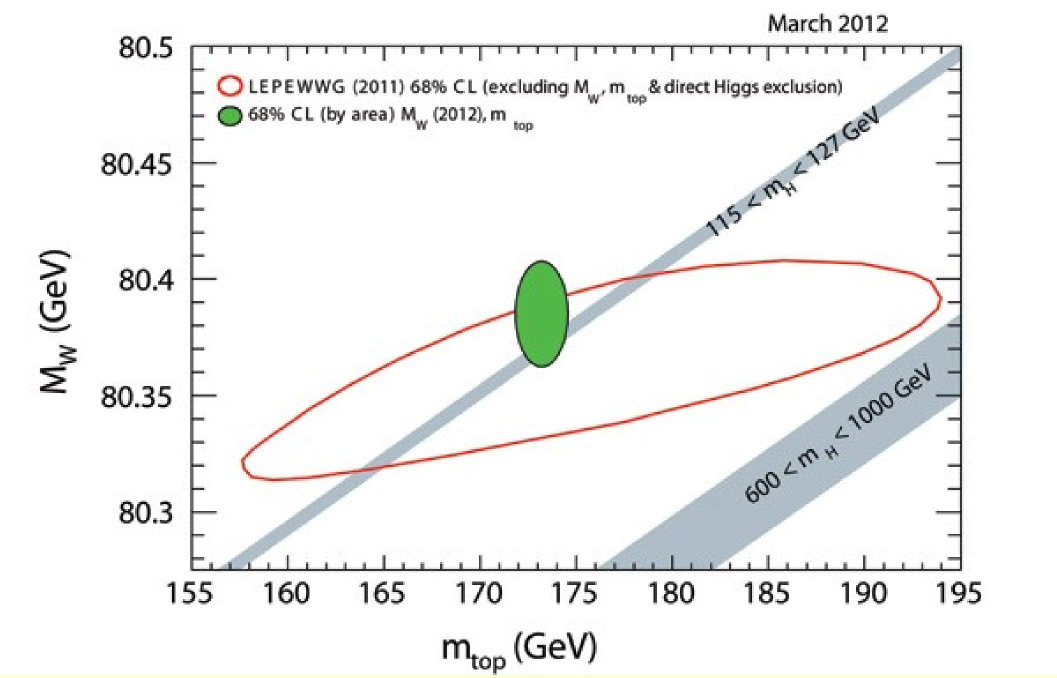
Closing in on the Higgs boson



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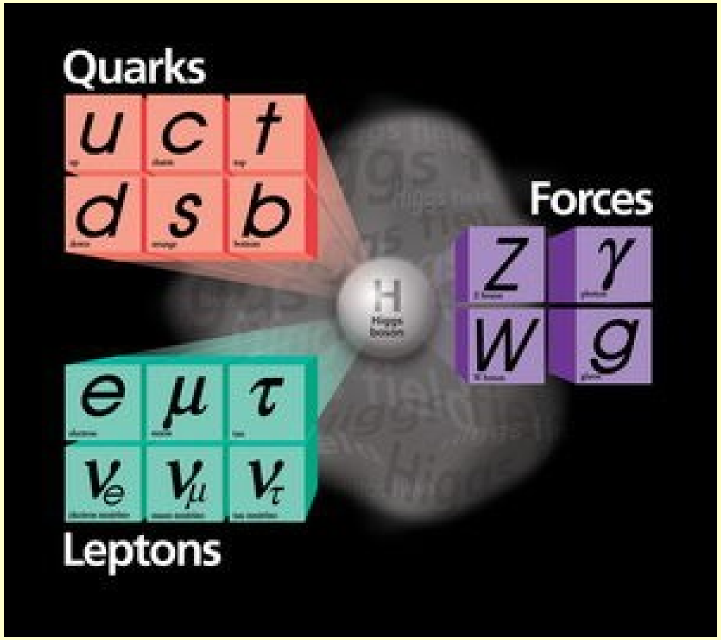
Brown University

Seminar @UC Davis

April 24th, 2012



- Outline
  - Motivation
  - Higgs search at Tevatron
  - Current limits
  - Future

Introduction

Standard Model

- The Standard Model is defined by the symmetries of the Lagrangian:
  - $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Interactions: strong, weak, and electromagnetic
  - carriers: gluons – g, weak bosons $W^{\pm}$, Z, and photon
- matter particles:
  - leptons and quarks
- and the pattern of spontaneous symmetry breaking
  - complex scalar field
  - breaks $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{EM}$

The Higgs Mechanism

- Essential ingredient of the Standard Model
  - Complex scalar field with potential
- Used to break the el. weak symmetry...

$$M_W=\frac{1}{2}vg \qquad M_Z=\frac{1}{2}vg/\cos\theta_W=M_W/\cos\theta_W$$

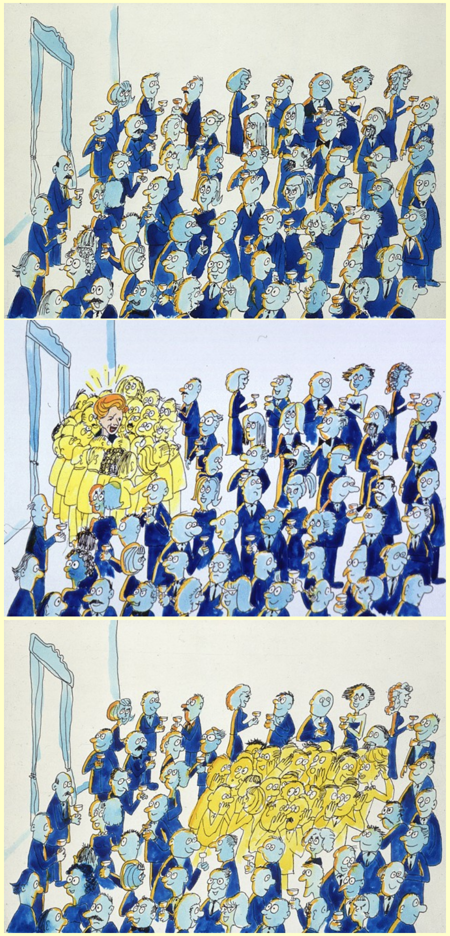
- ... and to generate fermion masses:

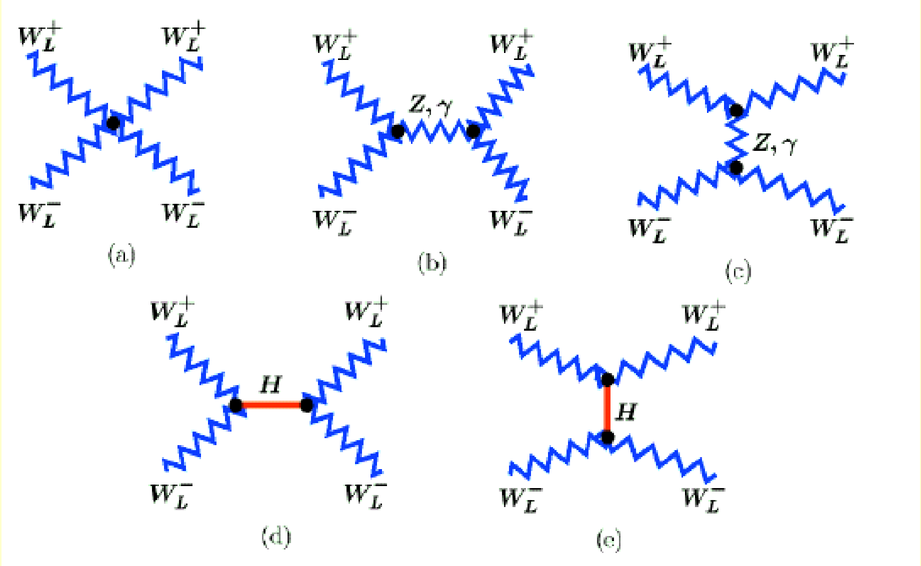
$$m_f=g_f v/\sqrt{2} \;\Rightarrow g_f=m_f\sqrt{2}/v$$

- Unitarity requires a Higgs boson or similar

  - cross section for WW scattering diverges like s/M_W^2

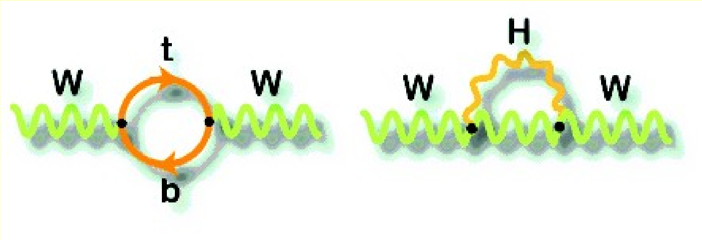
  - scalar Higgs boson cancels divergences

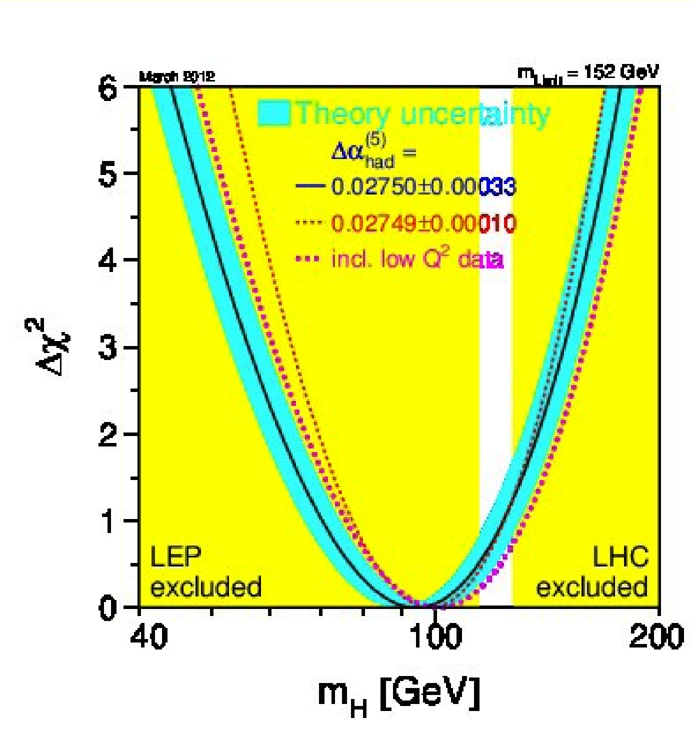




Bounds on Higgs mass

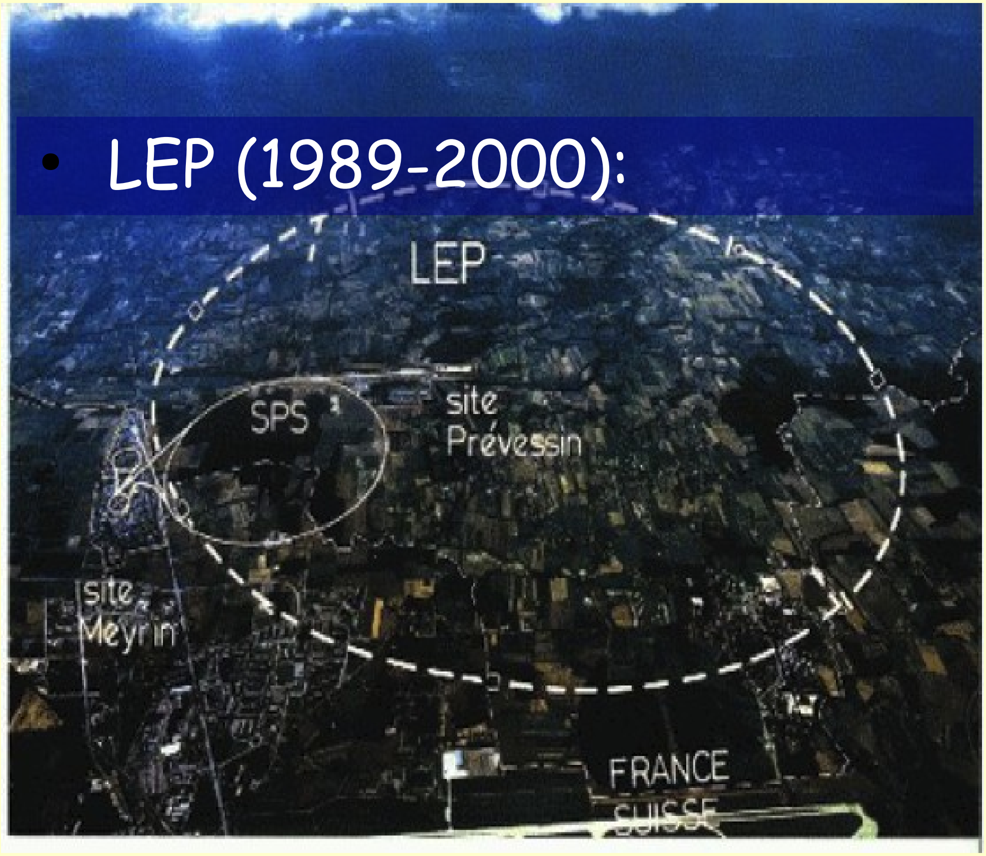
- Global SM electroweak fits provide upper limit
- The best fit gives $m_H = 94^{+29}_{-24}\,GeV$
- Limit from fit $m_H < 152$ GeV



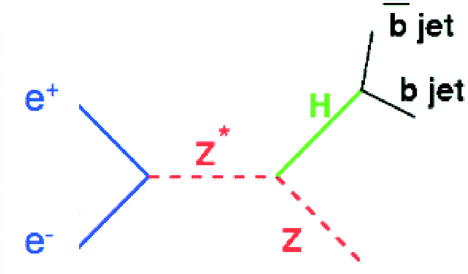


Bounds on Higgs mass

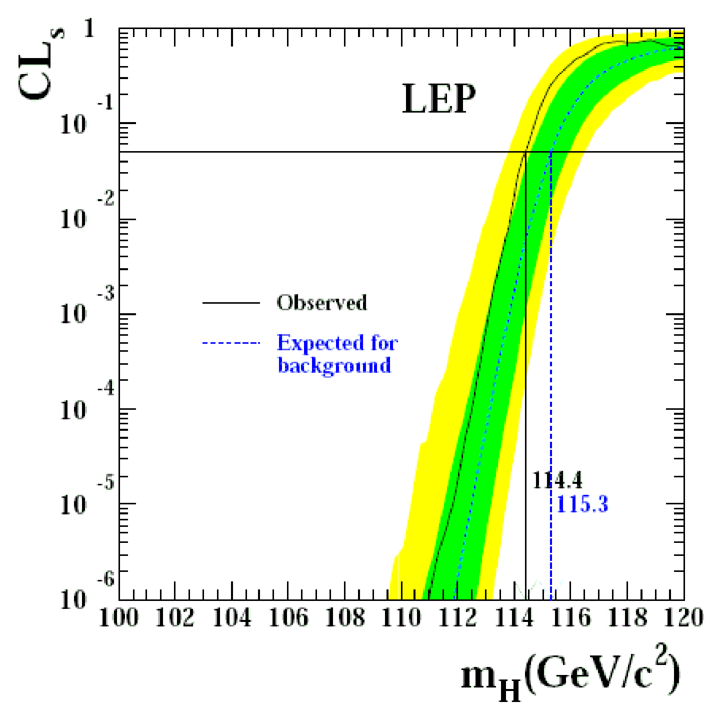
- LEP (1989-2000):



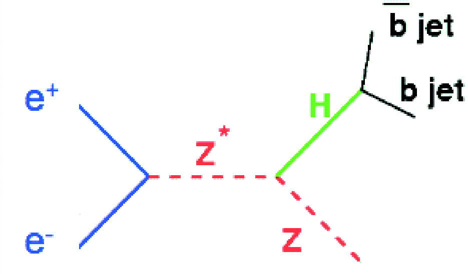
Bounds on Higgs mass



- LEP (1989-2000):
  $m_H > 114.4$ GeV@95% CL



Bounds on Higgs mass



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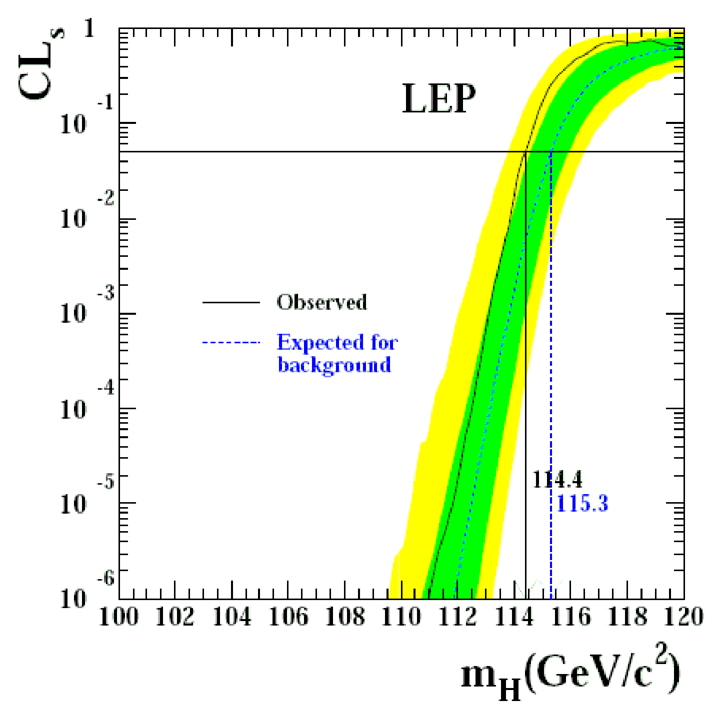
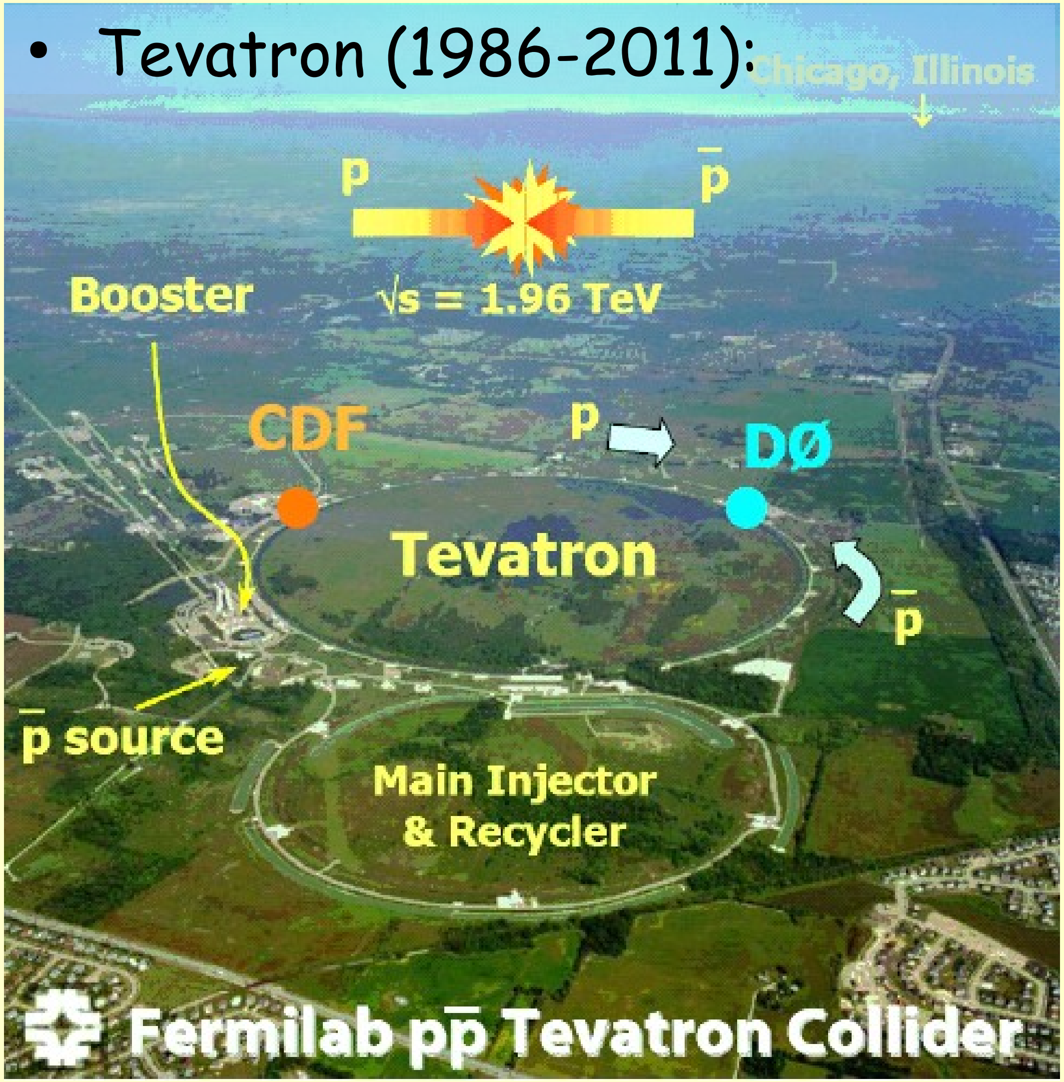
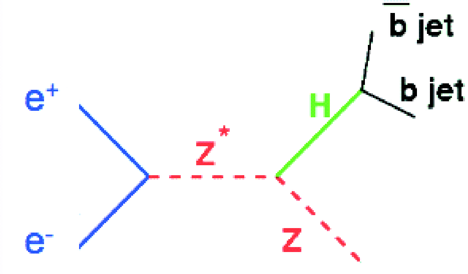


- Tevatron (1986-2011):



Bounds on Higgs mass



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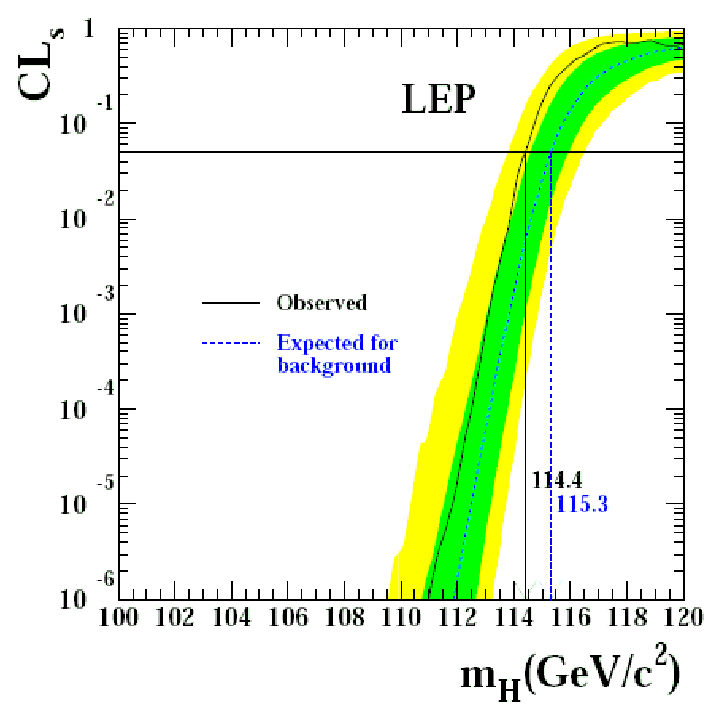
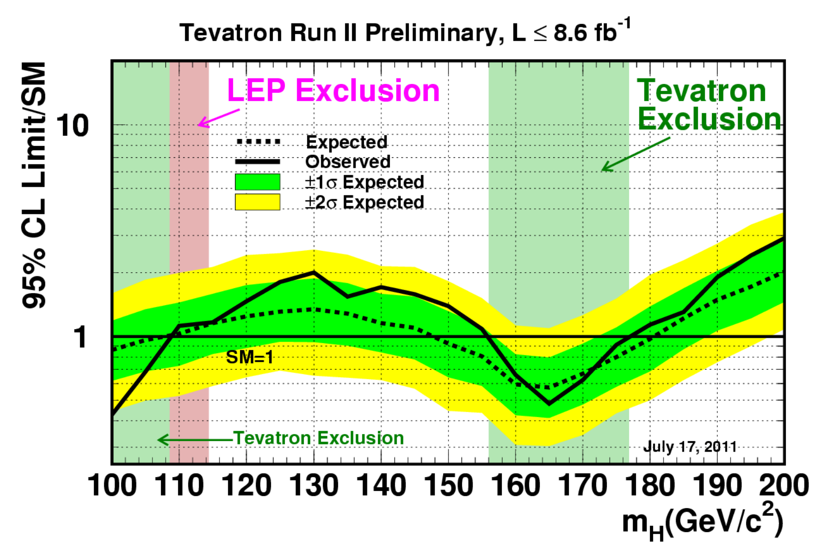
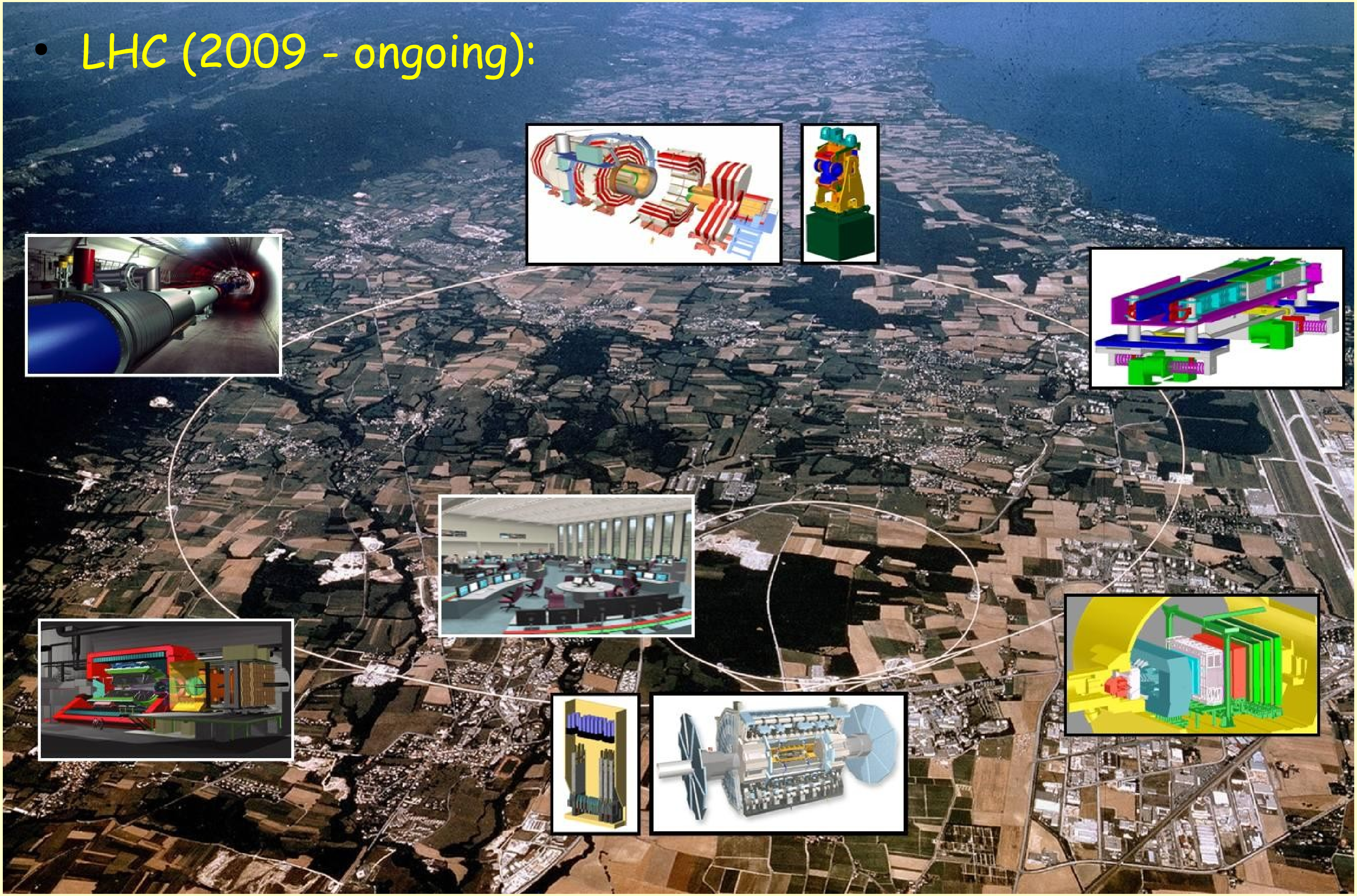


- Tevatron (1986-2011):
  Summer 2011:
  Exclude: 156 – 177 GeV and
  100 – 108 GeV



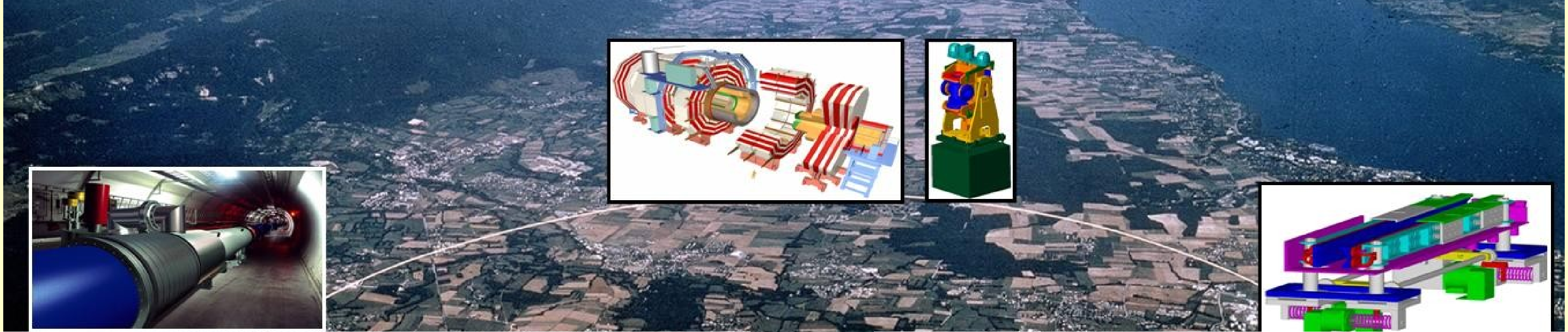
Bounds on Higgs mass

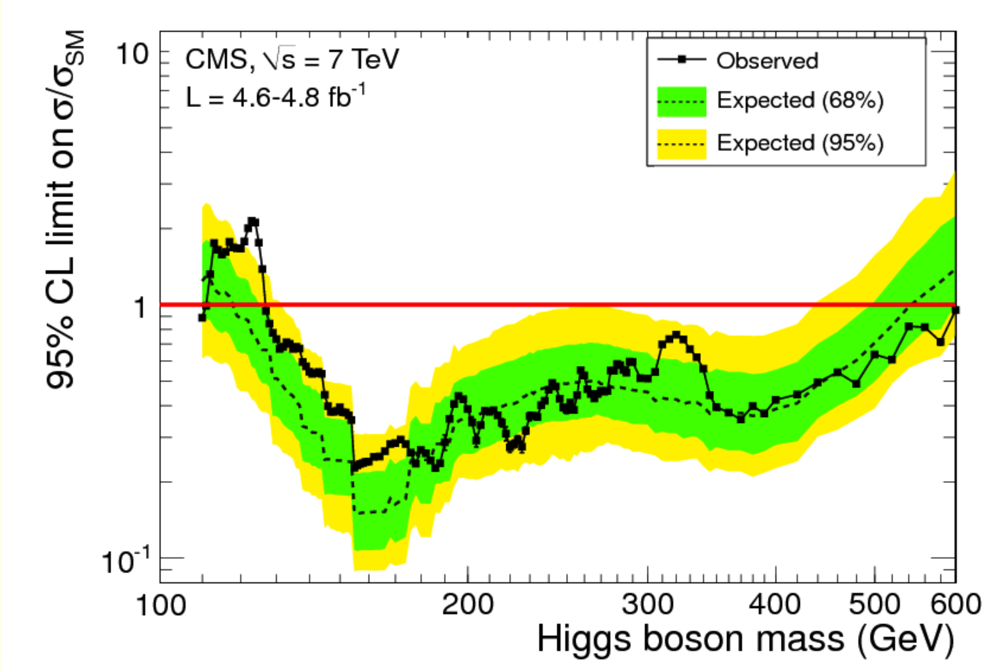
- LHC (2009 - ongoing):

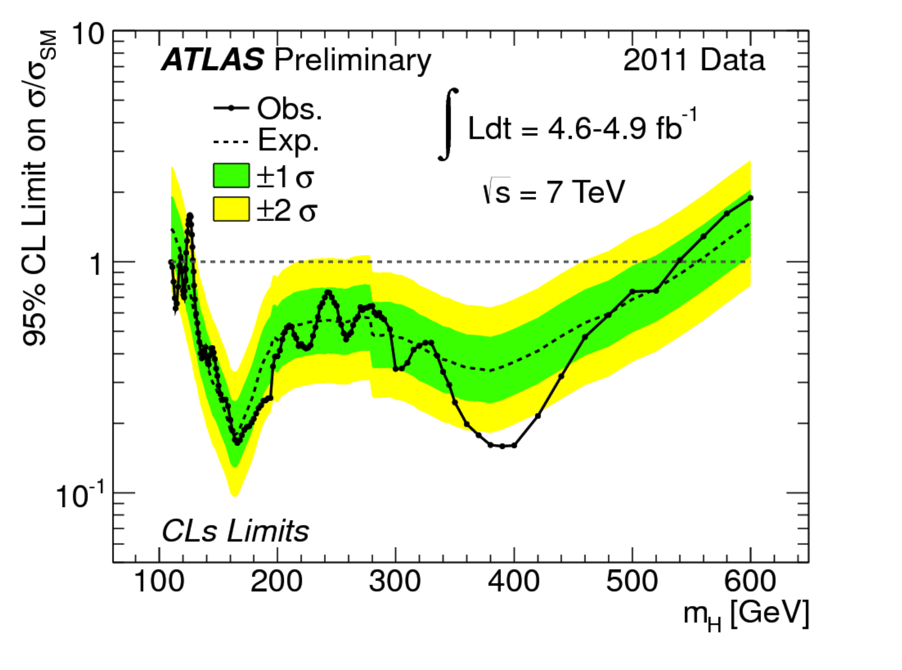


Bounds on Higgs mass

- LHC (2009 - ongoing): only 122.5-127 GeV is allowed





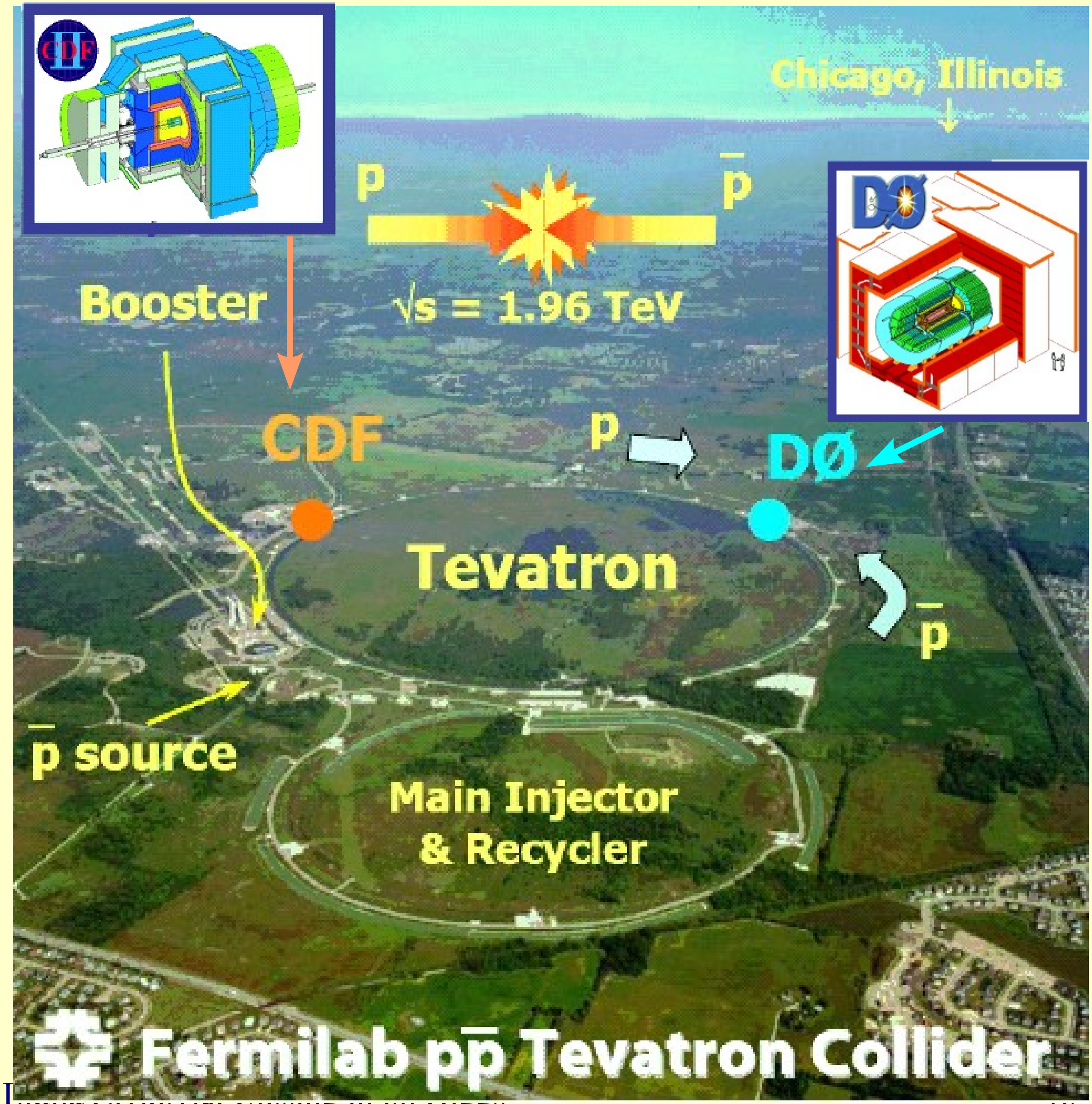


Experiments

The Tevatron

$p\bar{p}$ collisions

- Ran for 25 years
  - 9 in Run II
- Center of mass energy $\sqrt{s}$ = 1.96 TeV
- Discovered top quark
- Excluded high mass range of the Higgs boson
- The most precise measurement of the W and top mass
- It stopped running on September 30th, 2011



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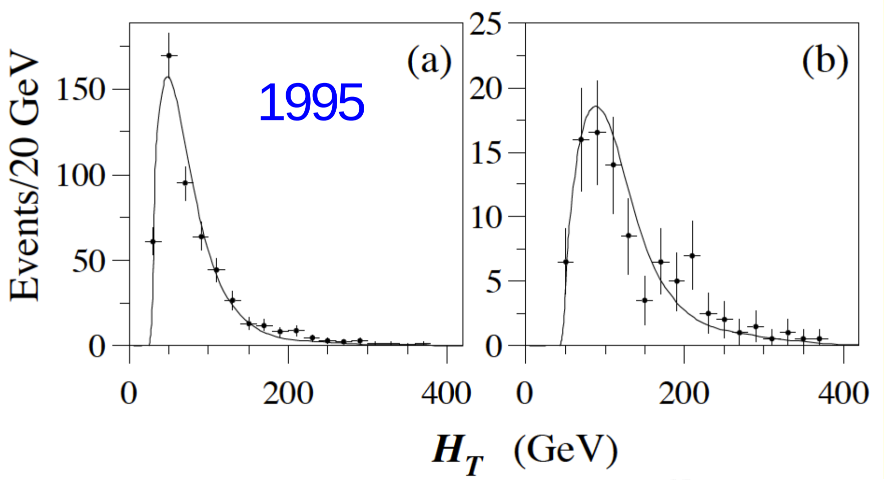
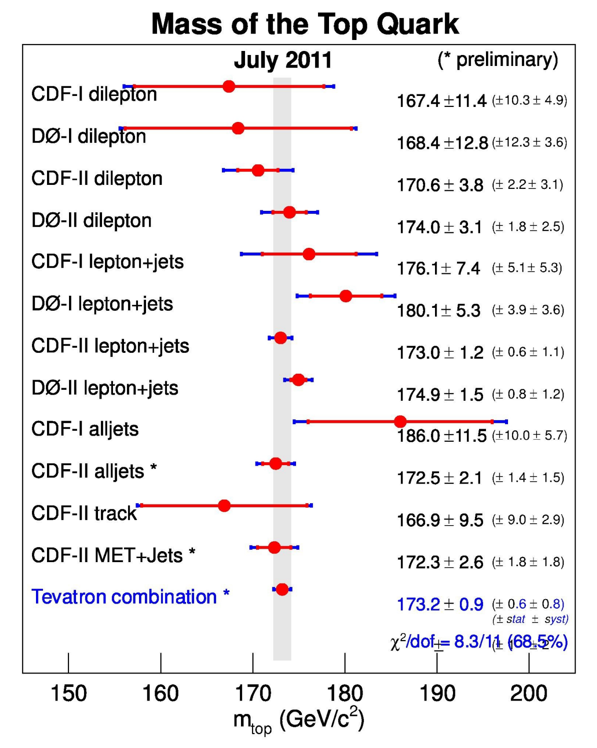
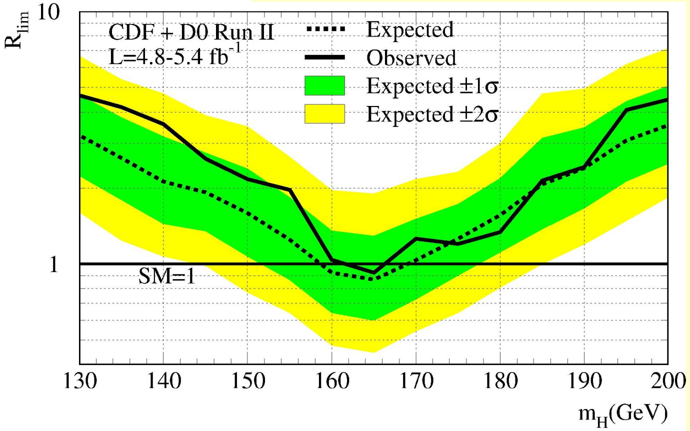
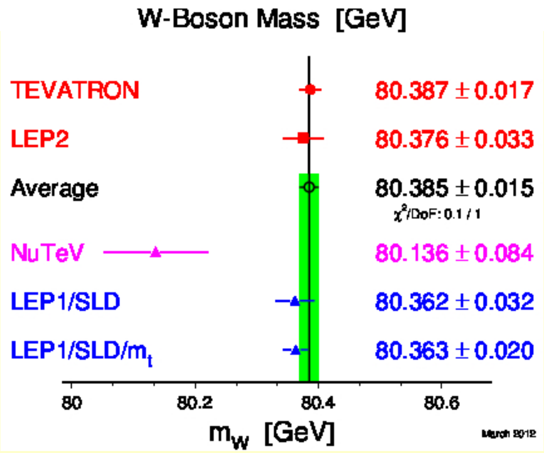


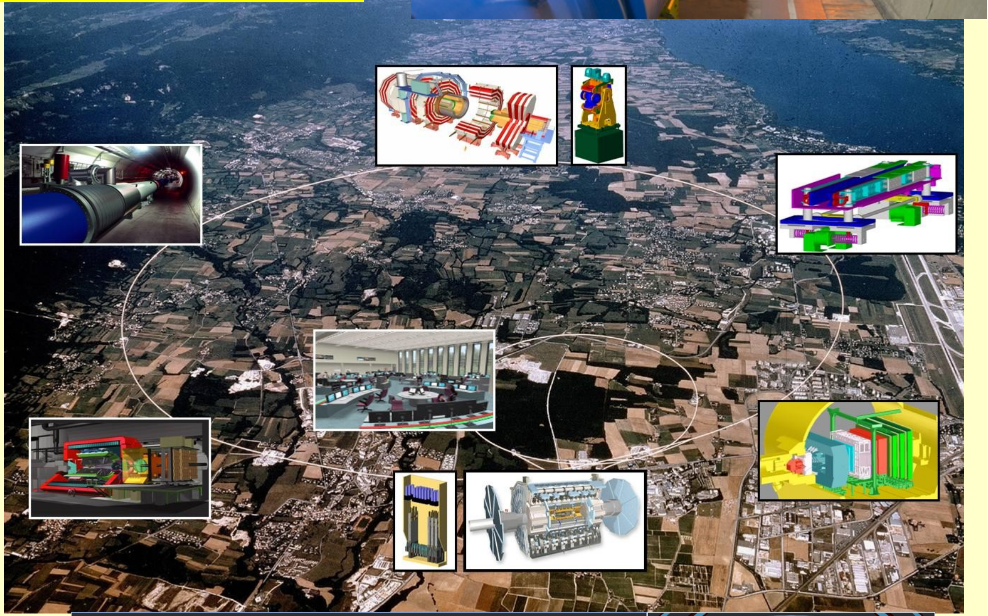




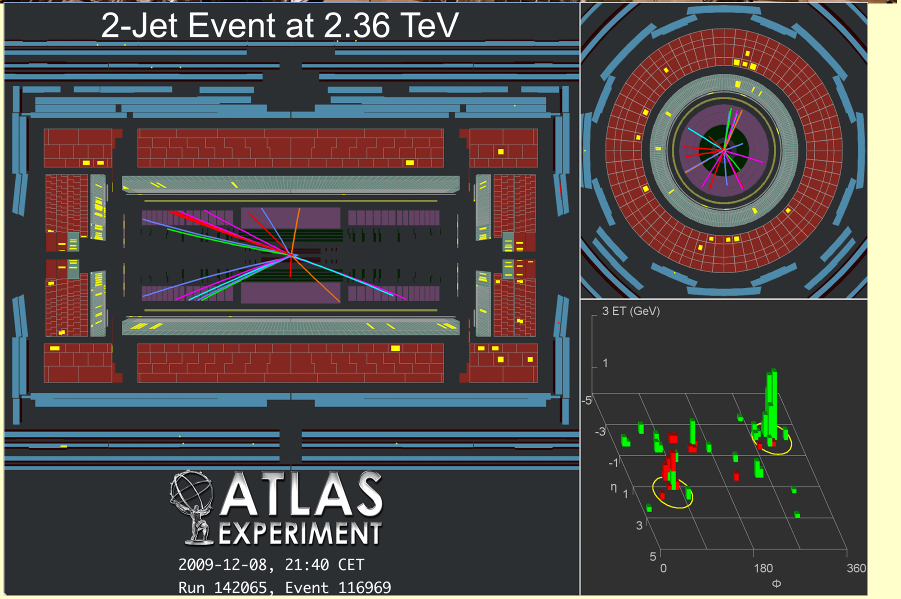


The LHC

pp collisions



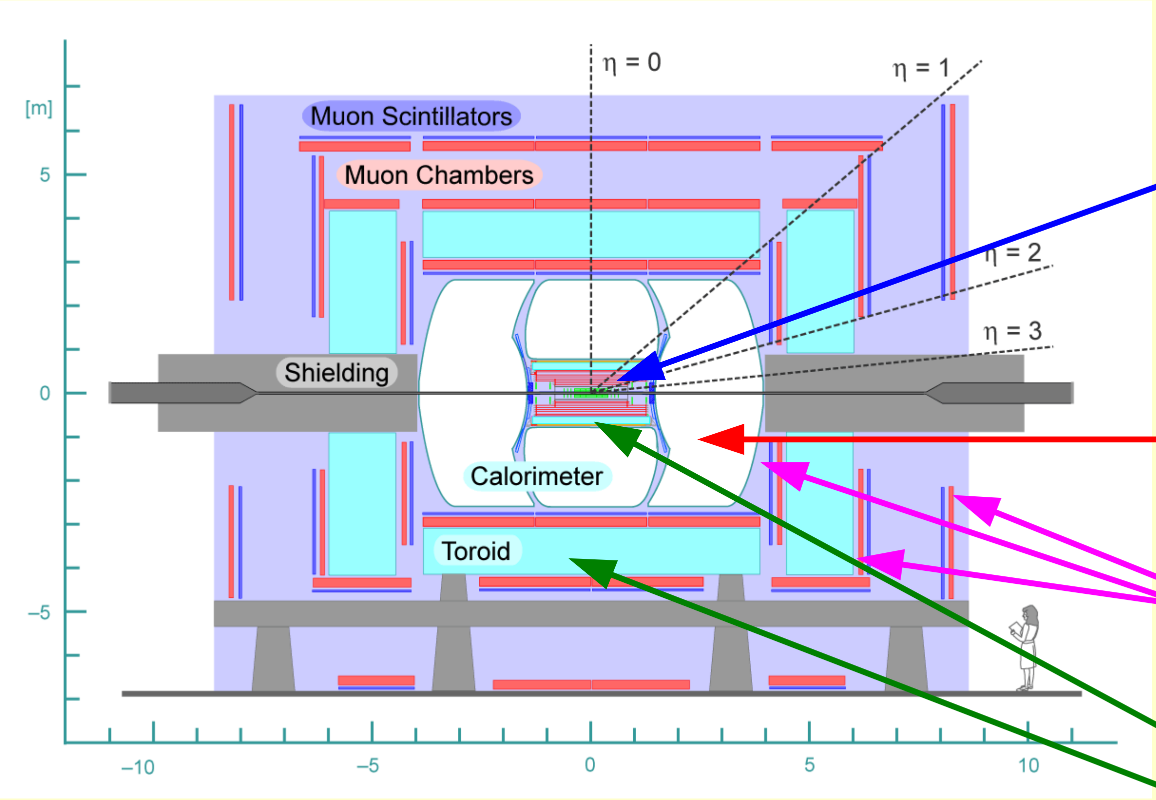
- First beam on September 10th 2008
- First collisions end of 2009
- Goal is $\sqrt{s}$ = 14 TeV (exp. 2014)
  - Collisions at $\sqrt{s}$ = 2.36 TeV in December 2009
  - It was running at $\sqrt{s}$ = 7 TeV through 2010 and 2011
  - It will be running at $\sqrt{s}$ = 8 TeV in 2012
- Goal is to collect 10 fb^{-1}/yr and later 50 fb^{-1}/yr
  - It collected ~40 pb^{-1} by the end of 2010, 5 fb^{-1} in 2011, expected at least that much in 2012
  - 100 fb^{-1} possible in 2016
- Will discover or exclude Higgs boson



2-Jet Event at 2.36 TeV

DØ experiment

500 scientists
85 institutions
19 countries

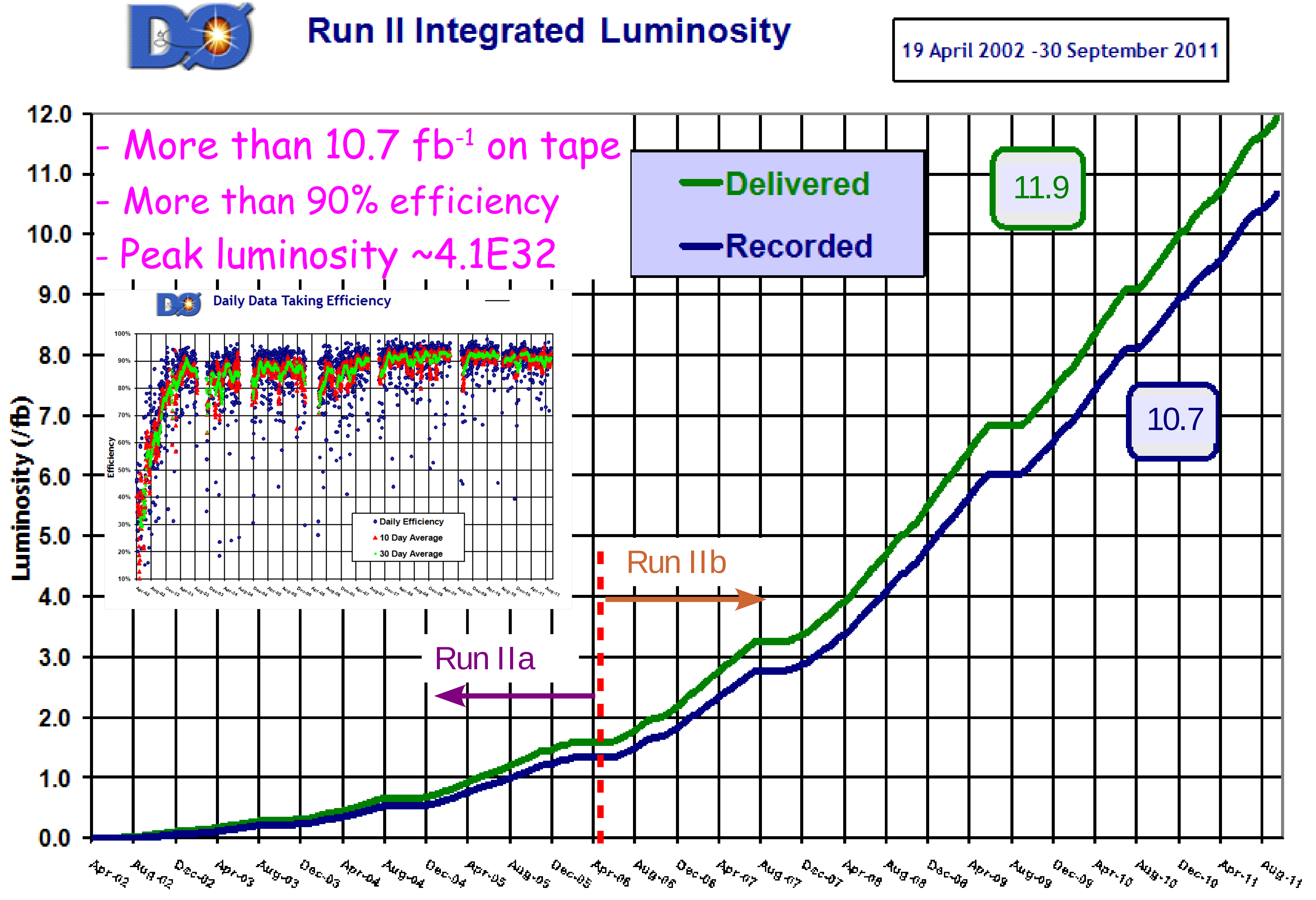


- Silicon microstrip vertex detector
- Scintillating fiber tracker
- Uranium/liquid argon calorimeter
- Wire chamber + scintillation counter muon detector system
- 2T solenoid magnet & 1.8 T toroid magnet

3-Level trigger system:
Collision rate 1.7 MHz
Level 1 (hardware): 2.5 kHz
Level 2 (software): 1 kHz
Level 3 (software): 100 Hz
We save ~25MB/s

Angular coverage	|η|
Muon ID	~2
Tracking	~2.5
EM / Jet ID	~4

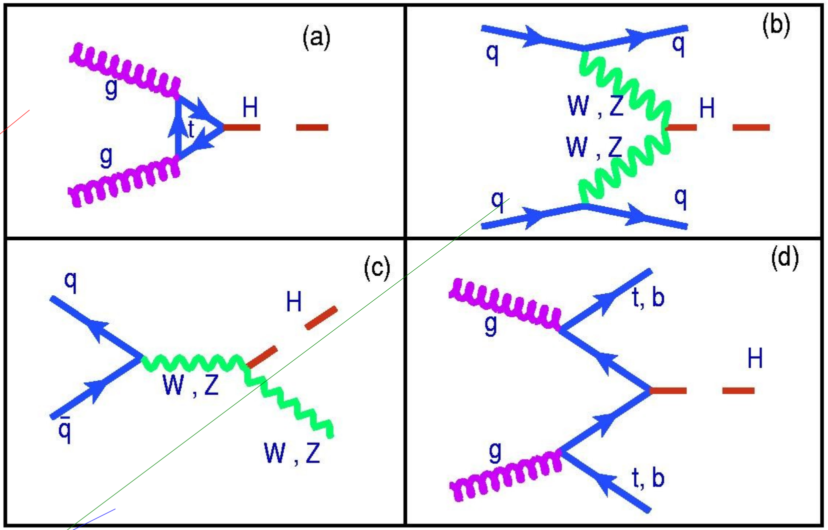
Data taking



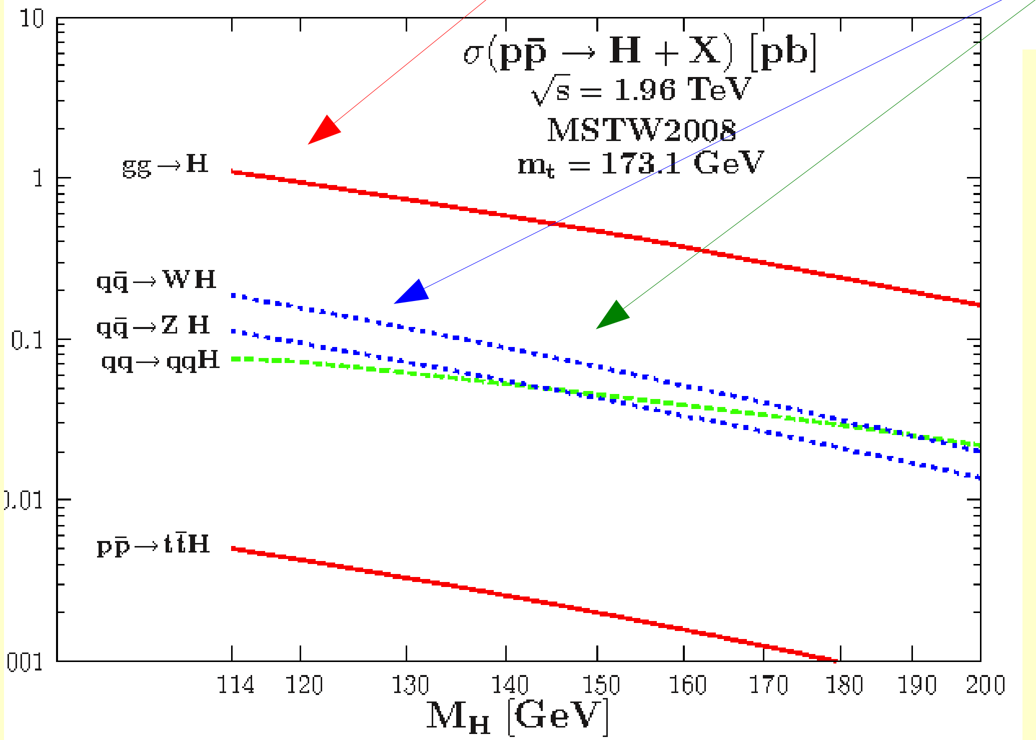
- More than 10.7 fb^{-1} on tape
- More than 90% efficiency
- Peak luminosity ~4.1E32

Higgs searches at Tevatron

Production …

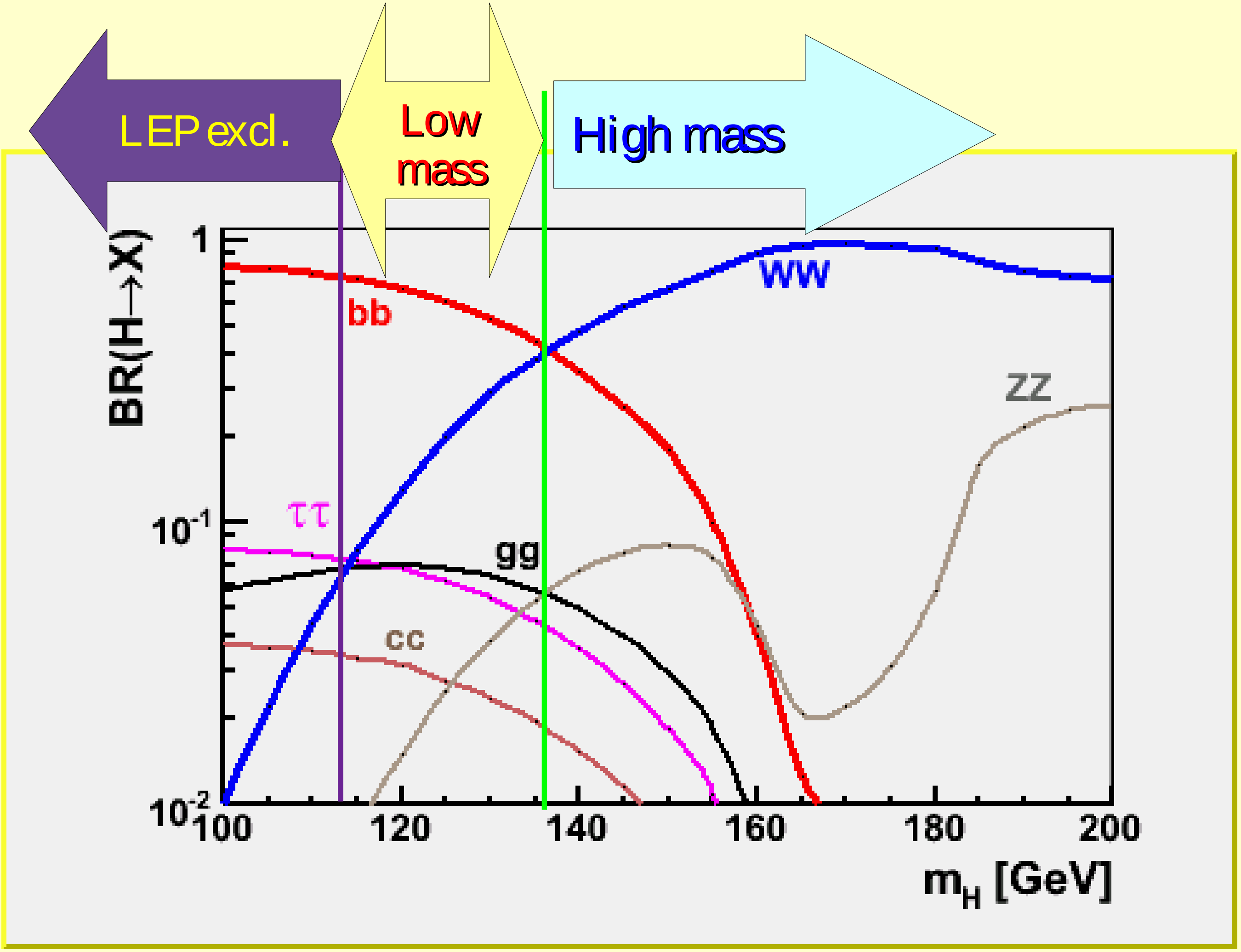


- Main production process is gluon fusion



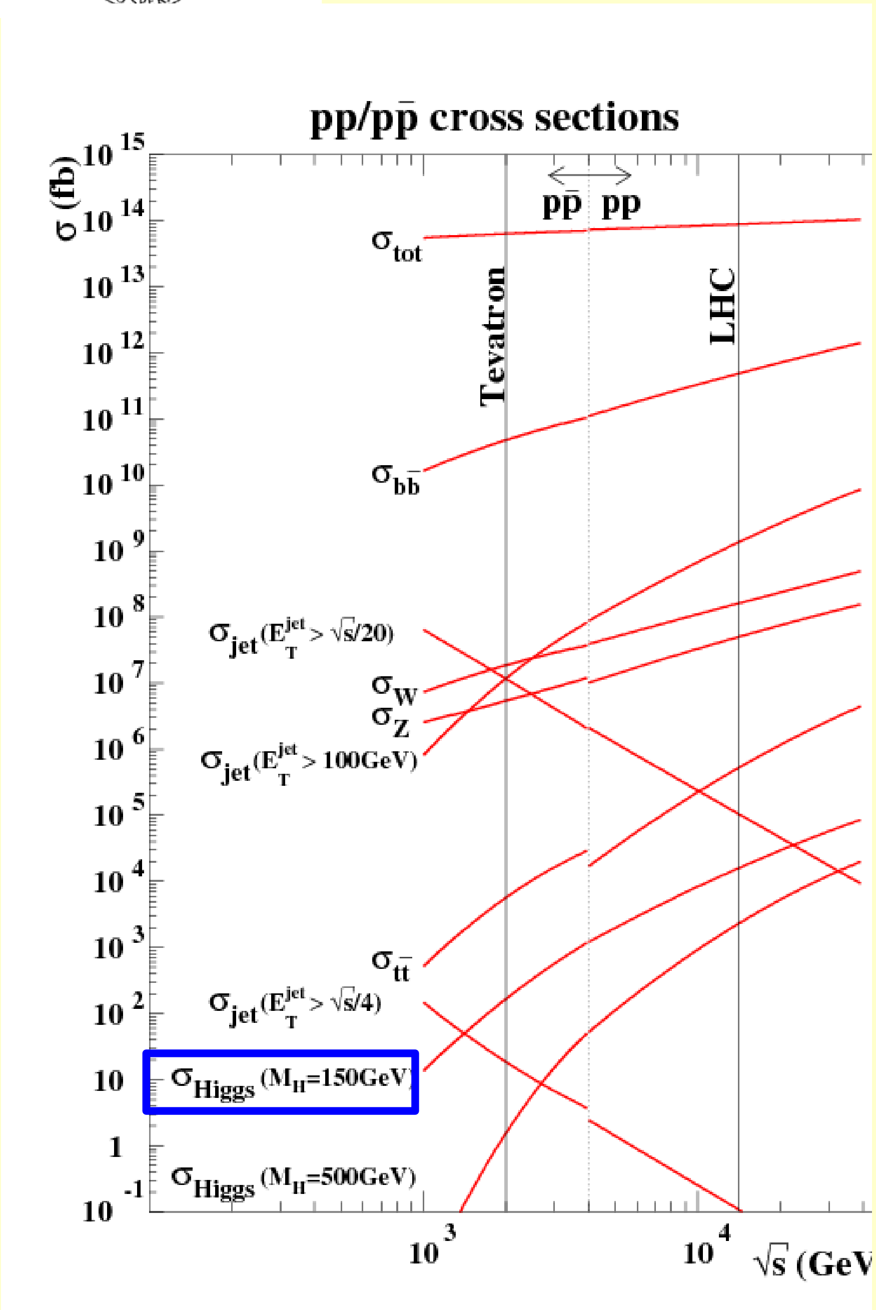
- Associated with vector boson, and vector boson fusion are significant

… and Decay



- At lower masses dominant decays to bb
- At higher masses dominant decays to WW
- Due to the small σ×BR other processes are less usable at Tevatron

How do we search?



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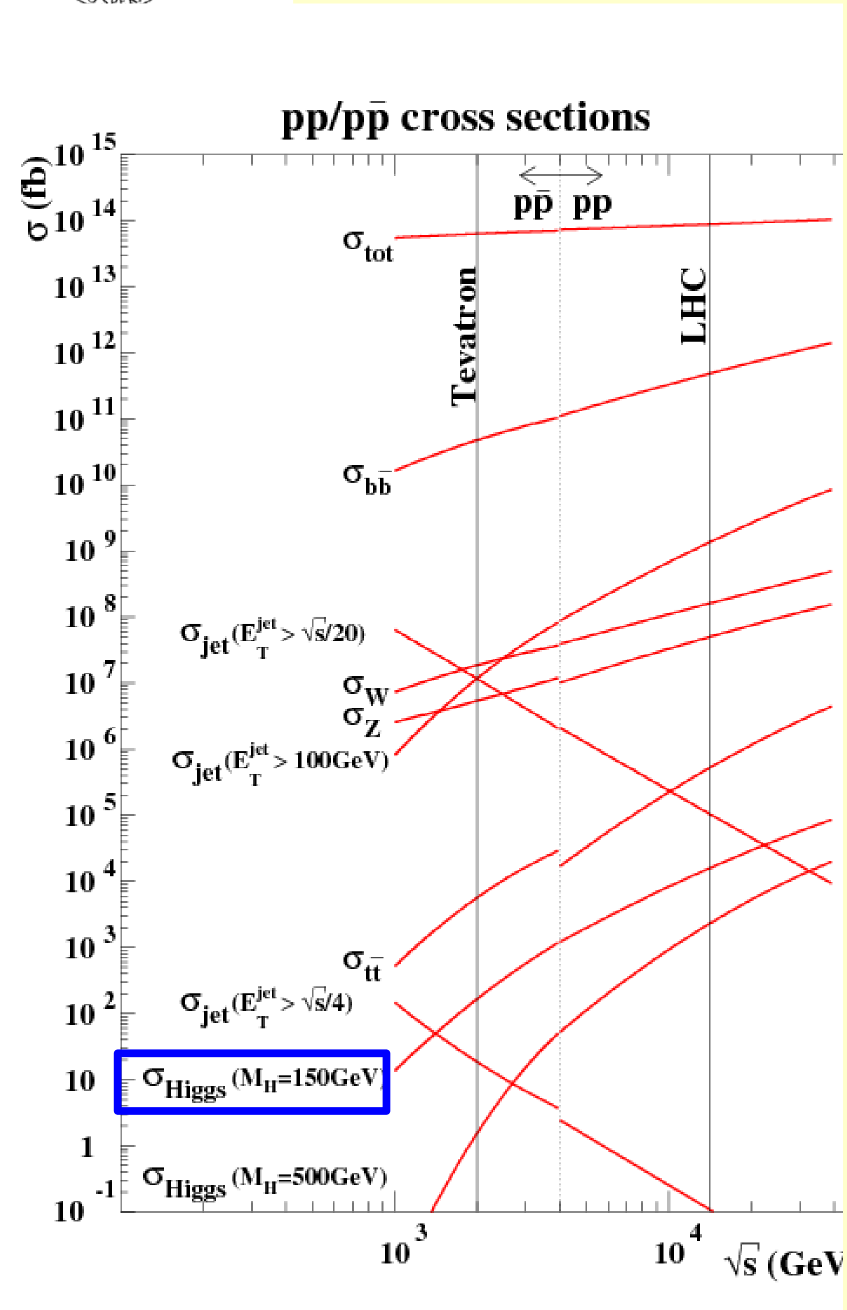
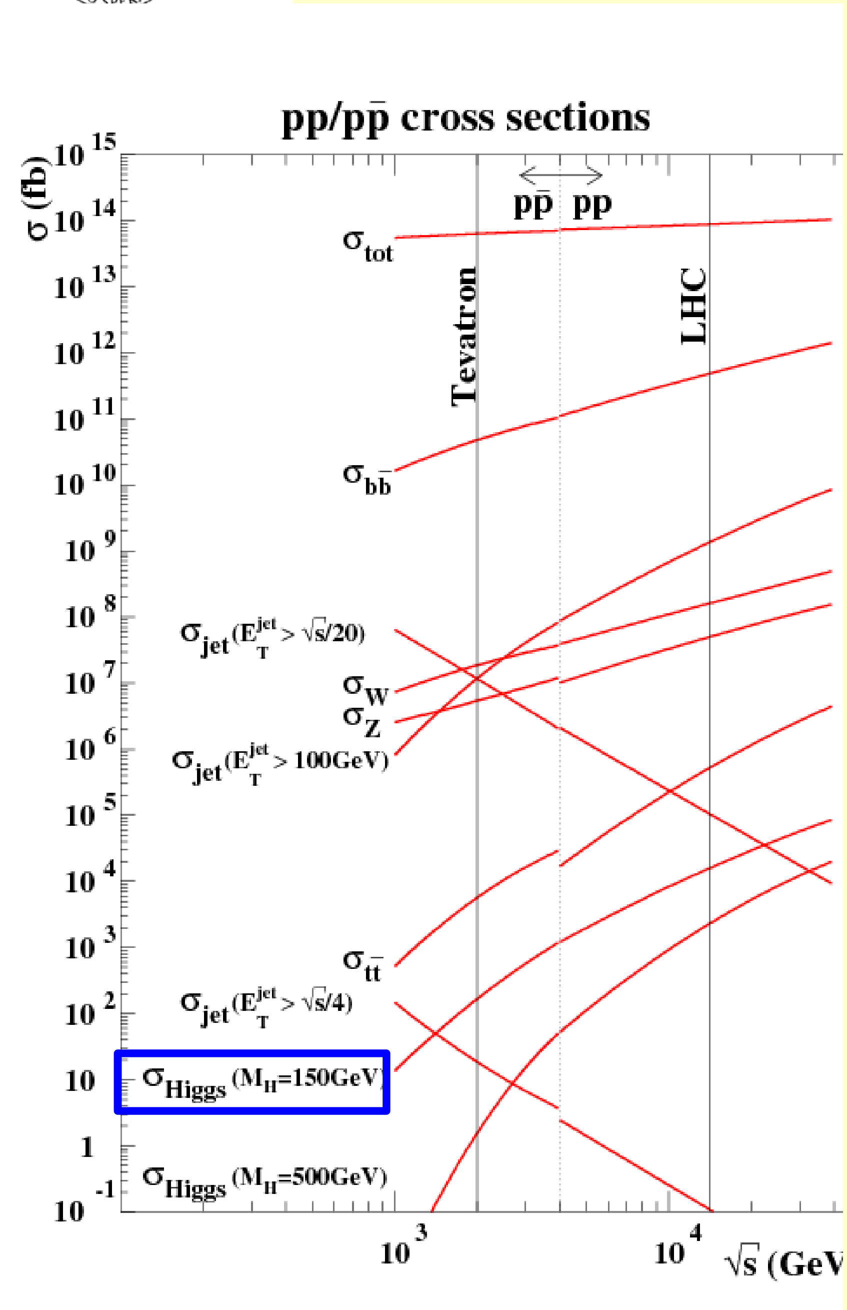
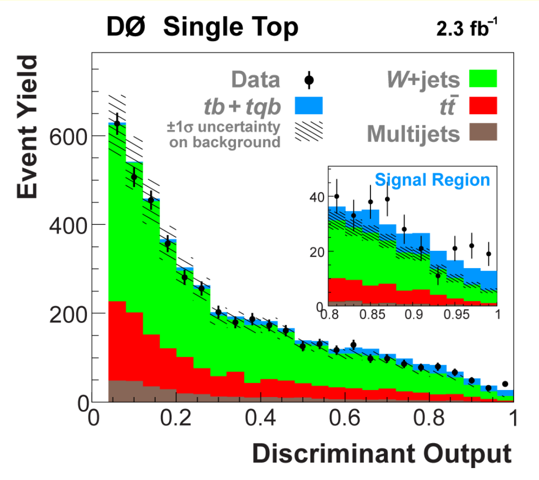
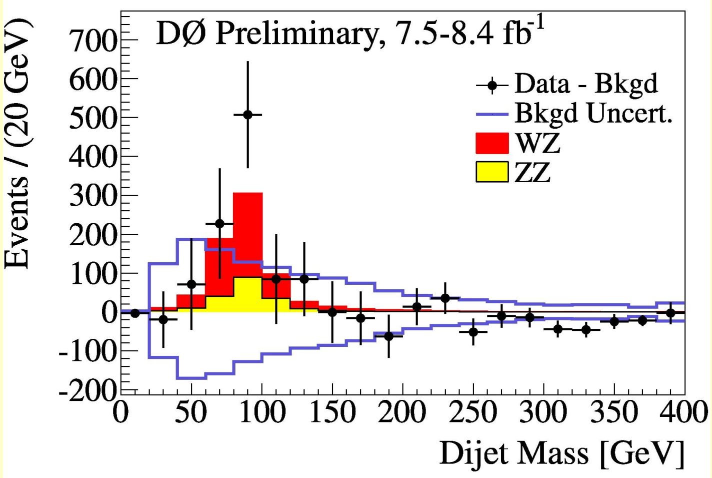


- We need to extract tiny signal from huge background
  - We have to be able to measure known processes
    - Good background modeling
  - Extensive application of advanced analysis techniques to find phase space regions with good signal and background separation
  - Measurements of low cross-section SM processes like single top, WW, WZ and ZZ, are a proof of principle.

How do we search?







- *Measurements of low cross-section SM processes like single top, WW, WZ and ZZ, are a proof of principle.*

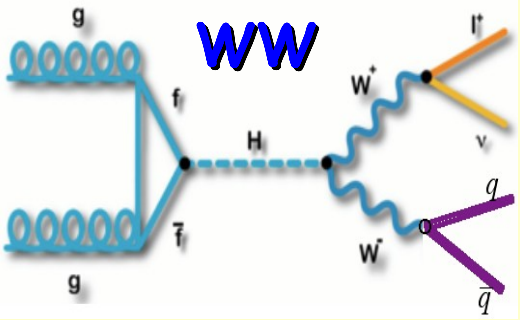
Overview of the Higgs search at DØ

Overwhelmed by multijet production if searched for in $gg\rightarrow H$

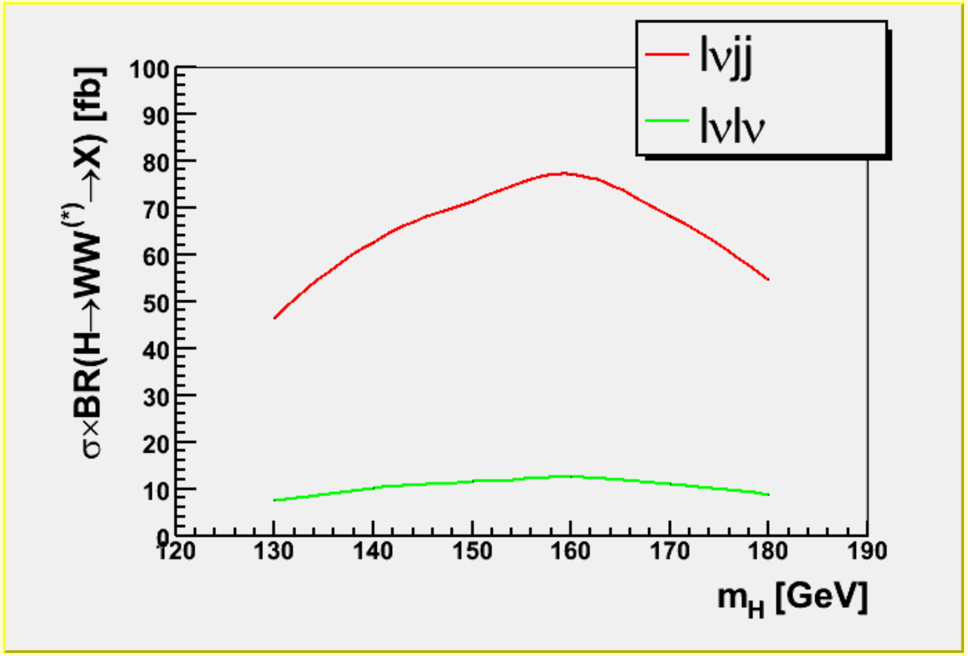
	Gluon fusion	VH
$H\rightarrow bb$		$V=W\rightarrow l\nu$, low mass
$H\rightarrow bb$		$V=Z\rightarrow ll$, low mass
$H\rightarrow bb$		$V=Z\rightarrow \nu\nu$, $W\not\rightarrow l\nu$, low mass
$H\rightarrow \gamma\gamma$	Low mass	Low mass
$H\rightarrow \tau\tau$		Low mass
$H\rightarrow WW\rightarrow l\nu+X$		$V=W\rightarrow l\nu$, High mass
$H\rightarrow WW\rightarrow l\nu l\nu$	High mass	
$H\rightarrow WW\rightarrow l\nu jj$	High mass	

- Common challenges:
  - lepton and jet id, missing transverse energy (MET) reconstruction, b tagging, QCD estimation, systematics
- Recent improvements:
  - Better trigger and b-tagging algorithms, better lepton ID, improved dijet mass resolution

$H \rightarrow WW \rightarrow l\nu jj$ - Motivation

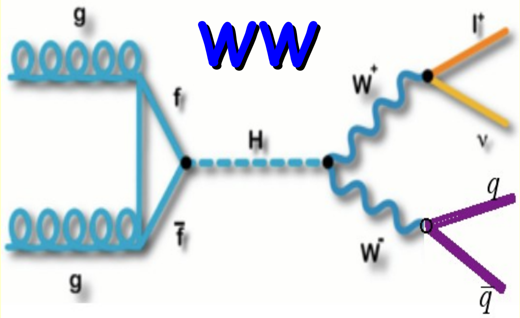


- $H \rightarrow WW^{(*)}$ is very important for Higgs searches for m_H > 130 GeV
  - Searches in dilepton channel led to the first Tevatron and LHC exclusions
  - $l\nu jj$ has ~6 times bigger cross section × Branching Ratio
    - but also huge W+jets background
    - on the other hand, we can fully reconstruct Higgs mass for m_H >~160 GeV



- It has the same final state as $WH \rightarrow l\nu bb$ before b-tagging

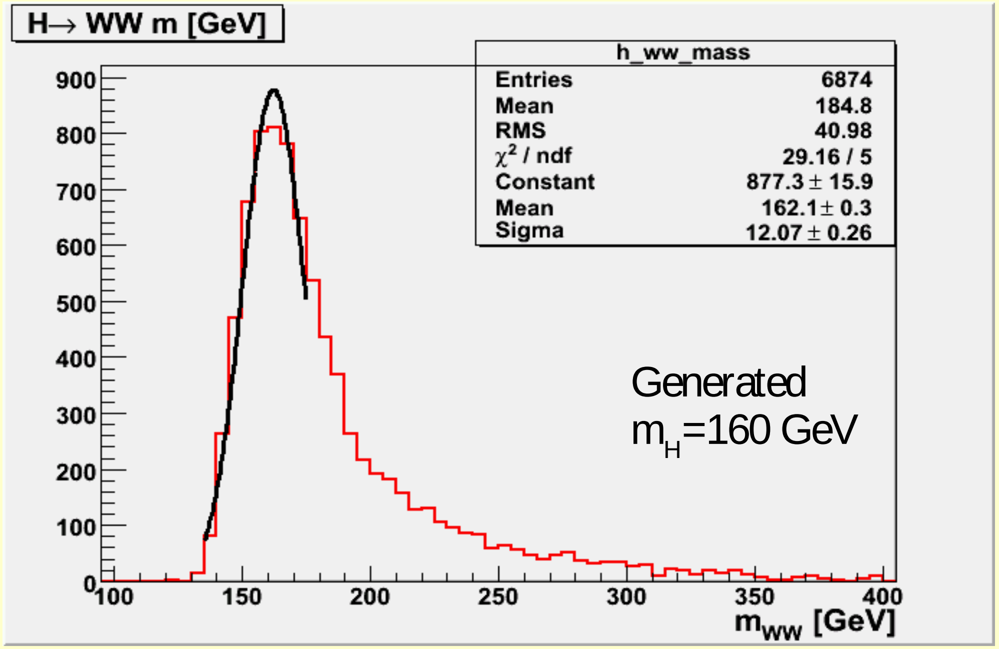
Reconstructing the signal



- Real Missing E_T (MET) is coming only from W→lν

$$m(W)^2 = E(W)^2 - |\vec{p}(W)|^2$$

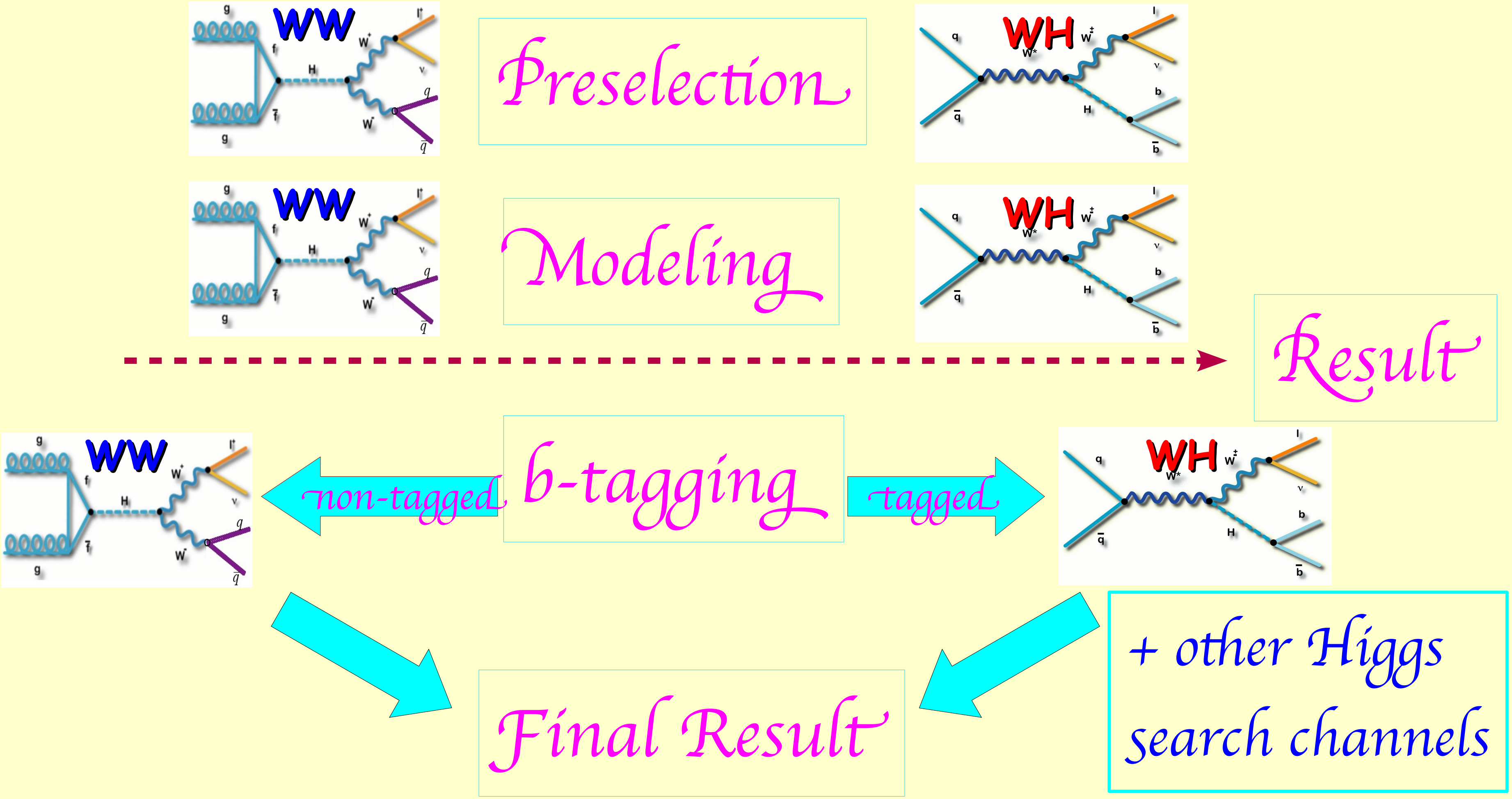
$$m(W)^2 = [E(e) + E(\nu)]^2 - |\vec{p}(e) + \vec{p}(\nu)|^2$$



h_ww_mass	
Entries	6874
Mean	184.8
RMS	40.98
χ^2 / ndf	29.16 / 5
Constant	877.3 ± 15.9
Mean	162.1 ± 0.3
Sigma	12.07 ± 0.26

  - we can derive p_z and thus full momentum of neutrino
  - we can reconstruct full Higgs mass

Search for the Higgs boson in final states with one lepton, MET and at least two jets



Preselection

Modeling

Result

non-tagged

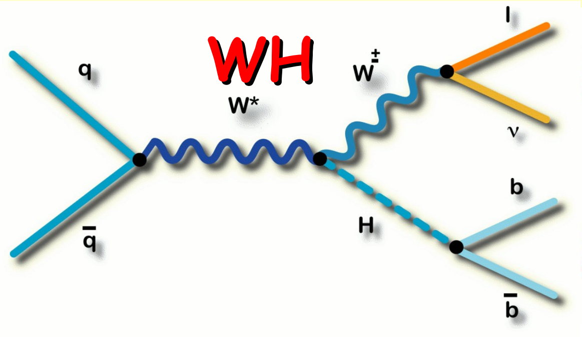
b-tagging

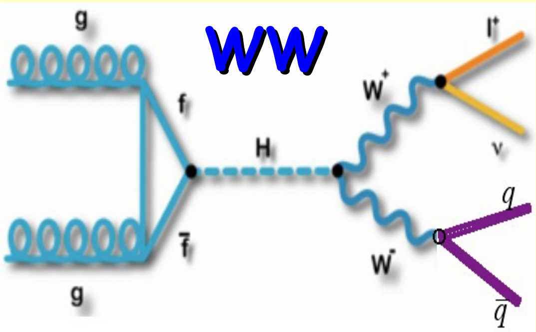
tagged

Final Result

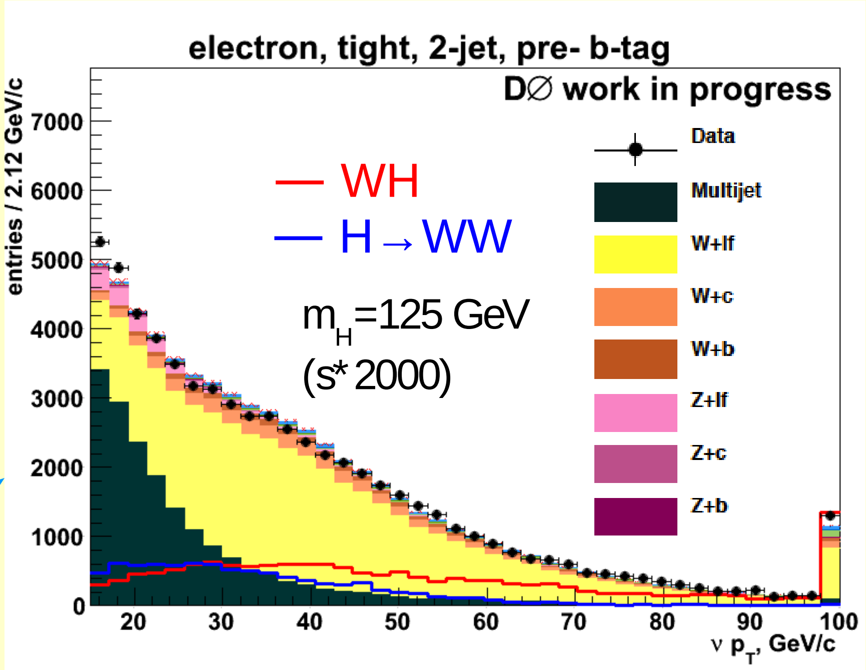
+ other Higgs search channels

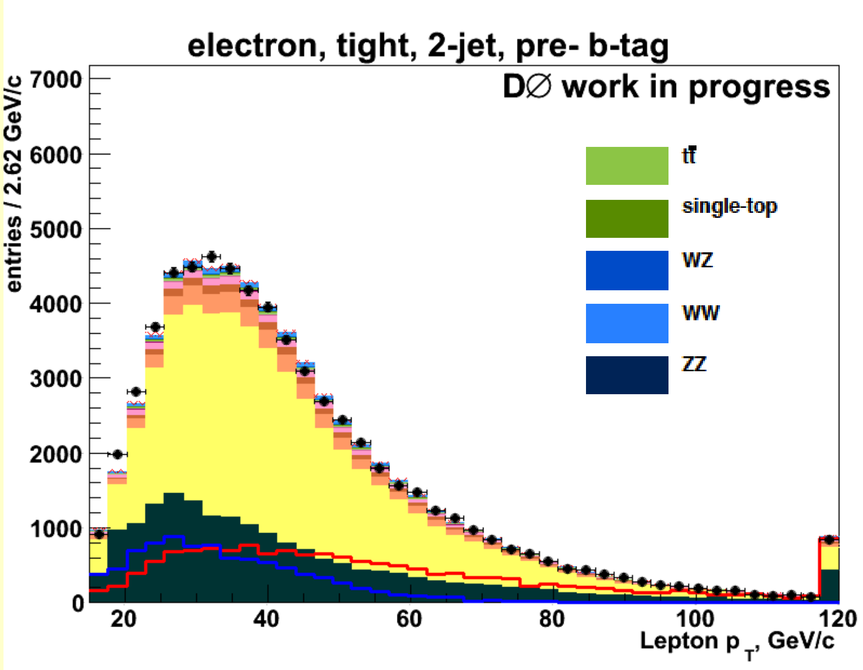
Event Selection





- Missing E_T - MET > 15 GeV
  - calculated from calorimeter cells
- Electron (lepton)
  - combine track and calorimeter information
  - p_T > 15 GeV





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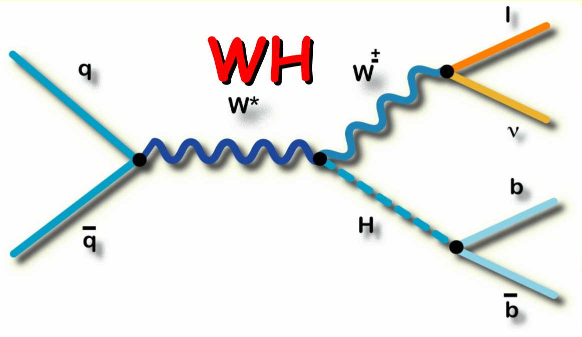
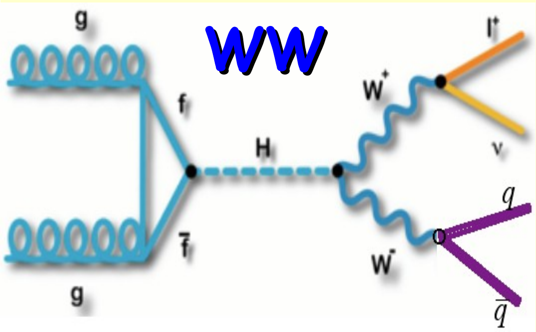
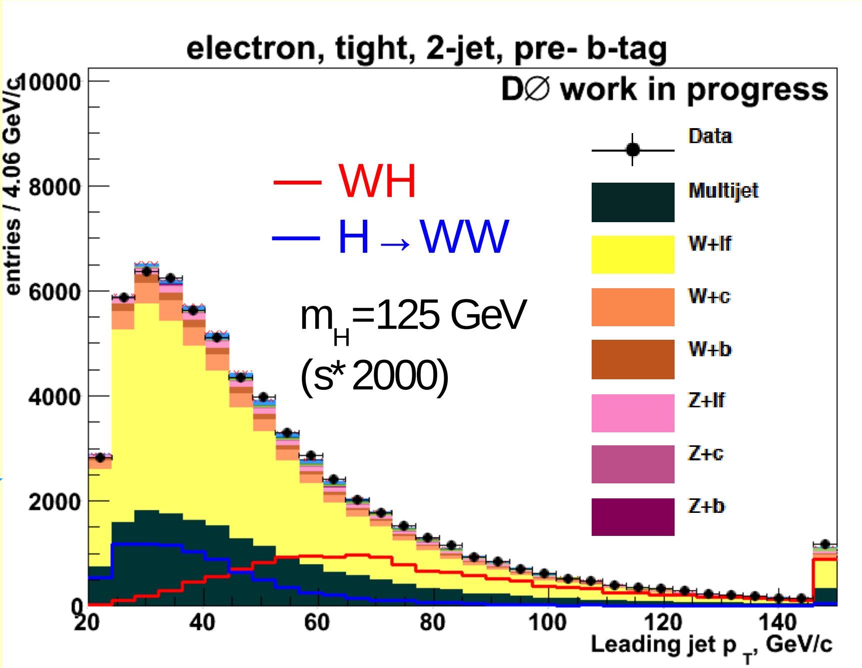
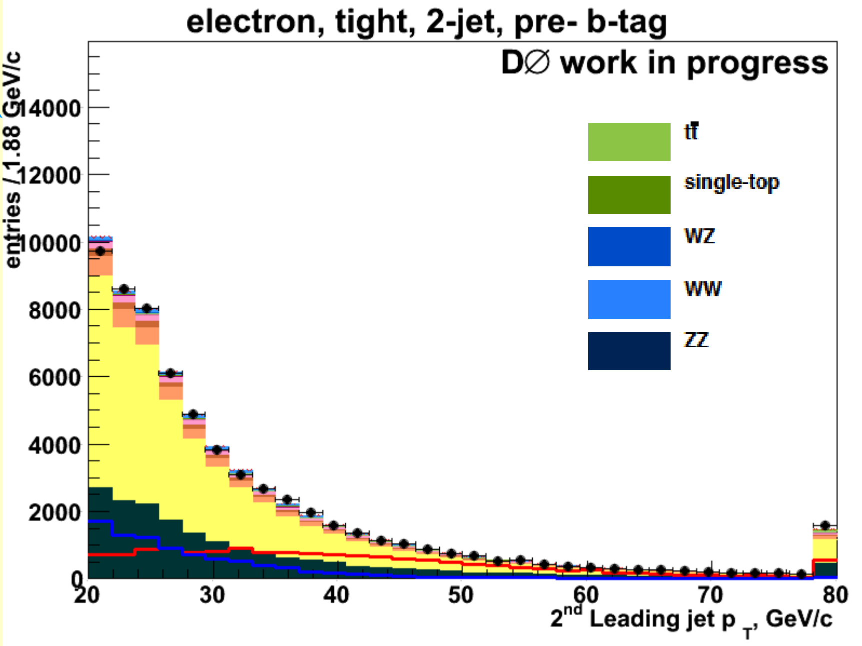




- At least 2 jets:
  - jet p_T > 20 GeV
- QCD reduction
  - electron faking jet
  - missmeasured jet energies give MET
- Triangle cut between transverse mass and MET



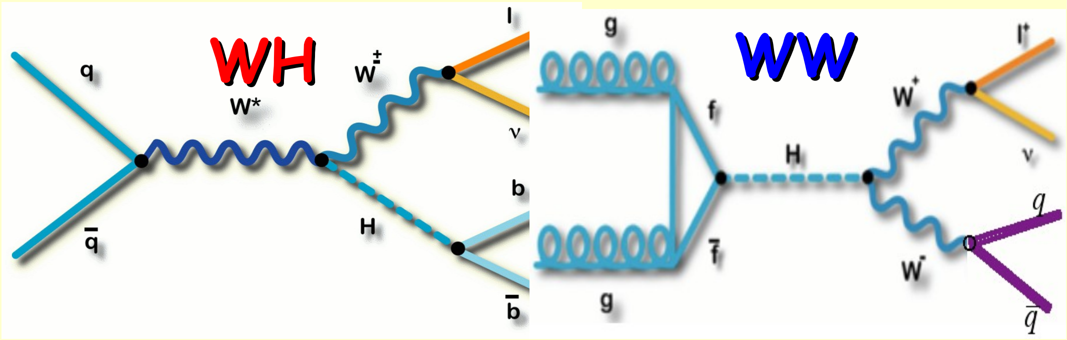


Event Selection

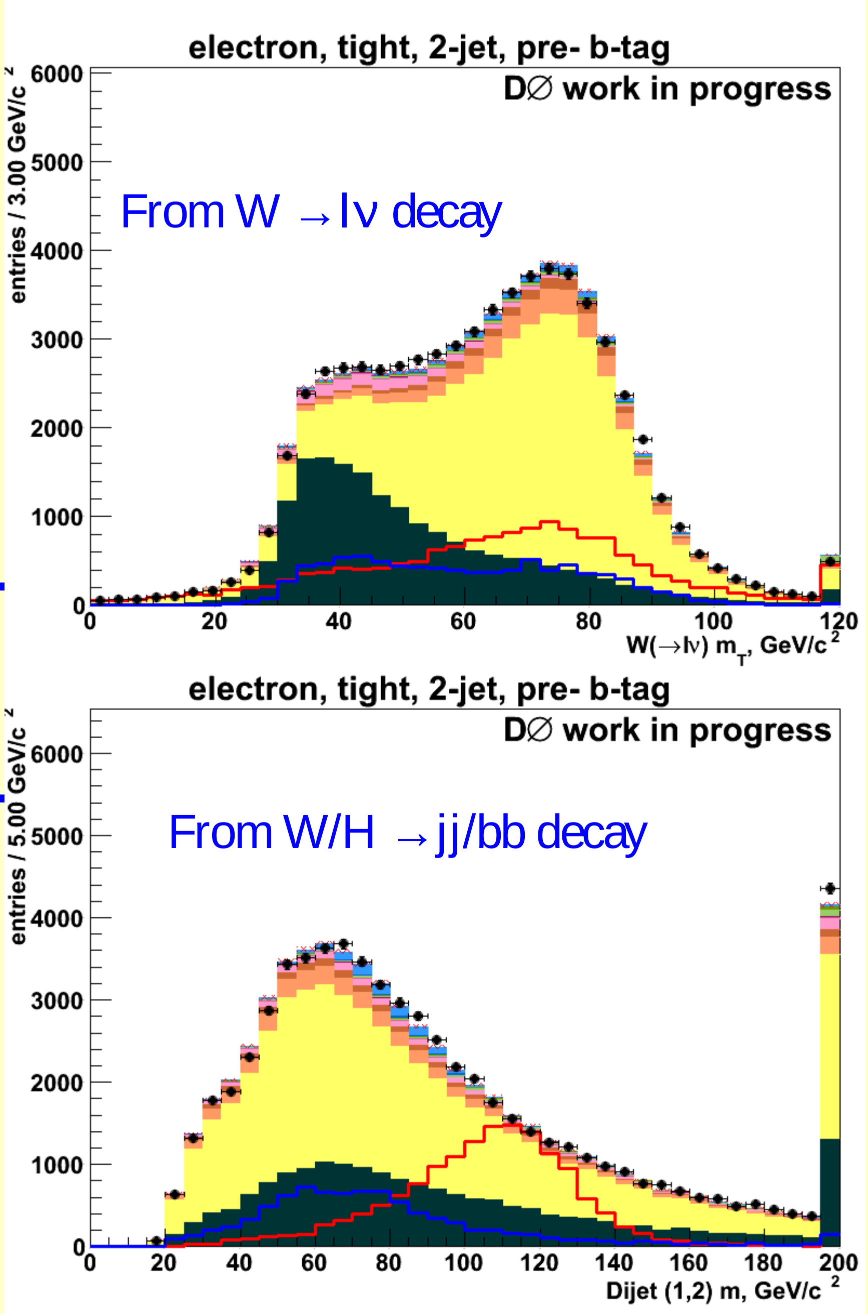
$$m_{TR} = \sqrt{E^2 - p_x^2 - p_y^2}$$

High p_T lepton

High missing E_T



At least two high p_T jets



electron, tight, 2-jet, pre- b-tag

From W → lν decay

electron, tight, 2-jet, pre- b-tag

From W/H → jj/bb decay

- —●— Data
- ■ Multijet
- ■ W+lf
- ■ W+c
- ■ W+b
- ■ Z+lf
- ■ Z+c
- ■ Z+b
- ■ $t\bar{t}$
- ■ single-top
- ■ WZ
- ■ WW
- ■ ZZ

— WH

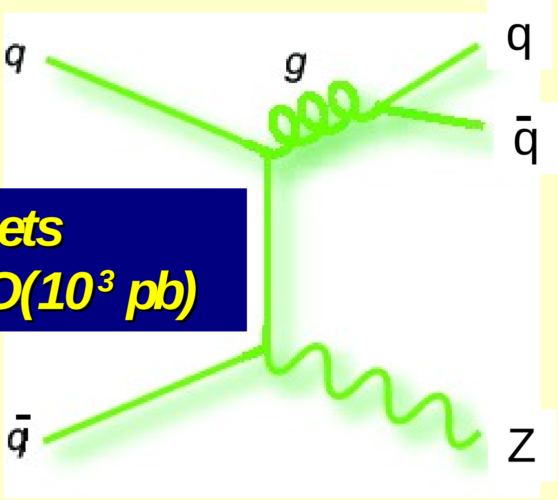
— H → WW

m_H=125 GeV
(s* 2000)

Modeling of the background

- We model background processes with Alpgen+Pythia, Pythia and CompHEP
- Normalized with the highest order cross section available (NLO or better)

Z+jets
σ~O(10³ pb)



W+jets
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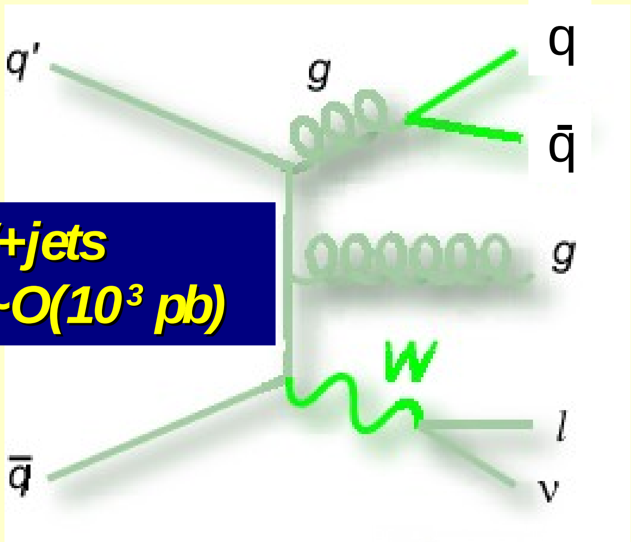
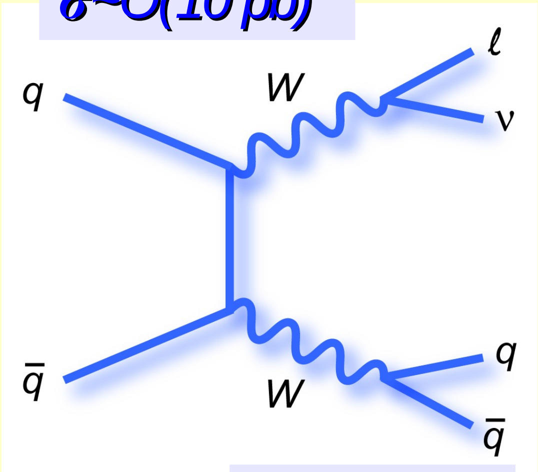
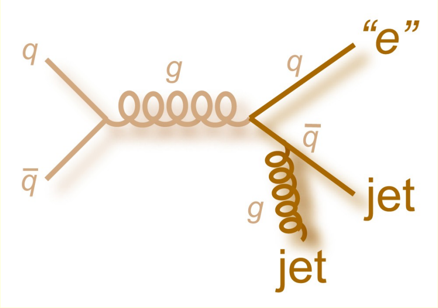


diBoson
σ~O(10 pb)

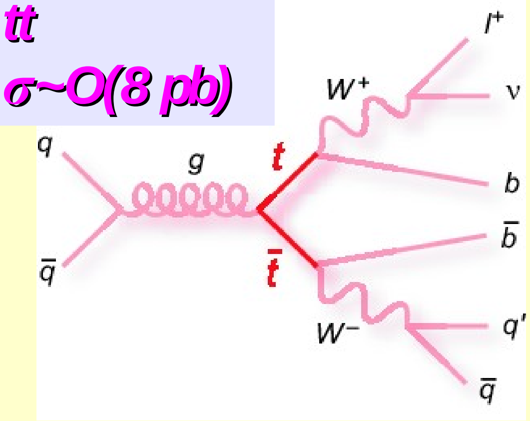


Higgs signal
σ~O(0.1 pb)

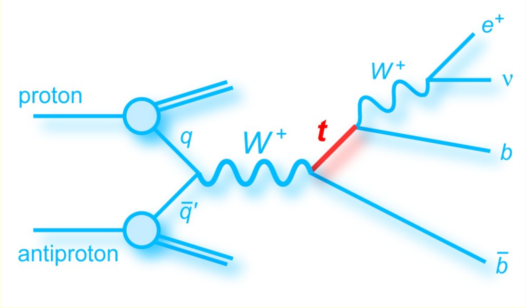
Multijet (QCD)
from data



tt
σ~O(8 pb)

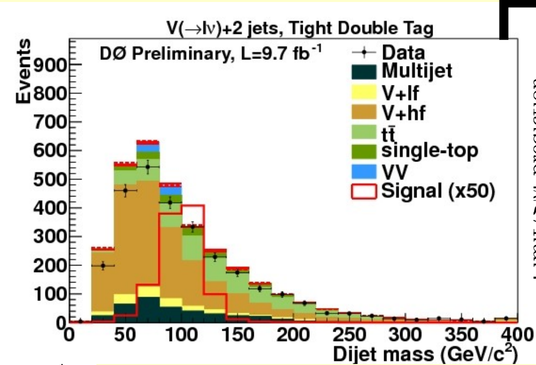


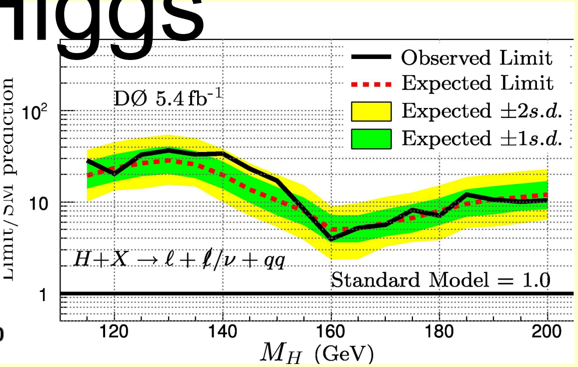
Single top
σ~O(3 pb)



Modeling of the W+jets

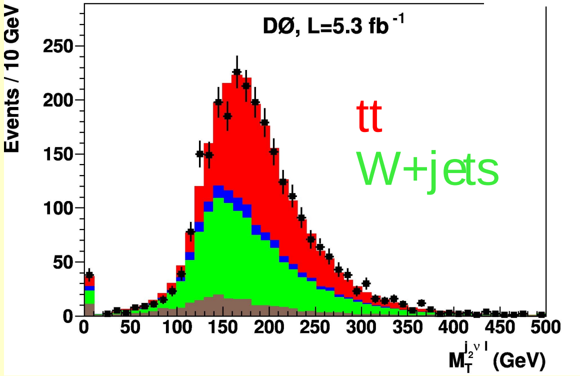
Higgs



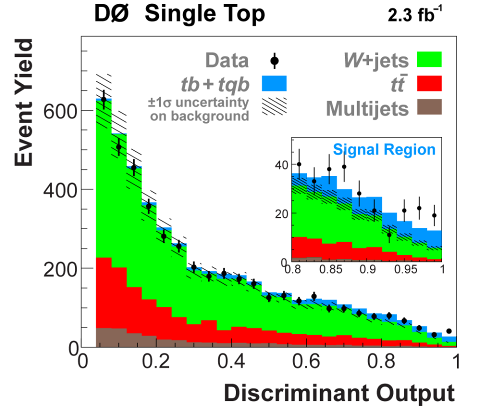


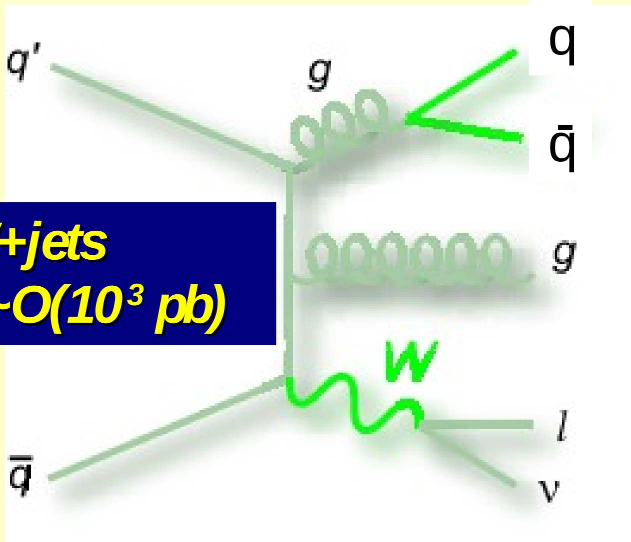
Top quark

Cross section, mass, properties

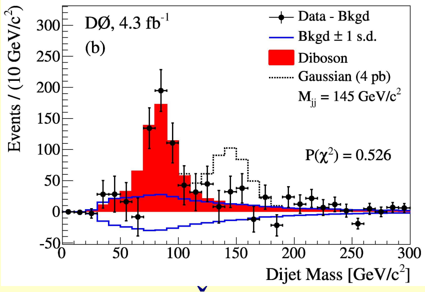


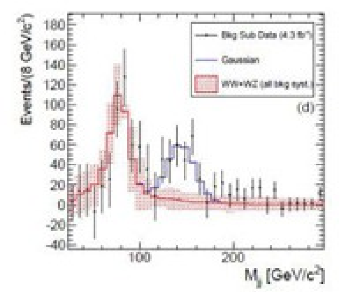
Single top observation



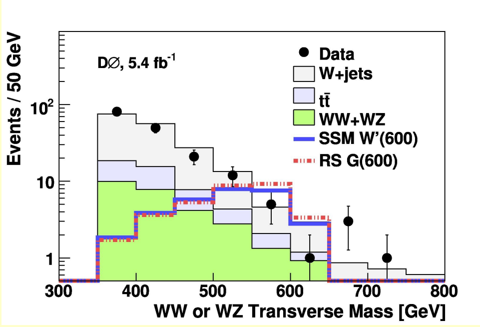


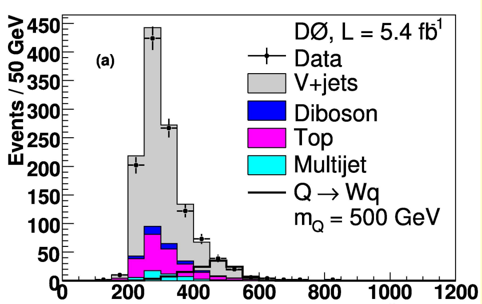
W+jets
σ~O(10^3 pb)

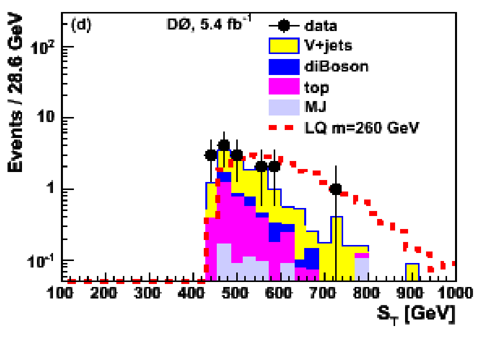




New physics

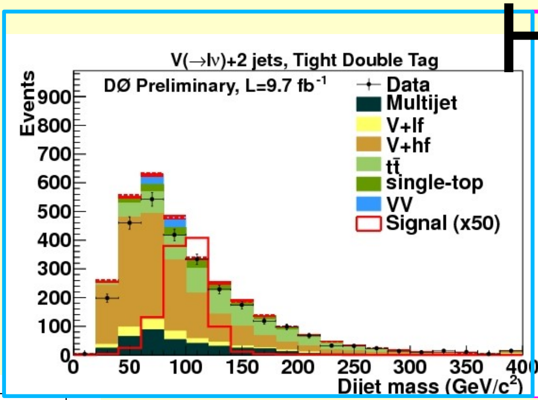


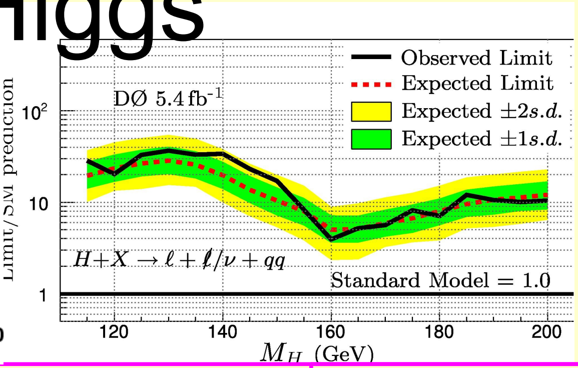




Modeling of the W+jets

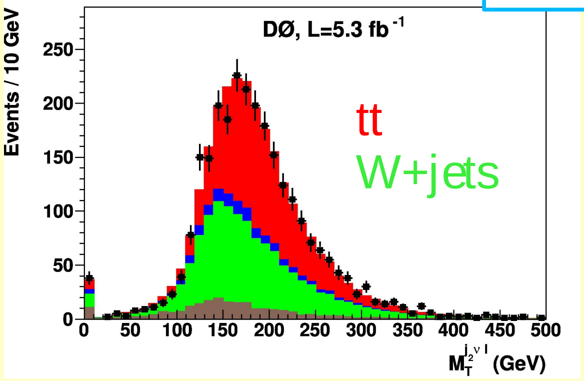
Higgs



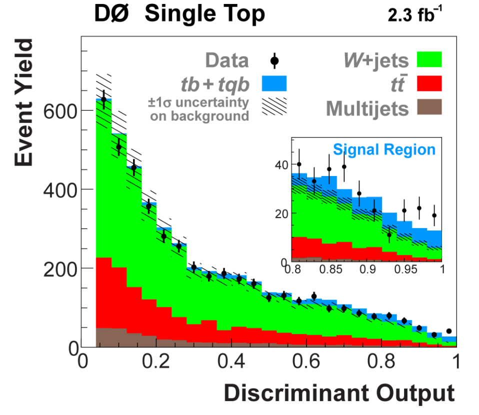


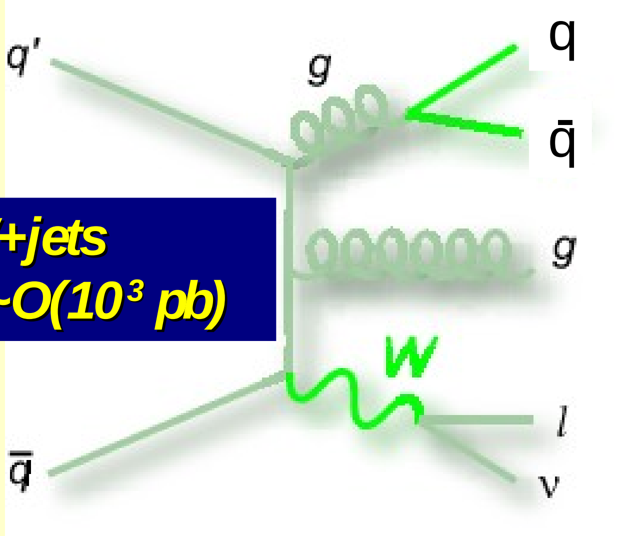
Top quark

Cross section, mass, properties

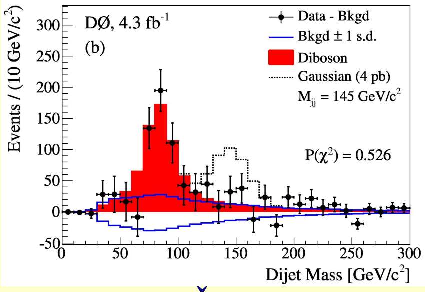


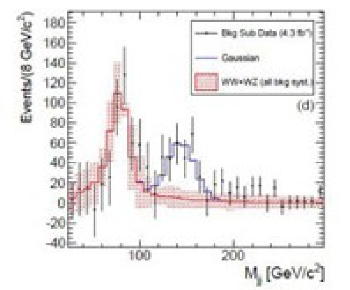
Single top observation



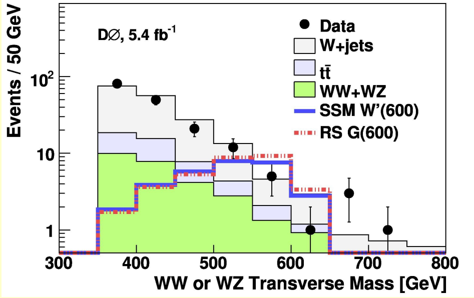


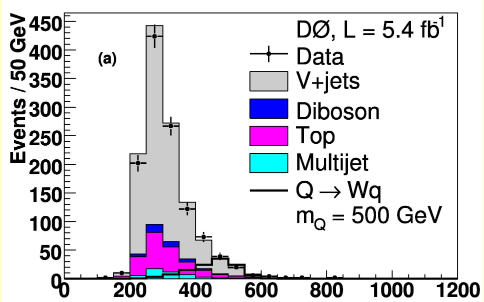
W+jets
σ~O(10³ pb)

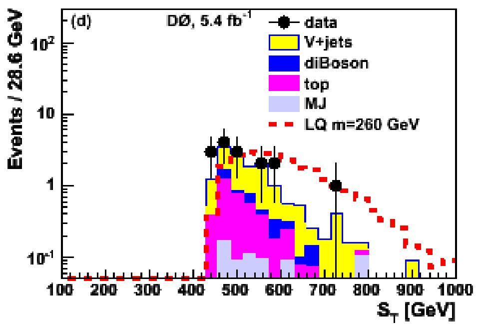




New physics

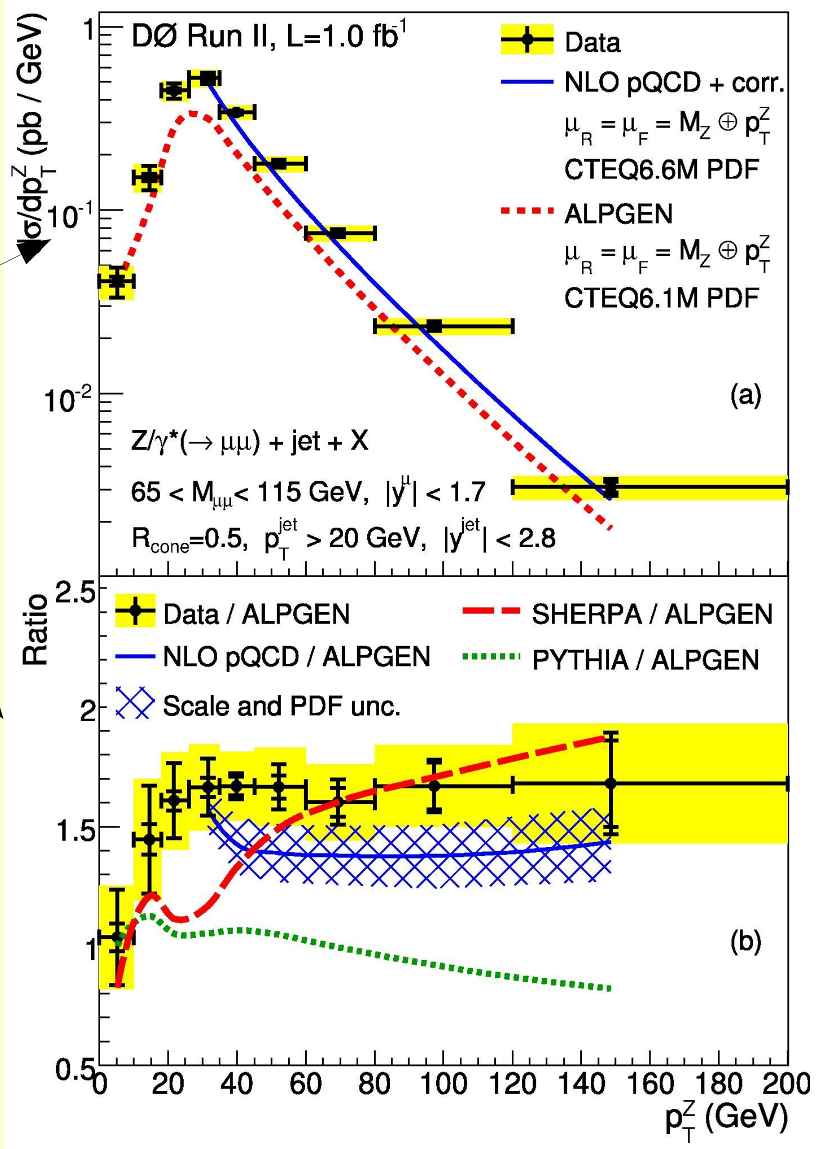






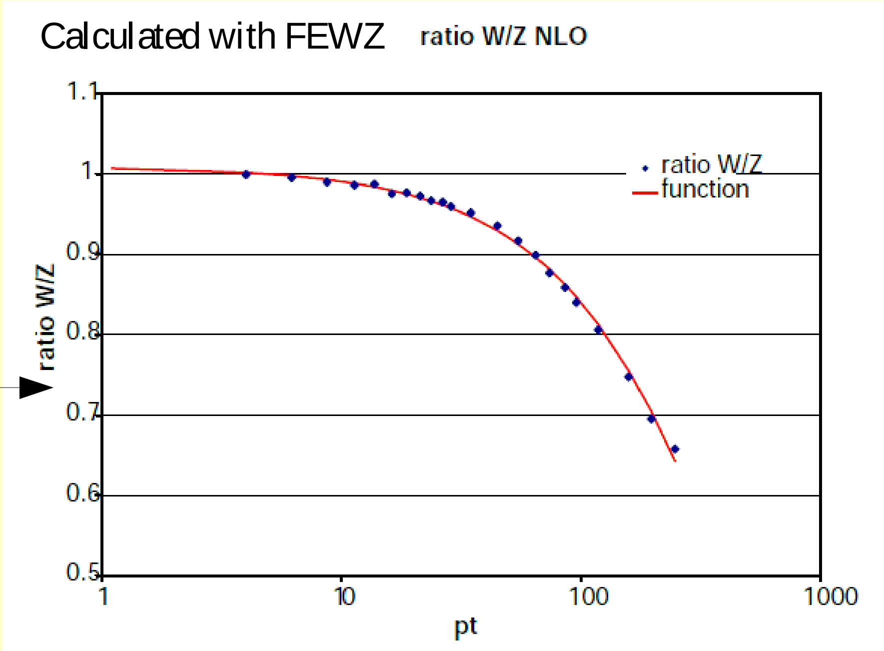
Modeling of the background - Z p_T

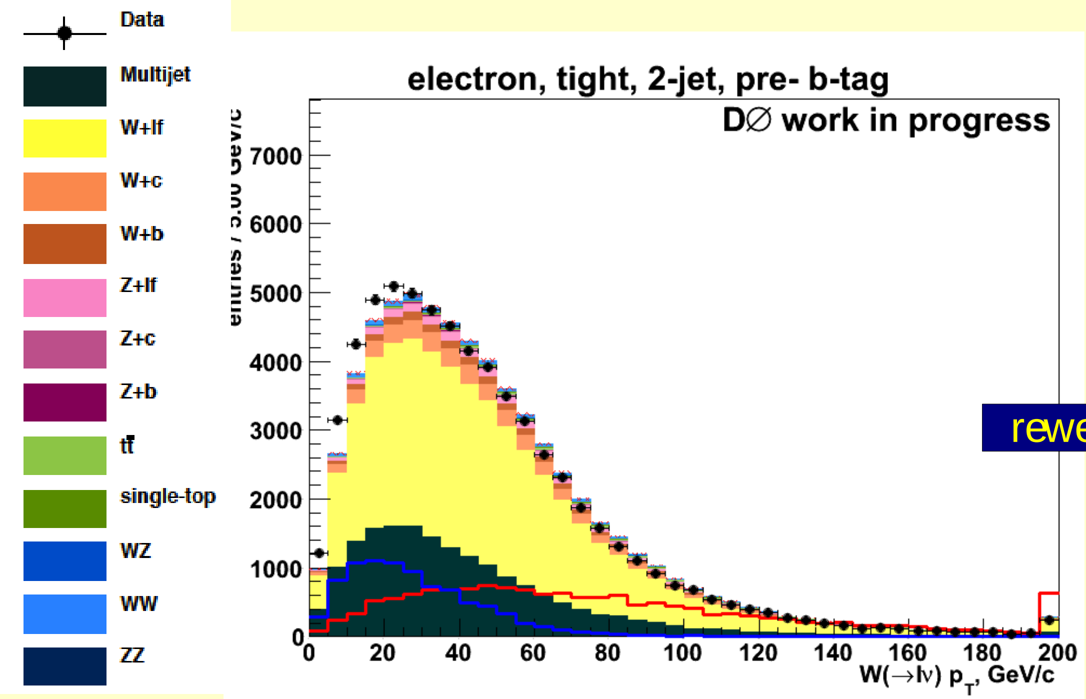
- Our generators do not describe vector boson (W or Z) p_T correctly
- We measured differential cross section $d\sigma/dp_T^Z$ and used that measurement to correct the Monte Carlo



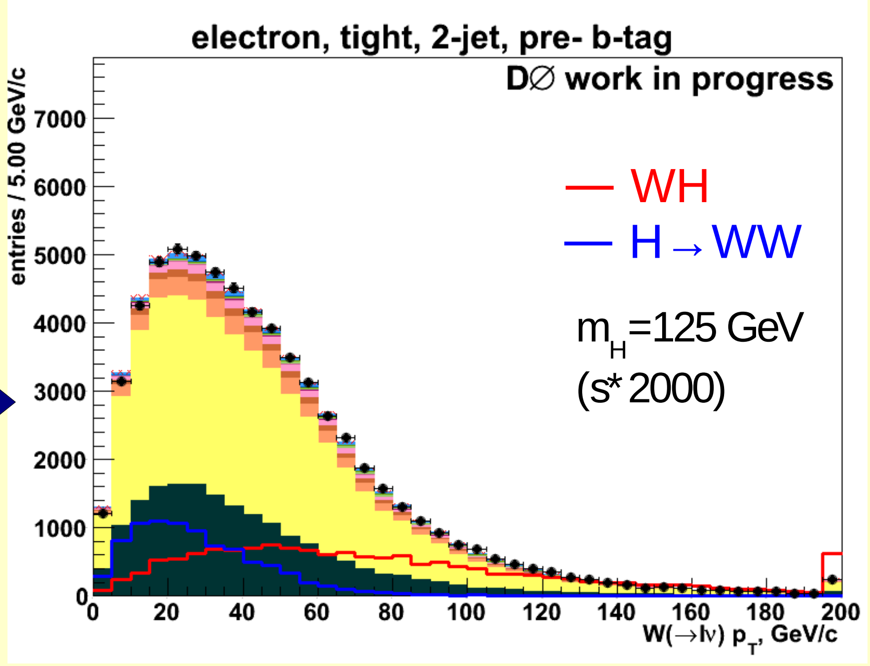
Modeling of the background - W p_T

- To determine the correct shape of W p_T we compared it to the measurement of the Z p_T corrected to the predicted NLO ratio between W and Z p_T
  - Compare to data to correct the remaining difference





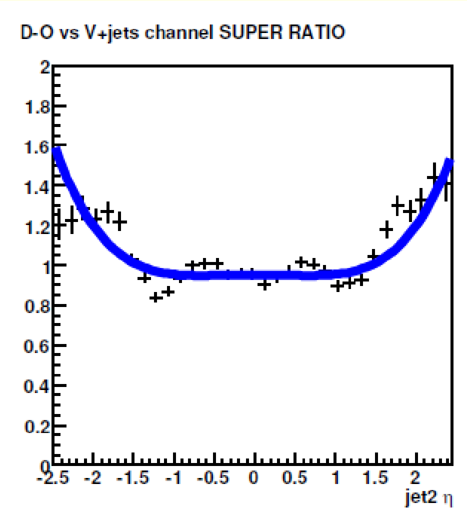
reweight

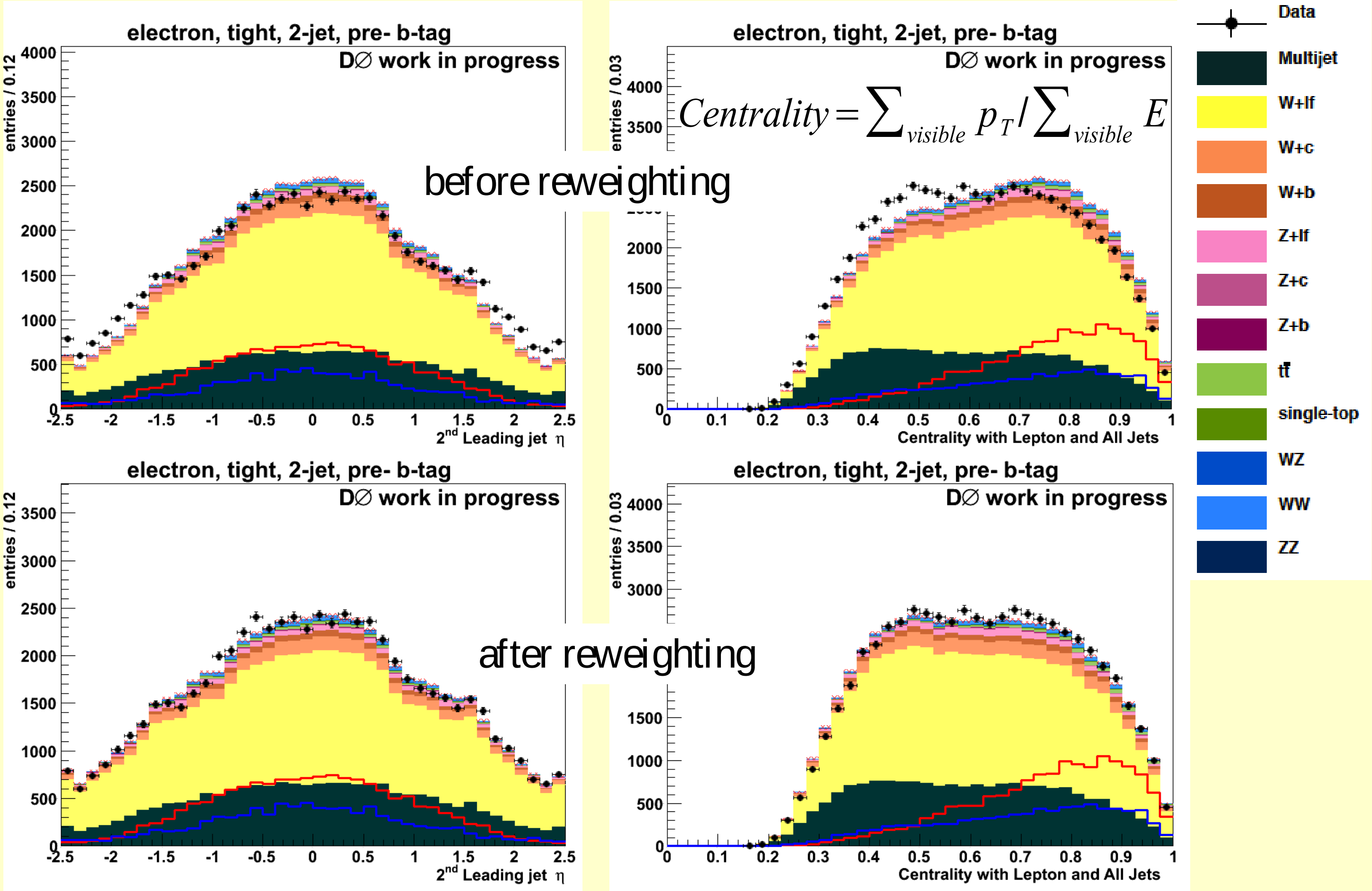


Modeling of the backgrounds – jet angles

- MC generators that we use do not describe jet angles correctly
- Correct distributions based on data, inclusive Z+jets and other generators

$$\eta=-\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$





$$Centrality=\sum_{visible}p_T/\sum_{visible}E$$

before reweighting

after reweighting

— WH
— H → WW
m_H=125 GeV
(s* 2000)

Yields after selection

L= 5.4 fb^{-1}		Number of Signal Events								
Higgs mass [GeV]	115	125	135	145	155	160	165	175	185	195
Gluon fusion signal	2.09	6.85	15.46	26.73	37.32	44.03	45.00	39.29	30.00	23.49
Additional signals	16.67	11.33	9.1	8.22	7.53	8.44	8.67	8.16	6.96	6.21

	Data	Total Background	V+Jets	Diboson	Top	QCD
L=5.4 fb^{-1}	67627	67627	52140.9	1584.5	2429.6	11471.9

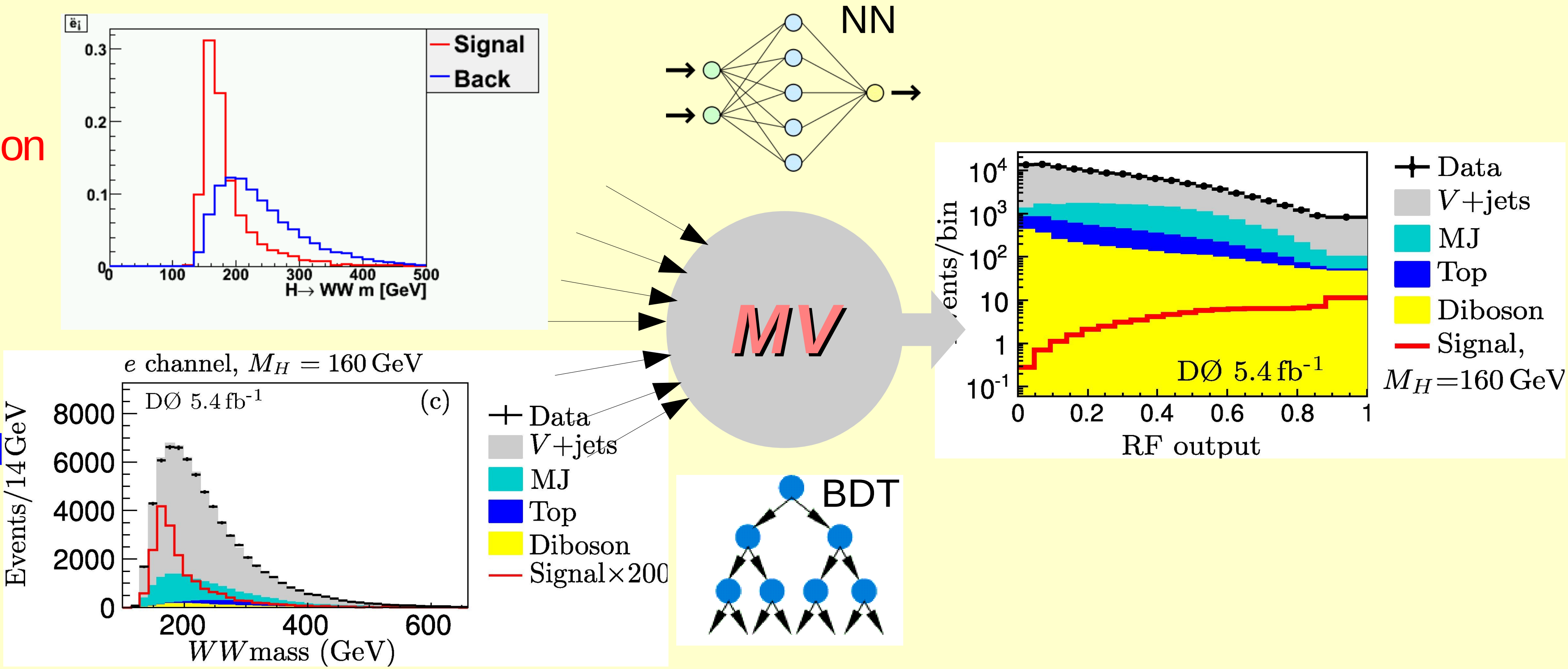
- Include everything that has lepton, missing energy and at least two jets
  - Added almost 20% @m_H=165 GeV
  - Lower masses dominated by the WH signal
- Expected 53.67 signal events for the Higgs mass of 165 GeV, and 67627 background events - s:b~1:1300
- But
  - Uncertainties on the background are larger than expected signal
  - Simple counting experiment will not work.

Multivariate techniques

- Multivariate techniques are more powerful than simple cut method
  - They exploit correlations between different observables
- One output, usually between 0 (background like) and 1 (signal like events)

Good separation power

Well modeled

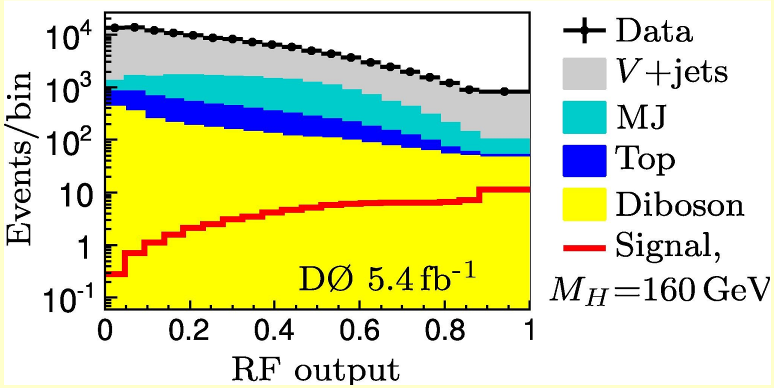


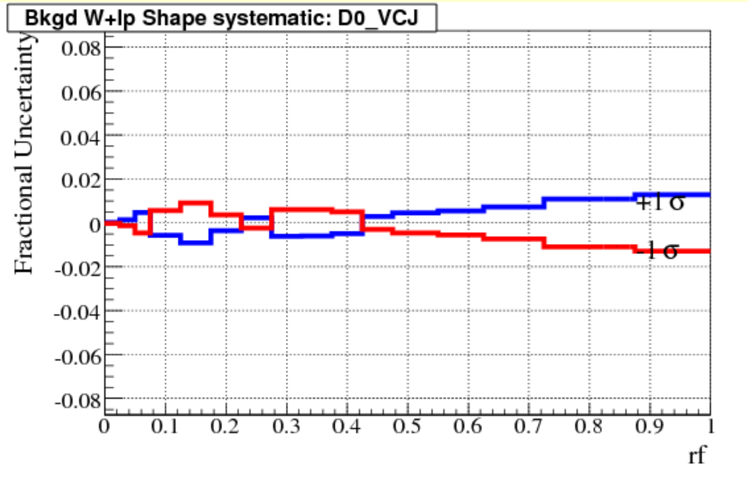
Systematics

- Uncertainties affect both the normalization (luminosity, cross section,...)

	Background	Signal
Luminosity	6.10%	6.10%
Cross section	3-10%	10.00%
QCD nomalization	20.00%	x
lepton ID	3.00%	3.00%

- and the differential distributions (Jet Energy Scale, ID and resolution, QCD shape, reweighting)

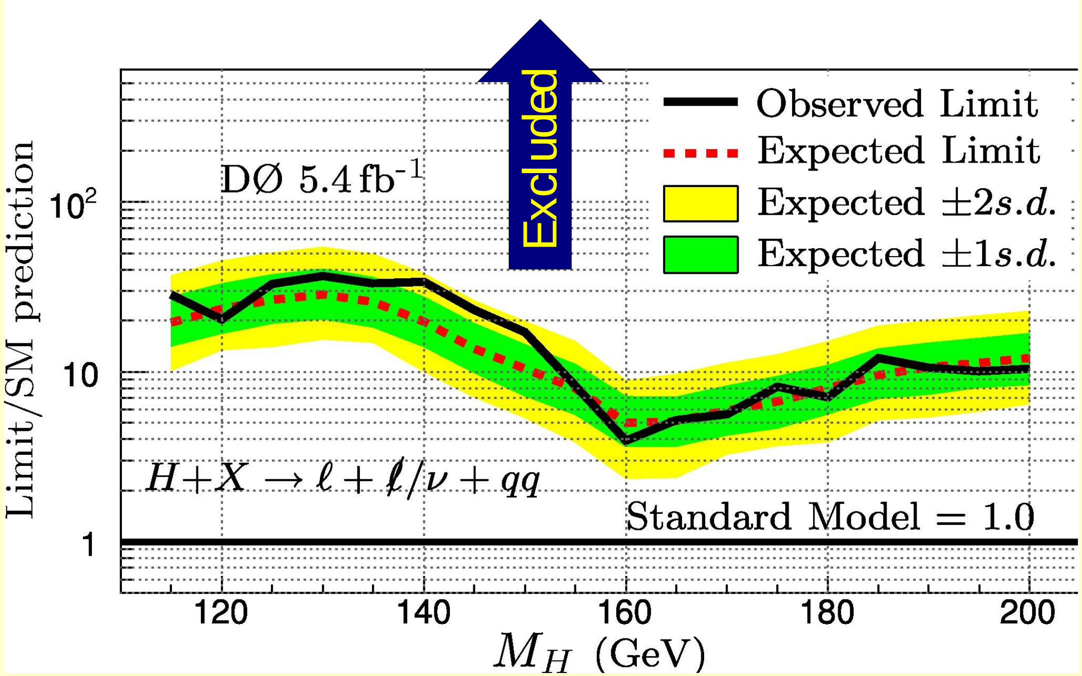




Limits on $H \to WW \to l\nu jj$

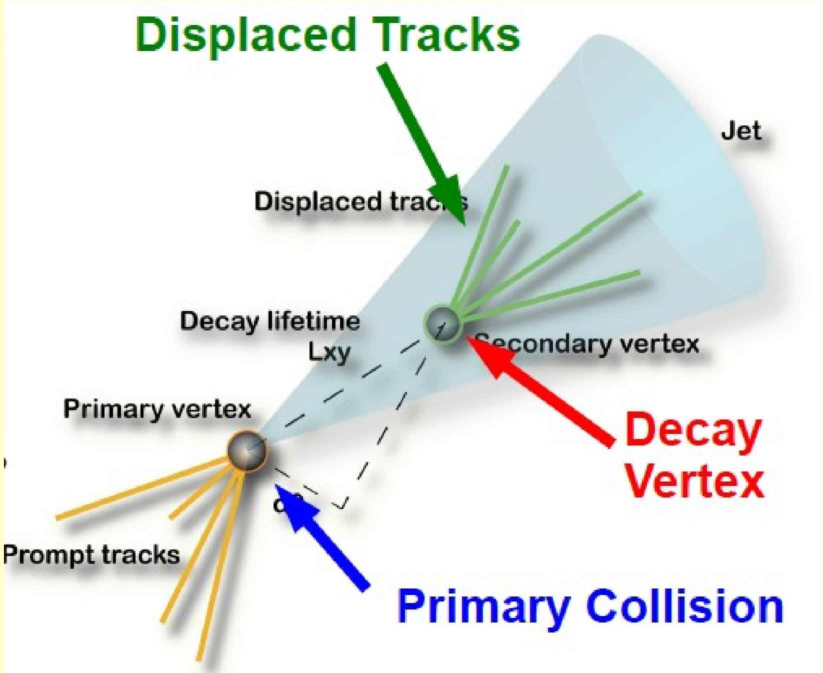
- When we don't observe any excess in data we set limits on production
- Use RF output distributions as discriminant to set upper limits
- Combine electron and muon final states
- The first result on the search for the Higgs boson in this final state

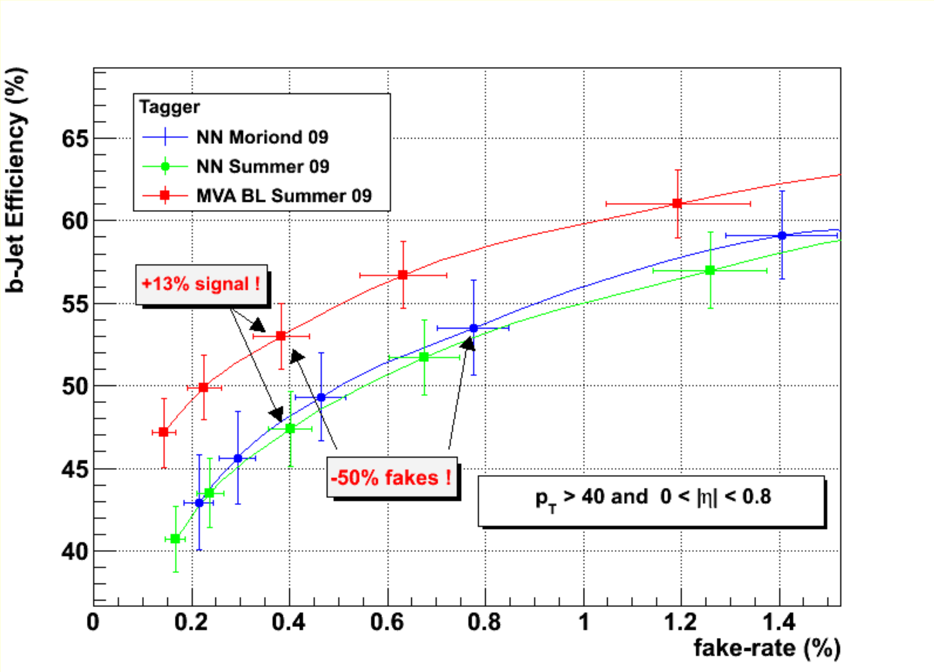
D0 (5.4 fb^{-1})	**Exp.**	**Obs**
M_H = 165 GeV	**5.09**	**4.01**

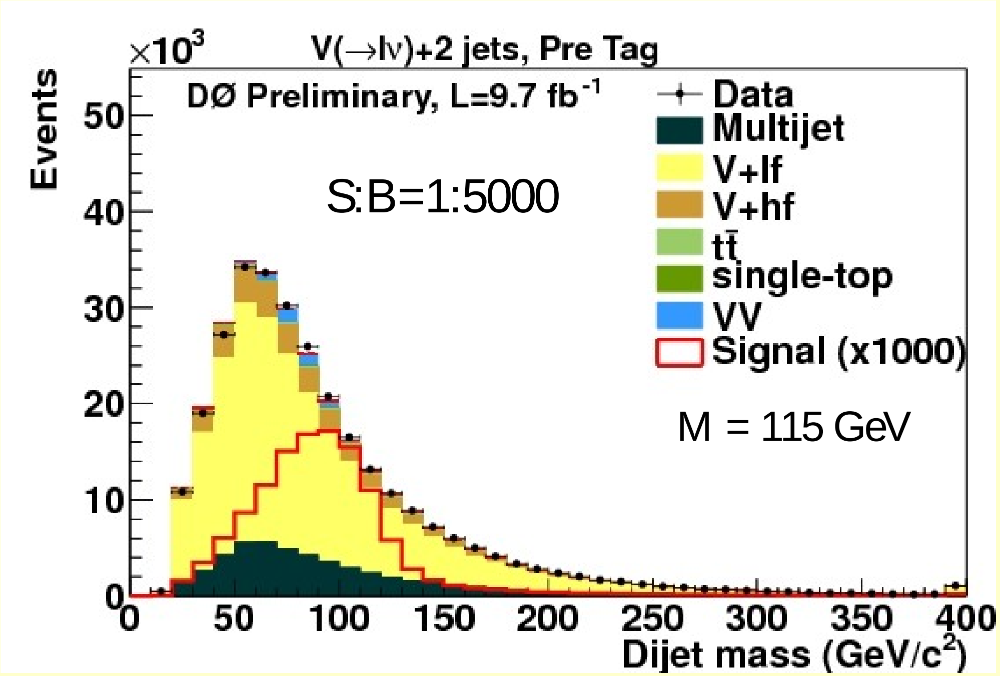


b-tagging

- Several b hadron properties can be exploited to tag the b-jets:
  - long B lifetime (1.57±0.01 ps)
  - high mass (~5.2 GeV/c2)
  - high charged decay multiplicity (4.97 ± 0.06) - more tracks
- Combined information used in multivariate tagger







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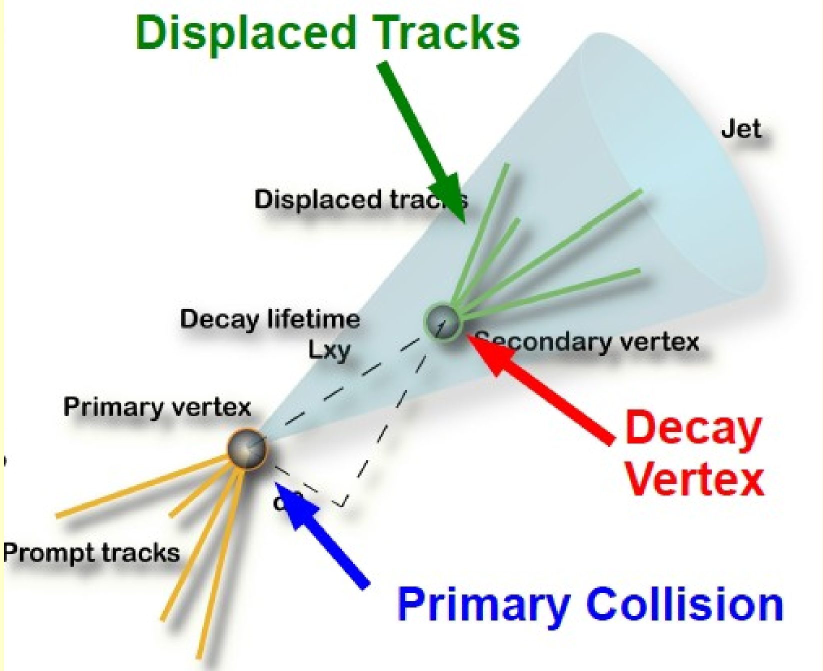

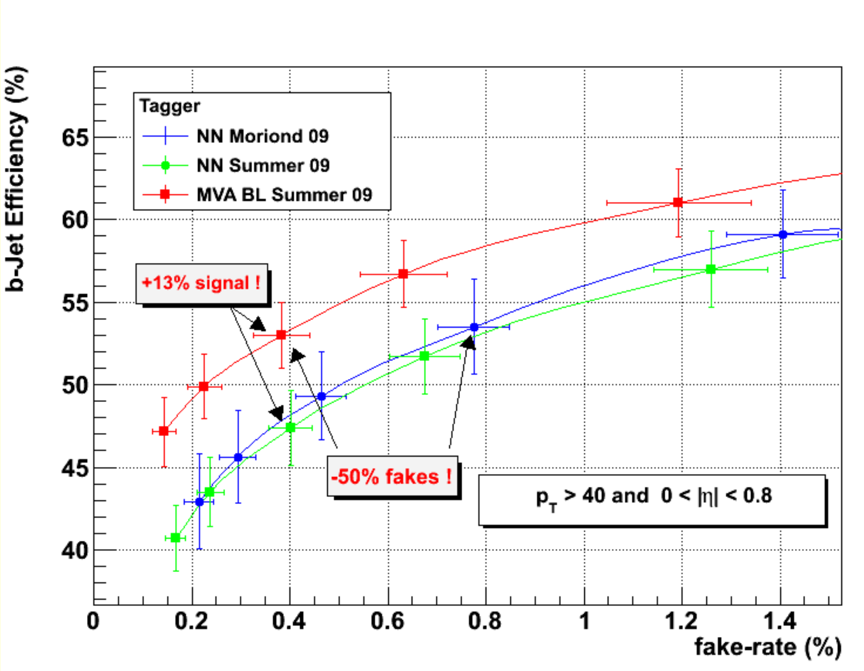

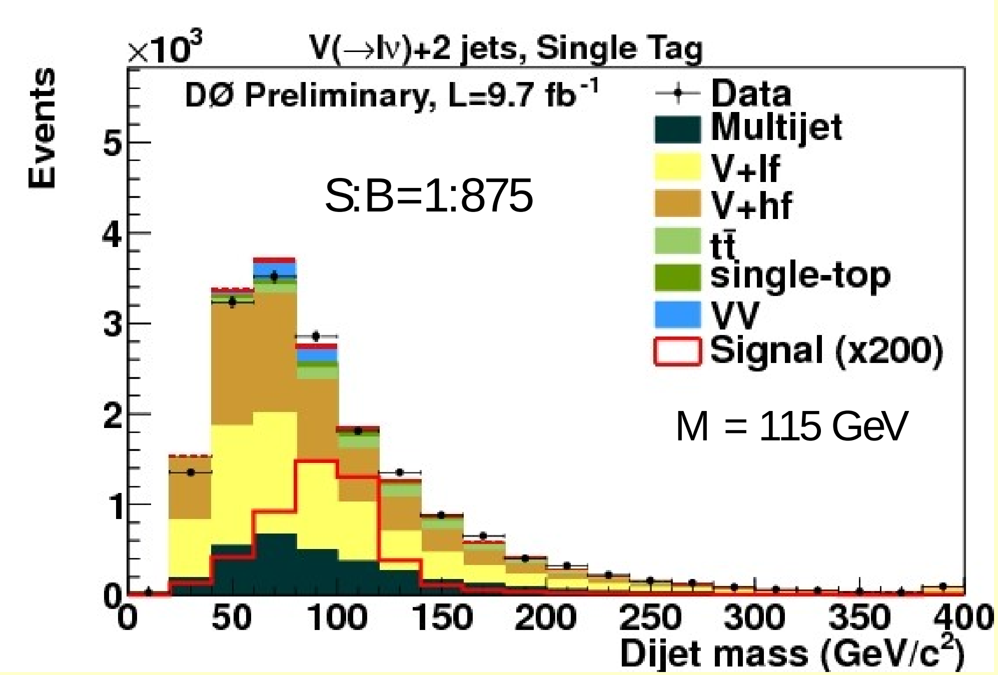

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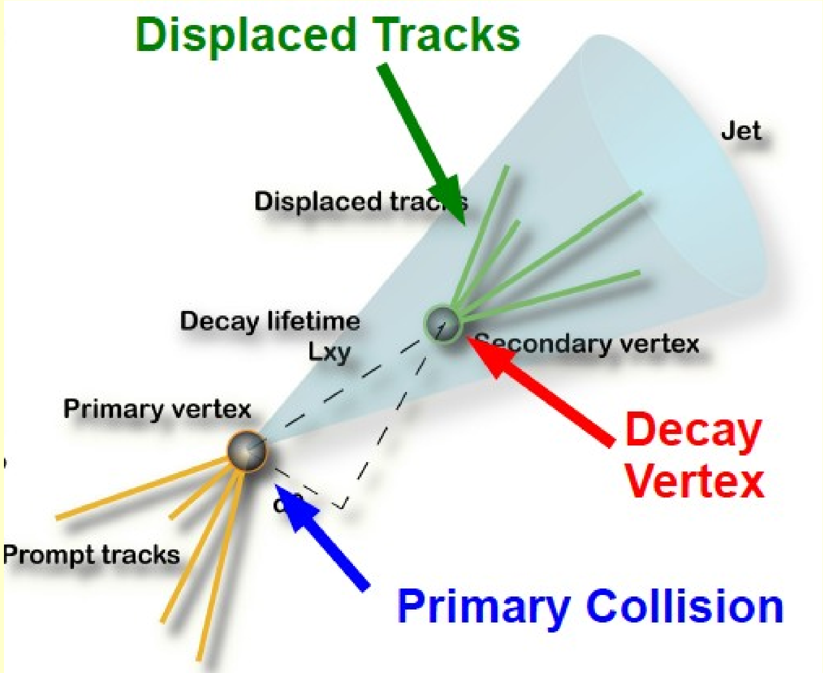
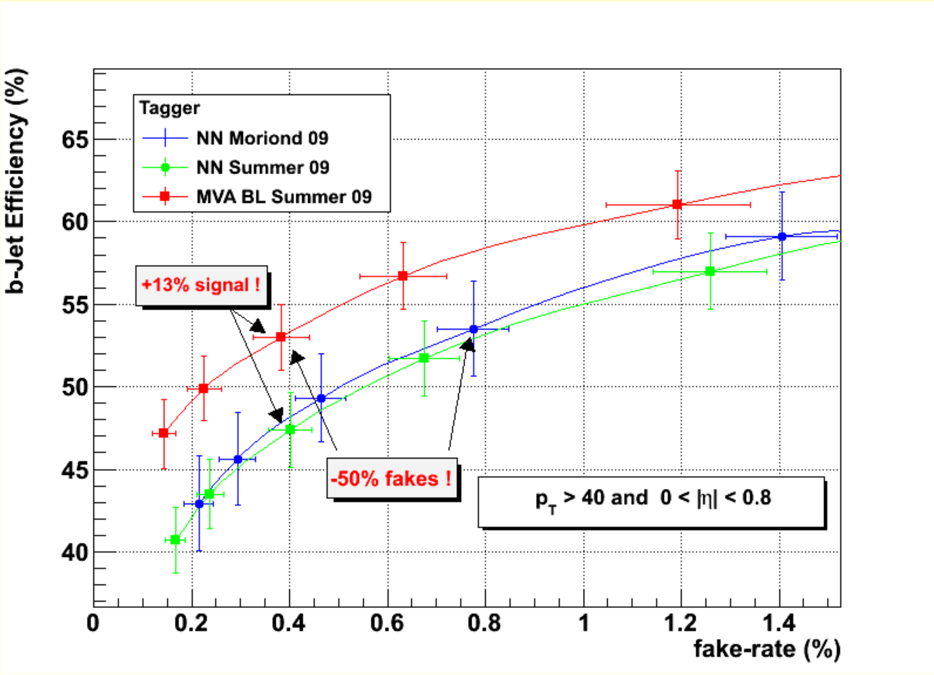
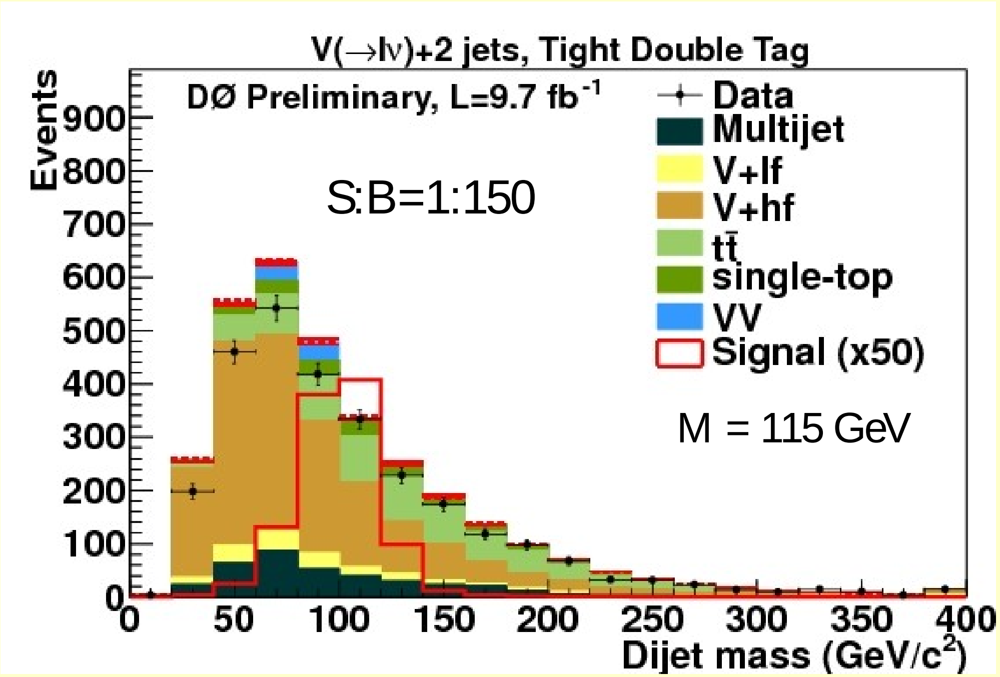


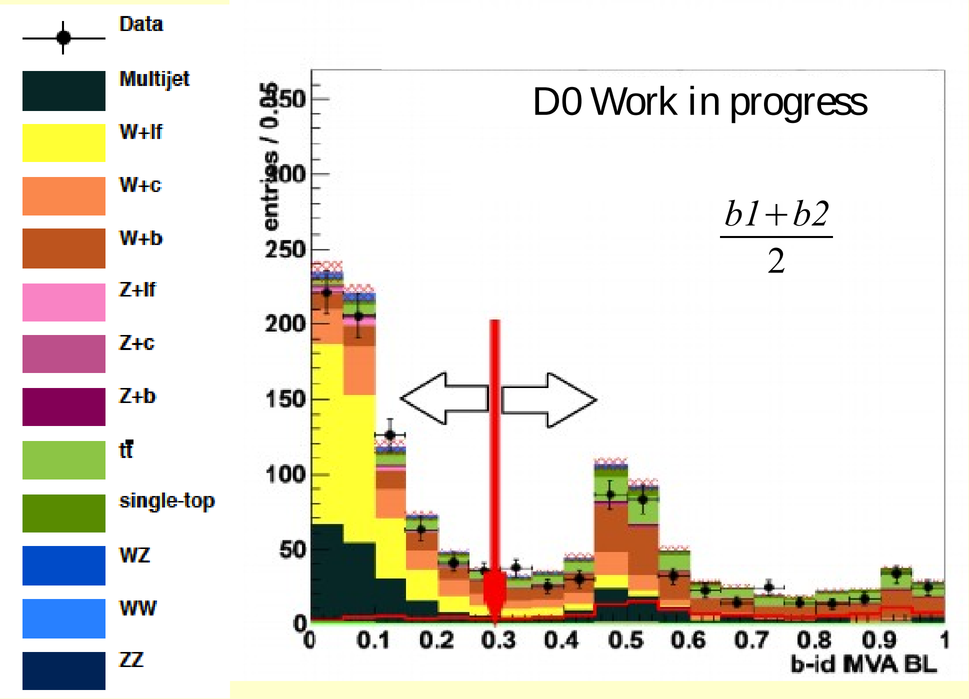




Further optimization with b-tagging

- Multivariate tagger allows for different configurations
  => Increase sensitivity of the search

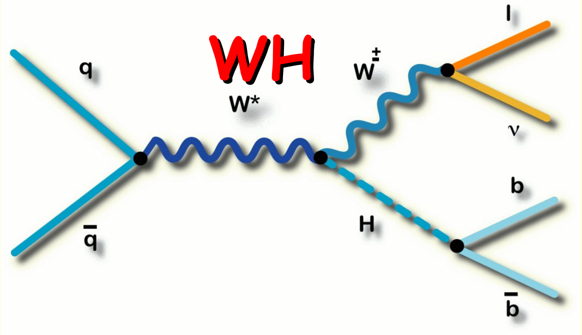
	2 jets excl.	3 jets excl.	4 jets incl.
0 tag	H → WW → lvjj		WH → WWW vbf H → WW
1 loose tag			
1 tight tag	WH → lvbb		ttH
2 loose tags			
2 tight tags			



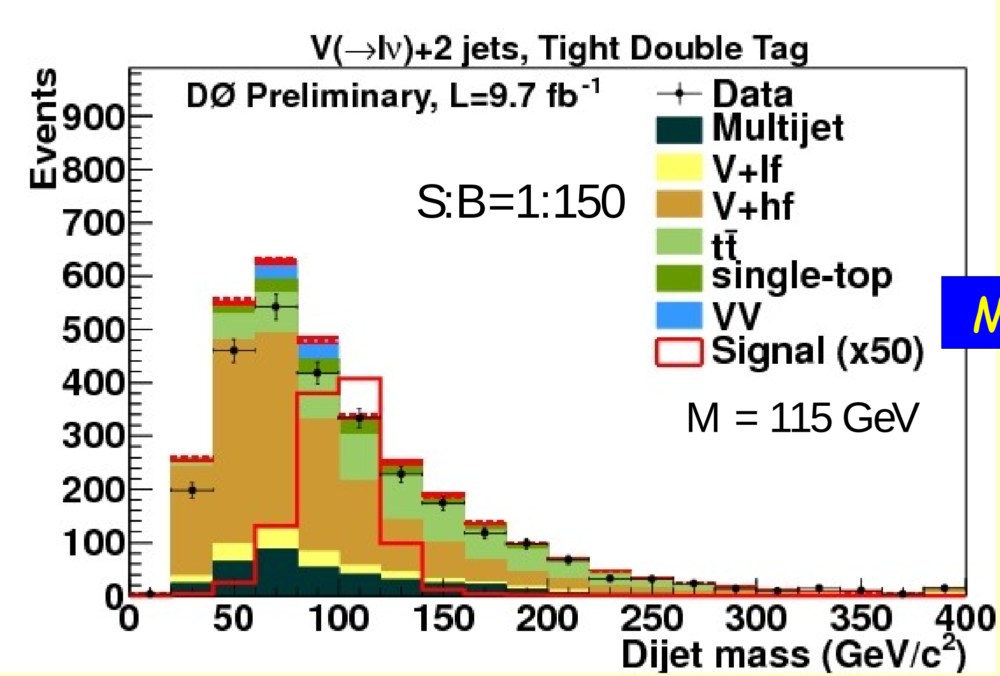
— WH
— H → WW

2 jets excl. Tag	~ 4 fb^{-1} Data	H → WW	125 WH	WWW
pretag	42102	2.9	5.6	2.2
0 tag	31656	2.2	0.8	1.5
1 loose tag	6711	0.5	0.6	0.4
1 tight tag	2724	0.2	1.8	0.2
2 loose tags	597	0.0	0.5	0.1
2 tight tags	414	0.0	2.0	0.0

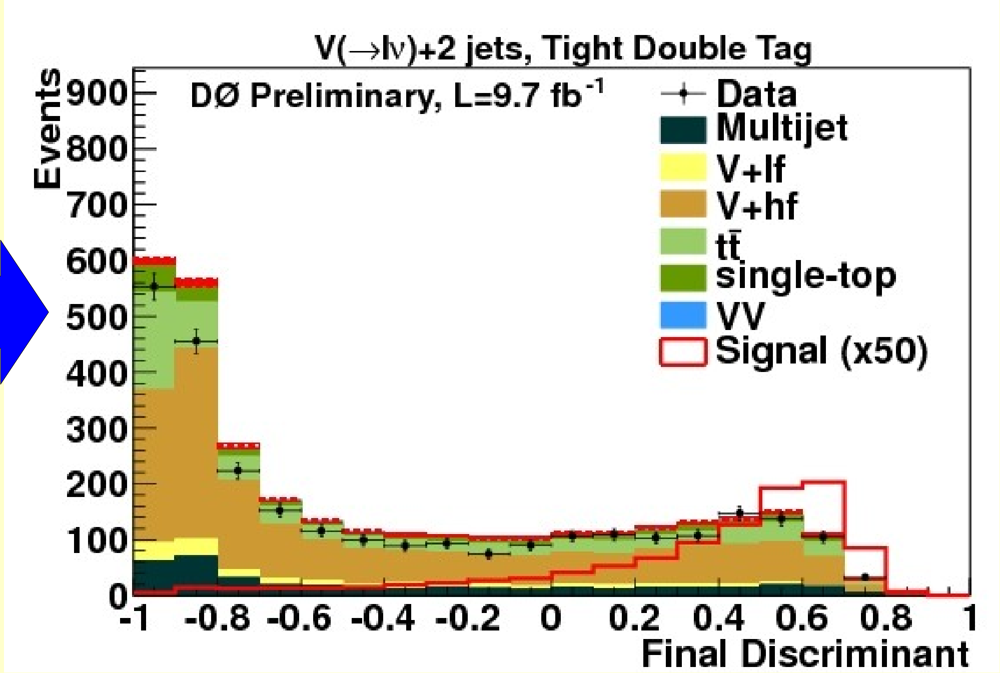
WH → lνbb result



- S/B in the most sensitive channel: O(1/100)
- Signal extraction relies on multivariate techniques

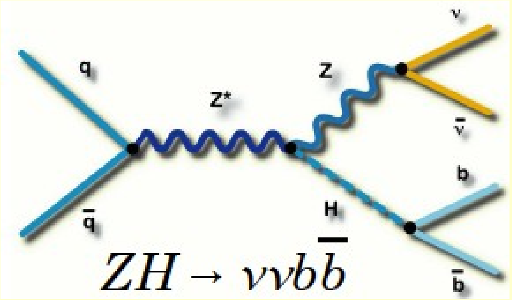


MVA



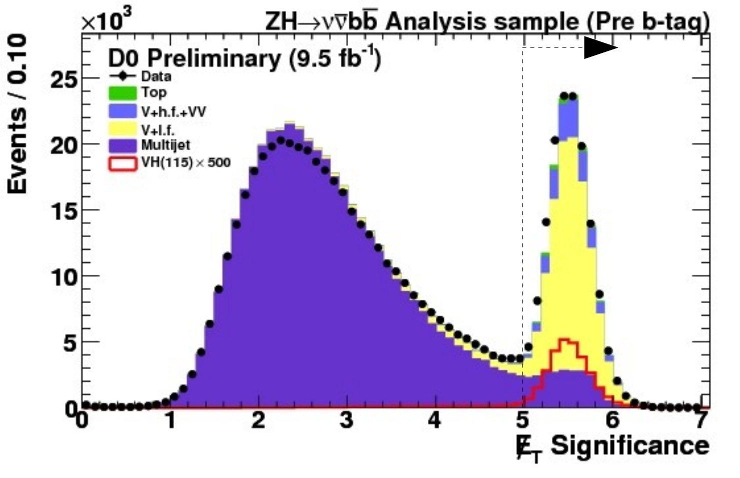
DØ (9.7 fb^{-1})	**Exp.**	**Obs**
M_H = 115 GeV	**3.15**	**3.96**
M_H = 125 GeV	**4.81**	**6.25**

Low Higgs mass -VH→$\not\!\!E_T$bb

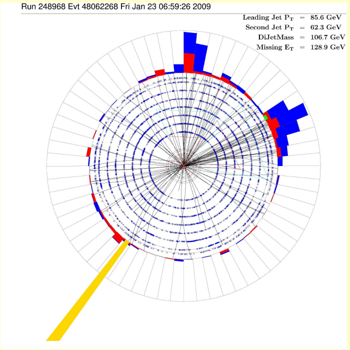


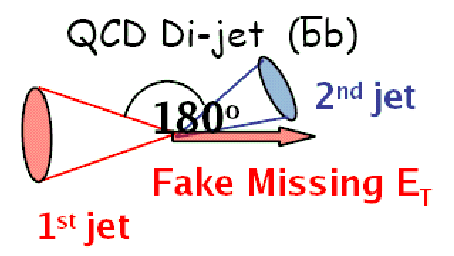
$ZH \to \nu\nu b\bar{b}$

Remove events with low $\not\!\!E_T$ significance ($\approx \not\!\!E_T/\sigma_{\not E_T}$)



- Excellent b-tagging, trigger modeling and measurement of the missing energy
- Multijet mostly from the mismeasurement of jets

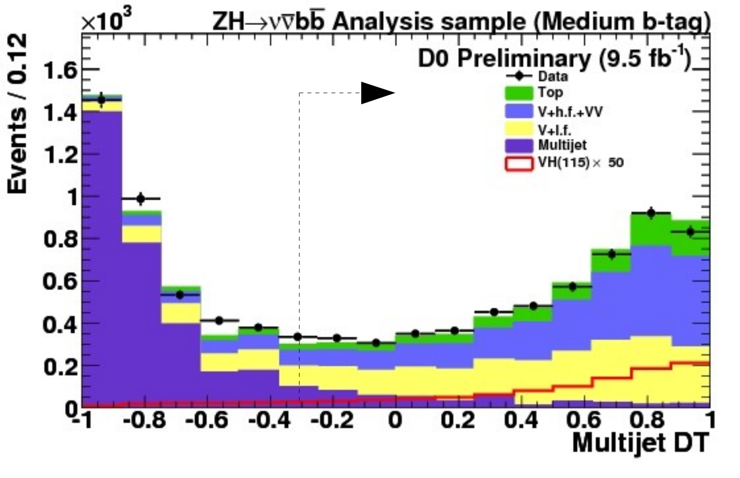



QCD Di-jet ($\bar{b}$b)

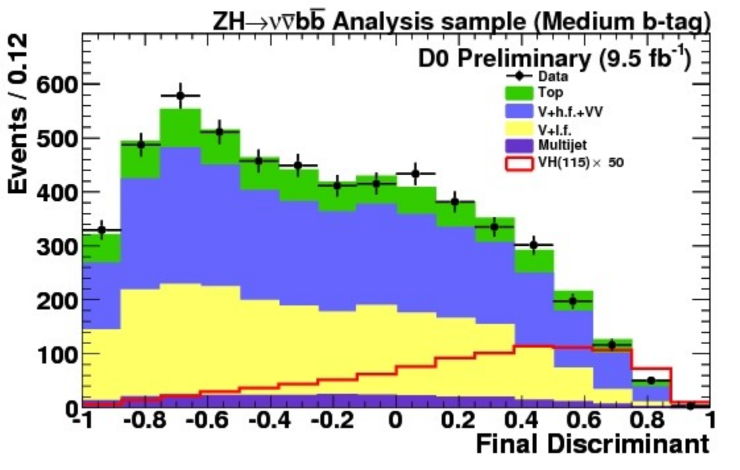
Fake Missing E_T

DØ (9.5 fb^{-1})	Exp	Obs
M_H = 115 GeV	3.0	2.5
M_H = 125 GeV	4.3	3.8

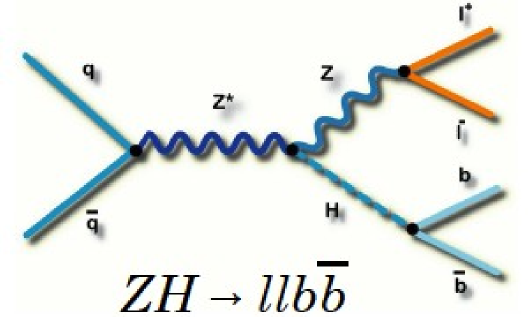
Dedicated MVA against multijet events + medium b-tag



Final MVA

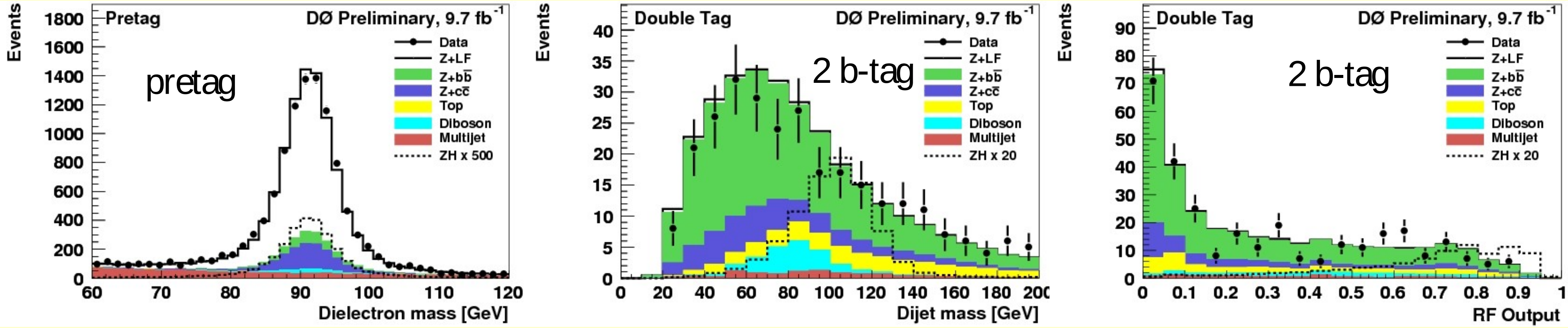


Low Higgs mass - ZH→llbb



- Select events with two leptons consistent with Z boson, and 2 or 3 jets
  - Excellent modeling of Z+jets is crucial
- To gain maximum sensitivity several lepton ID criteria are used
- Low missing E_T allows for a fit to improve dijet mass resolution

DØ (9.7 fb^{-1})	Exp	Obs
M_H = 115 GeV	4.2	3.7
M_H = 125 GeV	5.9	6.9

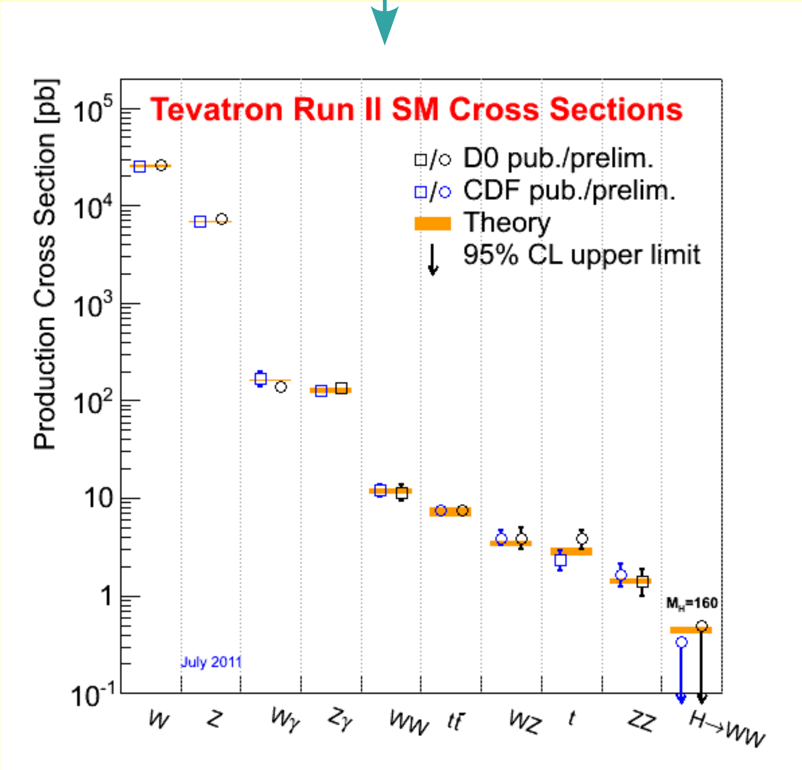


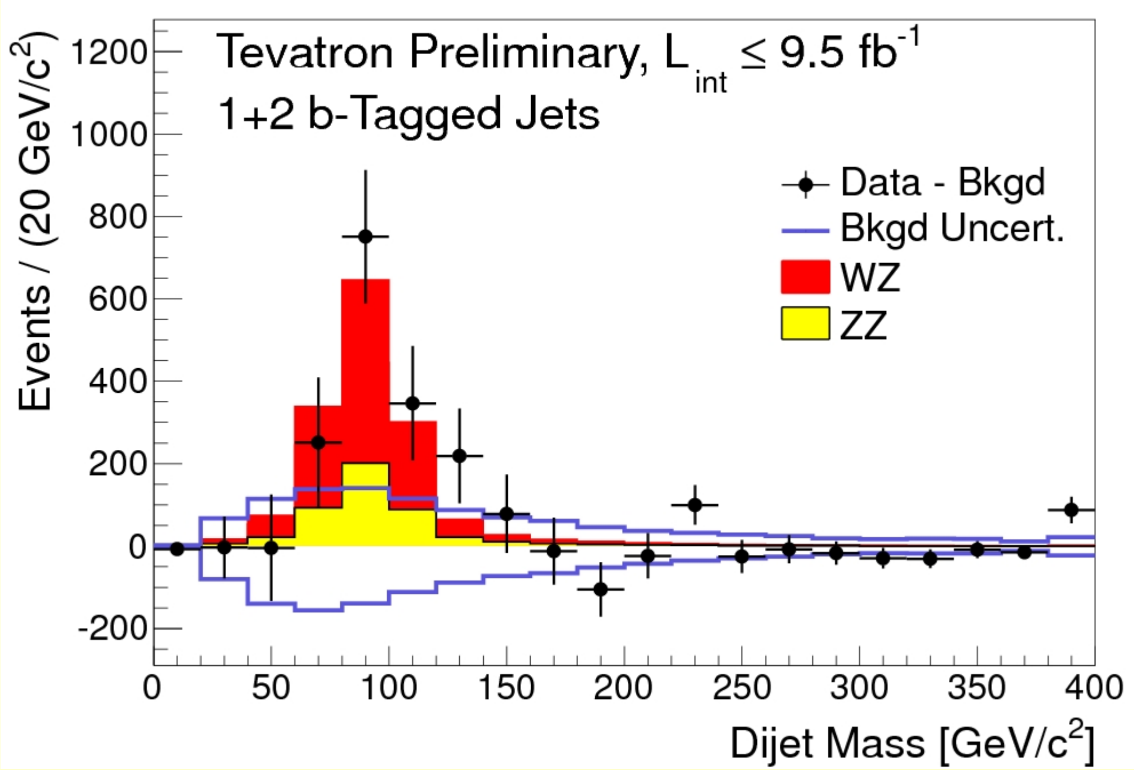
Validation of the search

- Tevatron has measured many SM processes
- Some of them with very low cross sections

- The latest is the W/Z+Z → bb
  - ~4-5 higher cross section than the Higgs signal with m_H = 115 GeV
  - Exactly the same analysis

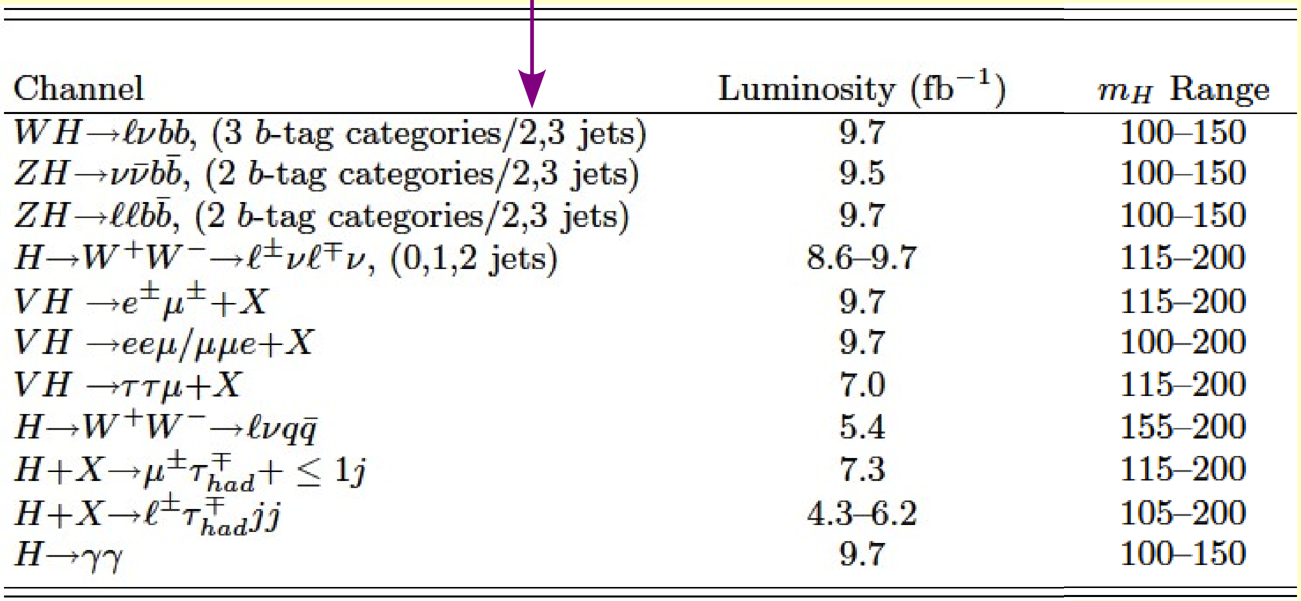
$$W/Z+Z \rightarrow bb : \sigma = (1.01 \pm 0.21) \times \sigma_{SM}$$



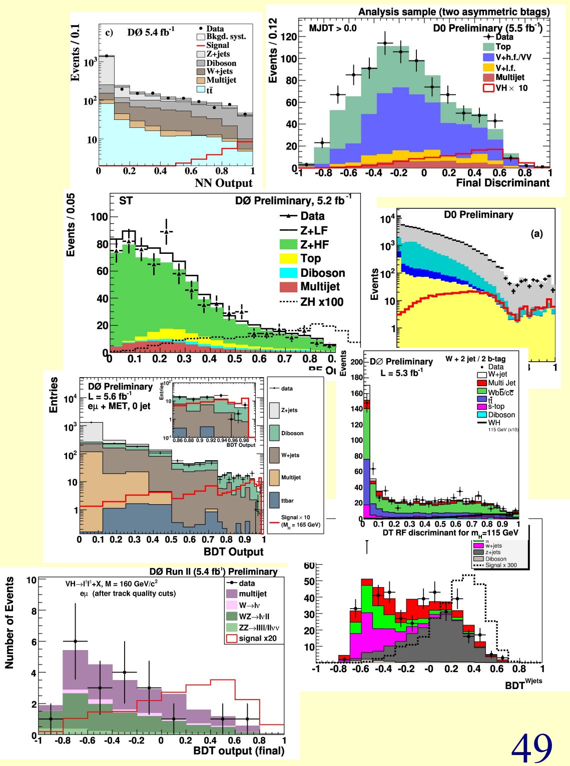


Combining channels

- Our goal is to understand the theory of the SM Higgs boson
  - The answer is either "The SM Higgs is there" or "It's not there"
- We test our data for compatibility with one of two hypotheses:
  - SM+Higgs or SM-Only
- Combine many channels: DØ + CDF

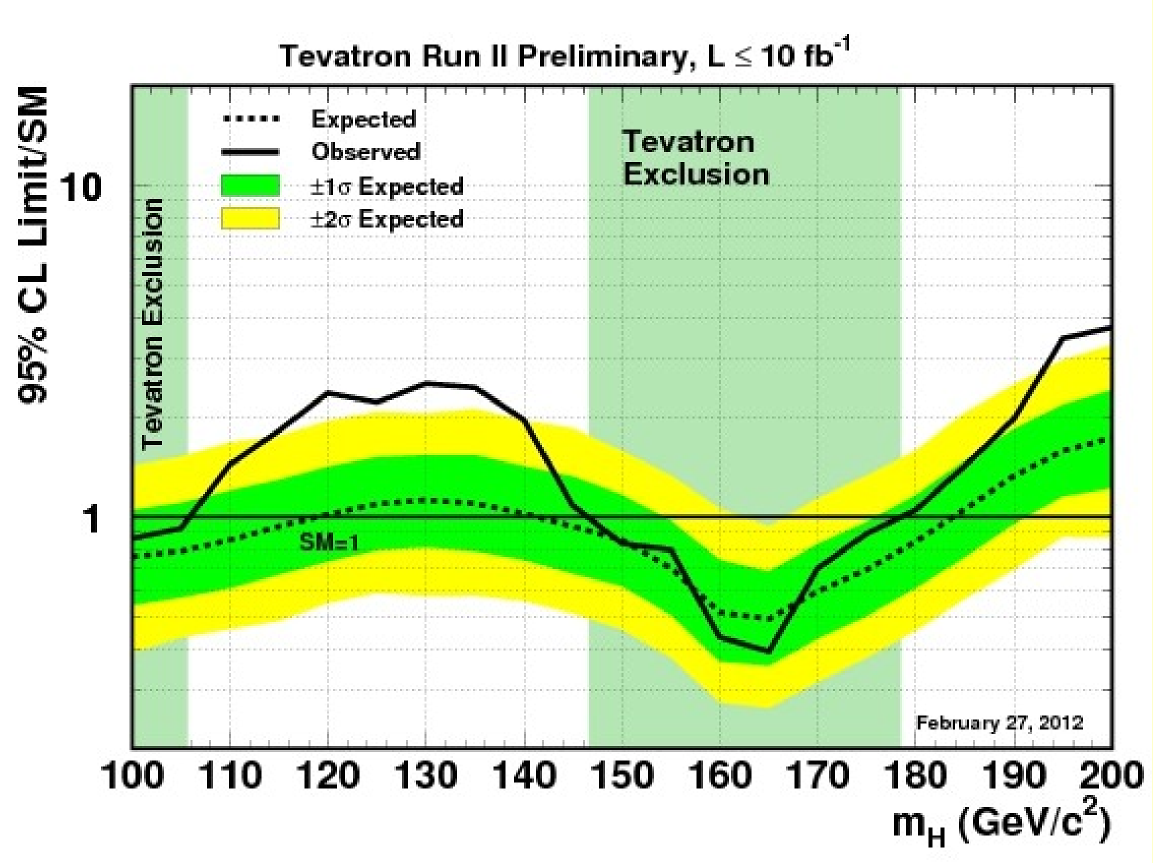


Channel	Luminosity (fb^{-1})	m_H Range
$WH \rightarrow \ell\nu b\bar{b}$, (3 b-tag categories/2,3 jets)	9.7	100–150
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$, (2 b-tag categories/2,3 jets)	9.5	100–150
$ZH \rightarrow \ell\ell b\bar{b}$, (2 b-tag categories/2,3 jets)	9.7	100–150
$H \rightarrow W^+W^- \rightarrow \ell^\pm\nu\ell^\mp\nu$, (0,1,2 jets)	8.6–9.7	115–200
$VH \rightarrow e^\pm\mu^\pm + X$	9.7	115–200
$VH \rightarrow ee\mu/\mu\mu e + X$	9.7	100–200
$VH \rightarrow \tau\tau\mu + X$	7.0	115–200
$H \rightarrow W^+W^- \rightarrow \ell\nu q\bar{q}$	5.4	155–200
$H + X \rightarrow \mu^\pm\tau^\mp_{had} + \leq 1j$	7.3	115–200
$H + X \rightarrow \ell^\pm\tau^\mp_{had}jj$	4.3–6.2	105–200
$H \rightarrow \gamma\gamma$	9.7	100–150



The new Tevatron limit

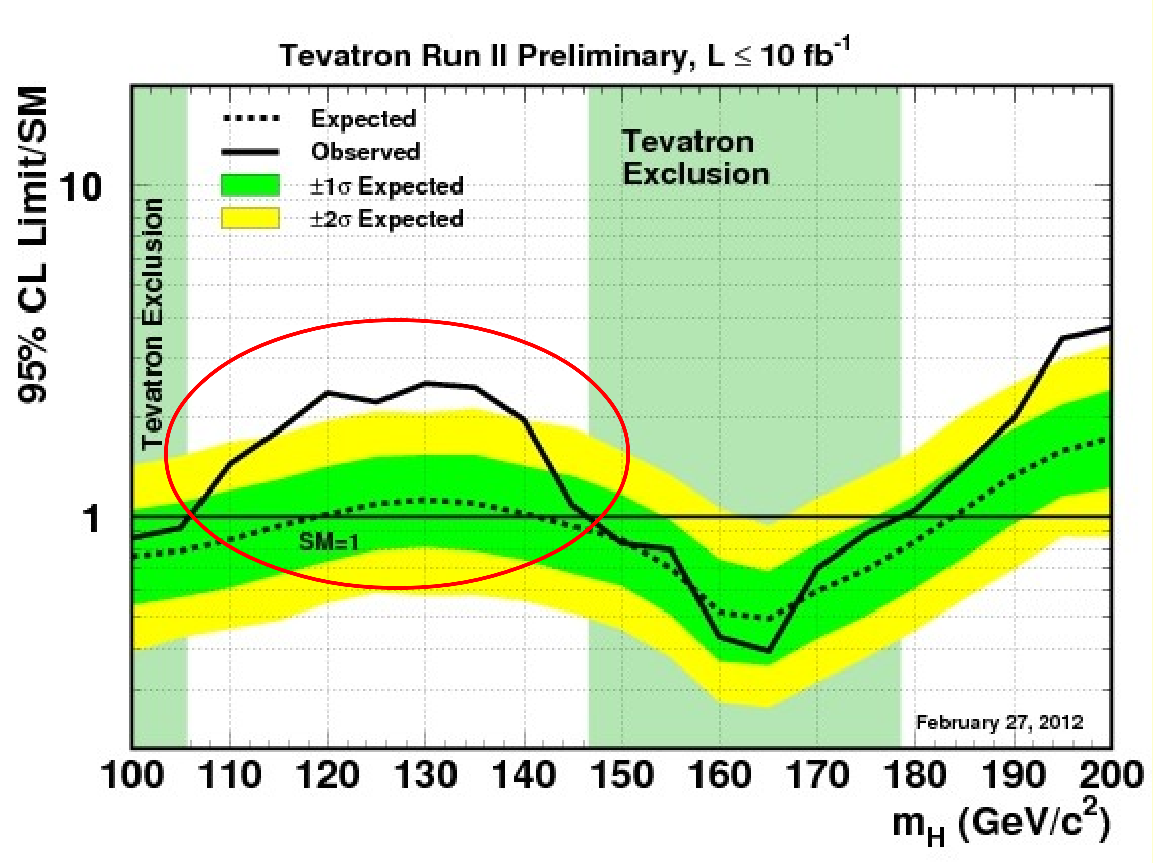
- The new Tevatron exclusion
  - Higgs mass is not between 147 and 179 GeV @95% CL (141-184 GeV expected)
  - In addition, region between 100 and 106 GeV is excluded (100-119 GeV expected)



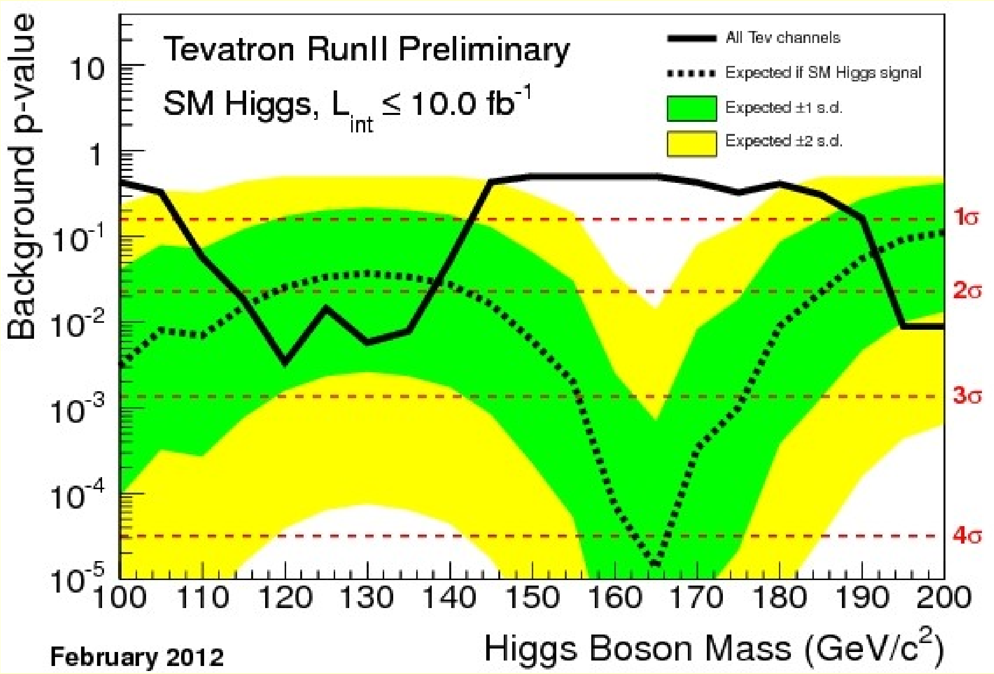
The new Tevatron result

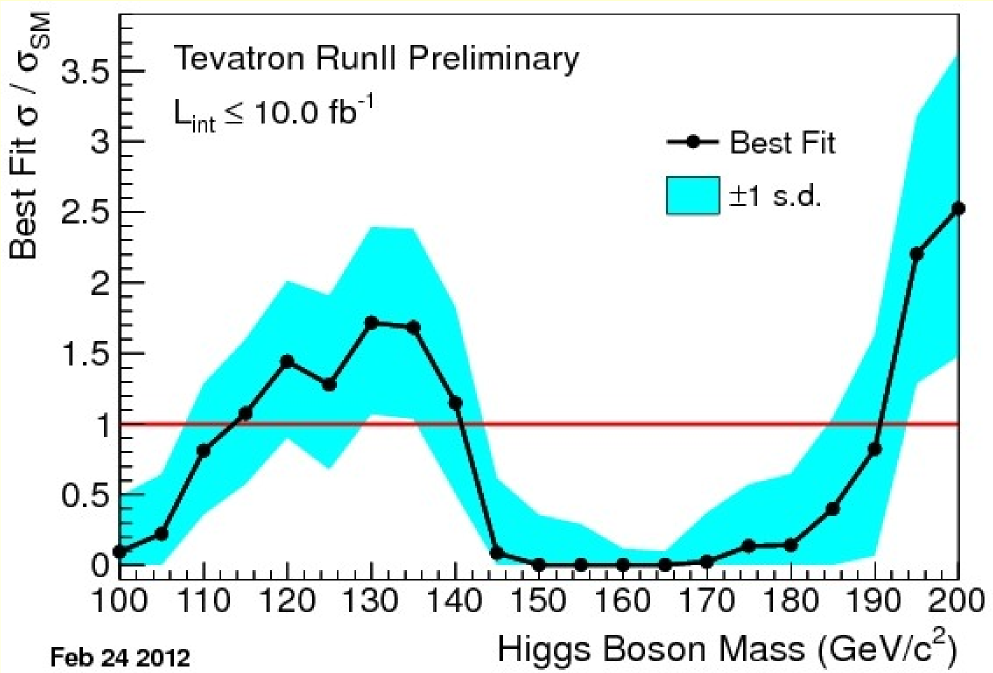
- Look at the low mass

TeV (≲10 fb^{-1})	Exp.	Obs
M_H = 120 GeV	1.01	2.36
M_H = 125 GeV	1.10	2.22
M_H = 130 GeV	1.12	2.52



Quantifying the excess

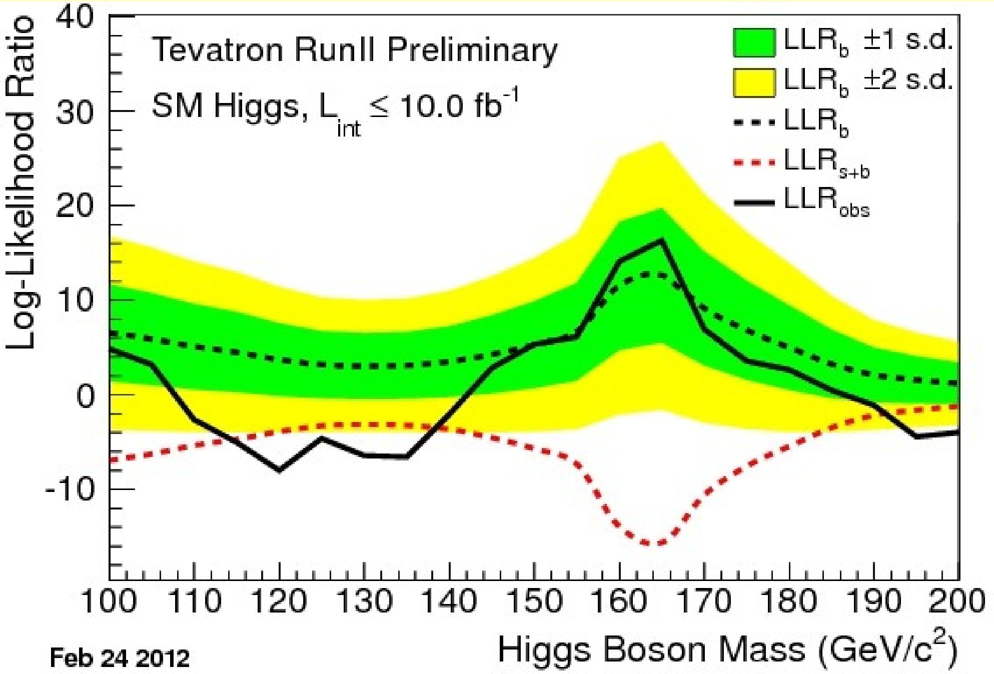




- Local p-value distribution for background only expectation.
  - Minimum local p value: 2.7 standard deviation
  - Global p value with Look Elsewhere Effect: 2.2 standard deviations
- Best fit for the signal, signal strength, consistent with SM within 1σ

How the signal would look like

Real data

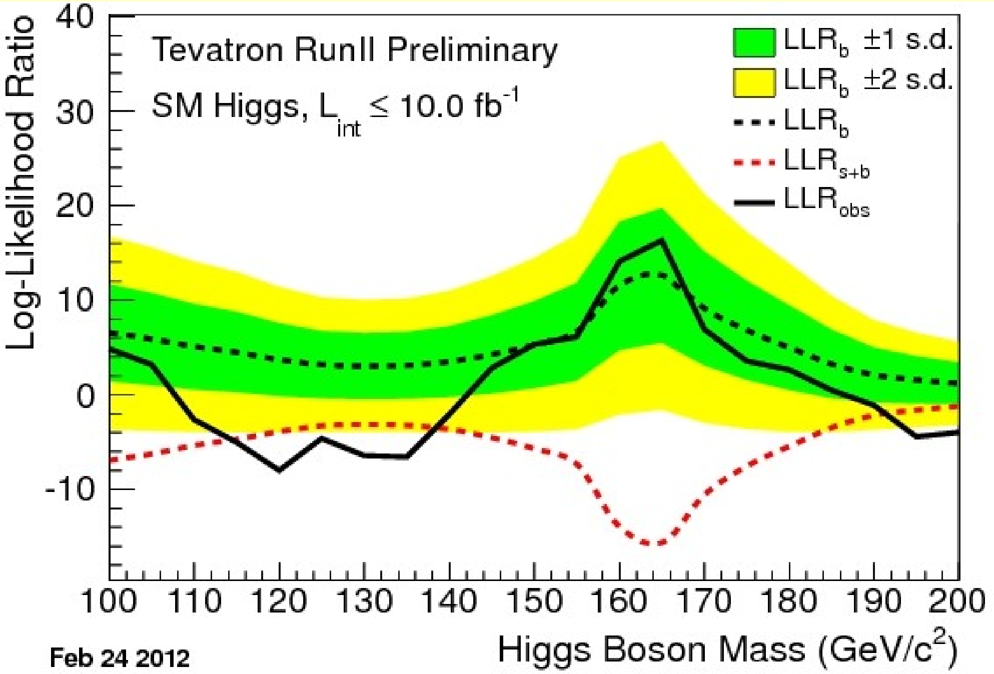


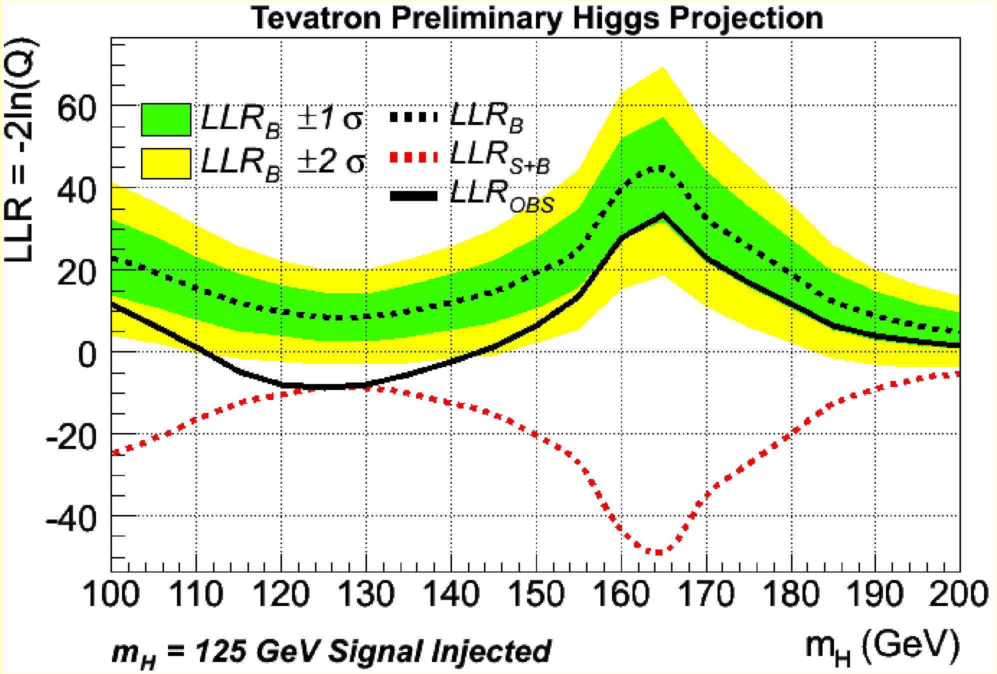
- If there is a signal, how would it look like?

How the signal would look like

Real data

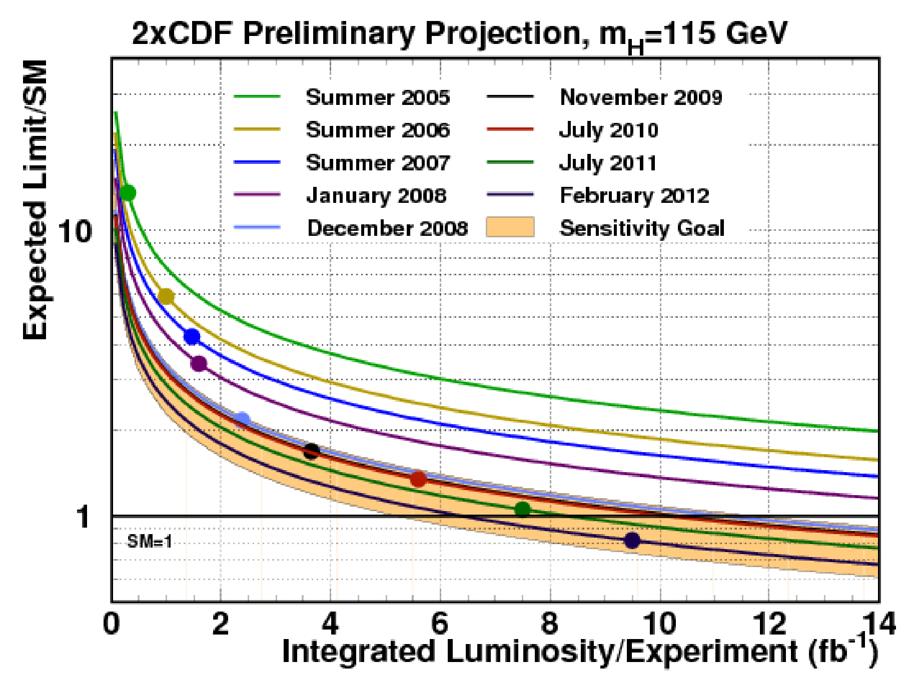
3σ signal injection





- If there is a signal, how would it look like?
- We injected a signal with m_H=125 GeV and scaled a luminosity so excess would be 3σ
  - Expect broad excess over a whole mass range

Tevatron progress

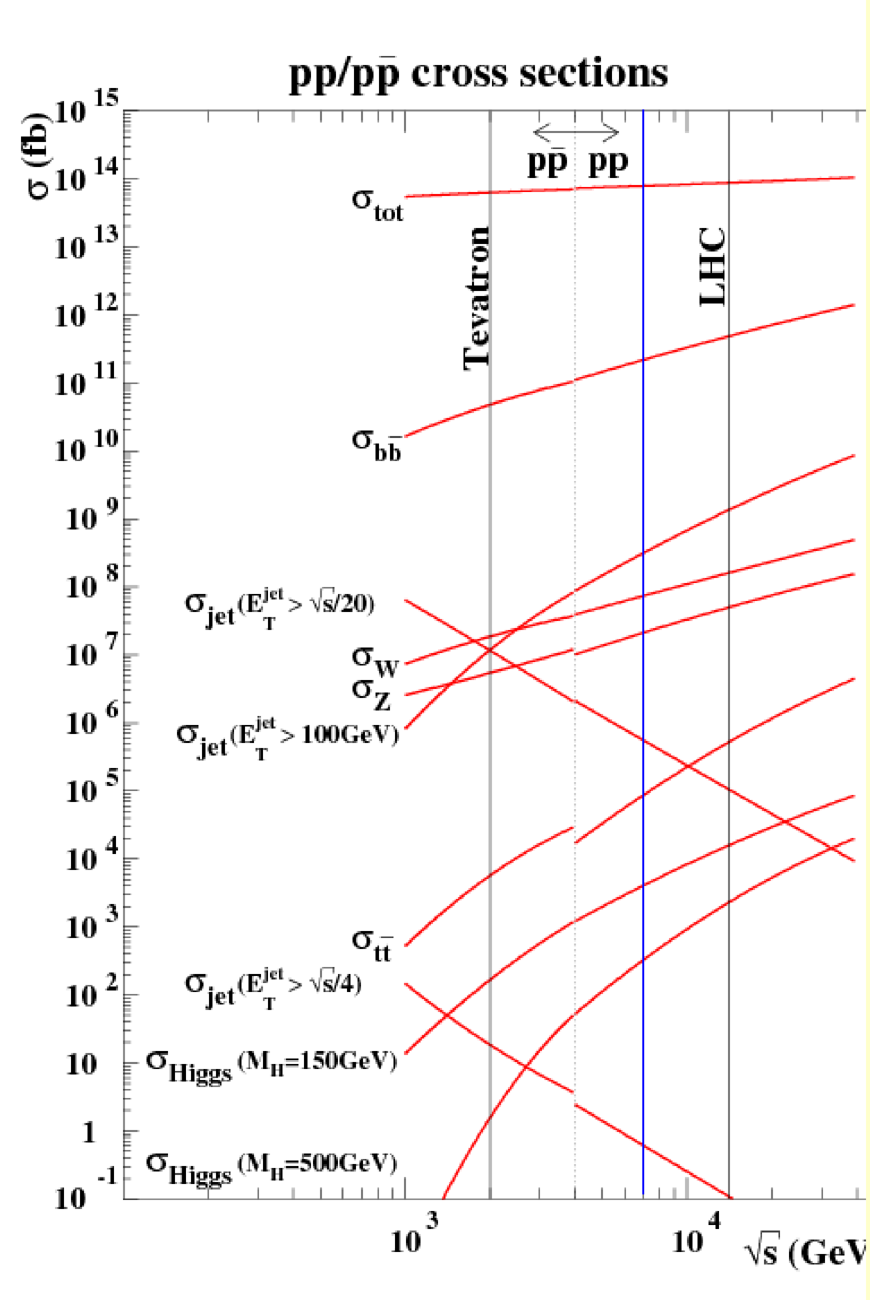


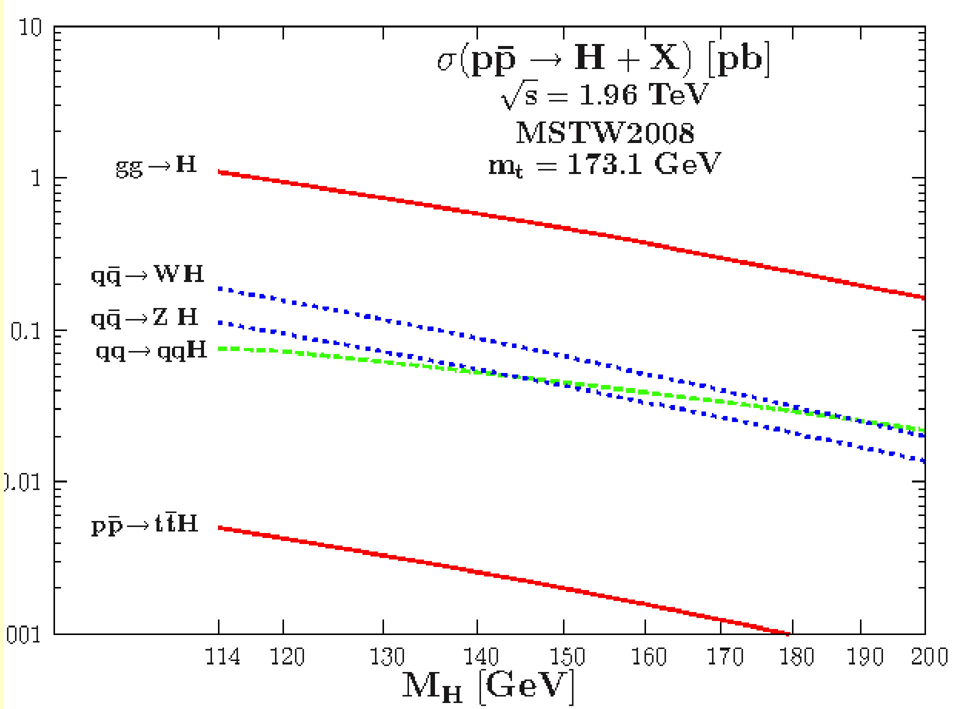
- Recent improvements include MVA for EM id and b-tagging, improved trigger, improved muon smearing, improved jet energy scale and resolution, improved dijet mass resolution, improved background modeling...

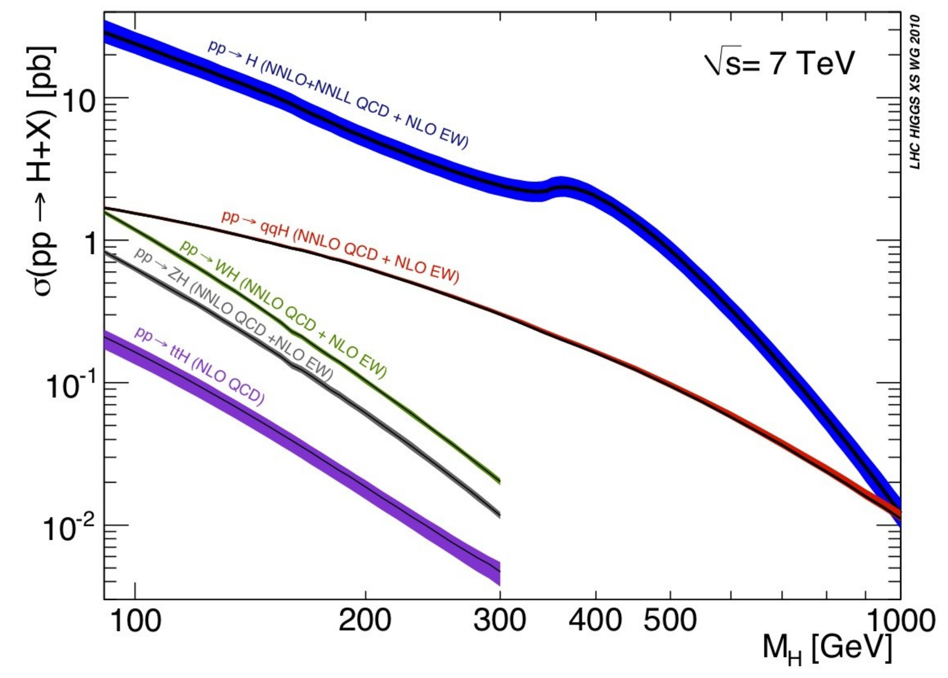
- Projected median expected upper limits on the SM Higgs boson cross section, scaling CDF performance to twice the luminosity.
- The solid lines are 1/√L projections, as functions of integrated luminosity per experiment.
- Improvements better than expected from 1/√L

Higgs future

Tevatron vs. LHC



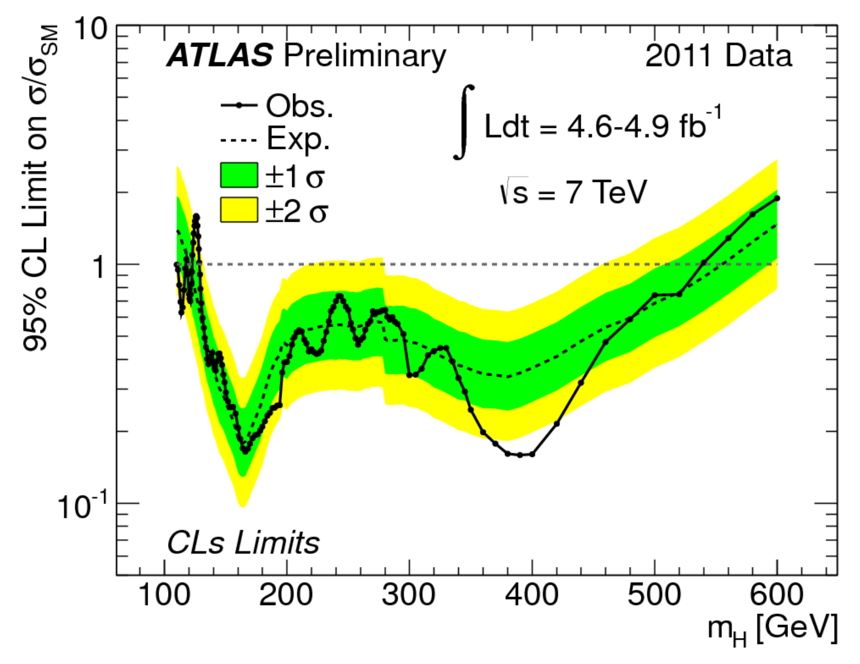


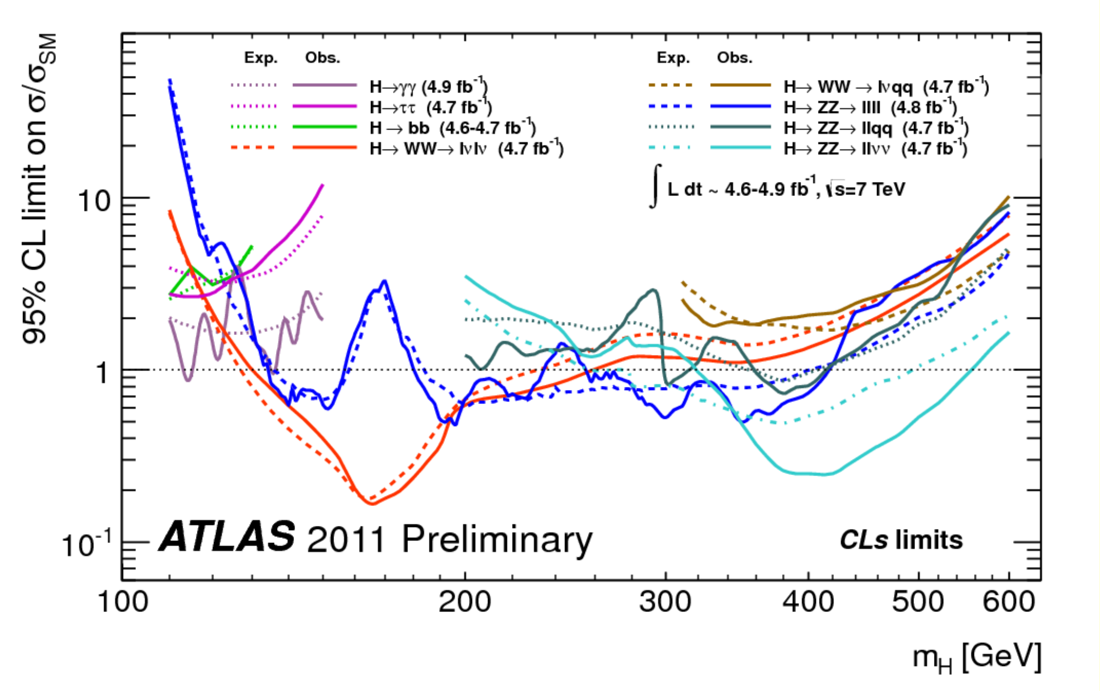


Higgs at LHC

- Some years ago I had in my talk the following sentence:
  "The SM Higgs boson will be discovered or excluded in the first year of physics running"
  - This was with expectation of 14 TeV run and with 10 fb^{-1} collected in that first year

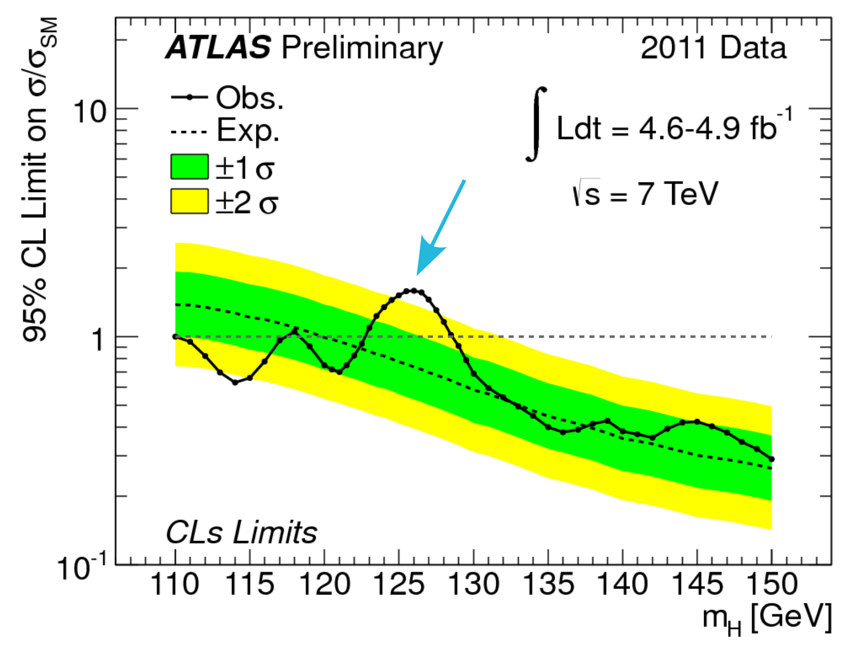
- Today, with 7 TeV and 5 fb^{-1} SM Higgs boson is almost excluded and almost found

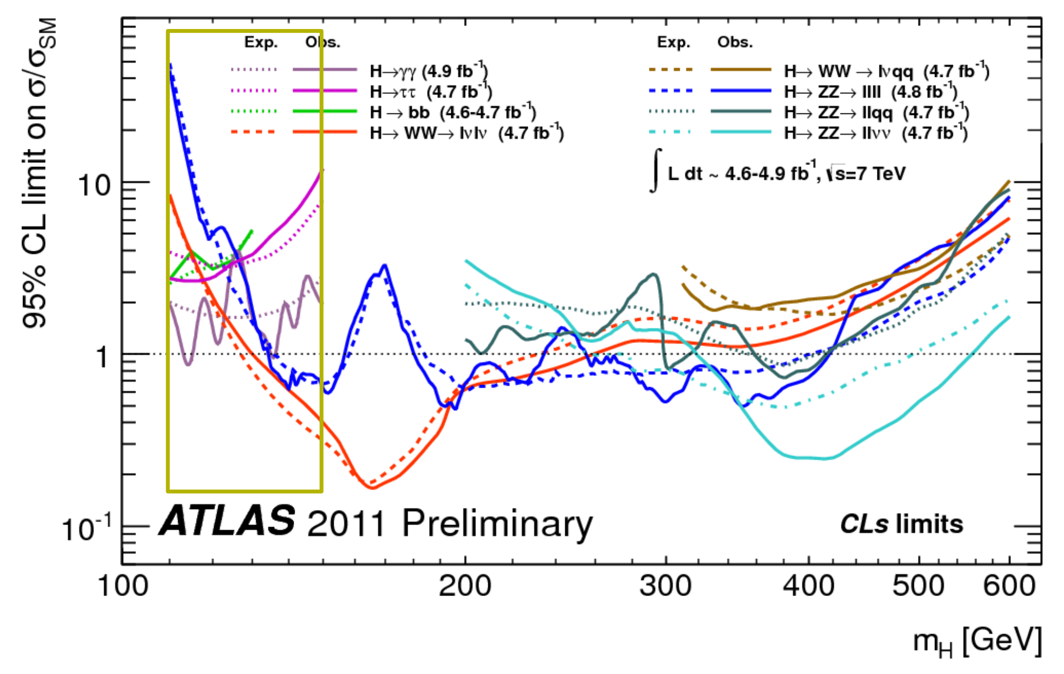




Higgs at LHC

- It is expected that Higgs boson will be seen this year
  - Both experiments see excess around 125 GeV from γγ (and ZZ) channel(s): ATLAS: 2.5σ (LEE: 0.5σ) and CMS: 3.1σ (LEE: 1.5σ)





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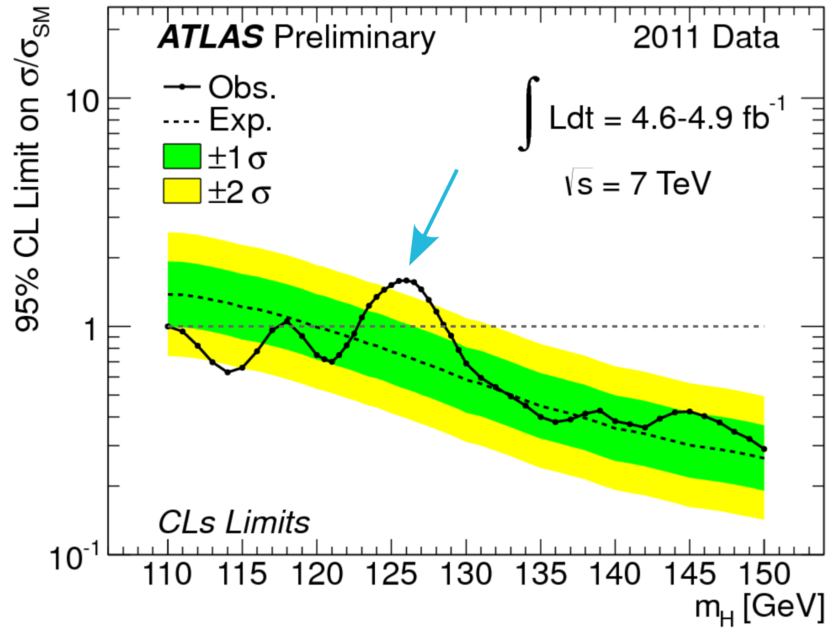

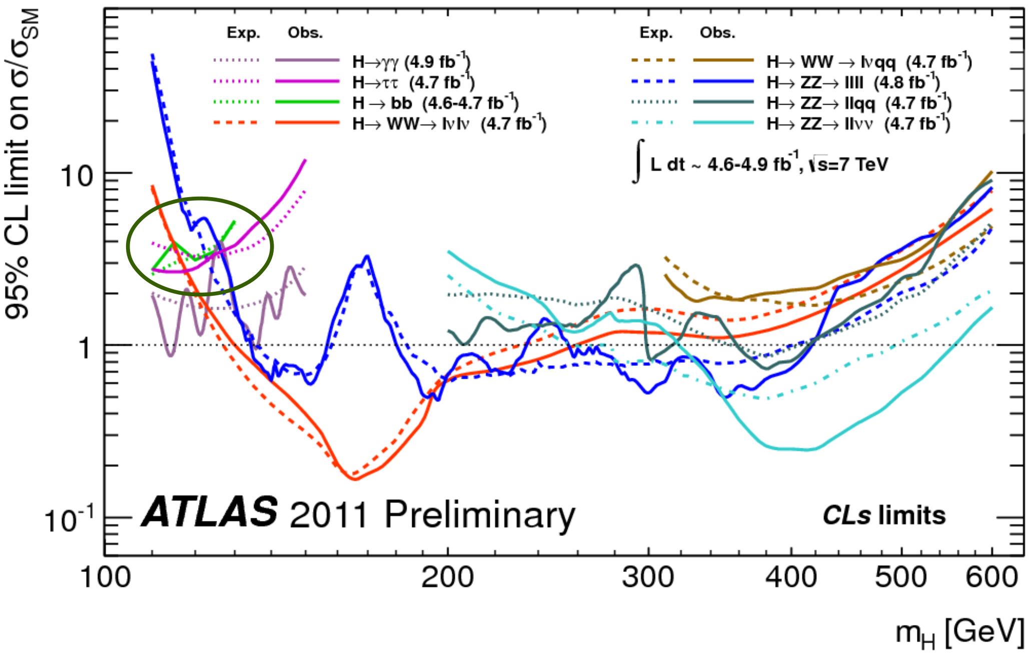

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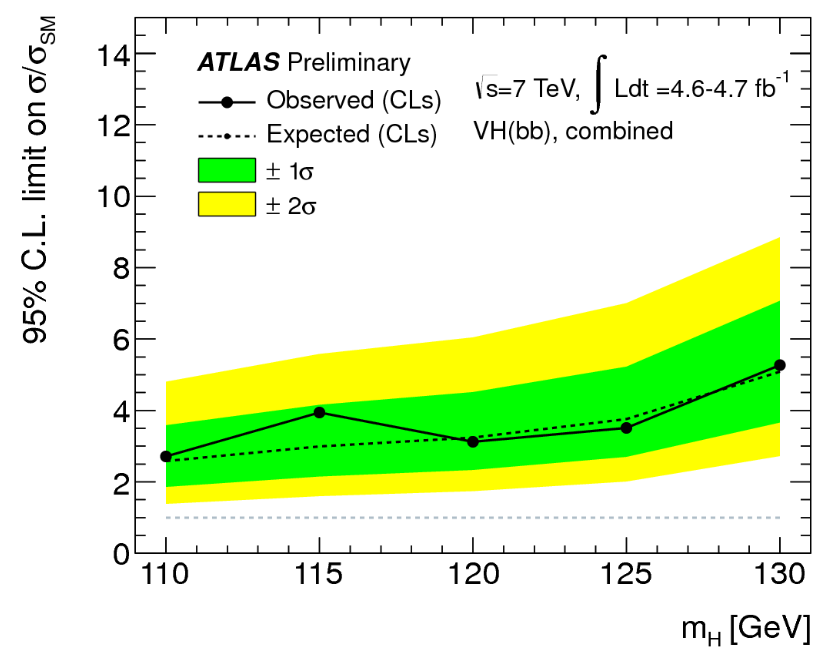
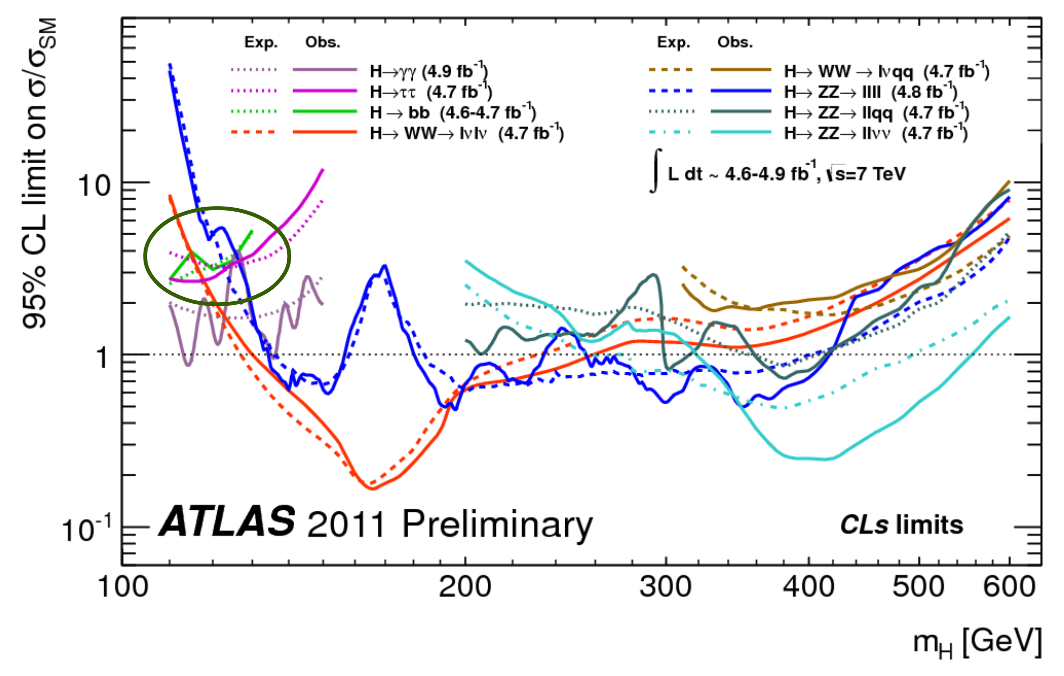
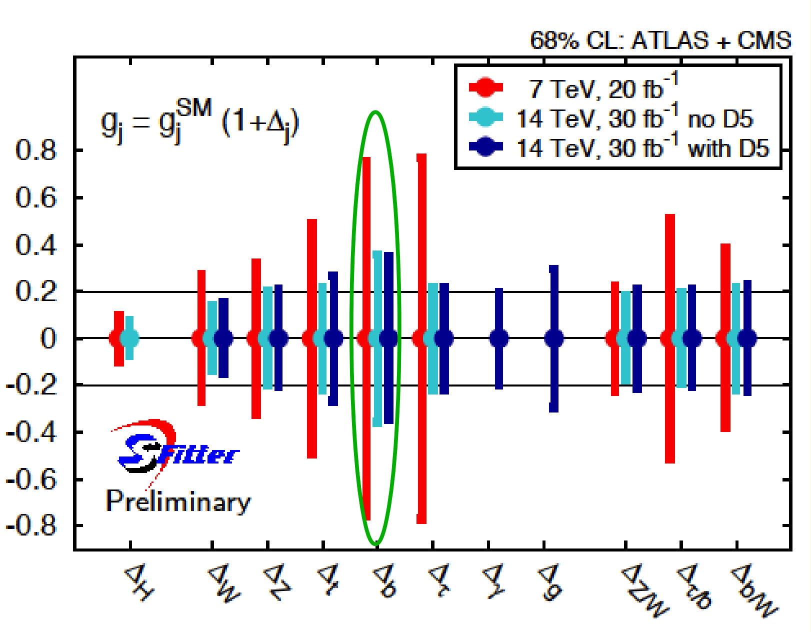




Finding the Higgs boson

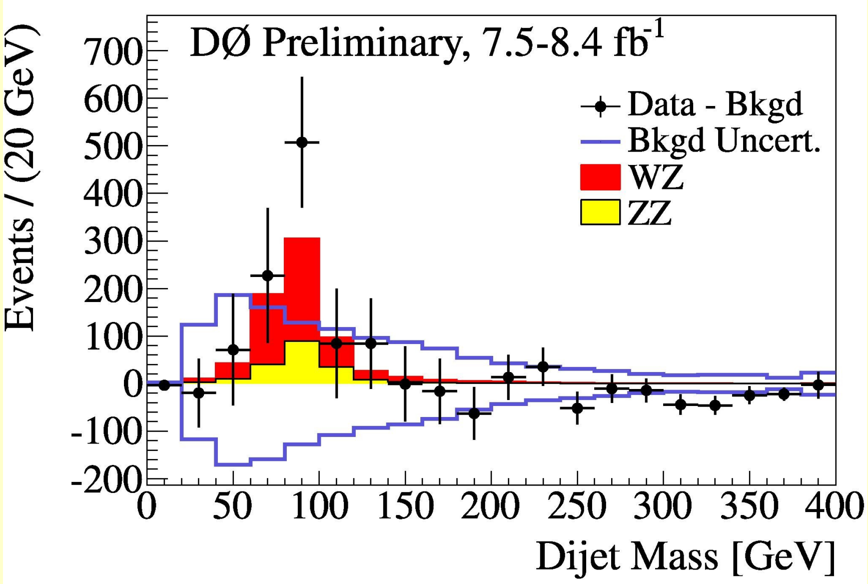
- We may discover Higgs boson in 2012 in H → $\gamma\gamma$ and H → ZZ → llll
  - Afterward we need to verify the nature of the new particle
    - Measure its mass, width and spin
    - Measure its couplings
- Recent study shows that it would be possible to measure coupling to a b-quark with a precision of ~80% if mass is 125 GeV, with 7 TeV and 20 fb^{-1}



  - It would be ~30% with 14 TeV and 30 fb^{-1}
- H → bb will be very important channel in the next few years of the LHC Higgs program

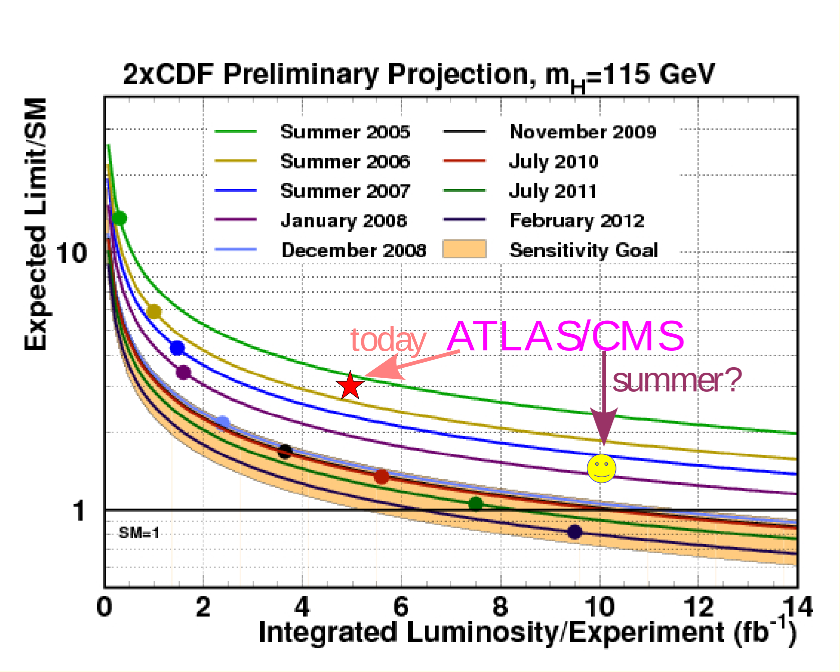
Current status of VH → Vbb searches

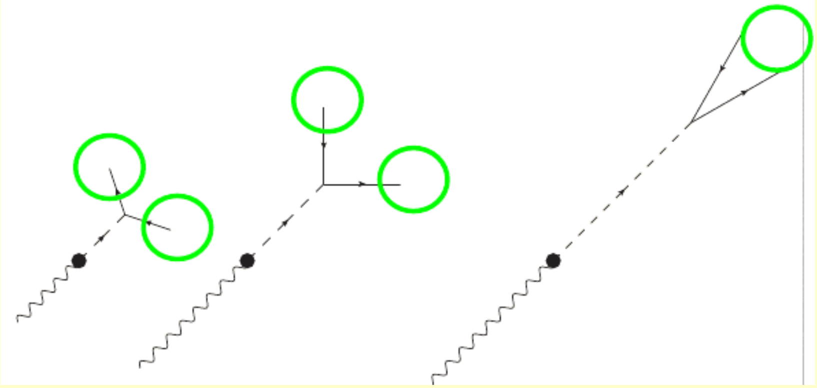
- Both Atlas and CMS presented results with a full dataset
- Atlas and CMS: select leptons and jets with higher p_T, higher MET, introduce cuts on V p_T, more cleaning cuts, only one b-tagging category (limit between 2 and 3 times σ_{SM})
- CDF and D0: lower lepton and jets p_T, less cleaning cuts, multiple lepton and b-tagging categories, excessive use of multivariate techniques
  - Many precise measurements performed, some still on their way
  - The latest is the evidence of the diboson production with b-jets in final state

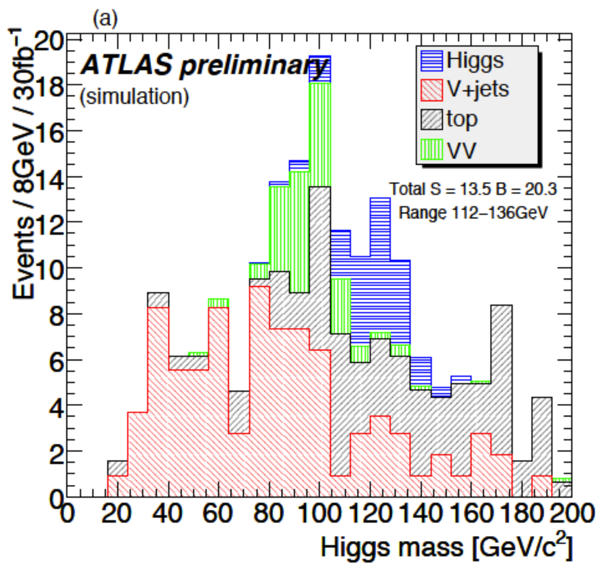


Prospects for the VH → Vbb searches

- Great potential for improvements
  - Understanding of the SM processes is crucial
- Recent development with jet substructure techniques can further increase sensitivity
  - Monte Carlo study shows potential of 3.7σ evidence for Higgs with mass of 120 GeV with 30 fb^{-1} and 14 TeV







Summary

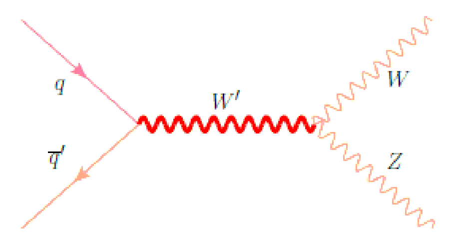
- The year 2012 will be very exciting
  - Tevatron experiments excluded Higgs boson with masses between 147 and 179 @95% C.L.
  - LHC experiments narrowed down the allowed region to 122.5-127 GeV
- Both Tevatron and LHC see an excess of ~2.5σ above background prediction
  - Higgs boson will be found or excluded this year
- If found, the next step may be even more difficult – to verify its nature
  - Every possible channel will play a role
  - Tevatron experiences will help these efforts

Beyond Higgs

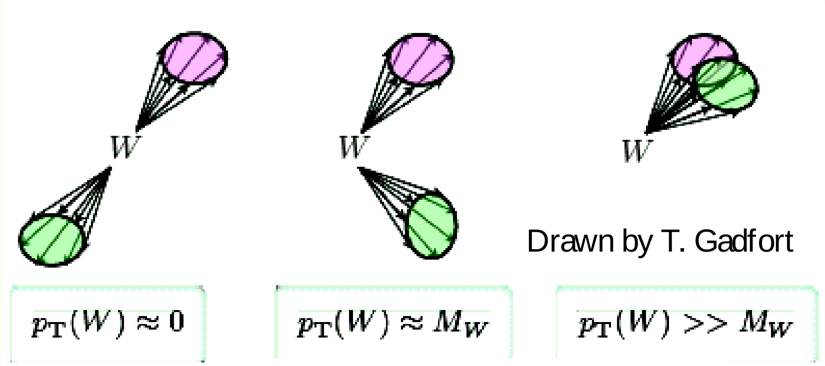
If no Higgs boson

- Still need something to unitarize WW scattering
  - Final states will often contain pair of gauge bosons
  - W + 2 jets will play a crucial role in investigations of these processes
  - Since W/Z bosons will be boosted, jet substructure techniques will be powerful tools

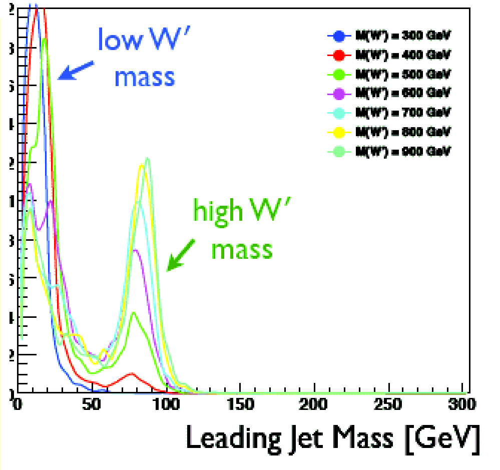
Diboson resonances

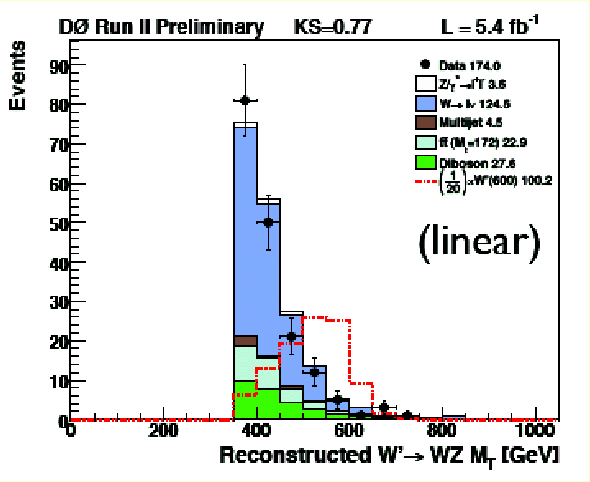


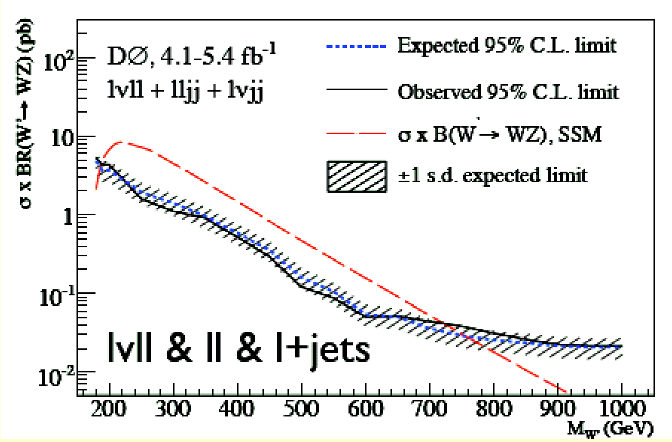
- Many extensions of the Standard Model predict new gauge groups with associated spin-1 gauge bosons
  - They can decay to two bosons
  - For high masses W(Z) is boosted, decay products are close
    - Two jets are merged into one single heavy jet



Drawn by T. Gadfort

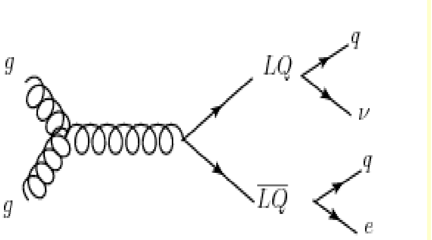






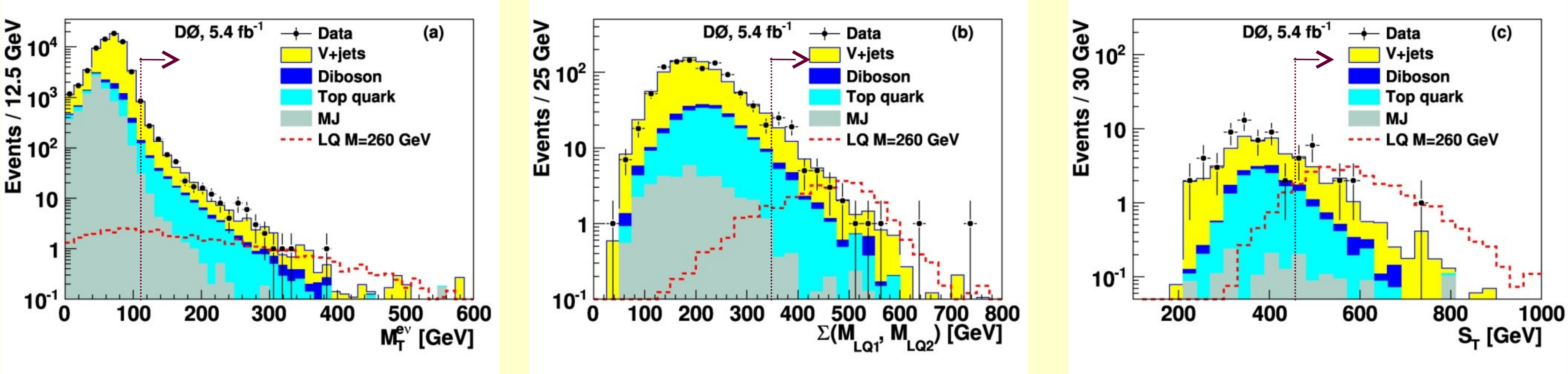
At high resonance mass l+jets is dominant

Leptoquark or what a summer student can do in eight weeks

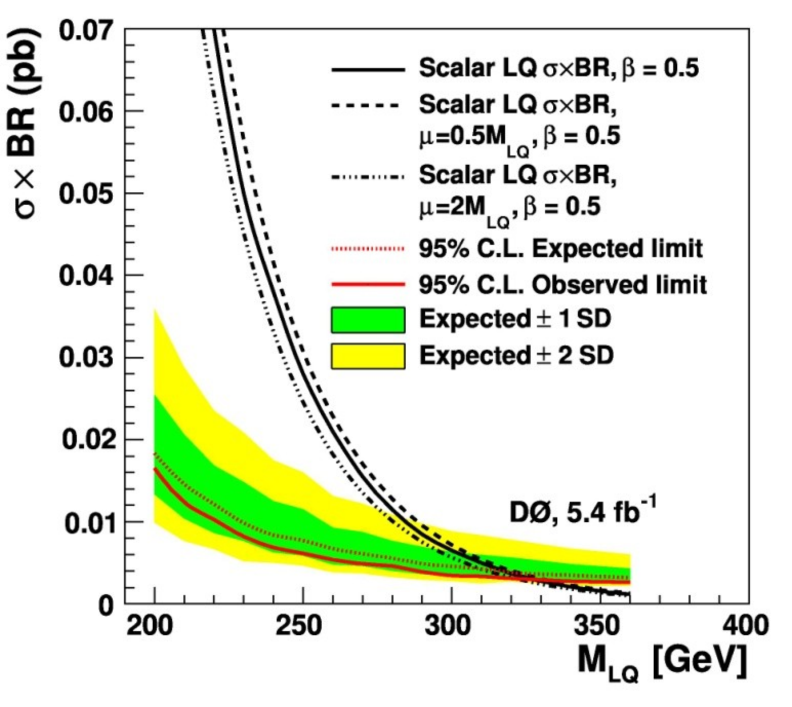


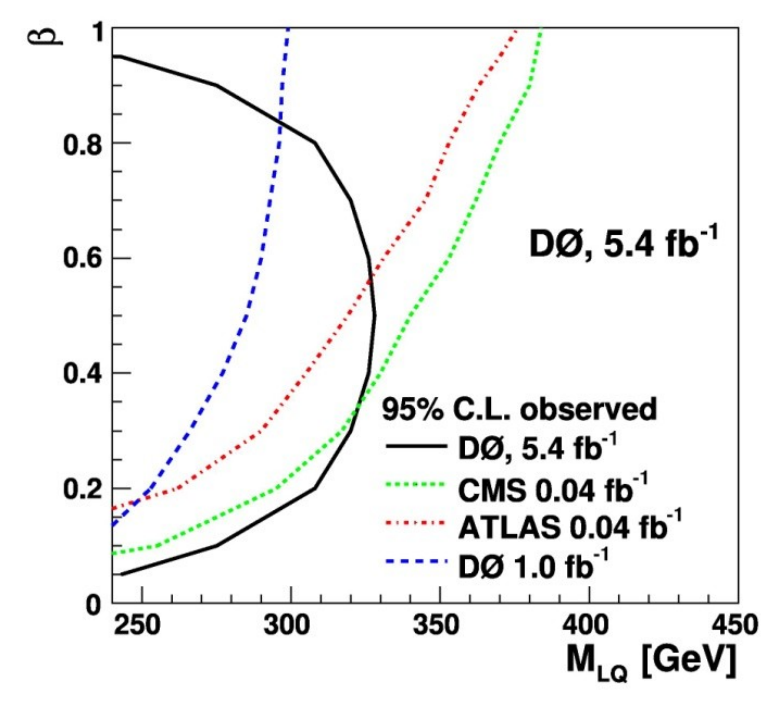
- Leptoquarks are predicted by many extensions of the Standard Model (SUSY, GUT, technicolor, etc.)
  - Composite, short-lived and decays to a lepton and a quark
- Developed an algorithm to correctly assign pairs of lepton (e,ν) and jets to parent LQ
- Simple cuts

Signal	50 → 25
Background	69000 → 15



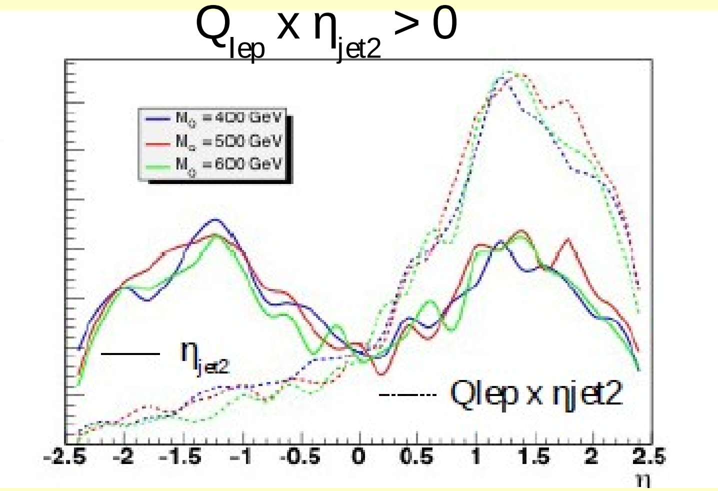
Leptoquark - result





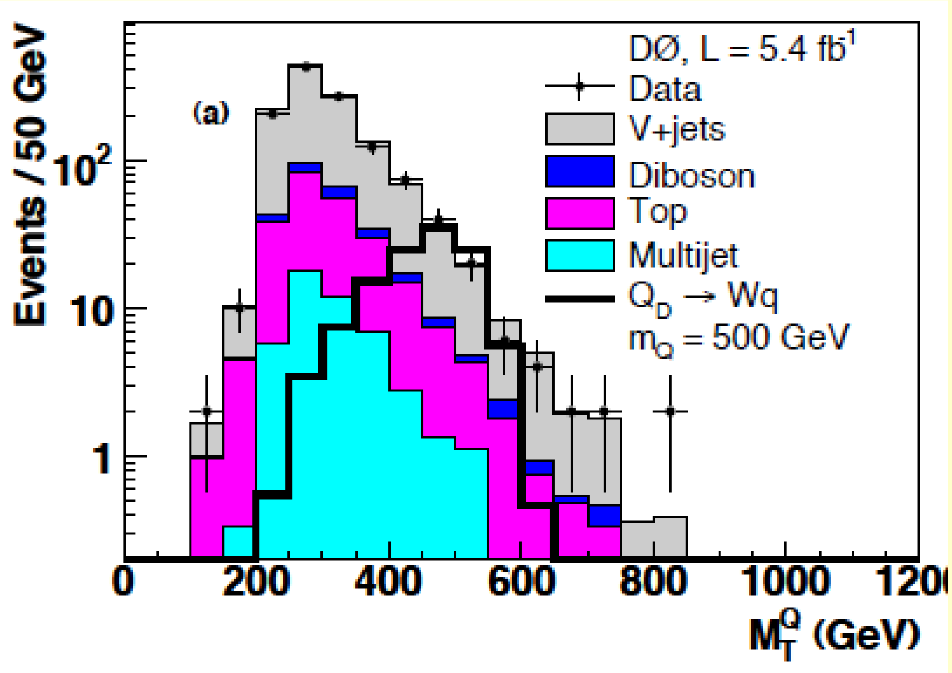
Vector quark

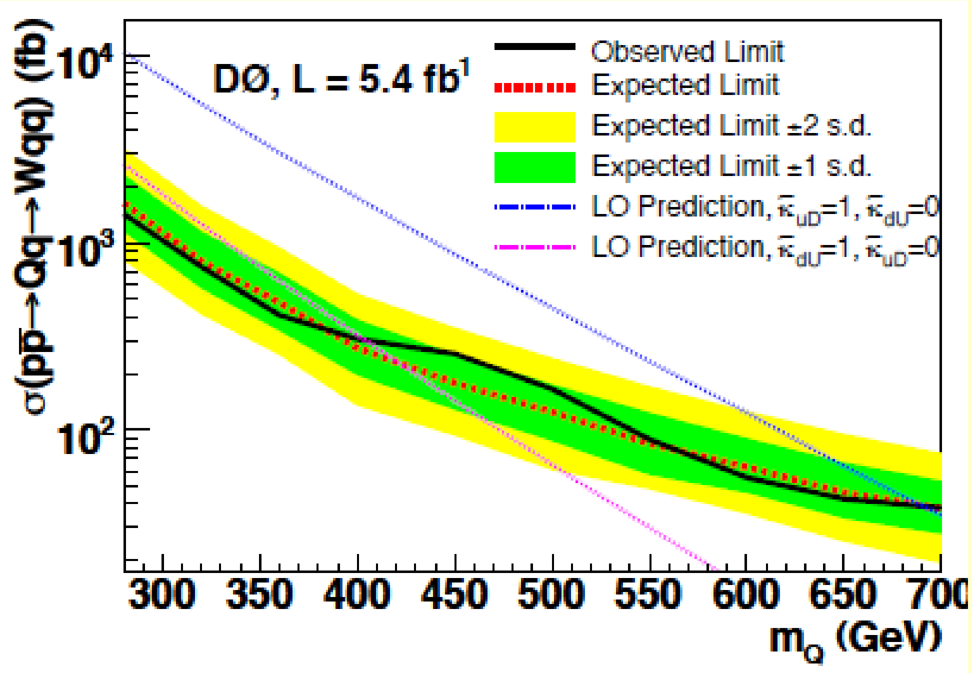
- Many new theories predict vector-like quarks:
  - Little Higgs
  - Warped extra dimensions
  - Universal extra dimensions => lowest KK excitation of SM fermions comprises a vector-like 4th generation
- Vector-like quarks are:
  - Fermions despite the name
  - Their left- and right-handed components transform in the same way under $SU(3)xSU(2)_LxU(1)$
- 2^{nd} jet in Qq->Wqq signal comes from SM quark produced in association with vector quark
  => forward, relatively soft
- Direction of 2nd jet is correlated with production of VQ/anti-VQ, and therefore correlated with the sign of the lepton in W decay mode



Vector quark

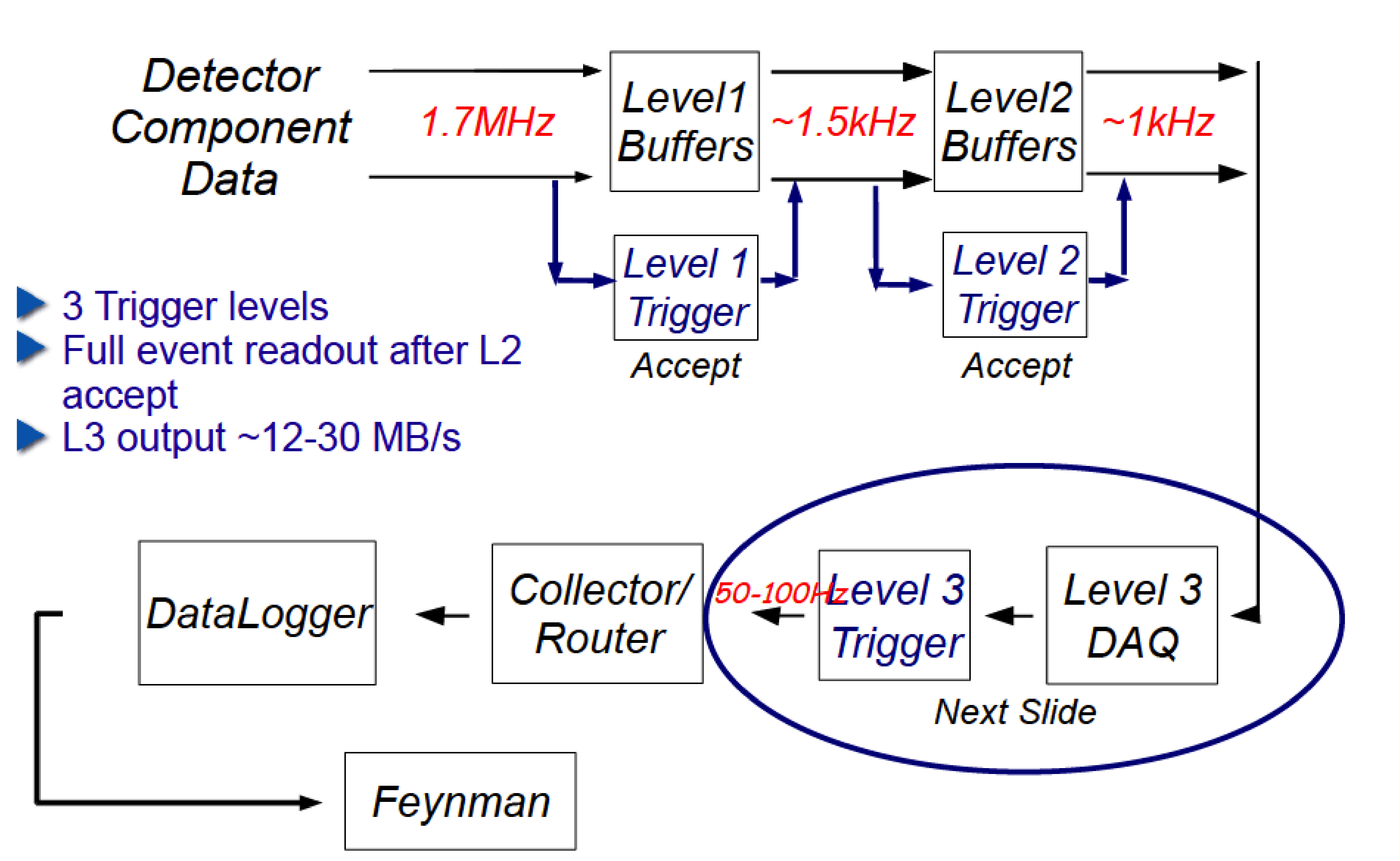
- W+q
- m_T(l+ν+lead jet) used to search for a signal
- In the absence of the significant excess, limits are set





Backup

DØ DAQ and Trigger System



Detector Component Data

1.7MHz

Level1 Buffers

~1.5kHz

Level2 Buffers

~1kHz

Level 1 Trigger

Accept

Level 2 Trigger

Accept

Level 3 DAQ

Level 3 Trigger

50-100Hz

Collector/ Router

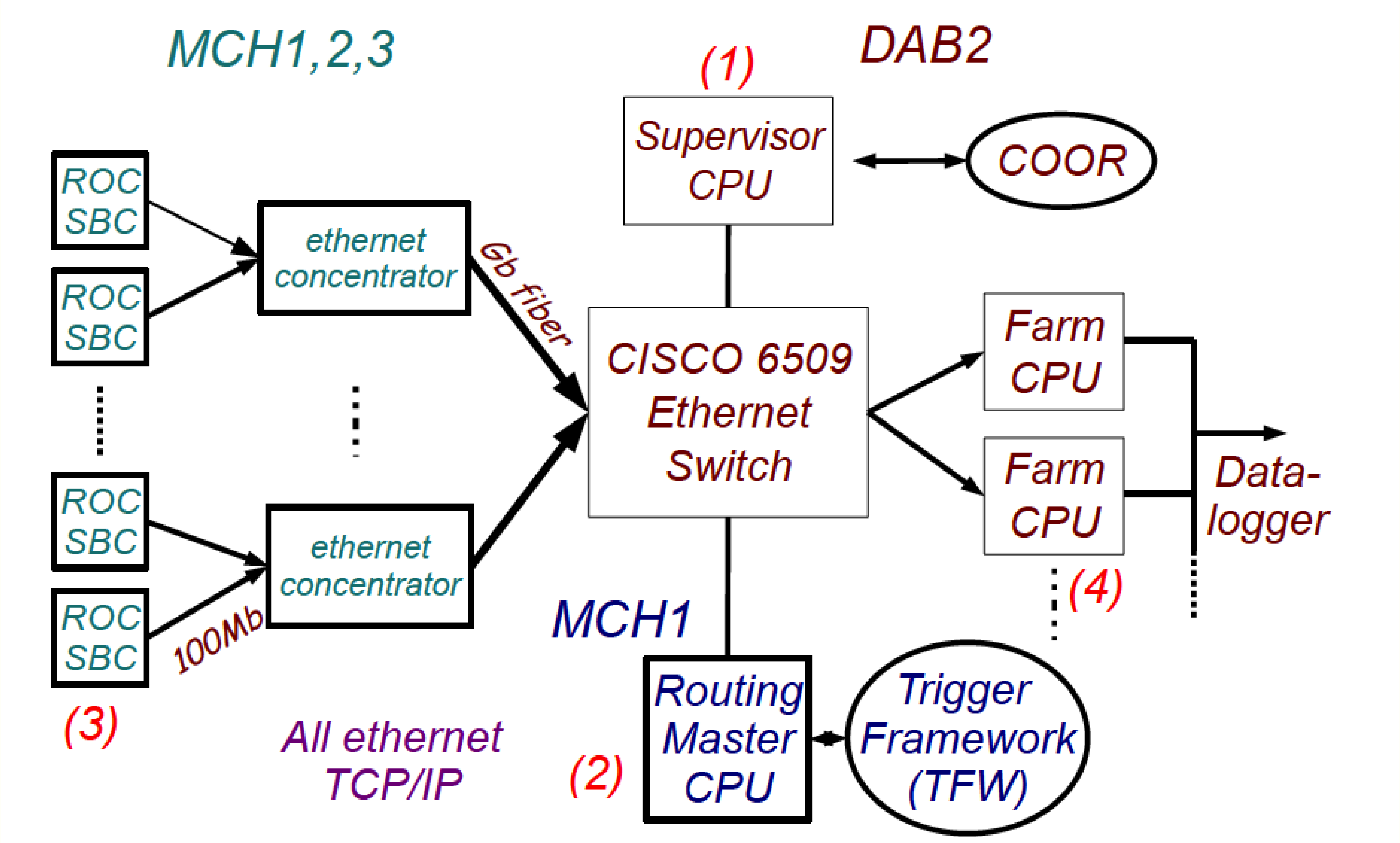
DataLogger

Feynman

Next Slide

- 3 Trigger levels
- Full event readout after L2 accept
- L3 output ~12-30 MB/s

L3/DAQ Data Flow Chart



L3/DAQ Data Flow Chart

- L3 Supervisor: Interface with COOR:

  Start of a run:

  (1) Pick crates with CRATER

  (2) Download trigger with TAKER

  (3) COOR tells Supervisor who is in the run

  Supervisor Sends Run Info:

  (1) Crate list, farm node list, and trigger information → Routing Master

  (2) L3 trigger programming sent to farm nodes

- Routing Master:

  Serves two purposes - Event routing and Connection to Trigger Framework

  Event Routing:

  (1) Choose farm node (free buffers)

  (2) Tell farm node which crates to expect

  (3) Tell SBC where to send data

  Connection to TFW:

  (1) Collect trigger bitmask

  (2) Apply L3 disable if no farm nodes are available

L3/DAQ Data Flow Chart

- Process
  - L2 accept from TFW
  - Controller → SBC "get the data"
  - SBC stores data in memory
  - Match route number and event number
    - If fail, event is dropped
  - Send data to farm node determined by RM
- ~300 farm nodes at the end of the run

- Recap: The RM told each SBC where to send their data and it told the particular farm node which SBCs are sending data.
- EventBuilder strings together all the SBC data fragments into an "event".
- EVB will wait for 1 second for the SBCs to send their data.
- If it does not receive what is expected, the event is dropped

DAQ Shifter Station in CR (circa 2004)

DAQ Dialog
uMon
fuMon
L2 GUI

COOR
Connections

Big Brother
Alarm Display

Luminosity

DAQ AI
Problems.txt
Runs.txt, etc...

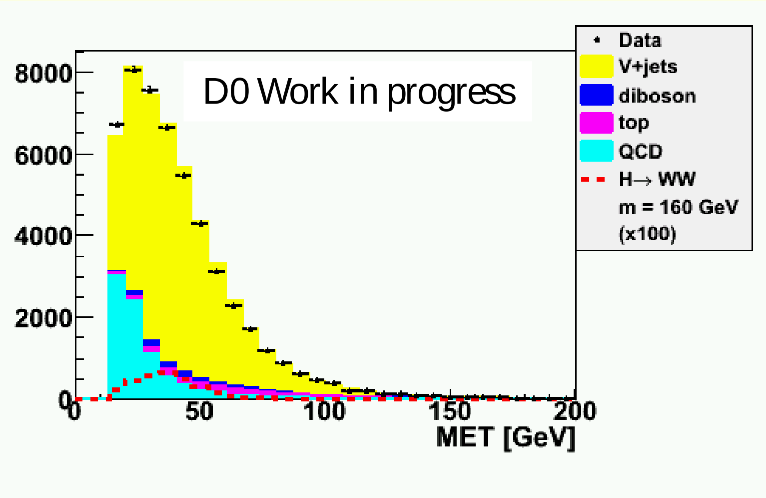
Reconstructing the event

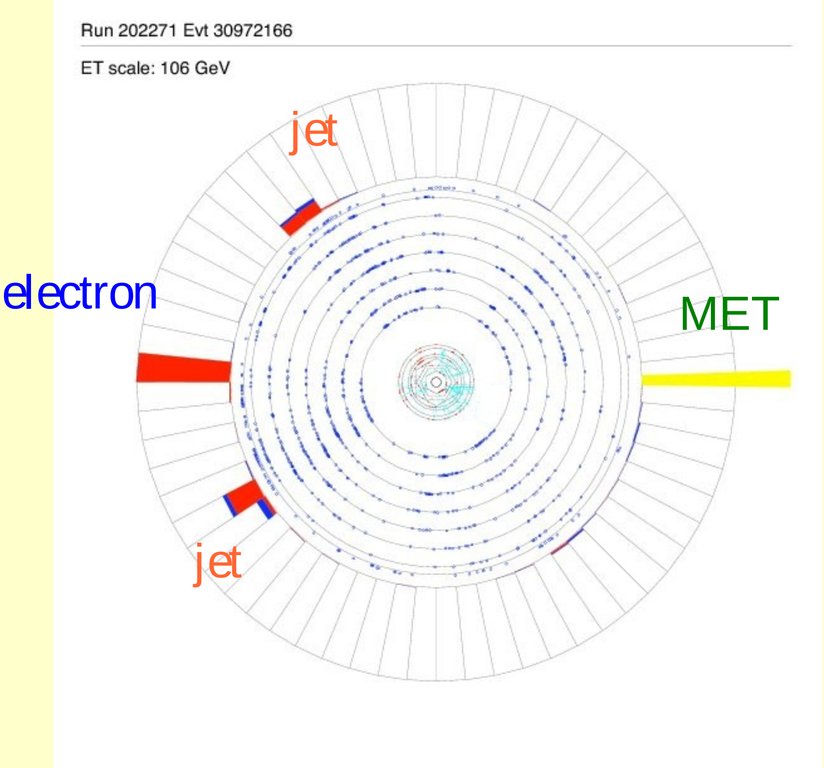
- Neutrinos interact weakly
  - Escape detection
- Ascertain presence by absence
  - Conservation of momentum

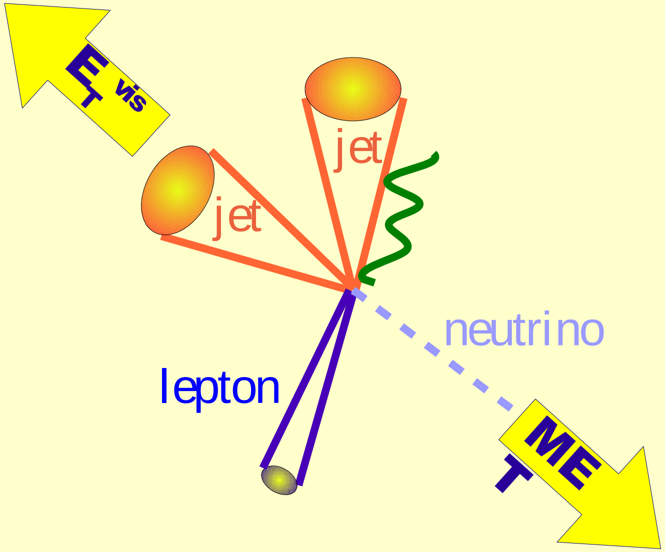
$$E_T^{initial} = 0 \Leftrightarrow E_T^{final} = 0$$

- Missing transverse energy (MET)

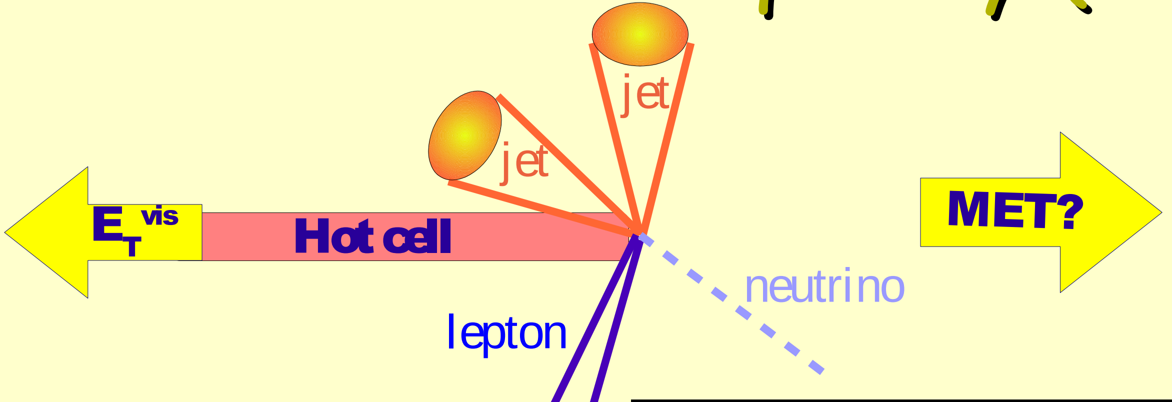
$$MET = E_T^{visible}$$



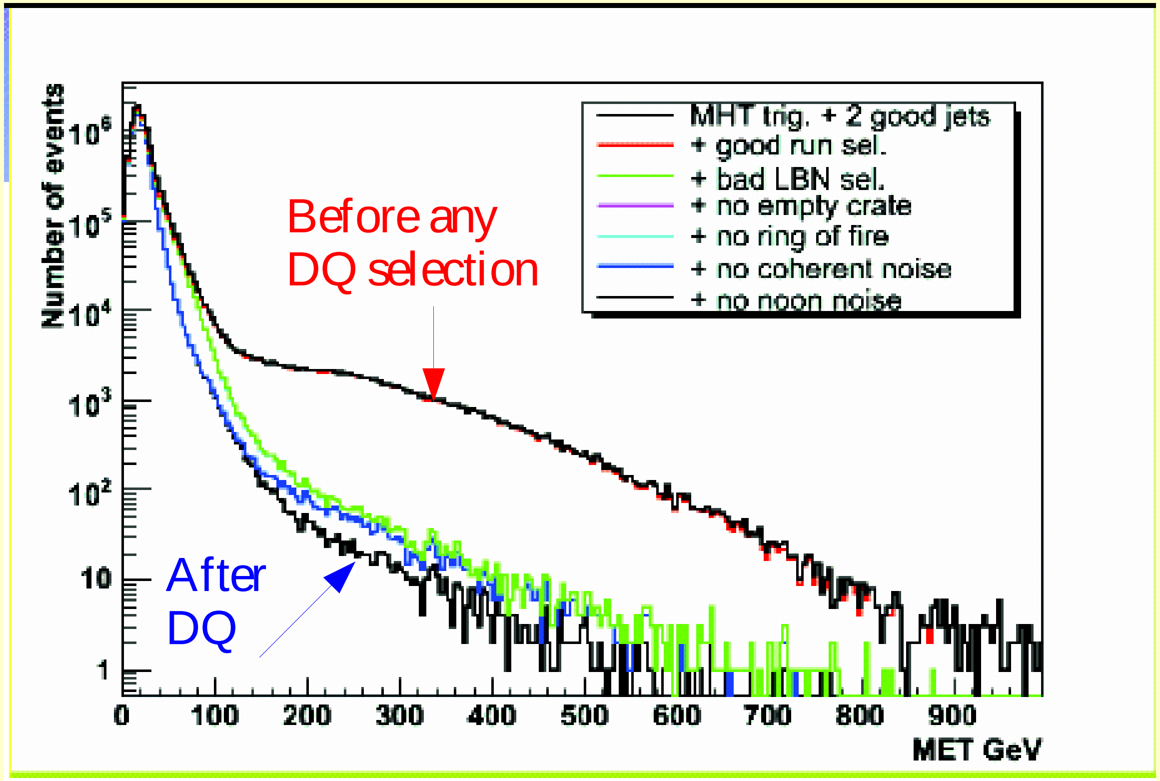




Missing transverse energy (MET) and data quality (DQ)

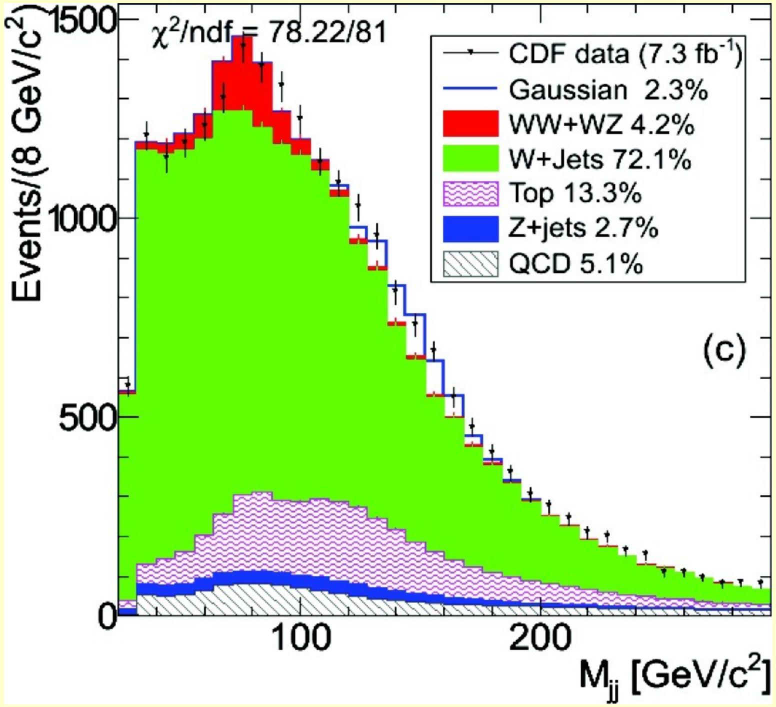


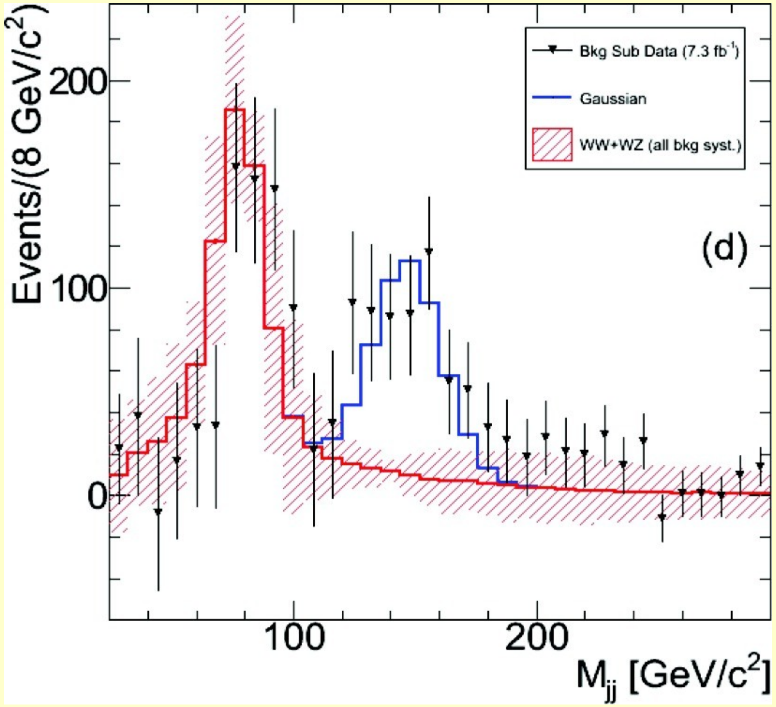
- Any calorimeter problem can appear as an event with large MET
  - Lot of “new physics”



Dijet mass bump

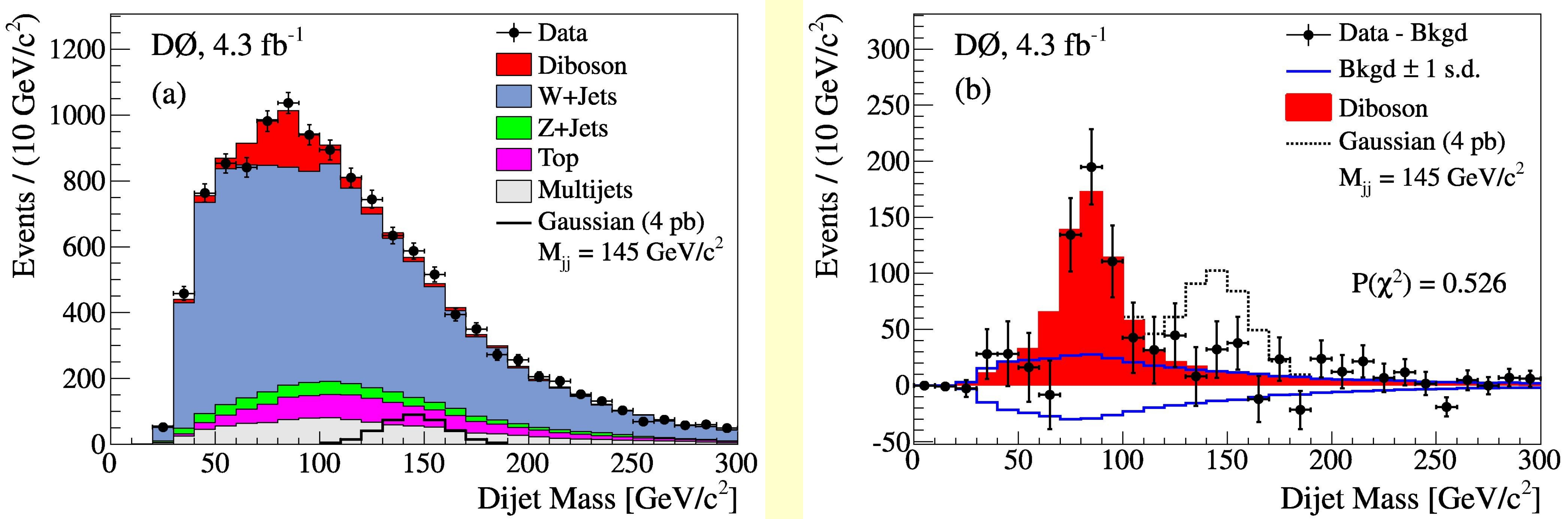
- In early 2011 CDF has reported an excess of events in the dijet mass spectrum above the expected Standard Model contributions
- With 4.3 fb^{-1} integrated luminosity the CDF data show an excess of 3.2 standard deviations around a dijet mass ~145 GeV
  - with 7.3 fb^{-1} significance of excess exceeds 4σ
- If this is a resonance from some new particle, X, then $\sigma(pp \rightarrow WX) \approx 4$ pb





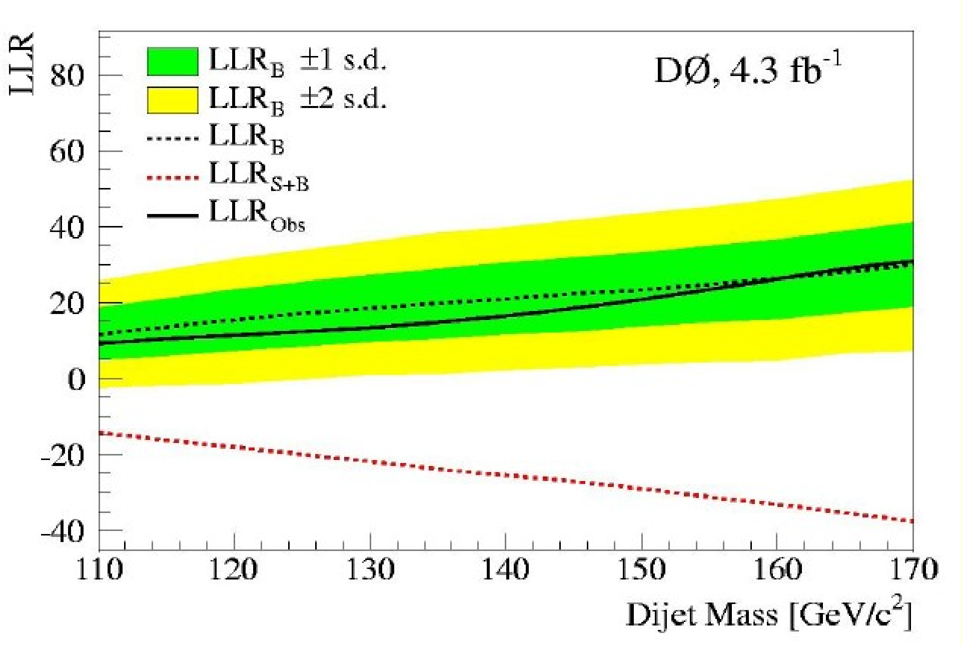
Dijet mass bump

- The dijet mass distributions after fitting the SM processes to the data
- The DØ data are consistent with the SM prediction

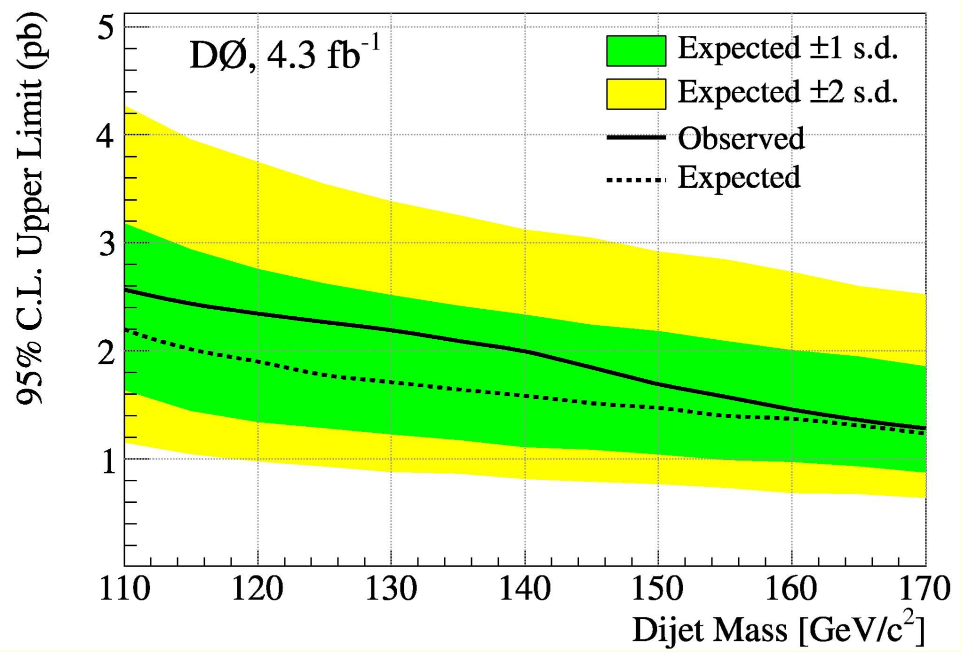


Dijet mass bump

- Compare observed LLR to the predicted LLR distributions over the range of dijet mass



- 95% CL upper limits on WX→lvjj as a function of reconstructed M_{jj}

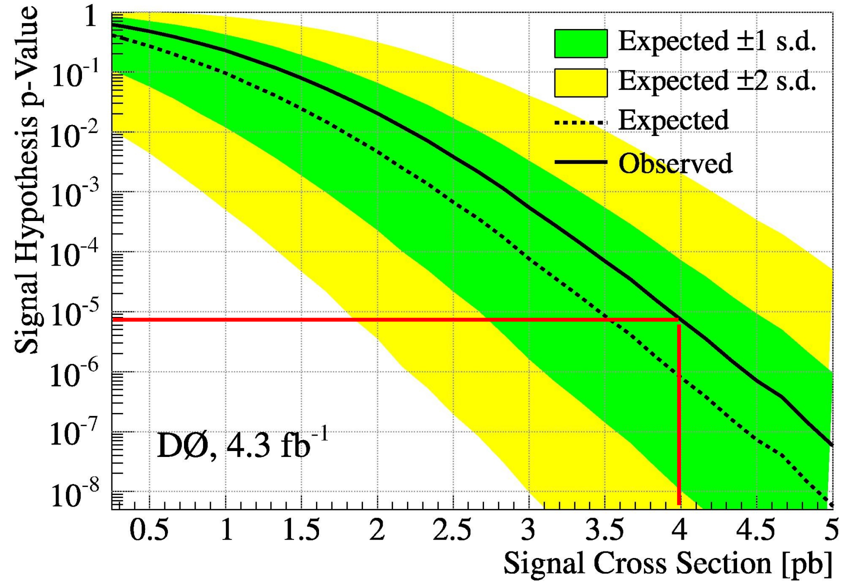


- For M_{jj} = 145 GeV 95% CL exclusion for cross sections greater than 1.9 pb

Dijet mass bump

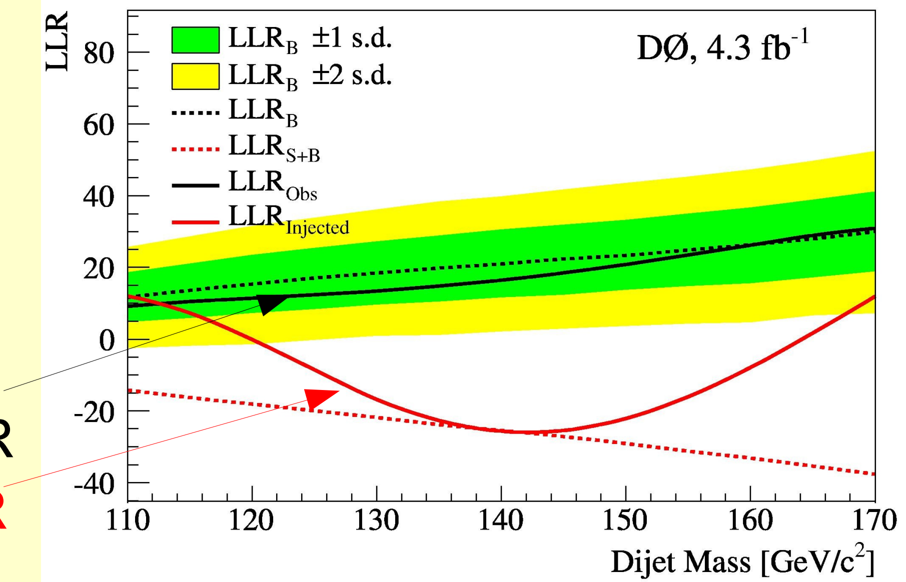
- For a cross section of 4 pb as reported by CDF
  - Exclude at 99.999% CL
  - 4 standard deviations
- The DØ data are not consistent with the excess seen by CDF

- Make a signal-injected mock "data" sample
- Composed of data + WX template @ 145 GeV
- Confirm that our studies would find that signal
- We clearly would have seen a 4 pb excess if it was there



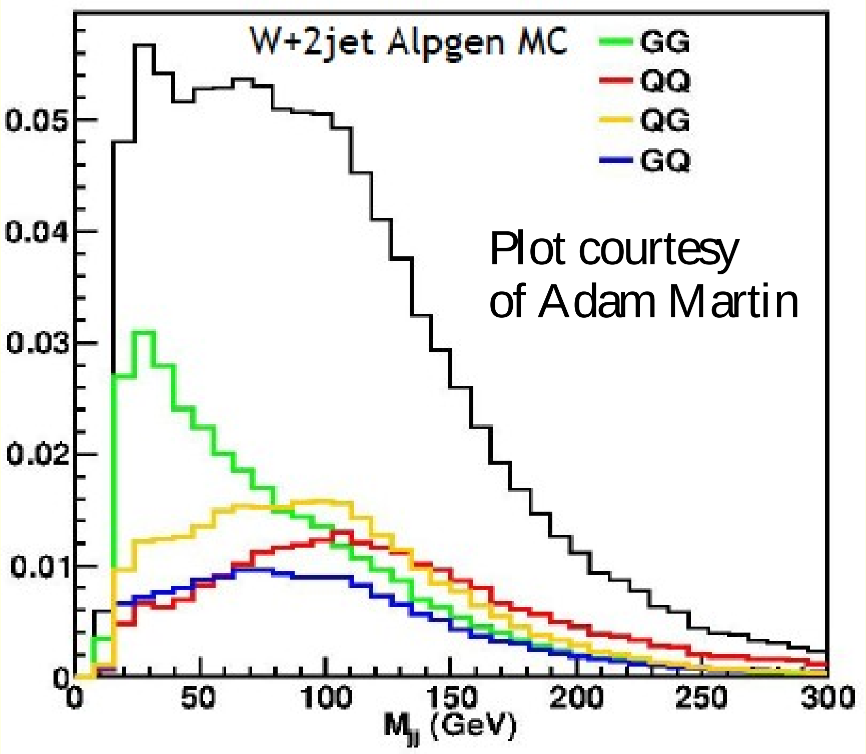
Observed Data LLR

Signal-Injected LLR



Jet reconstruction

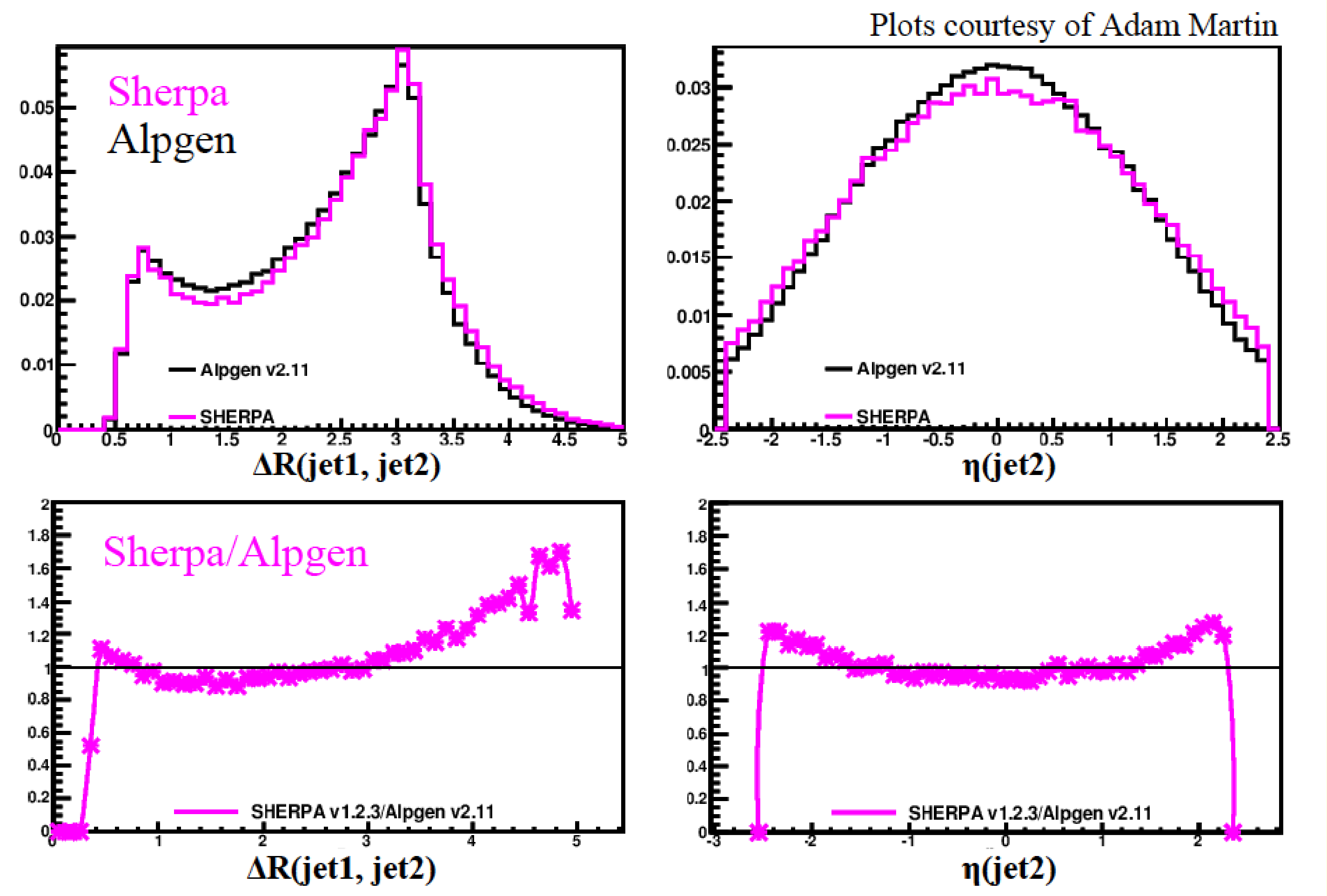
- Reconstruction:
  - D0 iterative mid-point cone algorithm with radius R=0.5
  - Must be a hadronic shower and does not contain noisy calorimeter cells
  - At least two tracks fro primary vertex
- Jet Energy Scale
  - Measured in γ+jets events
  - Correct energy to particle level
    - For detector response, out of cone showering, overlap with pileup energy
- Relative data/MC correction
  - Measured in Z+jets events
  - Different correction depending on quark vs gluon content



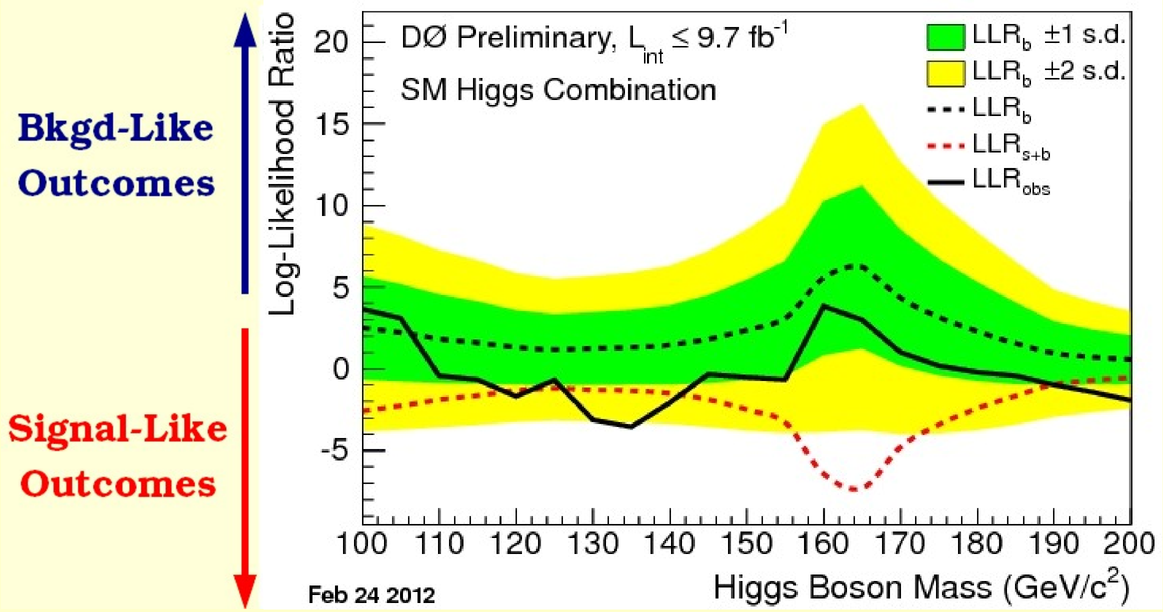
Plot courtesy of Adam Martin

W+jets modeling

- Alpgen does not describe data properly
  - We know it from measurements
  - And from comparison with other generators

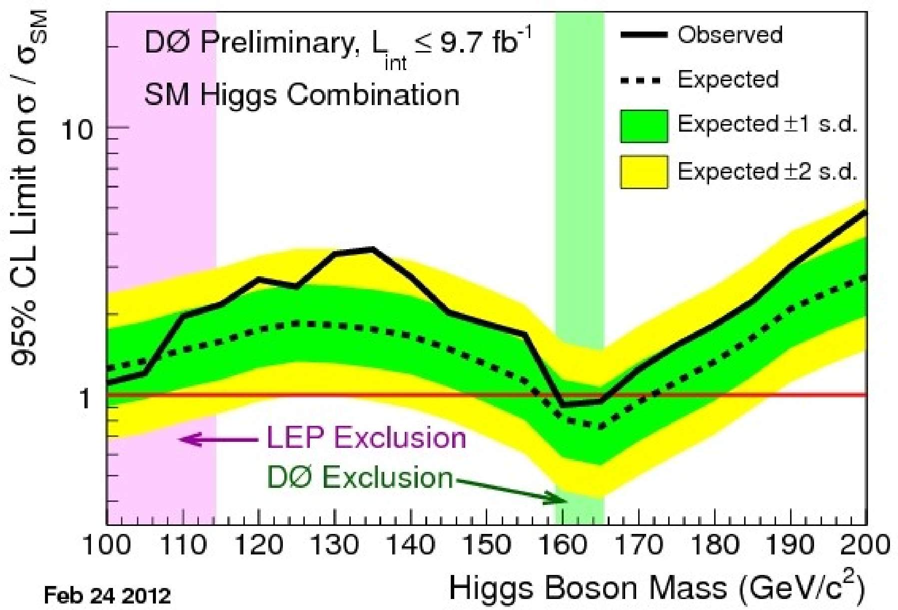


DØ limits



- The width of the Log Likelihood Ratio, LLR$_b$, distribution (1σ and 2σ bands) provides an estimate of how sensitive the analysis is to a signal-like background fluctuation in the data, taking account of the presence of systematic uncertainties
  - For example, when a 1σ background fluctuation is large compared to the signal expectation, the analysis sensitivity is thereby limited.
- The value of LLR$_{obs}$ relative to LLR$_{s+b}$ and LLR$_b$ indicates whether the data distribution appears to be more like signal-plus-background or background-only.

DØ limits

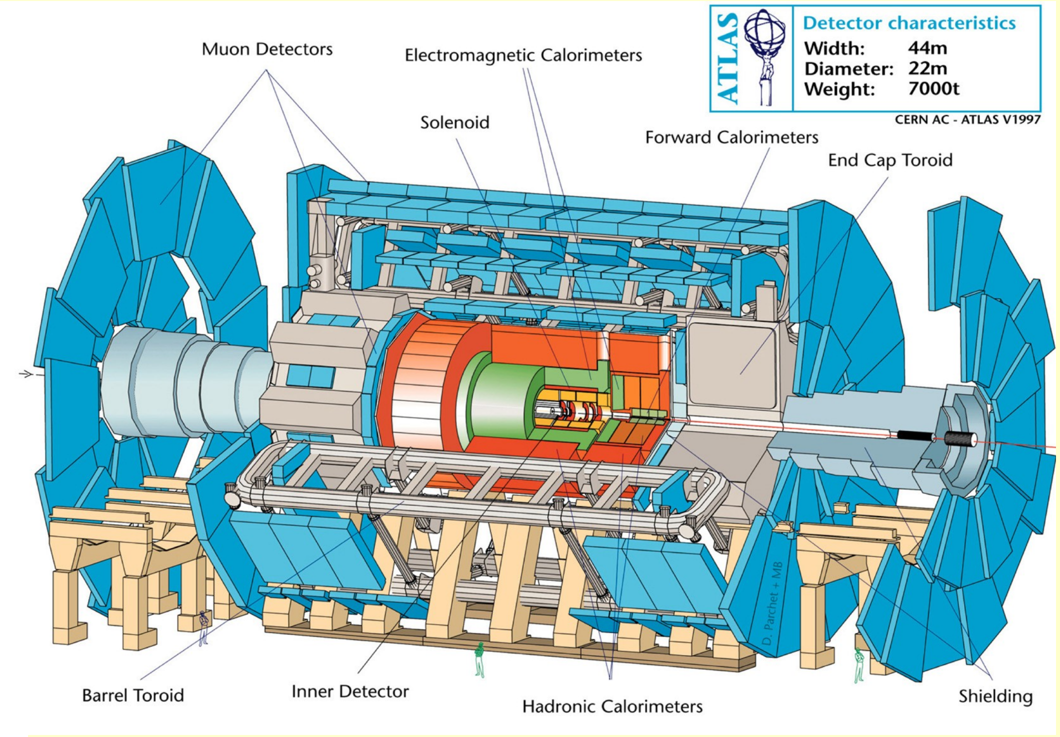


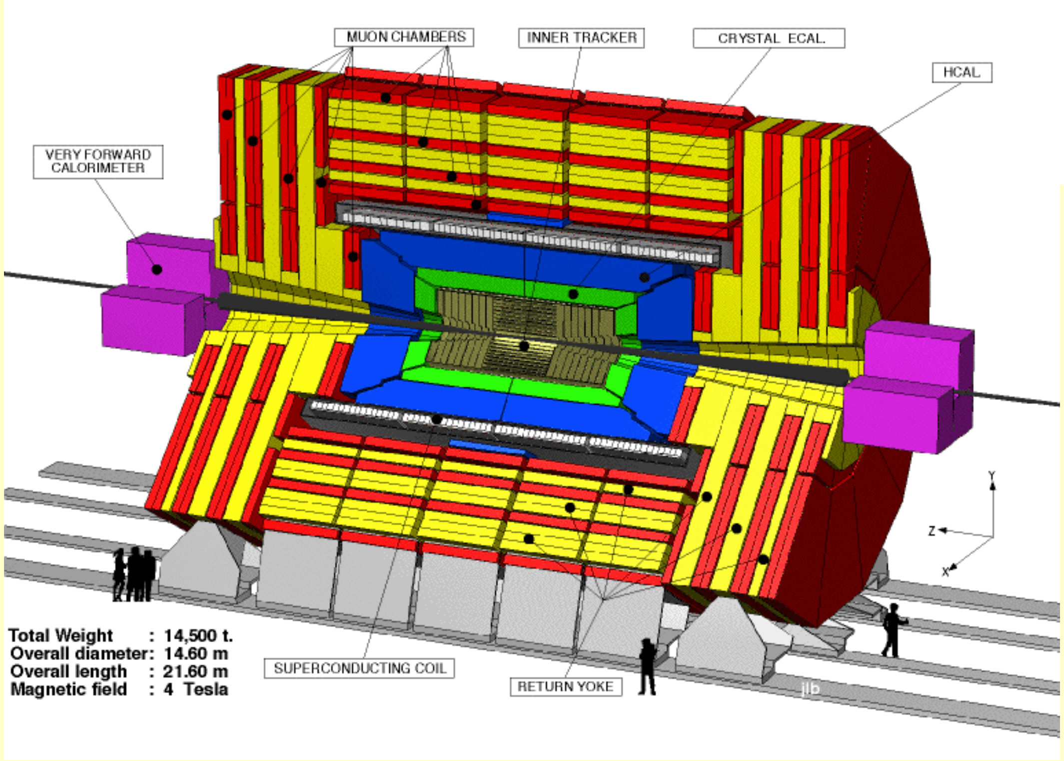
- DØ exclusion: $159 < m_H < 166$ GeV
- Expected exclusion of $157 < m_H < 172$ GeV
- Expected limit less than $2 * \sigma_{SM}$ for all masses < 190 GeV

DØ ($\leq 9.7\ fb^{-1}$)	Exp.	Obs
M_H = 165 GeV	0.76	0.94
M_H = 125 GeV	1.82	2.53

ATLAS and CMS

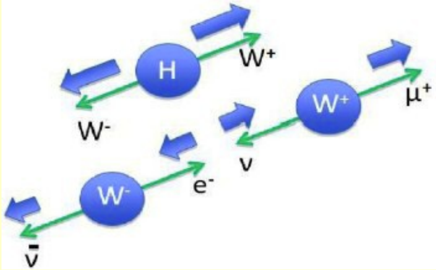
- ATLAS
  - Largest detector in a world
  - liquid Argon Calorimeter
  - excellent muon id



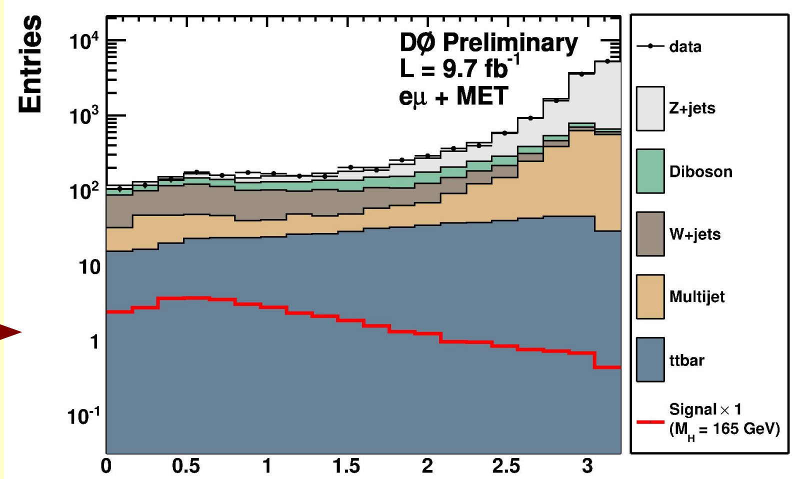


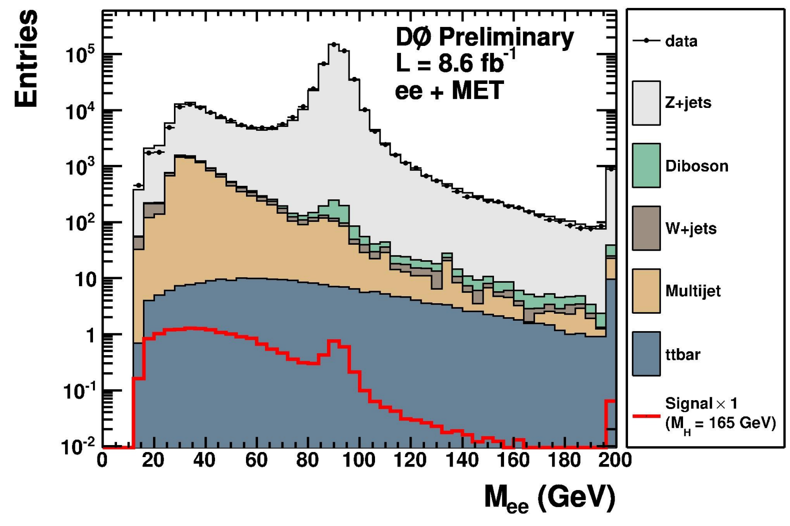
- CMS
  - Lead Tungstate crystal EM calorimeter
  - superior energy resolution

High mass Higgs - H → WW → lνlν

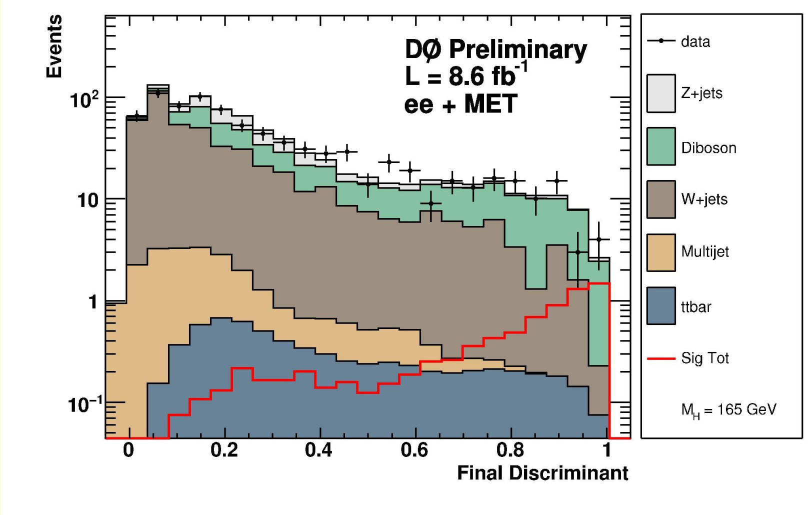


- Characteristics:
  - In signal WW pair is coming from spin 0 Higgs boson
  - Leptons prefer to point in same direction
  => Di-lepton opening angle $\Delta\varphi_{ll}$ discriminates again irreducible WW background.
  - Dilepton mass is small and broad
  => Discriminates against Drell-Yan





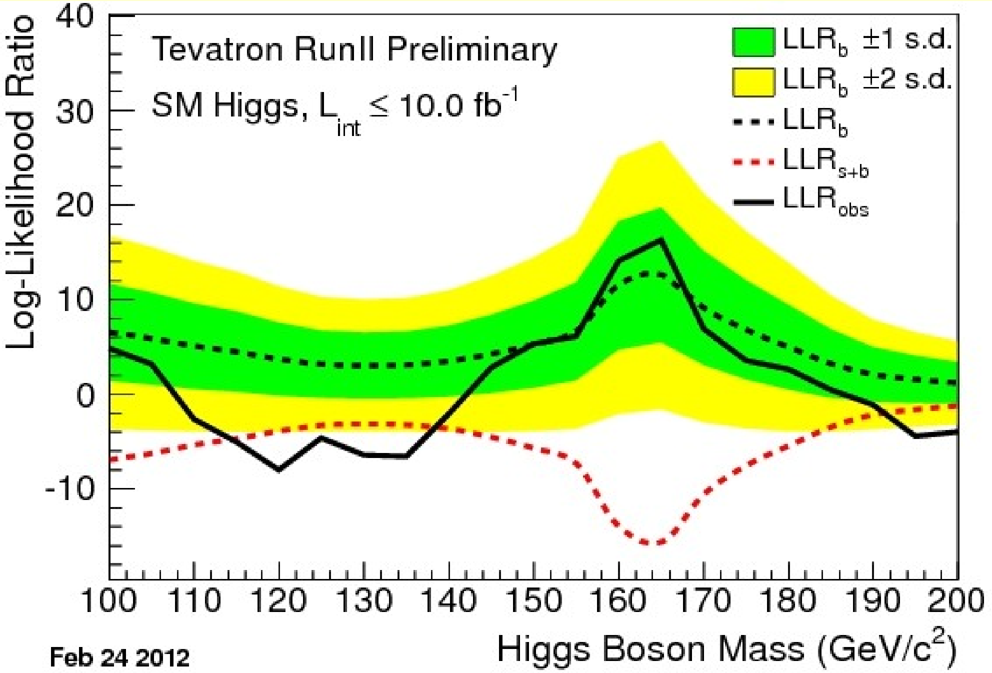
- Dedicated MVA rejects Z+jets events
- Another MVA used to search for Higgs
- This search contributed to the first Tevatron exclusion

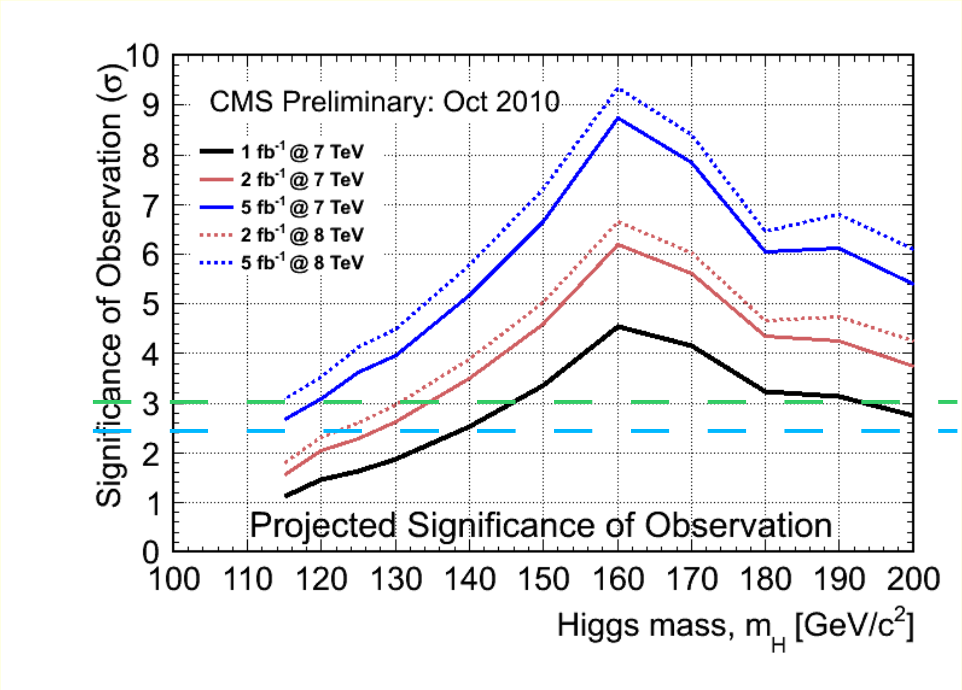


DØ (9.7 fb^{-1})	Exp.	Obs
M_H = 165 GeV	0.82	1.16
M_H = 125 GeV	3.77	4.23

Standard Model Higgs prospectives

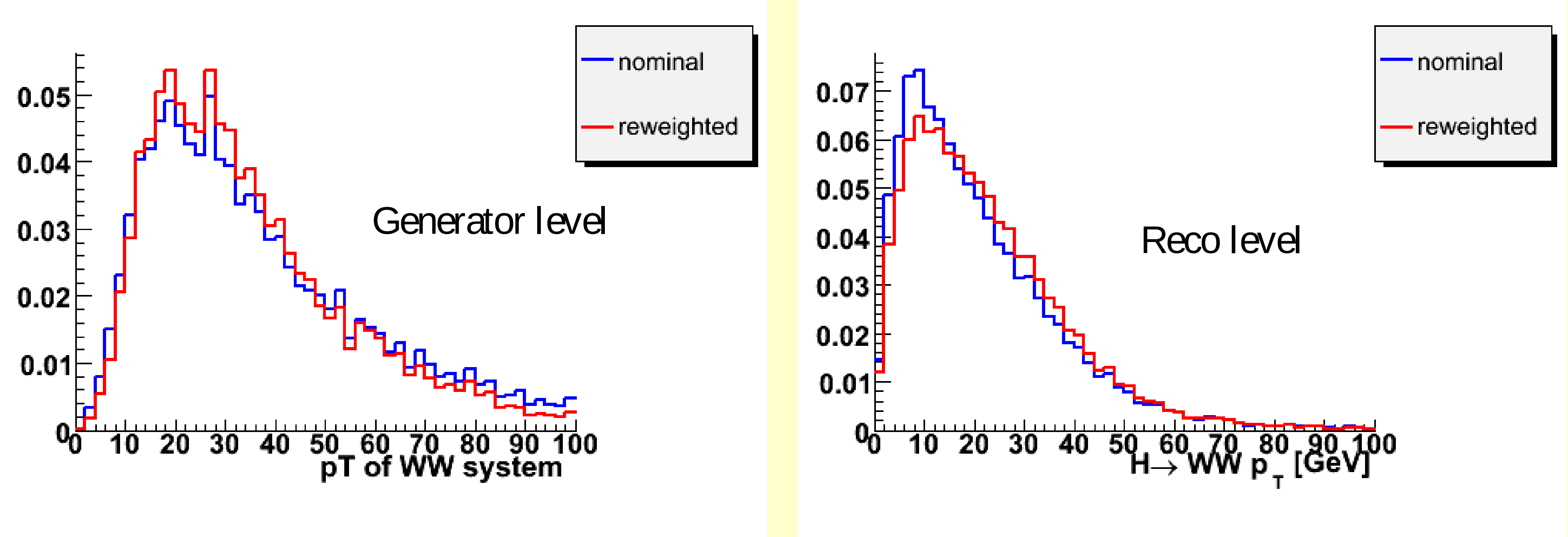
- Tevatron end game:
  > 2.5σ expected sensitivity across the whole mass range
- LHC 2012:
  possible evidence!



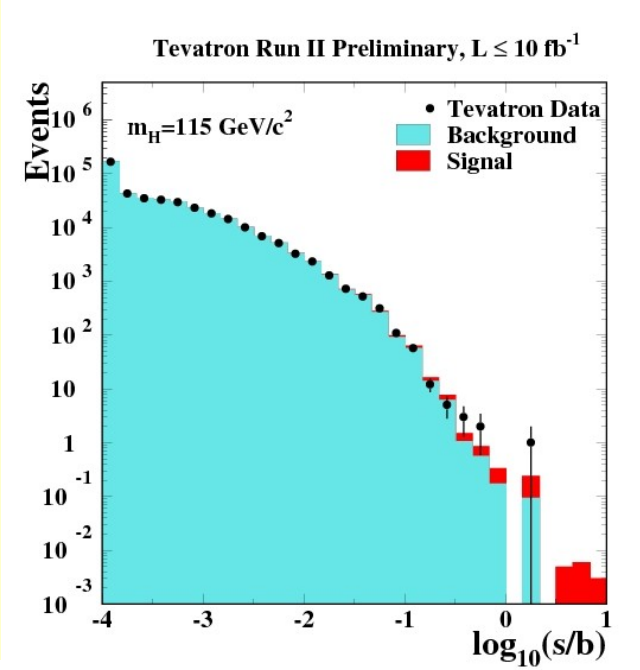


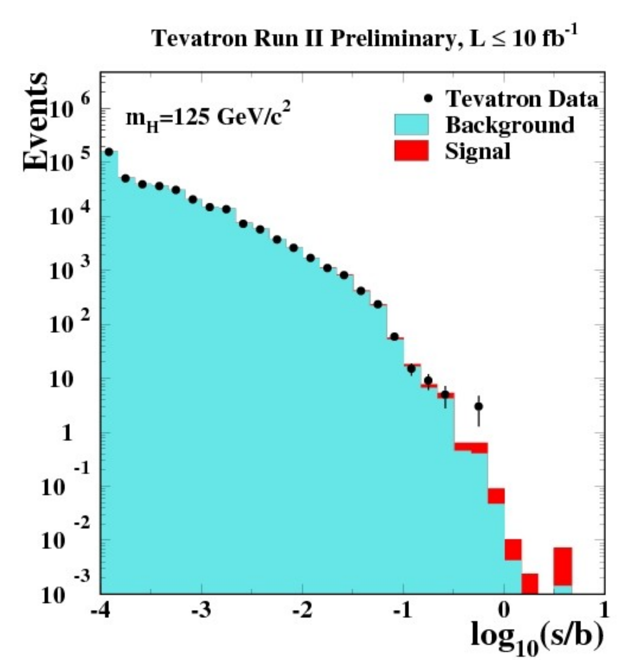
Modeling of the signal

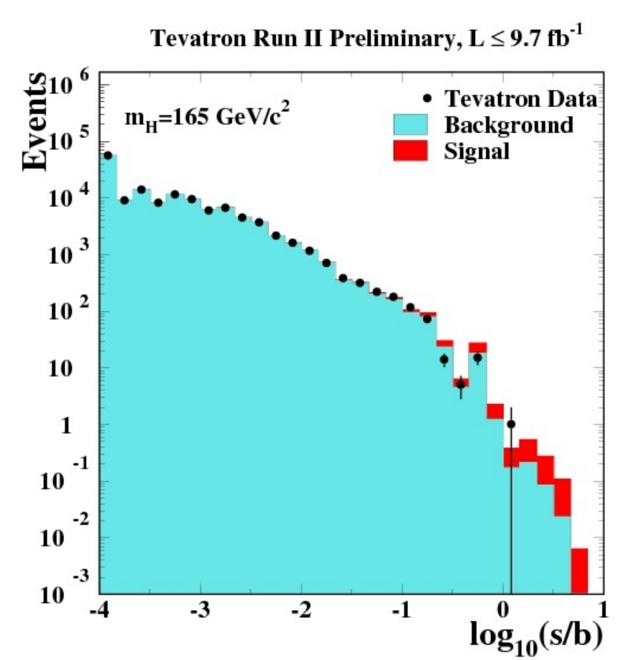
- We model our signal with PYTHIA
  - But we know that PYTHIA has some issues
  - We use other generators for comparison, MC@NLO with Herwig, Sherpa or recently the HqT program, for the signal modeling
    - provides Higgs p_T distributions up to NNLL+NNLO

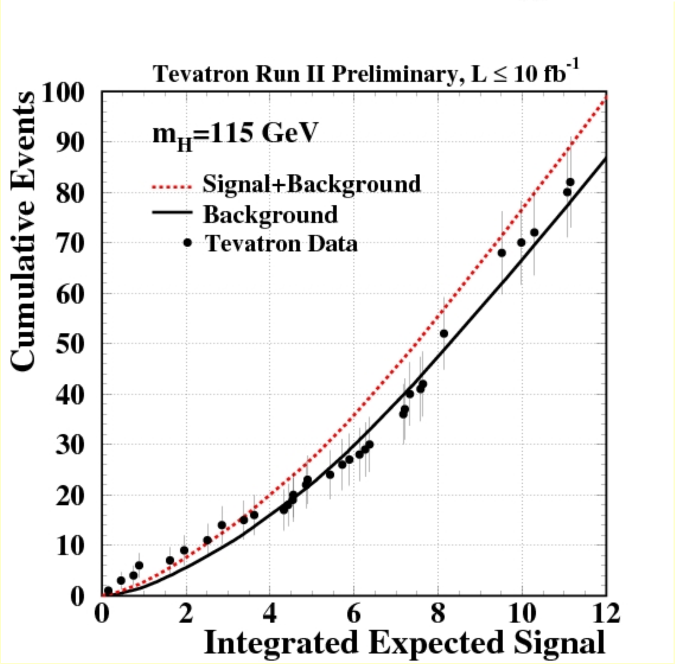


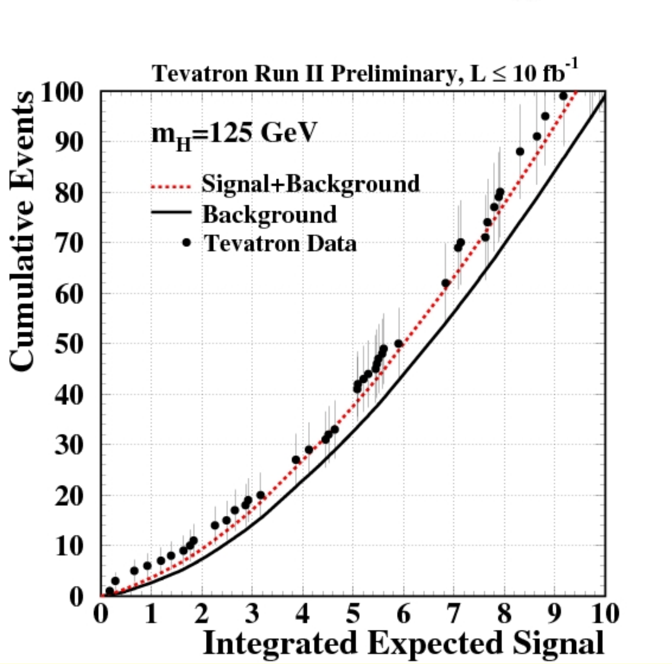
Cumulative distributions

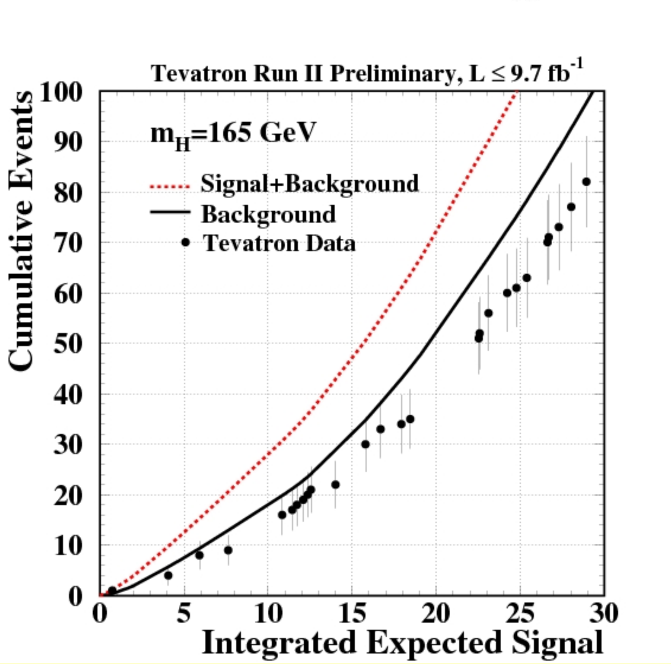

Tevatron Run II Preliminary, L ≤ 10 fb^{-1}


Tevatron Run II Preliminary, L ≤ 10 fb^{-1}

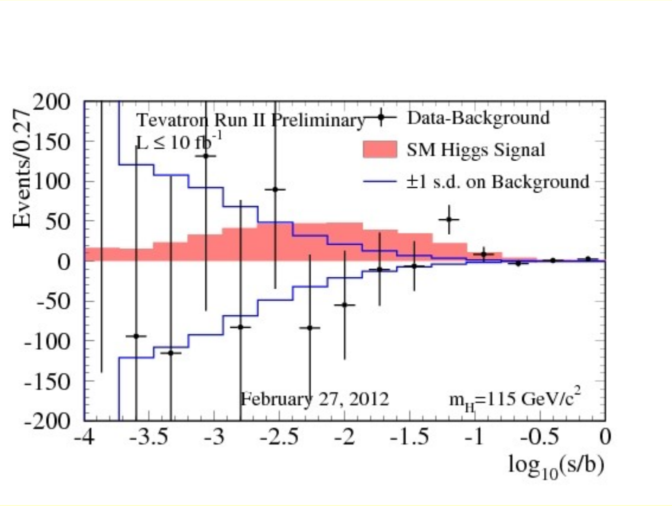

Tevatron Run II Preliminary, L ≤ 9.7 fb^{-1}

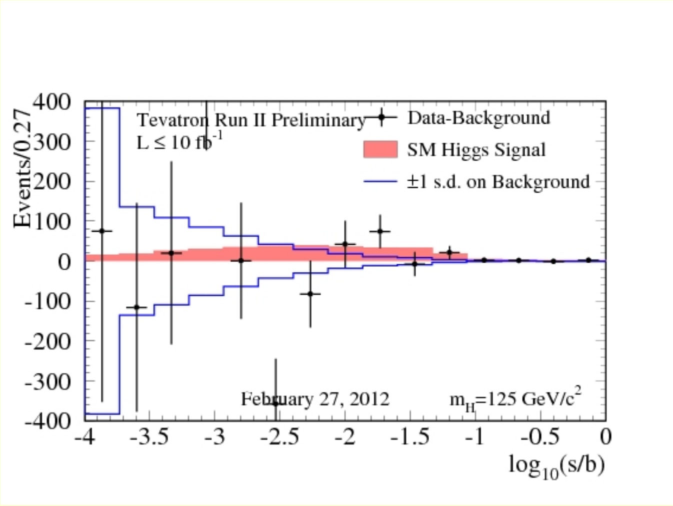

Tevatron Run II Preliminary, L ≤ 10 fb^{-1}

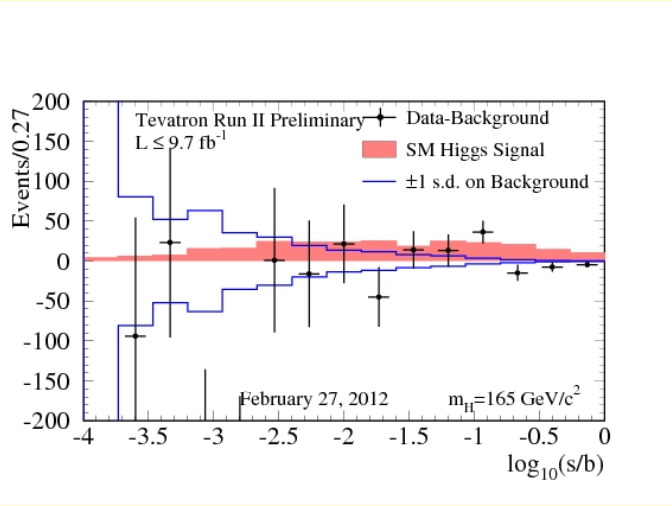

Tevatron Run II Preliminary, L ≤ 10 fb^{-1}


Tevatron Run II Preliminary, L ≤ 9.7 fb^{-1}

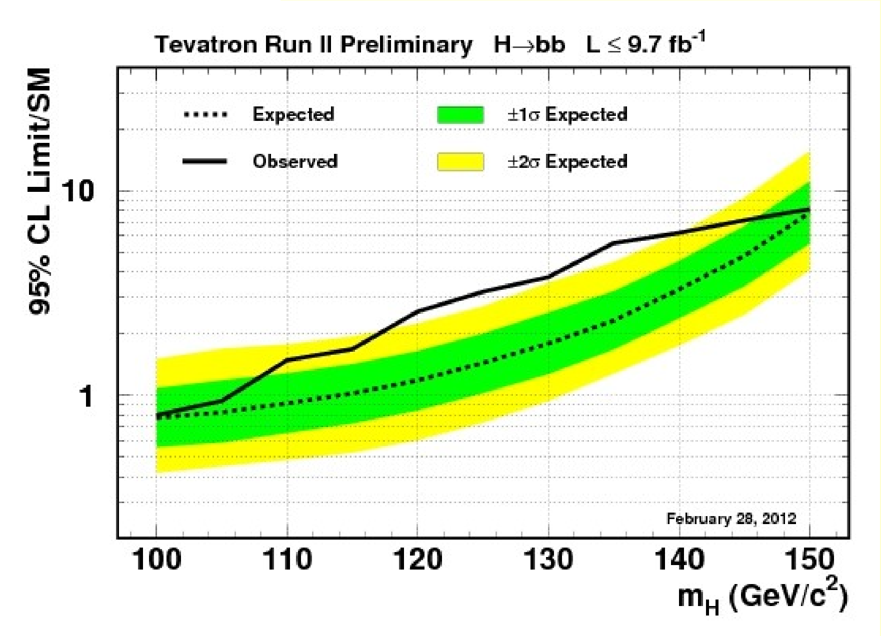
Data - Background

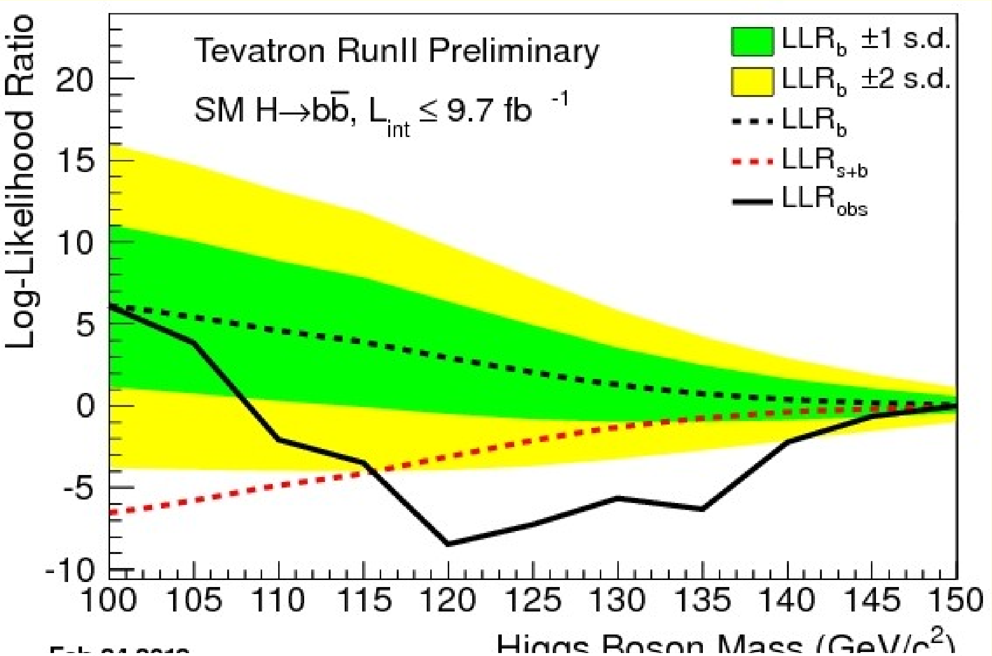


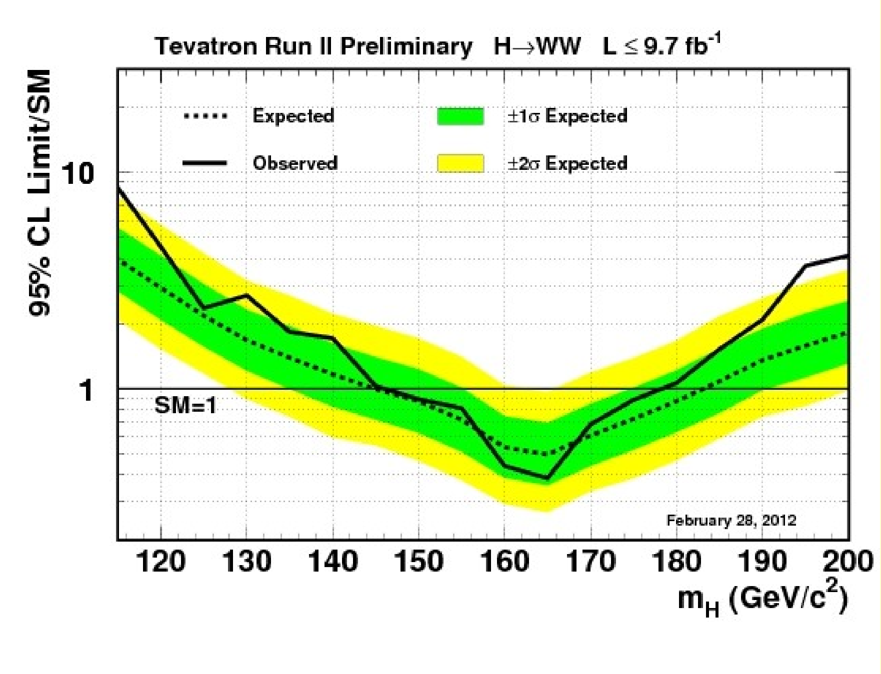


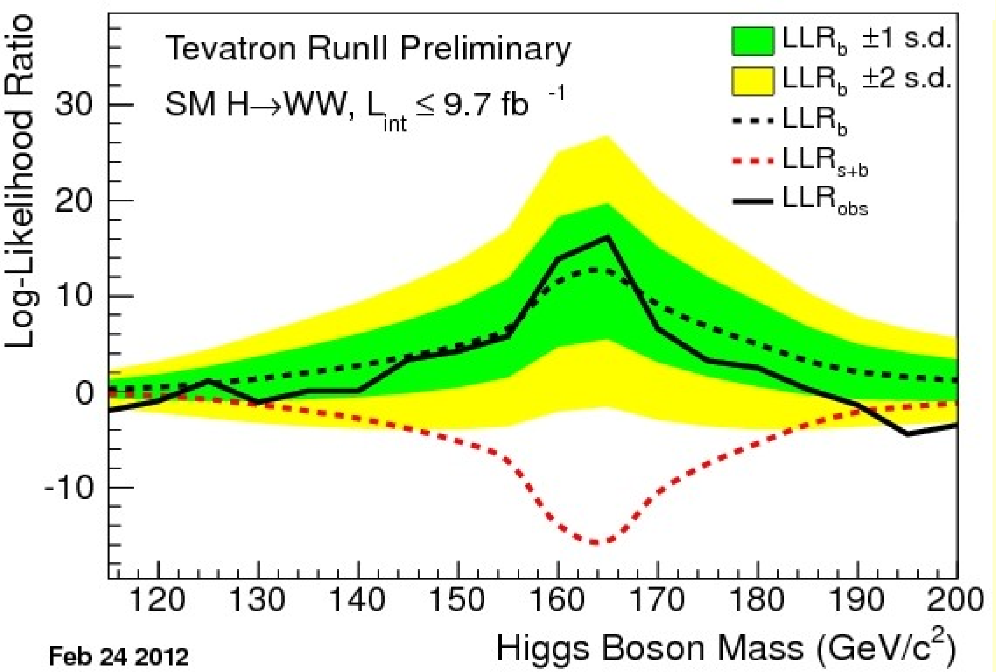


Separate limits

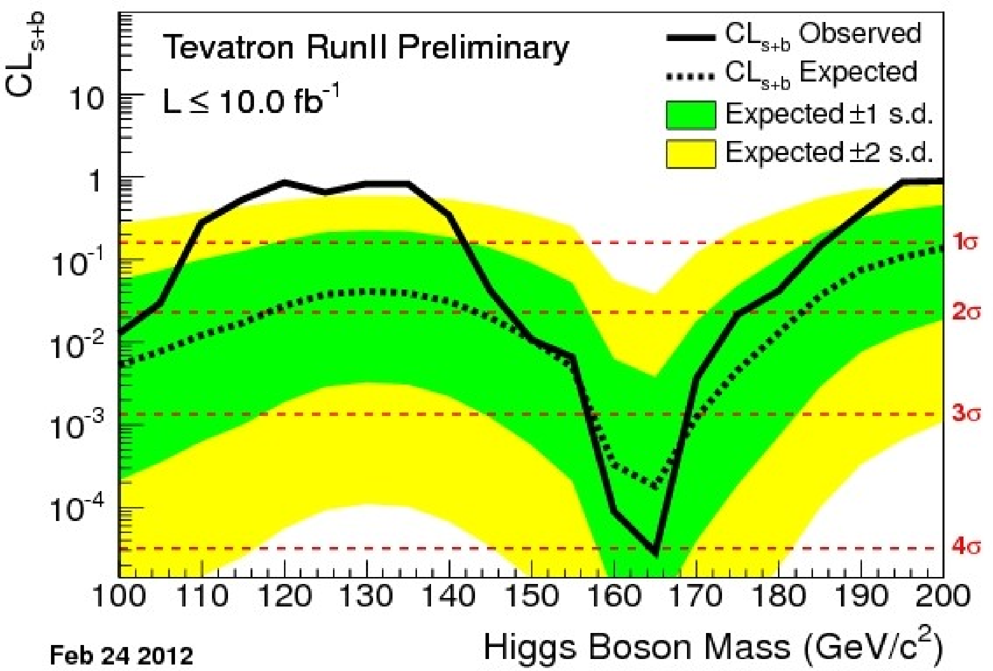


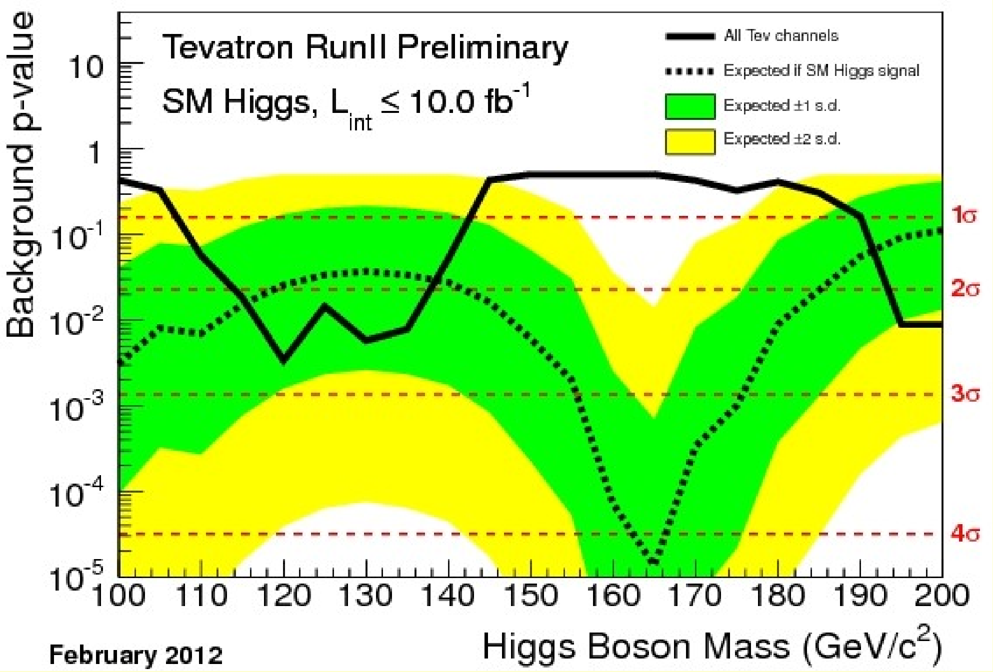






Quantifying excess

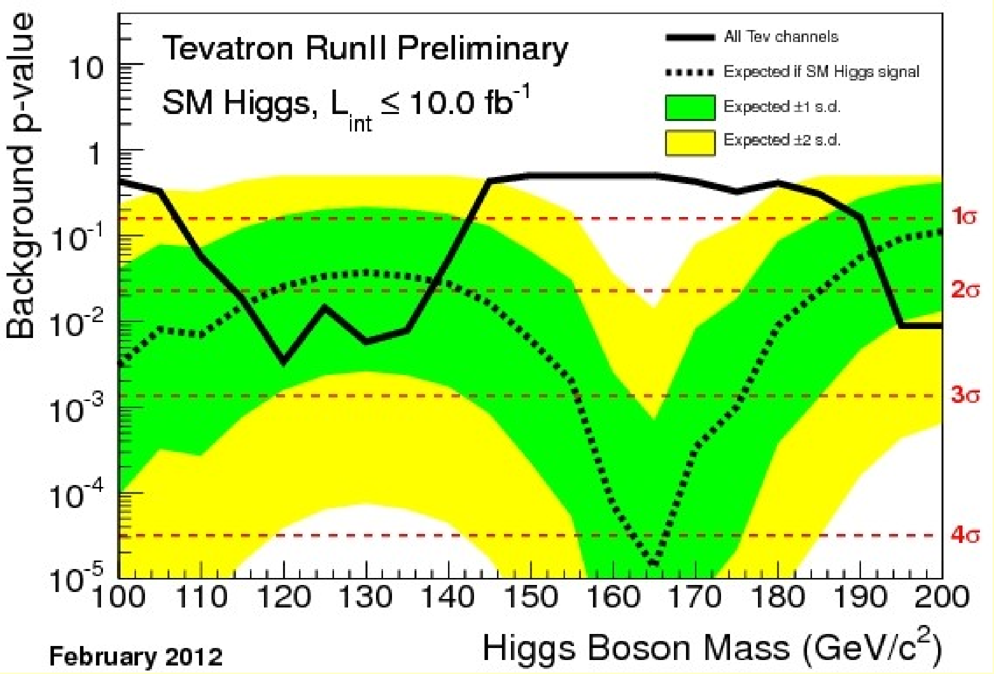


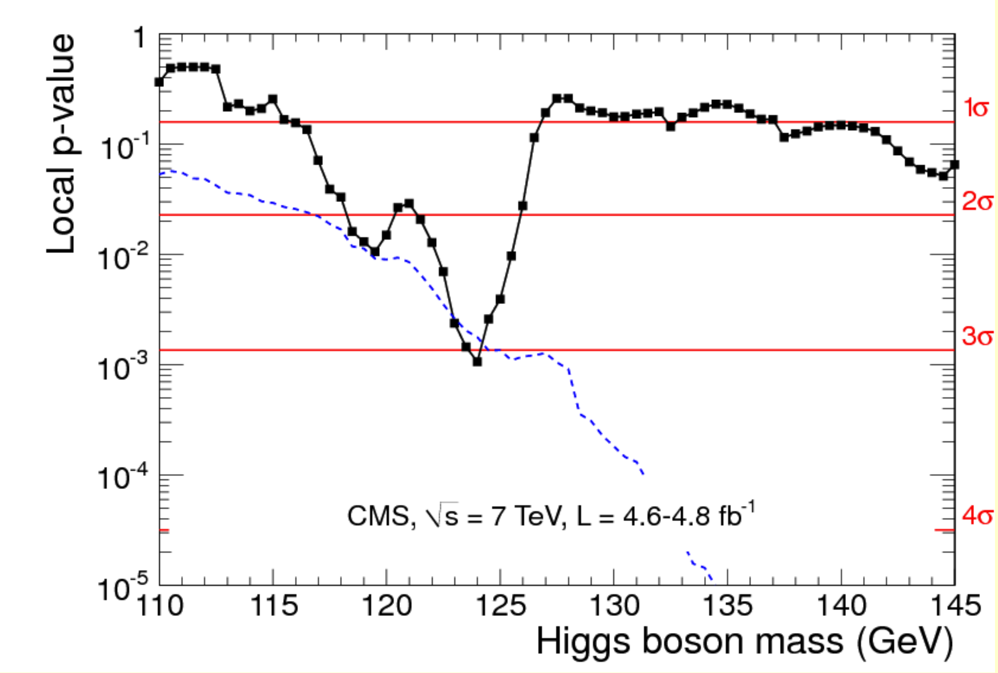


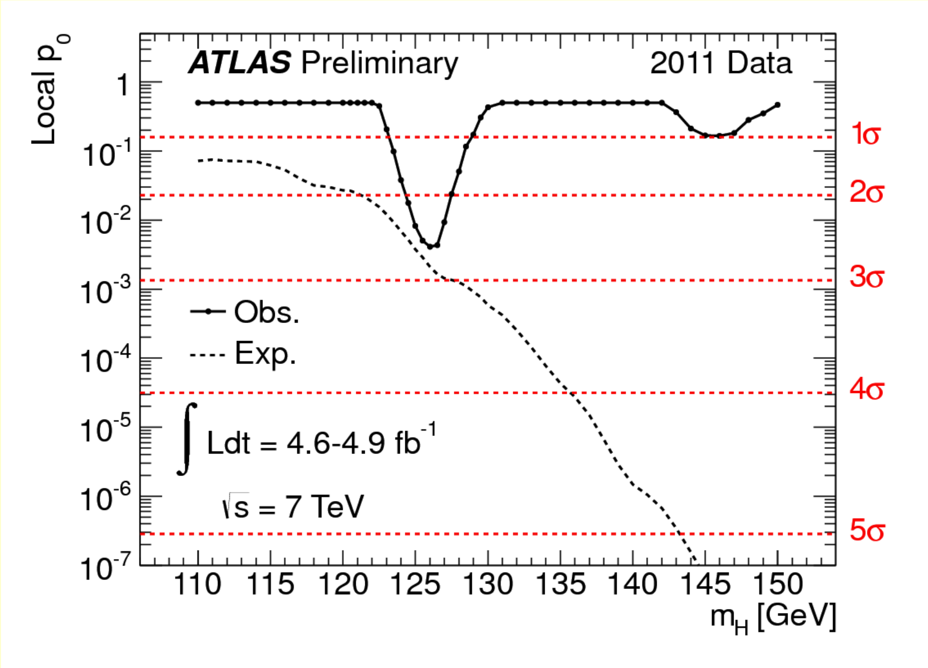
- Small value disfavors hypothesis, while value close to 1 favors it
  - Left: S+B hypothesis disfavored for mH=165 GeV and favored for mH~130 GeV
  - Right: the opposite; it can translate to an excess of 2.7s over the background prediction

Quantifying excess

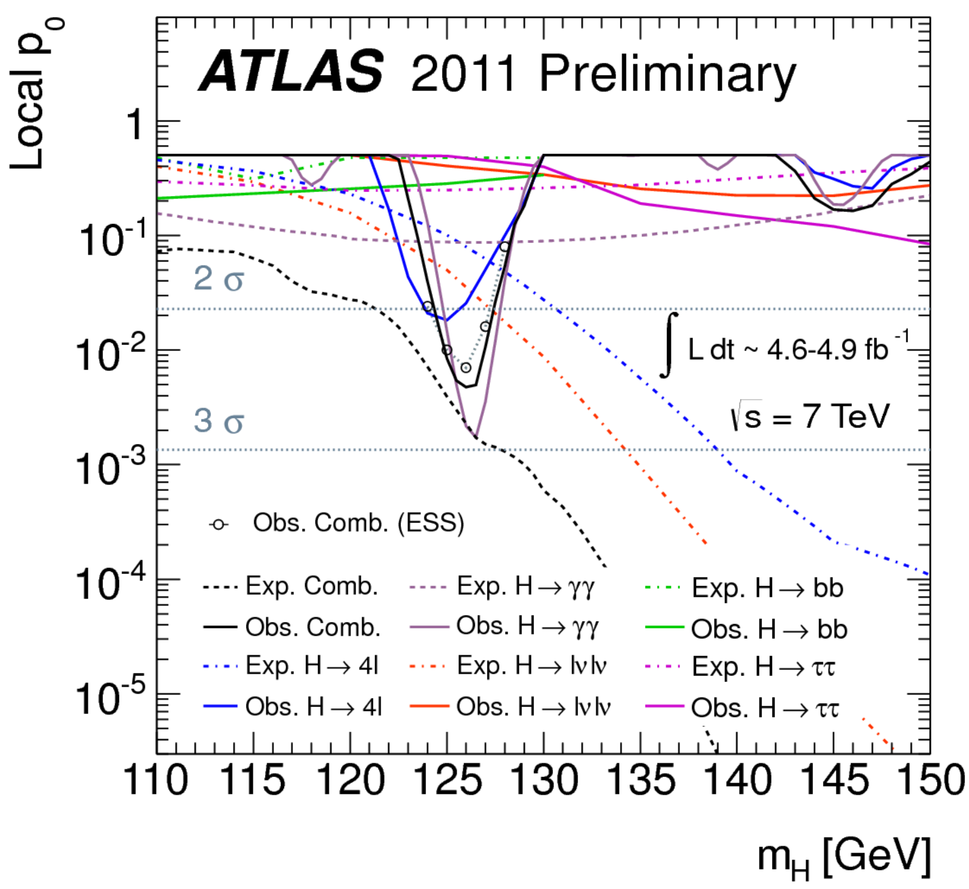
- Tevatron: 2.7σ (LEE: 2.2σ)
- ATLAS: 2.5σ (LEE: 0.5σ)
- CMS: 3.1σ (LEE: 1.5σ)

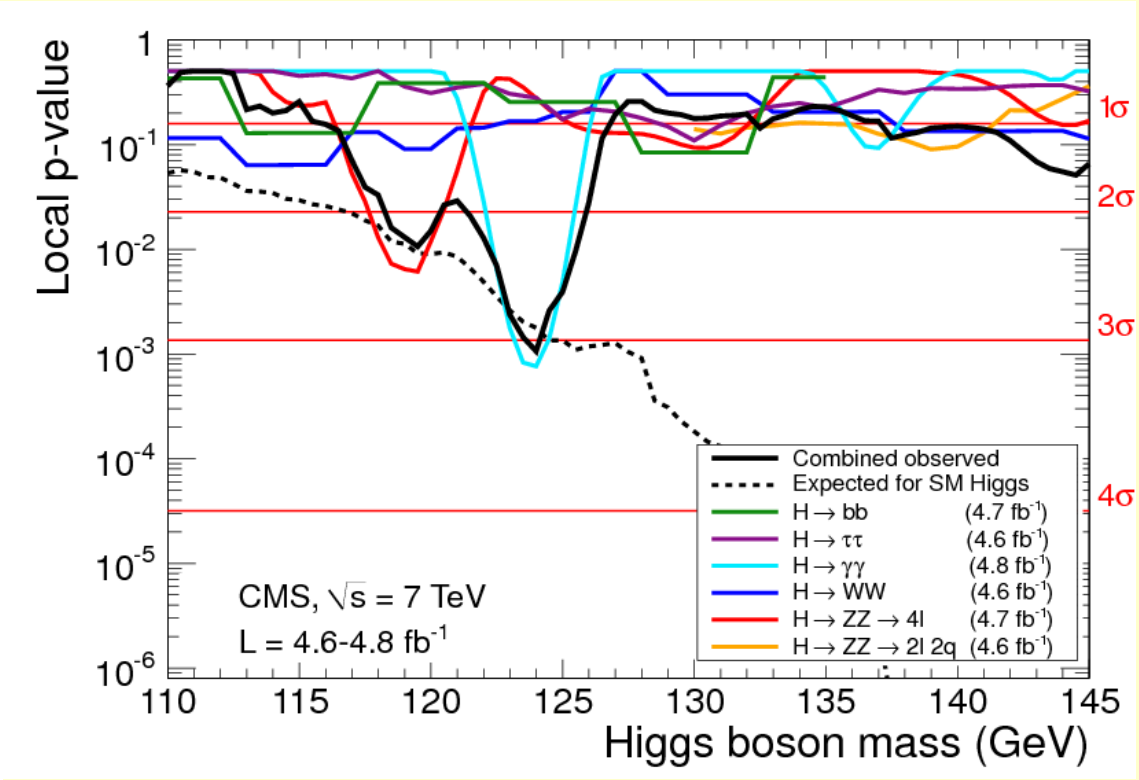




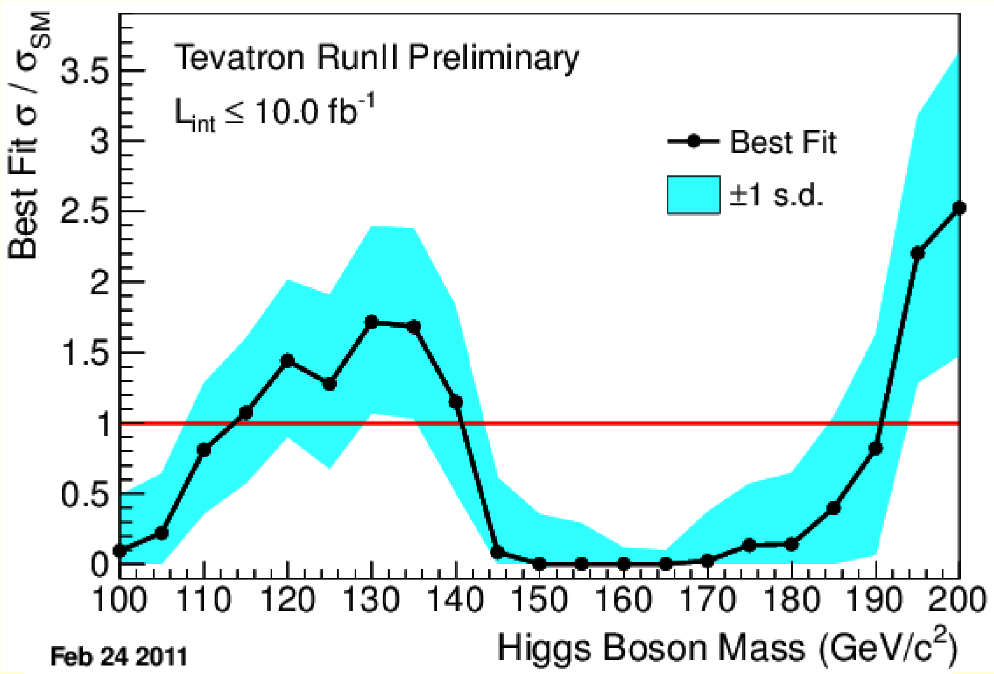


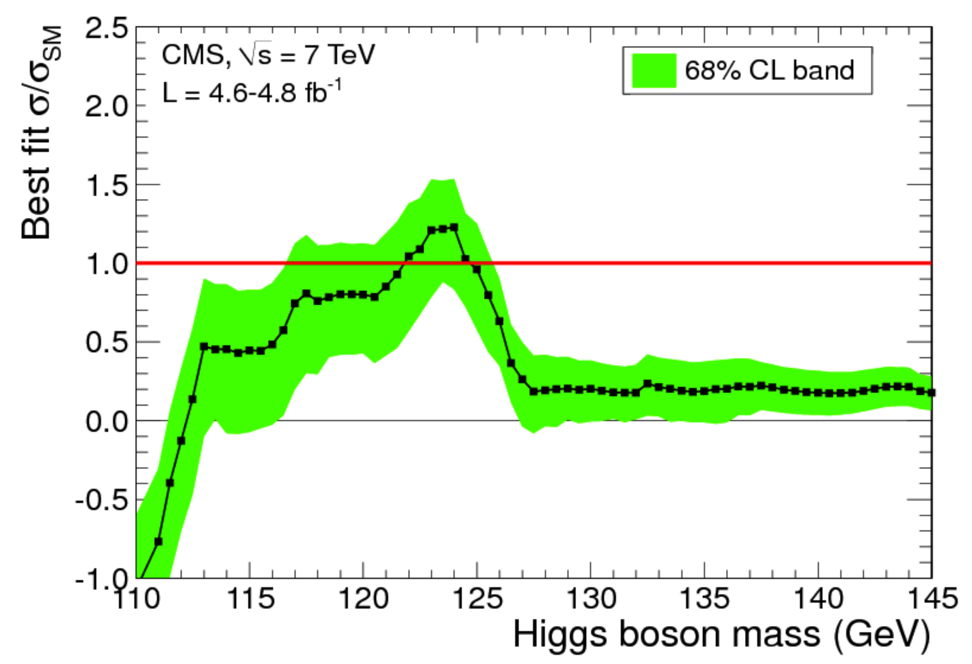
Quantifying excess

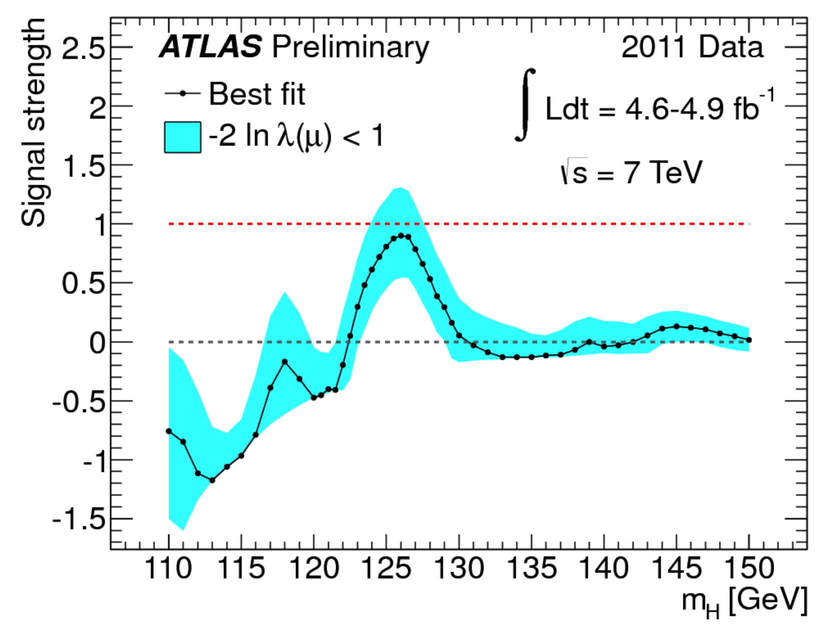




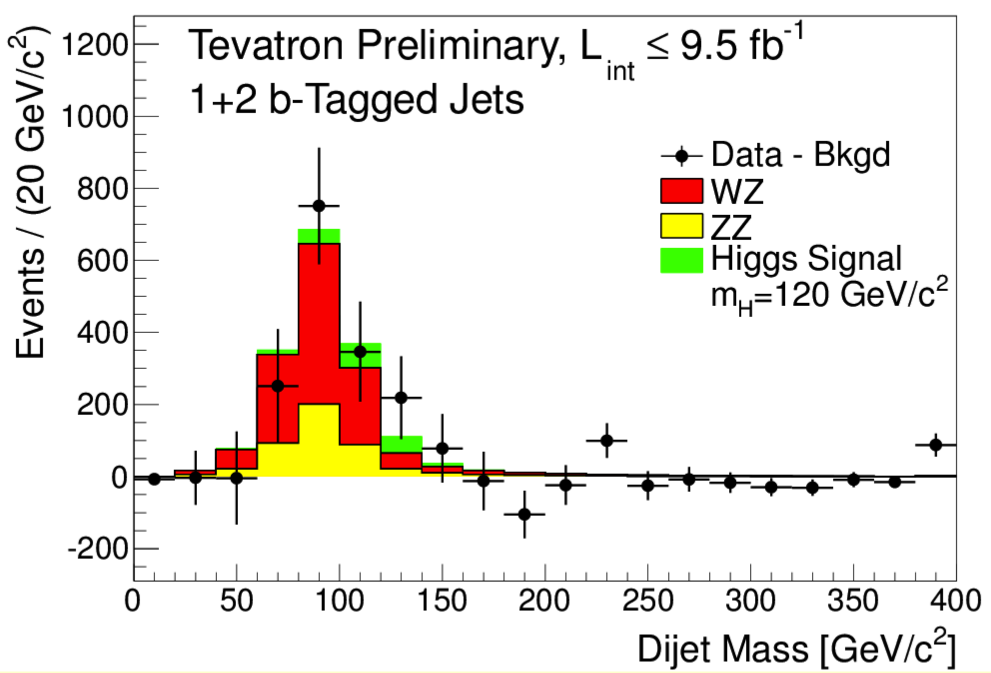
Quantifying excess



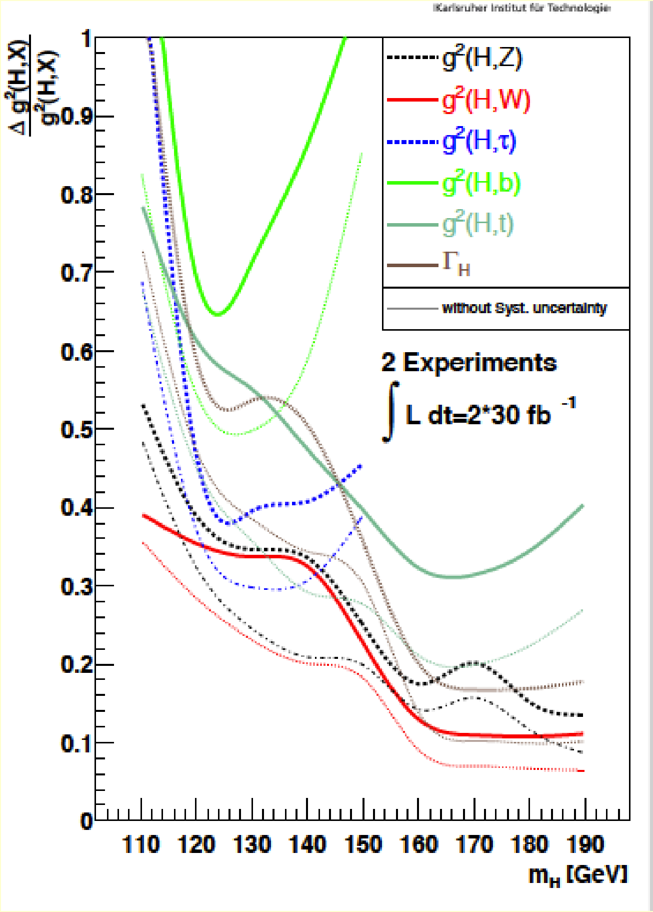




Signal added to diboson

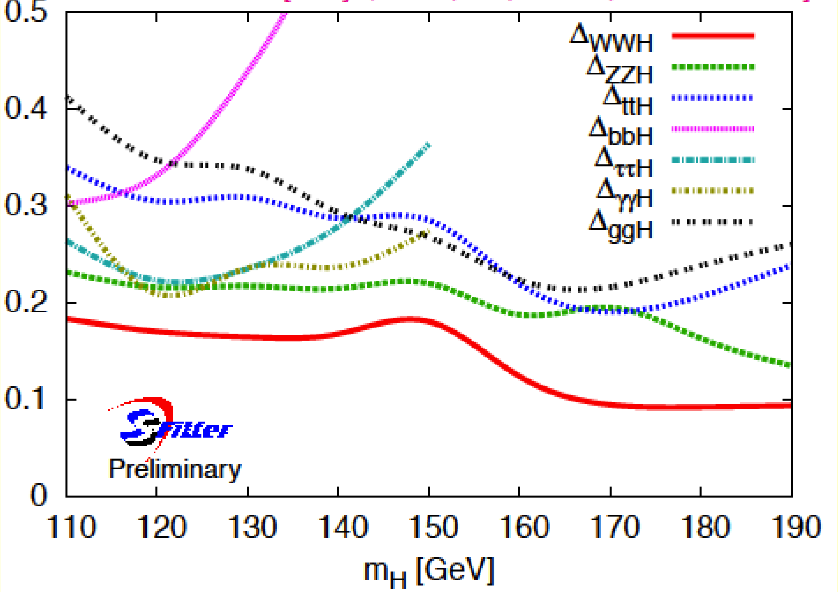


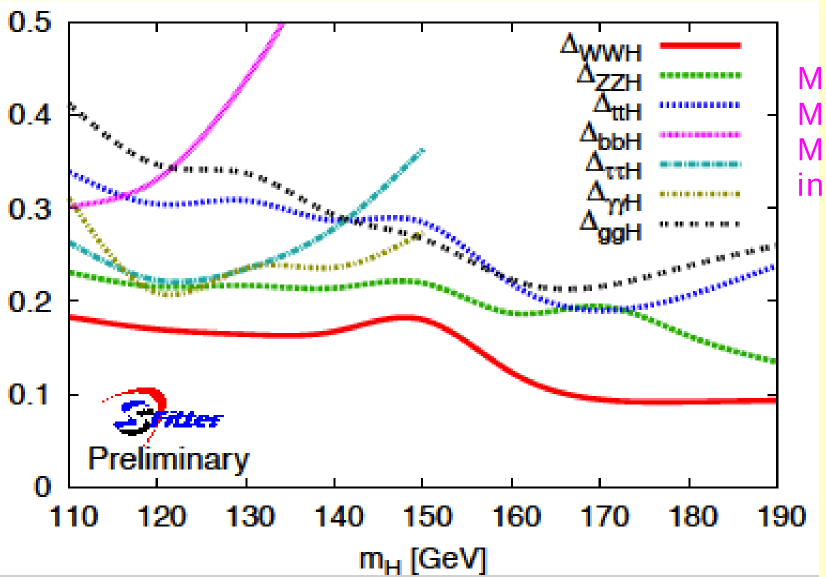
Measurements



[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

[Lafaye, Plehn, MR, Zerwas, Dührssen 2009]



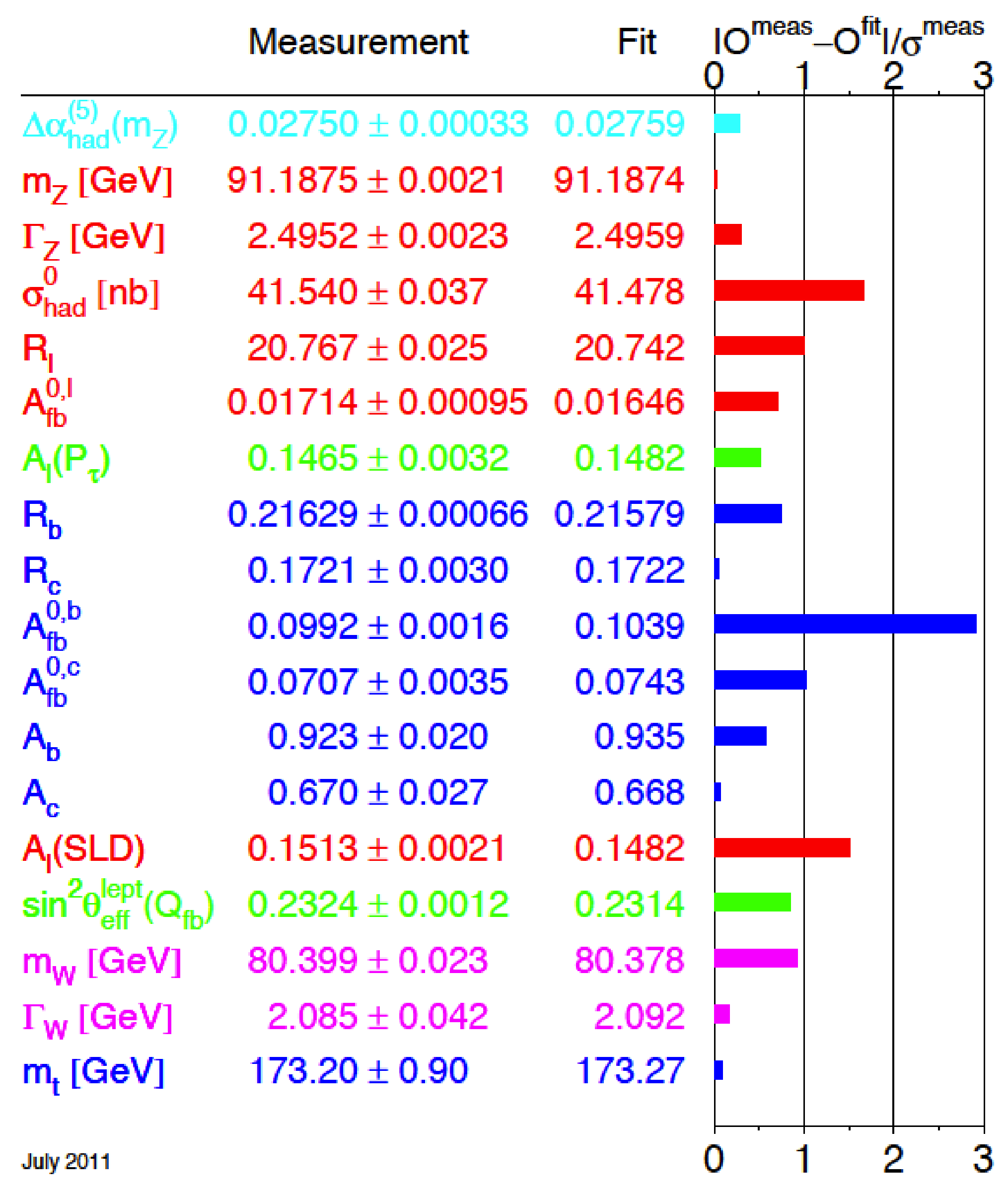


M. Rauch, talk at Moriond EW 2012;
M. Klute, R. Lafaye, T. Plehn,
M. Rauch, D. Zerwas, M. D¨uhrssen,
in preparation

Look Elsewhere Effect

- We estimate the LEE effect in a simplified manner. In the mass range 100–125 GeV/c2, where the low-mass H→bb searches dominate, the reconstructed mass resolution is approximately 10-15%, or about 15 GeV/c2. We therefore estimate a trials factor of ~ 2 for the low-mass region. For the high-mass searches, the H→W+W– searches dominate the sensitivity. There is little-to-no resolution in reconstructing mH in these channels due to the presence of two neutrinos in the final state of the most sensitive analyses. We expect a trials factor of approximately two for the high-mass searches. In total, we expect that there are roughly four possible independent locations for uncorrelated excesses to appear in our analysis. The global p-value is therefore 1–(1–pmin)4, using the Dunn-Sidak correction [56]. The global significance for such an excess anywhere in the full mass range is estimated to be 1.52σ.

SM fits



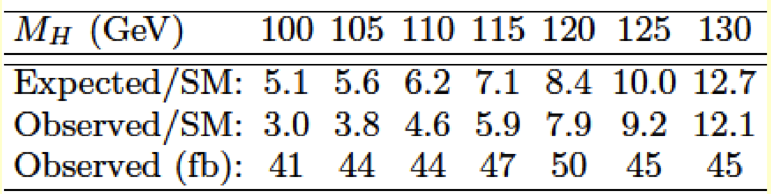
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27

July 2011

Lessons from Tevatron

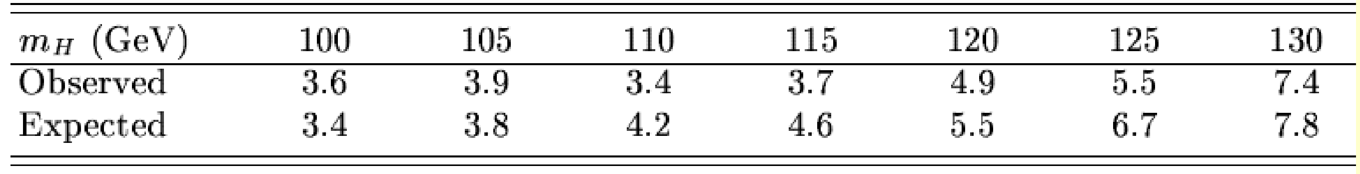
- Efficient data taking
  - Lower downtime to fix problems in control room, providing data of the best quality
- Object reconstruction and identification
  - High efficiency and purity
- Excellent modeling of known processes
  - Understanding the problems
- Powerful multivariate techniques
  - They are not an answer, but valuable tool
- Systematic uncertainties
- Superb statistical tools

D0 llbb with 4.2 fb^{-1}



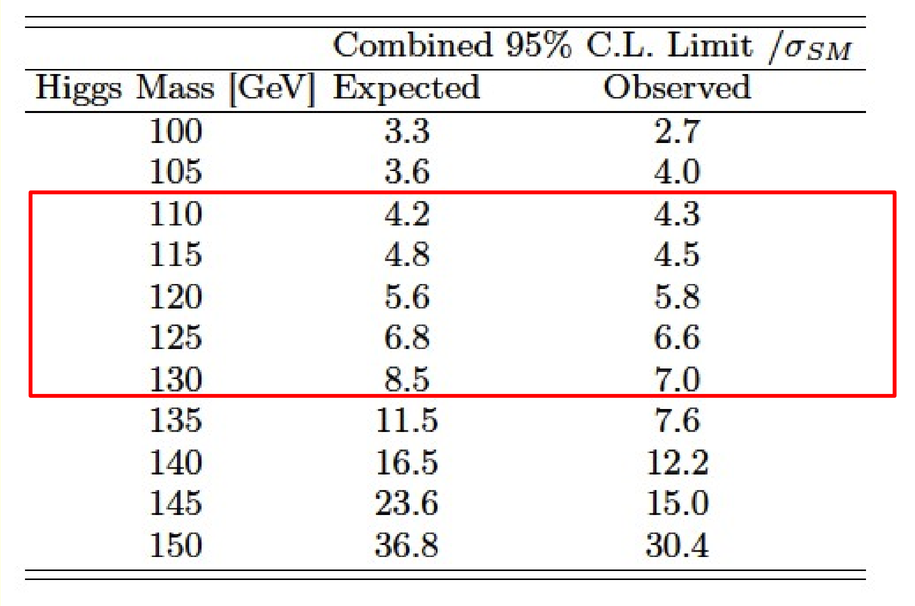
M_H (GeV)	100	105	110	115	120	125	130
Expected/SM:	5.1	5.6	6.2	7.1	8.4	10.0	12.7
Observed/SM:	3.0	3.8	4.6	5.9	7.9	9.2	12.1
Observed (fb):	41	44	44	47	50	45	45

D0 ννbb with 5.3 fb^{-1}



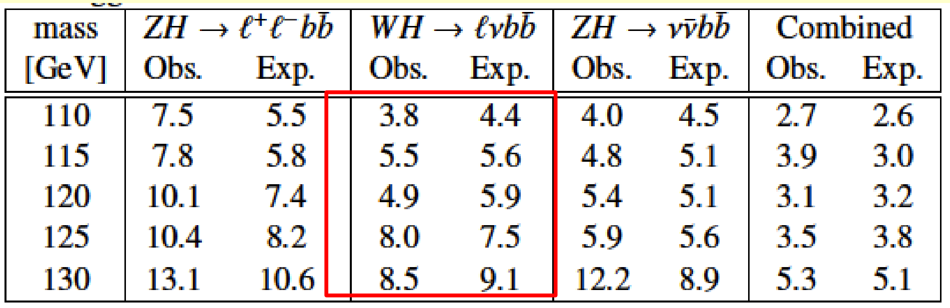
m_H (GeV)	100	105	110	115	120	125	130
Observed	3.6	3.9	3.4	3.7	4.9	5.5	7.4
Expected	3.4	3.8	4.2	4.6	5.5	6.7	7.8

D0 WH with 5.4 fb^{-1}



	Combined 95% C.L. Limit /σ_{SM}	
Higgs Mass [GeV]	Expected	Observed
100	3.3	2.7
105	3.6	4.0
110	4.2	4.3
115	4.8	4.5
120	5.6	5.8
125	6.8	6.6
130	8.5	7.0
135	11.5	7.6
140	16.5	12.2
145	23.6	15.0
150	36.8	30.4

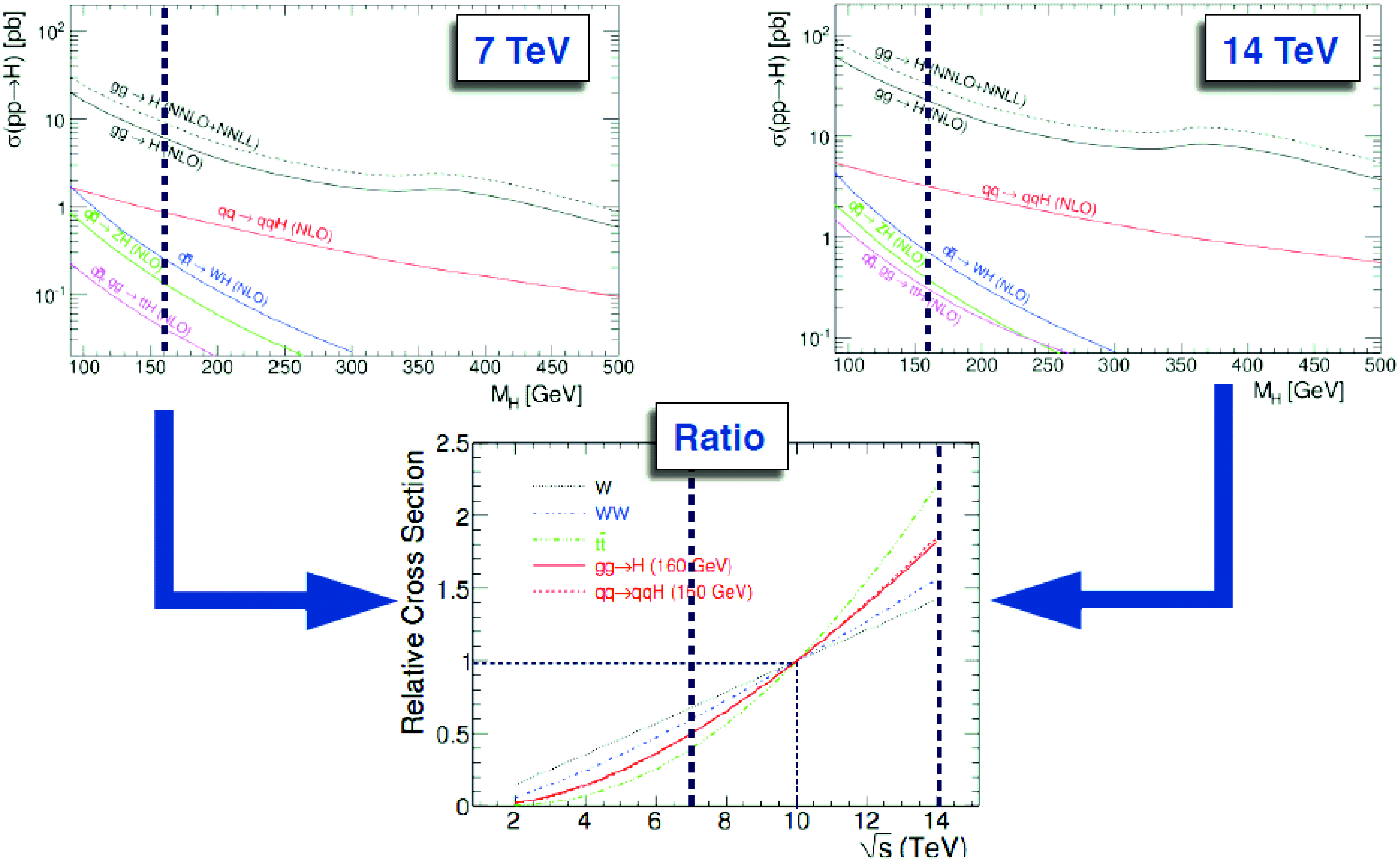
ATLAS VH with 4.7 fb^{-1}



mass	$ZH \to \ell^+\ell^- b\bar{b}$		$WH \to \ell\nu b\bar{b}$		$ZH \to \nu\bar{\nu} b\bar{b}$		Combined	
[GeV]	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
110	7.5	5.5	3.8	4.4	4.0	4.5	2.7	2.6
115	7.8	5.8	5.5	5.6	4.8	5.1	3.9	3.0
120	10.1	7.4	4.9	5.9	5.4	5.1	3.1	3.2
125	10.4	8.2	8.0	7.5	5.9	5.6	3.5	3.8
130	13.1	10.6	8.5	9.1	12.2	8.9	5.3	5.1

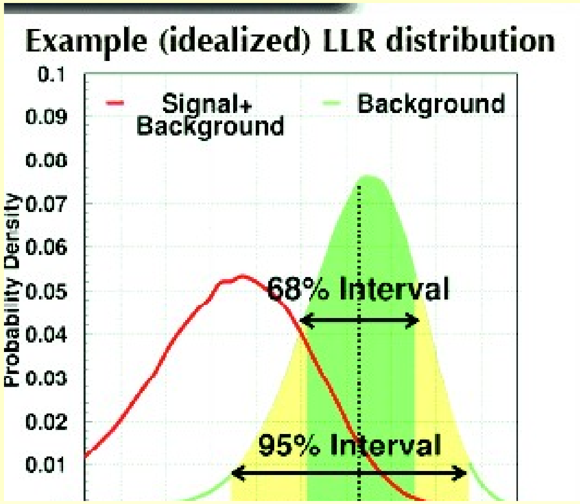
Cross sections

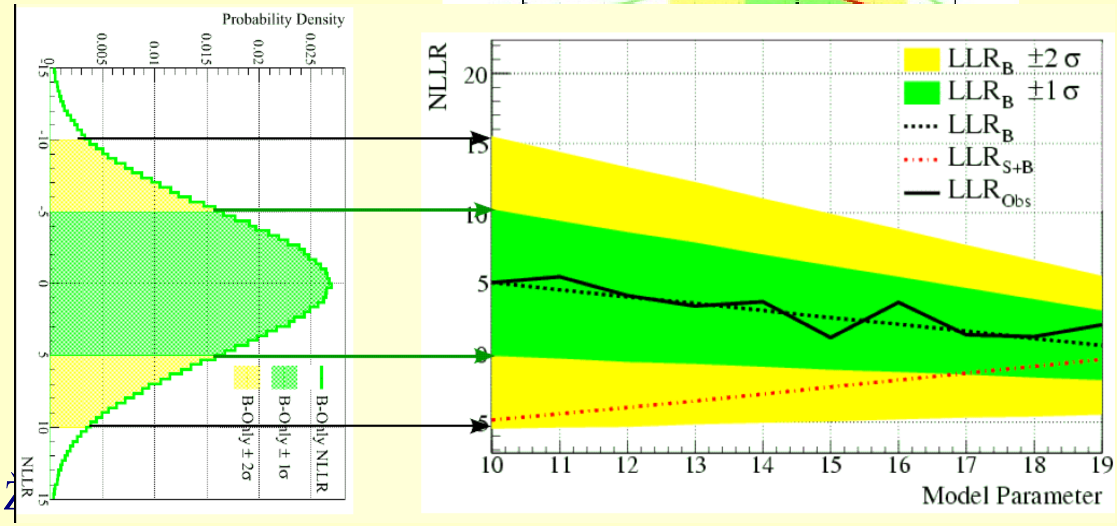
- Higgs
  ggH: D. de Florian and M. Grazzini, Phys. Lett. B 674, 291 (2009)
  C. Anastasiou, R. Boughezal and F. Petriello, JHEP 0904, 003 (2009)
  W/ZH: J. Baglio and A. Djouadi, arXiv:1003.4266v2
  VBF: P. Bolzoni, F. Maltoni, S. -O. Moch and M. Zaro, arXiv:1109.3717.
  (Signal is generated with Pythia with CTEQ6L1 LO parton distribution functions, normalized with MSTW 2008 NNLO PDF (ggh))
- Diboson: J. M. Campbell and R. K. Ellis, Phys. Rev. D 60, 113006
- tt: U. Langenfeld, S. Moch and P. Uwer, Phys. Rev. D 80, 054009 (2009)
- Single top: N. Kidonakis, Phys. Rev. D 74, 114012 (2006)
- W/Z+jets: ultimately from data but in agreement with (FEWZ):R. Gavin, Y. Li, F. Petriello and S. Quackenbush, Comput. Phys. Commun. 182, 2388 (2011).
  h.f. fraction from(MCFM) J. M. Campbell and R. K. Ellis, Phys. Rev. D 65, 113007 (2002).


7 TeV
σ(pp→H) [pb]
10^2
10
1
10^{-1}
gg → H (NNLO+NNLL)
gg → H (NLO)
qq → qqH (NLO)
$q\bar{q}$ → ZH (NLO)
$q\bar{q}$ → WH (NLO)
$q\bar{q}$, gg → $t\bar{t}$H (NLO)
100
150
200
250
300
350
400
450
500
M_H [GeV]
14 TeV
Ratio
Relative Cross Section
0
0.5
1
1.5
2
2.5
2
4
6
8
10
12
14
√s (TeV)
W
WW
$t\bar{t}$
gg→H (160 GeV)
qq→qqH (160 GeV)

Limit settings

- Limits derived using semi-frequentist CLs method where test statistic is
  LLR = -2LogQ
  = -2Log[P(s+b)/P(b)]
  - P are probability distribution functions for the signal+background and background only hypotheses
  - P are populated via random Poisson trials with mean values given by the expected number of events in each hypothesis
- Systematic uncertainties are incorporated by varying the expected number of events in each hypothesis according to the size and correlations of the uncertainties





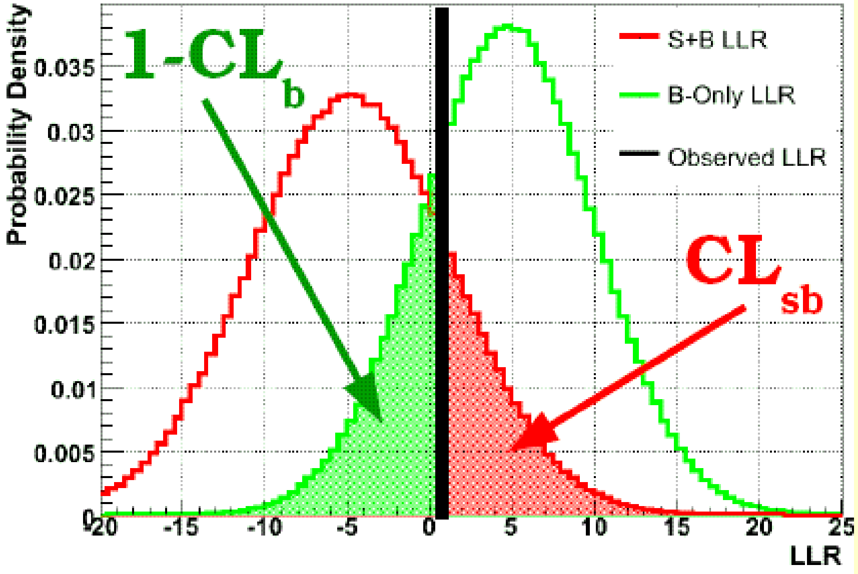
- In the case of the Higgs search, we seek to set limits on potential signal rates
  - ⇒ Similar test, comparing signal+background and background-only hypotheses
  - ⇒ Signal rate is now a fixed parameter to be tested

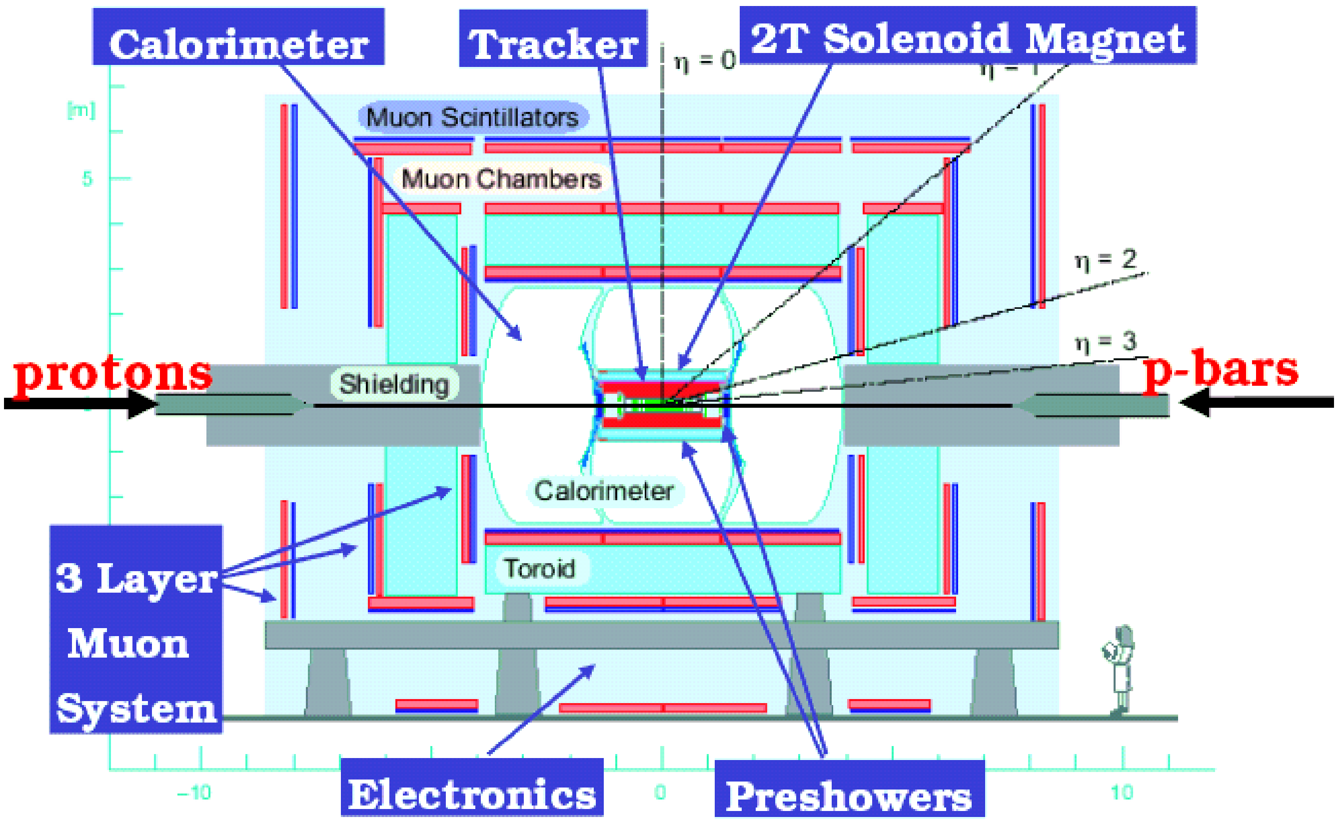
$$Q = \frac{L(D|S+B)}{L^{\dagger}(D|B)} \longleftarrow$$

Two independent likelihood maximizations are performed over nuisance parameters: one for each hypothesis (S+B & B-Only)

$$LLR \;=\; -2\,\ln Q \;=\; \chi^2(D|S+B) \;-\; \chi^2(D|B)$$

- The relative frequency of outcomes from S+B and B-Only pseudo-experiments allows us to test the signal rate
  - CLsb: fraction of S+B pseudo-experiments more background-like than data
  - CLb: fraction of B-Only pseudo-experiments more background-like than data
  - 1-CLb: fraction of B-Only pseudo-experiments more signal-like than data



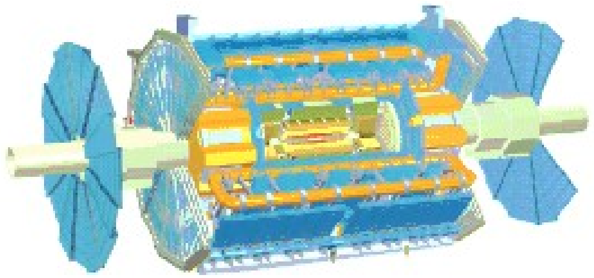


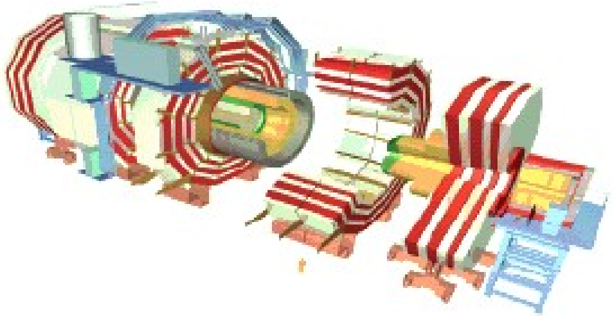
- Silicon microstrip vertex detector
- Scintillating fiber tracker
- Uranium / liquid argon calorimeter
- Wire chamber + scintillation counter muon detector system
- 2T solenoid magnet & 1.8T toroid magnet

Angular Coverage	$|\eta|$
Muon ID	**~2**
Tracking	**~2.5**
EM / Jet ID	**~4**

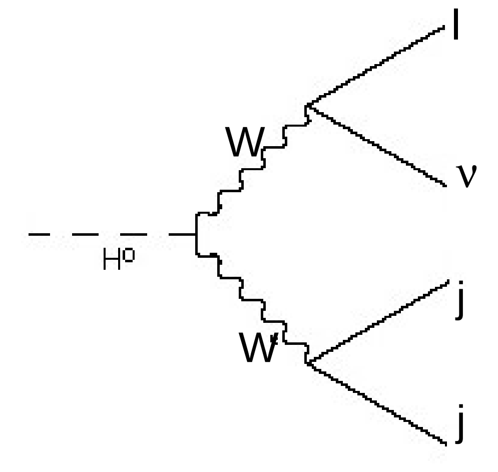
ATLAS vs CMS

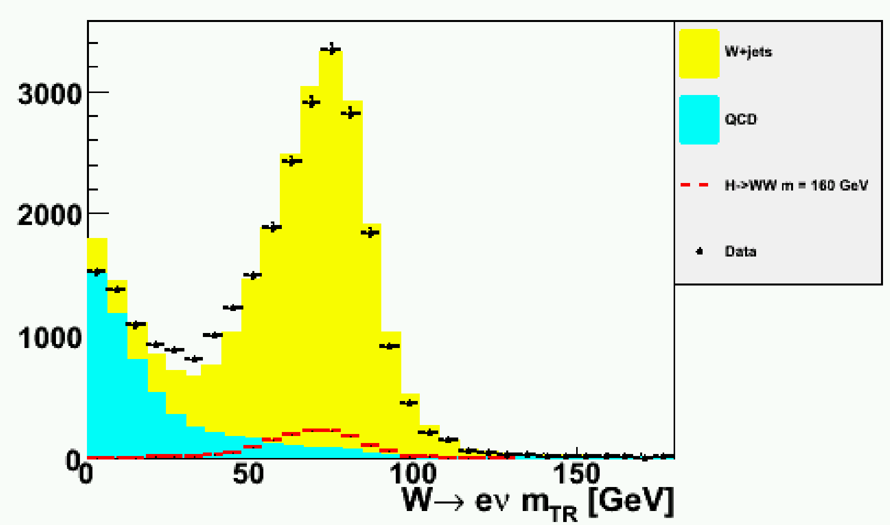
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)

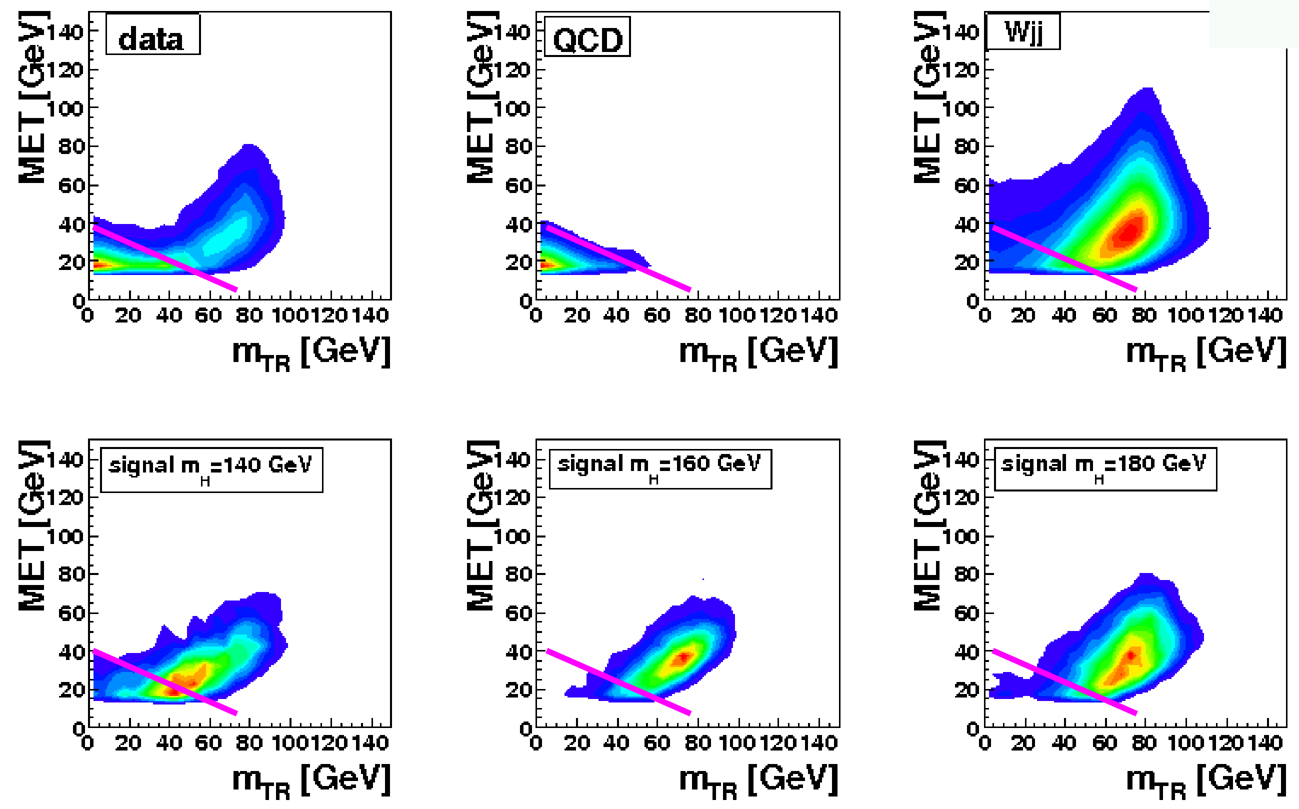




Event Selection

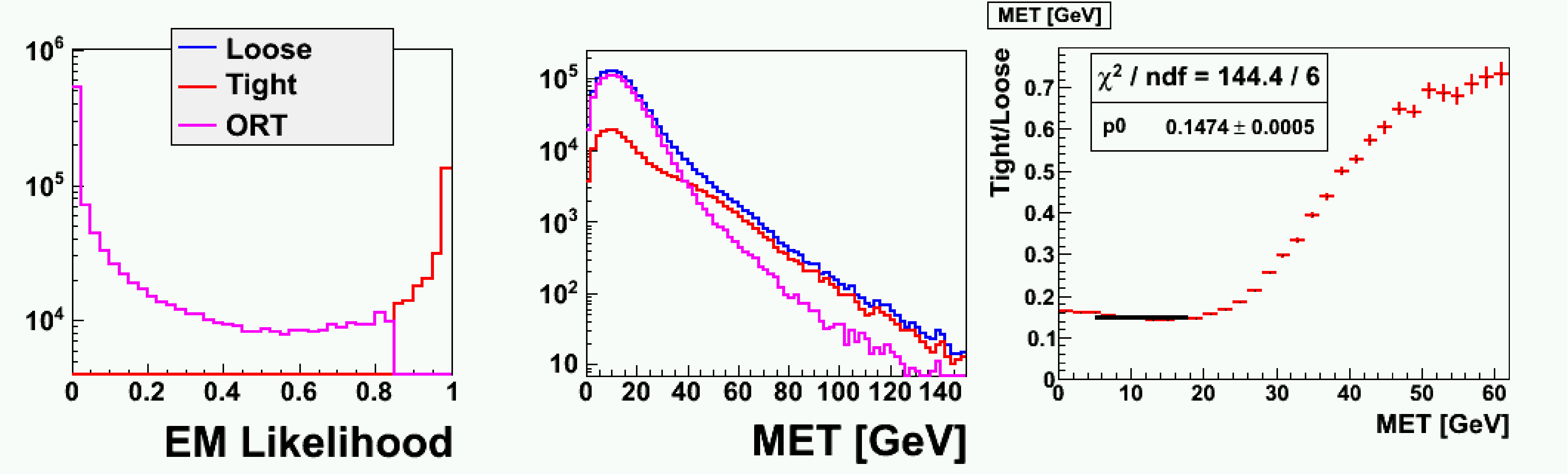




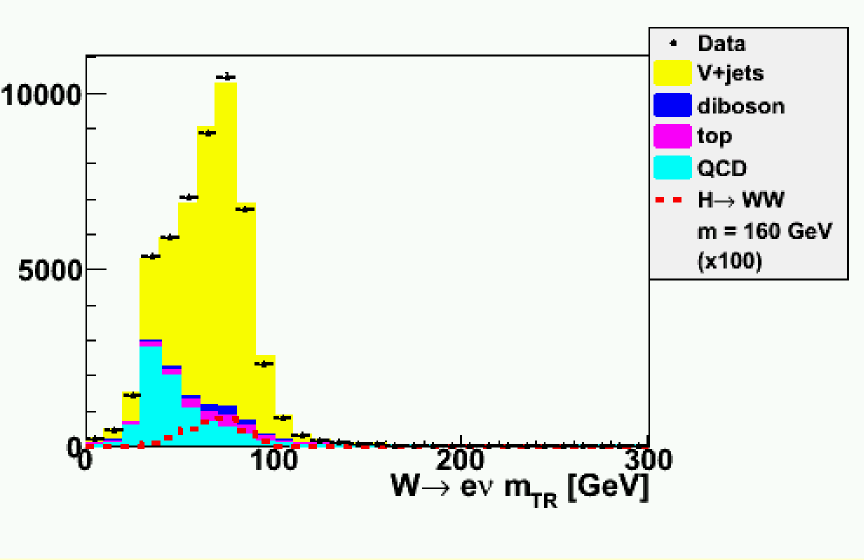


- QCD reduction
  - electron faking jet
  - missmeasured jet energies give MET
- Triangle cut between transverse mass and MET

QCD estimation



- We use so called matrix method
  - Define 3 different sample: Loose, Tight and Orthogonal:
    - Loose and Tight are used to measure efficiency of QCD and "signal" events in data, ε_{QCD} and ε_{Sig}, and to obtain normalization
    - Orthogonal is used to get the correct shap
  - It may depend on the p_T of lepton



NLO pQCD calculations & MC Models

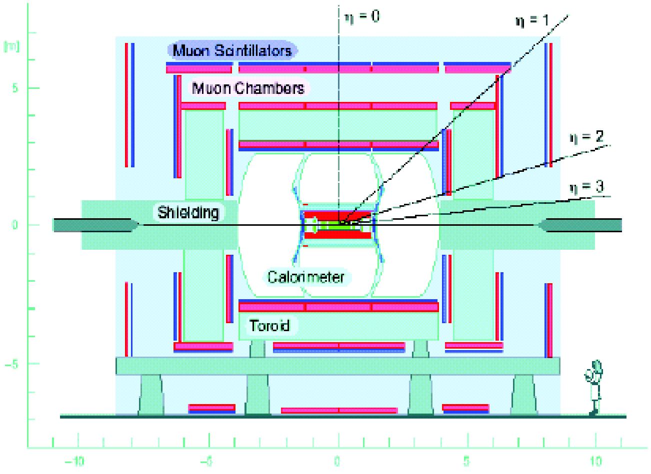
- pQCD predictions calculated with MCFM, JetPhoX
- Many LO MC programs on the market:
  - MEPS: Alpgen, Sherpa, Madgraph, Helac, Madevent, ...
  - PS: Pythia, Herwig, Ariadne, ...
- CKKW
  - the separation of ME and PS for different multijet processes is achieved through a kT-measure
  - undesirable jet configurations are rejected through reweighting of the matrix elements with analytical Sudakov form factors and factors due to different scales in alpha_s
- MLM
  - matching parameters chosen, ME and PS jets matched in each n-parton multiplicity, events vetoed which do not have complete set of matched jets
  - further suppression required to prevent double counting of n and n+1 samples (replaces Sudakov reweighting in CKKW)

The DØ Detector

Tracking:
Silicon Microstrip Tracker
Central Fiber Tracker
2 T Solenoid

Calorimeter:
Liquid Argon Calorimeter
Inter Cryostat Detector
Pre-shower

Muon:
Drift Tubes
Scintillators
1.8 T Toroid

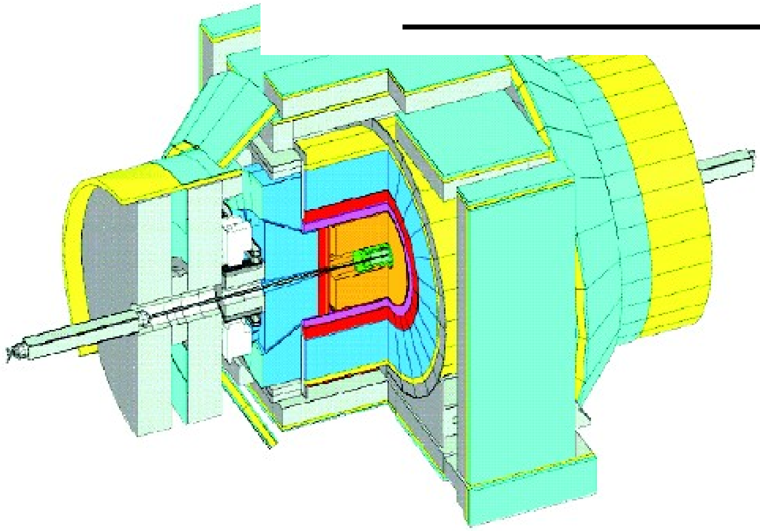


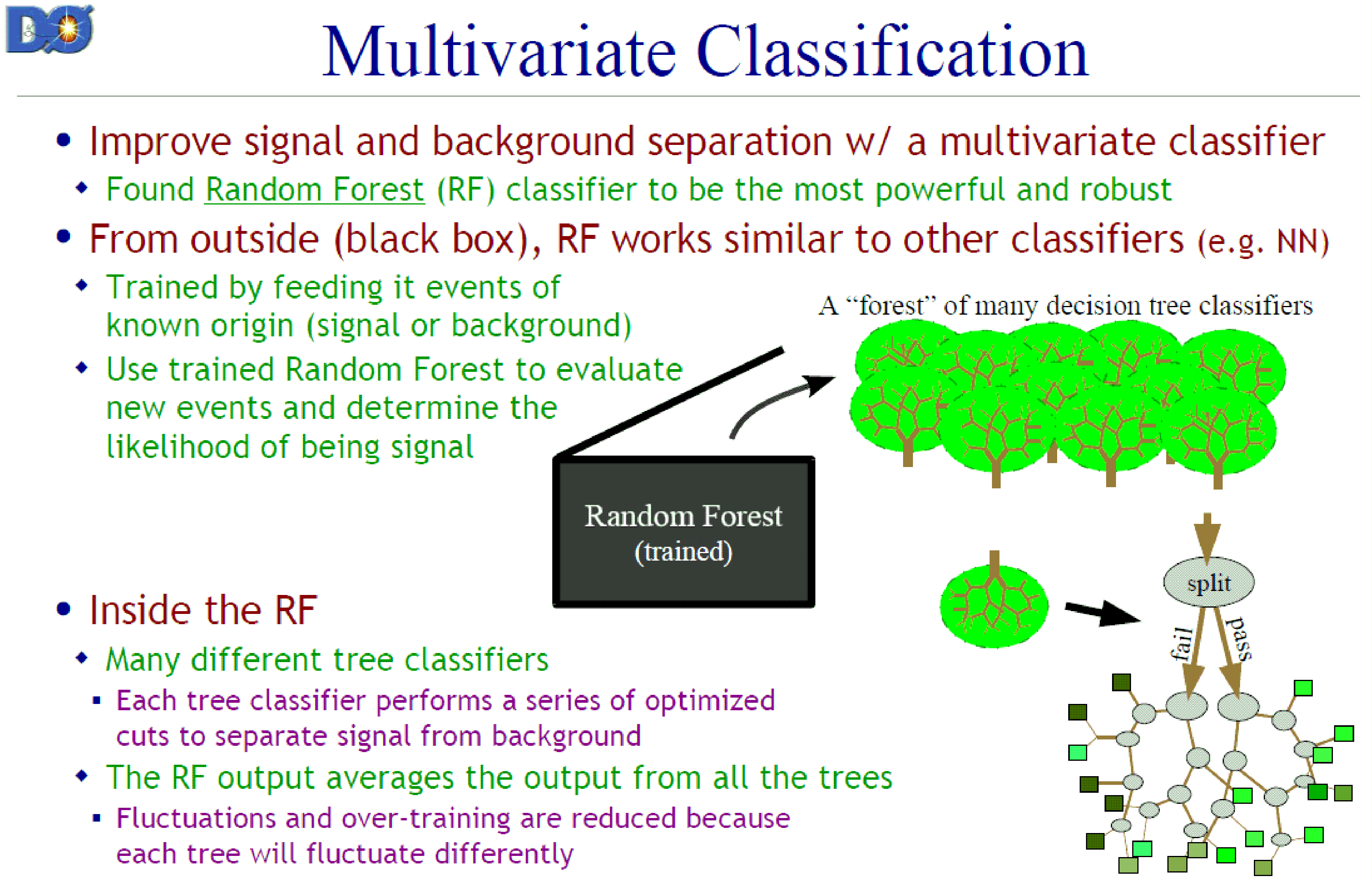
The CDF De

Tracking:
Silicon Vertex Tracker
Central Tracker
1.4 T Solenoid

Calorimeter:
EM Calorimeter
(lead/scintillator)
HAD Calorimeter
(iron/scintillator)

Muon:
Drift Chambers
Scintillators





Multivariate Classification

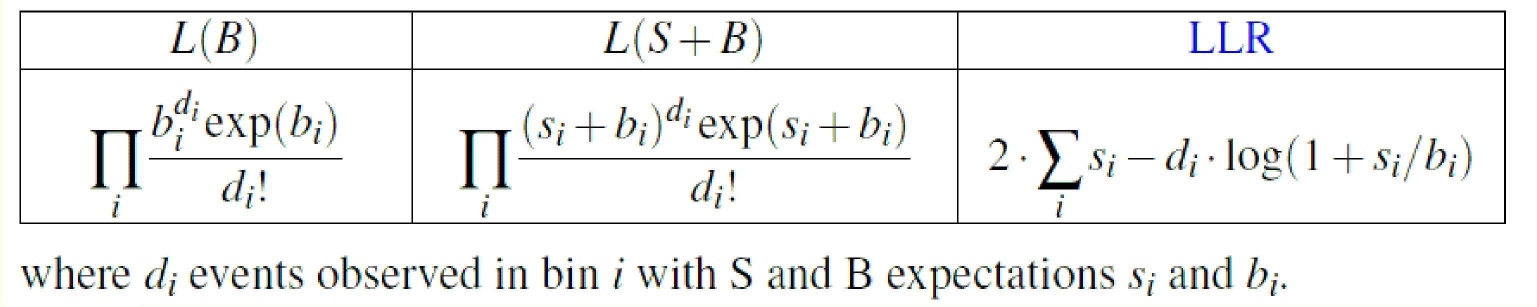
- Improve signal and background separation w/ a multivariate classifier
  - Found Random Forest (RF) classifier to be the most powerful and robust
- From outside (black box), RF works similar to other classifiers (e.g. NN)
  - Trained by feeding it events of known origin (signal or background)
  - Use trained Random Forest to evaluate new events and determine the likelihood of being signal
- Inside the RF
  - Many different tree classifiers
    - Each tree classifier performs a series of optimized cuts to separate signal from background
  - The RF output averages the output from all the trees
    - Fluctuations and over-training are reduced because each tree will fluctuate differently

An example of limits settings

- Our goal is to understand the theory of the SM Higgs boson
  - The answer is either “The SM Higgs is there” or “It's not there”
- We test our data for compatibility with one of two hypotheses:
  - SM+Higgs = signal-like or SM-Only = b-only
- DØ uses a frequentest approach to setting limits:
  - If this experiment is repeated many times, how often would we obtain a result which is as signal-like as what we have observed?
- A 95% CL observed exclusion means:
  - If the excluded signal exists in nature, then only 5% of the time would we obtain a result as background-like as observed in this case.

An example of limits settings

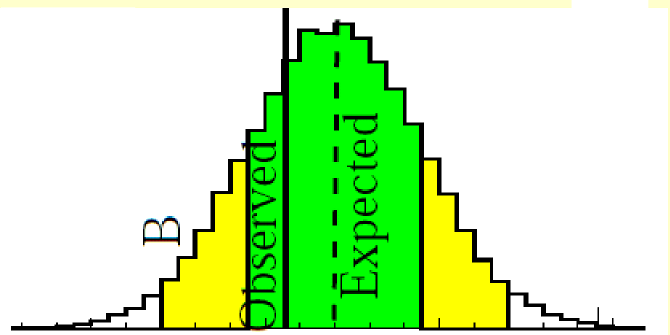
- Compare Poisson likelihood of B hypothesis to S+B hypothesis, and calculate their negative log likelihood ratio (LLR):

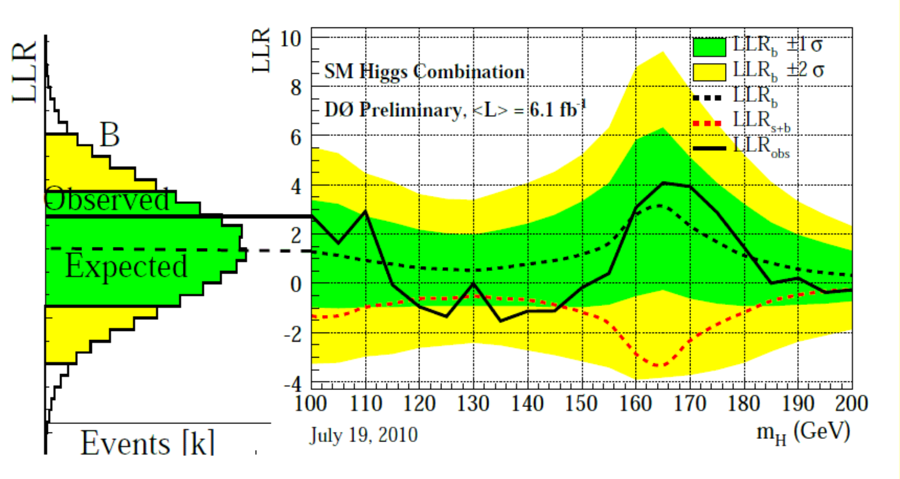


$L(B)$	$L(S+B)$	LLR
$\prod_i \frac{b_i^{d_i}\exp(b_i)}{d_i!}$	$\prod_i \frac{(s_i+b_i)^{d_i}\exp(s_i+b_i)}{d_i!}$	$2\cdot\sum_i s_i - d_i\cdot\log(1+s_i/b_i)$

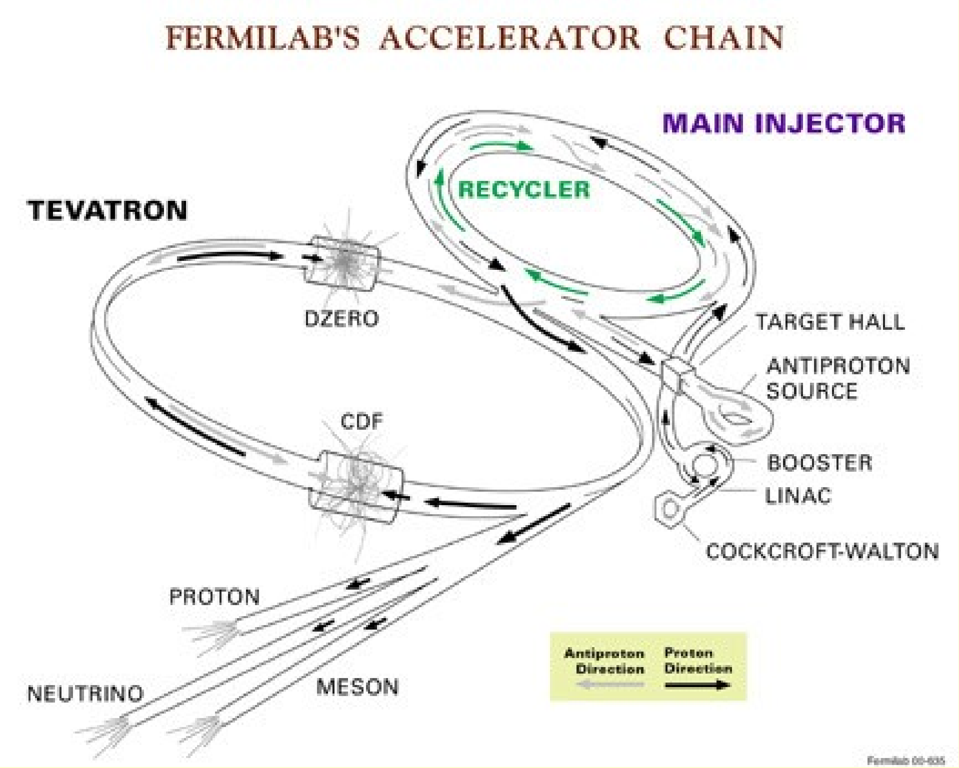
where d_i events observed in bin i with S and B expectations s_i and b_i.

- Sum over all bins gives observed LLR
- Repeat calculation but with pseudo-data obtained by a Poisson fluctuation of b_i in each bin (B) or s_i+b_i in each bin (S+B)
- Repeat many times to obtain LLR distribution: median is Expected LLR





Tevatron accelerator



- The Cockcroft Walton accelerates negative hydrogen ions to 740 KeV. The negative ions are then accelerated down the LINAC to 400 MeV. The particles enter the booster where the electrons are stripped off, leaving the protons. In the Booster, the protons are then accelerated to 8 GeV. Once the protons enter the Main Injector, they are accelerated to 150 GeV. From here, the protons are injected into the Tevatron. The Tevatron accelerates protons and antiprotons to nearly 1 TeV.
- Fermilab makes antiprotons by smashing protons against a nickel target. The Antiproton Source in Fermilab's accelerator complex makes about 20 antiprotons for every 100 million protons they smash on the target. Fermilab then collects the antiprotons in the accumulator, one of the complex's 10 accelerators. The antiprotons are transferred over to the Recycler ring and then cooled. Cooling the antiprotons makes them easier to manipulate and accelerate and increase the rate of collisions.