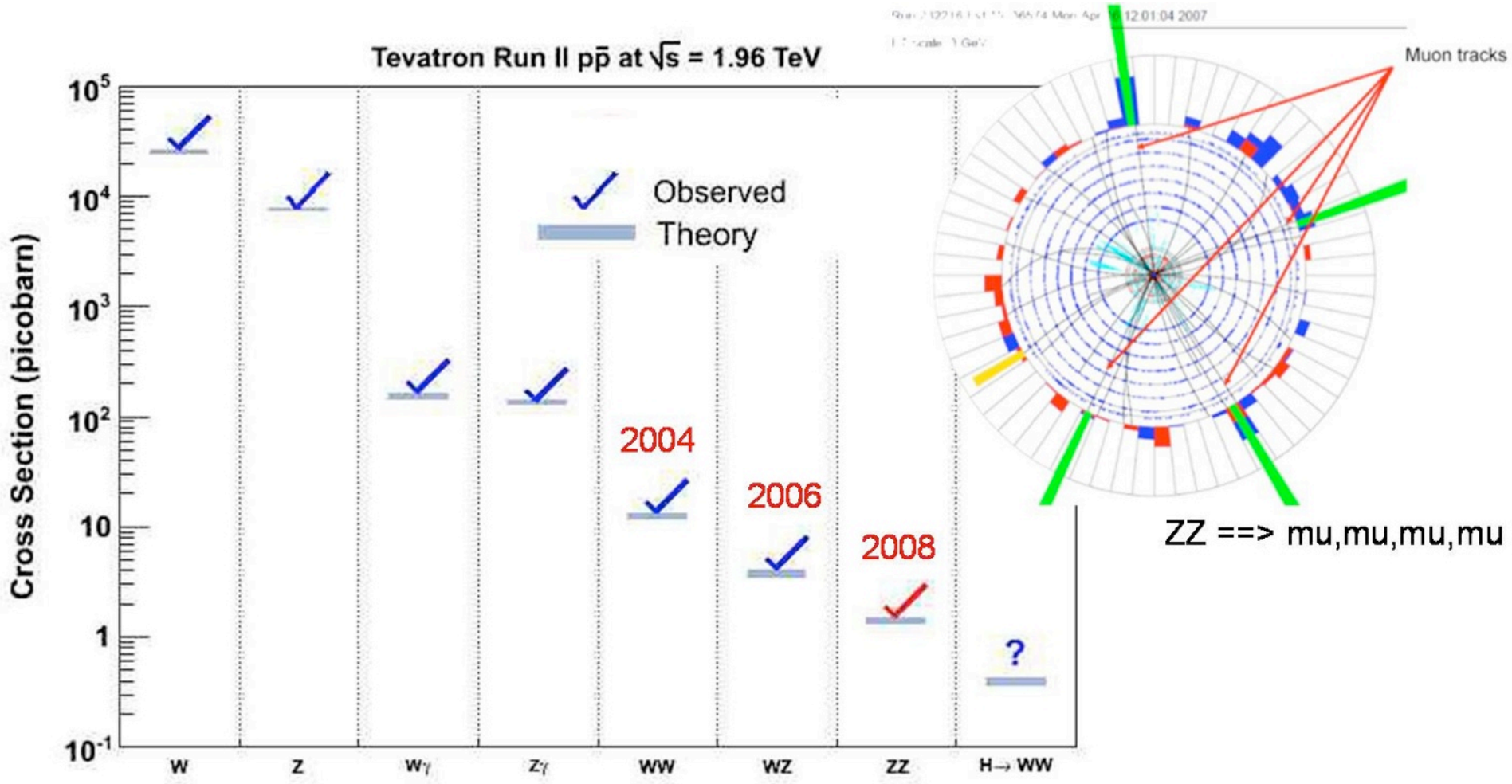
Di-bosons at the Tevatron



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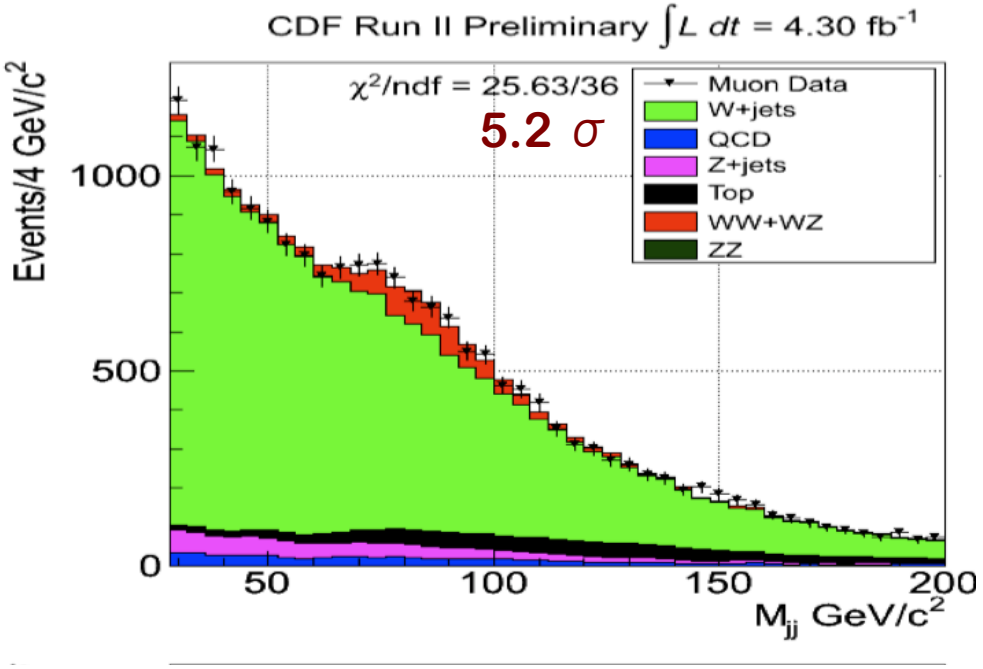
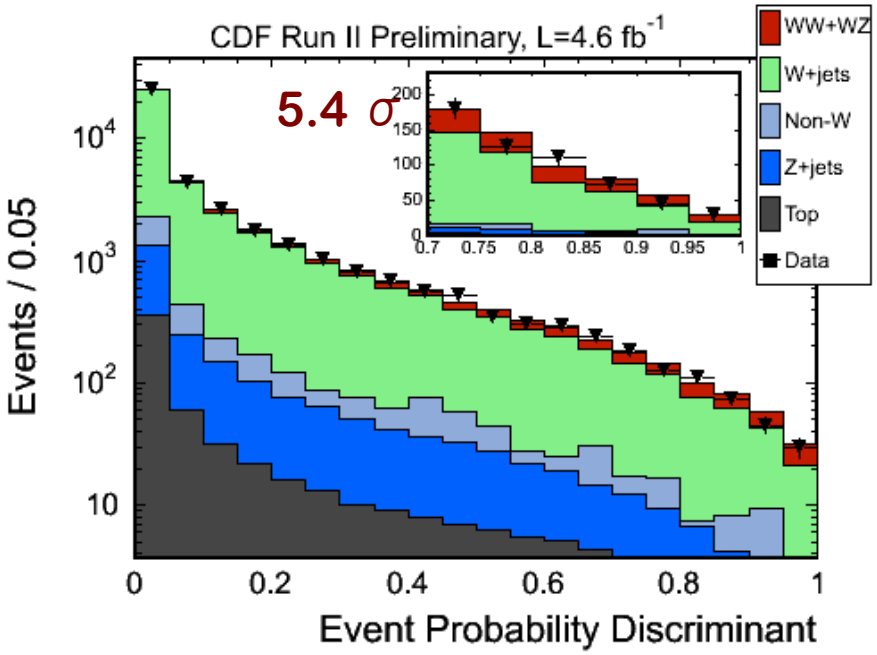
Reaching further with Di-bosons

- WW/WZ measurements in Lepton + Jets
- Using matrix element techniques and m_{jj} calibration with 4.3-4.6 fb^{-1}



$\sigma = 18.1 +3.3_{stat} \pm 2.5_{sys}$ pb



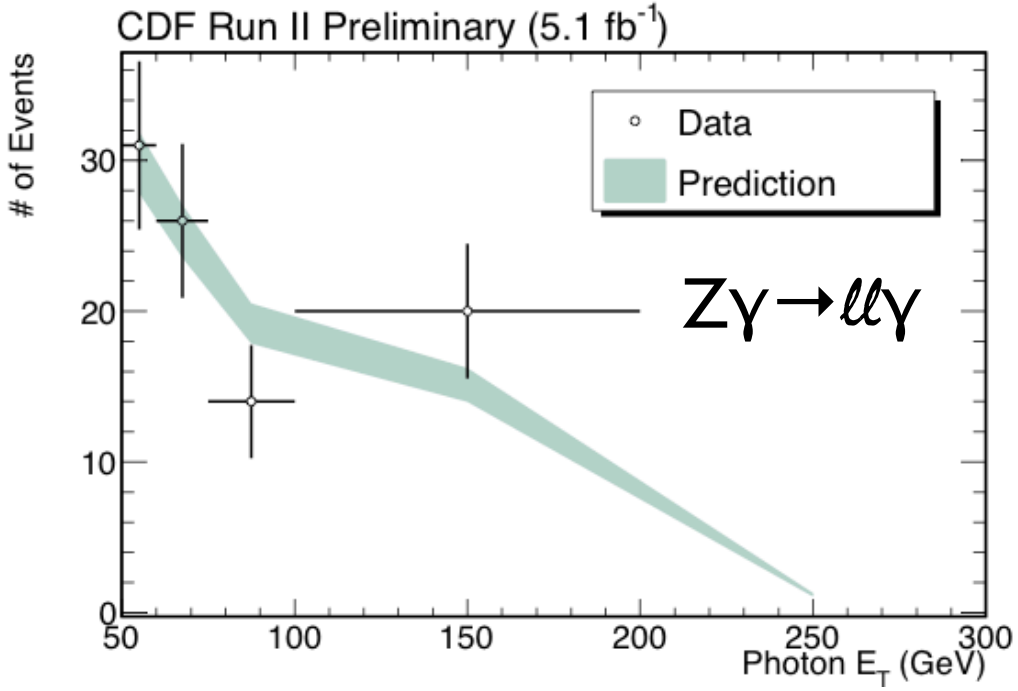
$\sigma = 16.5 +3.3/-3.0_{stat} \pm 3.5_{sys}$ pb

SM = 15.1 ± 0.9 pb

27

Other recent electroweak

- Z-gamma production from CDF
- W charge asymmetry from D0
- Di-boson resonances from both!



Zγ: probes for anomalous triple gauge couplings

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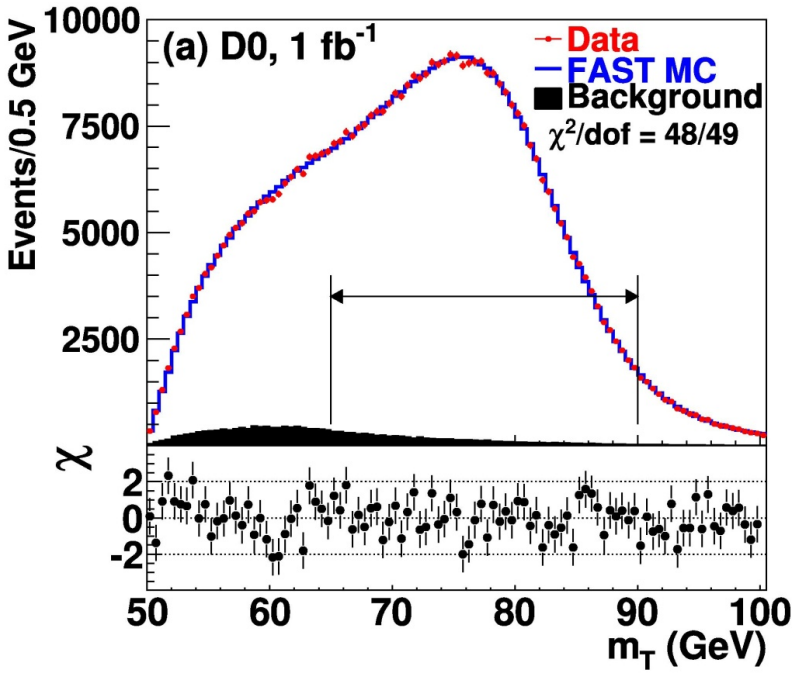
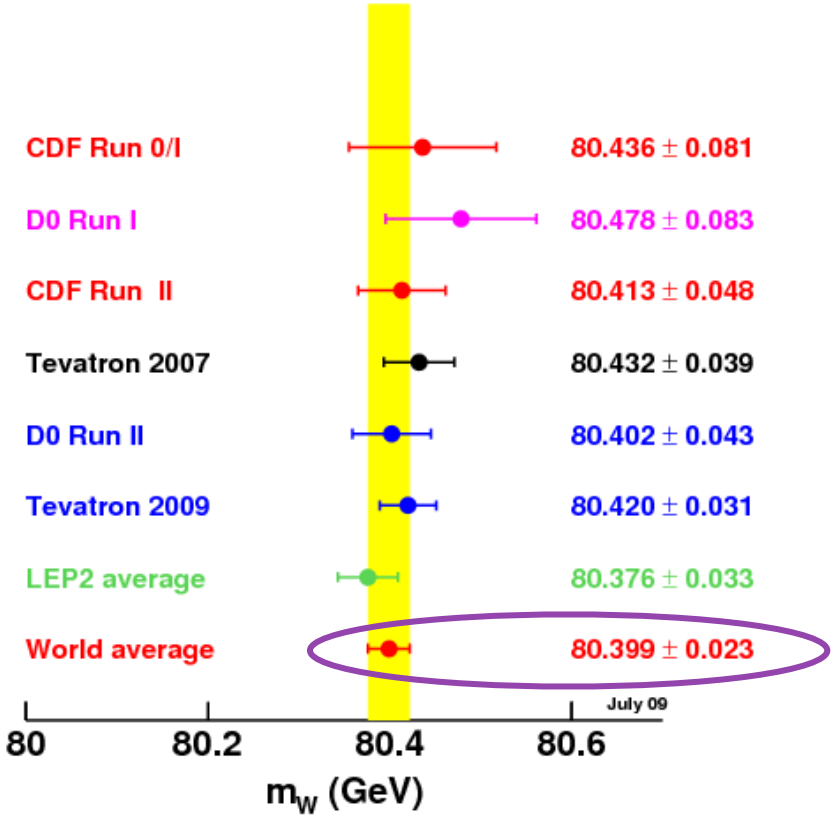
W mass

Tevatron has the world's best measurements.





$M_W = 80.399 \pm 0.023$ GeV

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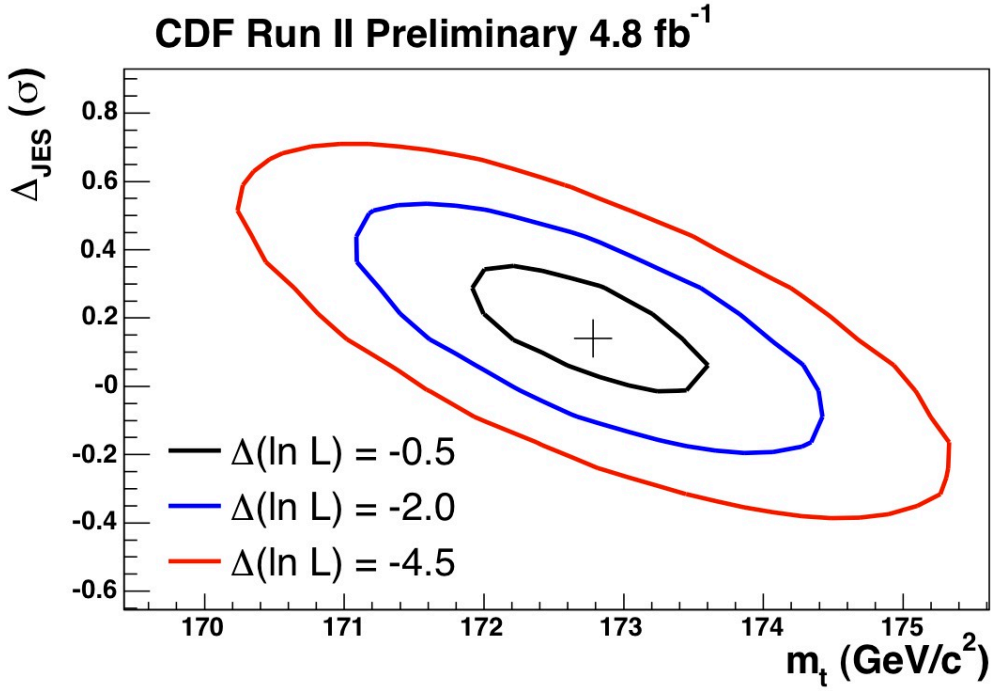
Top Mass

- Most precise: Combined NN/ Matrix element technique or ME only in Lepton+Jets.
- New: single measurement precision now compares well with overall combo.



See talk by Brandt

172.8 ± 0.9(stat+JES) ± 0.8(syst) GeV/c²

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Toward Achieving Precision

- D0 and CDF working group on top mass systematics is an ongoing effort. Examples:
  - Symmetrizing uncertainties
  - JES uncertainty categories
  - MC modeling uncertainties: hadronization, color reconnection
  - ISR/FSR, PDFs, higher order effects
  - Backgrounds, fits/MC stats, multiple interactions
  - other experimental issues, such as lepton Pt

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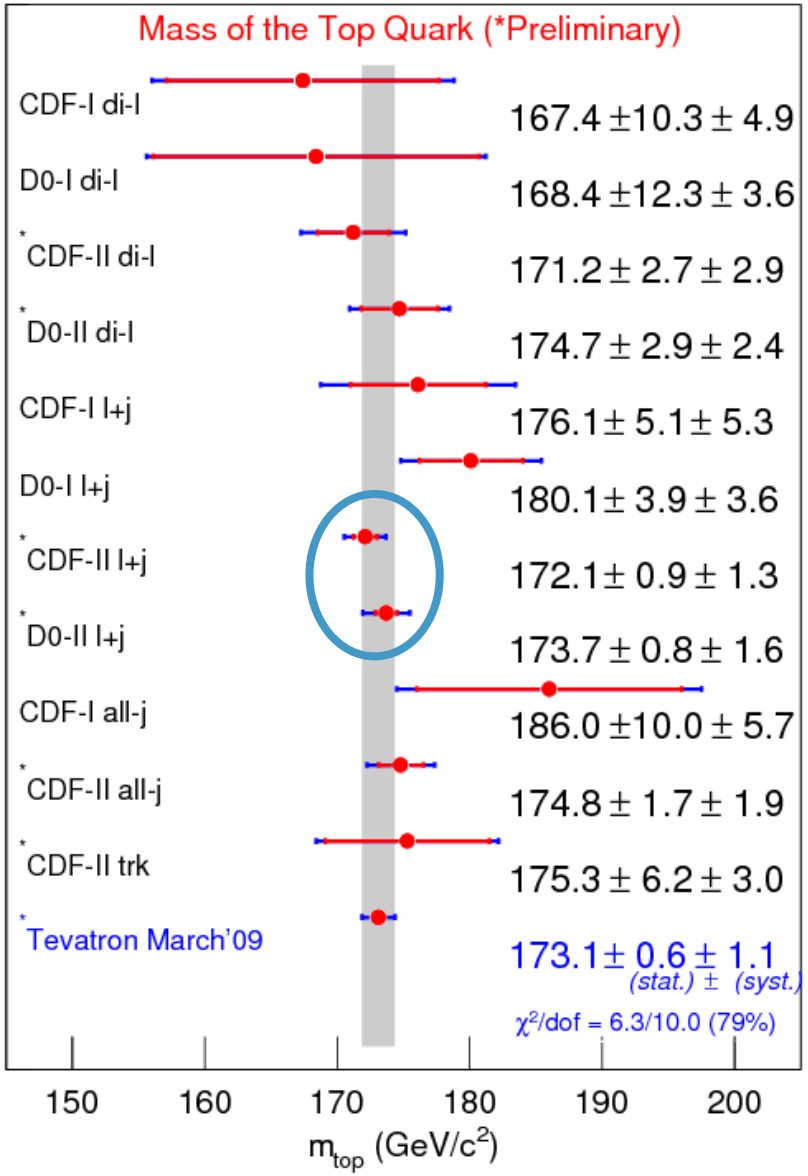
Top Mass Combo



- Achieved less than 1%-- better than anticipated.
- Dominated by systematics, careful treatment needed.
- Dileptons becoming more precise, but all-hadronic is the unexpected contender.

M(top)=173.1±0.6±1.1 GeV

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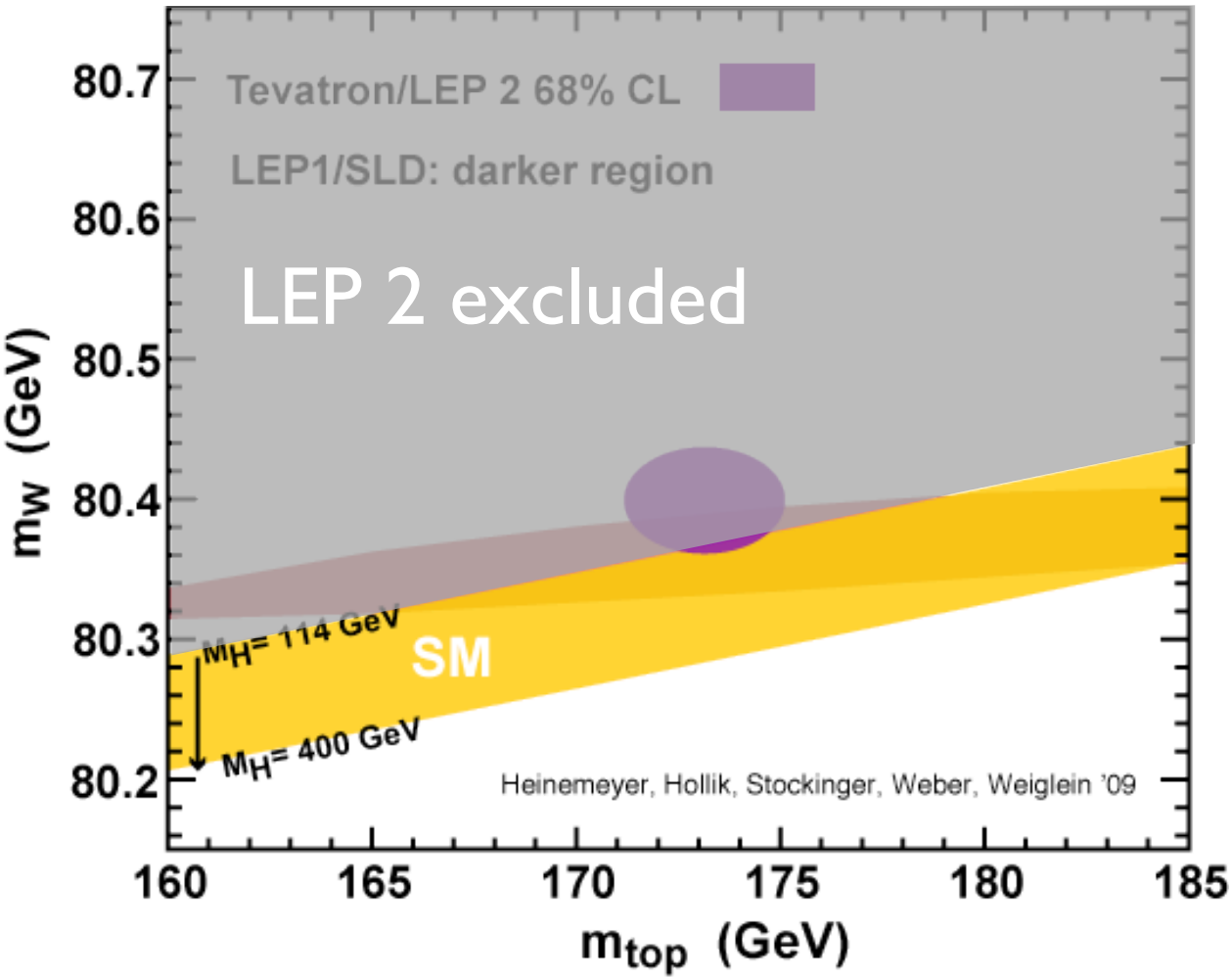
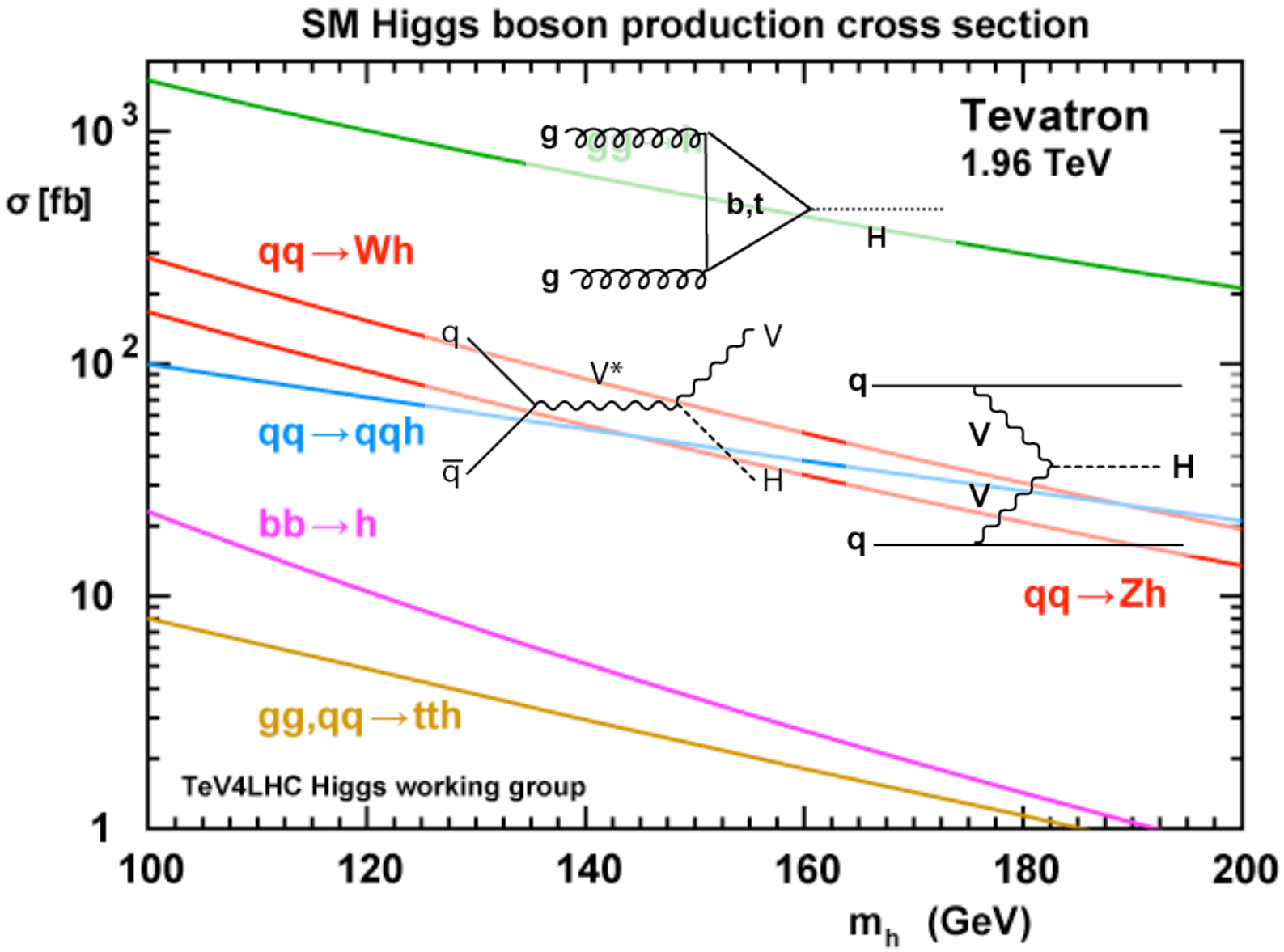
Where is the Higgs?

$$m_H = 87 \pm^{35}_{26} \text{ GeV}$$
$$m_H < 157 \text{ GeV} @ 95\% \text{C.L.}$$
$$m_H > 114 \text{ GeV(direct)}$$



W and top quark mass tells us Higgs mass

Higgs Production



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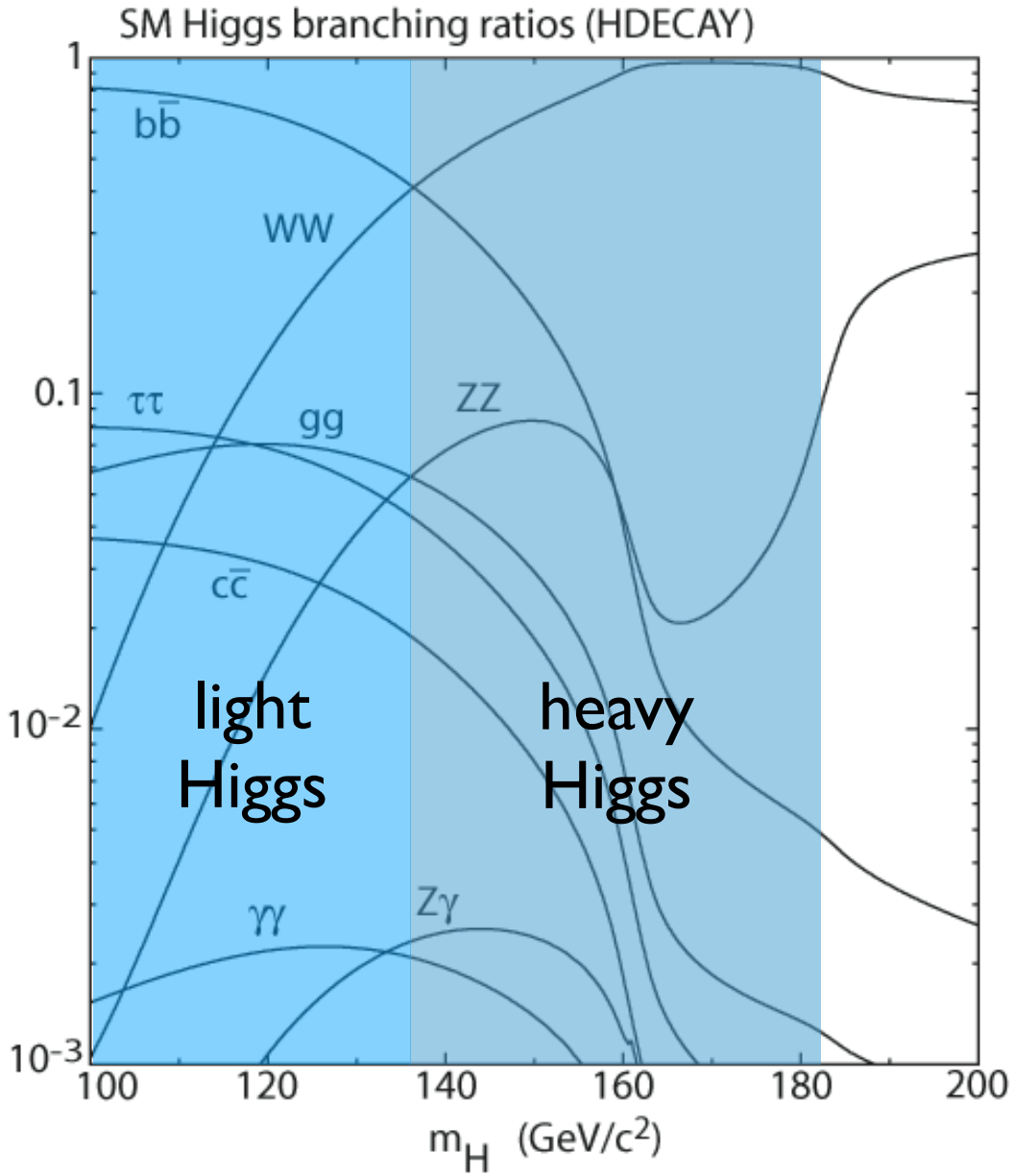
Higgs Signatures

Light SM Higgs boson

bb decay dominates
ττ plays a role

Heavy SM Higgs boson

WW decay dominates
ZZ: ℓℓ BR too small



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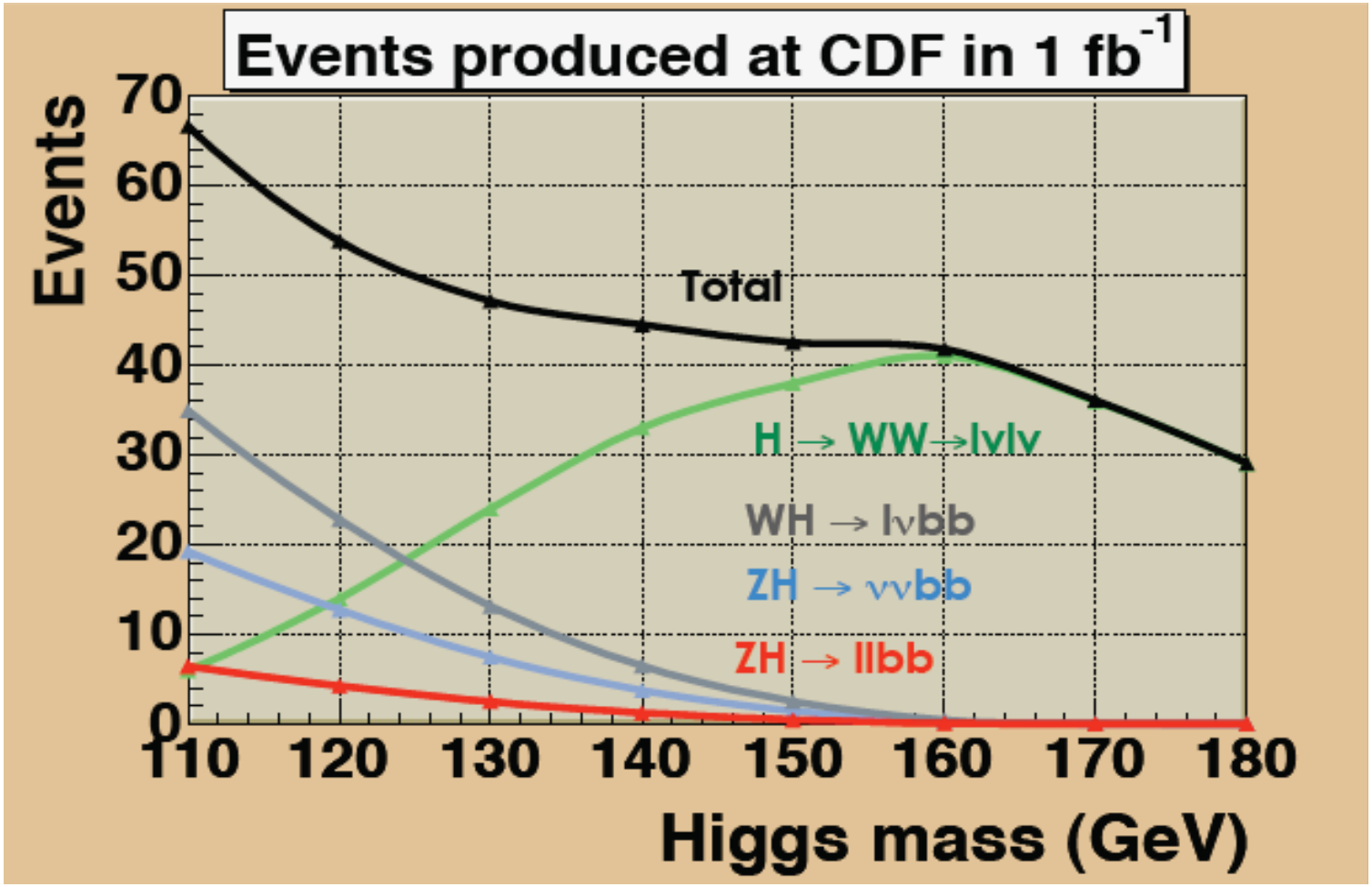
The Challenge



These are production numbers – trigger, acceptance, ID efficiency not yet factored in…

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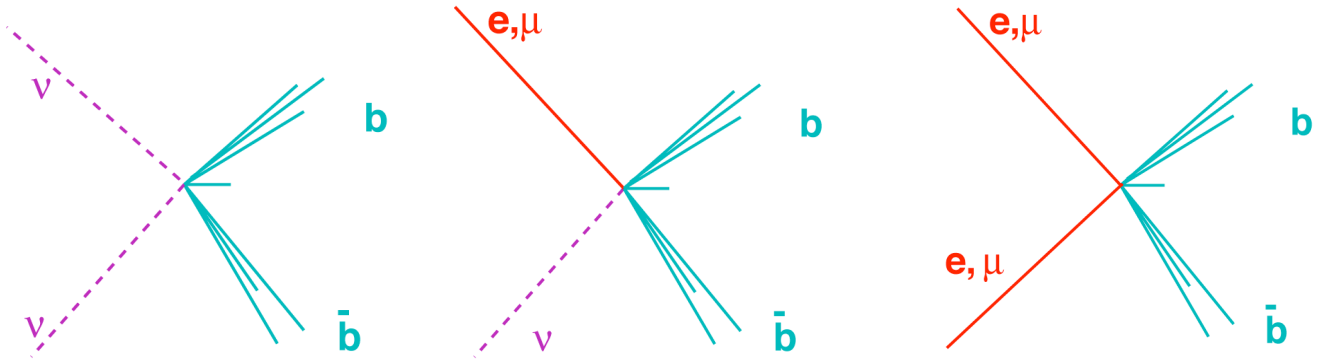
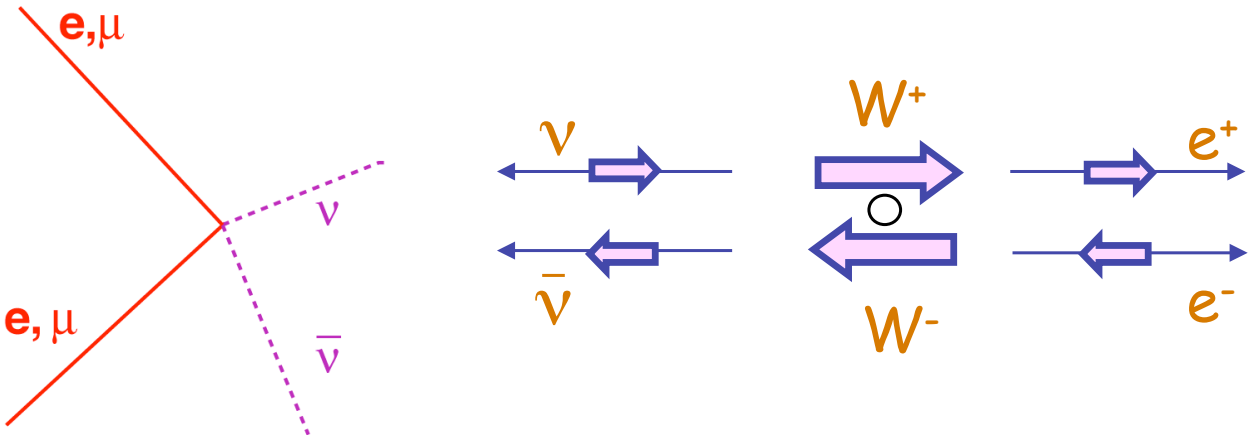
Tevatron Channels

gg→H→bb/ττ suffer too much background



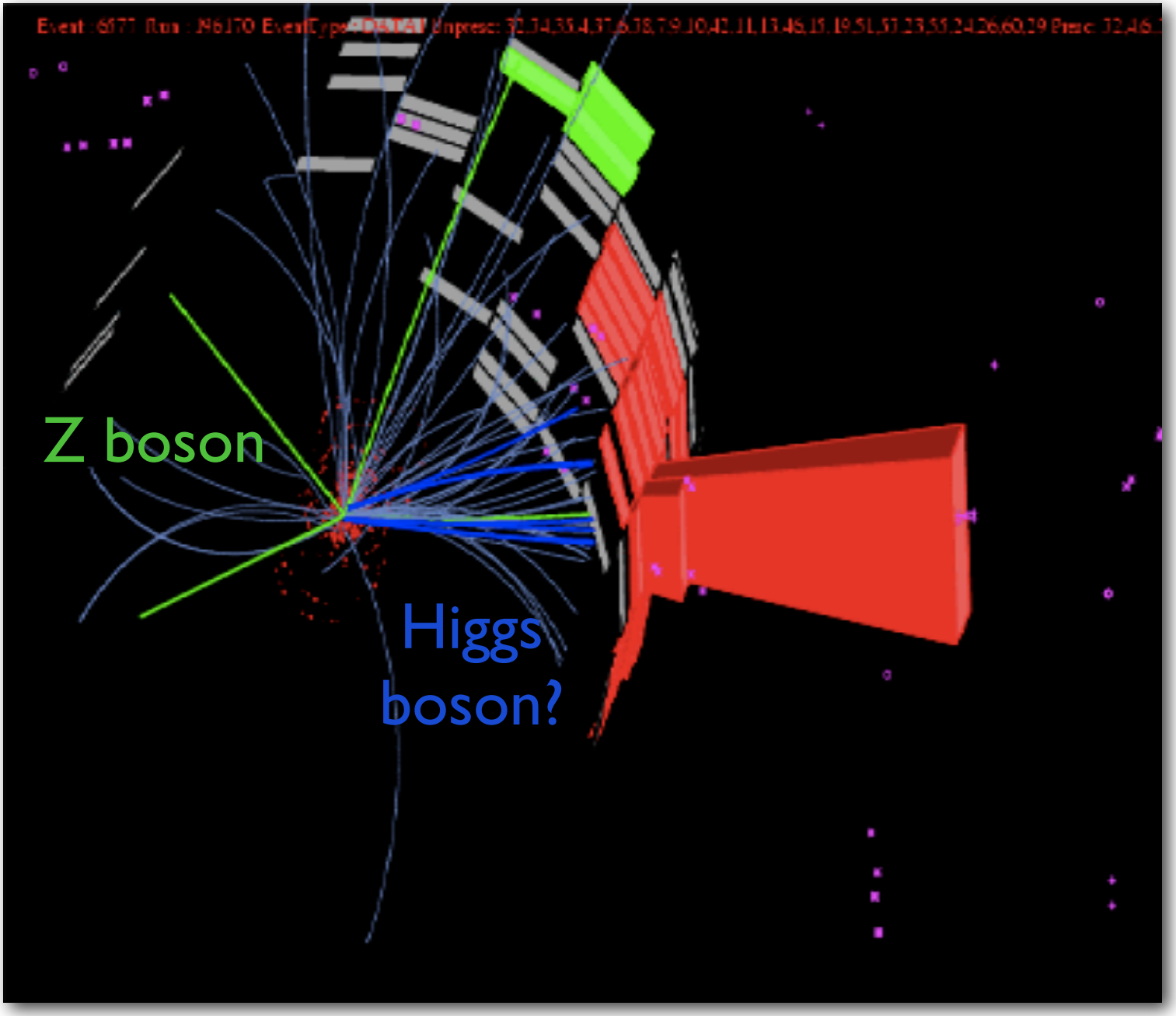
⇒ low mass channels: WH and ZH (with leptons)



⇒ high mass channels: H→WW and VH→VWW

37

CDF *ll*bb candidate event



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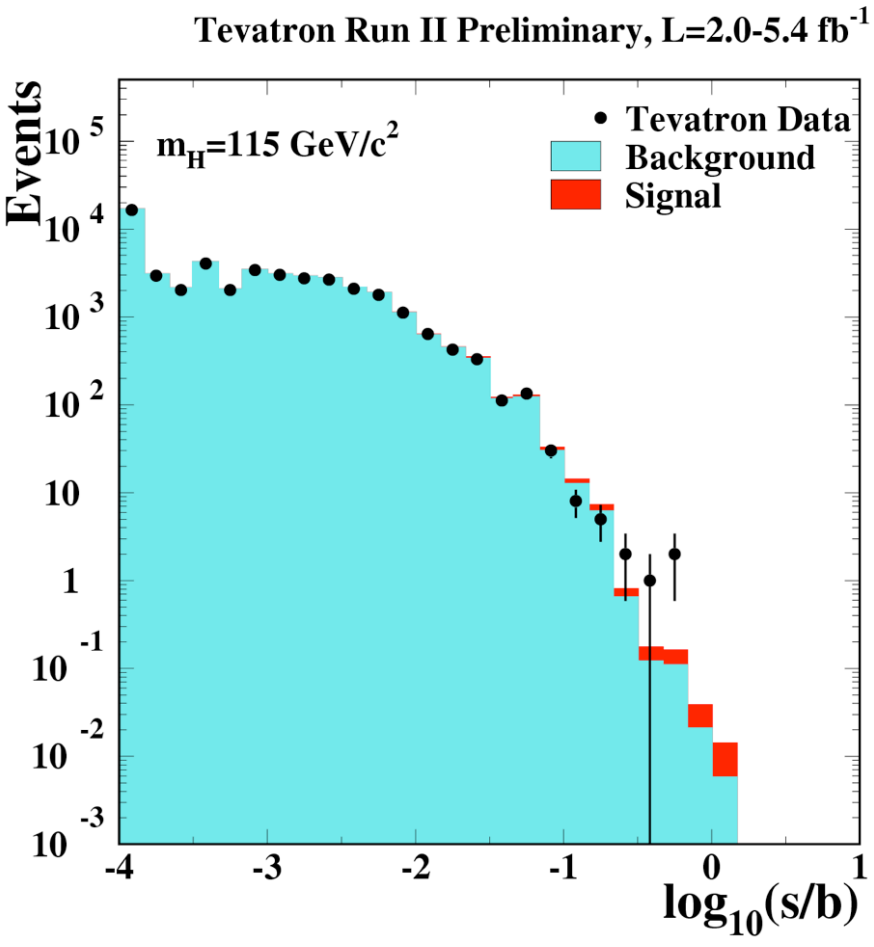
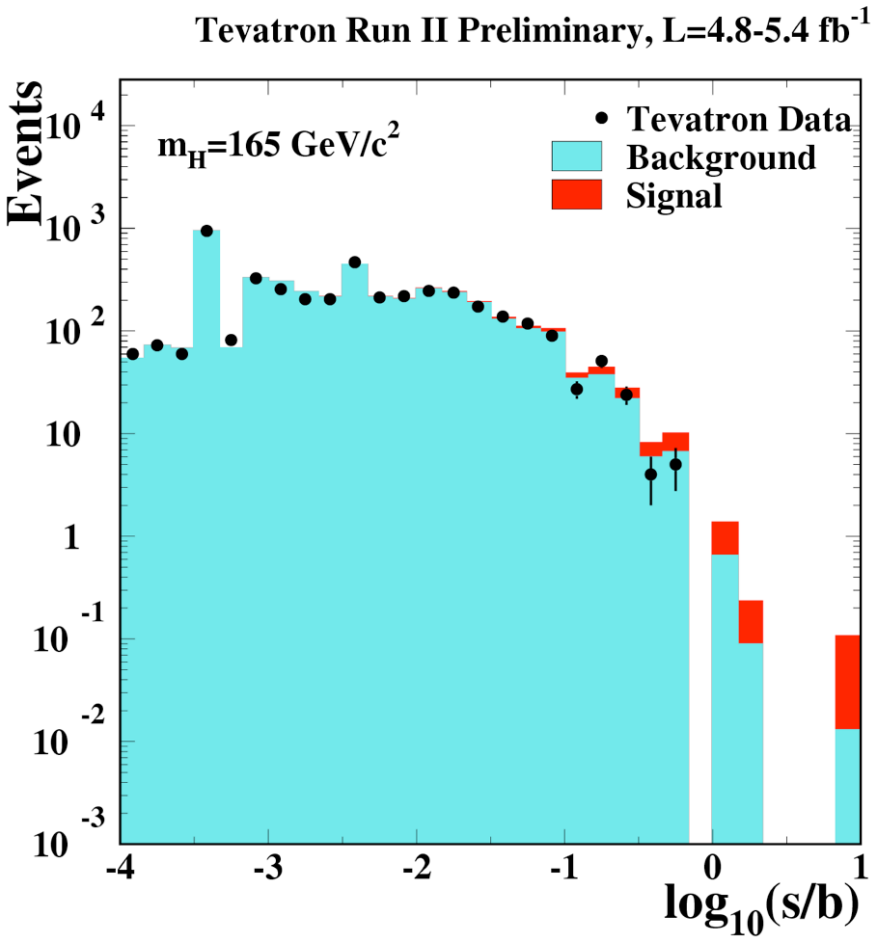
Combined Tevatron Results



low mass Higgs



high mass Higgs

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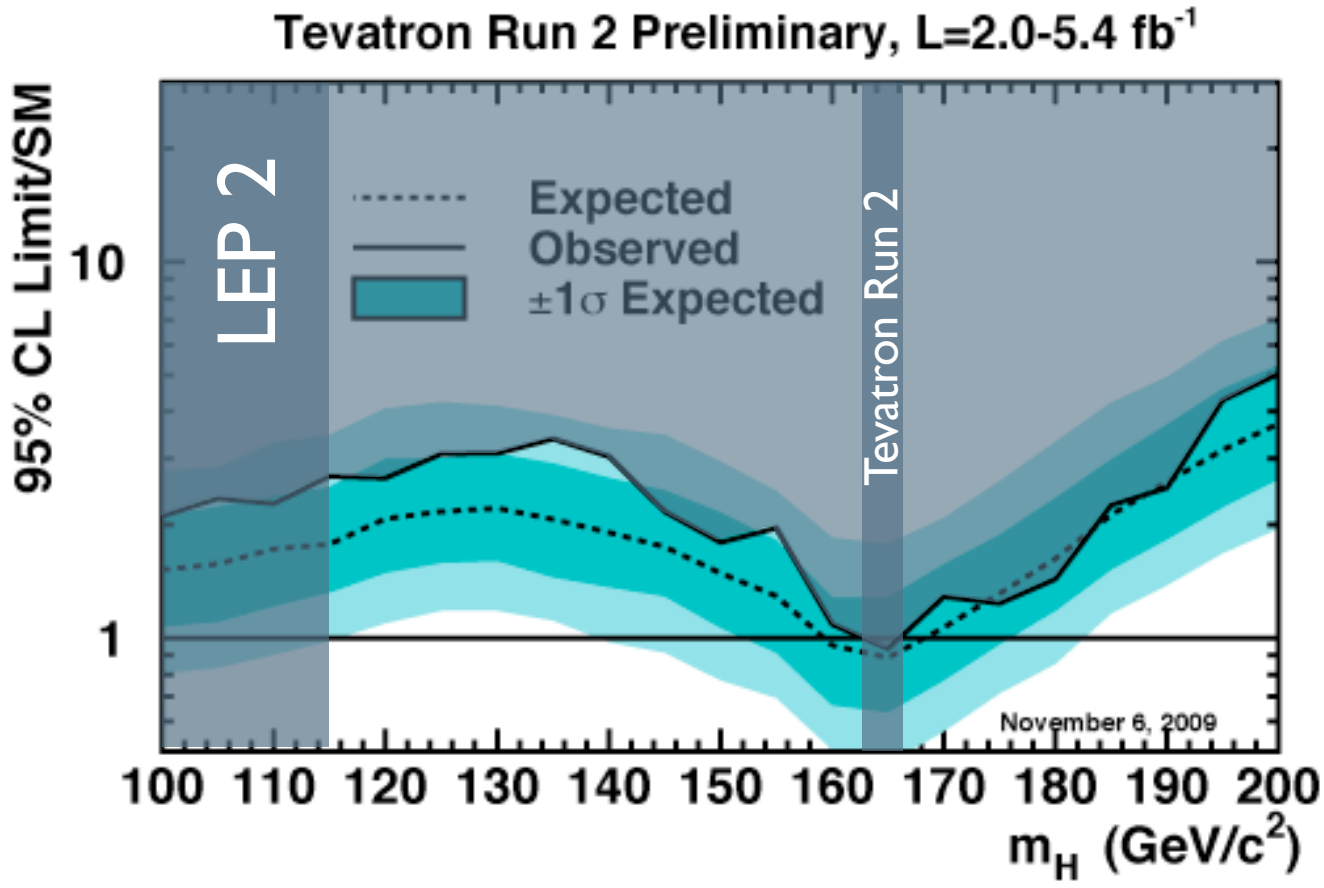
Current Tevatron Limits

So far, can only exclude certain mass ranges, but approaching single-experiment exclusion.



Tevatron can potentially observe a SM Higgs boson, but it takes a lot of data!

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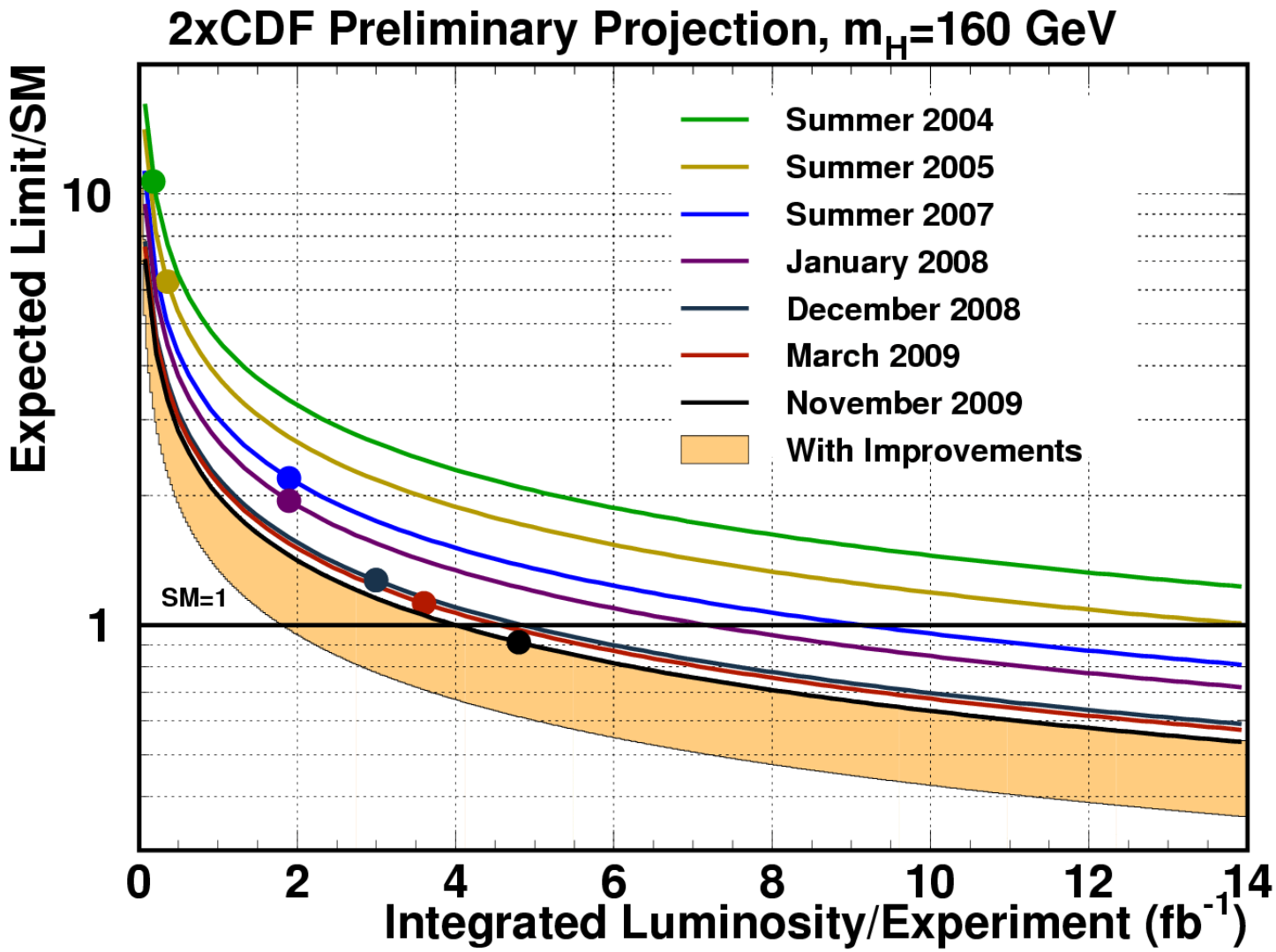
Making steady progress...



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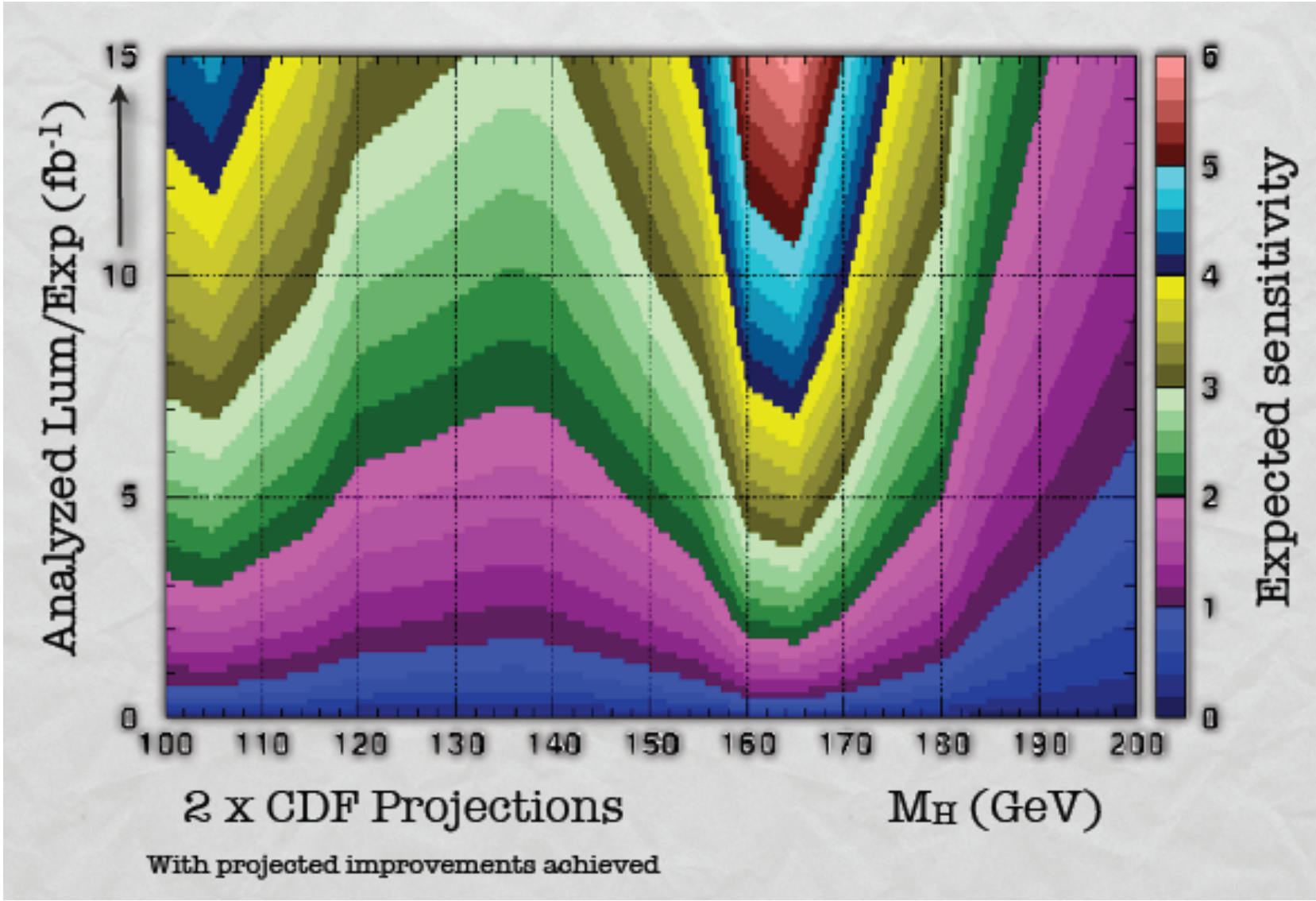
How well can we do?



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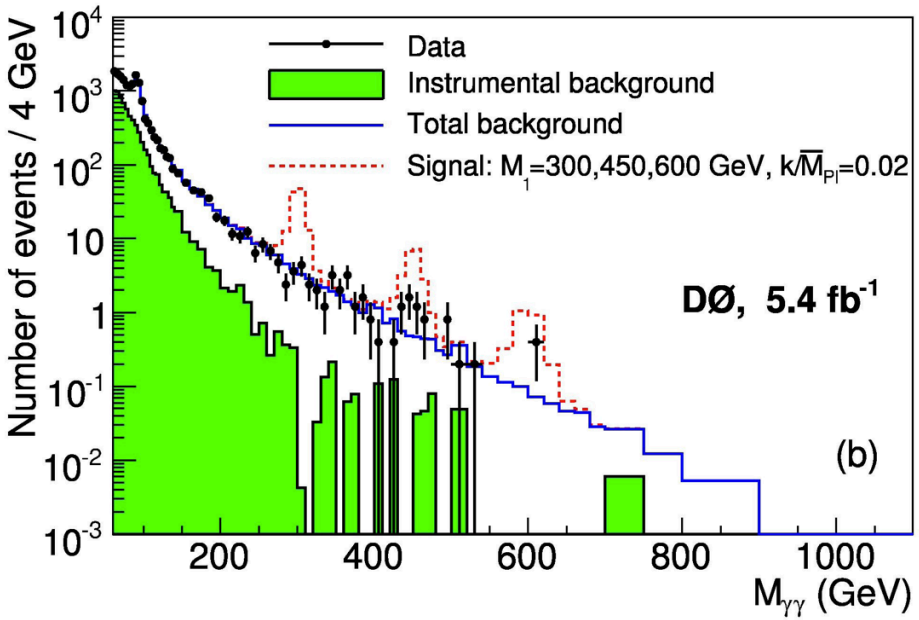
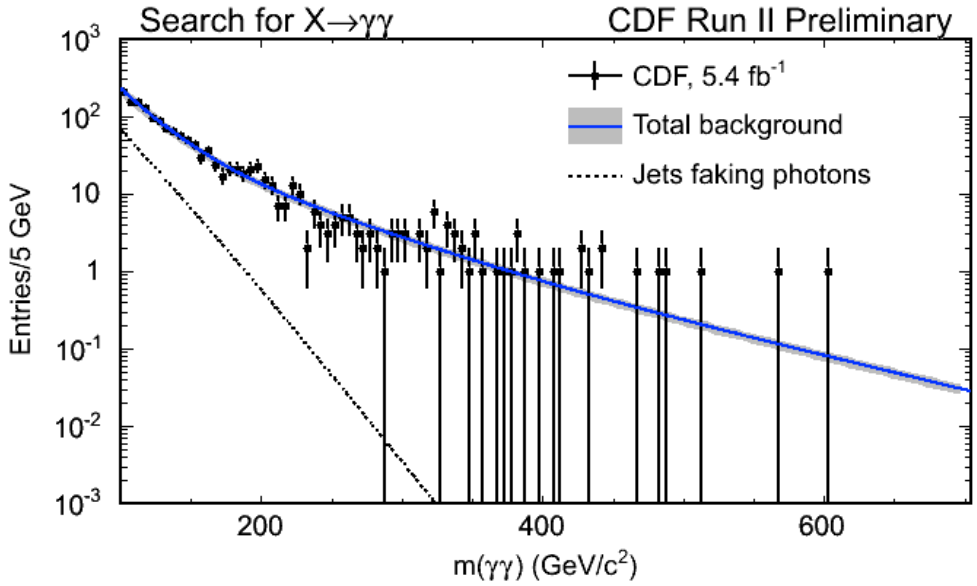
BSM Searches

Recent topics: Dark photons, chargino/neutralino production, GMSB in γγMET, scalar bottoms, 3rd gen LQs, 4th gen quarks...





D0: new RS graviton limits with Z′→ee/γγ

CDF: new limits on Z′→μμ and RS gravitons to γγ

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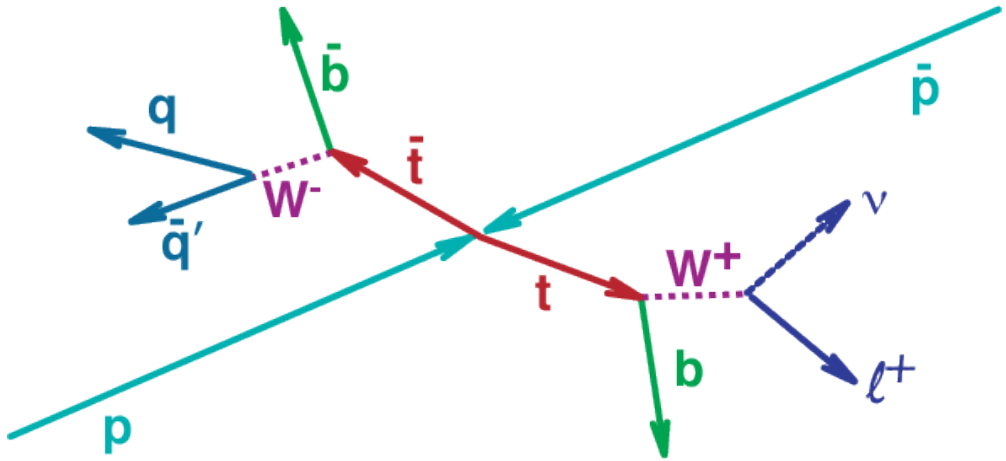
On to the TOP-ic for the meeting...

Highest energy collider in the world... until December.



The only place producing top quarks up until ~now. We are still learning a lot!

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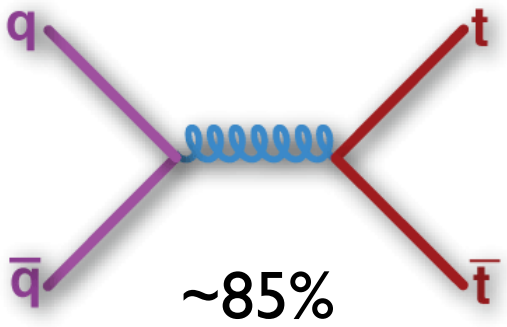
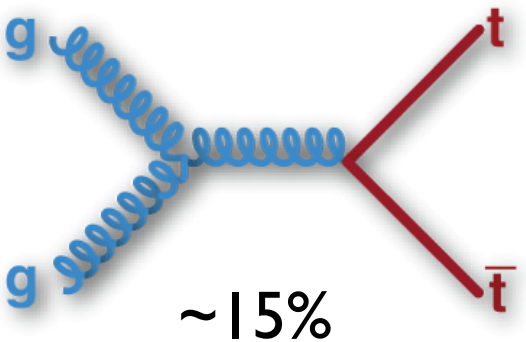
Tevatron Top Pair Production

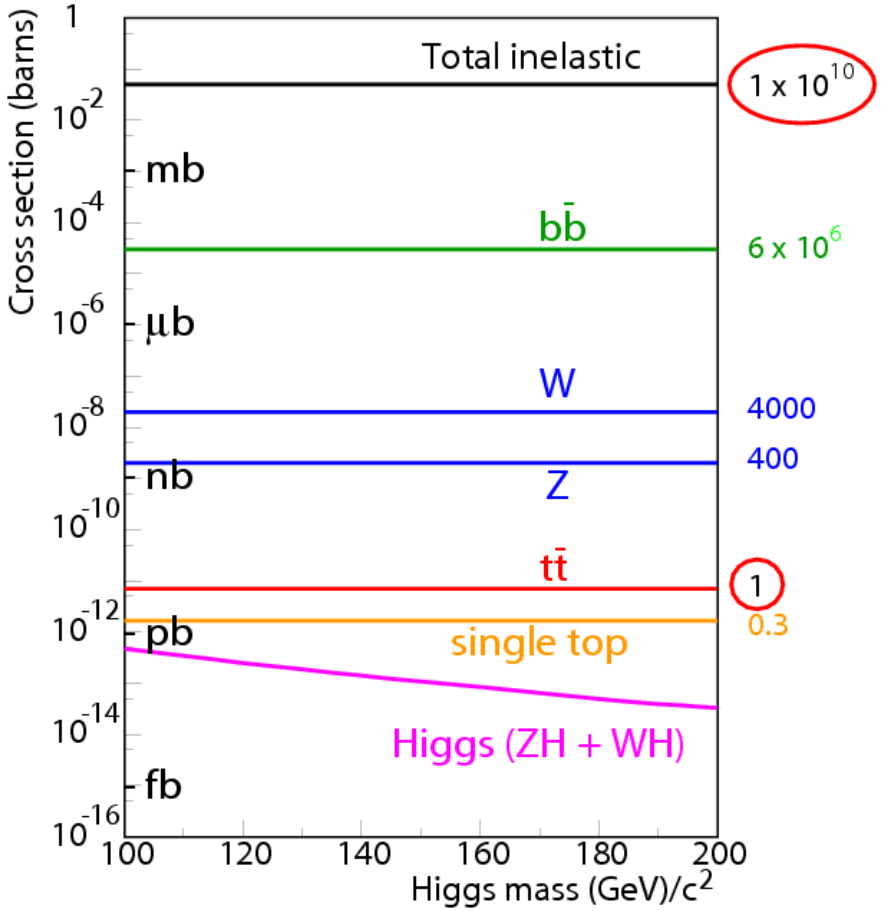


~85%

Strong Pair Production at the Tevatron



~15%



One top pair each 10^{10} inelastic collisions at $\sqrt{s}$ = 1.96 TeV

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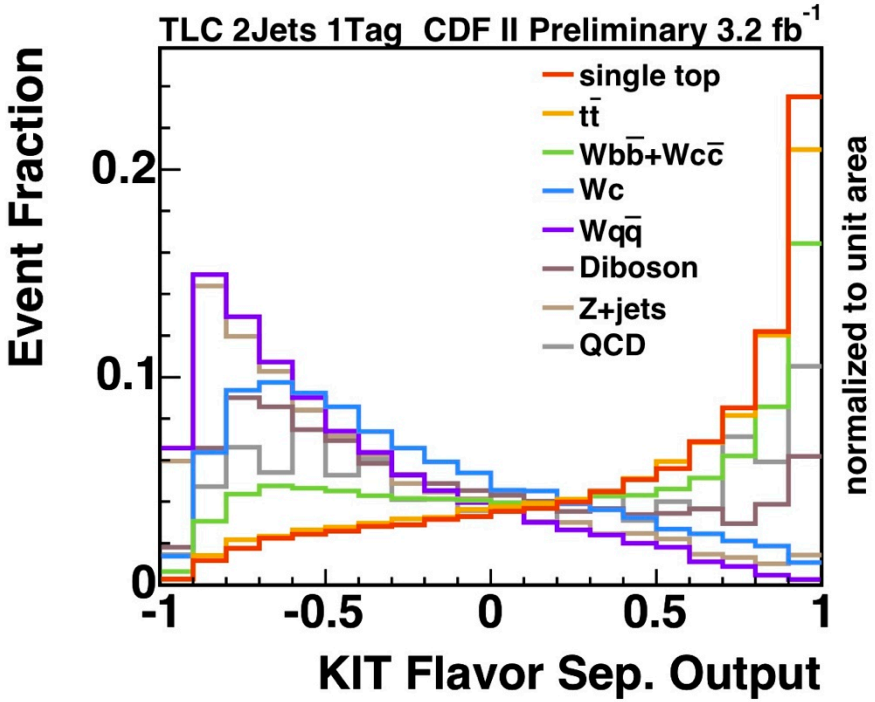
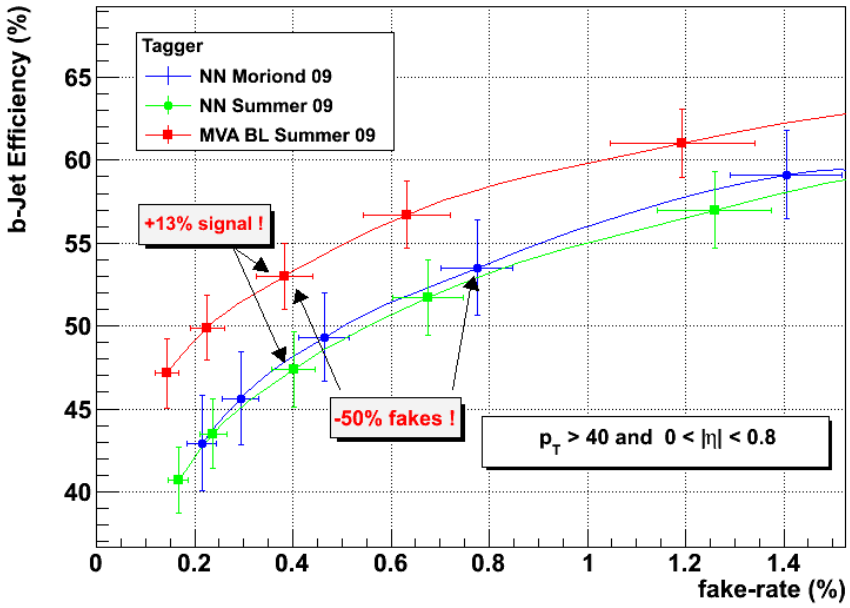
b-Jet Tagging

- CDF: Neural network flavor separator for top and Higgs physics. *(Higgs driving overhaul of b-tagging.)*
  - Separation of charm, bottom, light backgrounds, Wc, etc.
  - Have neural net *b* tagger, not deployed widely for top.
- D0: Neural network *b*-jet tagger used widely.





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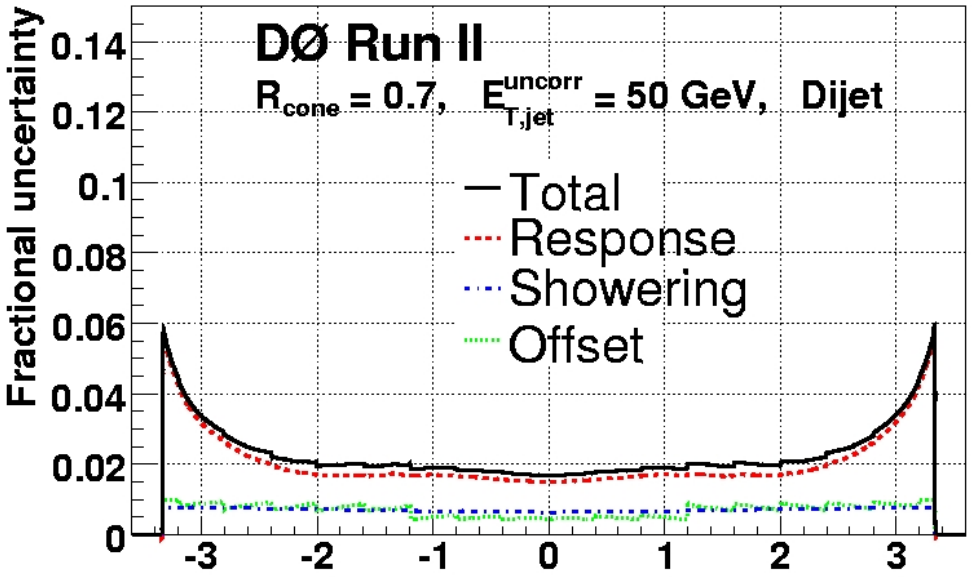
Understanding Jets



- Jet energy scales used to severely limit top physics.
- Has become less important with the W→jj calibration (simultaneous fit) in lepton+jets and all-hadronic, even applied to dilepton.
- Still limits some measurements, try to find creative ways around...

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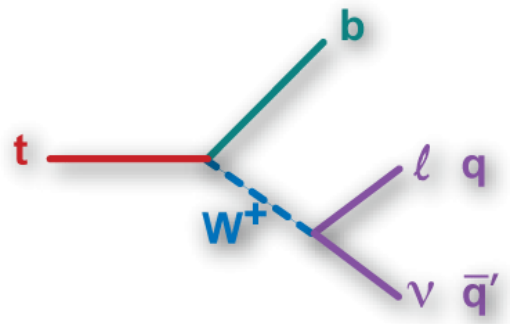
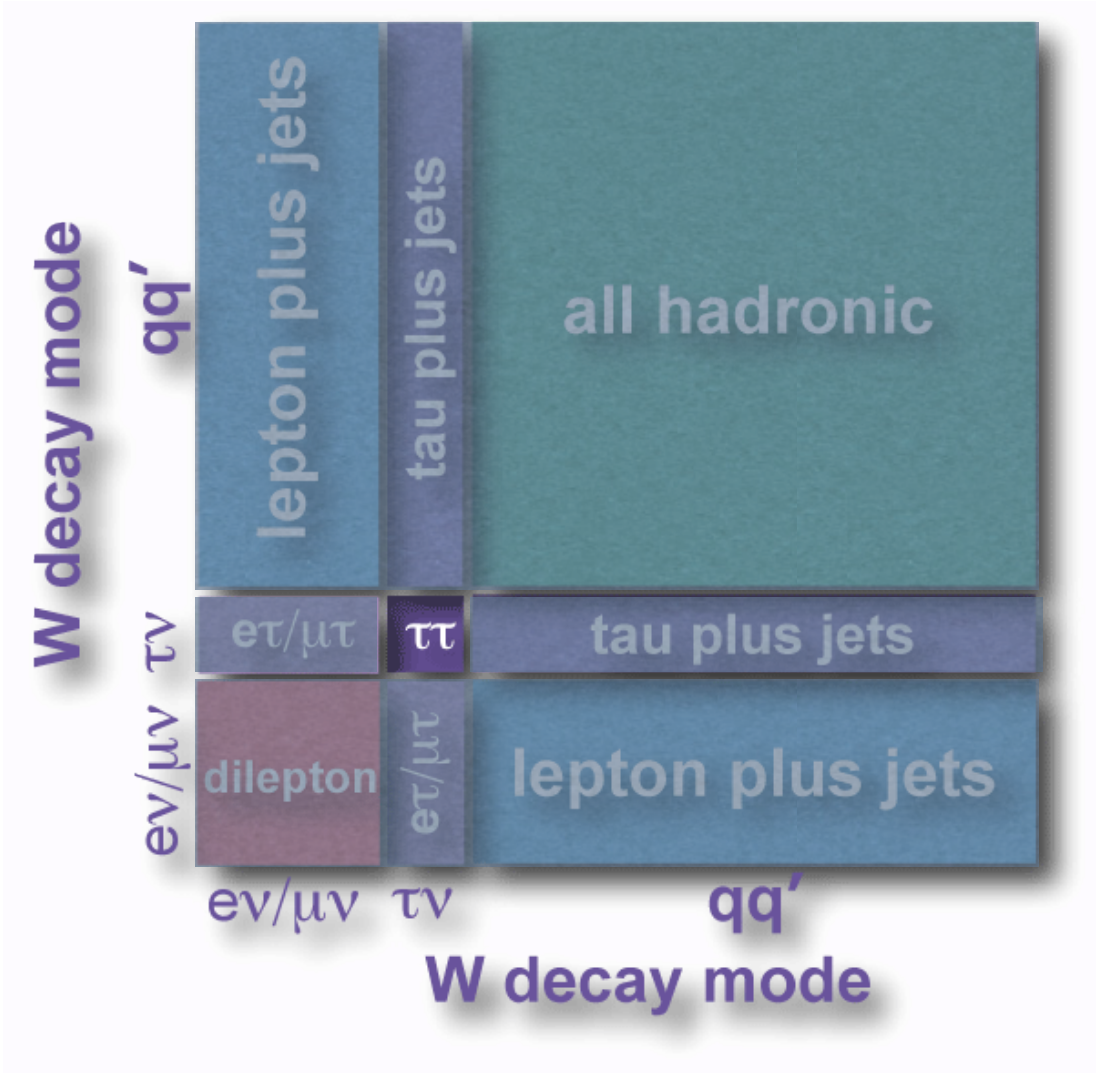
Testing top signatures



t→Wb ~ 100%

Cross section results now cover all but di-tau final states



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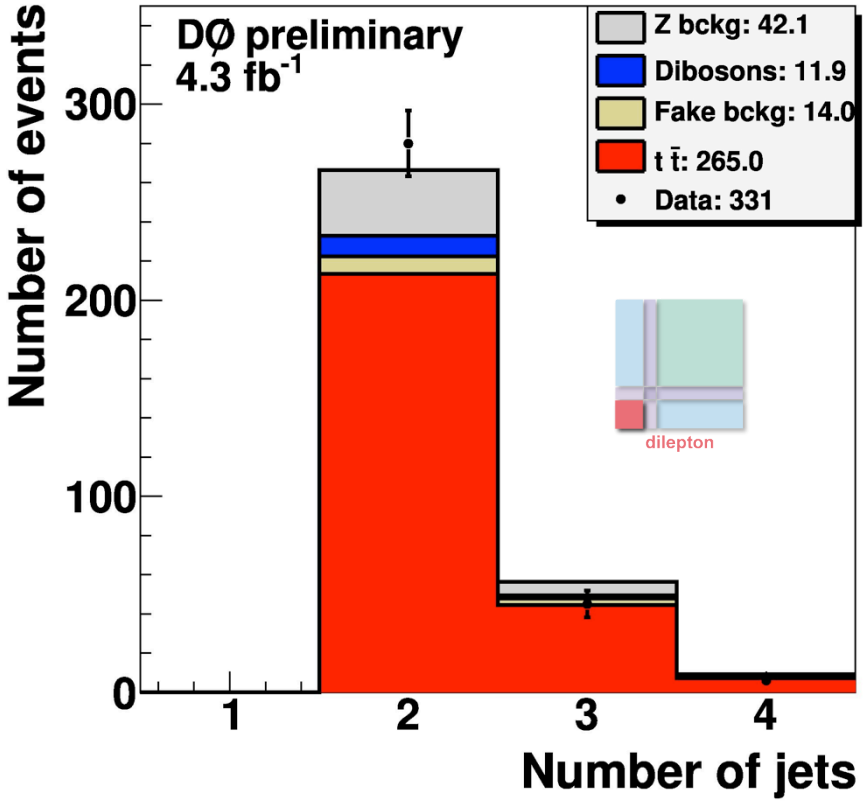
Challenging the Theory

- Lepton+Jets cross sections achieving 9%-11% relative precision. Pushing theory (~9%). S. Moch and P. Uwer, Nucl. Phys. Proc. Suppl. 183, 75 (2008).
- Dilepton channel (tagged, untagged, and topological) achieving excellent precision as well (13-14%).



See talk by Deloit

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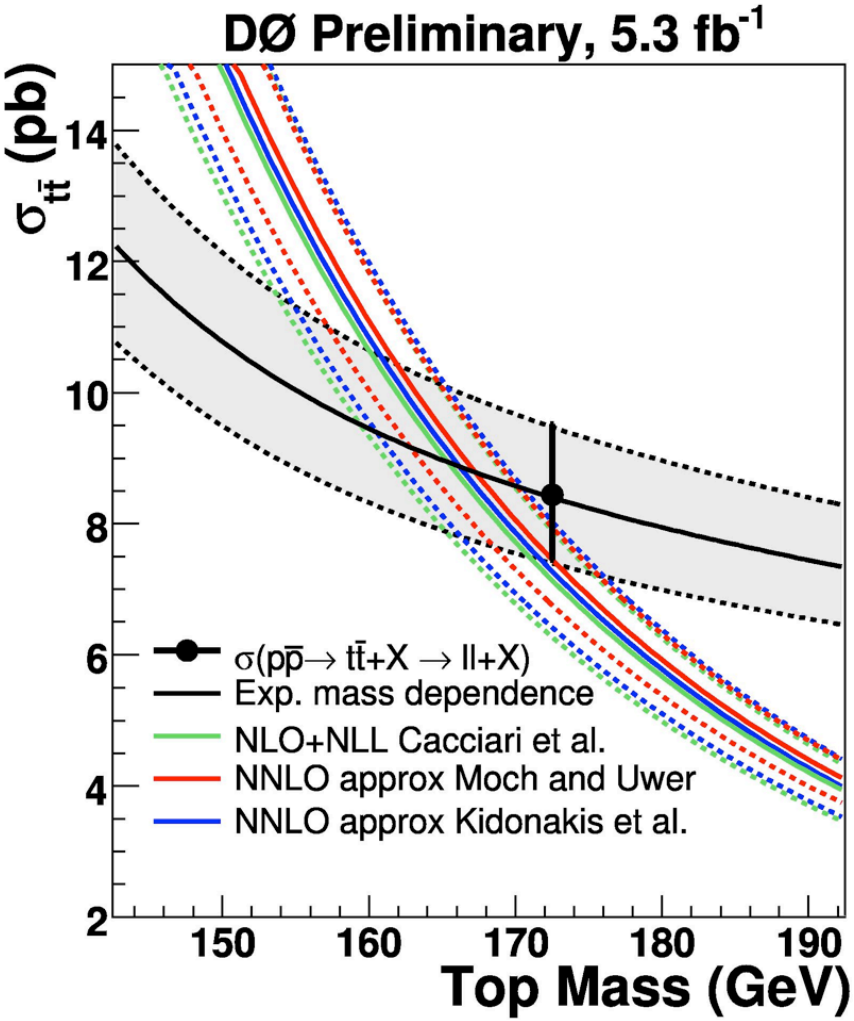
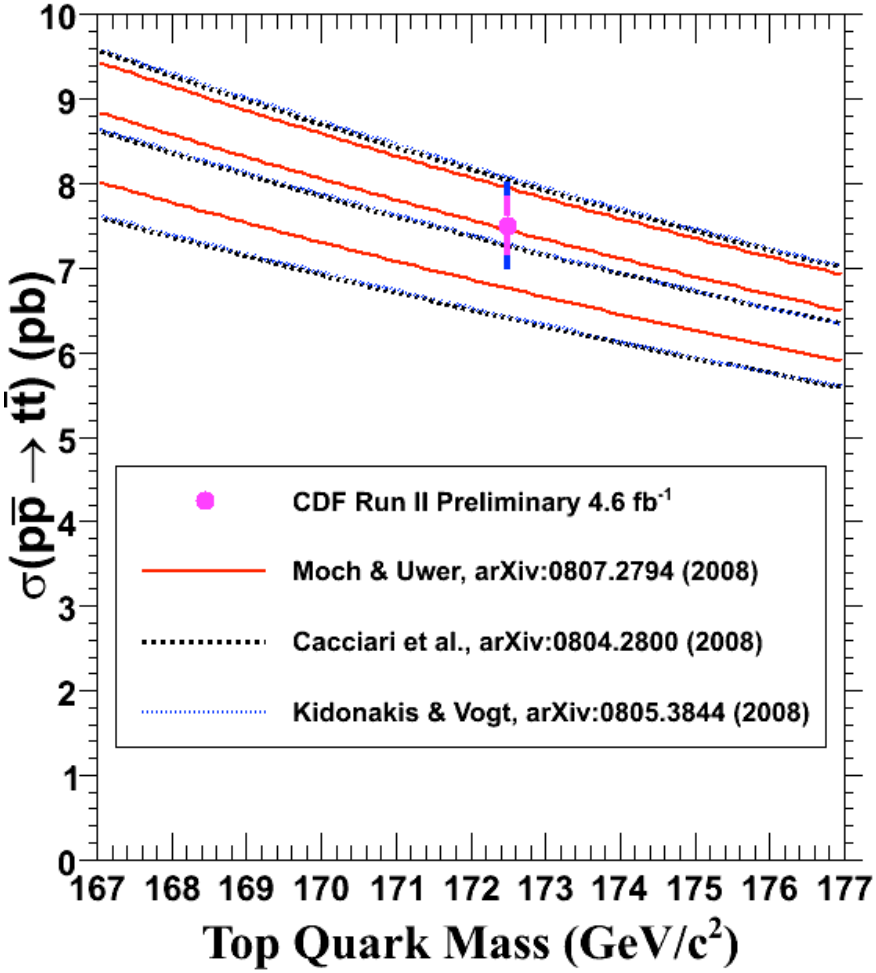
Testing the Theory



Extract top mass from cross section



Compare measured mass and cross section

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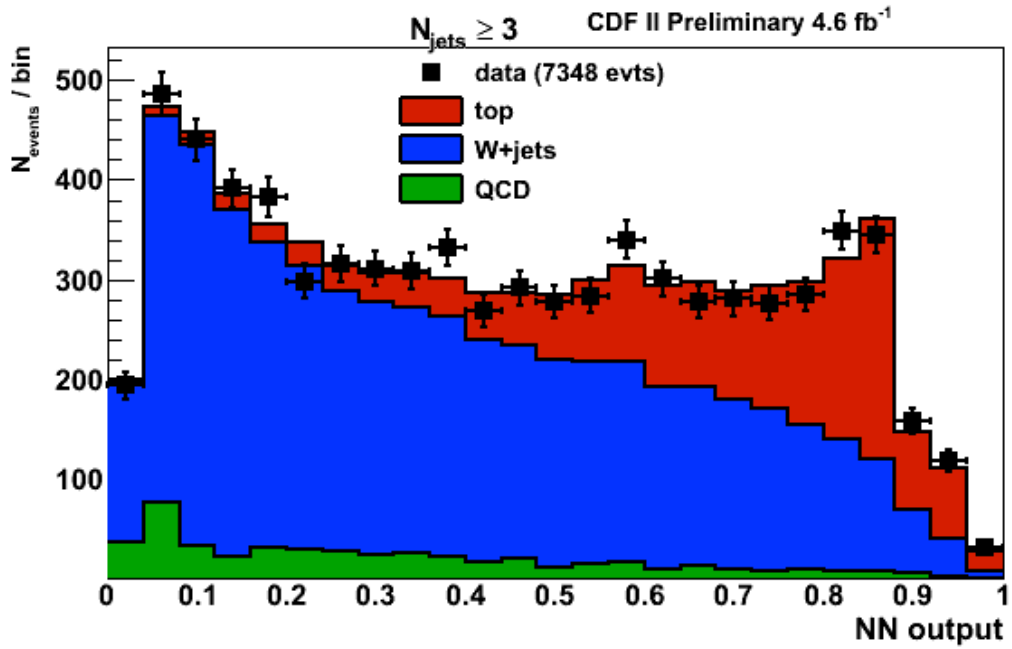
Challenging the Experiments

- Lepton+Jets channel limited by systematics, luminosity dominates at ~6%.
- Take ratio to Z cross section: trade for Z theory uncertainty



CDF topological (ANN) achieves 7% relative precision in ratio, 8.8% with luminosity uncertainty.

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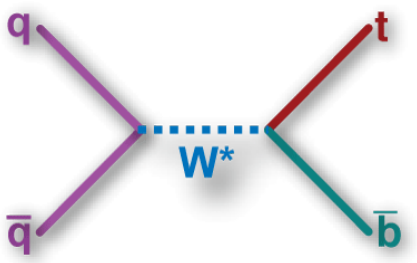
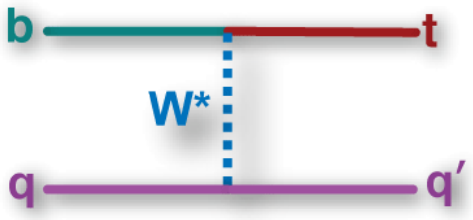
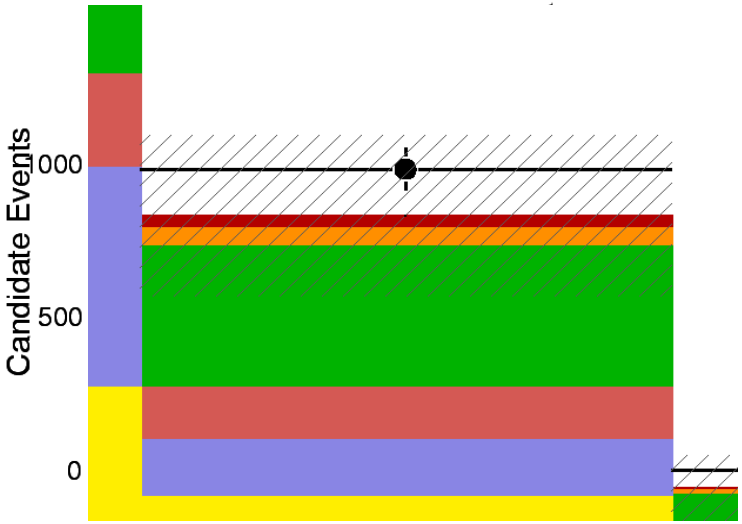
Challenging the Experiments

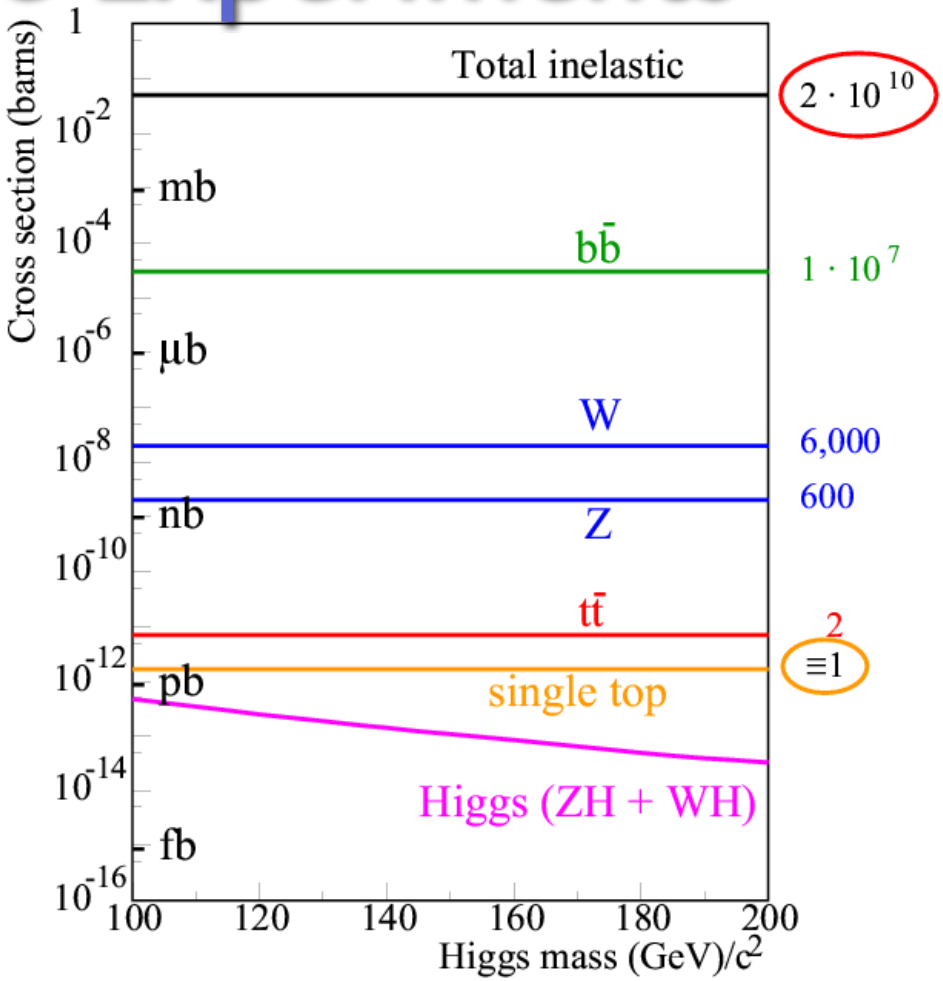


s-channel ~1 pb



t-channel ~2 pb





Single top backgrounds much larger than signal: Statistically & systematically challenging at the Tevatron

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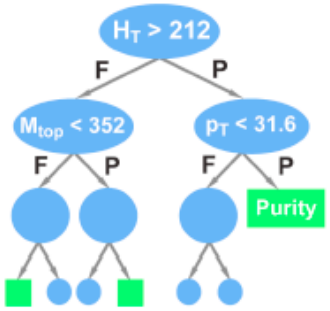
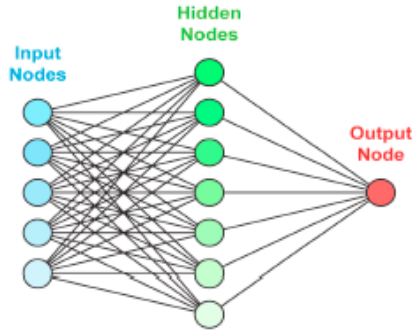
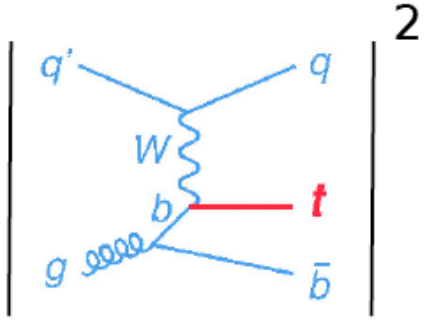
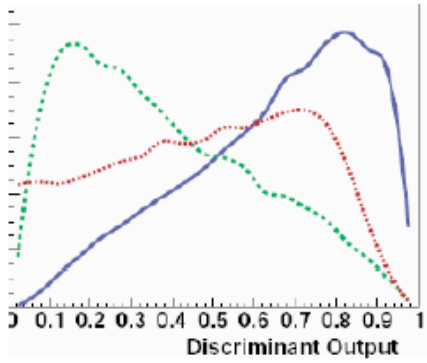
Single Top Production

Decision Trees | Neural Networks | Matrix Elements | Likelihoods









See techniques talk by F. Canelli

- Separate cross section measurements with each technique
- Combine techniques & expts: 60-90% correlated, gain significance
- New from D0: separate s- and t-channel results, results in tau +jets, top width/lifetime extraction
- New from CDF: simultaneous s- and t-channel measurement, top polarization
- Searches in single top sample: W′, FCNC...

See talks by Lueck, Heinson

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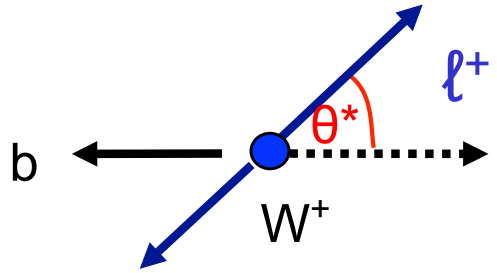
Top Decay Properties: Some being revisited with more data

- W helicity, top charge
- top width, lifetime



Some just now sensitive

- Spin correlations in dilepton and L+J
- Look for Tevatron combinations soon

See talks by Sorin/Datta, Harel

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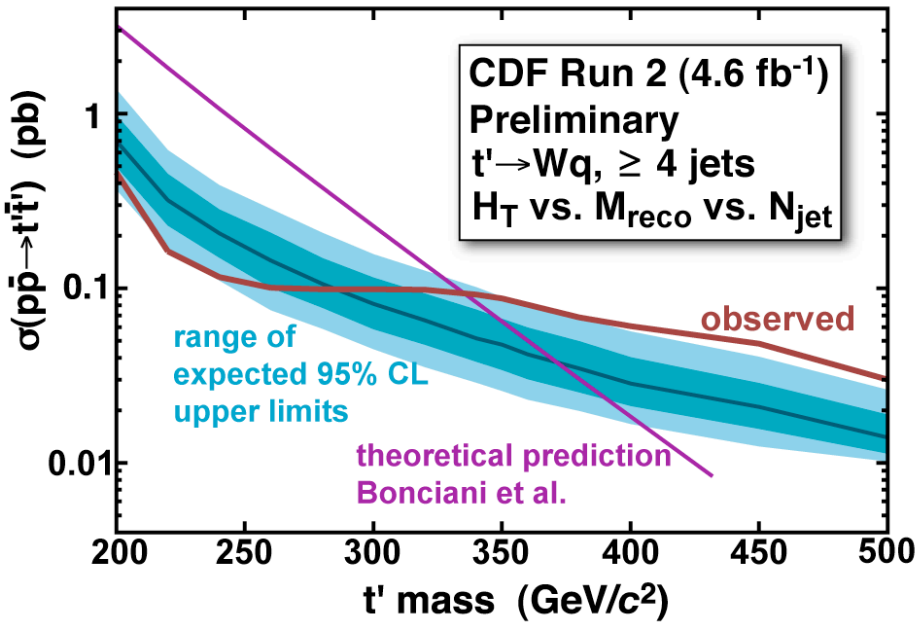
New or Anomalous Top Production

- Looking for anomalies in top properties or signs of new physics in the sample:
  - Top production asymmetry A_{fb}
  - $X \rightarrow tt$, most recently in all-hadronic!
  - Search for massive top
  - Charged Higgs, stop
  - ...

See talks by Sorin/Datta, Harel & Sinervo



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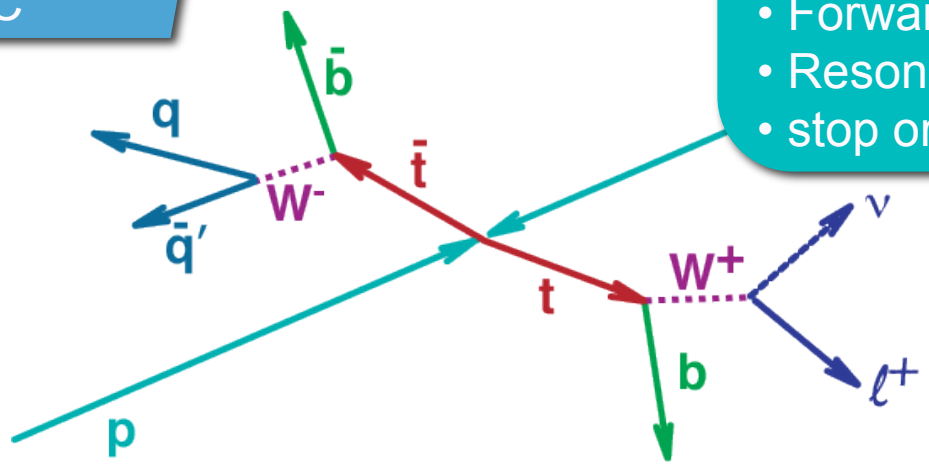
Lessons of the Top Quark

Top Event Decays
- W helicity (V-A)
- Branching ratios
- Top to charged higgs
- Top sample (W+HF)
- FCNC

Top Quark Production
- Mechanism
- Top Pair Cross Section
- Ewk Production (single top)
- Forward-backward asymmetry
- Resonances decaying to top
- stop or t' production



Top Properties
- Top Mass
- Top Quark Width
- Charge of Top Quark
- Mt – Mtbar & CPT

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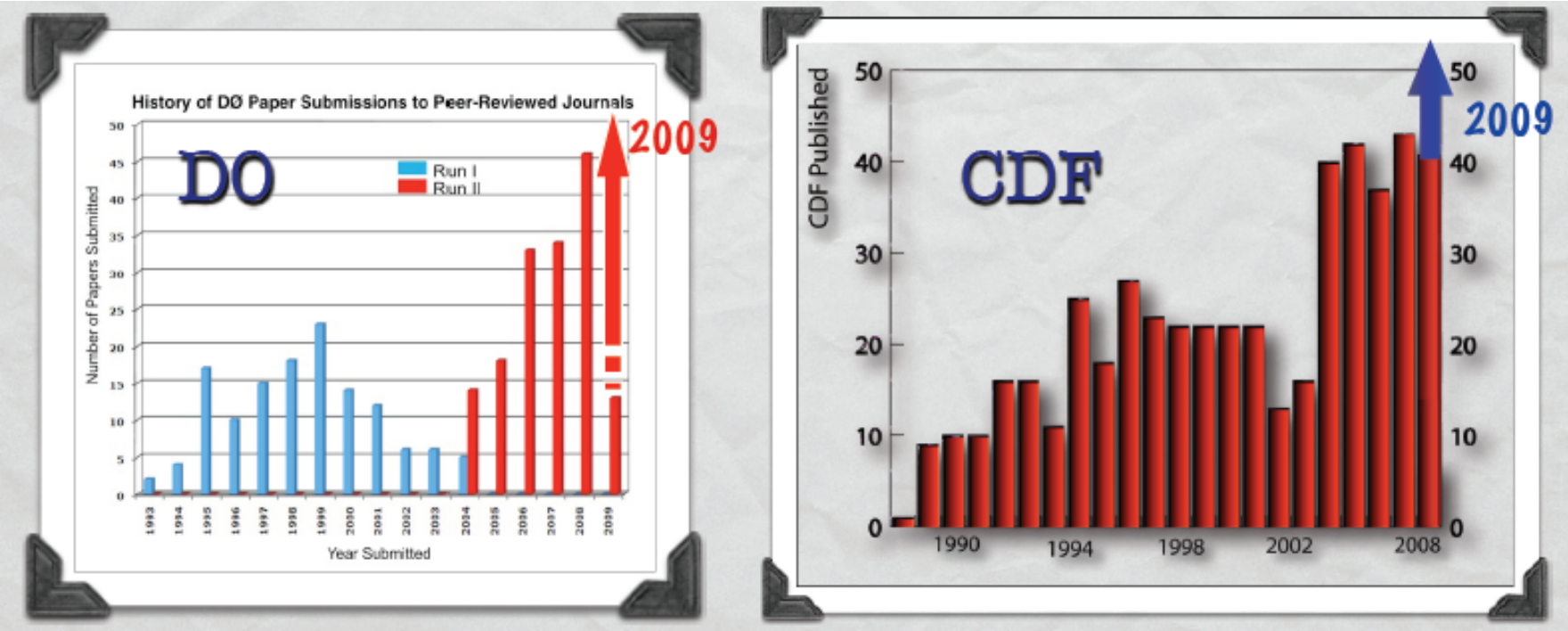
Everything we know about the top, we have learned from the Tevatron

...and will likely remain complimentary for a little while longer...

Tevatron Physics Output



- Tevatron experiments publishing >100 papers/year
- Graduating ~60 PhD's per year recently
- Present >200 talks at conferences each year

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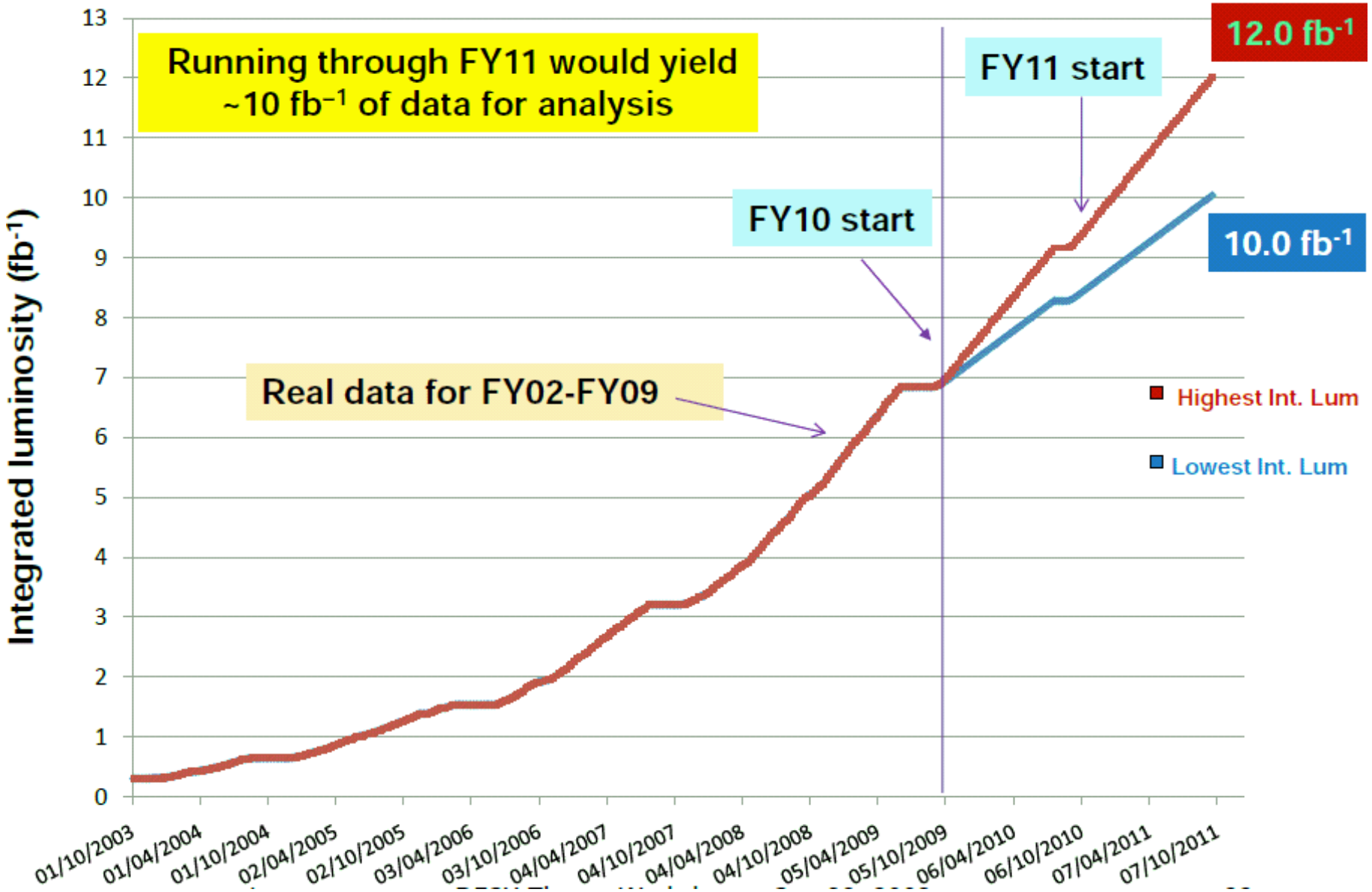
Will the Tevatron continue?



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Top may be the real story of the Tevatron

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