Tevatron Results

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Disclaimer and acknowledgements

The Tevatron physics programme is very strong and lively – it would take days of talks to cover it.

What I will show here necessarily is a tiny, biased, personal selection of recent results.

A lot of more detailed talks are available. I found these ones particularly helpful, and I have used them freely in the preparation of this talk:

Sabine Lammers, *"Recent results on QCD from DØ"*, CERN seminar, June 22nd, 2010.

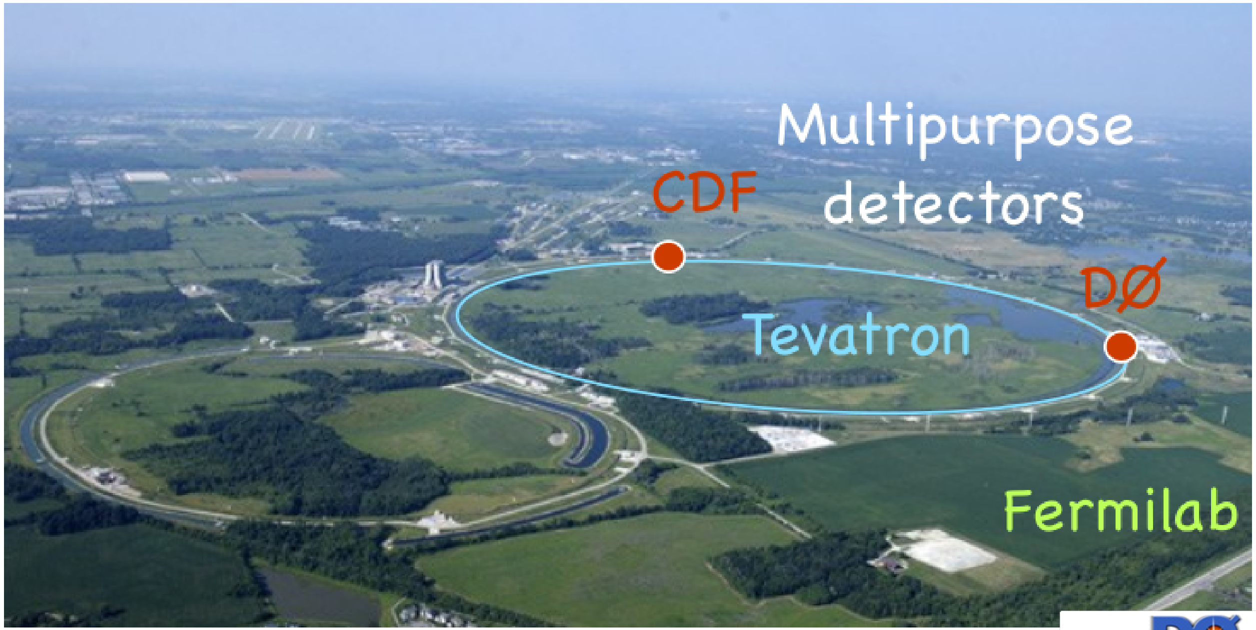
Marco Verzocchi, *"DØ results for ICHEP 2010"*,
Fermilab Wine&Cheese seminar, July 16th, 2010.

Volker Büscher, *"Searches for Supersymmetry"*,
22nd Rencontres de Blois, July 2010.

Elizaveta Shabalina, *"The physics of top, W and Z"*, plenary talk at ICHEP 2010.

Ben Kilminster, *"Higgs boson searches at the Tevatron"*, plenary talk at ICHEP 2010.

The Tevatron



Proton-antiproton collisions with centre-of-mass = 1.96 TeV

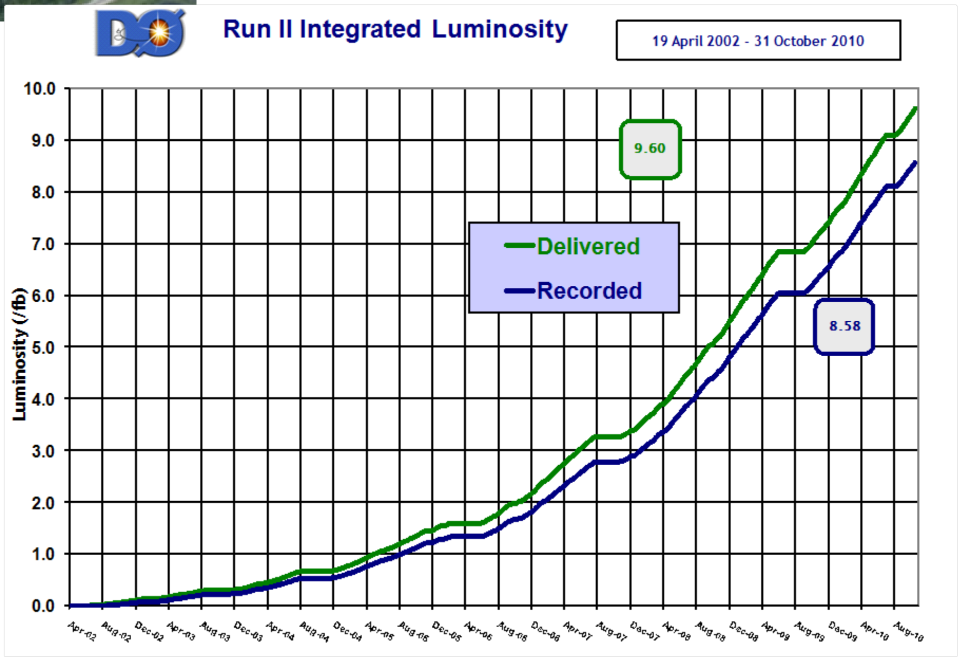
36 p and pbar bunches
396 ns between bunch crossing

Since a few years the Tevatron performance is truly excellent.

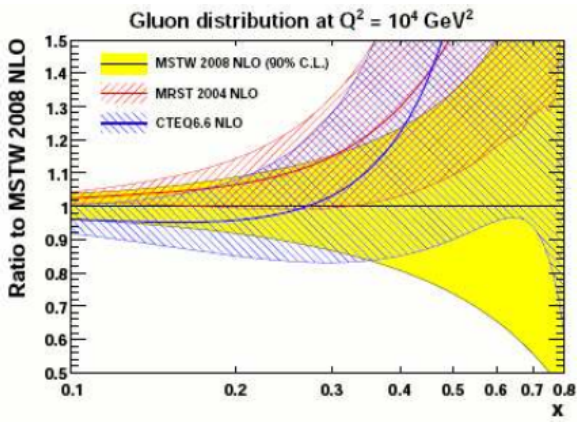
Peak initial instantaneous luminosity: $400 * 10^{30}$ cm^{-2} s^{-1}

Still the world's most powerful "boson factory".

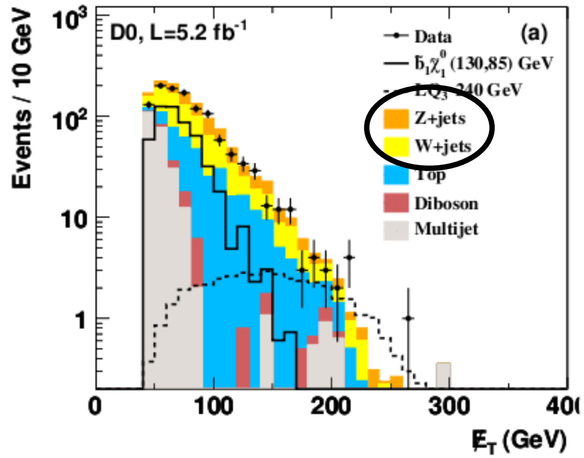
Both experiments are collecting data efficiently.



QCD analyses: main motivations

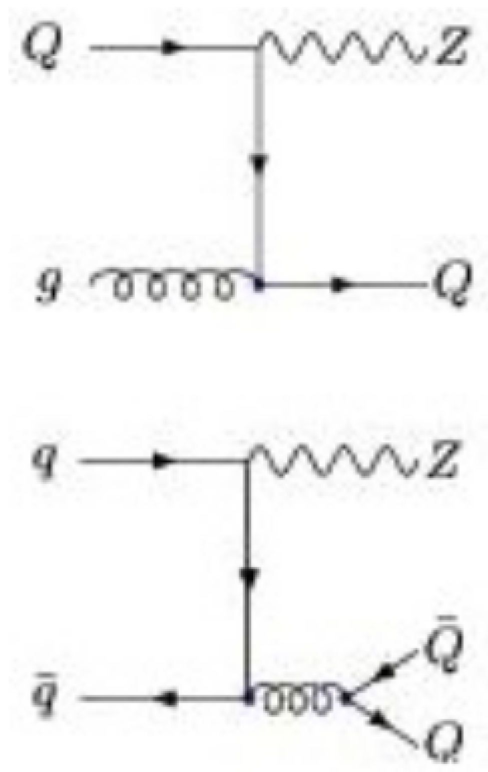


- **Test perturbative QCD**
  - Explore new kinematic regimes
  - provide important inputs to PDFs
- **Search for New Physics**
  - resonances can show up in jets too!
  - use SM as a guide
- **Measure important backgrounds to New Physics searches**
  - N(N)LO predictions not available for many processes of interest, particularly those with large jet multiplicities and heavy flavor components => data measurements crucial
  - New Physics share signatures with irreducible backgrounds that are currently being pinned down.
  - Interplay between fragmentation models, tunes, PDFs and scale choices needs to be understood to model SM backgrounds



σ(Z+b) / σ(Z+j)

Measure σ(Z+b) / σ(Z+j) ratio using 4.2 fb^{-1} of DØ data.

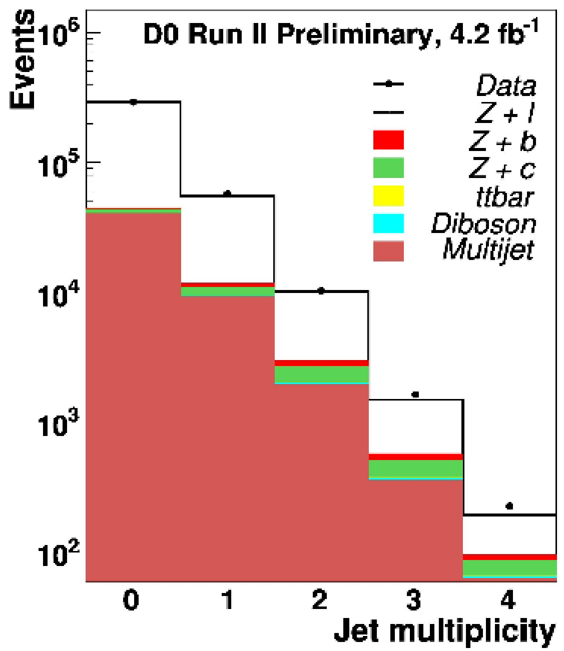


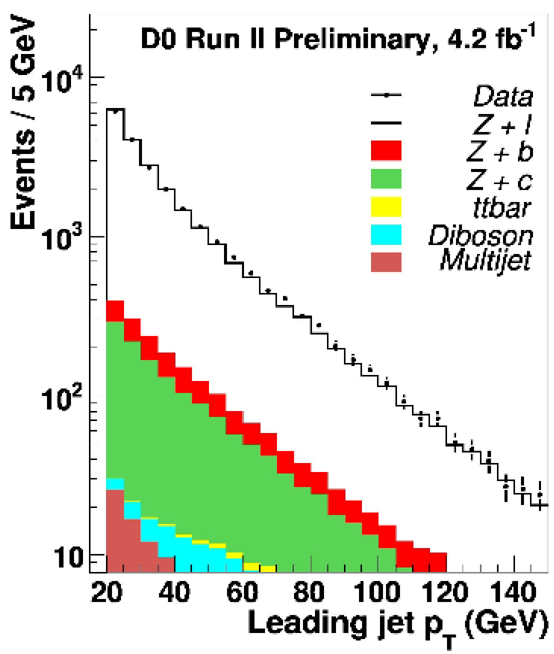
Use fit to distribution of b-tagging probability to extract fraction of signal/background in Z+jets sample.

For central jets ($|\eta|<1$) with p_T > 20 GeV:

σ(Z+b) / σ(Z+j) = 0.0176 ± 0.0024 (stat) ± 0.0023 (syst)

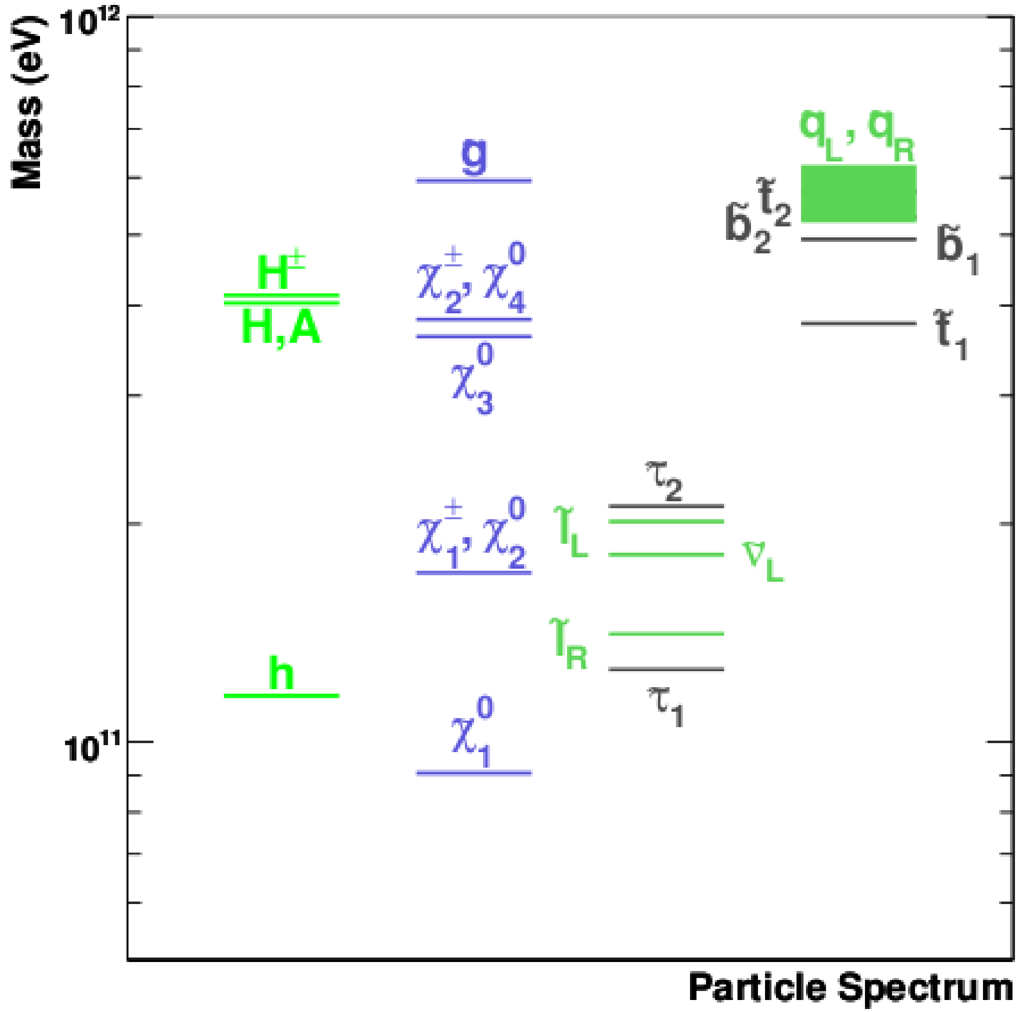
in agreement with NLO QCD calculations (0.018 ± 0.004).





TeV-scale superpartners ?

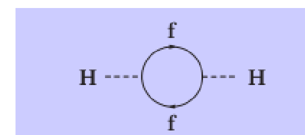
A typical SUSY mass spectrum:



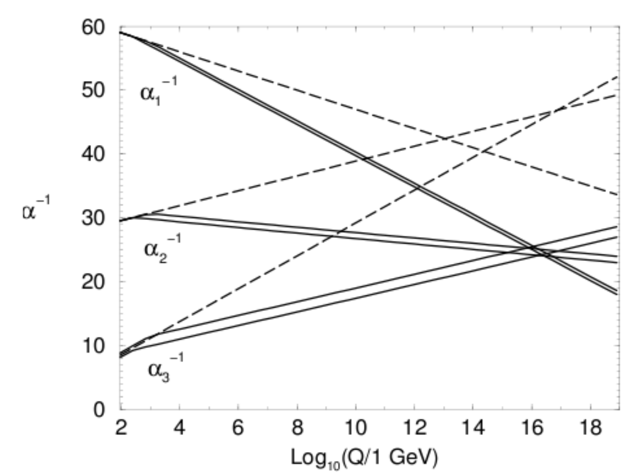
SUSY could be part of the solution to various puzzles:

- WIMP dark matter

- hierarchy problem



- grand unification



- ...

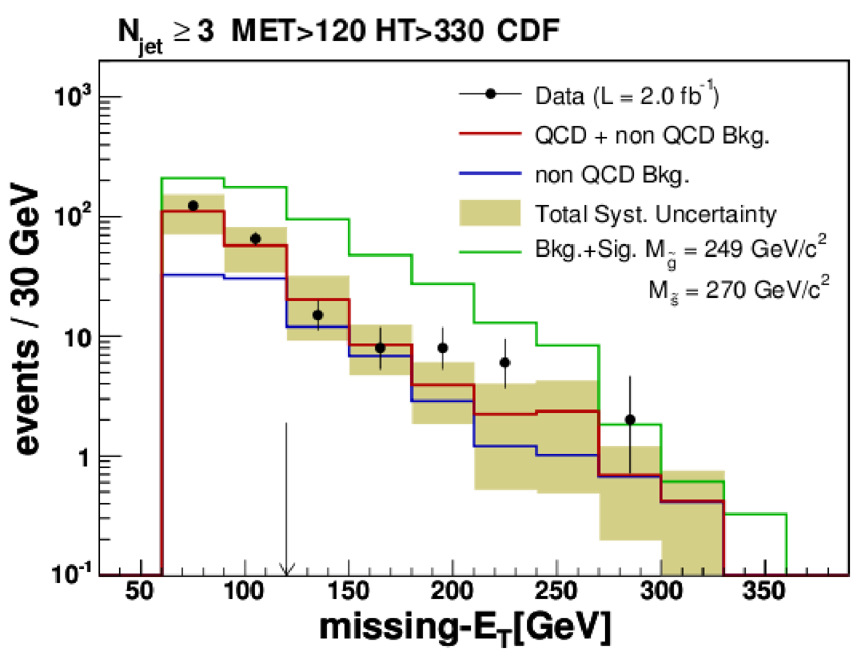
Inclusive search for squarks/gluinos

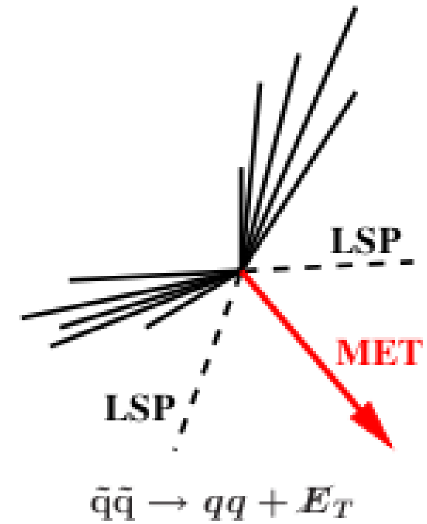
Squarks/gluinos produced via strong interaction

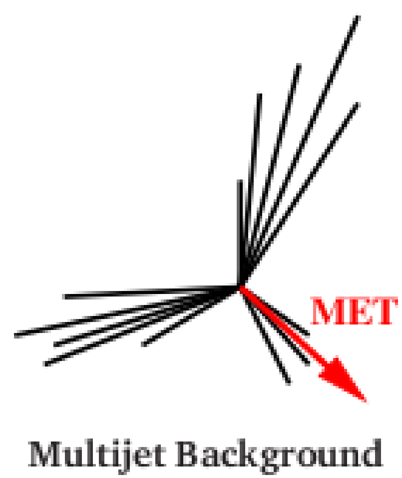
→ large cross sections at hadron colliders

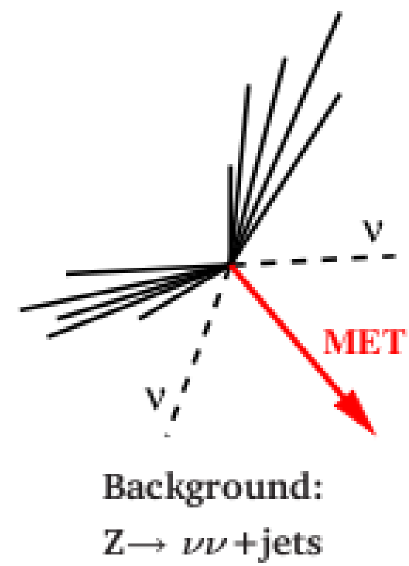
Decays: jets + LSP
LSP assumed to be stable (R-parity)

→ signature: jets + MET

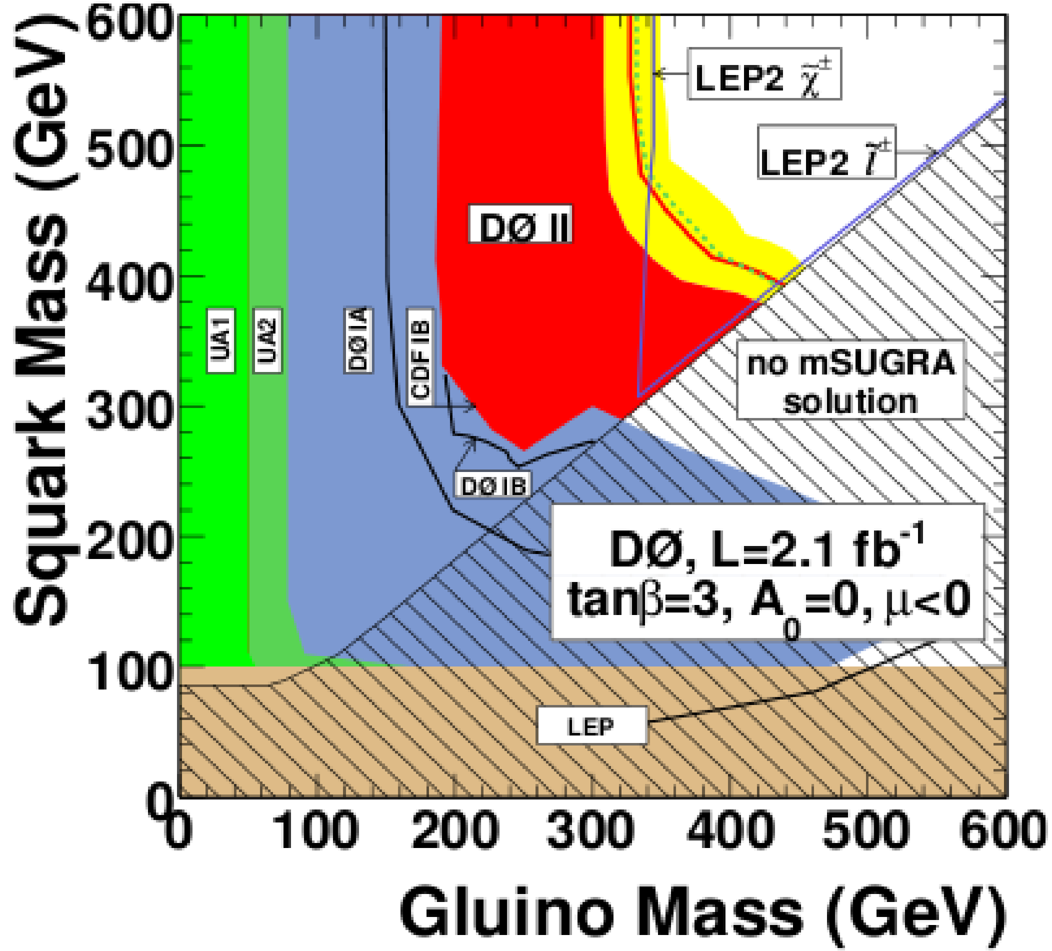








Inclusive search for squarks/gluinos

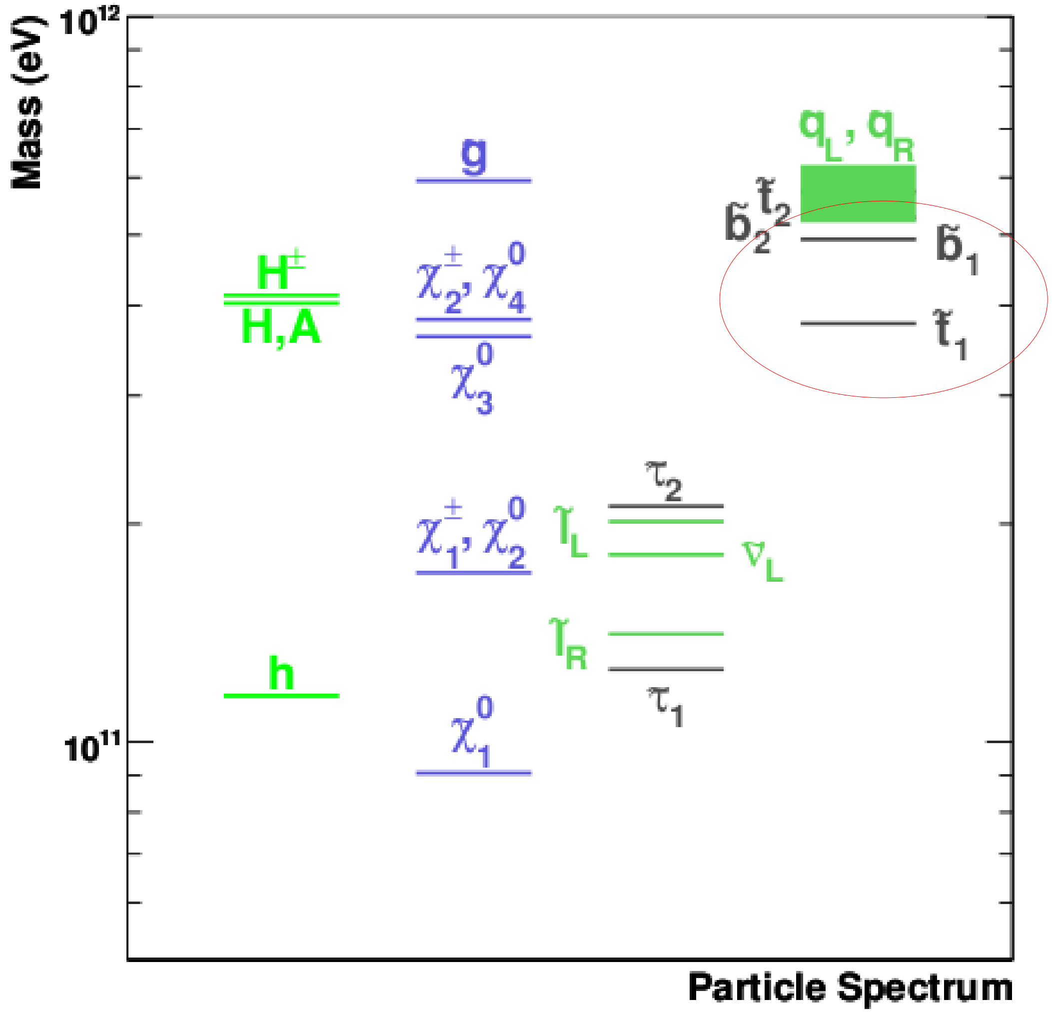


No evidence for squark/gluino production at Tevatron.

Limits in squark/gluino mass plane, probing squark/gluino masses up to 400/320 GeV.

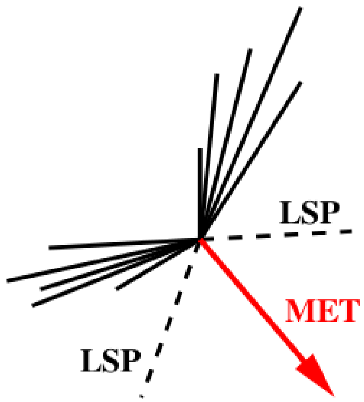
Which SUSY particles to look for ?

A typical SUSY mass spectrum:



stop/sbottom are expected to be (relatively) light

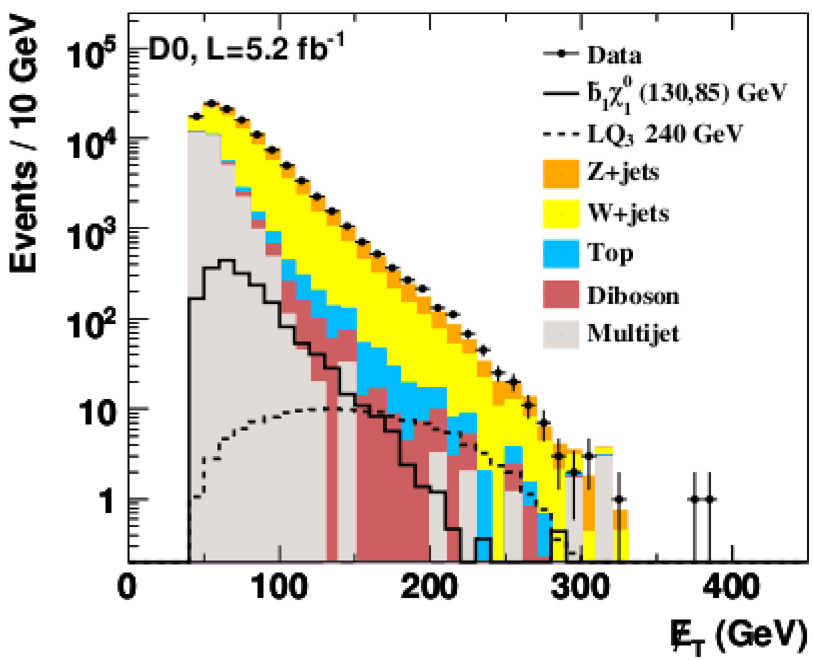
Sbottom quarks



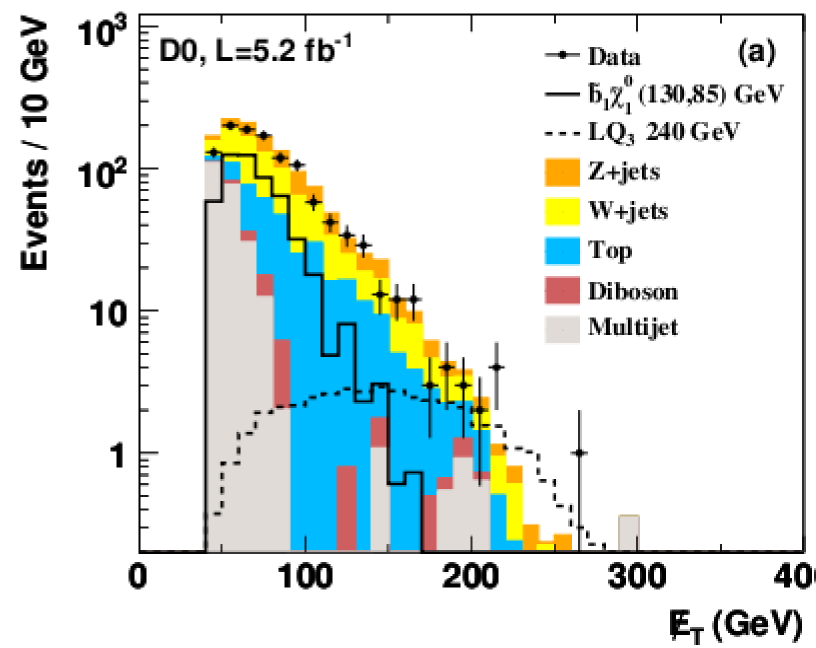
Decay: $\tilde{b} \rightarrow b + \tilde{\chi}_1^0$

$\rightarrow$ jets + MET analysis with b-tagging

New result: DØ, 5.2 fb^{-1}



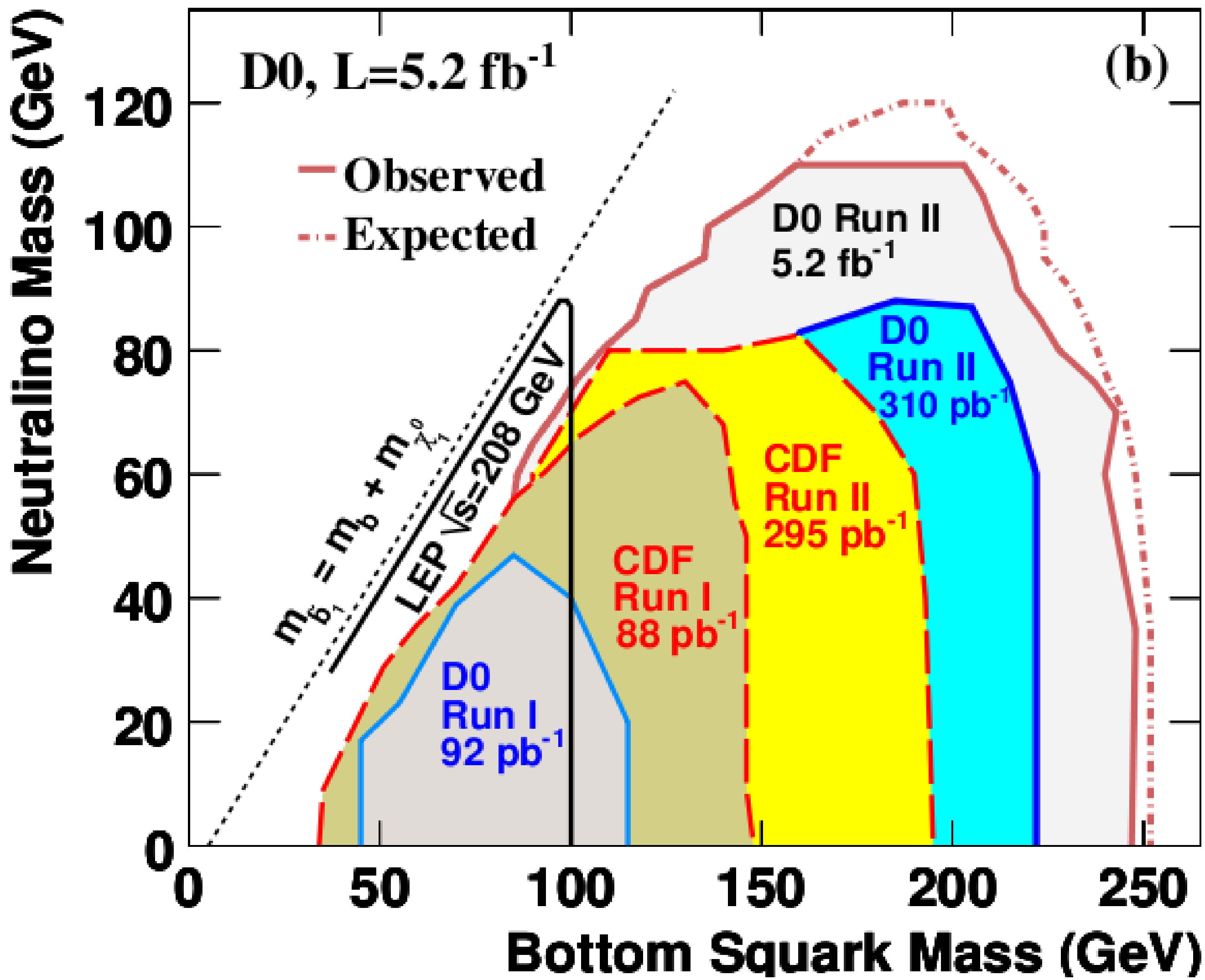
before b-tagging



after b-tagging

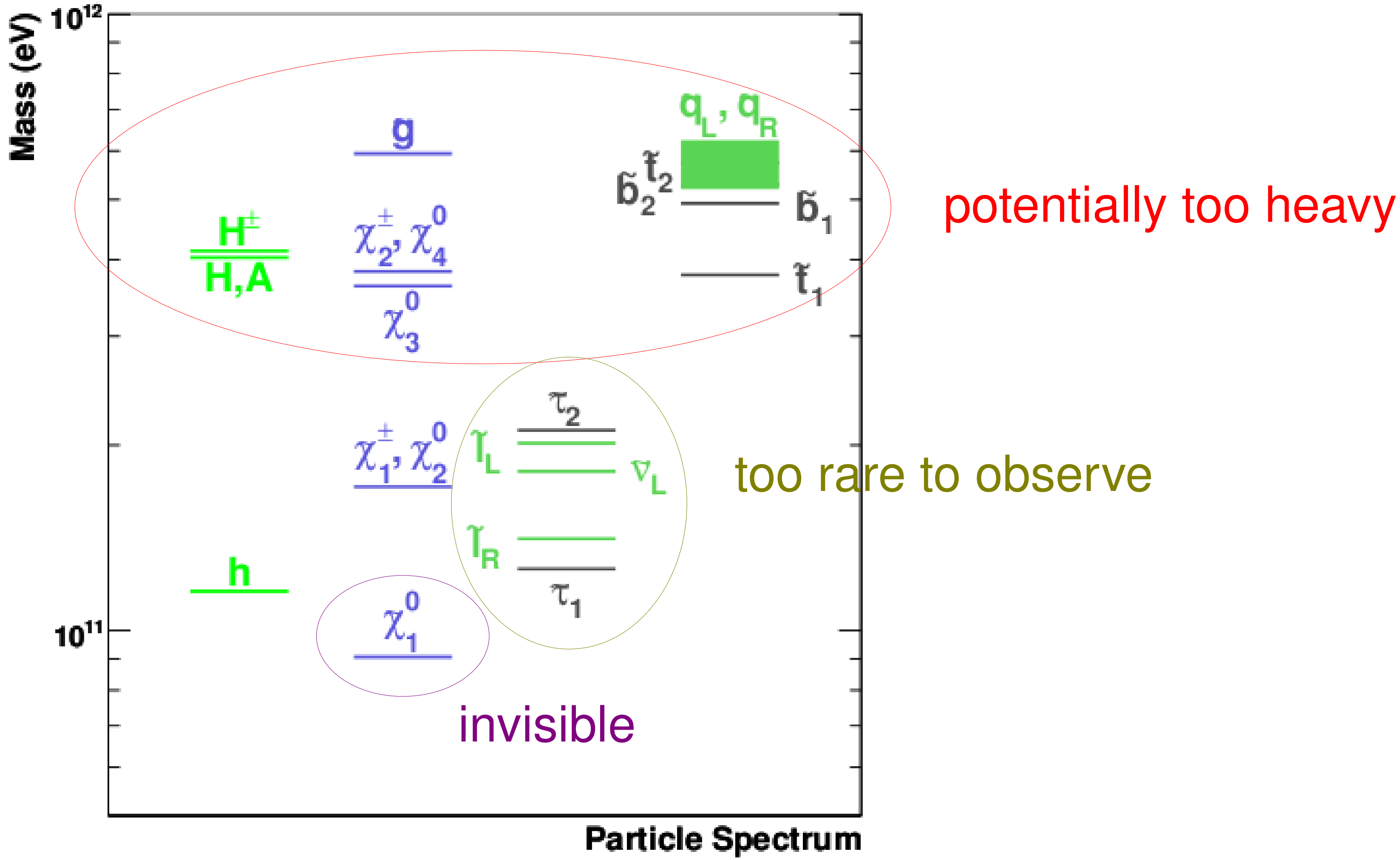
Sbottom quarks

Visible energy in the event depends on the $\tilde{b}$-$\tilde{\chi}_1^0$ mass difference
→ mass-dependent cuts.



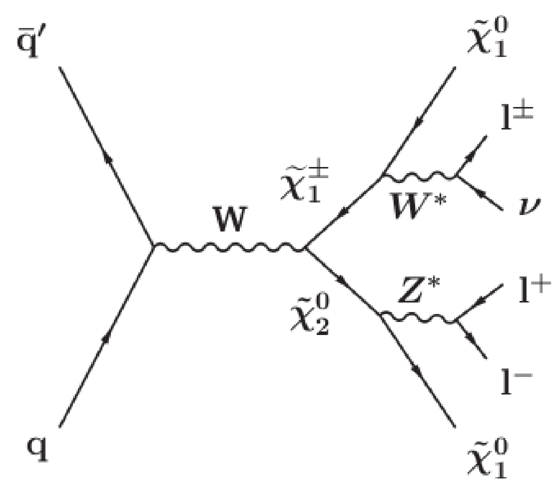
Which SUSY particles to look for ?

A typical SUSY mass spectrum:



Search for charginos and neutralinos

Most sensitive channel: $\tilde{\chi}^{\pm}\tilde{\chi}^{0}_{2} \rightarrow 3\ell + \not{E}_T$



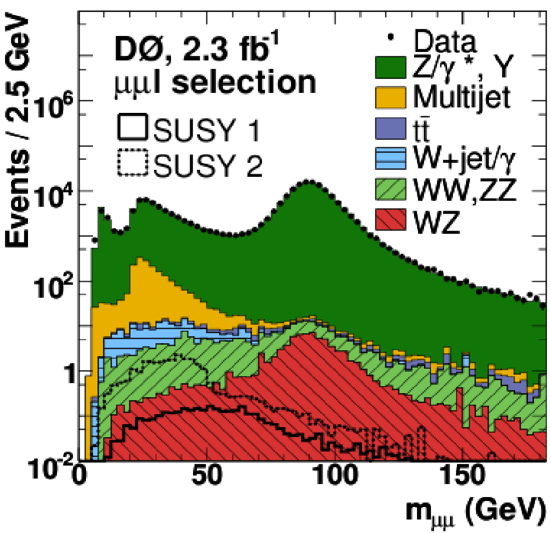
Challenges:

- production cross section (electroweak) relatively small
- low-p_T leptons

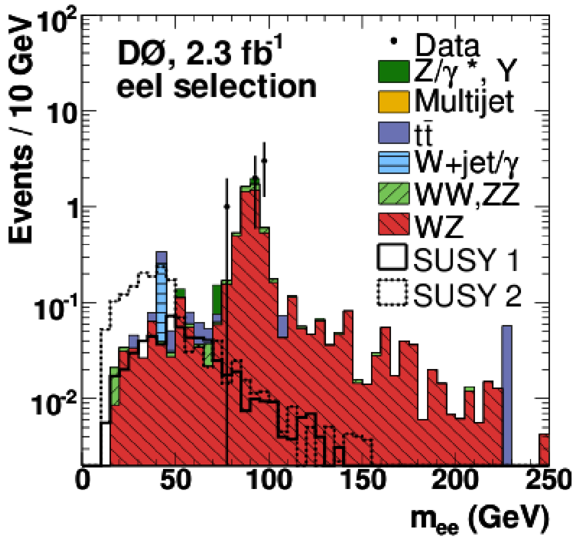
Large number of tri-lepton and d-ilepton plus track analyses from CDF and DØ

- p_T cuts as low as 3 GeV

requiring 2 leptons



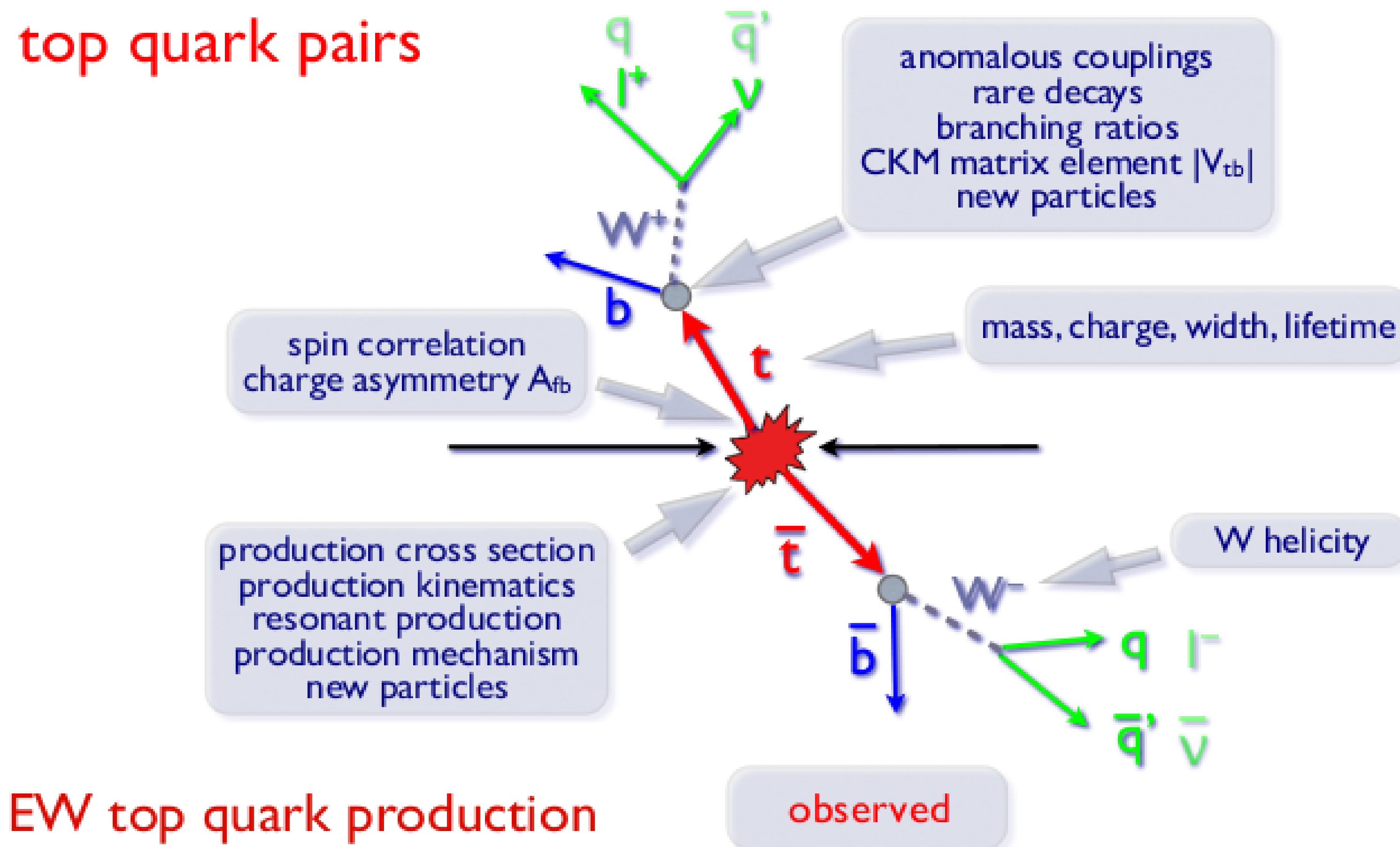
requiring 3 leptons



Analyses probing chargino masses up to 176 GeV (reach degrades with increasing tan β).

What do we know about the top quark ?

Very rich programme of top physics at the Tevatron:



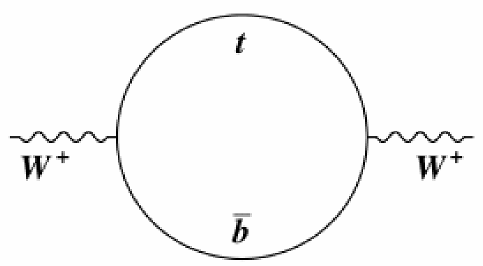
An oddity in any of these measurements could be a sign of new physics.

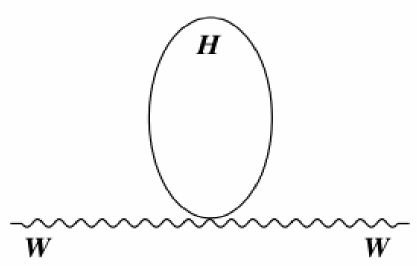
Top quark and W boson masses

W mass is a key parameter in the Standard Model. This model does not predict the value of the W mass, but it predicts this relation between the W mass and other experimental observables:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Radiative corrections (Δr) depend on M_t as $\sim M_t^2$ and on M_H as $\sim \log M_H$. They include diagrams like these:



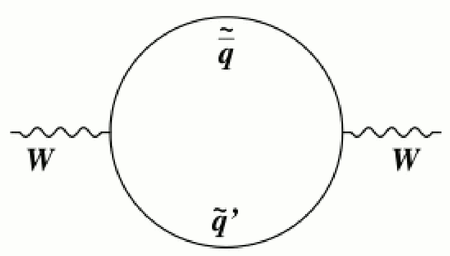


Precise measurements of M_W and M_t constrain SM Higgs mass.

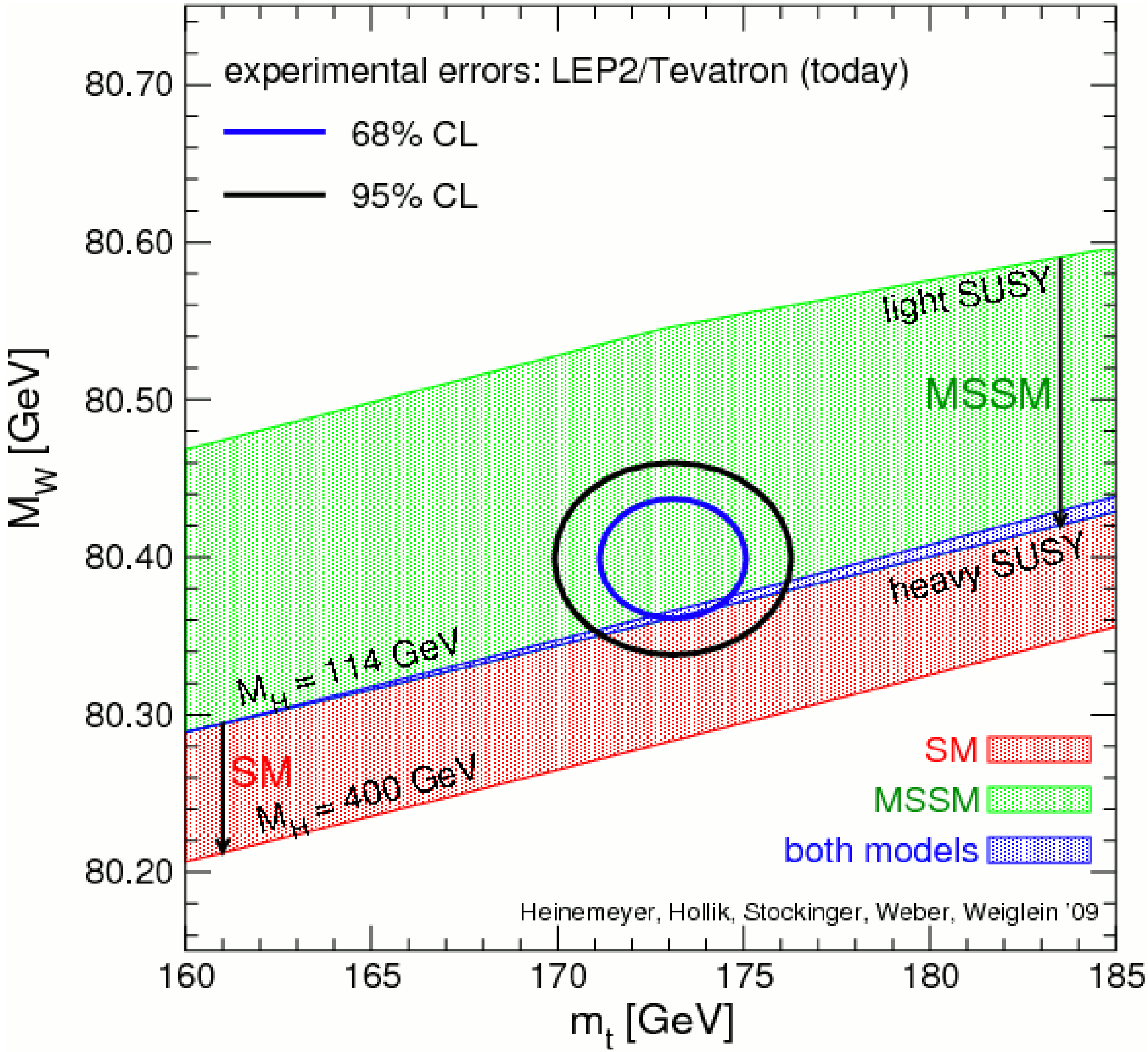
For equal contribution to the Higgs mass uncertainty need:
$\Delta M_W \approx 0.006\ \Delta M_t$.

The limiting factor here will be ΔM_W, not ΔM_t !

Additional contributions to Δr arise in various extensions to the Standard Model, *e.g.* in SUSY:



Motivation



For equal contribution to the Higgs mass uncertainty need:

$$\Delta M_W \approx 0.006 \; \Delta M_t .$$

Current Tevatron average:

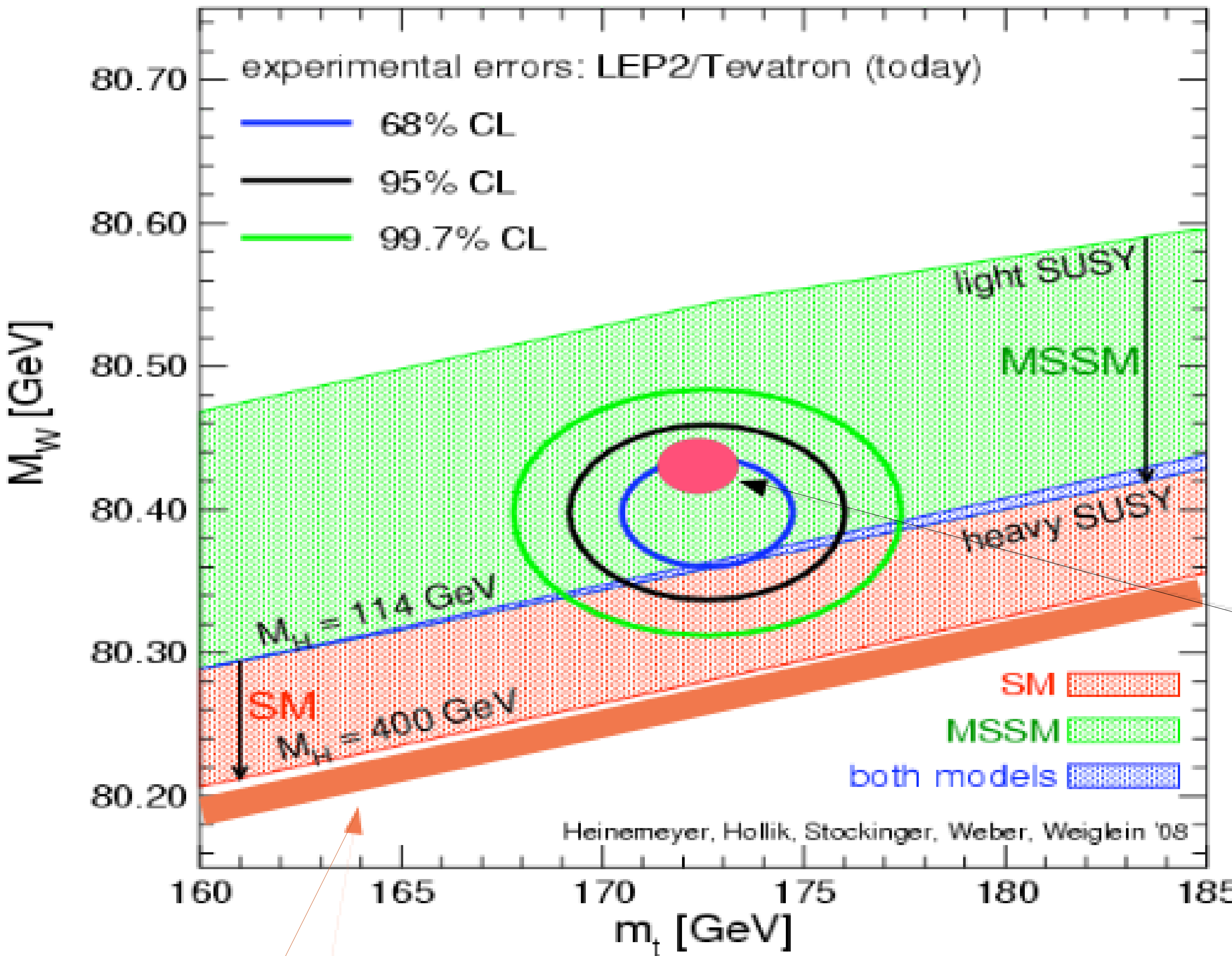
$\Delta M_t = 1.3$ GeV

$\Rightarrow$ would need: ΔM_W = 8 MeV

Currently have: $\Delta M_W = 25$ MeV

At this point, i.e. after all the precise top mass measurements from the Tevatron, the limiting factor here is ΔM_W, not ΔM_t .

A possible scenario for the next few years



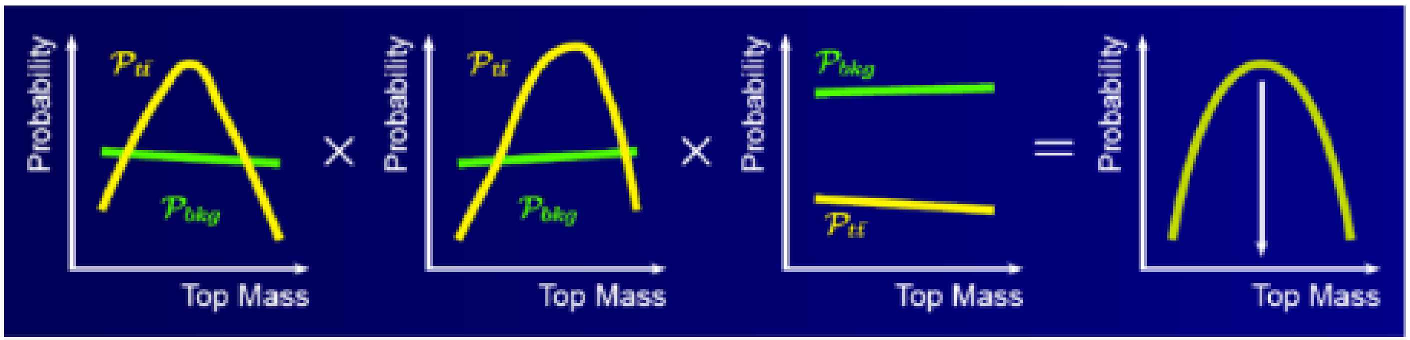
$\delta M_W = 10$ MeV

$\delta m_{top} = 0.5$ GeV

Higgs discovery with a large Higgs mass

Top quark mass measurement

- The most powerful method: matrix element method
  - Calculate probability for event to be signal or background as a function of top mass
  - Multiply event probabilities to extract the most likely mass

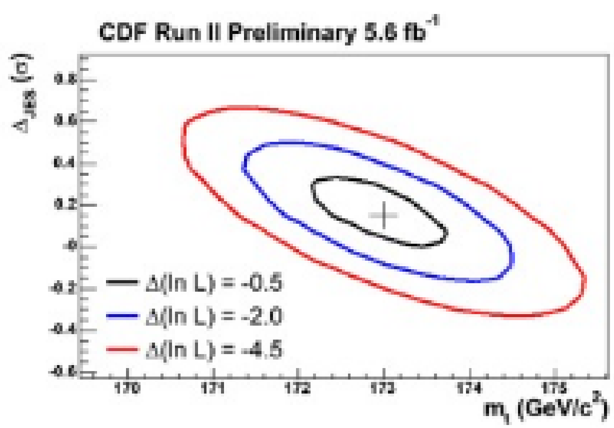


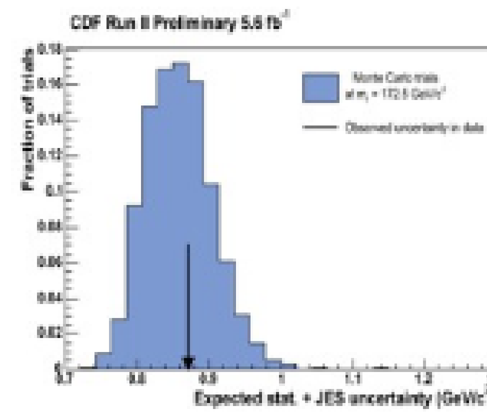
Maximizes statistical power by using full event information

l+jets channel

Top mass and jet energy scale extracted simultaneously from maximum likelihood fit to data

$\Delta_{JES} = 0.15 \pm 0.18\ \sigma$ 5.6 fb^{-1}

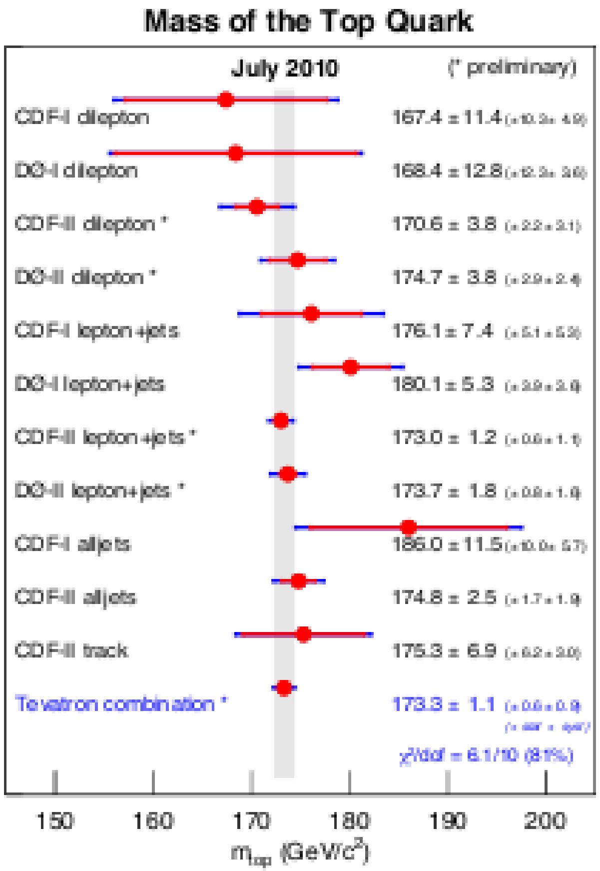




m_{top}=173.0±0.7(stat)±1.1(syst) GeV ±1.2(total) GeV

the most precise single measurement: ±0.7%

Top mass Tevatron combination



new

0.6% relative uncertainty

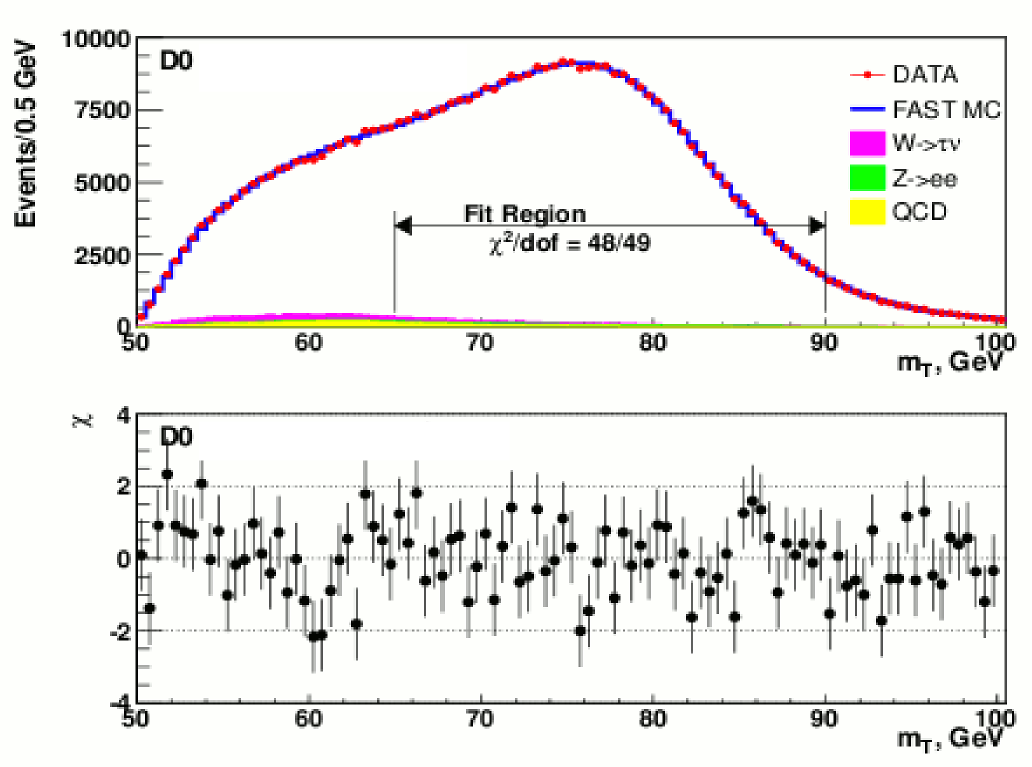
m_{top}=173.3±1.1(total) GeV

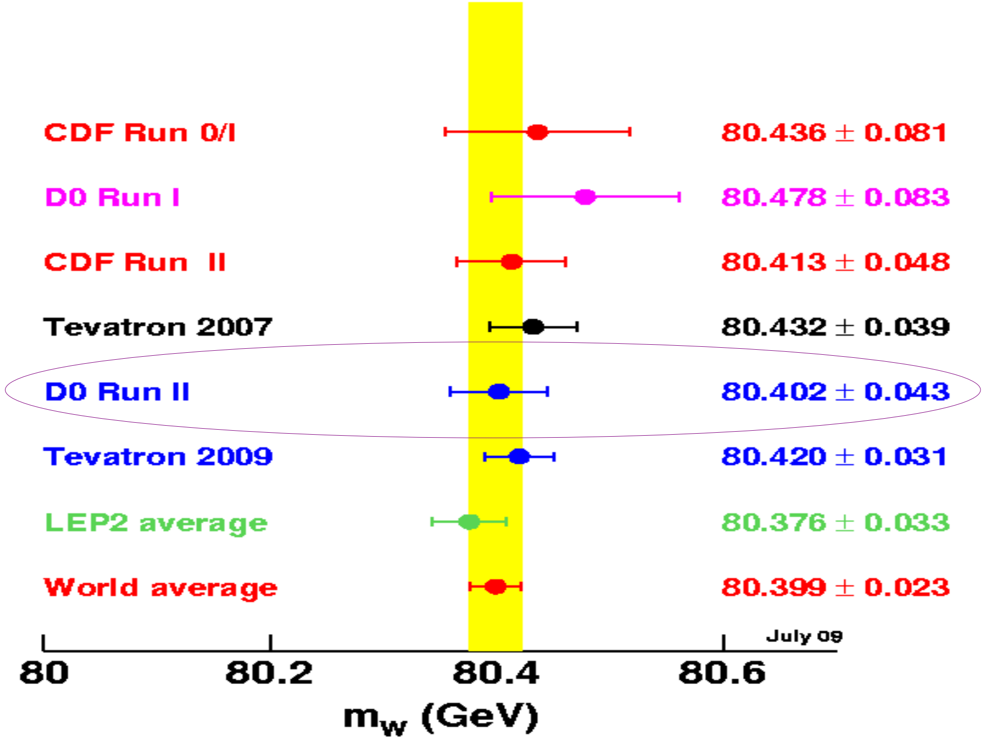
- Measurement in different channels consistent with each other
- Different methods produce consistent results

statistical component of JES
b-jet response
b-jet energy scale
modeling uncertainties
residual JES
detector response
ISR/FSR, PDF, NLO
showering model

Systematic source	δm_{top} (GeV)
iJES	0.46
aJES	0.21
bJES	0.20
cJES	0.13
dJES	0.19
rJES	0.15
Lepton p_T	0.10
Signal model	0.19
Background	0.23
Fit	0.11
MC generator	0.40
Color reconnection	0.39
Multiple interactions	0.08
Total	1.06

W mass: first DØ Run II result (1 fb^{-1})





DØ Run II (1 fb^{-1}): world's single most precise measurement.

Uses the $W \rightarrow e\ \nu$ channel with central electrons ($|\eta|<1.05$).

~ 500k $W \rightarrow e\ \nu$ events
~ 19k $Z \rightarrow e\ e$ events (critical calibration sample)

W mass: DØ projections

With 1 fb^{-1} uncertainties are mainly statistical (including 'systematics' from limited data control samples). Let's extrapolate:

source of uncertainties	1 fb-1	6 fb-1	10 fb-1
Statistics	23	10	8
Systematics			
Electron energy scale	34	14	11
Electron resolution	2	2	2
Electron energy offset	4	3	2
Electron energy loss	4	3	2
Recoil model	6	3	2
Electron efficiencies	5	3	3
Backgrounds	2	2	2
Total Exp. systematics	35	16	13
Theory			
PDF	9	6	4
QED (ISR-FSR)	7	4	3
Boson Pt	2	2	2
Total Theory	12	8	5
Total syst+theory	37	18	14
(if theory unchanged)		20	17
Grand total	44	21	16 (20)

At end of Run II, expect total uncertainty on W mass of 16 MeV from DØ alone.

Expect similar performance from CDF, and combined error of 12 MeV.

This legacy measurement will be in the textbooks for decades to come.

Could be an important contribution to getting the standard model into trouble in the near future:

with δm_W = 15 MeV, δm_t = 1 GeV
and m_W = 80.400 GeV :

$$m_H = 71^{+24}_{-19} \text{ GeV} \quad < 117 \text{ GeV @ } 95\% \text{ cl}$$

(P. Renton, ICHEP 2008)

New experimental constraints on "$p_T(Z)$"

Measure $d\sigma/dp_T$ for inclusive Z boson production (455k $Z \rightarrow ee$/ 511k $Z \rightarrow \mu\mu$ decays) in 7.3 fb^{-1} of DØ data.

Investigate possibility of small-x broadening of Z p_T distribution at low p_T.

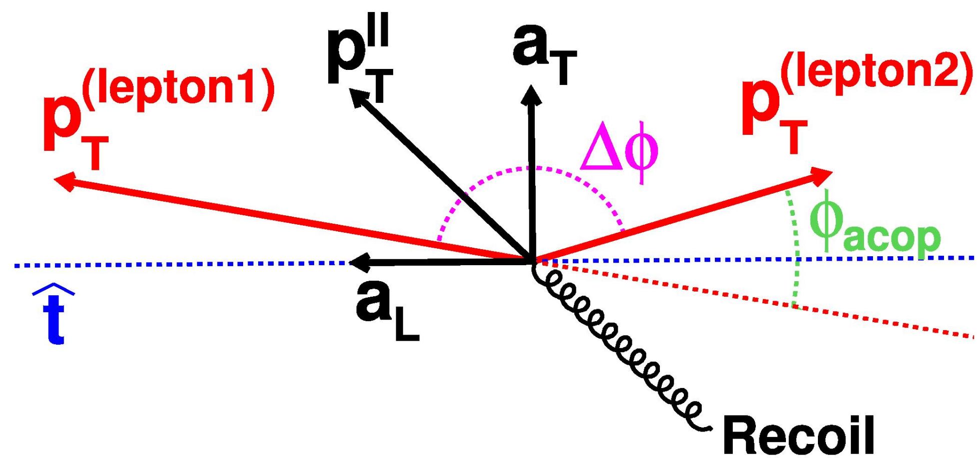
Minimise detector resolution effects: use novel technique requiring only measurements of lepton **directions**.

Define:

$\phi_{acop} = \pi - \Delta\phi_{ll}$

$\cos\theta^*_\eta = \tanh((\eta^- - \eta^+)/2))$

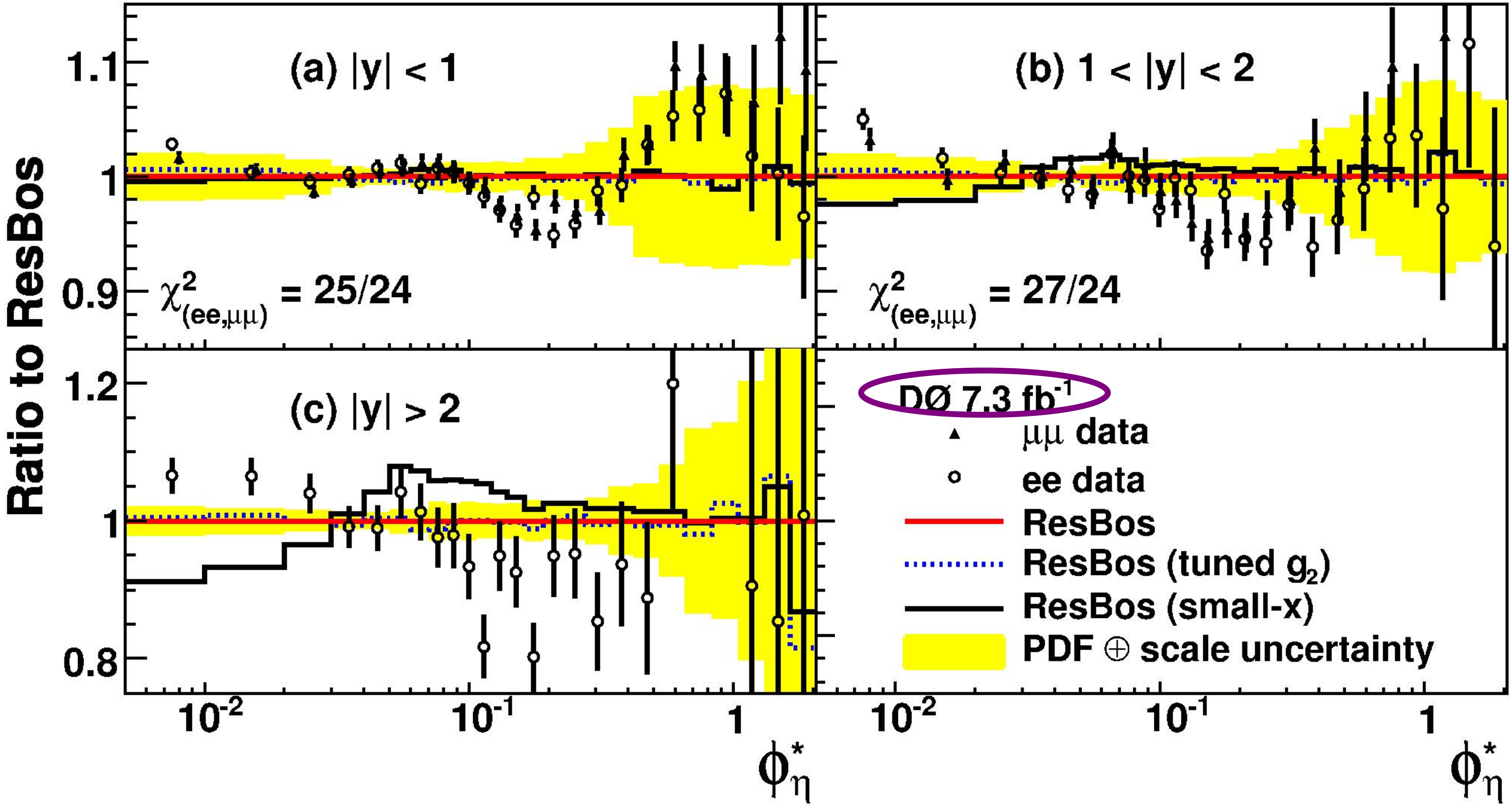
$\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$



Perform measurement of $d\sigma/d\Phi^*_\eta$ in bins of Z boson rapidity y.

New experimental constraints on "$p_T(Z)$"

Comparison of the unfolded data to (three flavours of) ResBos:



W charge asymmetry

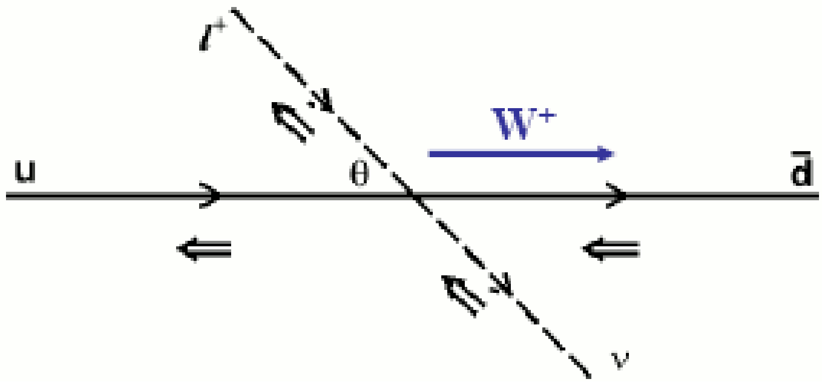
$W^{\pm}$ rapidity measurement constrains PDF of u and d quarks.

$$x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y}$$

Different u, d momentum:
$W^{\pm}$ produced asymmetrically.

→ charge asymmetry of l, ν from W decay

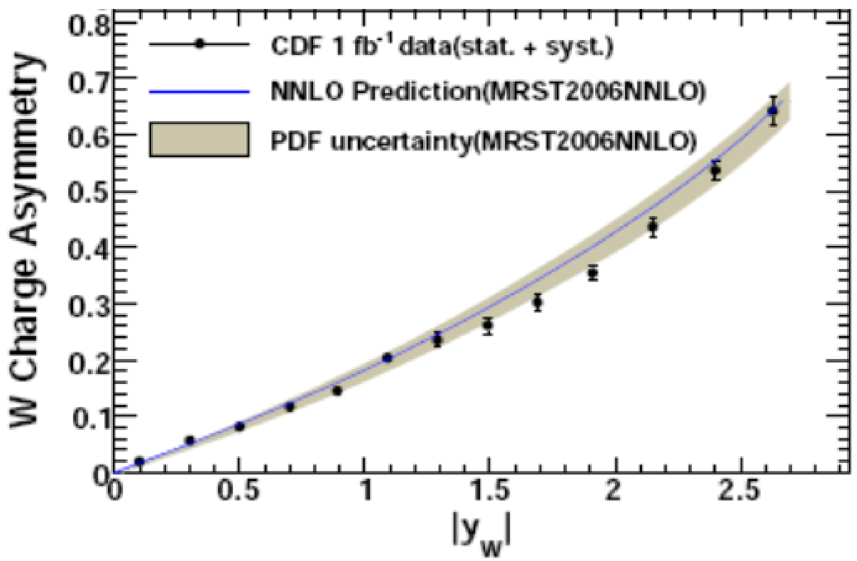
But V-A interaction: **reduces** the observable **asymmetry** in the lepton rapidity distributions.



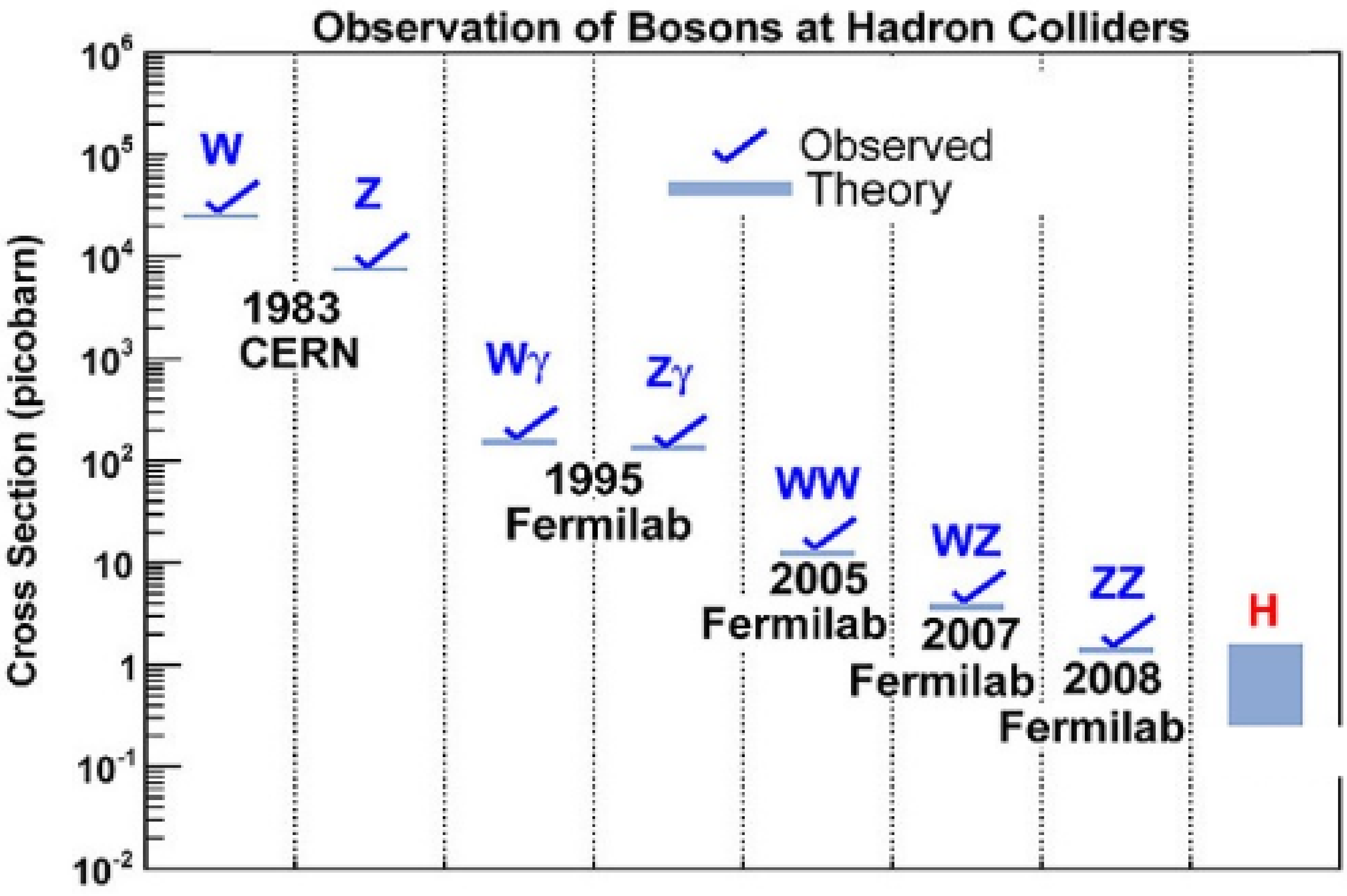
First direct measurement of W charge asymmetry from CDF

Find the two neutrino four-vectors which are solutions for m(l ν) = M(W).

Despite additional complication of multiple solutions, it works !



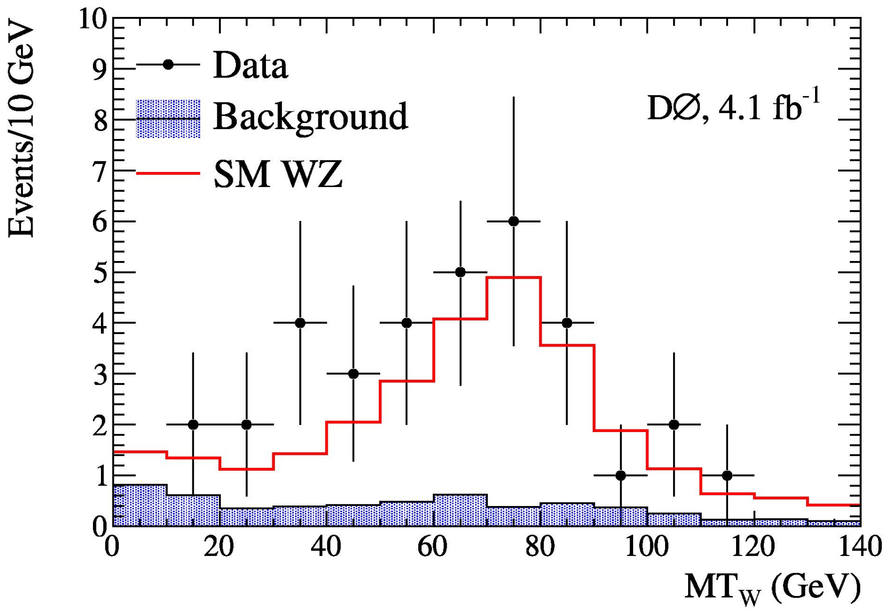
Observation of di-boson signals



All di-boson signals observed by both CDF and D0 in many different final states.

Di-bosons: examples

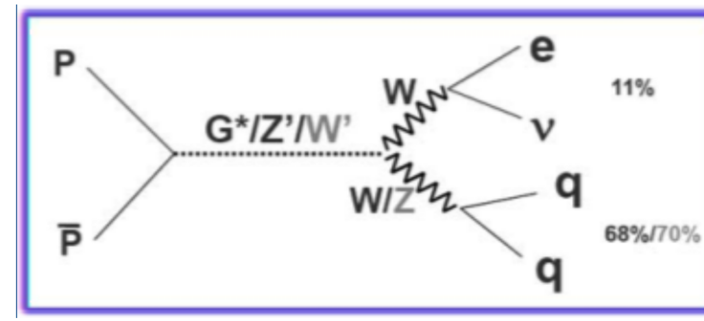
Measurement of σ(WZ) in the tri-lepton + MET final state:

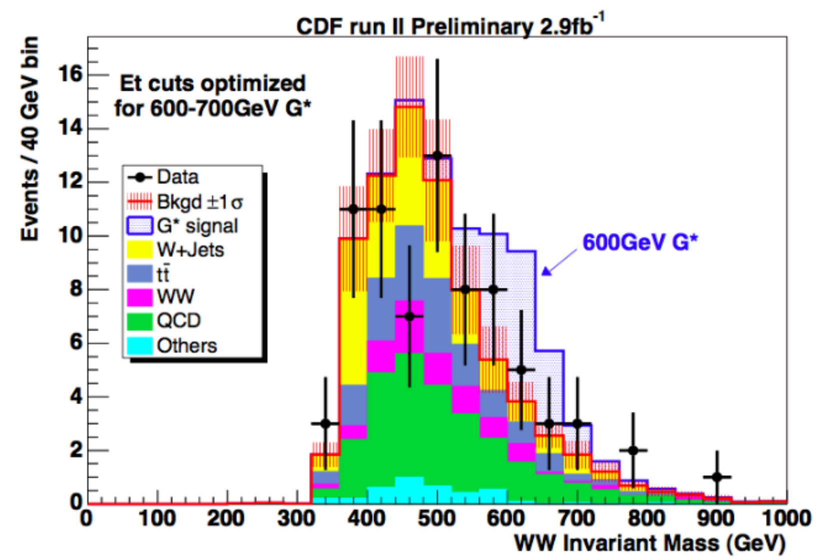


$\sigma = 3.90^{+1.06}_{-0.90}$ pb

(SM: 3.45 pb)

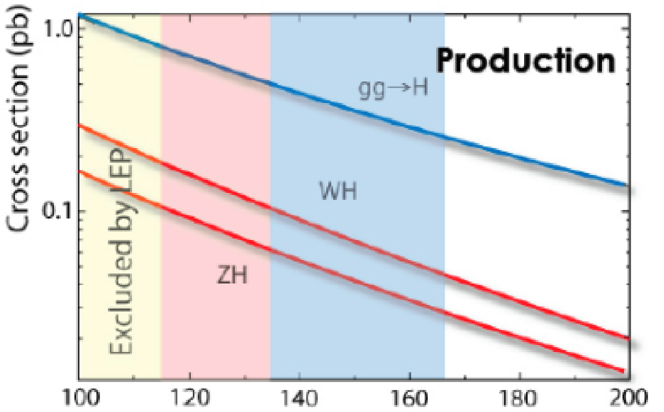
Search for anomalous triple gauge couplings in the e jet jet + MET final state:





$M_G > 607$ GeV ($k/M_p = 0.1$)

Direct Higgs searches

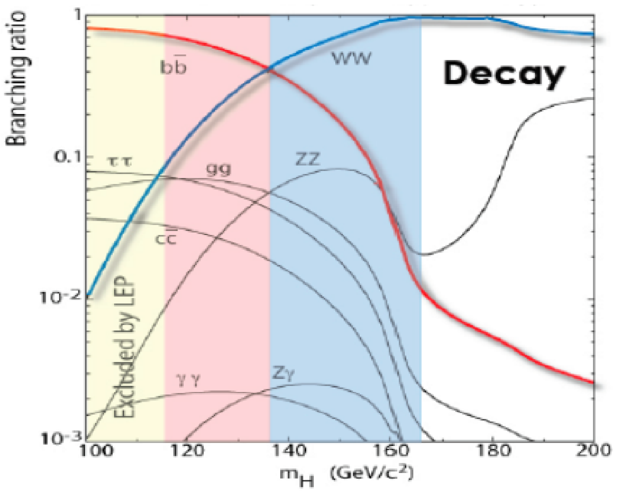


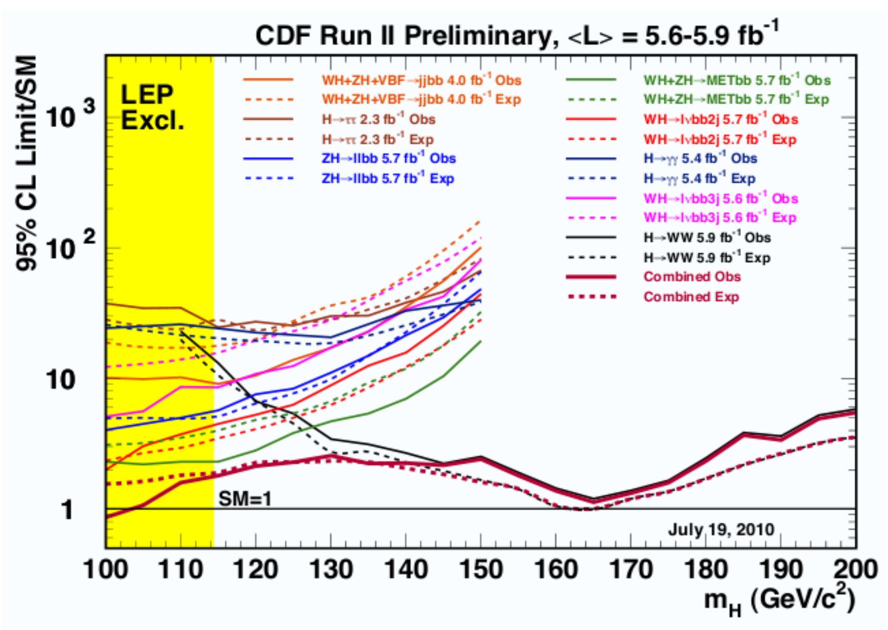
Low mass Higgs:

- H→ bb, QCD bb background is overwhelming
- use associated production to reduce background

High mass Higgs:

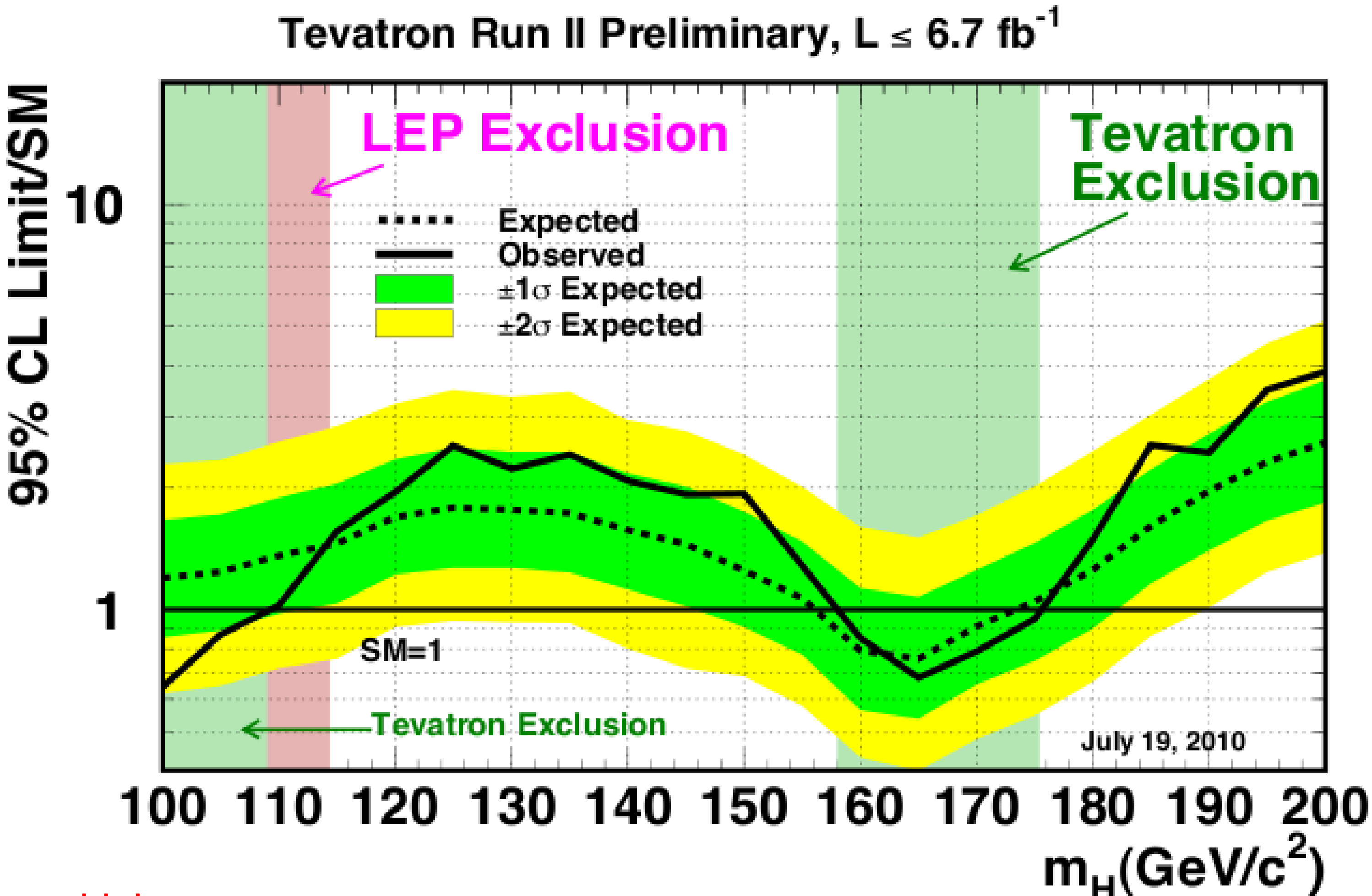
- H→ WW → lνlν decay available
- take advantage of large gg → H production cross section





Final result is the combination of many channels.

Tevatron combination



Low mass sensitivity
approaching LEP exclusion

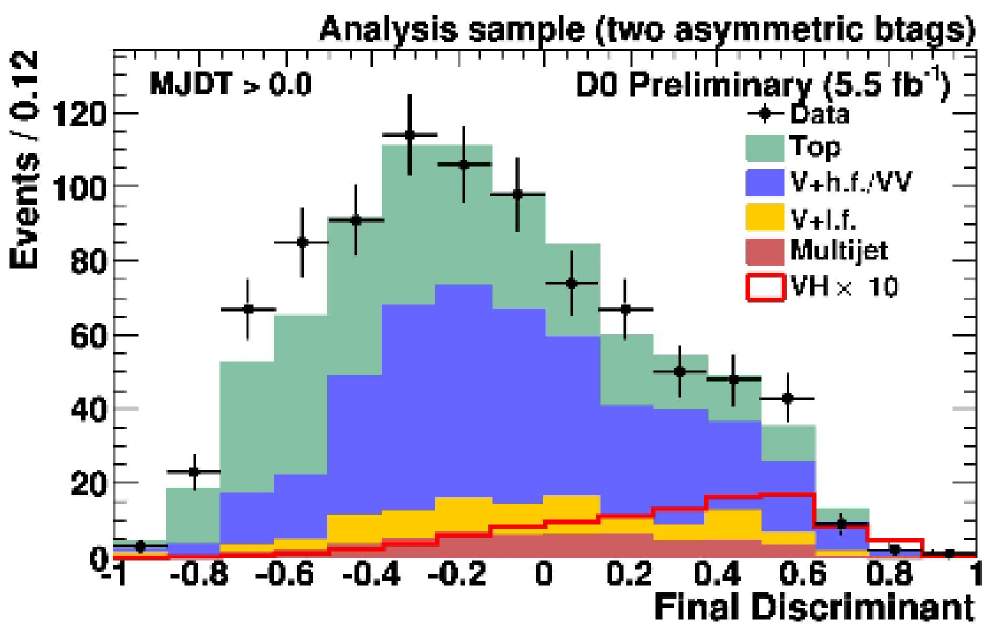
High mass 95% CL exclusion:
$158 < m_H < 175$ GeV

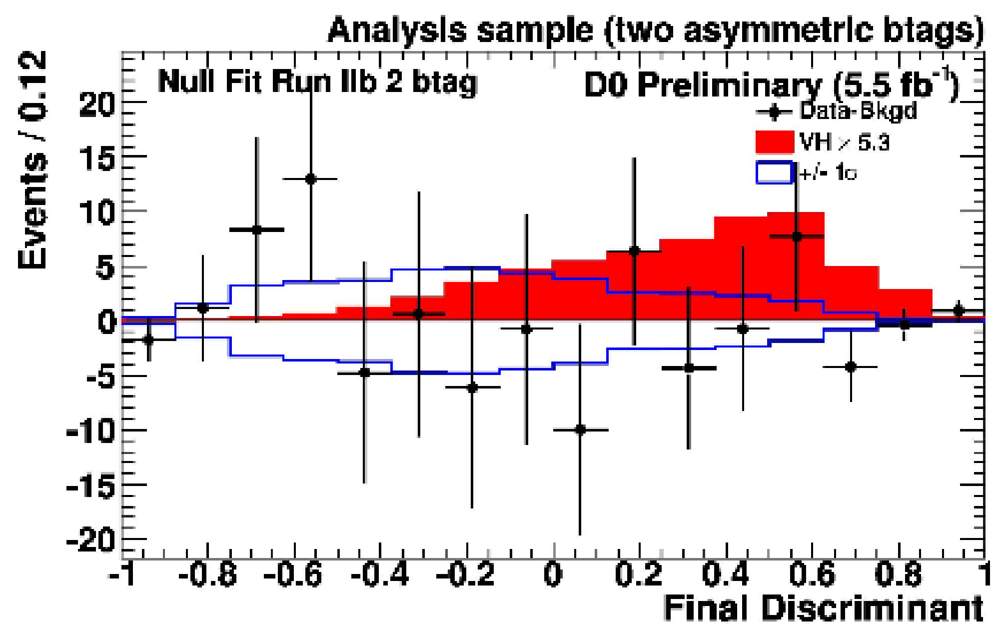
One example: ZH

Search for ZH associated production with Z $\rightarrow \nu\nu$, H$\rightarrow$ bb

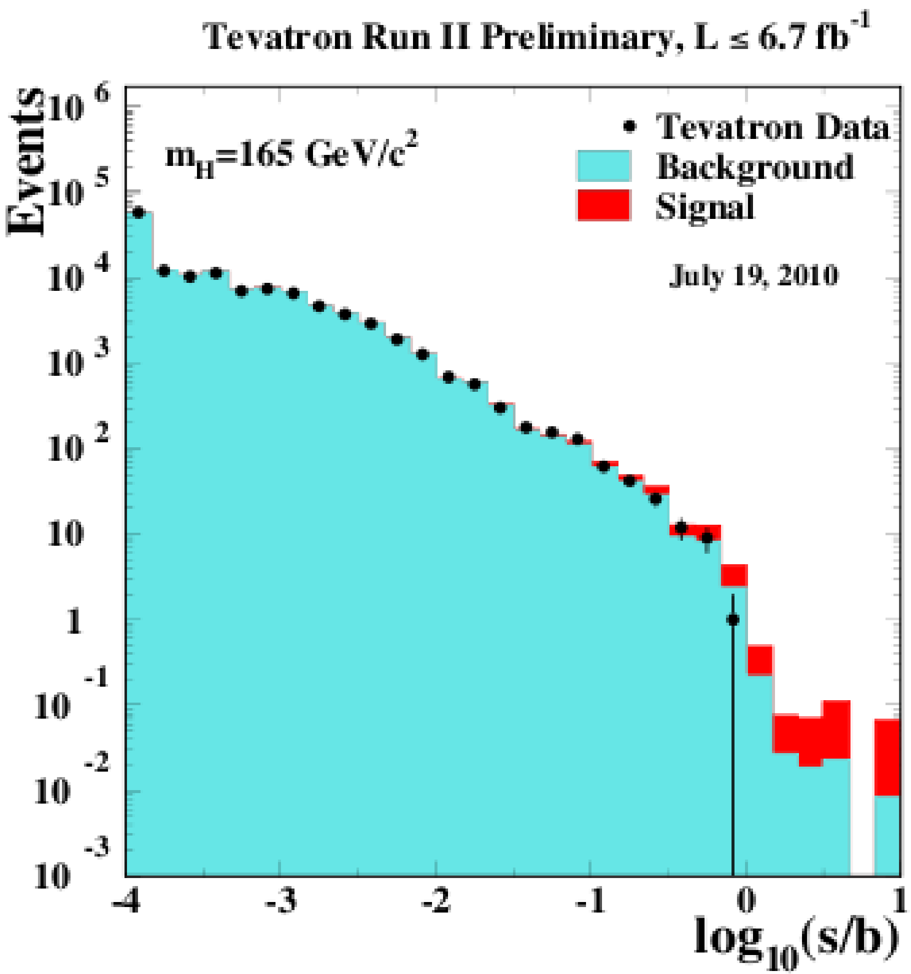
Final state with two acoplanar jets and MET.

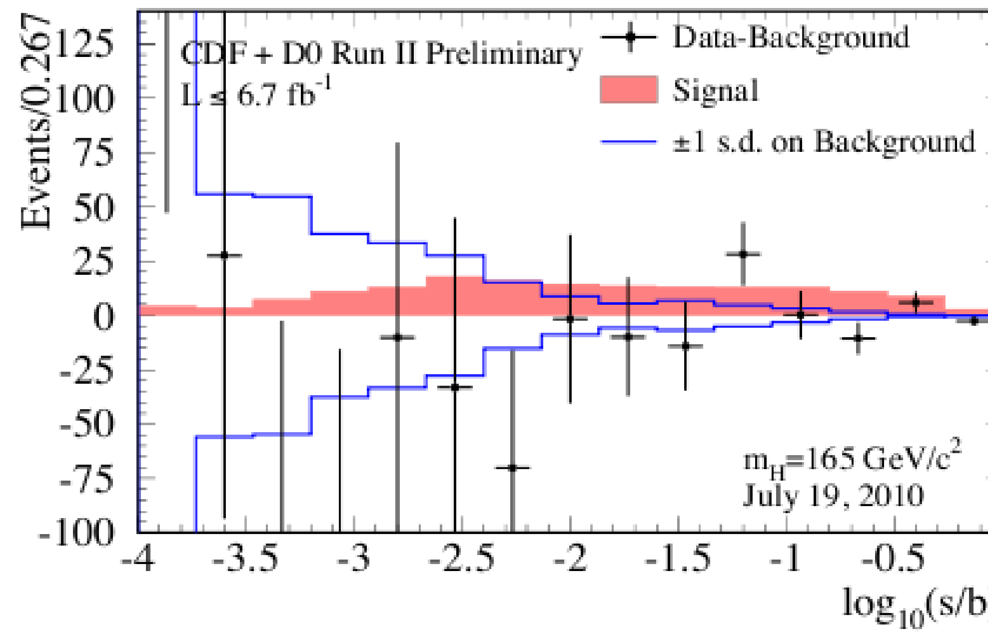
Updated double tag results based on 6.4 fb-1 of data.





Hypothesis: m_H = 165 GeV

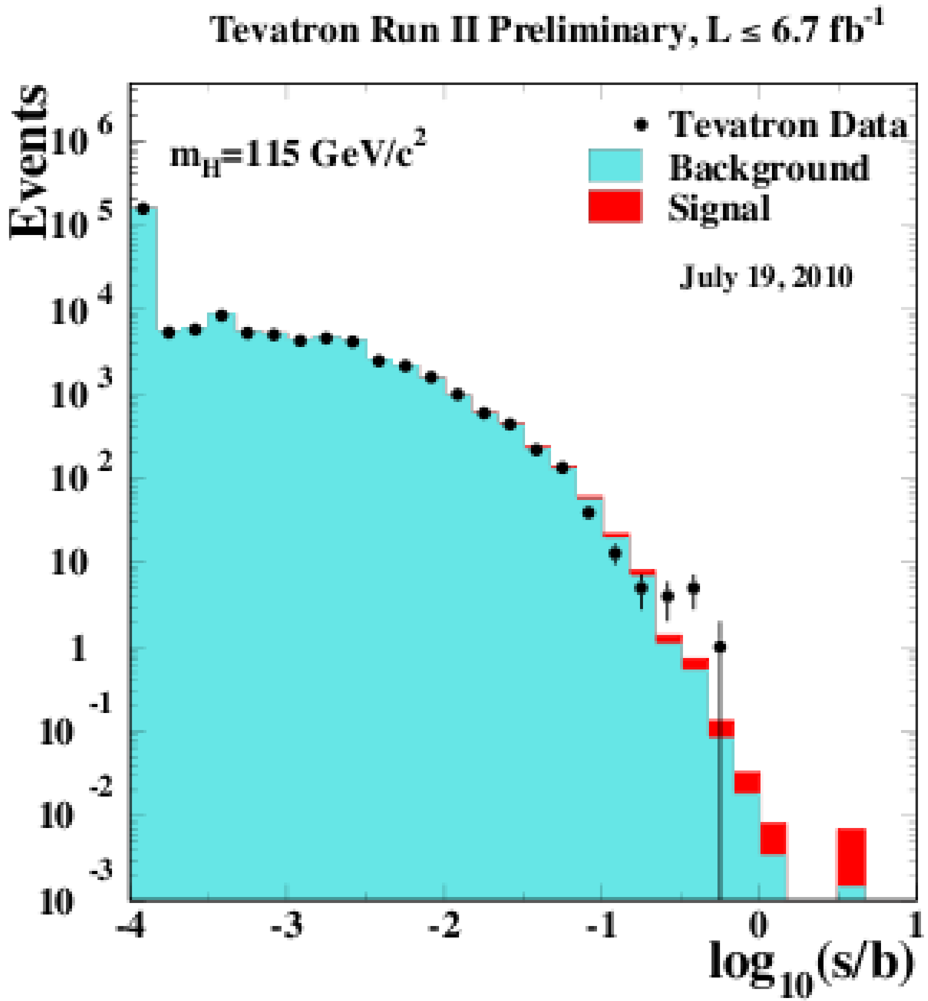


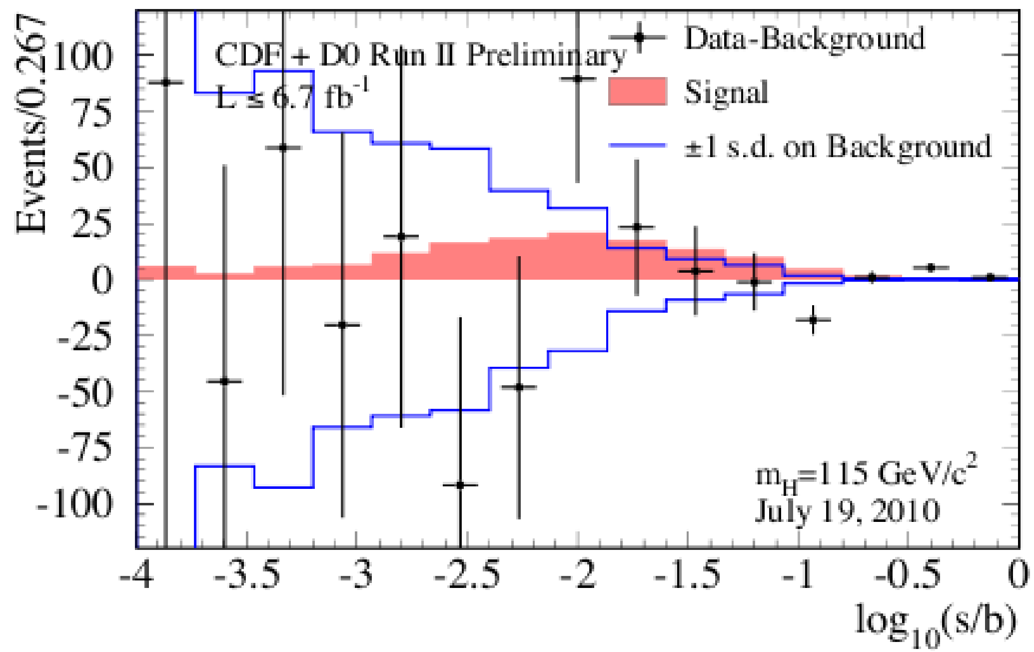


Data – background shown compared to signal in red.

All bins of all sub-channels of all channels.

Hypothesis: m_H = 115 GeV

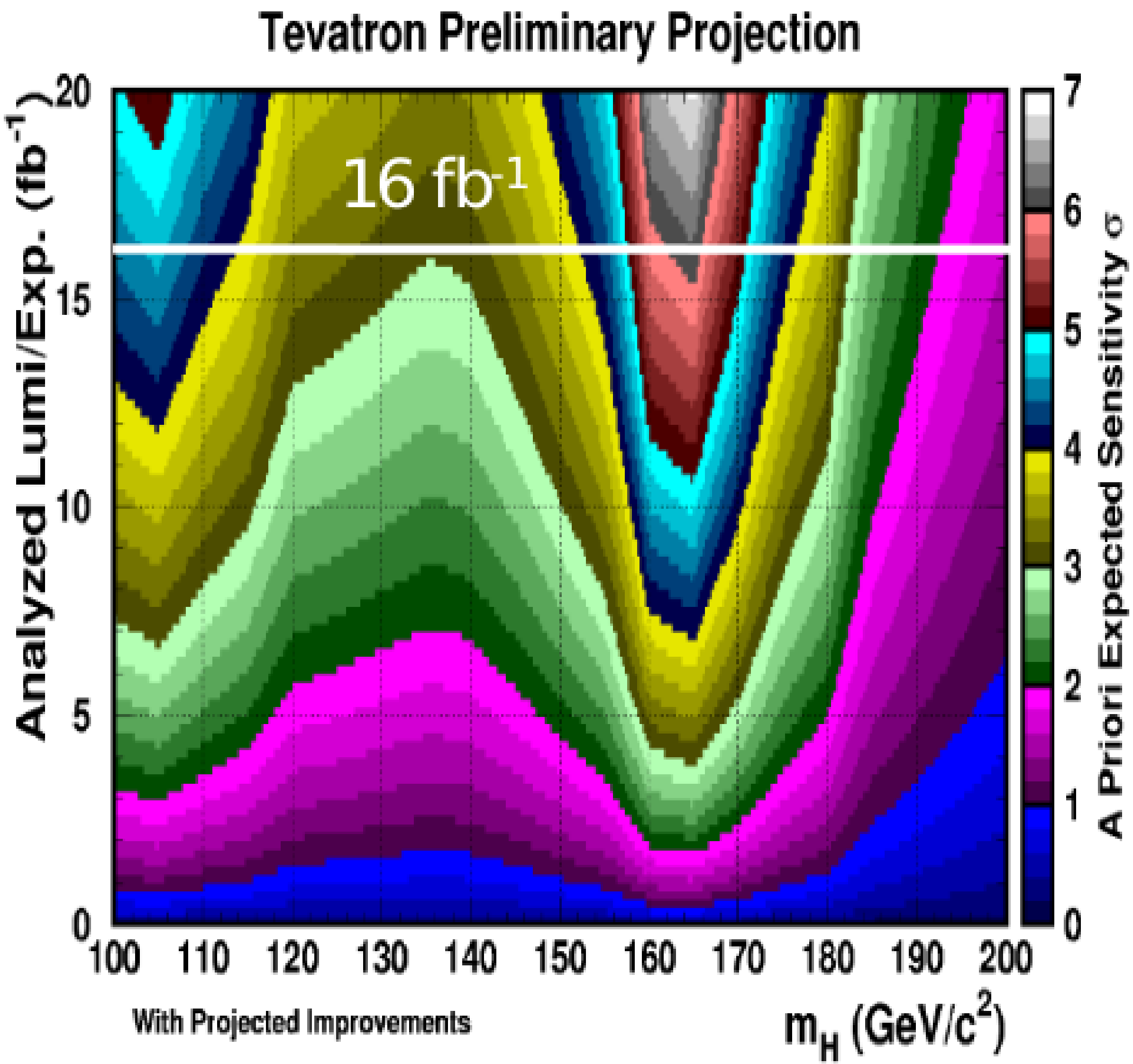




Data – background shown compared to signal in red.

All bins of all sub-channels of all channels.

Outlook 2012-2014



Strong motivation to collect data beyond 2011 !

A three-year extension of the Tevatron Run II (until 2014) is under consideration by the funding agencies.

With 16 fb^{-1} available for analysis, with Tevatron run extension, we will be able to see evidence of the Higgs in all allowed mass range

Conclusions

The Tevatron physics programme is very strong and exciting.
Have attempted to show a few selected highlights.

The Tevatron is still highly competitive with the LHC,
and it will always be complementary to the LHC:

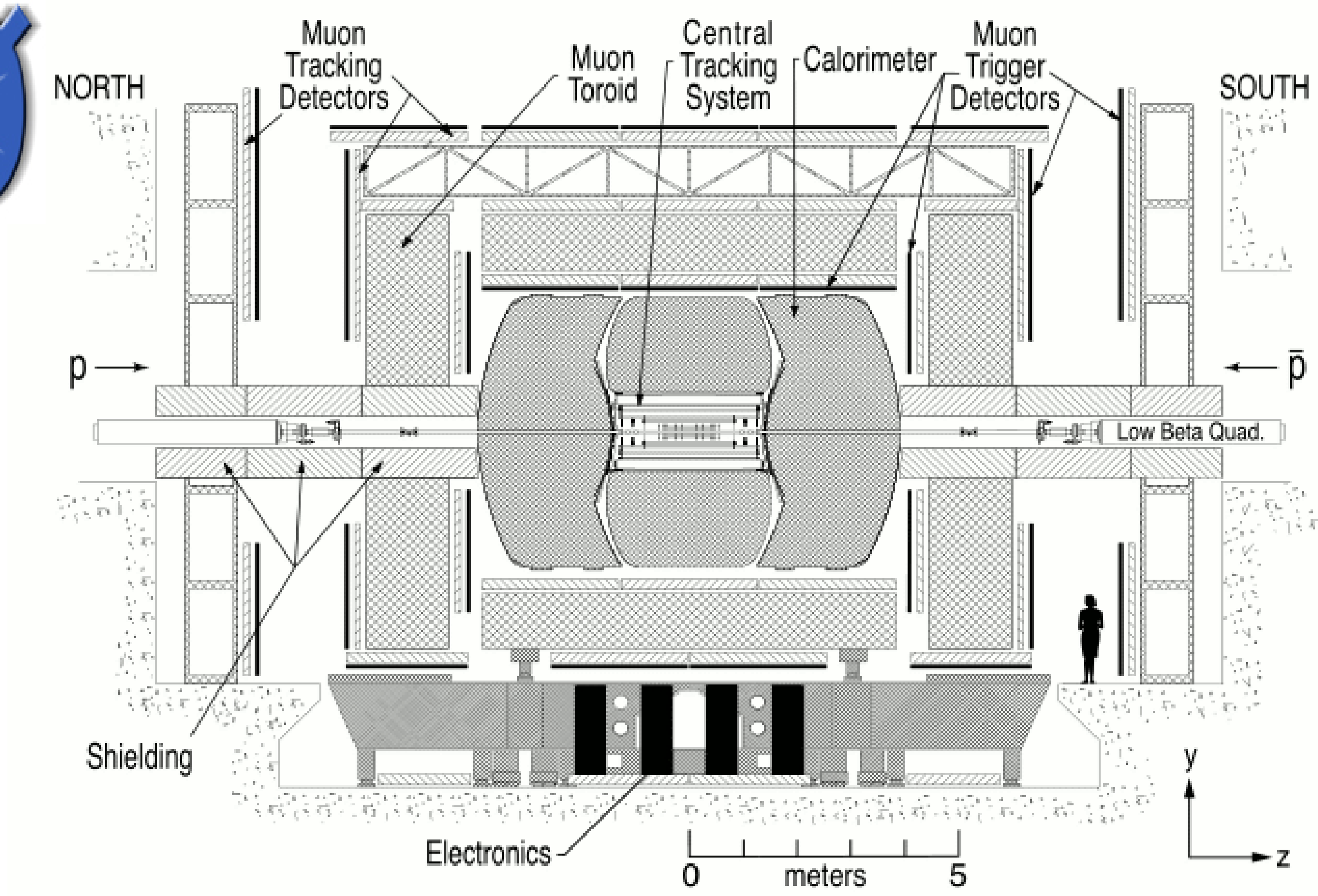
- Searches for new physics: LHC benefits from larger $\sqrt{s}$ and has started to take over in some selected signatures.
- Tevatron will remain the leader in precision measurements for quite some time: top quark properties, QCD precision tests, ...
- In some key measurements it will be impossible for another hadron collider to beat the final Tevatron results by a significant fraction: top quark mass, W boson mass
- Some Tevatron measurements simply cannot be done at the LHC, because the Tevatron is p pbar at 2 TeV:

  W boson charge asymmetry, di-muon charge asymmetry, top spin correlations, ...
- Low mass Higgs is tough for everybody.

Strong hunger for more data, and strong motivation to extend the run even beyond 2011.

Backup slides

The upgraded Dzero detector

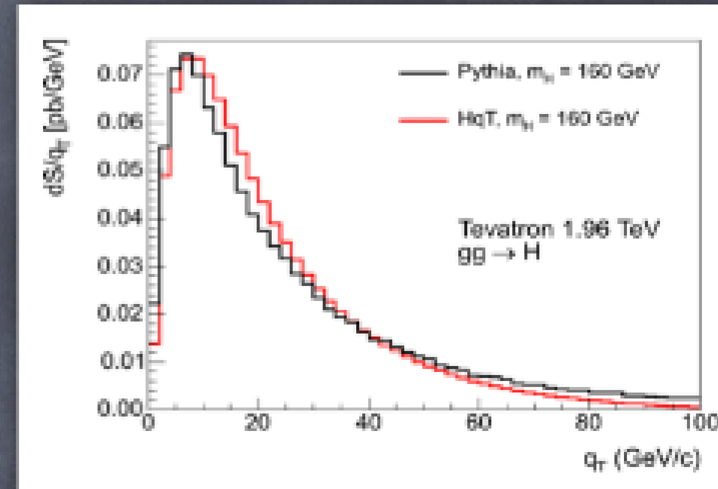


Theory & uncertainties

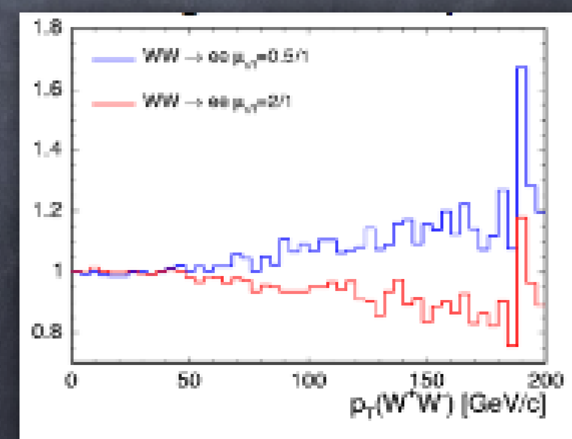
- We make use of well-motivated and state of the art gluon fusion cross-section calculations and uncertainties
  - gg → H uses NNLL + NNLO calculations
    - "Next to Next to Leading Log/Order"
  - de Florian & Grazzini (Phys.Lett.B674:291-294, 2009)
    - Soft-gluon resummation treatment
    - MSTW2008 Parton Density Function
  - Anastasiou, Boughezal, Petriello (JHEP:0904:003, 2009)
    - Proper treatment of b-quarks at NLO
    - Inclusion of two-loop electroweak effects

- For those interested in a detailed explanation of our choices and comparison with more extreme approaches :

http://tevnphwg.fnal.gov/results/SMHPubWinter2010/gghtheoryreplies_may2010.html



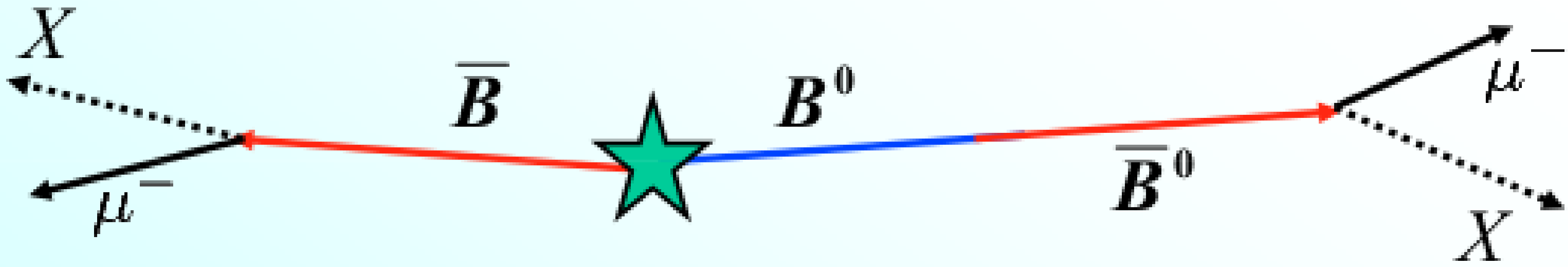
Reweight PYTHIA Higgs kinematics to full NNLL calculation



Consider same variations for dominant WW bkg

Ben Kilminster, ICHEP 2010 18

Di-muon charge asymmetry



- We measure *CP* violation in mixing using **the dimuon charge asymmetry of semileptonic *B* decays:**

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

  - N_b^{++}, N_b^{--} – number of events with two b hadrons decaying semileptonically and producing two muons of the same charge
  - One muon comes from direct semileptonic decay $b \rightarrow \mu^- X$
  - Second muon comes from direct semileptonic decay after neutral B meson mixing: $B^0 \rightarrow \overline{B}^0 \rightarrow \mu^- X$

Di-muon charge asymmetry

- A^b_{sl} is equal to the charge asymmetry of "wrong sign" semileptonic B decays:

$$a^b_{sl} \equiv \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}$$

  - See Y. Grossman, Y. Nir, G. Raz, PRL 97, 151801 (2006)
  - "Right sign" decay is $B \to \mu^+ X$
  - "Wrong sign" decays can happen only due to flavour oscillation in B_d and B_s
  - Semileptonic charge asymmetry can also be defined separately for B_d and B_s :

$$a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}; \quad q = d, s$$

Di-muon charge asymmetry

- In this analysis we measure a linear combination of a^d_{sl} and a^s_{sl}:

$$A^b_{sl} = 0.506\, a^d_{sl} + 0.494\, a^s_{sl}$$

- Obtained result agrees well with other measurements of a^d_{sl} and a^s_{sl}