Physics at the LHC

Motivation, Machine, Experiments, Physics

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DESY Summer Student Programme
Hamburg, August 2010

OUTLINE

- Part 1 – Motivation: Why the LHC?
- Part 2 – Realisation: How the LHC?
  - The accelerator.
  - The experiments ALICE, LHCb, TOTEM and LHCf.
  - ATLAS and CMS.
- Intermezzo: Basics of pp physics
- Part 3 – Results: What at the LHC (and the Tevatron)?
  - ATLAS and CMS: Commissioning and performance
  - LHC: The rediscovery of the Standard Model.
  - Higgs boson searches at Tevatron and LHC.
  - Searches for Supersymmetry and other BSM physics at Tevatron and LHC.

PART 3

Results: What at the LHC?

Standard Model

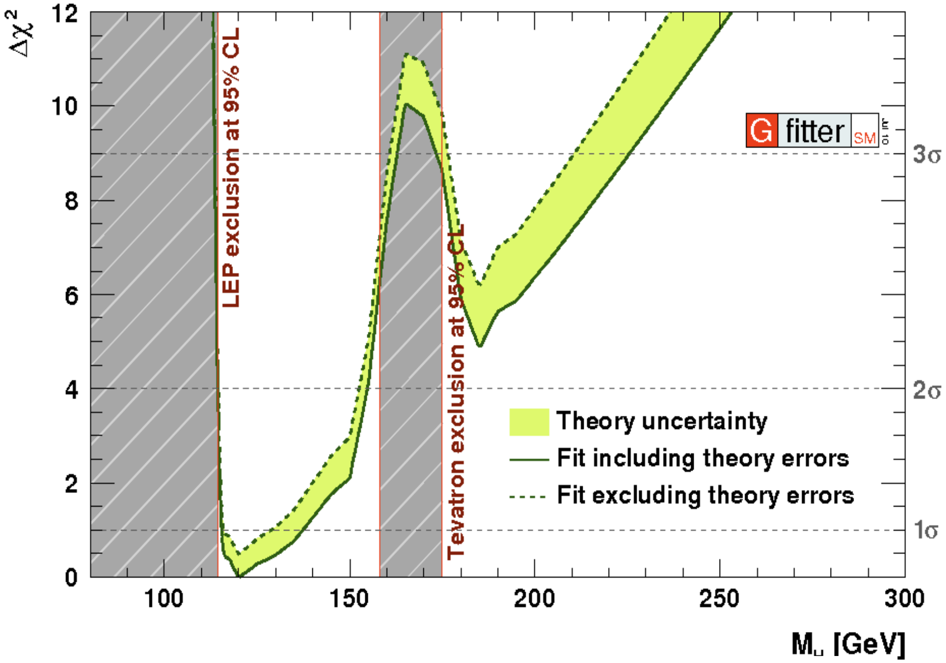
Searches – Higgs, SUSY, etc.

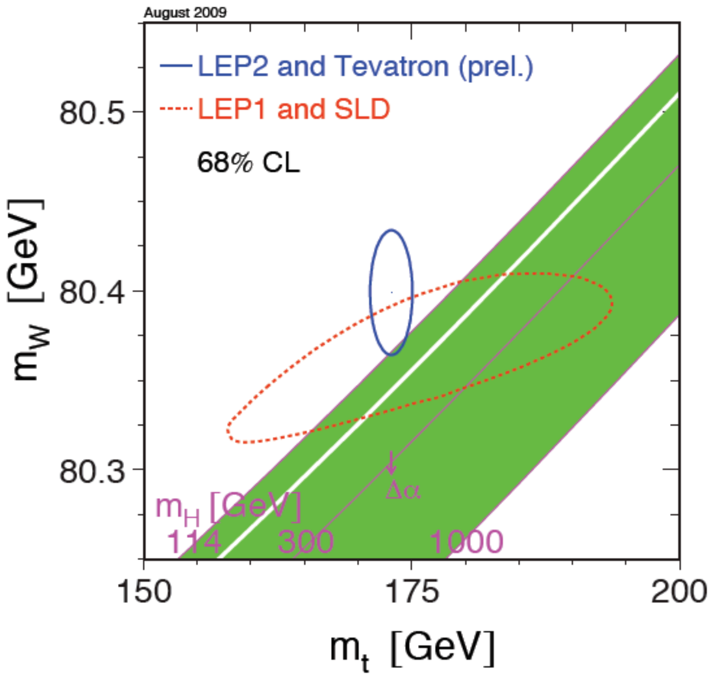
SM HIGGS

(will not discuss non-SM – largely similar techniques, and weaker conclusions)

SM HIGGS PHYSICS

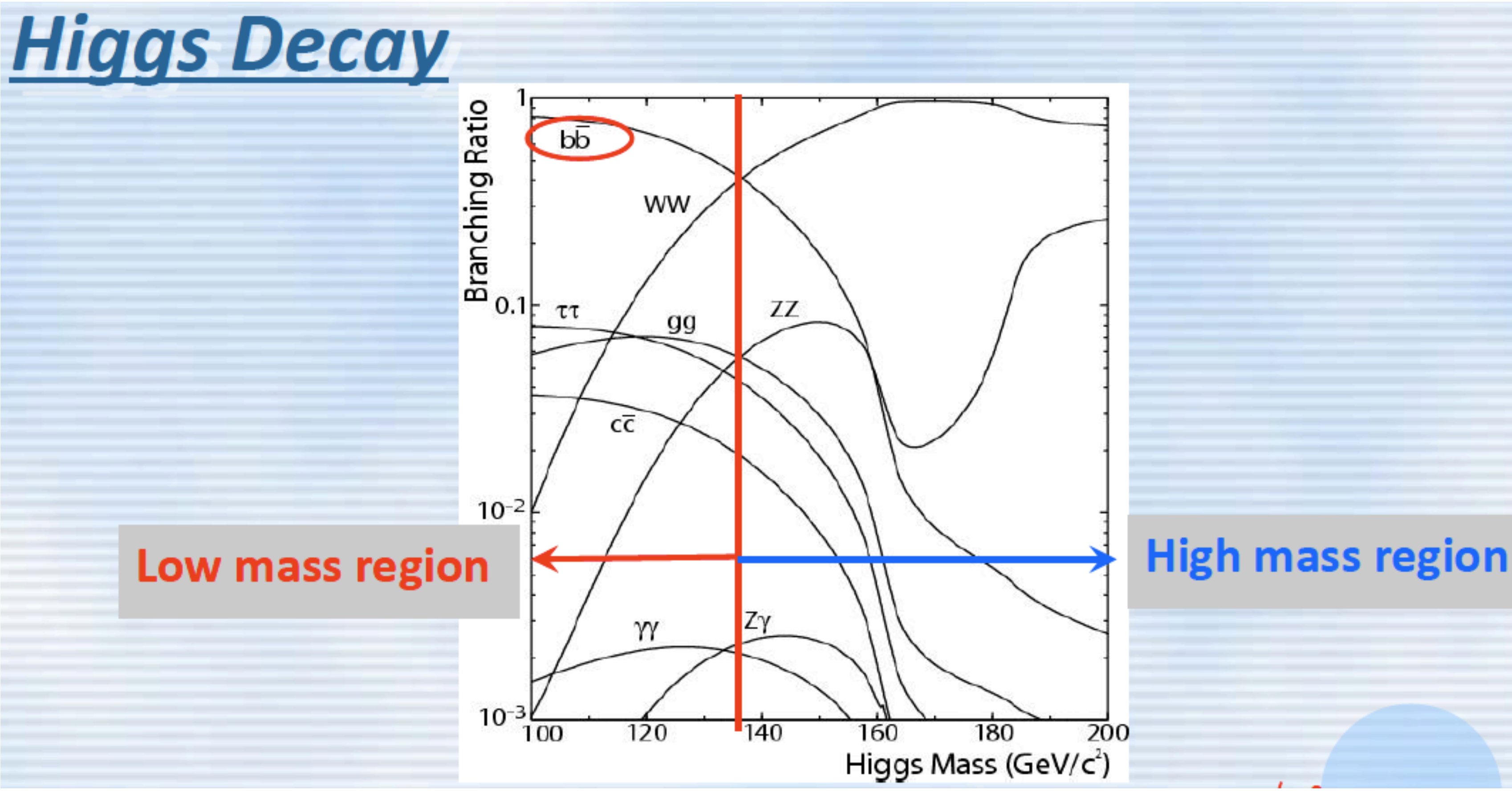
- Higgs has several tasks in the SM
  - Gives masses to bosons (via spontaneous broken symmetry) and to fermions (Yukawa coupl.).
  - Prevents divergencies of SM cross sections at around 1 TeV.
- Present situation: Long searched for at many maschines. Last to search: LEP and Tevatron! Nothing found ➔ limits on Higgs mass!
- EW precision fits to LEP and other data
  ➔ indirect constraints on Higgs mass; indicating low mass, in fact lower than limit from direct searches!
- Nothing from LHC yet, discuss Tevatron !



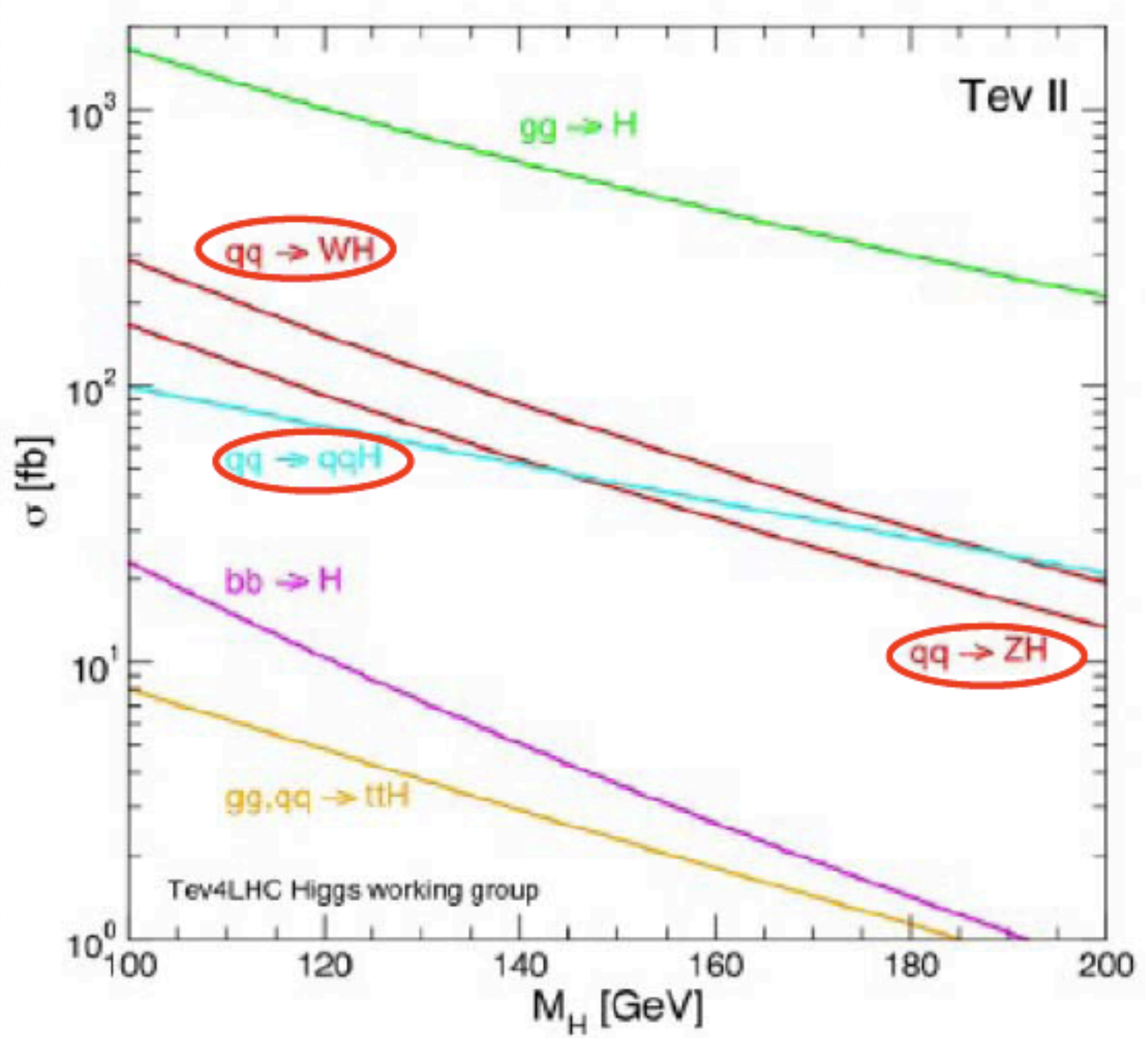


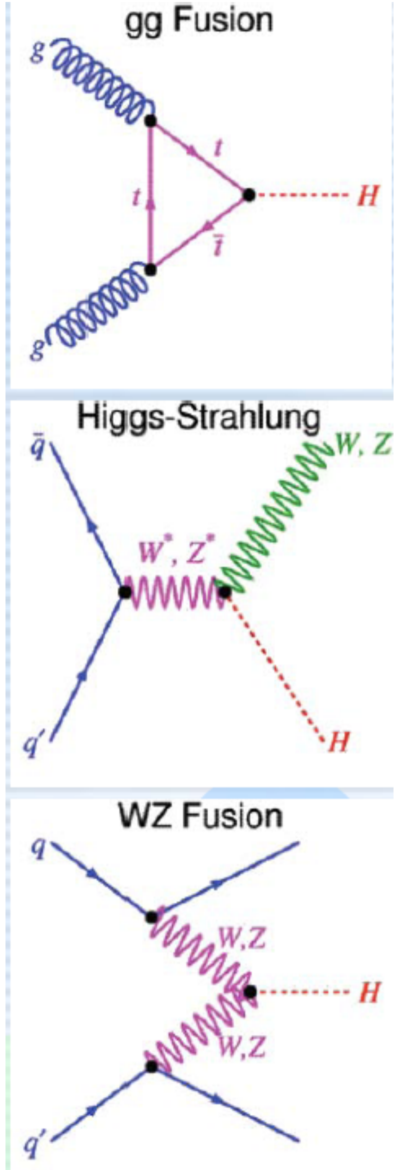
SM HIGGS AT TEVATRON

- Numerous channels – typically divided between high and low higgs mass.

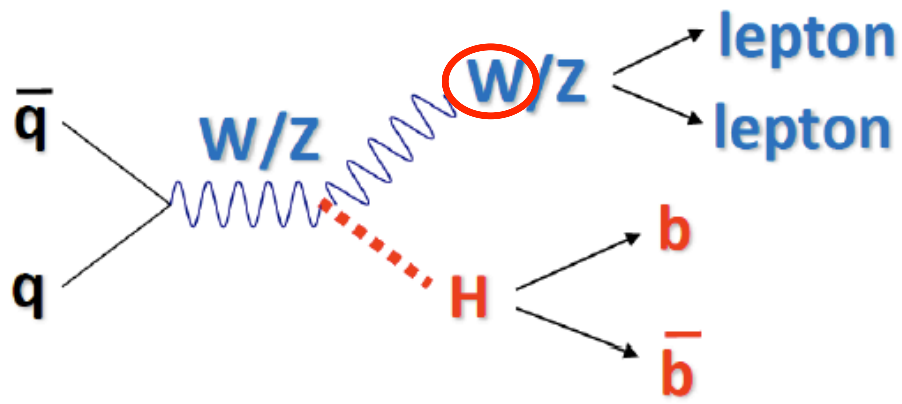


SM HIGGS PRODUCTION AT TEVATRON





HIGGS: ANALYSIS FLOW



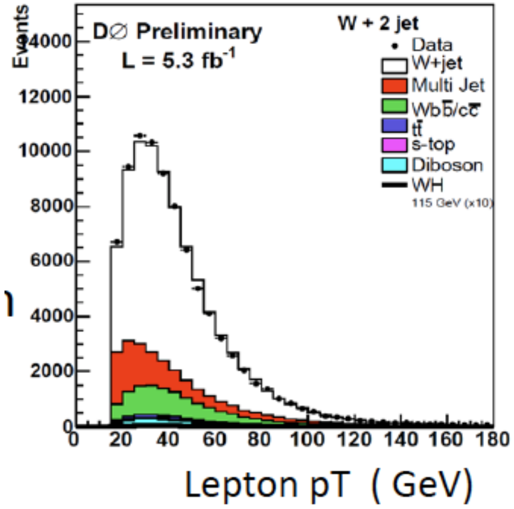
1. W or Z boson reconstruction

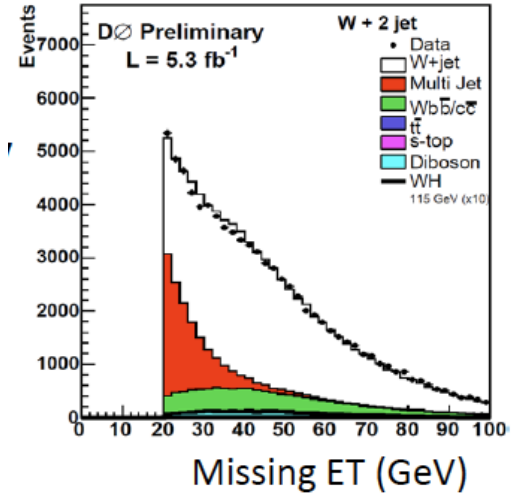
   W→lν, Z→ll, Z→νν

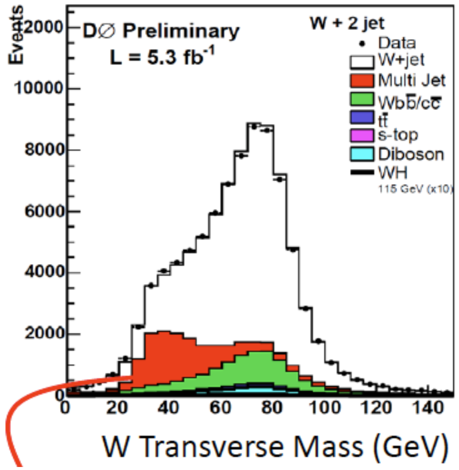
2. Higgs candidate reconstruction

   Dijet mass, b-jet tagging.

3. MultiVariate Analysis (MVA)
4. Result







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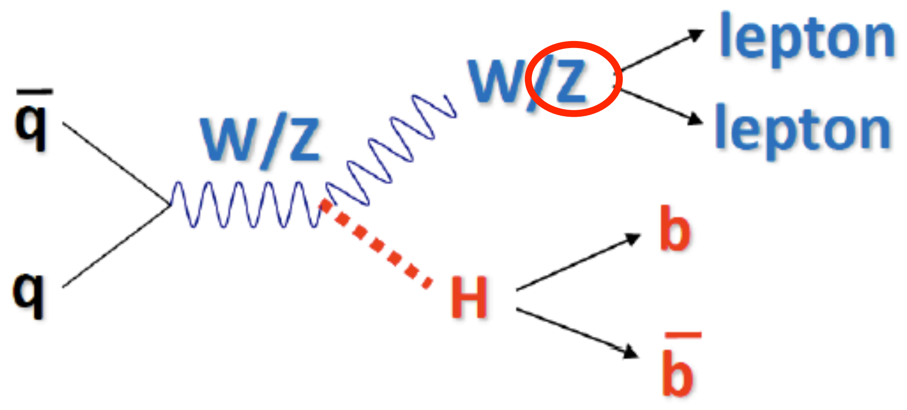

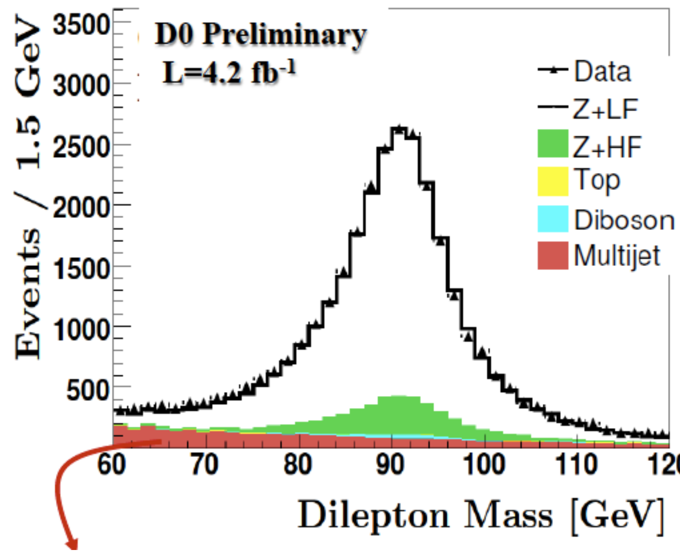

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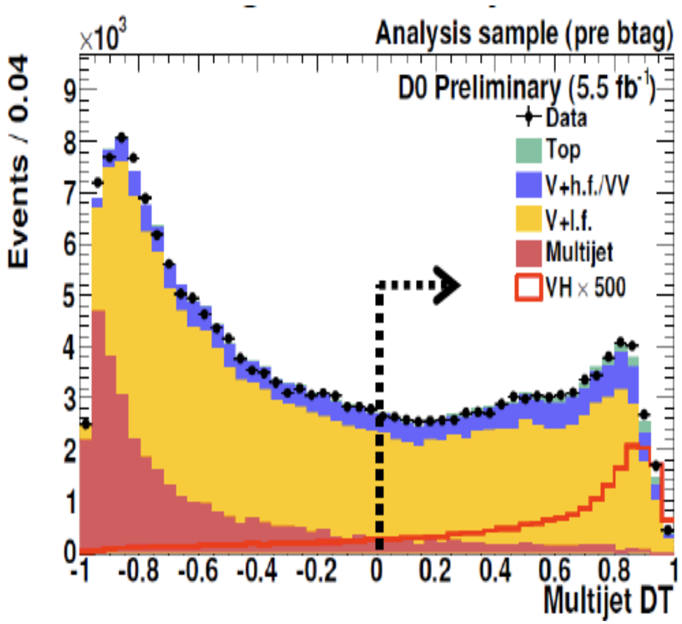

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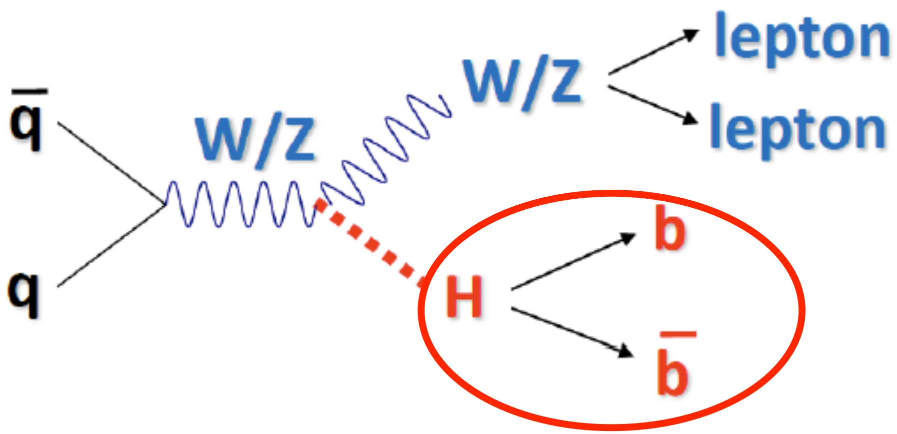

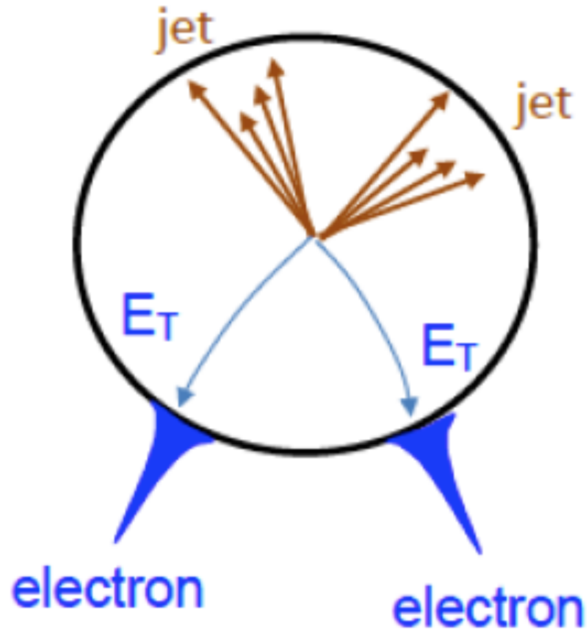

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   $W \rightarrow l\nu$, $Z \rightarrow ll$, $Z \rightarrow \nu\nu$

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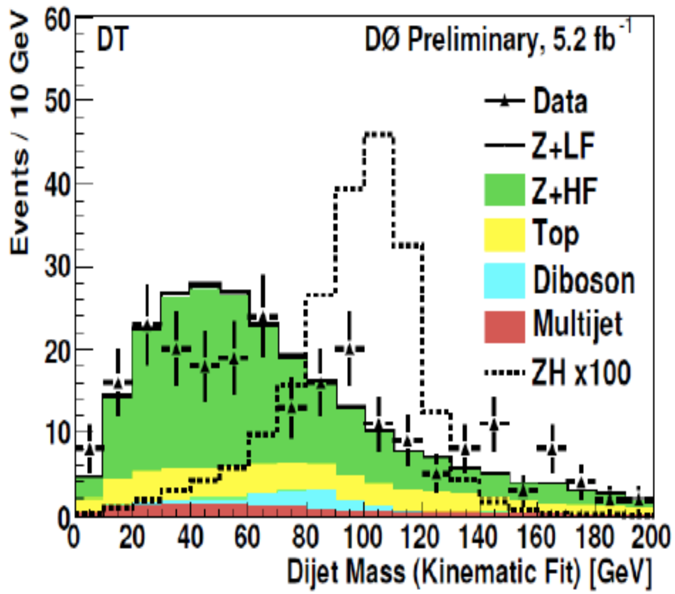

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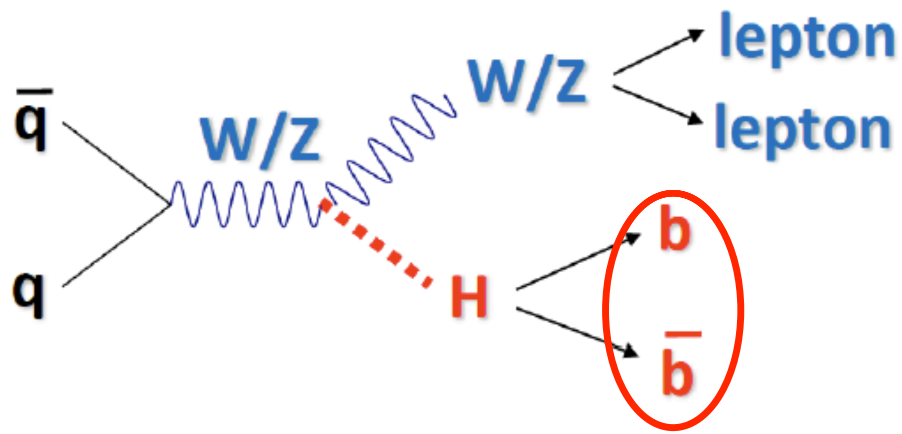

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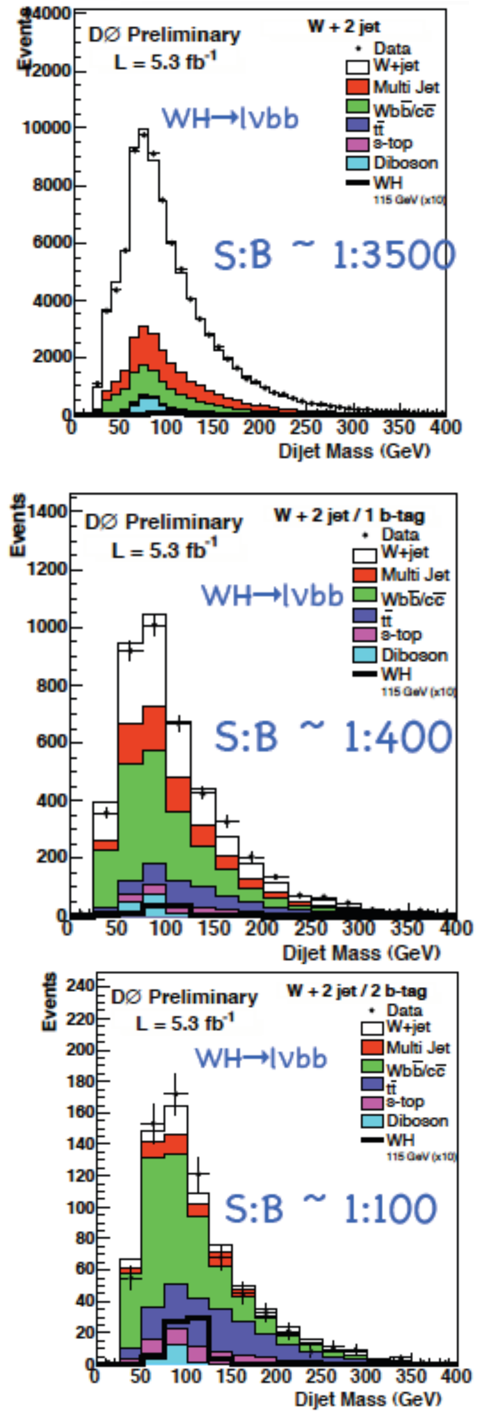

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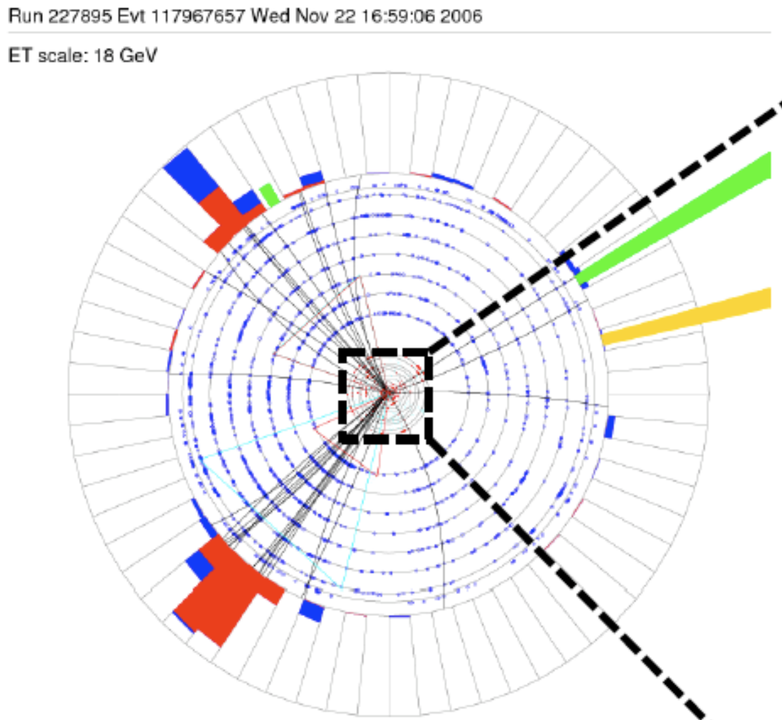
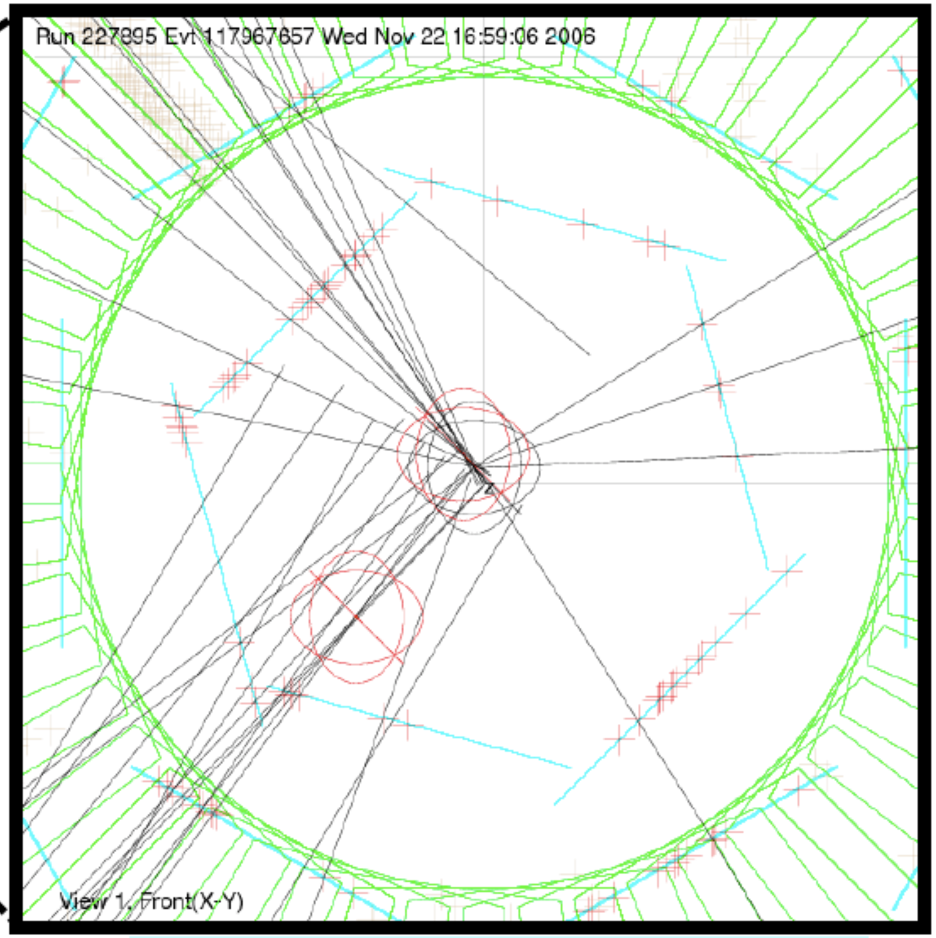
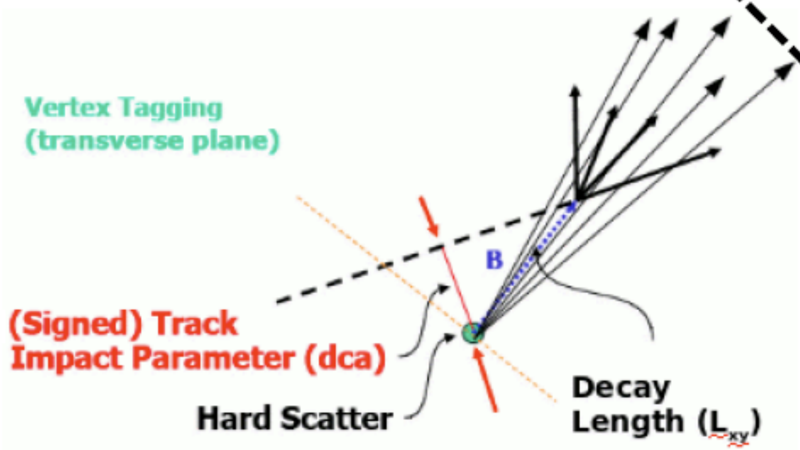


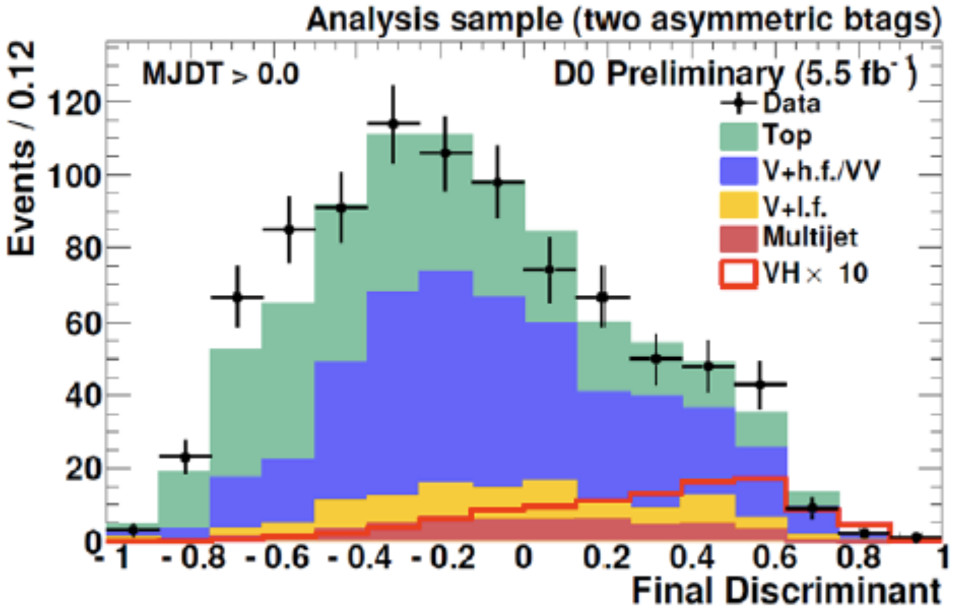




Neural Net b-tagger

- Combination of SV & dca
  - Loose: 70% eff, 4.5% fake
  - Tight : 50% eff, 0.3% fake

HIGGS: ANALYSIS FLOW



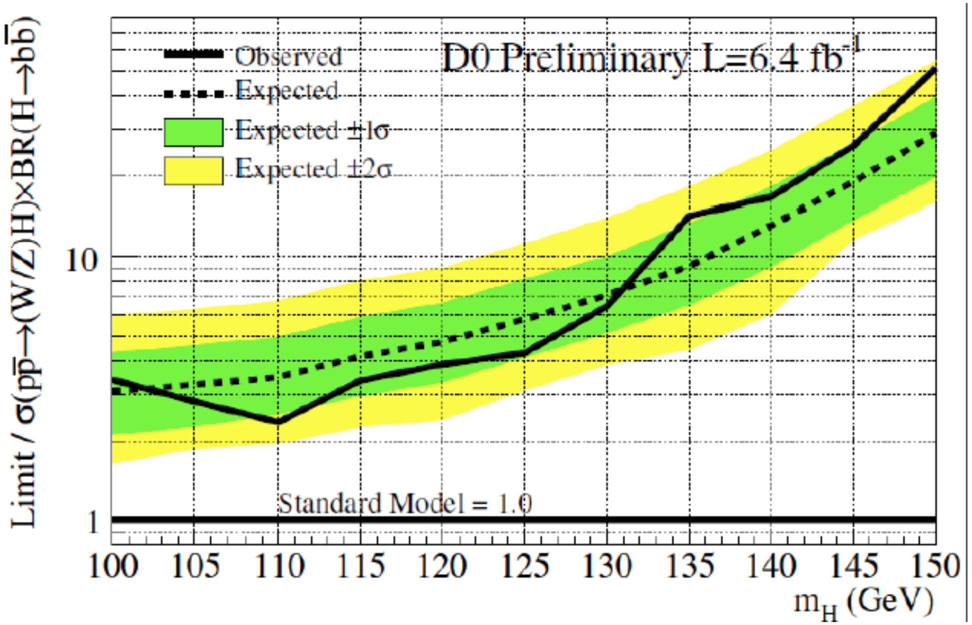
$\int \mathcal{L} dt = 6.4\ fb^{-1}$

M_H=115 GeV

Exp./SM = 4.2

Obs./SM = 3.4

@ 95% C.L.



Higgs acceptance

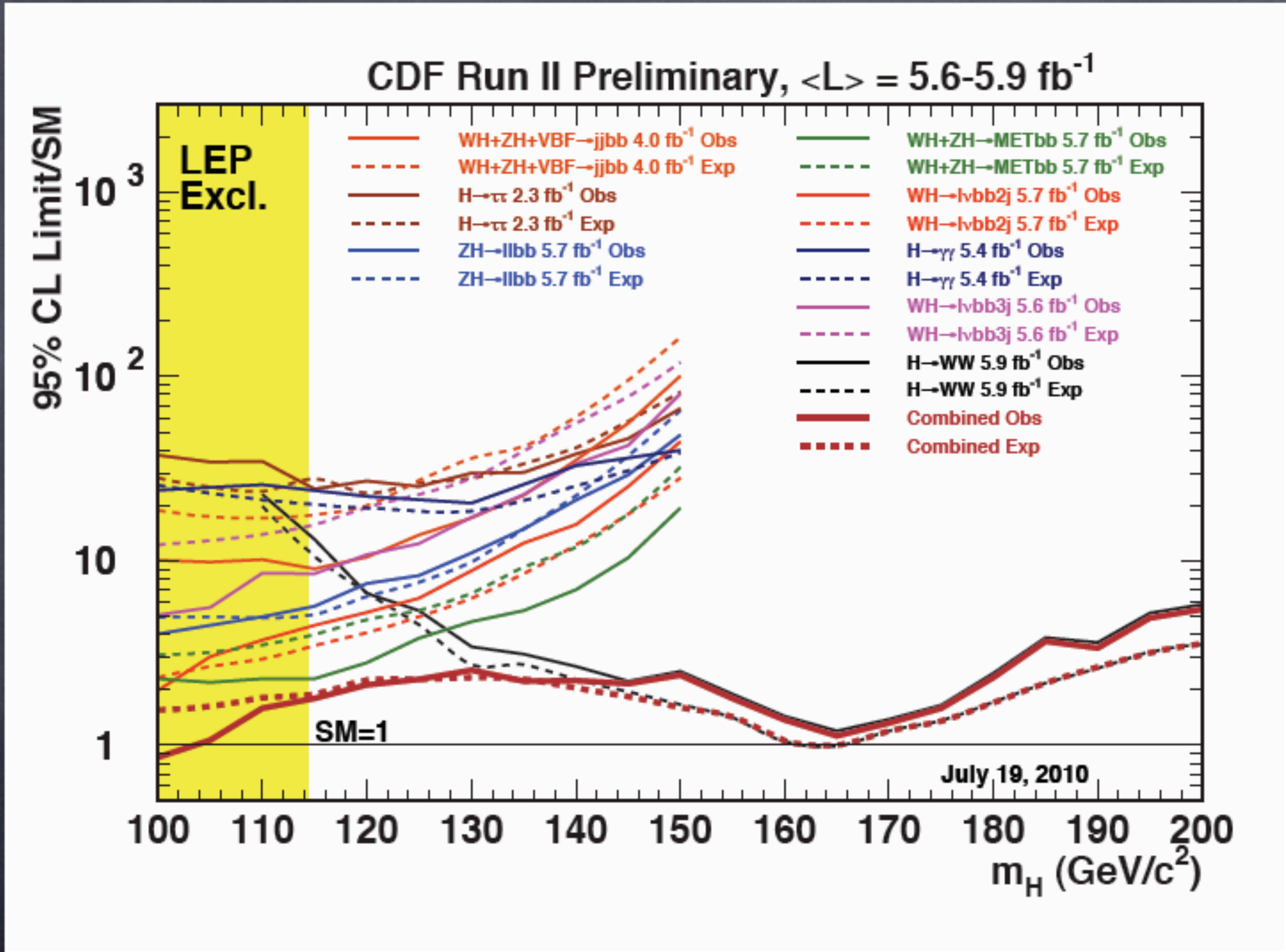
Higgs rate small, we reconstruct additional topologies

Production:	Decay:	W , Z decays :
$gg \rightarrow H$	$H \rightarrow WW$	$W \rightarrow l\nu$
$qq \rightarrow H + W$	$H \rightarrow bb$	$Z \rightarrow ll$
$qq \rightarrow H + Z$	$H \rightarrow \tau\tau$	$Z \rightarrow \nu\nu$
$qq \rightarrow H + qq$	$H \rightarrow \gamma\gamma$	$W \rightarrow \tau\nu$
		$W \rightarrow qq$

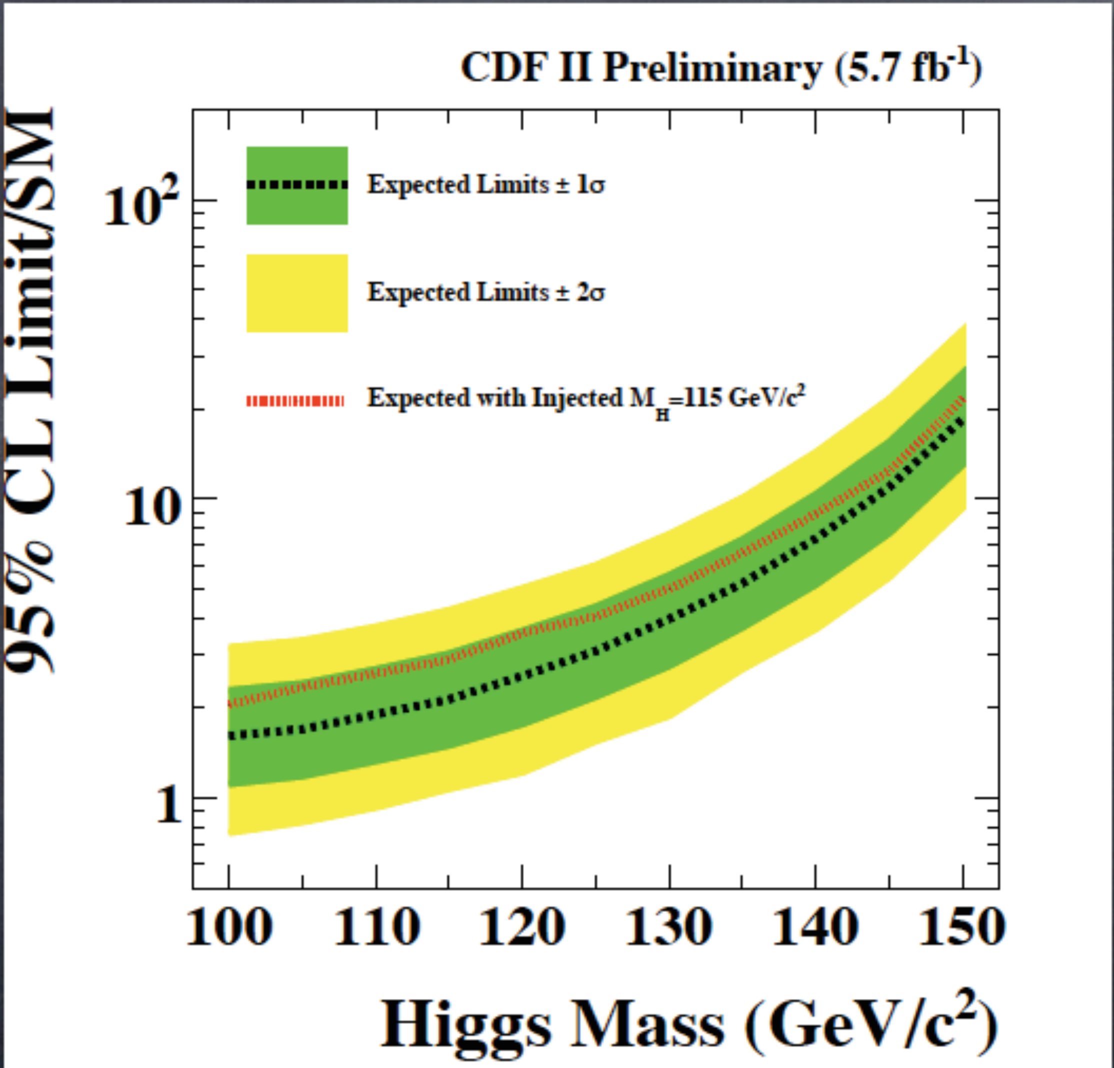
Summary of low & high mass results

Channel	Expt	Dataset now	Increase since Nov. 2009 combination
$H \rightarrow WW$	D0	6.7	24%
$H \rightarrow WW$	CDF	5.9	23%
$WH \rightarrow l\nu bb$	CDF	5.7	30%
$WH \rightarrow l\nu bb$	D0	5.3	6%
$ZH/WH \rightarrow METbb$	CDF	5.7	60%
$ZH/WH \rightarrow METbb$	D0	6.4	23%
$ZH \rightarrow llbb$	CDF	5.7	40%
$ZH \rightarrow llbb$	D0	6.2	45%
$H \rightarrow \gamma\gamma$	CDF	5.4	New!
$H \rightarrow \gamma\gamma$	D0	4.2	0%
$H \rightarrow \tau\tau$	CDF	2.3	15%
$H \rightarrow \tau\tau$	D0	4.9	0%
$ZH/WH \rightarrow qqbb$	CDF	4	100%
ttH	D0	2.1	0%

What goes into the combination?



What would a signal look like ?



CDF test:

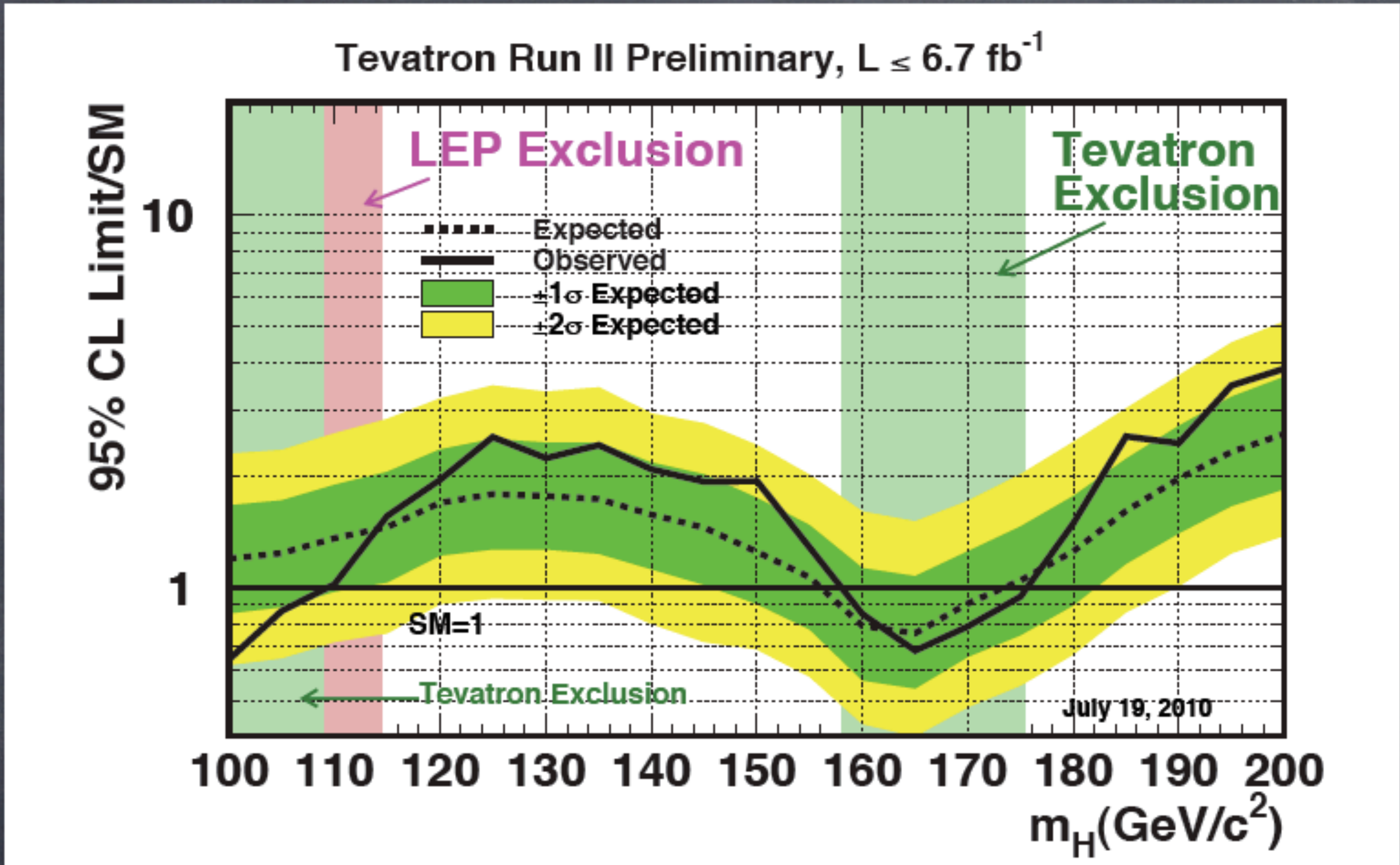
* Inject m_H = 115 GeV signal into pseudoexperiments

(just CDF ZH→llbb, WH→lνbb, ZH→ννbb)

1 sigma high effect would get more pronounced with other channels and D0 as well

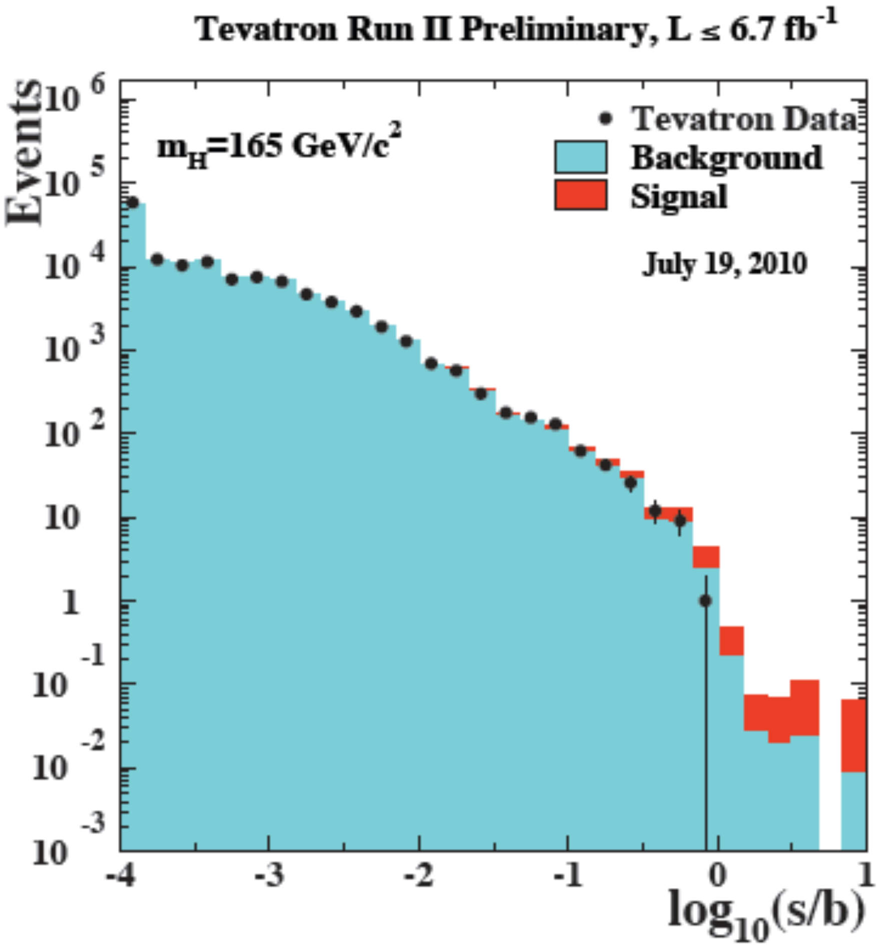
Tevatron combination

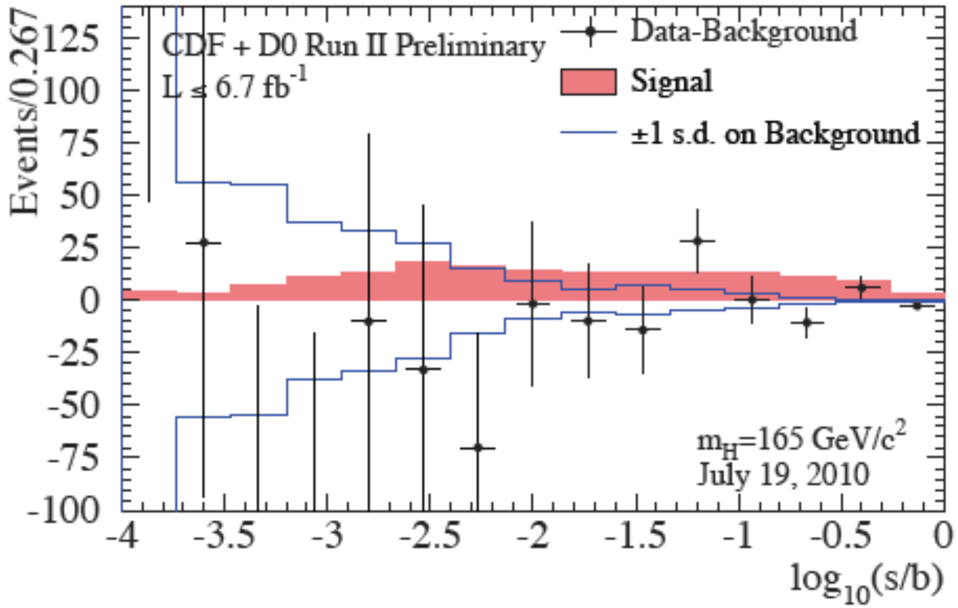
"Expected sensitivity"



- Low mass sensitivity approaching LEP exclusion :
  - Expected 1.45*SM @ 115 GeV
  - Expected 1.24*SM @ 105 GeV
- High mass 95% CL exclusion :
  - 158 < m_H < 175 GeV
    - 4 times previous (162 - 166 GeV)
    - Expected (156 < m_H < 175 GeV)

HIGGS: FINAL TEVATRON COMBINATION





Prospects for Higgs evidence

~16 fb^{-1} :*

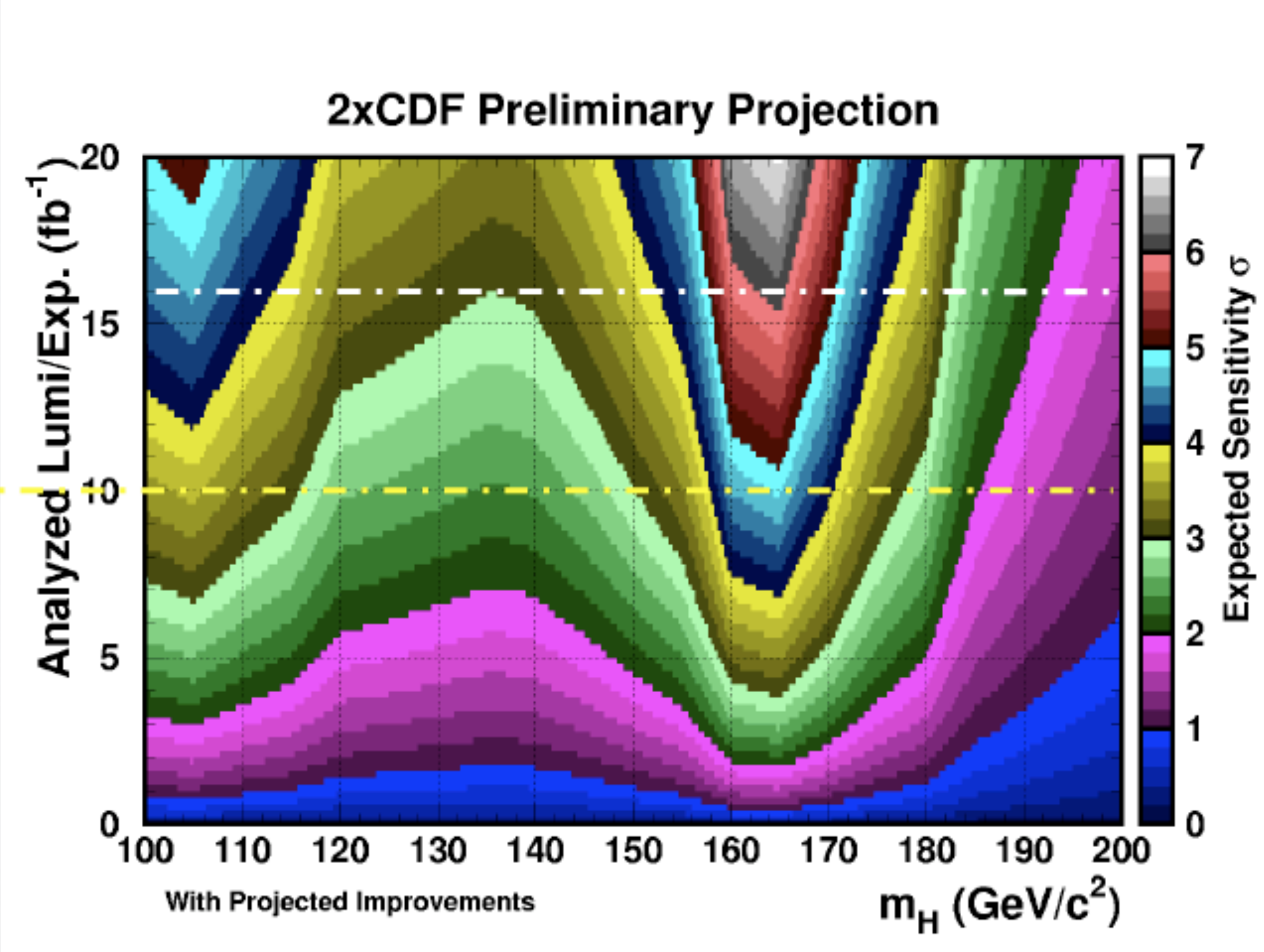
> 3 σ expected sensitivity from 100 – 185 GeV

4 σ @ 115 GeV

End of 2011:

> 2.4 σ expected sensitivity across mass range

3 σ at 115 GeV



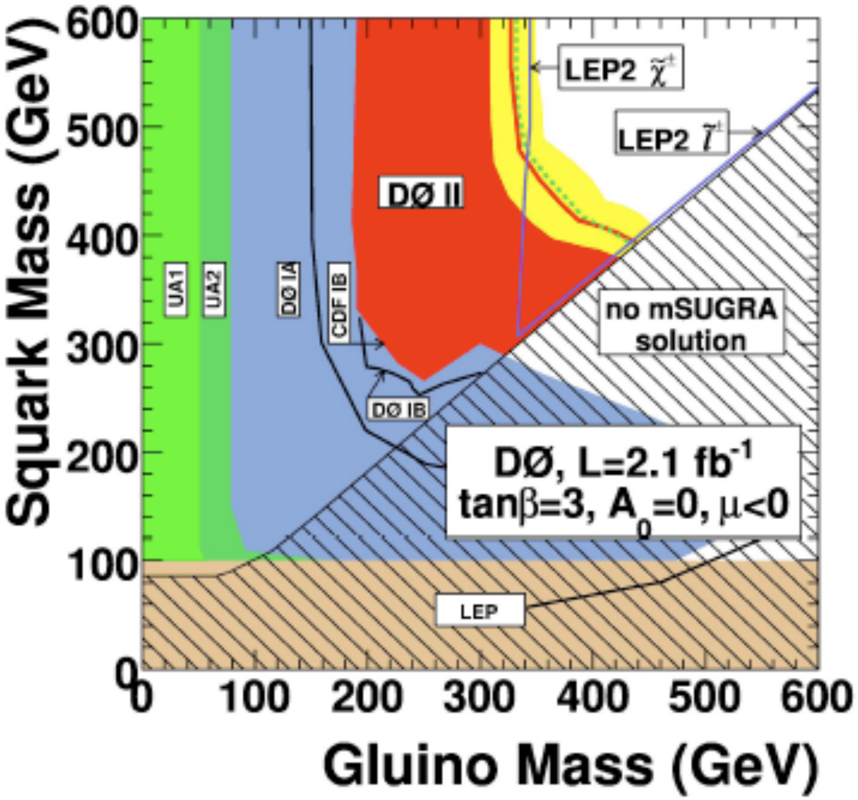
* 16 fb^{-1} : based on "Run III" proposal to run 3 more years

SUSY

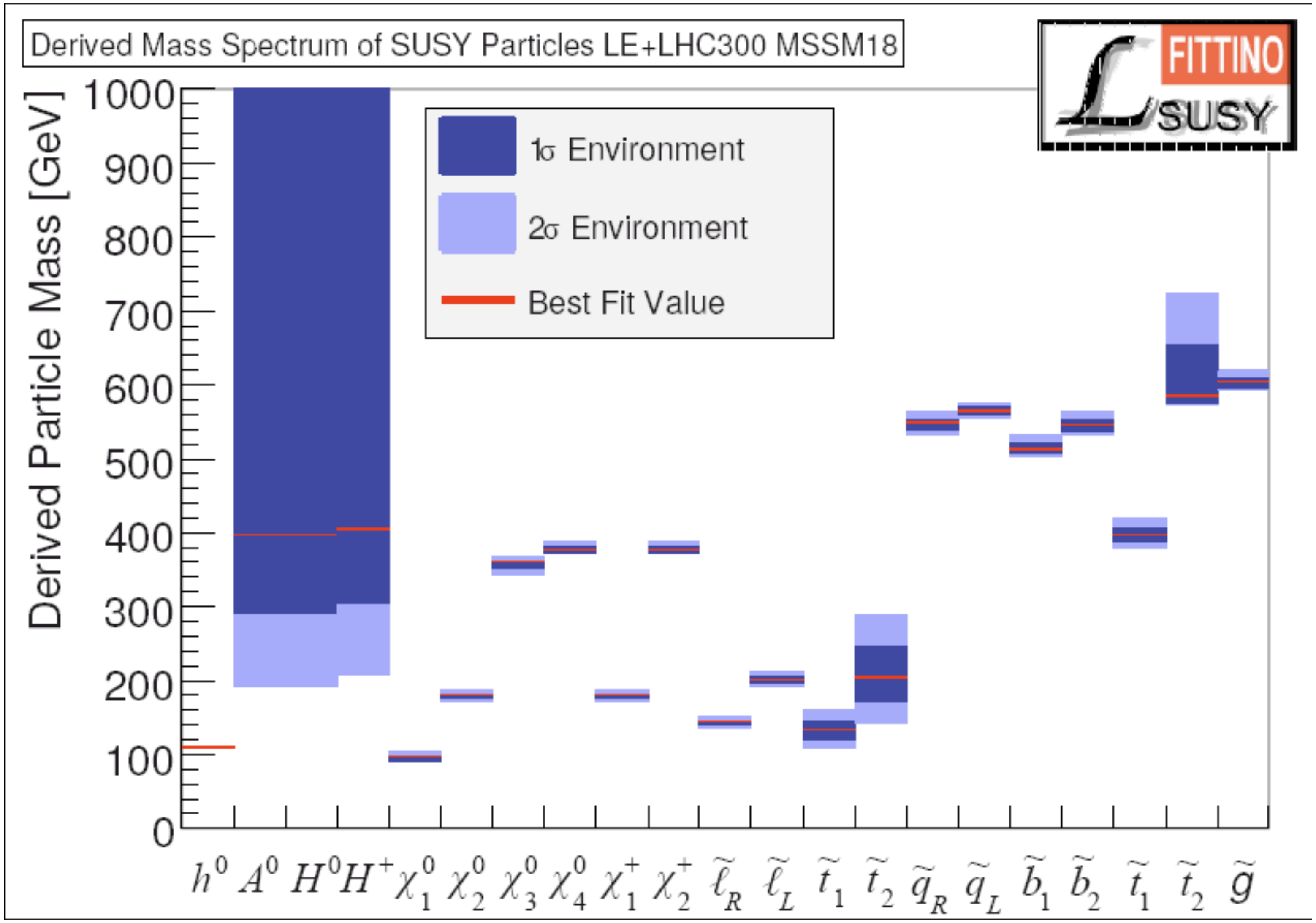
(not discussing all the rest … no time and too much detail …)

SUSY - INTRODUCTION

- SUSY provides solution for a number of questions to the SM
  - Hierarchy and fine-tuning, dark matter candidate, connection to gravity, unification of forces and masses
- Tevatron experiments currenlty have about 8 fb-1 on tape and analysed about 5.3fb-1; data taking continues for at least one more year.
- SUSY is extremely broad field – can only cover certain channels; typically results lead to limits on certain parameters under certain assumptions – plots like this one:
- Important parameters: tanβ, sign(μ), A, m_0, $m_{1/2}$.
- At LHC, competetive with Tevatron already in 2010 / 2011 in certain regions of parameter space.



SUSY – SPARTICLE SPECTRA



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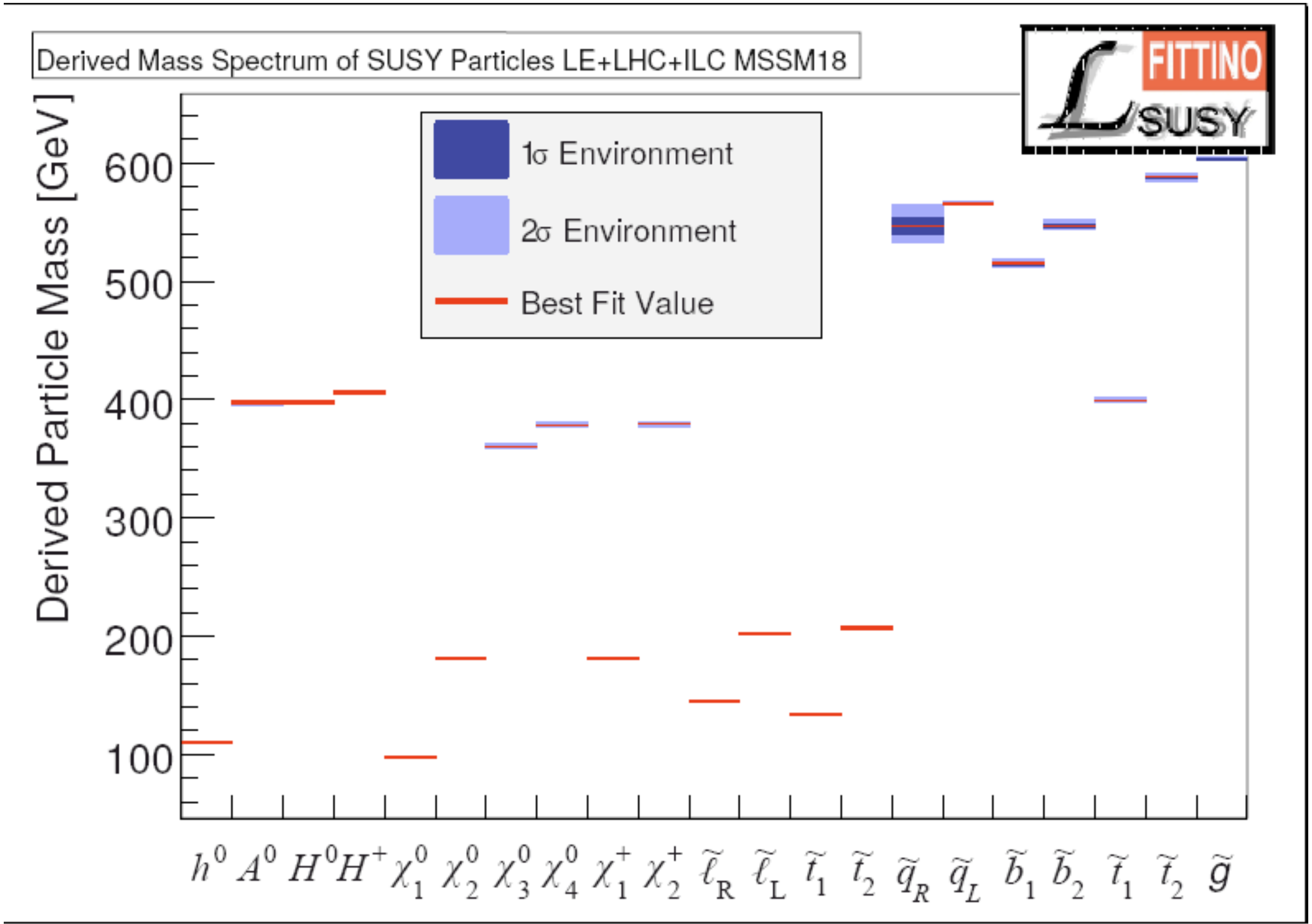
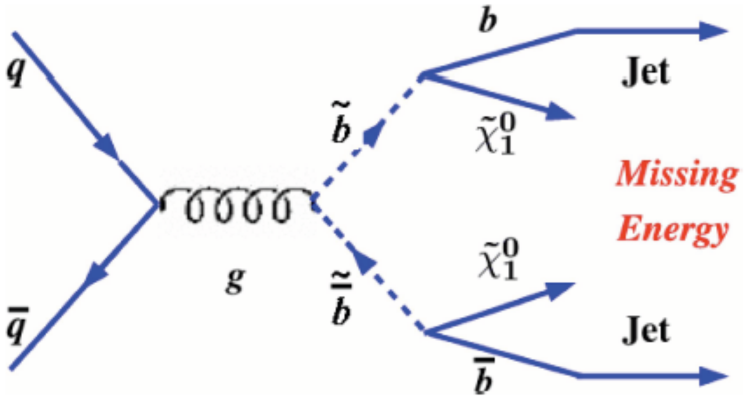
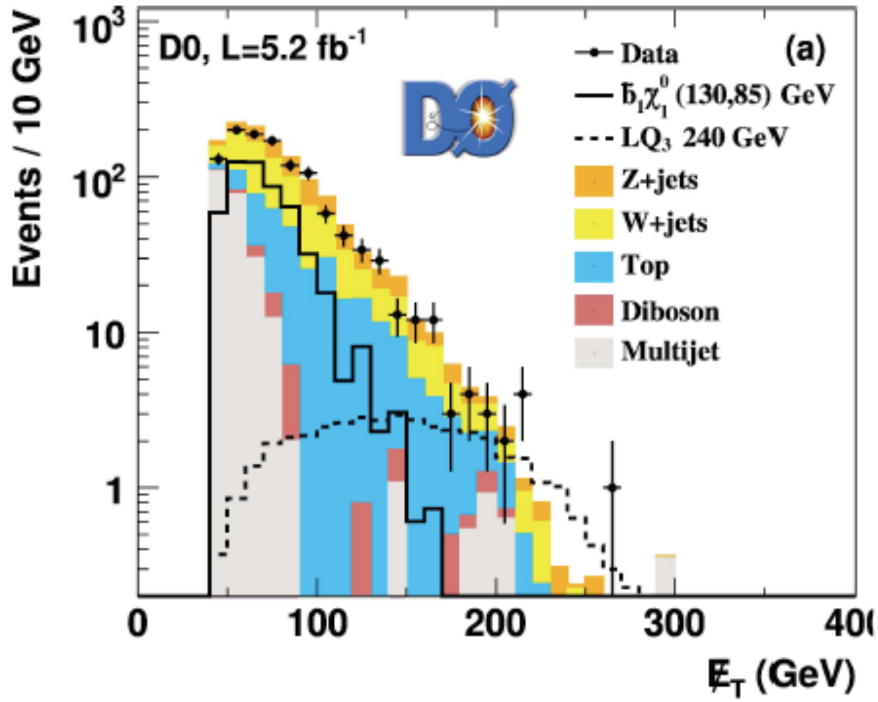


EXAMPLE ANALYSIS: SBOTTOM

- Sbottom squark b_1 could be lightest coloured SUSY particle.
- Signatures: 2 b jets, missing ET, since sbottom decays 100% to b and LSP (→ MET).
- Selection:
  - Large angle between b jets and MET direction.
  - Symmetric MET and HT
  - Cut on ()pT1+PT2/HT against top BG.
- Typically good agreement between data and SM expectation
  - Derive limit on sbottom mass!





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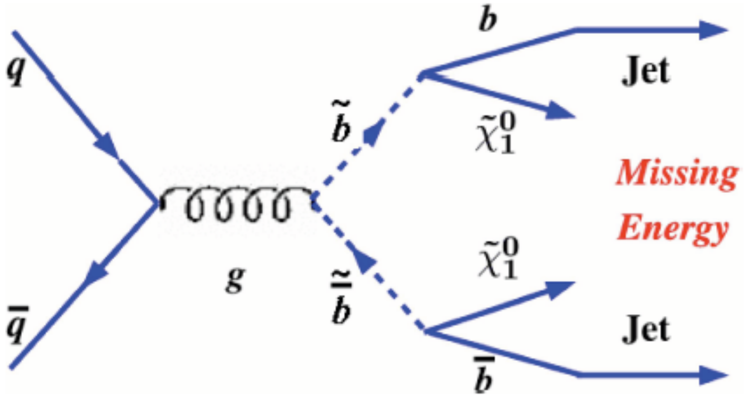
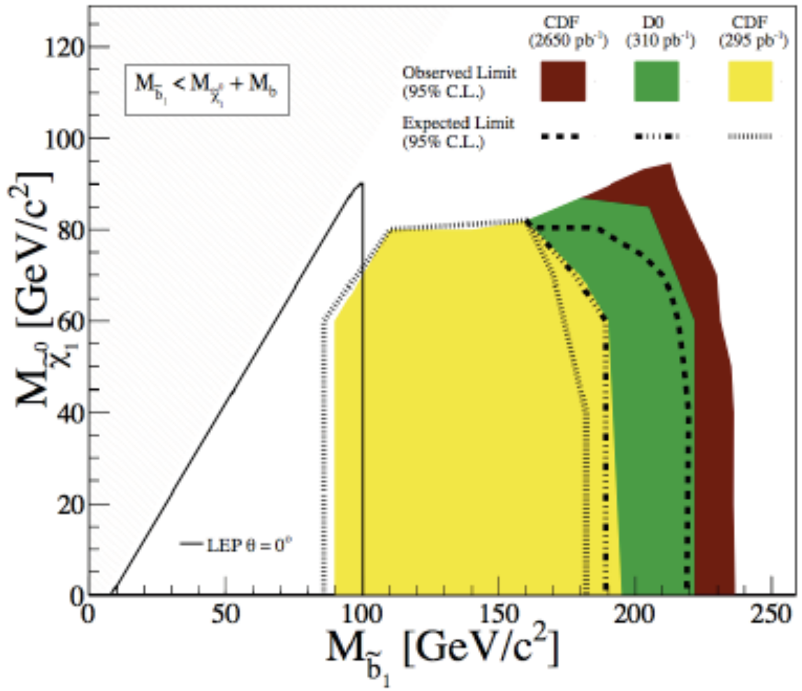
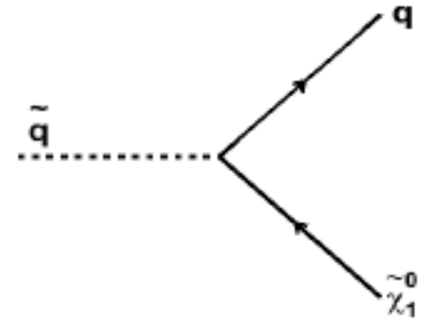
- Similarly for stop etc.

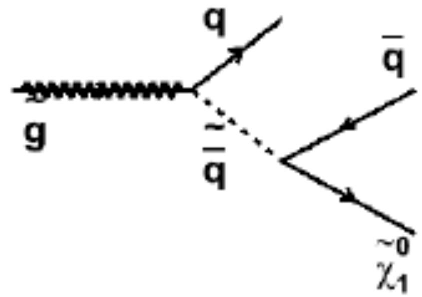


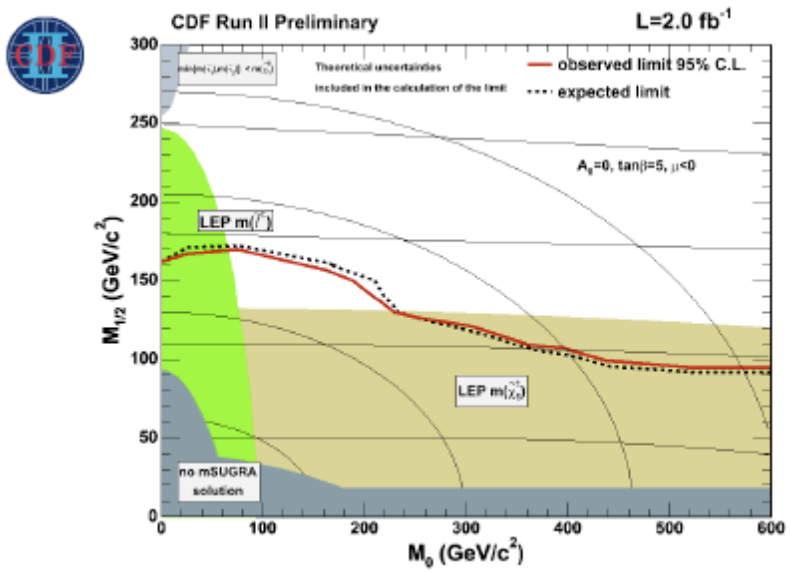


EXAMPLE : SQUARKS / GLUINOS

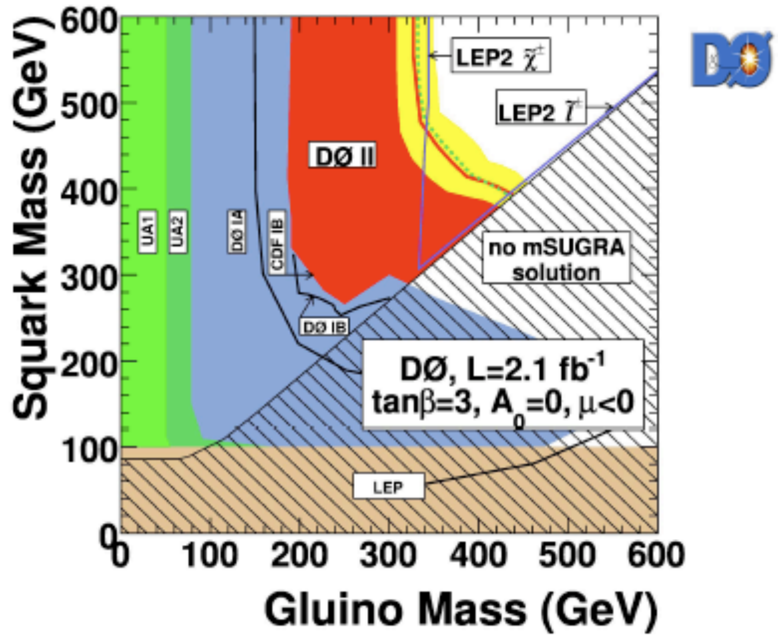
- Pair production of squarks and gluinos
- Decay to jets and missing ET (from the LSP – typically neutralino).
- Optimise precise cuts according to scenario, number of jets, etc.
- For 2fb-1: data and SM agree.
  - Limit at 95% CL at 300 GeV for gluinos and 380 GeV for squarks.





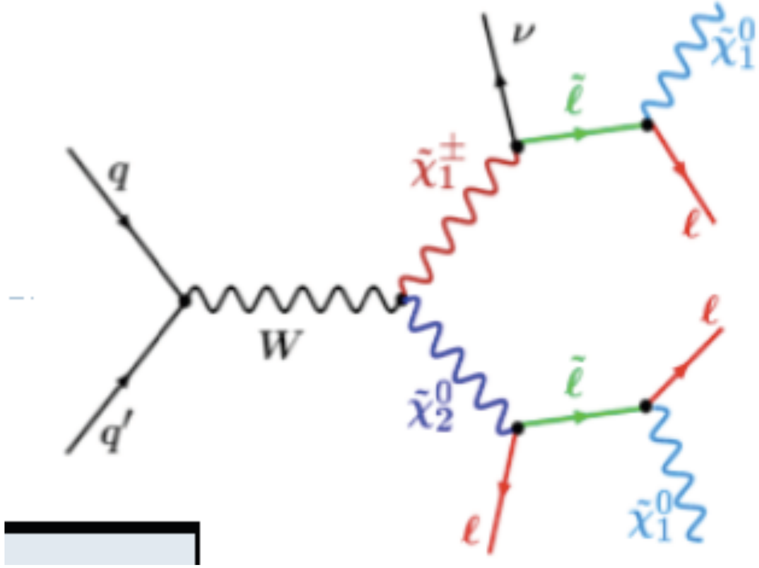


PRL 102 (2009) 121801

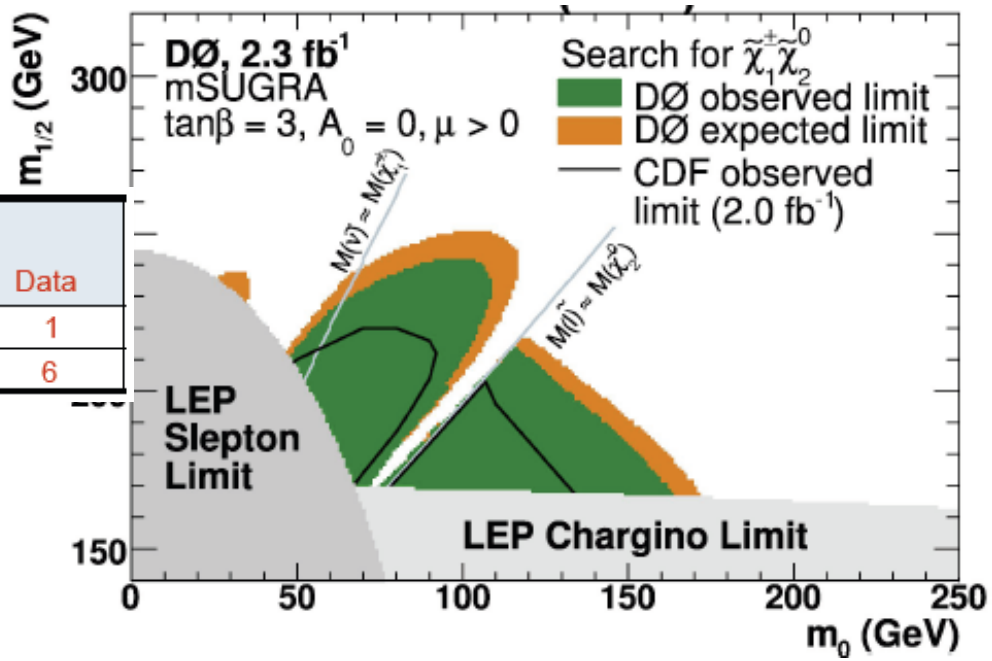


EXAMPLE : CHARGINOS / NEUTRALINOS

- So-called golden channel with three leptons and missing ET in the final state (two neutralino)
- Low cross section and branching fraction, but clean signature, very little background.
- Mass limits at around 160 GeV
  - For the specific mSUGRA case of tanbeta=3, A0=0, sign(mu)=+1



DØ (2.3 fb^{-1})			CDF (3.2 fb^{-1})		
Channel	SM expected	Data	Channel	SM expected	Data
Low p_T	5.4 ± 0.6	9	Trilepton	1.5 ± 0.2	1
High p_T	3.3 ± 0.4	4	Dilepton+trk	9.4 ± 1.4	6

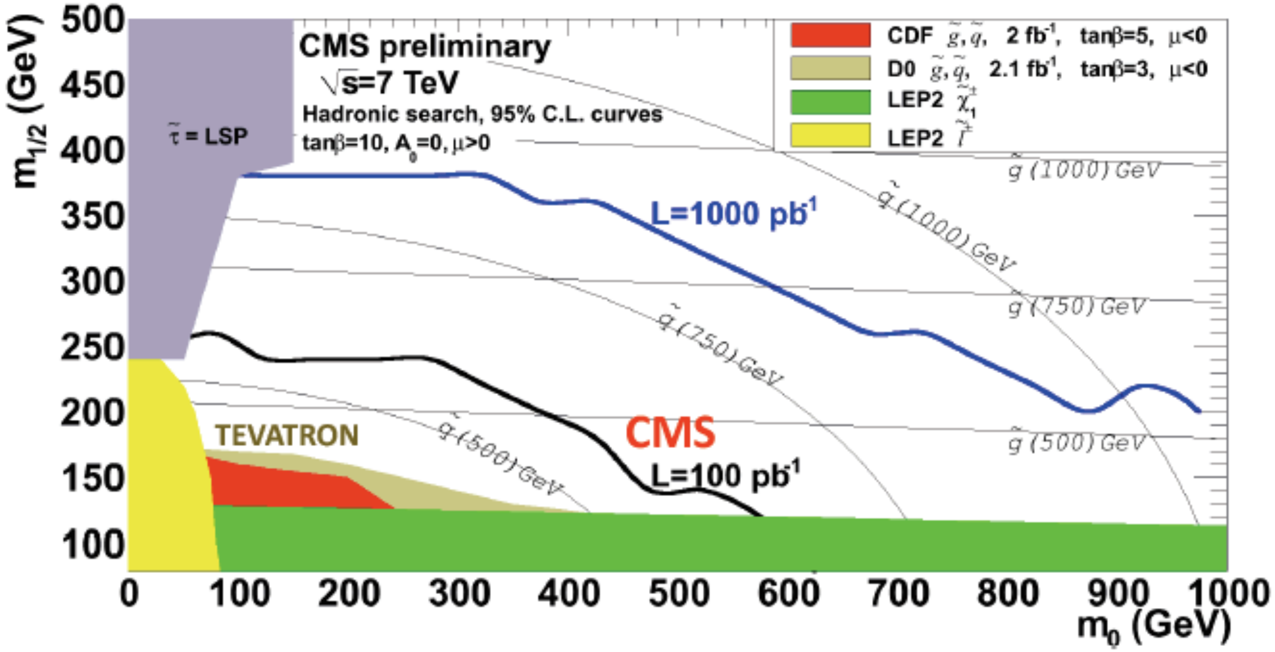


CONCLUSIONS: TEVATRON

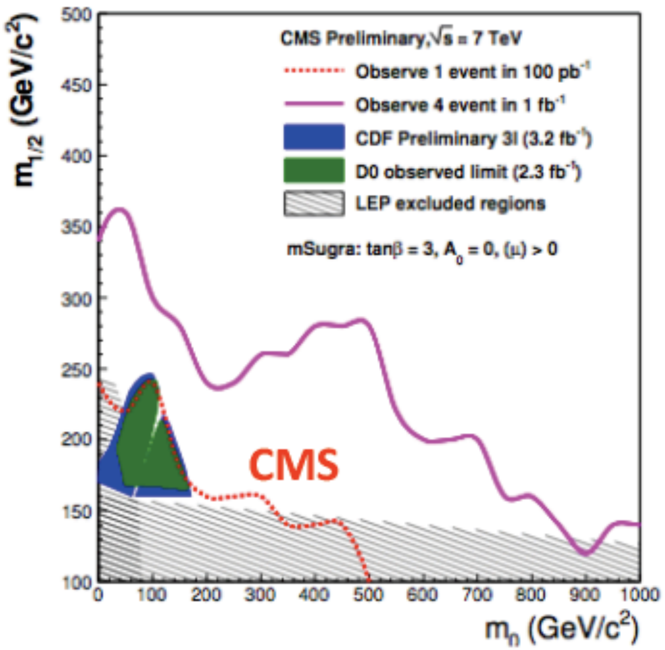
- Tevatron experiments continue to search for evidence of SUSY
  - Variety of final states / signatures
  - No evidence for SUSY so far
- Tevatron running very well!
  - Analyses shown performed with up to 5.3 fb^{-1}
    - More data in the can
      - 9 fb^{-1} delivered and counting
  - 11-12 fb^{-1} expected to be delivered by the end of Run II
- Keep looking until either we find something or LHC takes over

… AND AT LHC …

sensitivity to mSUGRA with fully hadronic signaure



Sensitivity with Same-Sign di-lepton



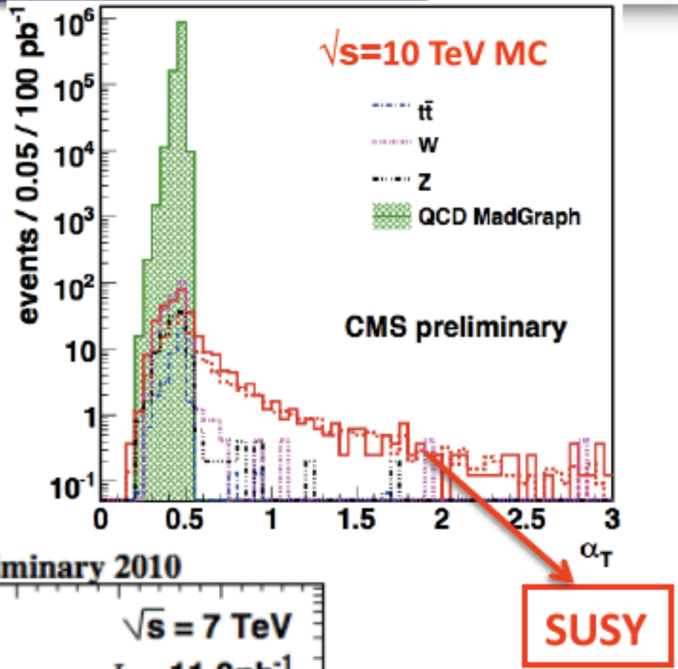
- 7 TeV data of ~100 pb^{-1} should provide sensitivity to SUSY parameter space well beyond the current limits set by TEVATRON
- The sensitivity reach strongly depends on how well we understand the SM backgrounds

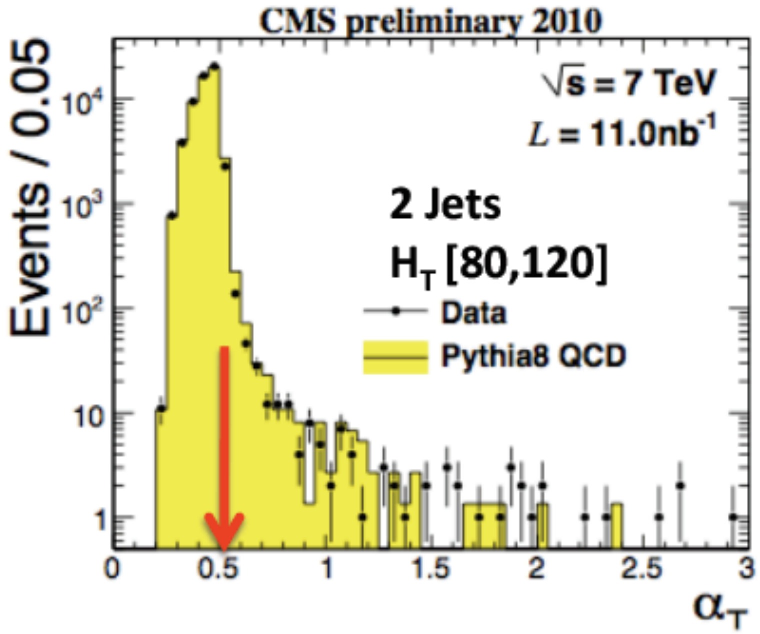
Suppressing QCD with α_T

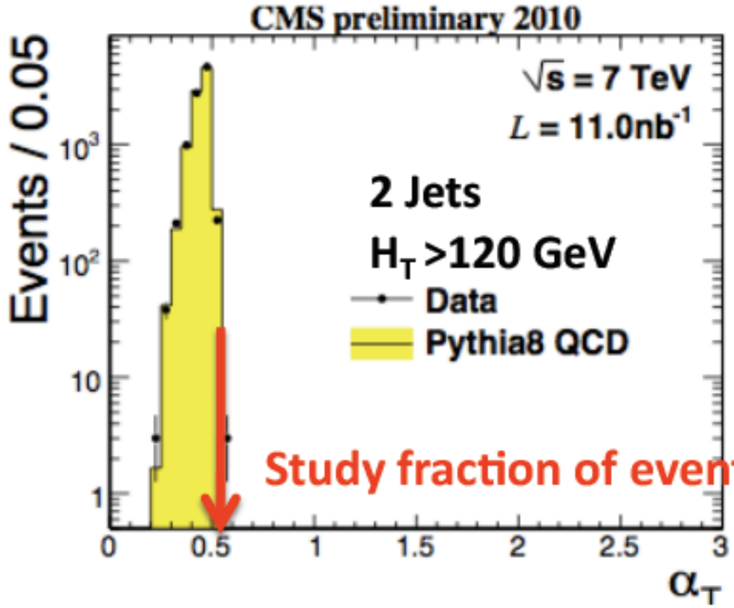
- A powerful variable for suppressing mis-measured QCD

$$\alpha_T \equiv \frac{p_{T2}}{M_T} \qquad \alpha_T = \frac{\sqrt{p_{T2}/p_{T1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$

- Well measured back-to-back di-jet system $\alpha_T \approx 0.5$, if one jet is mis-measured $\alpha_T < 0.5$







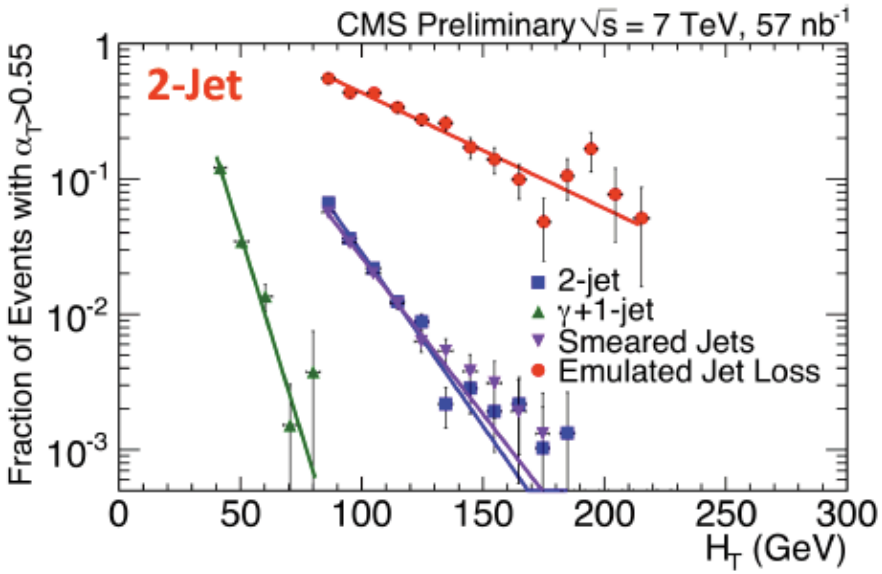
$$H_T = \sum_i p_T(\mathrm{jet}_i)$$

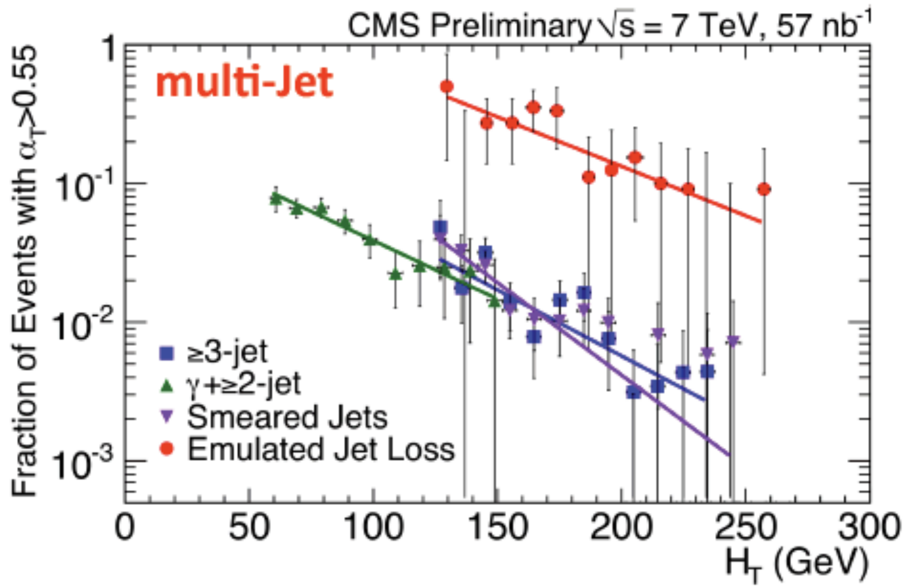
Study fraction of events with $\alpha_T > 0.55$

✓ The data shows the expected sharp fall around $\alpha_T \sim 0.5$, improves for higher H_T

H_T dependence of α_T

- Rejection power of α_T is expected to get better with increasing H_T
- Examine this assumption in the available H_T range:





✓ Expected decrease (approx. exponential) with H_T is observed for both 2-jet and ≥3-jets

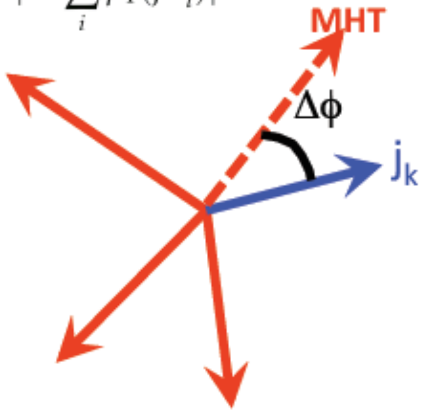
✓ Better performance with increasing H_T holds also for:

- In γ+jet(s) events where photon is treated as a jet
- Emulating extreme jet losses
- Smearing jet energies

✓ Extended also for leptonic search channels (not shown here)

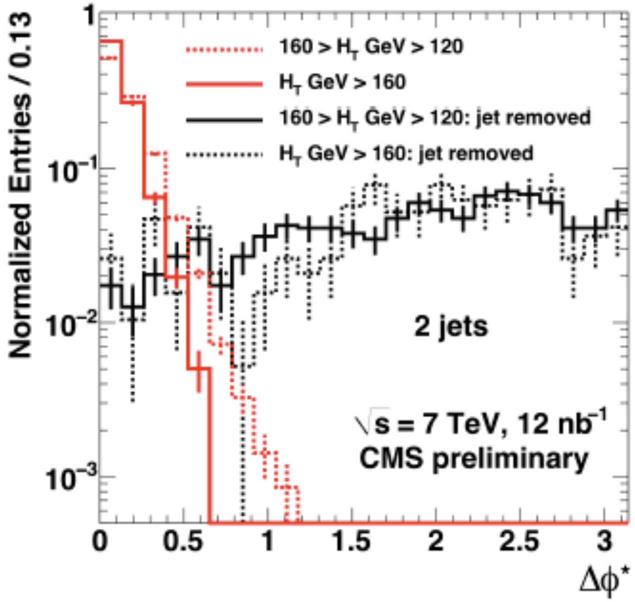
Suppressing QCD with $\Delta\phi^*$

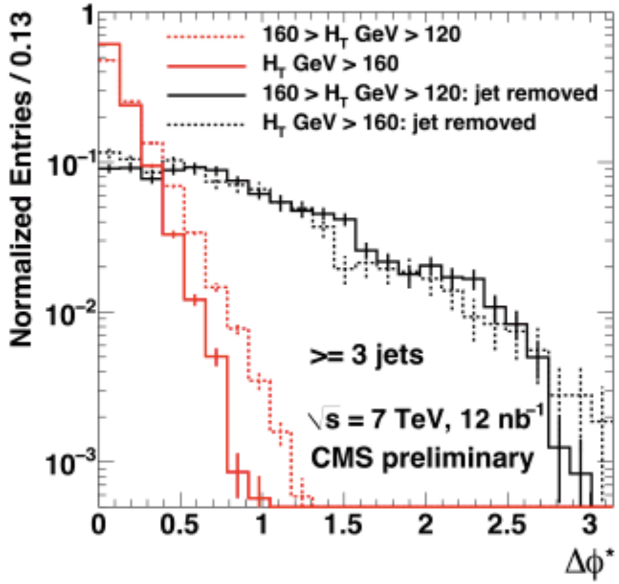
$$\mathrm{MHT} = |-\sum_i \vec{p}_\mathrm{T}(\mathrm{jet}_i)|$$



- A complementary observable, $\Delta\phi^*$, to diagnose background events where one jet mis-measured.
- Test each jet to see if it is responsible for the MHT (vectorial sum of the jet p_T)

$$\Delta\phi^* \equiv \min_{\text{jets } k}\left(\left|\Delta\phi(\vec{p}_k, -\sum_{\text{jets } i\neq k}\vec{p}_i)\right|\right)$$





- expect small $\Delta\phi^*$ for QCD
- more uniform for real MET (emulated by removing one jet)

✓ **Data confirms the expected behavior in both di- and multi-jets**

✓ **Resolution improves with H_T**

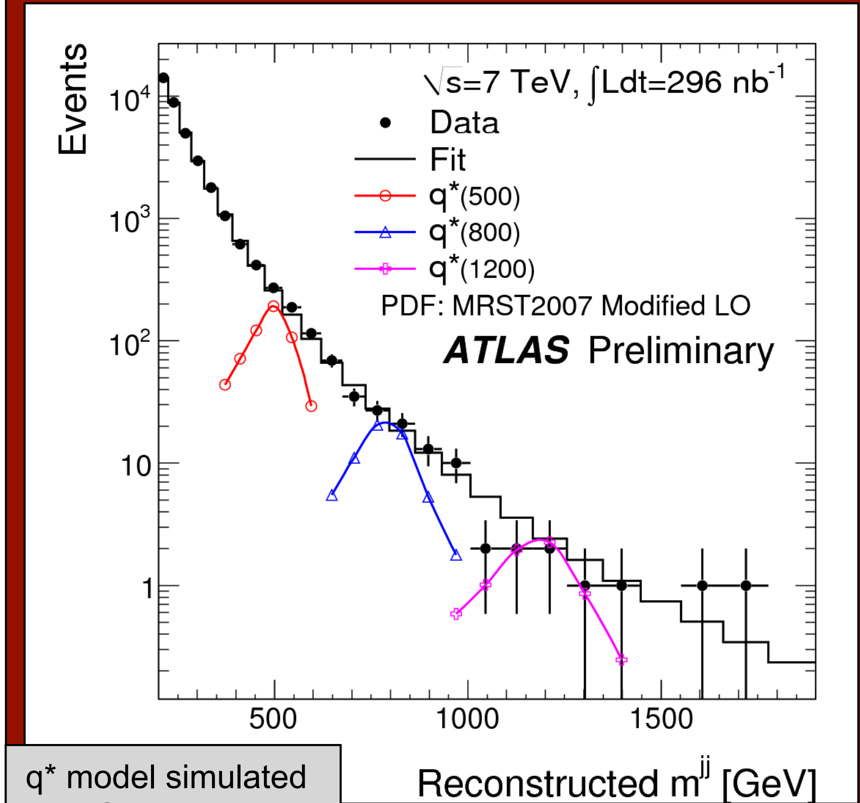
Searches for excited quarks: q*→ jj

Full data sample analysed

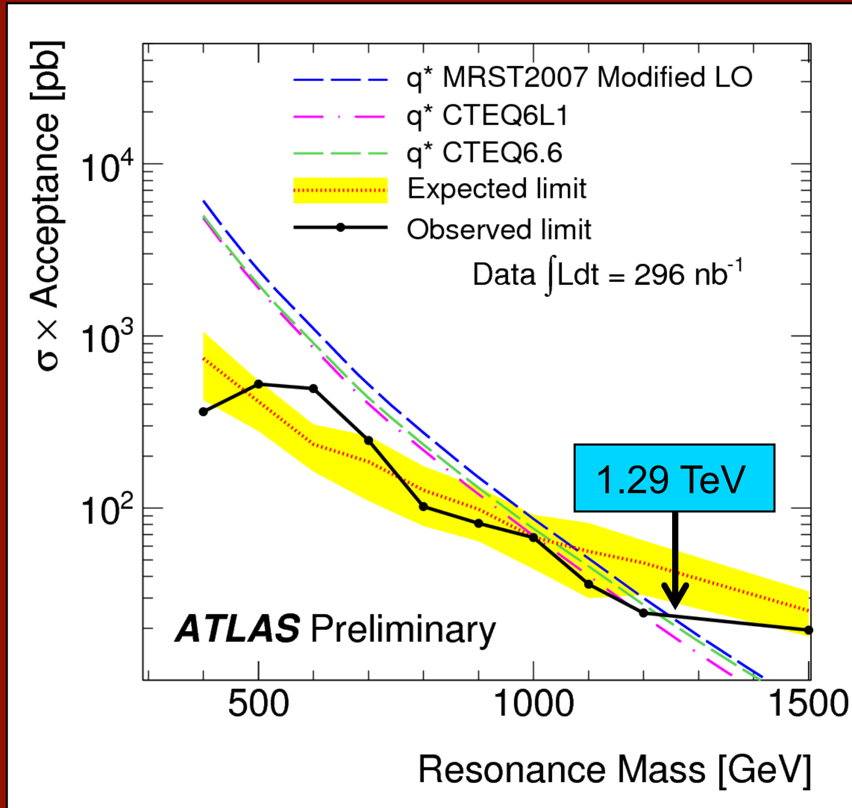
Looked for di-jet resonance in the measured M(jj) distribution
→ spectrum compatible with a smooth monotonic function → no bumps

➡ 0.4 < M (q*) < 1.29 TeV excluded at 95% C.L.

Latest published limit:
CDF: 260 < M (q*) < 870 GeV



q* model simulated with Geant4



- ❑ Experimental systematic uncertainties included: luminosity, JES (dominant), background fit, ..
- ❑ Impact of different PDF sets studied → with CTEQ6L1: 0.4 < M (q*) < 1.18 TeV