



Challenging the Standard Model at the Tevatron Collider

Frank Filthaut

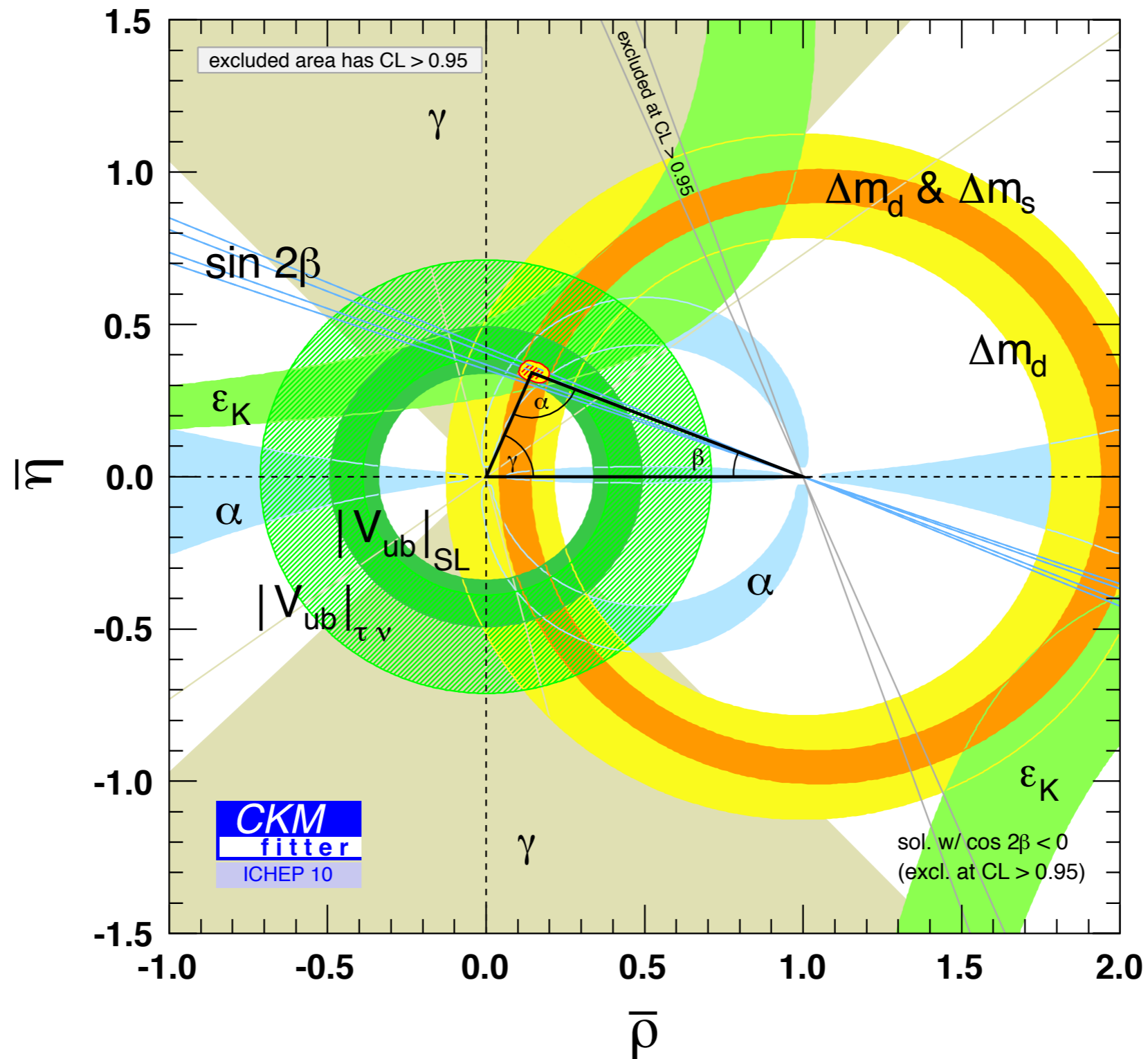
Radboud University Nijmegen / Nikhef
for the D0 and CDF Collaborations

Kruger 2010 Workshop, December 5-10, 2010

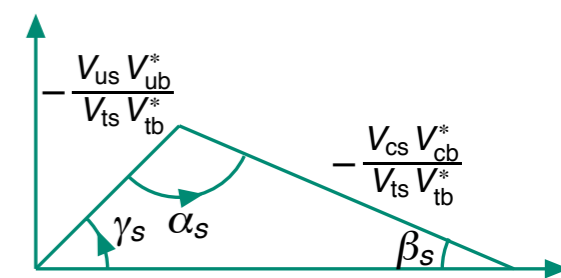
B Physics

CP Violation in the B_s System

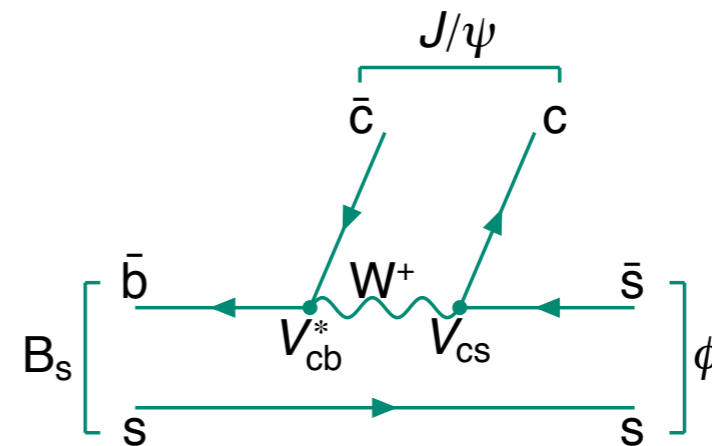
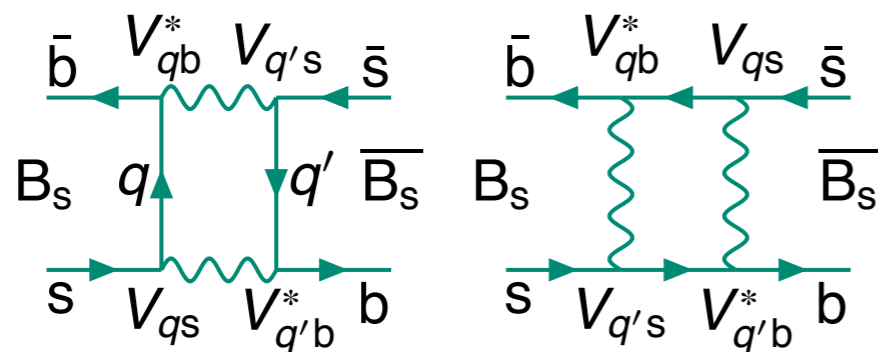
This is not the only unitarity triangle!



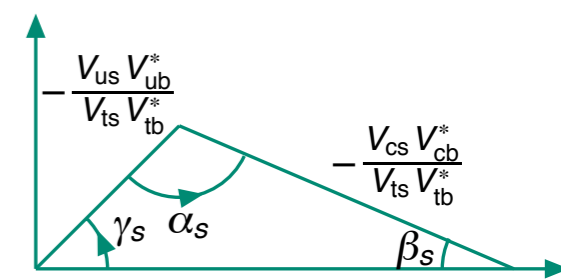
CP Violation in the B_s System



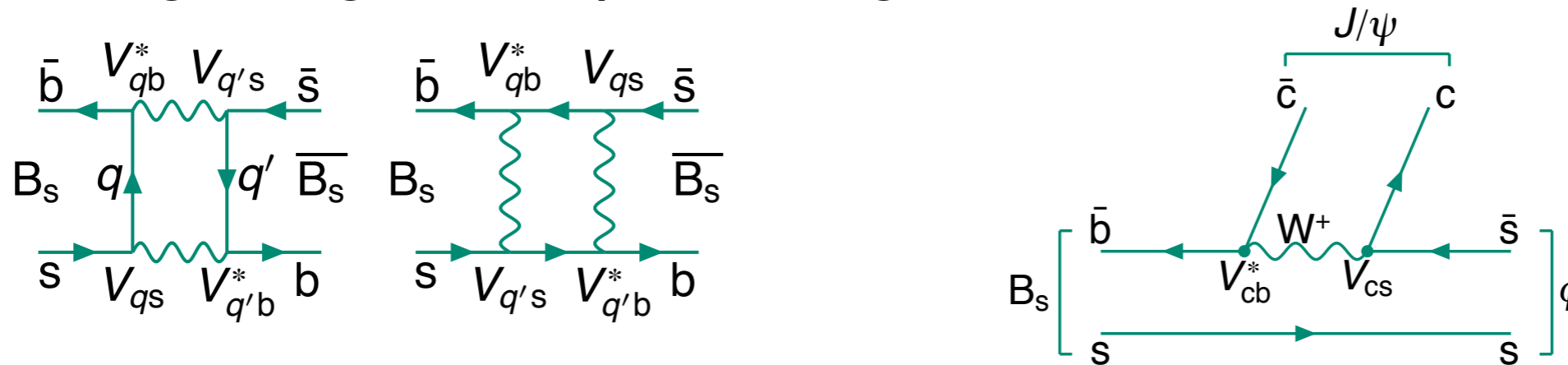
The B_s system is (largely) the domain of hadron colliders. Exploit by combining mixing and decays to CP eigenstates in $b \rightarrow ccs$ transitions:



CP Violation in the B_s System

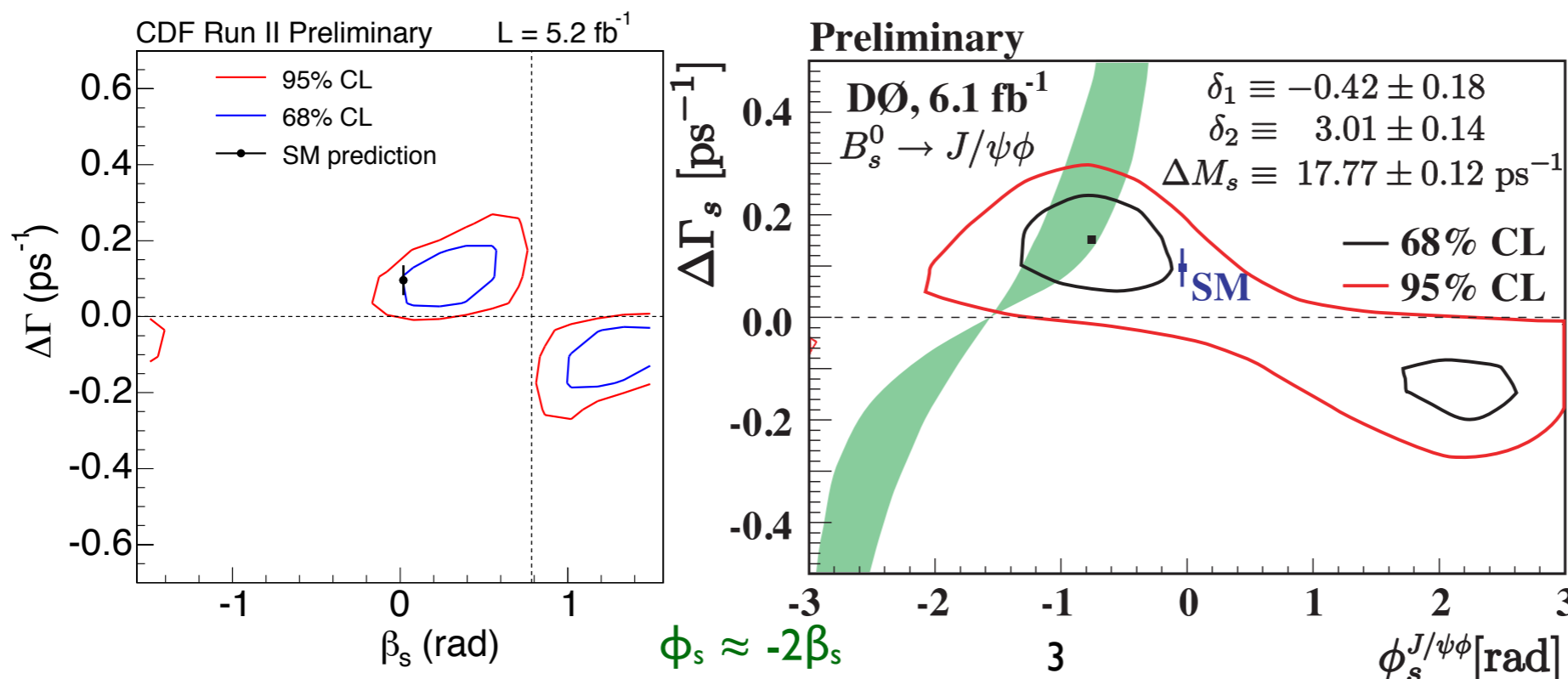


The B_s system is (largely) the domain of hadron colliders. Exploit by combining mixing and decays to CP eigenstates in $b \rightarrow ccs$ transitions:



CDF and D0 have analyzed the $\mu^+\mu^-K^+K^-$ final state using 5-6 fb^{-1} of data

- J/ψ and ϕ : spin 1, “transversity” analysis considering 3 decay angles



Tantalizing hints for non-SM β_s (2.8 fb^{-1}) have disappeared...
 A new combination would be welcome

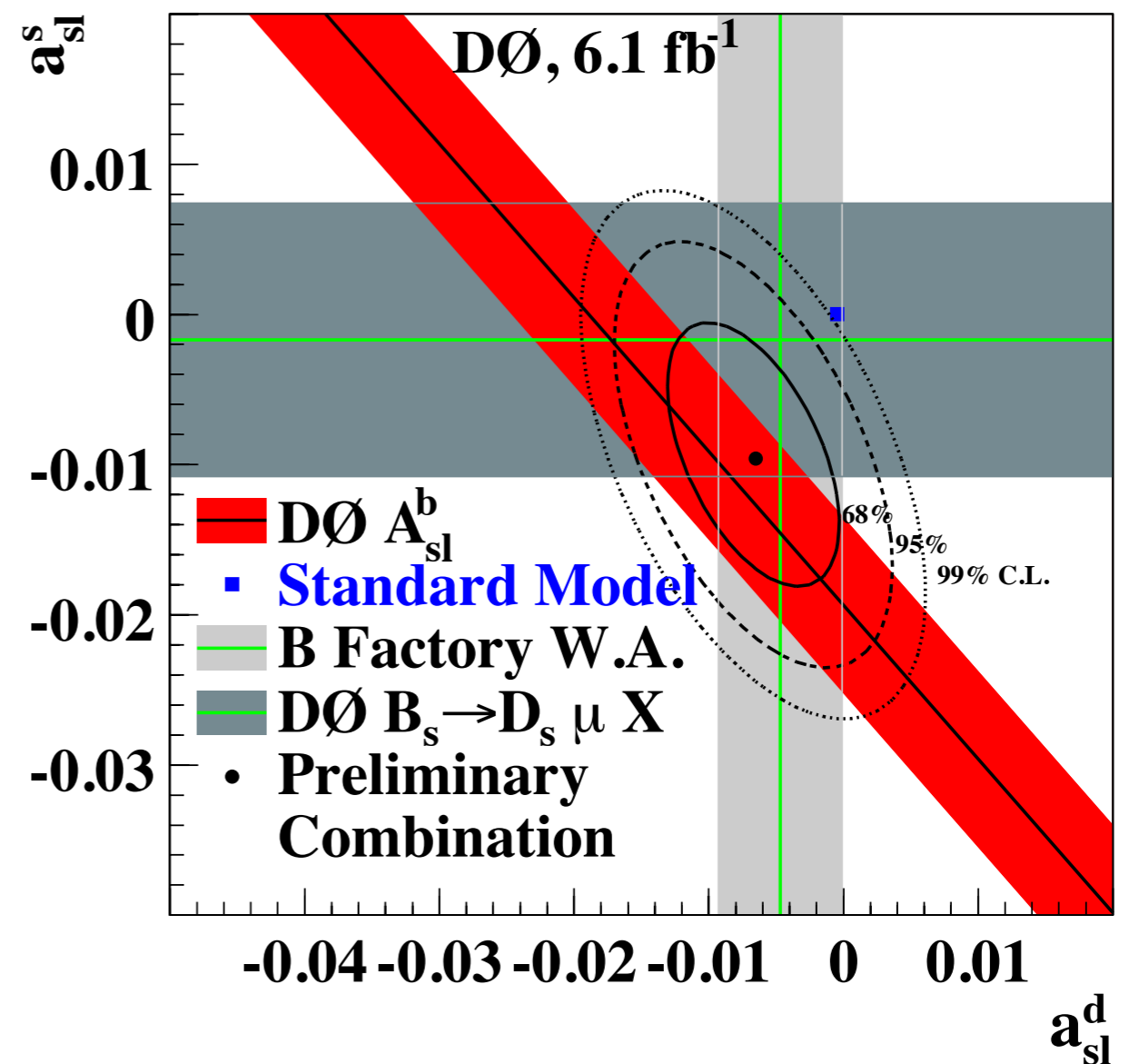
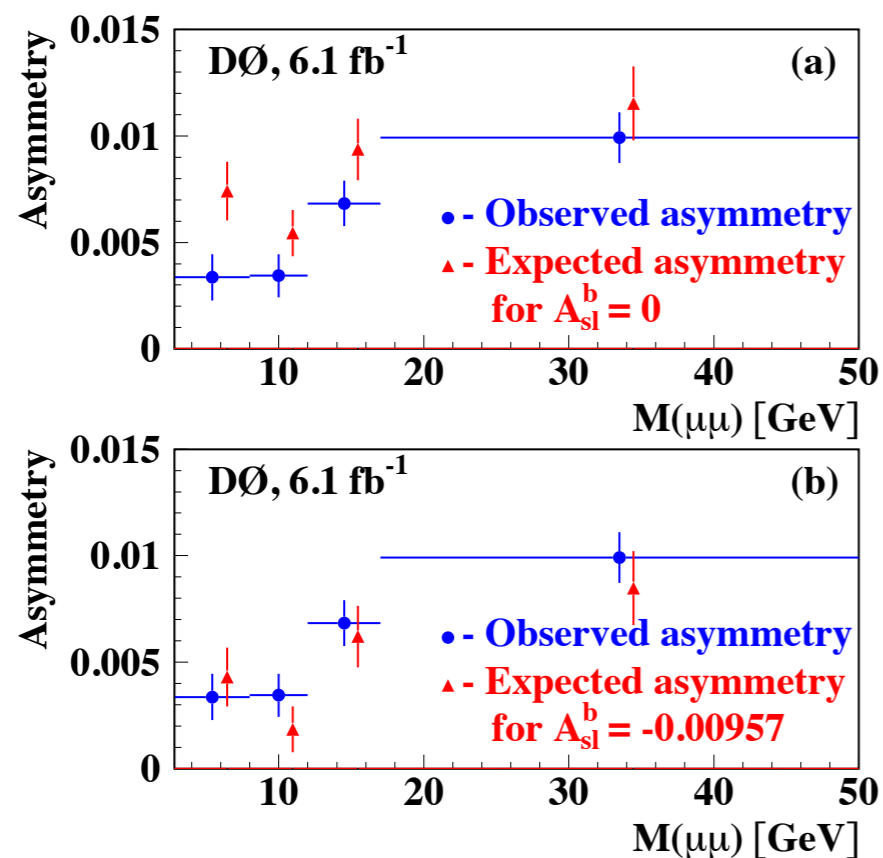
CDF also observe $B^+ \rightarrow Y(4140)K^+$,
 $Y(4140) \rightarrow J/\psi \phi$

CP Violation in the $B_{d/s}$ System

New DØ (6 fb^{-1}) inclusive like-sign dimuon charge asymmetry measurement

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

- sensitive to CP violation in mixing
- complicated analysis: small effect, sensitive to material asymmetries, muon detection asymmetries, ...

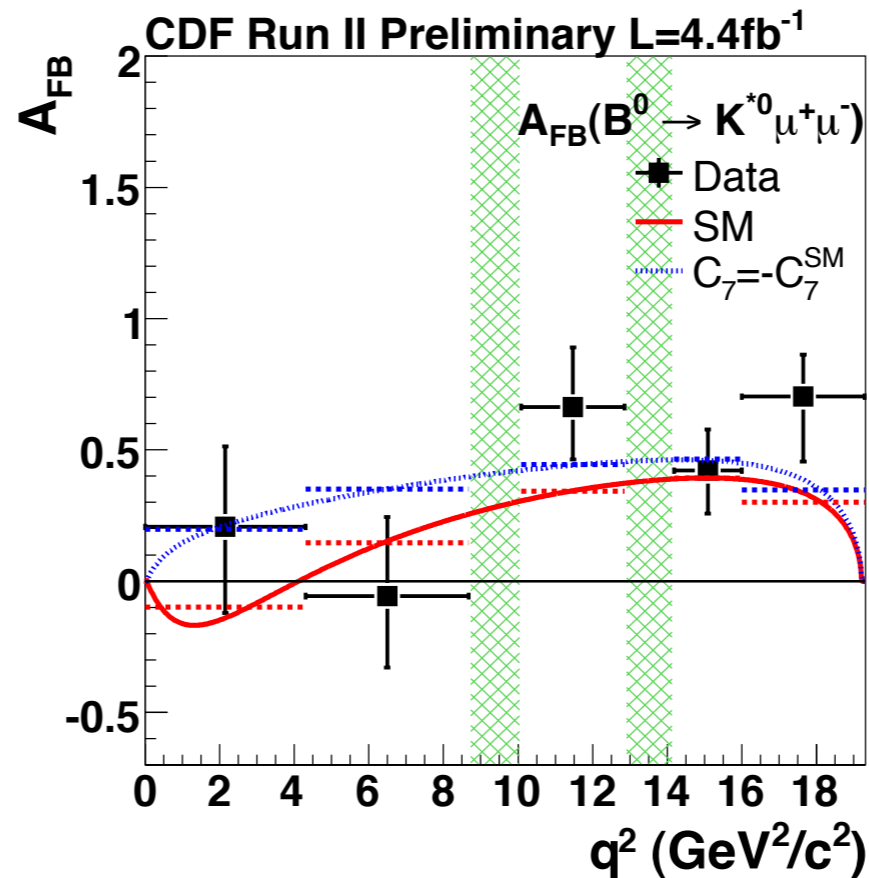
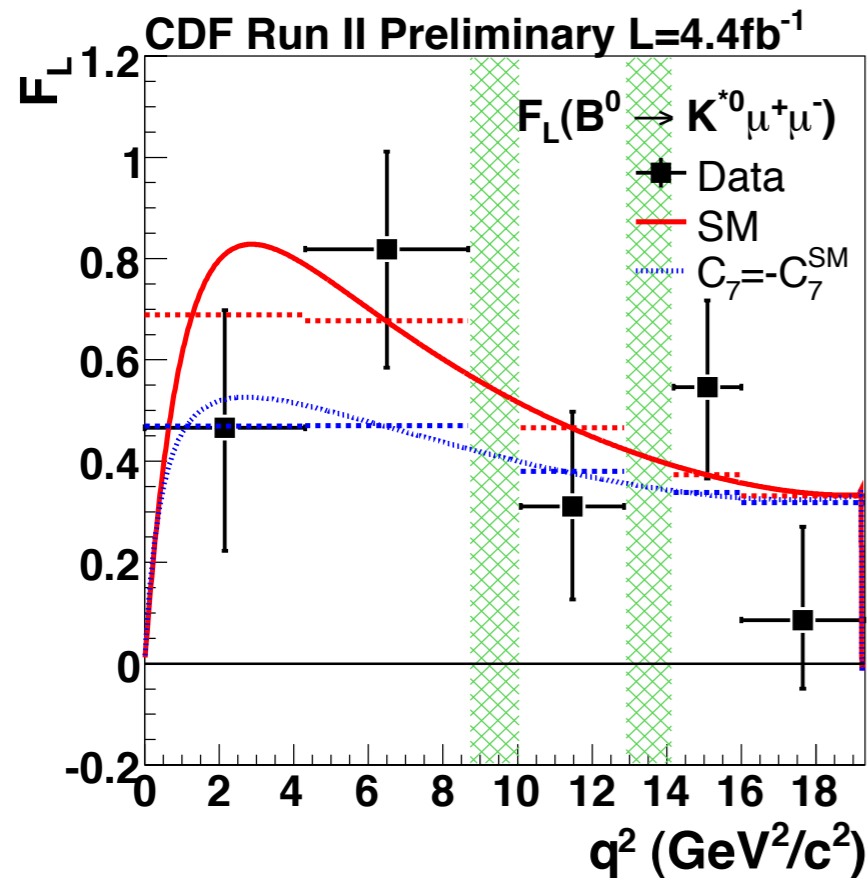
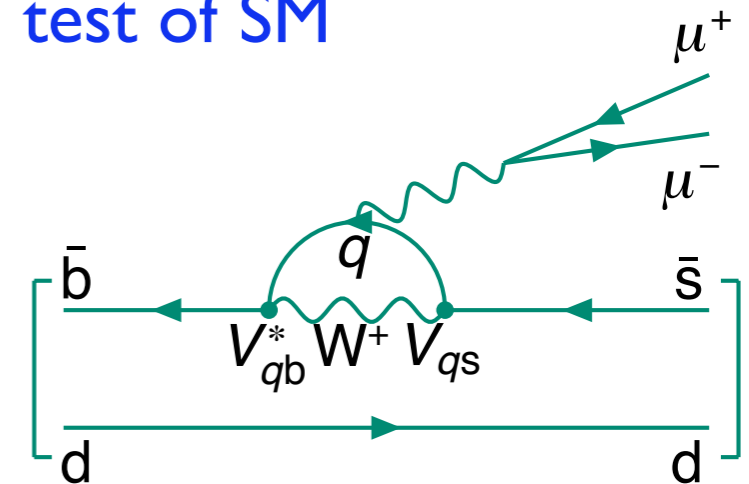


First evidence (3.2σ) for anomalous CP violation in B mixing!

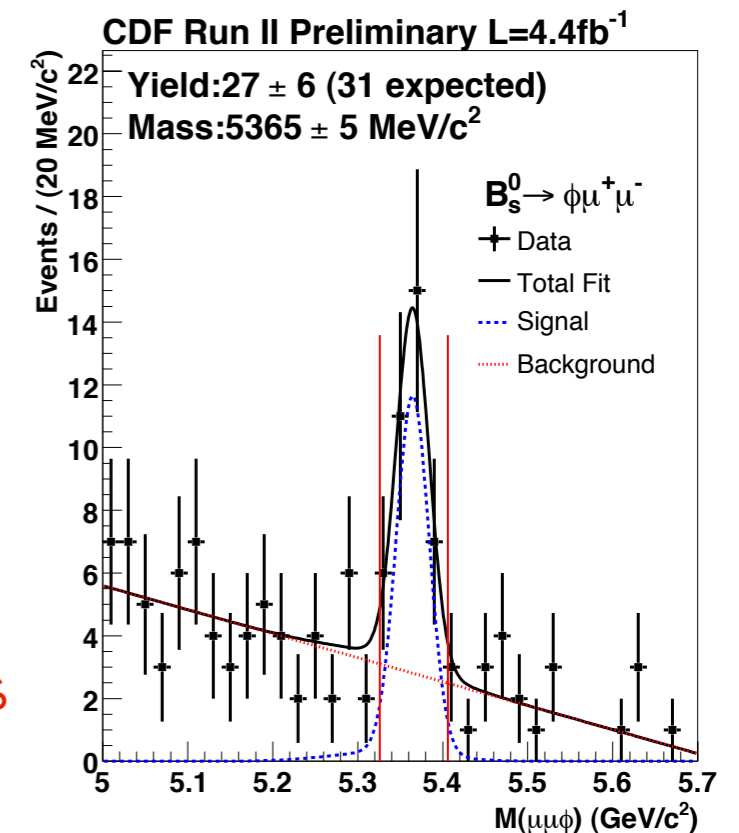
$B \rightarrow K^* \mu^+ \mu^-$

$B \rightarrow K^* \mu^+ \mu^-$ decay: rare FCNC decay, theoretically clean test of SM

- B, K^* longitudinal polarization F_L , $\mu^+ \mu^-$ A_{FB} sensitive to values of Wilson coefficients (C_7, C_9, C_{10}) used in Operator Product Expansion



Results competitive
(and compatible)
with B-factories



Bonus: first observation of $B_s \rightarrow \phi \mu^+ \mu^-$:
 $B = (1.44 \pm 0.33 \text{ (stat)} \pm 0.46 \text{ (syst)}) \cdot 10^{-6}$

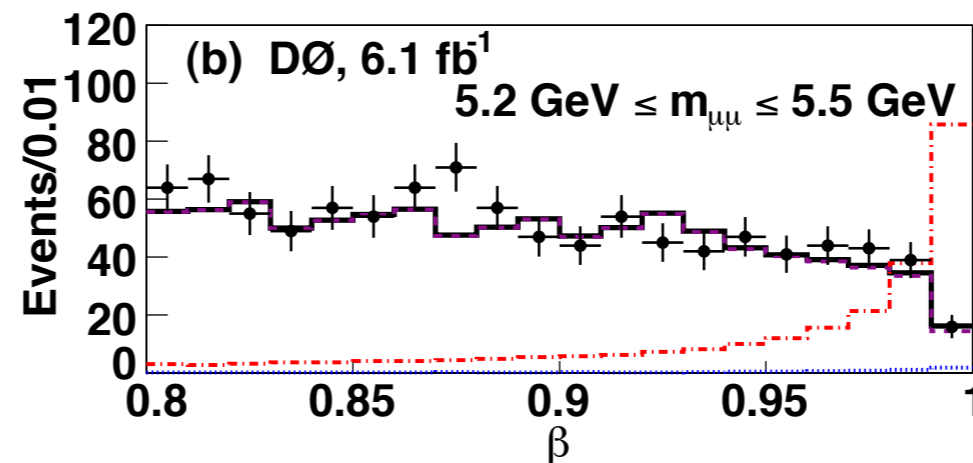
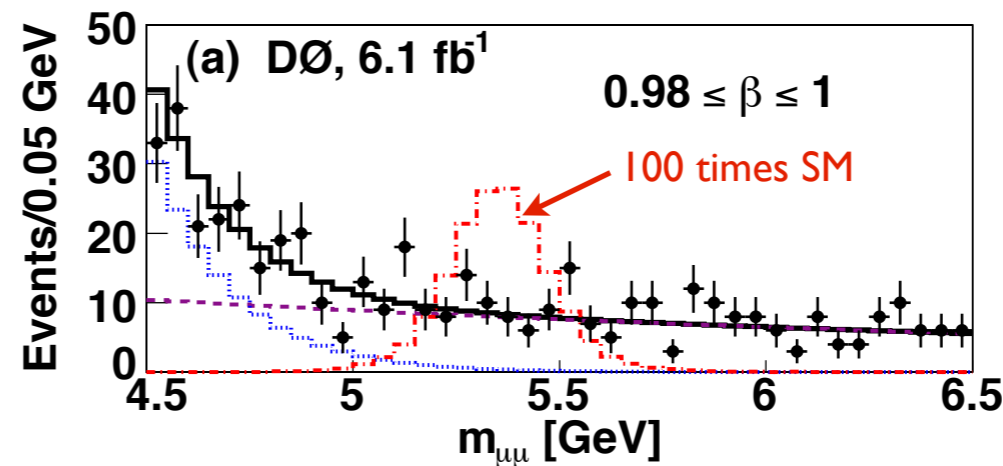
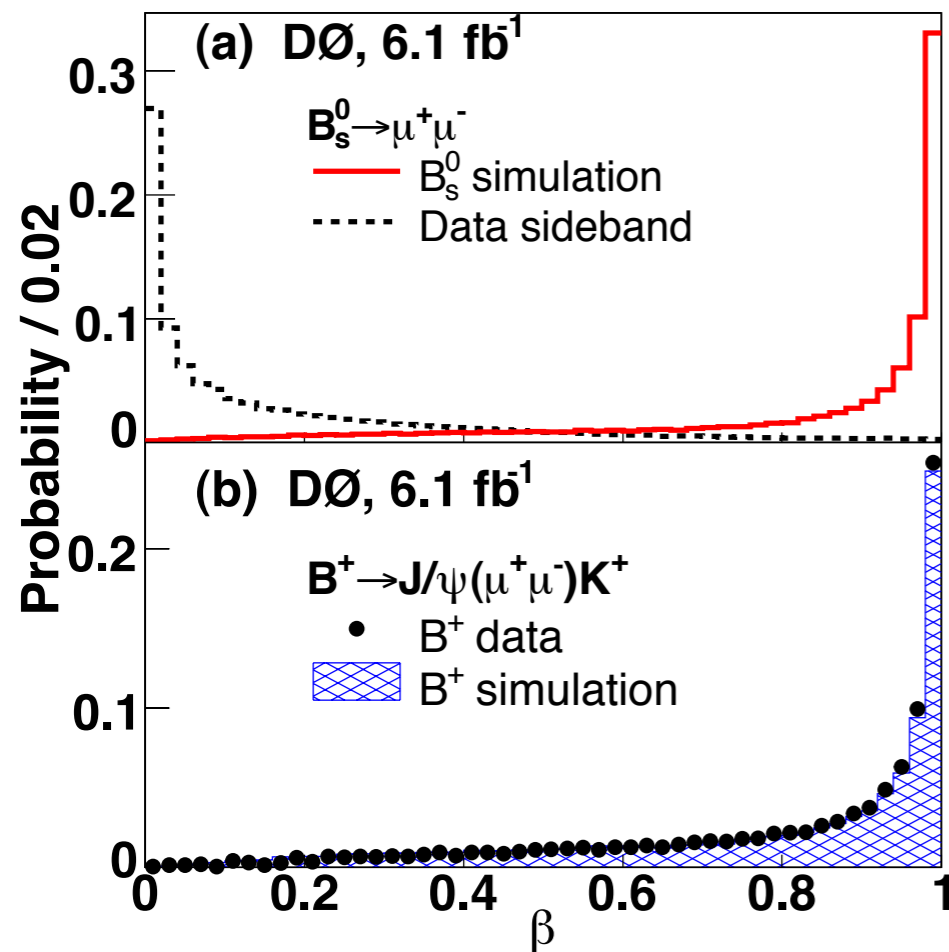
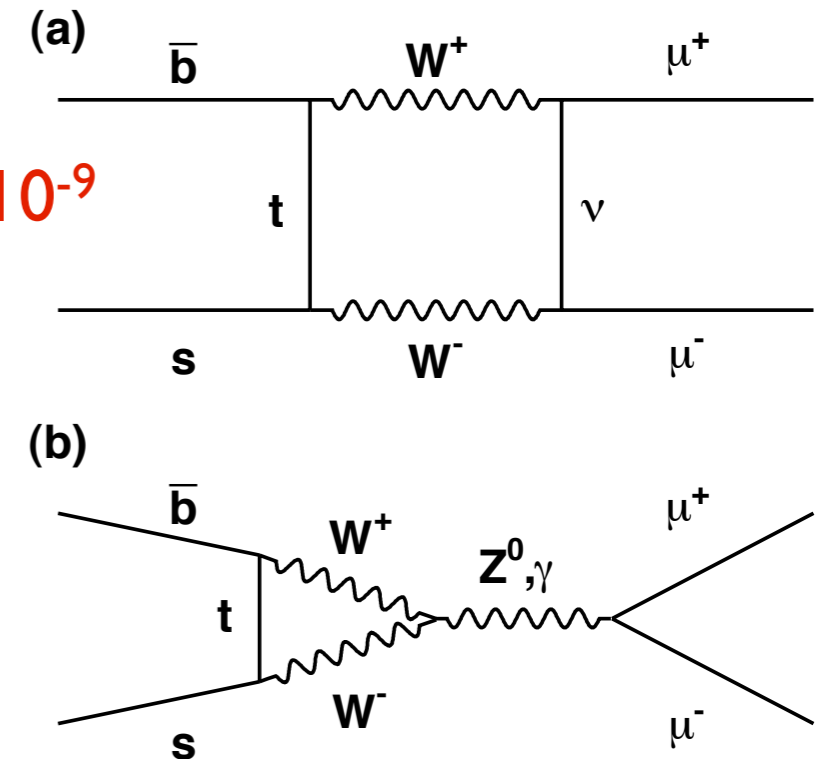
Search for $B_s \rightarrow \mu^+ \mu^-$

Another rare FCNC process! In the SM: $B = (3.6 \pm 0.3) \cdot 10^{-9}$

- powerful test of BSM models

The challenge: backgrounds. D0 analysis (6.1 fb^{-1}):

- train multivariate analysis using tracking/vertexing variables in sidebands
- verify with $B^+ \rightarrow J/\psi K^+$ decays

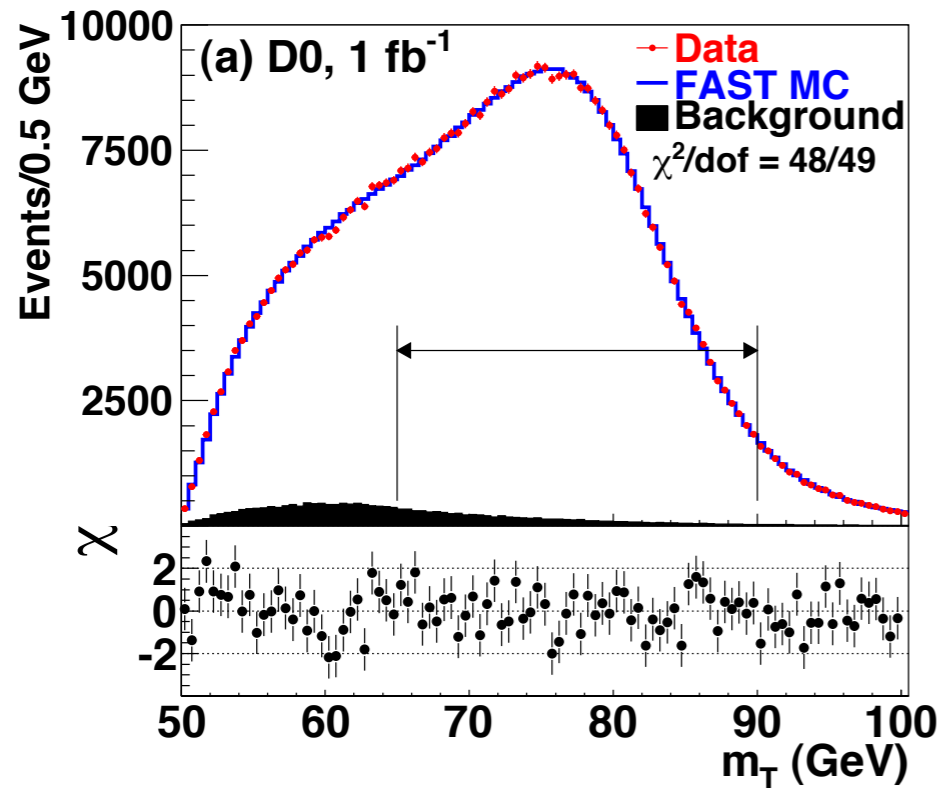


Results (95% CL):

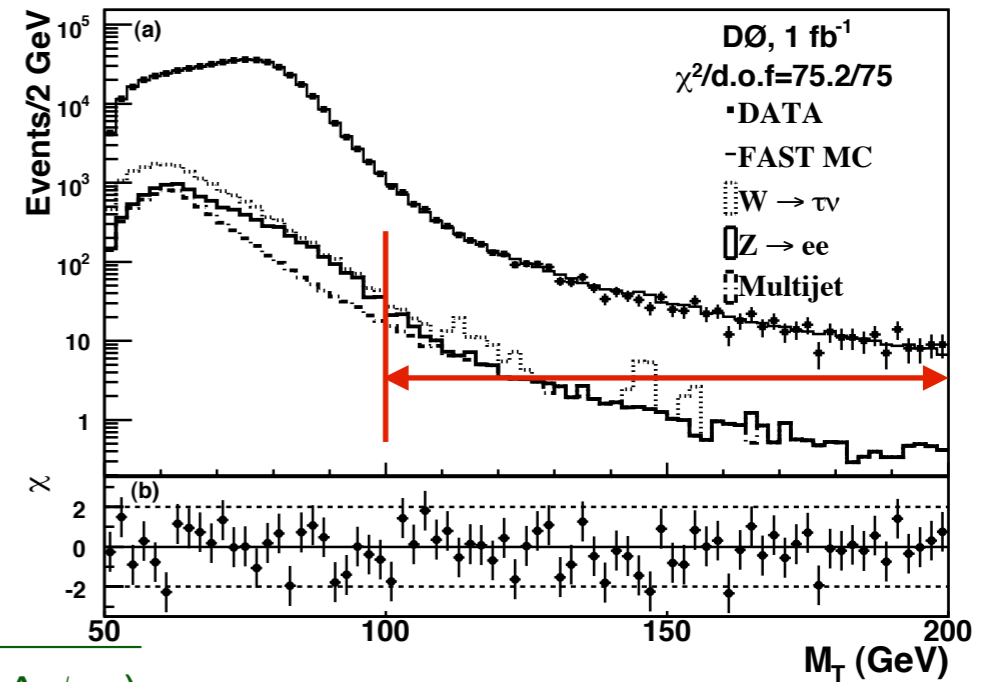
- D0: $B < 5.1 \cdot 10^{-8}$
- CDF: $B < 4.3 \cdot 10^{-8}$

Electroweak Physics

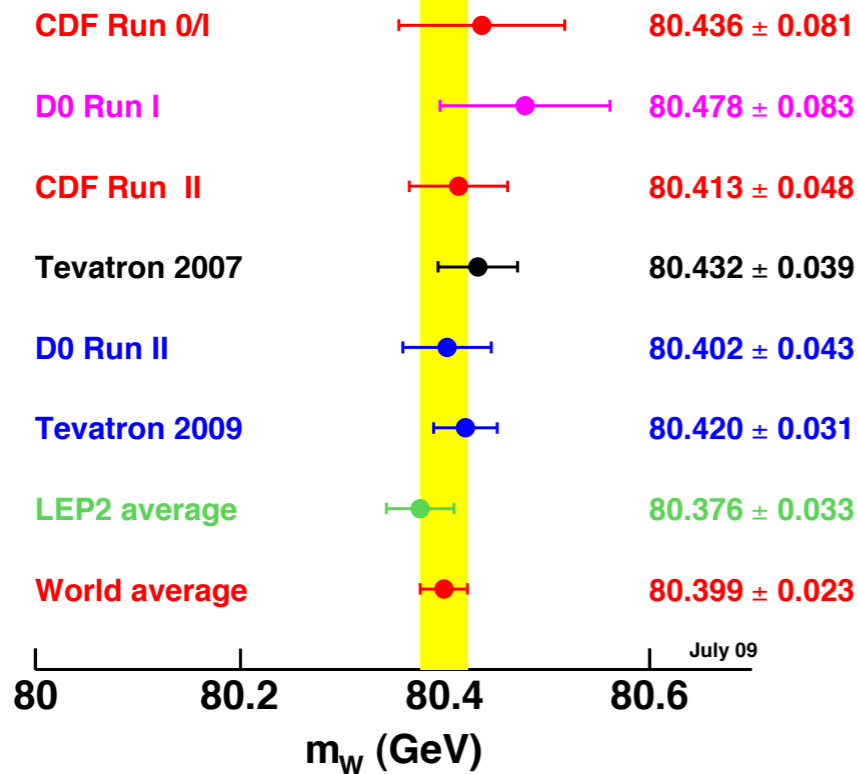
W Boson Properties: Mass and Width



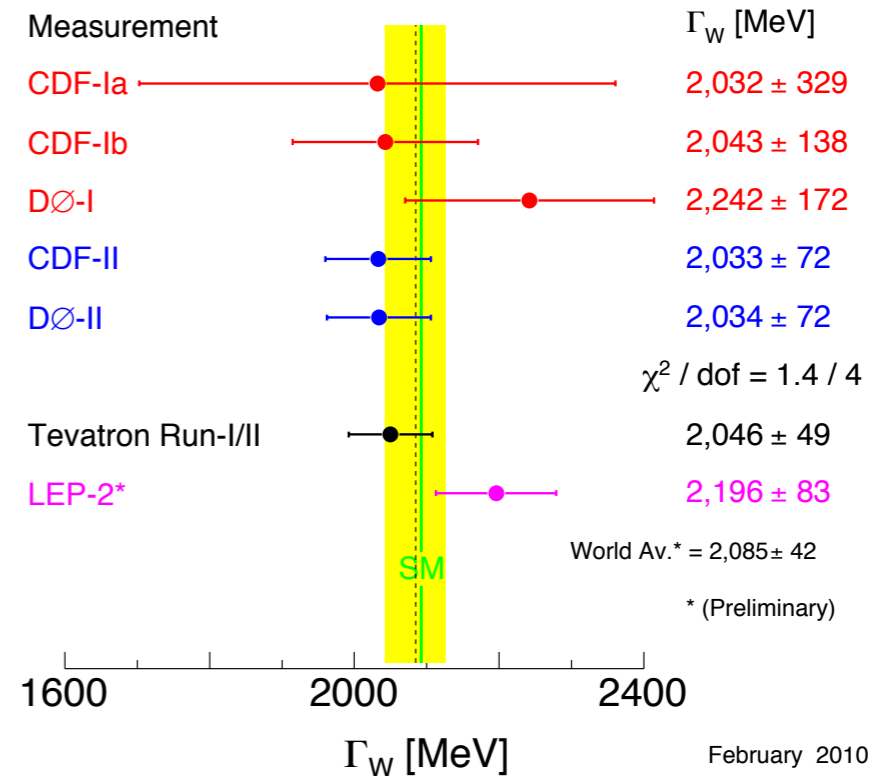
Extremely challenging from systematics point of view



$$M_T = \sqrt{p_T^l p_T^\nu (1 - \cos \Delta\phi_{l\nu})}$$

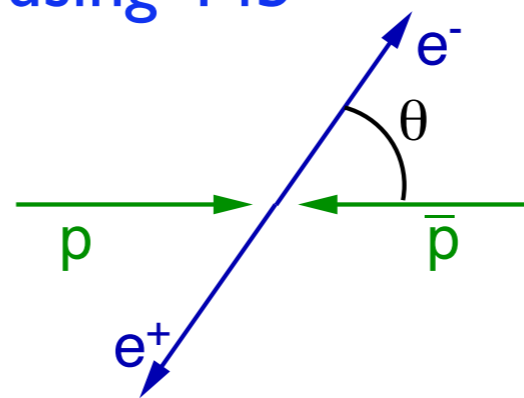
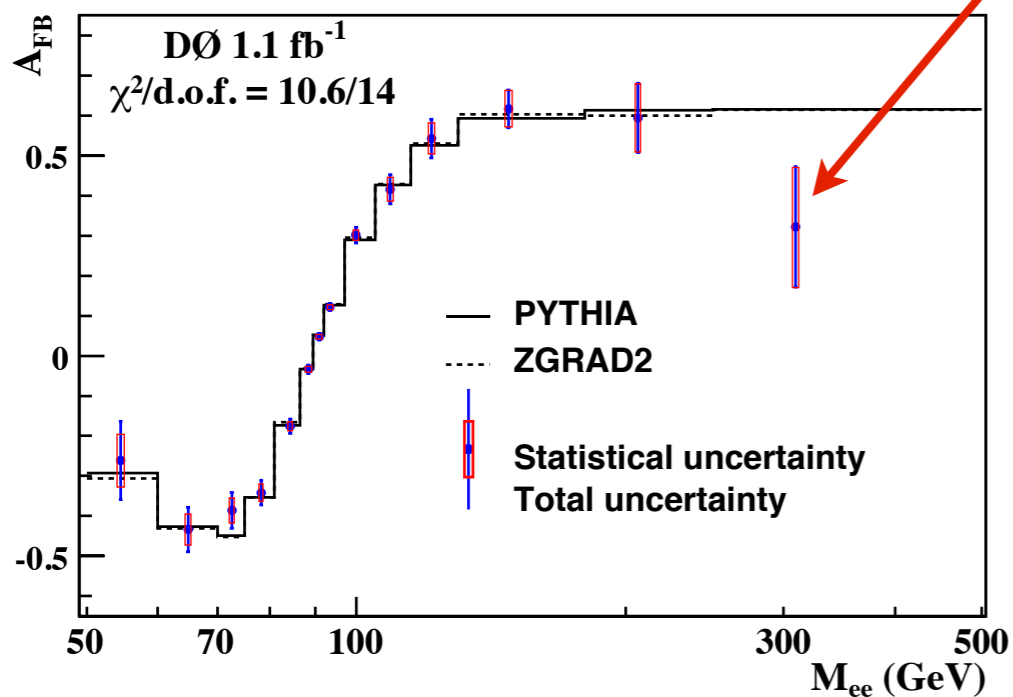


Width of the W Boson



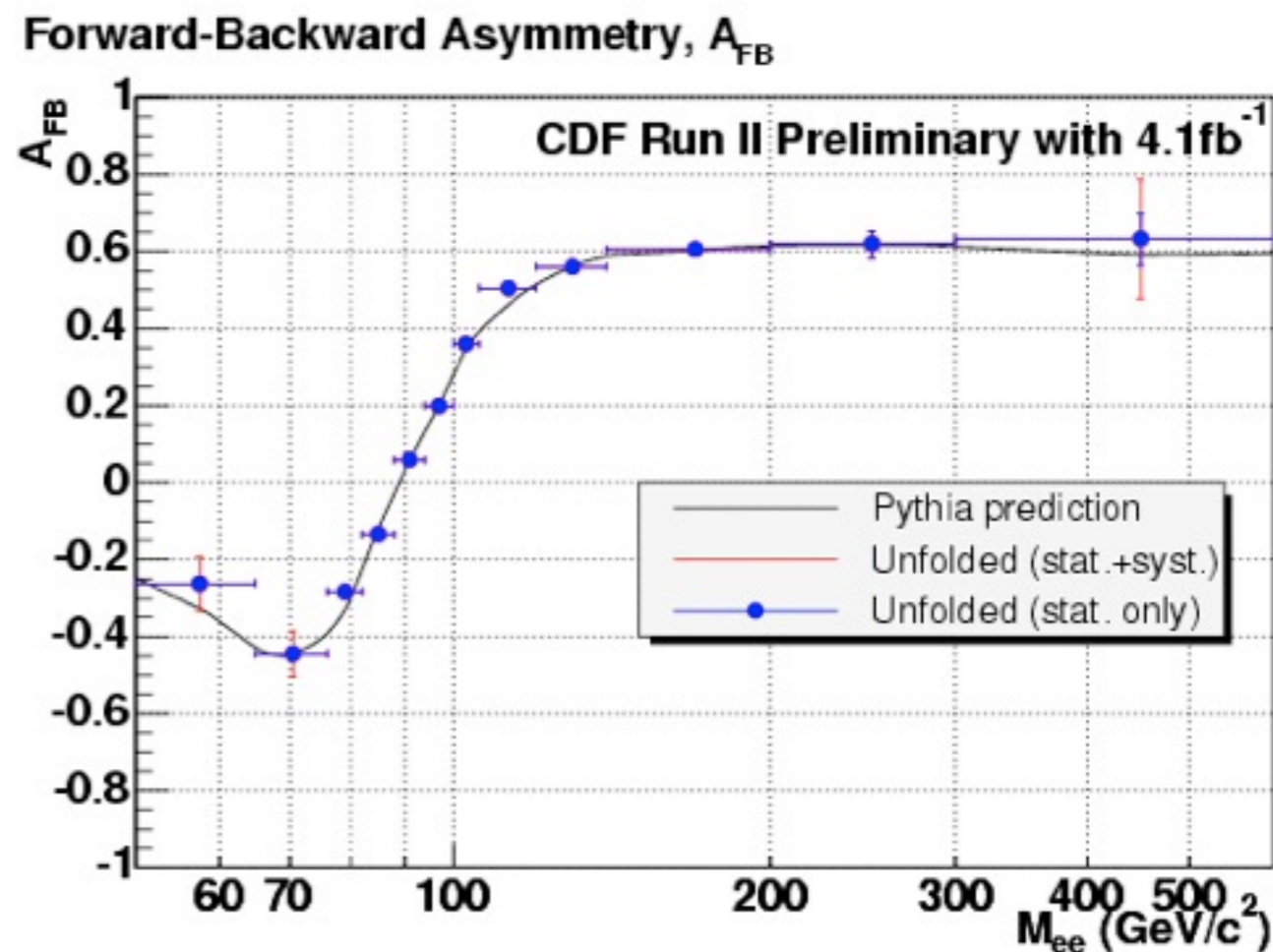
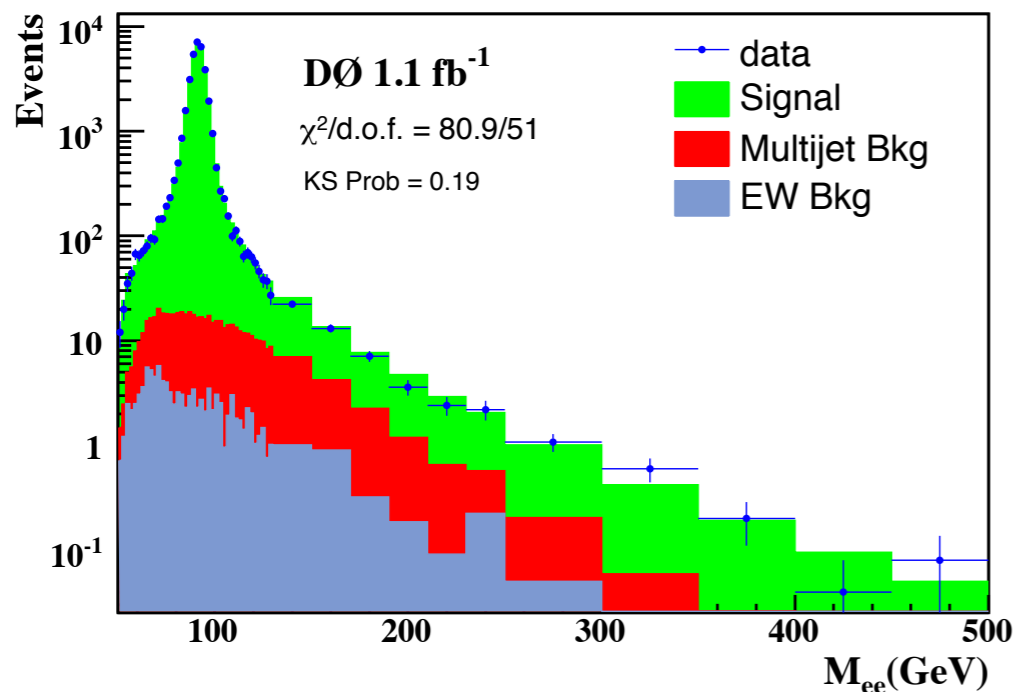
Forward-Backward Asymmetry in Drell-Yan

D0's 2008 measurement: hint for deviation at high M_{ee} (e.g. Z' ?), limited by statistics. Now remeasured by CDF using 4 fb^{-1}



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

(use Collins-Soper frame to deal with parton p_T)



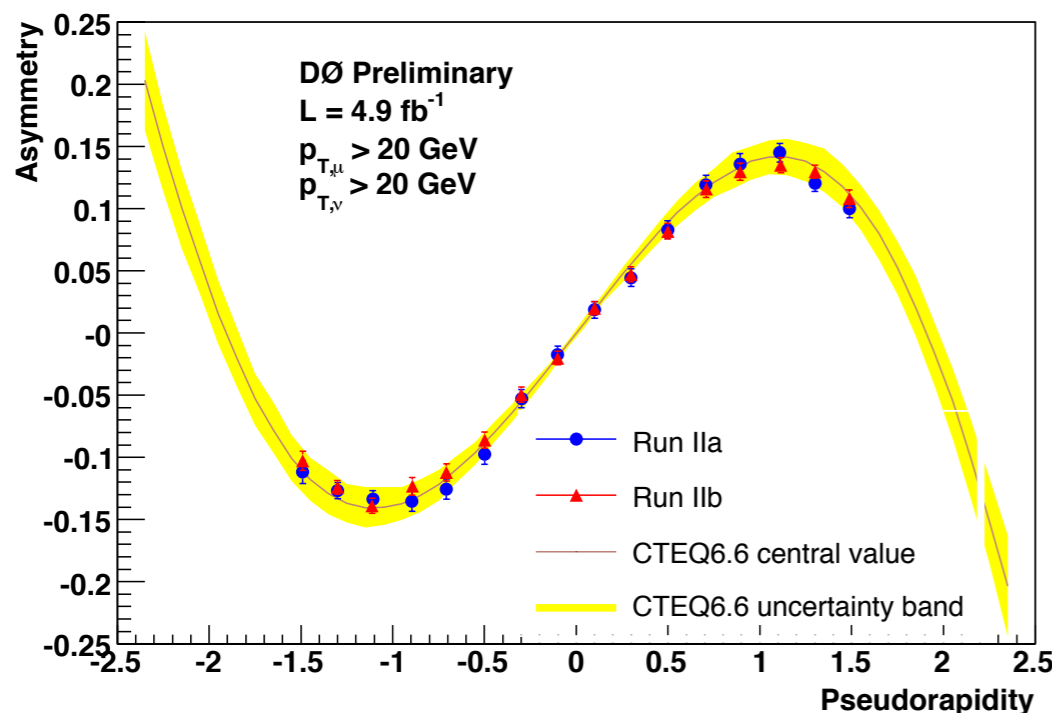
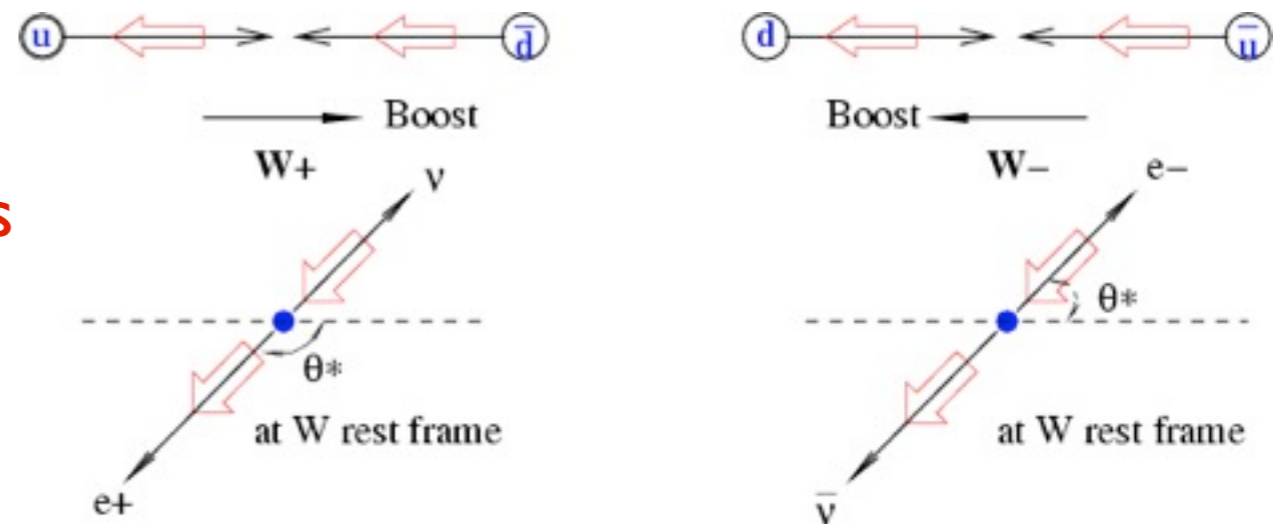
W Boson Charge Asymmetry

Sensitive test of u, d PDFs

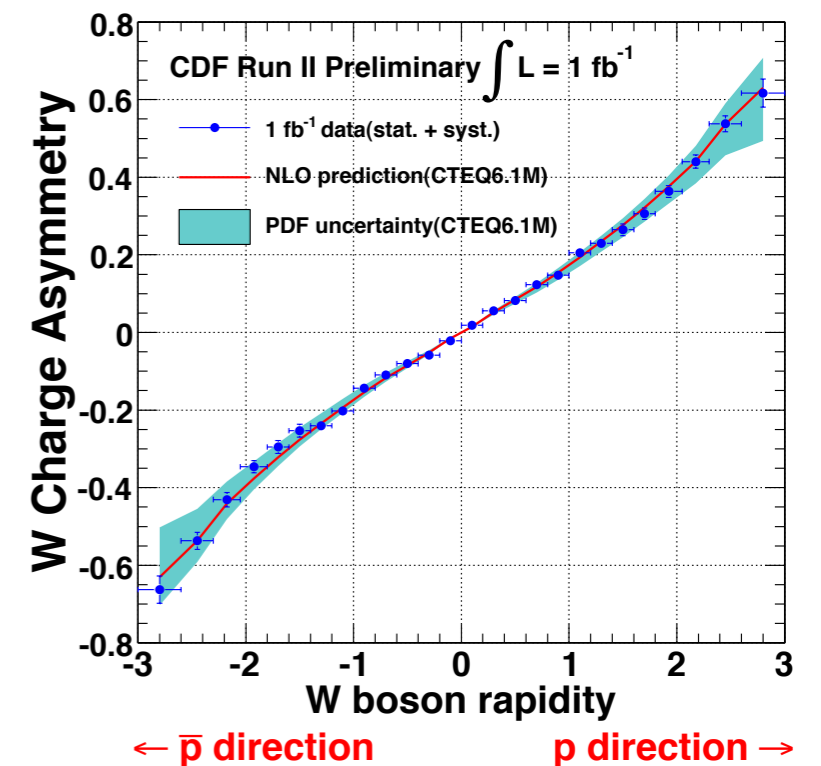
- problem: two solutions for neutrino's p_z component (assuming on-shell W)

Earlier (2008) CDF analysis (1 fb^{-1} , $W \rightarrow e\nu$): explicitly use both solutions, correct for mis-assignment

New D0 analysis (4 fb^{-1} , $W \rightarrow \mu\nu$): don't reconstruct the W , consider directly the lepton charge asymmetry



Results consistent with earlier D0 $W \rightarrow e\nu$ analysis



An "interesting" challenge for PDF fitting (e.g. CT10W)

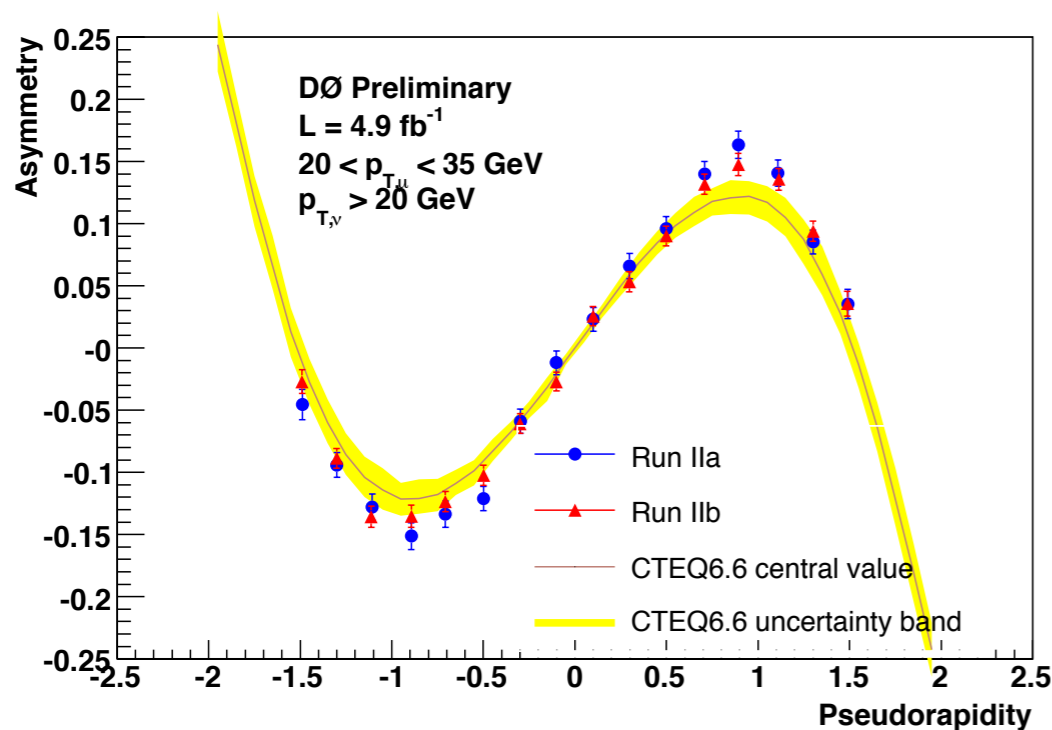
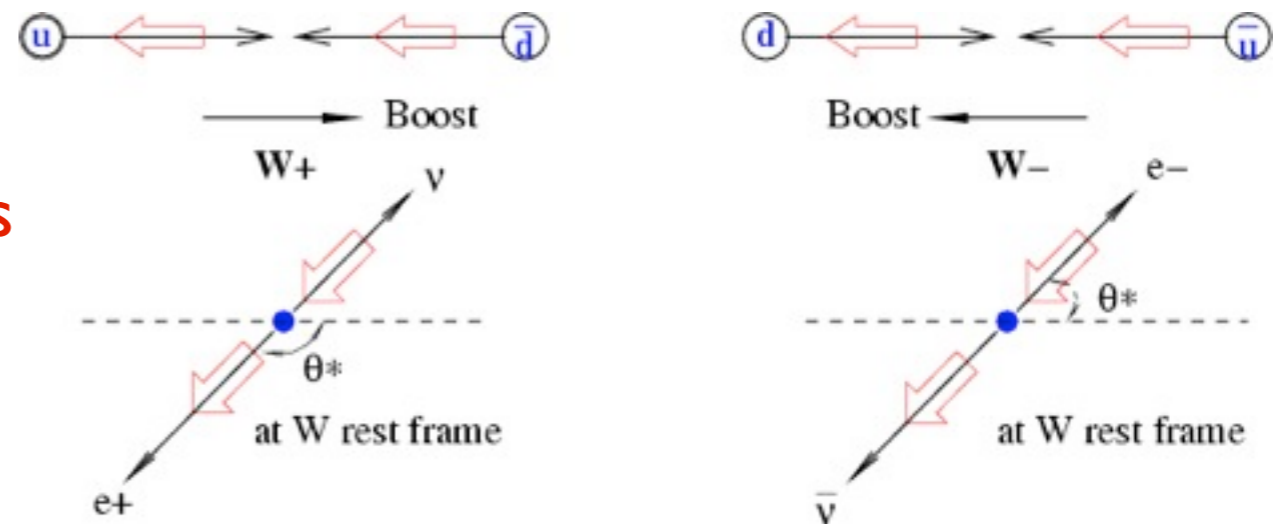
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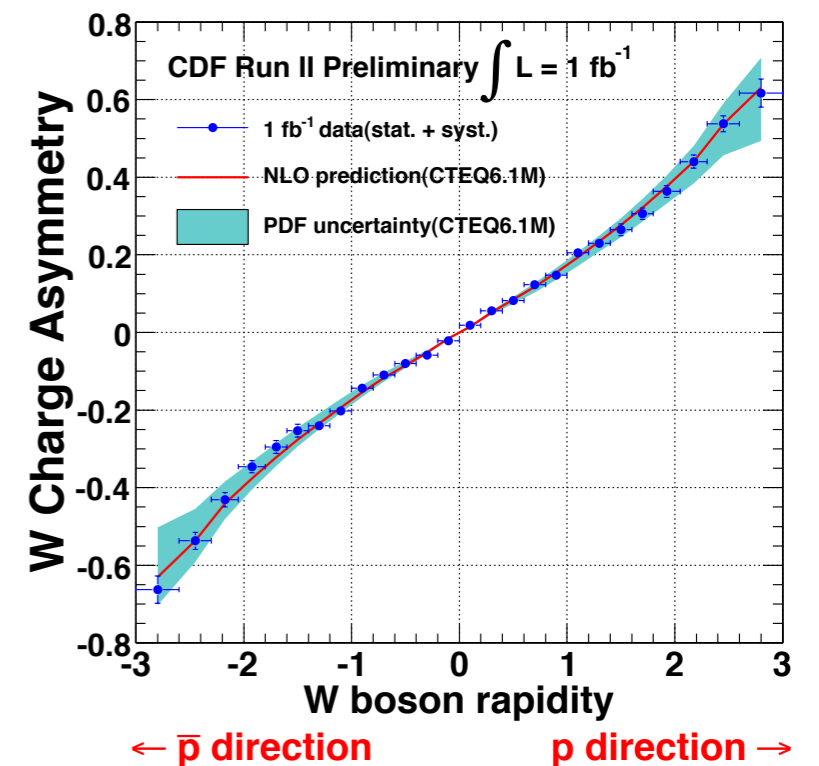
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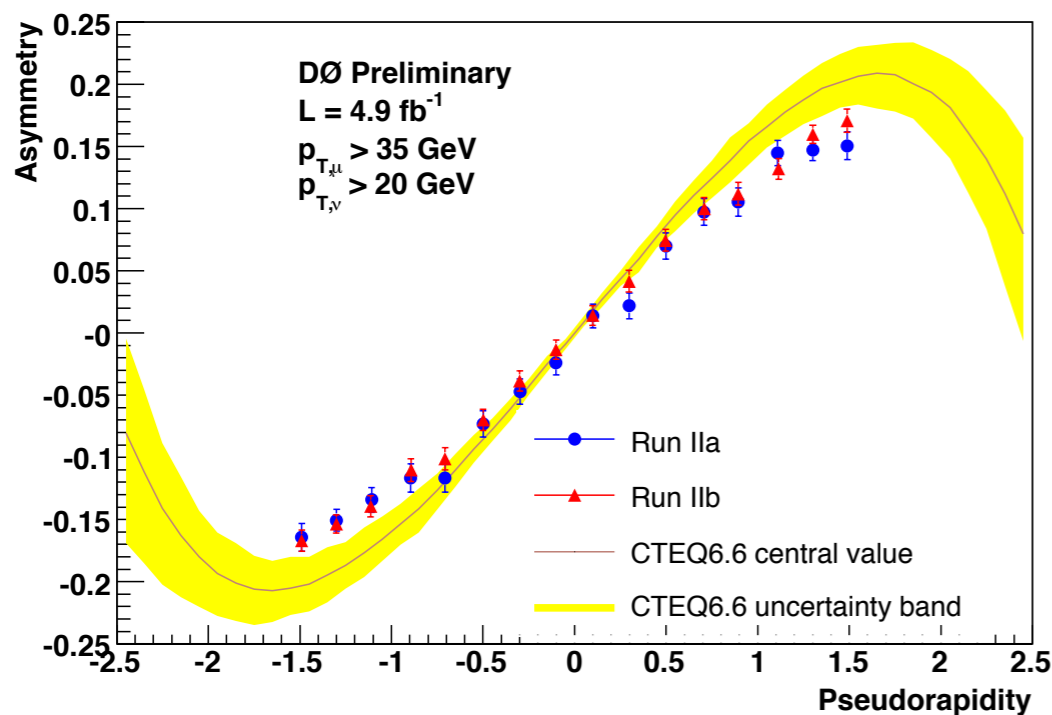
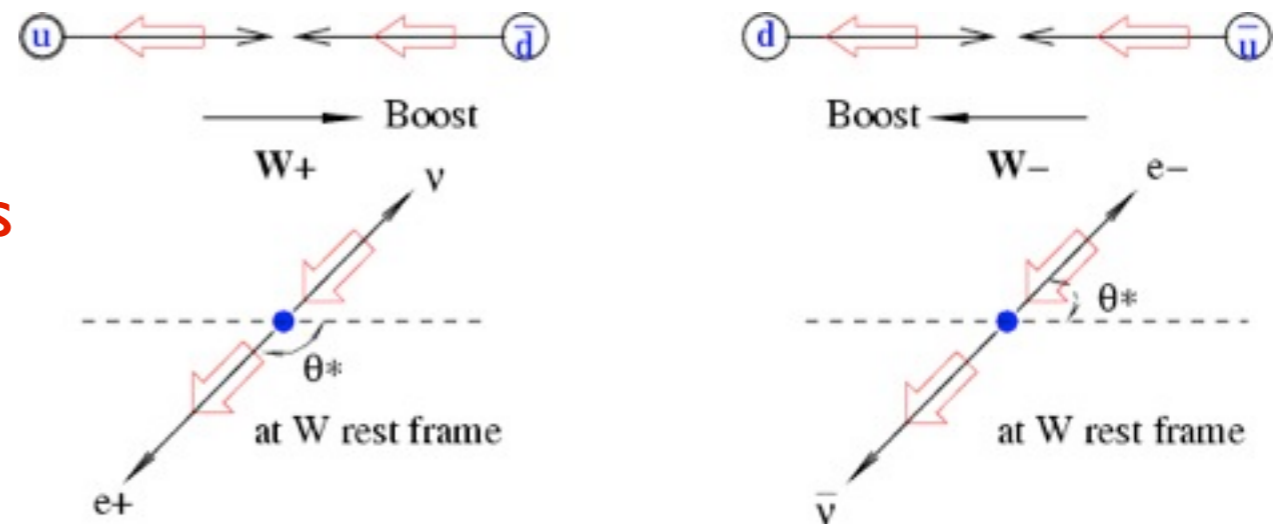
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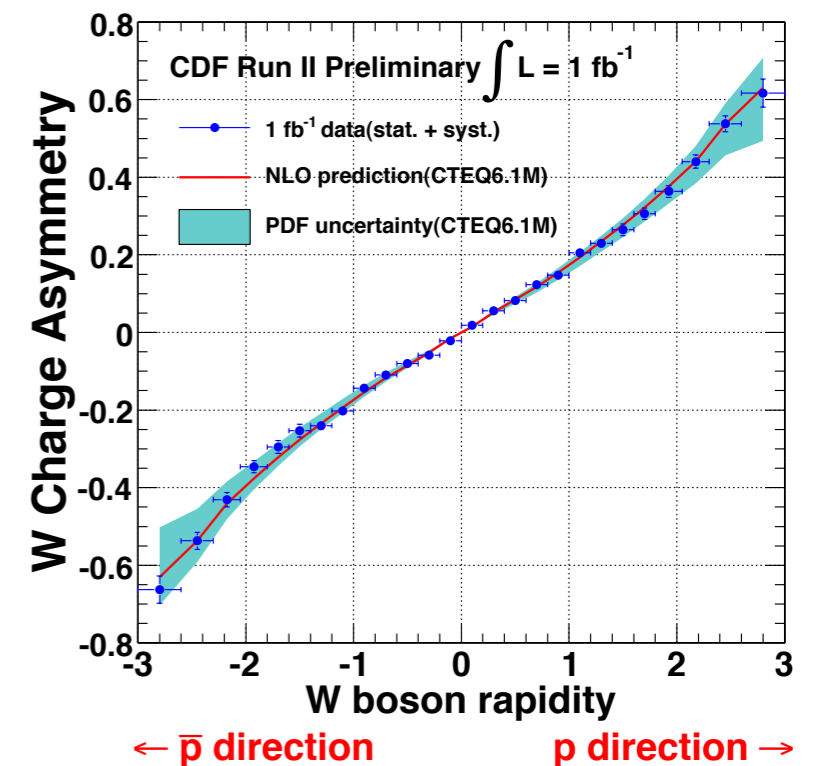
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Results consistent with earlier D0 $W \rightarrow e\nu$ analysis

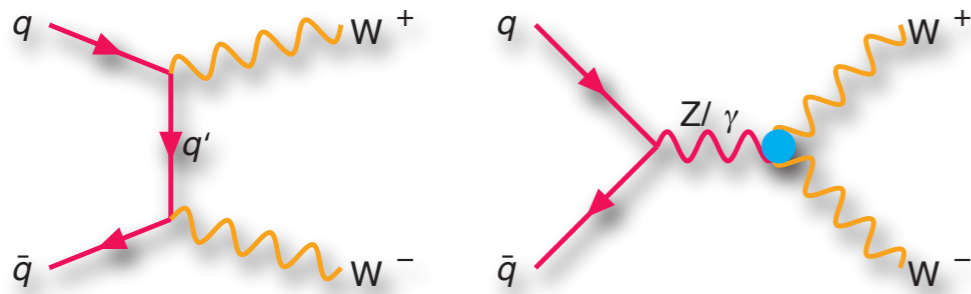


An “interesting” challenge for PDF fitting (e.g. CT10W)

Di-Boson Production

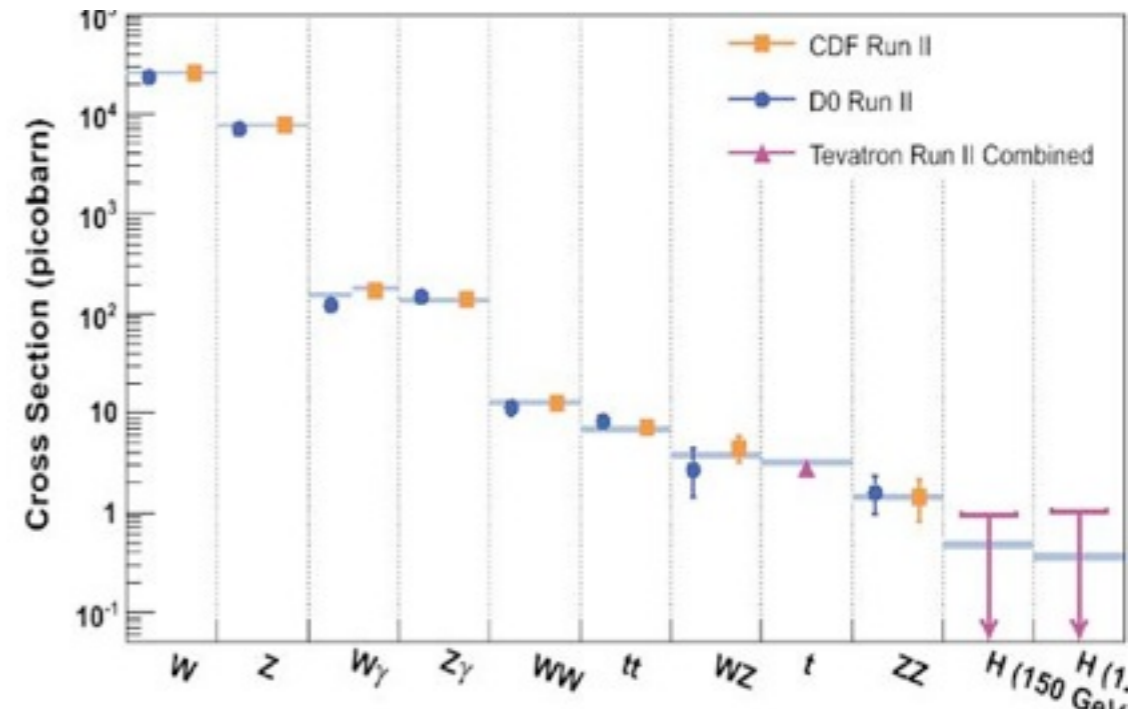
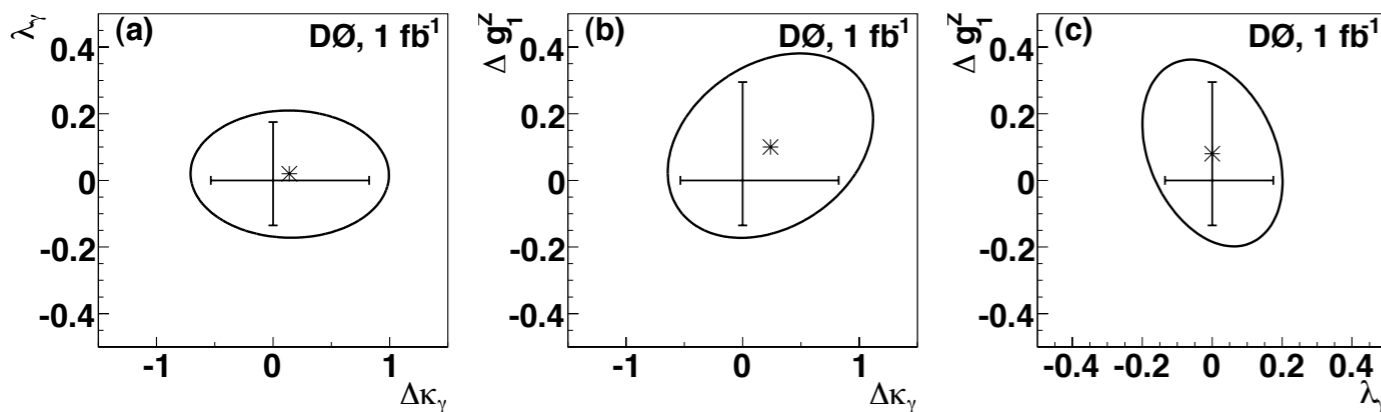
The name of the game:
 probing Triple Gauge-boson Couplings
 (besides being interesting decay products
 of other bosons...)

- e.g. for WW production (Wγ/WZ production sensitive to only WWγ/WWZ):

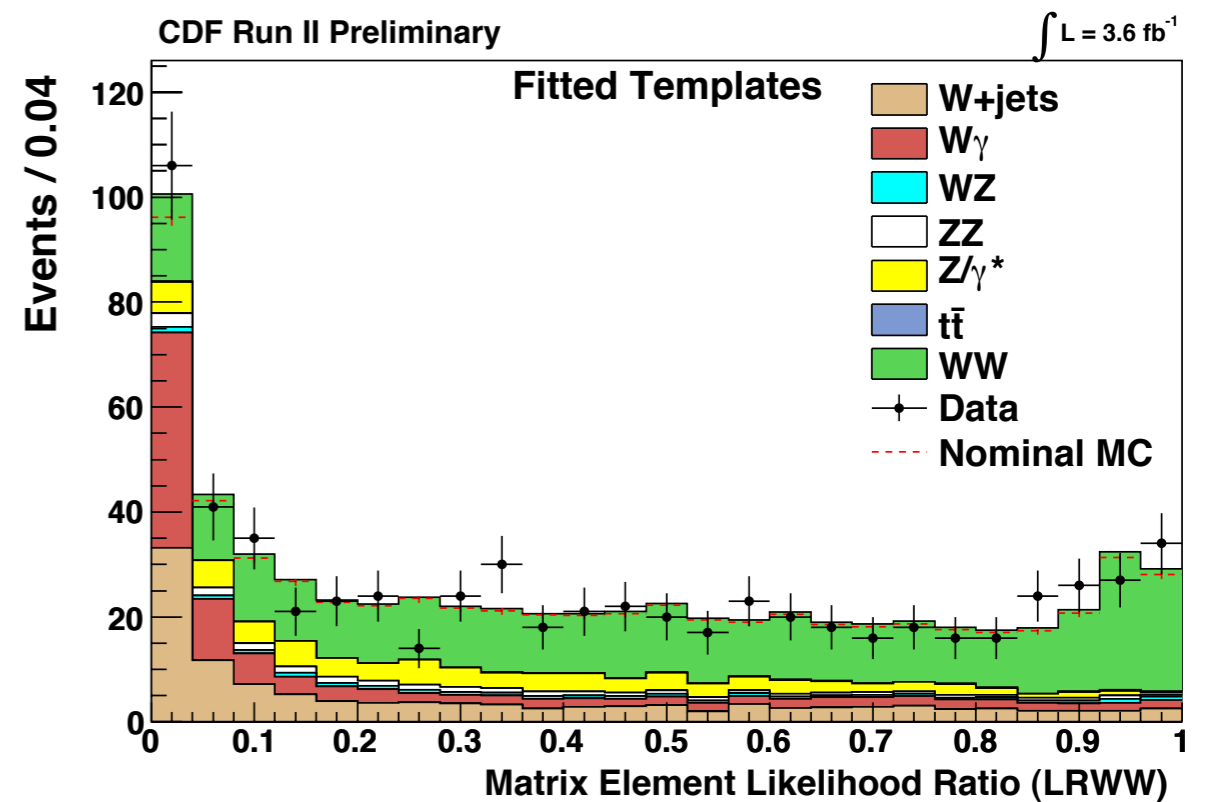


$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V (W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W^\mu_\nu V^{\nu\lambda},$$

$$g_1^\gamma = 1, \quad \lambda_Z = \lambda_\gamma, \quad \kappa_Z = g_1^Z - (\kappa_\gamma - 1) \tan^2 \theta_W$$



Gallery of Tevatron EW (mostly) measurements



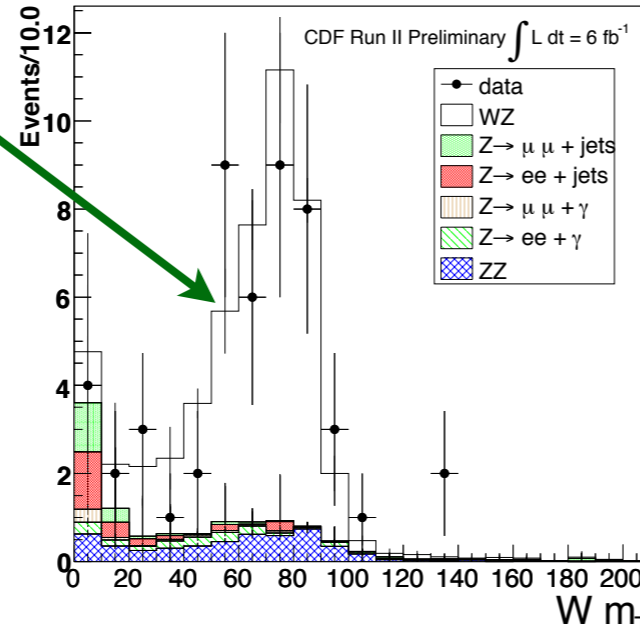
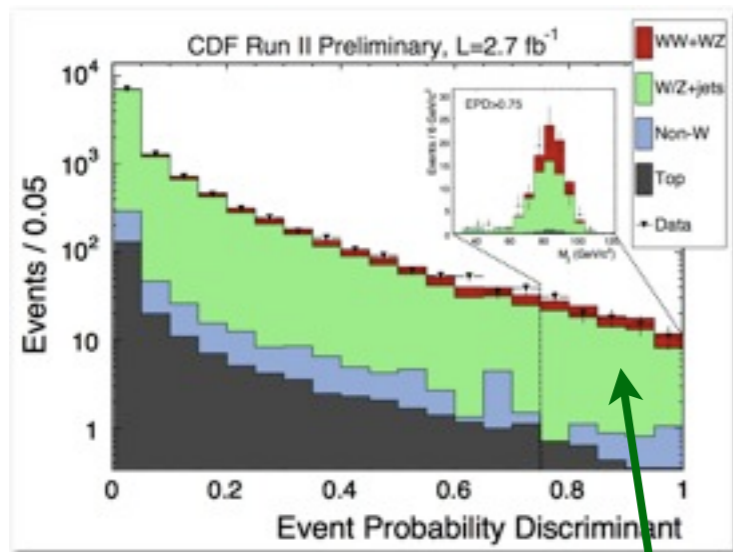
$$\sigma(p\bar{p} \rightarrow WW) = 12.1 \pm 0.9(\text{stat.})^{+1.6}_{-1.4}(\text{syst.}) \text{ pb}$$

Di-Boson Production (2)

Also: observation of WZ final states

- in llv final states

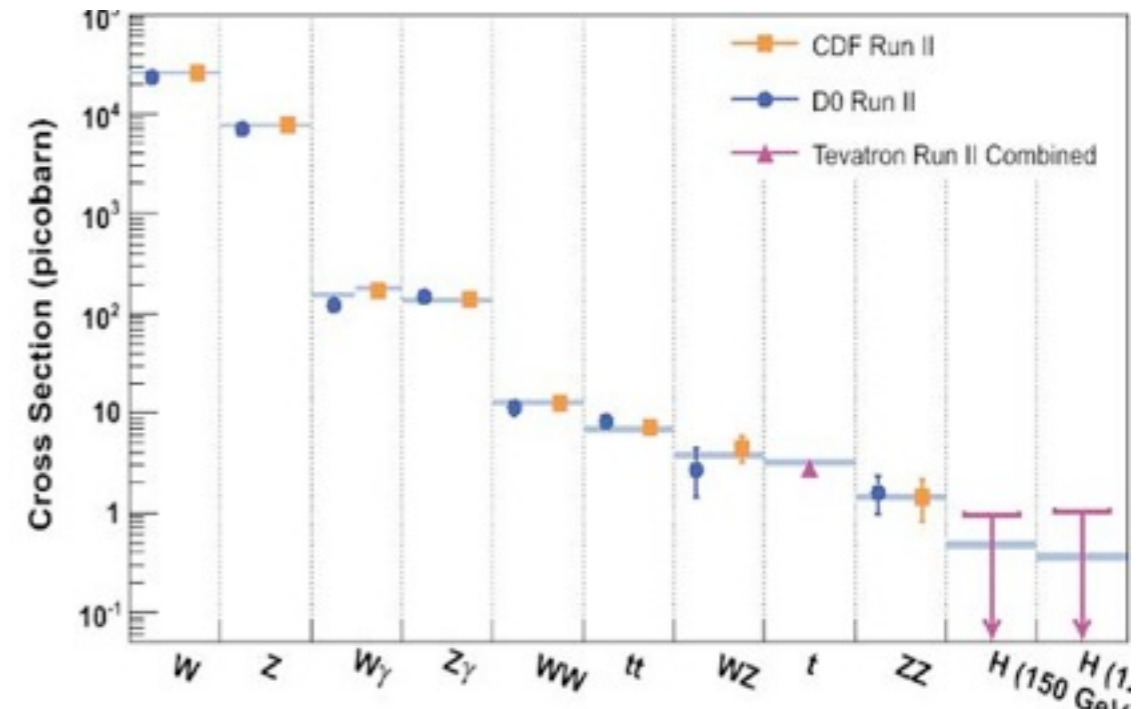
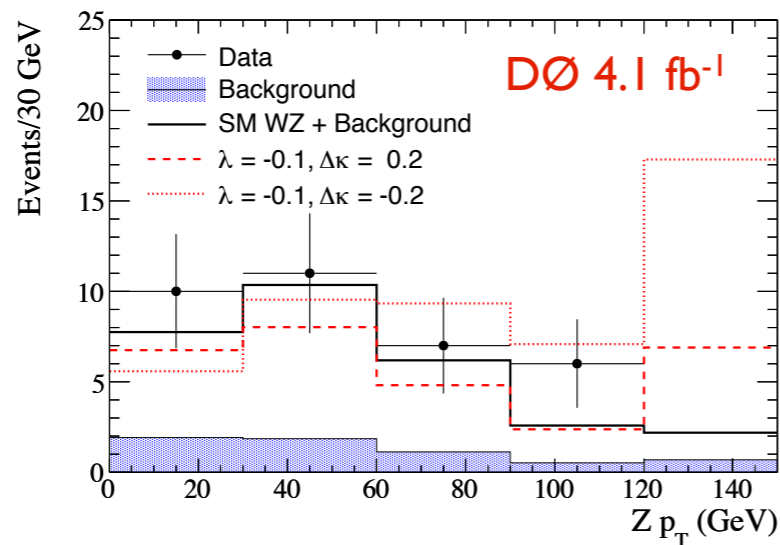
$$\sigma(p\bar{p} \rightarrow WZ) = 4.1 \pm 0.7 \text{ pb}$$



$$\sigma(p\bar{p} \rightarrow WZ, WW) = 17.7 \pm 3.9 \text{ pb}$$

- WW/WZ in lvjj final states

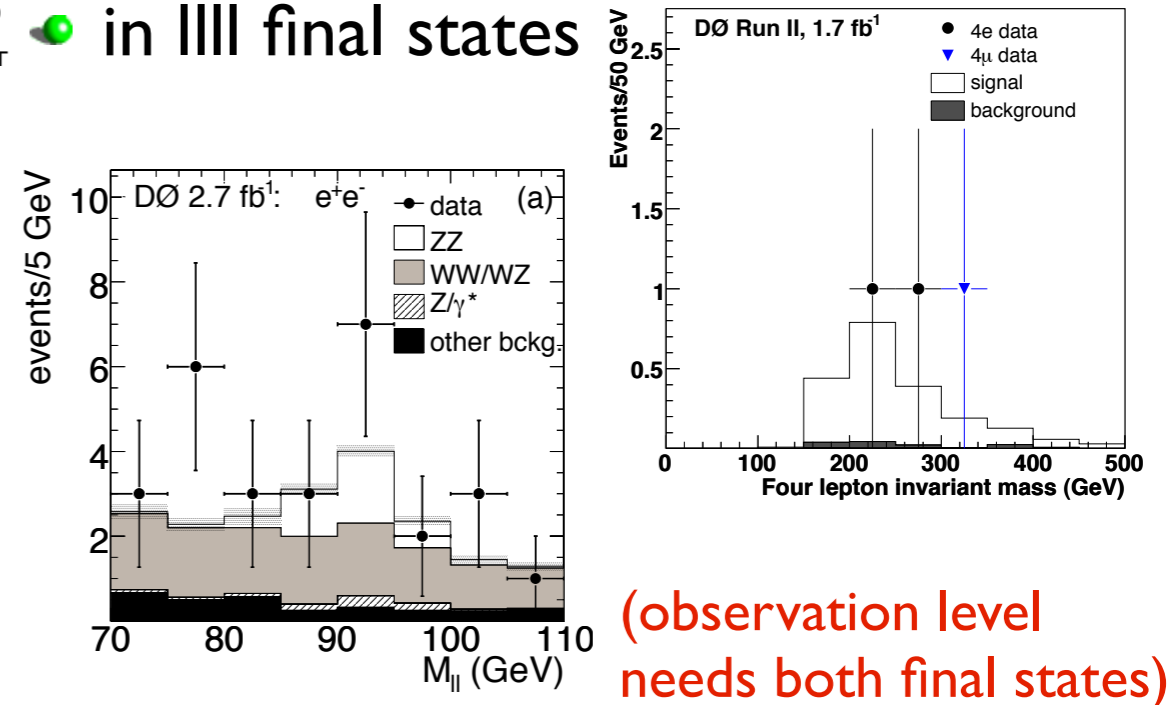
- constraints on anomalous couplings



Gallery of Tevatron EW (mostly) measurements

Observation of ZZ final states

- in llv final states



(observation level needs both final states)

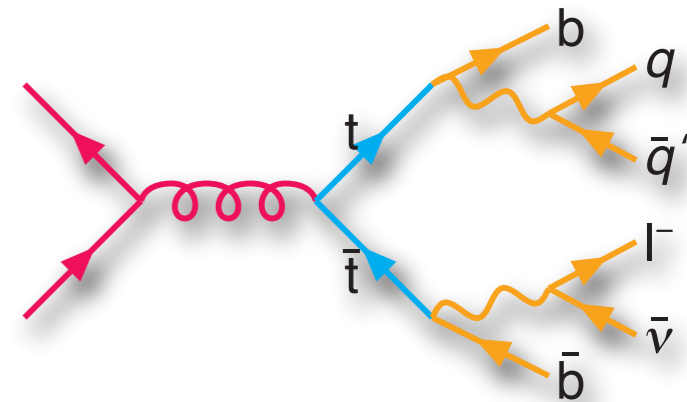
- in llvv final states

- similar analysis of TG couplings

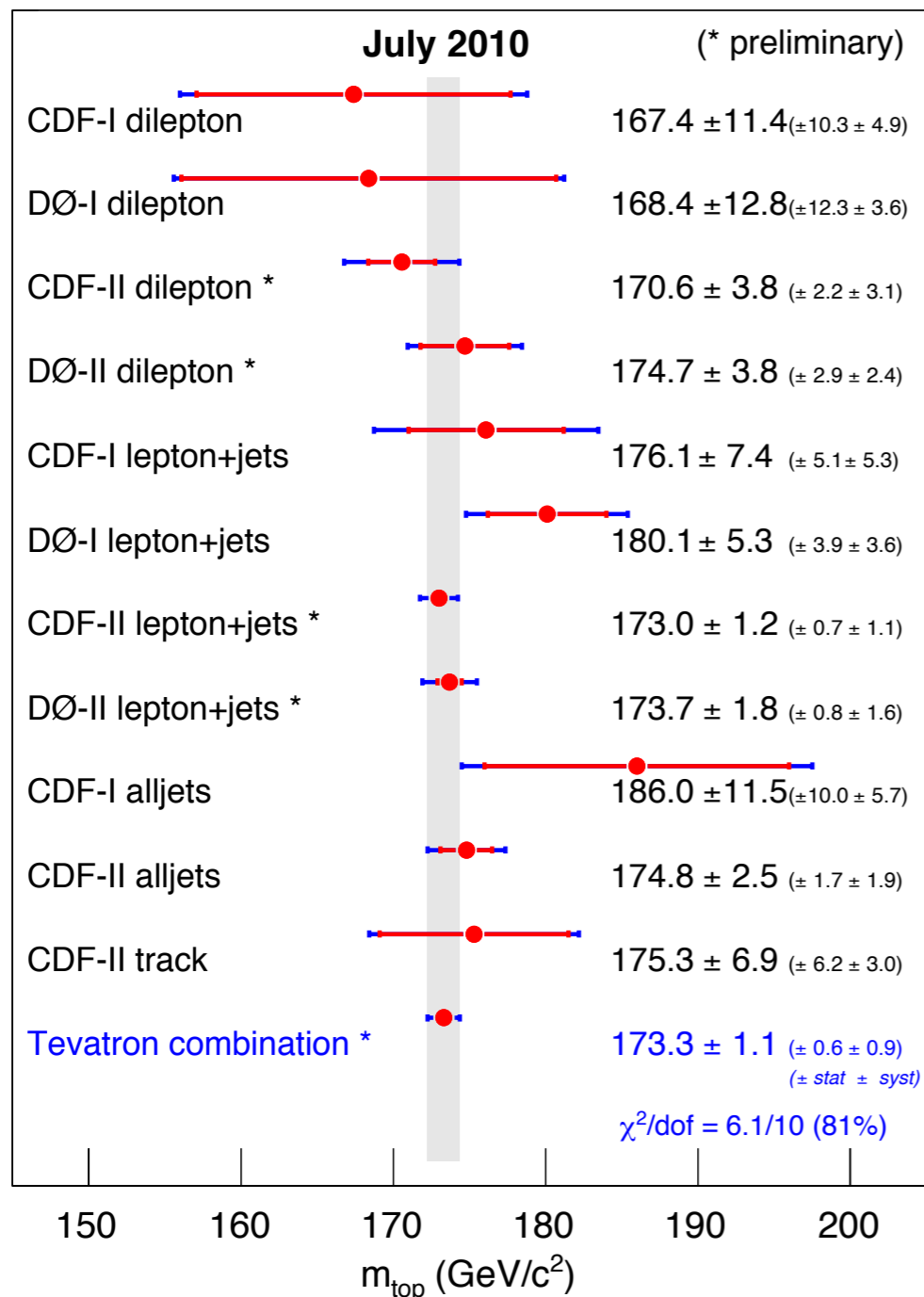
Top Quark Physics

Top Quark Mass & Width

Top quark mass: another area of high precision measurements

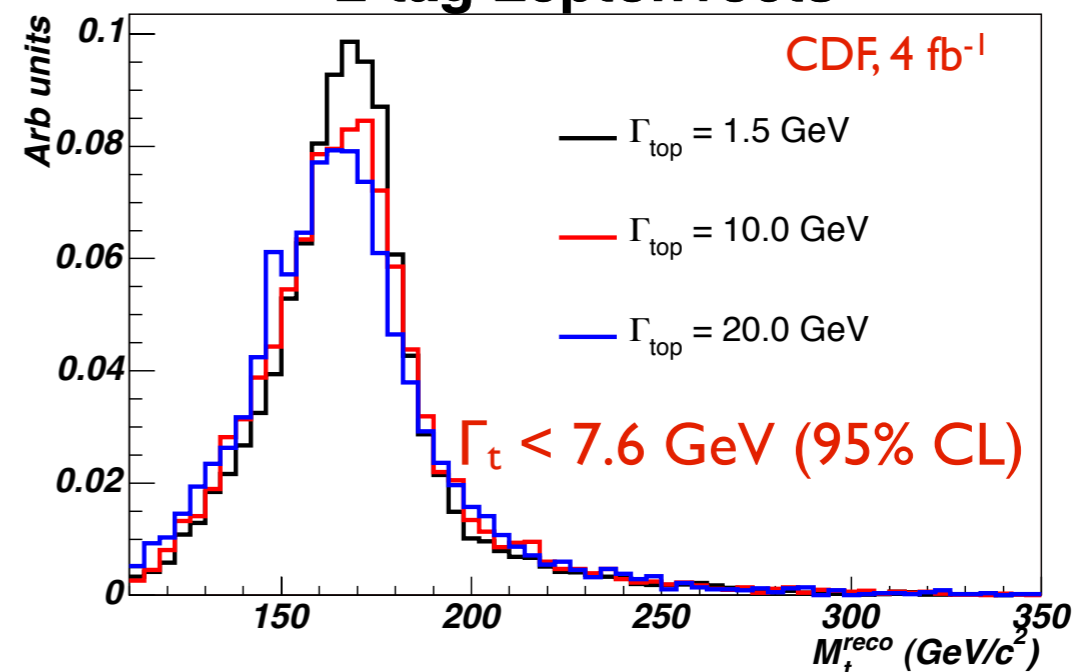


Mass of the Top Quark



l+jets final states also allow a direct measurement of top quark width...

2-tag Lepton+Jets



but difficult to compete with indirect measurement (D0, 2.3 fb⁻¹)

- combining t-channel single top production cross section and $B(t \rightarrow Wb)$ measurements in l+jets:

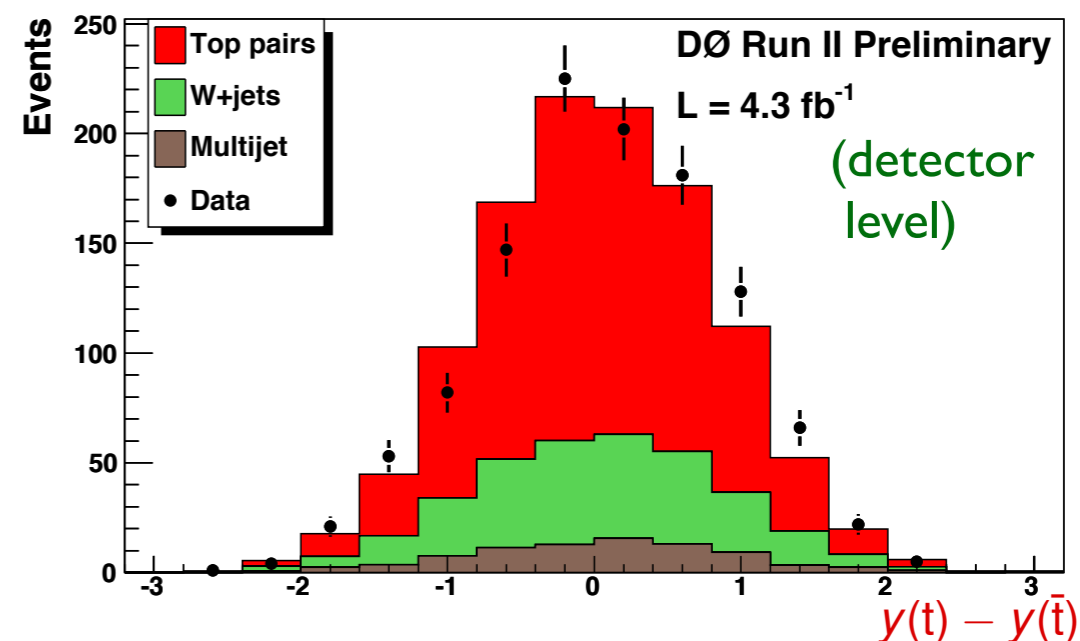
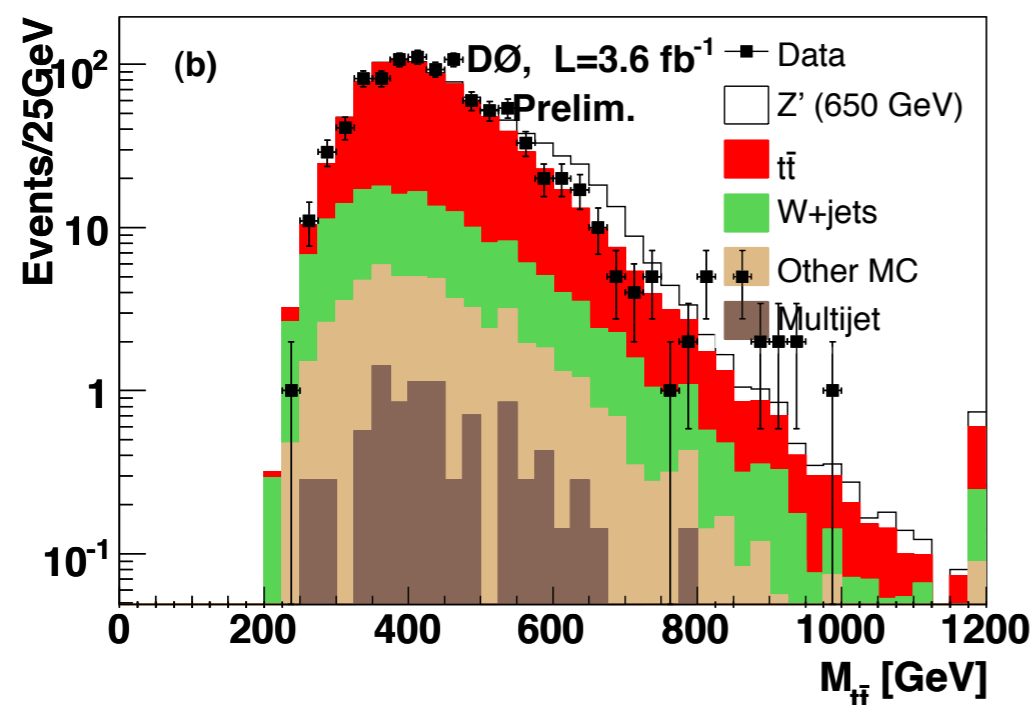
$$\Gamma_t = 1.99^{+0.69}_{-0.55} \text{ GeV}$$

Top Quark Pair Resonances & A_{fb}

Looking for non-SM contributions to (l+jets) top quark pair production...

Directly as a (narrow) resonance

Or through production asymmetry
(SM NLO interference effects: $A_{fb} \sim 1\%$ at detector level, $\sim 6\%$ at parton level)

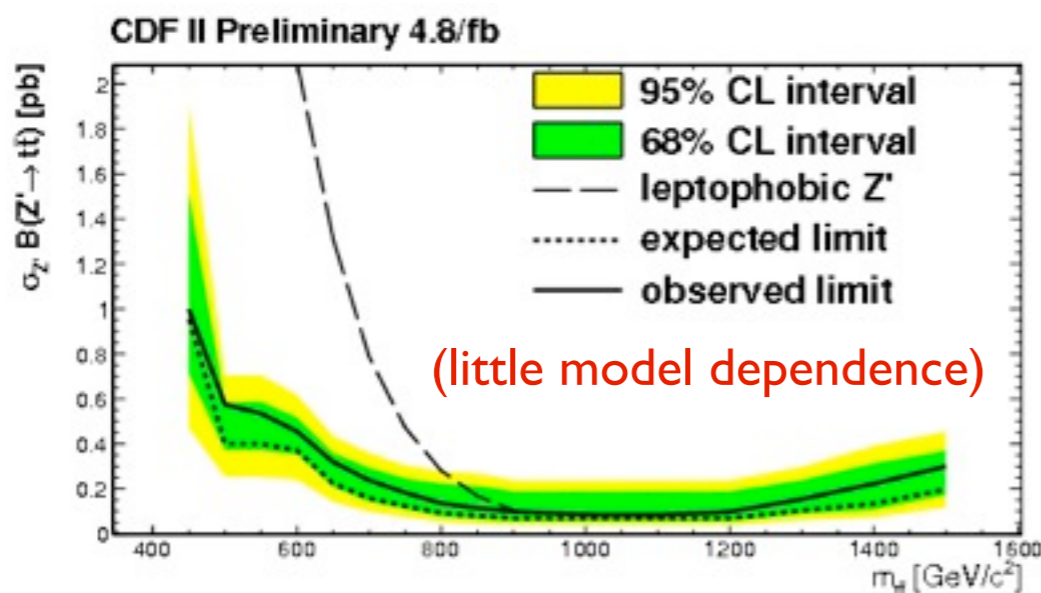


$$A_{fb} = 0.08 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.})$$

CDF also measures $y(t_{had})$ instead of rapidity difference (unfolded to parton level)

$$A_{fb} = 0.158 \pm 0.072(\text{stat.}) \pm 0.017(\text{syst.})$$

So far, no significant deviations



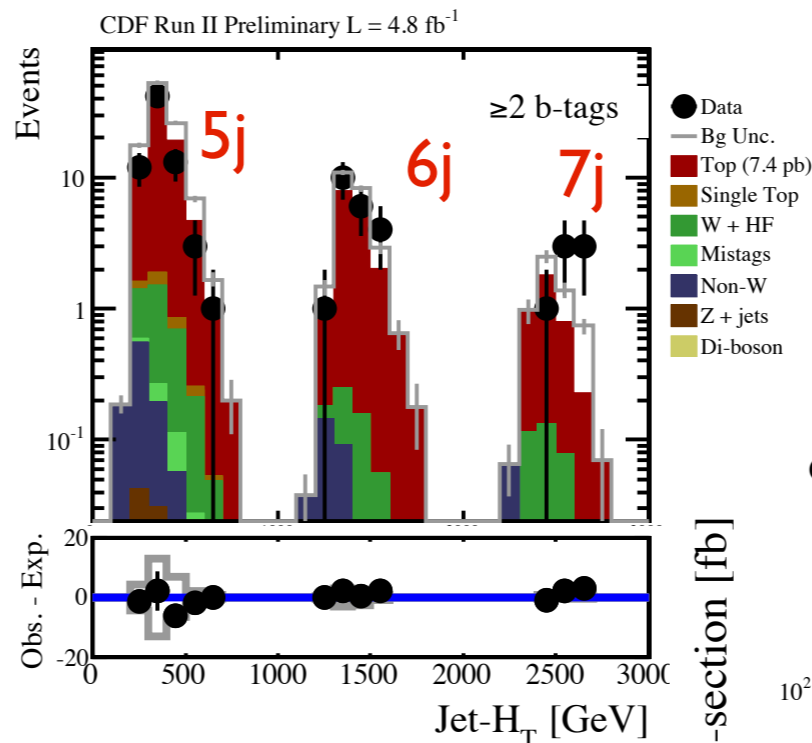
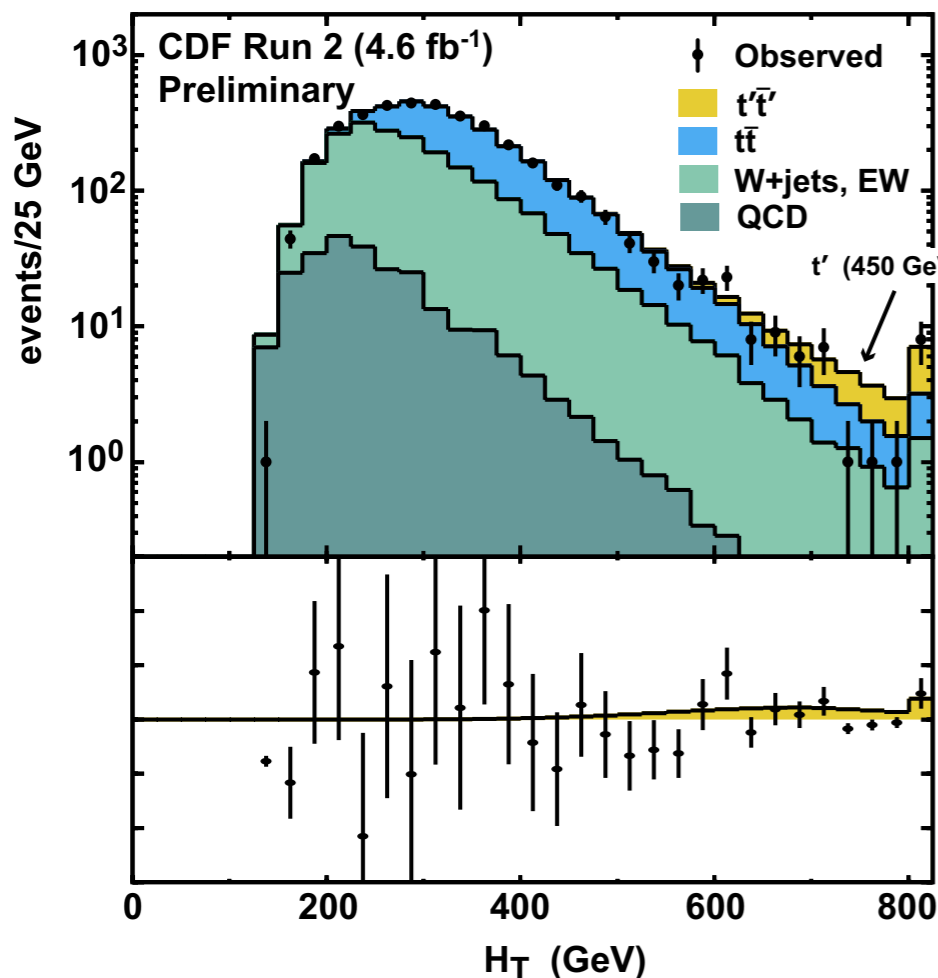
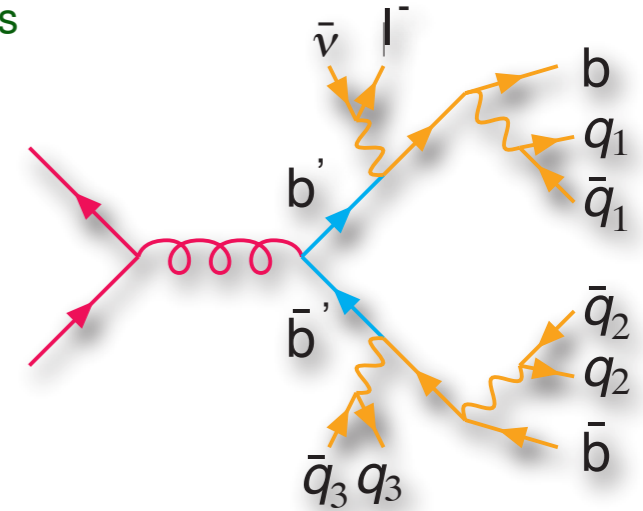
Fourth Generation Quark Searches

Following the pattern observed in the CKM matrix, assume that such quarks would primarily decay to the third family

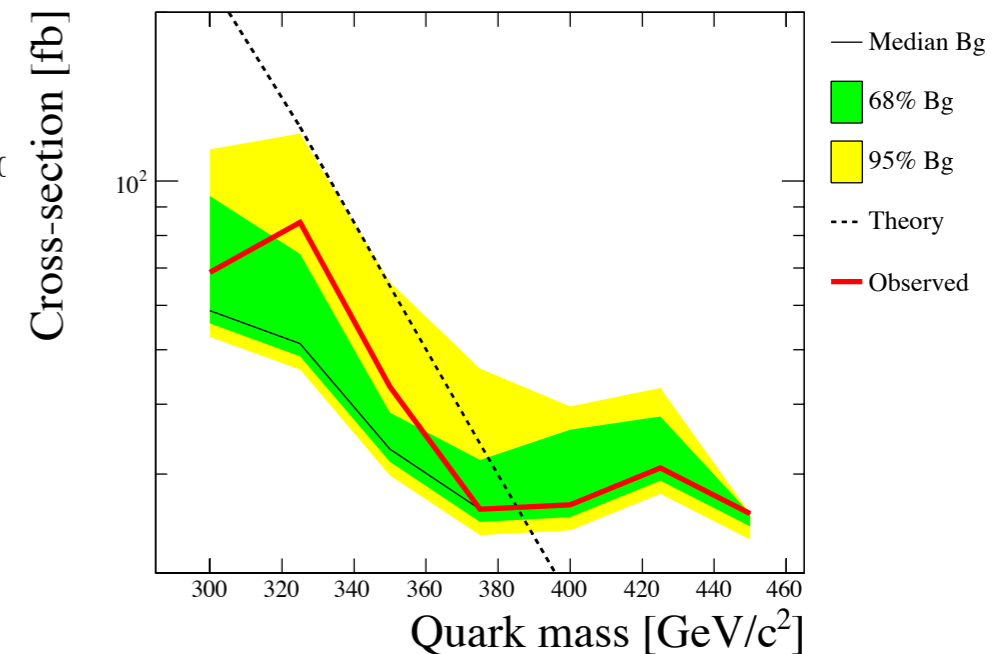
t' : structure in reconstructed “top”
mass distribution, H_T

b' : H_T , more jets
(consider events w/ ≥ 5 jets)

$$H_T = \sum_{j \in \text{jets}} E_{T,j} + E_{T,\ell} + E_T$$



CDF Run II Preliminary L=4.8 fb⁻¹



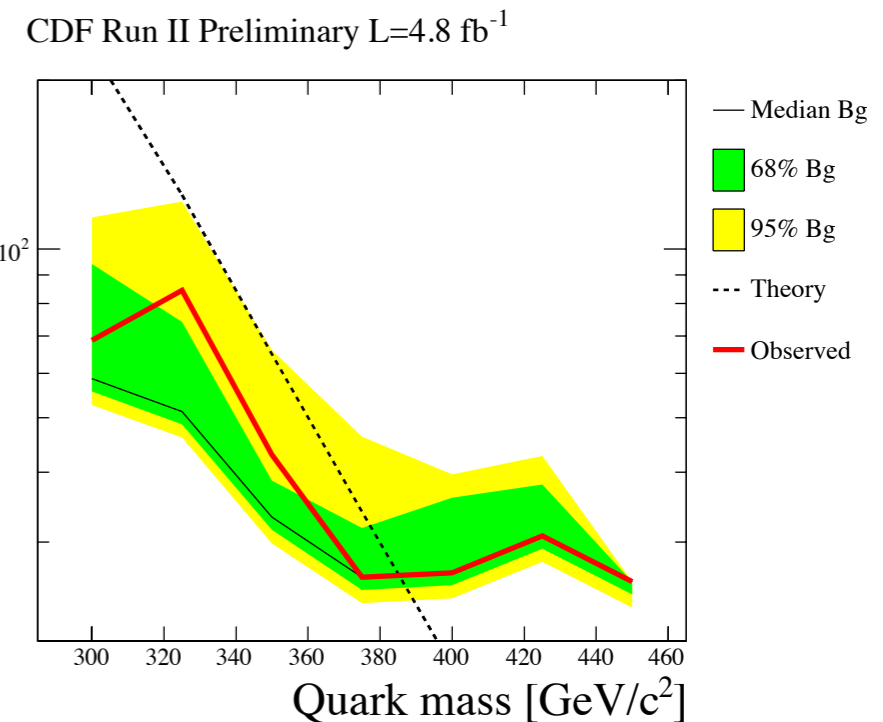
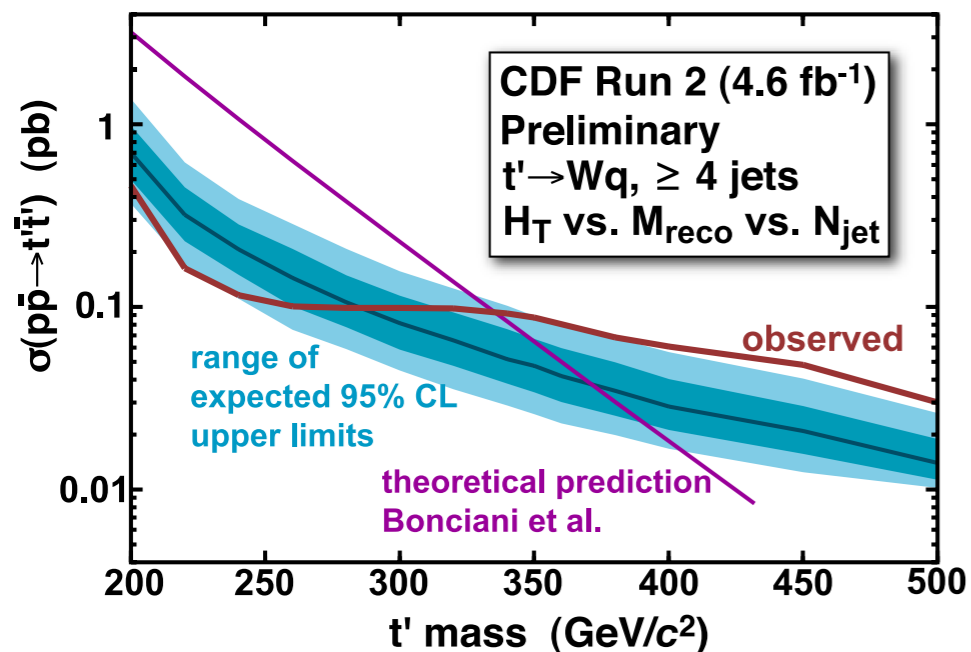
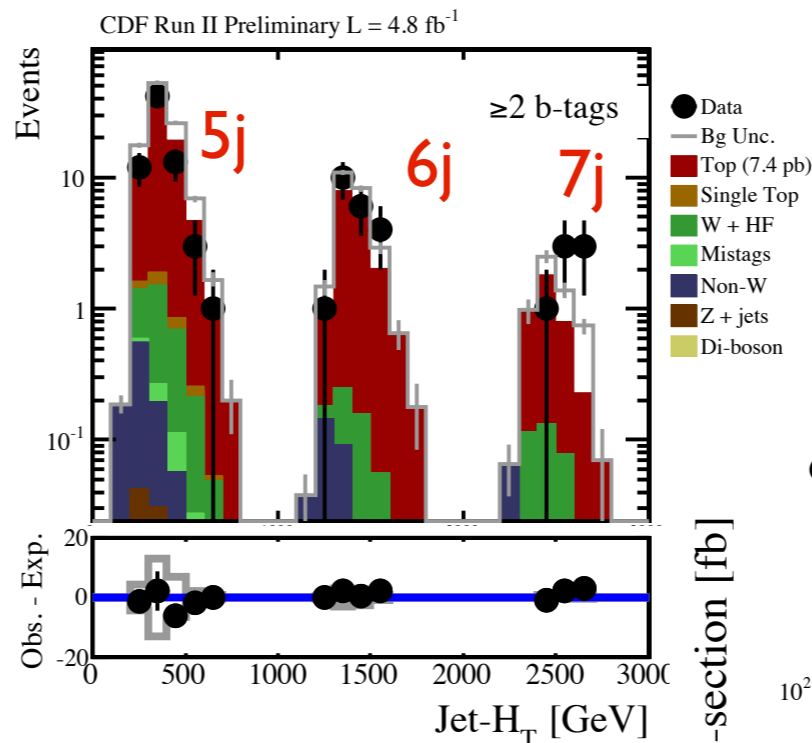
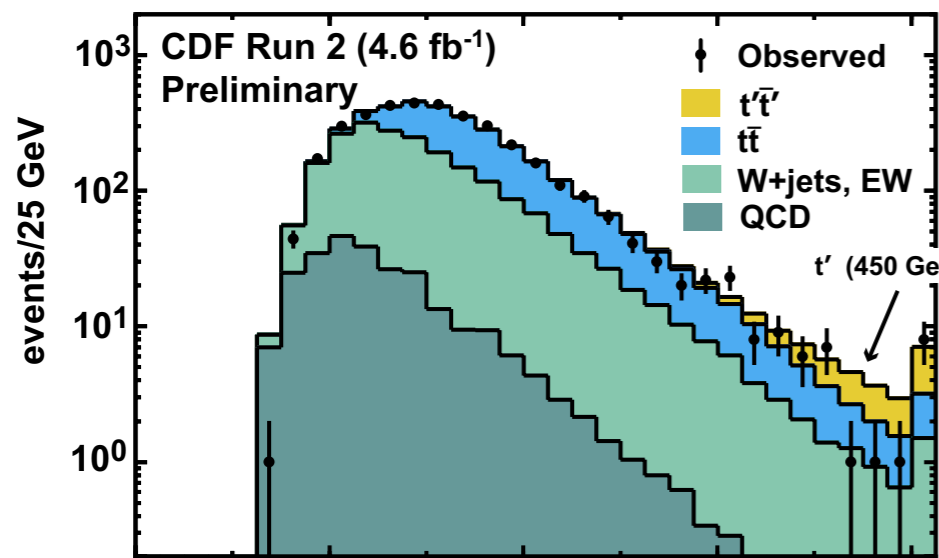
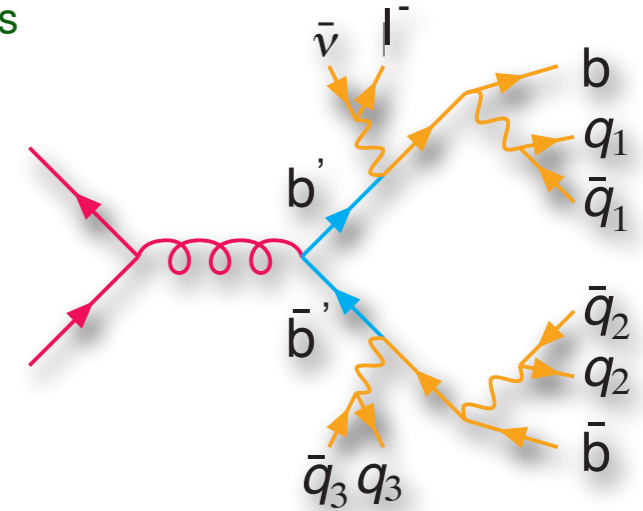
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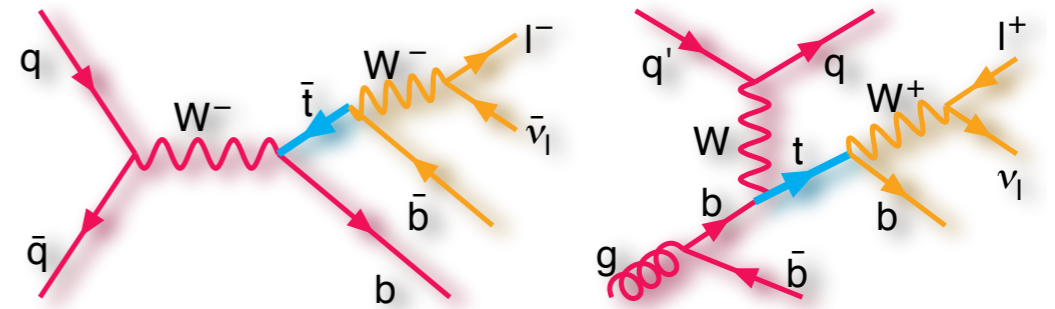


similar results by D0

Electroweak Single Top Quark Production

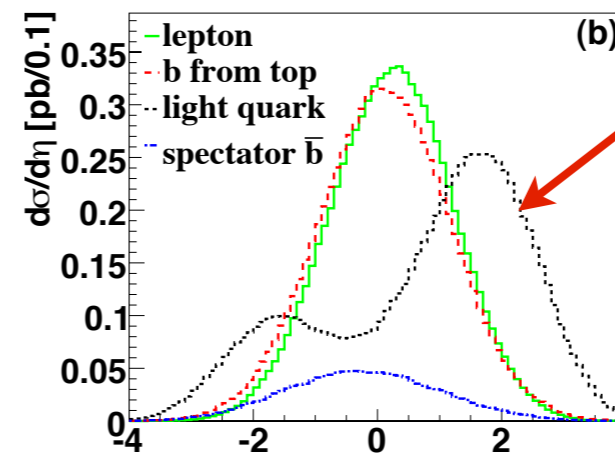
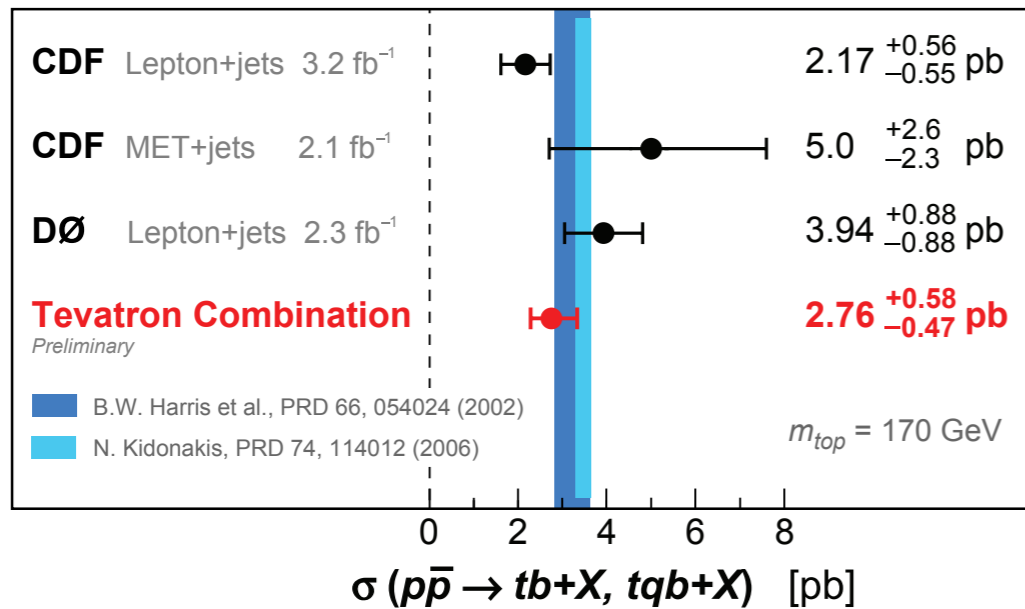
An experimental challenge by itself – and an important step on the road to one of the Tevatron’s prime Higgs channels

- full strength of multivariate analyses used for observation by both expts.



New: exploit also differences between s- and t-channel processes

Single Top Quark Cross Section August 2009



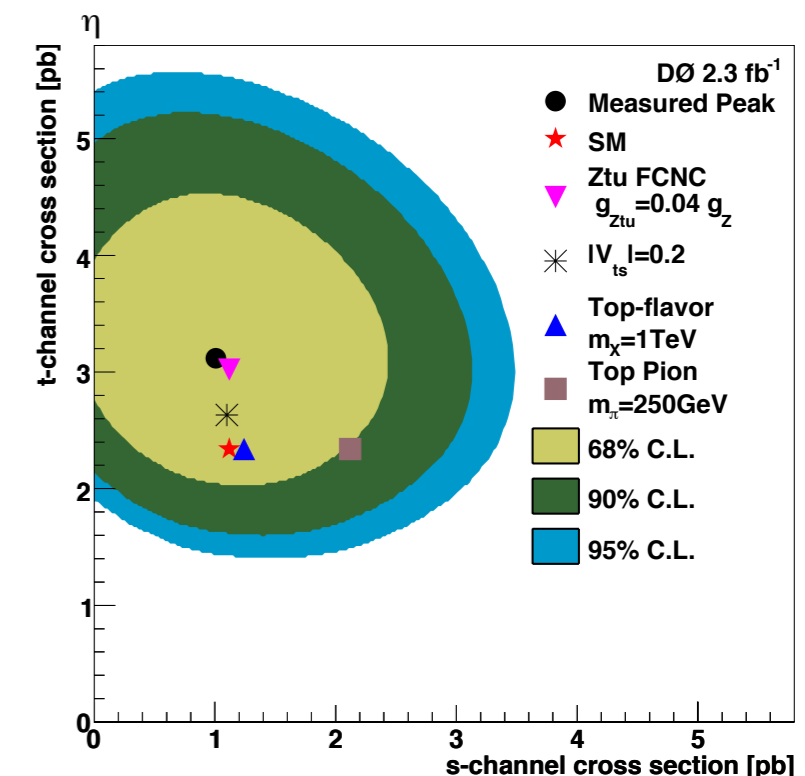
light-quark η distrib. in t-channel process

Both production cross sections are proportional to $|V_{tb}|^2$ → constrain

$$|V_{tb}| = 0.88 \pm 0.07 \quad (95\% \text{ CL})$$

(independent of 3-flavour unitarity used by more precise $B(t \rightarrow Wb)$ measurement)

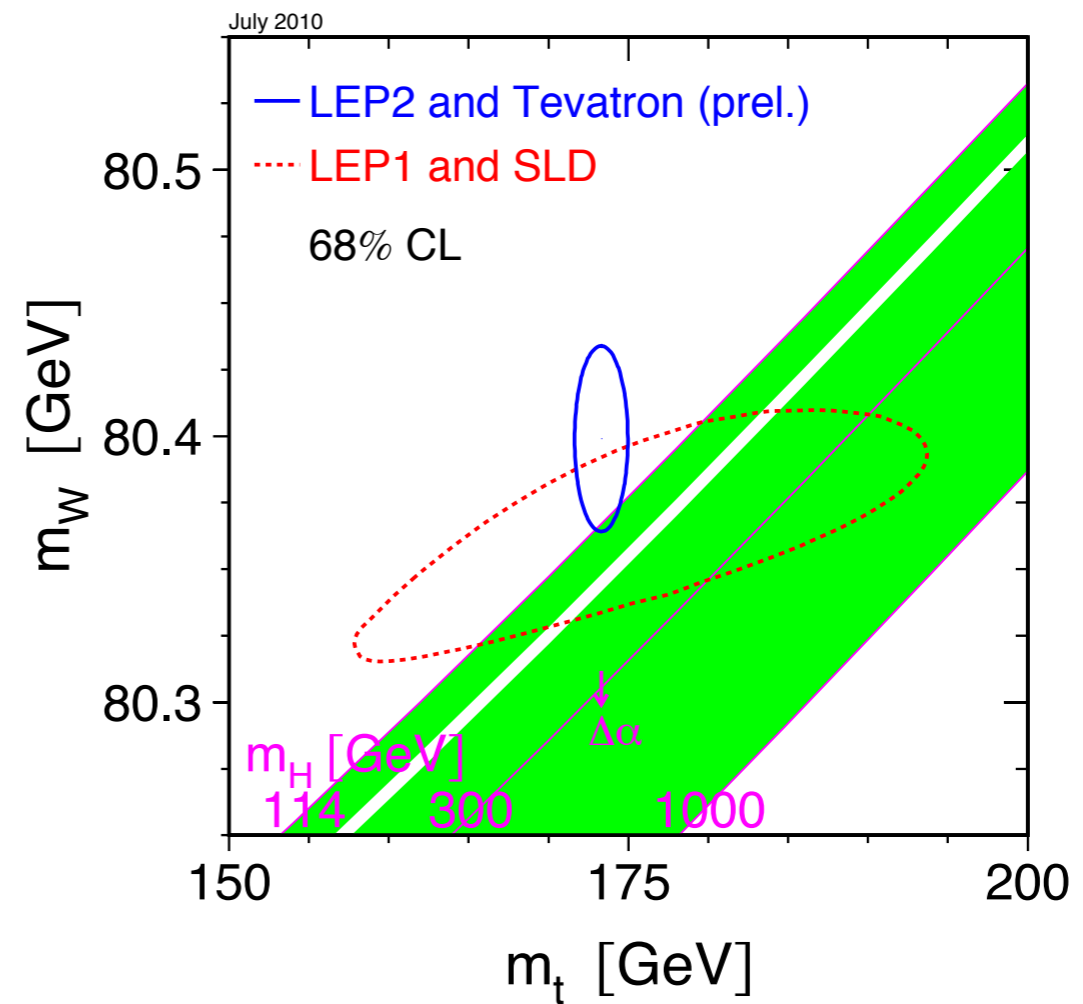
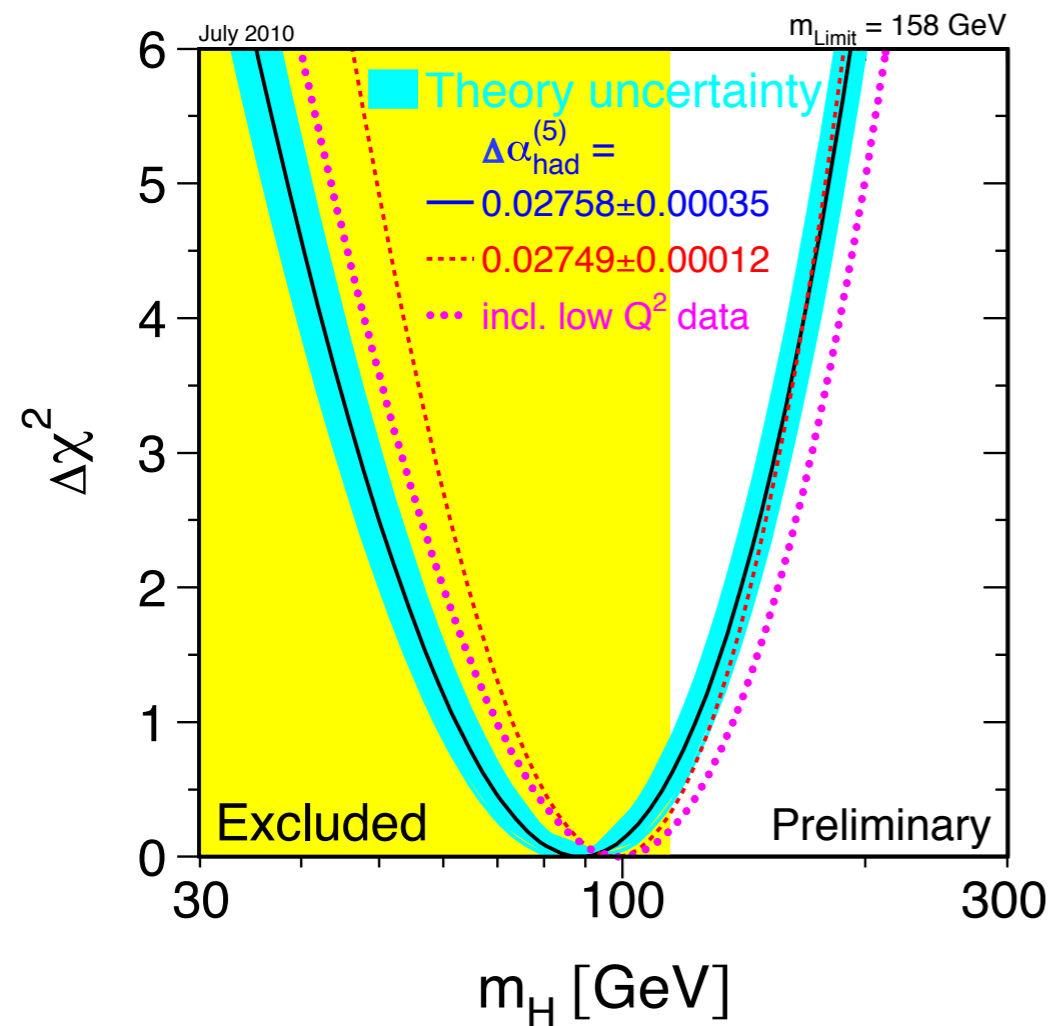
will be able to test new models with more statistics



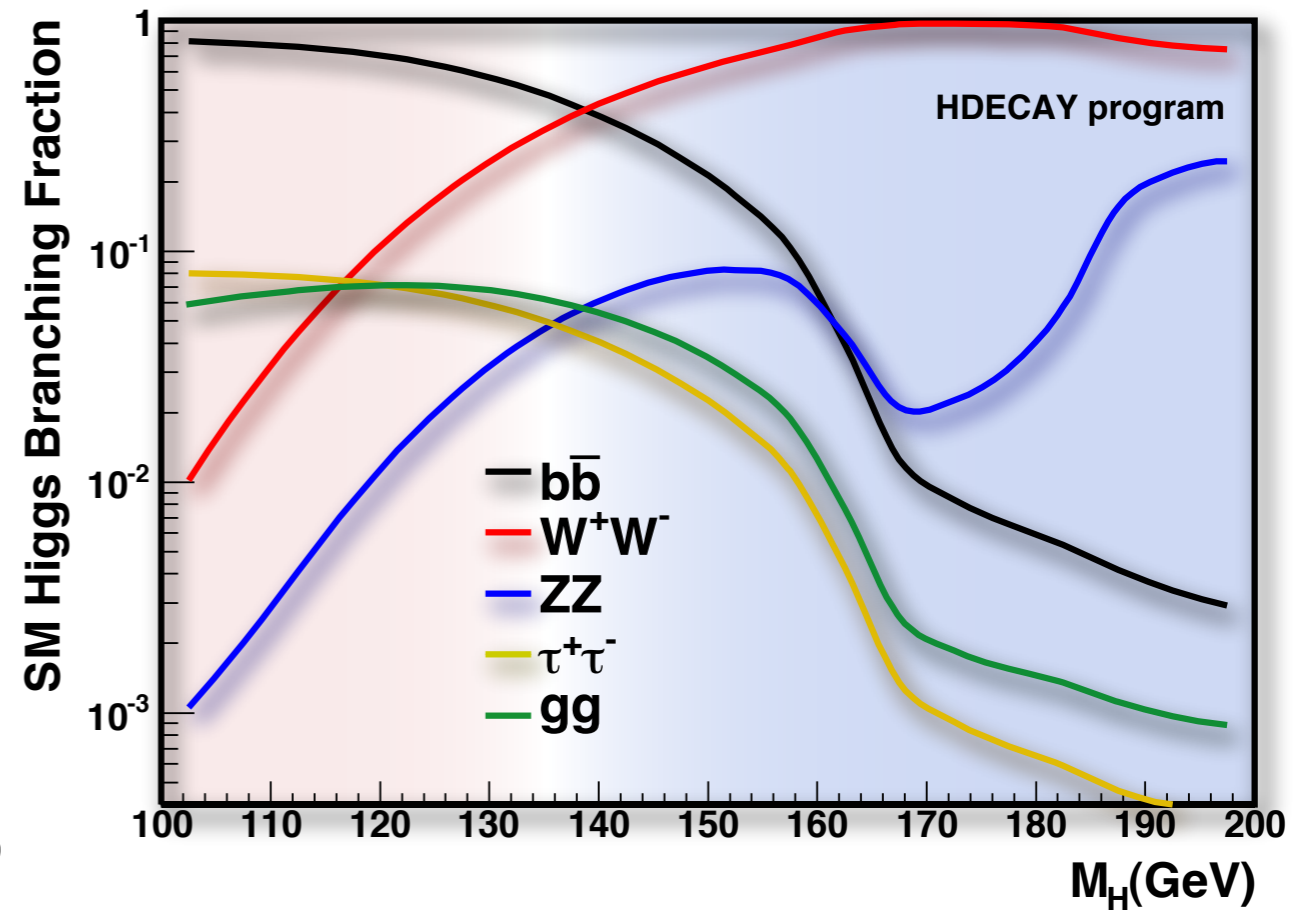
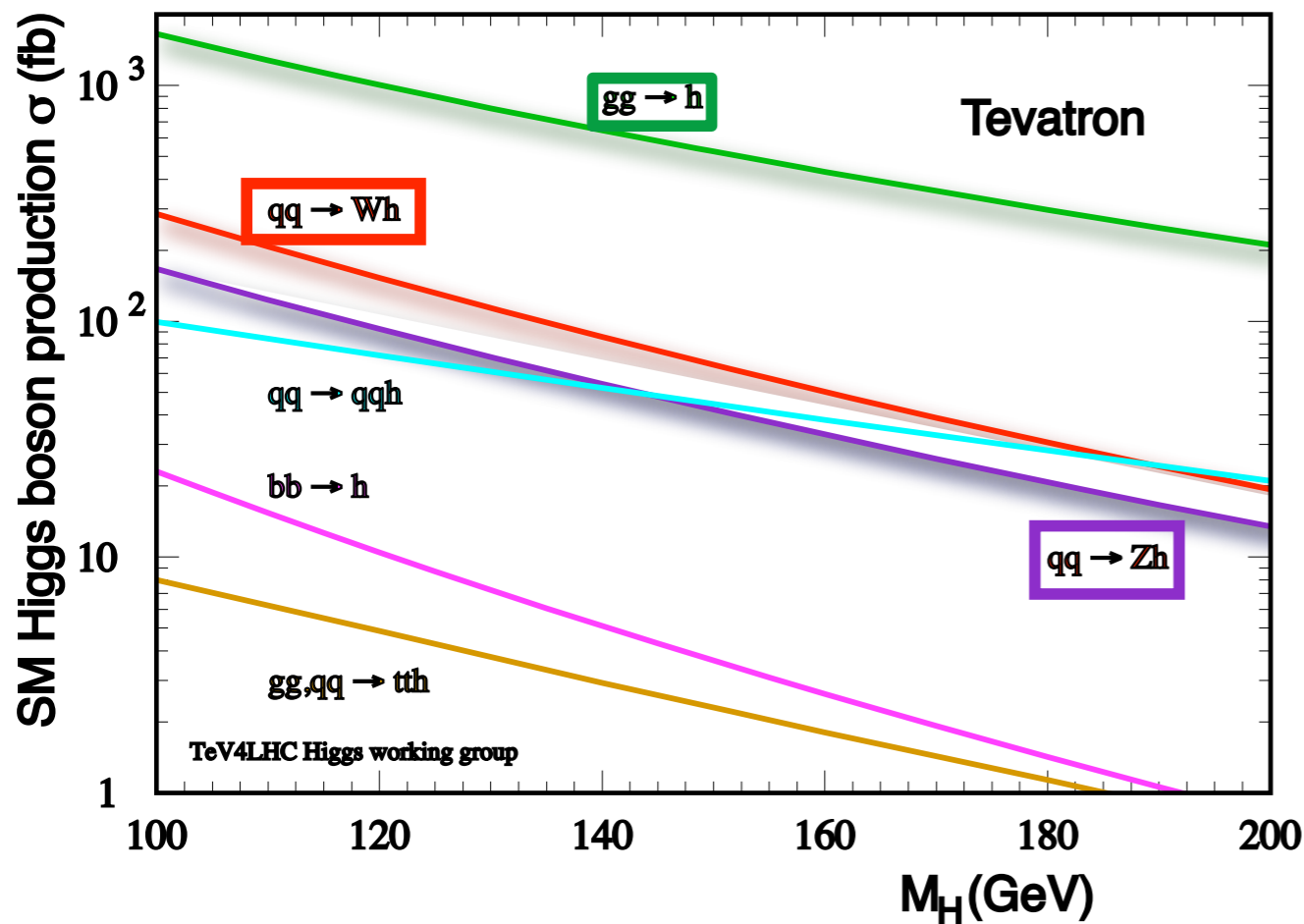
Higgs Boson Physics

Standard Model Higgs Boson Constraints

Constraints from electroweak measurements (dominated by the Tevatron's M_W and m_t measurements!) indicate a relatively light Higgs boson



Standard Model Higgs Boson Phenomenology



For $M_H > 135$ GeV, $H \rightarrow WW$ ($H \rightarrow ZZ$ difficult...) is the decay mode of choice

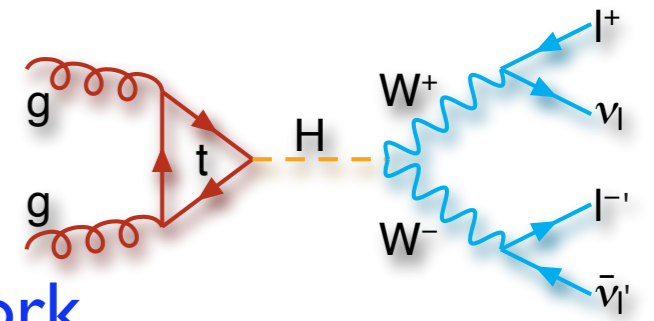
- like at the LHC

For $M_H < 135$ GeV: $H \rightarrow b\bar{b}$ hopeless if produced in isolation. Fortunately, in proton-antiproton collisions, antiquarks are readily available

- associated production: HW , HZ

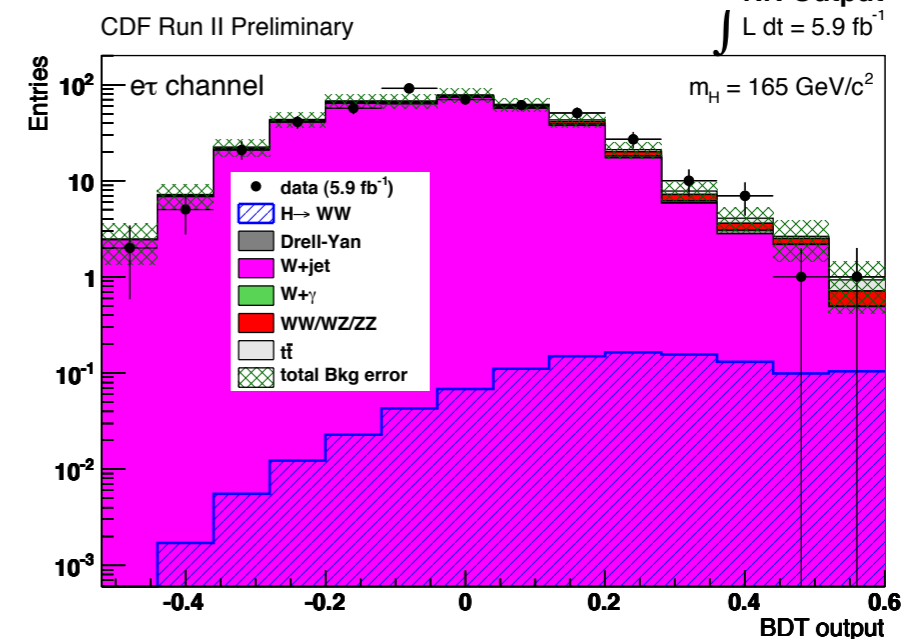
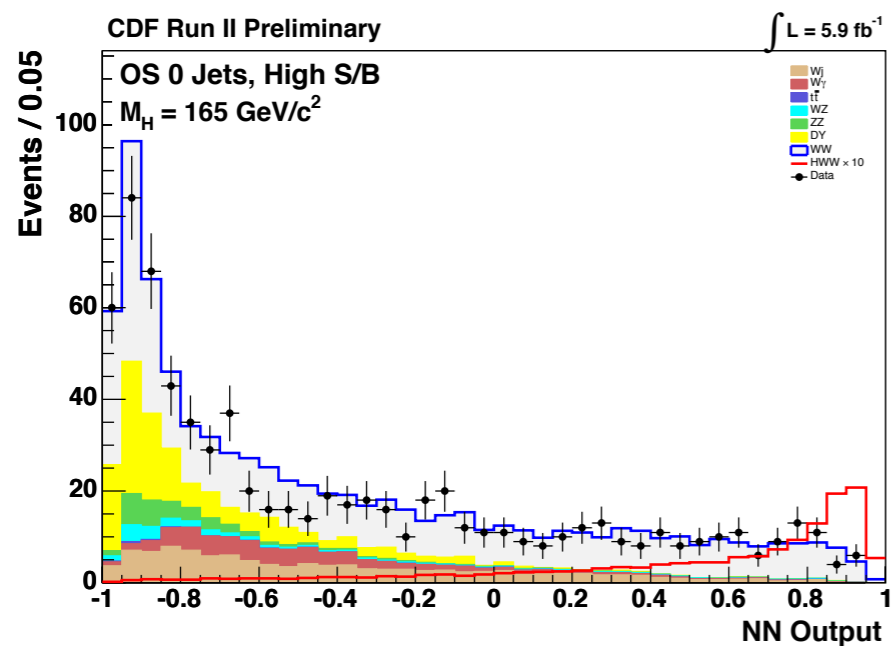
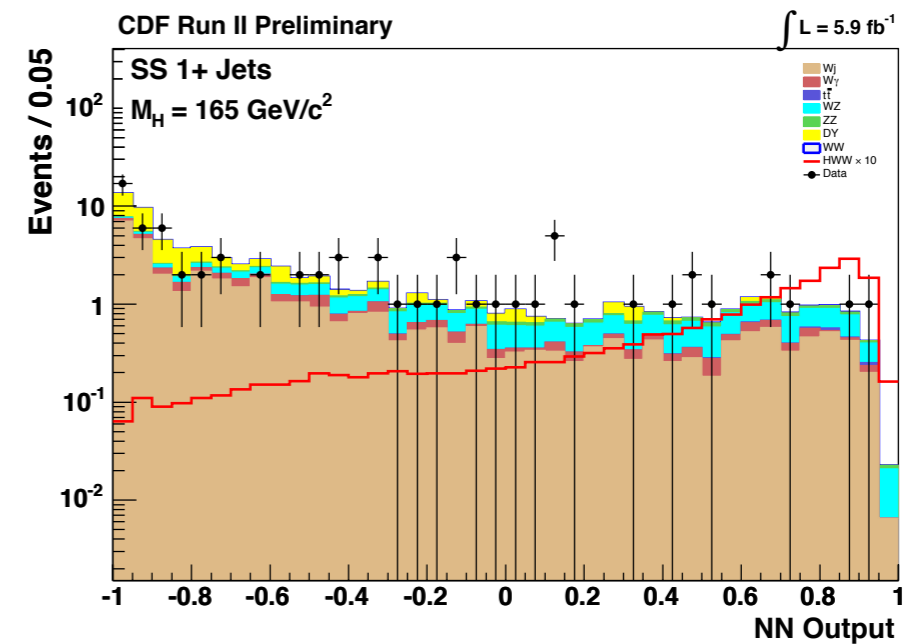
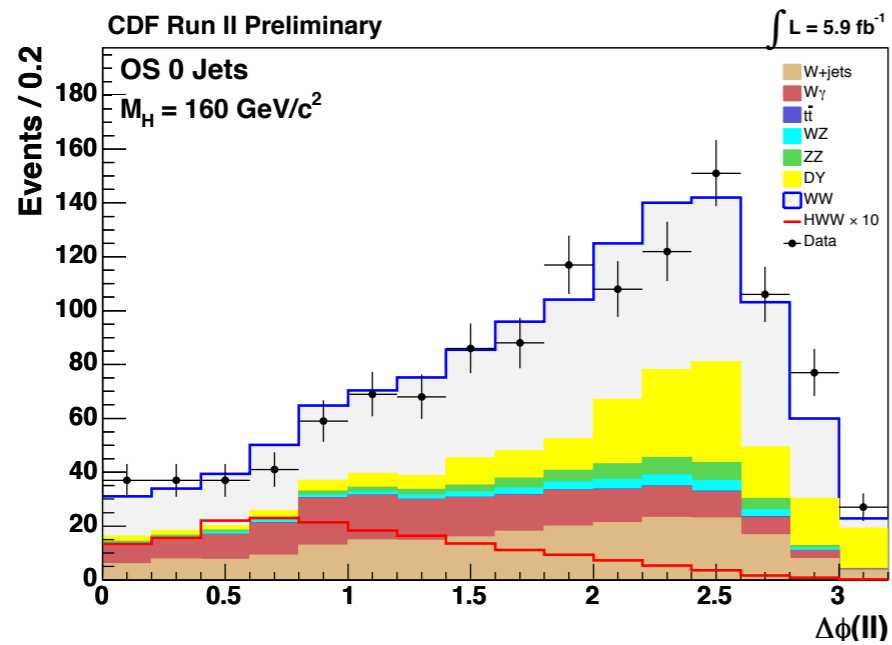
In the following, show merely 2 representative searches (~ 100 channels total!)

Example: High M_H



CDF $H \rightarrow WW$ analysis, 5.9 fb^{-1} : clean, but still needs hard work

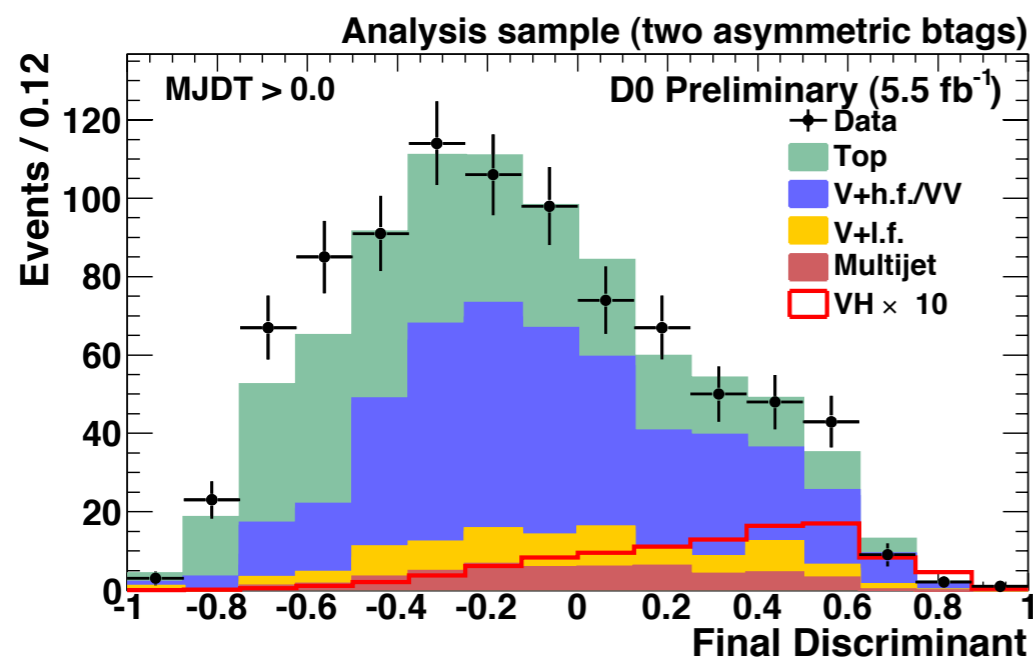
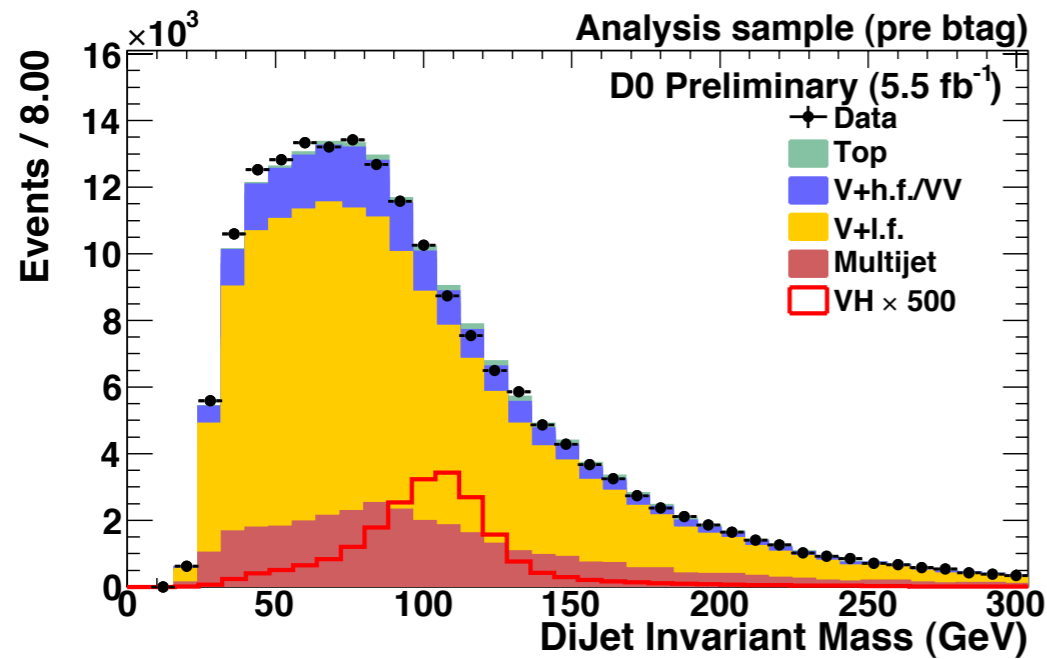
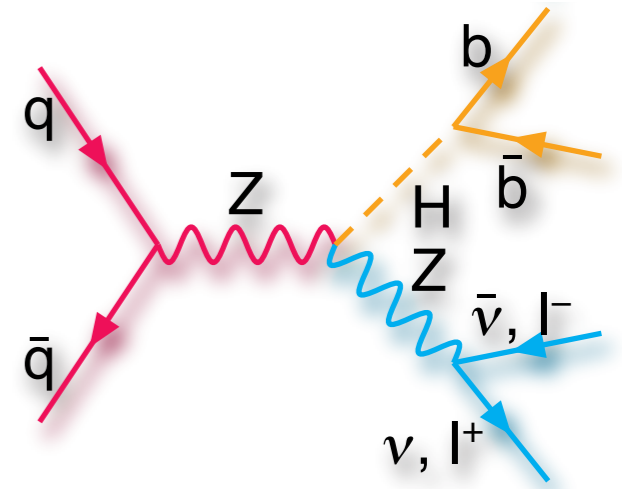
- DY rejection, spin correlations, NN/BDT using Matrix Element analyses
- include also WH (same-sign leptons), $WW \rightarrow l\tau\nu\nu$



Example: Low M_H

D0 $ZH \rightarrow \nu\nu b\bar{b}$ analysis (6.4 fb^{-1}): no charged leptons!

- need exquisite understanding of instrumental backgrounds
- use multivariate analyses, b-tagging



But this hard work pay off! This channel is now even more performant than the $WH \rightarrow l\nu$ one

- CDF/D0 performance generally very similar

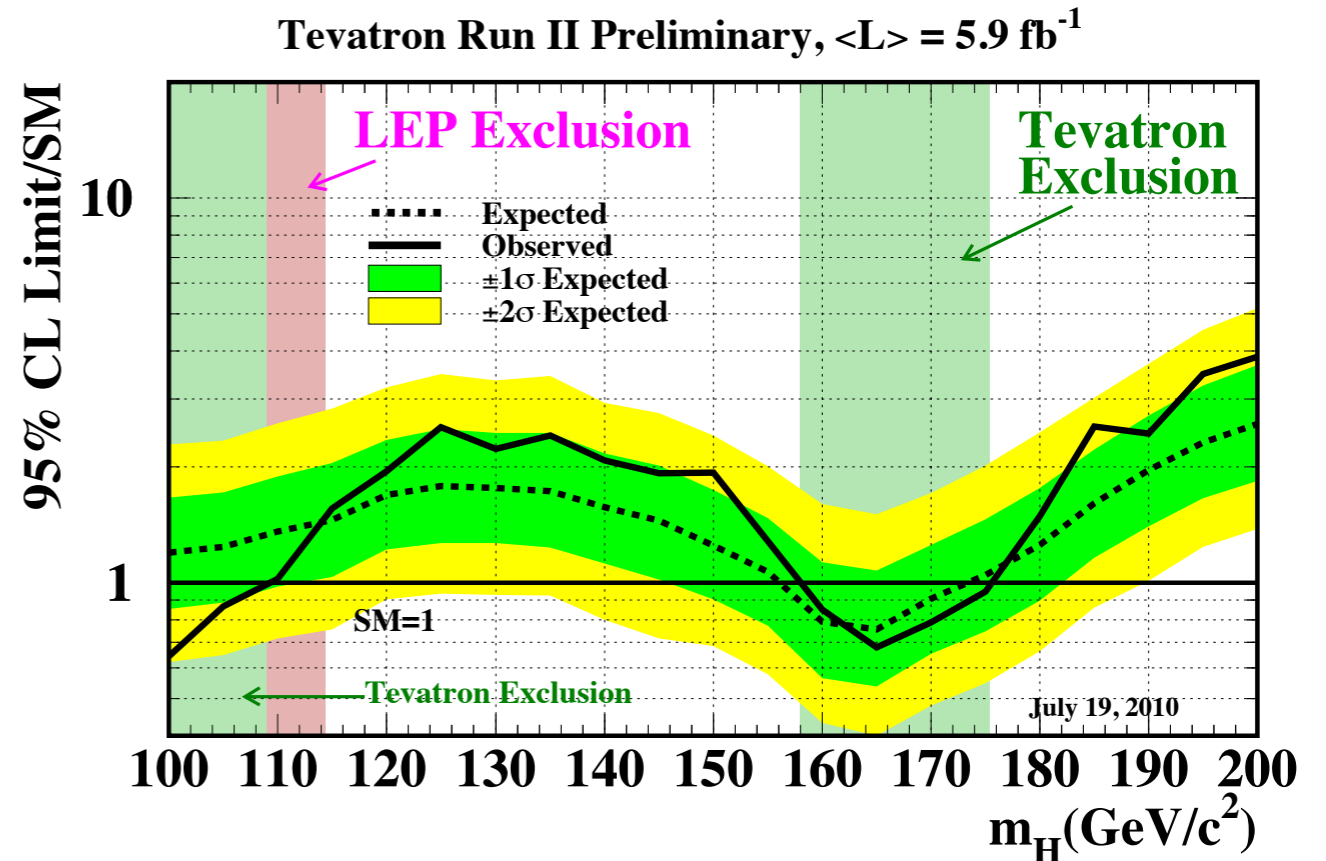
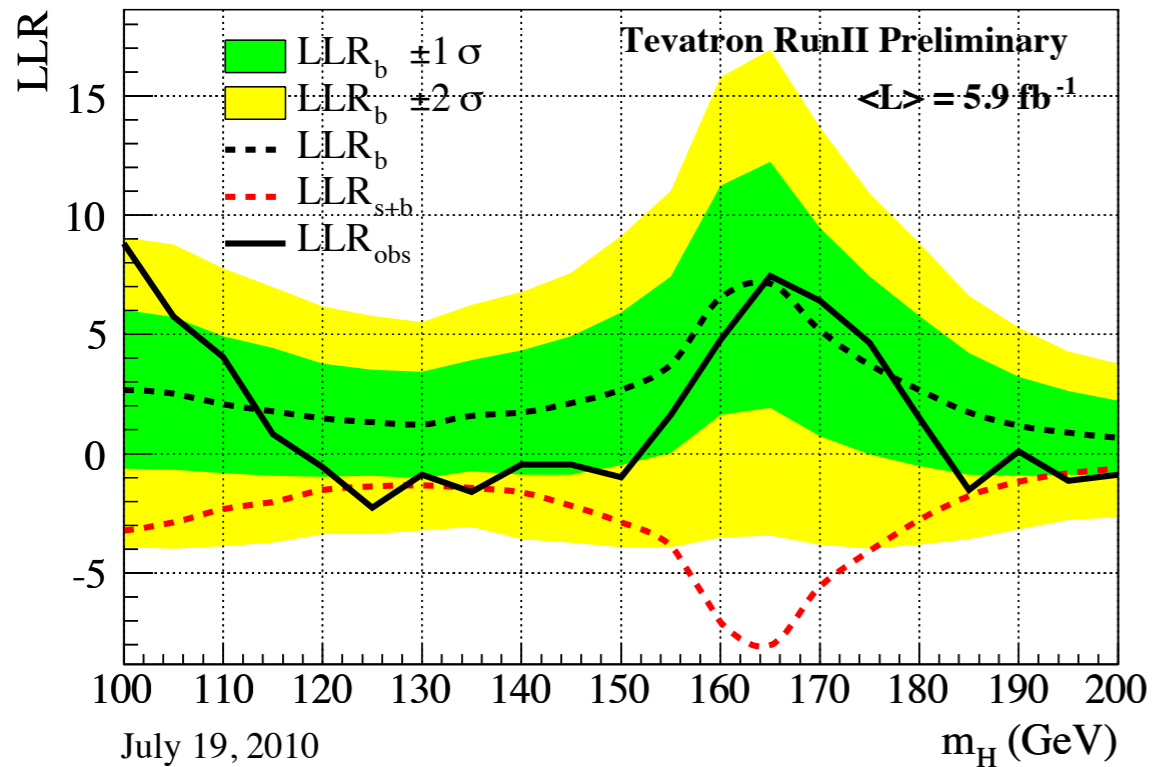
General strategy: combine all channels, including less performant ones

- WH (high M_H)
- $ZH \rightarrow ll b\bar{b}, WH \rightarrow \tau\nu$ (low M_H)

Combined Results

In the (unfortunate!) absence of an excess, set ever tighter limits

(NB: not yet using all latest results)

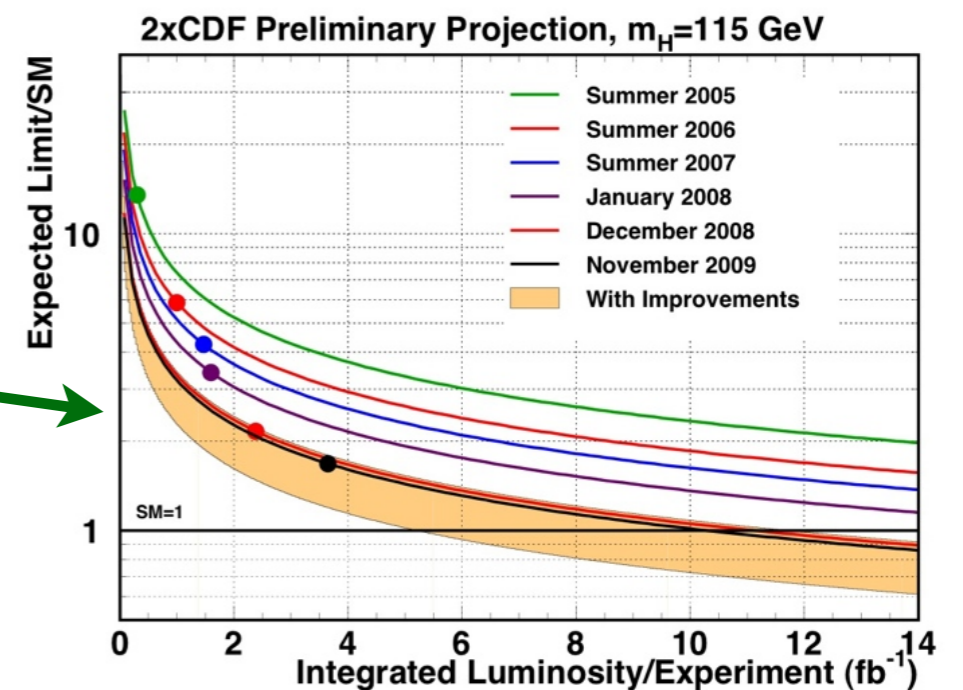


There are still envisaged improvements

- e.g. b-tagging, dijet mass resolution (and our track record is good...)

The case for an extended Tevatron run!

- recommended by P5, awaiting \$\$

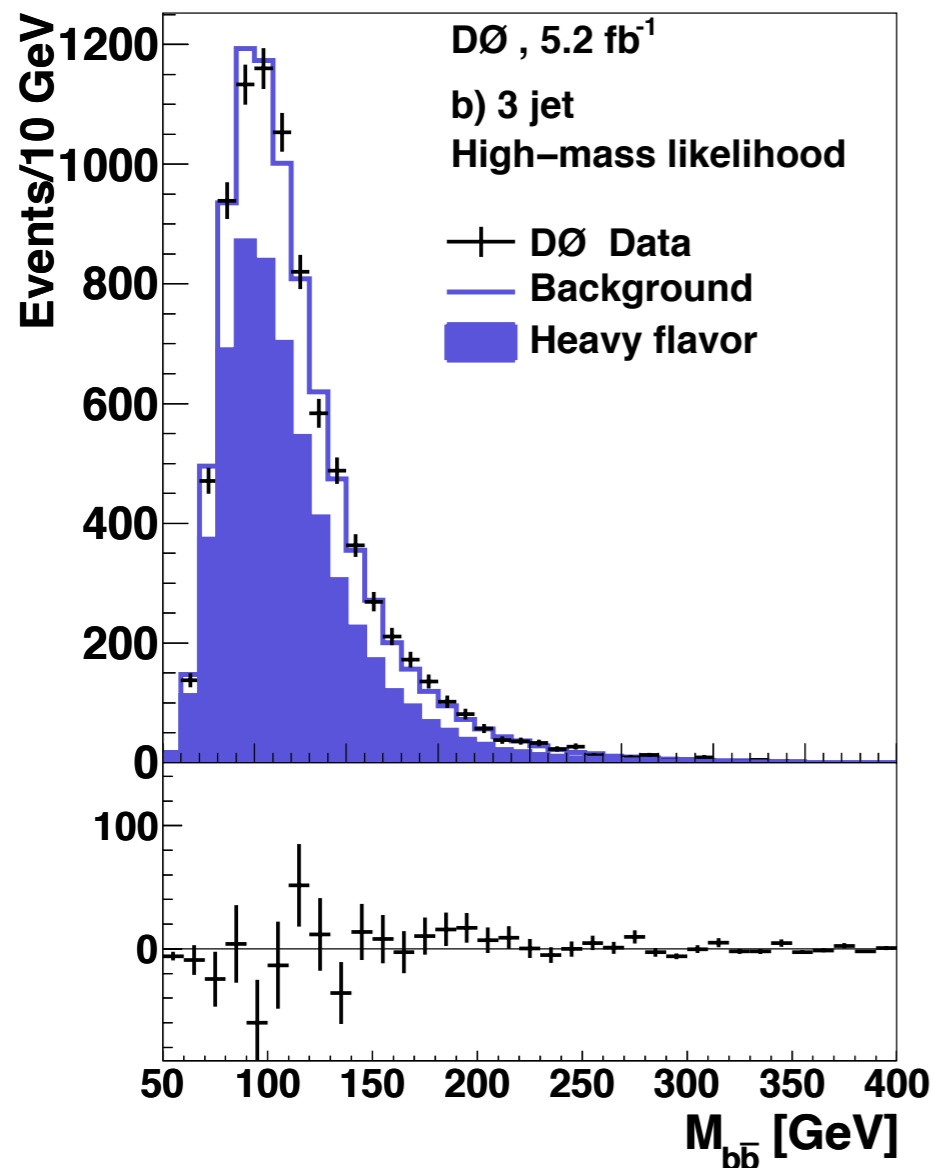


Neutral MSSM Higgs Bosons

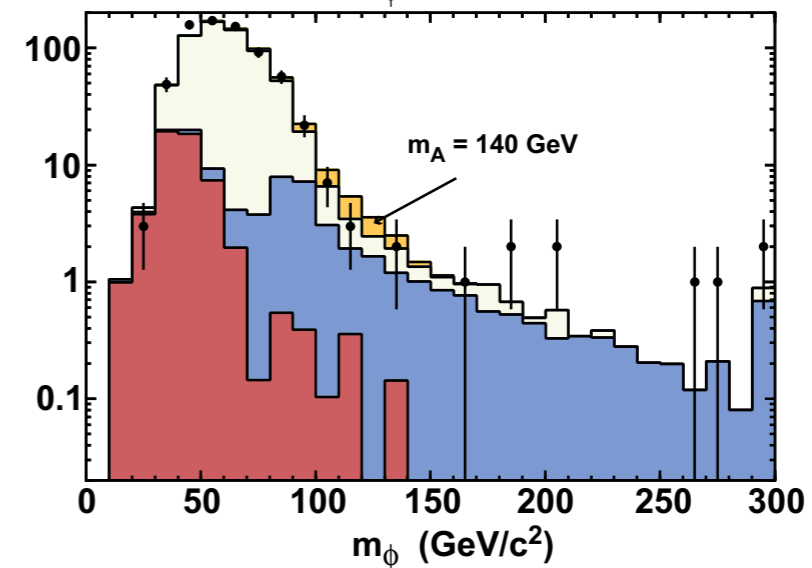
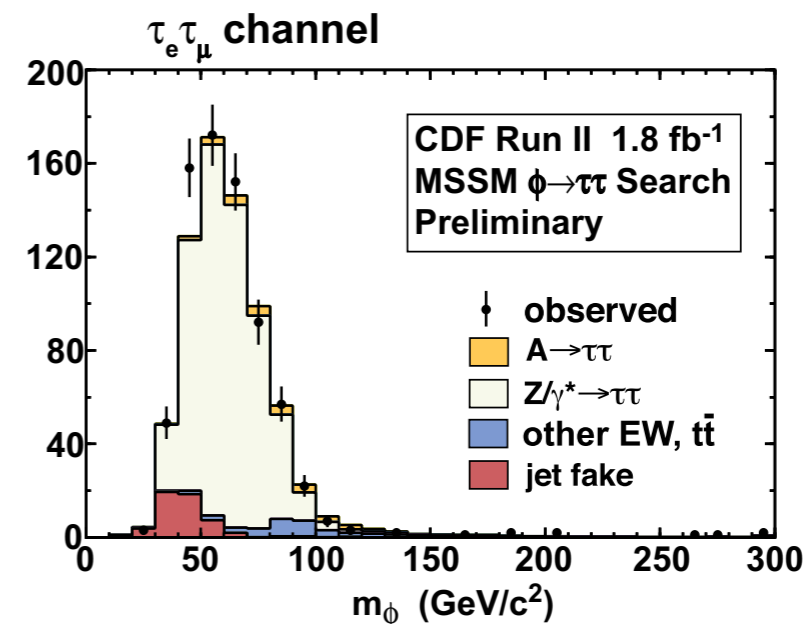
MSSM Higgs sector described by two parameters: M_A , $\tan\beta$ (radiative corr. aside)

Exploit increased coupling to b-quarks & τ leptons at high $\tan\beta$, near degeneracy between A and H/h (“ ϕ ”)

$\phi \rightarrow b\bar{b}$: in association with b-jet



$\phi \rightarrow \tau\tau$: both with/without addl. b-jet



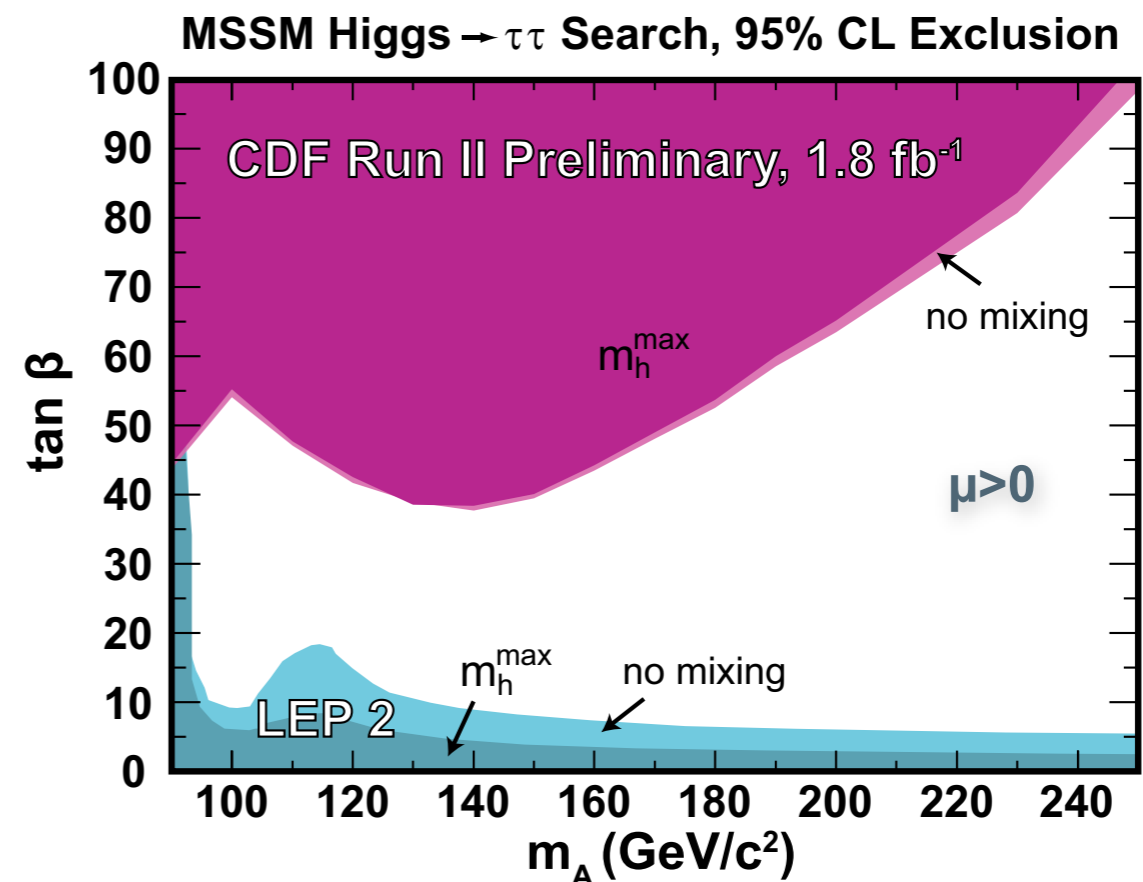
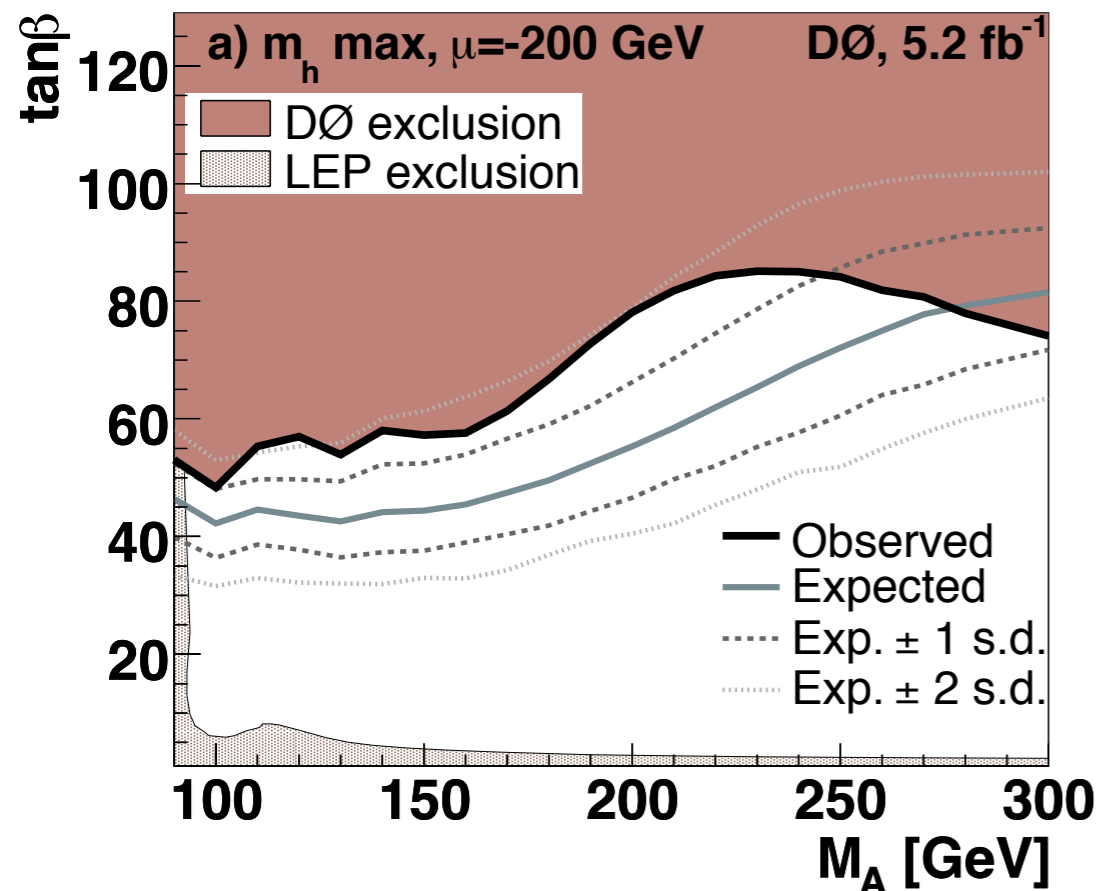
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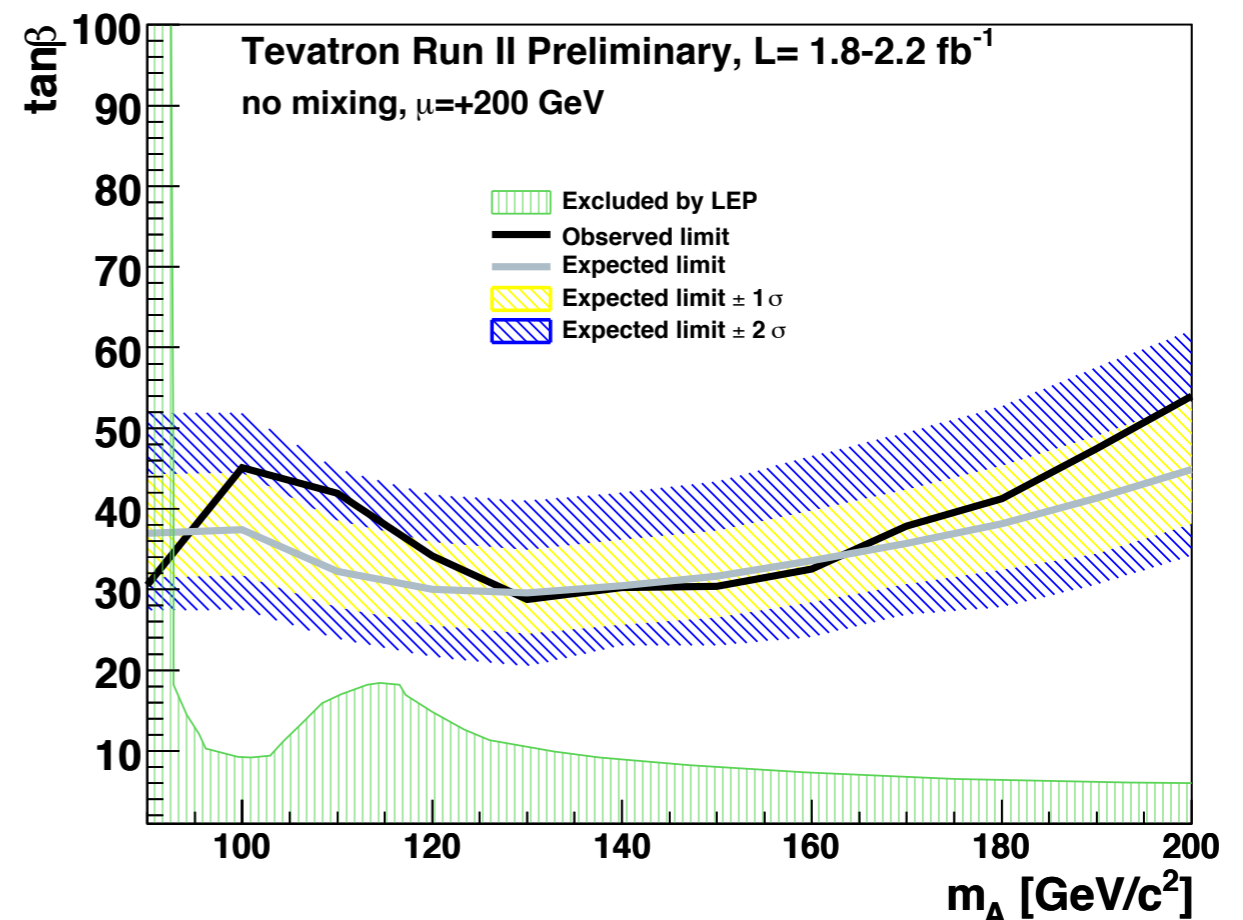
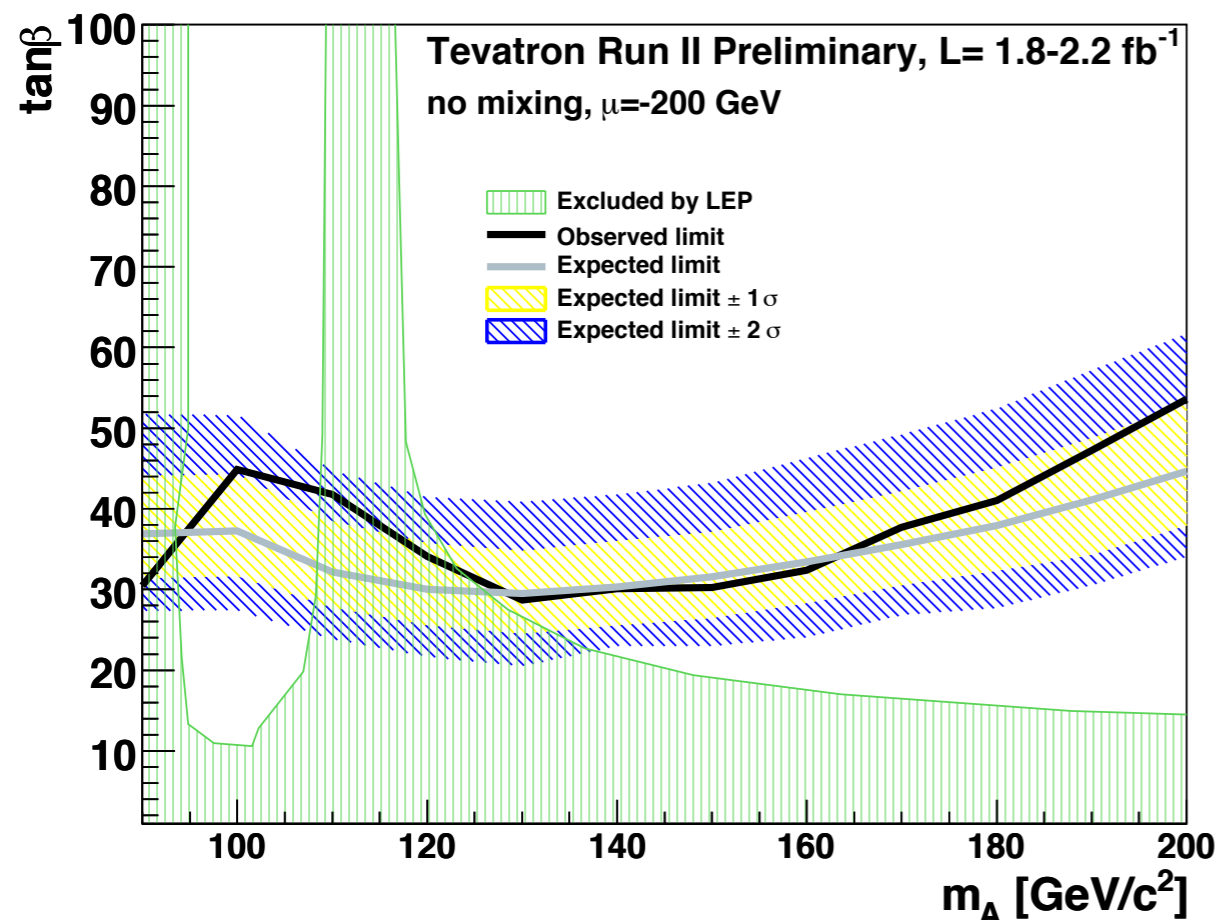
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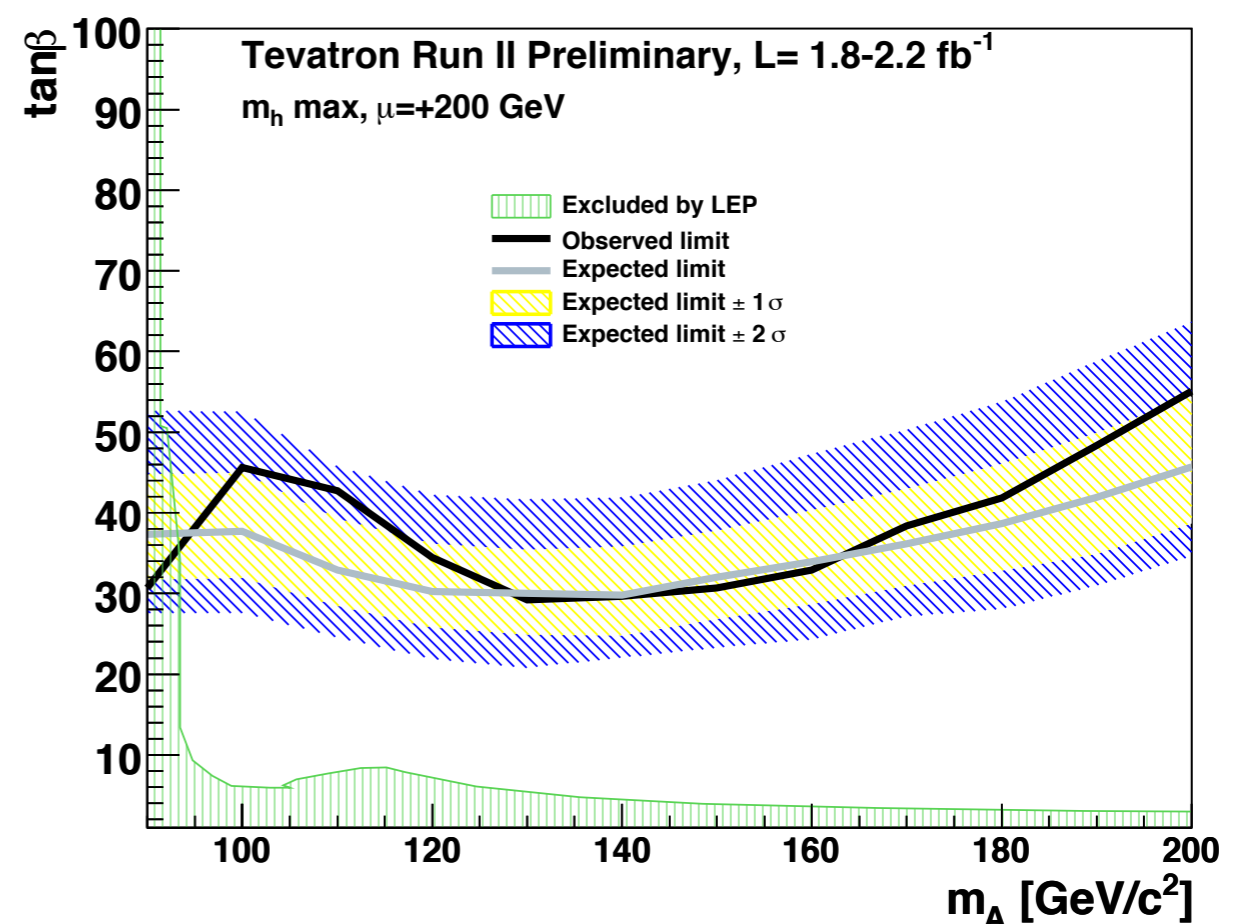
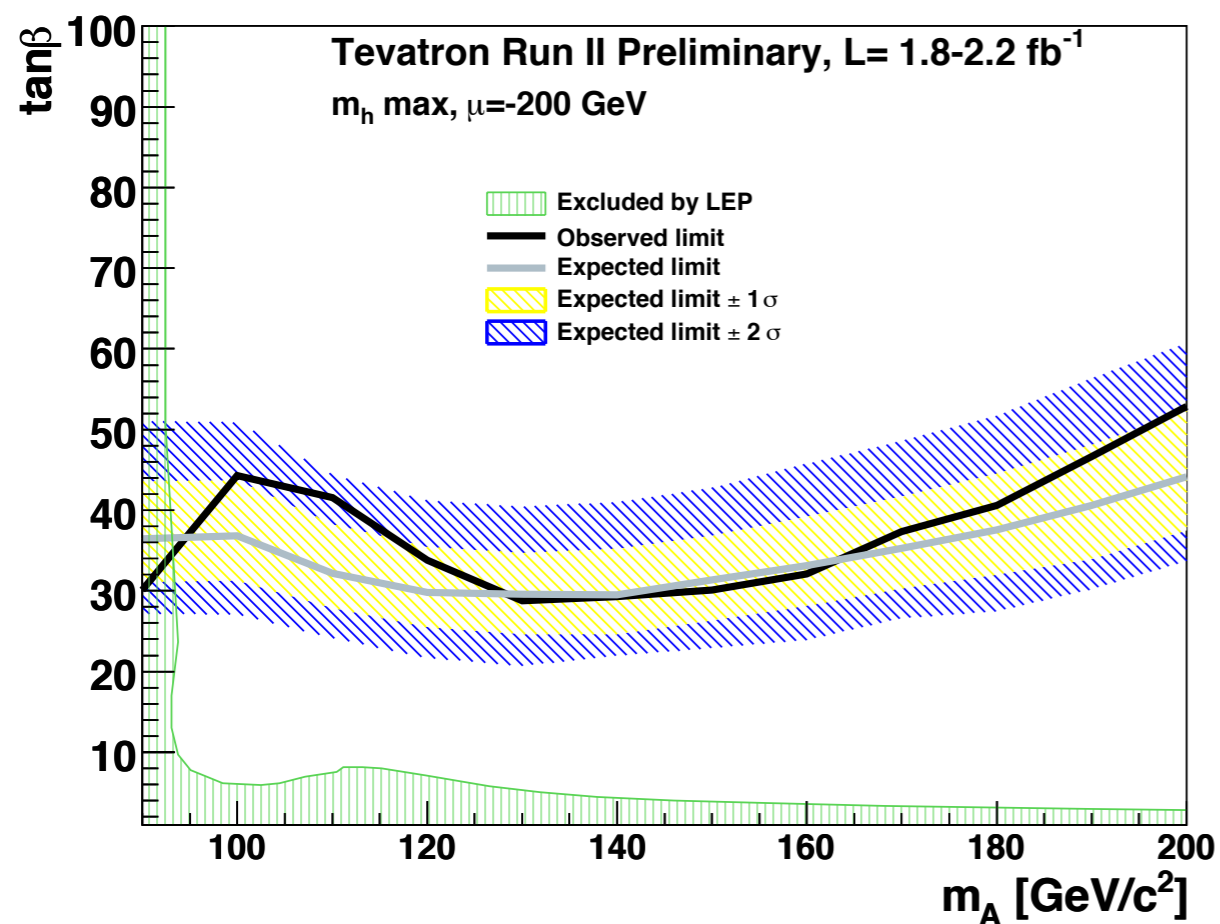
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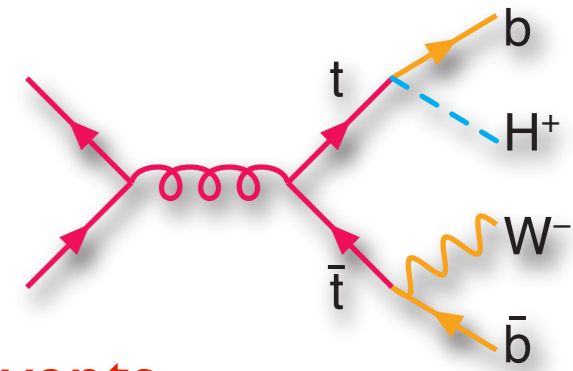
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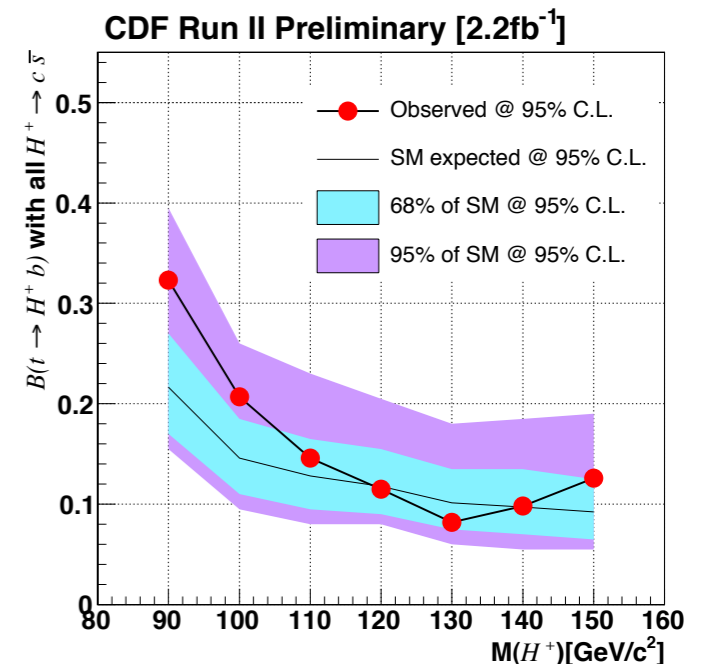
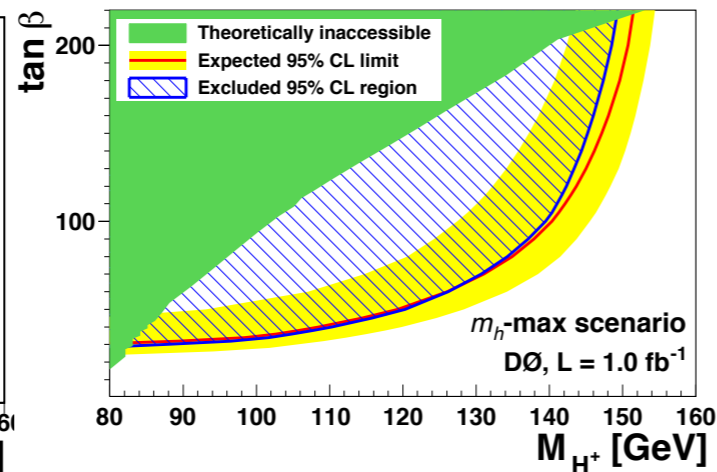
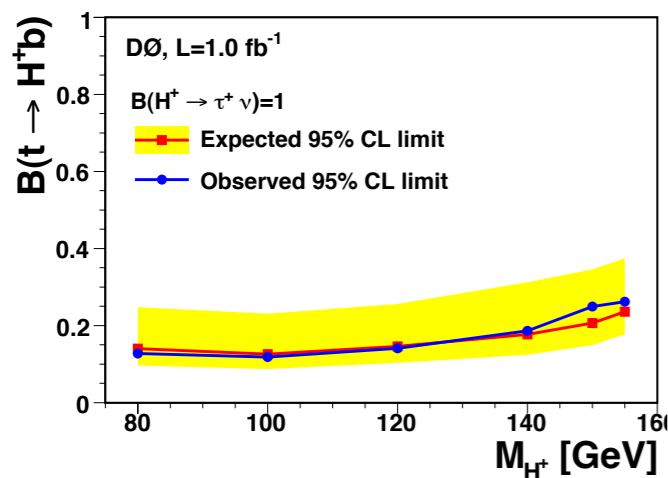
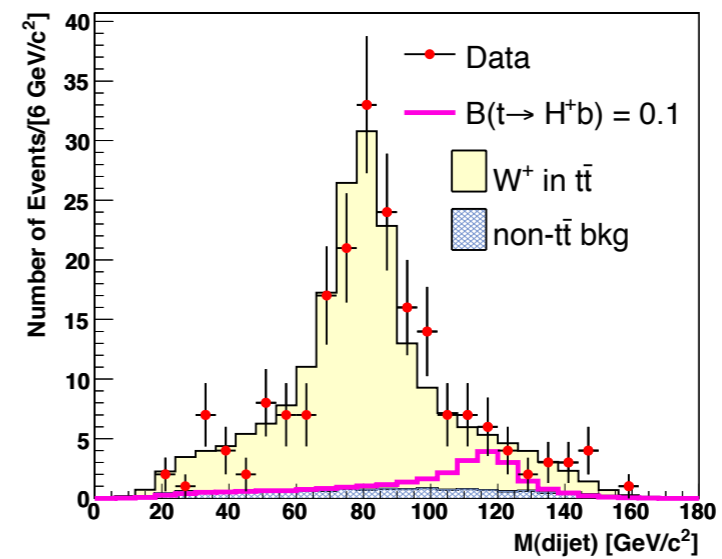
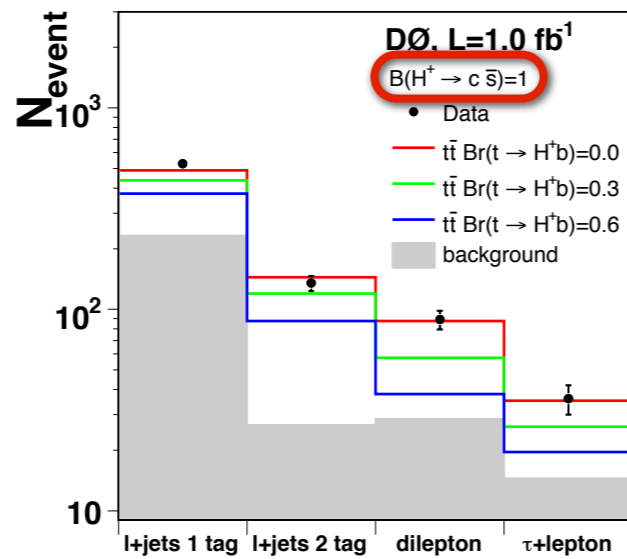
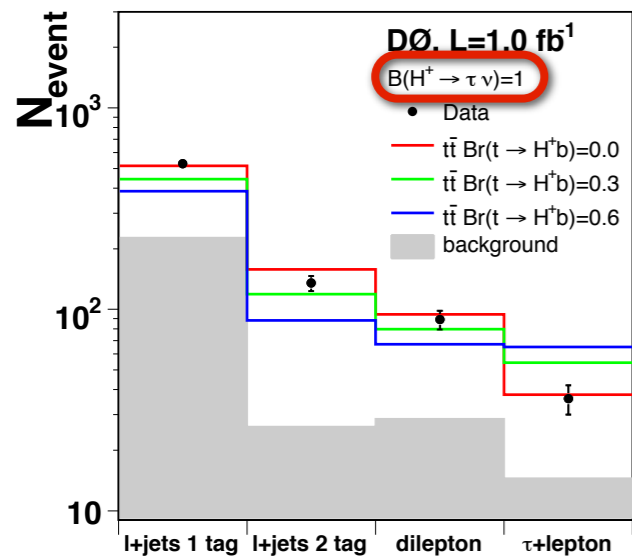
Charged MSSM Higgs Bosons



Focus on $t \rightarrow H^+ b$ decays (heavy $H \rightarrow tb$ out of Tevatron reach):
exploited in multiple ways to search for $H \rightarrow \tau\nu, cs$ decays in $t\bar{t}$ events

modified distribution of $t\bar{t}$ events
over $l+jets$, $l+l$, and $l+\tau_{had}$ FS

peak in $l+jets$ di-jet invariant
mass spectrum ($H \rightarrow cs$)



Conclusion & Outlook

The Tevatron has been the discovery machine we all hoped it to be

- the one missing discovery is the Higgs boson...

It will remain competitive in many areas

- if an extension of the current run happens

May the LHC be equally successful in its physics endeavours!

No time to discuss...

B physics:

- $D\bar{D}$ mixing, CP violation in $D^0 \rightarrow K\pi$
- Observation & study of $X(3872)$
- Observation of $\Omega_b, \Xi_b, \Sigma_b$

Electroweak physics:

- $W\gamma, Z\gamma$ production
- p_T of W and Z bosons
- $\sigma(Z+b)/\sigma(Z+jet)$

Top quark physics:

- $\sigma(tt), p_T(tt)$
- W helicity

Higgs physics:

- fourth-generation fermion effect on Higgs boson production
- CP violating scenarios
- NMSSM (neutral/charged) Higgs bosons
- Fermiophobic Higgs bosons
- $H^{\pm\pm}$