Challenging the Standard Model at the Tevatron Collider

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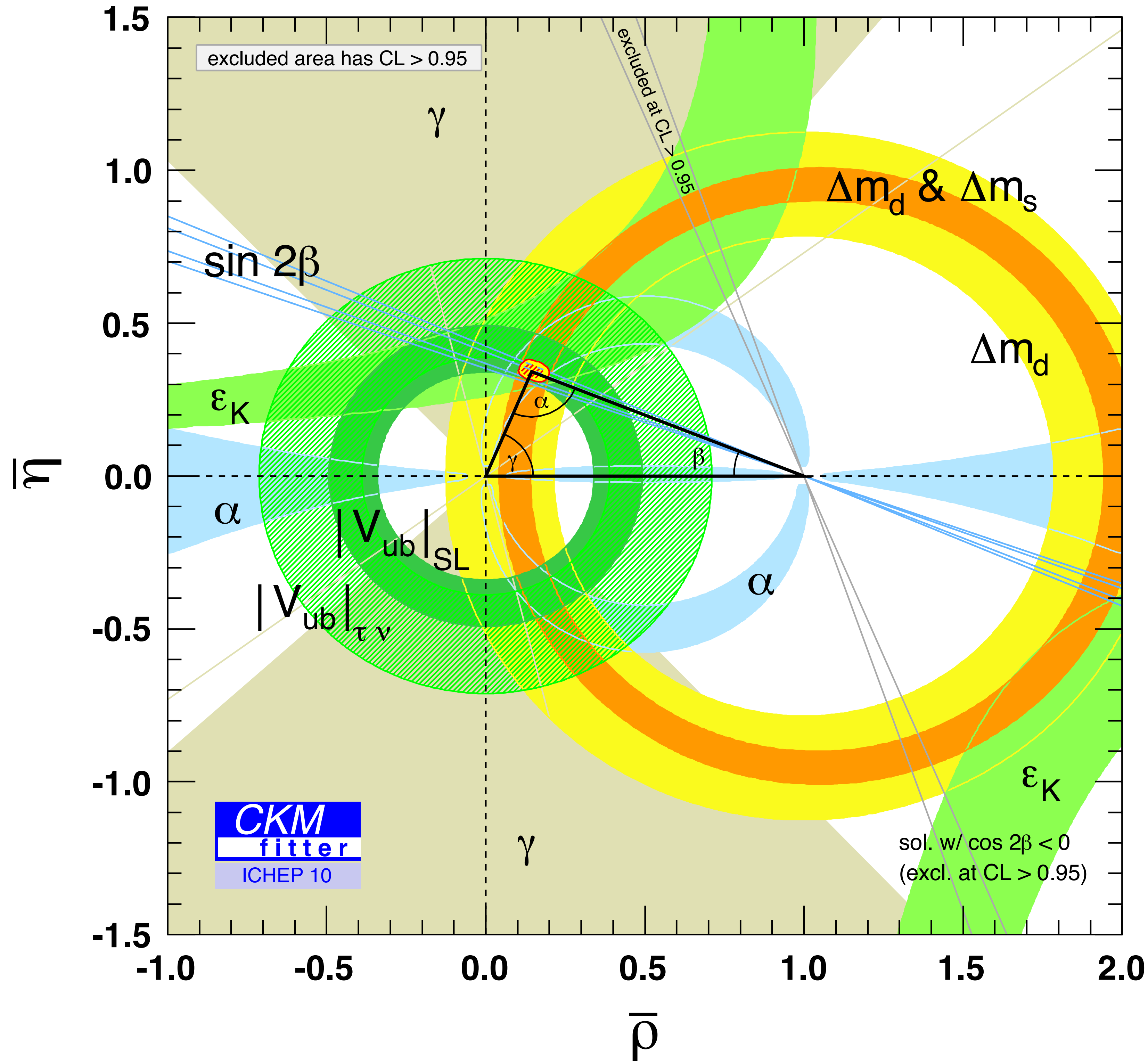
for the D0 and CDF Collaborations

Kruger 2010 Workshop, December 5-10, 2010

B Physics

CP Violation in the B_s System

This is not the only unitarity triangle!



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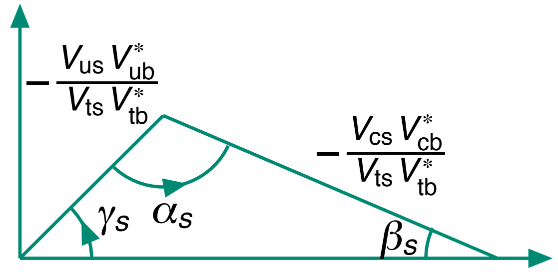
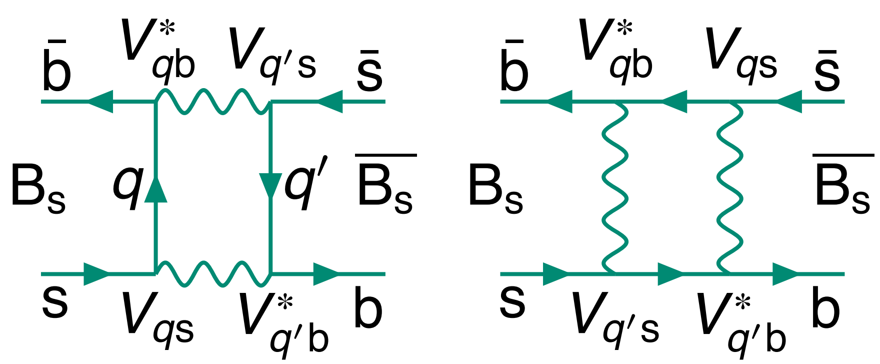
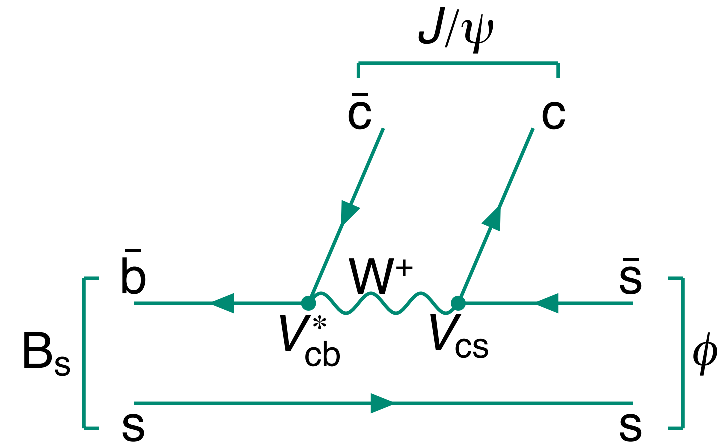


The B_s system is (largely) the domain of hadron colliders. Exploit by combining mixing and decays to CP eigenstates in $b \to ccs$ transitions:





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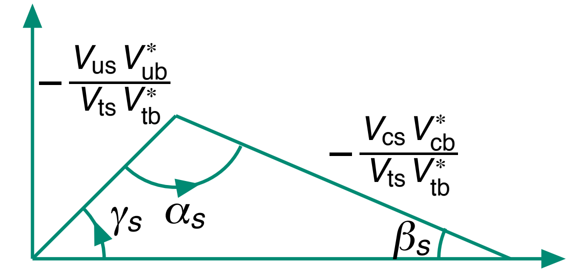

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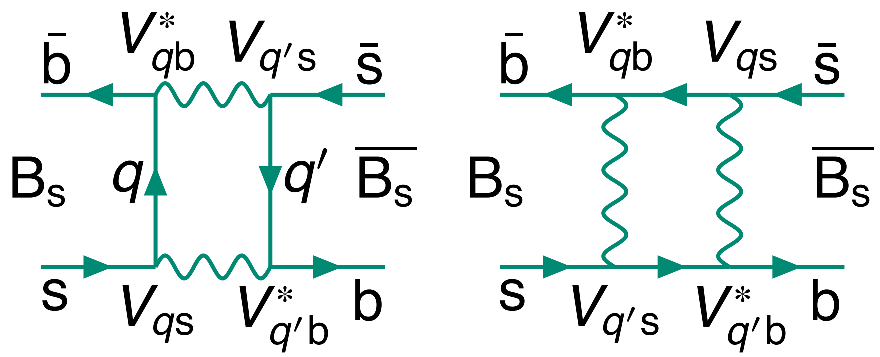
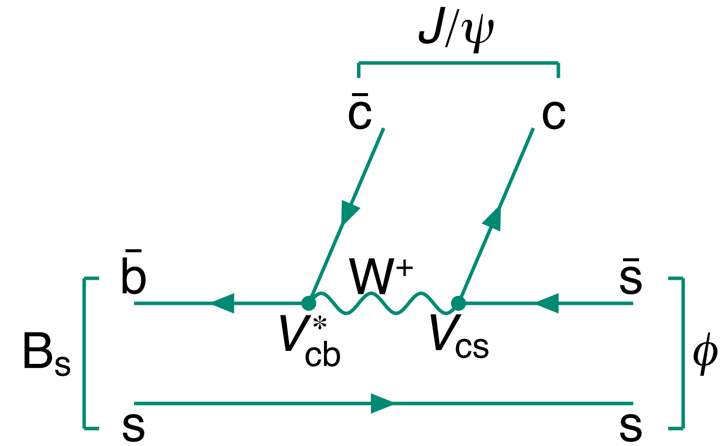
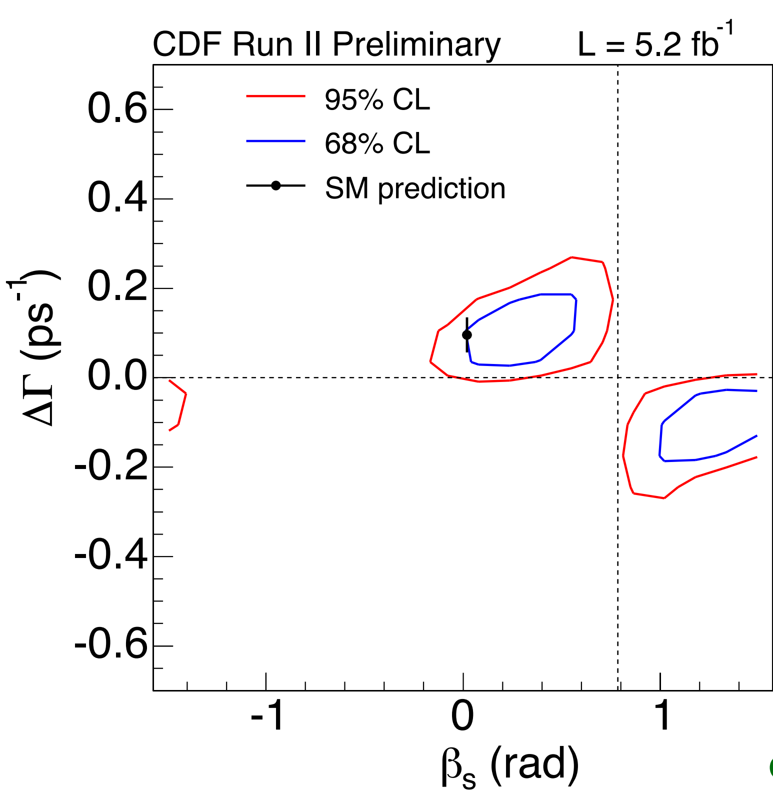


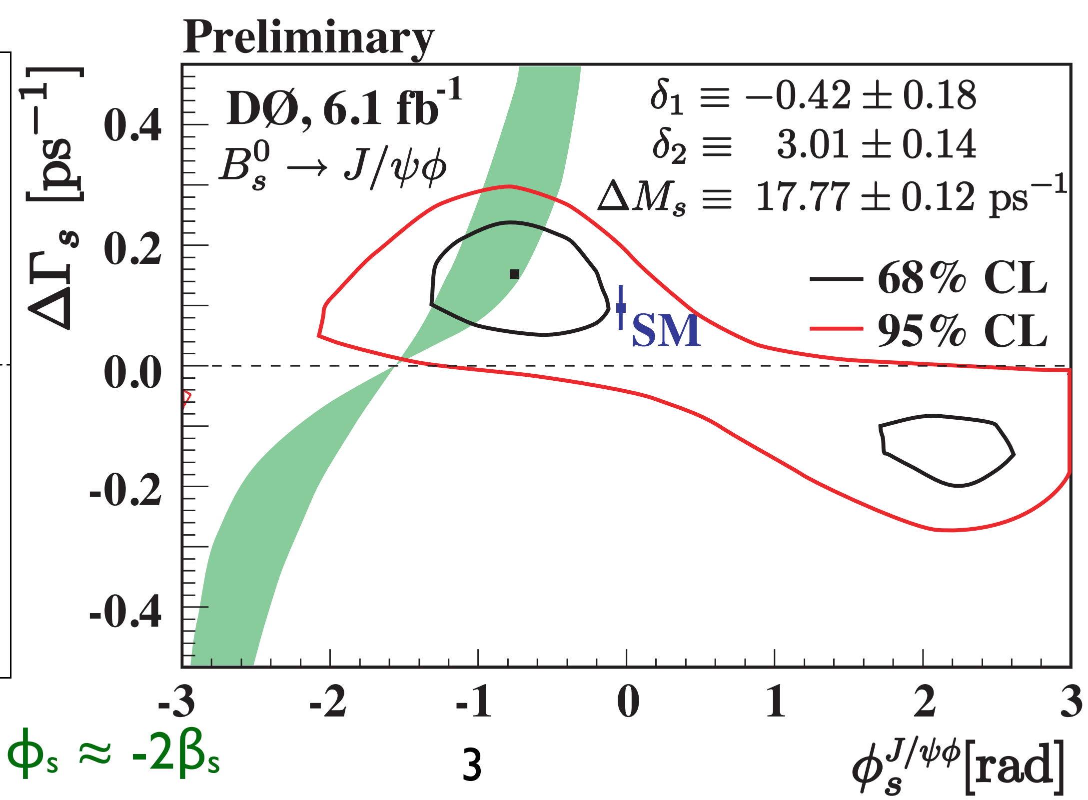


CDF and D0 have analyzed the $\mu^+\mu^-K^+K^-$ final state using 5-6 fb^{-1} of data

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



$\phi_s \approx -2\beta_s$



Tantalizing hints for non-SM β_s (2.8 fb^{-1}) have disappeared...

A new combination would be welcome

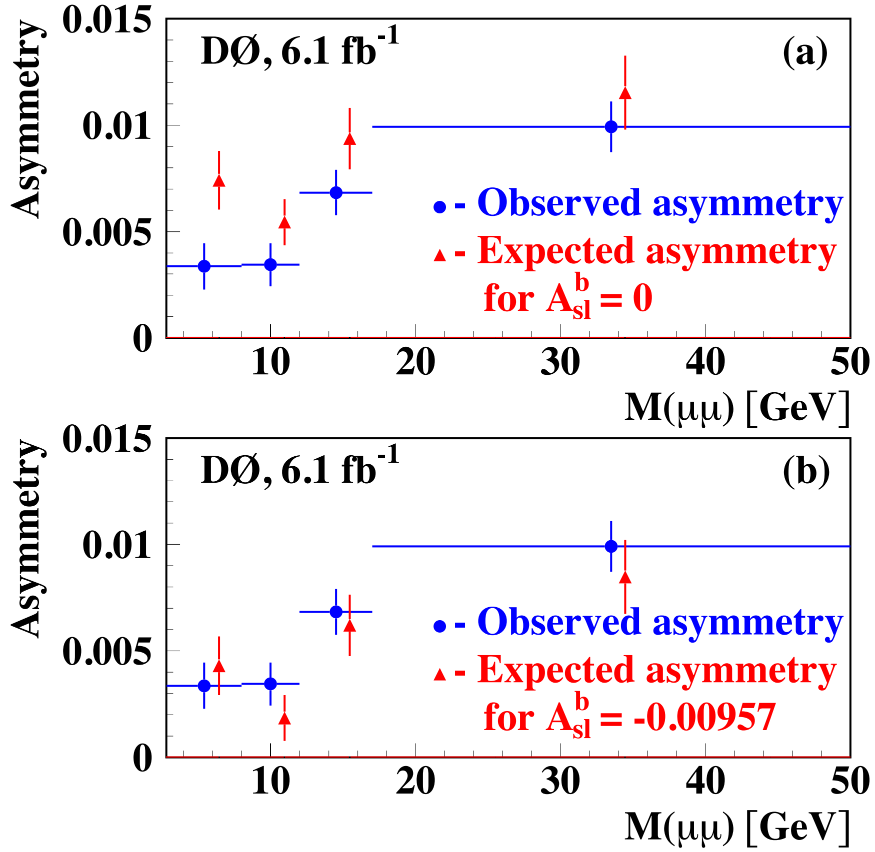
CDF also observe $B^+ \to Y(4140)K^+$, $Y(4140) \to J/\psi\ \phi$

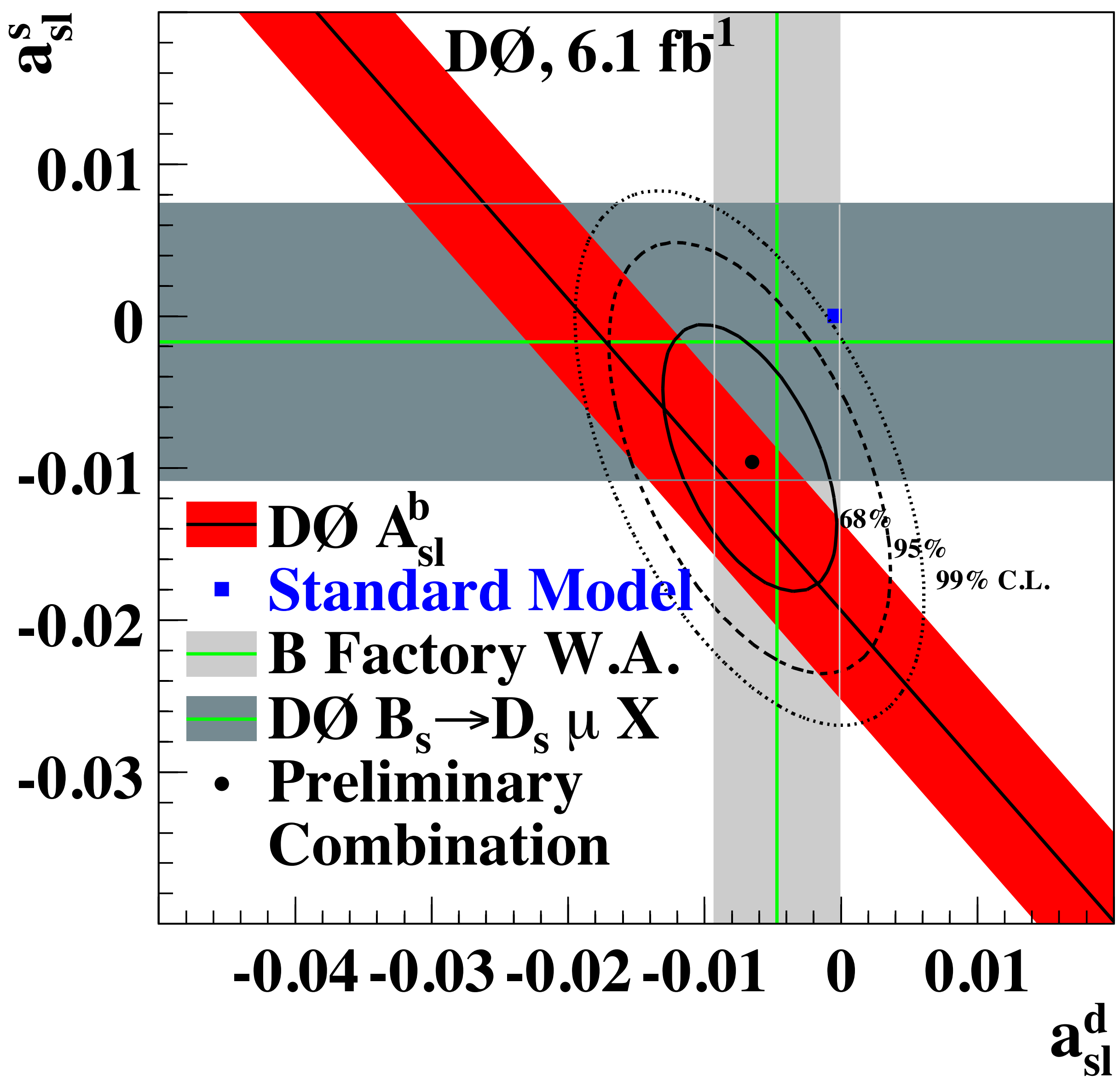
CP Violation in the $B_{d/s}$ System

New D0 (6 fb^{-1}) inclusive like-sign dimuon charge asymmetry measurement

$$A^b_{sl} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

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

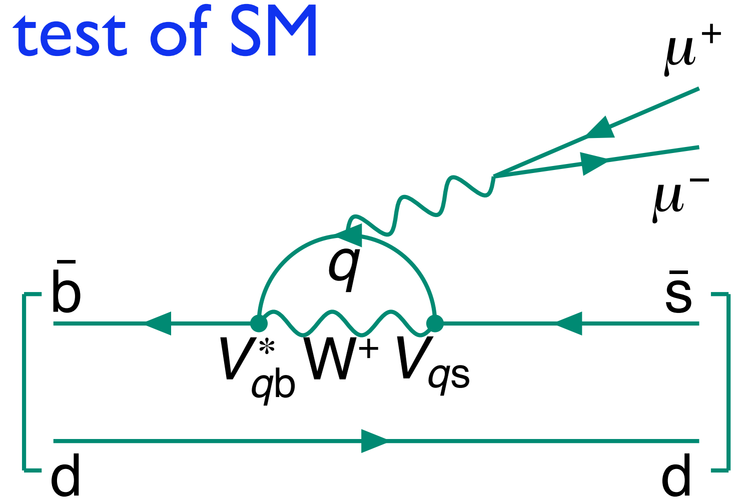




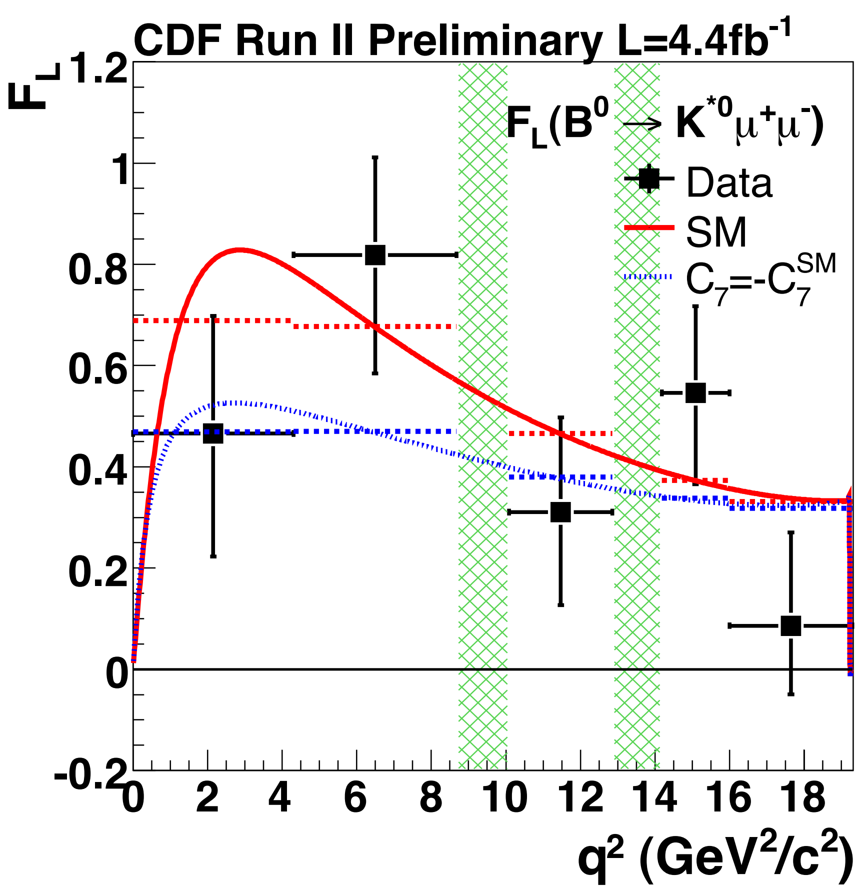
First evidence (3.2σ) for anomalous CP violation in B mixing!

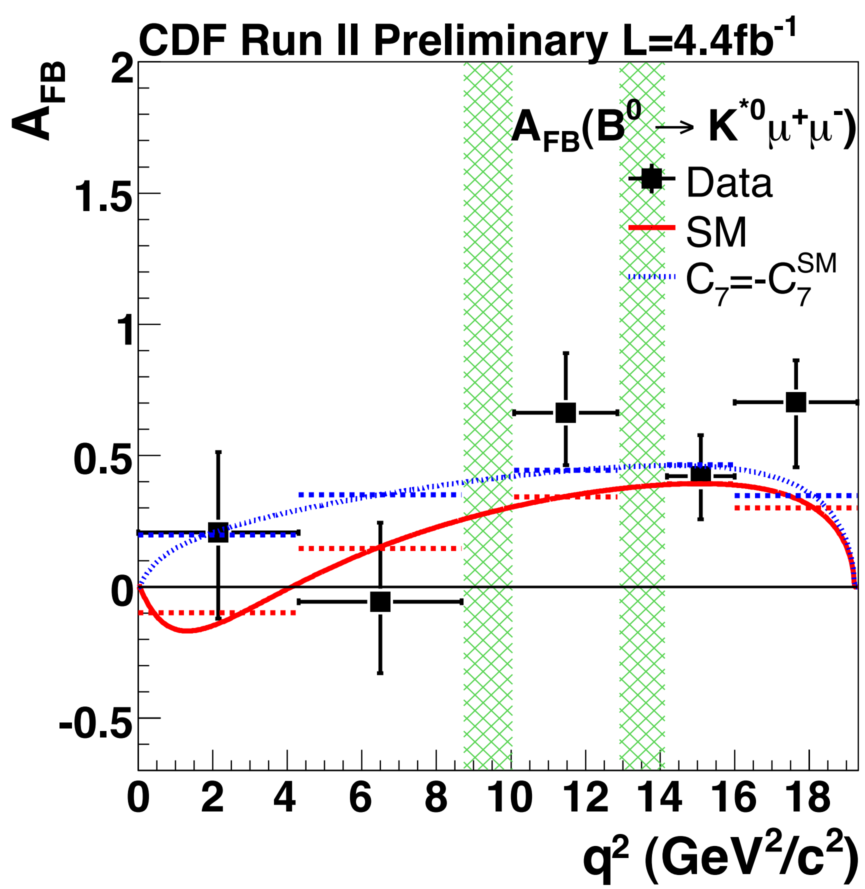
$B \to K^* \mu^+ \mu^-$

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

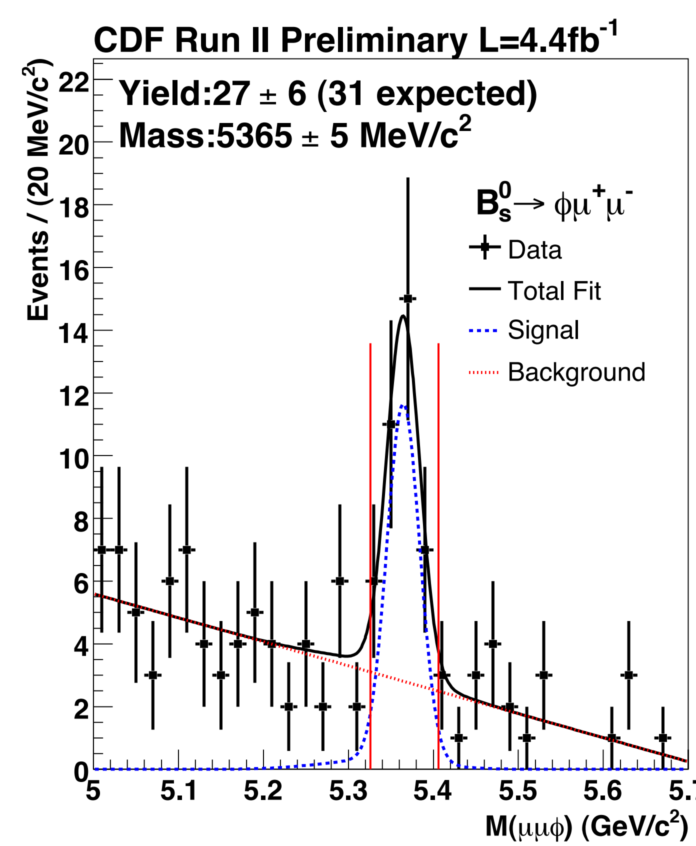


- B, K^* longitudinal polarization F_L, $\mu^+\mu^-$ A_{FB} sensitive to values of Wilson coefficients (C_7, C_9, C_{10}) used in Operator Product Expansion



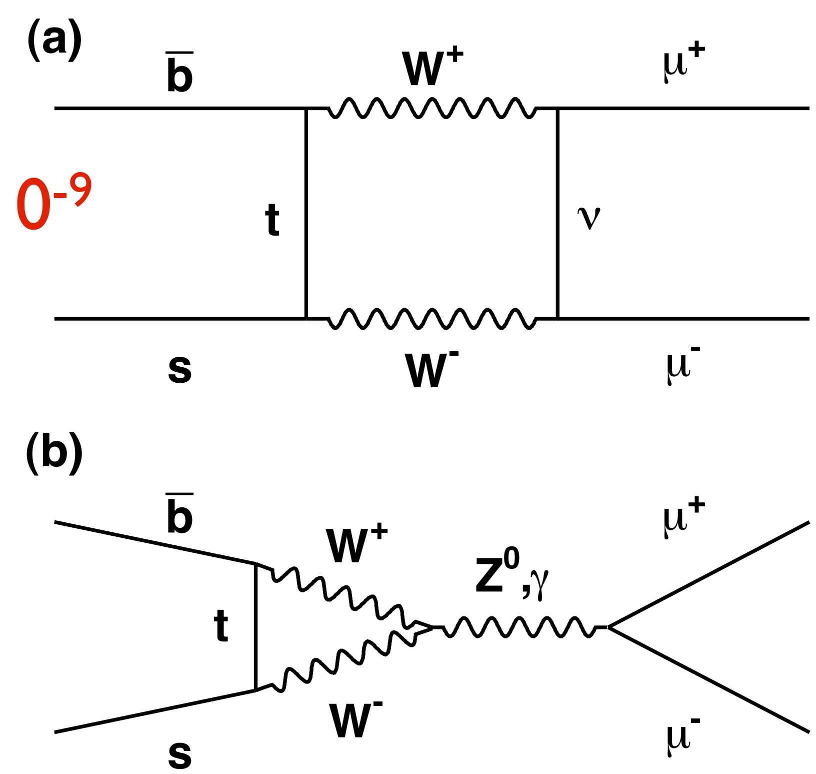


Results competitive (and compatible) with B-factories



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

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

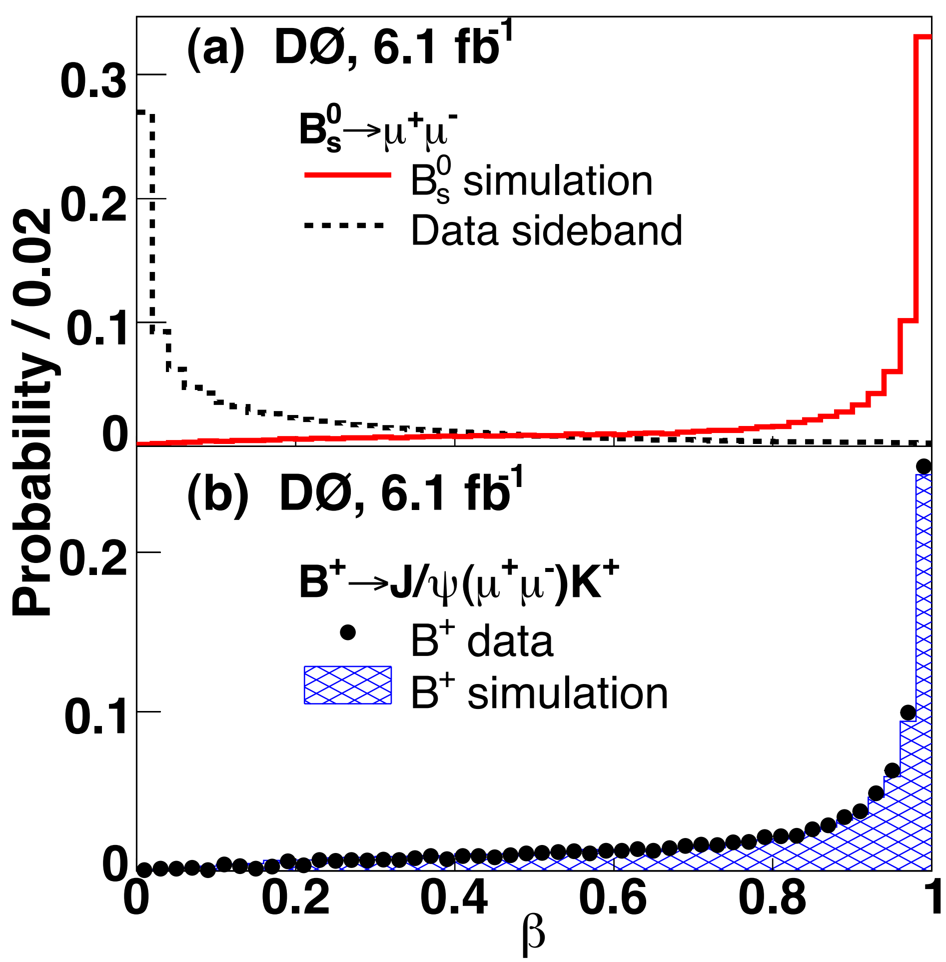


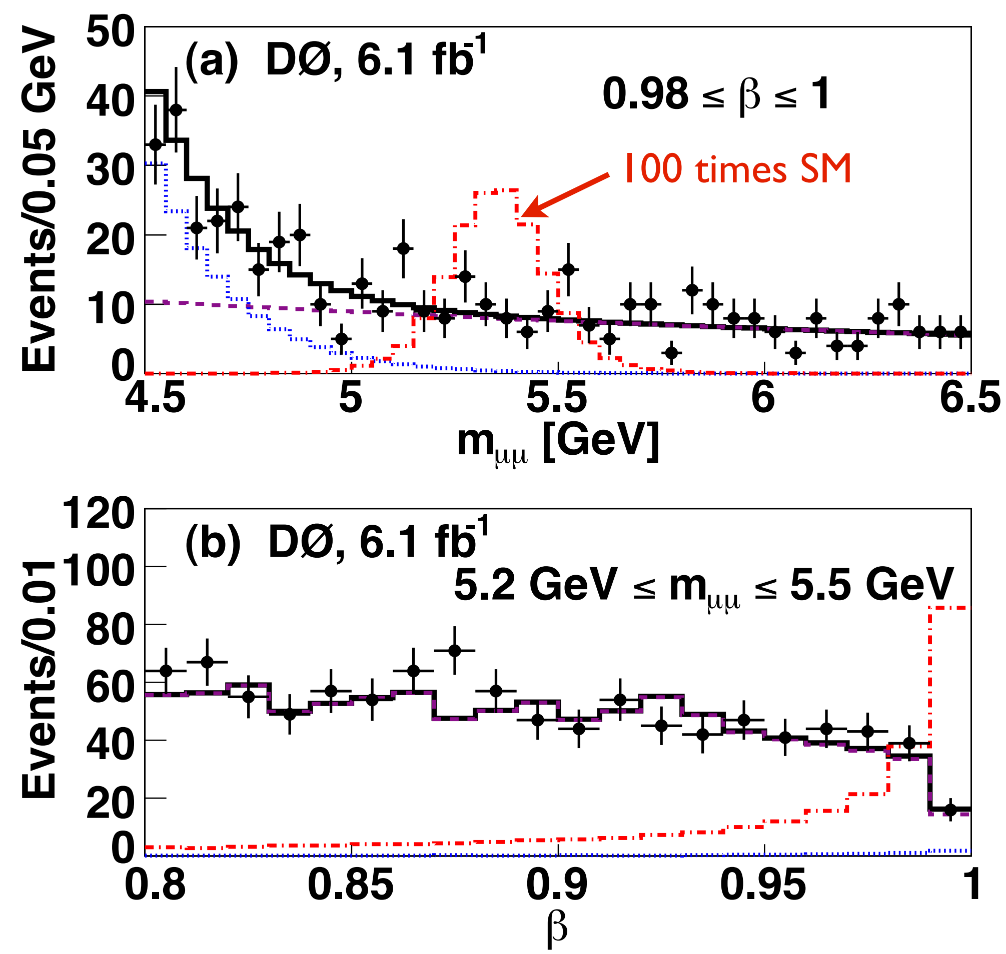
Another rare FCNC process! In the SM: $\mathcal{B}=(3.6\pm0.3)\cdot10^{-9}$

- 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 $B^+ \to J/\psi\, K^+$ decays



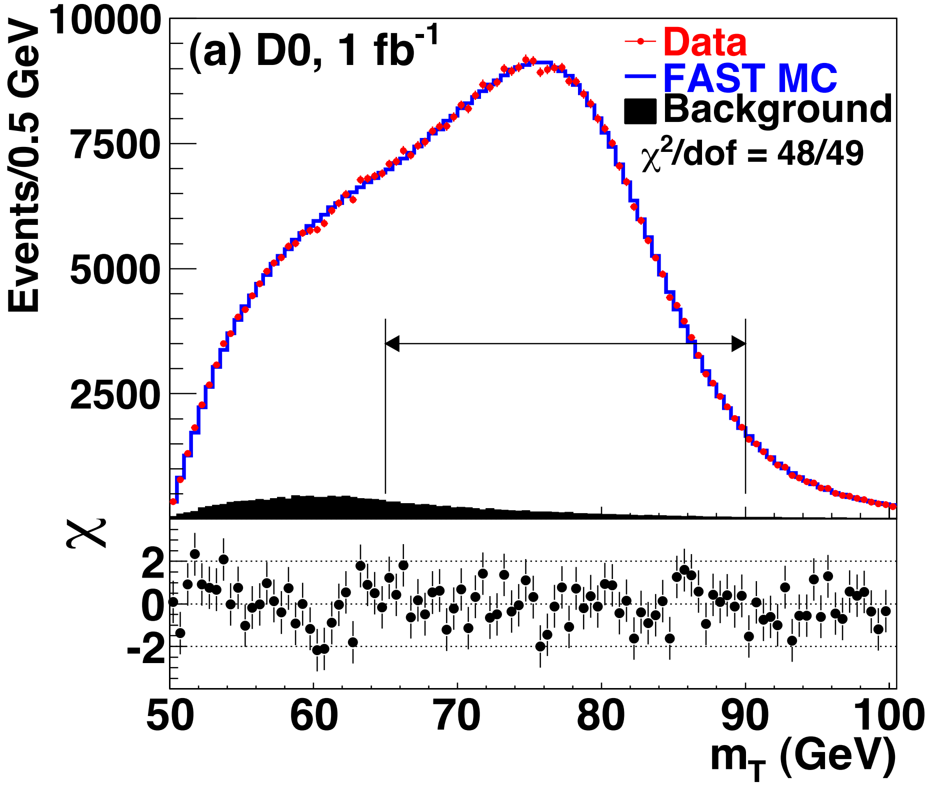


Results (95% CL):

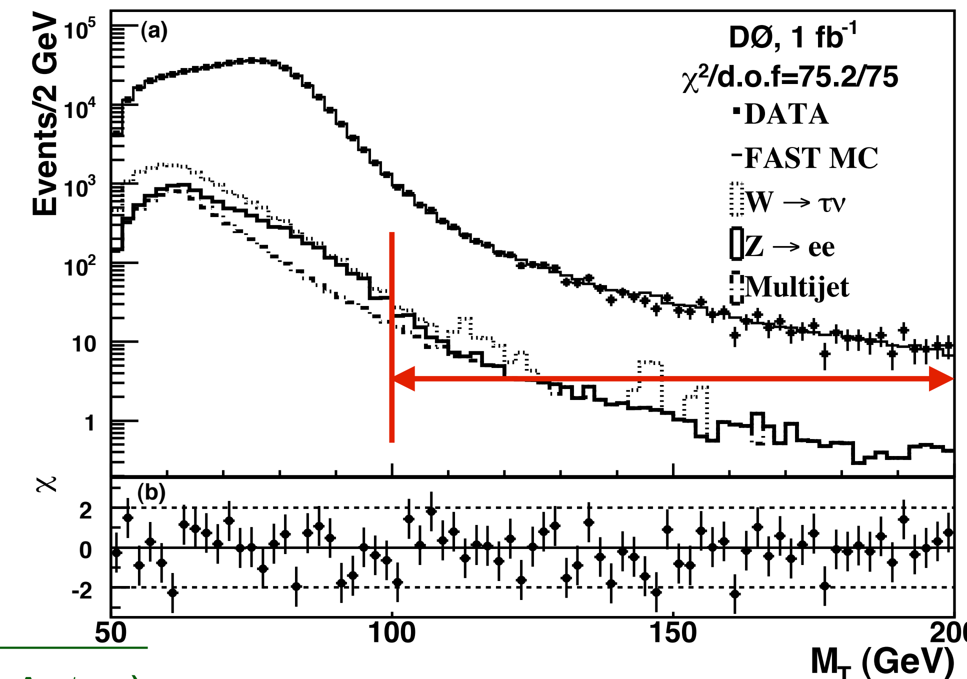
- D0: $\mathcal{B} < 5.1\cdot10^{-8}$
- CDF: $\mathcal{B} < 4.3\cdot10^{-8}$

Electroweak Physics

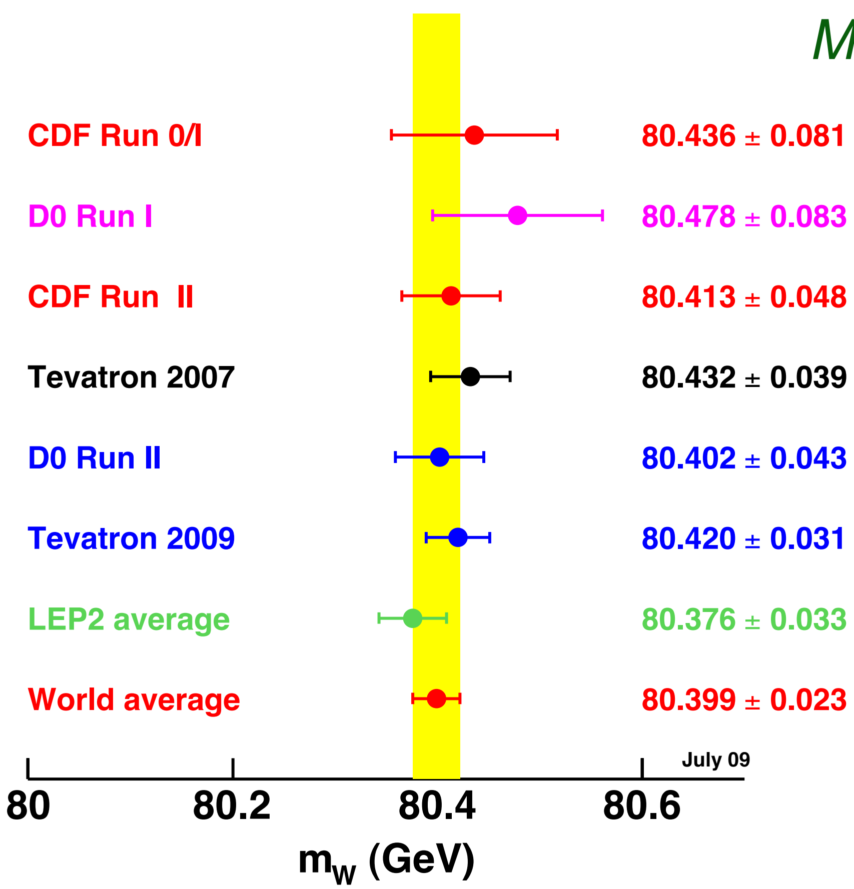
W Boson Properties: Mass and Width

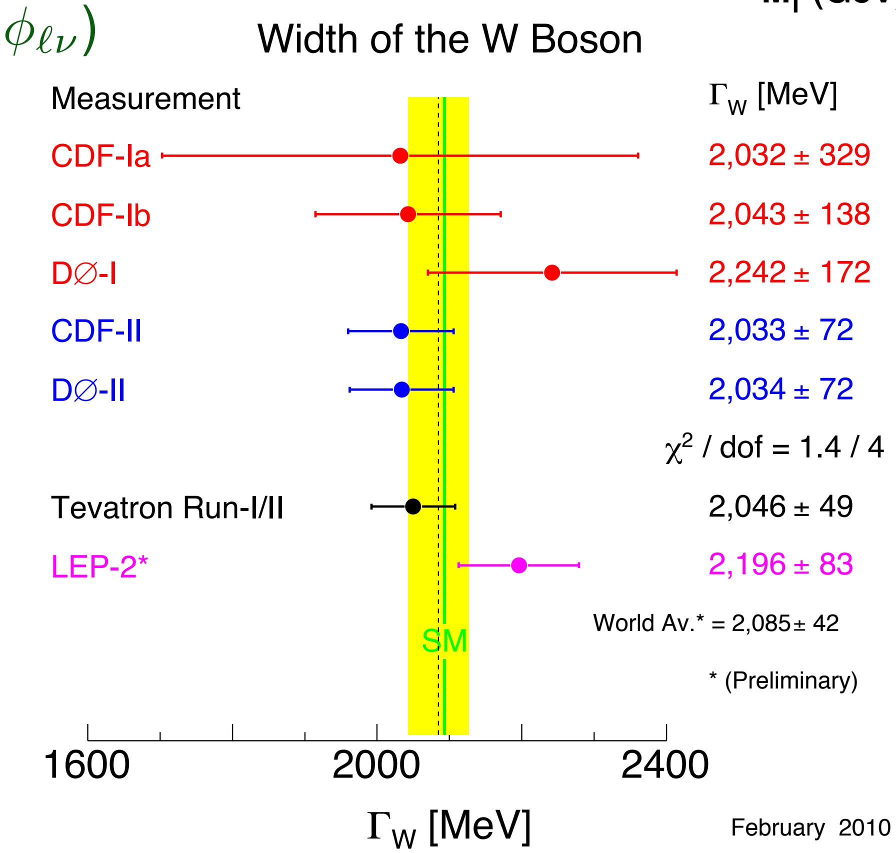


Extremely challenging from systematics point of view



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





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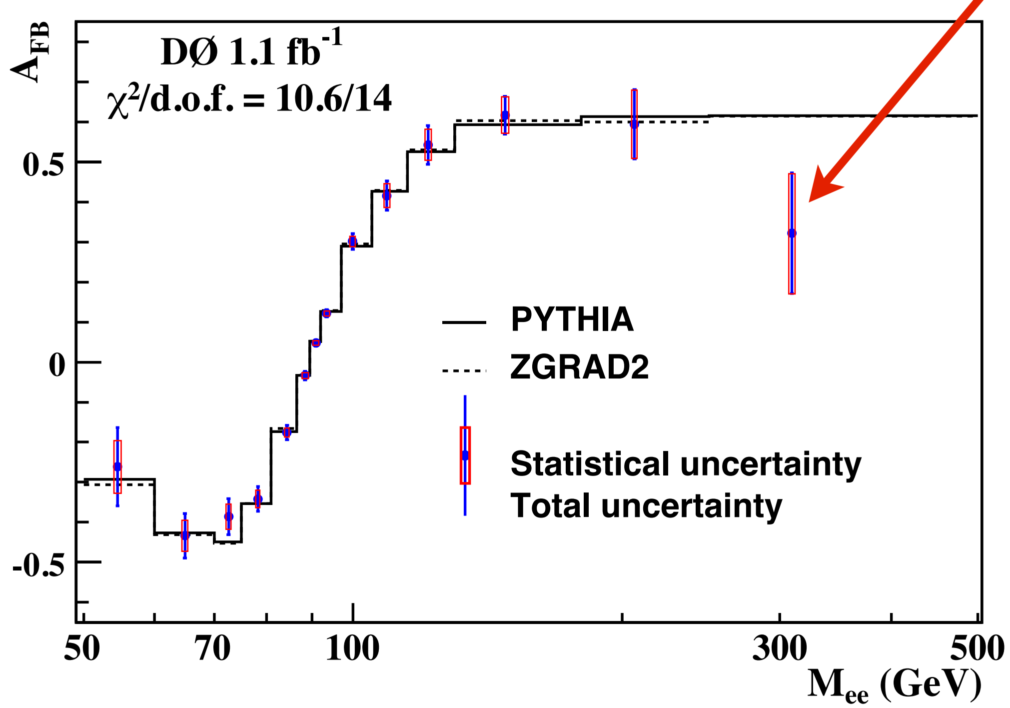
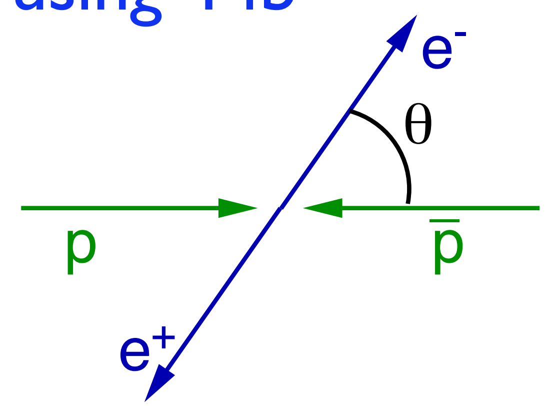
Forward-Backward Asymmetry in Drell-Yan

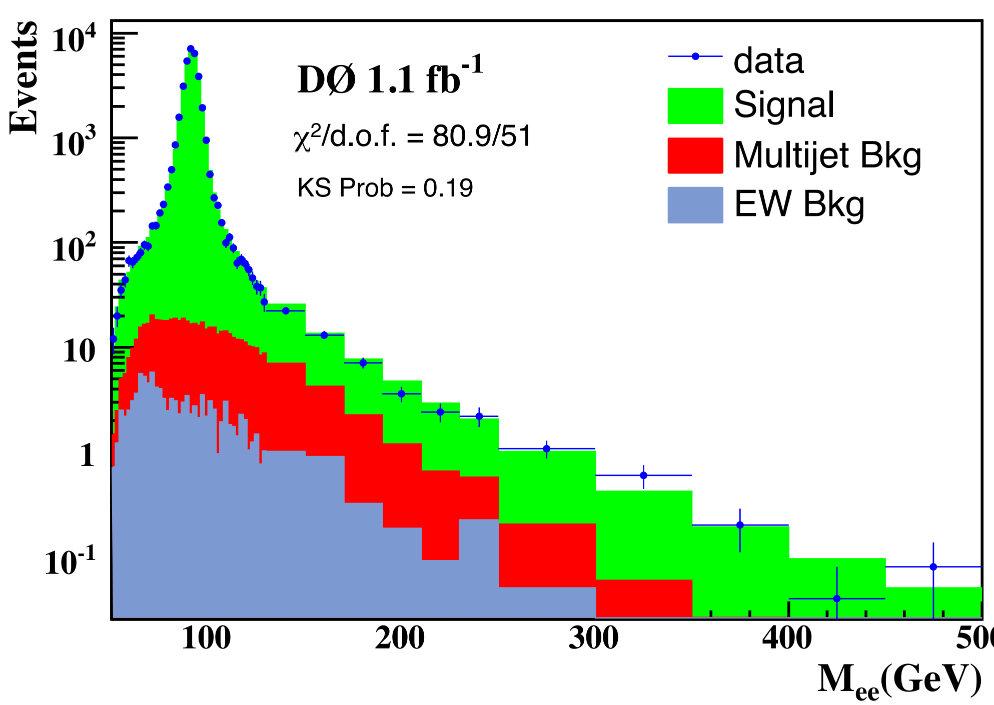
D0's 2008 measurement: hint for deviation at high M_{ee} (e.g. Z'?), limited by statistics. Now remeasured by CDF using 4 fb^{-1}

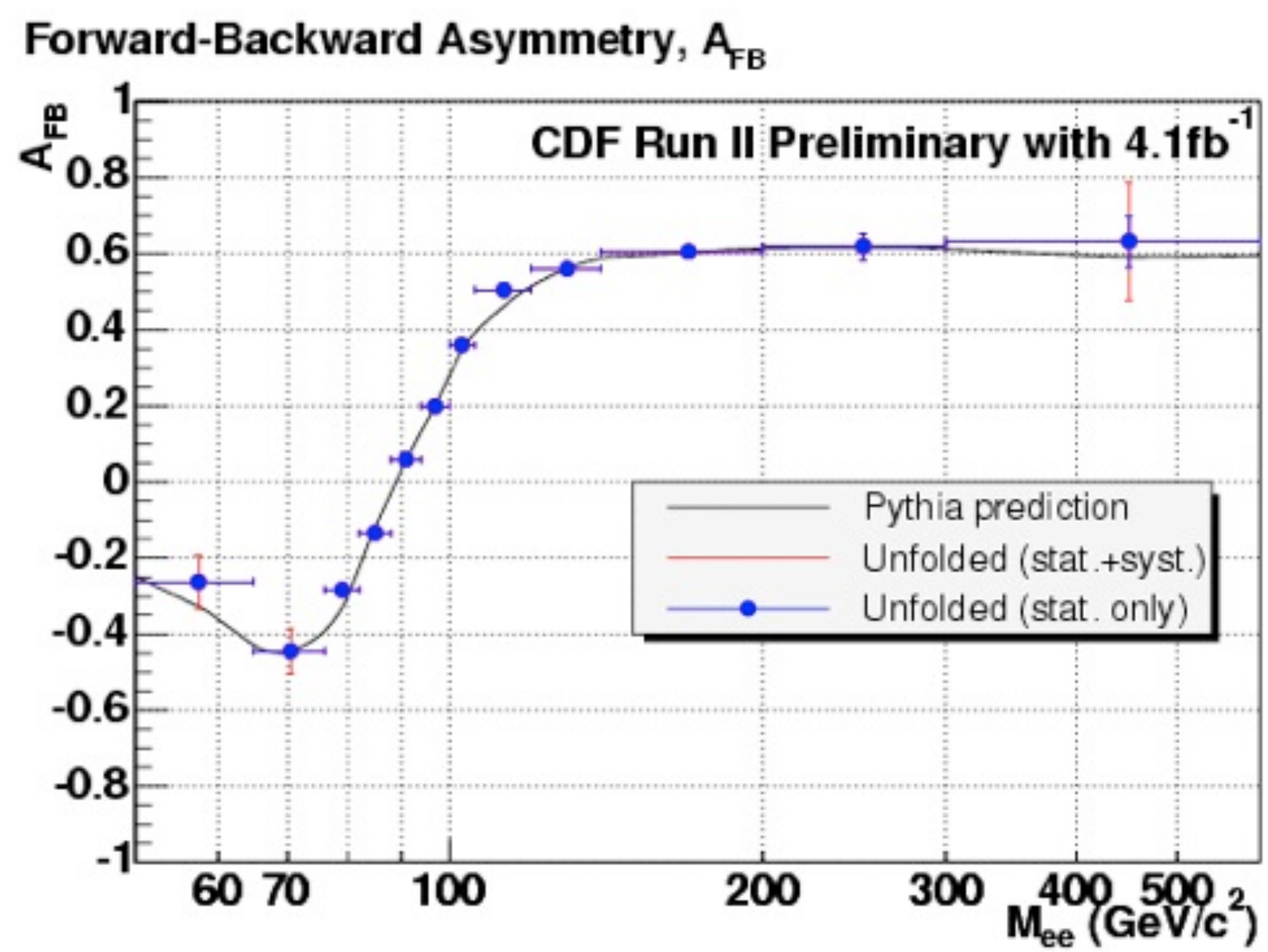
$$A_{fb} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

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









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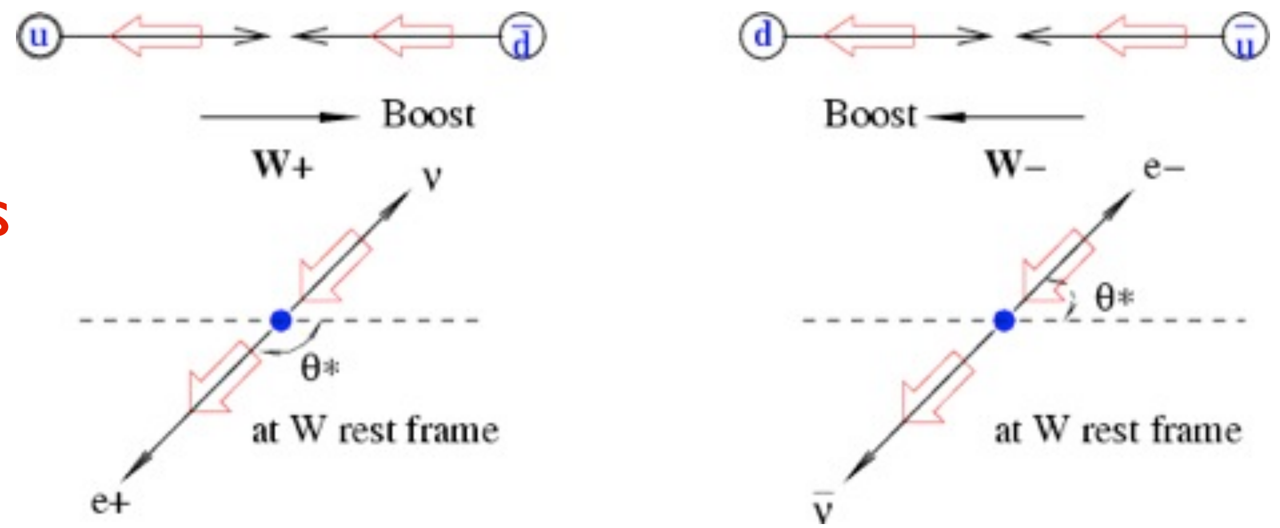
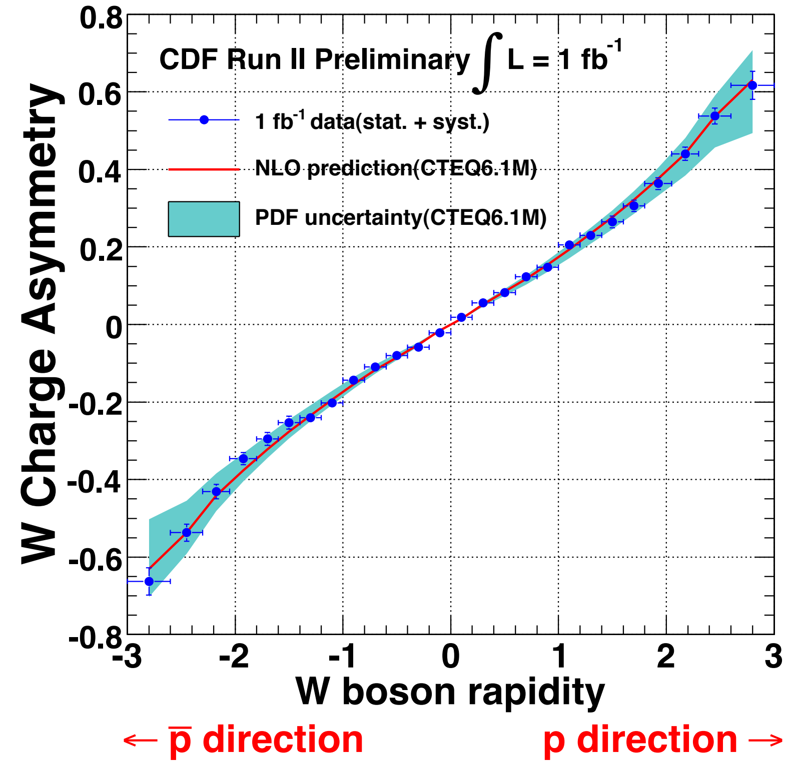
W Boson Charge Asymmetry



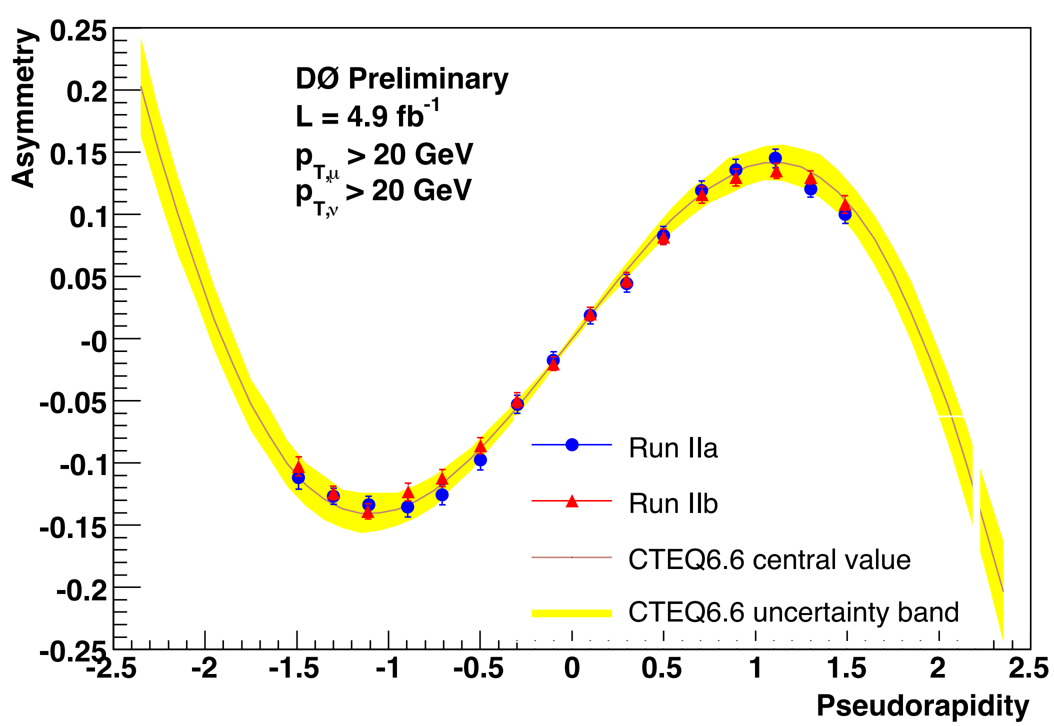
Sensitive test of u, d PDFs

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

Earlier (2008) CDF analysis (1 fb^{-1}, W→eν): explicitly use both solutions, correct for mis-assignment



New D0 analysis (4 fb^{-1}, W→μν): don't reconstruct the W, consider directly the lepton charge asymmetry



Results consistent with earlier D0 W→eν analysis

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

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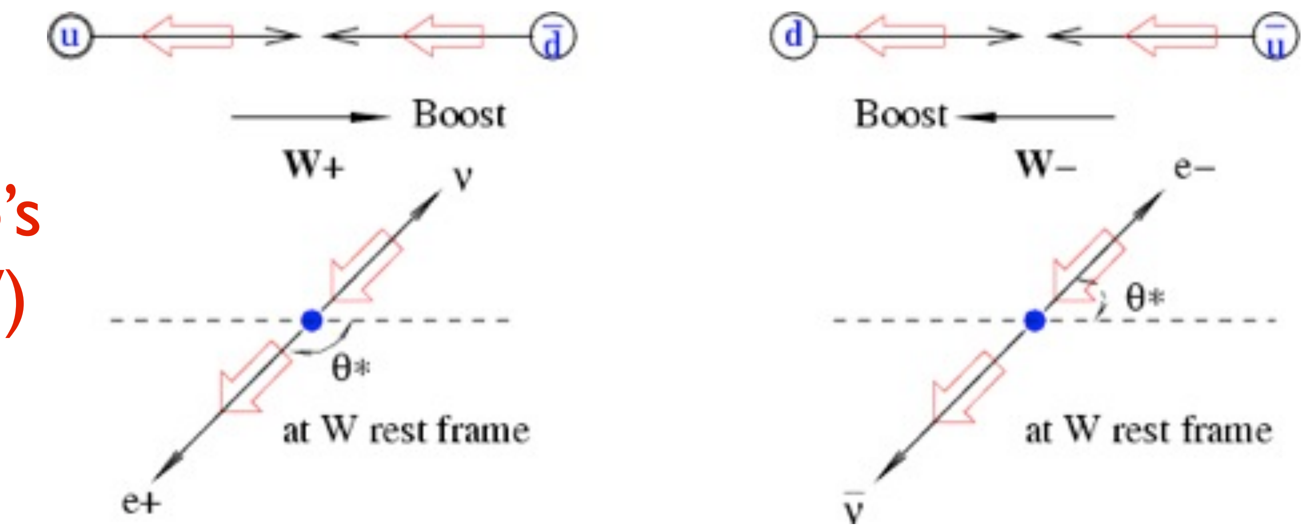

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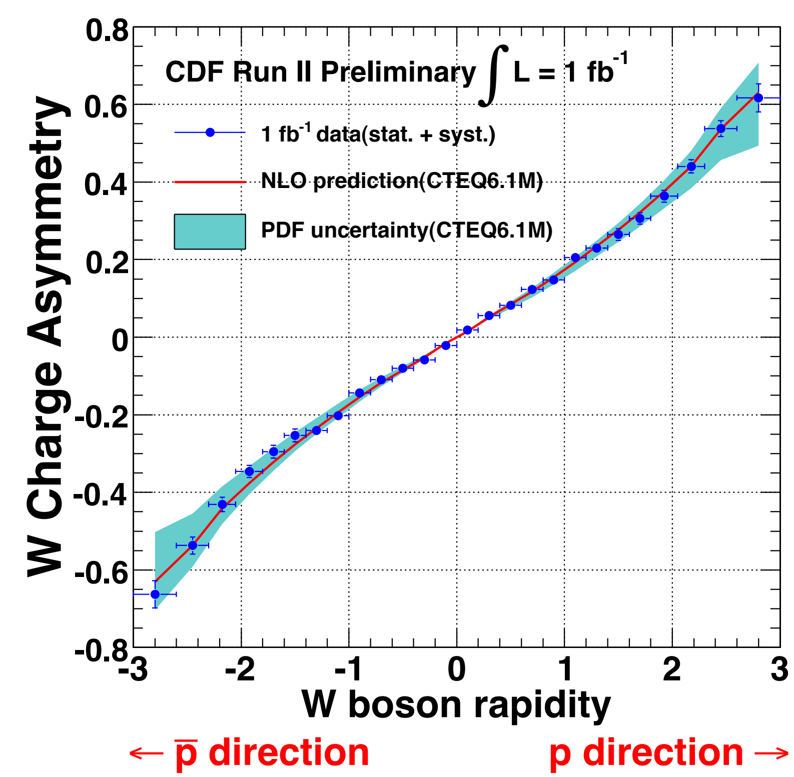

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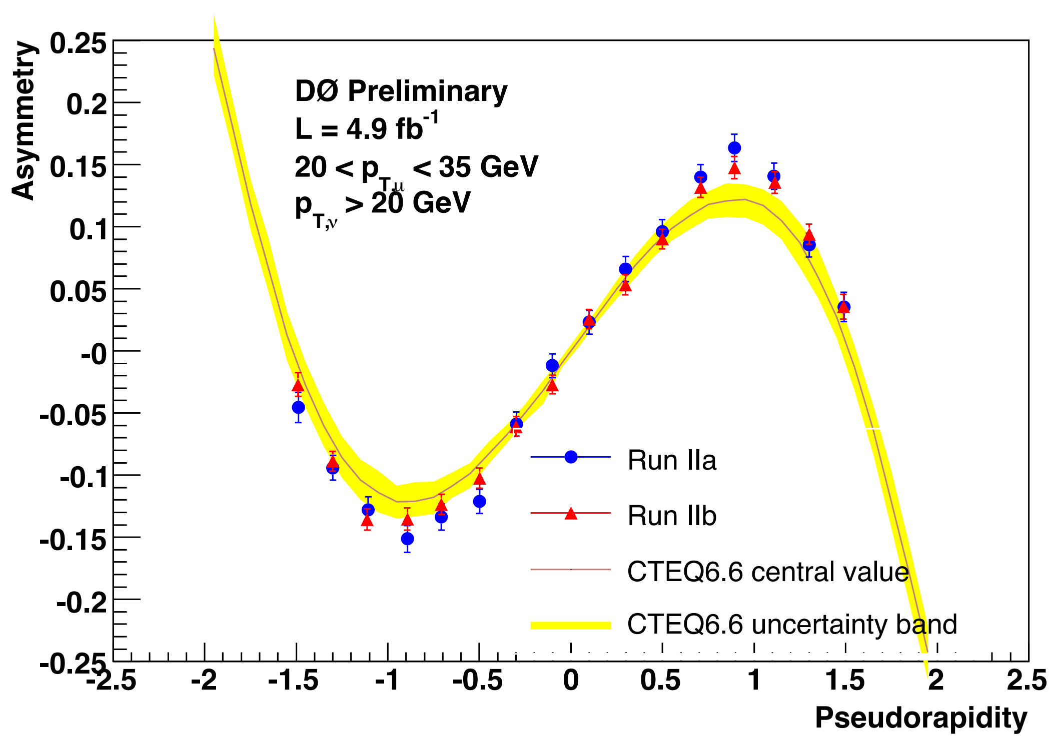

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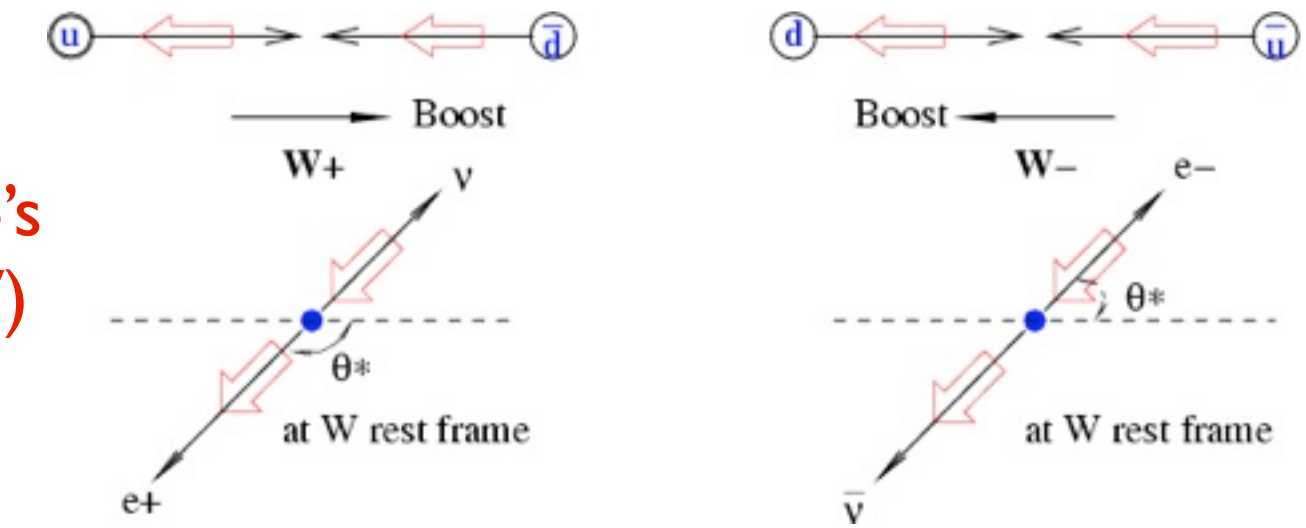

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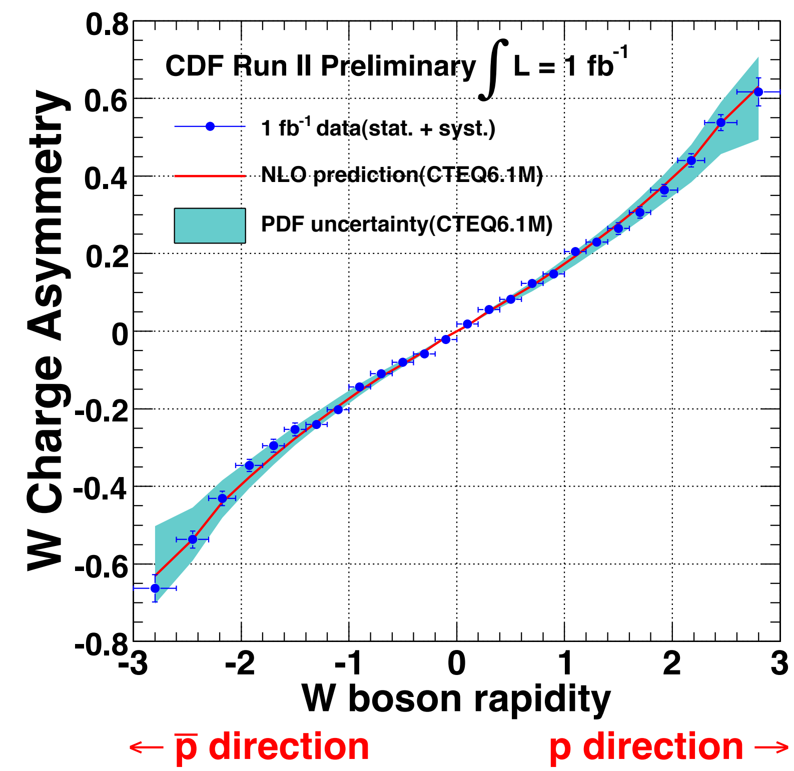

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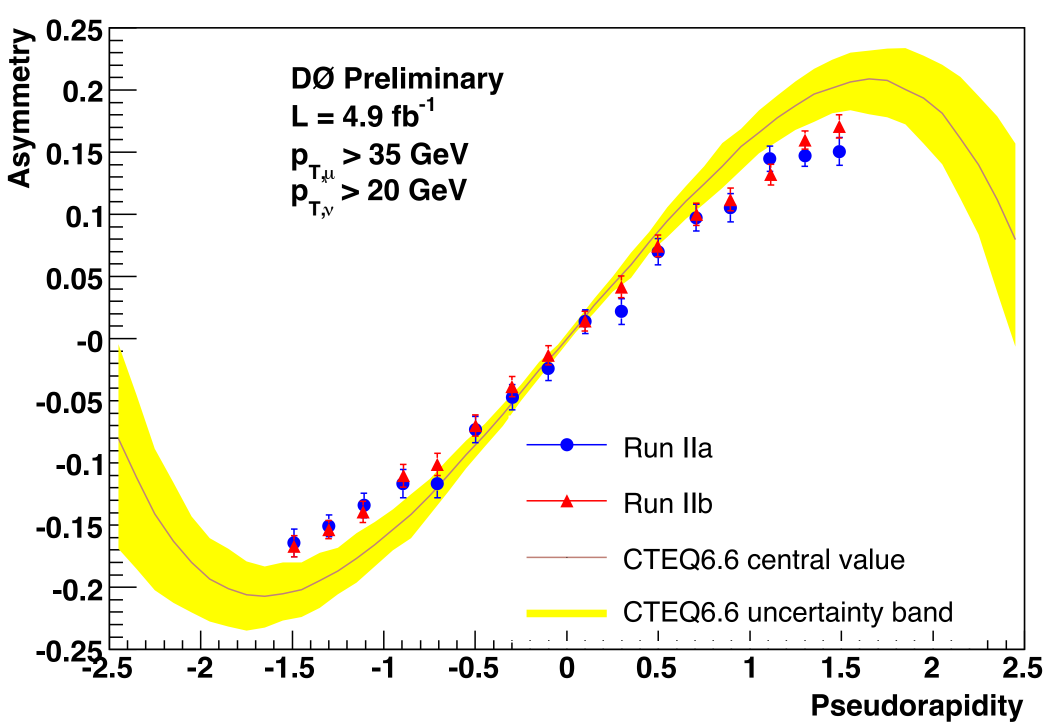

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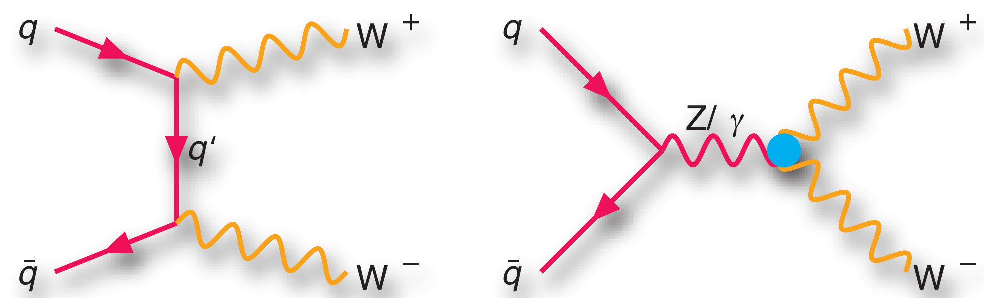
An "interesting" challenge for PDF fitting (e.g. CT10W)

Di-Boson Production

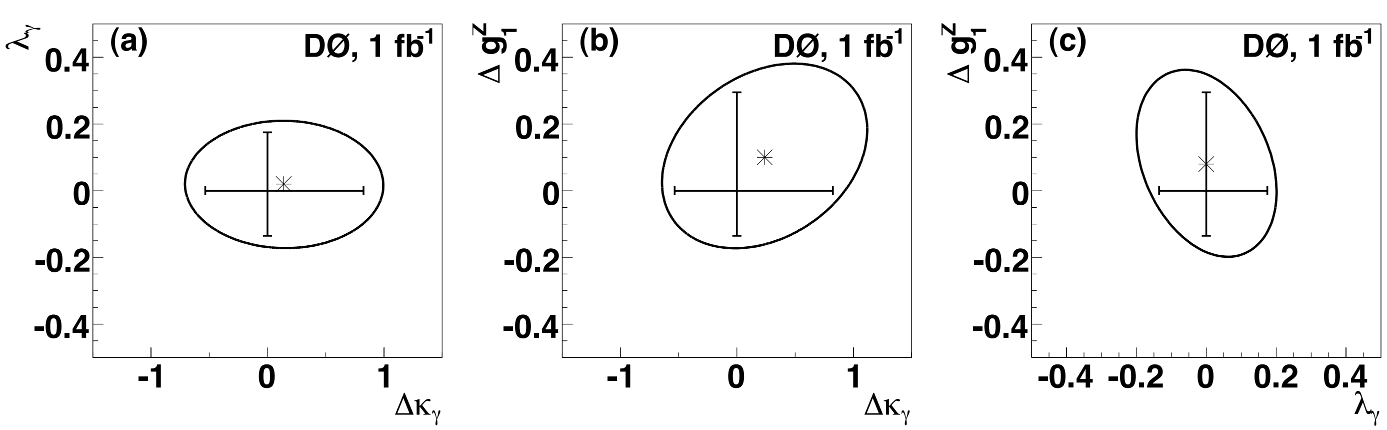
The name of the game:
probing Triple Gauge-boson Couplings
(besides being interesting decay products
of other bosons...)

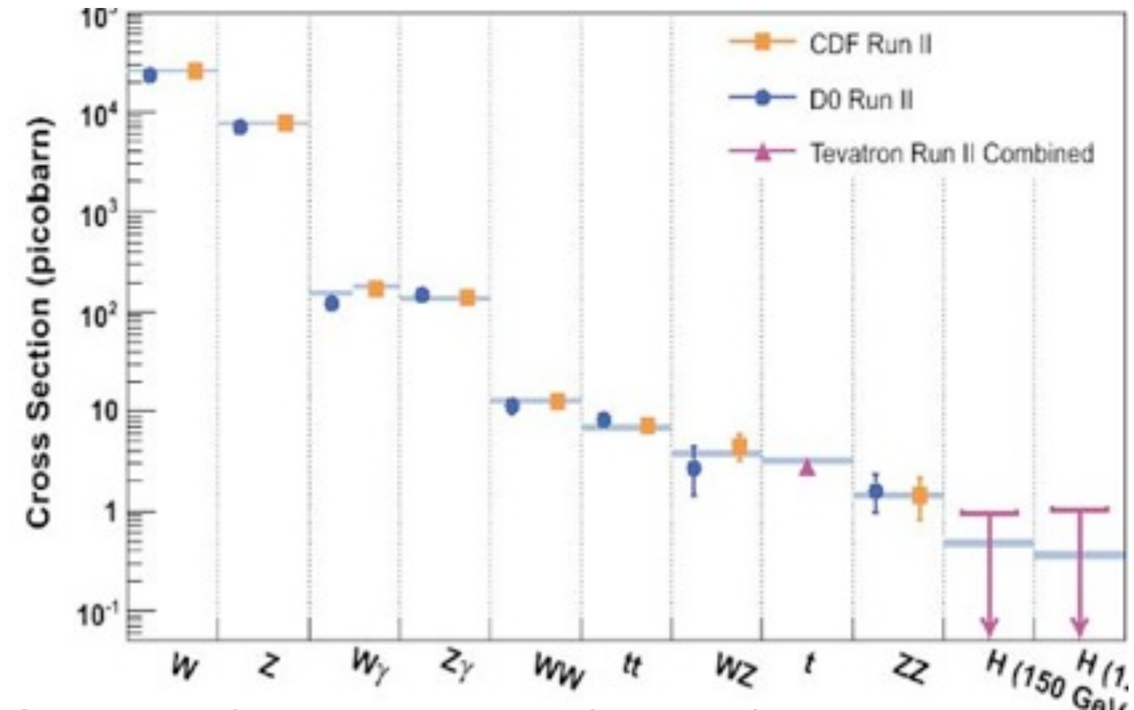
- e.g. for WW production ($W\gamma$/WZ production sensitive to only $WW\gamma$/WWZ):



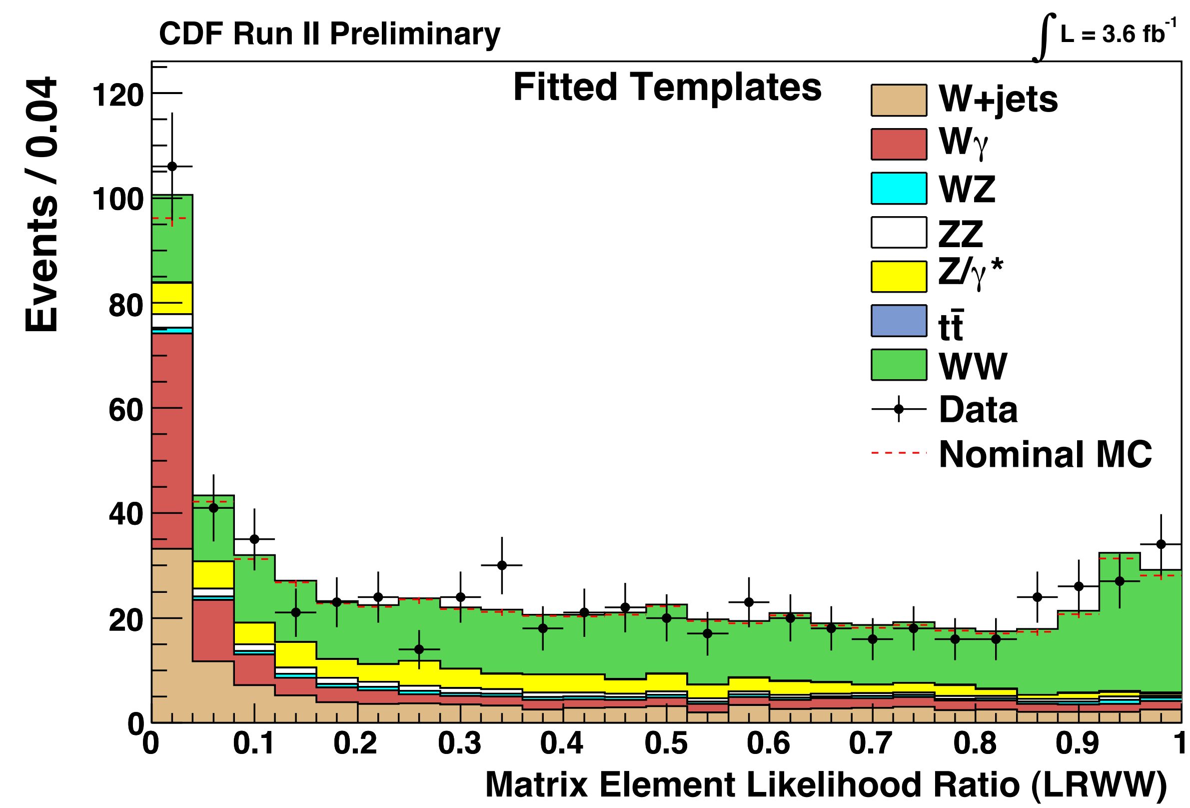
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu})$$
$$+ \quad i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda},$$

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





Gallery of Tevatron EW (mostly) measurements



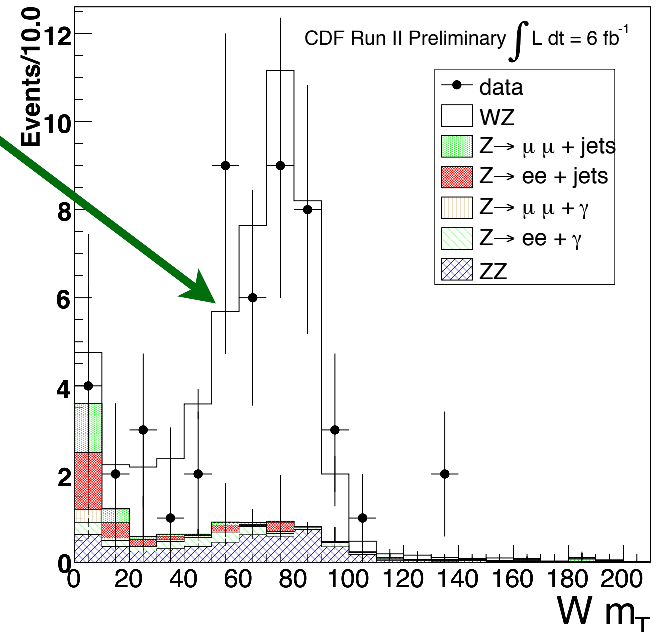
$$\sigma(p\bar{p} \to WW) = 12.1 \pm 0.9(\text{stat.})^{+1.6}_{-1.4}(\text{syst.})\ \text{pb}$$

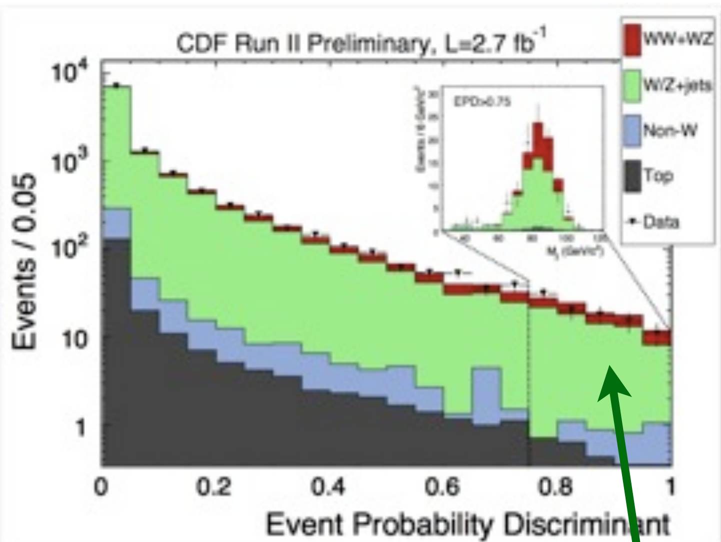
Di-Boson Production (2)

Also: observation of WZ final states

- in lllν final states

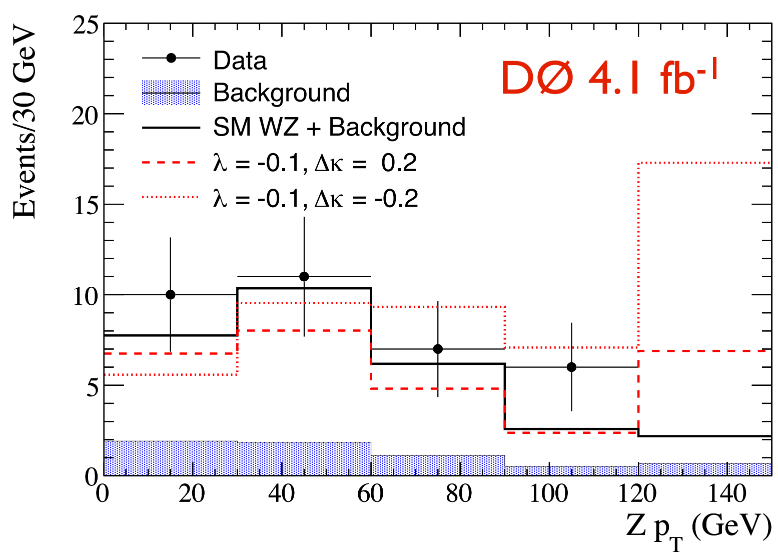
$\sigma(p\bar{p} \to WZ) = 4.1 \pm 0.7$ pb

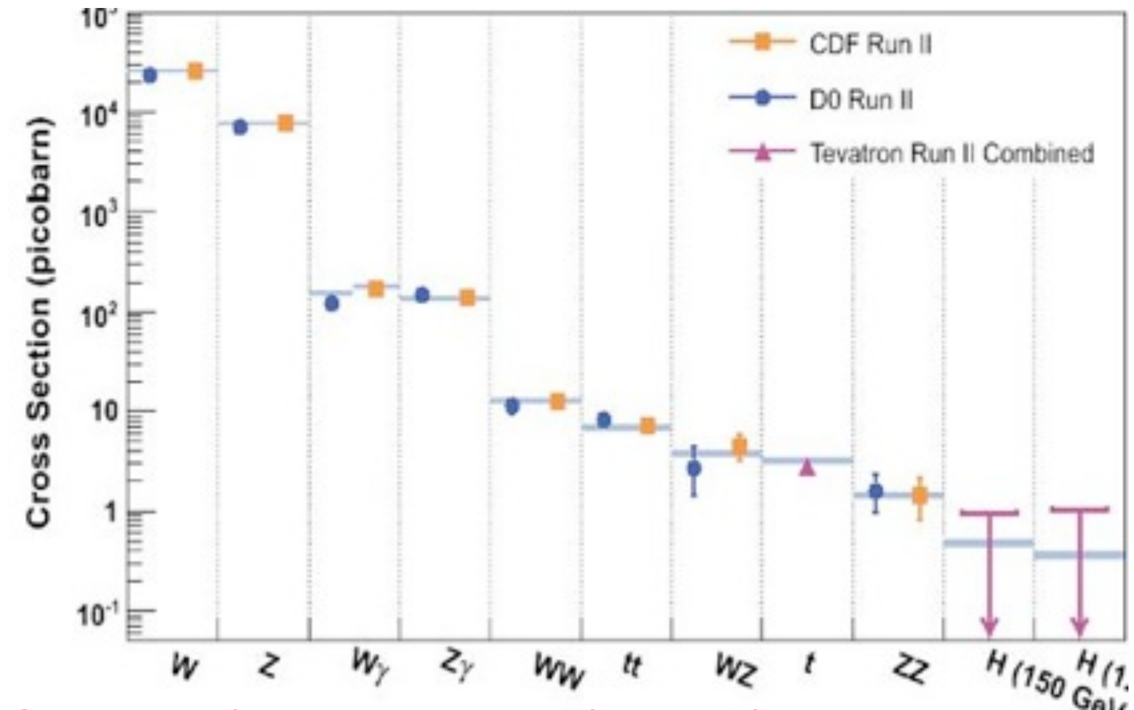




$\sigma(p\bar{p} \to WZ, WW) = 17.7 \pm 3.9$ pb

- WW/WZ in lνjj final states
- constraints on anomalous couplings

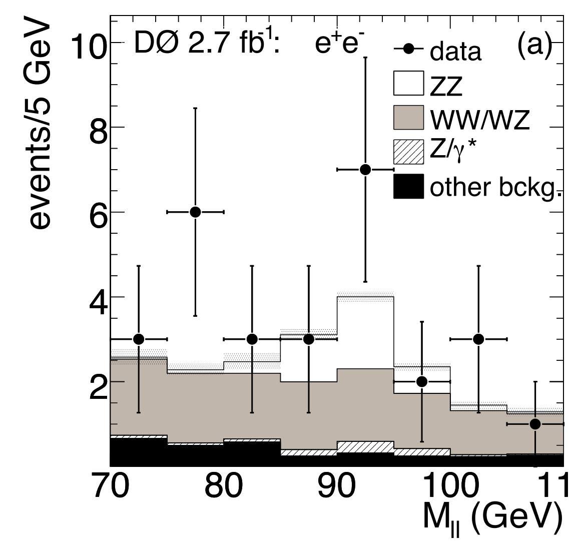


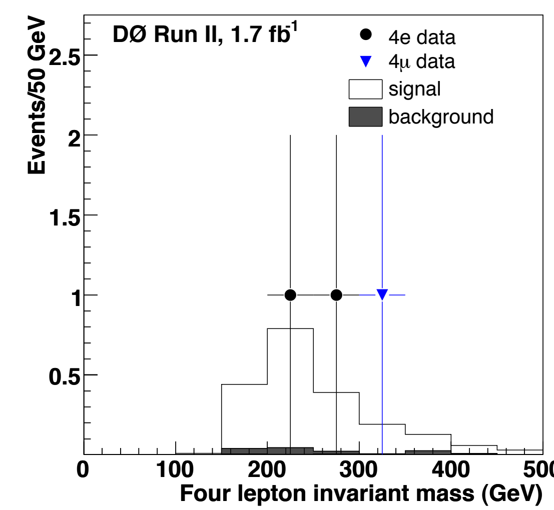


Gallery of Tevatron EW (mostly) measurements

Observation of ZZ final states

- in llll final states



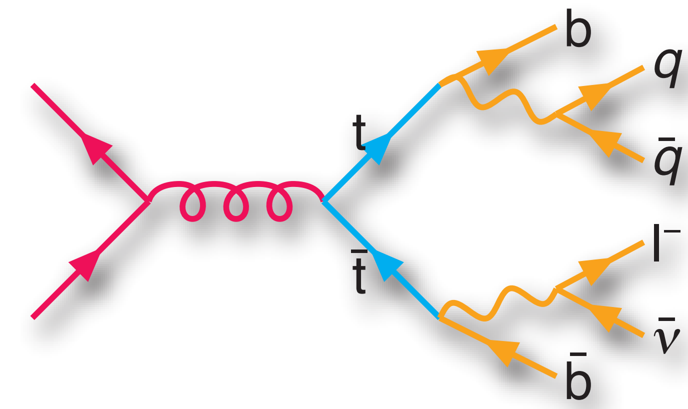


(observation level needs both final states)

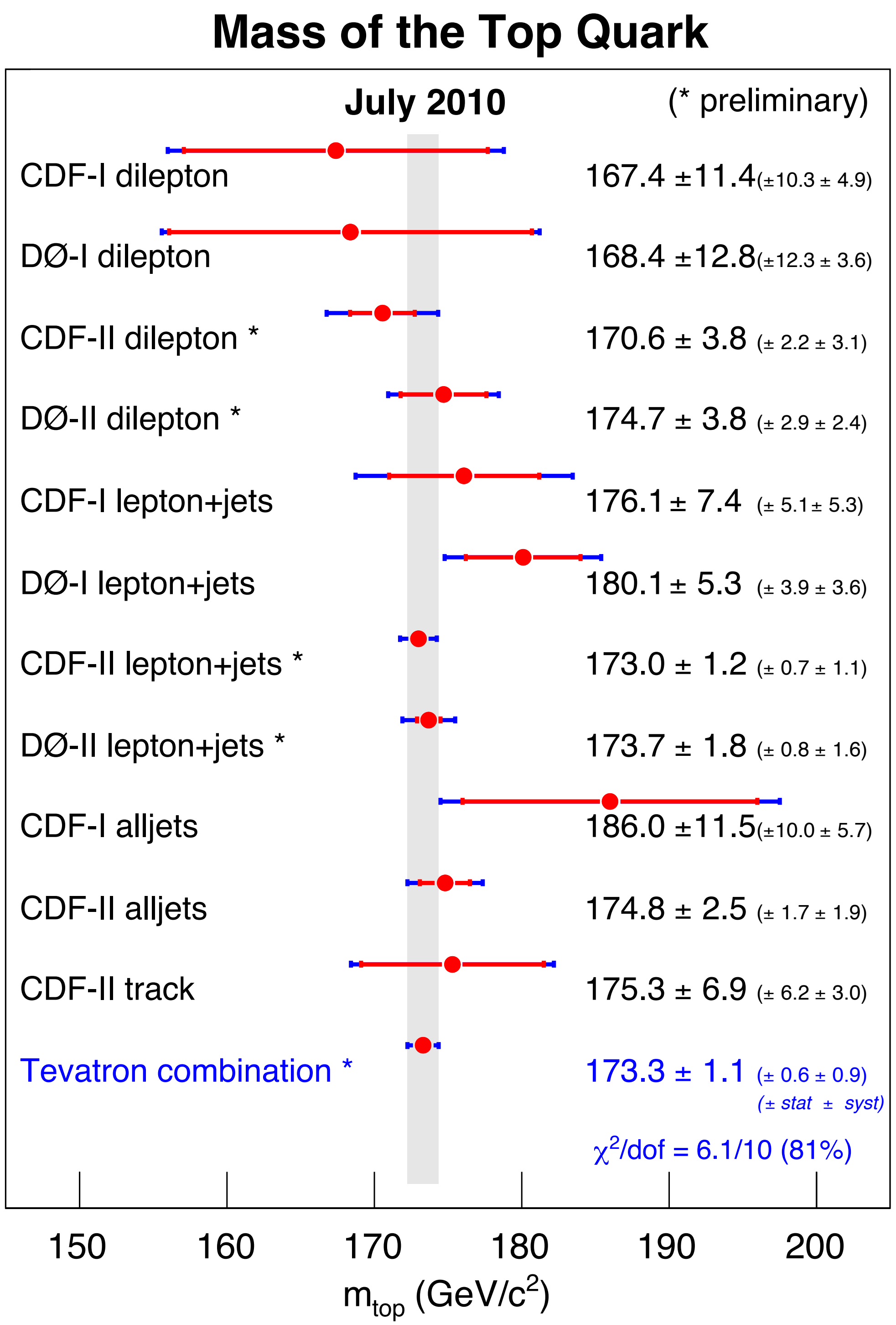
- in llνν final states
- similar analysis of TG couplings

Top Quark Physics

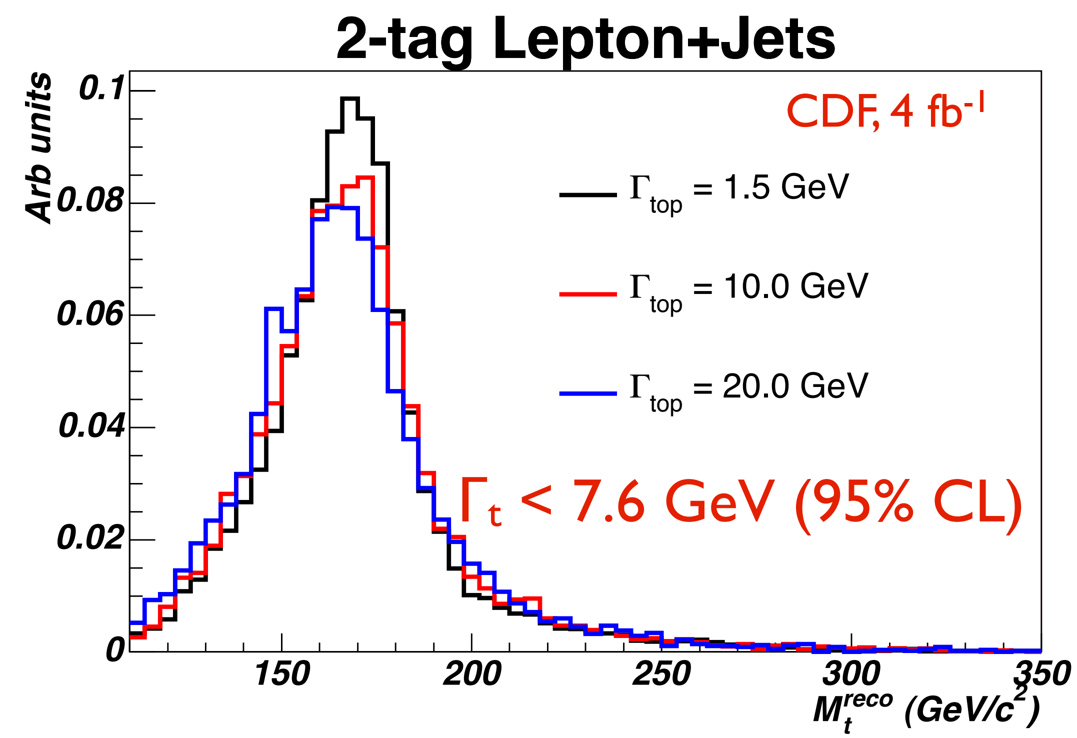
Top Quark Mass & Width



Top quark mass: another area of high precision measurements



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



but difficult to compete with indirect measurement (D0, 2.3 fb^{-1})

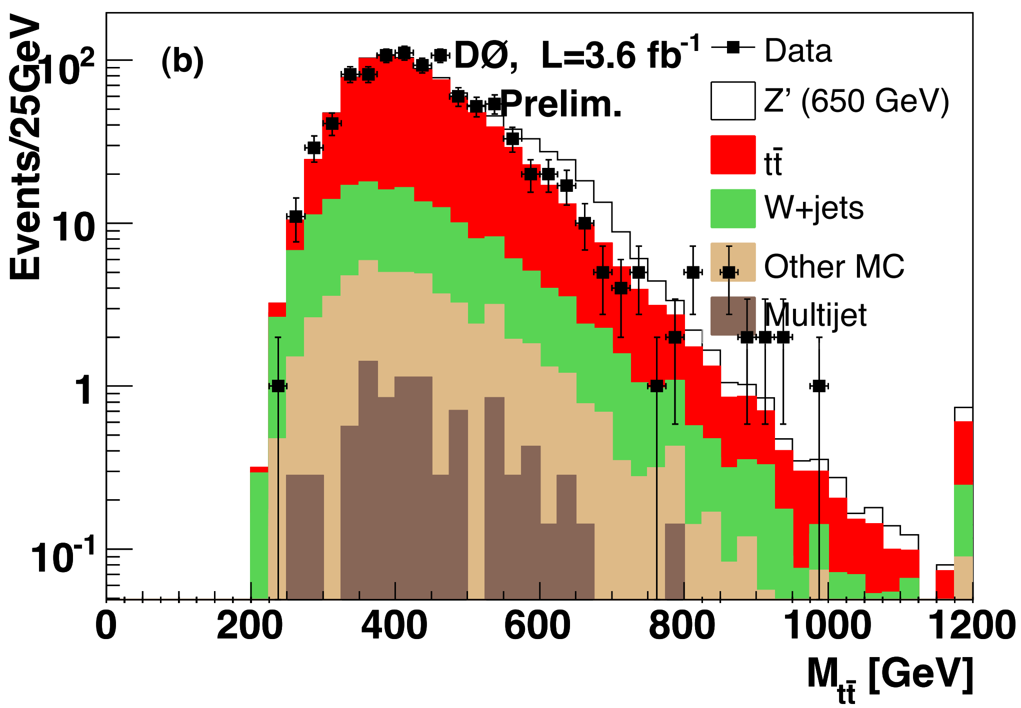
- combining t-channel single top production cross section and B($t \to Wb$) measurements in l+jets:

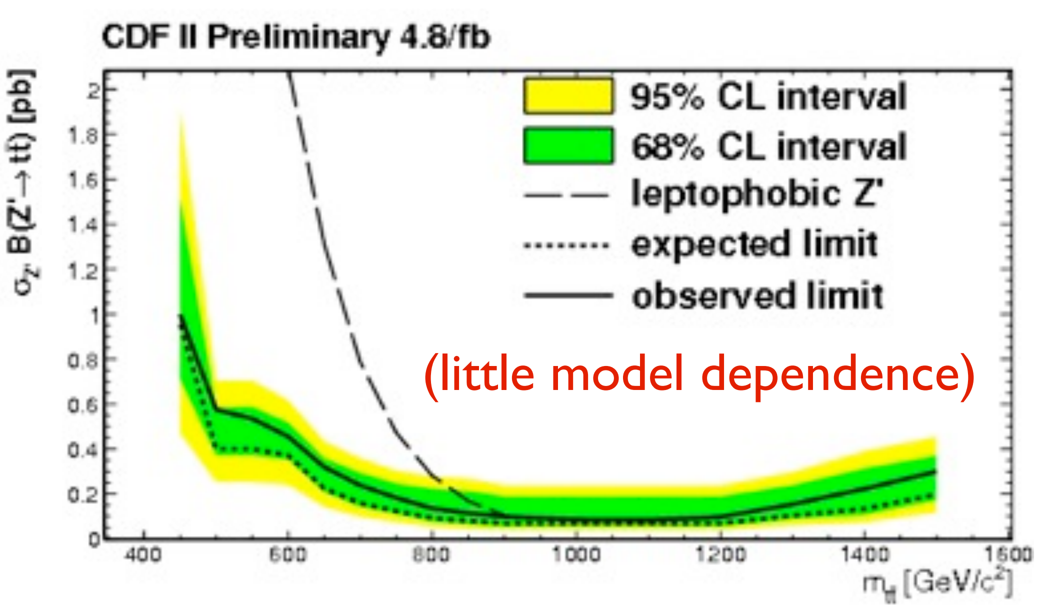
$$\Gamma_t = 1.99^{+0.69}_{-0.55} \text{ GeV}$$

Top Quark Pair Resonances & A_{fb}

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

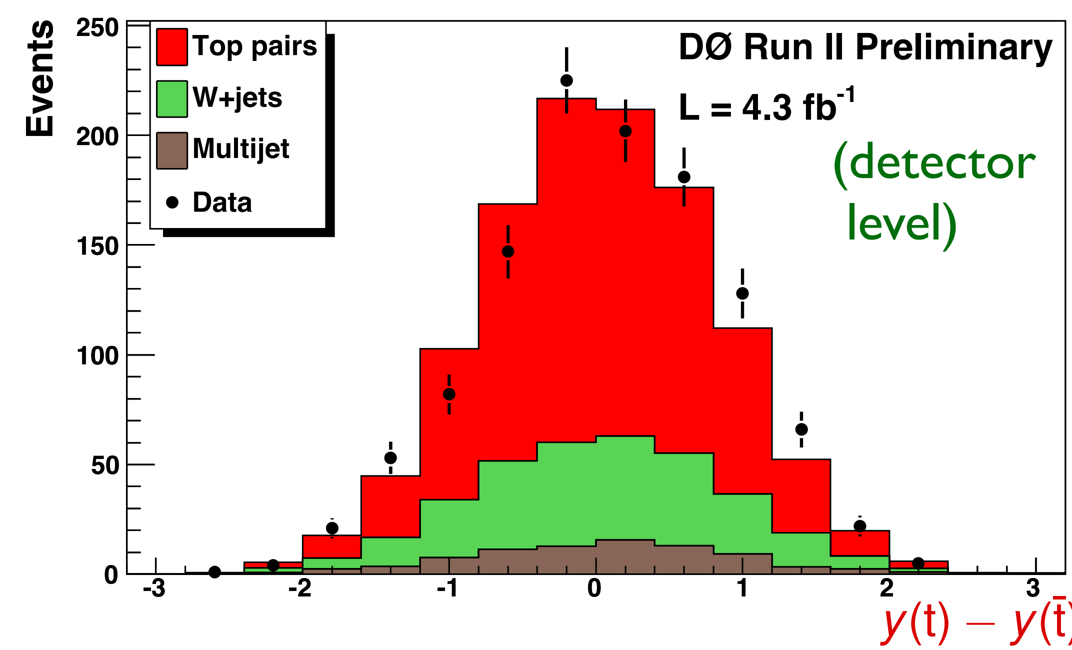
Directly as a (narrow) resonance





Or through production asymmetry

(SM NLO interference effects: A_{fb} ~ 1% at detector level, ~ 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)

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

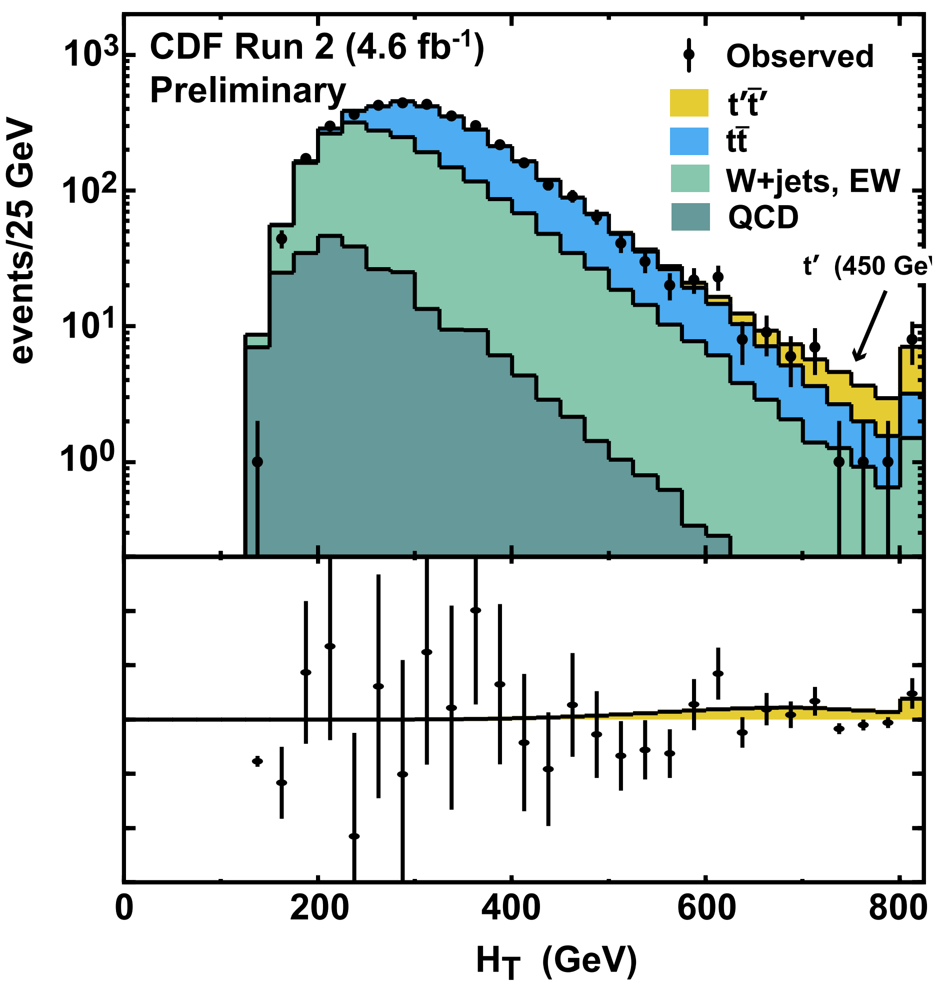
So far, no significant deviations

Fourth Generation Quark Searches

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

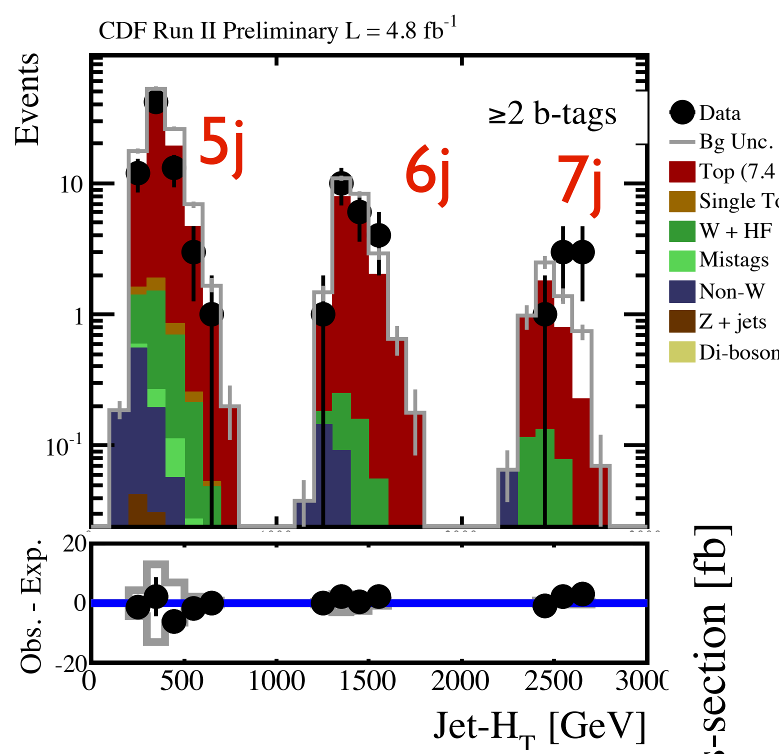
$$H_T = \sum_{j \in \mathrm{jets}} E_{T,j} + E_{T,\ell} + \not{E}_T$$

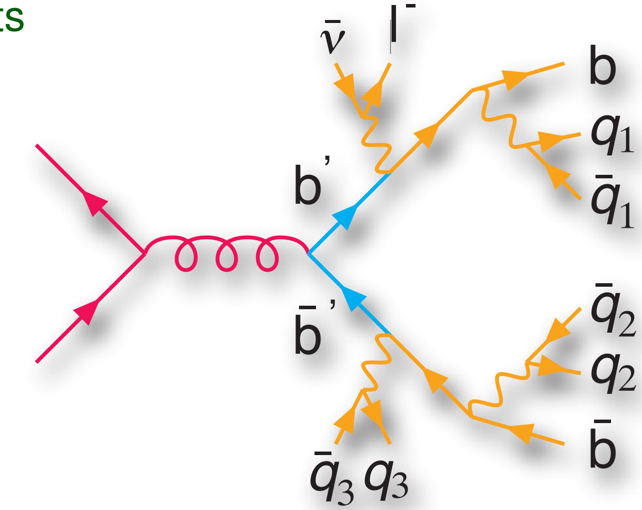
t': structure in reconstructed "top" mass distribution, H_T

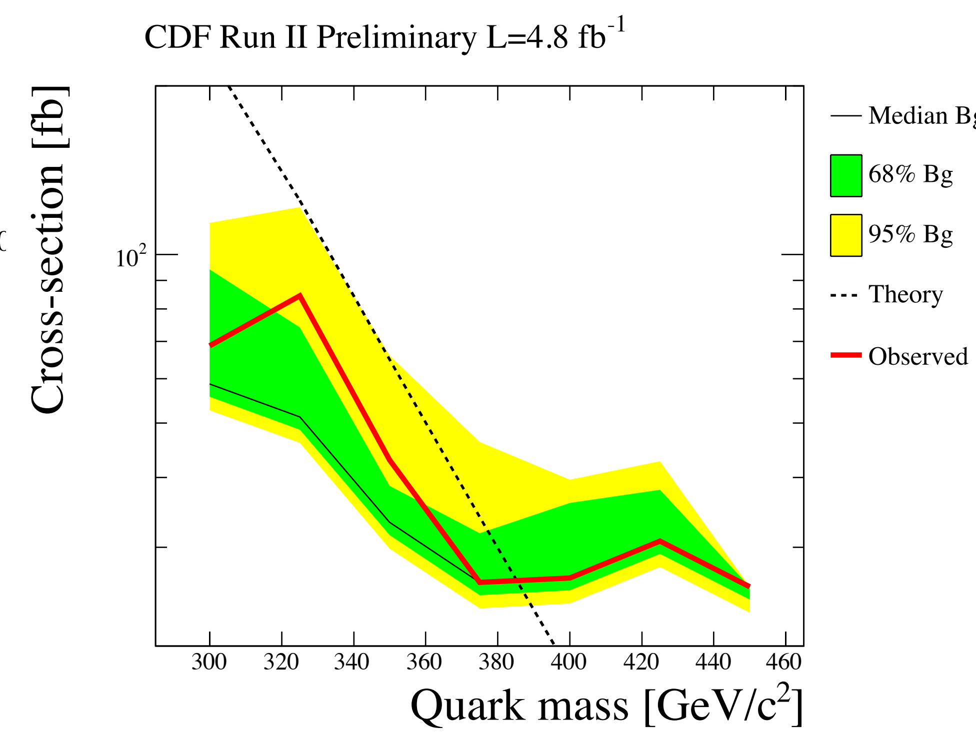


b': H_T, more jets

(consider events w/ ≥5 jets)







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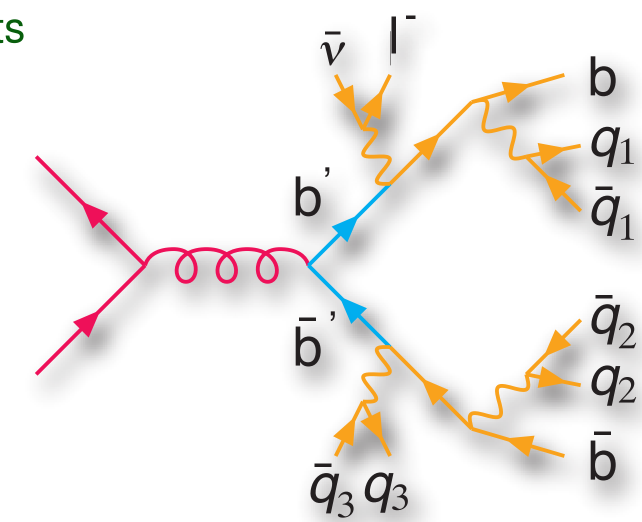
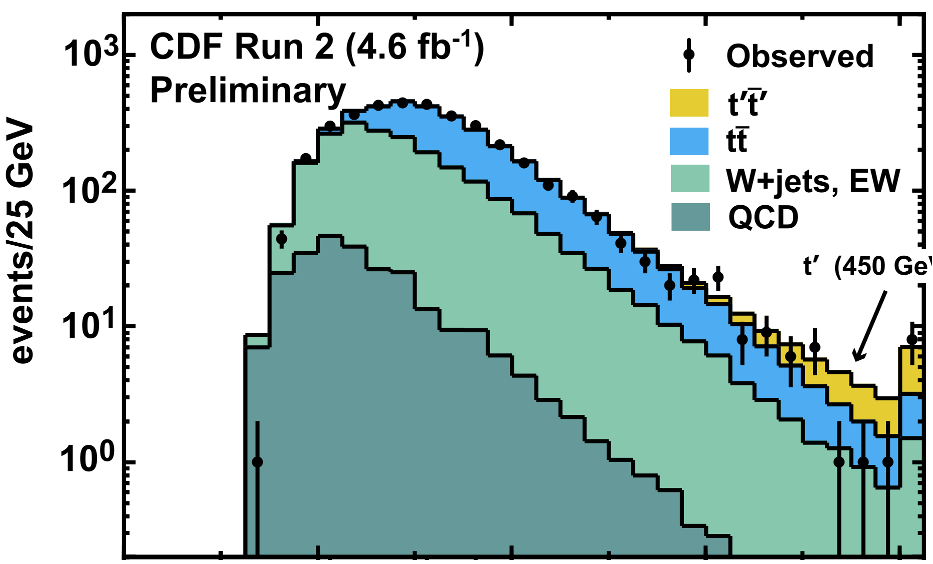
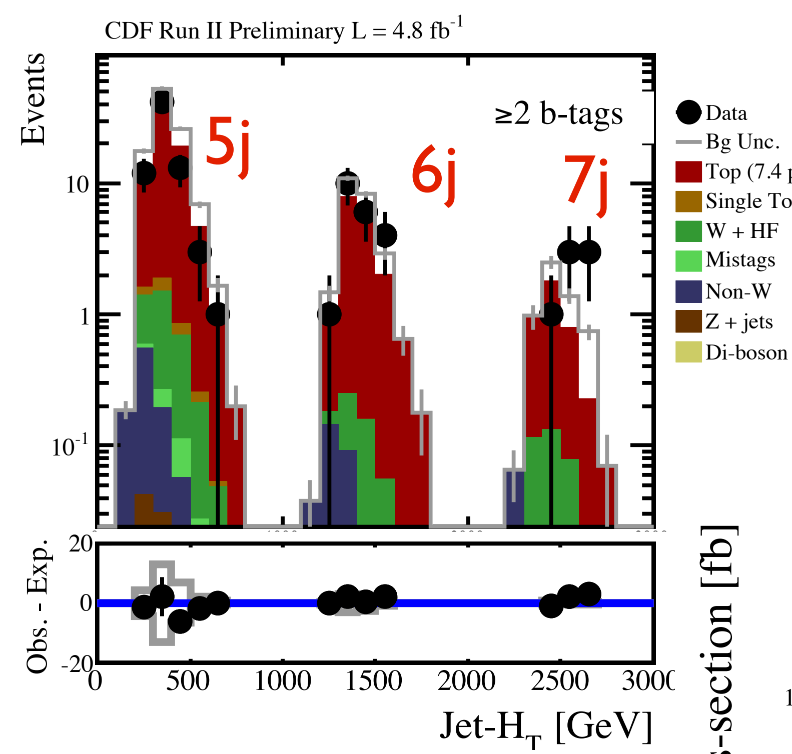
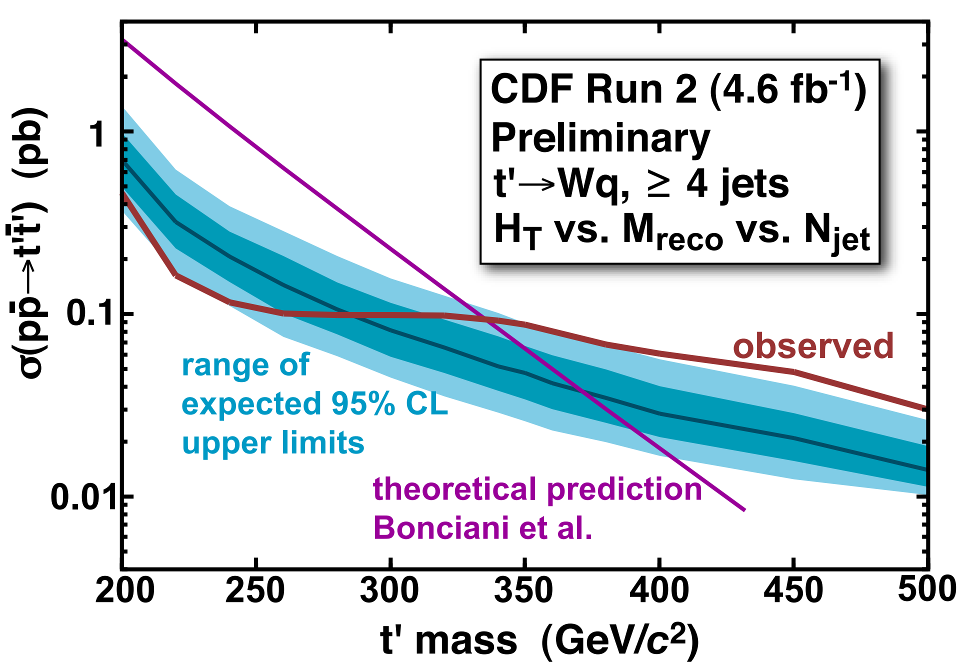
(consider events w/ ≥5 jets)

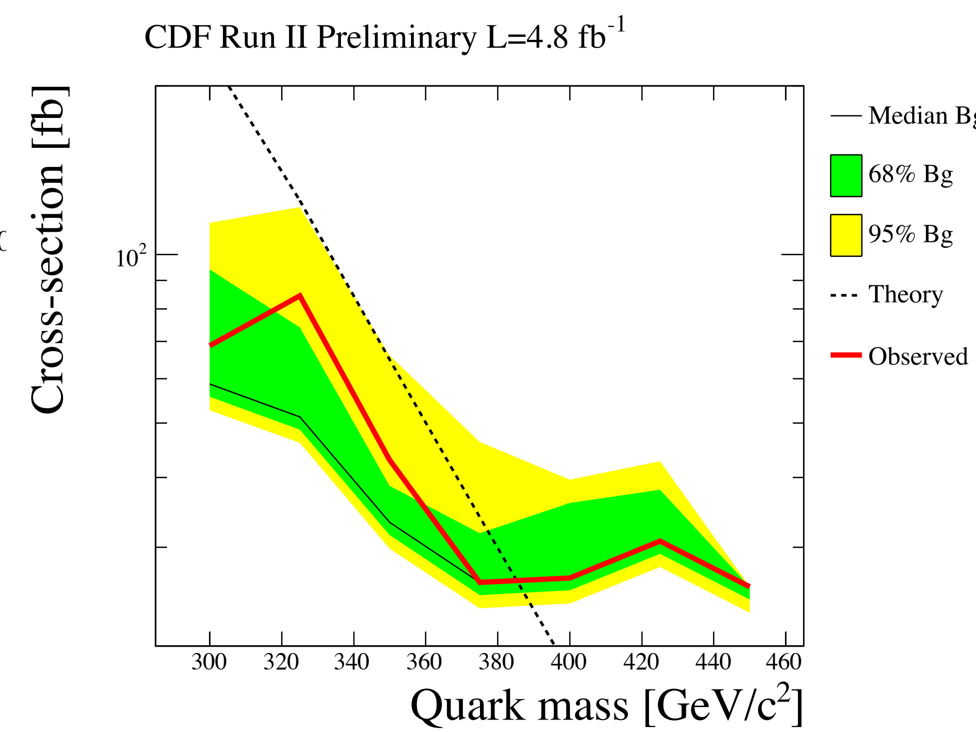








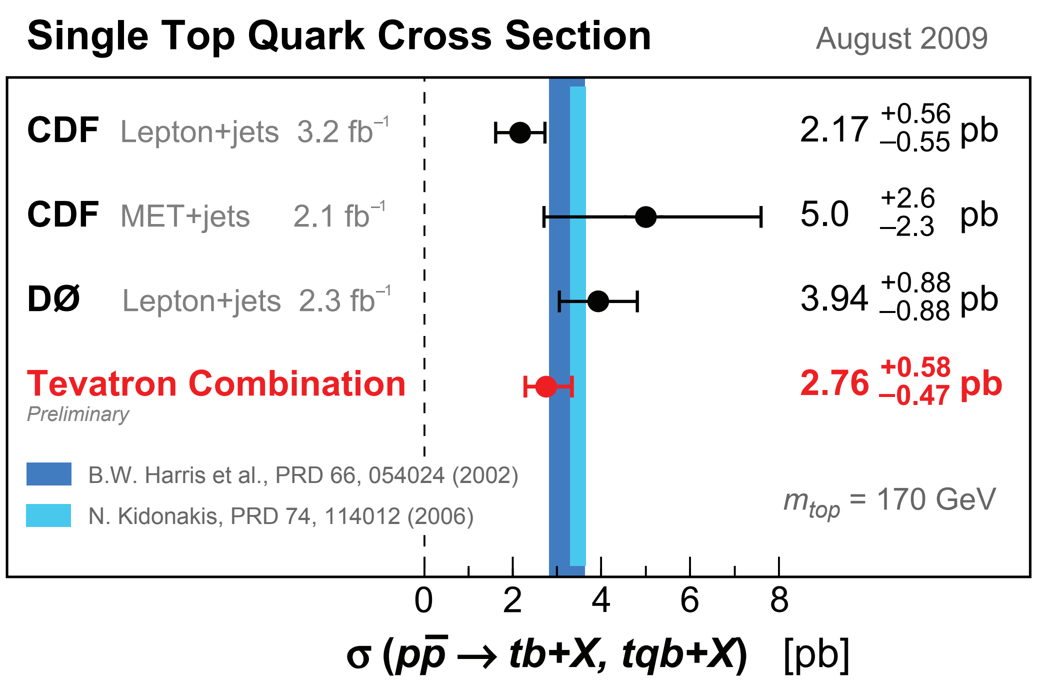
similar results by D0



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

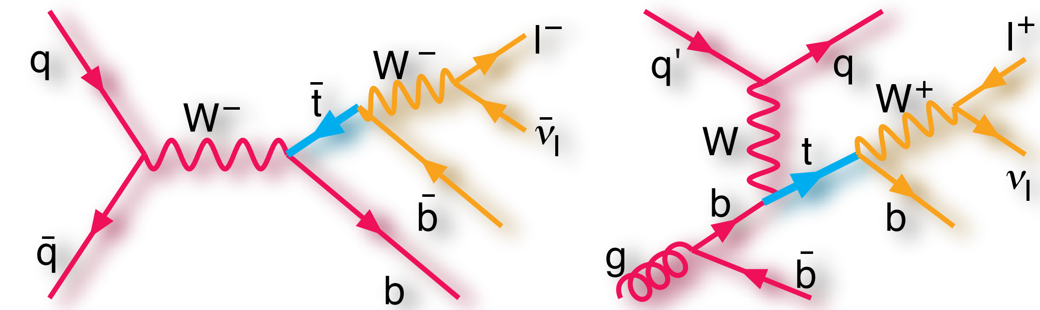
- full strength of multivariate analyses used for observation by both expts.



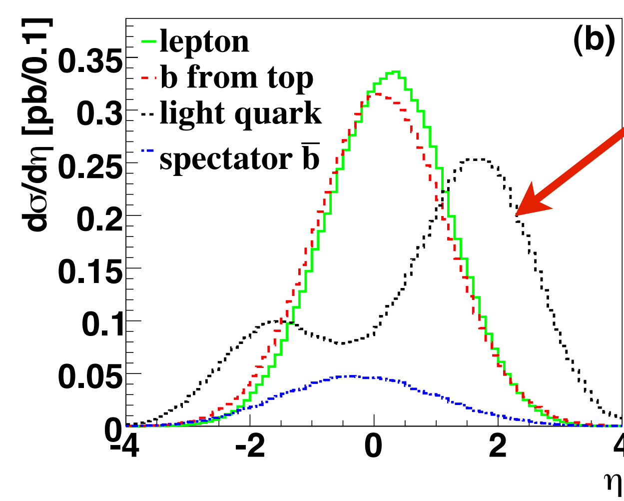
Both production cross sections are proportional to $|V_{tb}|^2$ ➠ constrain

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

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

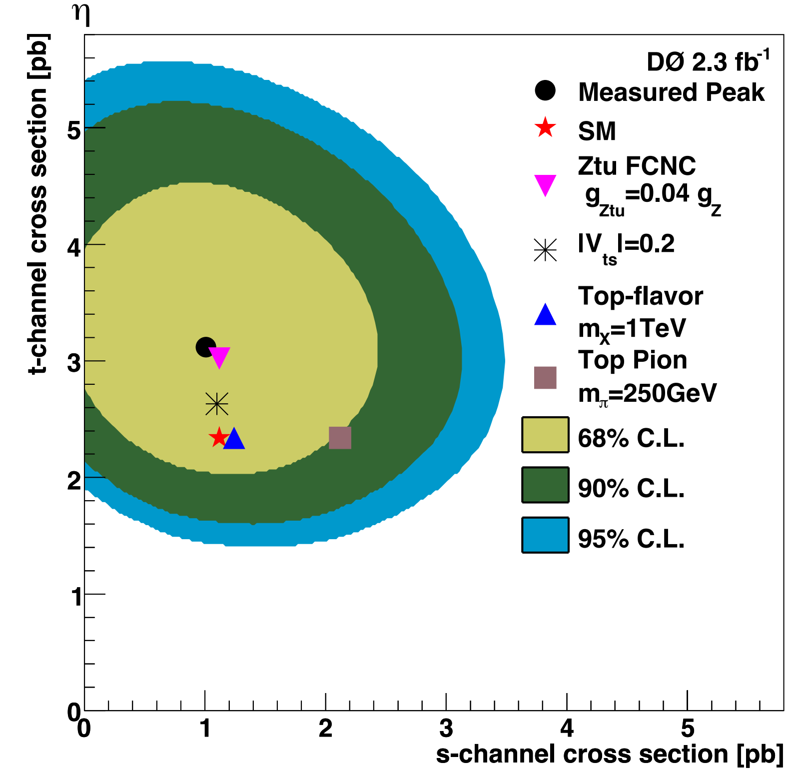


New: exploit also differences between s- and t-channel processes



light-quark η distrib. in t-channel process

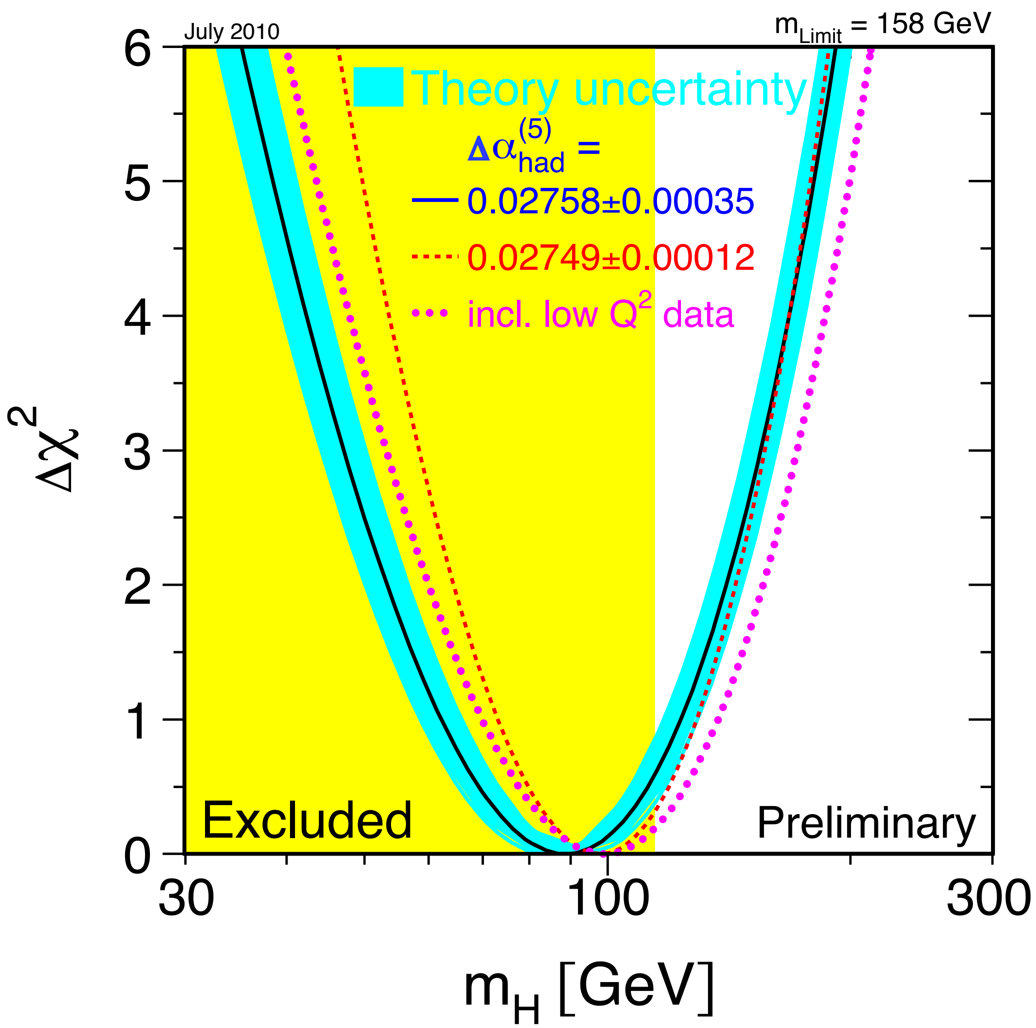
will be able to test new models with more statistics

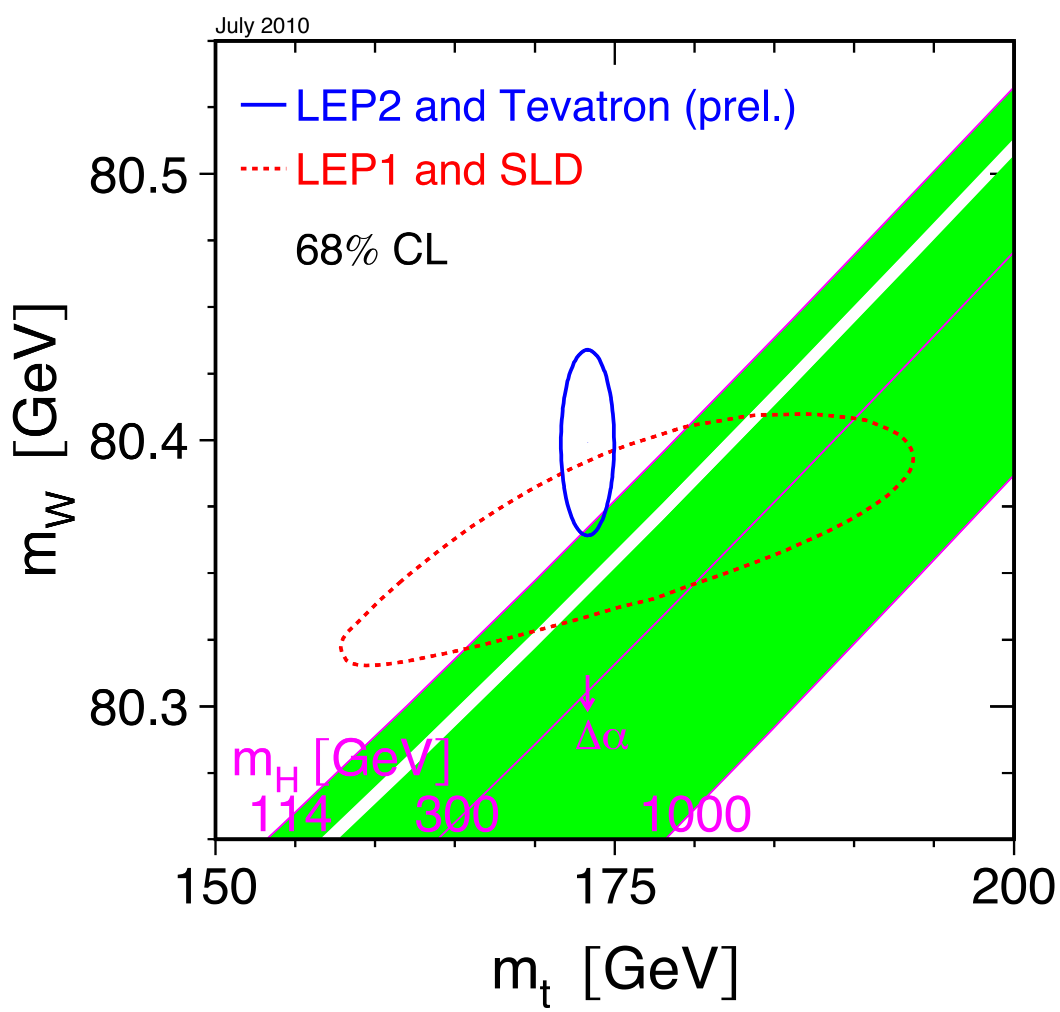


Higgs Boson Physics

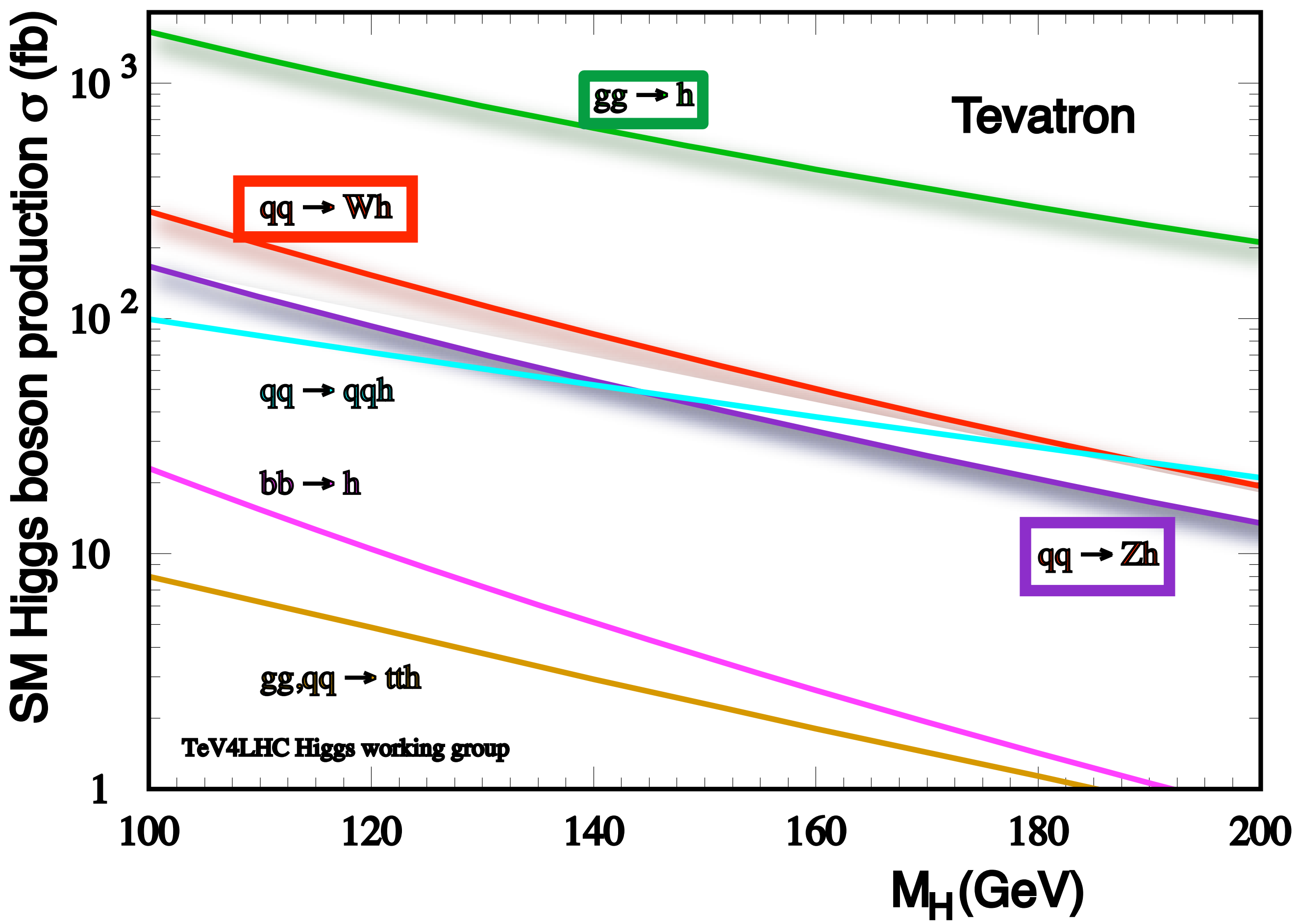
Standard Model Higgs Boson Constraints

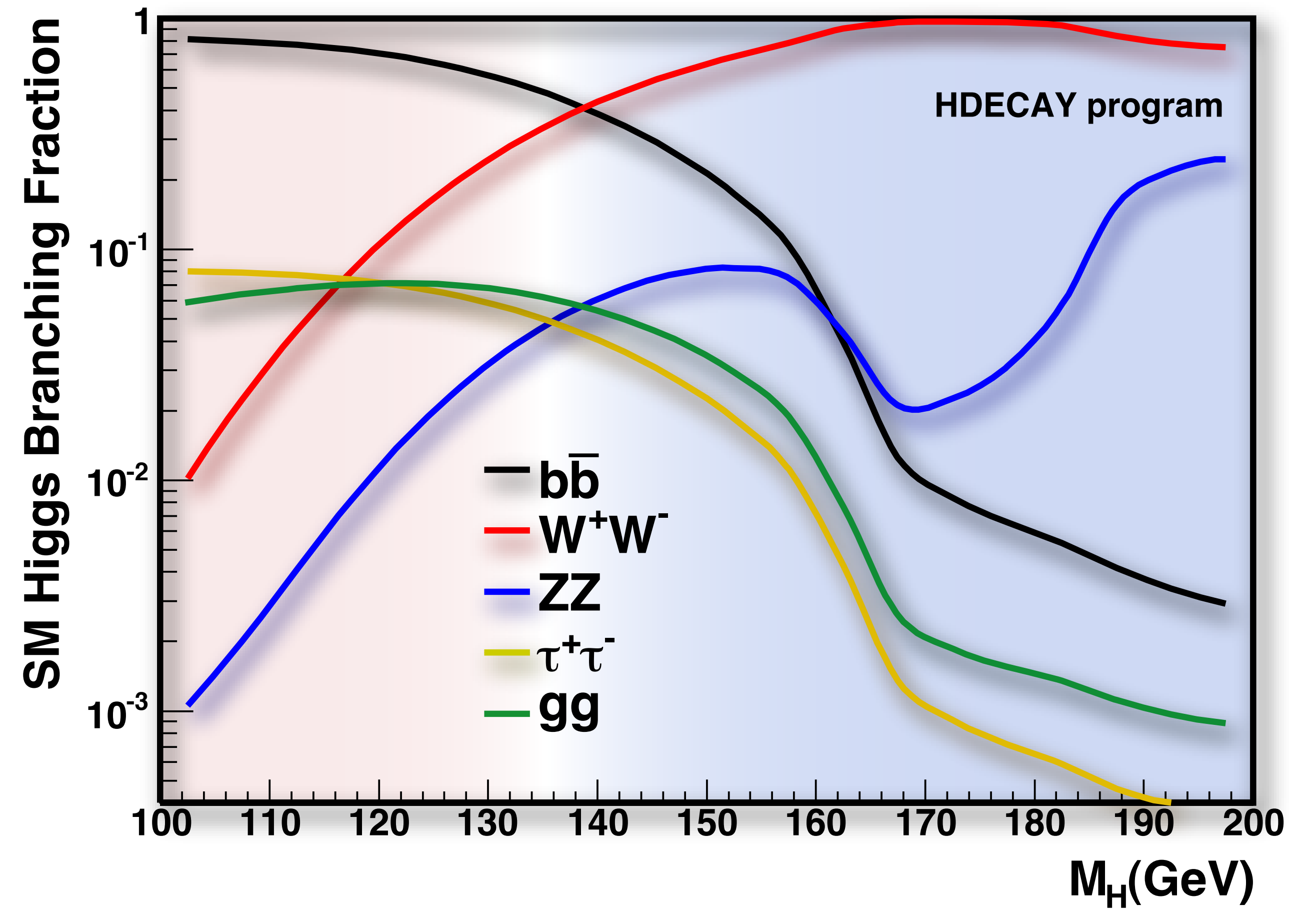
Constraints from electroweak measurements (dominated by the Tevatron's M_W and m_t measurements!) indicate a relatively light Higgs boson





Standard Model Higgs Boson Phenomenology





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

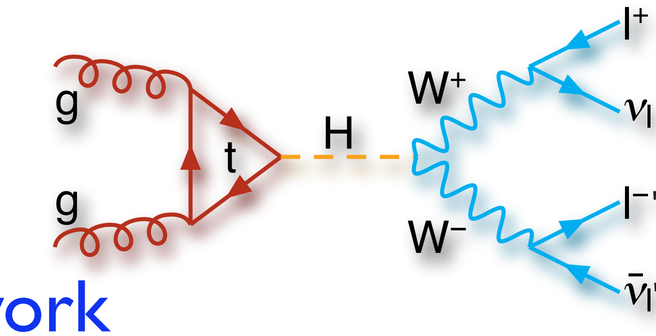
- like at the LHC

For M_H < 135 GeV: H→bb hopeless if produced in isolation. Fortunately, in proton-antiproton collisions, antiquarks are readily available

- associated production: HW, HZ

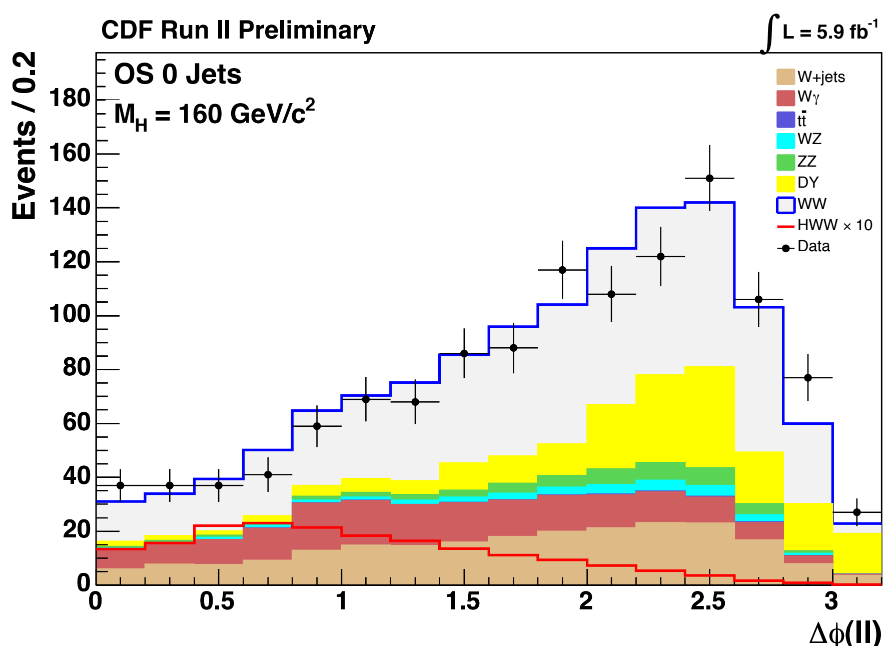
In the following, show merely 2 representative searches (~ 100 channels total!)

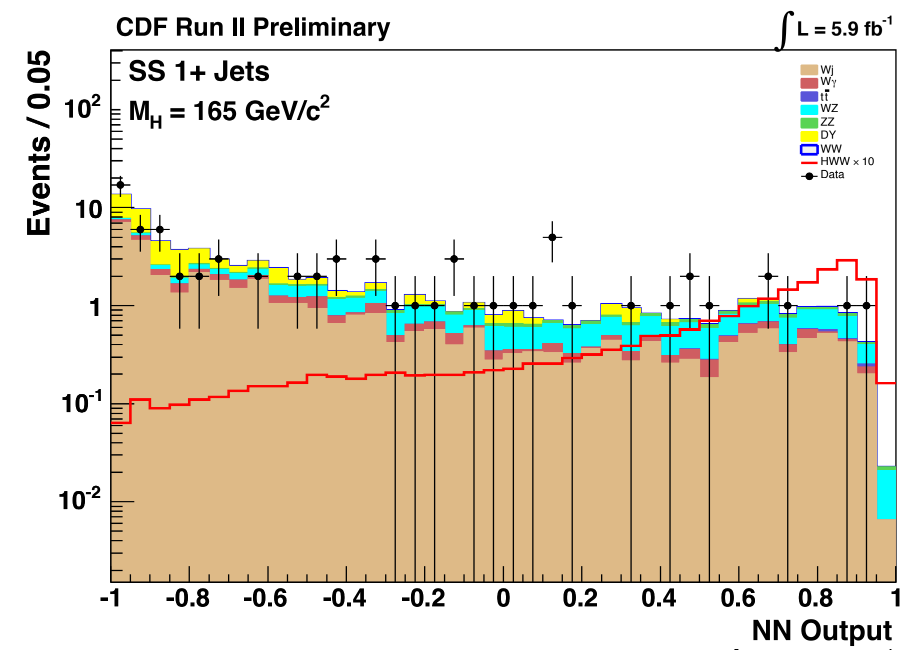
Example: High M_H

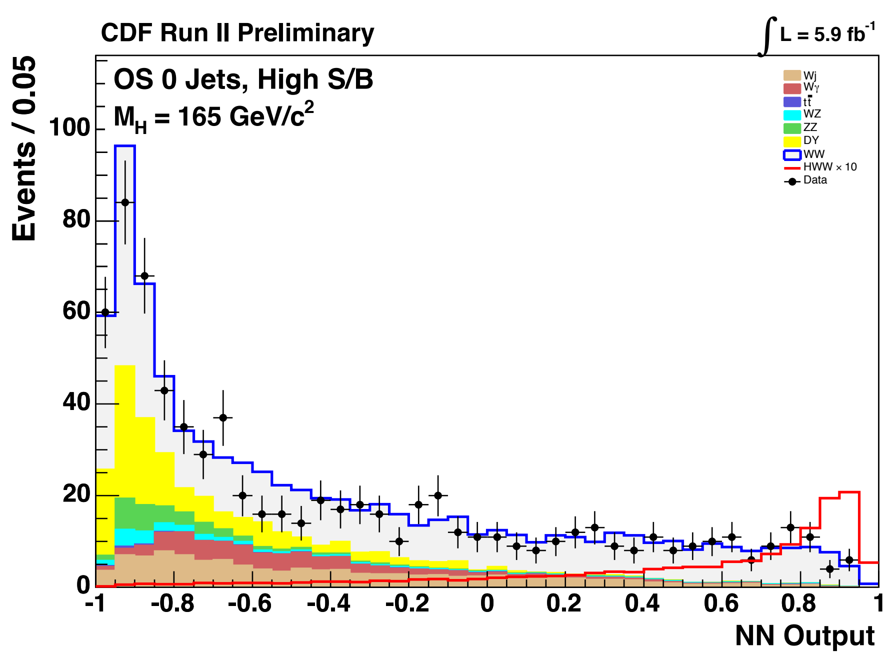


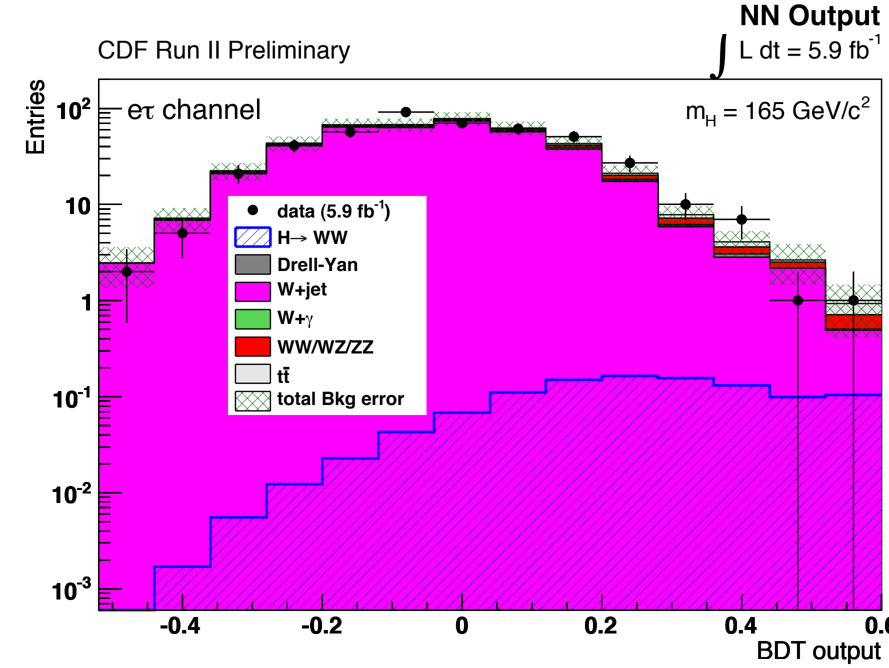
CDF H→WW analysis, 5.9 fb^{-1}: clean, but still needs hard work

- DY rejection, spin correlations, NN/BDT using Matrix Element analyses
- include also WH (same-sign leptons), WW→lτνν

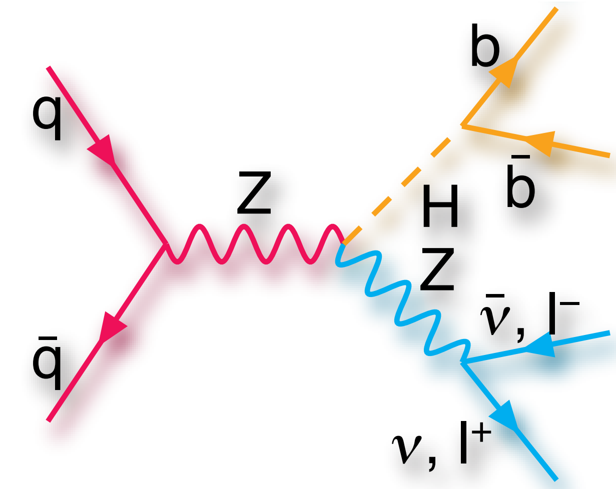






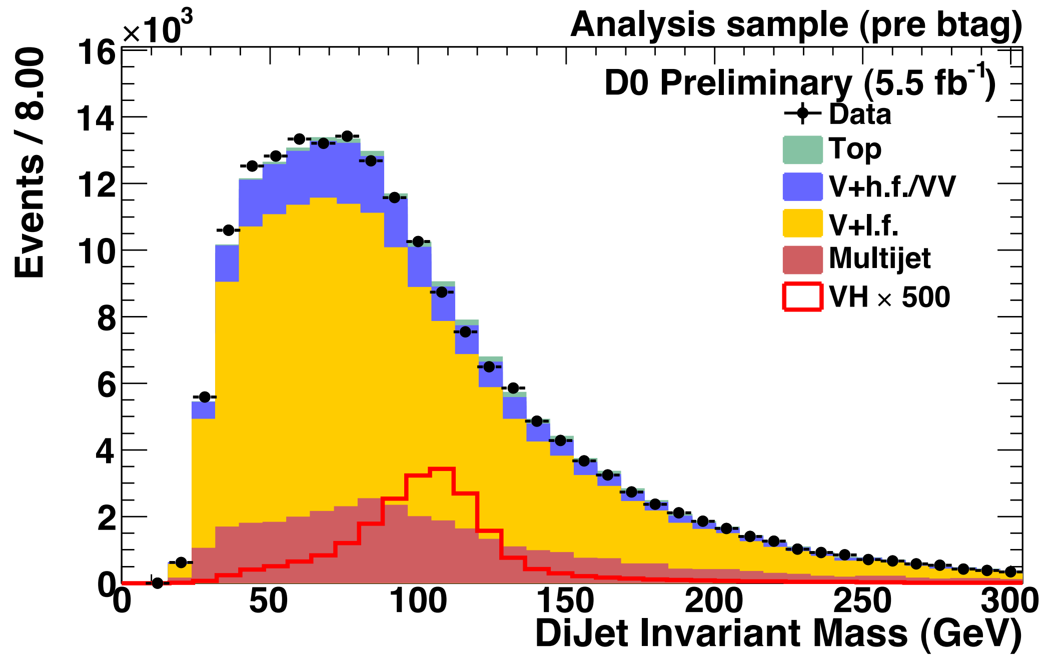


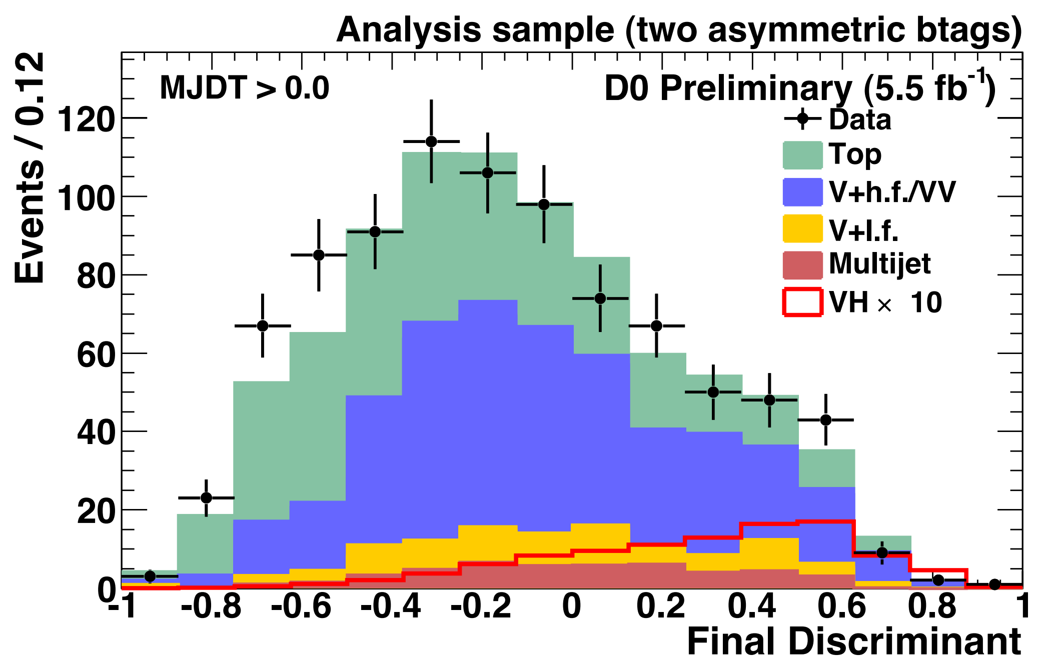
Example: Low M_H



D0 ZH→ννbb 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→lν one

- CDF/D0 performance generally very similar

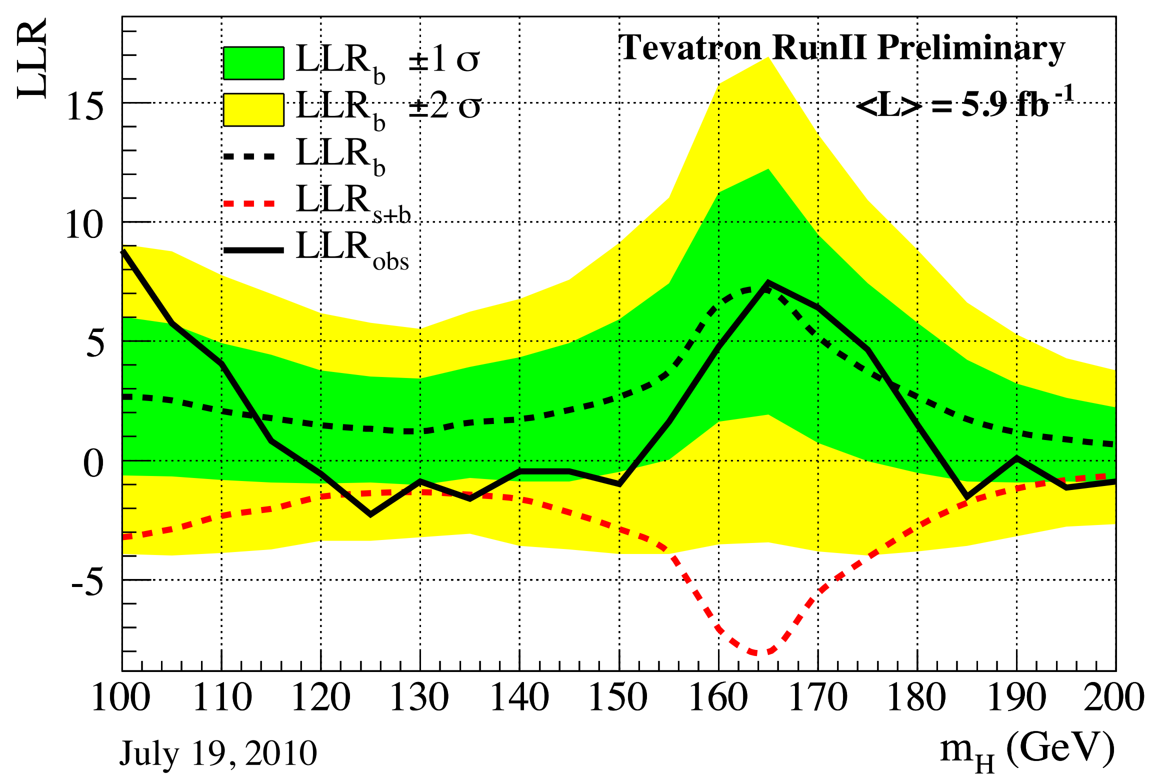
General strategy: combine all channels, including less performant ones

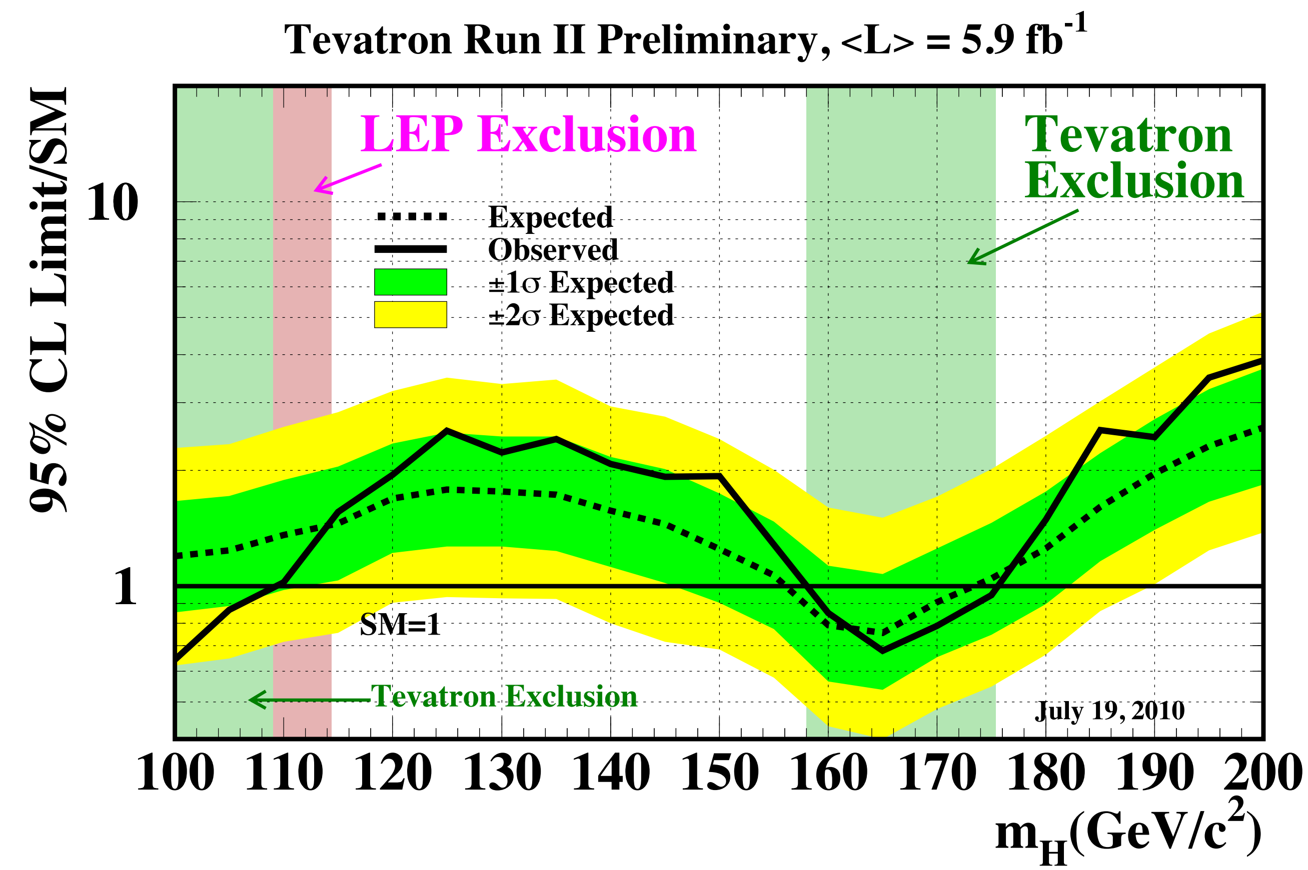
- WH (high M_H)
- ZH→llbb, WH→τν (low M_H)

Combined Results

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

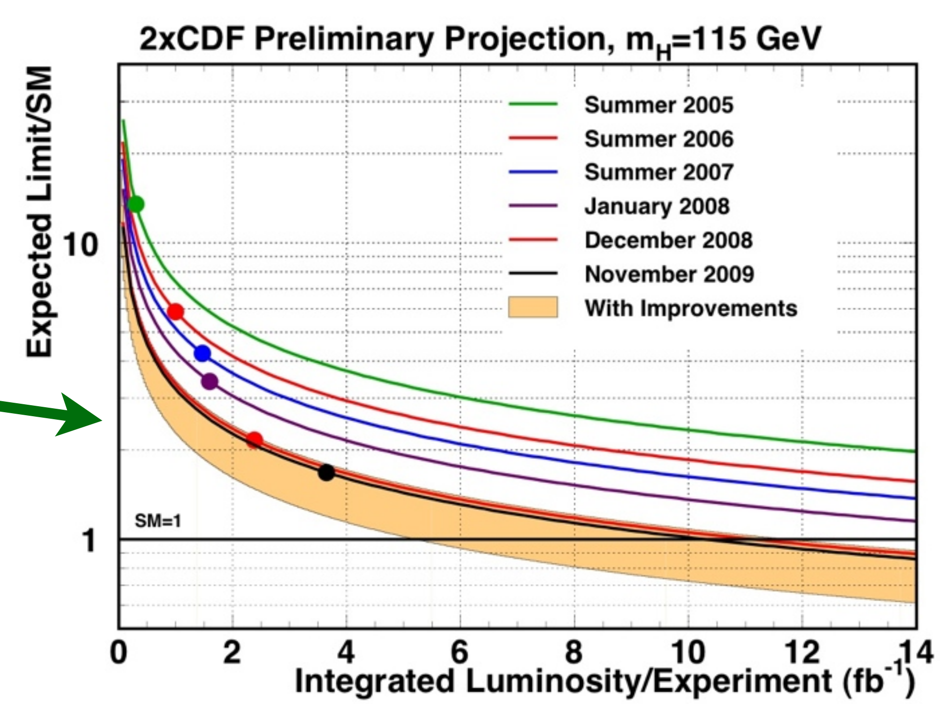
(NB: not yet using all latest results)





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!

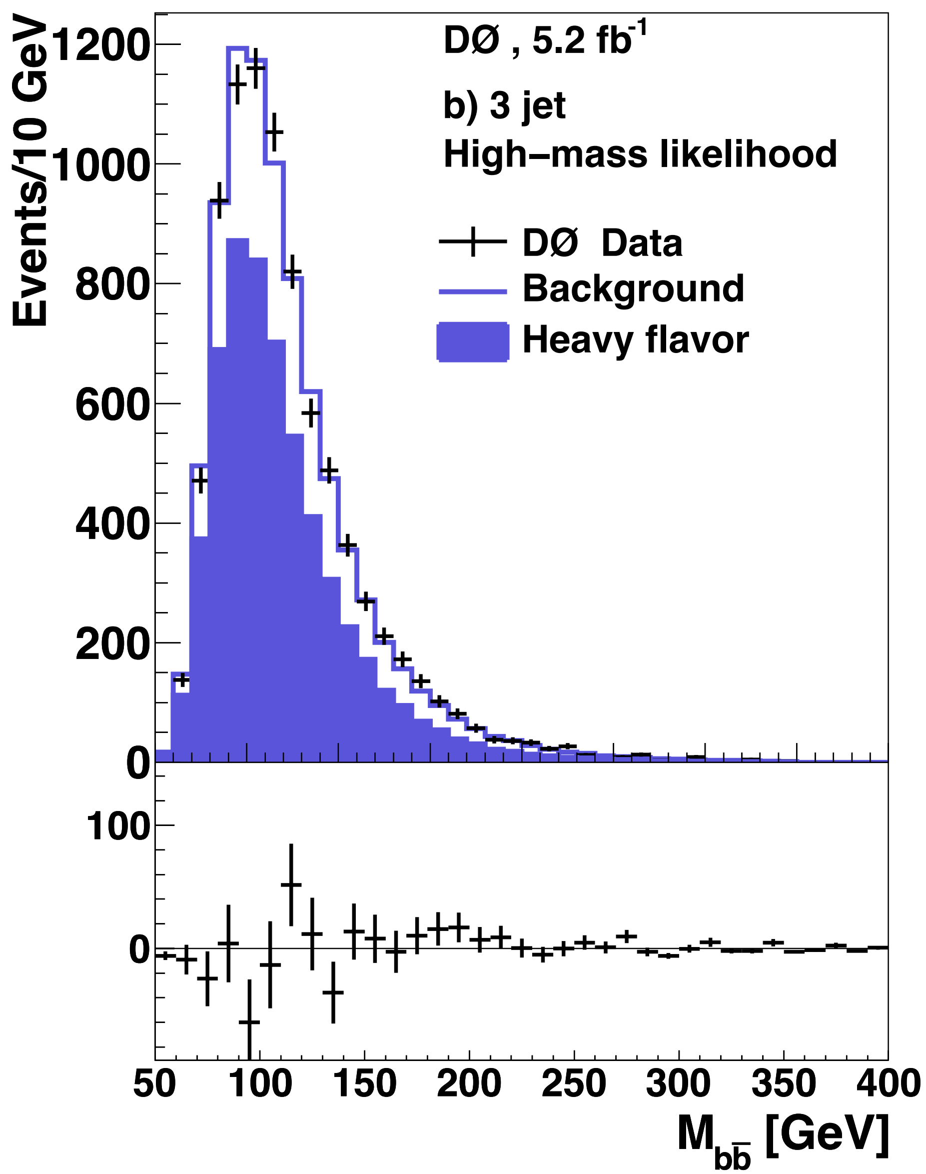
- recommended by P5, awaiting $$

Neutral MSSM Higgs Bosons

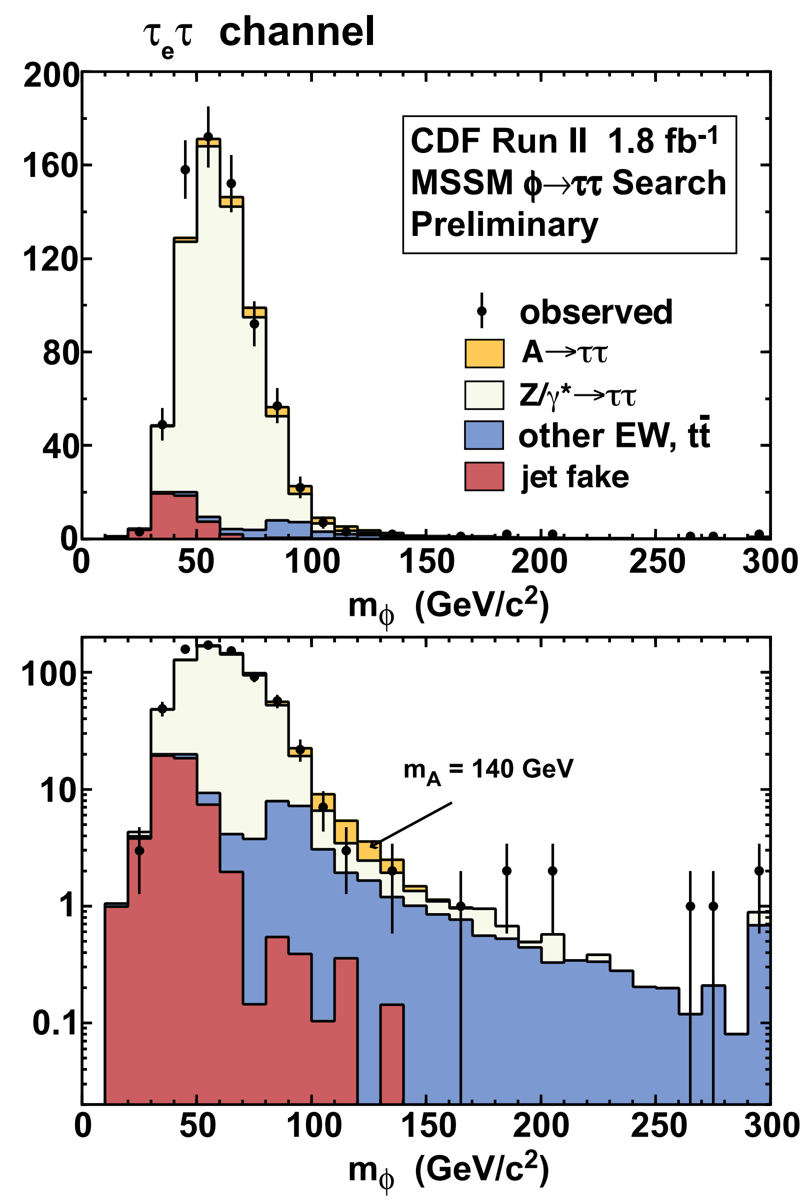
MSSM Higgs sector described by two parameters: M_A, tanβ (radiative corr. aside)

Exploit increased coupling to b-quarks & τ leptons at high tanβ, near degeneracy between A and H/h ("ϕ")

ϕ→bb: in association with b-jet



ϕ→ττ: both with/without addl. b-jet



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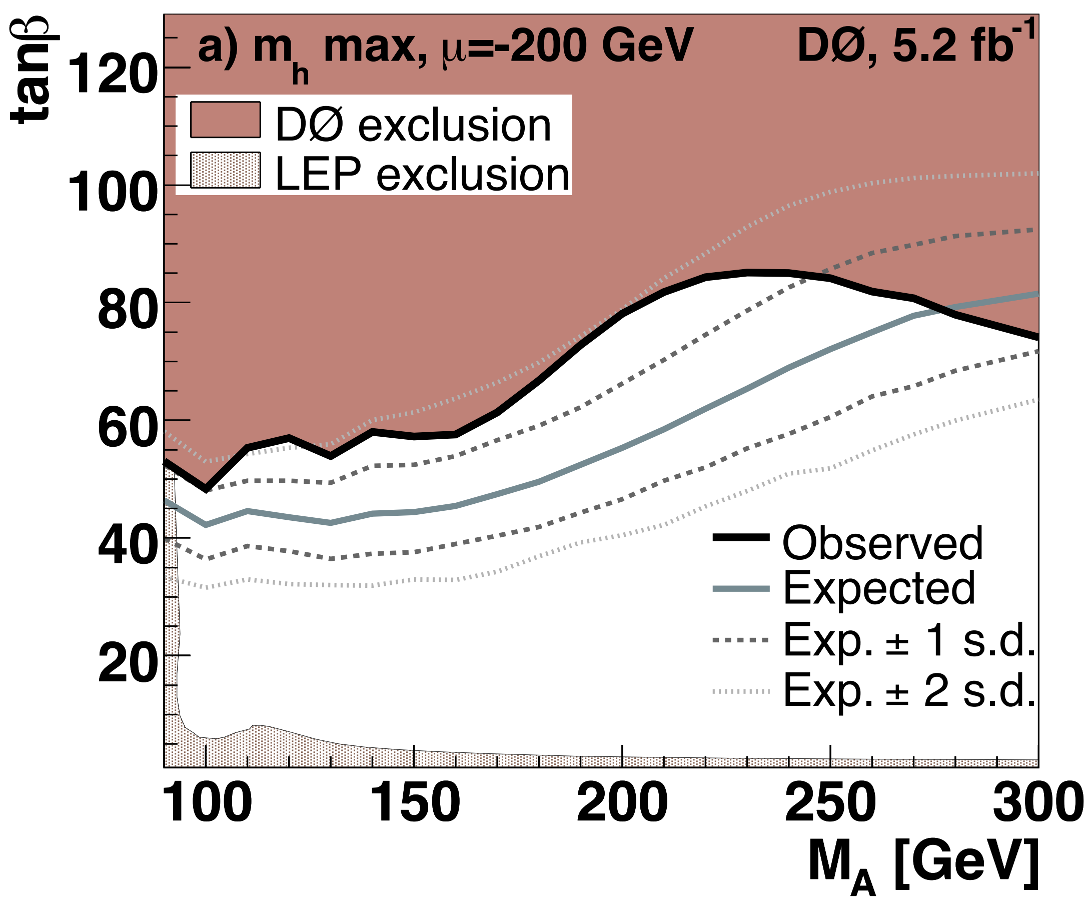
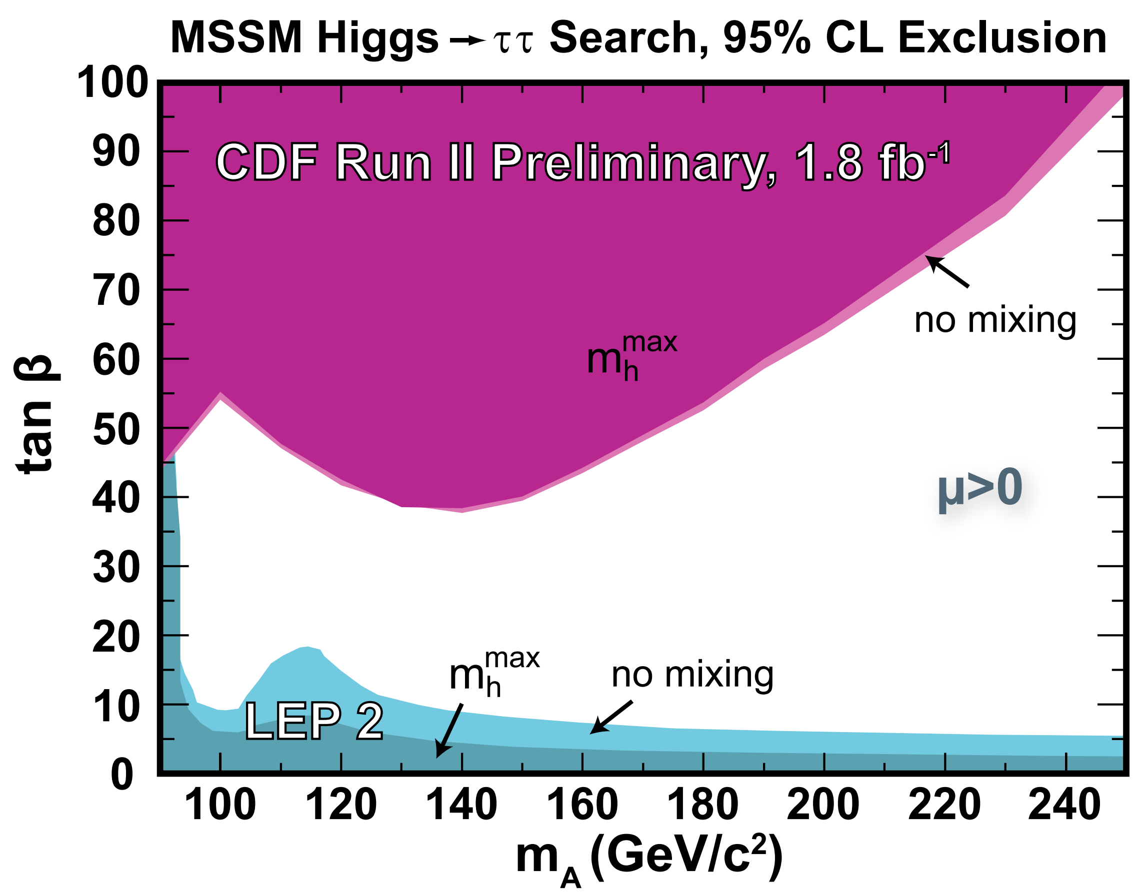
$\phi \to bb$: in association with b-jet

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





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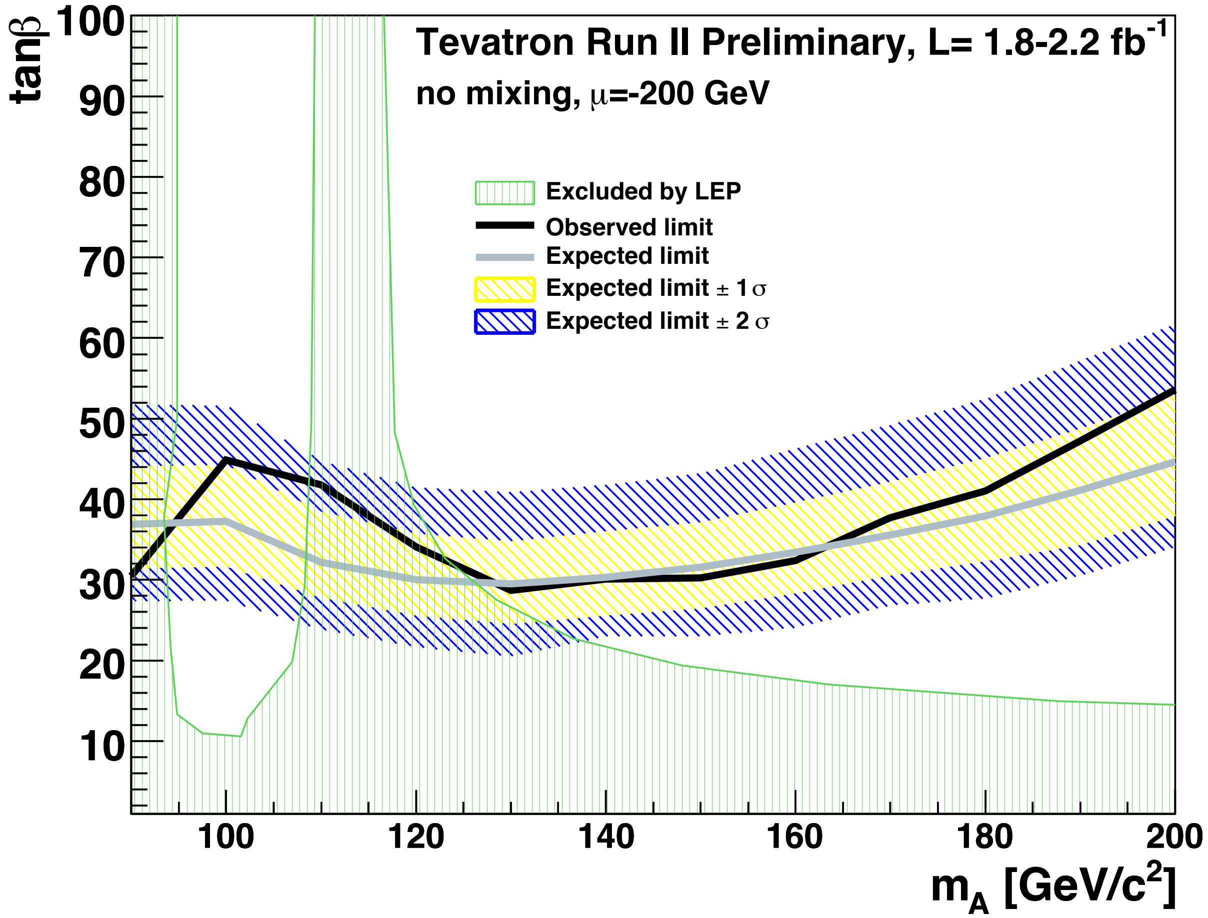

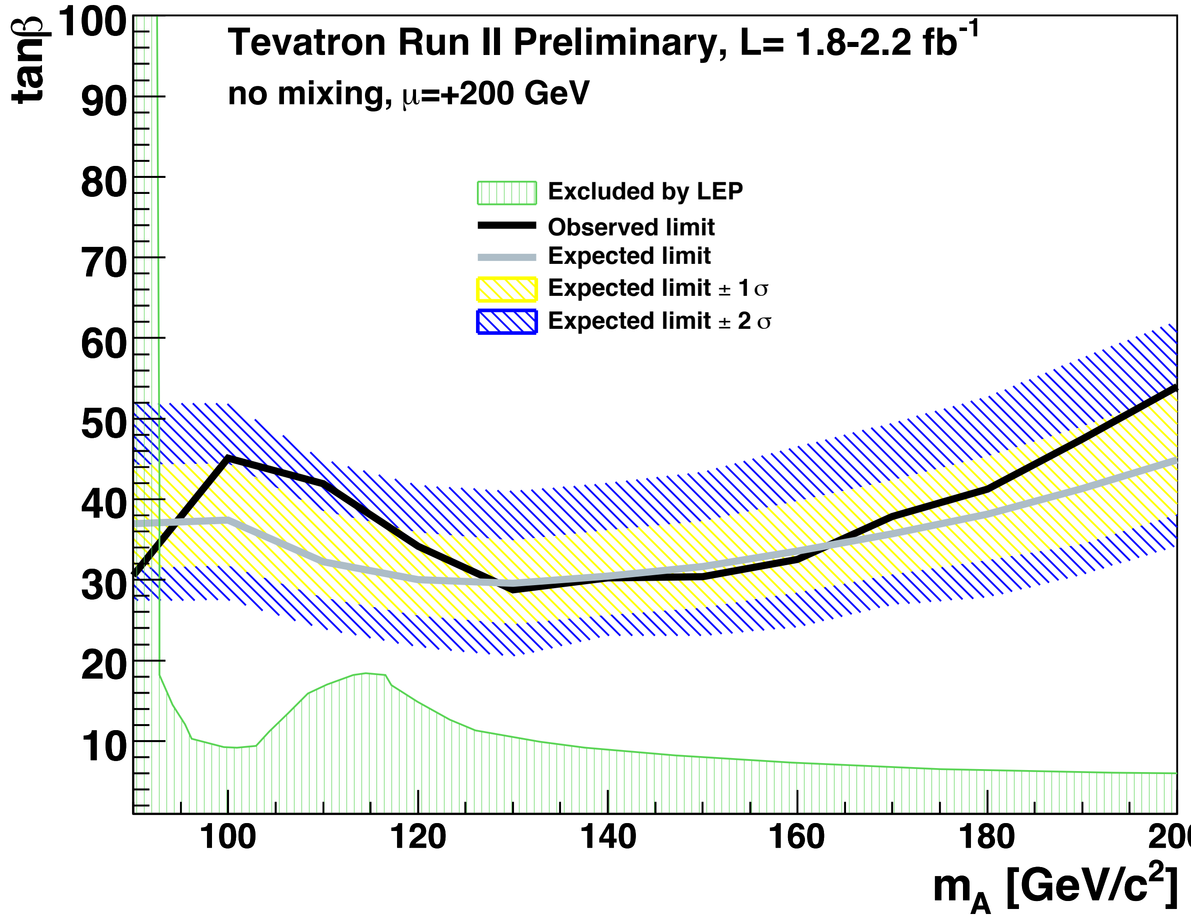

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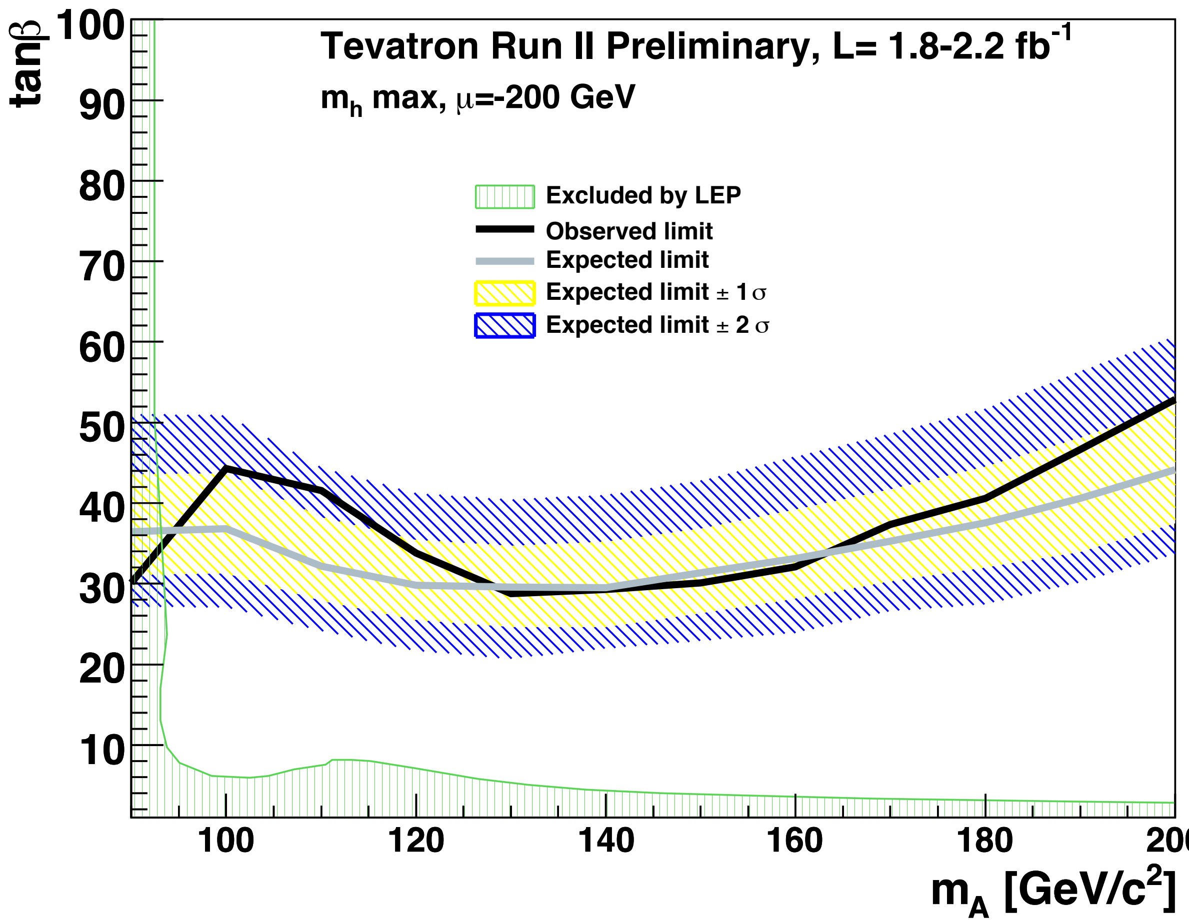
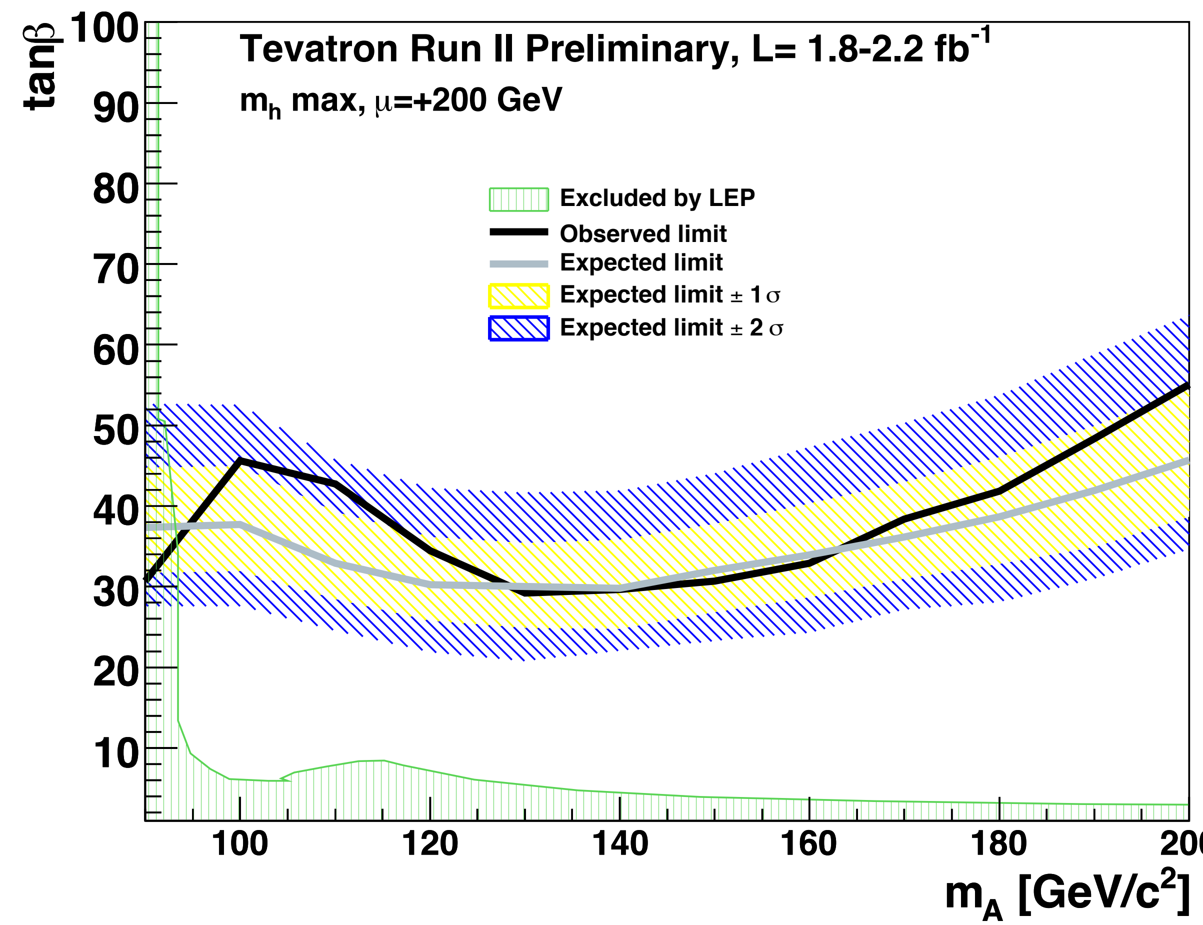
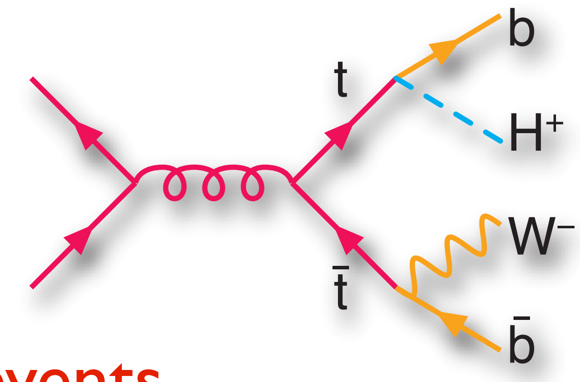




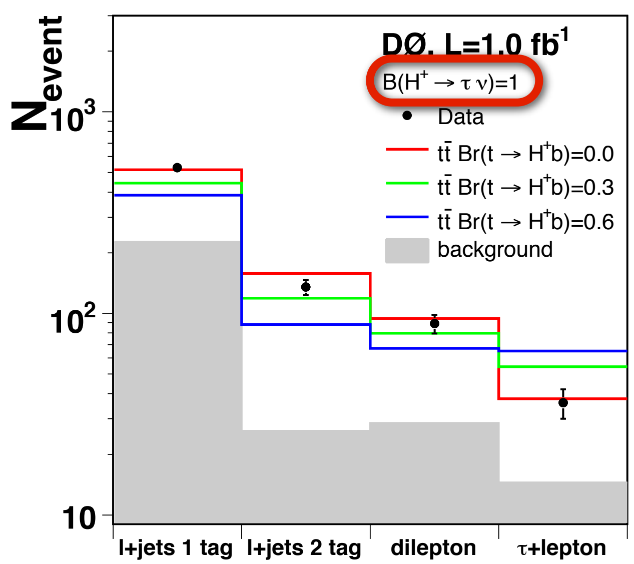
Charged MSSM Higgs Bosons

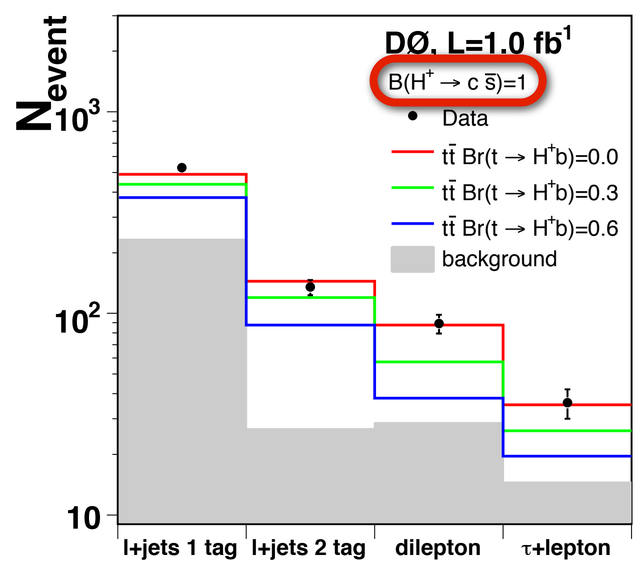


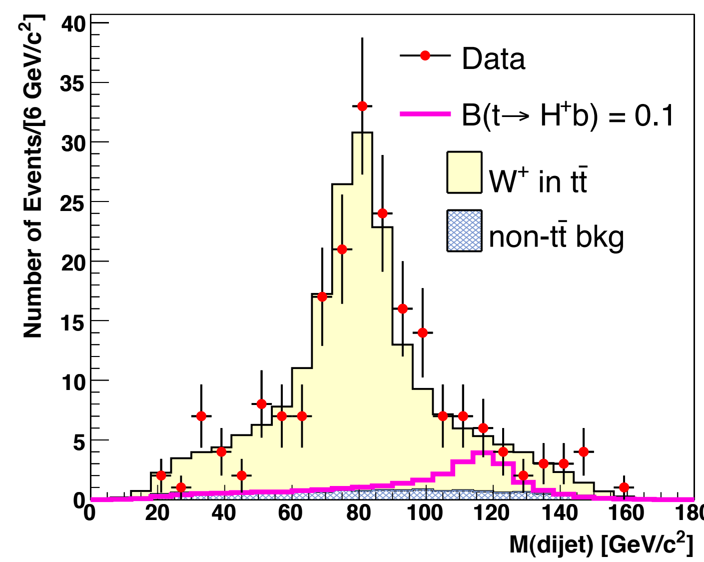
Focus on $t \to H^+b$ decays (heavy $H \to tb$ out of Tevatron reach):
exploited in multiple ways to search for $H \to \tau\nu$, cs decays in tt events

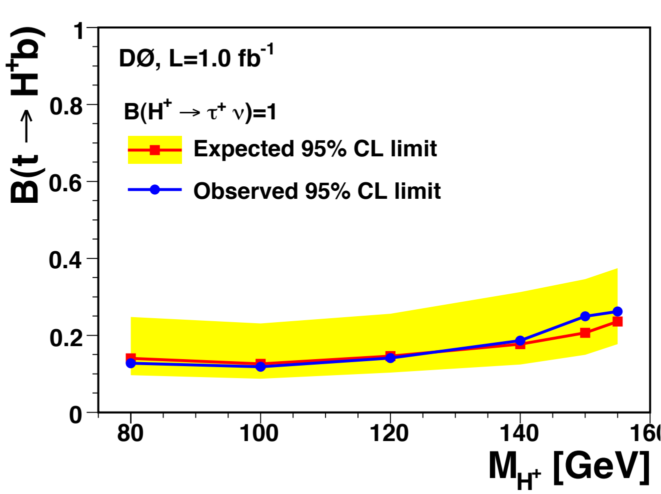
modified distribution of tt events over l+jets, l+l, and l+τ_{had} FS

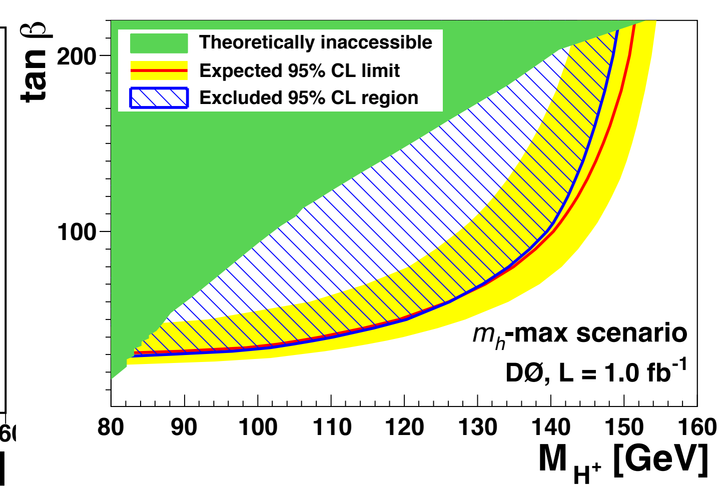
peak in l+jets di-jet invariant mass spectrum ($H \to cs$)

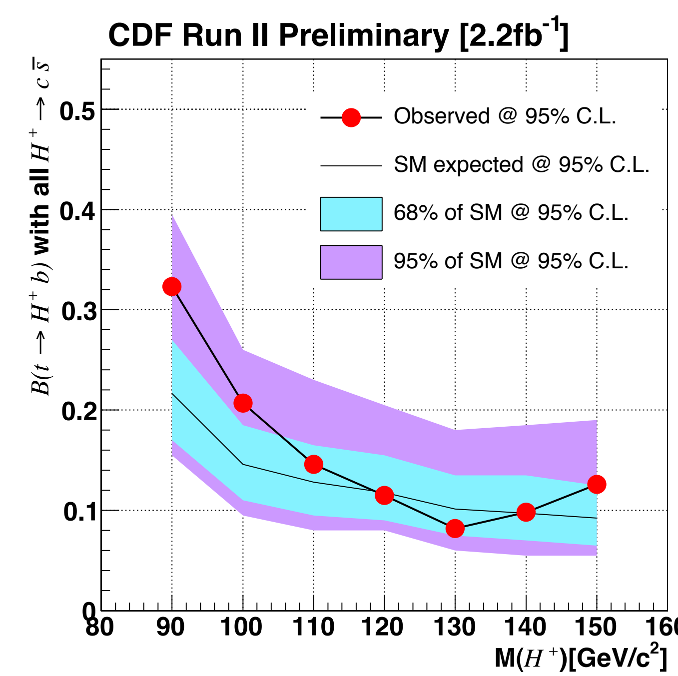












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Conclusion & Outlook

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:

- $D\overline{D}$ mixing, CP violation in $D^0 \rightarrow K\pi$
- Observation & study of X(3872)
- Observation of Ω_b, Ξ_b, Σ_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

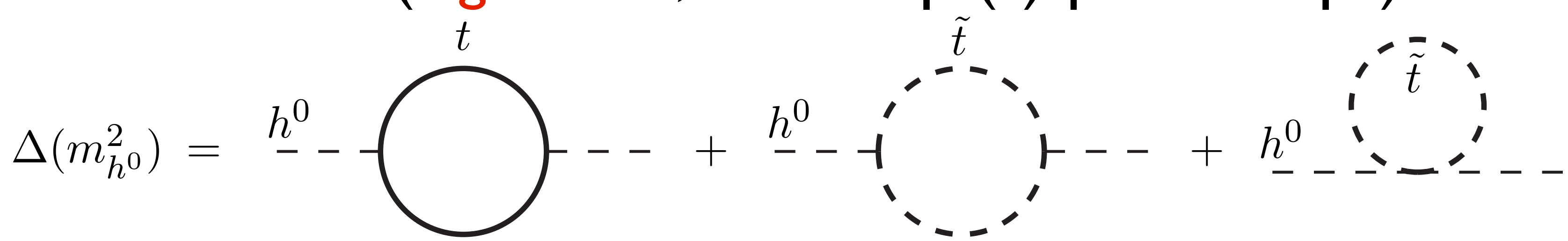
Higgs physics:

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

Backup

Beyond Tree Level

Substantial corrections (e.g. to m_h, from top (s)quark loops)



- mass/coupling dependence on other SUSY parameters

Embodied in several scenarios (allowing to evade LEP bounds)

Scenario	m_h^{max}	no-mixing	gluophobic	small α_{eff}
$\tilde{t}_1$, $\tilde{t}_2$ mixing parameter X_t	2 TeV	0	-0.75 TeV	-1.1 TeV
Higgs bilinear coupling μ	$\pm$200 GeV	$\pm$200 GeV	$\pm$300 GeV	2 TeV
SU(2) gaugino mass M_2	200 GeV	200 GeV	300 GeV	500 GeV
gaugino mass $m_{\tilde{g}}$	0.8 TeV	1.6 TeV	0.5 TeV	0.5 TeV
sfermion SUSY breaking parm. M_{SUSY}	1 TeV	2 TeV	0.35 TeV	0.8 TeV

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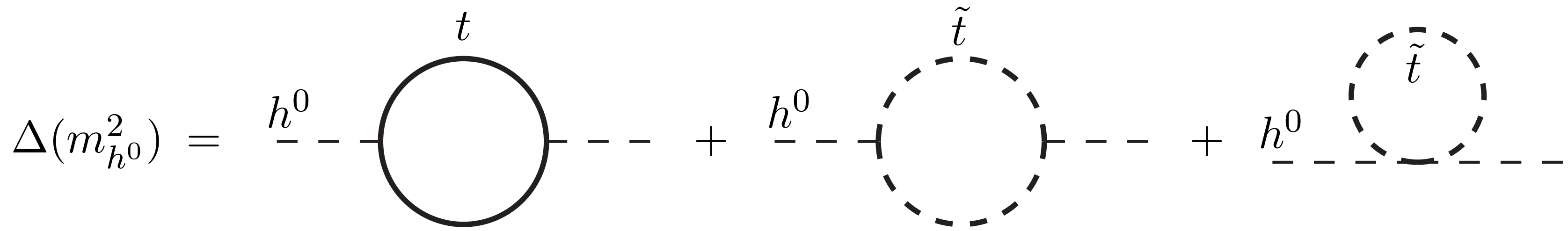

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tuned to maximize m_h

between top squarks

suppressed $gg \to h$

suppressed $h \to bb, \tau\tau$

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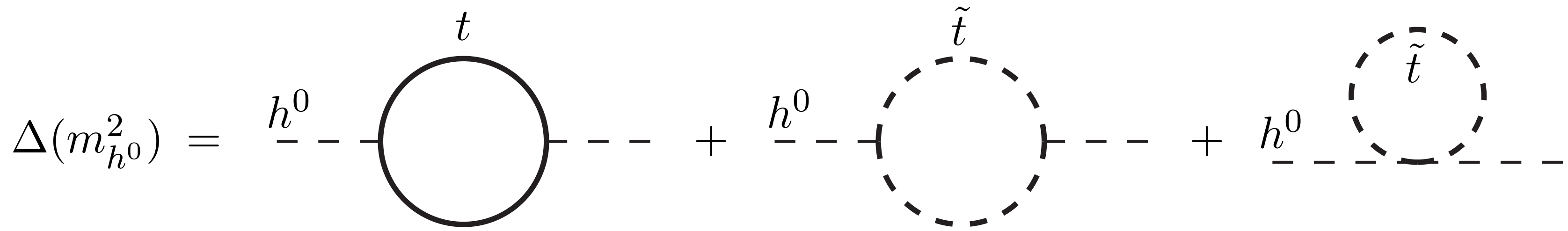

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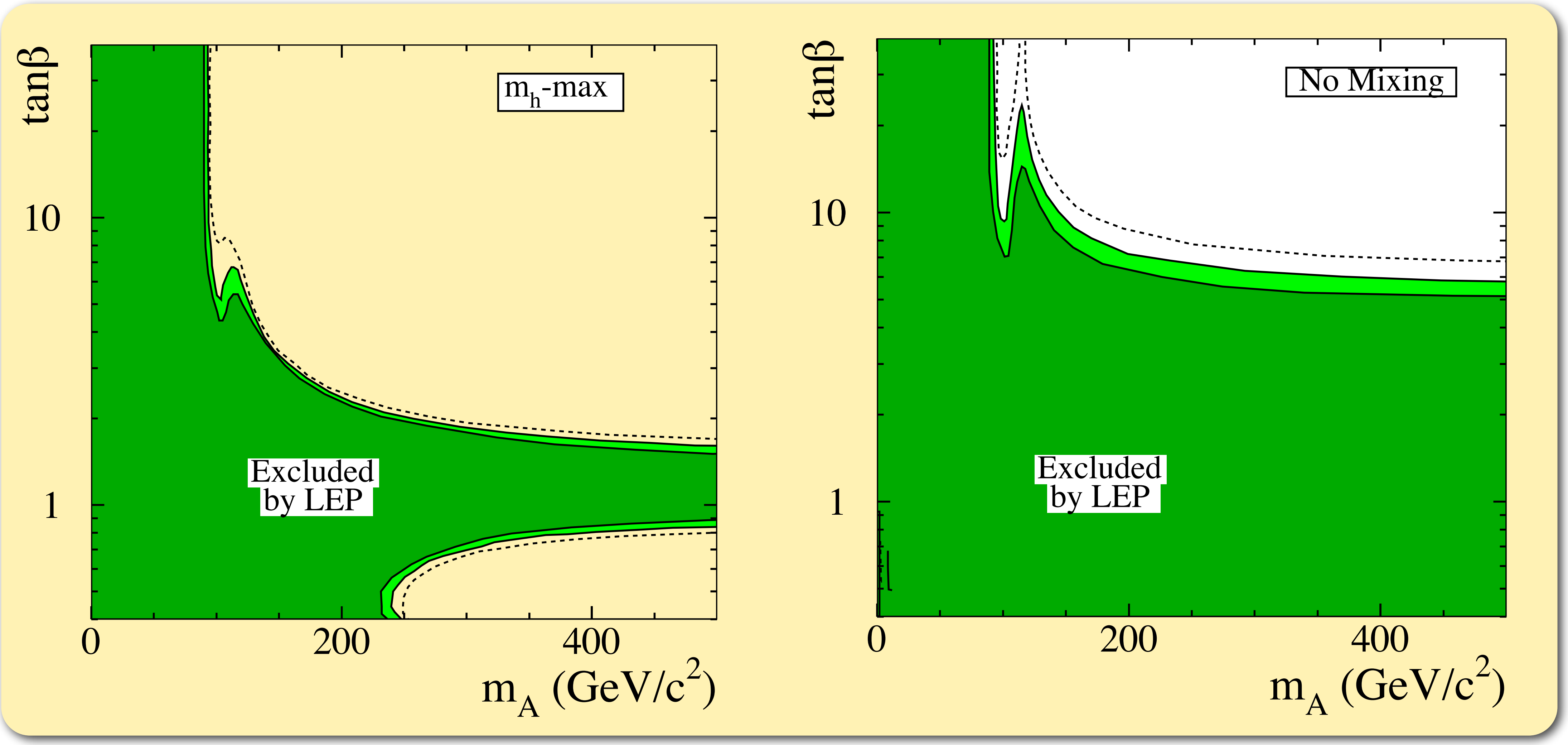
Main focus of Tevatron analyses

MSSM Higgs Production at the Tevatron

LEP analyses focused on ZH associated production

exclusion mainly at low tanβ



MSSM Higgs Production at the Tevatron

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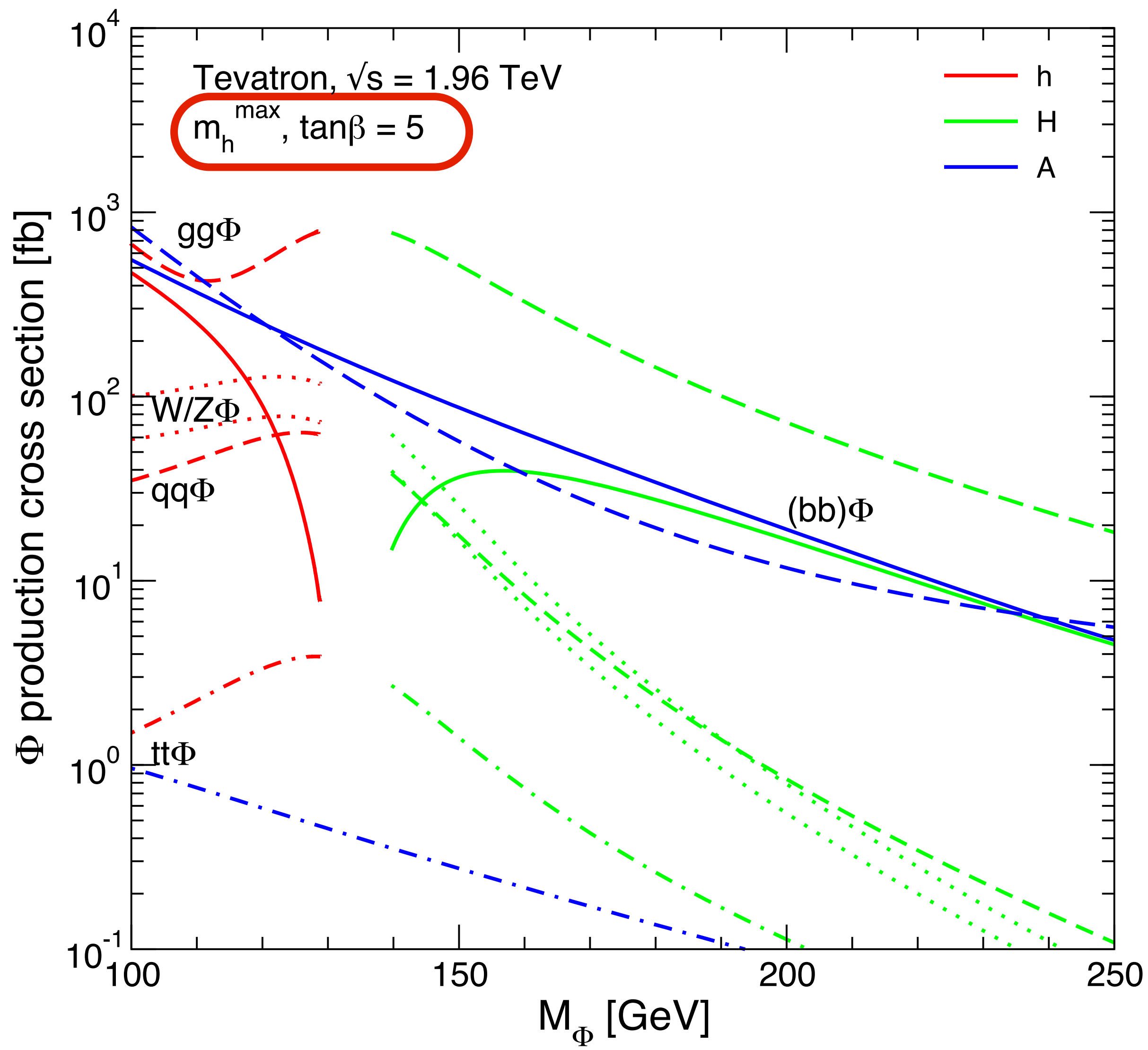
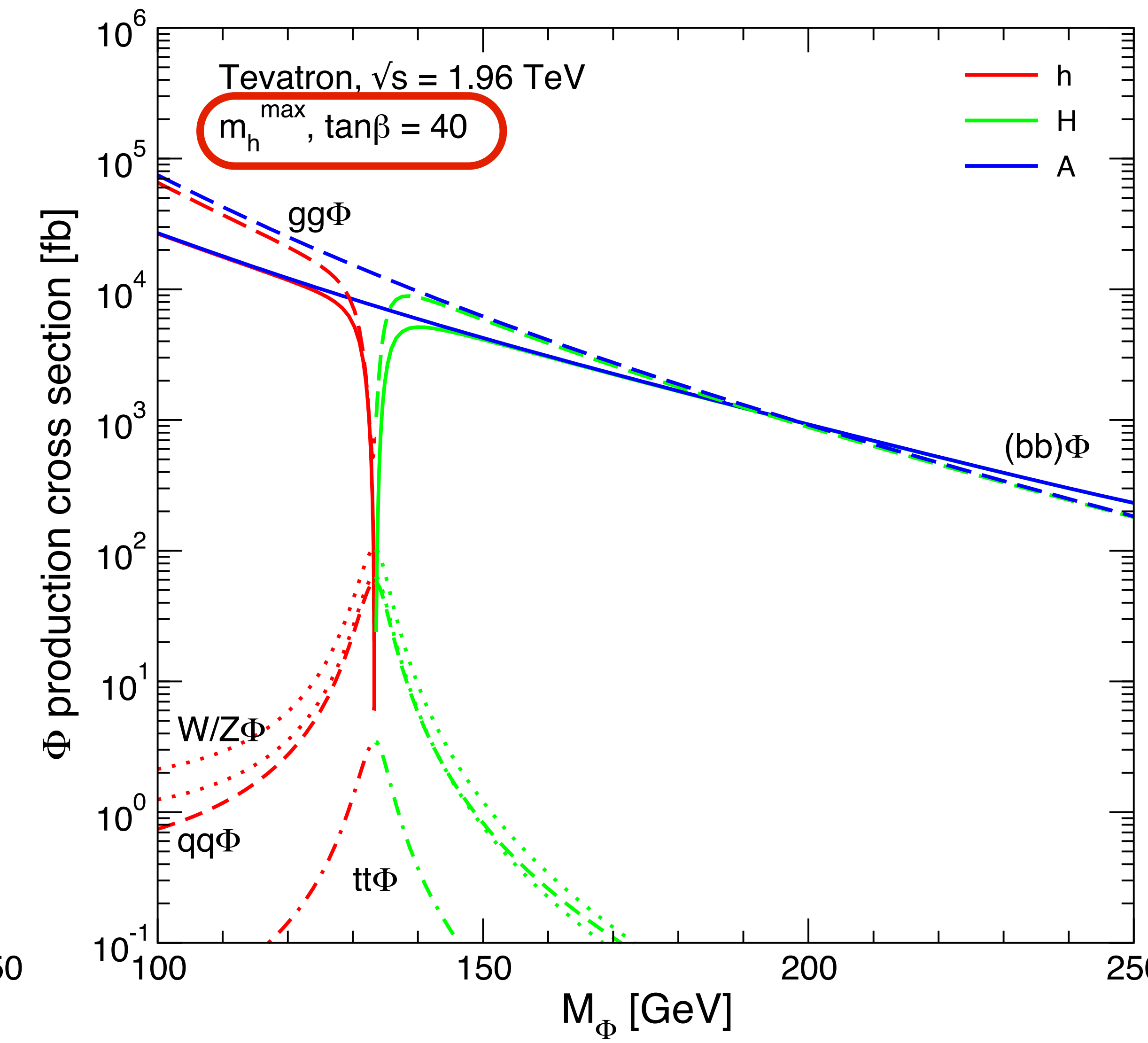
Most of the Tevatron programme focuses on high tanβ ➠ complementarity: different production mechanisms





(Tev4LHC WG)

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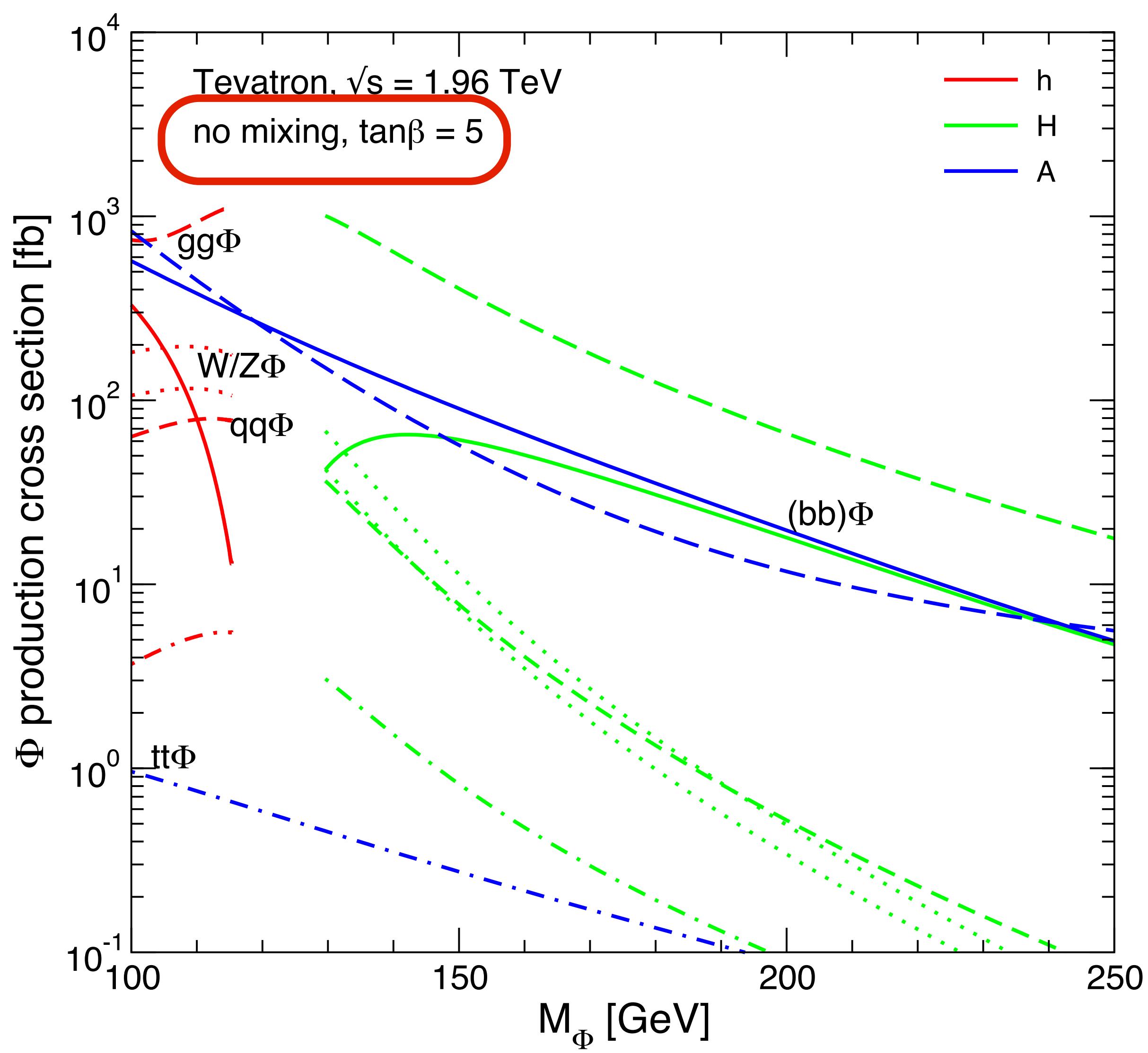

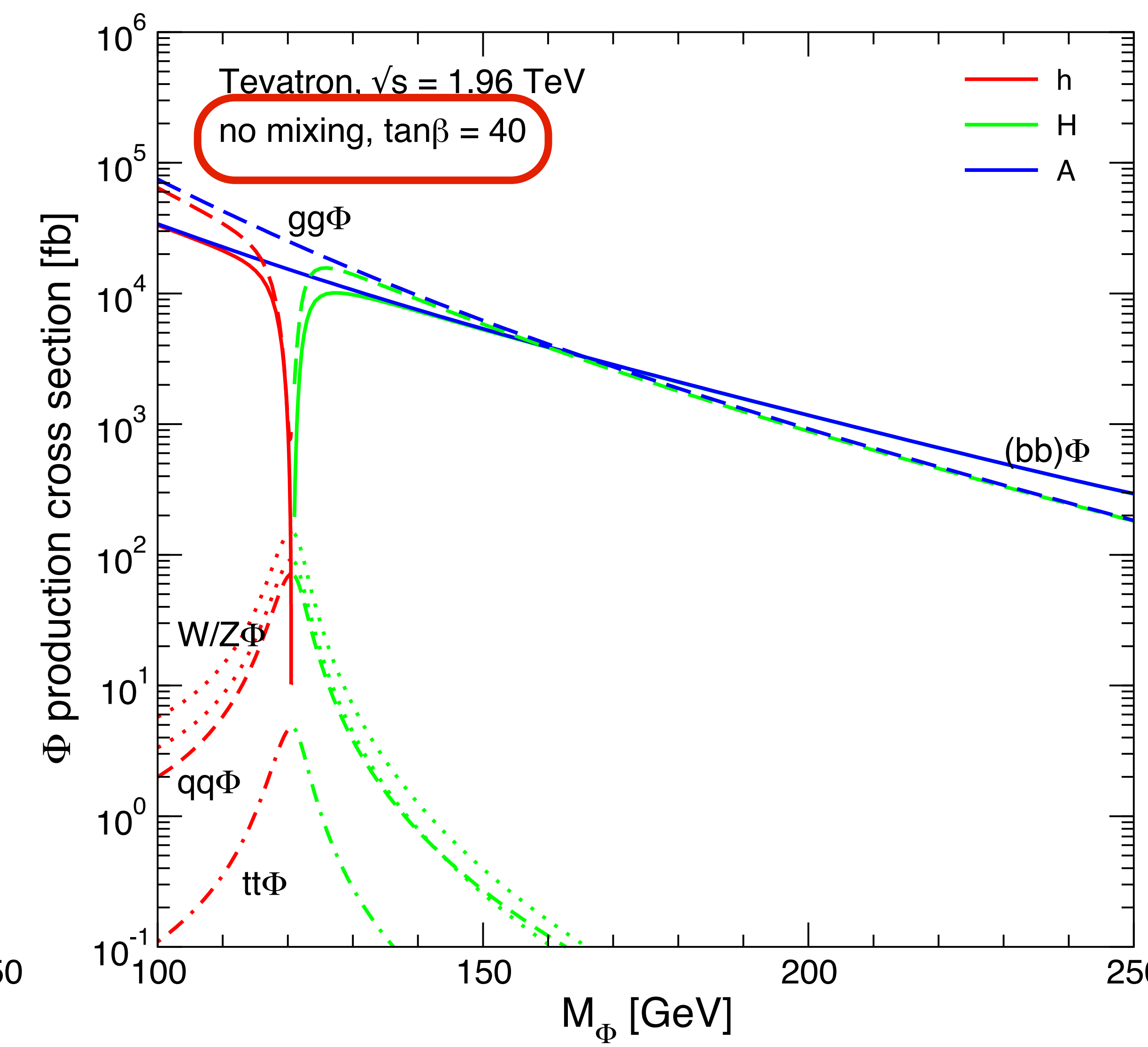

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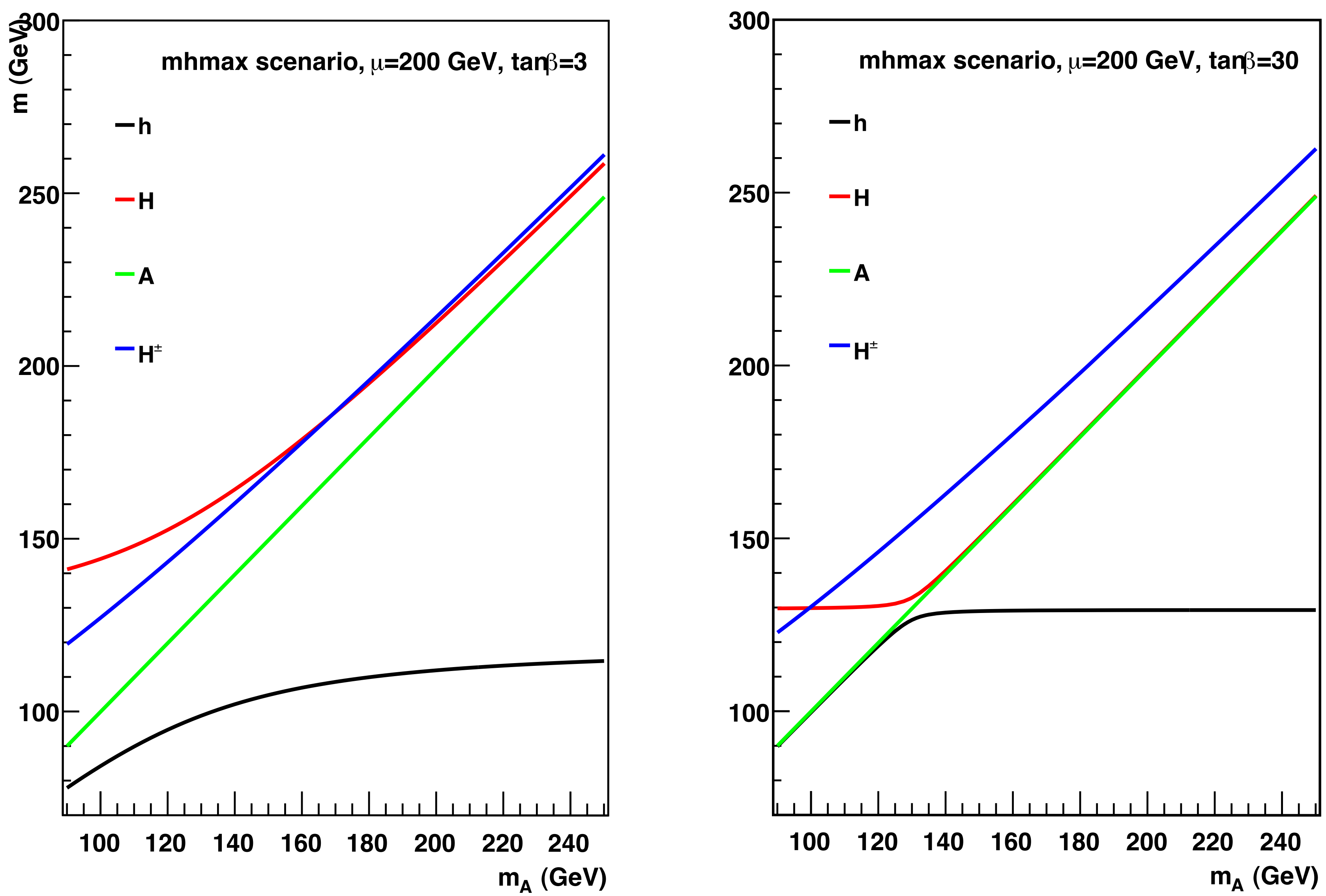

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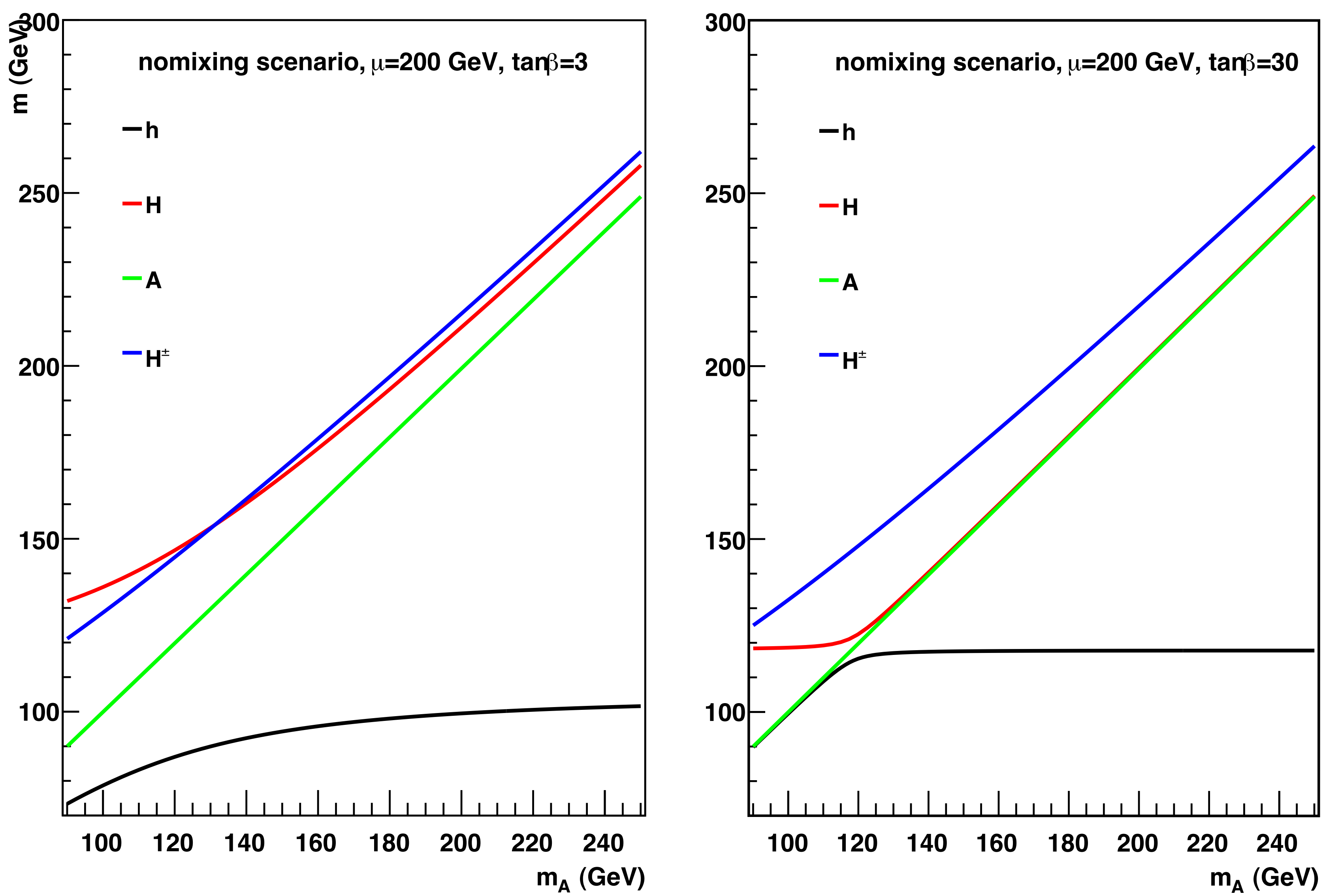

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General feature:

- masses, production cross sections for A, h/H very similar ➠ "Φ"
- production of "other CP-even boson (H/h) ~ negligible

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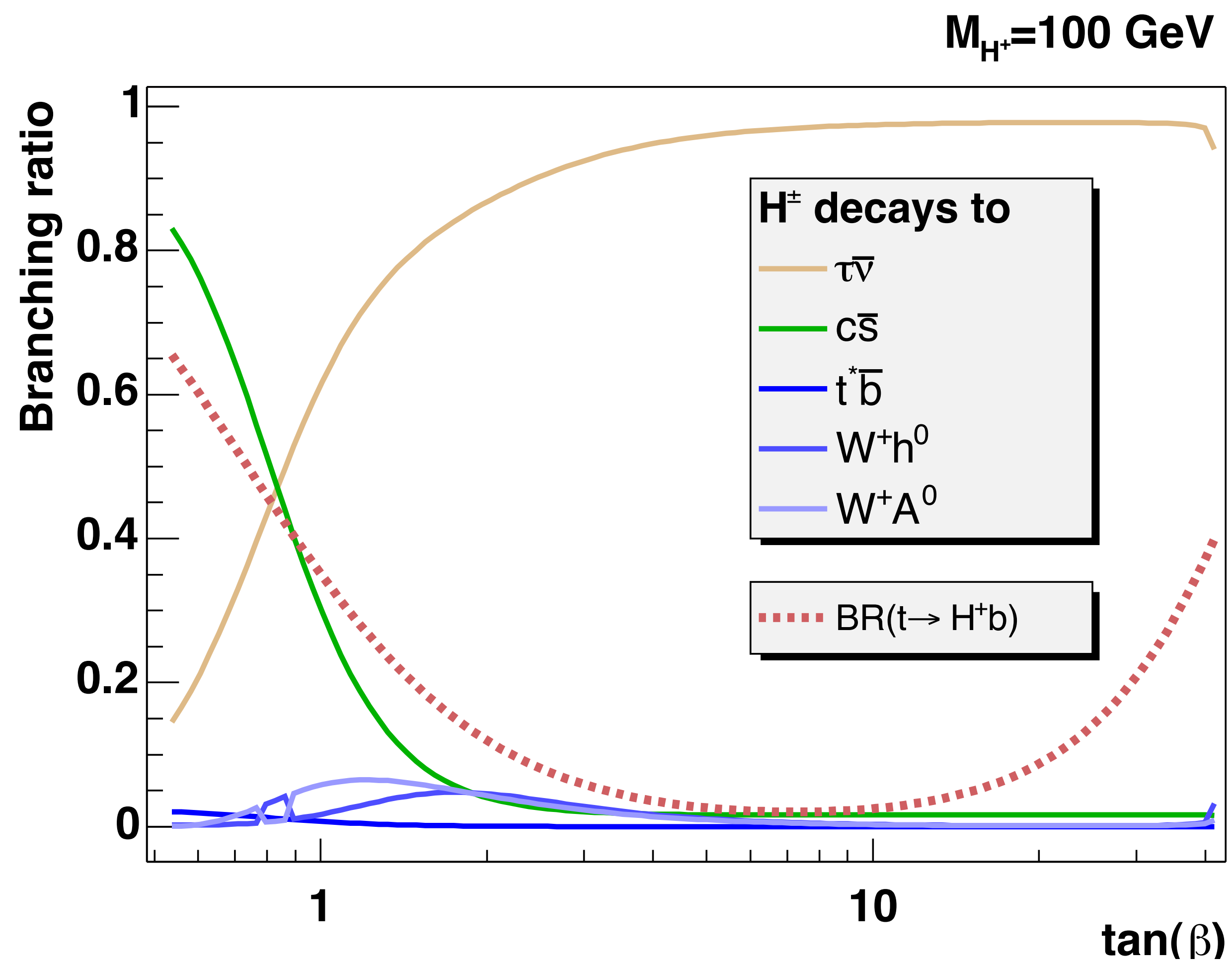
General feature:

- masses, production cross sections for A, h/H very similar ➠ "Φ"
- production of "other CP-even boson (H/h) ~ negligible

Analyses don't attempt to identify individual Higgs bosons, but look for an overall excess instead



M_{H^+}=100 GeV
Branching ratio
1
0.8
0.6
0.4
0.2
0
1
10
tan(β)
H± decays to
τν̄
cs̄
t*b̄
W+h0
W+A0
BR(t→ H+b)

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NMSSM Higgs Phenomenology

NMSSM: adds one gauge singlet superfield

- preserves $\rho=1$
- SSB: replaces μ (MSSM) with dimensionless coupling constant

Higgs sector:

- additional CP-odd (a) and CP-even (h) Higgs boson

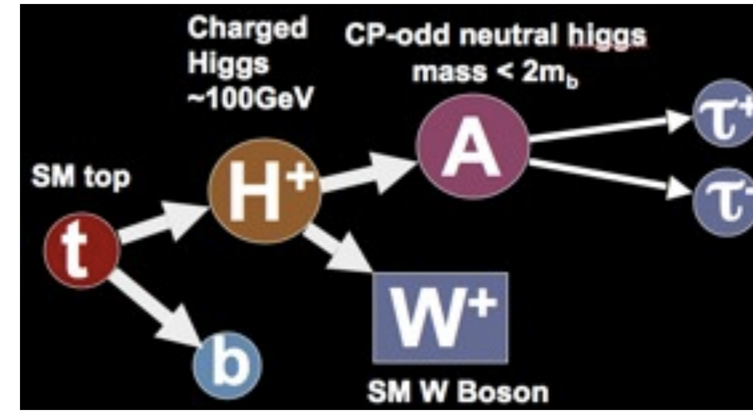
Allows for Higgs loophole at LEP:

- SM-like h (within LEP kinematic reach), decaying mostly as $h \to aa$
- $M_a < 2m_b$: $a \to \tau\tau$, gg, cc
  ➠ only looked for by OPAL in MSSM context
  - limited to $m_h < 86$ GeV

NMSSM: Charged Higgs Boson

new

CDF analysis (2.7 fb-1): search in l+jets sample
(regular tt event w/ extra $\tau^+\tau^-$ pair)



- soft τ's ➠ identify through add'l isolated track
- backgrounds:
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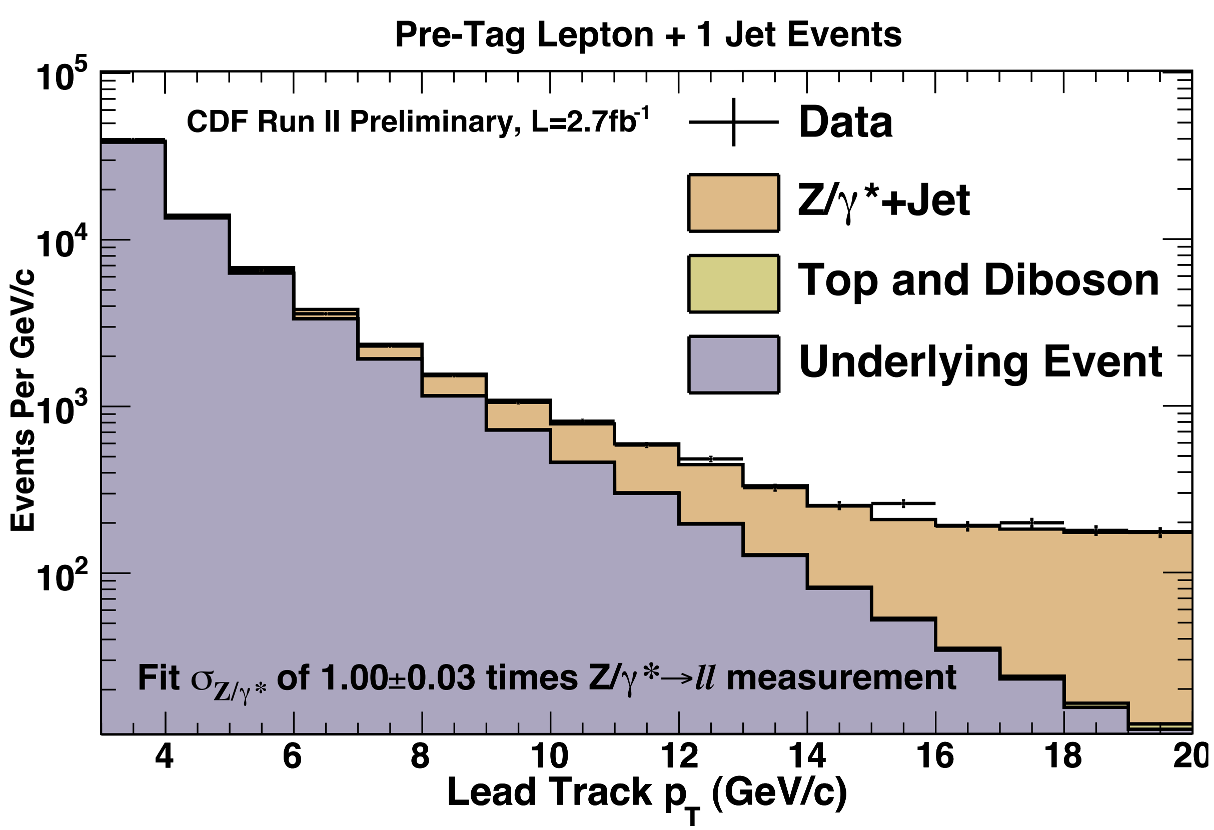

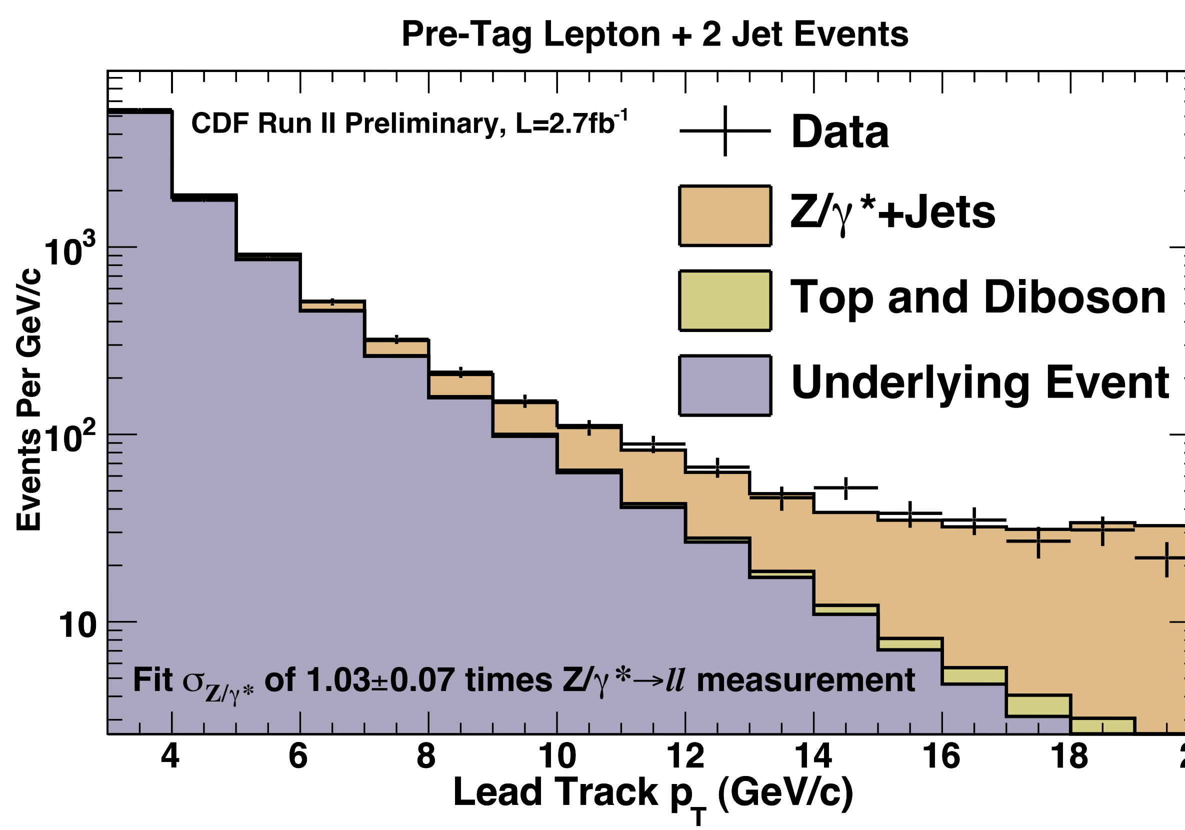

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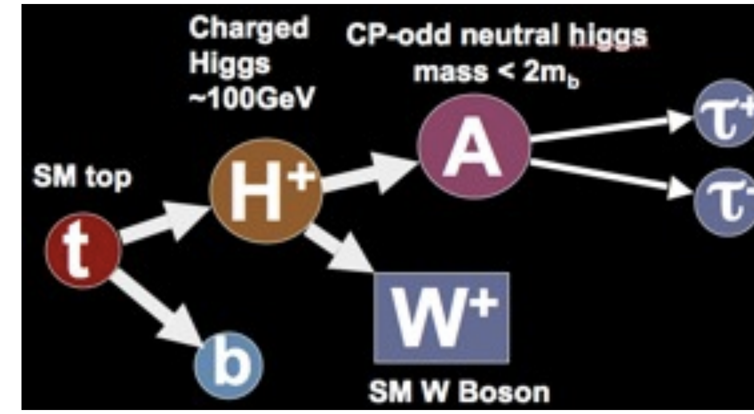

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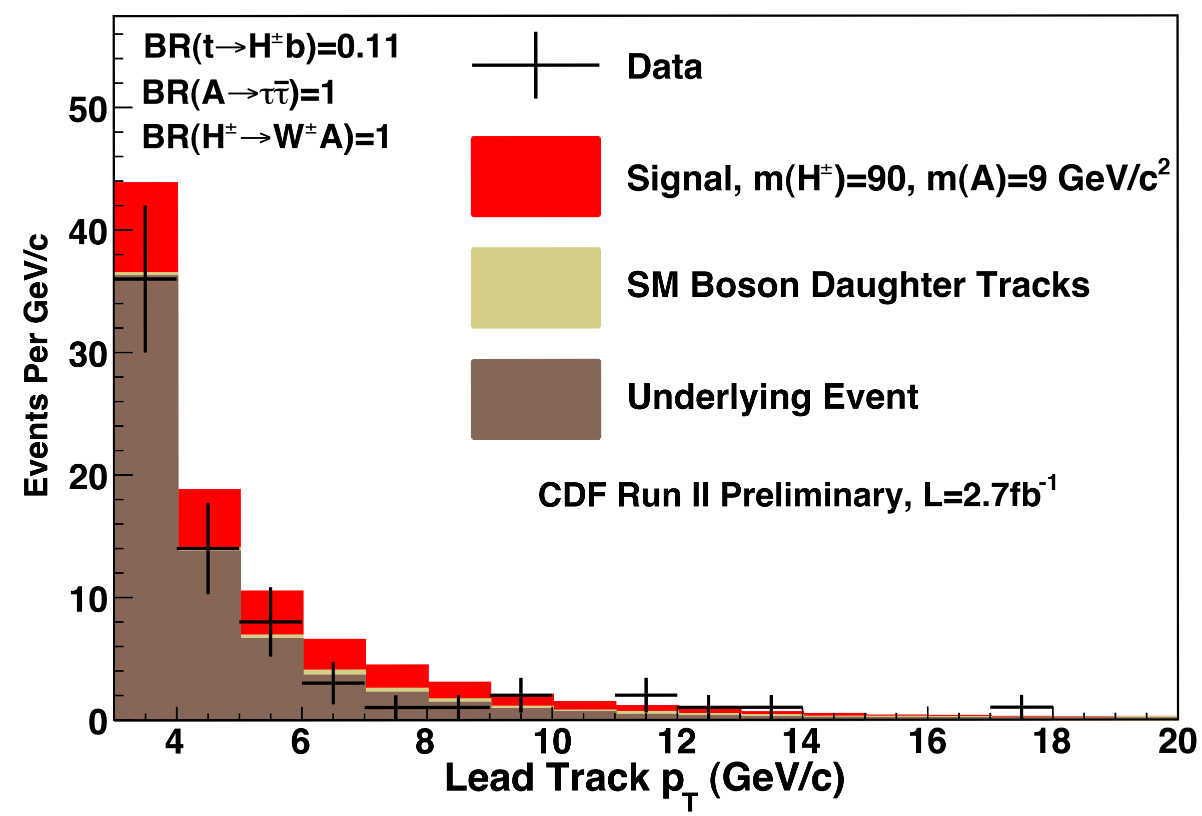
Fit as function of both m_a and M_H
- UE normalisation inferred from b-tagged 3-jet data
- signal shown at exclusion level



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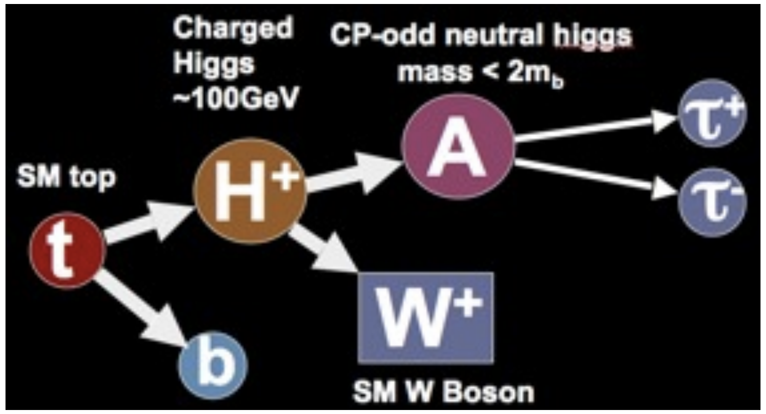

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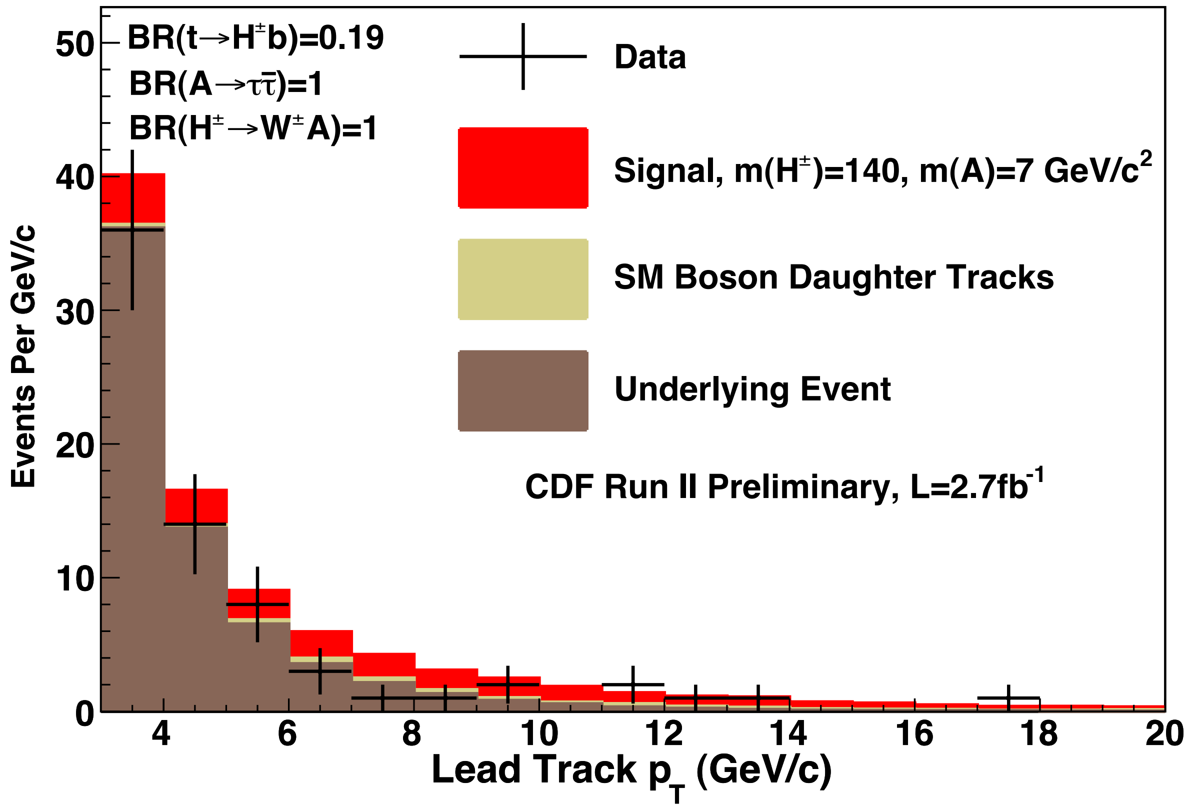

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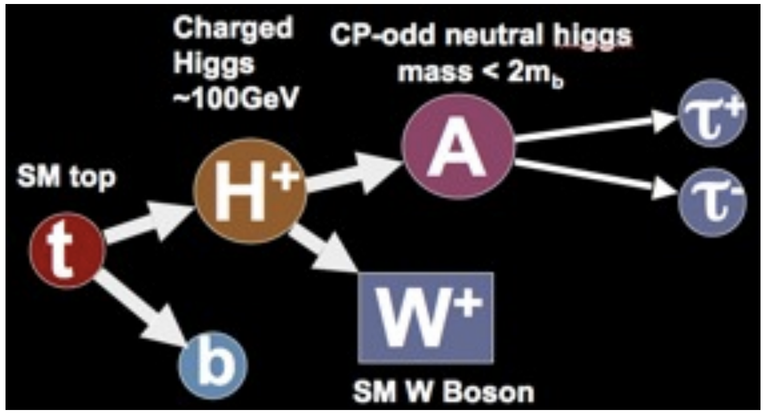

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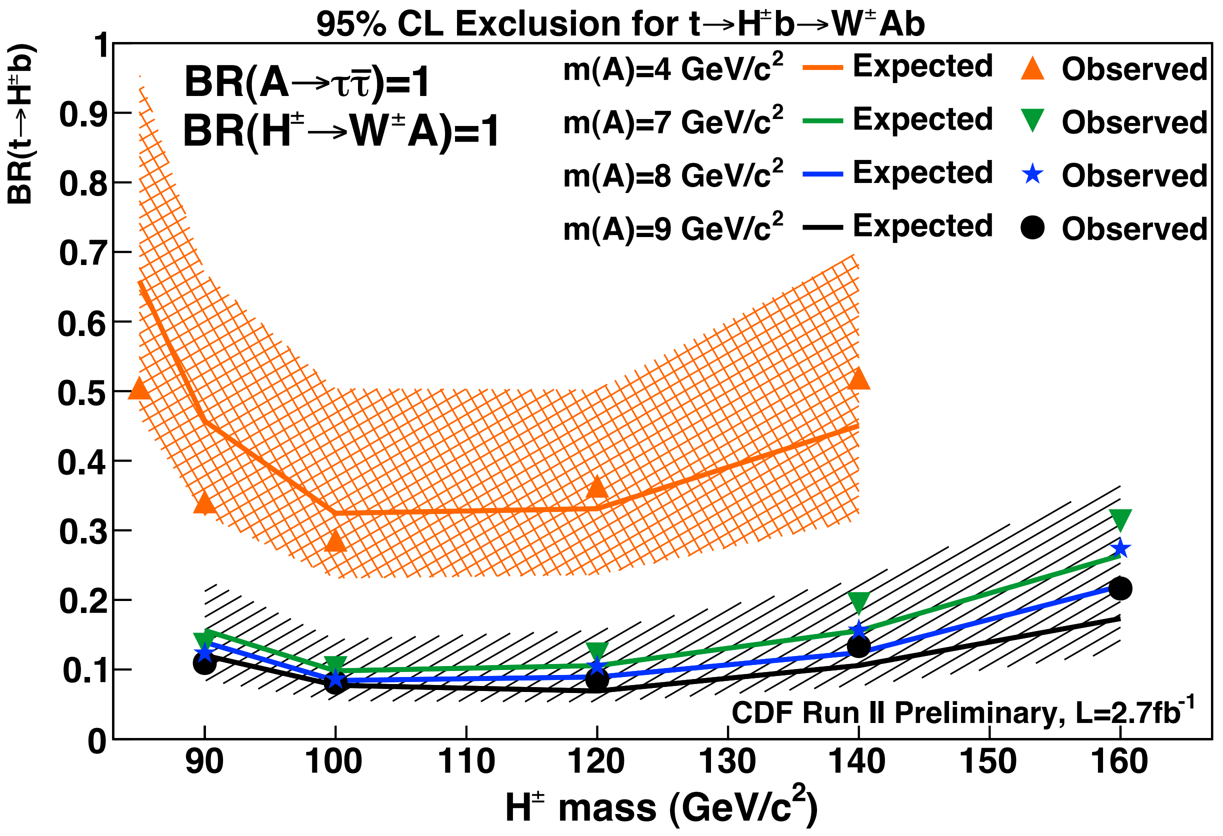
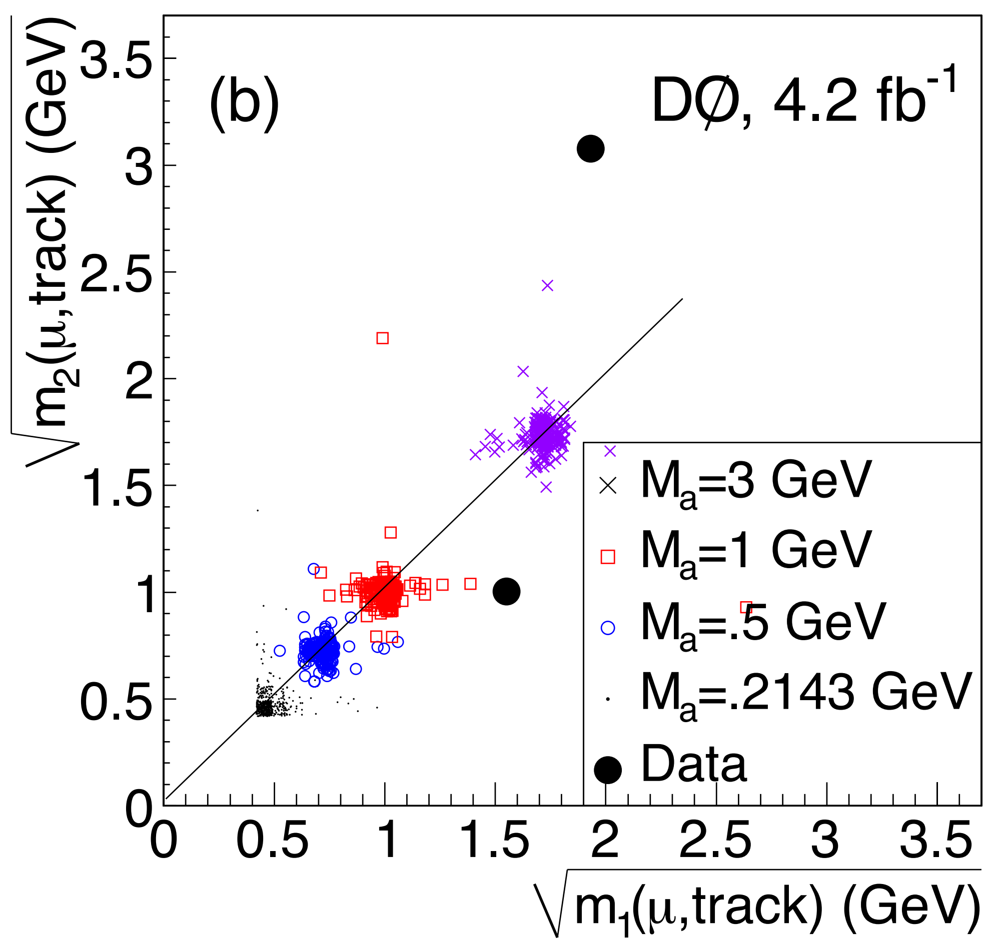


NMSSM: Neutral Higgs Boson

published



- tight (μ+track) isolation criteria
- efficiency for collinear tracks from K_S

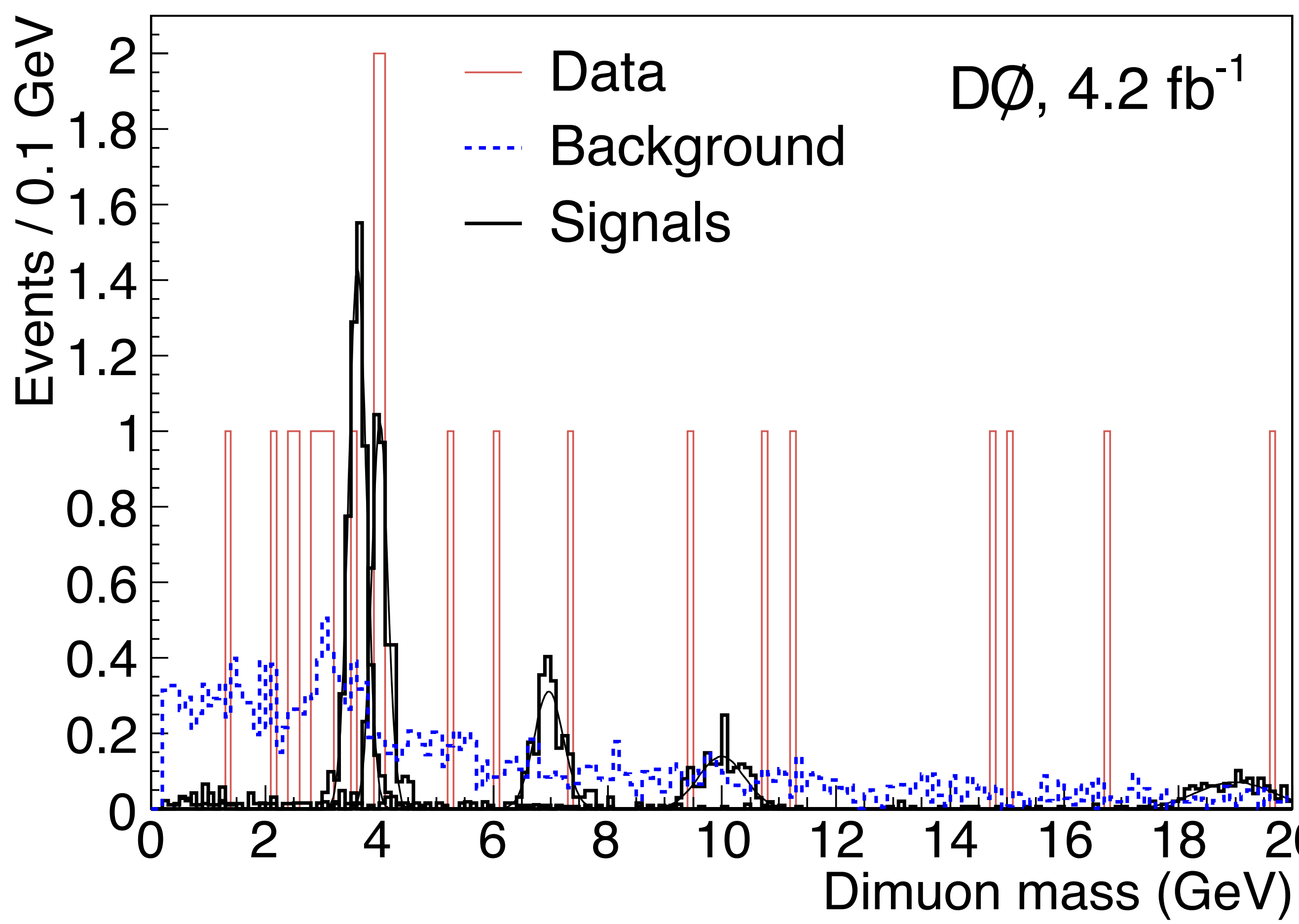
$$\sigma(p\bar{p} \to h + X) \cdot B(h \to aa) \cdot B(a \to \mu^+\mu^-)^2 < 10\,\text{fb}$$

NMSSM: Neutral Higgs Boson

published

D0 analysis (4.2 fb^{-1}): search for $gg \to h \to aa$, with $a \to \mu^+\mu^-/\tau^+\tau^-$ in inclusive dimuon events ($p_T > 10$ GeV)

- $2m_\mu < m_a < 2m_\tau$: muons too collinear to be reconstructed separately ➠ association with track ($R < 1$) only (NB: BF uncertain)
- $m_a > 2m_\tau$ ($\mu^+\mu^-\tau^+\tau^-$): reconstruct $a \to \mu^+\mu^-$ candidates explicitly
  - use of muons ➠ low efficiency



- collimated τ not individually identified: $\not{E}_T$ / μ / e
- background estimated from low-$\not{E}_T$ region

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