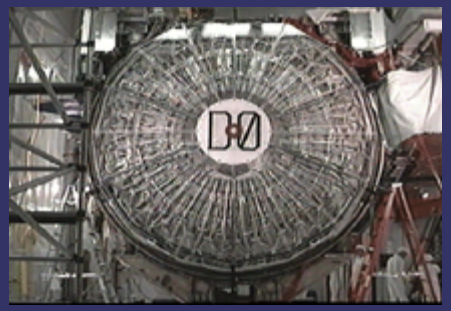
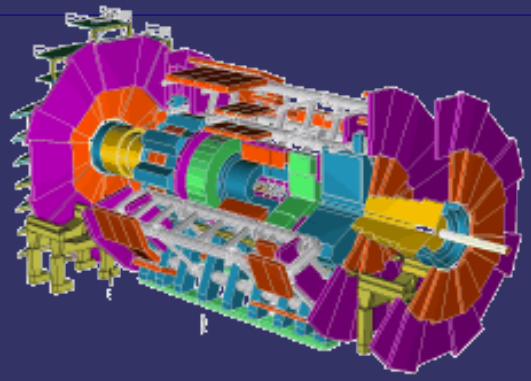
Bob Hirosky

Today at the Tevatron, Tomorrow at the LHC





Most powerful terrestrial tools to confront and study the standard model

Question #1: "What is the Universe made of ?"

big questions

Related questions

- Are there undiscovered principles of nature: new symmetries, new physical laws?
- What is dark matter?
- How can we solve the mystery of dark energy?
- Are there extra dimensions of space?
- What happened to the antimatter?

Explore (most of these) at hadron colliders through:

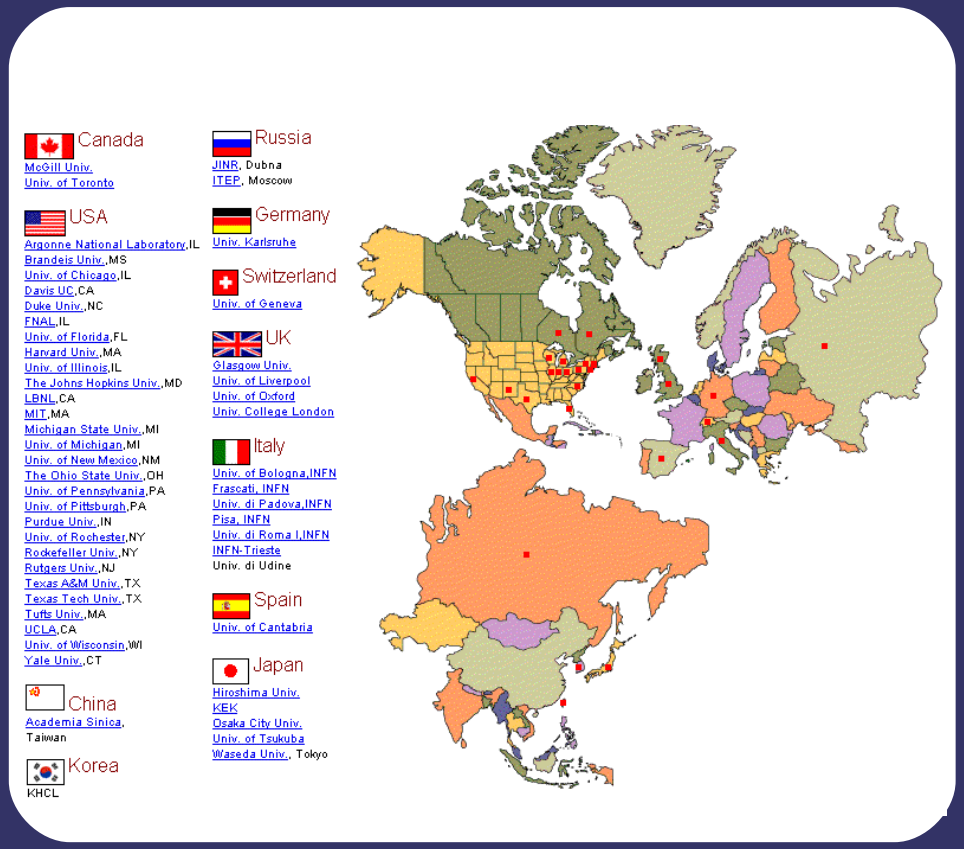
- Gauge, Flavor, EWSB Sectors;
- Search for new symmetries, forces, extra dimensions;

or something completely different...

http://interactions.org/quantumuniverse/qu2006/discovering/mysteries.htm

Tevatron Experiments
CDF and DØ Collaborations

O(700) physicists and students per experiment

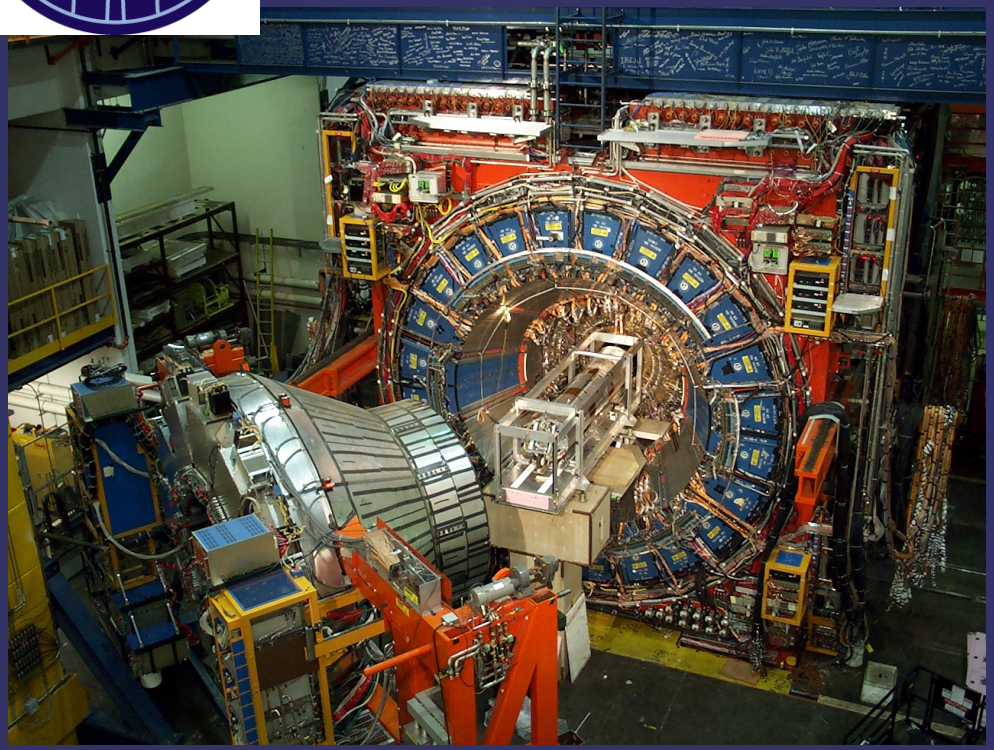


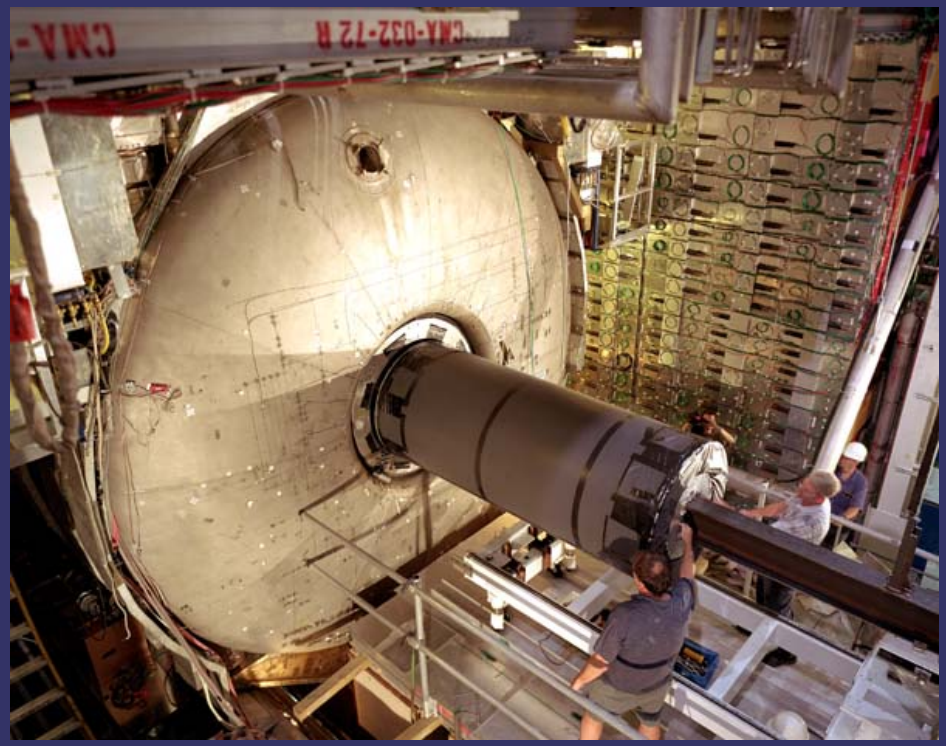
13 nations and 61 institutions

20 nations and 91 institutions

Truly world-wide efforts. Currently engaged in 2nd major data runs: RunII

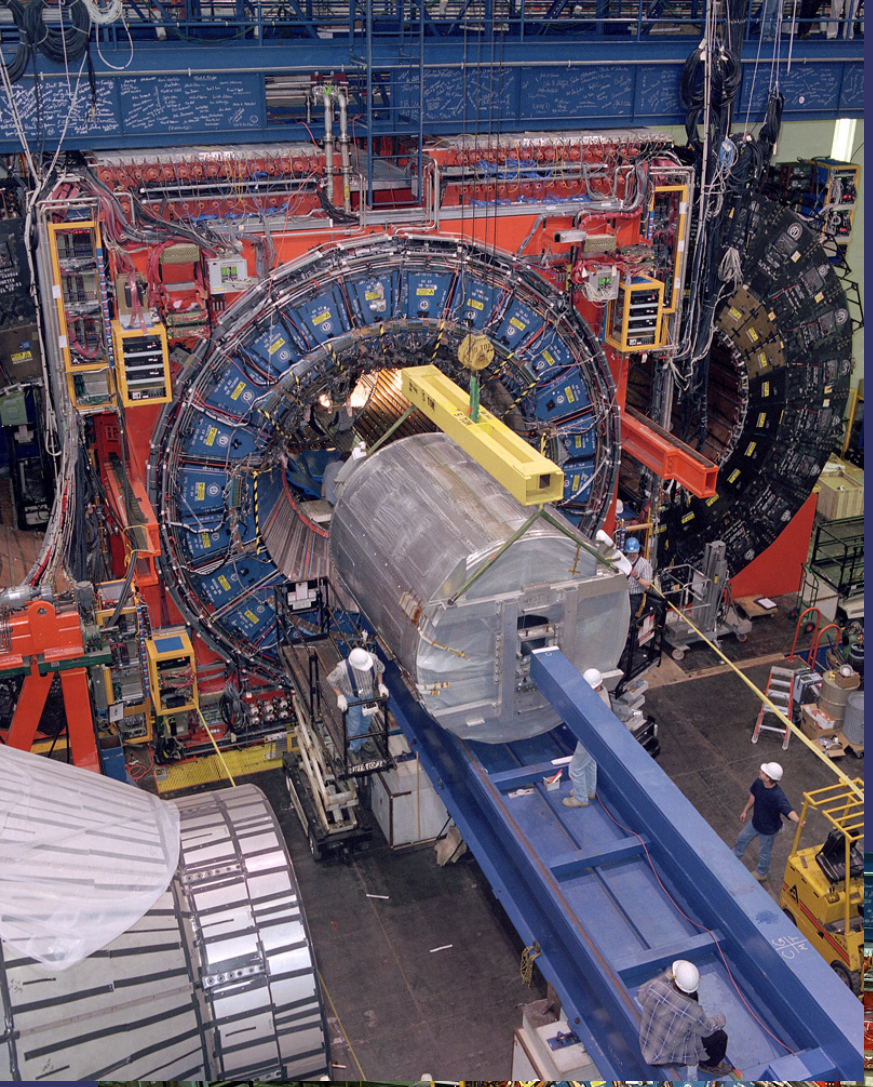
Tevatron Detectors

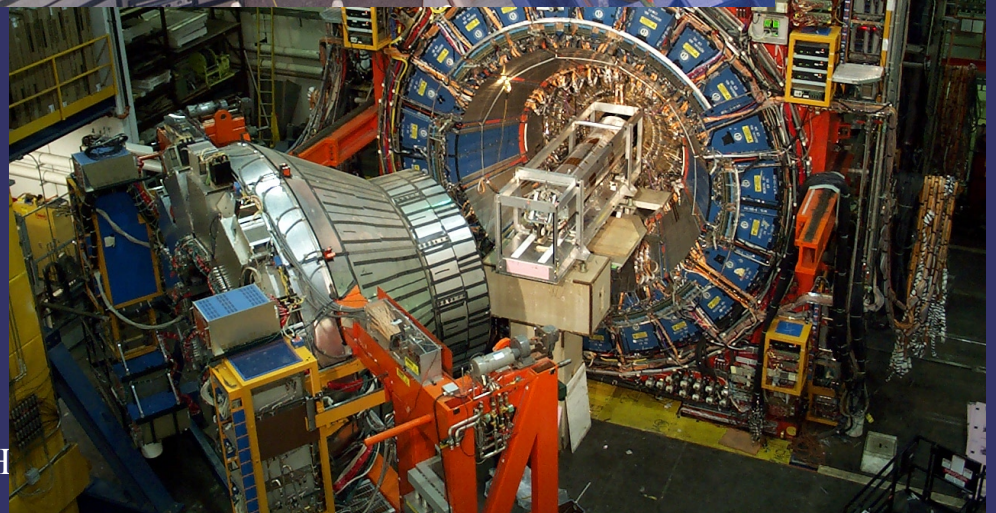


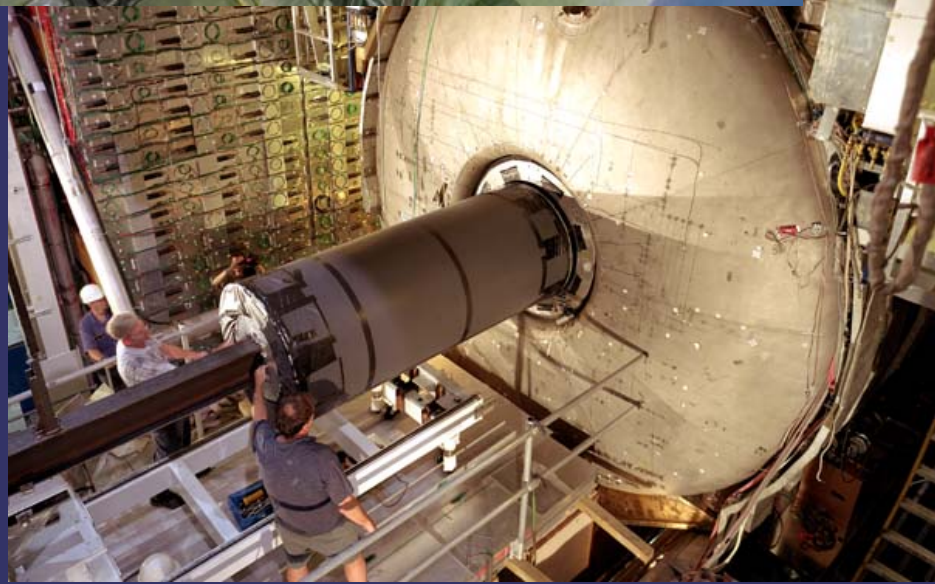


Excellent general-purpose detectors -
tracking, b-tagging, calorimetry, muon, …

CDF Strengths: momentum resolution, particle ID(K,π)
DØ Strengths: muon coverage, calorimeter energy resolution

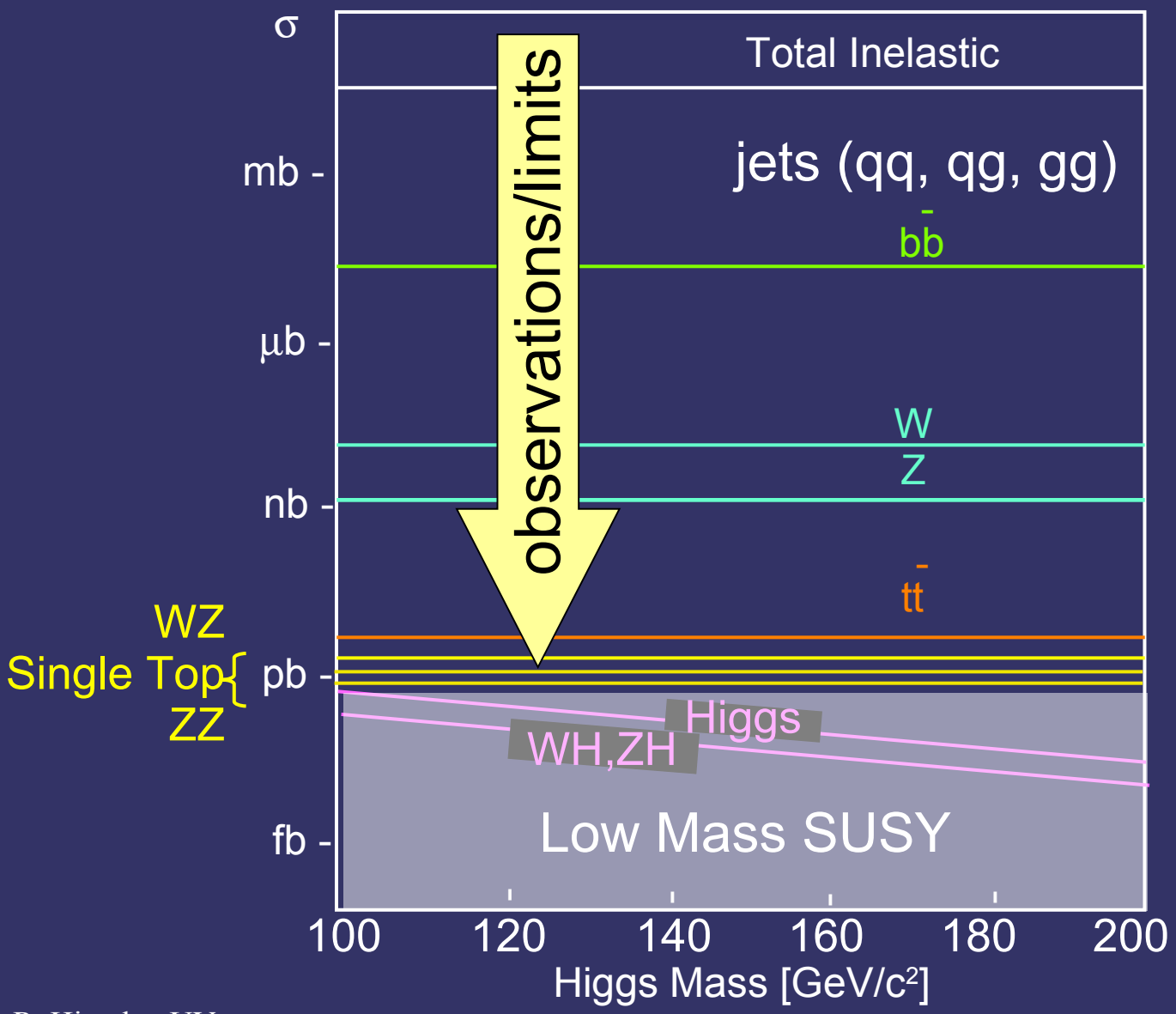






R. H

Physics Accessible at the Tevatron



produced *
with 1 fb^{-1}

1.4×10^{14}

1×10^{11}

3×10^{7}
1×10^{7}

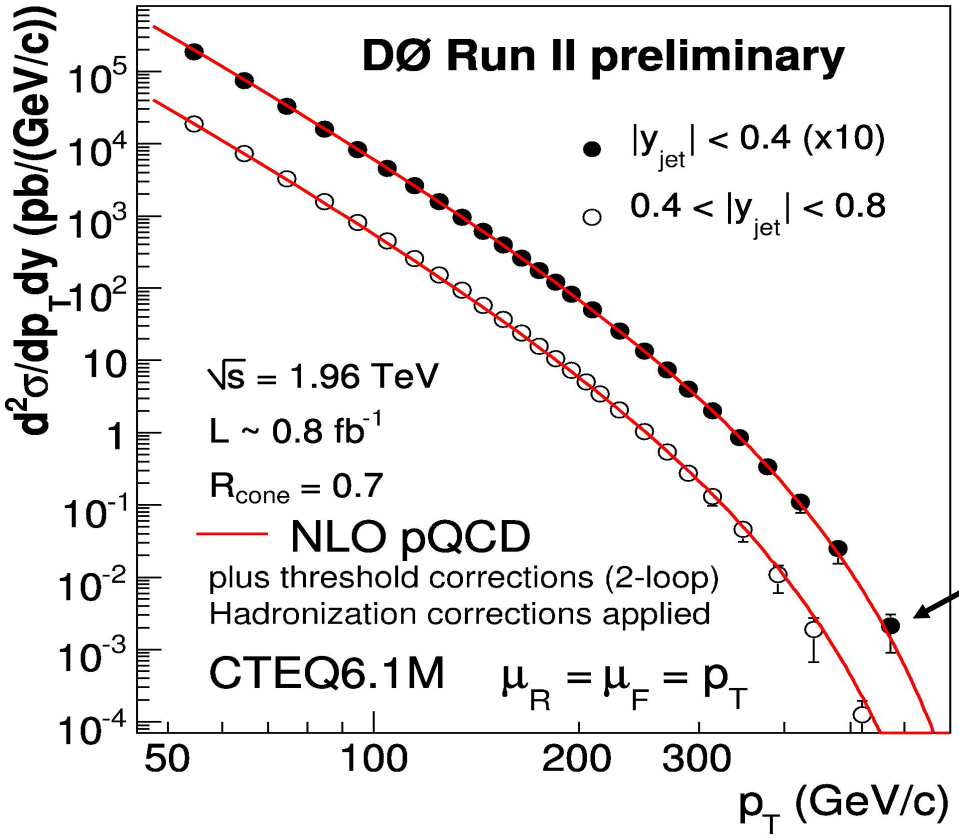
14,000
8,000-3,000

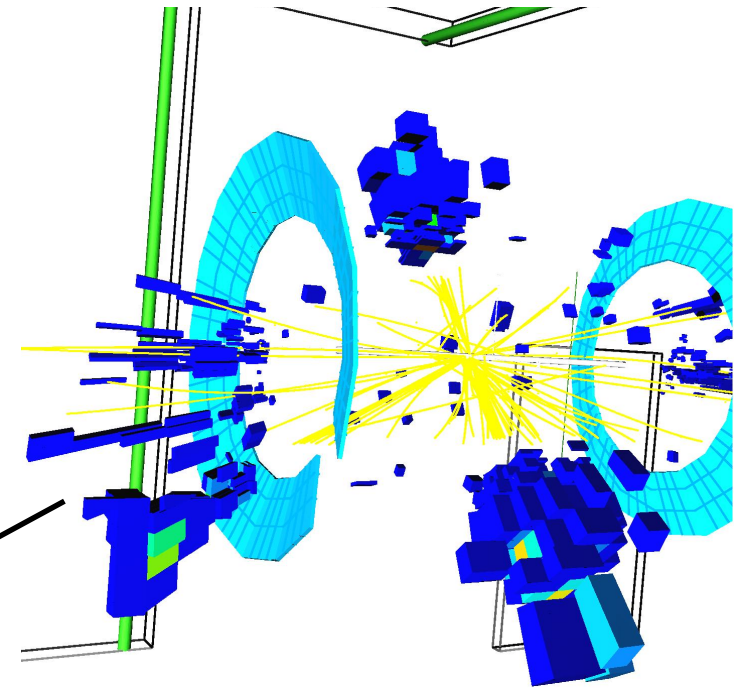
2000 ~ 200
200 ~ 20

R. Hirosky, UVa

* not necessarily on tape, YMMV

Jets (gluons and quarks)





1 TeV Total Energy!

probe elementary nature of quarks, proton structure

9 orders of magnitude in cross section!
Distance scales O(10^{-19}m)

Gauge Sector: (Di)Boson Production

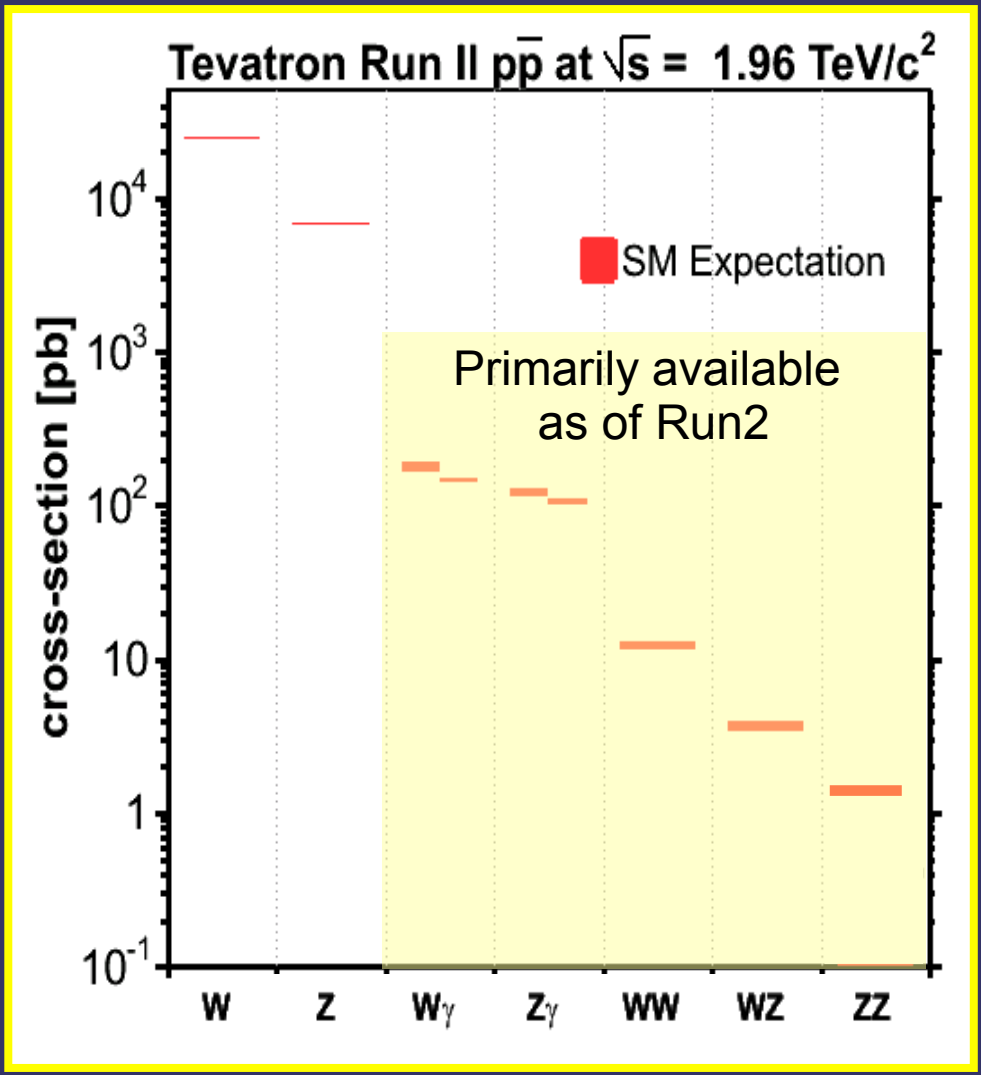
(W, Z) production:

Weν, Wμν, Wτν, Zee, Zμμ, Zττ couplings + searches for heavy gauge bosons (W', Z')

Diboson (Wγ, Zγ, WW, WZ) production:

Gauge boson self-interactions

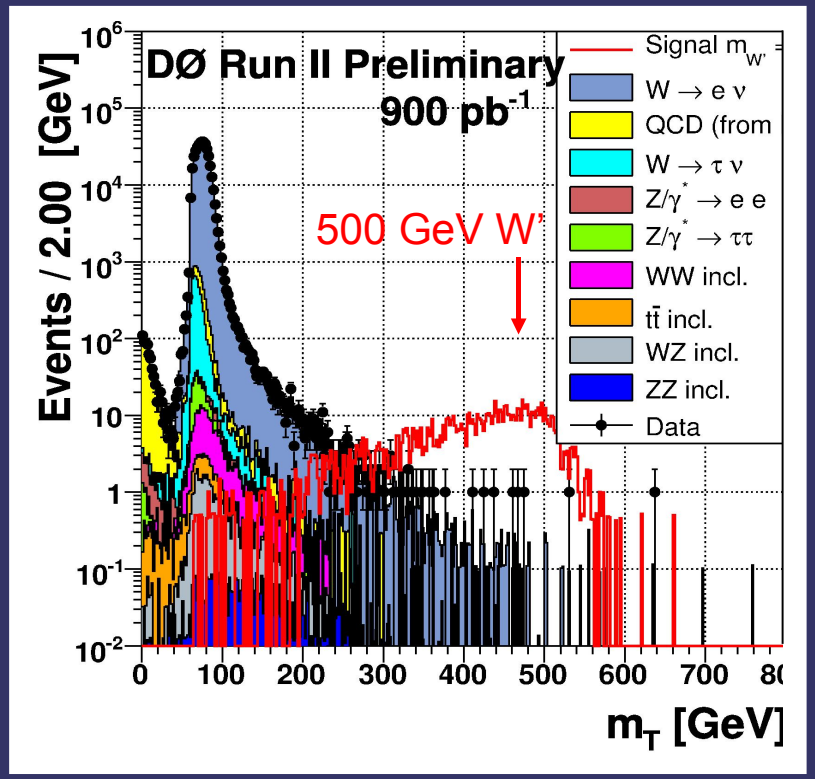
(WWγ, WWZ, ZZγ, Zγγ)



Explore S.M.,

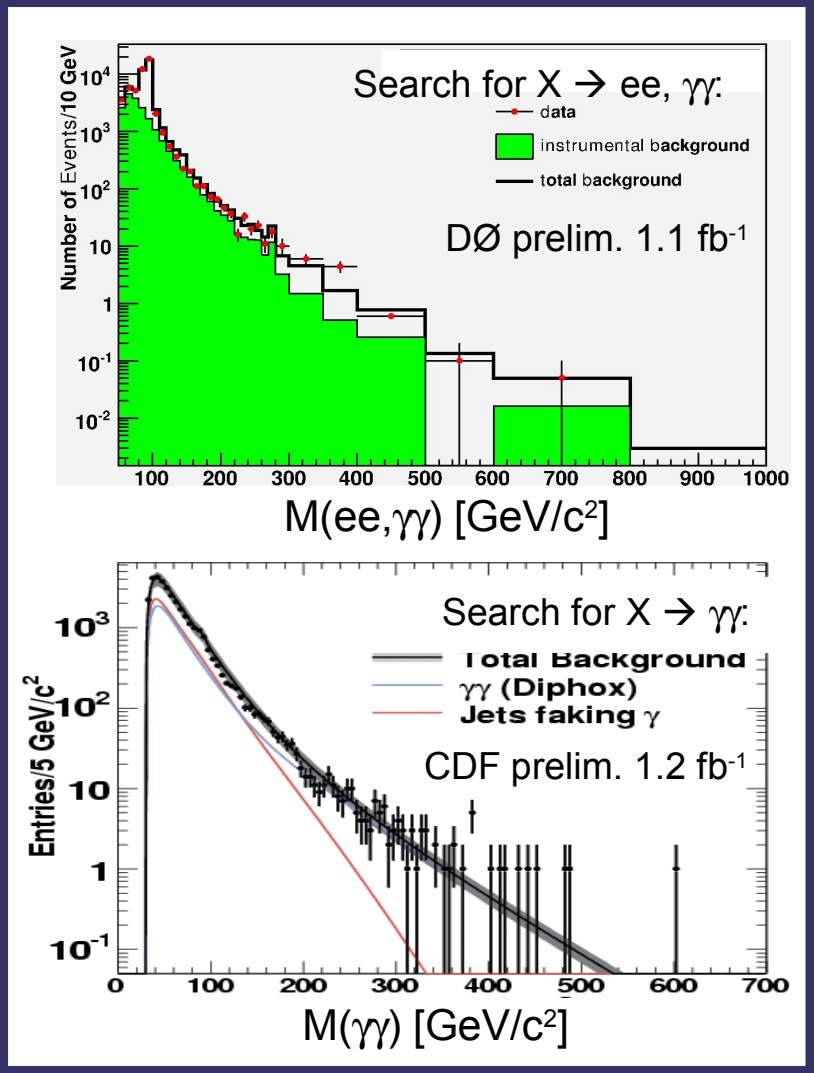
Sensitive to New Forces, Extra Dimensions, …

W: W' → ℓ ν



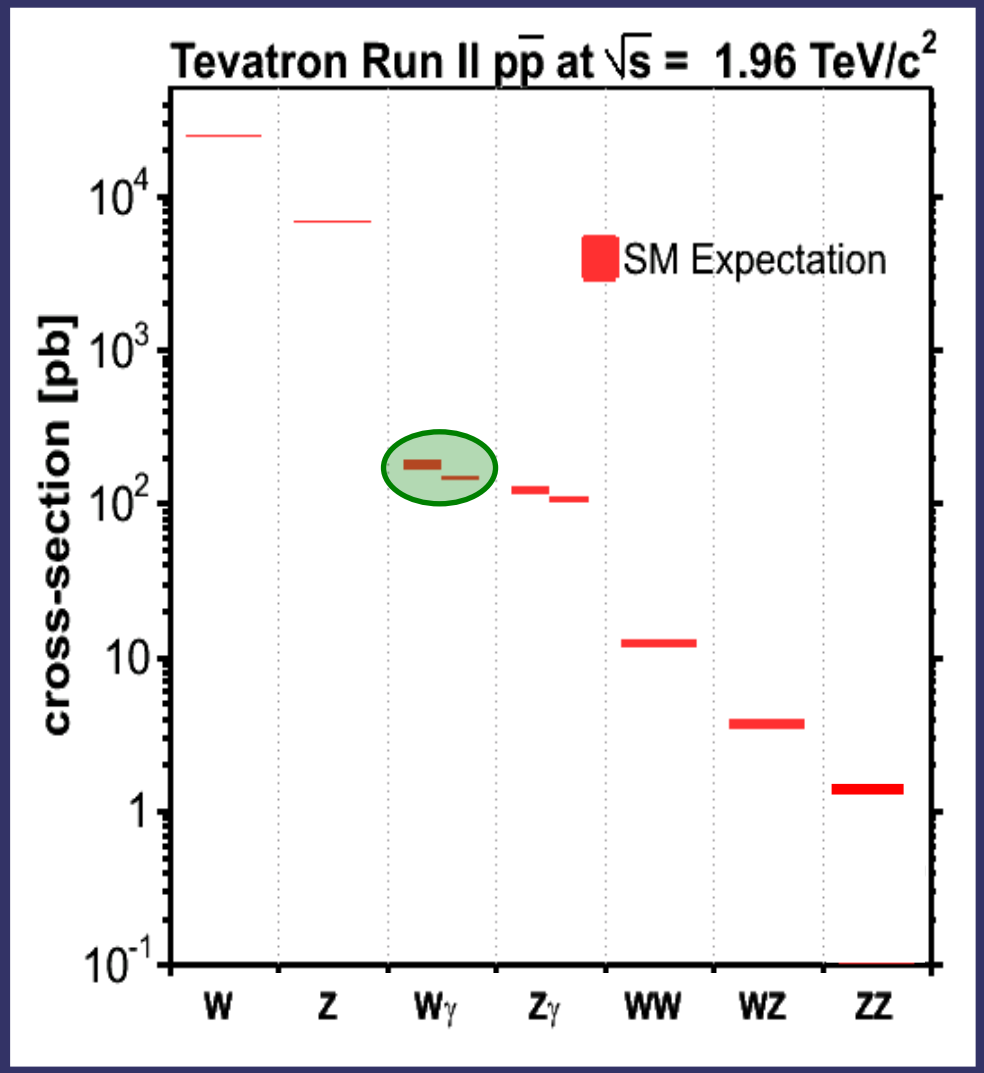
New Gauge Boson (W '):
Limit < ~1 TeV at 95% CL

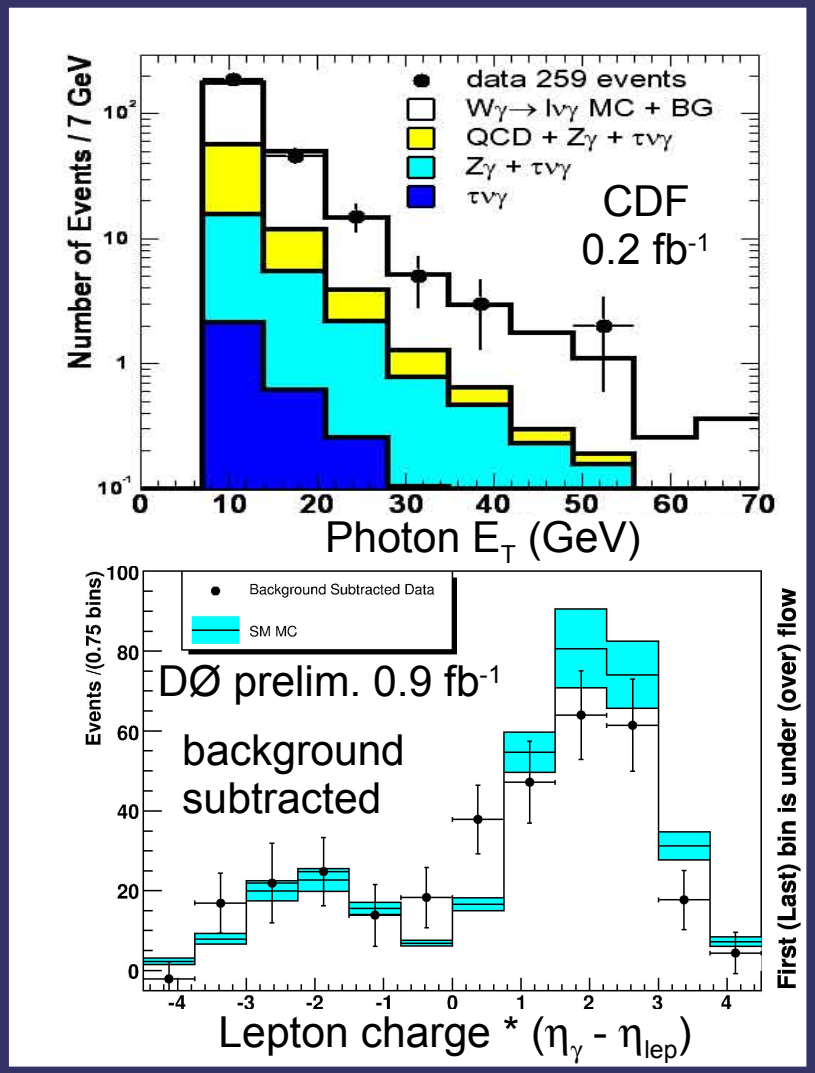
Z: Z'→ee, G→ee+γγ, γγ+X Generic Searches



(Z'): Limit < ~1 TeV at 95% CL
Explore Extra Dimensions to ~1 TeV

Wγ

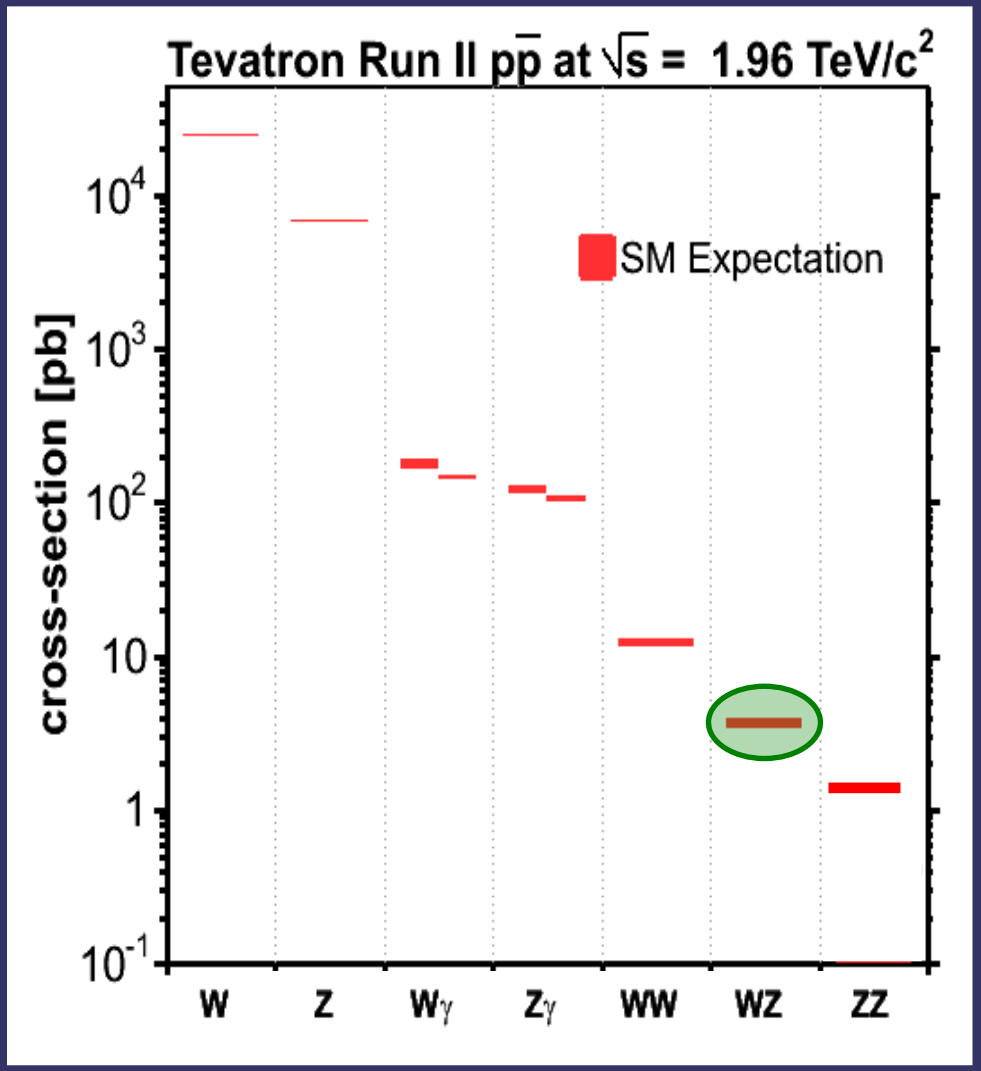


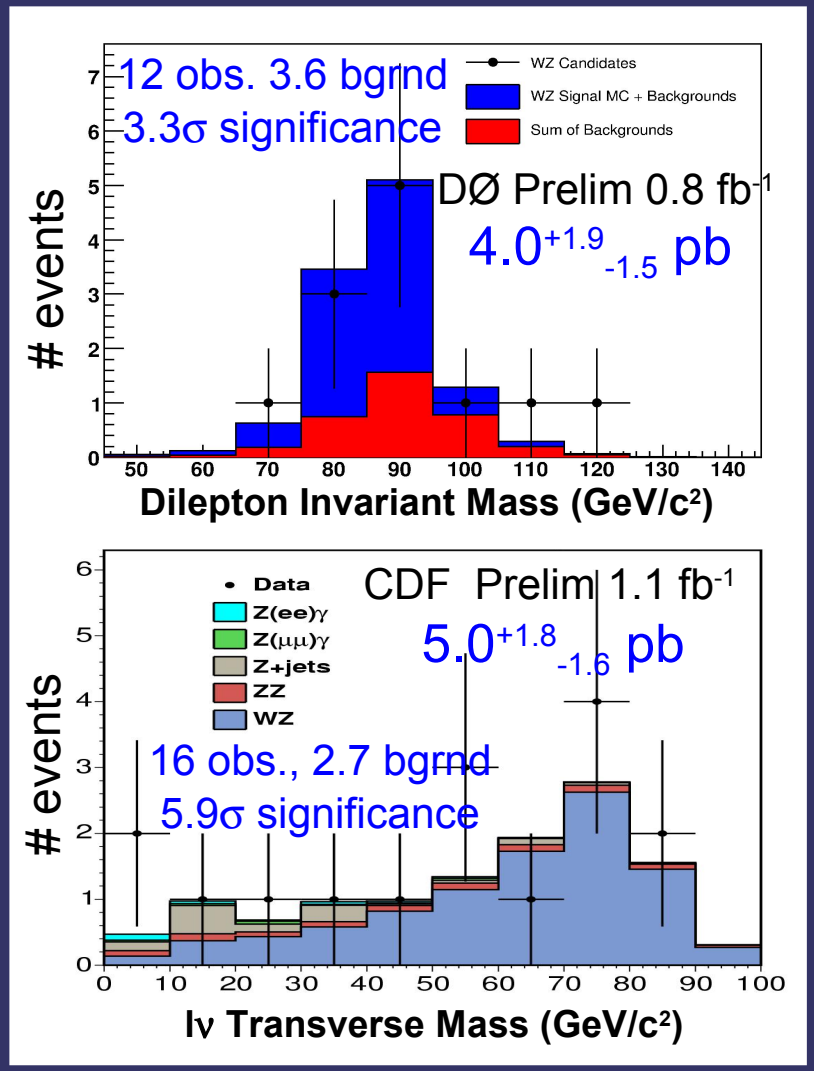


Have ~10^3 Wγ's in 1 fb^{-1}.

Observe "radiation 0" expected from interference of Wγ diagrams

WZ

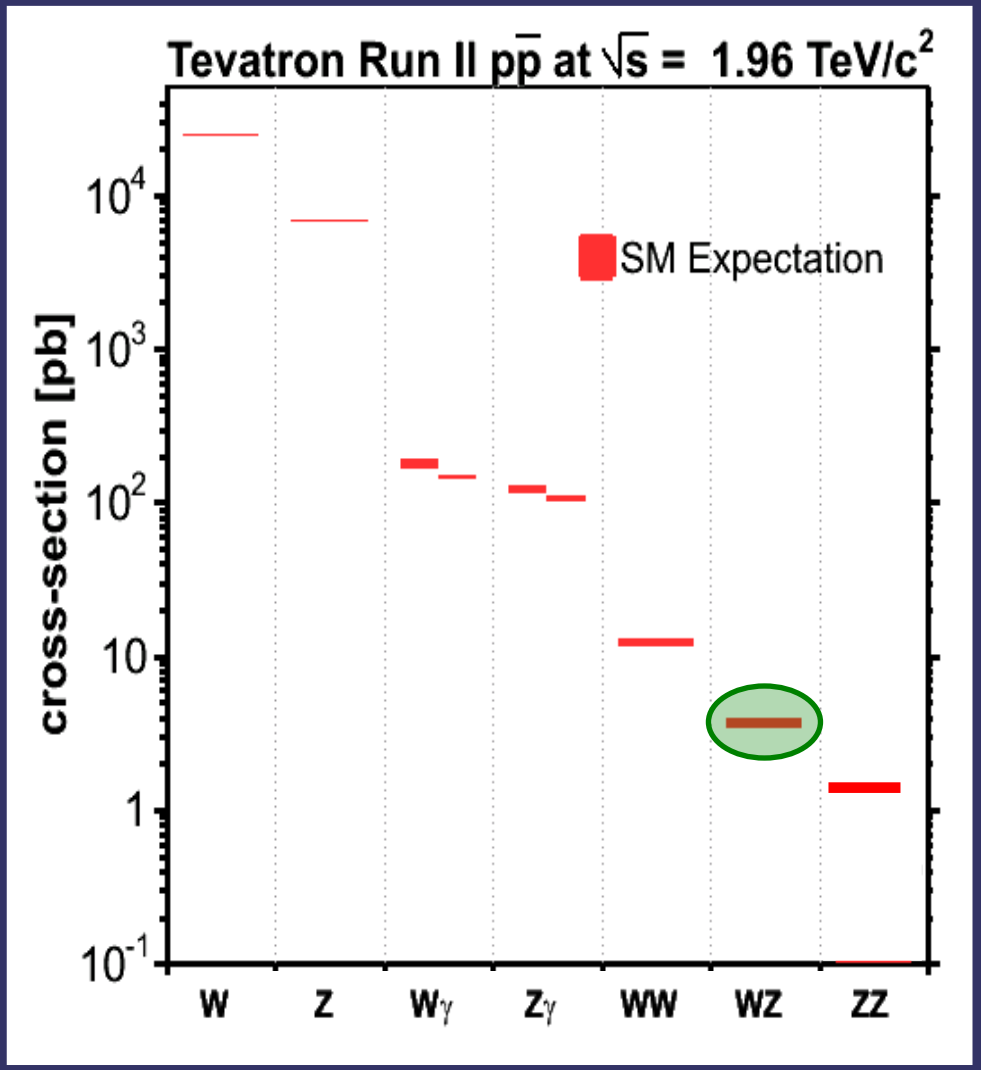


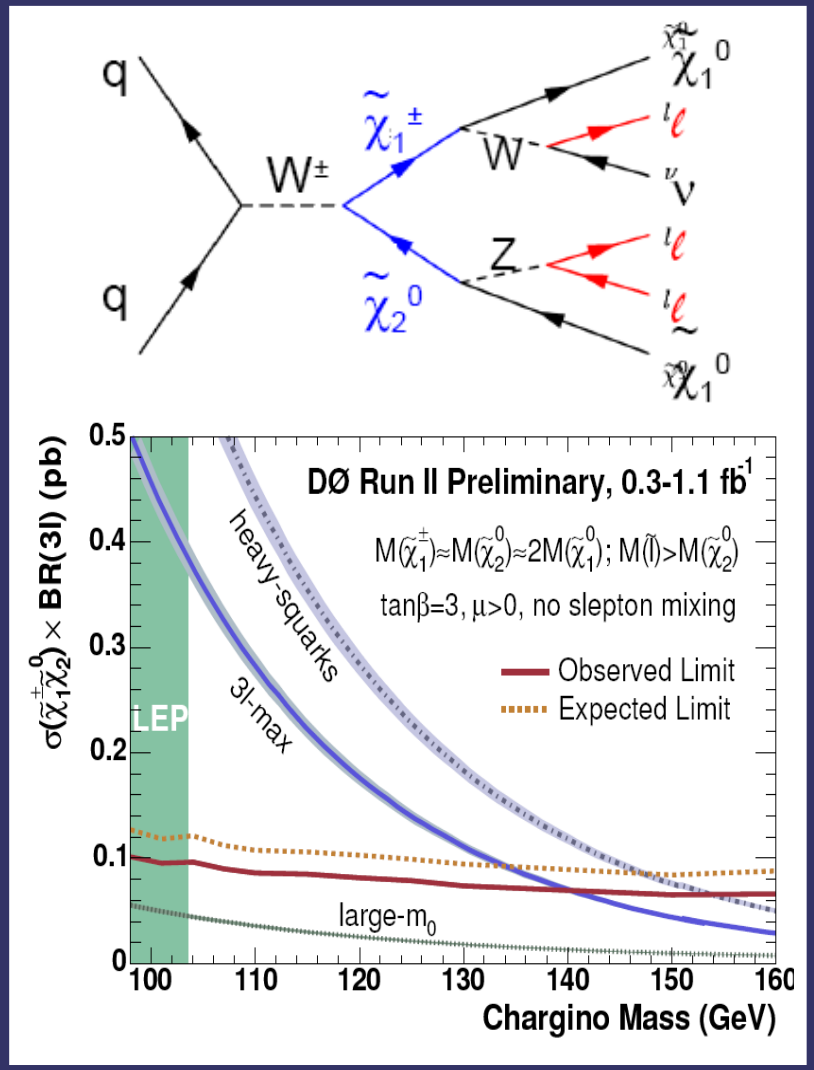


$W^{\pm}Z \rightarrow \ell^{\pm}\nu\, \ell^{+}\ell^{-}$: 28 observed, 6.3 background expected:

First Observation! An important channel...

$W^{\pm}Z \rightarrow \ell^{\pm}\nu\, \ell^{+}\ell^{-}$: SUSY $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ Signal





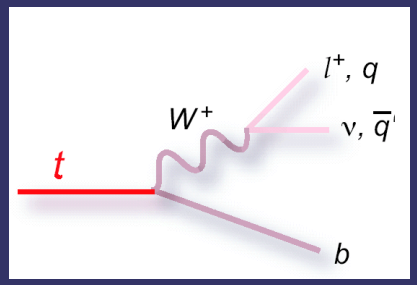
Further constraining SUSY parameter space

Top Quark Production and Decay

- In proton anti-proton collisions at Tevatron energies, top quarks are primarily produced in pairs via strong interactions

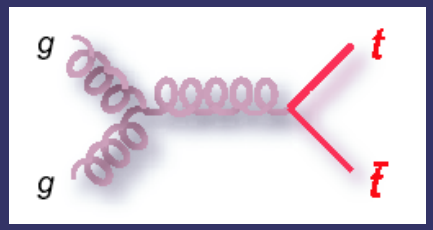
- Br(t→Wb) ~100%

$M_t > M_w + M_b$, and $V_{tb} >> V_{ts}, V_{td}$

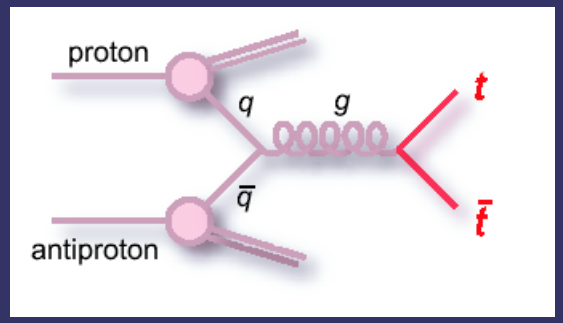


LO diagrams

15%

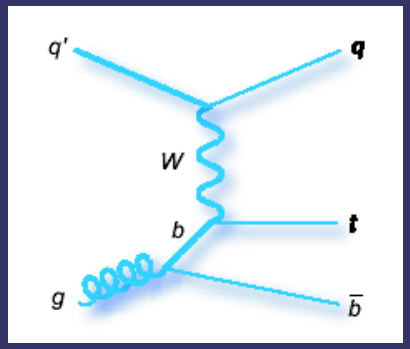


85%

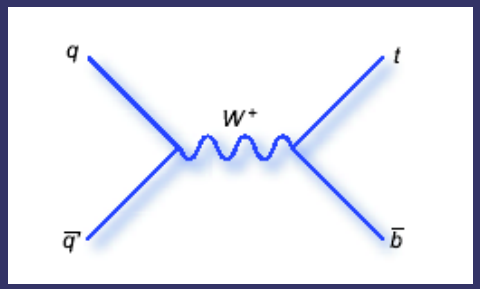


Production cross-section: $\sigma \sim 7$ pb at Tevatron

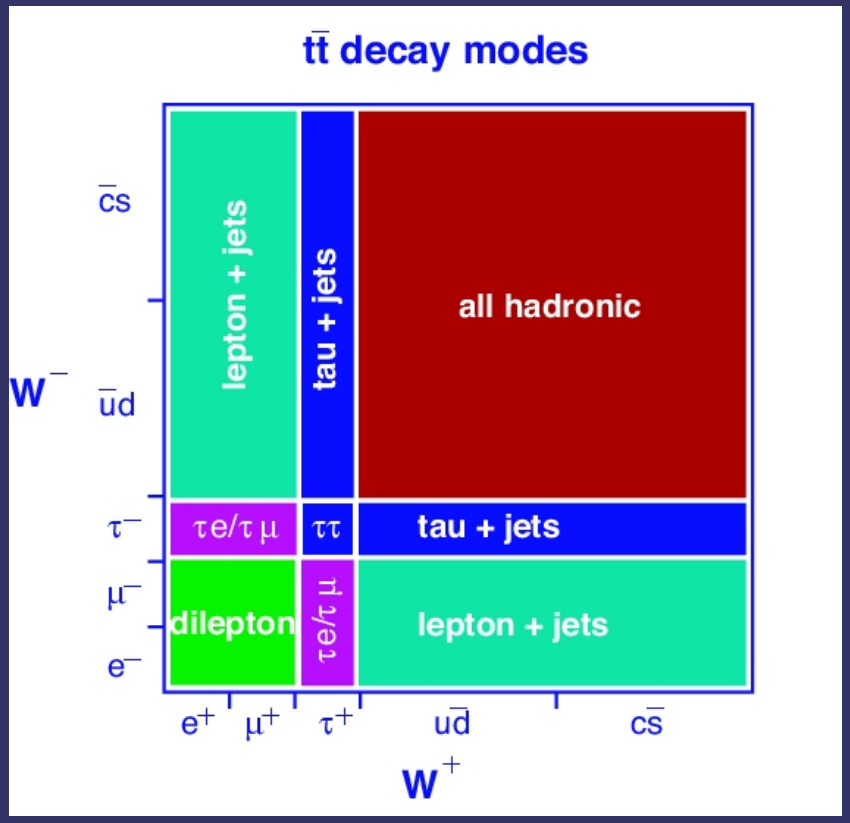
- EW single top production: not yet observed (but close!)



t-channel



s-channel



Final state determined by W decays

Top Mass Measurements

"Lepton+Jets"
(~500 events in 1 fb^{-1}, high purity)

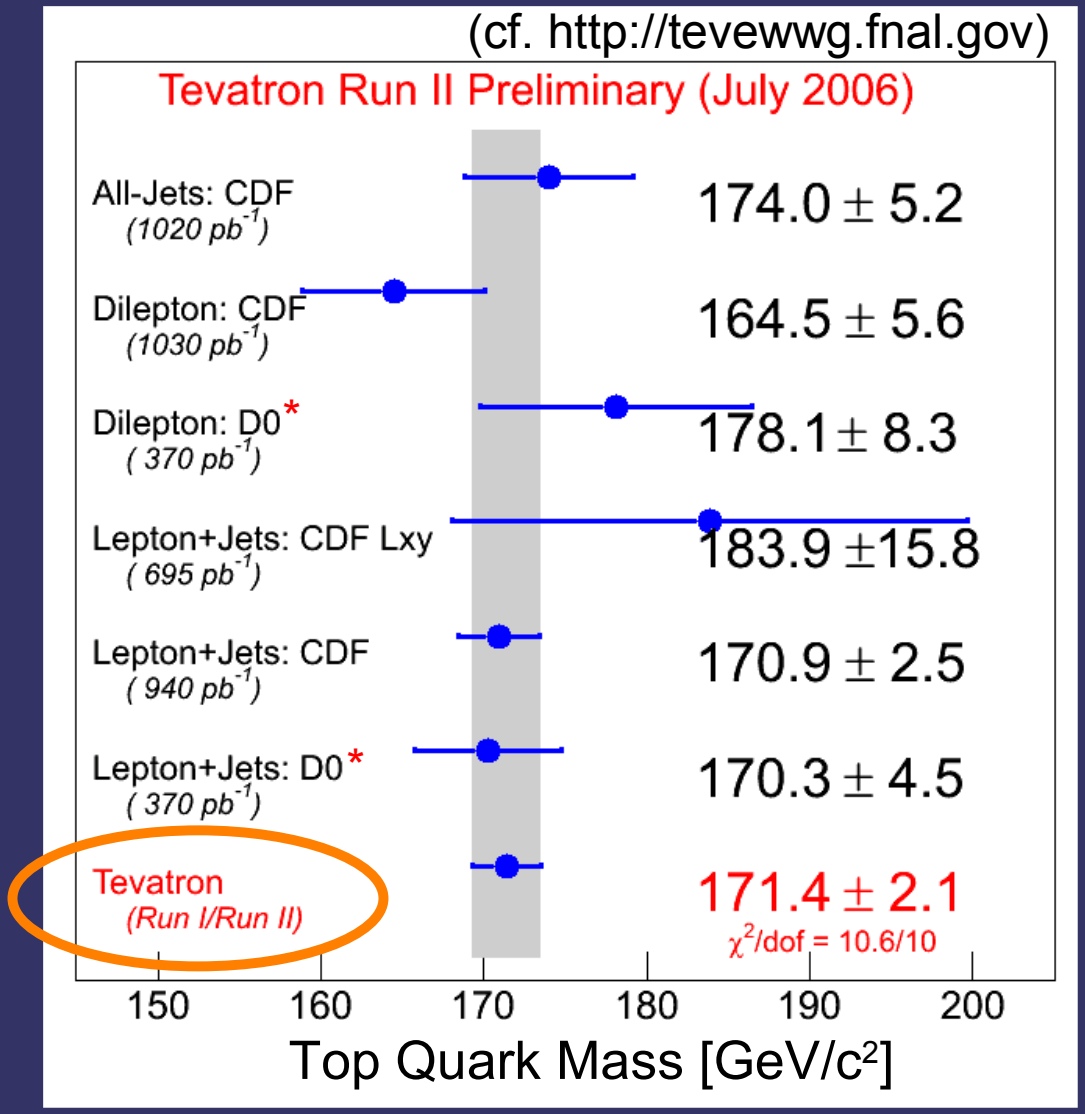
$$t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow l^+\nu q\bar{q}b\bar{b}$$

"All Jets"
(~400 events in 1 fb^{-1}, ~30% purity)

$$t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}q\bar{q}b\bar{b}$$

"Di-Lepton"
(~100 events in 1 fb^{-1}, high purity)

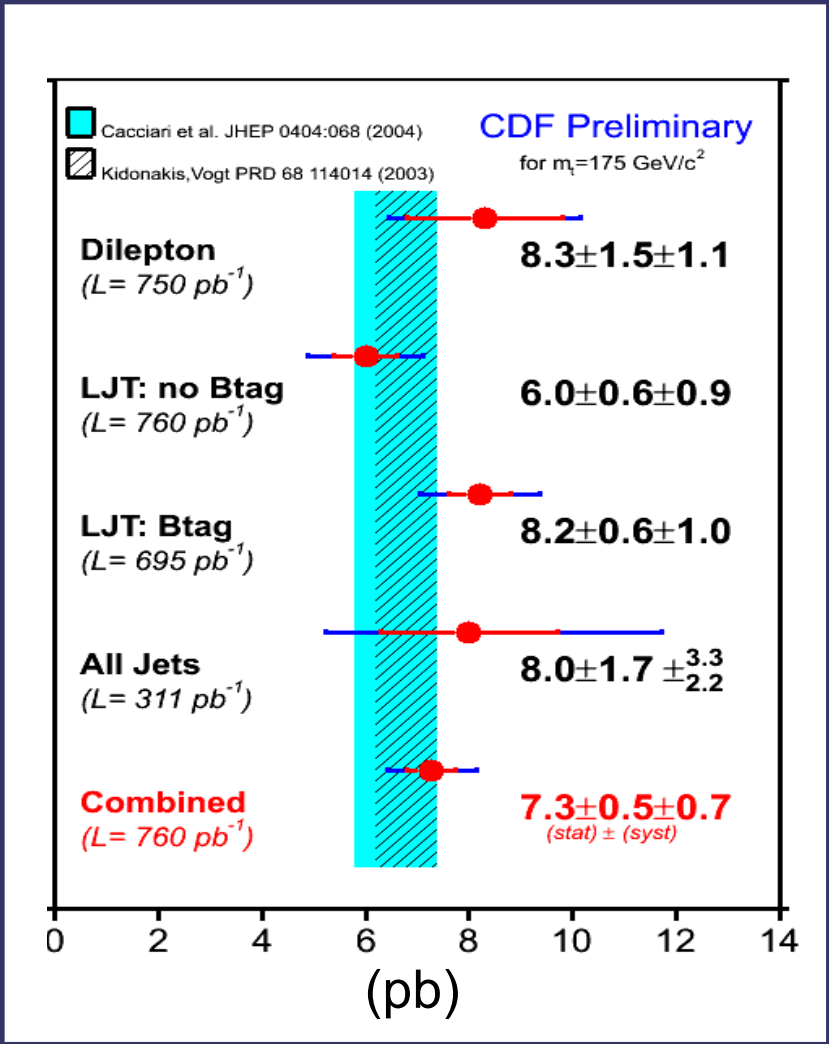
$$t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow l^+\nu l^-\bar{\nu}q\bar{b}\bar{b}$$

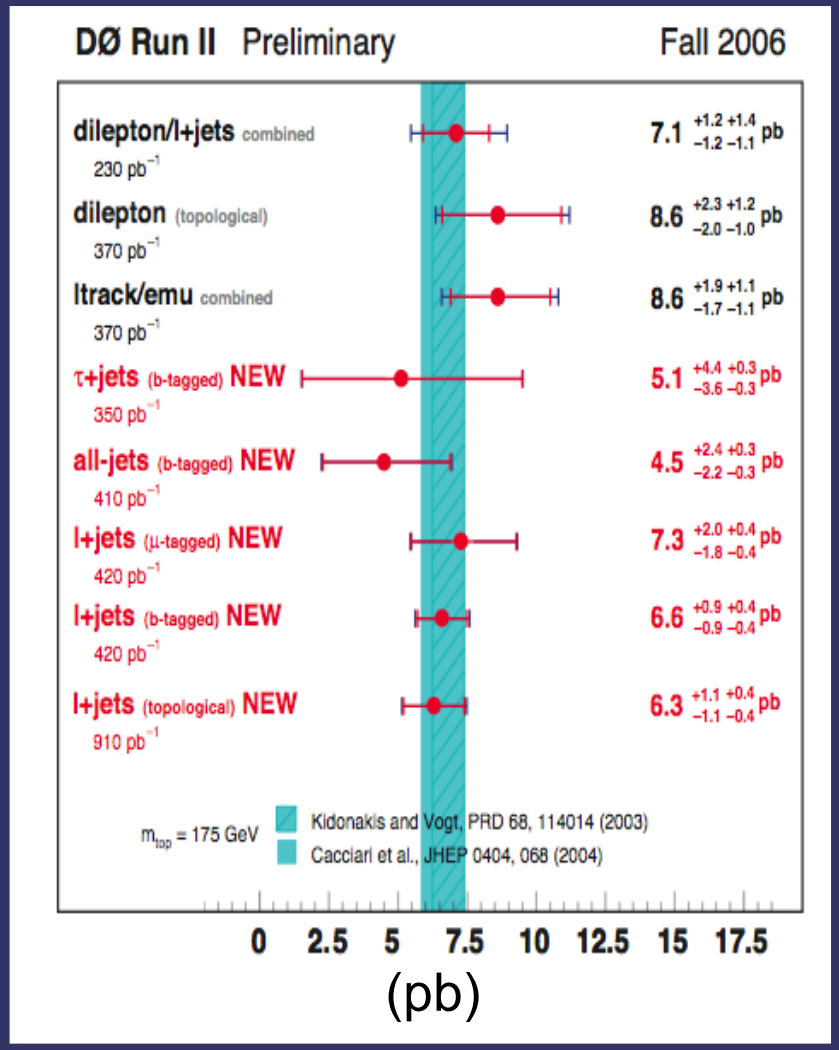


M_{top} determined to 1.2%! Have surpassed 2 fb^{-1} goal.

* New (not yet included in combination)

Top Pair Production Cross Section





Cross-sections and kinematics agree well with Standard Model.

Probing V_{tb}

Through t-tbar: by counting # of b-tagged jets in top events

$$R = \frac{B(t \to WB)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2| + |V_{ts}|^2| + |V_{tb}|^2|}$$

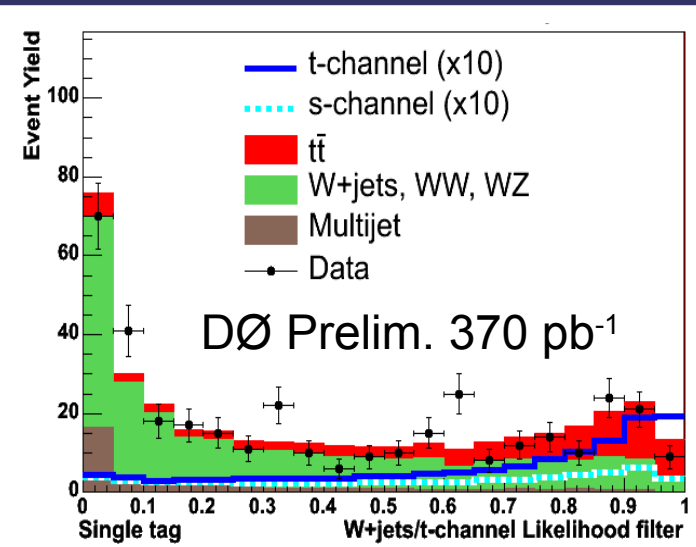
$|V_{tb}|$ limit extracted assuming $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$

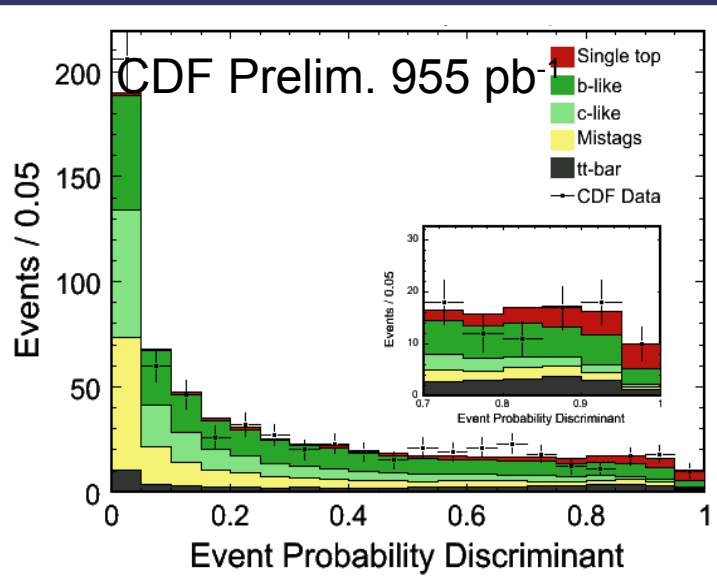
(DØ: 230 pb^{-1}) $R = 1.03 \pm^{0.19}_{0.17}$

(CDF: 162 pb^{-1}) $R = 1.21 \pm^{0.21}_{0.19}$

$$SM : |V_{tb}| \approx 0.999 \Rightarrow R \approx 0.998$$

Through Single Top Production: C.S. propto $|V_{tb}|$





DØ

$\sigma_{s\text{-channel}} < 5.0$ pb

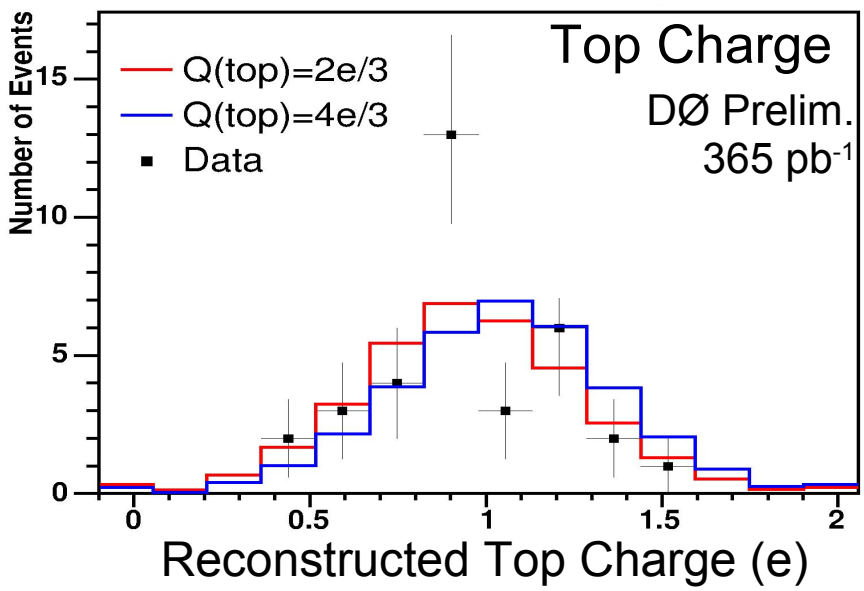
$\sigma_{t\text{-channel}} < 4.4$ pb

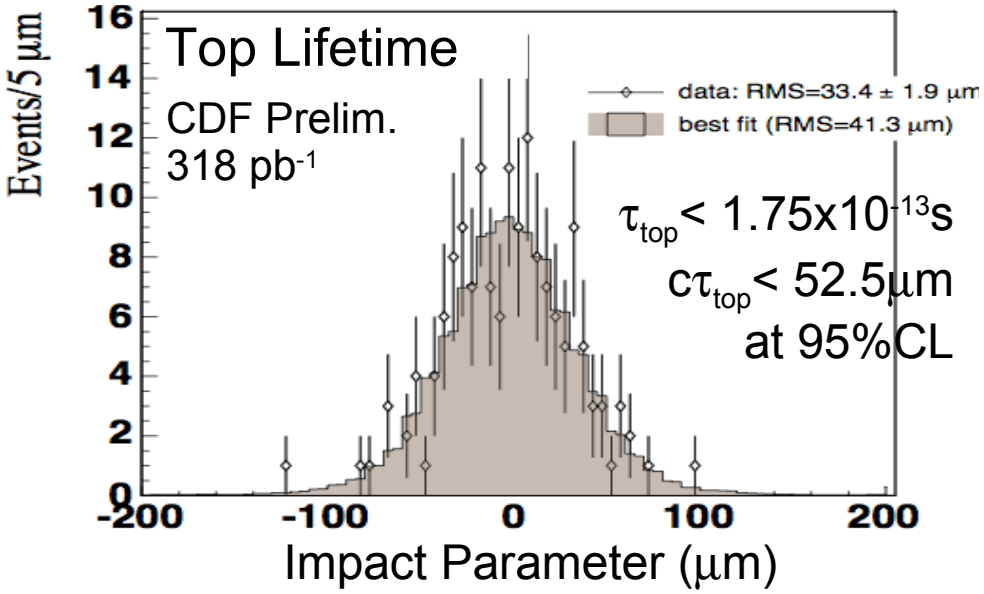
CDF

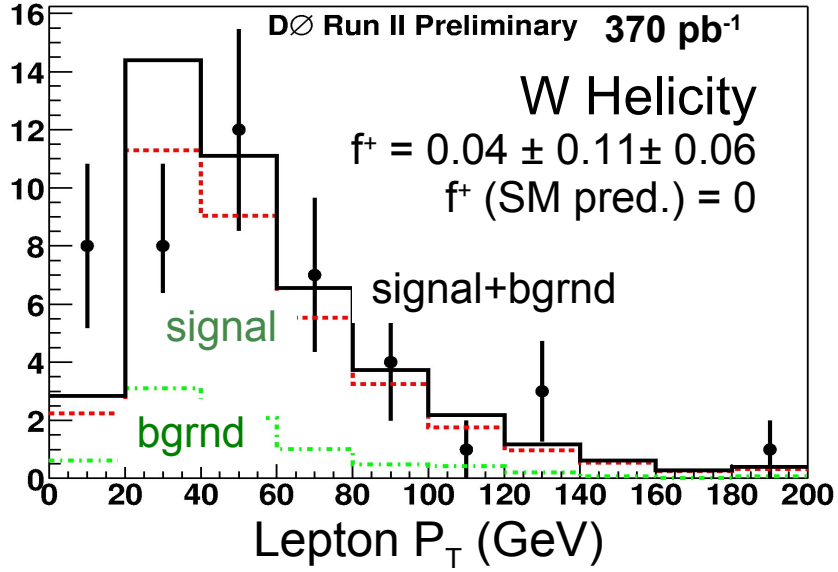
$\sigma_{s+t} = 2.7\ ^{+1.5}_{-1.3}$ pb

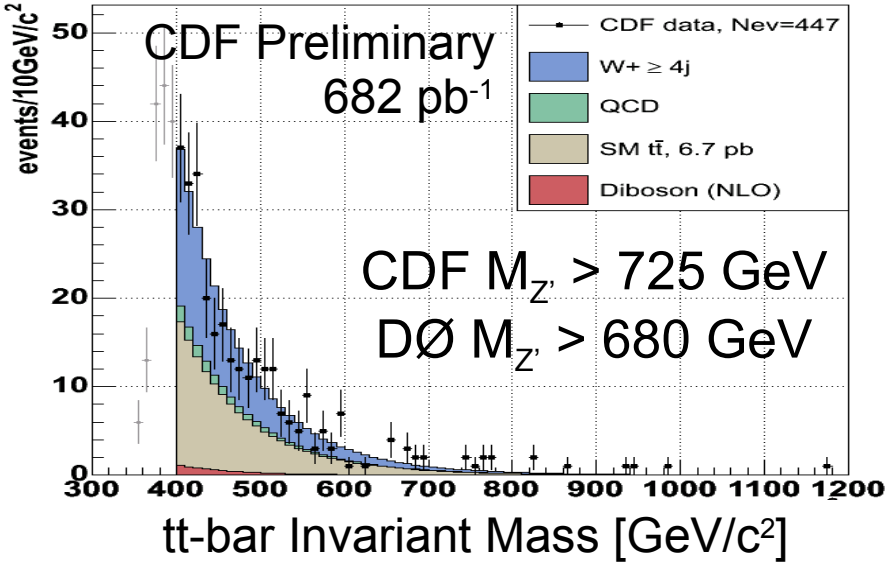
P-value = 1% (2.3 σ)

Top Properties



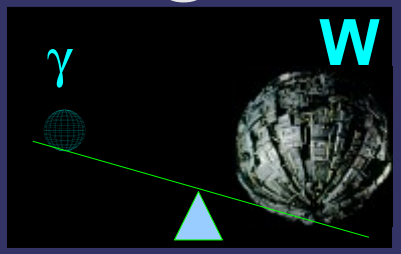






top is now a physics workhorse!

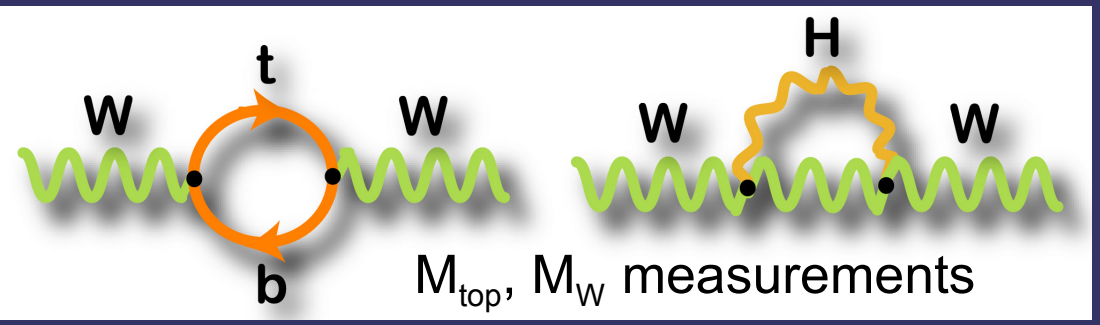
Electroweak Symmetry Breaking Sector:Origin of Mass



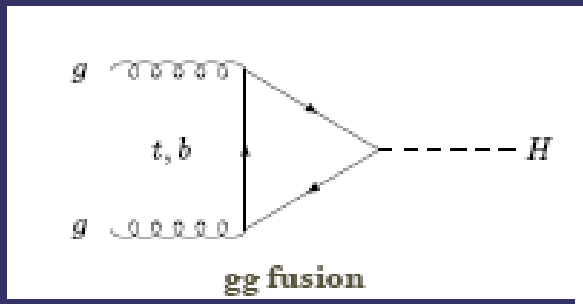
The Higgs is the only SM particle we've not seen yet!

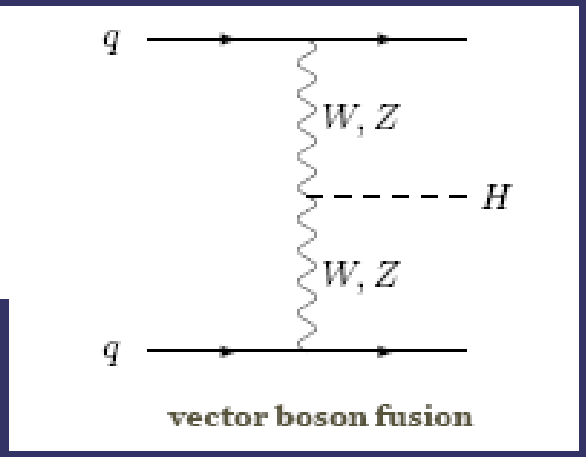
EW symmetry VERY broken
Adding complex doublet of scalar fields
Keeps the symmetries of the original $SU(2)_L \times U(1)_Y$
Correctly describes weak force
W^+, W^-, and Z^0 bosons are massive
and ⇒ Non zero VEV and a Higgs!!

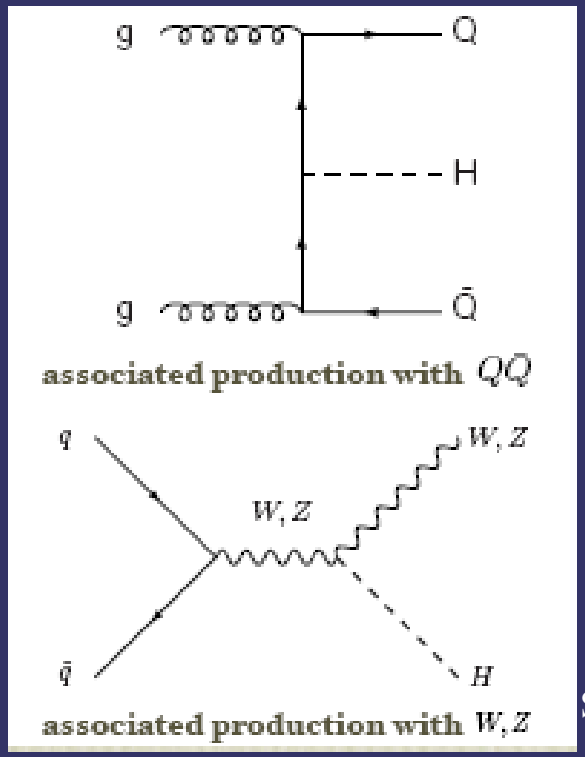
- Probe Higgs via Quantum Corrections



- Direct Searches



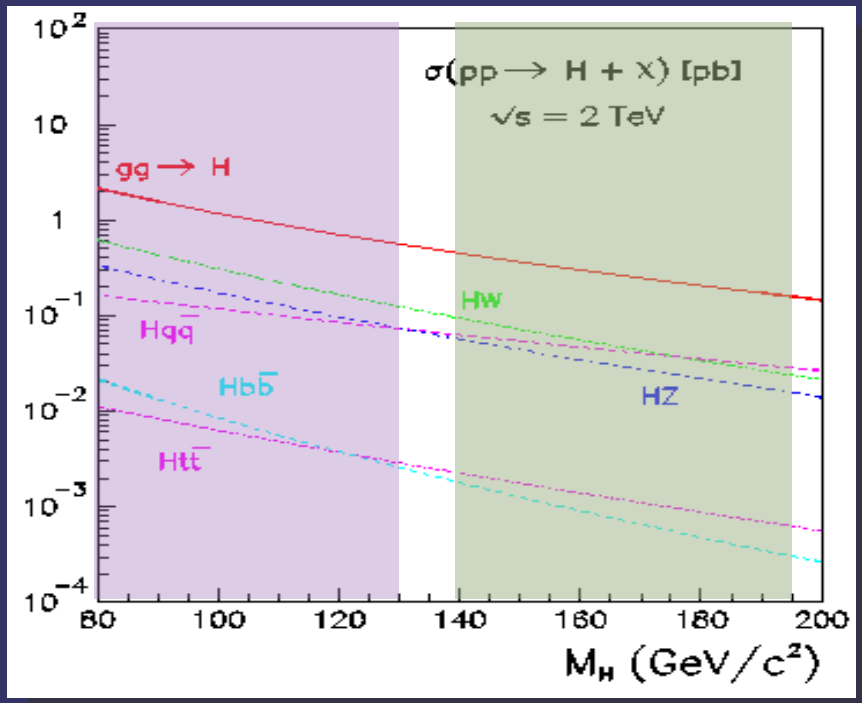




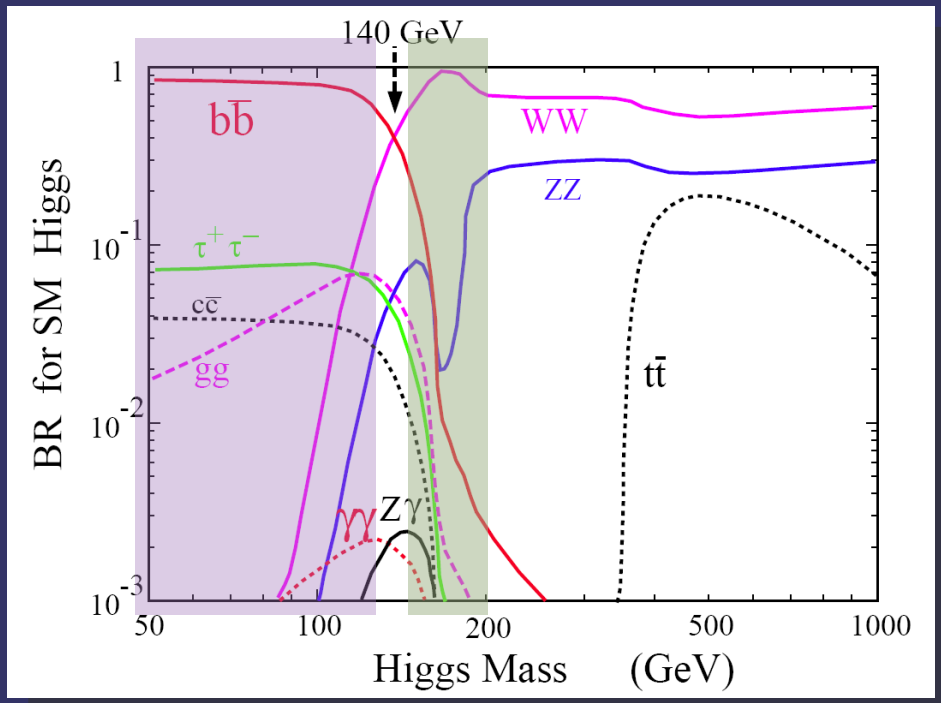
SM Higgs: Production and Decay

And search strategies

Direct/associated production



Higgs branching ratios



M_H < 130 GeV/c² - Low Mass

Associated production and H→bb
Good lepton ID, Missing E_T, jet resolution, b-tagging

M_H > 150 GeV/c² - High Mass

Gluon Fusion and H→WW, ZZ
Good lepton ID and resolution

WH → eνbb
WH → μνbb
WH → WWW* → ℓℓ (ℓ), ℓ = e,μ

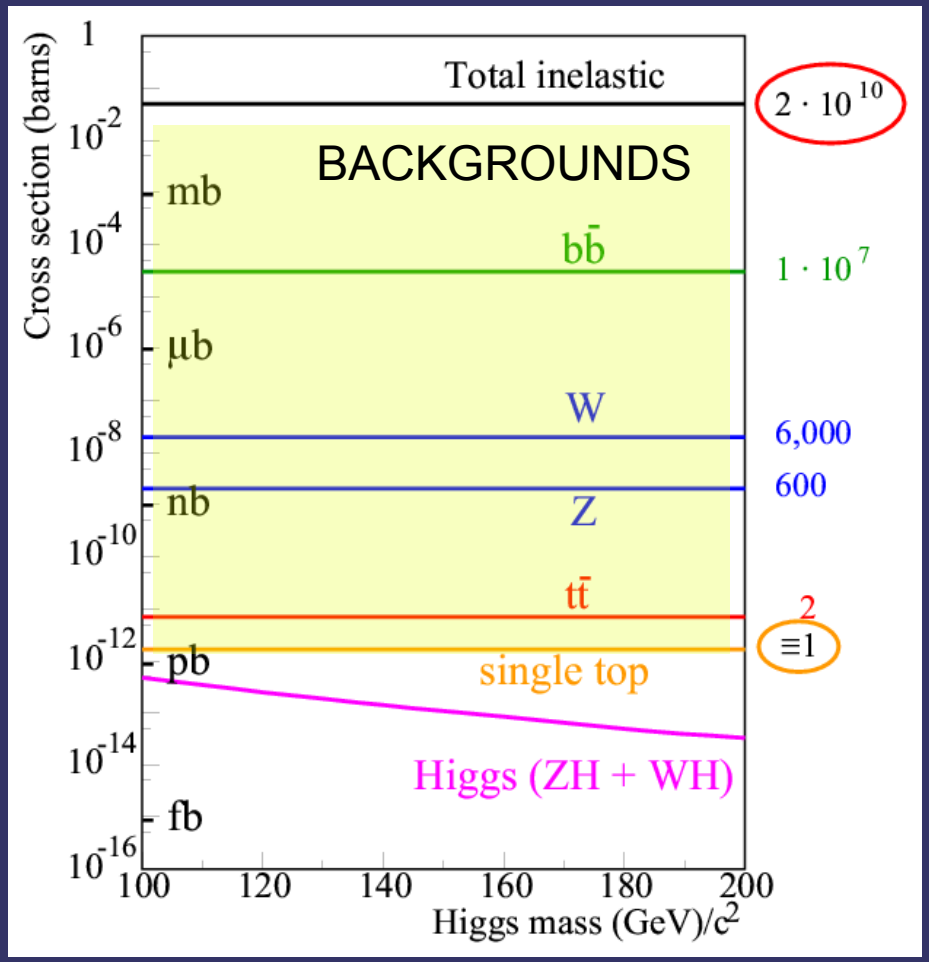
ZH → eebb
ZH → μμbb
ZH → ννbb

H → WW, WW* → ℓℓ, ℓ = e,μ

Challenges...

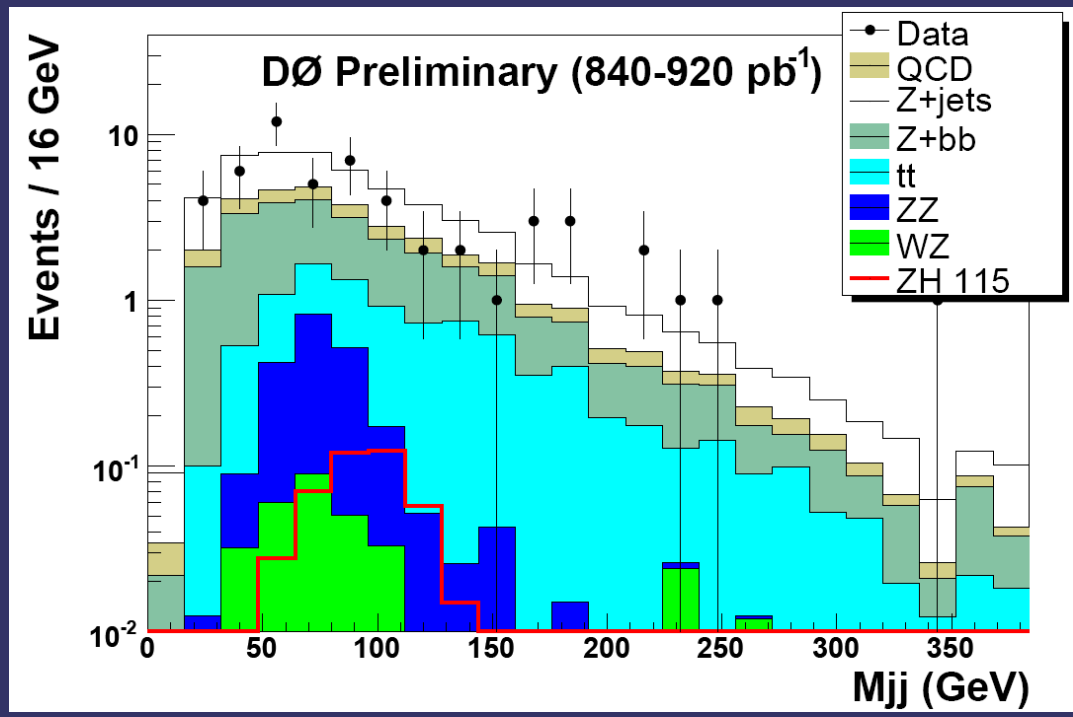
Cross Sections at the Tevatron

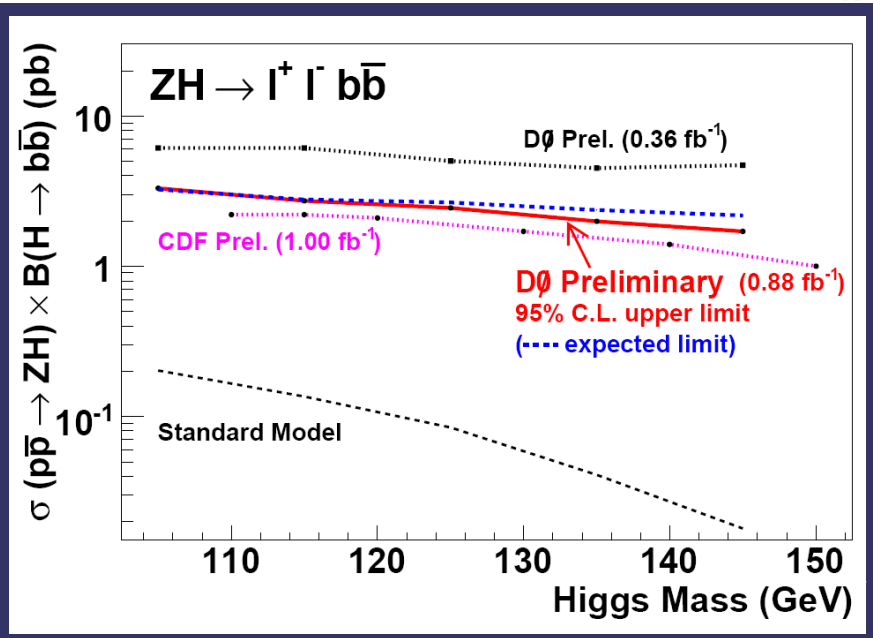
Relative production rates



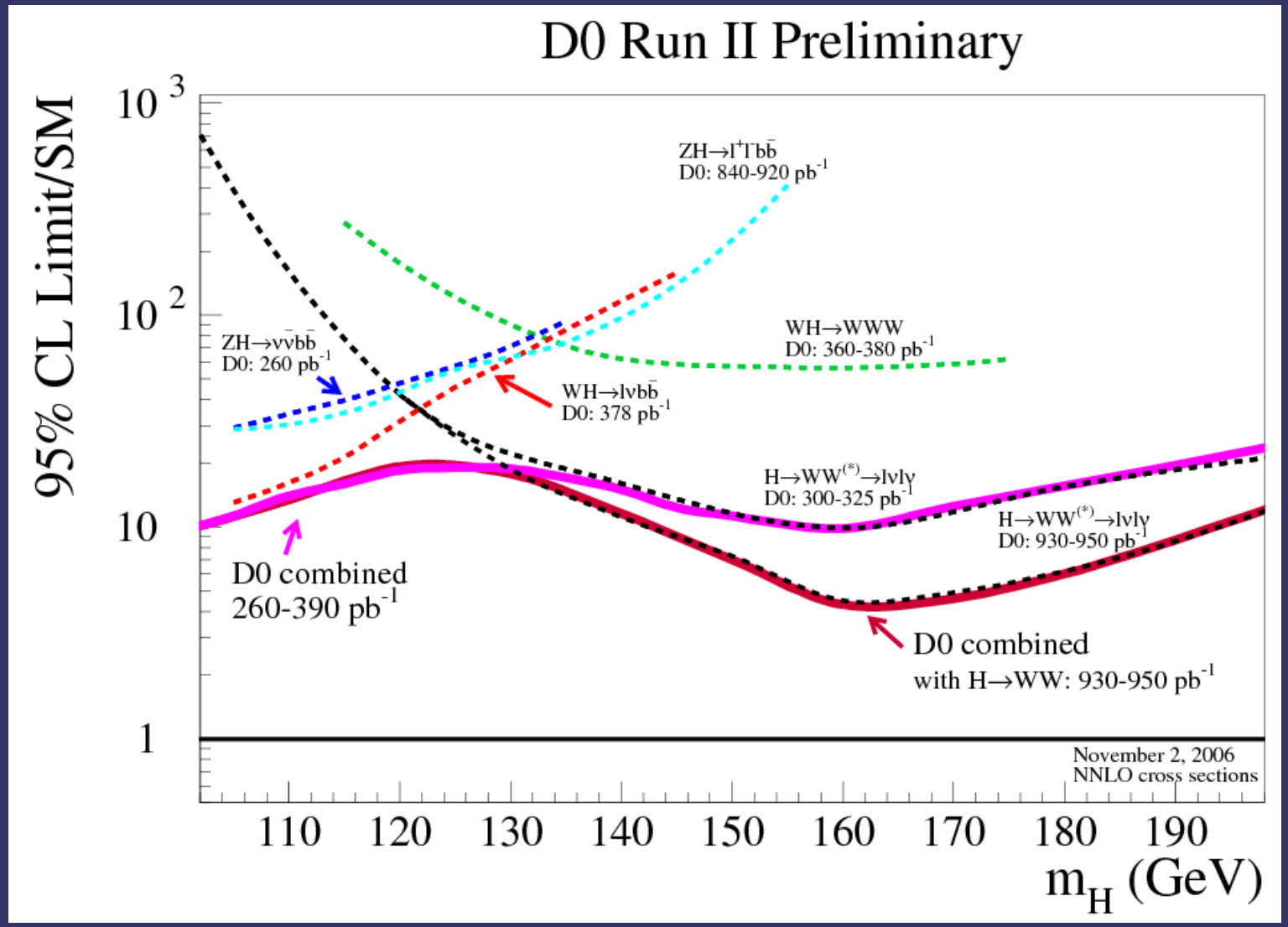
ZH associated production

- $105 < M_H < 155$





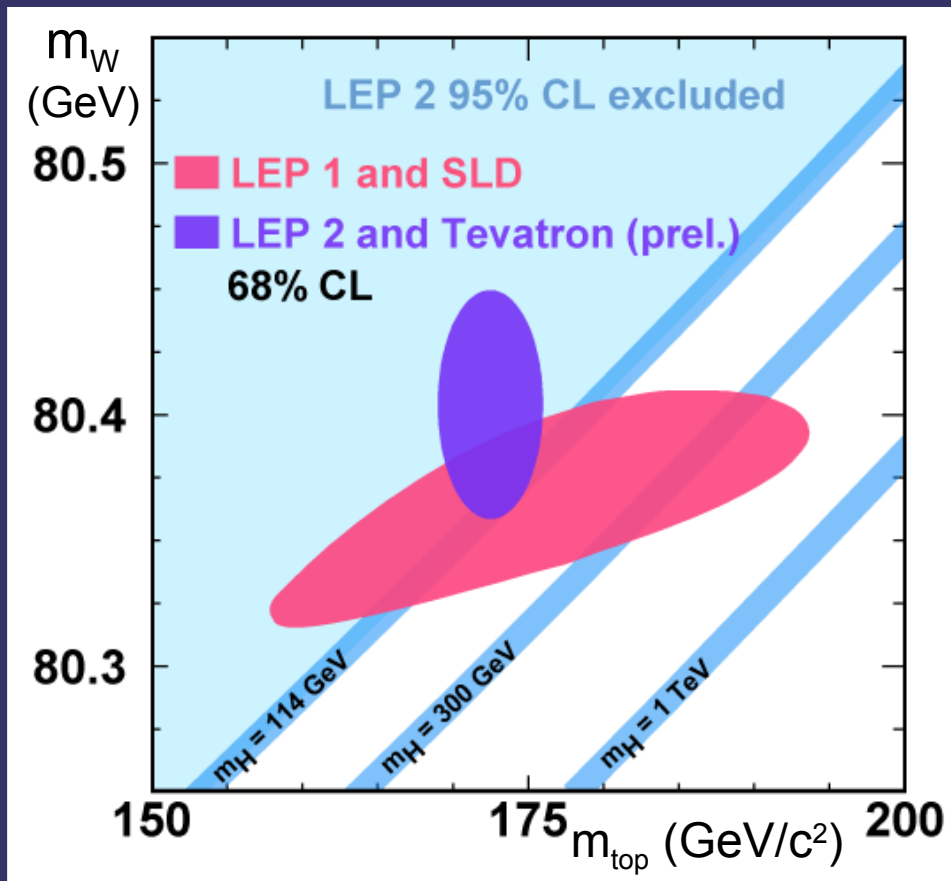
DØ Limits

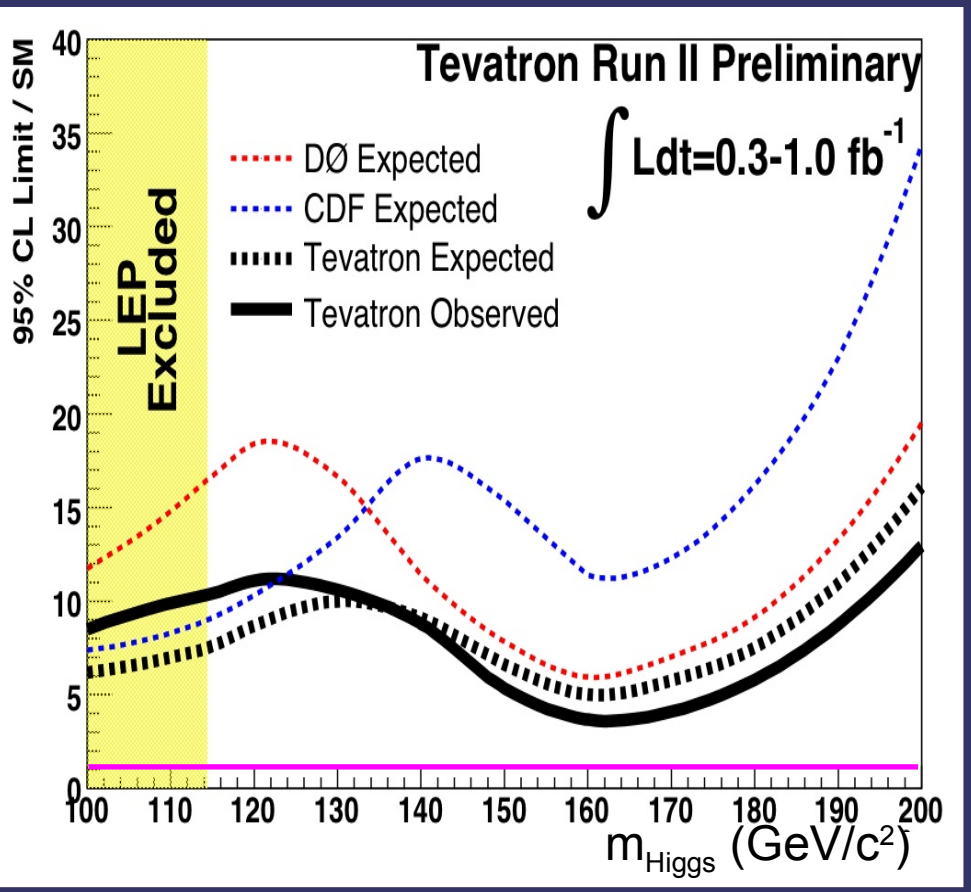


varying sensitivities depend on B.R.'s(M_H), production cross sections, and backgrounds

M_W, M_{top}, and SM Higgs

Summer 2006





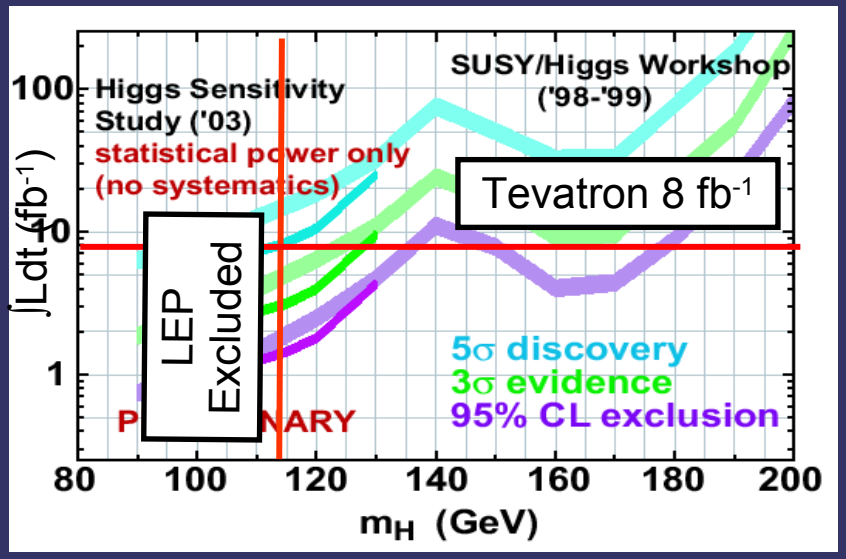
Current precision measurements indicate Higgs is light (<166 GeV@95%CL), where Tevatron sensitivity is best!

Tevatron limits: "Distance" from SM APS-DPF 2006 + JPS 2006: ~20% improvements since summer 06

As RunII continues...

The 2003 Higgs Sensitivity Study

- Sensitivity in the mass region above LEP limit (114 GeV) starts at ~2 fb^{-1}
- With 8 fb^{-1}: exclusion 115-135 GeV & 145-180 GeV, 5 - 3σ discovery/evidence @ 115 – 130 GeV



The Tevatron New Phenomena & Higgs Working Group

- First Combination released Summer 2006
- Results better than either experiment individually

This is a joint CDF/DØ endeavor!

Recent DØ detector upgrade program designed to improve Higgs sensitivity

Higgs Searches will play a major roll in the future of the Tevatron

Heavy Flavor

Numerous channels Unique to the Tevatron:

top, Σ_b, Λ_b, B_c, B_s, …

Precise measurements challenge theory predictions

Recently hot: B_d, B_s mixing results

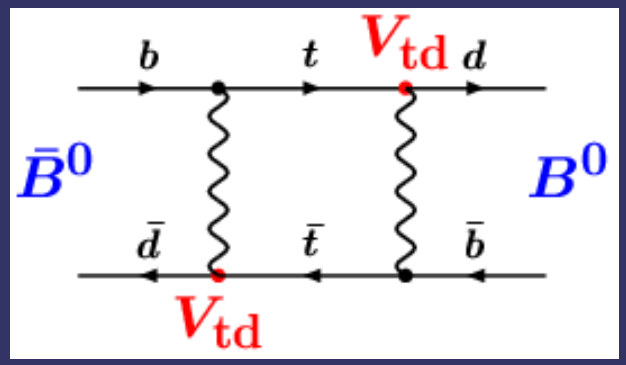
Oscillation frequencies (Δm_d, Δm_s) determine poorly known V_{td}, V_{ts}

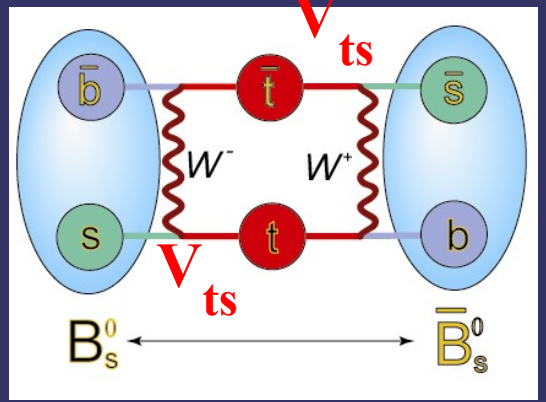
$|V_{td}/V_{ts}|$ measures one side of Unitary Triangle – reduced theory uncertainties in ratio enables measurement precision of ~4%

New particles in loops alter expectations
⇒ test Standard EWK Model

weak ◄—— eigenstates ——► mass

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$





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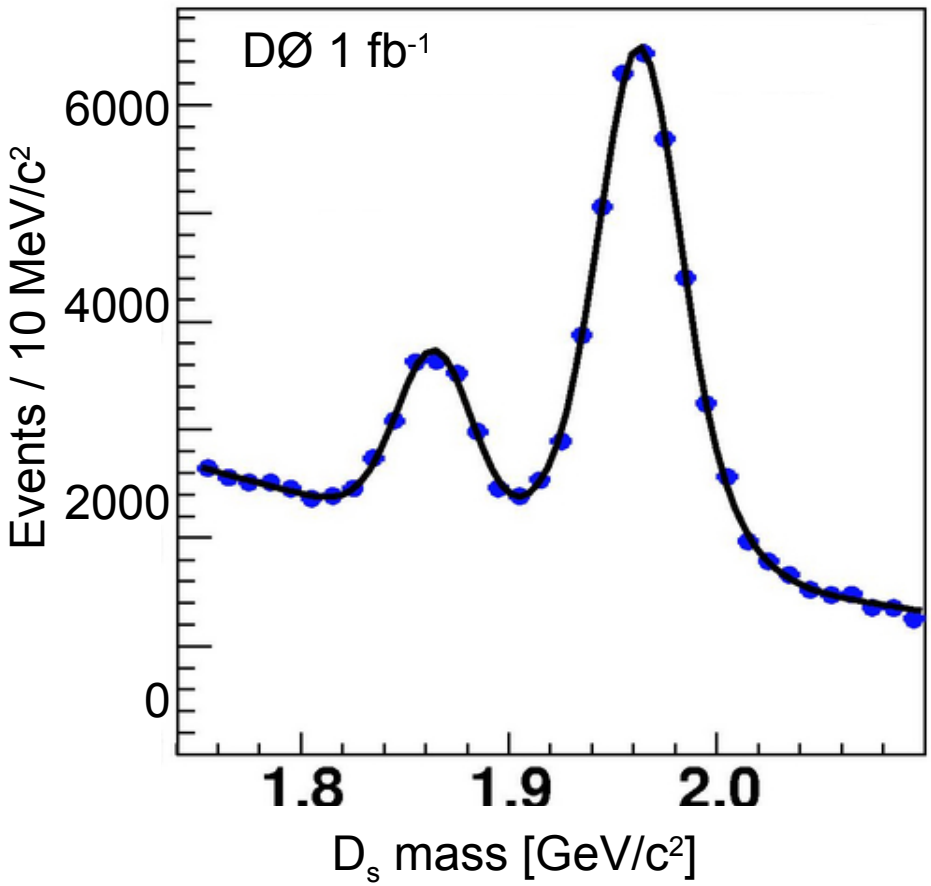
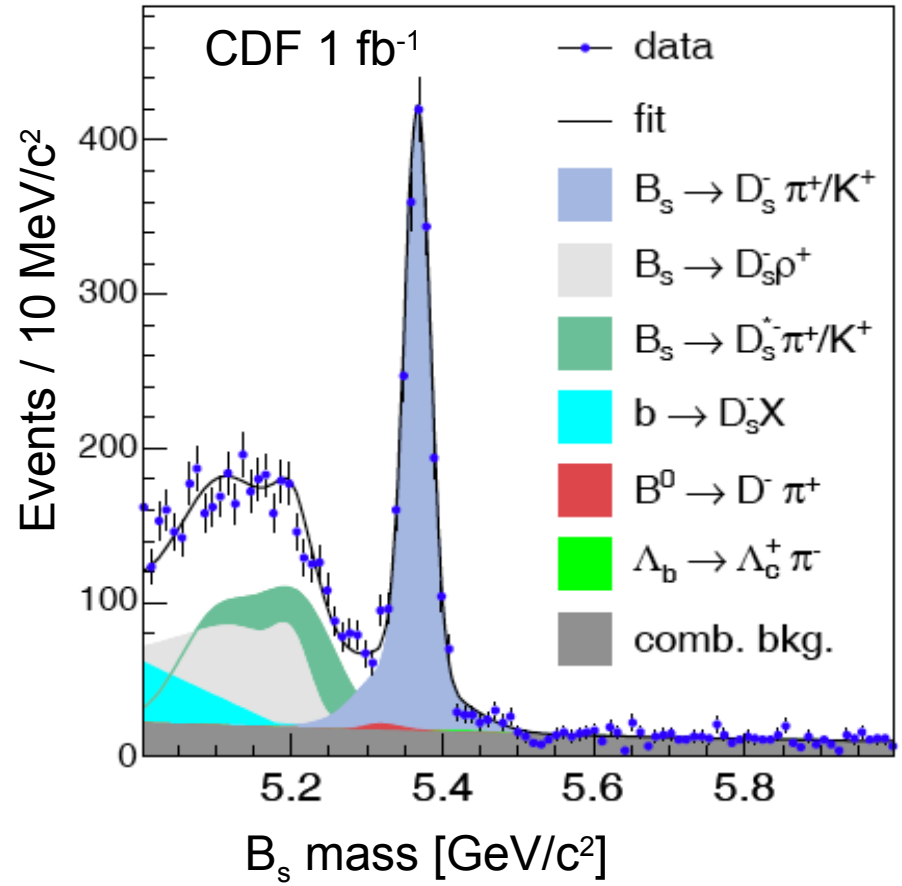
B_s Particles

$$B_s \to D_s^- e^+ \nu \,,\, D_s^- \mu^+ \nu$$



$$B_s \to D_s^- \pi^+ \,,\, D_s^- \pi^+ \pi^- \pi^+$$



Summary of CDF Results on B^0_s Mixing

A. Abulencia et al., hep-ex/0609040, accepted by Phys. Rev. Lett.

Observation of B_s Oscillations and precise measurement of Δm_s

$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{ps}^{-1}$$

Precision: 0.7% Probability random fluctuation mimics signal: $O(10^{-8})$

(2.83 THz, 0.012 eV)

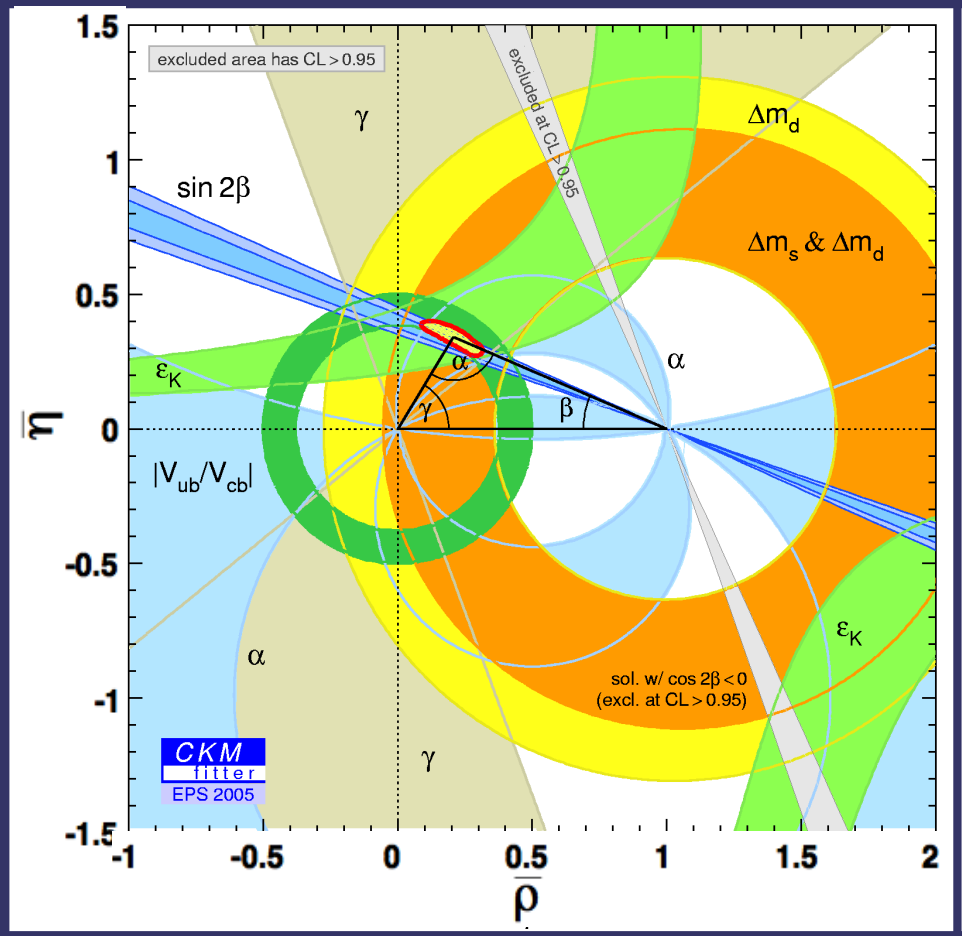
Most precise measurement of $|V_{td}/V_{ts}|$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\text{exp.})^{+0.0081}_{-0.0060}\,(\text{theo.})$$

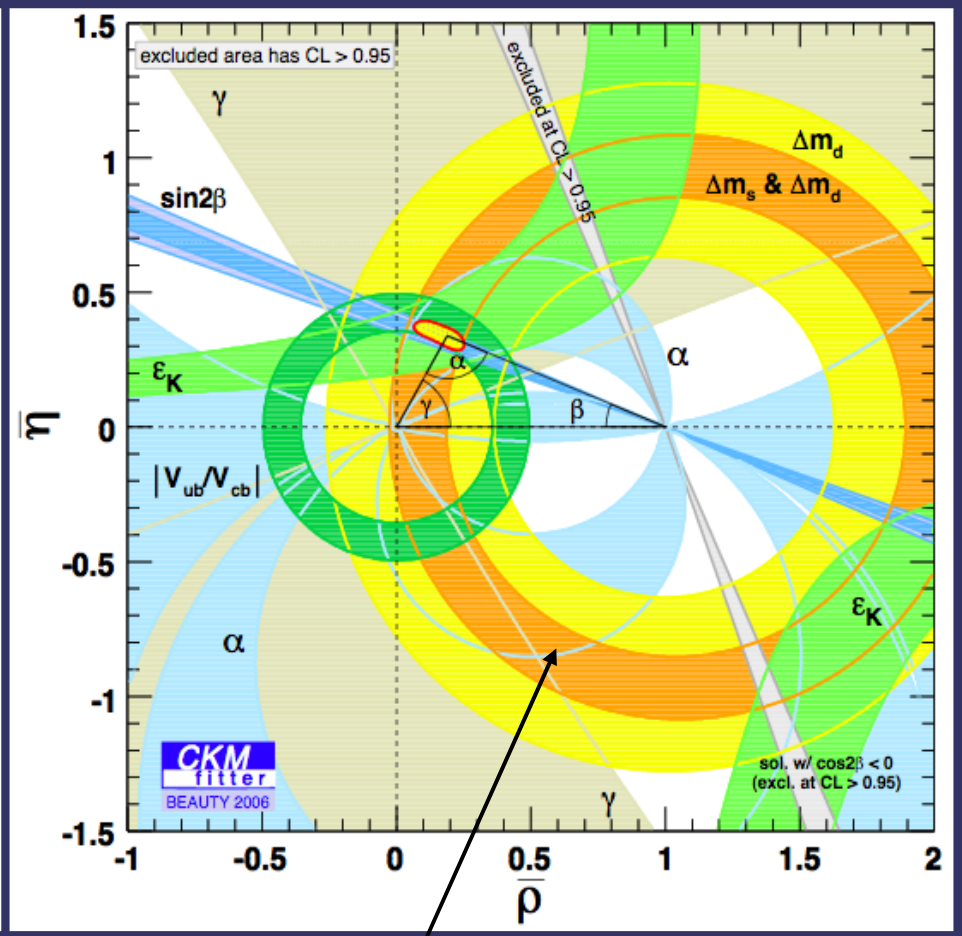
20 years in the making!

B_s Oscillation - Impact on the Unitarity Triangle

Summer 2005



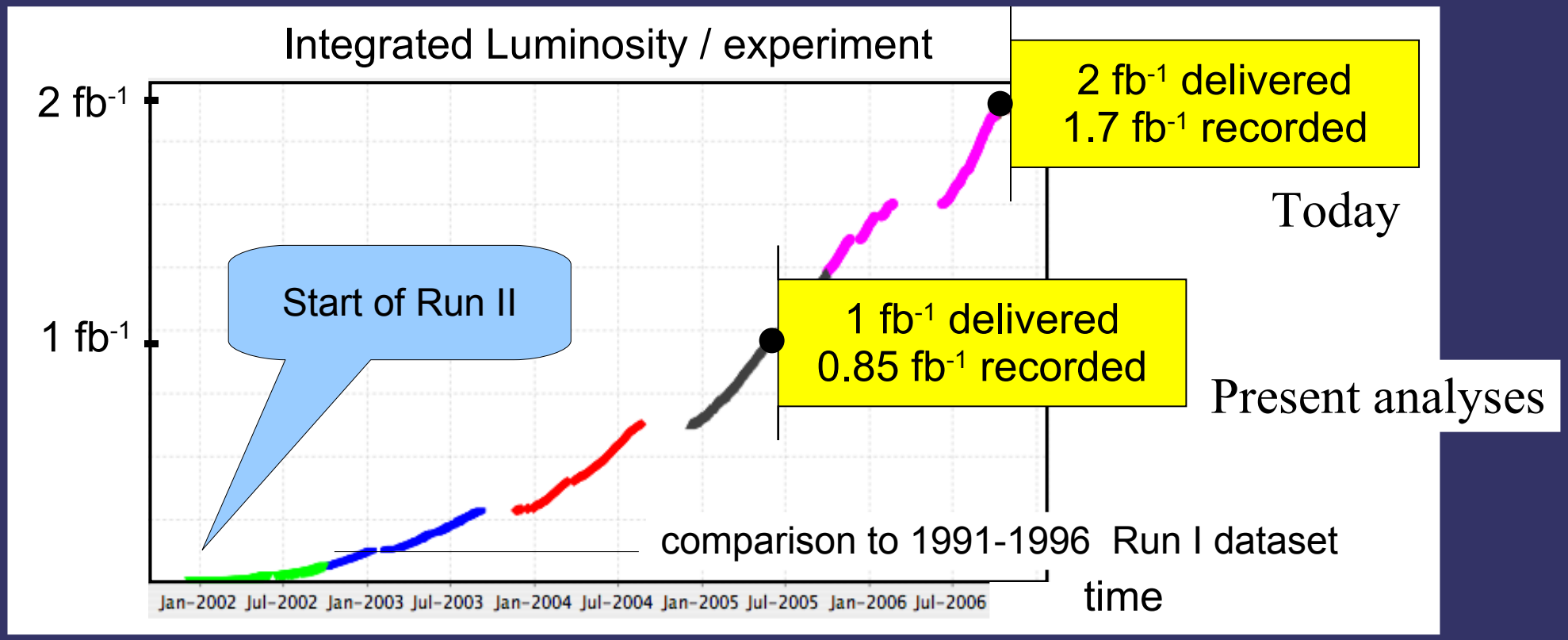
Fall 2006



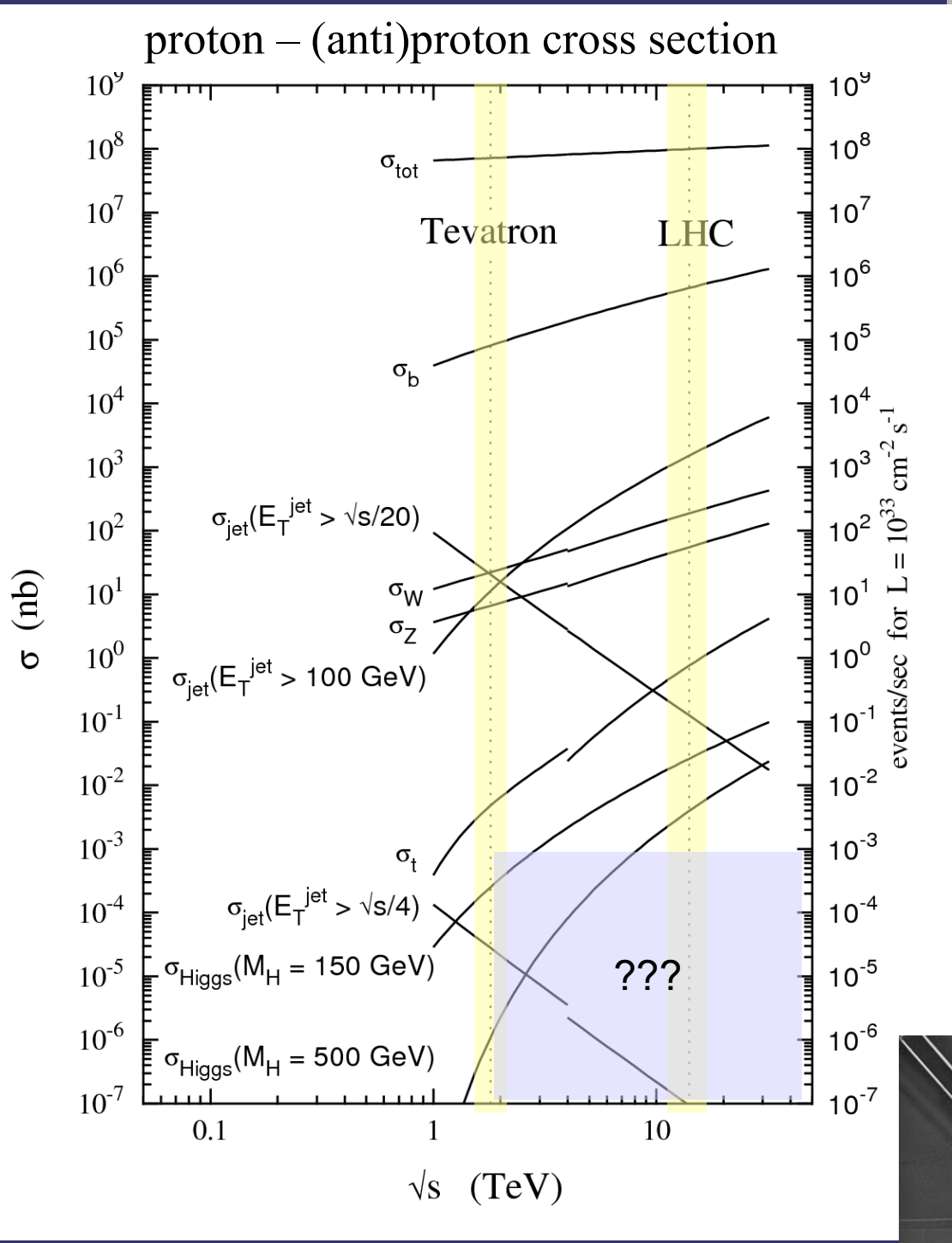
$|V_{td} / V_{ts}| = 0.2060 \pm 0.0007\ (\text{expt.})\ ^{+0.0081}_{-0.0060}\ (\text{theory})$

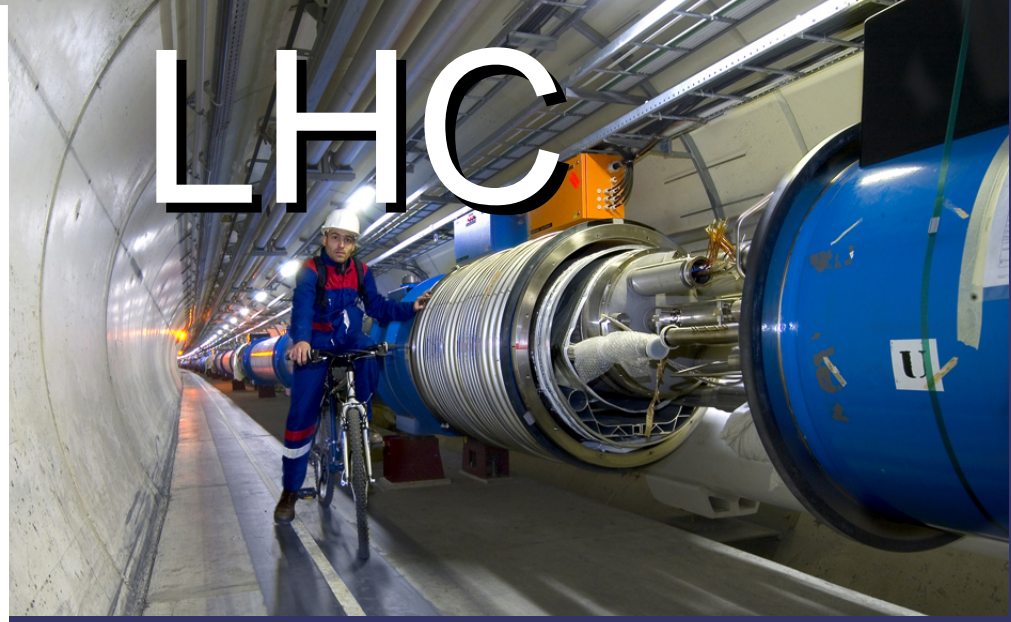
Tevatron Uncertainty ~ 0.1 x Theory (Lattice QCD) Uncertainty

Tevatron Run II, so far

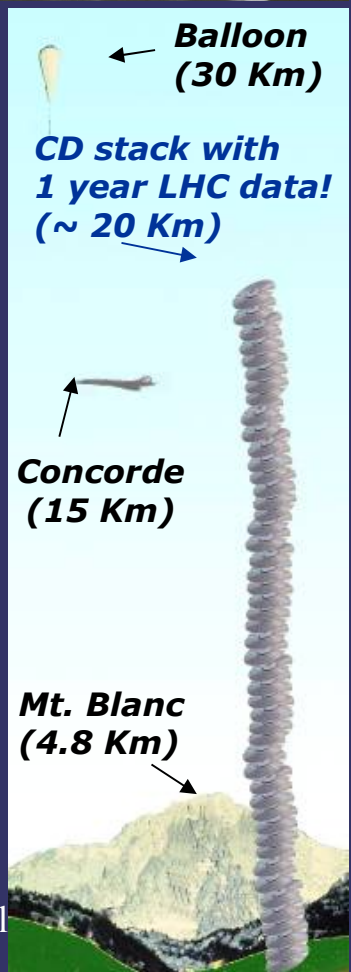


- Run I: ~140 pb^{-1} / experiment
- Run II:
  - First Collisions: April 2001
  - First Physics: Early 2002
  - 1 fb^{-1}: June 2005
  - 2 fb^{-1}: October 2006
  - 4 fb^{-1}: Early 2008
  - 8 fb^{-1}: End of 2009



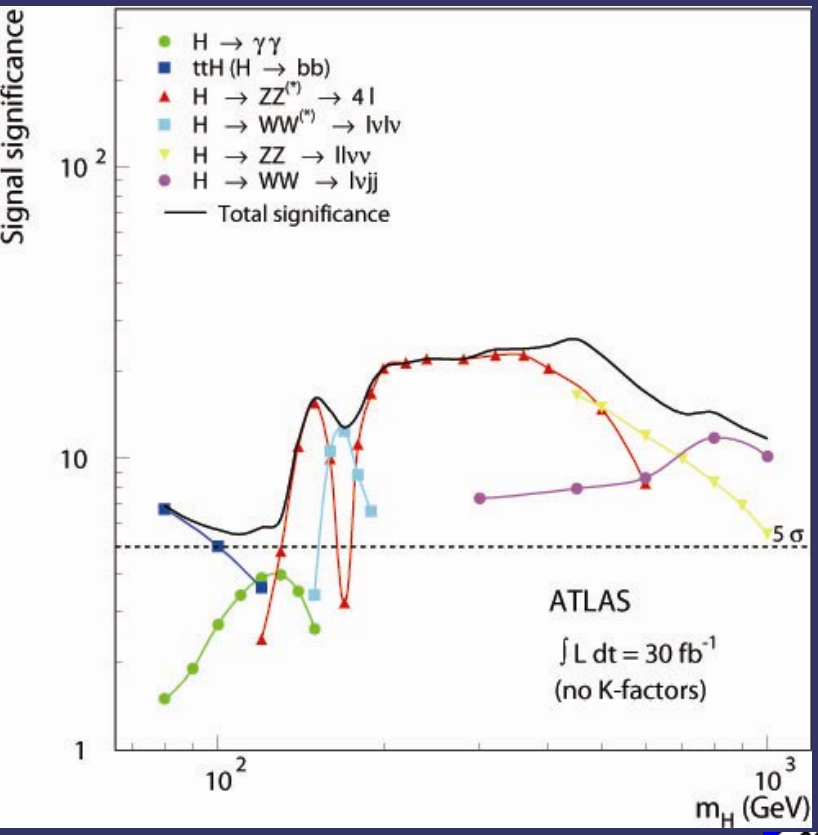


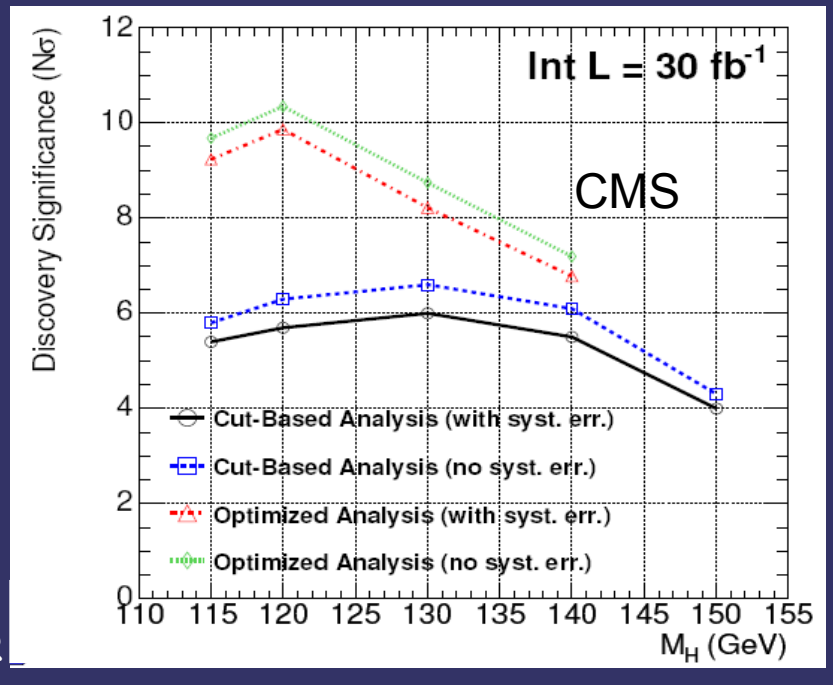
What does 14 TeV buy us?



SM Higgs at LHC

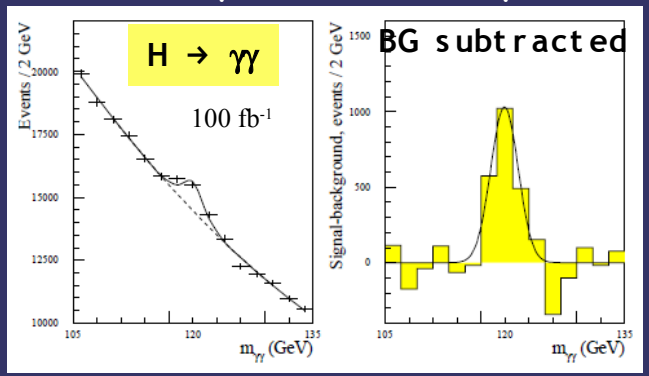
CMS low mass Higgs: m_H between 114 GeV and 200 GeV

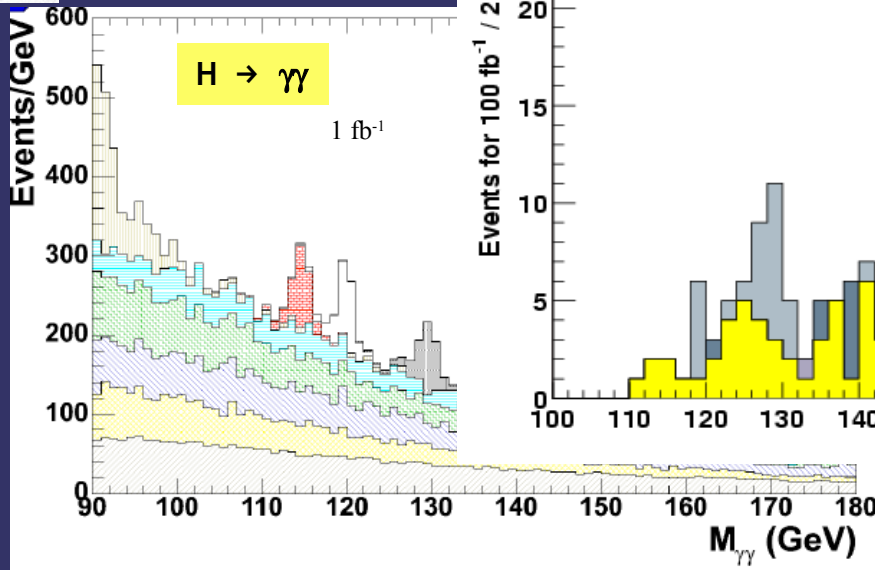


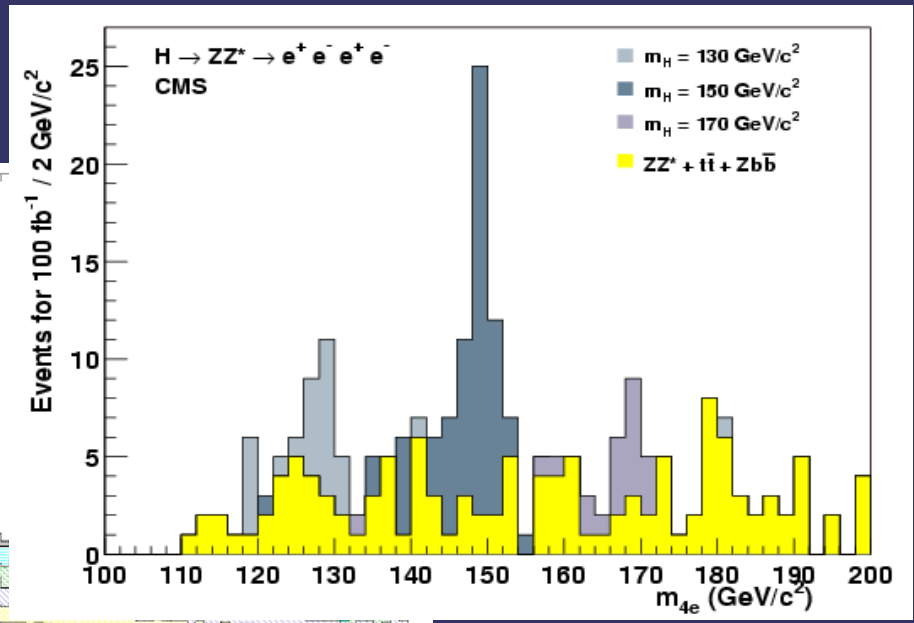


CMS Physics TDR (June 2006)

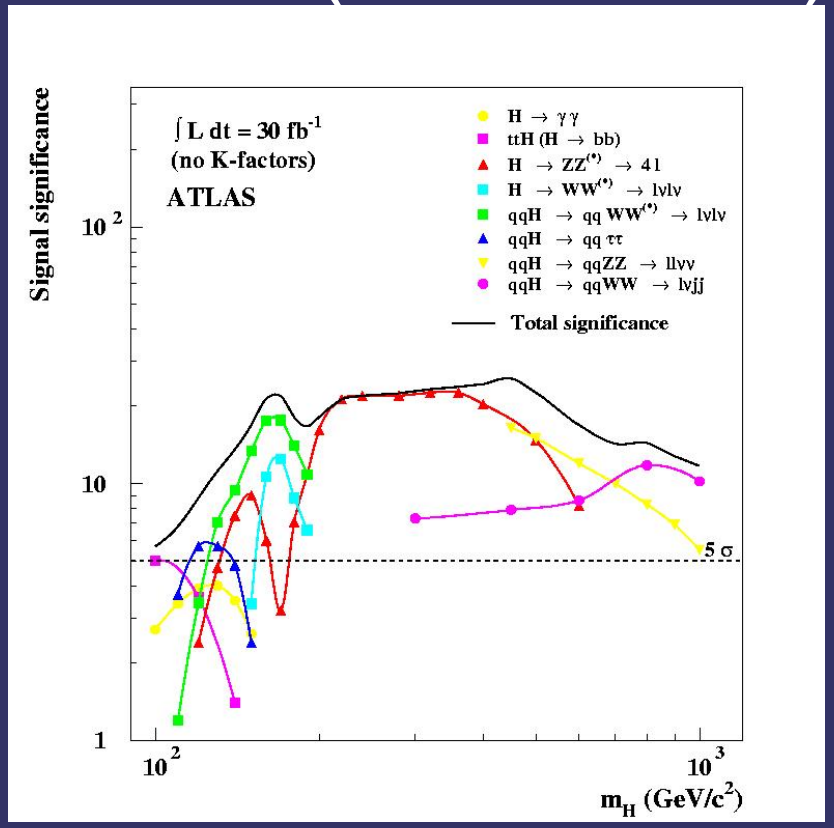
ATLAS Physics TDR (May 1999)

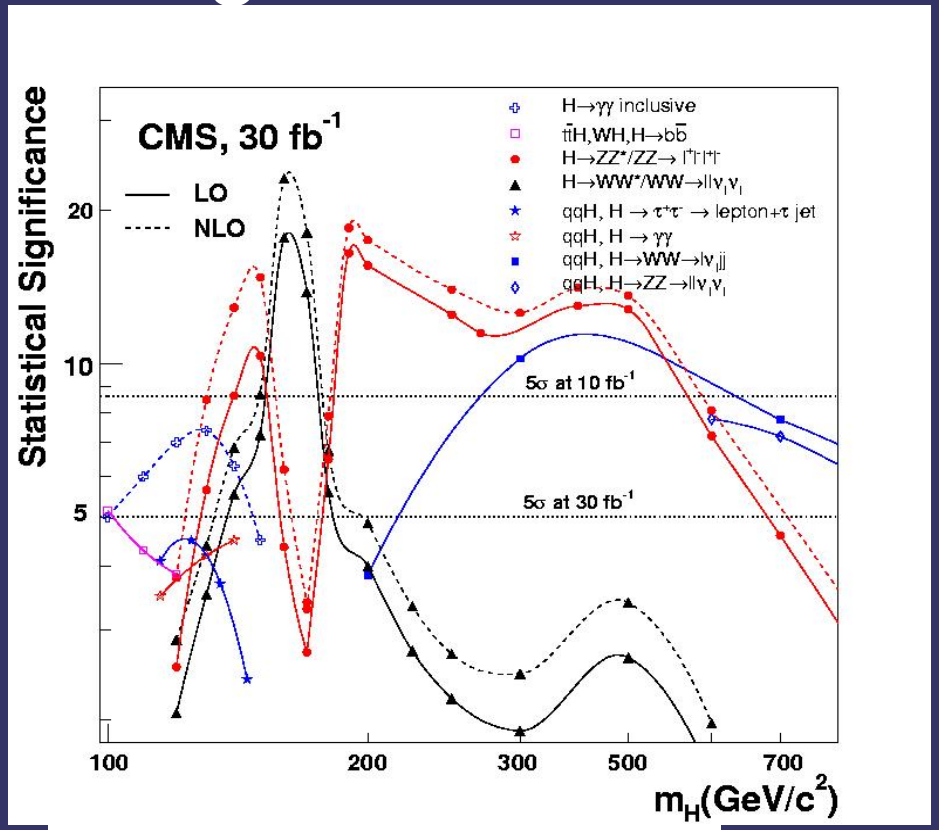




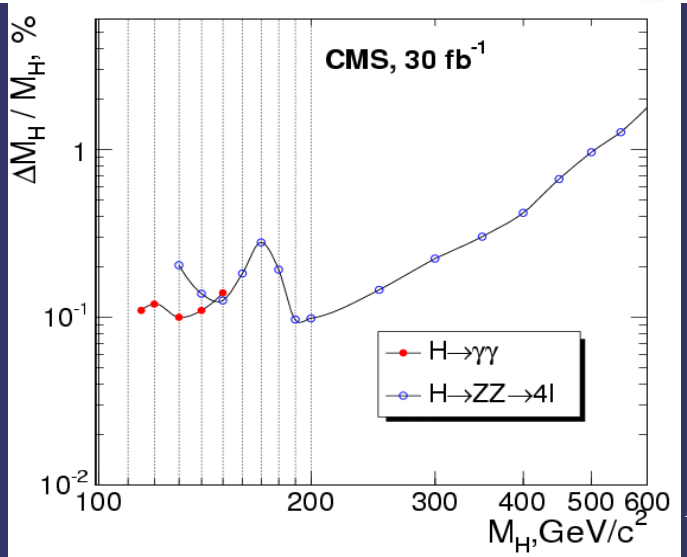


SM Higgs even accessible early on (2009/2010) at higher masses

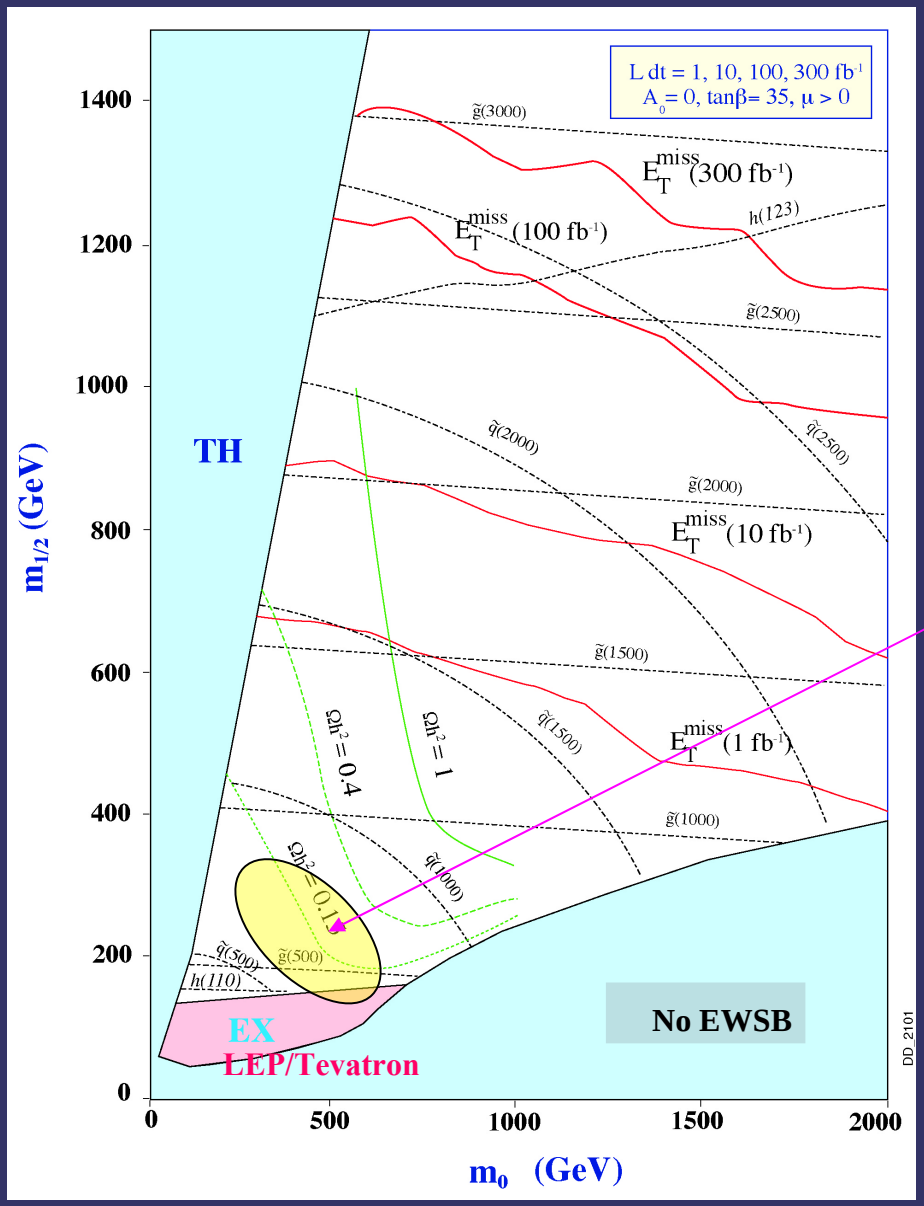




Mass resolution from CMS studies



Discovery potential for SUSY (nSUGRA)



- If low energy Supersymmetry exists, LHC will almost certainly observe it
- Squarks and Gluinos detectable up to 2.5-3 TeV mass with 300 fb^{-1}

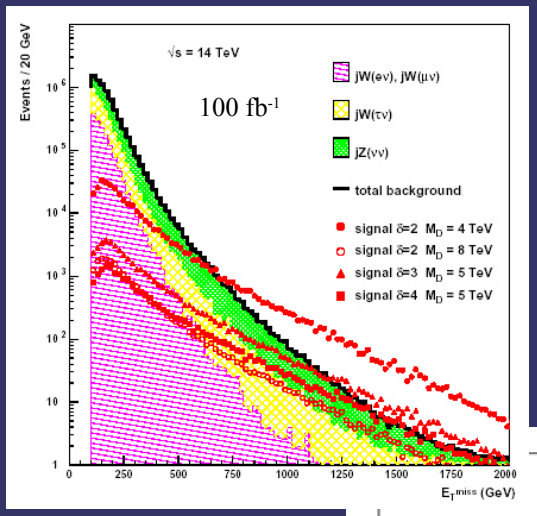
Need only short run time to cover interesting region for Cold DM

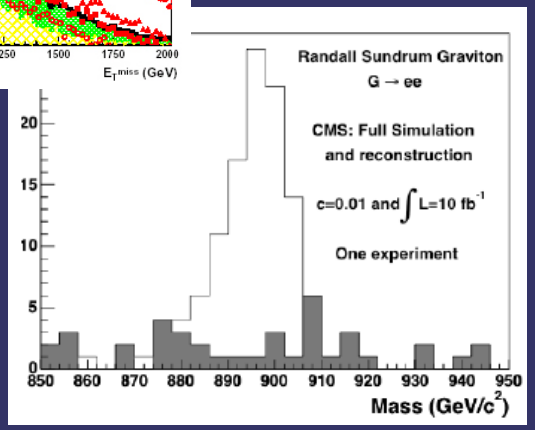
Word of caution: requires excellent understanding of detector performance and SM backgrounds

$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
$\tan\beta$: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

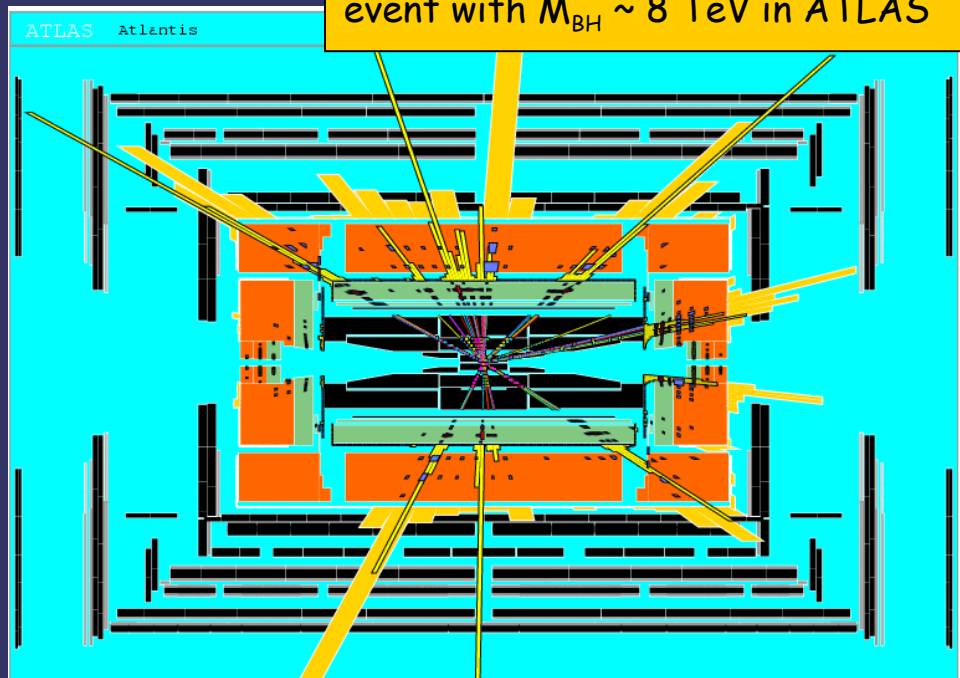
Extra Dimensions / Black Holes

$E_T(\text{jet}) > 1$ TeV





Simulation of a mini black hole event with $M_{BH} \sim 8$ TeV in ATLAS



R. Hirosky, UVa

LHC Physics Reach Summary

SM Higgs	100 GeV -> 1 TeV
MSSM Higgs	covers full (m_A, $\tan\beta$)
SUSY (squark, gluino)	2.5 - 3 TeV (300 fb^{-1})
New gauge bosons (Z')	< 4.5 TeV (100 fb^{-1})
Quark substructure (Λ_C)	< 25/40 TeV (30/300 fb^{-1})
q*, l*	< 6.5/3.4 TeV (100 fb^{-1})
Various ED Models	< ~9 TeV (100 fb^{-1})
Black holes	< 6 ~ 10 TeV
M(top quark)	σ_M ~ 1 GeV (~ 0.5 %)
M_W	σ_M ~ 15 MeV
CP-violation in B-decay	$\sigma(\sin 2\beta)$ ~ 0.016 (30 fb^{-1})
Rare B-decay ($B_S \rightarrow \mu\mu$)	~ 5σ (130 fb^{-1})

Discovery for sure
+ some measurements

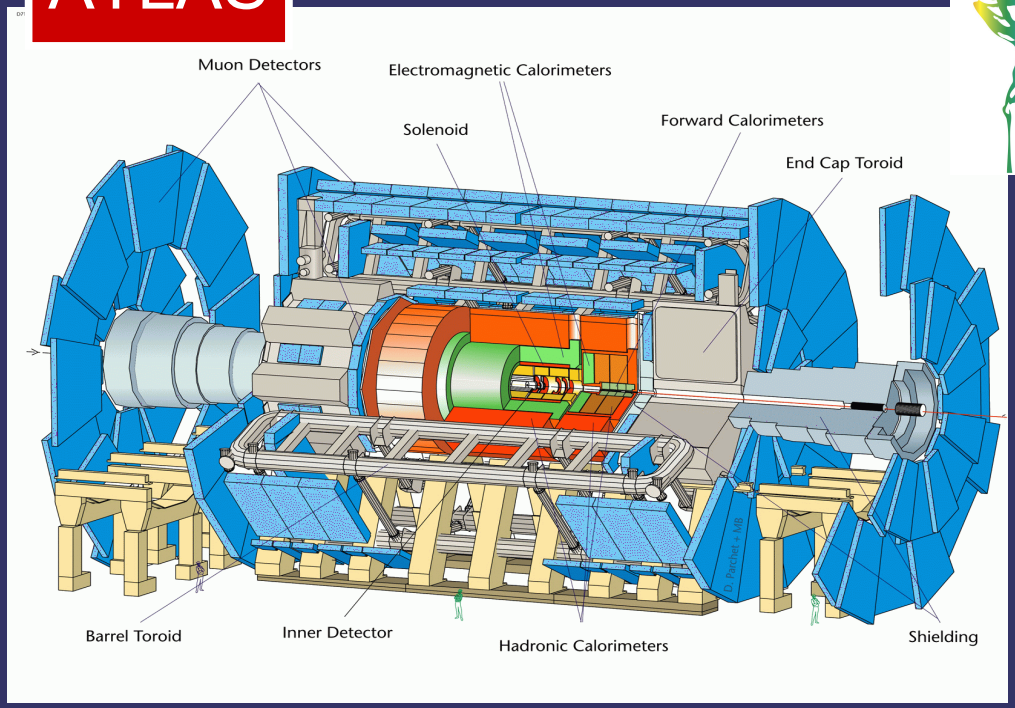
can say "final word"
about (low E) SUSY

Both experiments can also cope with the new physics possibilities which were not foreseen at the beginning of the project.

Any one of those would change the understanding of our universe !

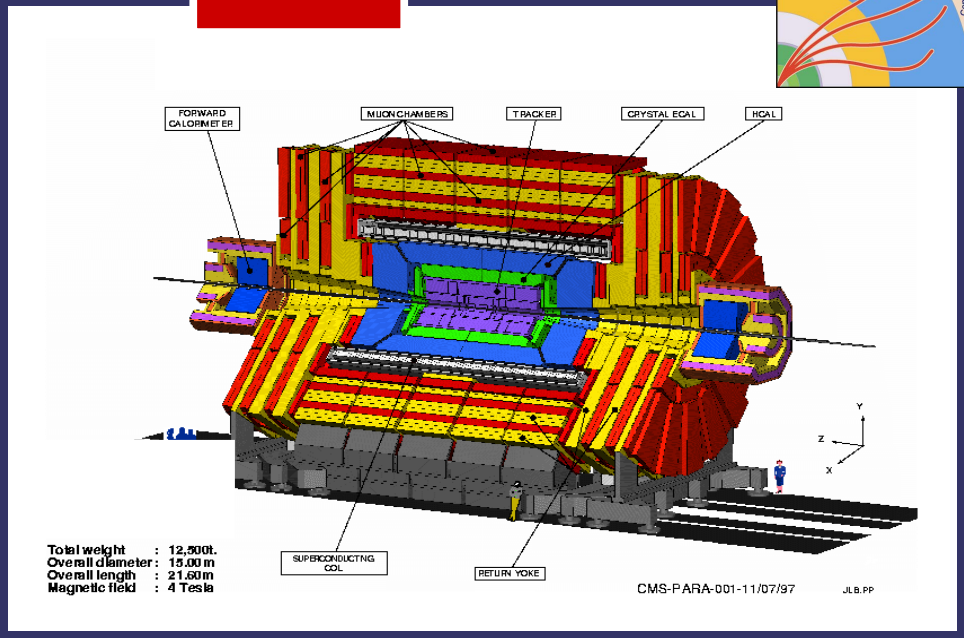
General purpose detectors for pp collisions

ATLAS



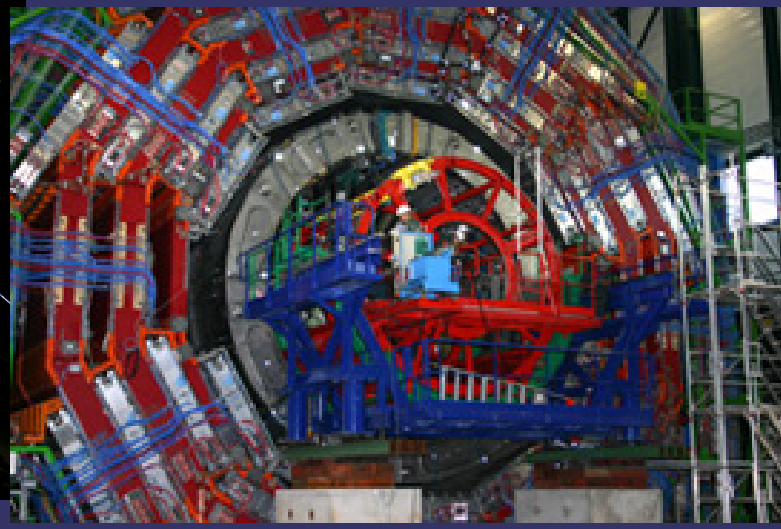
Length : ~45 m ; Diameter : ~24 m
Weight : ~ 7,000 tons
Solenoid : 2 T, Air-core toroids

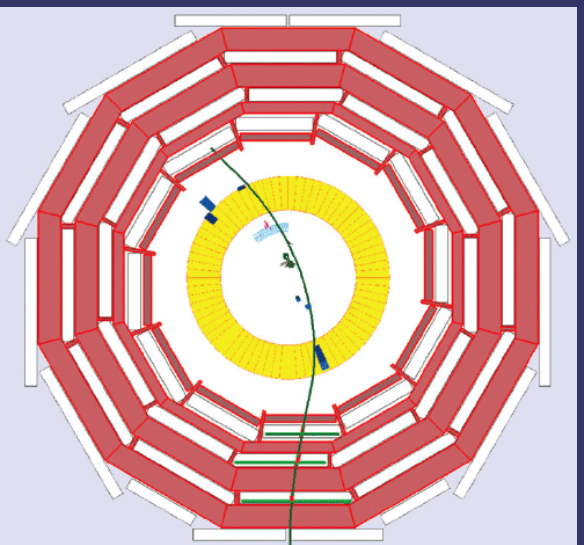
CMS



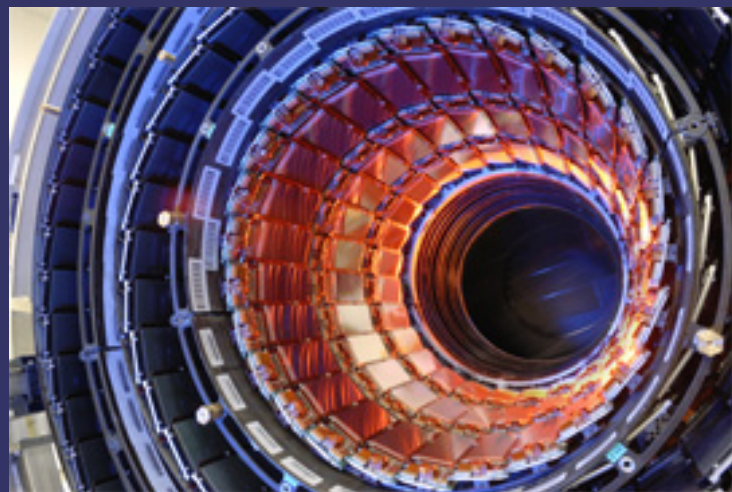
Length : ~22 m ; Diameter : ~14 m
Weight : ~ 12,500 tons
Solenoid : 4 T, Fe yoke

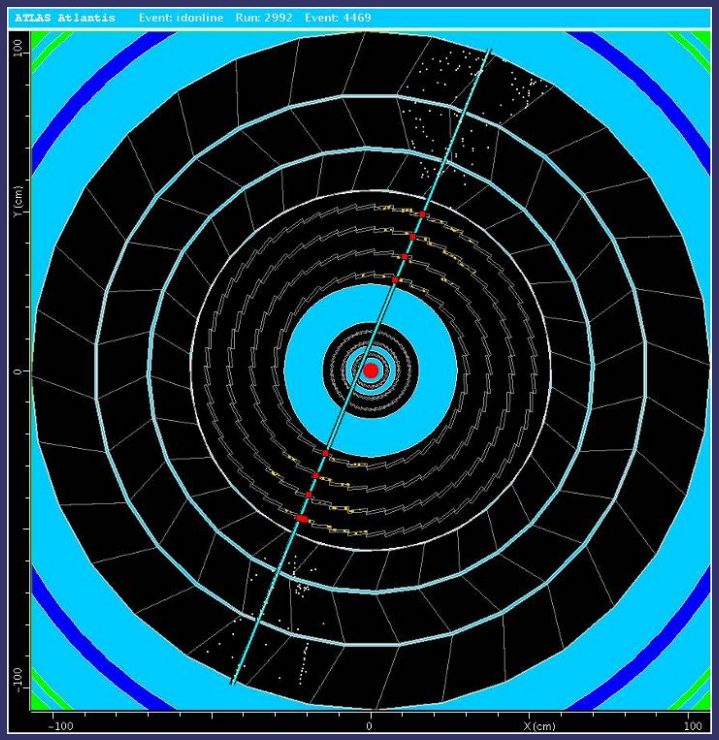
	ATLAS	CMS
TRACKER	Si pixels + strips, TRT	Si pixels + strips
EM CALO	Pb-liquid argon	$PbWO_4$ crystals
HAD CALO	Fe-scint. + Cu-liquid argon (≥ 10 λ)	Brass-scint. (≥ 5.8 λ + catcher)
MUON	MDT, CSC, RPC, TGC	DT, CSC, RPC

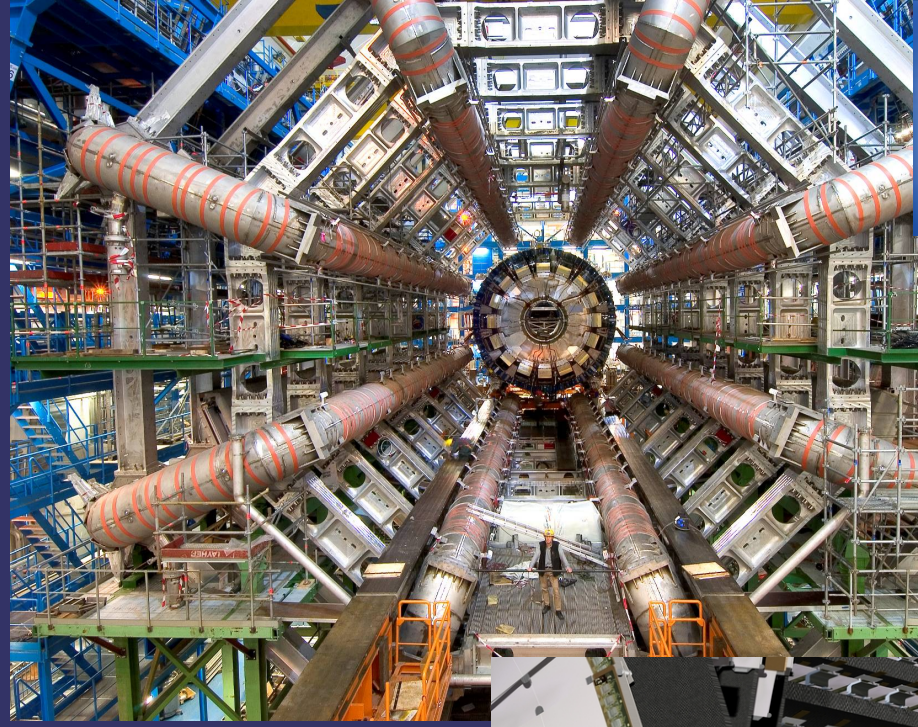


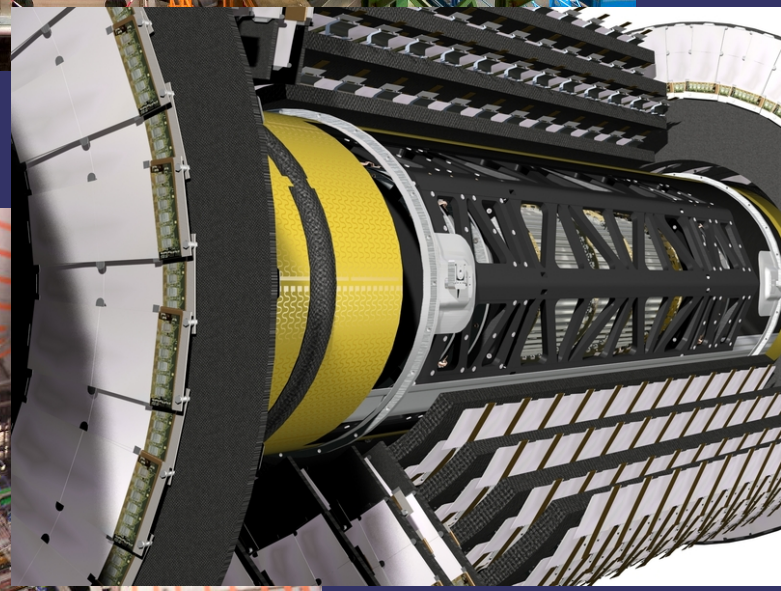


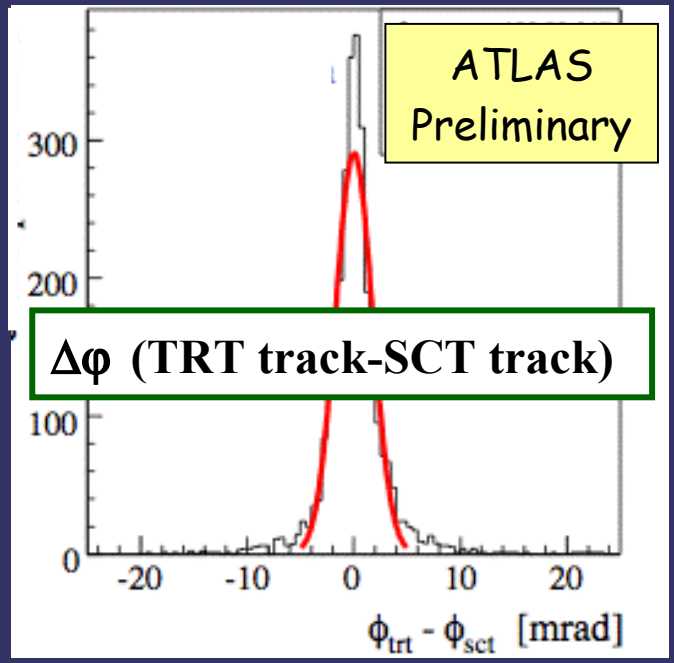
A cosmic track recorded at full field(4T) in a “slice” of CMS detector (Aug. 2006)

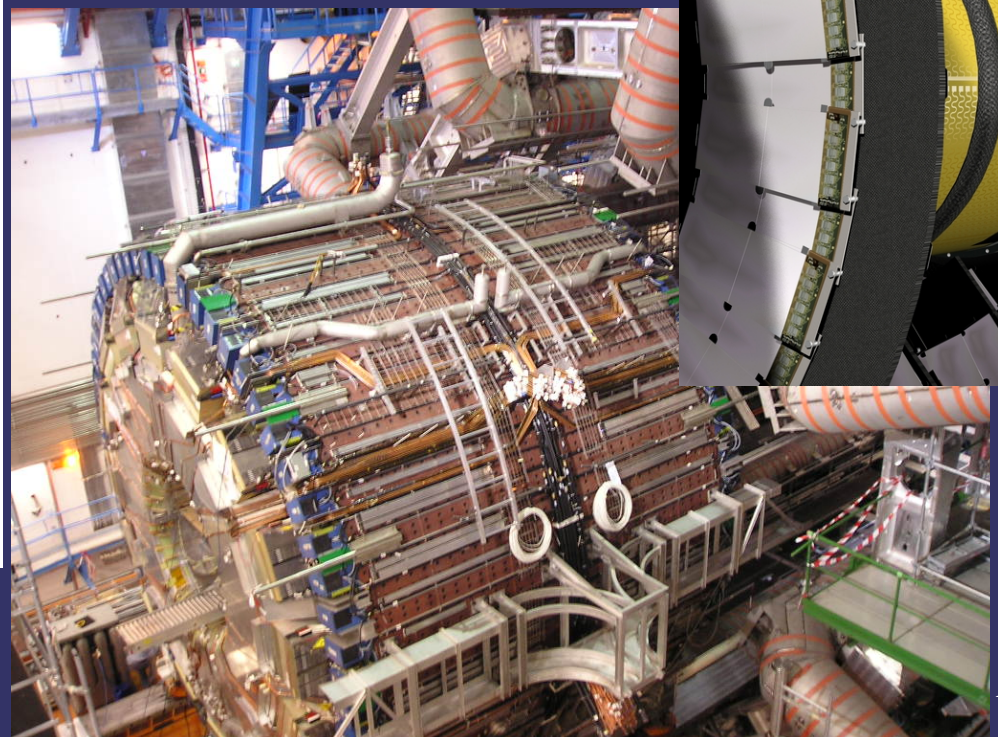












Cosmics data taken in barrel SCT+TRT

LHC Schedule, "Are we there yet???"

- Last magnet installed : March 2007
- Machine and experiments closed : 31 August 2007
- First collisions ($\sqrt{s}$ = 900 GeV, L~10^{29} cm^{-2} s^{-1}) : November 2007
- Commissioning run at injection energy until end 2007, then shutdown (3 months ?)
- First collisions at $\sqrt{s}$=14 TeV (followed by first physics run): Spring 2008

Goal : deliver integrated luminosity of few fb^{-1} by end 2008

It's just around the corner!

In conclusion...

It's a great time to be doing collider physics!

Many opportunities for students and posdtocs to join still cutting edge Tevatron analyses, and...

...to be part of the Revolution. How will the LHC change our view of the universe over the next decade??? You can be there!!!