Selected Results on *Electroweak, Top and Higgs Searches* from the Tevatron

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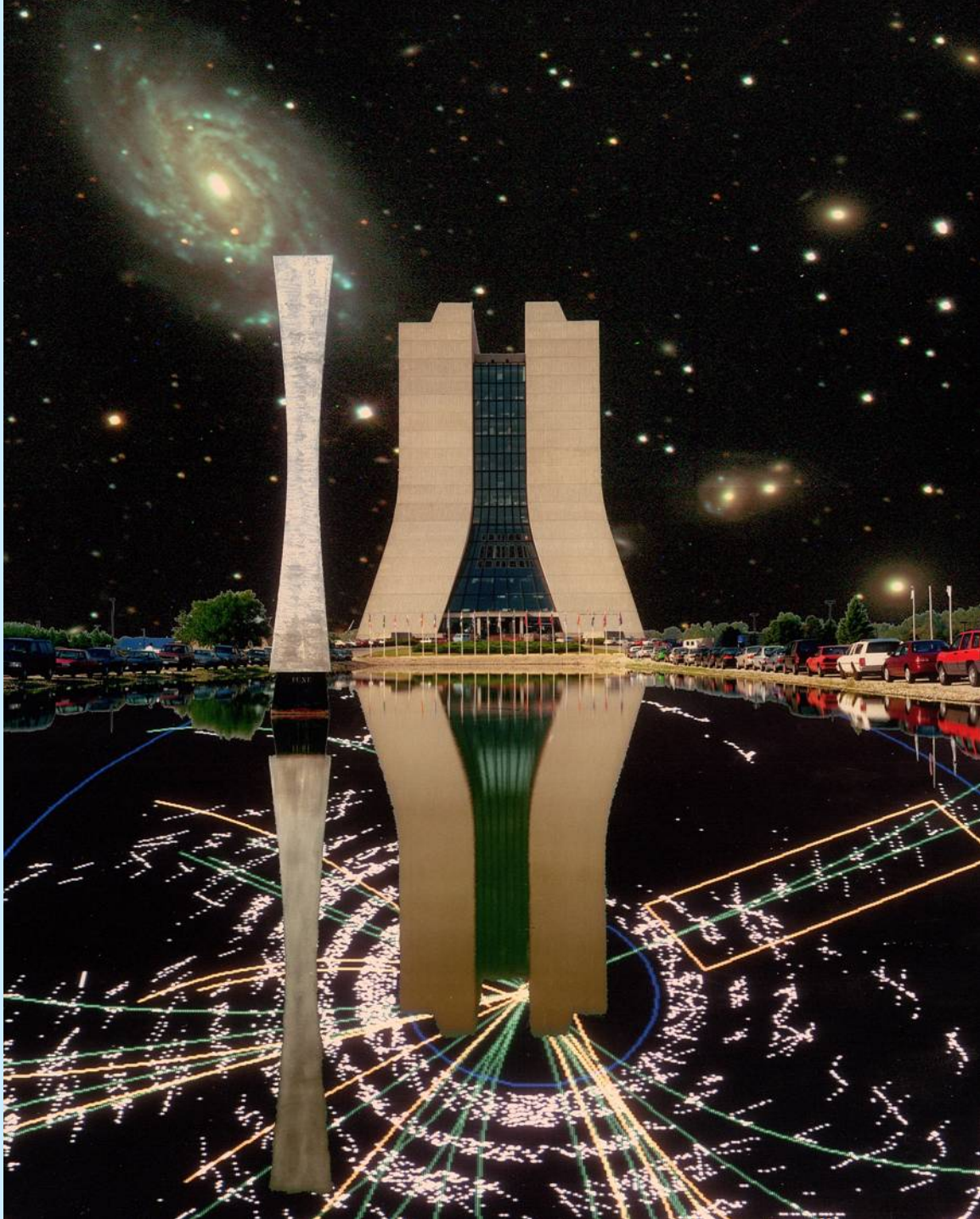
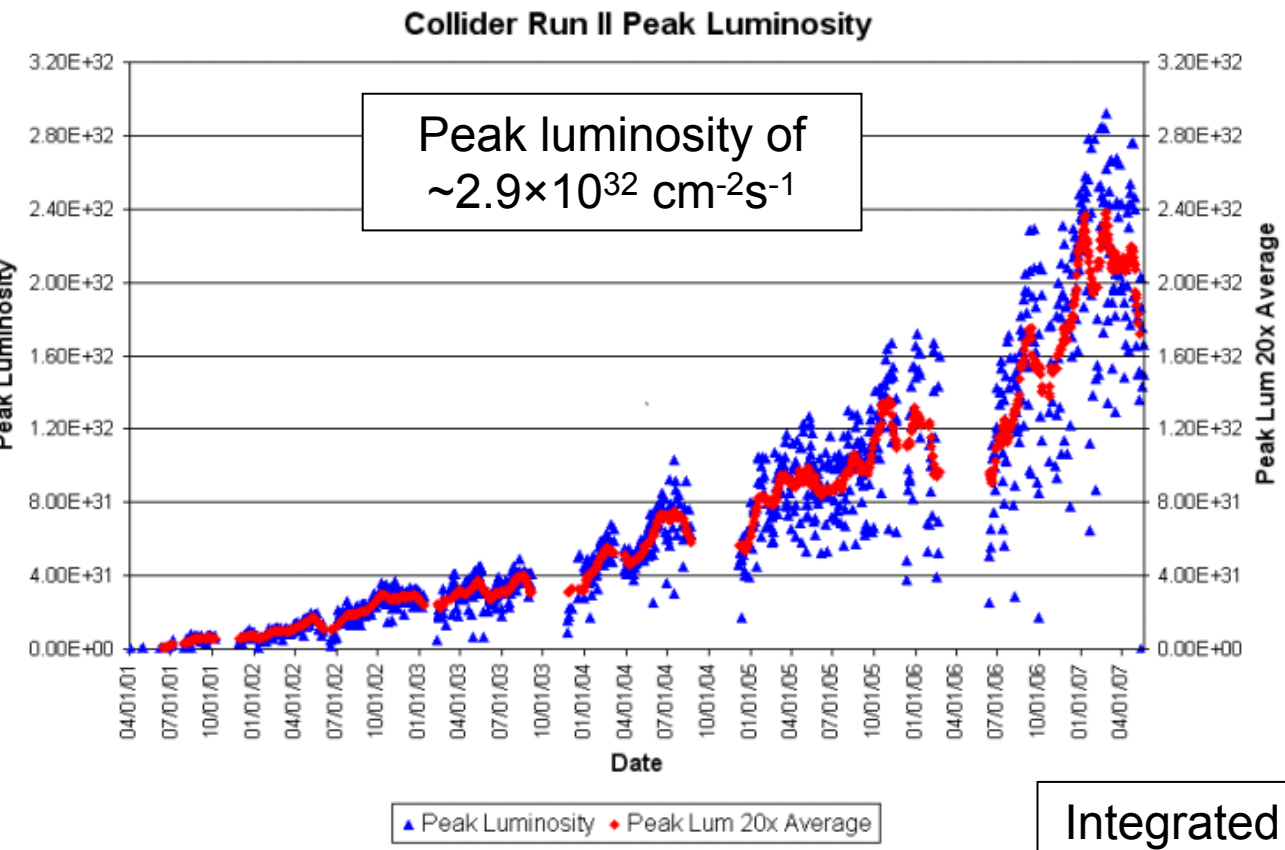
Outline

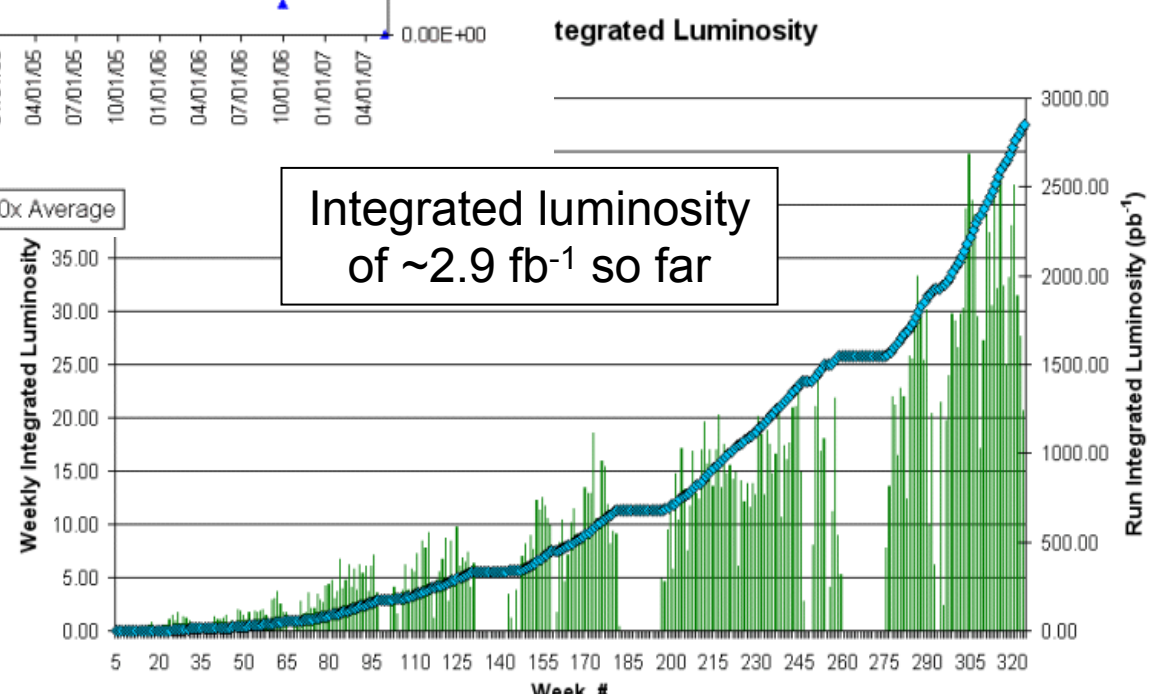
- **Introduction**
  - Tevatron, CDF and DØ
- **Electroweak measurements**
  - W mass
  - ZZ production
- **Top physics**
  - Cross section, mass
  - Single top
- **Higgs searches**
  - The SM
    - $WH \rightarrow e\nu bb$
    - $H \rightarrow WW^* \rightarrow \ell^+\ell^-\nu\nu$
  - SUSY
    - $bh/bbh(\rightarrow bb)$
    - $h \rightarrow \tau\tau$
- **Summary**



Tevatron peak and integrated luminosities, May '07



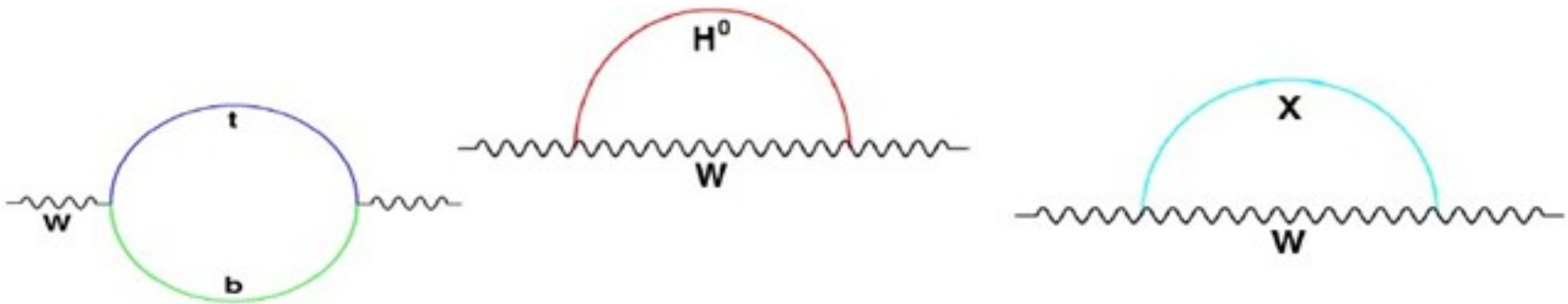
- Delivered integrated luminosity ~2.9 fb^{-1}
- Data set has doubled every year
- Expect 4 – 8 fb^{-1} by the end of 2009



- CDF/DØ operate at ~85% efficiency
- Following results are based on 0.2 – 1.5 fb^{-1} of data

W mass measurement: motivation

- m_W is a parameter of the SM – must be measured as precisely as possible
- Higher order corrections due to heavy quark, Higgs and new particles



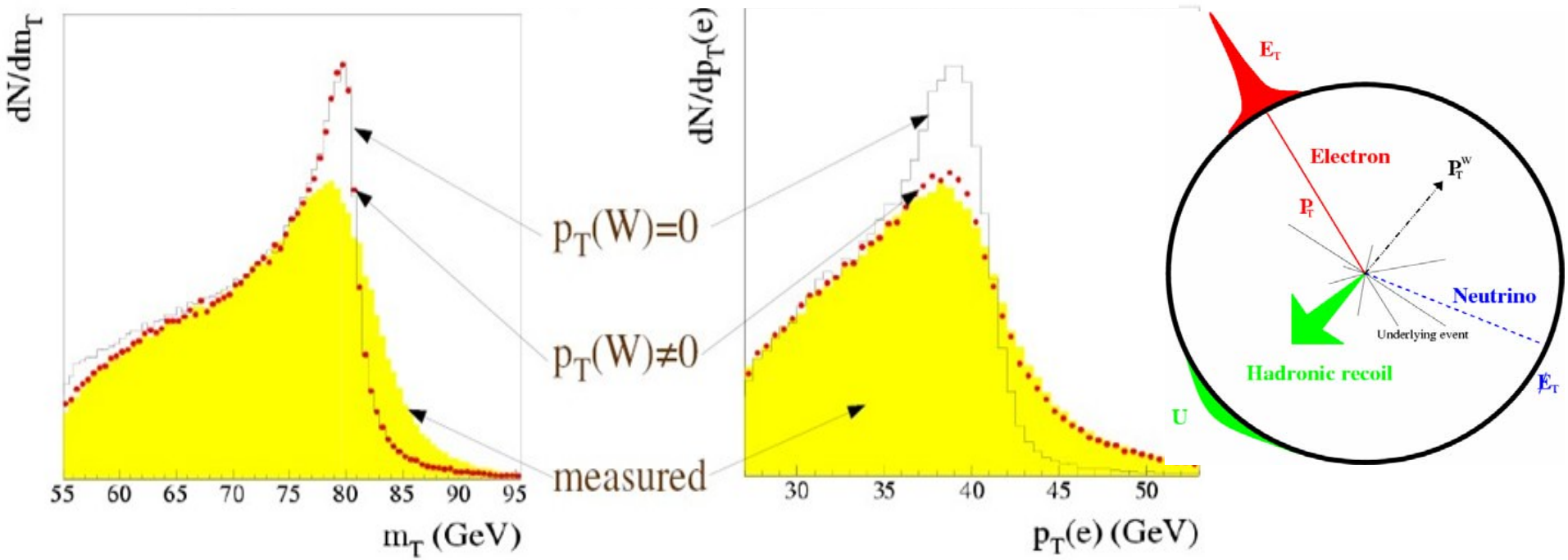
$$\rho = \frac{m_W^2}{m_Z^2(1-\sin^2\theta_W)} \equiv 1 + \Delta r$$

$$\Delta r = \frac{3G_F}{8\pi^2\sqrt{2}} m_t^2 + \frac{\sqrt{2}G_F}{16\pi^2} m_W^2 \left[\frac{11}{3}\ln\left(\frac{m_H^2}{m_W^2}\right) + \ldots\right] + \ldots$$

- Along with the top mass, m_W constrains the mass of the Higgs boson

W mass measurement techniques at the Tevatron

- W mass is related to the location of Jacobian edge



1. W transverse mass

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} \left(1 - \cos\phi_{\ell\nu}\right)}$$

Insensitive to $p_T(W)$ to 1st order

Reconstruction of $p_T(\nu)$ is sensitive to hadronic response and multiply interactions

2. $p_T(\ell)$ fit: needs theoretical model for $p_T(W)$; provides cross-check of production model

3. $p_T(\nu)$ fit provides cross-check of hadronic recoil model

CDF: W mass systematic uncertainties and results

L_{int} ~ 200 pb^{-1}

Transverse Mass Fit Uncertainties (MeV)

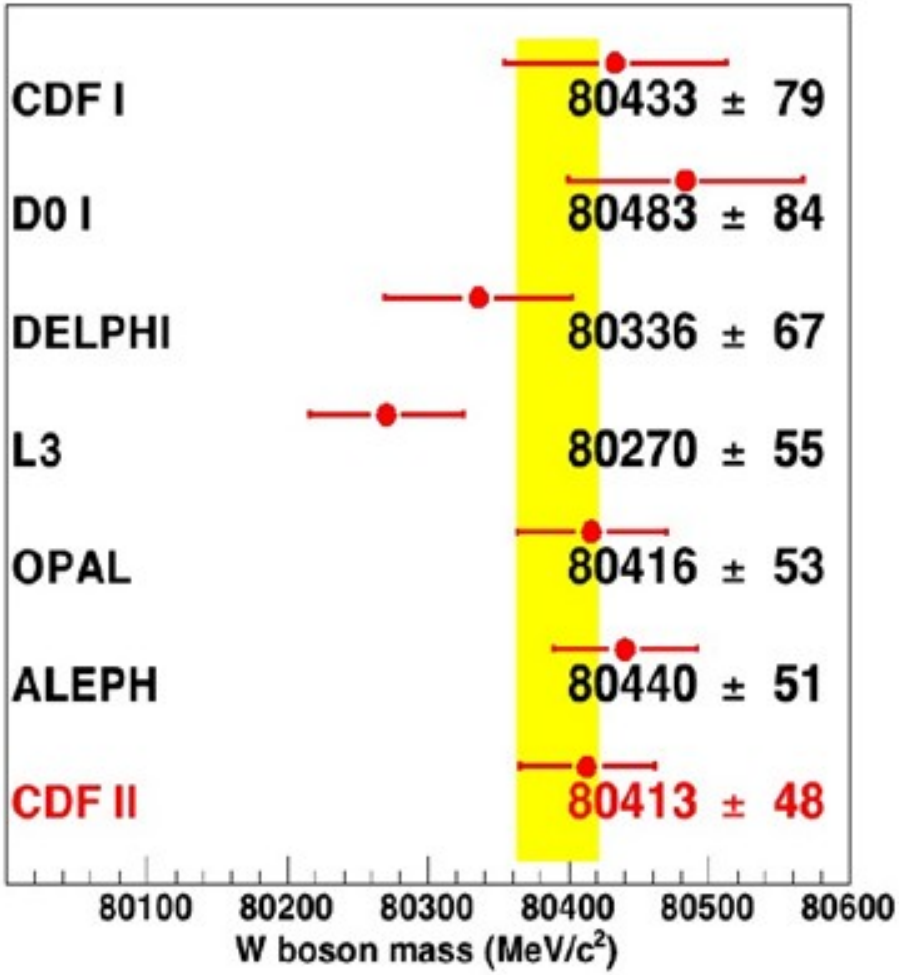
	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
pT(W) model (g2,g3)	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

Systematic uncertainties shown in green: statistics-limited by control data samples

- Combined electrons (3 fits): M_W = 80477 ± 62 MeV, $P(\chi^2)$ = 49%
- Combined muons (3 fits): M_W = 80352 ± 60 MeV, $P(\chi^2)$ = 69%
- All combined (6 fits): M_W = 80413 ± 48 MeV, $P(\chi^2)$ = 44%

W mass: new world average

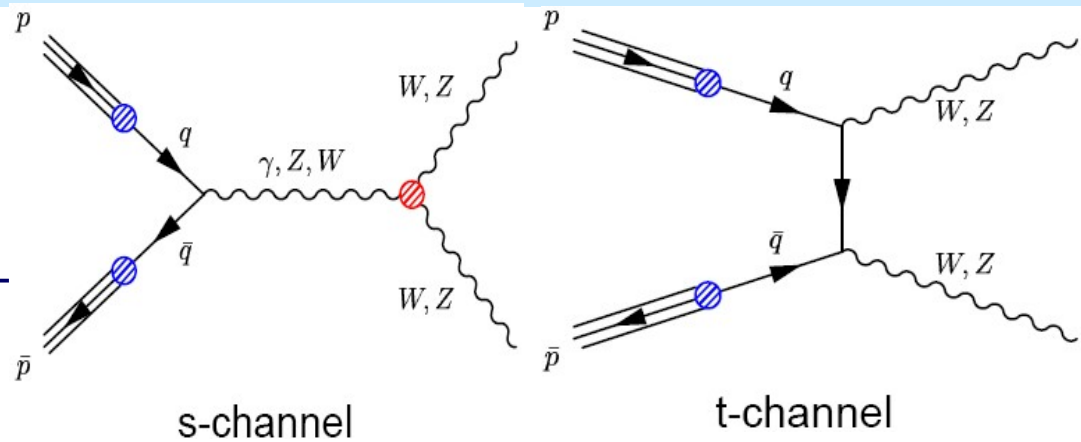
	W mass (MeV)
DELPHI	80336 ± 67
L3	80270 ± 55
OPAL	80416 ± 53
ALEPH	80440 ± 51
CDF-I	80433 ± 79
D0-I	80483 ± 84
LEP Average	80376 ± 33
Tevatron-I Average	80454 ± 59
Previous World Average	80392 ± 29
CDF-II (preliminary)	80413 ± 48
New Tevatron Average	80429 ± 39
New World Average	80398 ± 25



- The CDF Run II result is the most precise measurement to date

Di-boson production

- Measure cross sections and anomalous couplings
  - Probe non-Abelian nature of $SU(2)_L \otimes U(1)_Y$ gauge boson self-interactions
  - Rate inconsistent with the SM expectation would indicate new physics



$q\bar{q}' \to W^{(*)} \to W\gamma$: $WW\gamma$ only

$q\bar{q}' \to W^{(*)} \to WZ$: WWZ only

$q\bar{q} \to Z/\gamma^{(*)} \to WW$: $WW\gamma, WWZ$

$q\bar{q} \to Z/\gamma^{(*)} \to Z\gamma$: $ZZ\gamma, Z\gamma\gamma$

$q\bar{q} \to Z/\gamma^{(*)} \to ZZ$: $ZZ\gamma, ZZZ$

Absent in SM

- Excursions from the SM can be described via effective Lagrangian:

$$L_{WWV}/g_{WWV} = \boxed{g_V^1}(W^+_{\mu\nu}W^\mu V^\nu - W^+_\mu V_\nu W^{\mu\nu})$$

$$+\boxed{\kappa_V} W^+_\mu W_\nu V^{\mu\nu} + \frac{\boxed{\lambda_V}}{M_W^2} W^+_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

where $V = Z, \gamma$

- In SM:

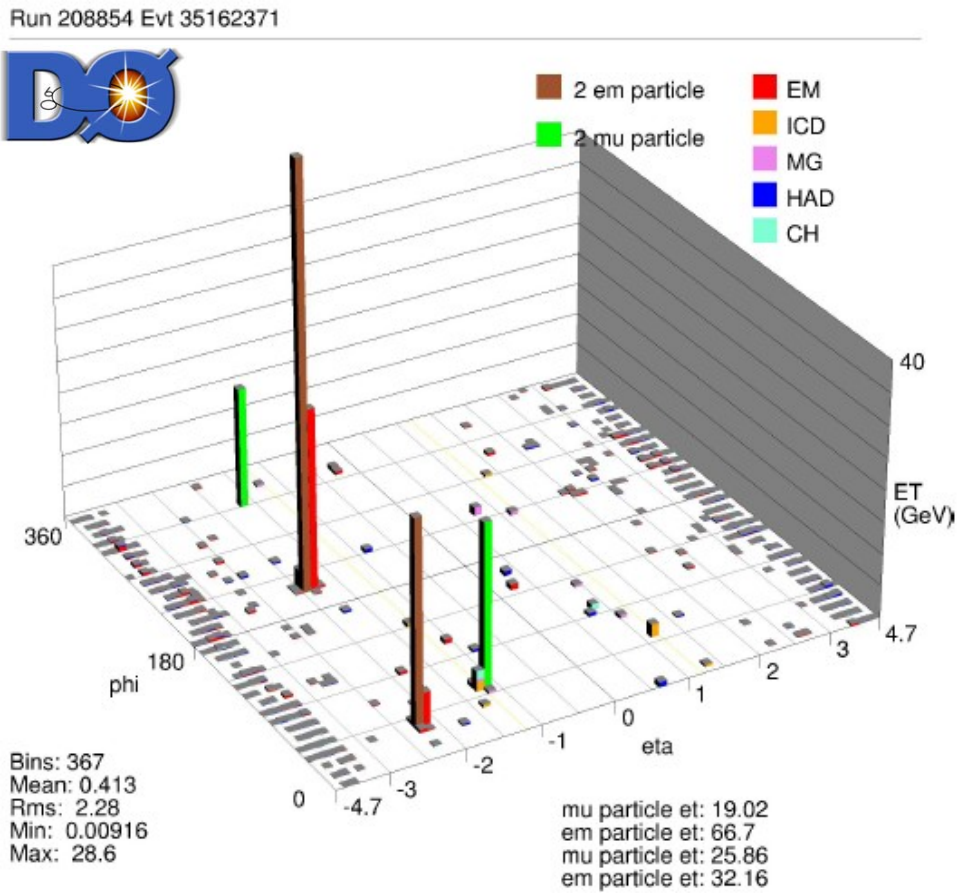
$$g_V^1 = \kappa_V = 1, \quad \lambda_V = 0$$

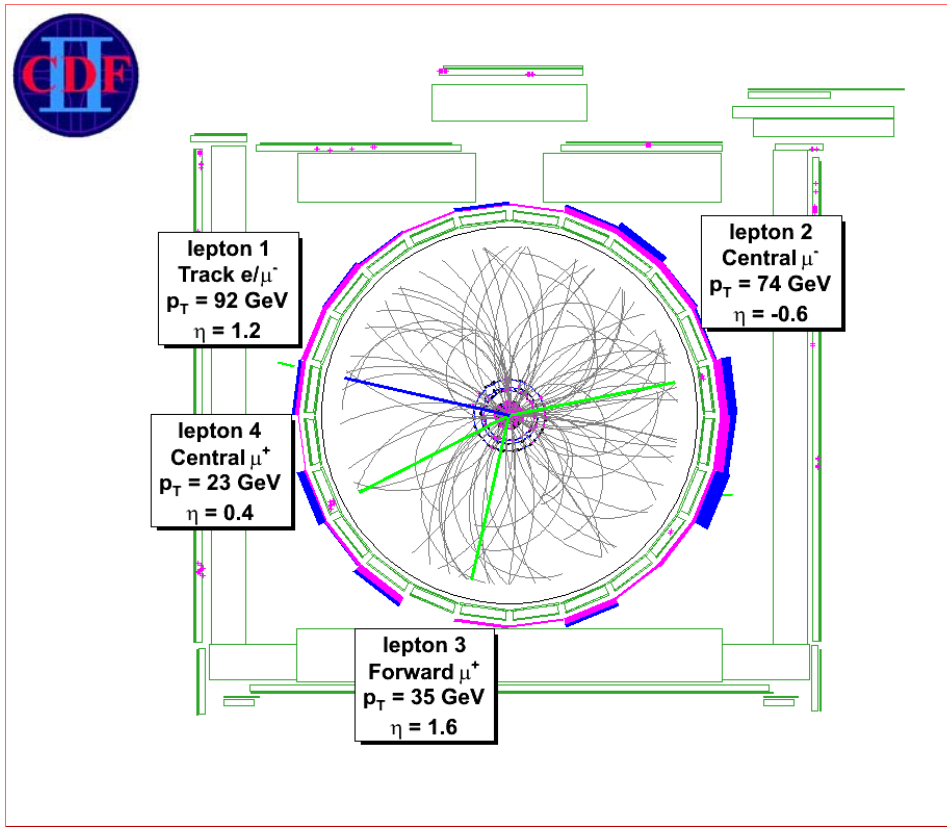
- Determine deviation from SM values:

$$\Delta g_V^1 = g_V^1 - 1, \quad \lambda_V, \quad \Delta\kappa_V = \kappa_V - 1$$

ZZ → ℓℓℓℓ / ℓℓνν

- ZZ production has not been observed at the Tevatron so far
- Each experiment has one clean 4 lepton candidate event

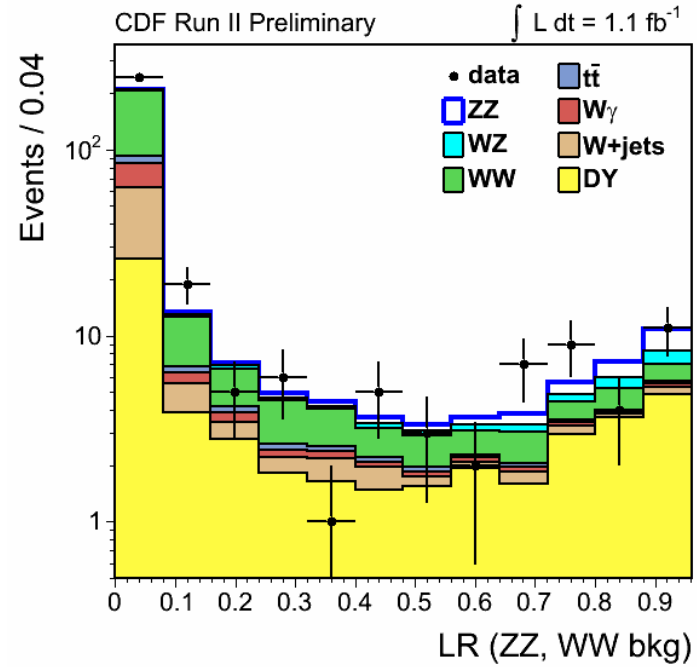




- ZZ → ℓℓνν final states have larger BR but are more challenging to extract

CDF: ZZ → ℓℓνν analysis

- The largest physics bkgd from WW production
- It is reduced by employing event likelihood ratio based on LO ME for WW and ZZ production and decay
- Cross-check the method, modeling of data, etc., in high/low S/B ratio regions, and for various processes



- ZZ → ℓℓνν summary

Category	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Total	Data
$e\ e$	22.8	2.8	4.3	1.5	4.8	10.8	12.1	59.1 ± 5.0	61
$\mu\ \mu$	17.7	2.1	3.5	1.4	15.9	0.0	2.6	43.1 ± 4.2	50
e trk	18.7	1.4	1.8	1.4	2.2	2.5	5.2	33.1 ± 2.4	42
μ trk	10.0	0.8	1.2	0.8	1.1	0.3	3.4	17.5 ± 1.3	29
Total	69.2	7.1	10.7	5.1	24.0	13.6	23.2	152.9 ± 11.6	182

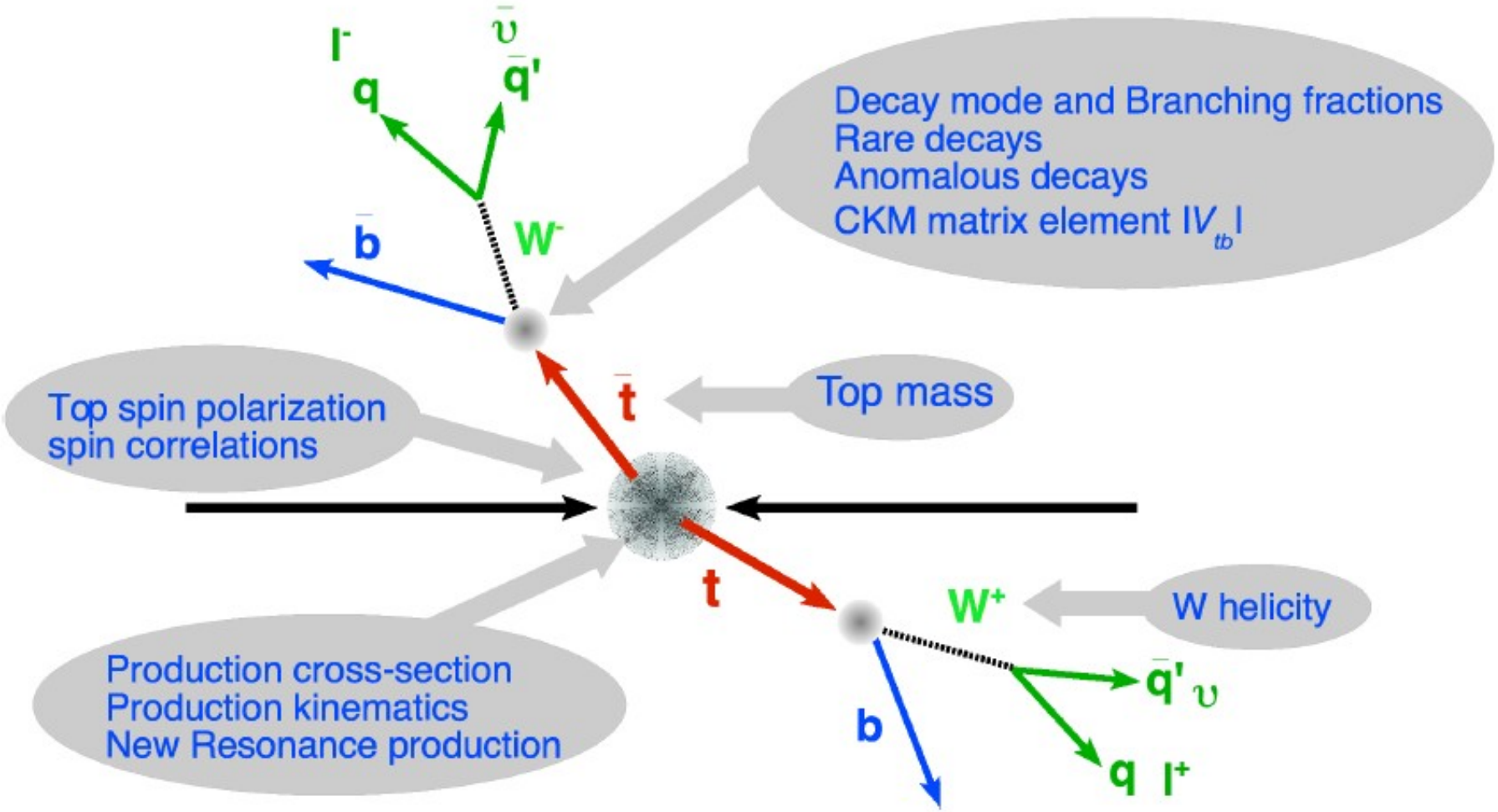
- First evidence at 3σ level for ZZ → ℓℓℓℓ/ℓℓνν production:

$$\sigma(p\bar{p} \to ZZ) = 0.75^{+0.71}_{-0.54}\ (\text{stat.} + \text{syst.}) \pm\ 0.05\ (\text{lumi.})\ \text{pb}$$

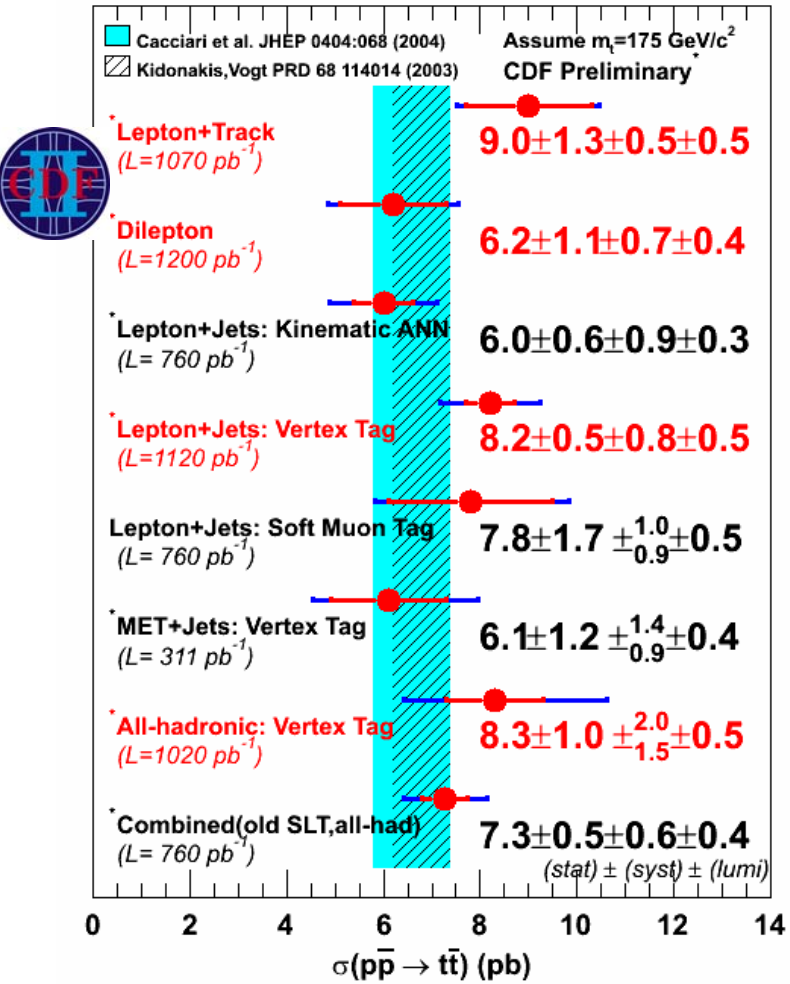
Consistent with on-shell ZZ production cross-section of 1.4 ± 0.1 pb at NLO

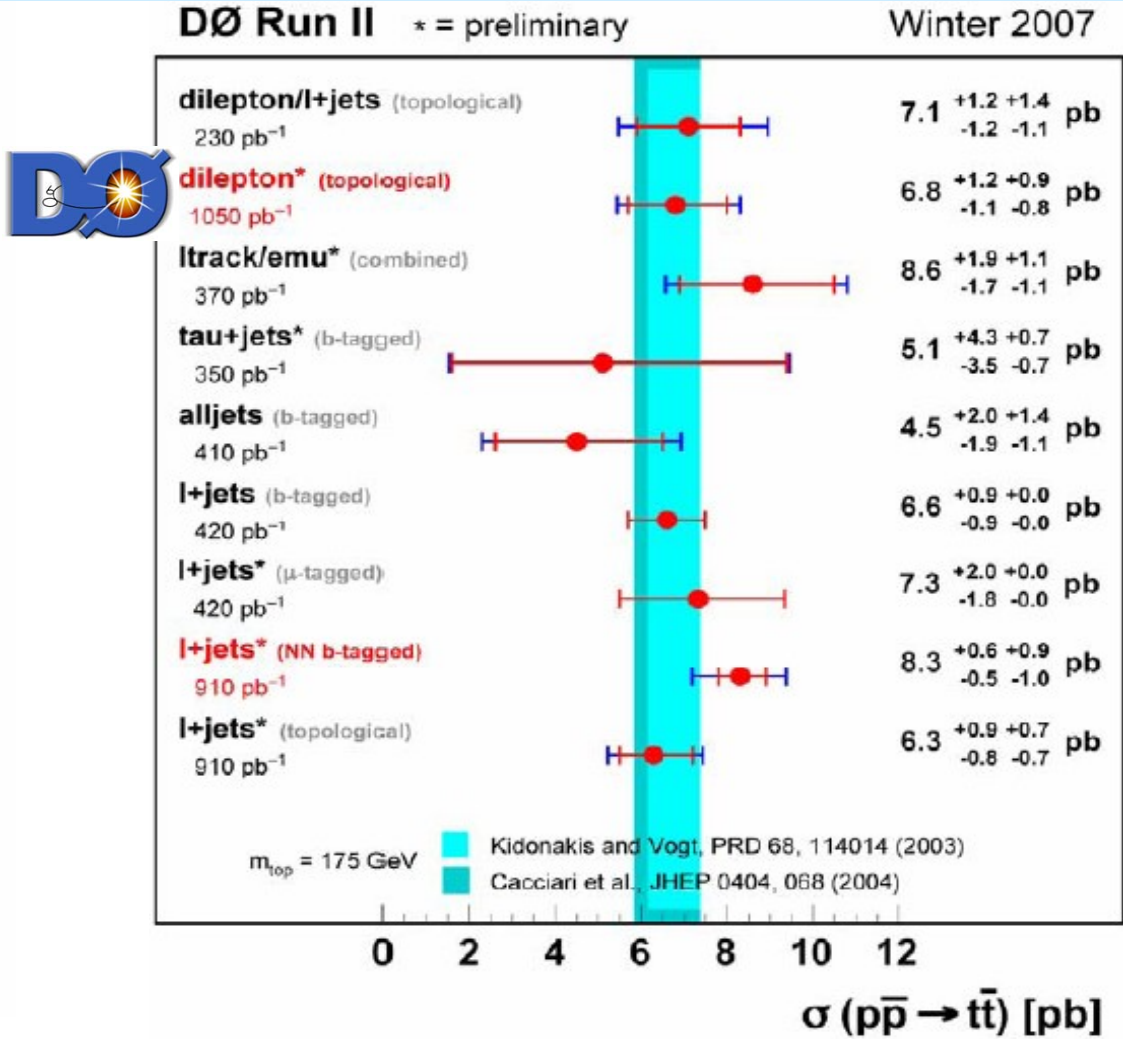
Top quark studies: motivation

- Heaviest elementary particle – may hold a key for EW symmetry braking
- Unique opportunity to study bare quark since decays before hadronization



tt cross section summary

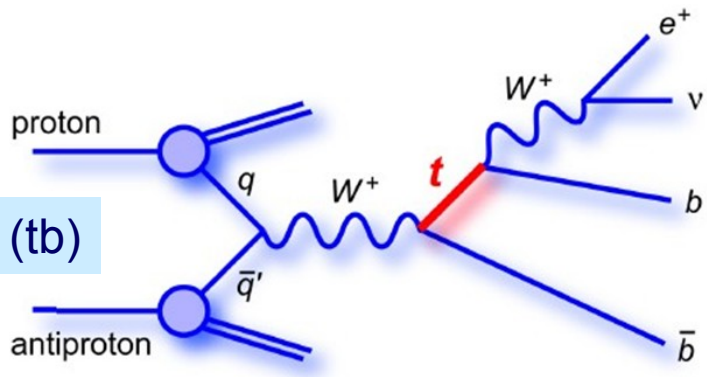




- Different channels and techniques are all in agreement
- Precision approaches theoretical uncertainty
- Sources of systematic: luminosity, b-tagging, JES, PDF, event modeling

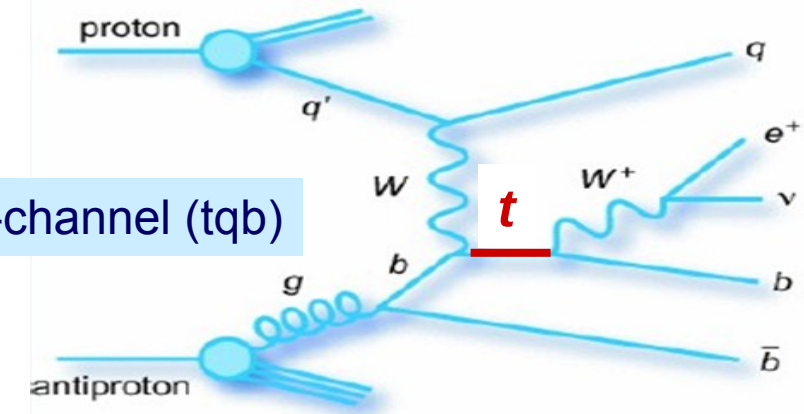
Single top production: motivation

s-channel (tb)



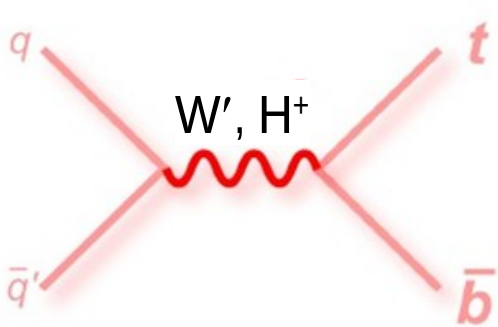
$\sigma_{NLO} \approx 0.9$ pb

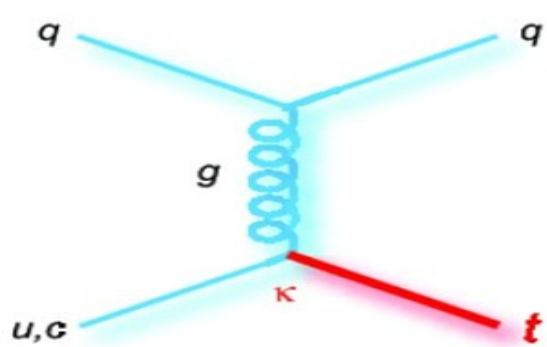
t-channel (tqb)

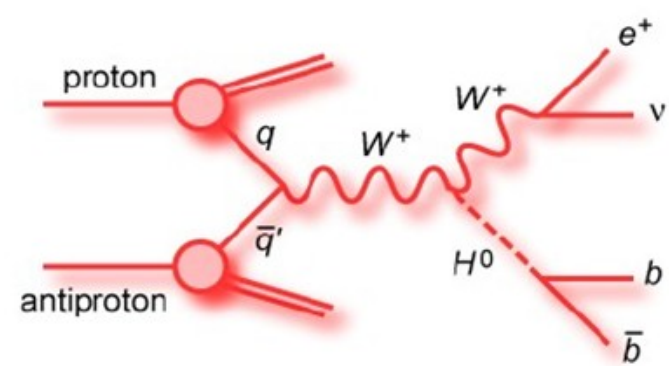


$\sigma_{NLO} \approx 2$ pb

- Directly measure V_{tb}: $\sigma_{single\ top} \sim (V_{tb})^2$
- Cross section sensitive to new physics
  - Heavy *W′* boson, charged Higgs boson, etc.
  - Flavor changing neutral currents: *t-Z/γ/g-c* couplings
- Source of ~100% polarized top quarks
- Important background to the SM Higgs searches







DØ: single top event selection

- Select events with isolated leptons, large missing E_T and jets

Signal acceptance and S/B ratio in lepton + jets sample

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

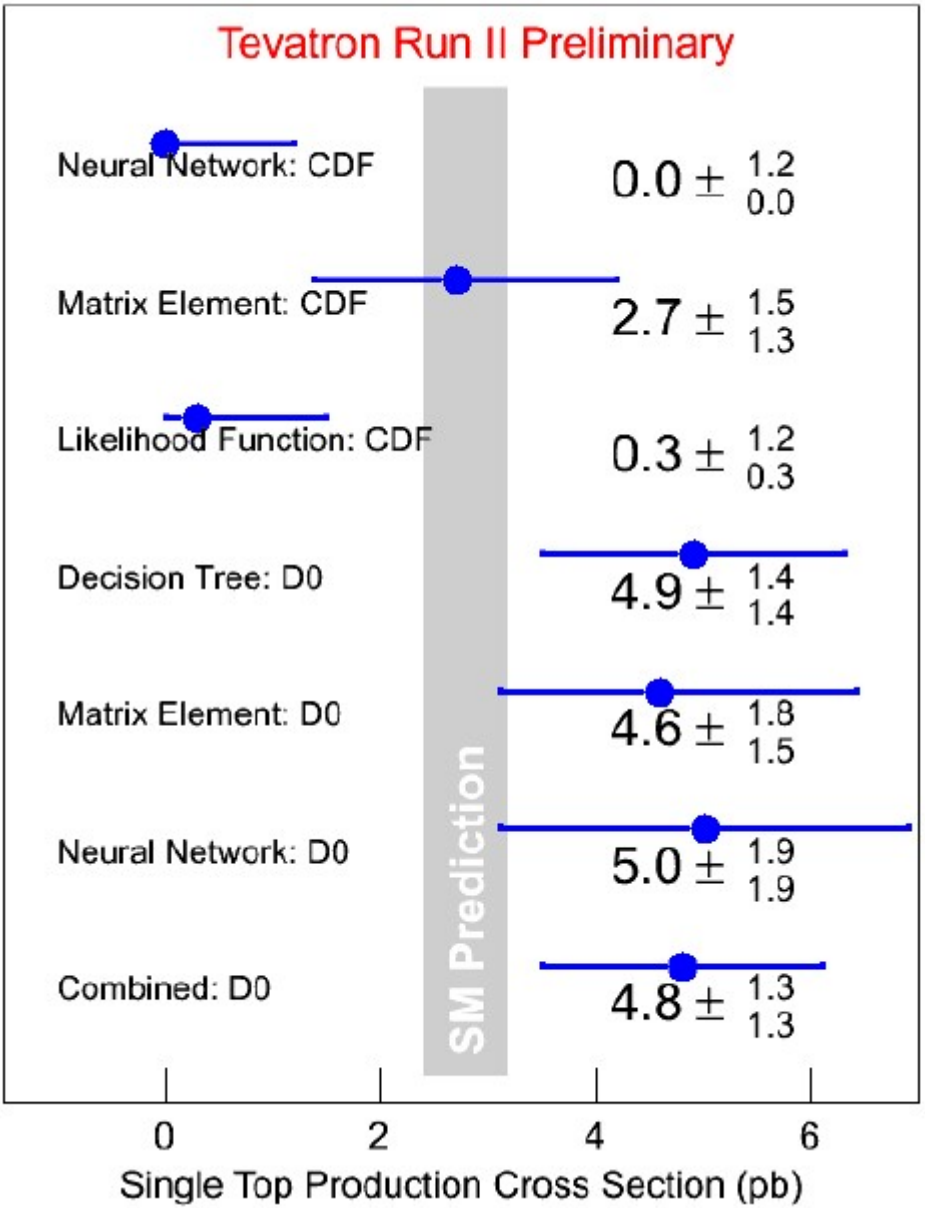
DØ: single top analysis strategy

Composition of lepton + jets sample with 1 or 2 b-tags

Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined		
	2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 131	460 ± 75	253 ± 42
Data	697	455	246

- Employ several multivariate analysis techniques to extract the signal
  - Decision Trees, Matrix Elements method, Bayesian Neural Network

CDF and DØ results on single top searches



	Multivariate method	Expected and observed significance	
CDF	Likelihood	2.0σ	-
	NN	2.6σ	-
	ME	2.5σ	2.3σ
DØ	ME	1.8σ	2.9σ
	Bayesian NN	1.3σ	2.4σ
	DT	2.1σ	3.4σ
DØ Combined			3.5σ

- The s+t channel cross section

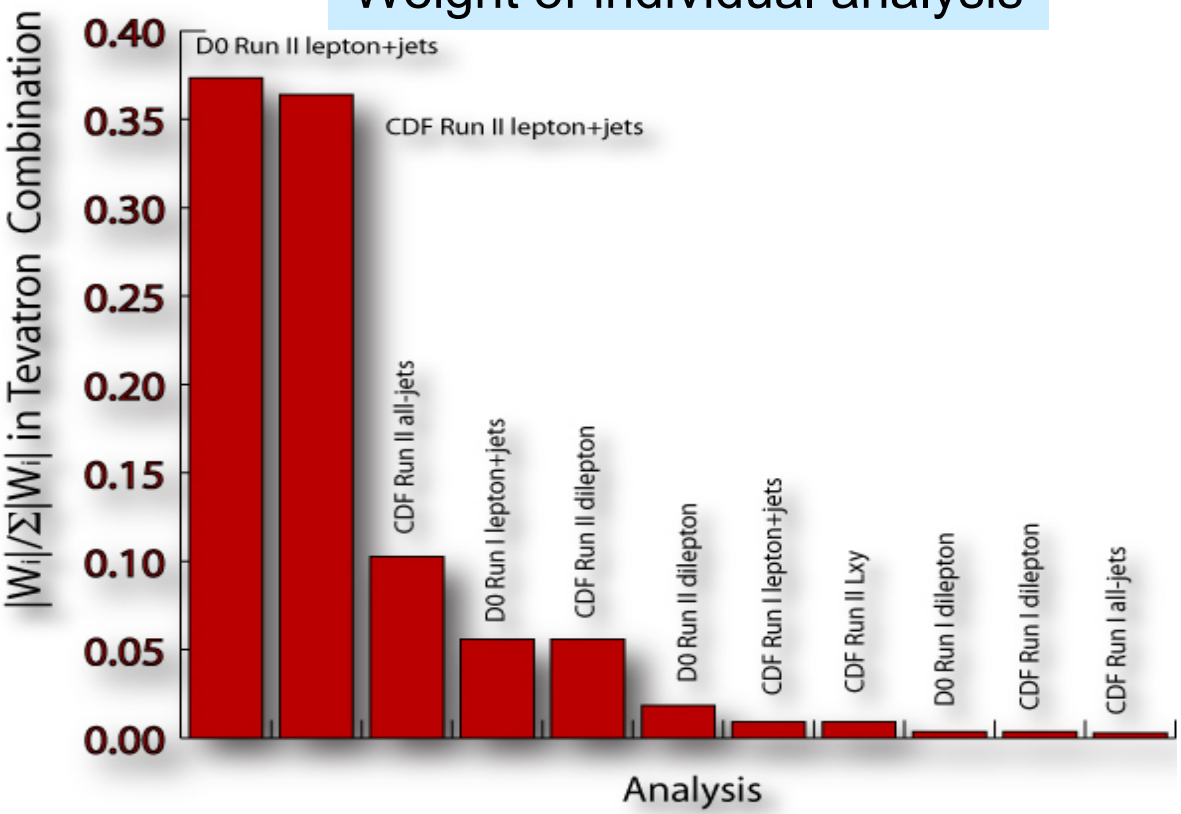
4.8 ± 1.3 pb

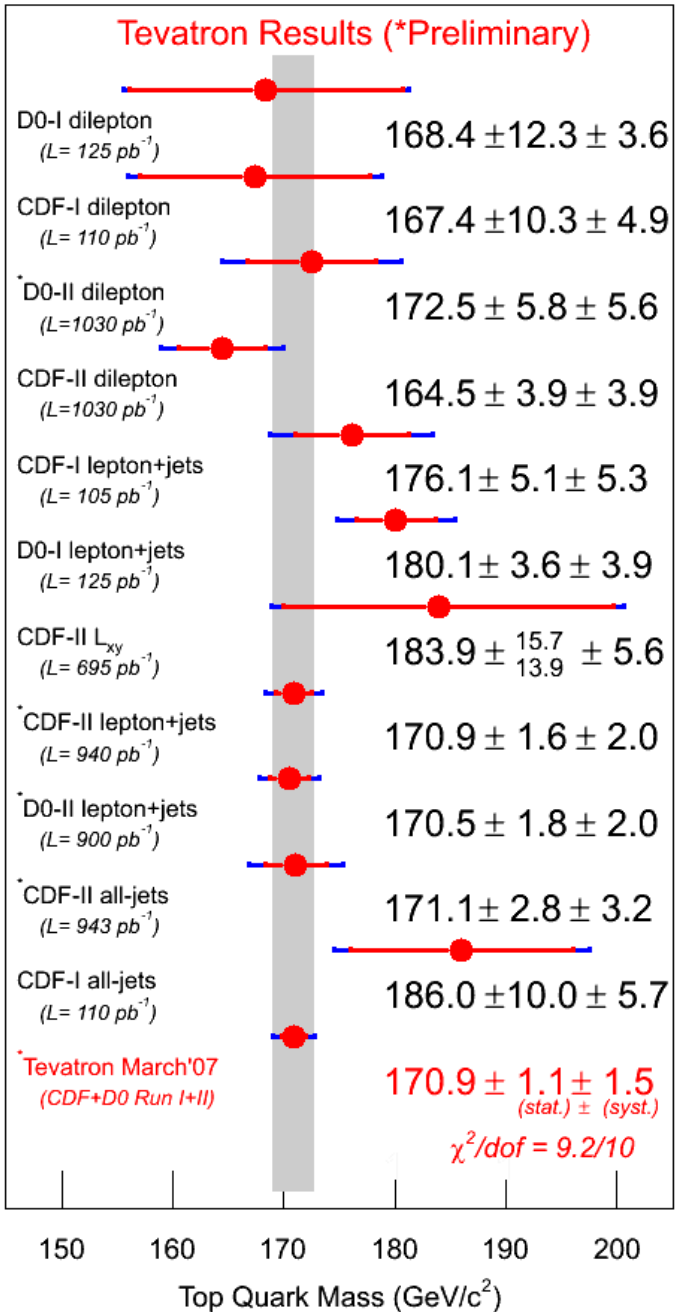
Top quark mass summary (March '07)

- Combined CDF+DØ, Run I+Run II results

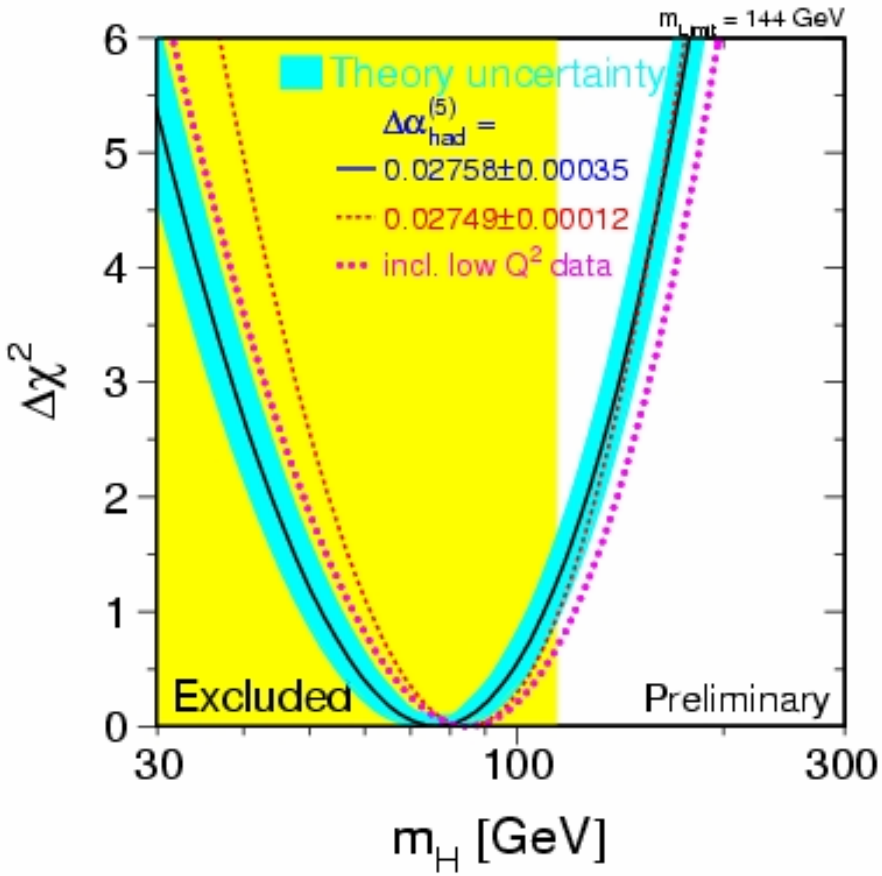
  m_t = 170.9±1.1 (stat)**±1.5** (syst) **= 170.9 ± 1.8 GeV**
- JES dominates the systematic uncertainty
- Other contributing factors
  - b-tagging, bkgd evaluation, NLO effects, PDF

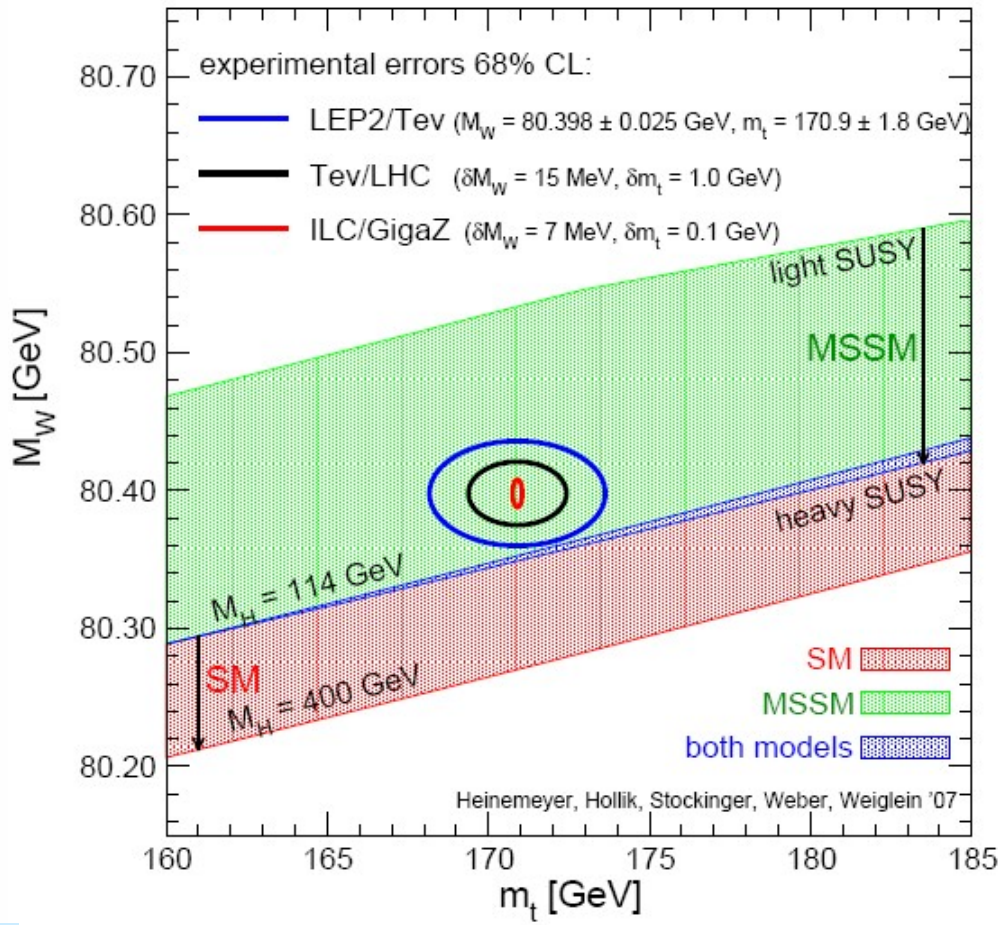
Weight of individual analysis





Impact on Higgs boson mass





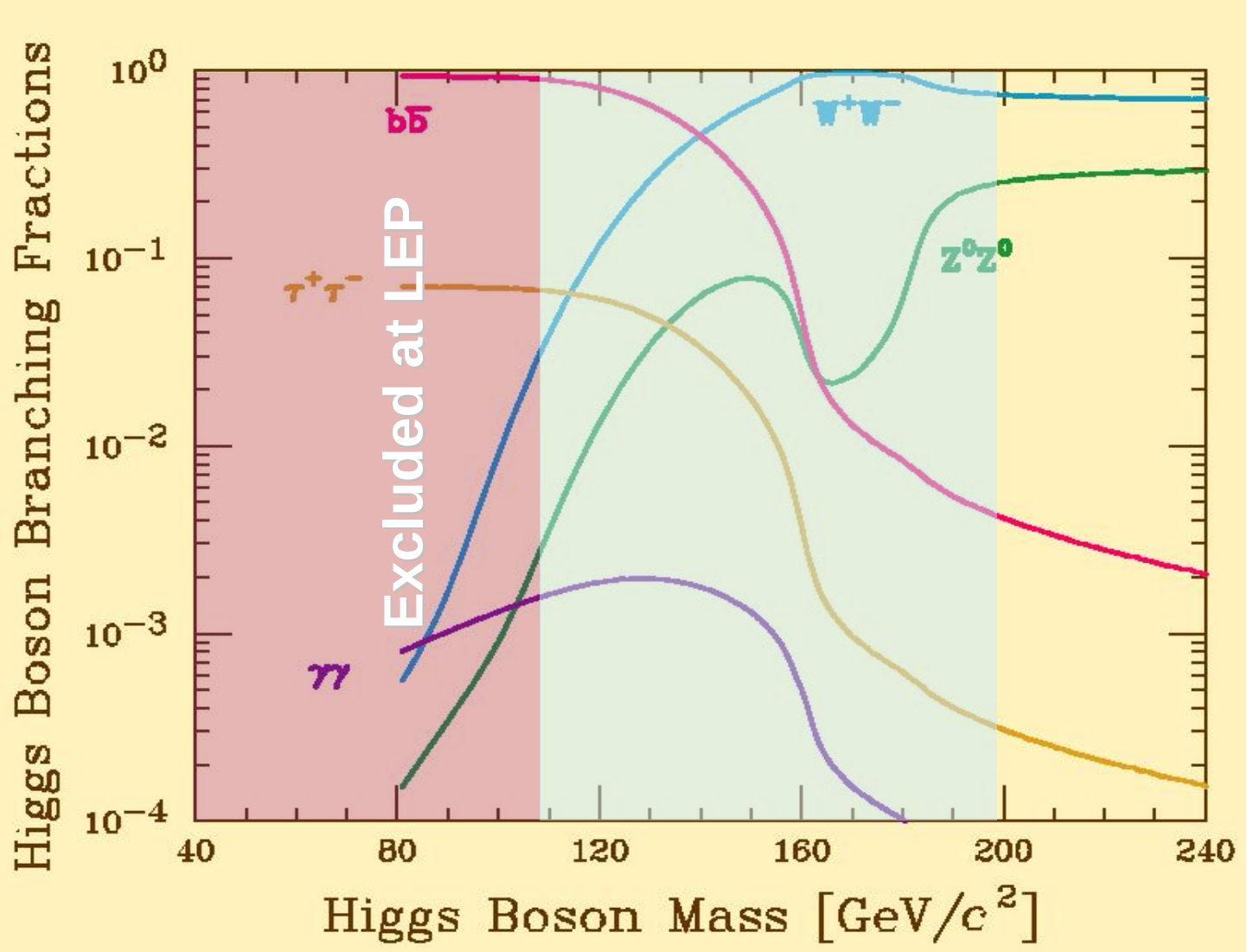
Central value for m_H is down to

76^{+33}_{-24} GeV

(LEP EWWG March'07 preliminary)

- Is SUSY Higgs preferred ?

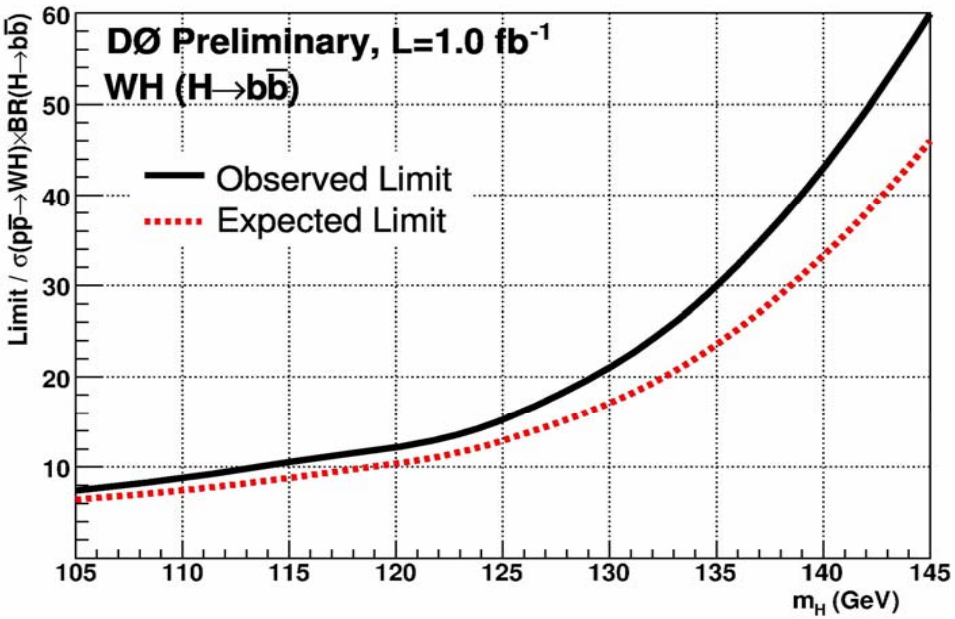
The SM Higgs boson decays

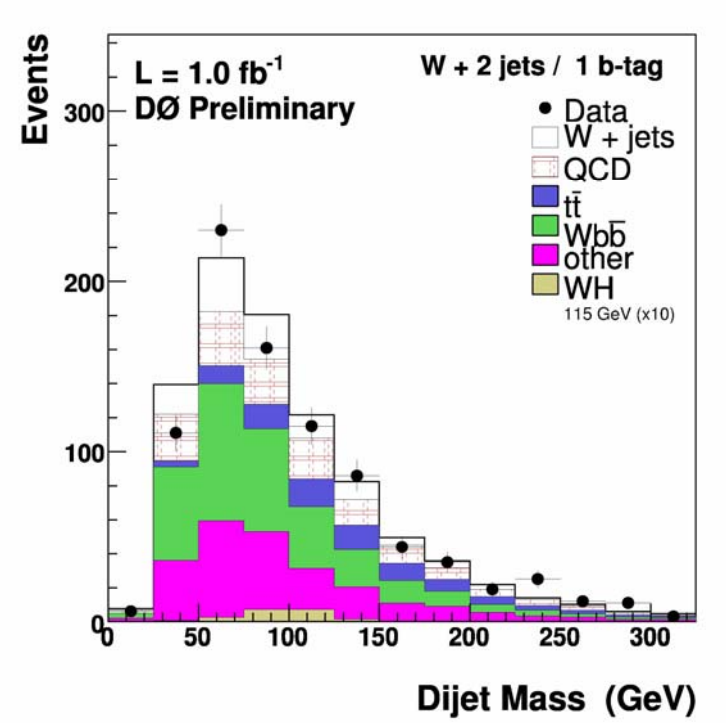


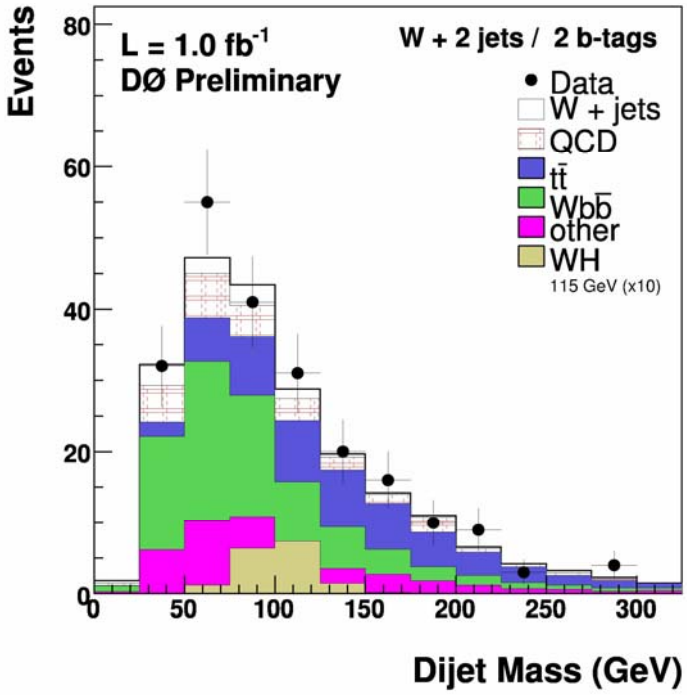
Tevatron can explore bb and WW decay modes

WH → ℓνbb channel

- DØ: recent improvements
  - Gain ~50% acceptance by "OR"-ing all muon triggers
  - Use of NN b-tagger
- Treat one/two b-tag samples separately, combine results
- Combine e and μ channels

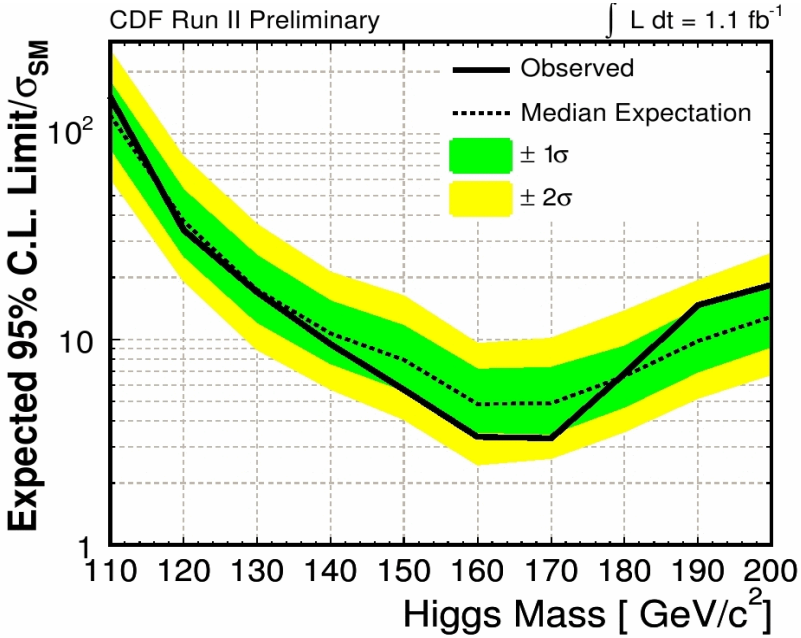


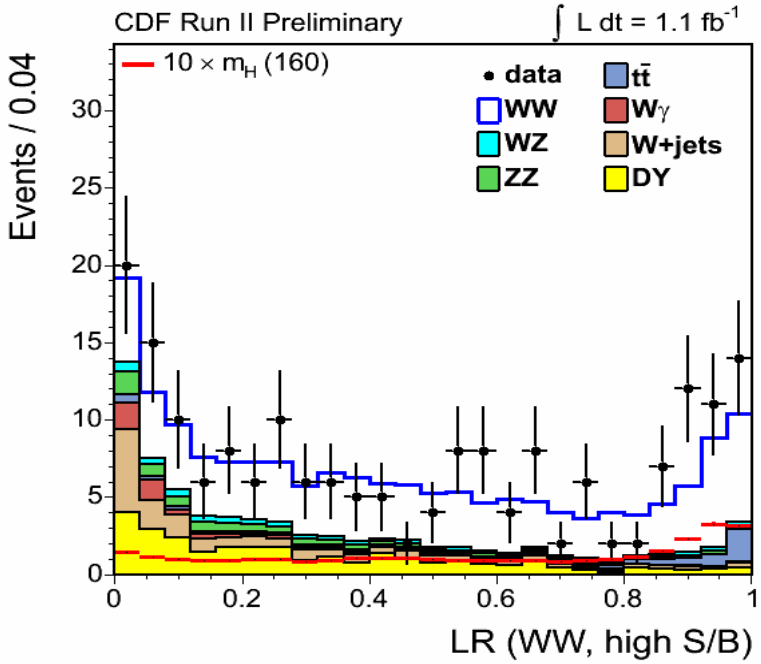


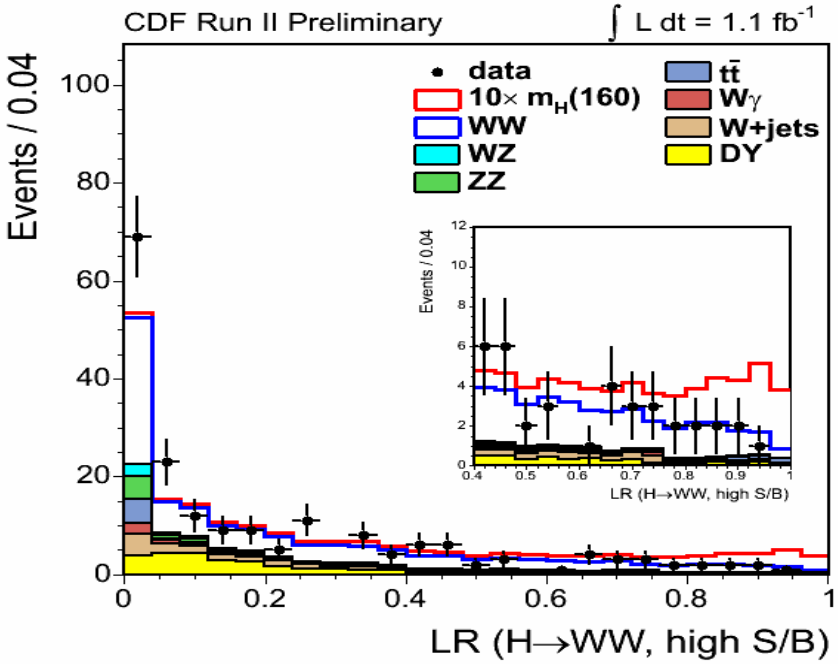


H → WW* → ℓνℓν

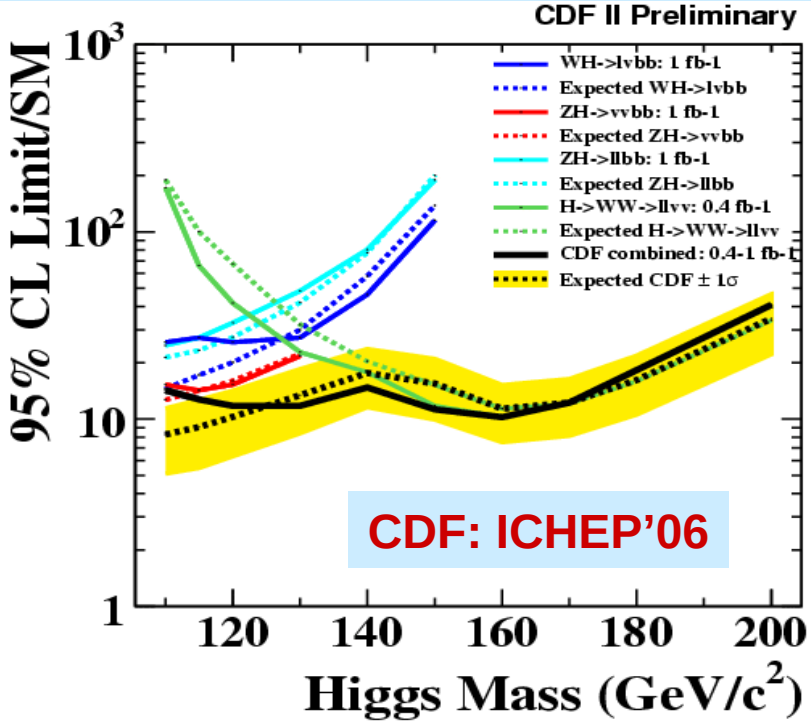
- CDF: recent improvements
  - Optimize lepton identification
  - Add isolated track sample
    - No matching calorimeter cells or hits in muon system
  - ME method used to calculate event probability and construct a likelihood ratio discriminator
  - Cross-check the method in high/low S/B ratio regions, and for various processes

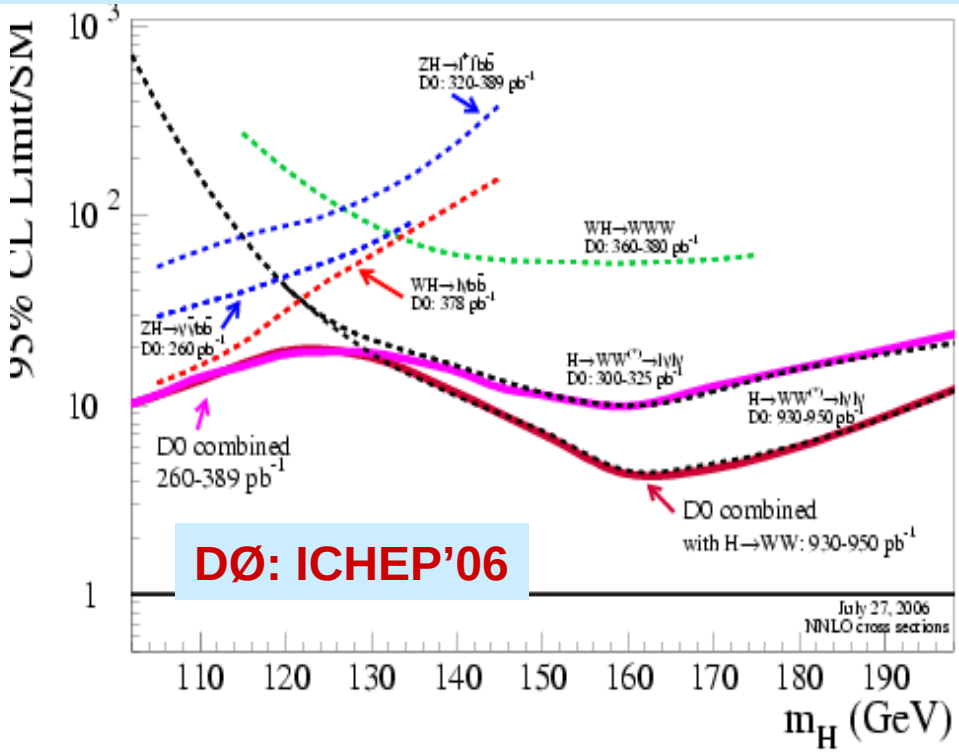


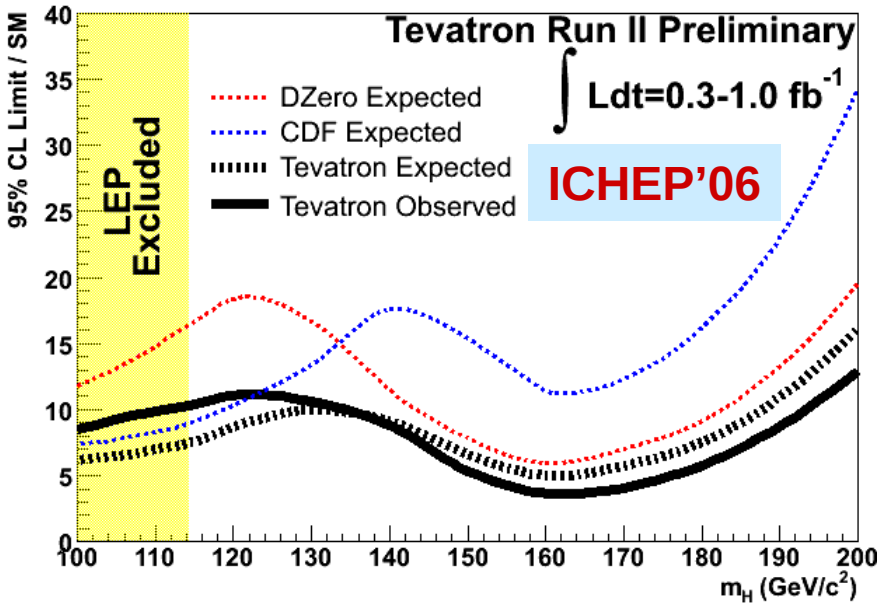


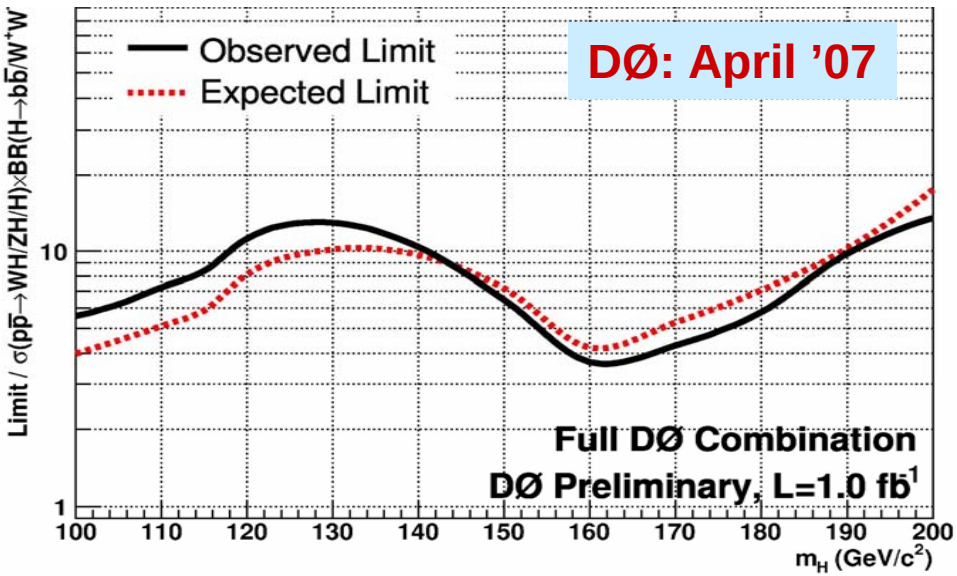


ICHEP'06 (CDF+DØ) and April '07 (DØ) summaries





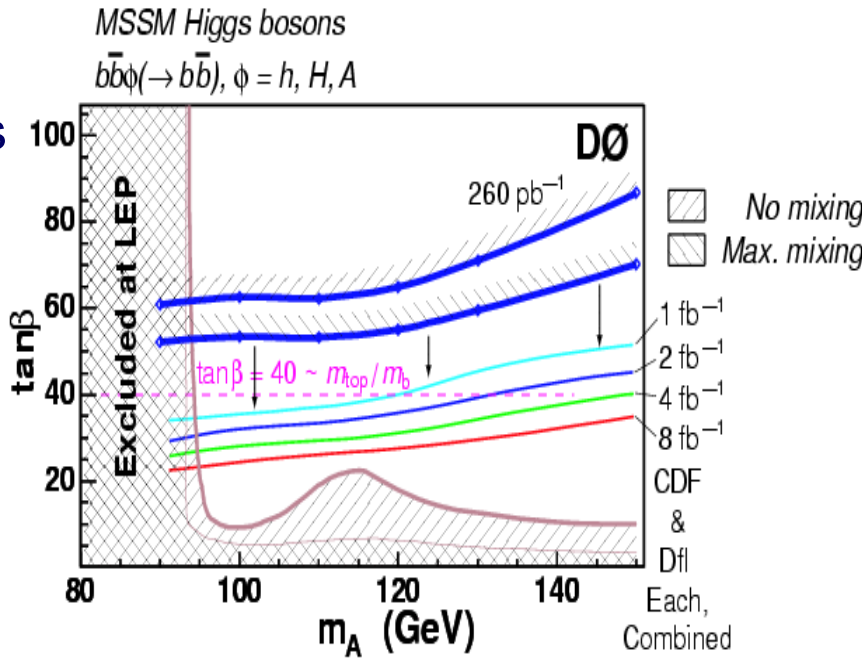




MSSM higgs searches: CDF and DØ published results

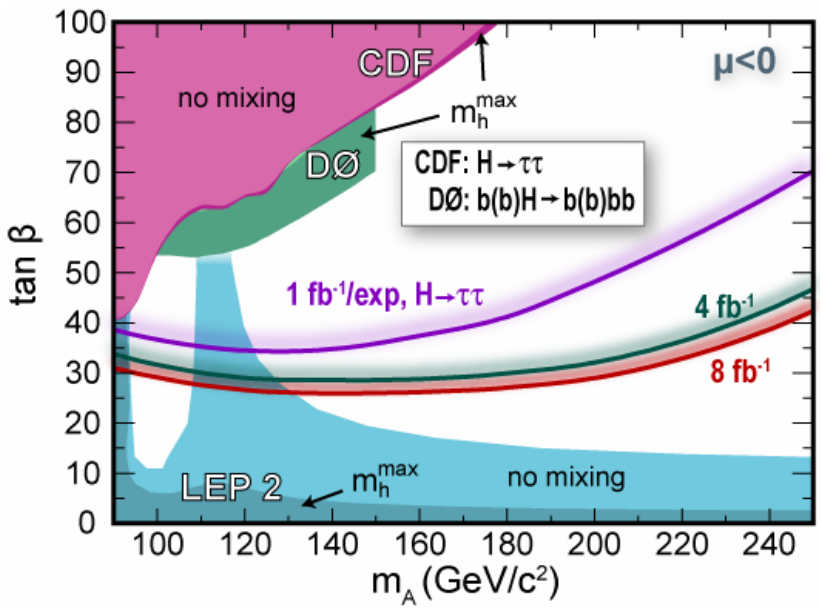
Associated production with b quarks

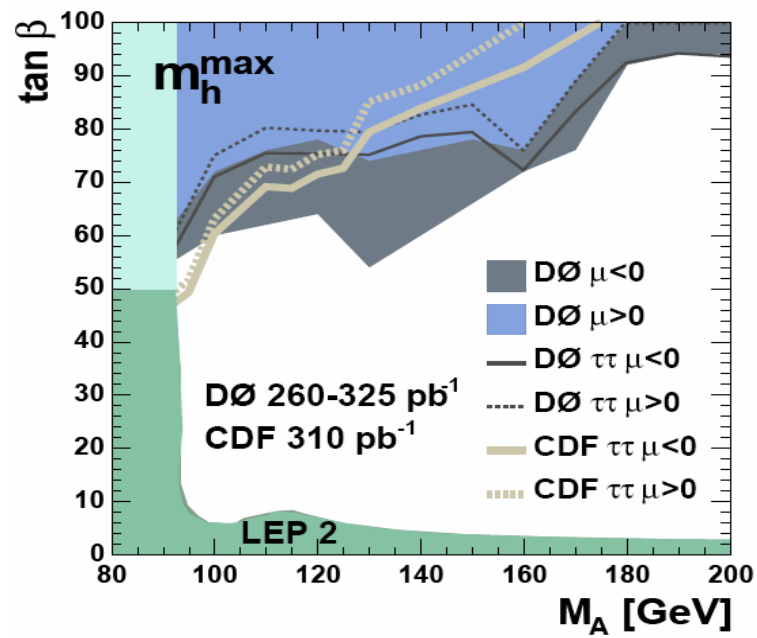
- DØ: bh/bbh(→bb) → 3/4 b's in final states
  - Require ≥ 3 b-tagged jets
  - Background evaluated from data
  - Look for excess in di-jet mass window



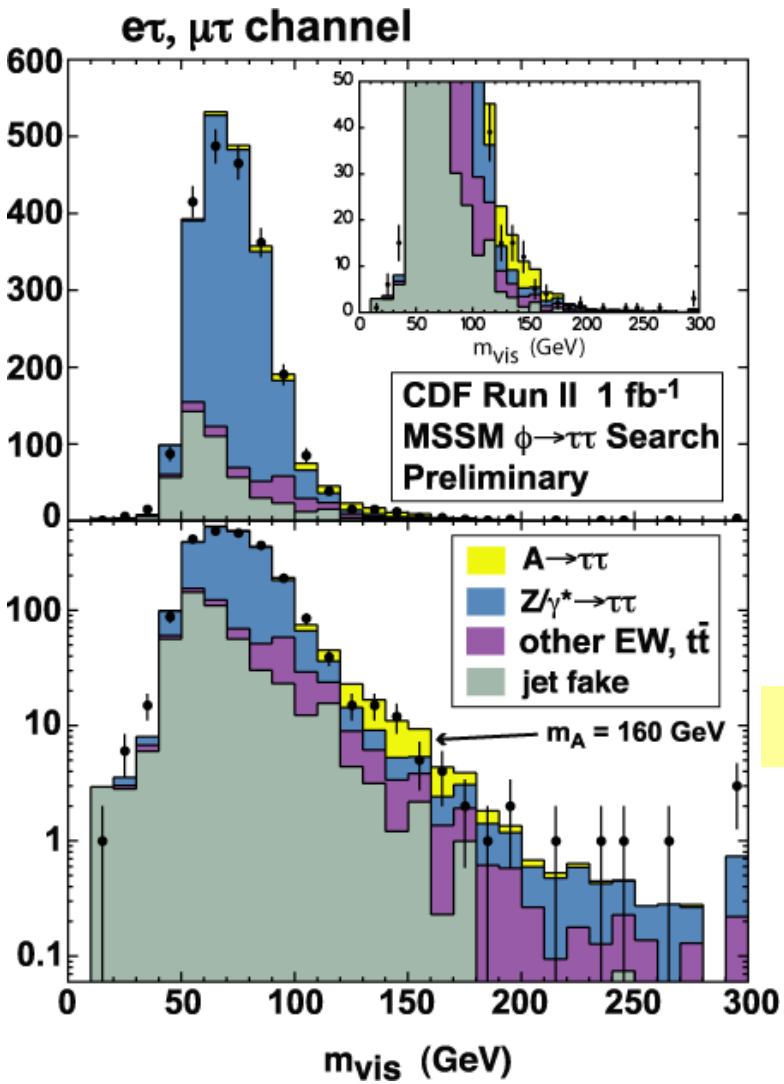
Inclusive production

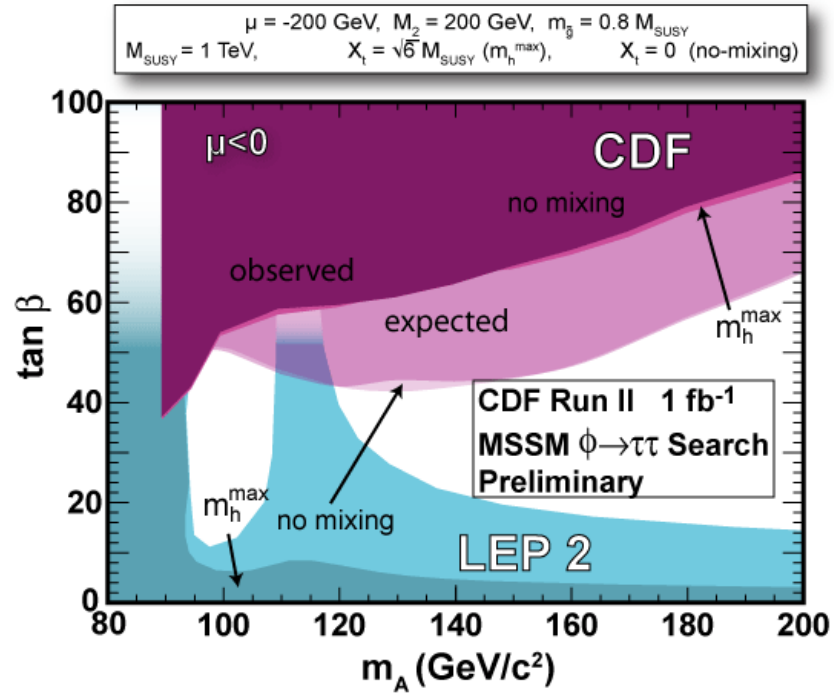
- CDF and DØ: h → ττ → $e\tau_h$, $\mu\tau_h$, or eμ
  - Look for excess in m_{vis} (= mass of visible τ decay products and missing E_T) spectrum



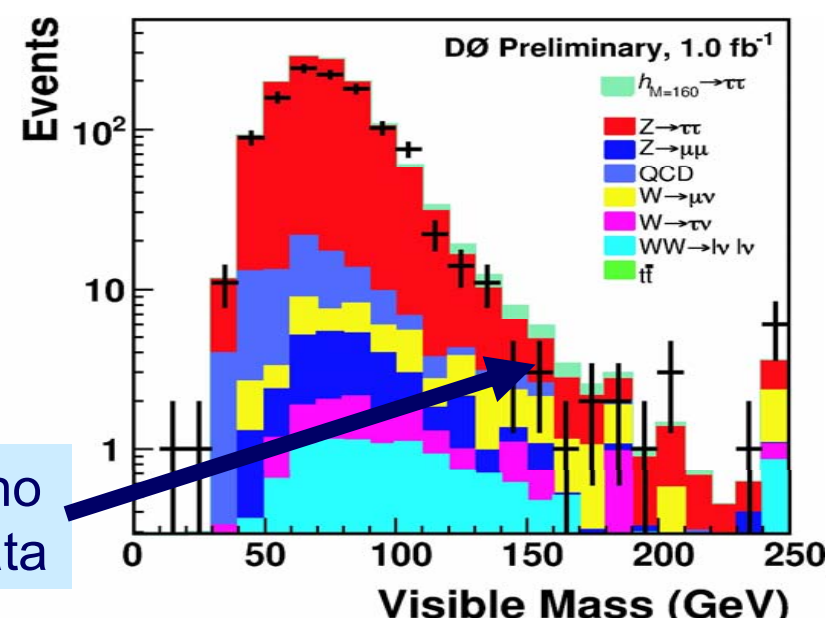


h → ττ: preliminary with 1 fb^{-1}





Excess?



- eμ channel agrees with data (not shown here)
- DØ reports no excess in data

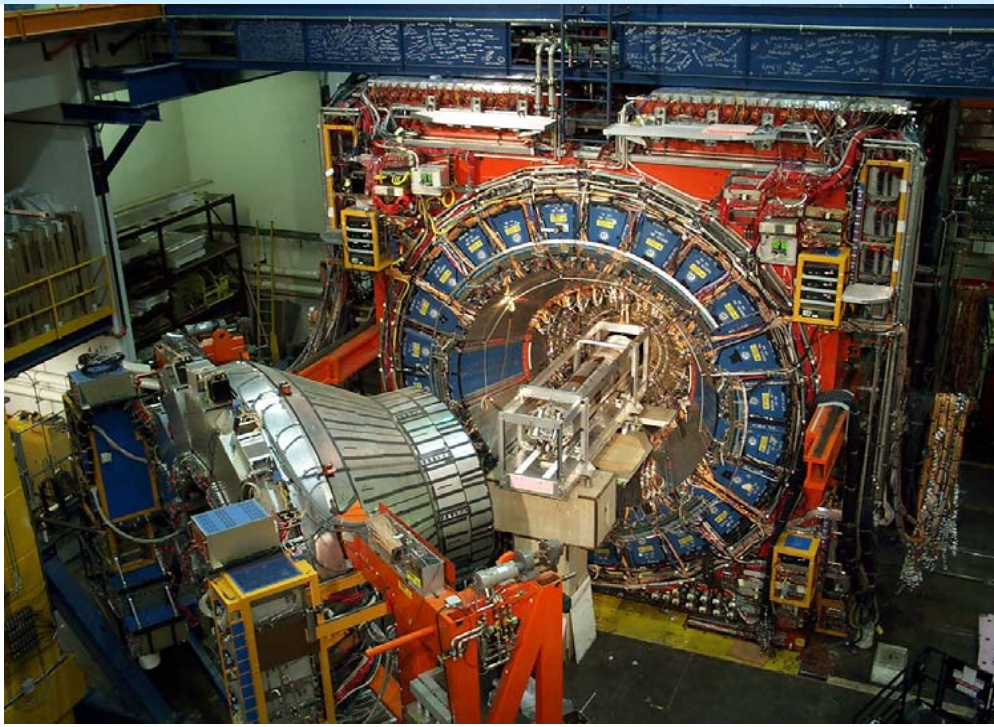
Summary

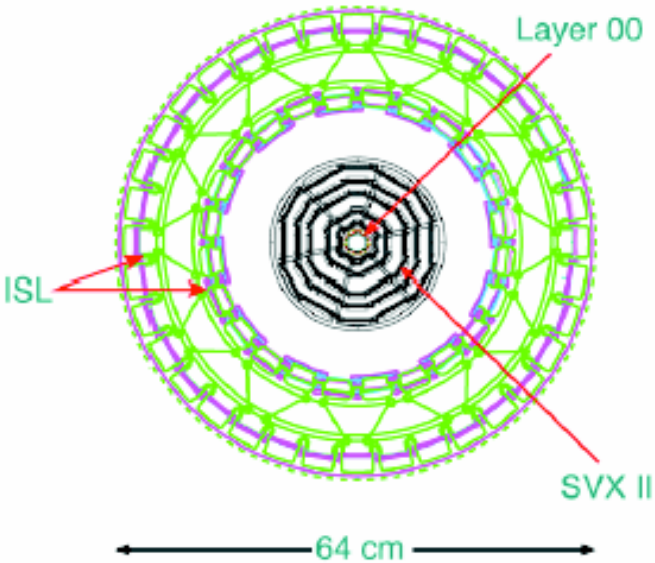
- Upgraded for Run II Tevatron, CDF and DØ are performing well and contribute to world class physics at the energy frontier
- Most of Run I Electroweak measurements are improved and new processes are established, such as di-boson production
  - Good agreement with the SM so far
- Both experiments are in the era of precision top quark measurements
  - Many results are now systematics limited that will improve with more data
- In coming years, the CDF and DØ concerted efforts will offer a real opportunity to find (exclude) the SM, or non-SM, Higgs boson
  - Tevatron will complement LHC's reach in a very interesting low mass region

Backups

The upgraded CDF II

- Major upgrades for Run II:
  - Drift chamber: COT
  - Silicon: SVX, ISL, L00 at r ~ 1.5 cm
    - 8 layers
    - 700 k readout channels
    - 6 m^2
    - material:15% X_0
  - Forward calorimeters
  - Forward muon system
    - Improved central muon system
  - Time-of-flight
  - Preshower detector
  - Timing in EM calorimeter
  - Trigger and DAQ



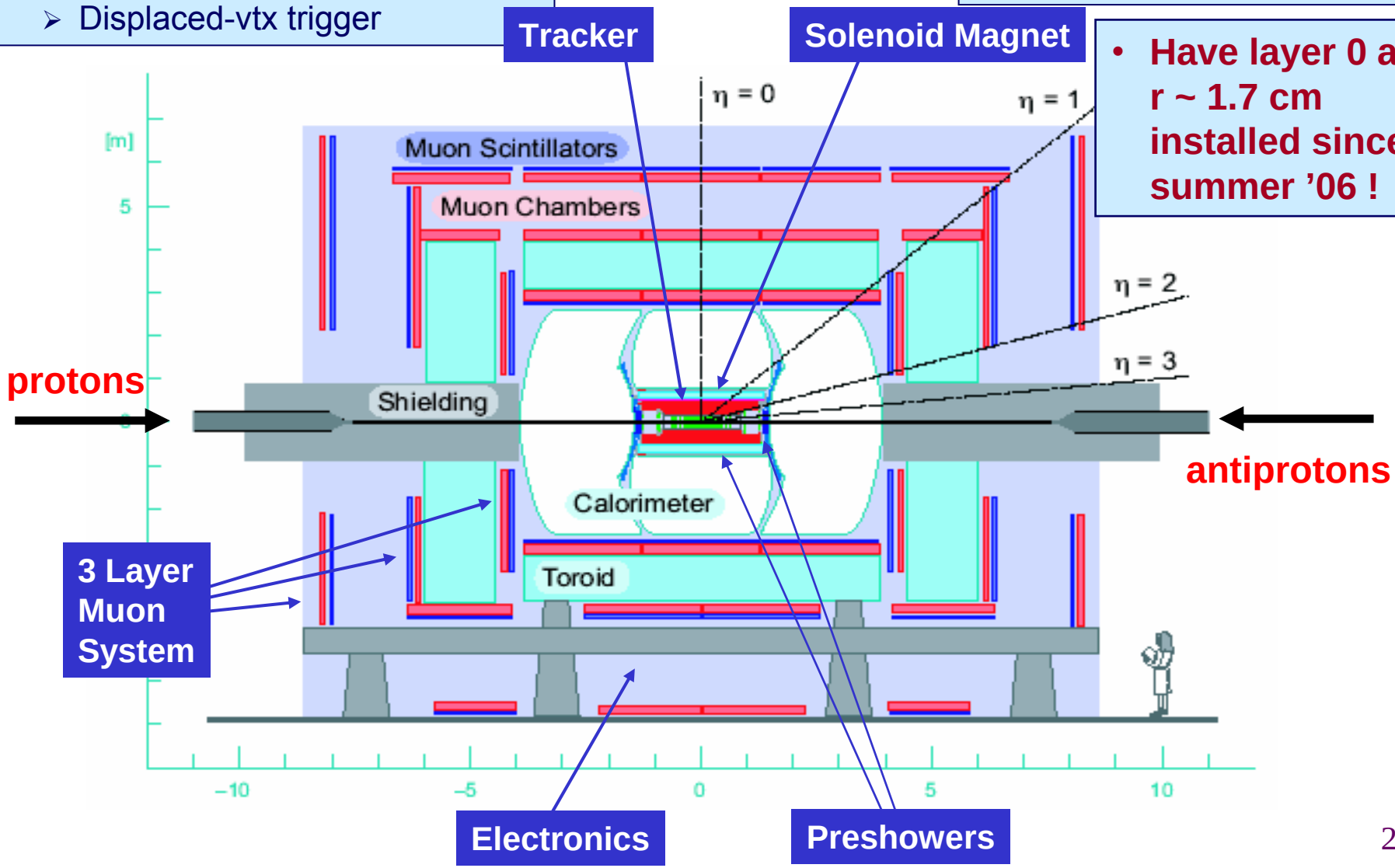


The upgraded DØ detector in Run II

- Upgraded
  - Muon system, cal. electronics
  - DAQ, (track) trigger system
  - Displaced-vtx trigger

- New (tracking in B-field)
  - Silicon detector
  - Fiber tracker

- **Have layer 0 at r ~ 1.7 cm installed since summer '06 !**



Searches for SUSY Higgs bosons

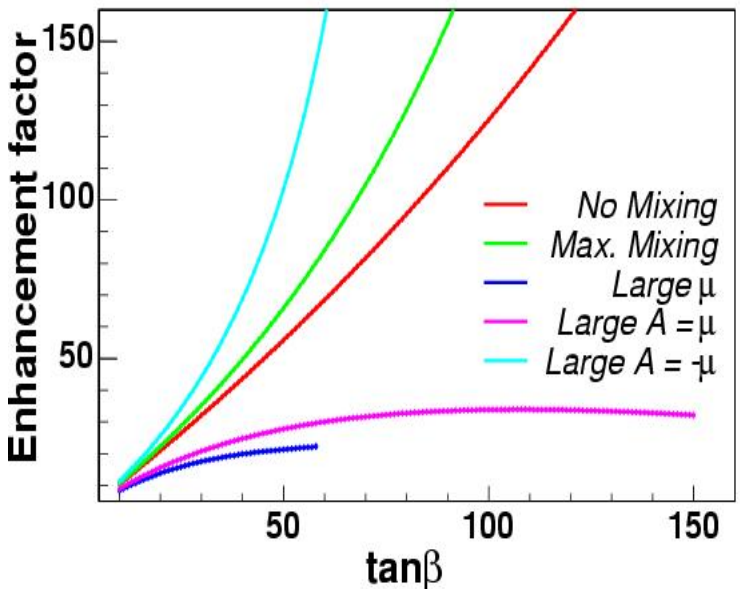
- In MSSM have two Higgs doublet fields
  - H_u (H_d) couple to up- (down-) type fermions
  - The ratio of their VEV's
    $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - 5 Higgs particles after EWSB
    h, H, A, H^+, H^-
  - h is "guaranteed" to be light
    m_h <~ 130-140 GeV

- At large $\tan\beta$, coupling to down-type quarks, i.e. b's, is enhanced wrt SM
  - At tree level ~ $\tan\beta$ → production cross section rise as $\tan\beta^2$

- CP conservation is assumed in the following analyses

Loop level corrections to x-section and BR

$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

$$\text{with} \quad \Delta_b = \frac{\Delta h_b}{h_b} \times \tan\beta$$

Function of various SM/SUSY parameters: $X_t = A_t - \mu\cot\beta$, μ, M_g, M_q, etc.