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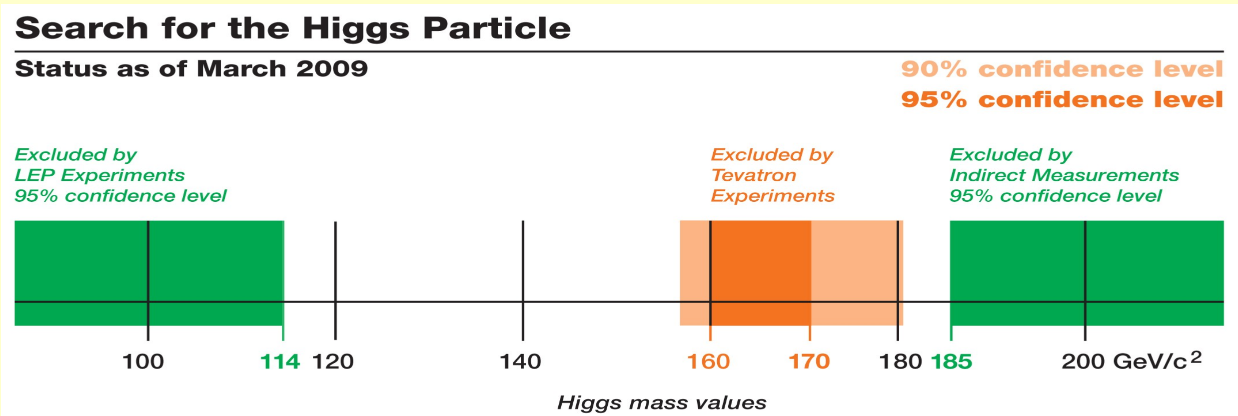
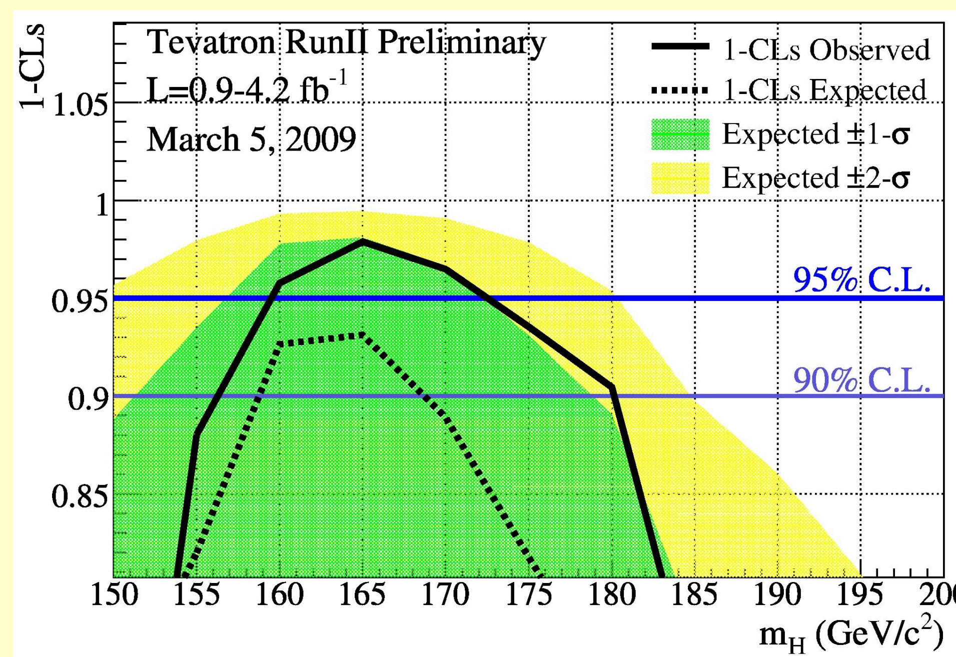
Closing in on the Higgs boson



Lidija Živković
Columbia University

Seminar @UVA
November 18th, 2009

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



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

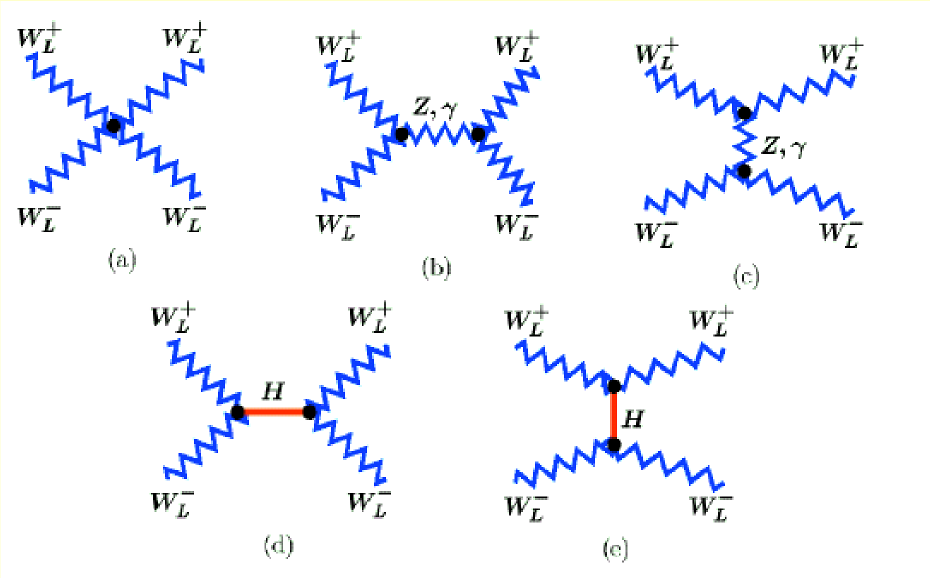
- Essential ingredient of the Standard Model
  - Complex scalar field with potential
- Used to break the el. weak symmetry……

$$M_{W^\pm} = \tfrac{1}{2} v g \qquad M_Z = \tfrac{1}{2} v g / \cos\theta_W = M_W / \cos\theta_W$$

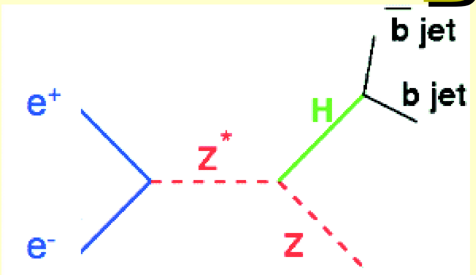
- ….. and to generate fermion masses:

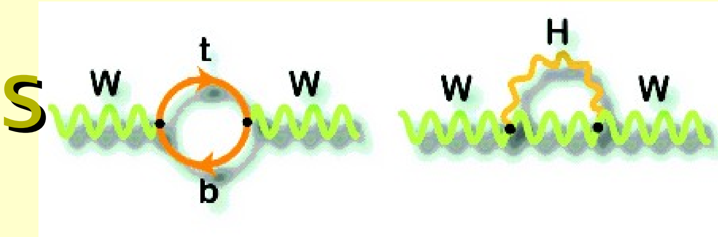
$$\mathbf{m_f = g_f v / \sqrt{2}} \qquad \mathbf{\Rightarrow g_f = m_f \sqrt{2} / v}$$

- Unitarity requires a Higgs boson or similar
  - cross section for WW scattering diverges like s/M_W^2
  - scalar Higgs boson cancels divergences



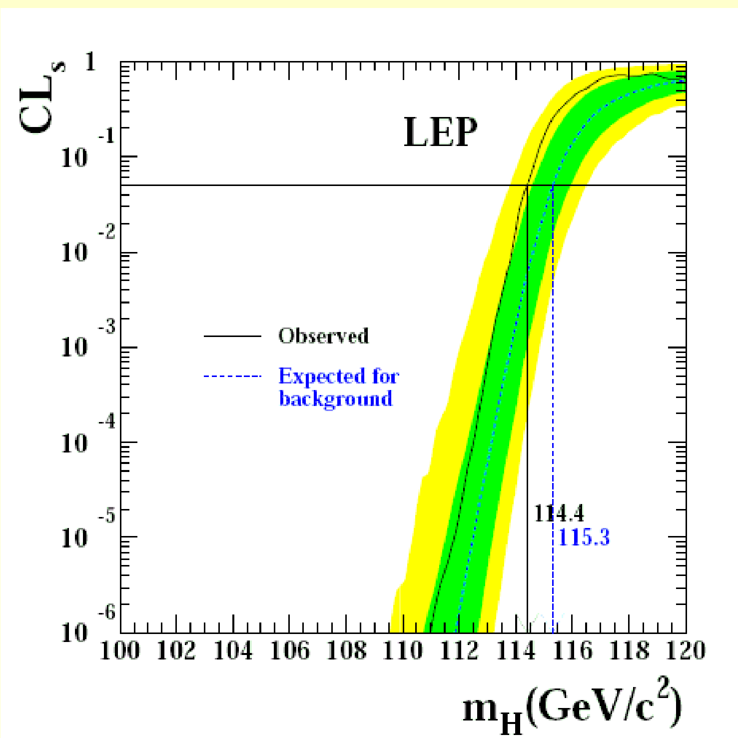
Bounds on Higgs mass

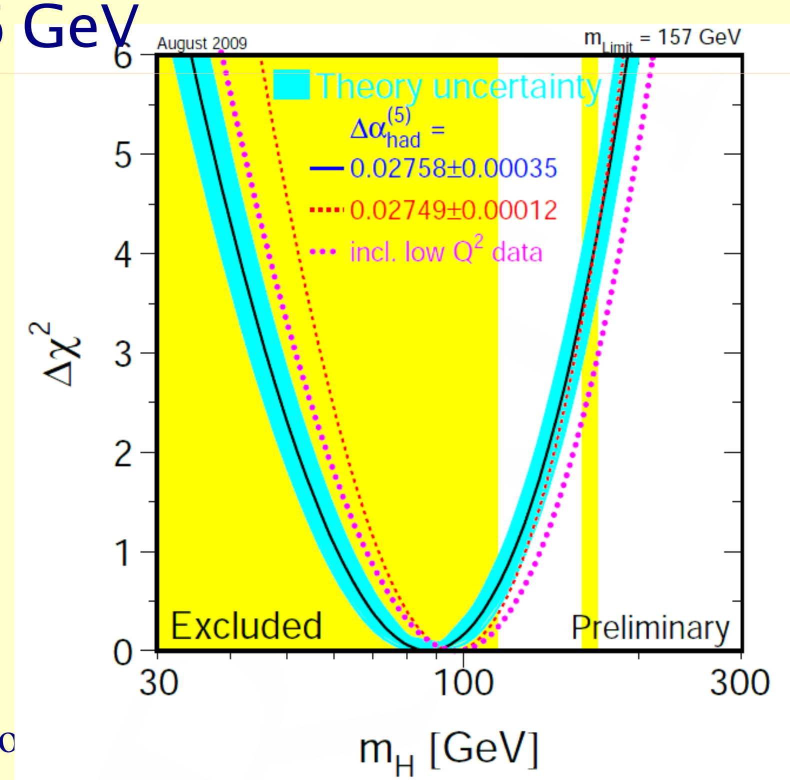




- Lower limits obtained from direct searches at LEP $m_H > 114.4$ GeV@95% CL

- global SM electroweak fits provide upper limit
- The best fit gives $m_H = 87^{+35}_{-26} GeV$
- Limit from fit $m_H < 157$ GeV
- Combined with direct searches: m_H ~< 186 GeV

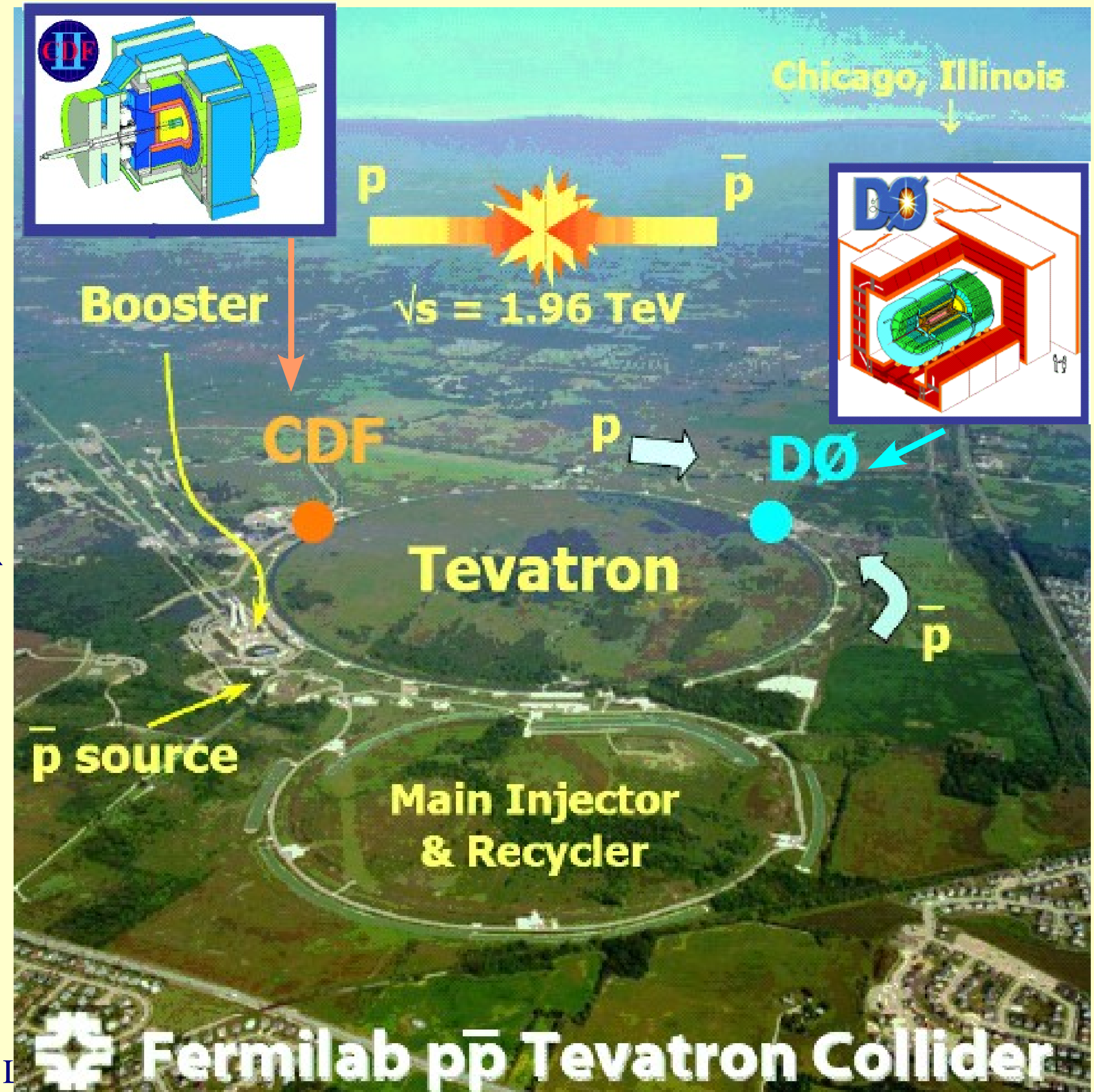




Experiments

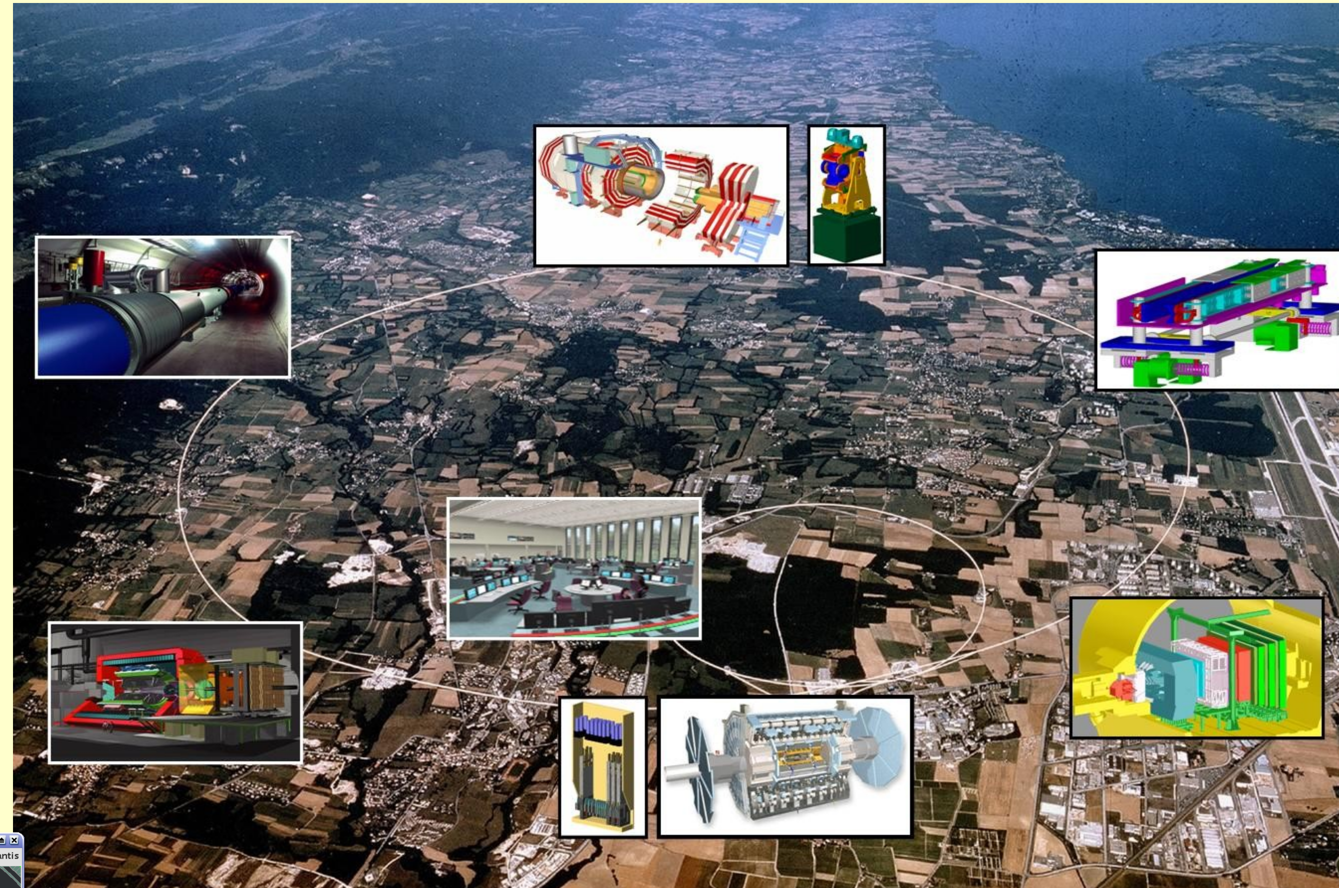
The Tevatron

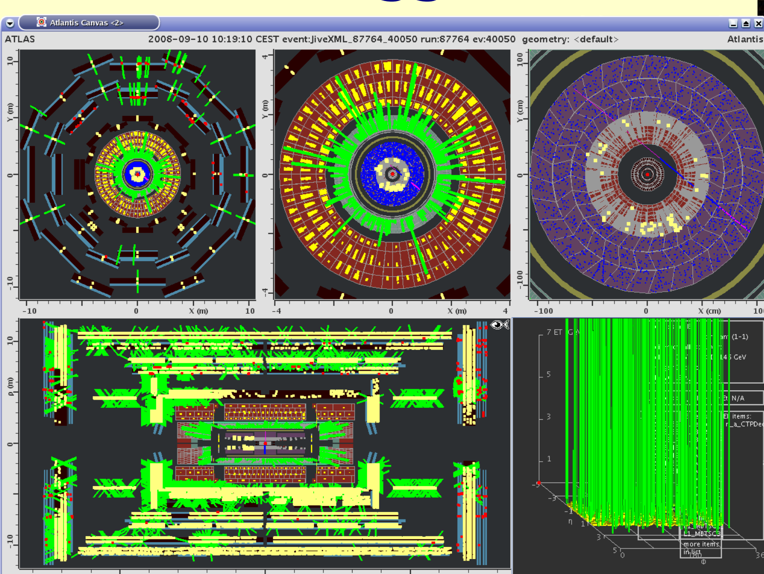
- Running for 14 years
  - 8 in run II
- *$p\bar{p}$ collisions*
- $\sqrt{s}$ = 1.96 TeV
- Discovered top quark
- Already excluded high mass range of the Higgs boson



The future - LHC

- First beam on September 10th 2008
- Expected first collisions in fall of 2009
- Goal is $\sqrt{s}$ = 14 TeV
- Will collect 10 fb^{-1}/yr
- Will give us answer about Higgs

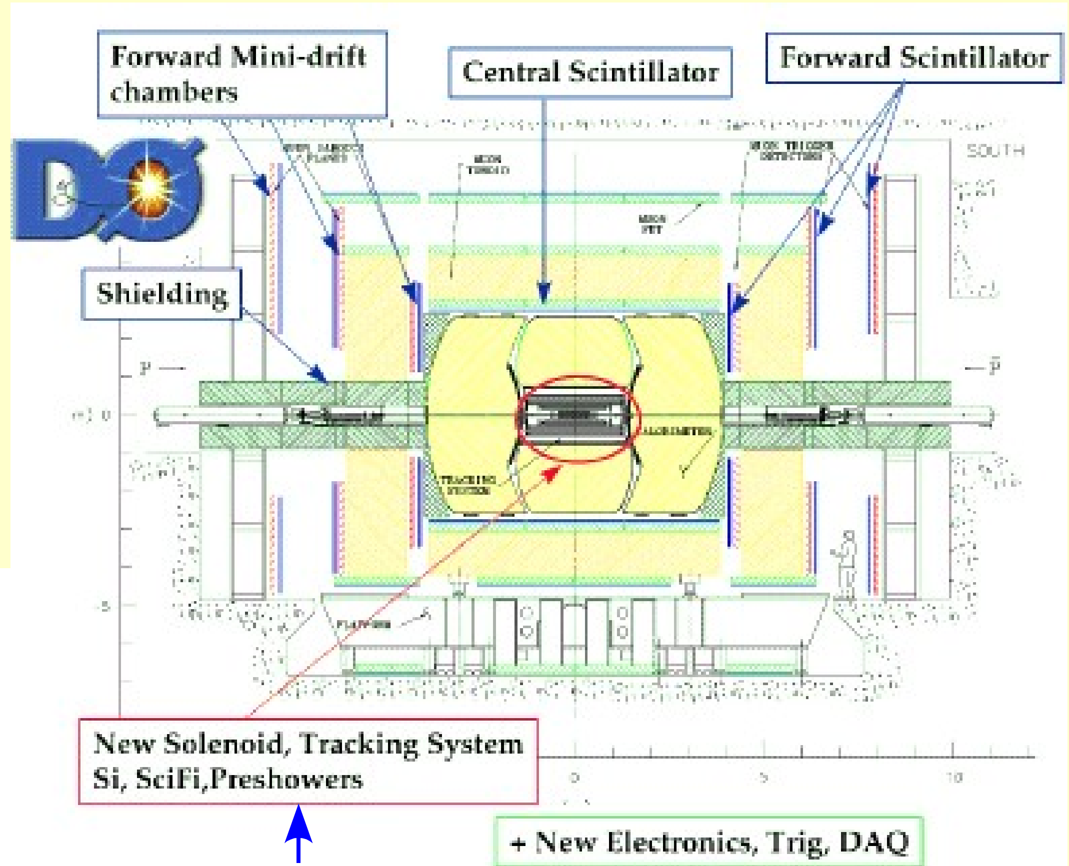




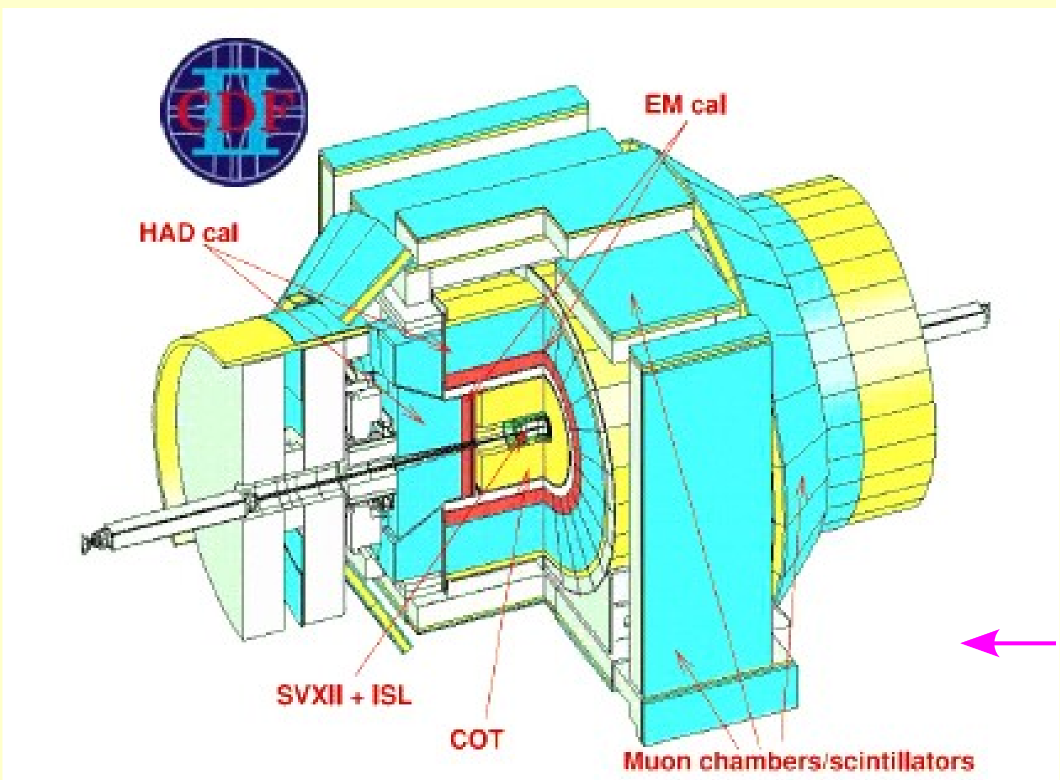
pp collisions

CDF and DØ experiments in Run II

- Both detectors are upgraded in Run II
  - New silicon micro-vertex trackers
  - New tracking systems
  - Upgraded muon chambers



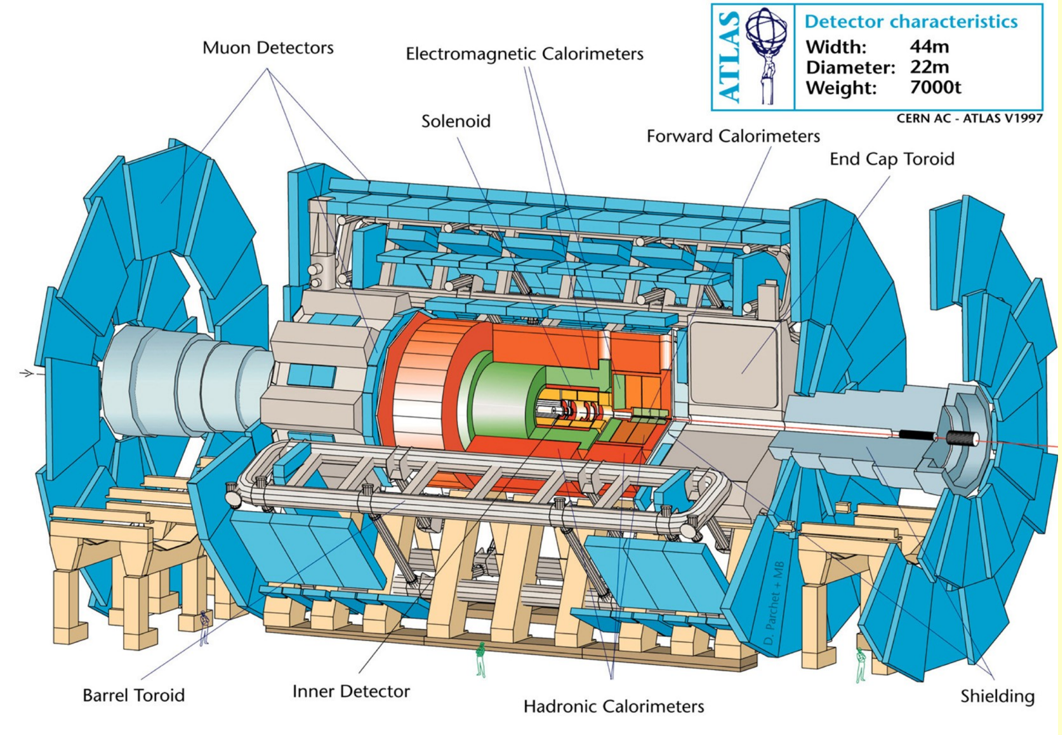
DØ: new solenoid, new pre-showers,
LØ for SMT in RunIIb, new L1Cal trigger

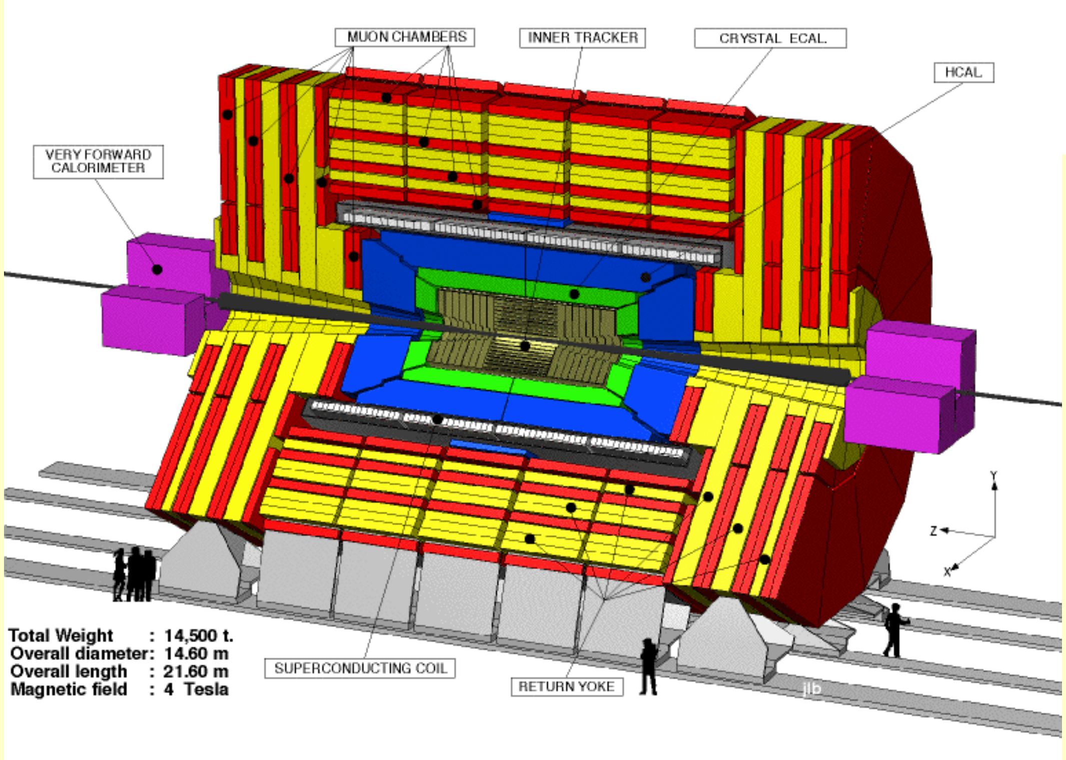


CDF: new Plug Calorimeters, new TOF

ATLAS and CMS

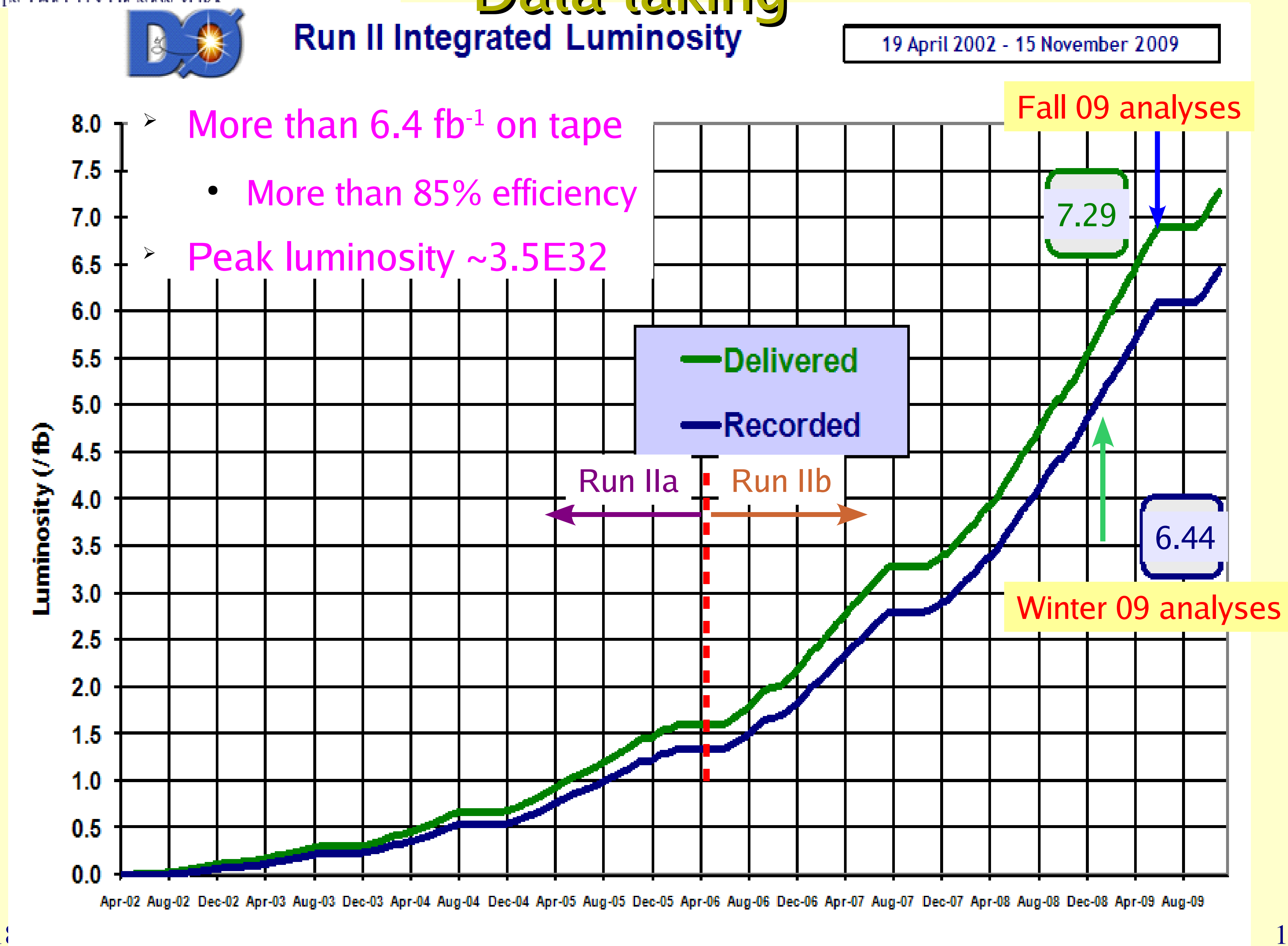
- ATLAS
  - Largest detector in a world
  - liquid Argon Calorimeter
  - excellent muon id





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

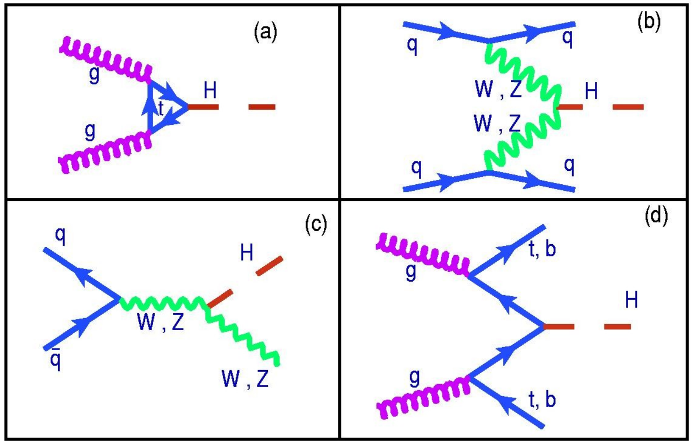
Data taking

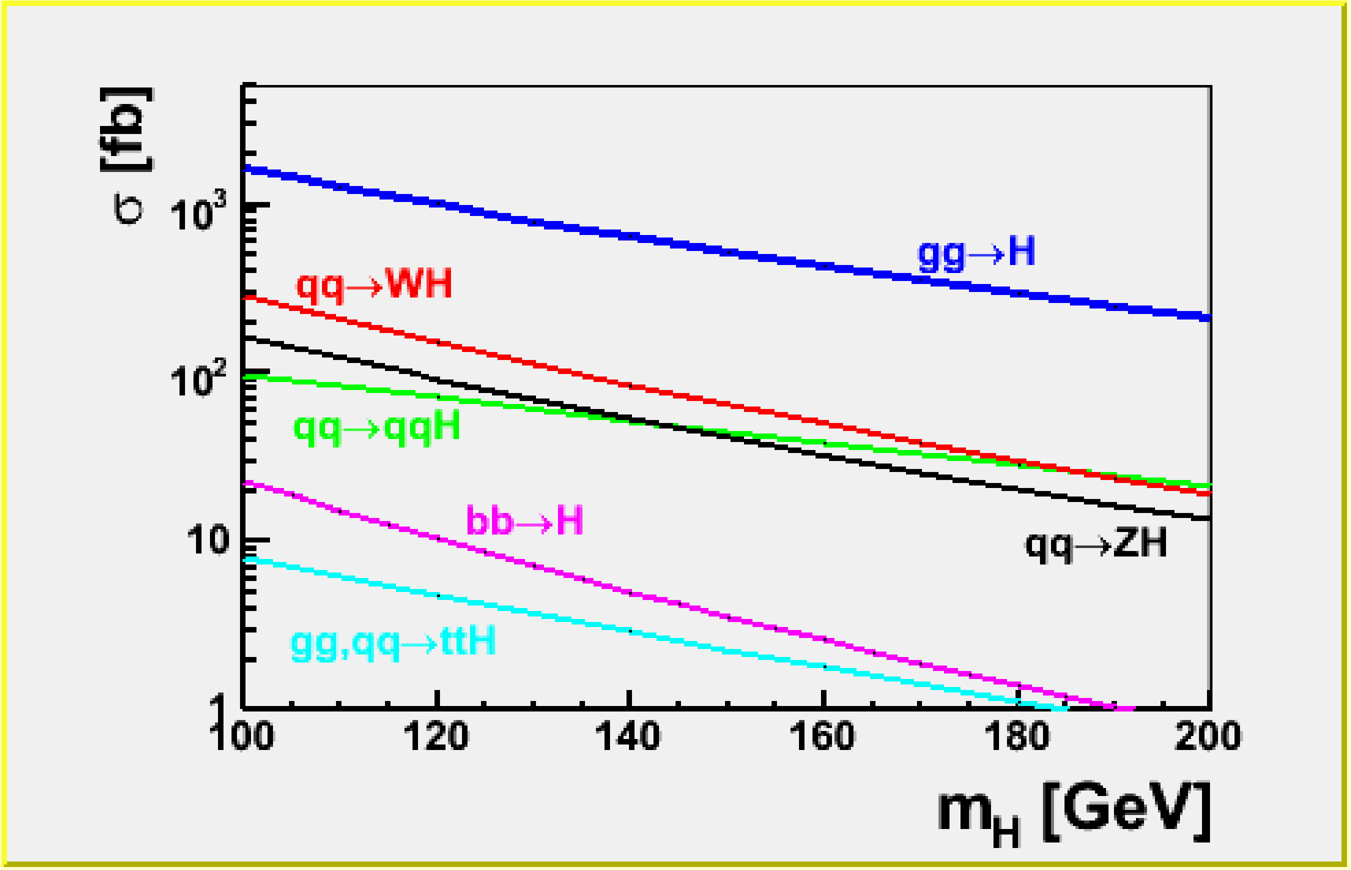

Run II Integrated Luminosity
19 April 2002 - 15 November 2009
More than 6.4 fb^{-1} on tape
More than 85% efficiency
Peak luminosity ~3.5E32
Fall 09 analyses
7.29
Delivered
Recorded
Run IIa
Run IIb
6.44
Winter 09 analyses
Luminosity (/fb)
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Apr-02 Aug-02 Dec-02 Apr-03 Aug-03 Dec-03 Apr-04 Aug-04 Dec-04 Apr-05 Aug-05 Dec-05 Apr-06 Aug-06 Dec-06 Apr-07 Aug-07 Dec-07 Apr-08 Aug-08 Dec-08 Apr-09 Aug-09

Higgs searches at Tevatron

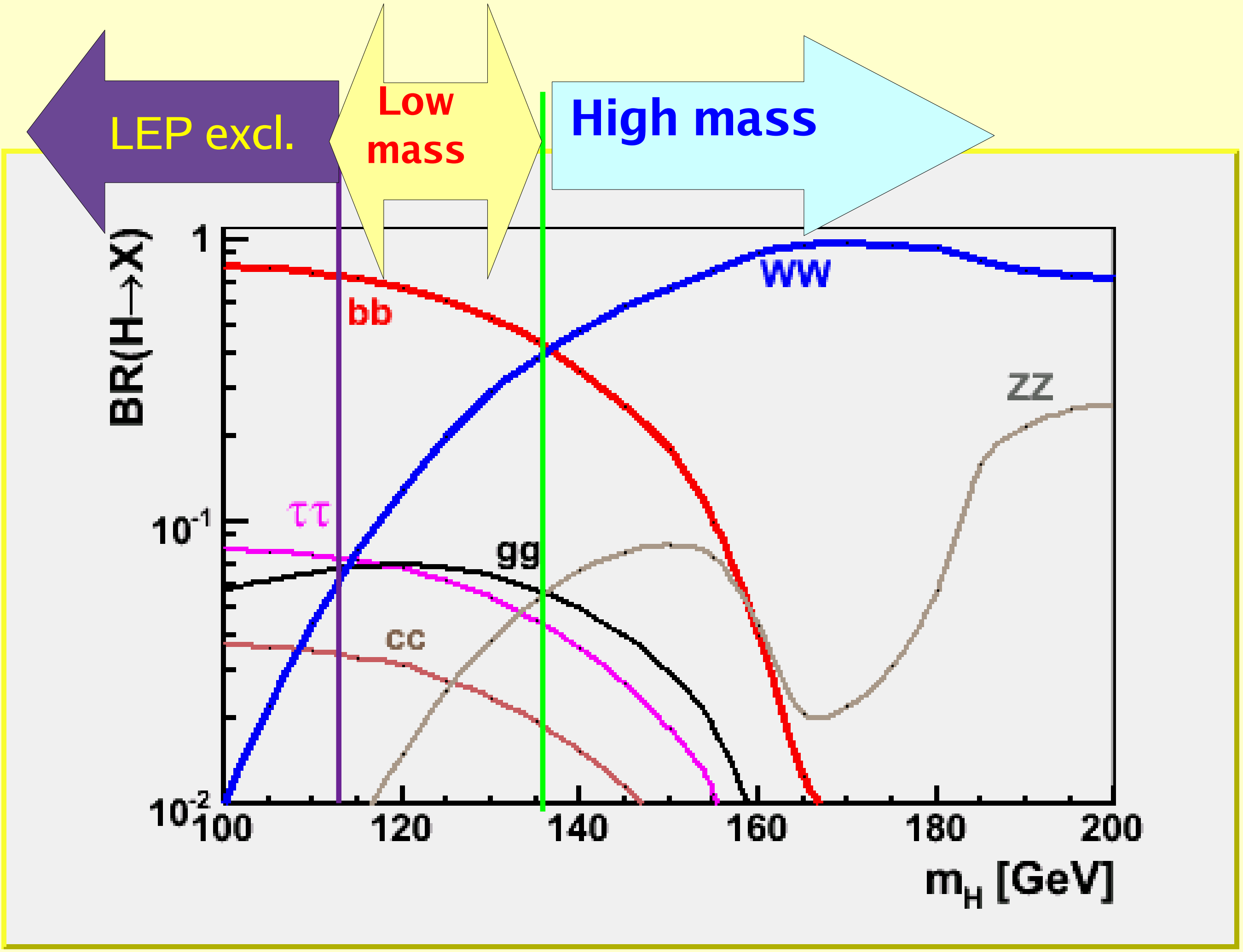
Production ...

- Main production process is gluon fusion
- Associated with vector boson, and vector boson fusion are significant



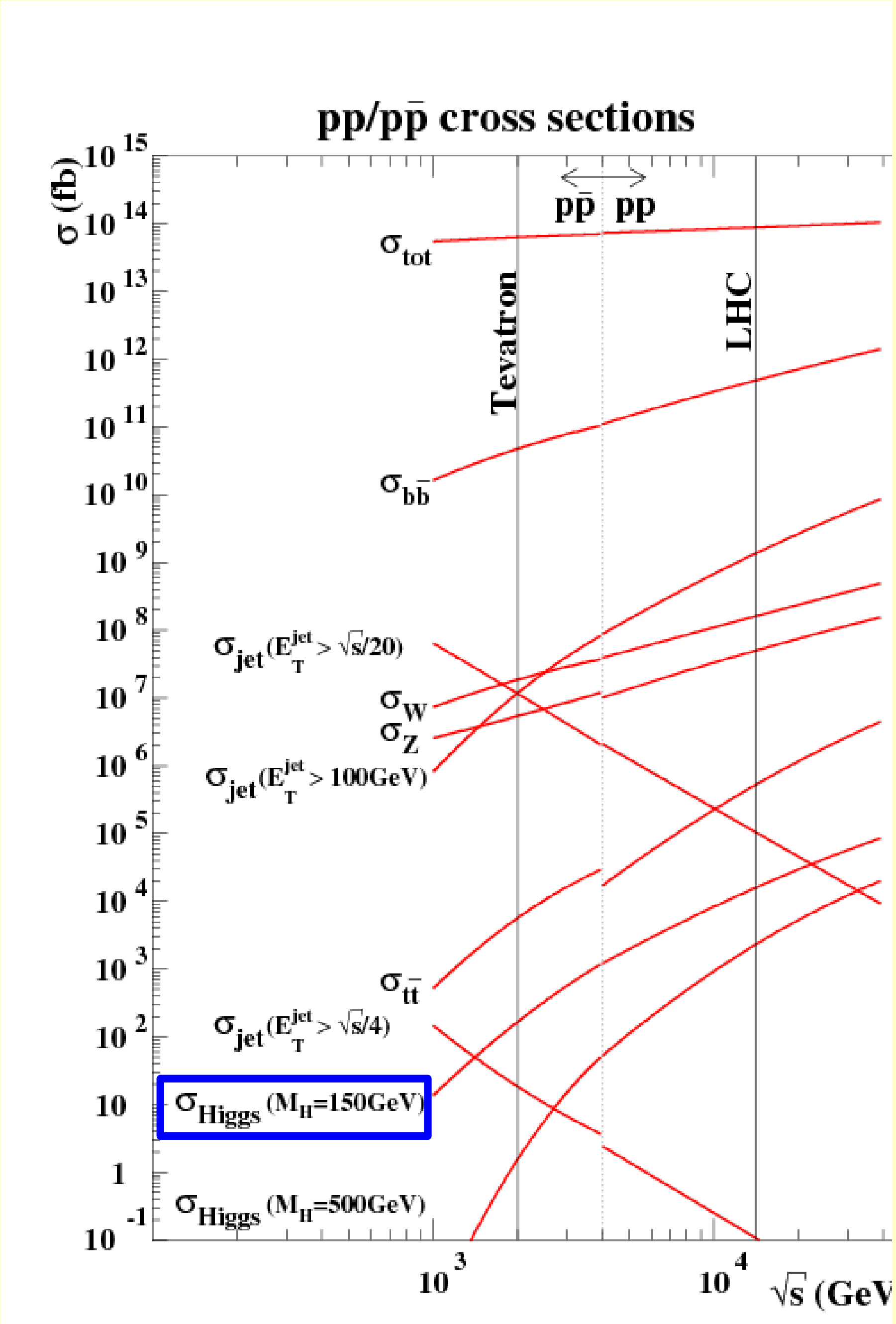


... and Decay



- At lower masses dominant decays to bb
- At higher masses dominant decays to WW

How do we search?



- We have to be able to measure known processes
  - Good background modeling
  - Good estimation of multijet production
  - Extensive application of advanced analysis techniques to find phase space regions with good signal and background separation
- Then we need to extract tiny signal from huge background
  - Measurement of low cross-section SM processes, like single top and VV, can help

Overview of the Higgs search at Tevatron

Overwhelmed by multijet production if searched for in gg->H

	Gluon fusion	VH
H->bb		V=W->lν, low mass
H->bb		V=Z->ll, low mass
H->bb		V=Z->νν, W->$\not{l}$ν, low mass
H->γγ	Low mass	Low mass
H->WW->lν+X		V=W->lν, Intermidiate mass
H->WW->lνlν	High mass	
H->WW->lνjj	High mass	

- Common challenges:
  - lepton and jet id, MET reconstruction, b tagging, QCD estimation, systematics
- Recent improvements:
  - Better trigger and b-tagging algorithms, better lepton ID, improved dijet mass resolution, precise measurements of some known SM processes

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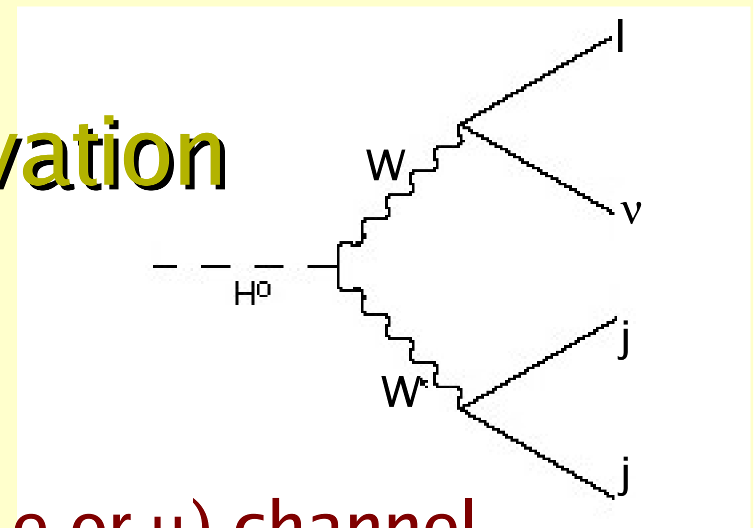
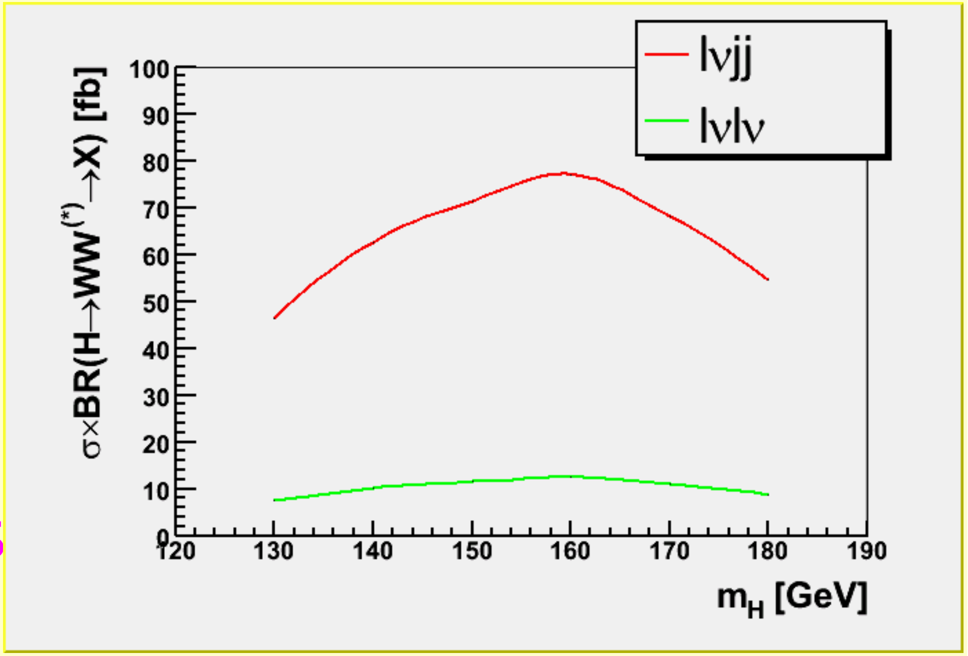
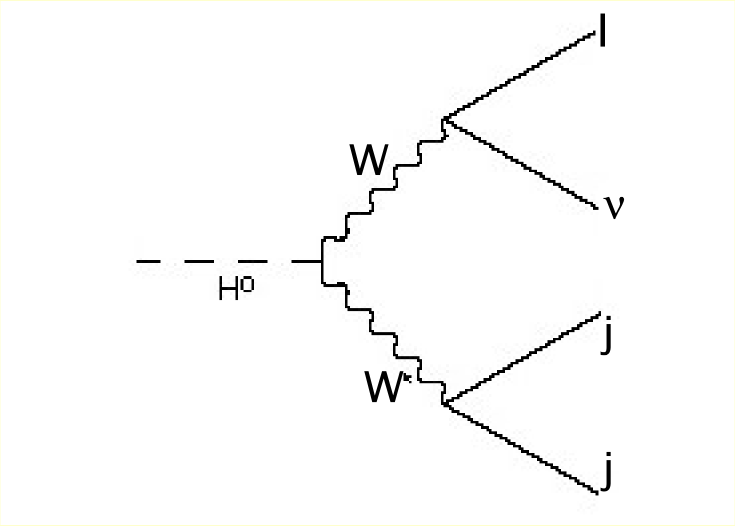
H->WW->lνjj - Motivation

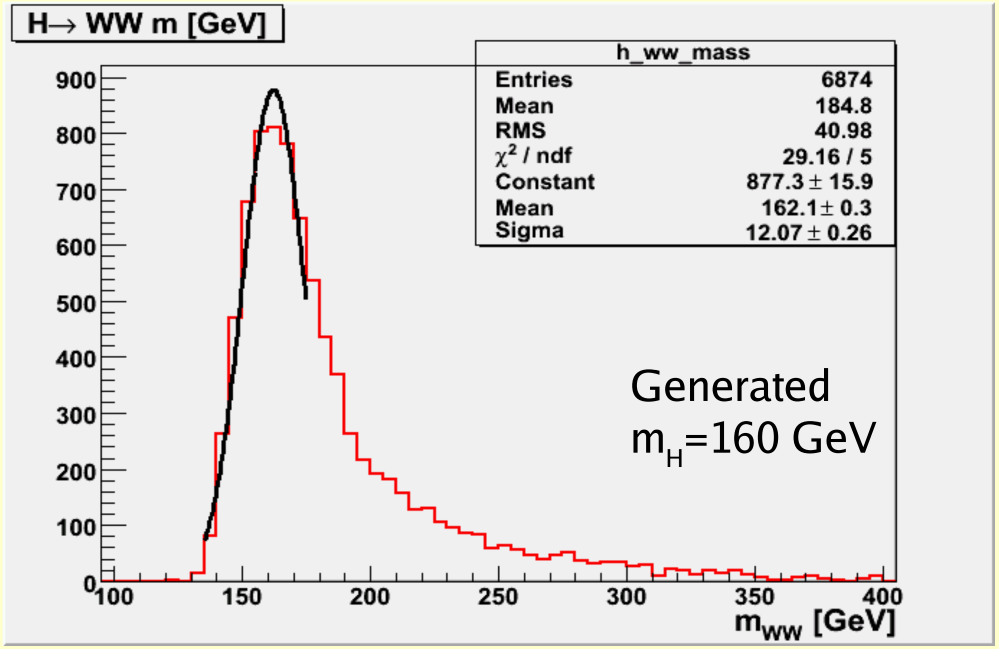


- H→WW^(*) is very important for Higgs searches for m_H > 130 GeV
  - Searches in dilepton (where lepton is e or μ) channel give sensitivity $\sigma_{excl}/\sigma_{SM}$<~1.5 per experiment
    - Already allowed exclusion when combined
  - lνjj has ~6 times bigger xs×BR
    - but also huge W+jets background
    - on the other hand, we can fully reconstruct Higgs mass for m_H >~160 GeV



Reconstructing the signal

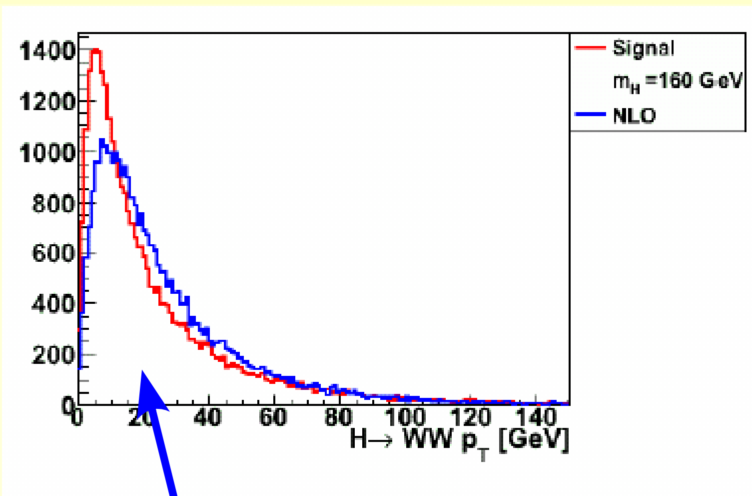


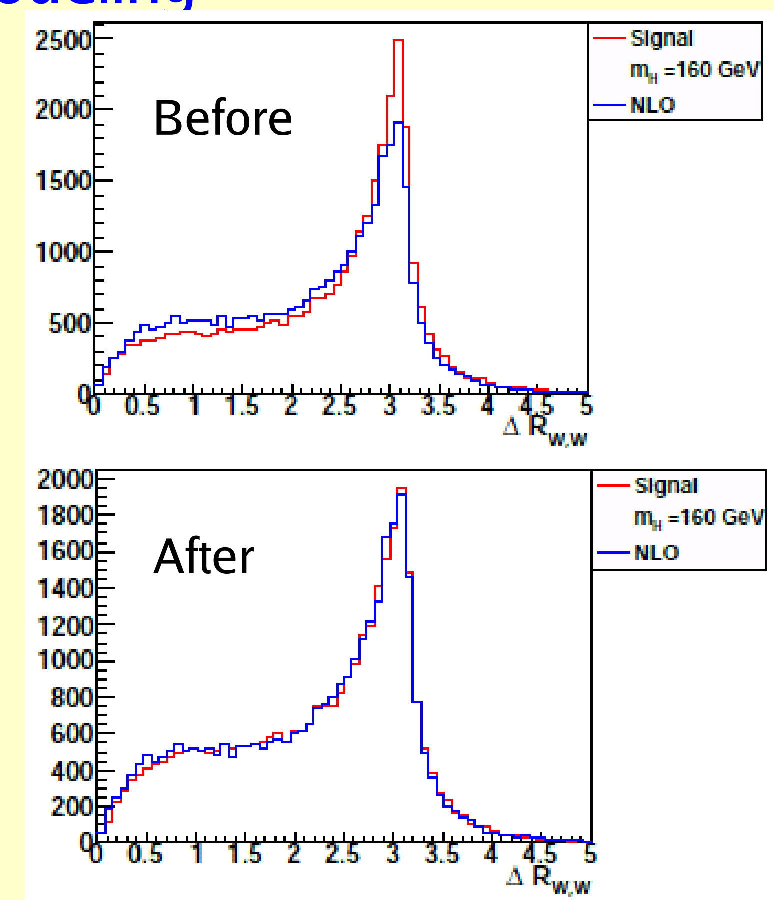


- Real Missing E_T (MET) is coming only from $W \to e\nu$
  - we can reconstruct p_z and then full momentum of neutrino
  - we can reconstruct full Higgs mass

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 or Sherpa, for the signal modeling





- Look for variables that are not modeled well
- Select the minimal set and reweight at parton level

Modeling of the background

- Many LO MC programs on the market:
  - MEPS: Alpgen, Sherpa, Madgraph, Helac, Madevent, ...
  - PS: Pythia, Herwig, Ariadne, ..
- 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

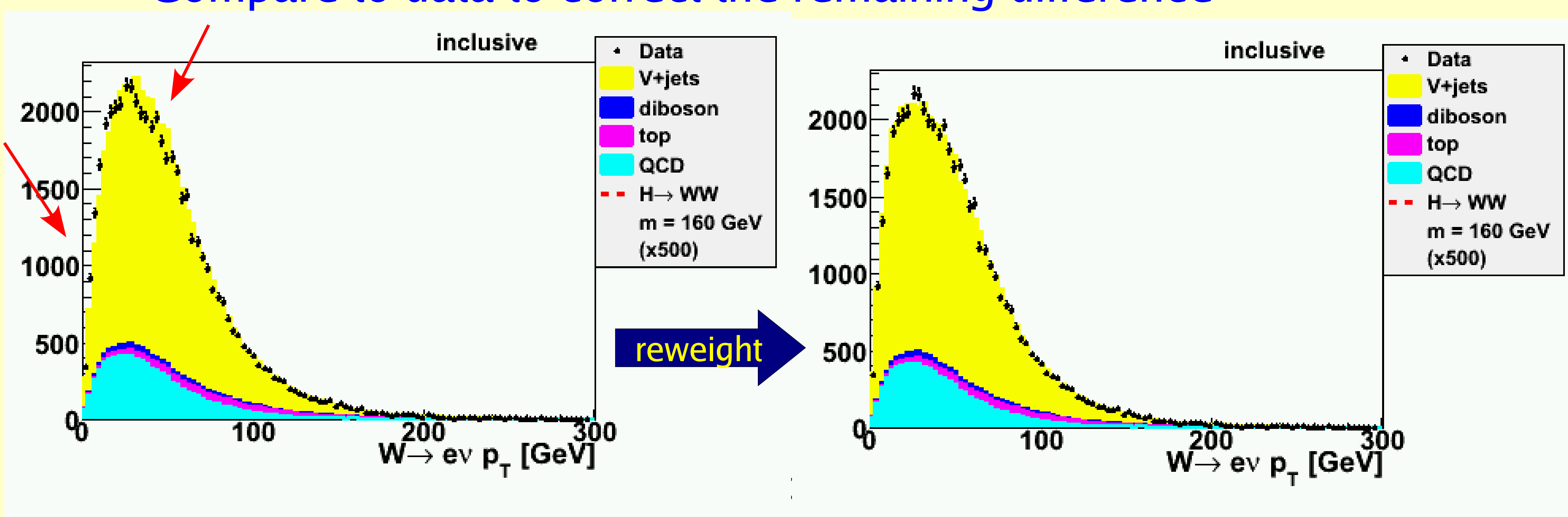
	Simulation	σ
W/Z+jets	ALPGEN + PYTHIA	O(10^3 pb)
tt	ALPGEN + PYTHIA	O(8 pb)
Single top	COMPHEP+PYTHA	O(3 pb)
DiBoson	PYTHIA	O(10 pb)
Multijet (QCD)	From data	

Modeling of the angular distributions of jets, V p_T is not correct

Normalized with highest order cross section available (NLO or better)

Modeling of the backgrounds – W/Z p_T

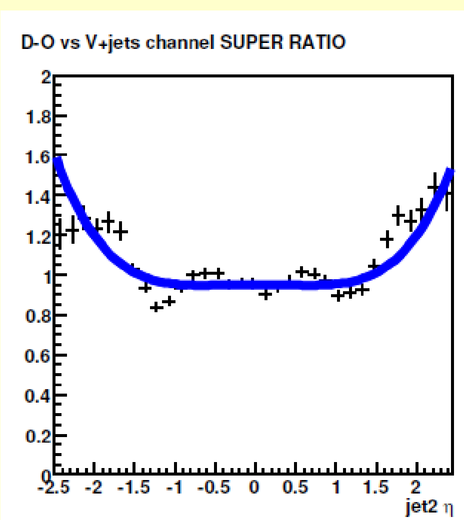
- ALPGEN+PYTHIA does not describe vector boson p_T
- Correct distributions from data or from other MC generators
- For the Z p_T we correct Alpgen to match the measurement
  - Measurement agrees with calculation from ResBos
- For W p_T we compare Alpgen with measured Z p_T corrected to the predicted NLO ratio between W and Z
  - Compare to data to correct the remaining difference

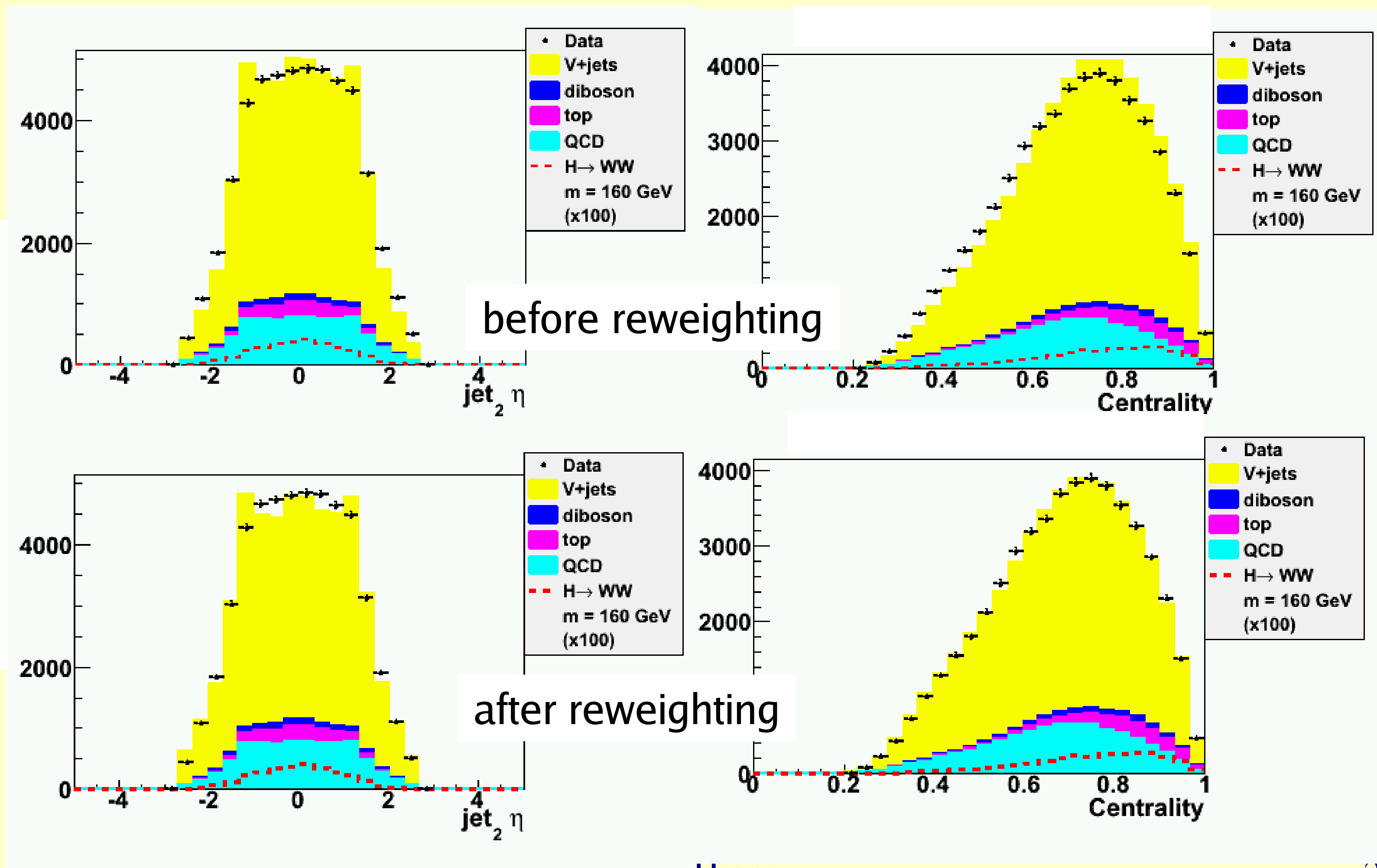


Modeling of the backgrounds – jet angles

- ALPGEN+PYTHIA does not describe jet angles correctly
- Correct distributions from data or from other MC generators (Sherpa)

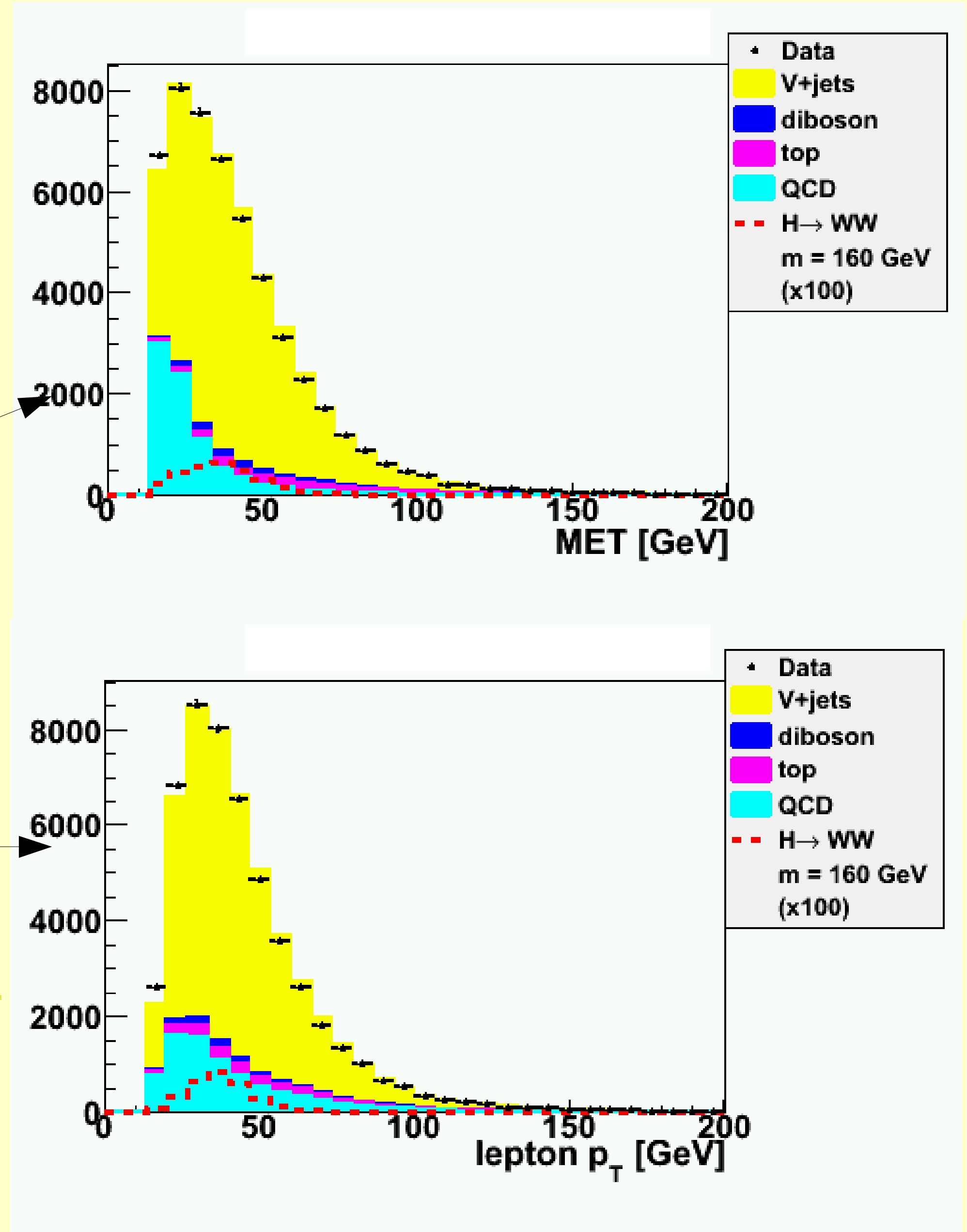
$$Centrality = \sum_{visible} p_T / \sum_{visible} E$$





Event Selection

- Data quality
  - ~81% efficiency
- Triggers
  - single electron or electron+jets
- Missing E_T MET > 15 GeV
  - calculated from calorimeter cells
- Electron (lepton)
  - combine track and calorimeter information
  - p_T > 15 GeV, $|\eta_e|$ < 1.1



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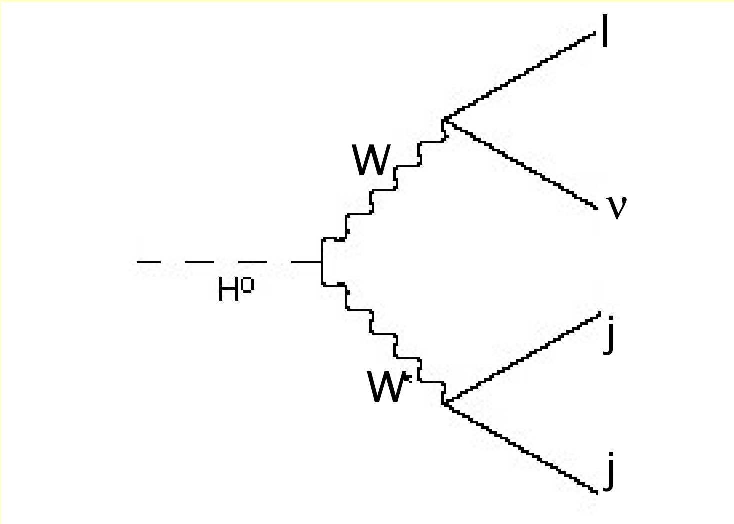
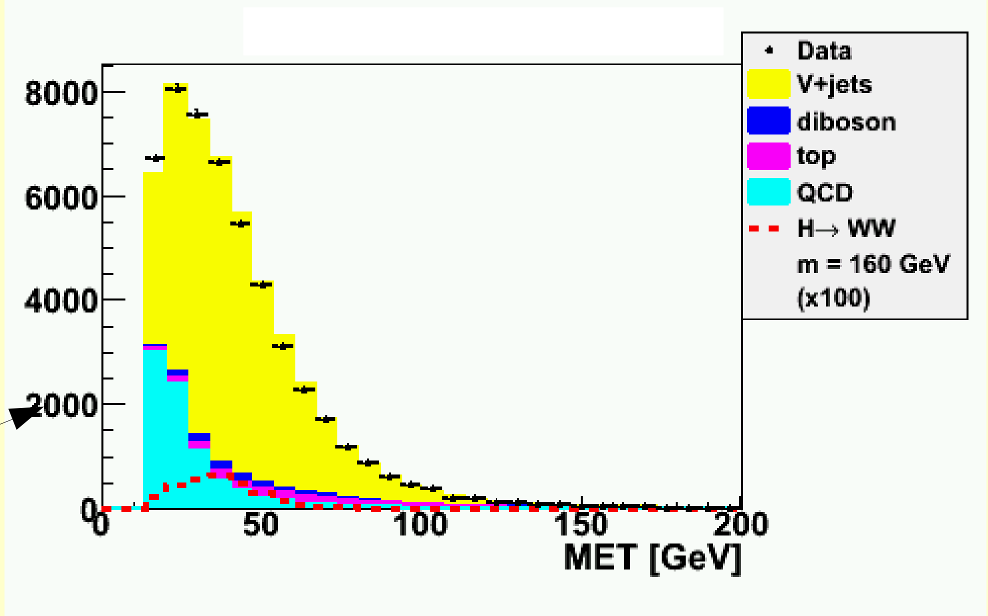
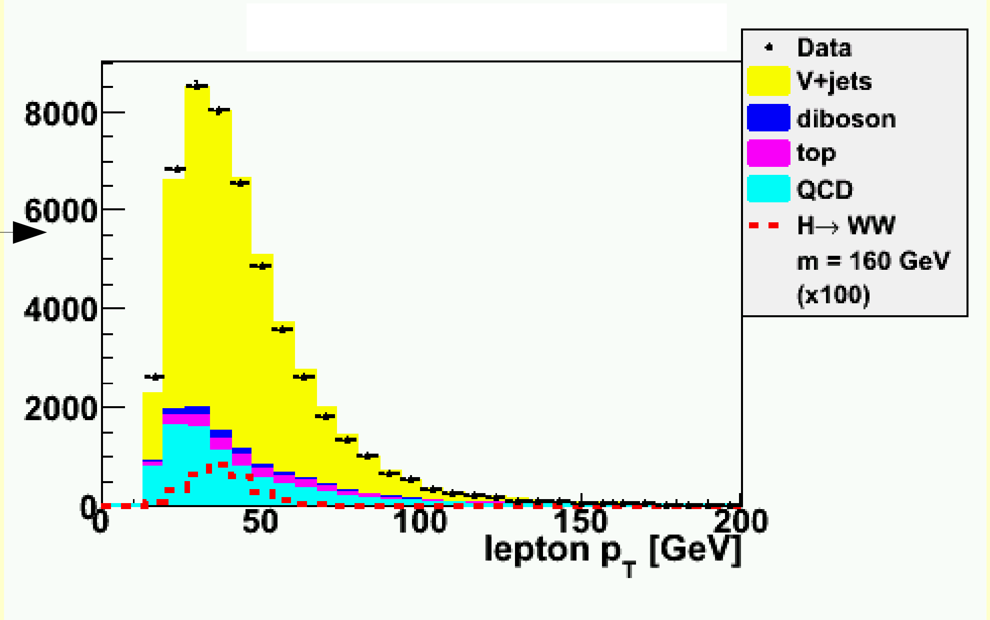
Event Selection







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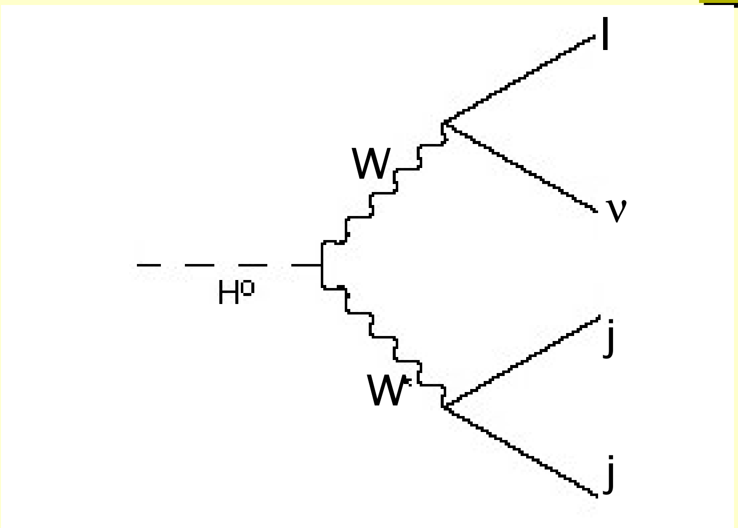
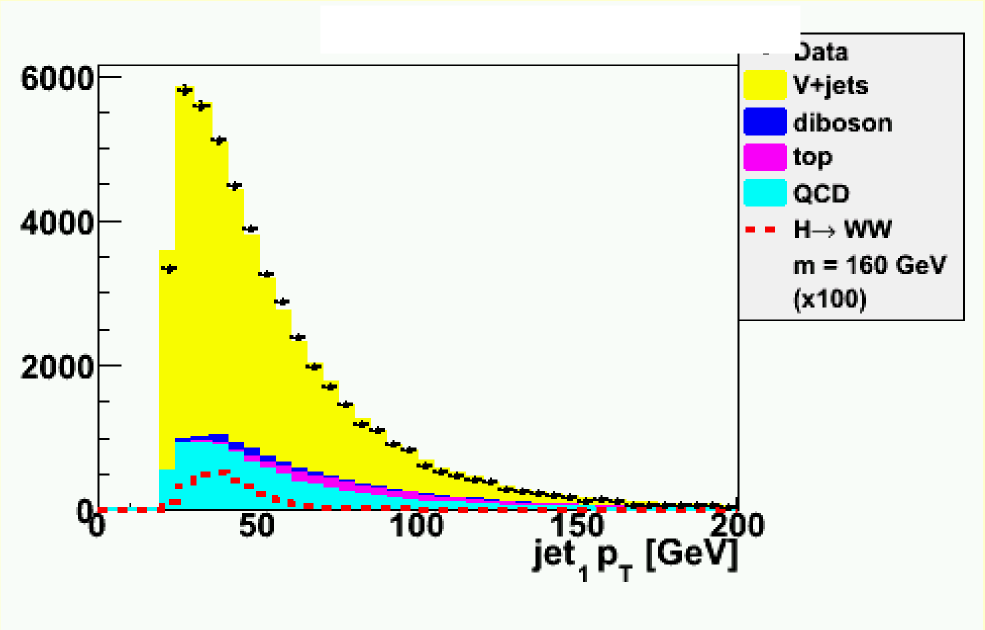
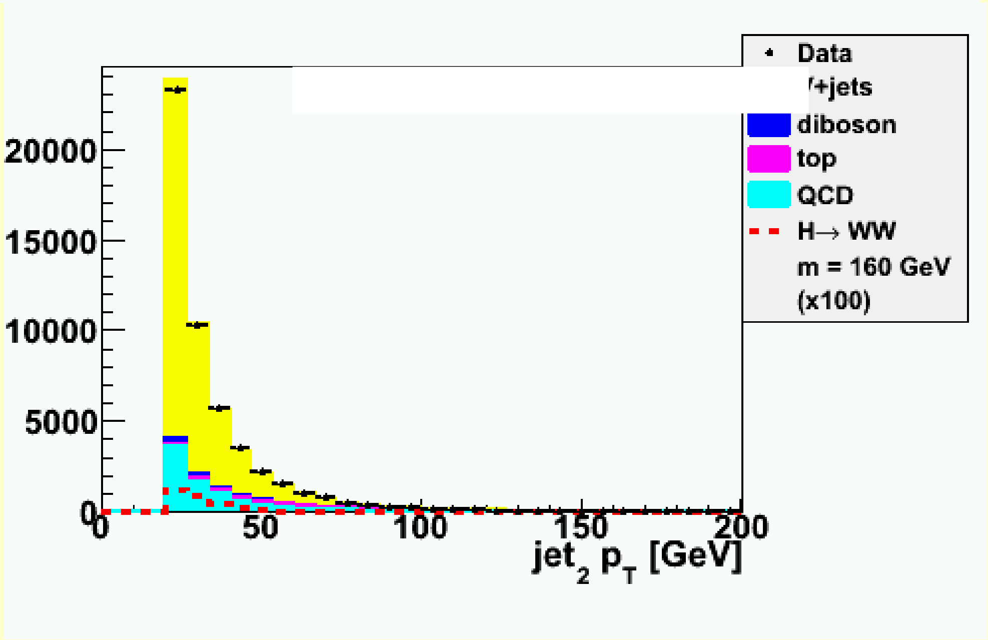
Event Selection

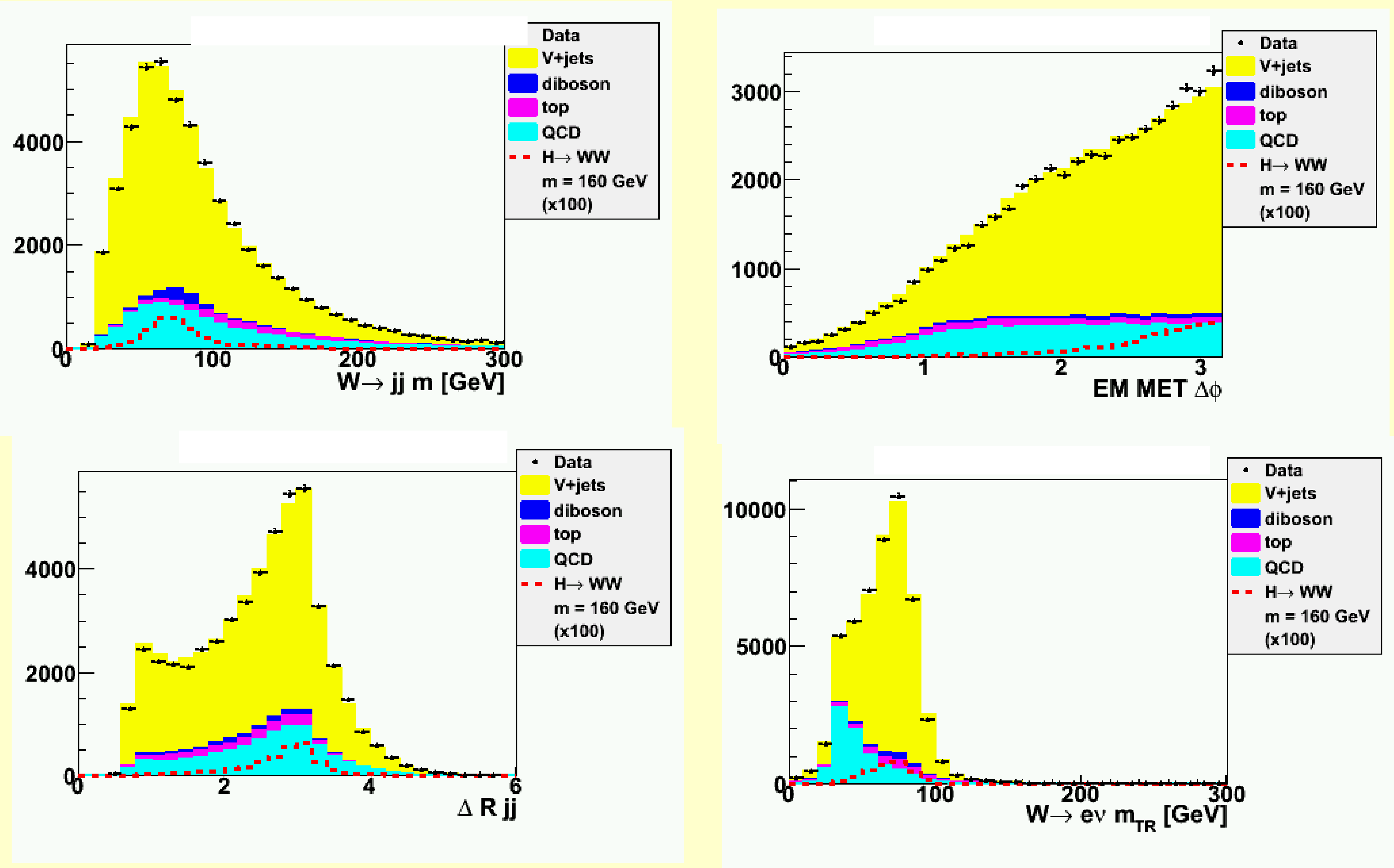






- At least 2 jets:
  - jet p_T > 20 GeV
- QCD reduction
  - electron faking jet
  - missmeasured jet energies give MET
- Triangle cut between transverse mass and MET

Data/MC Agreement



Yields after selection

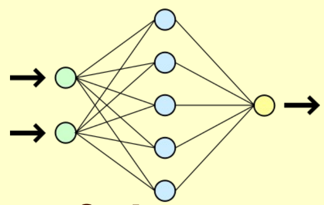
Number of Signal Events											
Higgs mass [GeV]	145	150	155	160	165	170	175	180	185	190	195
Run IIa 1.08 fb^{-1}	5.76	6.96	8.28	10.07	10.3	9.74	9.39	8.46	7.2	6.34	5.8
Run IIb 3.89 fb^{-1}	17.09	20.57	25.14	29.33	31.11	29.68	27.76	26.16	21.7	18.84	17.6

	Data	Total Background	V+Jets	Diboson	Top	QCD
Run IIa 1.08 fb^{-1}	21460	21431	16438	375	646	3972
Run IIb 3.89 fb^{-1}	50263	50279	39328	1018	1898	8035

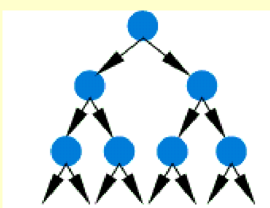
- Excellent agreement between observed data and expected prediction
- Expected 41.4 signal events for the Higgs mass of 165 GeV, and 71710 background events

Multivariate techniques

- Once we understand data, we want to try to extract signal
- Multivariate techniques are more powerful than simple cut method
- One output, usually between 0 (background like) and 1 (signal like events)
- Neural networks



  - trained on a set of discriminating variables for signal and background



- Decision trees
  - simple "yes/no" answers for different cuts
- Matrix elements $\int \mathcal{M}$
  - use LO matrix elements to calculate event probabilities

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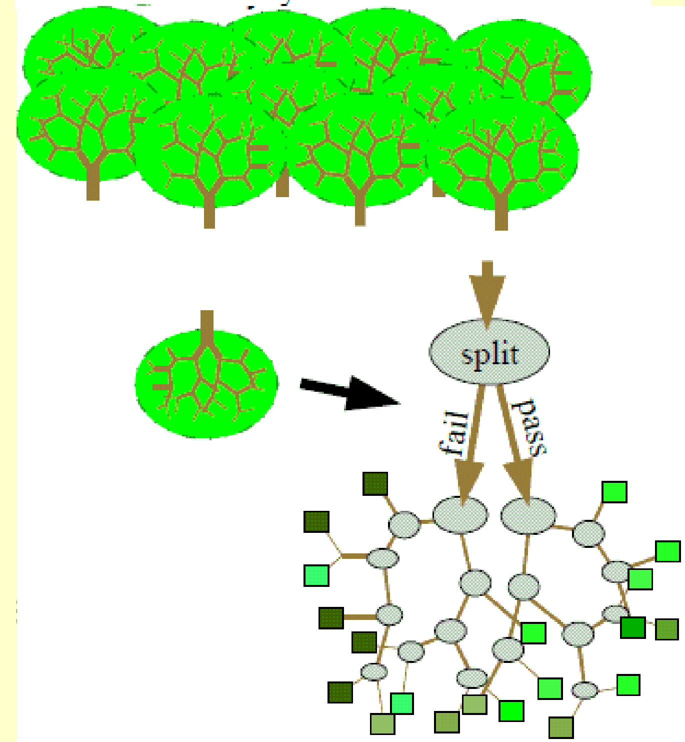
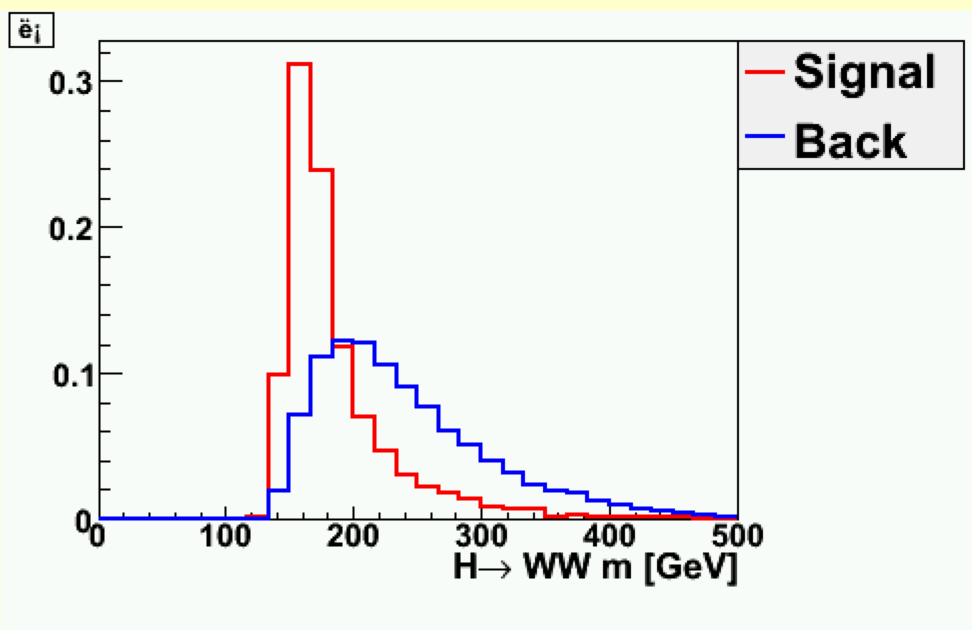
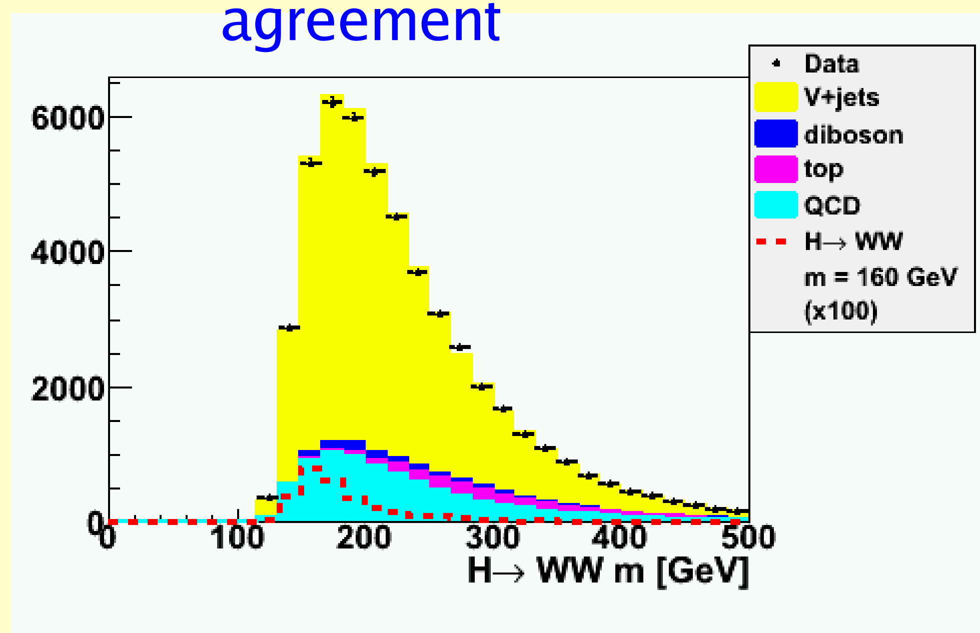
Random Forest

A "forest" of many decision tree classifiers

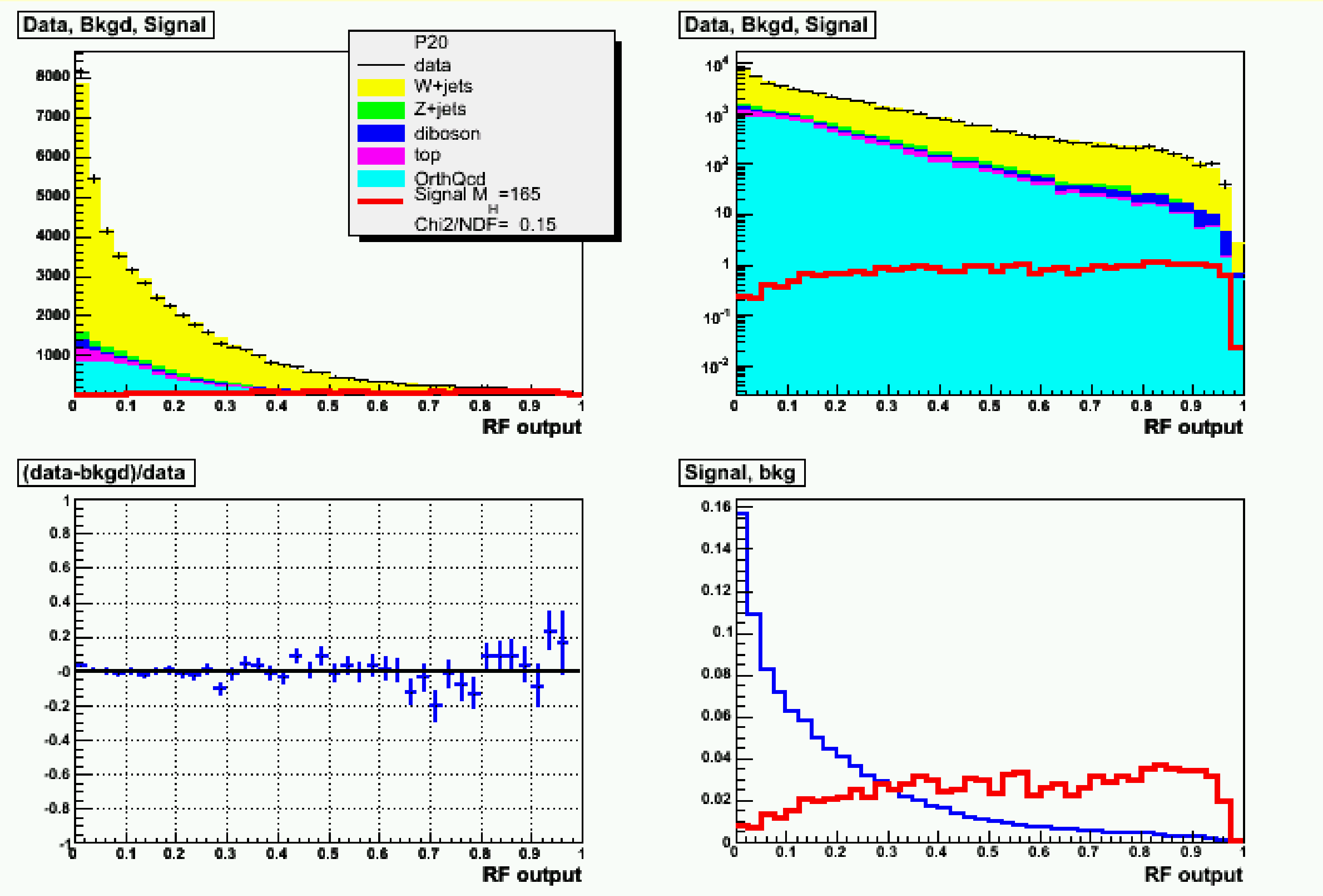


- Many different tree classifiers
  - Each tree classifier performs a series of optimized cuts to separate signal from background
- Train signal and combined background samples for each Higgs mass point
- Select variables based on two criteria:
  - discriminate signal vs. background
  - well modeled – good data/MC agreement





Random Forest



RF output is:

1. modeled well
2. discriminating well between signal and backgrounds

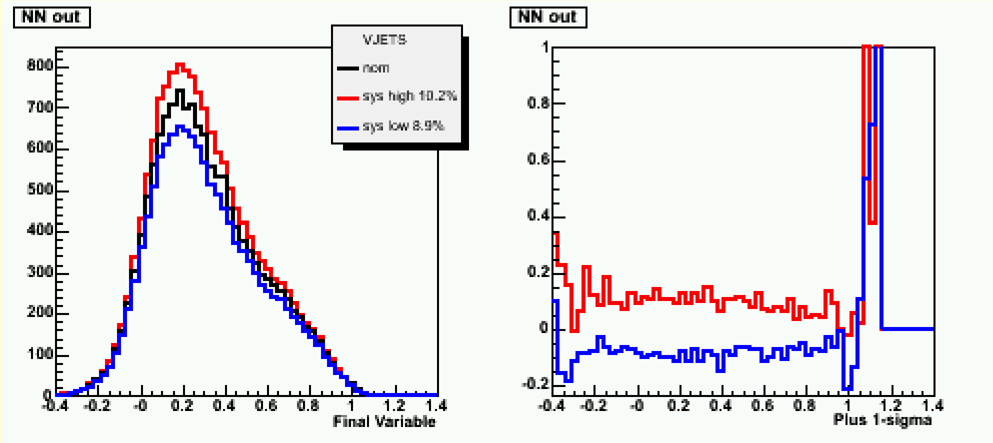
Systematics

- Uncertainties affect both the normalization (flat systematics) and the shapes (Jet Energy Scale, ID and resolution, QCD shape, reweighting)

Example of flat systematics

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

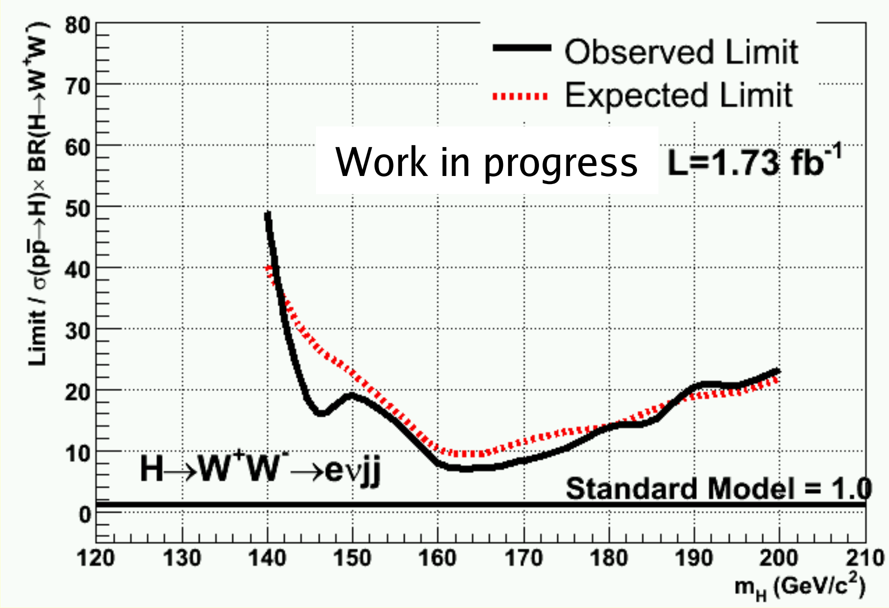
Example of shape systematics



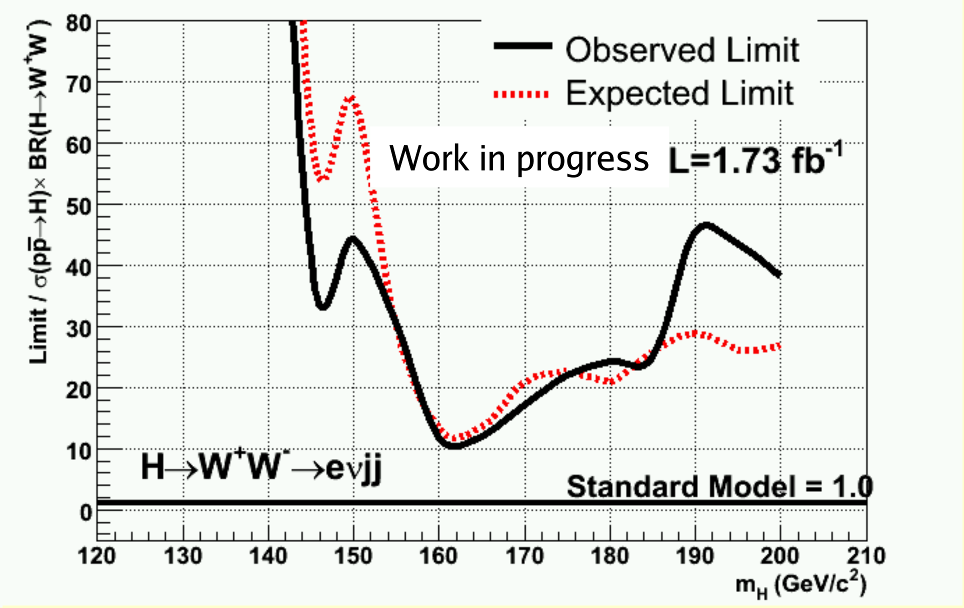
Limits on H->WW->eνjj

- When we don't observe any excess in data we set limits on production
- Use RF output distributions as discriminant to set upper limits
- Systematics have significant impact

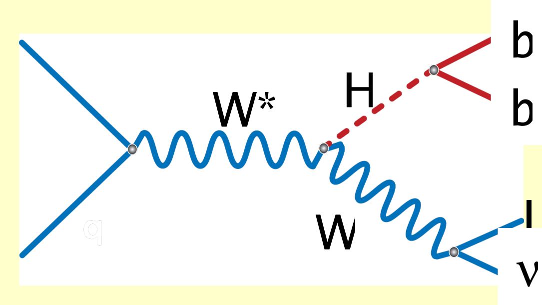
without systematics



with systematics

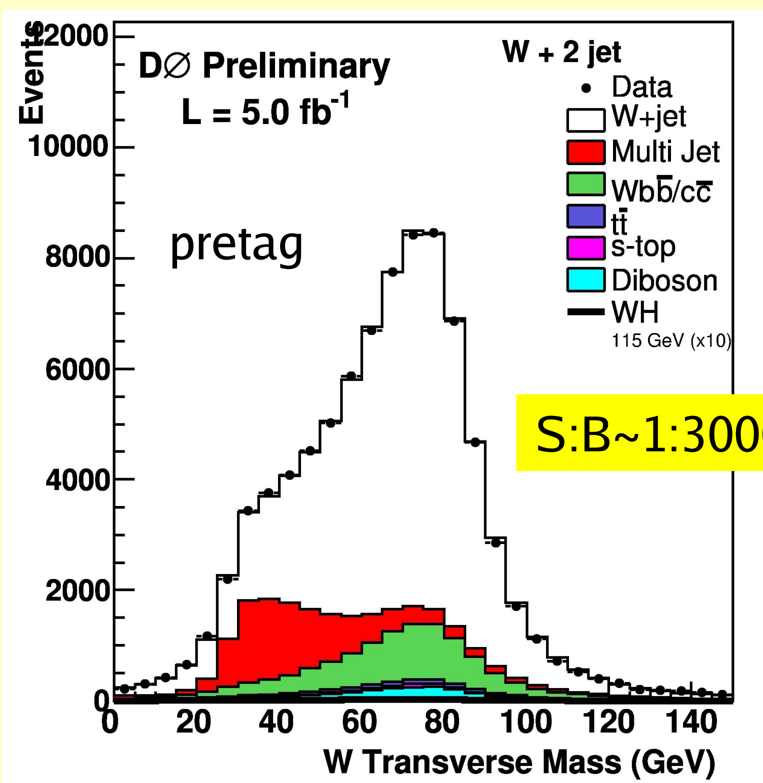


Low Higgs mass – WH->lνbb, l=e,μ

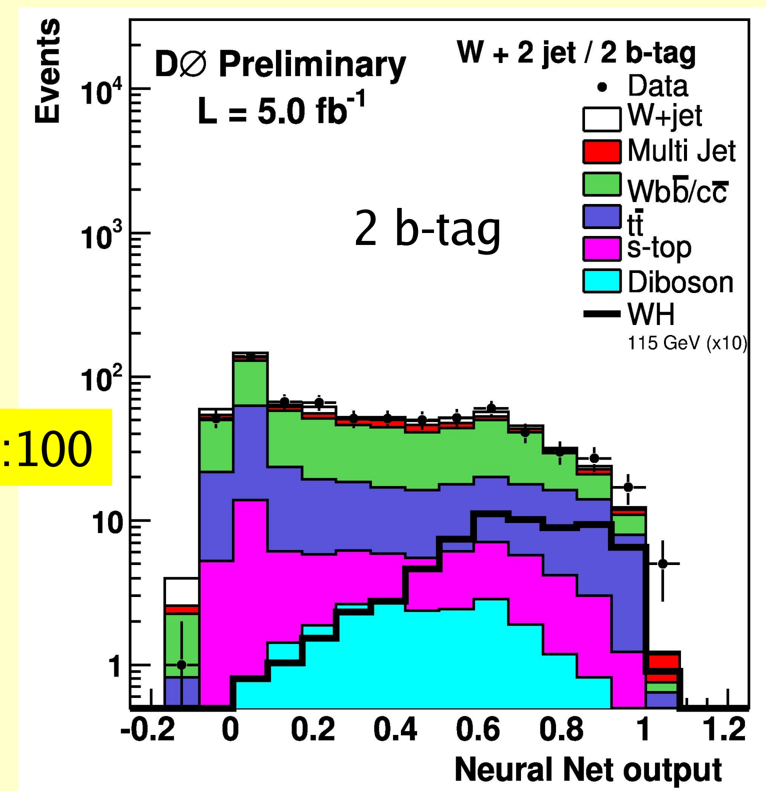


- Efficient lepton id and b tagging
- Combined Matrix elements and Neural Networks
- Systematics dominated by b-tagging – total 15-30%

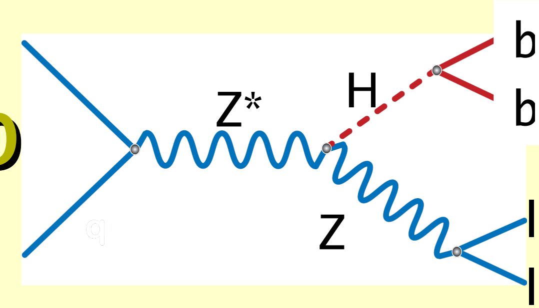
D0 (5.0 fb^{-1})	Exp.	Obs
M_H = 115 GeV	5.1	6.9
M_H = 130 GeV	9.4	10.7



S:B~1:3000 → 2 b-tag → S:B~1:100

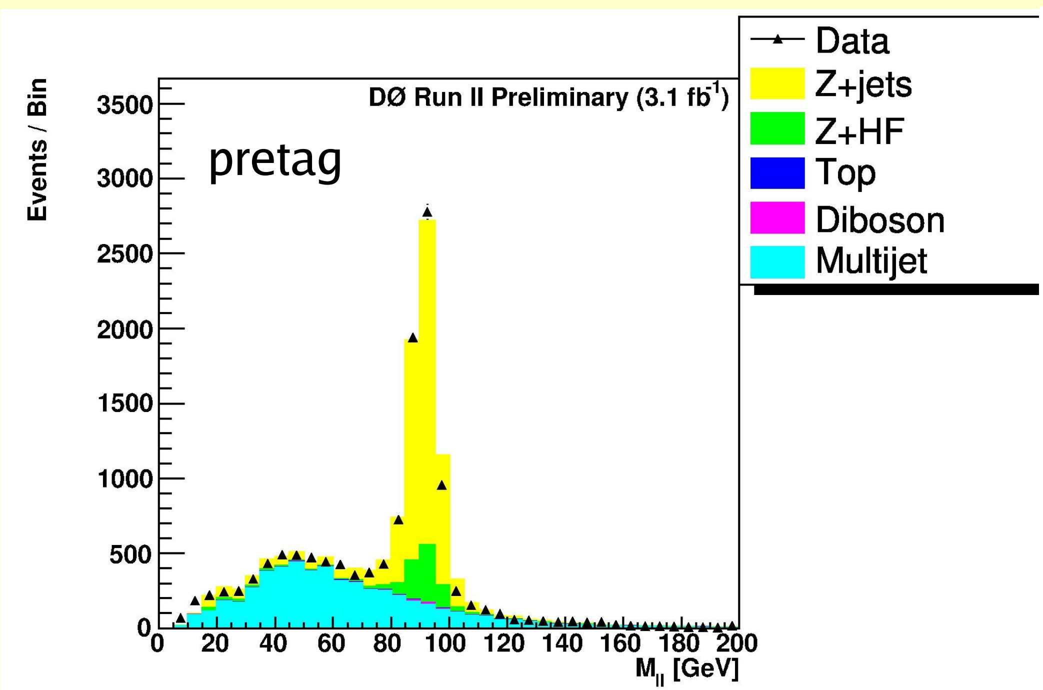


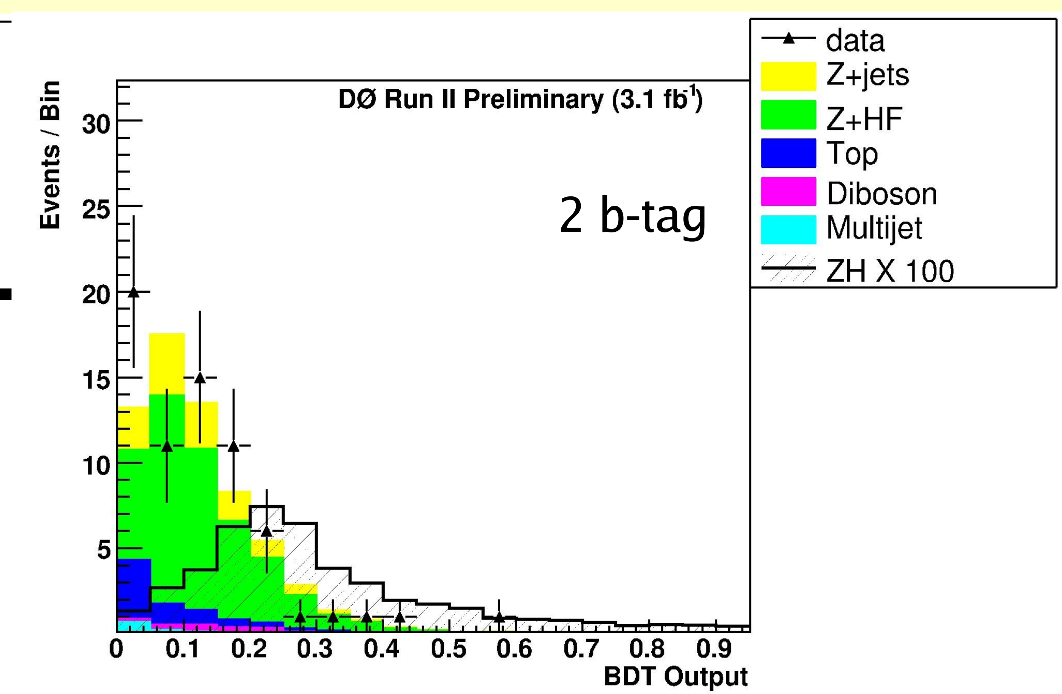
Low Higgs mass - ZH->llbb



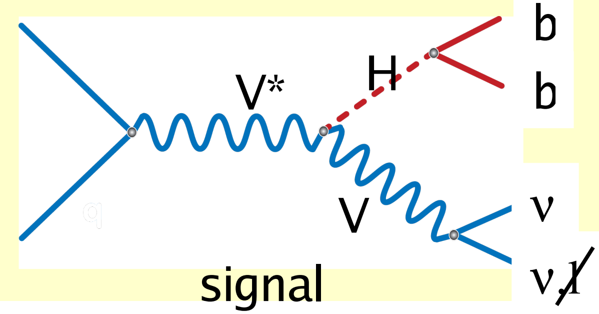
- Crucial understanding of Z+jets processes
- We employ both lepton ID and b-tagging to the maximum
- We use Boosted Decision Trees to separate signal and background

D0 (4.1 fb^{-1})	Exp.	Obs
M_H = 115 GeV	8.0	9.1
M_H = 130 GeV	14.5	20.3

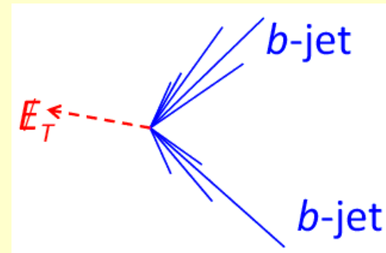


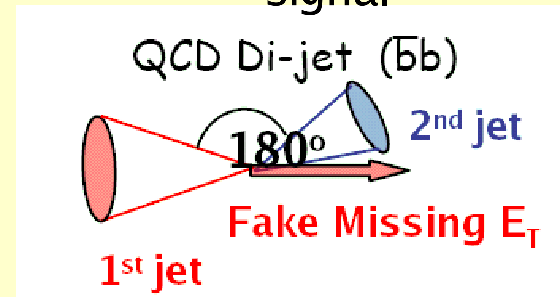


Low Higgs mass -VH->$\not\!E_T$bb

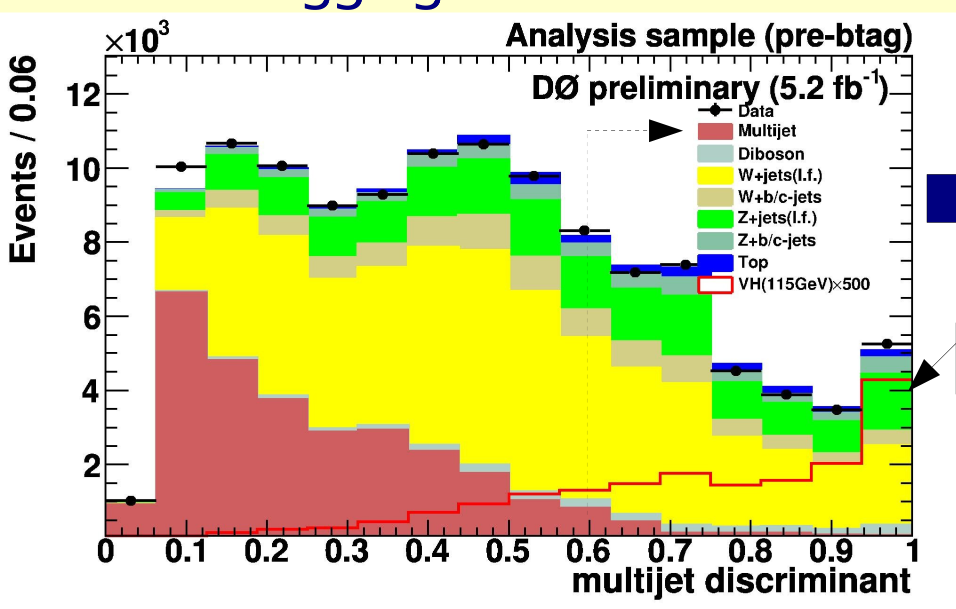


- Excellent b-tagging and measurement of the missing energy
- Multijet mostly from mismeasurement of jets
  - dedicated decision trees
- Systematics dominated with trigger and b-tagging

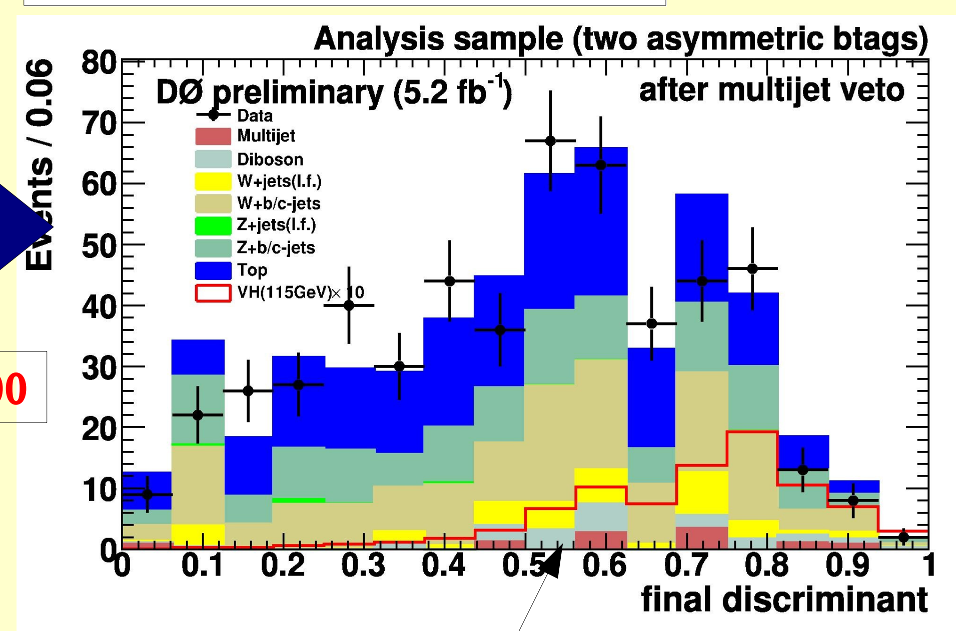




D0 (5.2 fb^{-1})	Exp.	Obs
M_H = 115 GeV	4.6	3.7
M_H = 130 GeV	7.6	8.2



2 b-tag



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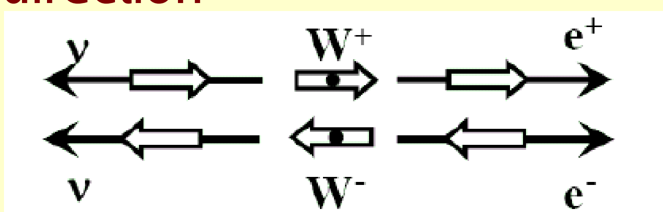
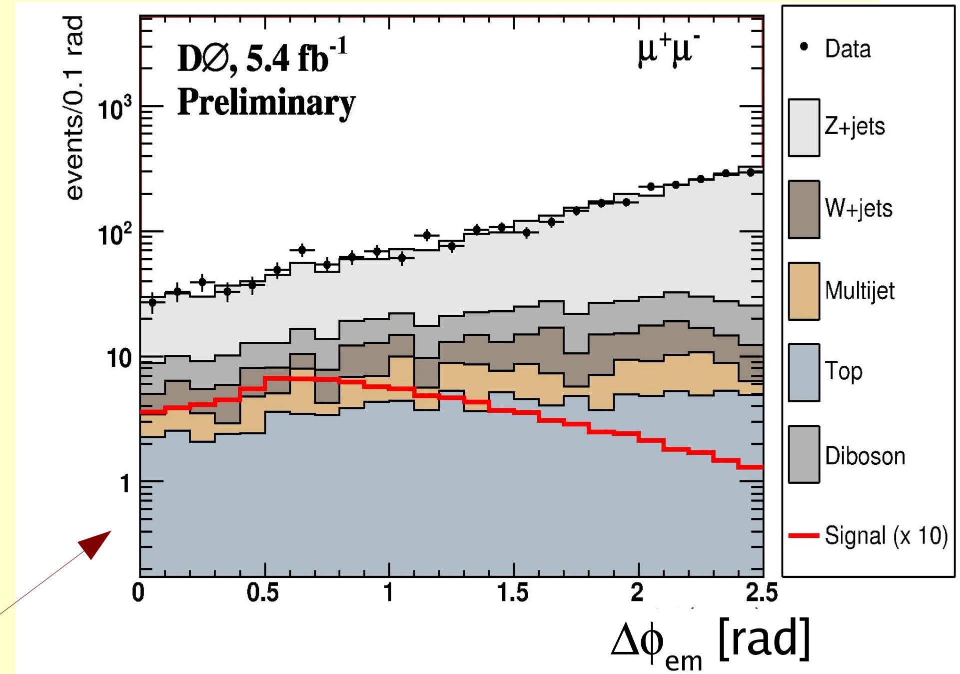
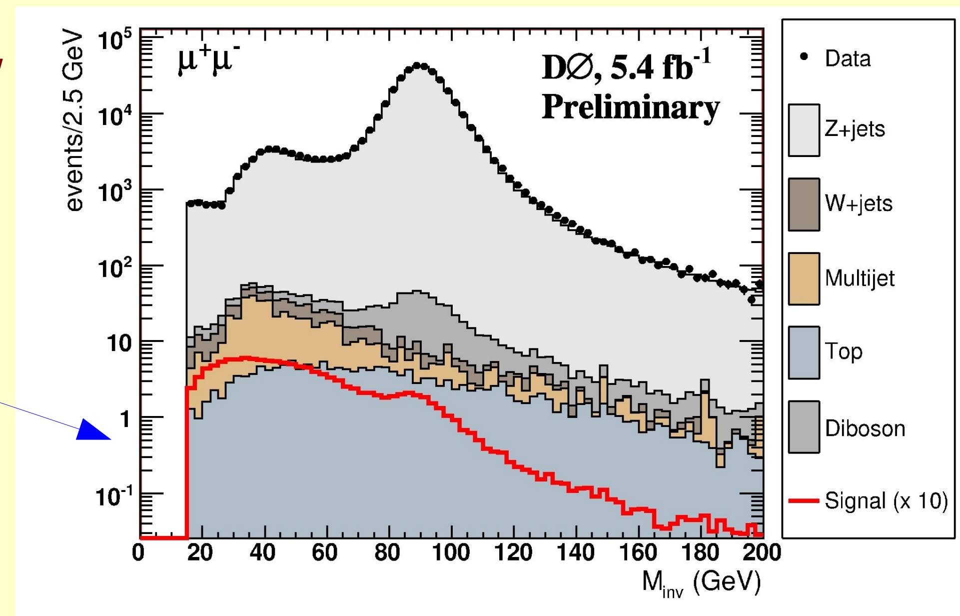
High mass Higgs - H->WW->lνlν

- Characteristics:
  - In signal WW pair is coming from spin 0 Higgs boson
    - Leptons prefer to point in same direction





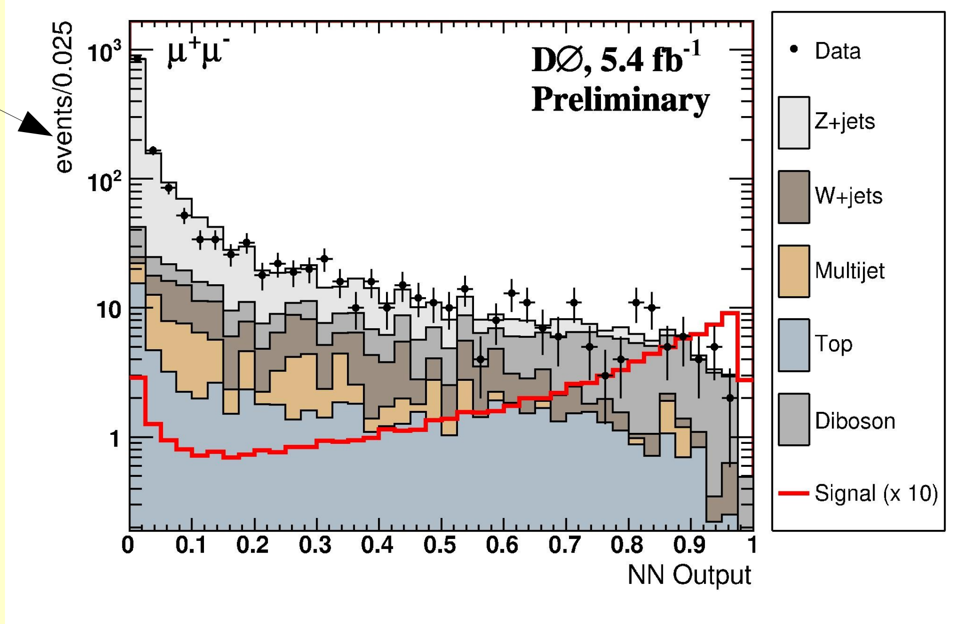
    - Di-lepton opening angle $\Delta\phi_{ll}$ discriminates against dominant WW background.
  - Dilepton mass is small and broad
    - Discriminates against Drell-Yan

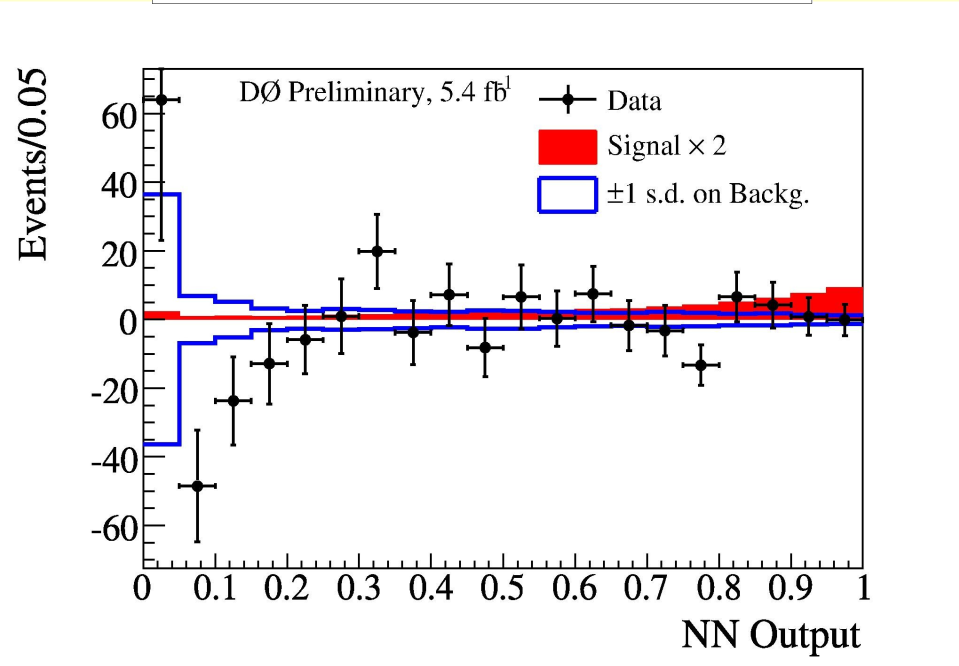


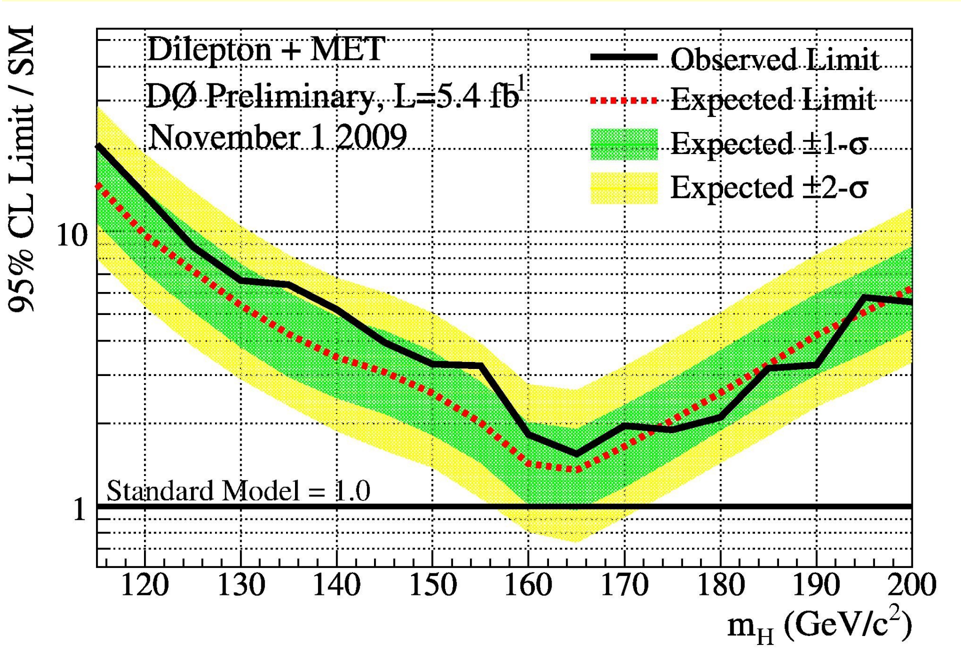
High mass Higgs - H->WW->lνlν

- Neural Network is used as final discriminant
- Detailed study of systematics
- This search contributed to the first Tevatron exclusion

D0 (5.4 fb^{-1})	Exp.	Obs
M_H = 165 GeV	1.36	1.55
M_H = 130 GeV	5.40	6.63

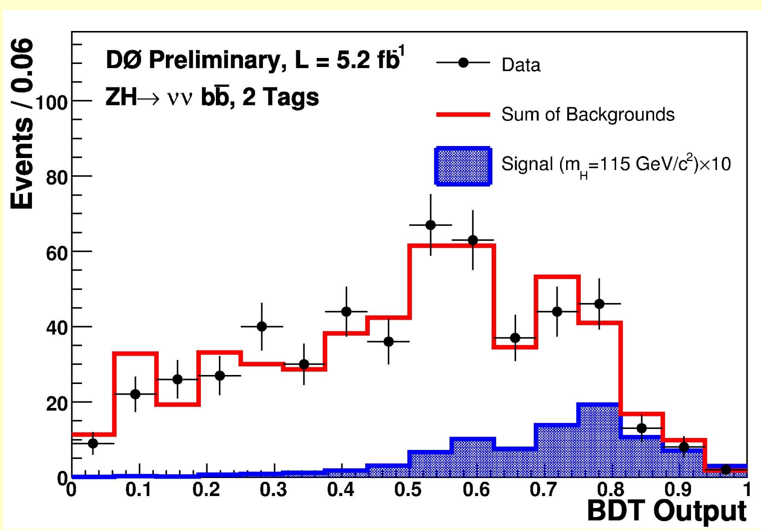


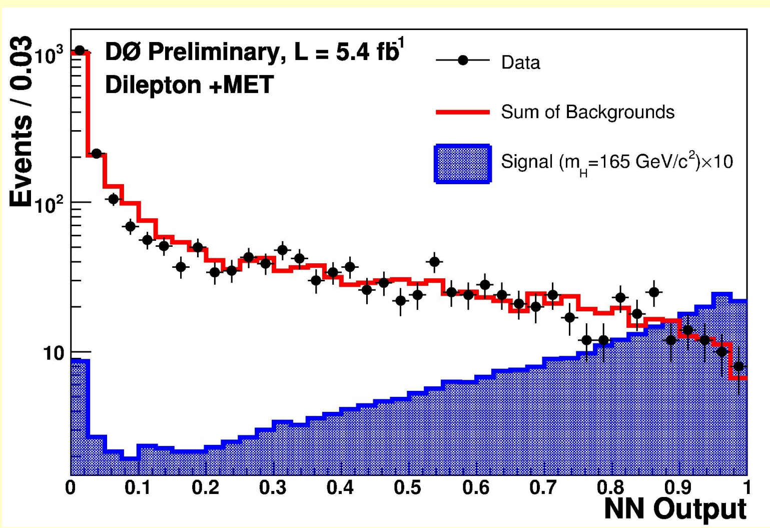




Combining channels

- 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
- We use a semi-Frequentest statistical model to perform this test





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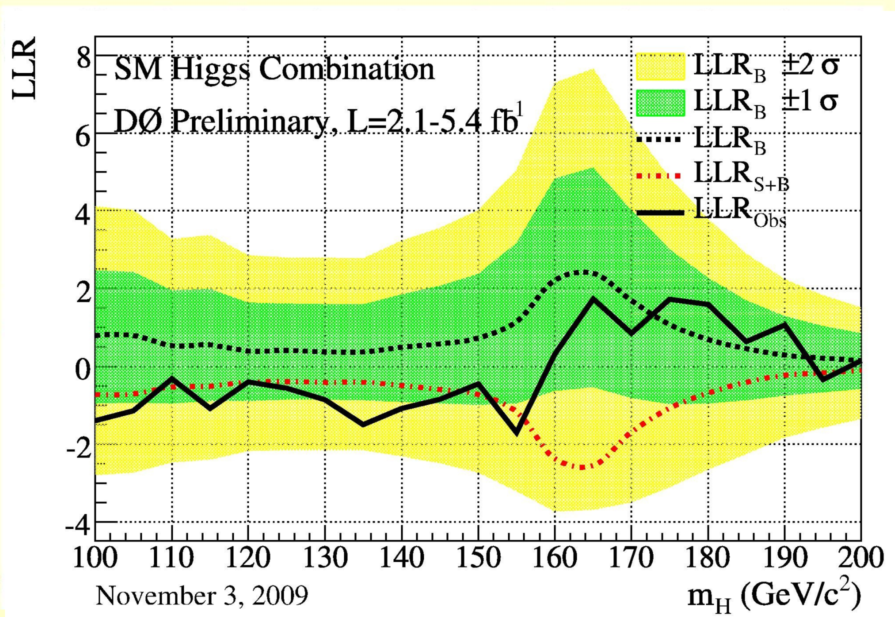
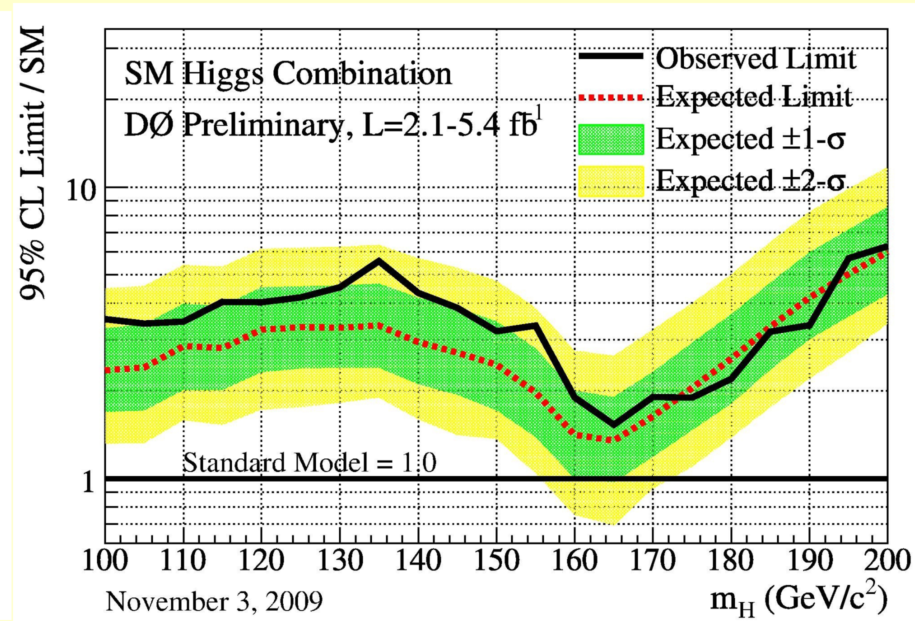
D0 limits

	expected			observed		
m_H [GeV]	115	130	165	115	130	165
Limit	2.80	3.30	1.35	4.05	4.53	1.53

Bkgd-Like Outcomes

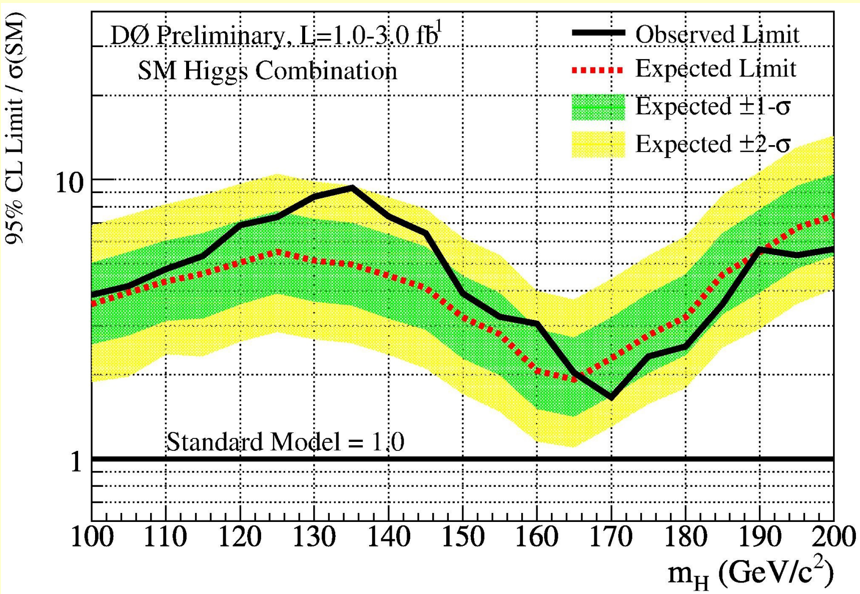
Signal-Like Outcomes



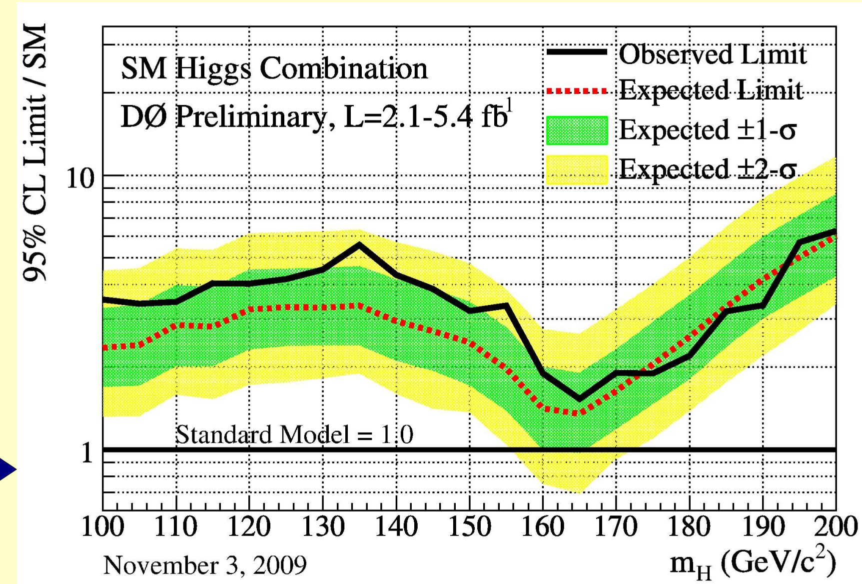


- The width of the LLR_b distribution (1σ and 2σ bands) provides an estimate of how sensitive the analysis is to a signal-like background fluctuation in the data, taking account of the presence of systematic uncertainties
  - For example, when a 1σ background fluctuation is large compared to the signal 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.

D0 progress



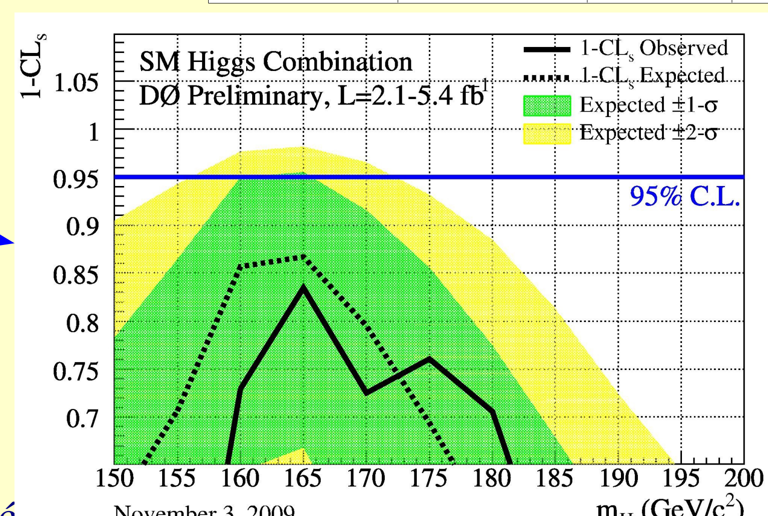
1 year



	expected		observed	
m_H [GeV]	115	165	115	165
Limit	4.6	1.9	5.3	2

	expected		observed	
m_H [GeV]	115	165	115	165
Limit	2.80	1.35	4.05	1.53

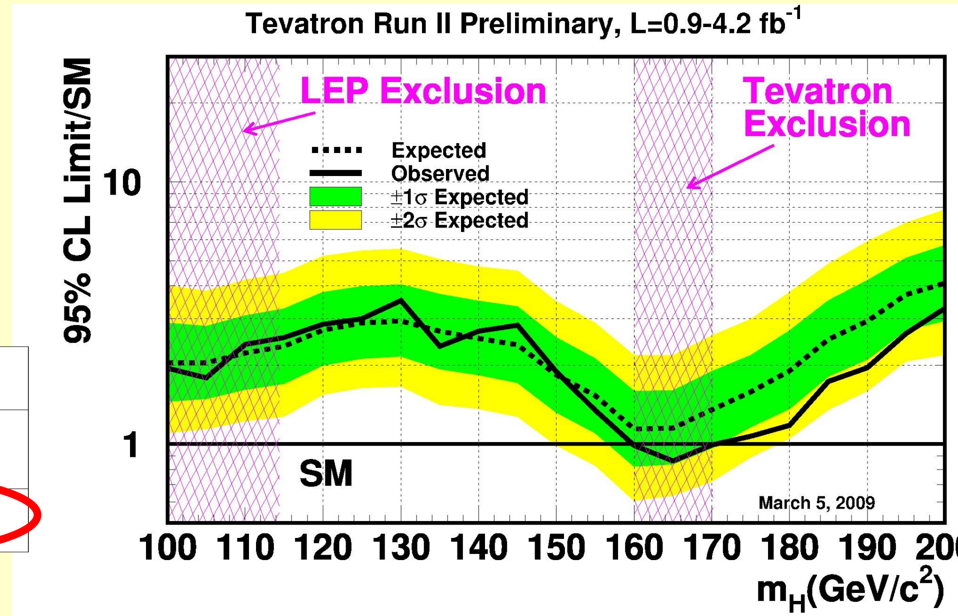
- We are approaching to the single experiment exclusion



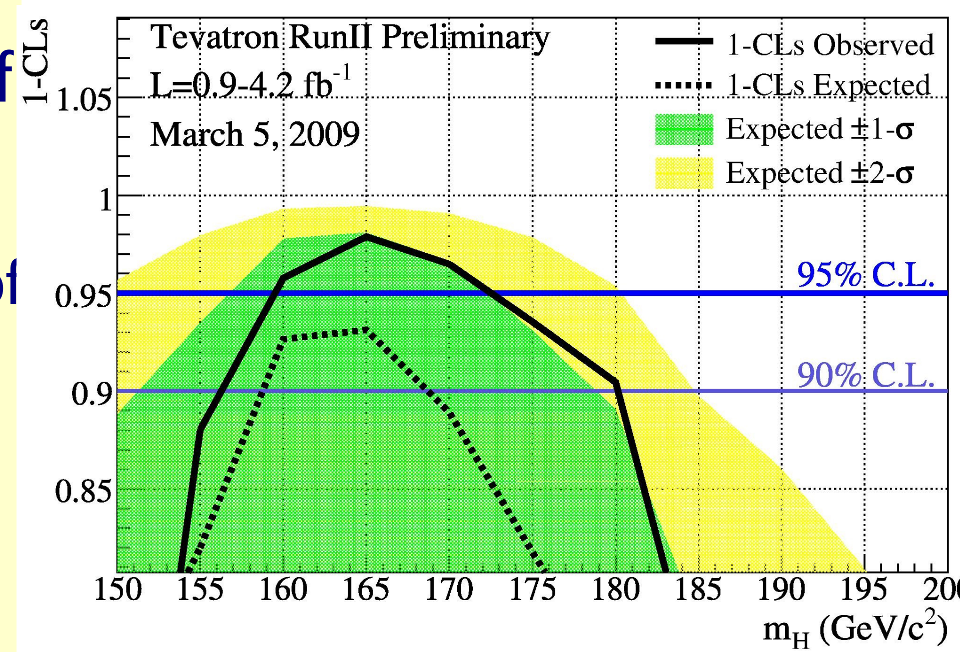
Tevatron limit - exclusion

- The first Tevatron exclusion
  - Higgs mass is not between 160 and 170 GeV @95% CL

	expected			observed		
m_H [GeV]	160	165	170	160	165	170
Limit	1.1	1.1	1.3	0.95	0.81	0.92



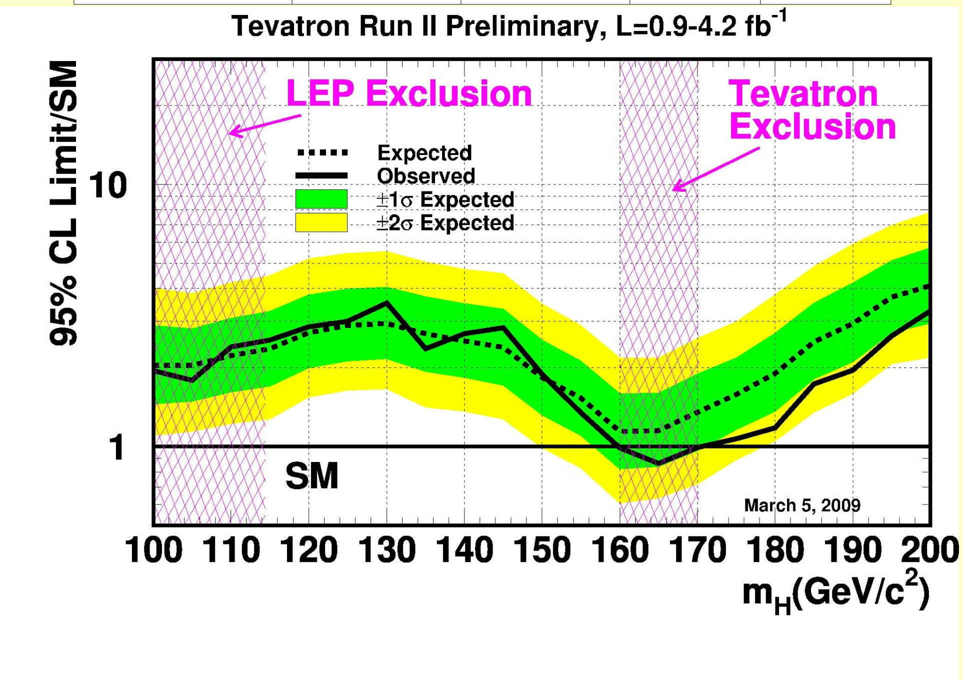
  - update will be released soon
- 1-CL_S distribution as a function of the Higgs boson mass
  - directly interpreted as the level of exclusion of our search
  - @90% CL we exclude range from ~156-180 GeV



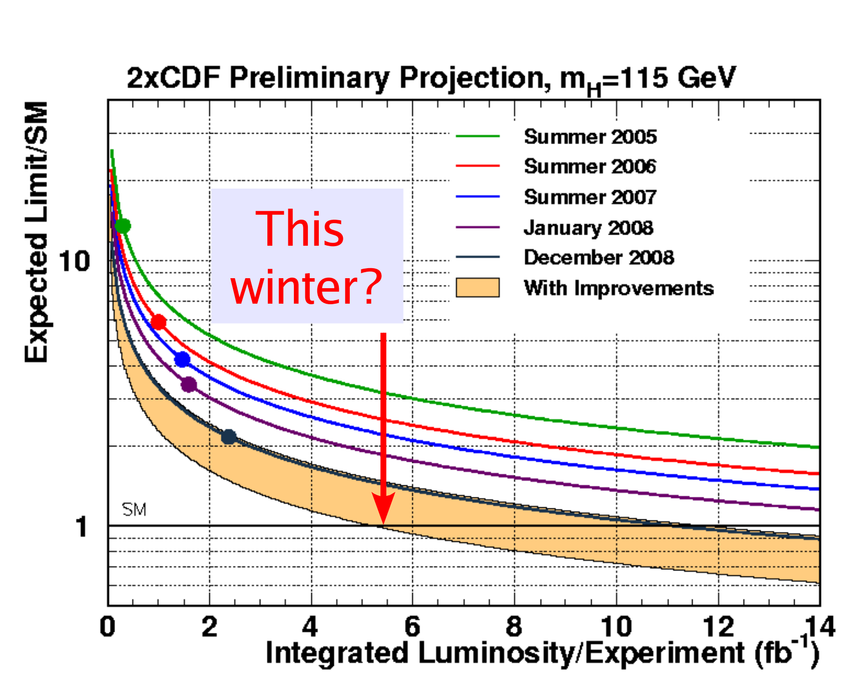
Tevatron limit – low mass

- We are coming closer to start excluding lower Higgs masses
- With improvements, we can be there within a year

	expected		observed	
m_H [GeV]	115	130	115	130
Limit	2.4	2.9	2.6	4.0



- Projected median expected upper limits on the SM Higgs boson cross section, scaling CDF performance to twice the luminosity.

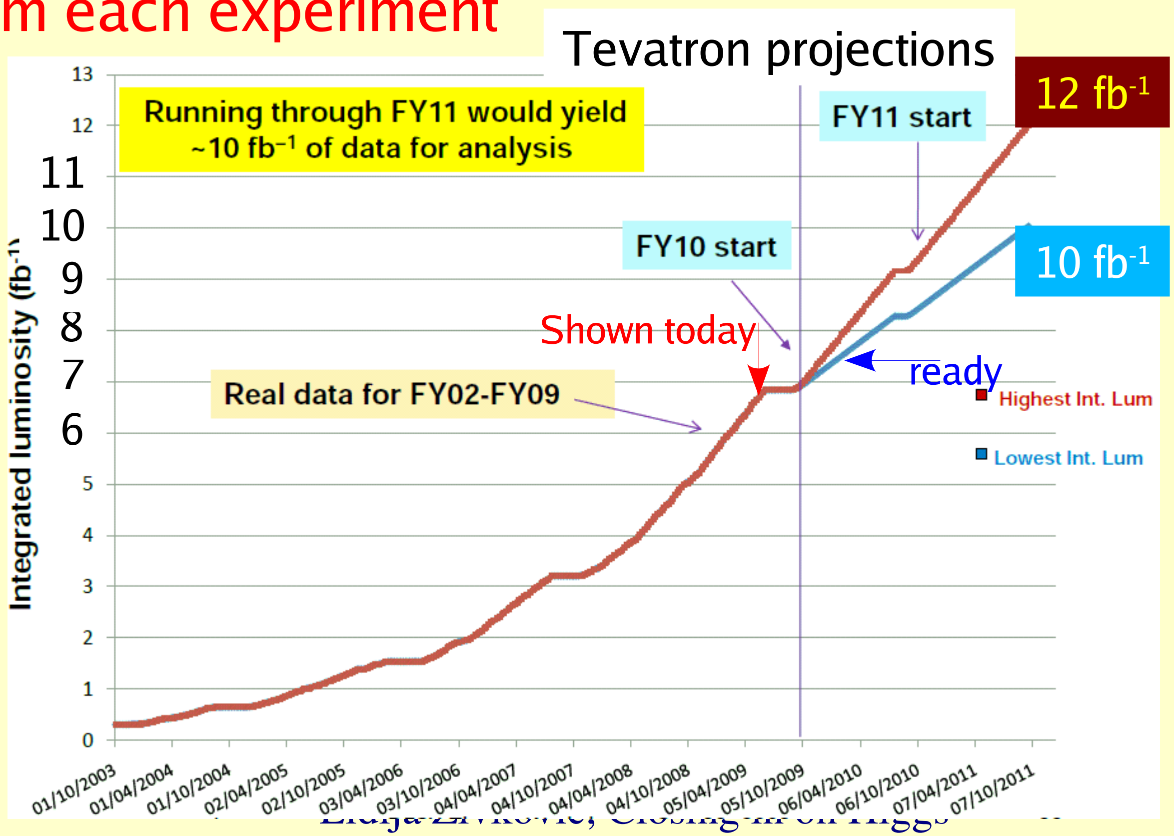


- The solid lines are 1/√(L) projections, as functions of integrated luminosity per experiment.

Tevatron perspectives

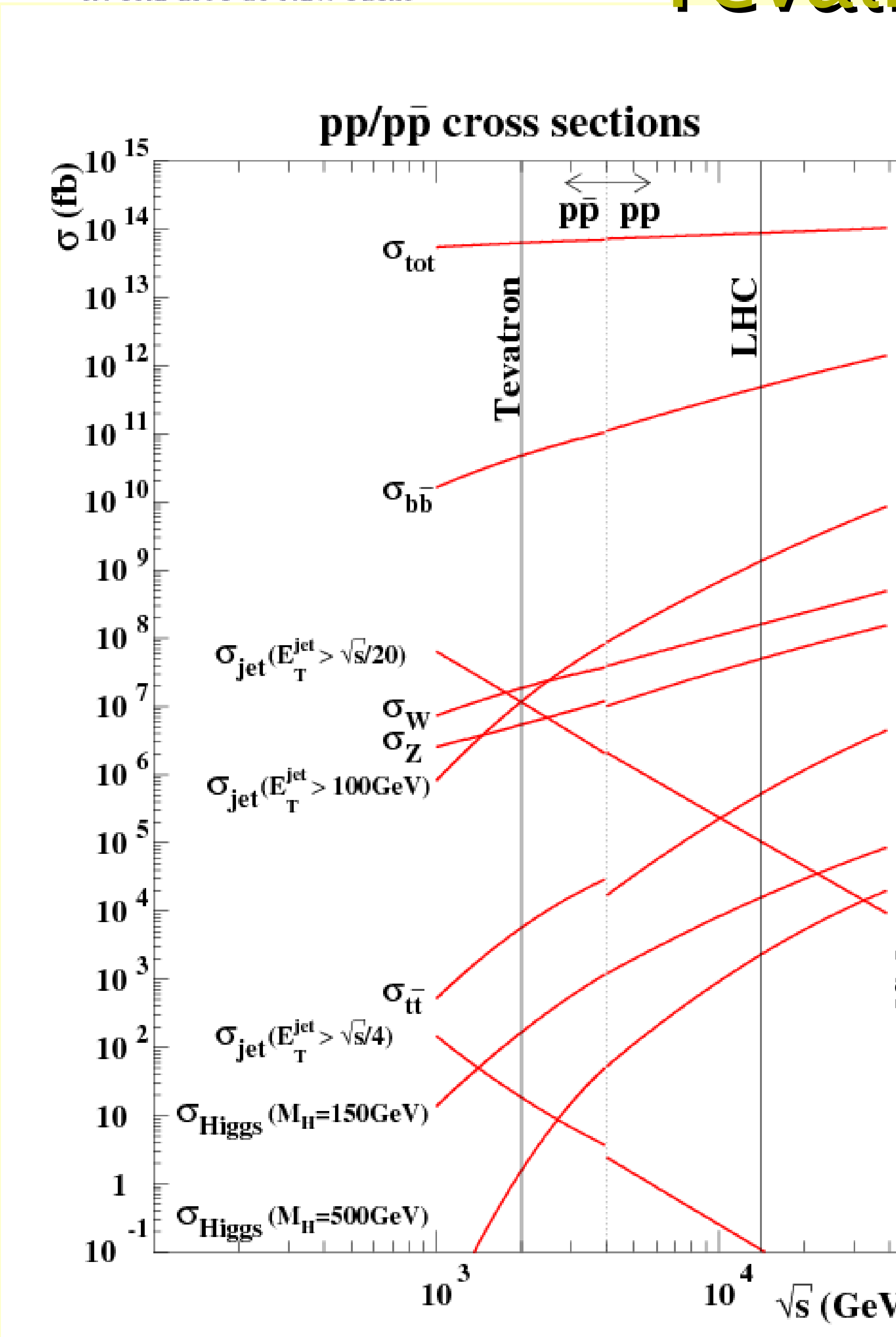
- Data set has doubled every year
- Expect ~ 8 fb^{-1} by the end of 2010 from Tevatron
- We could have more than 6.5 fb^{-1} from each experiment

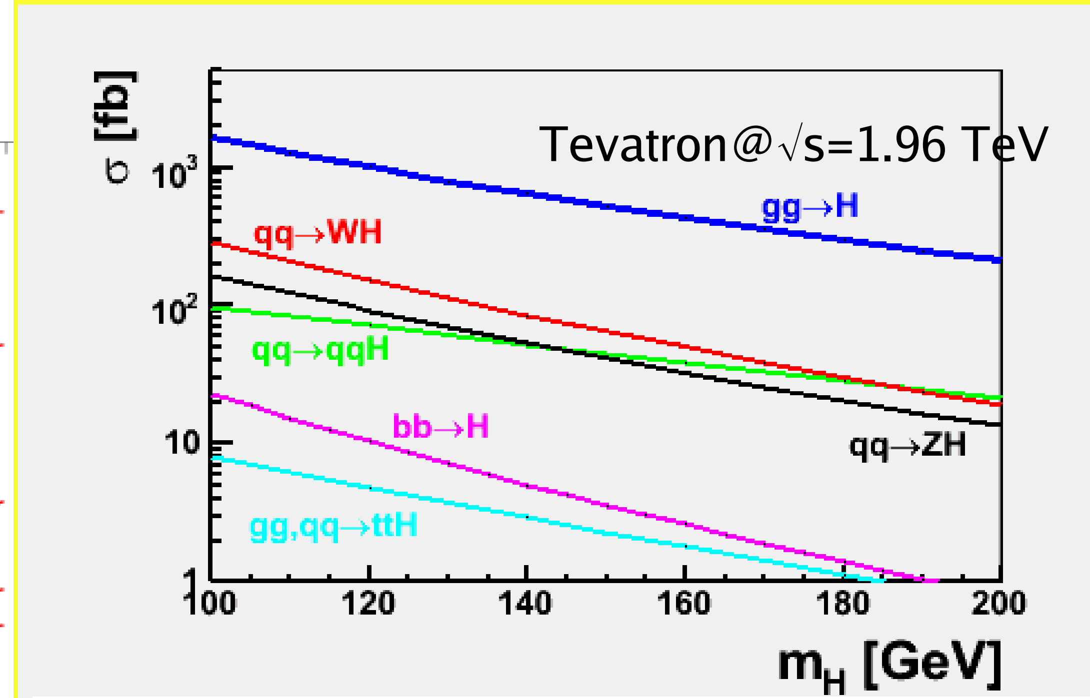
- Tevatron has a potential to exclude almost whole range of Higgs masses below 200 GeV
- Masses around 130 GeV are the most difficult

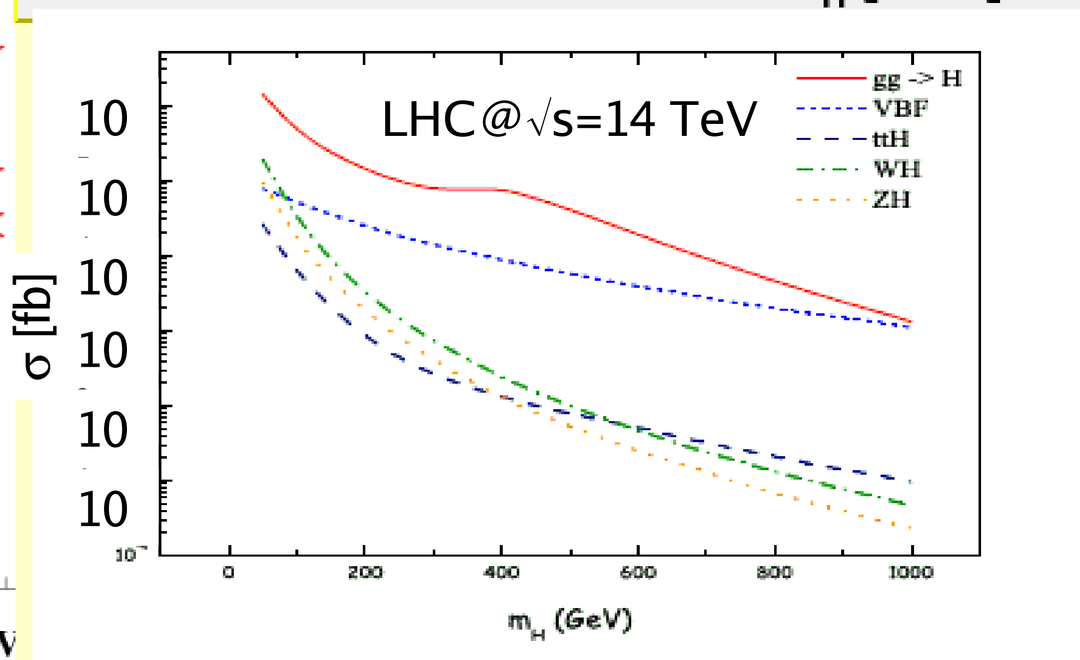


Higgs future

Tevatron vs. LHC

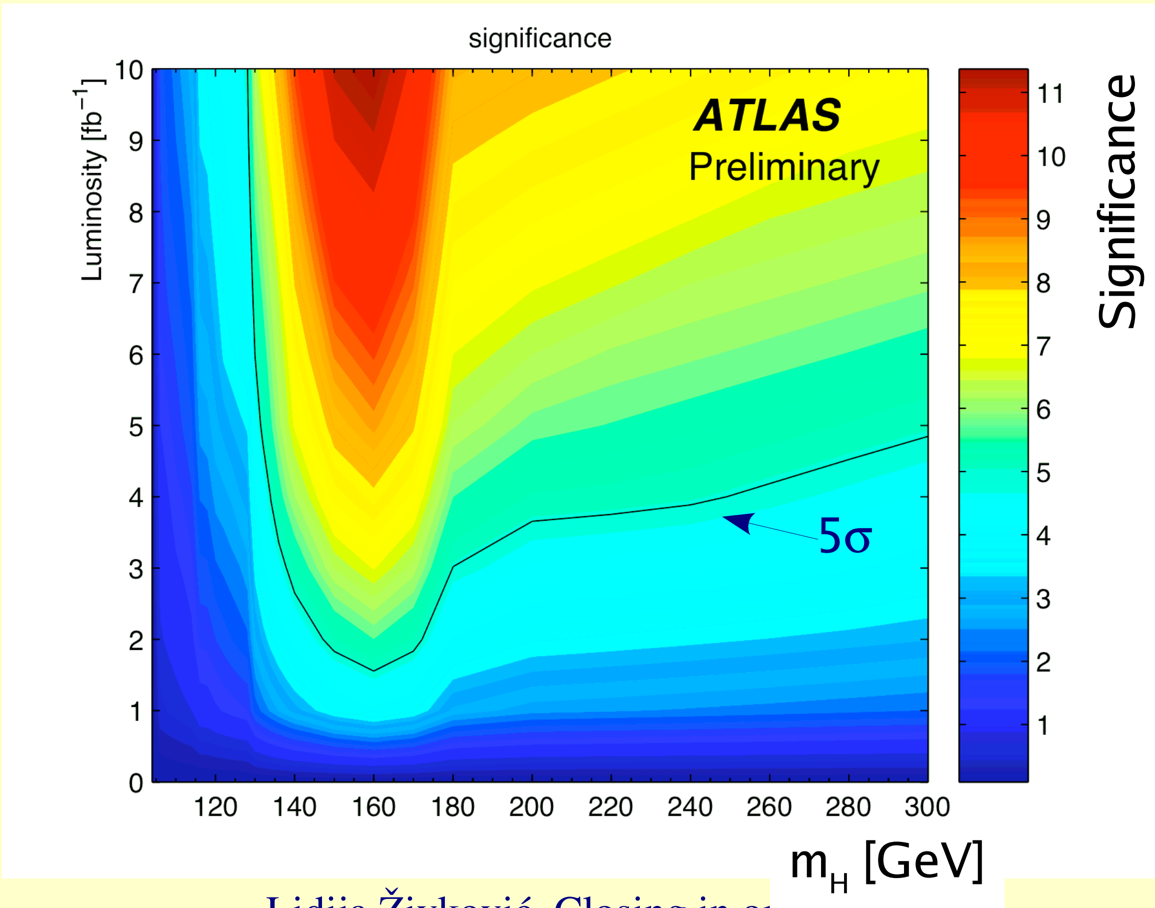




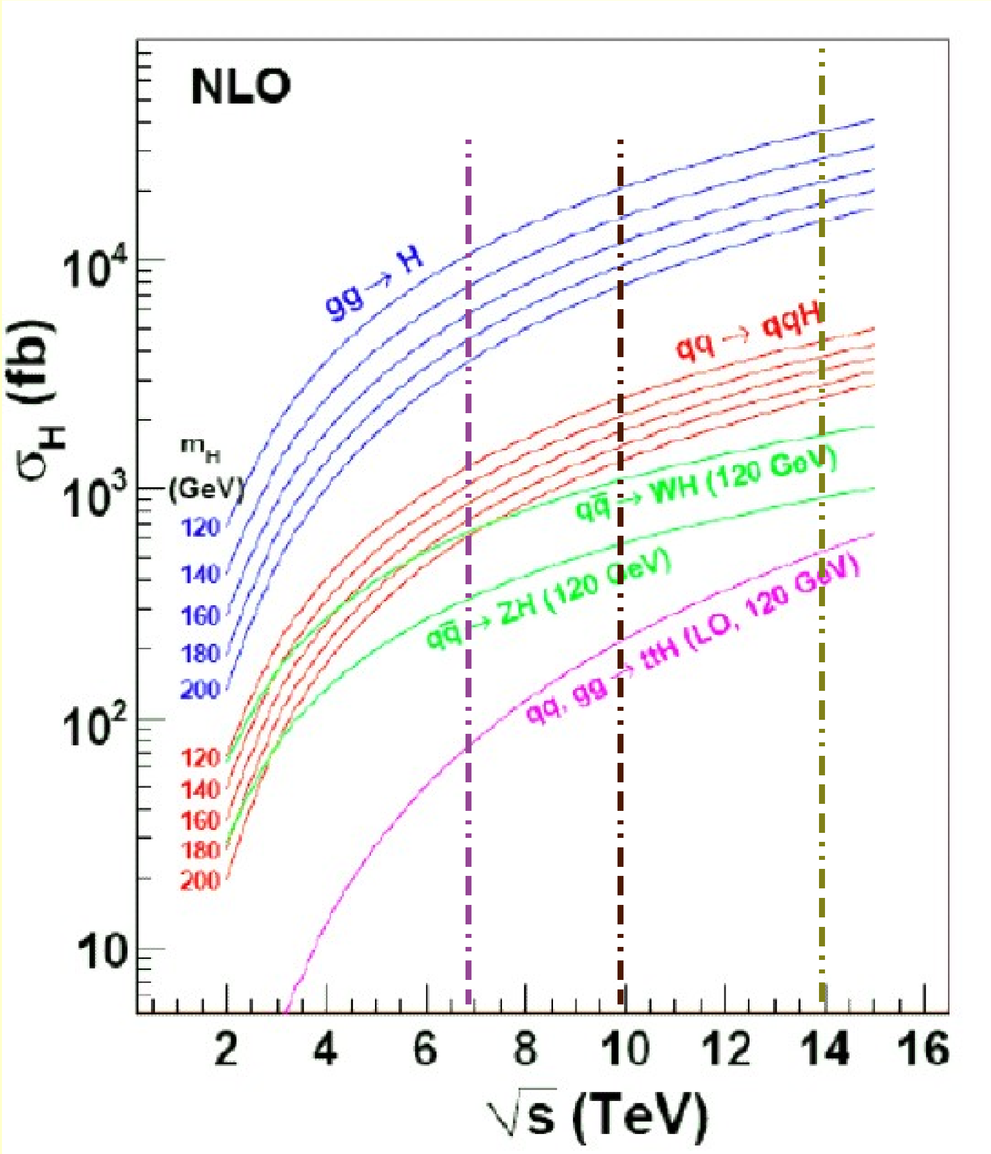


Higgs at LHC

- It is expected that Higgs boson will be found in the first few years of physics running
- Masses around 130 GeV are still the most difficult to access
  - One of the channels, ttH->ttbb, is not sensitive any more



First year



- LHC will start running at 900 GeV later this year
- Collisions expected at ~2.4 TeV at before 2010
- Run at 7 and then at 10 TeV after few months
- Collect few hundreds of pb^{-1}

m_h=140 GeV	gg	VBF	Vh	tth
$\sigma_{10\ TeV}/\sigma_{14\ TeV}$	0.56	0.56	0.63	0.41

Higgs LHC vs Tevatron

- Exclusion:
  - Combining ATLAS and CMS:
    - @ $\sqrt{s}$ = 14 TeV
      - 0.1-1 fb^{-1} of good data for 95% C.L exclusion
    - @$\sqrt{s}$ = 10 (7) TeV – needs ~1.6 (3) times more luminosity
    - Won't happen before 2012
  - Tevatron can exclude the whole accessible mass range by 2011

- Discovery (evidence):
  - Combining ATLAS and CMS:
    - @ $\sqrt{s}$ = 14 TeV
      - 0.5 – 5 fb^{-1} for 5σ discovery
  - Tevatron
    - 3σ for high masses within reach
      - currently excluded

Lessons from Tevatron

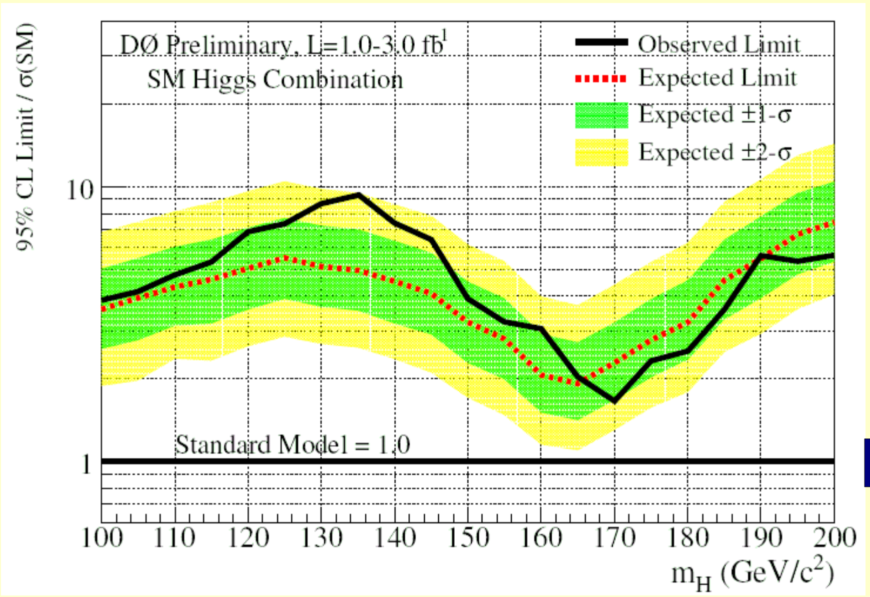
- Efficient data taking
  - Lower downtime to fix problems in control room, providing data of the best quality
- Object reconstruction and identification
  - High efficiency and purity
- Excellent modeling of known processes
  - Understanding the problems
- Powerful multivariate techniques
  - They are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

Summary

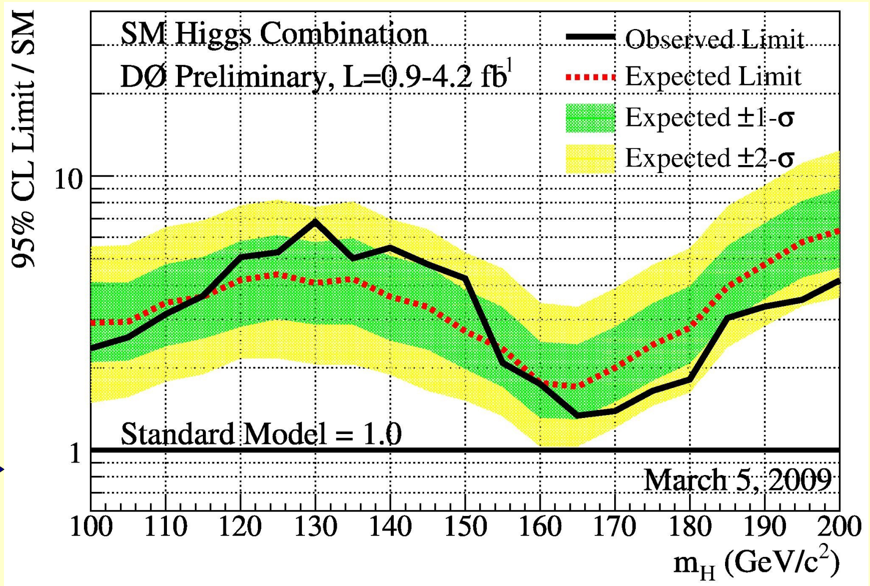
- The first exclusion at Tevatron
  - Higgs boson does not have mass between 160 and 170 GeV
- Searches at Tevatron are mature
  - improvements are still possible
- LHC will give the final answer about existence of the Higgs boson
- Lessons from Tevatron are very important for future searches
  - QCD handling, background modeling, estimation of systematics, advanced tools for data analysis
- Higgs is around the corner - watch out!

Backup

D0 progress



6 months

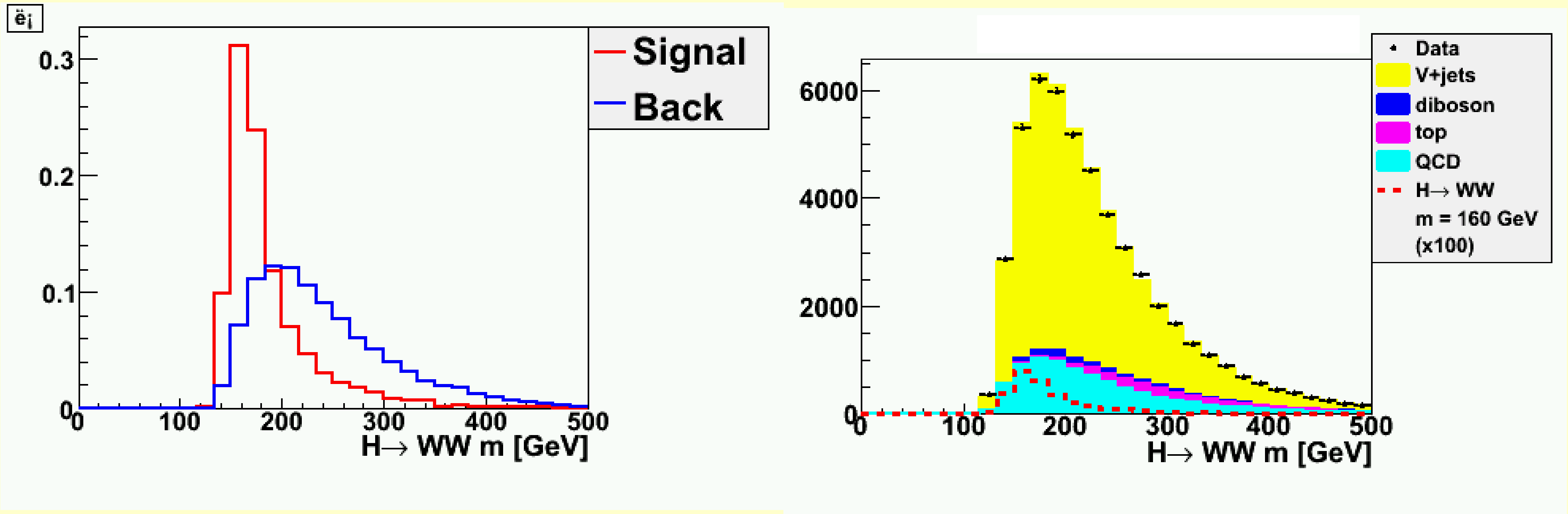


	expected		observed	
m_H [GeV]	115	165	115	165
Limit	4.6	1.9	5.3	2

	expected		observed	
m_H [GeV]	115	165	115	165
Limit	3.6	1.7	3.7	1.3

Neural networks

- Train signal and combined background samples for each Higgs mass point
- Select variables based on two criteria:
  - discriminate signal vs. background
  - well modeled – good data/MC agreement



- NN can depend on Higgs mass

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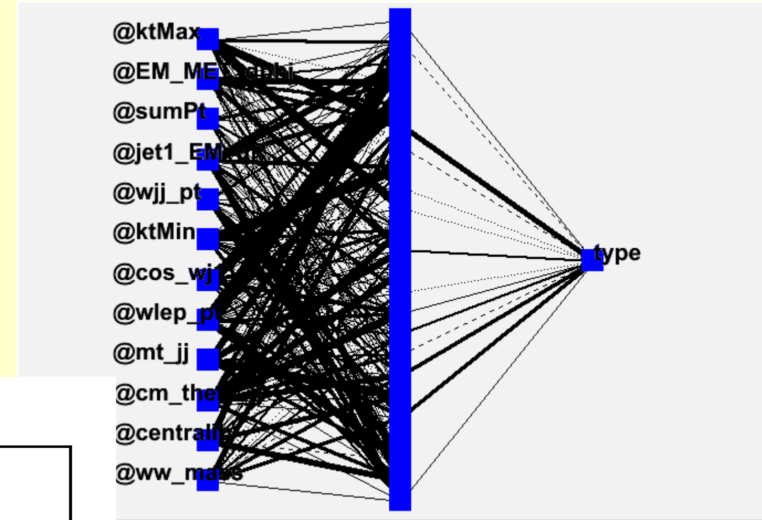
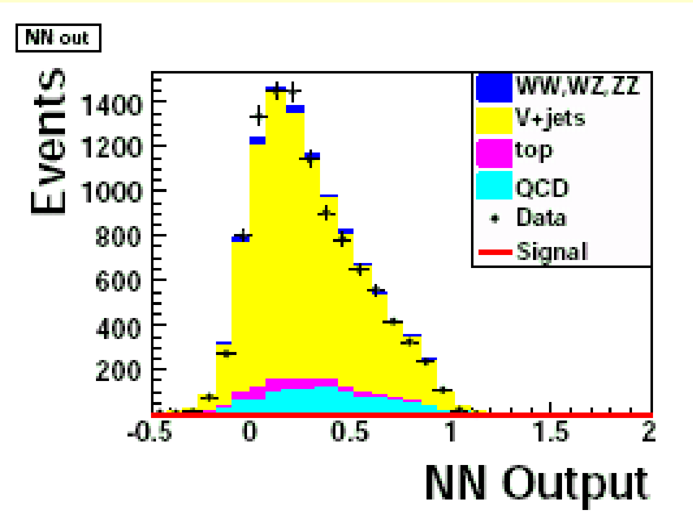
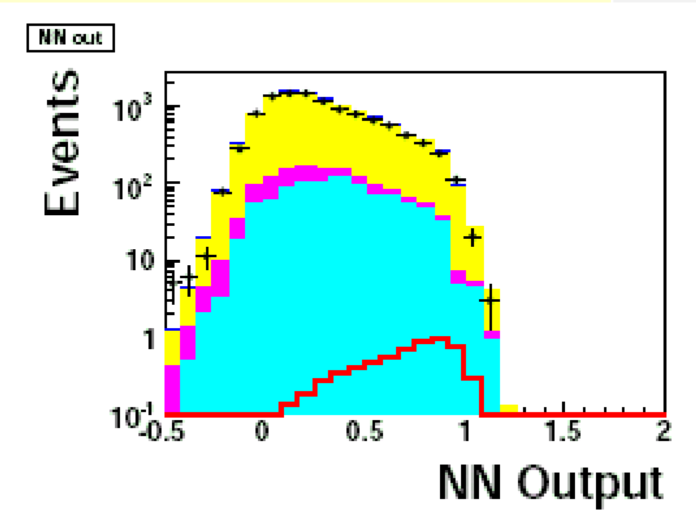
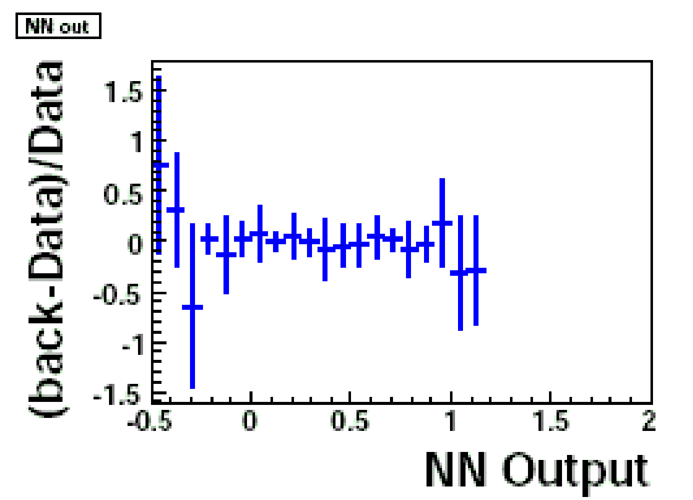
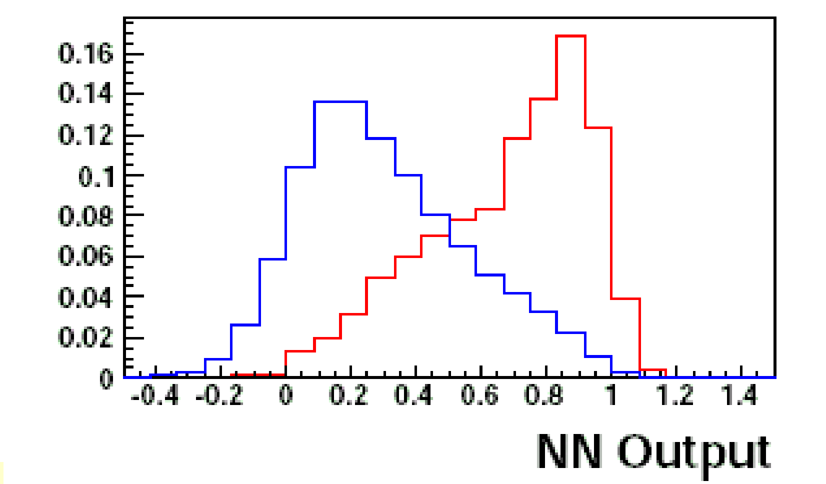
NN analysis











- NN output is:
  1. modeled well
  2. discriminating well between signal and backgrounds

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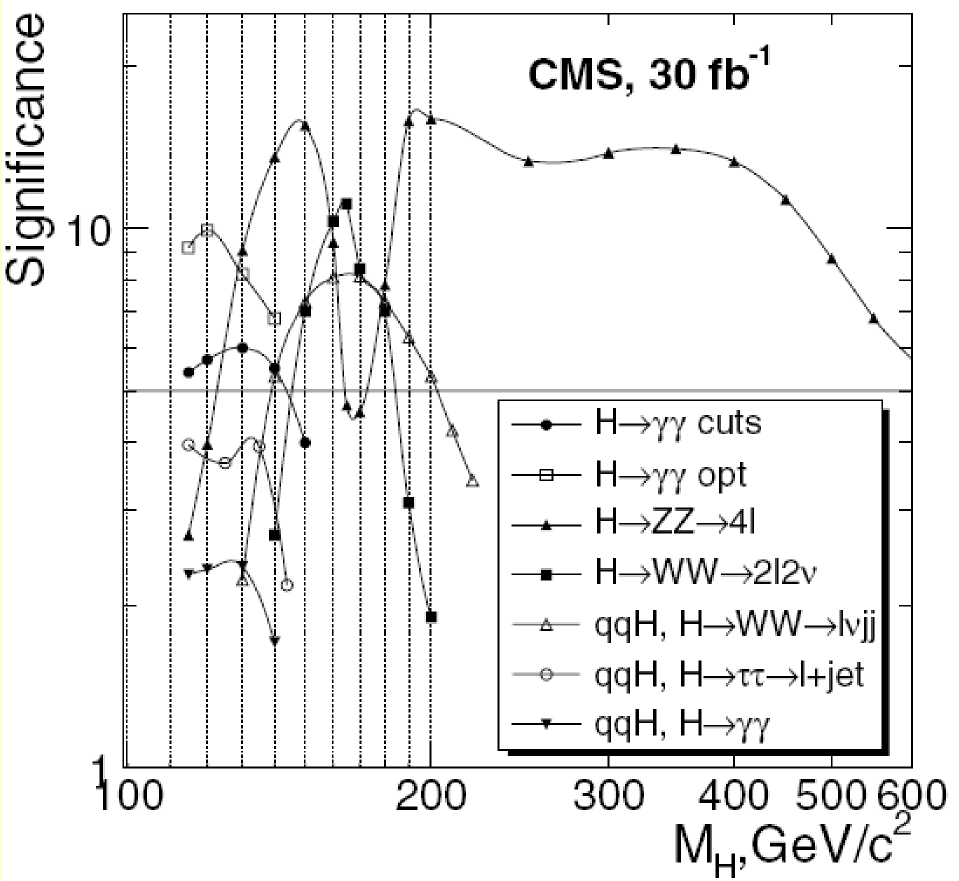
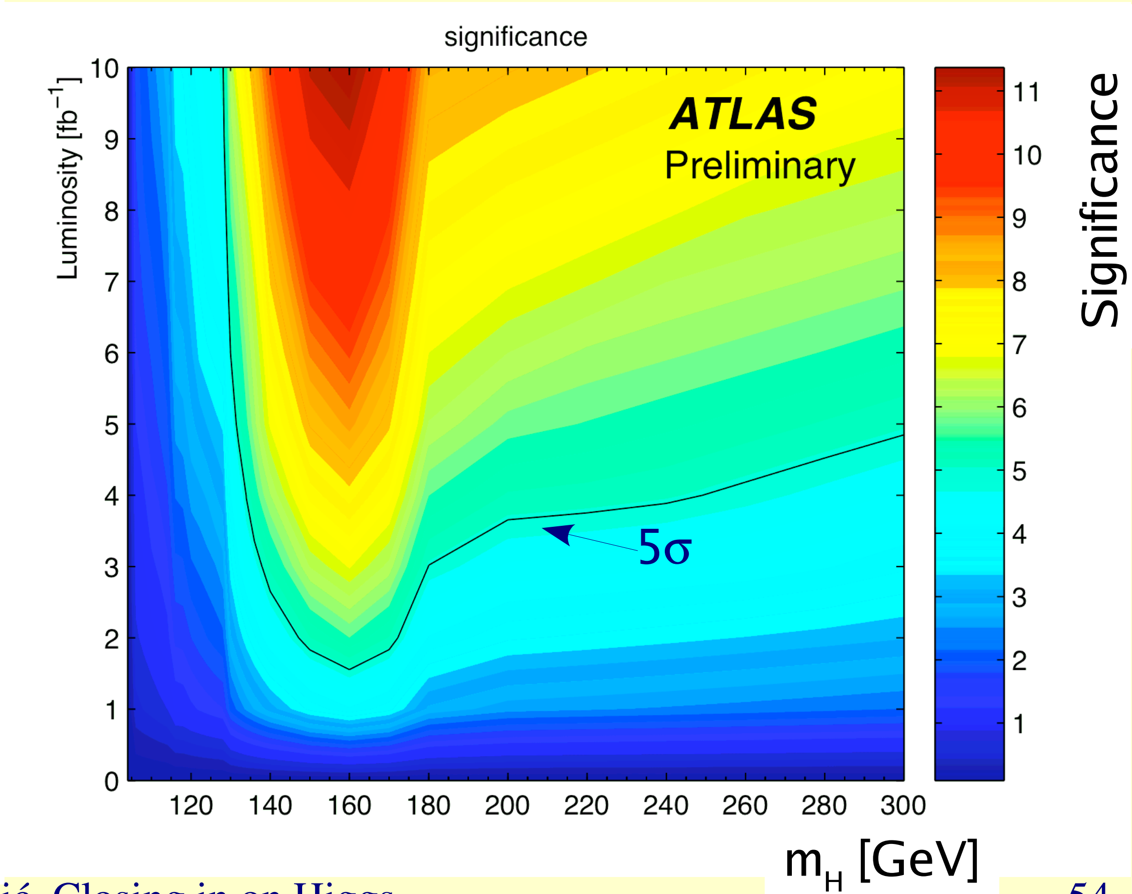
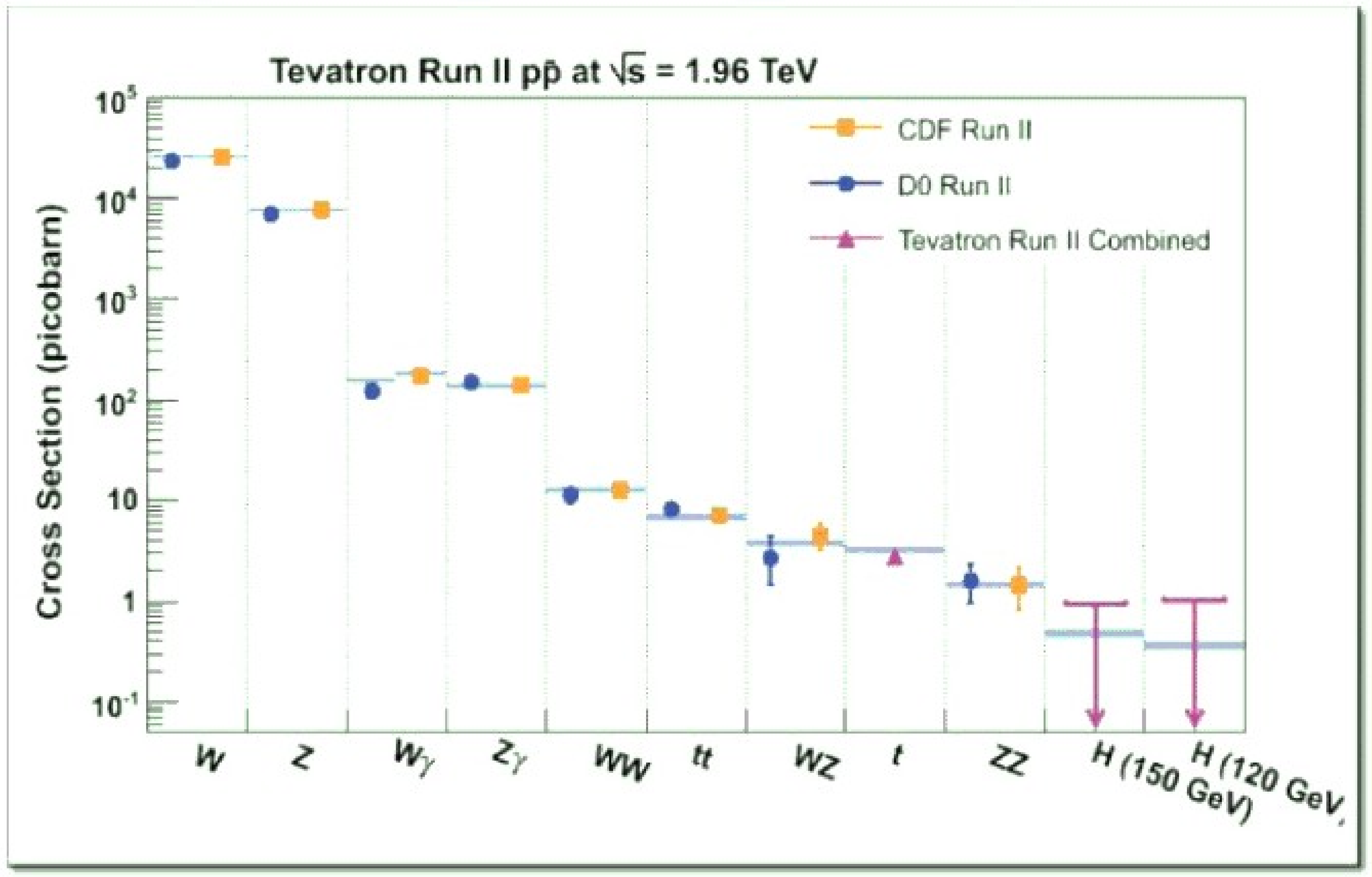
Higgs at LHC

- It is expected that Higgs boson will be found in the first few years of physics running
- Masses around 130 GeV are still the most difficult to access
  - One of the channels, ttH->ttbb, is not sensitive any more





Cross sections



Overview of the Higgs search at Tevatron

- Low mass:
  - WH->lνbb (l=e,μ,τ)
  - ZH->llbb (l=e,μ,τ)
  - ZH->ννbb and WH->(l)νbb
  - H->γγ
  - ttH->ttbb
  - VH->jjbb
- Intermidiate mass
  - WH->WWW->l±l±+X
- High mass
  - H->WW->lνlν
  - H->WW->lνjj

- Common challenges:
  - Lepton and jet id
  - MET reconstruction
  - b-tagging
  - multijet estimation
  - systematics
- Recent improvements:
  - Better trigger and b-tagging algorithms
  - Better lepton ID
  - Improved dijet mass resolution
  - precise measurements of some known SM processes

Combining ATLAS and CMS, $\sqrt{s}$ = 14 TeV:
0.1–1 fb^{-1} of good data for 95% C.L. exclusion
~0.5-5 fb^{-1} of good data for 5σ discovery
depending on the Higgs mass
$\sqrt{s}$ = 10 (7) TeV: need ~1.6 (~3) more luminosity

Higgs : LHC vs Tevatron

Tevatron:
"analyzable" luminosity: ~ 80% of delivered → 5.5 fb^{-1} in 2009
7.4 fb^{-1} in 2010
10 fb^{-1} in 2011

Note:
160-170 GeV
excluded already

	95% C.L exclusion	3σ
Tevatron 2009 (5.5 fb^{-1})	full range ≤180 except 118-146	156-170 GeV
Tevatron 2010 (7.4 fb^{-1})	full range <200 except 128-134	153-178 GeV
Tevatron 2011 (9.6 fb^{-1})	full range <180	<117, 148-185 GeV
LHC (1-2 fb^{-1})	full range < 1 TeV	> 125 (5σ: 140-500)

- No competition for exclusion: if the Higgs is not there, Tevatron will exclude almost all mass range below 200 GeV in 2010
- 2010: Tevatron has 3σ sensitivity ± 8 GeV window around the presently excluded region
- LHC becomes competitive (and ultimately takes over) starting with ~ 1 fb^{-1} (2011)

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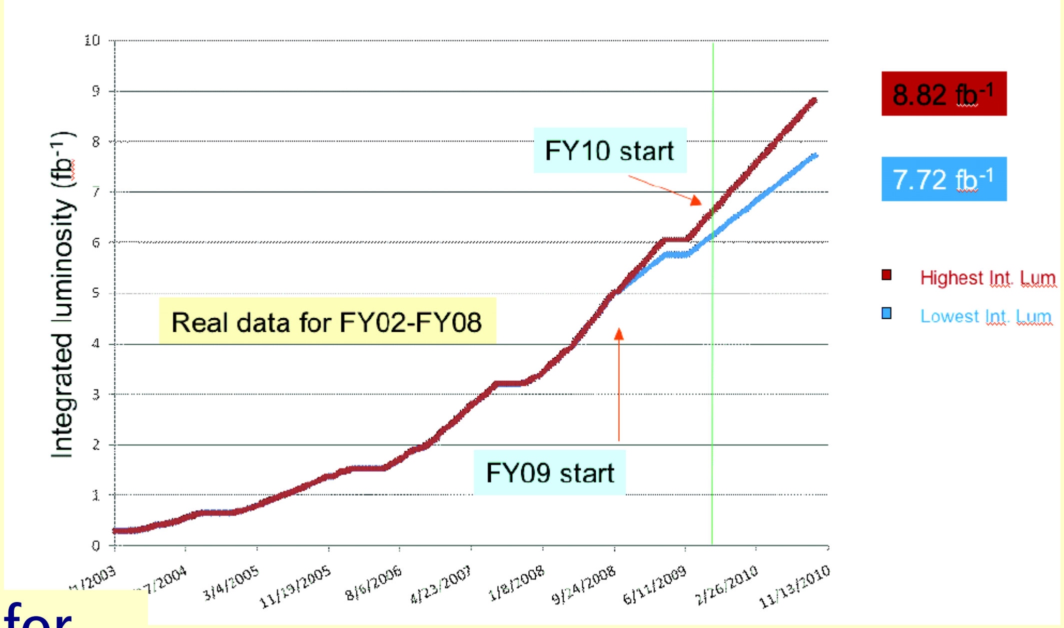
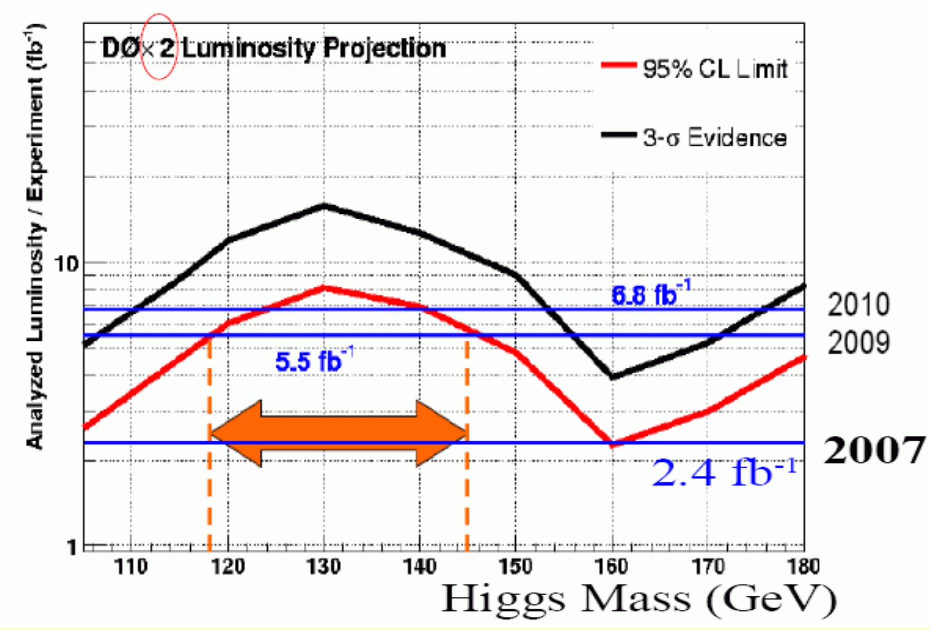
Tevatron projections

- Including data taking efficiency projected full data set will be:
  - between 7.7 and 8.8 fb^{-1} by the end of 2009



- Assumption: projected sensitivity for mH = 115 GeV 2 times higher than current for full data set
  - Improvement from 2005-2007 was ~1.7
  - Possibilities:
    - Better b-tagging
    - Better dijet mass resolution
    - Better multivariate techniques



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Evidence projection

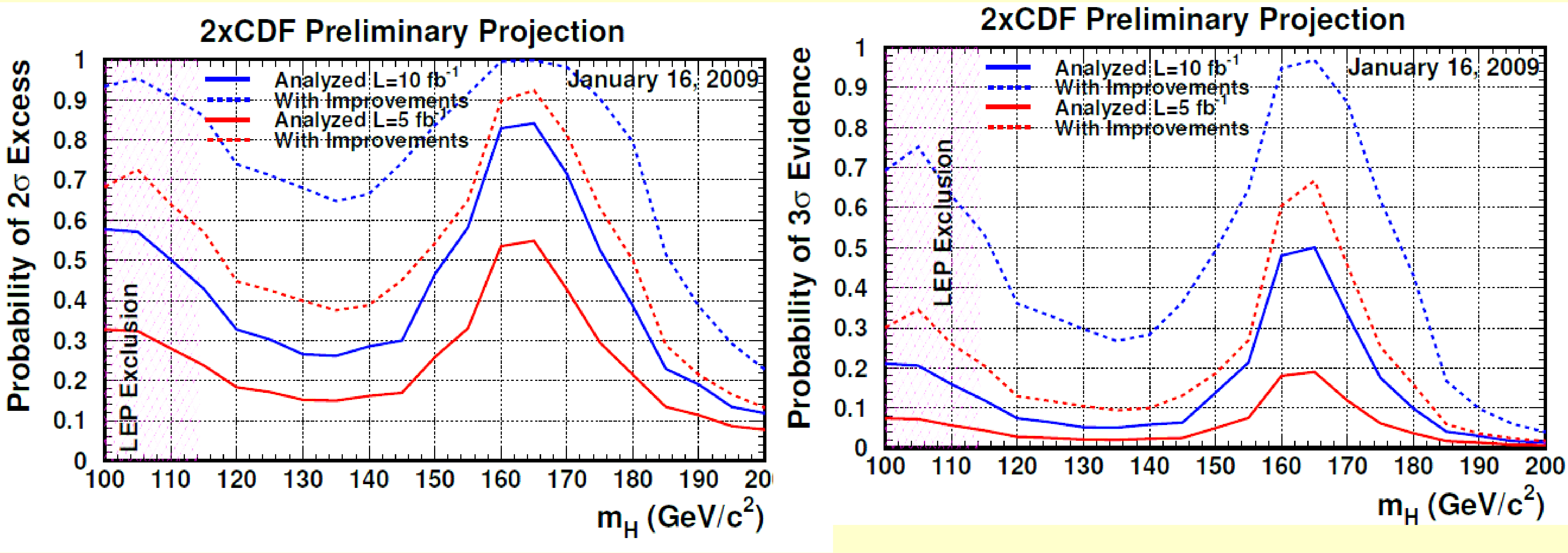
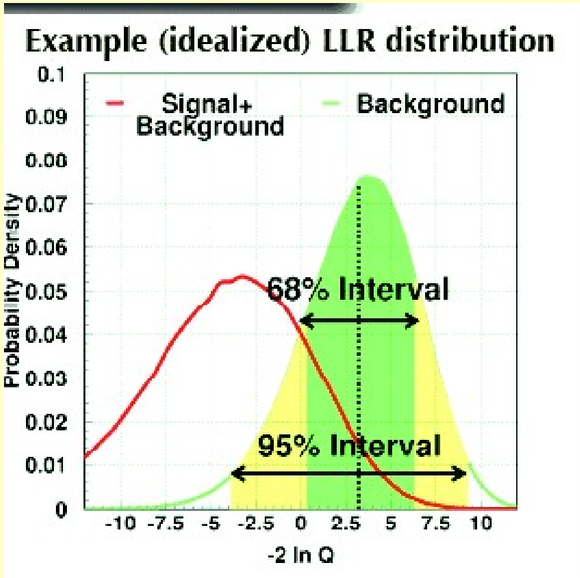
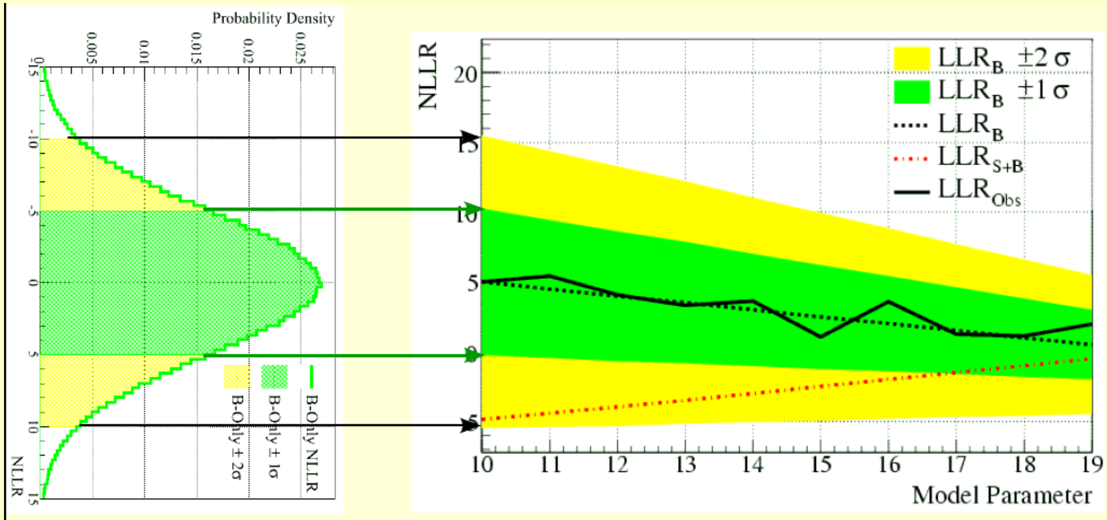


FIG. 10: Sensitivity projections as functions of m_H. These graphs show the chances of observing a 2σ excess (top) or a 3σ evidence (bottom), as functions of m_H, assuming a Higgs boson is present with production cross sections and decays at their SM values. CDF and D0 are assumed to contribute equally. The solid lines correspond to current performance as described in this note, and the dashed lines correspond to a performance level which corresponds to the bottom of the light orange bands in Figure 9. No account is taken of the data already collected and analyzed; existing excesses and deficits in the data do not affect these sensitivity projections. Two luminosity scenarios are considered: 5 fb^{-1} of analyzed luminosity per experiment (red lines) and 10 fb^{-1} of analyzed luminosity per experiment (blue lines).

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





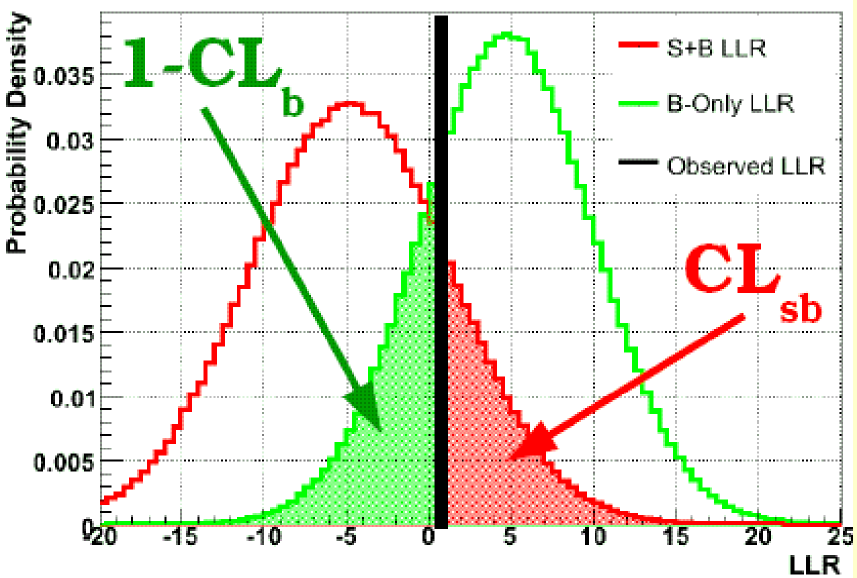
- In the case of the Higgs search, we seek to set limits on potential signal rates
  - ⇒ Similar test, comparing signal+background and background-only hypotheses
  - ⇒ Signal rate is now a fixed parameter to be tested

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

← 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



Tevatron limits at 95% CL

Bayesian	100	105	110	115	120	125	130	135	140	145	150
Expected	2.0	2.0	2.2	2.4	2.7	2.9	2.9	2.7	2.5	2.4	1.8
Observed	1.9	1.8	2.4	2.5	2.8	3.0	3.5	2.4	2.7	2.8	1.9

CL_S	100	105	110	115	120	125	130	135	140	145	150
Expected	1.9	1.9	2.1	2.4	2.6	2.7	2.9	2.7	2.5	2.2	1.8
Observed	1.7	1.7	2.2	2.6	2.8	2.9	4.0	2.6	3.1	2.8	2.0

Bayesian	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.4	1.6	1.9	2.2	2.7	3.5	4.2
Observed	1.4	0.99	0.86	0.99	1.1	1.2	1.7	2.0	2.6	3.3

CL_S	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.3	1.6	1.8	2.5	3.0	3.5	3.9
Observed	1.3	0.95	0.81	0.92	1.1	1.3	1.9	2.0	2.8	3.3

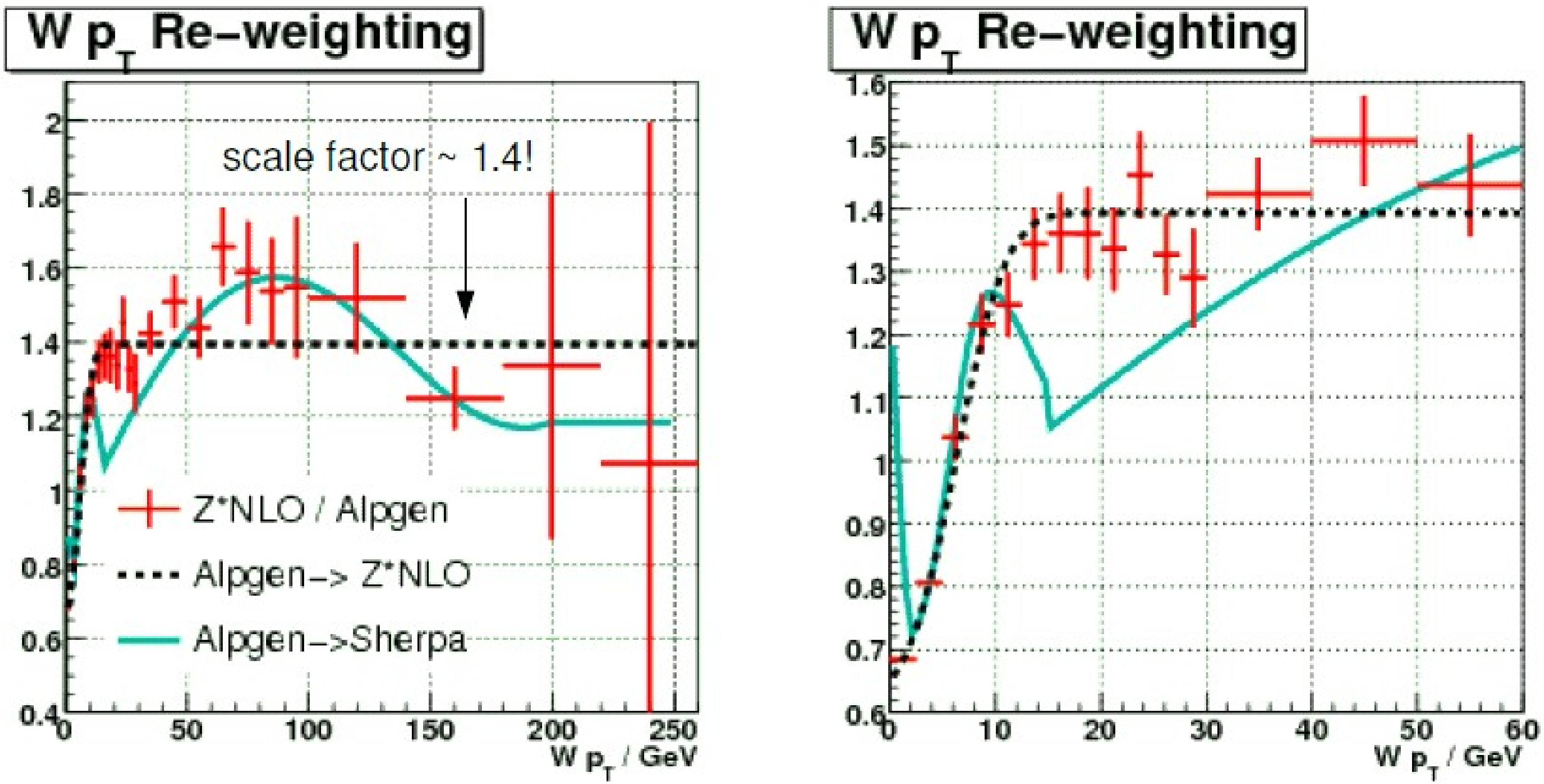
D0 limits at 95% CL

TABLE V: Combined 95% C.L. limits on $\sigma \times BR(H \to b\bar{b}/W^+W^-/\gamma\gamma/\tau^+\tau^-)$ for SM Higgs boson production. The limits are reported in units of the SM production cross section times branching fraction.

m_H (GeV/c^2)	100	105	110	115	120	125	130	135	140	145	150
Expected:	2.35	2.40	2.85	2.80	3.25	3.31	3.30	3.35	2.95	2.71	2.46
Observed:	3.53	3.40	3.47	4.05	4.03	4.19	4.53	5.58	4.33	3.86	3.20

m_H (GeV/c^2)	155	160	165	170	175	180	185	190	195	200
Expected:	1.98	1.41	1.35	1.64	2.05	2.58	3.32	4.19	5.04	6.00
Observed:	3.35	1.90	1.53	1.91	1.89	2.20	3.20	3.36	5.71	6.27

Inclusive W pT re-weighting:



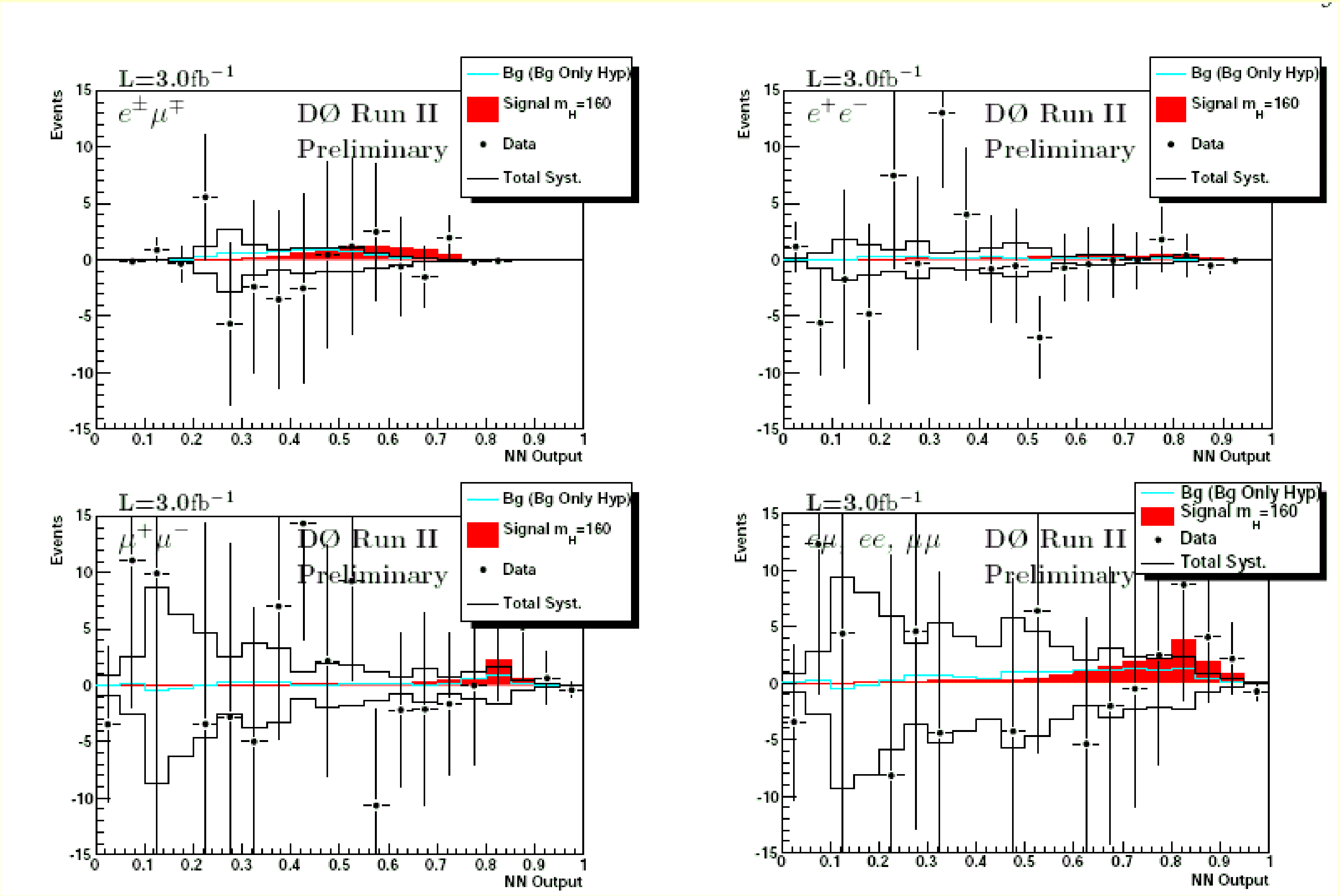
Systematics - D0

Source	$WH \to e\nu b\bar{b}$	$WH \to \mu\nu b\bar{b}$	$WH \to WW^+W^-$	$WH \to \tau\nu b\bar{b}$
Luminosity (%)	6.1	6.1	-	6.1
Normalization (%)	-	-	6.1	-
Jet Energy Scale (%)	3.0	3.0	-	3.0
Jet ID (%)	3.0	3.0	-	4.0
Jet Triggers (%)		-	5.5	-
Tau Energy Scale/ID (%)	-	-	-	7.0
Electron ID/Trigger (%)	6.0	-	11	-
Muon ID/Trigger (%)	-	7.0	11	-
b-Jet Tagging (%)	3-6	3-6	-	4-6
Background σ (%)	6-20	6-20	6-18	6-18
Multijet (%)	14	14	30-50	25
Shape-Dependent Bkgd Modeling (%)	5-10	5-10	-	5-20

Source	$ZH \to \nu\bar{\nu}b\bar{b}$	$ZH \to e^+e^-b\bar{b}$	$ZH \to \mu^+\mu^-b\bar{b}$
Luminosity (%)	6.1	6.1	6.1
Jet Energy Scale (%)	3.0	2.0	2.0
Jet ID (%)	2.0	5.0	5.0
Jet Triggers (%)	5.5	-	-
Electron ID/Trigger (%)	0	4.0	-
Muon ID/Trigger (%)	0	-	4.0
b-Jet Tagging (%)	6.0	3.0-7.5	3.0-7.5
Background σ (%)	6-16	10-30	10-30
Heavy-Flavor Scale (%)	50	-	-
Multijet (%)	-	41-50	50
Shape-Dependent Bkgd Modeling (%)	-	5-10	5-10

Source	$H \to W^+W^-$	$t\bar{t}H \to t\bar{t}b\bar{b}$	$H \to \gamma\gamma$	$H+X \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$
Luminosity (%)	-	6.1	6.1	6.1
Normalization (%)	4-6	-	-	-
Jet Energy Scale (%)	3.0	-	-	4.5
Jet ID (%)	1-2	-	-	2
Tau Energy Scale/ID (%)	-	-	-	8.0
Electron ID/Trigger (%)	3-10	2.5	3	-
Muon ID/Trigger (%)	7.7-10	2	-	4
b-Jet Tagging (%)	-	-	-	-
Background σ (%)	6-20	10-15	6	6-25
Signal σ (%)	10	-	10	0
Multijet (%)	5-20	1-5	1	5-40
Shape-Dependent Bkgd Modeling (%)	5-20	-	5-7	-

Systematics in H->WW



GFitter

$(M_H = 116.4^{+18.3}_{-1.3}\ \mathrm{GeV})$

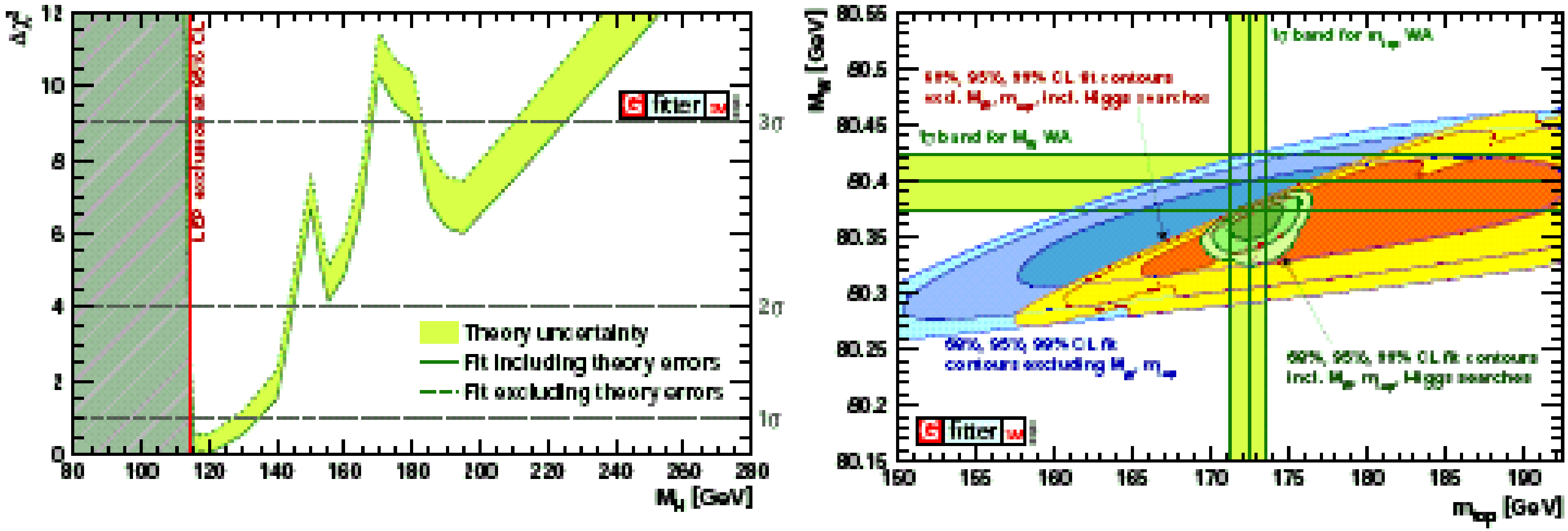
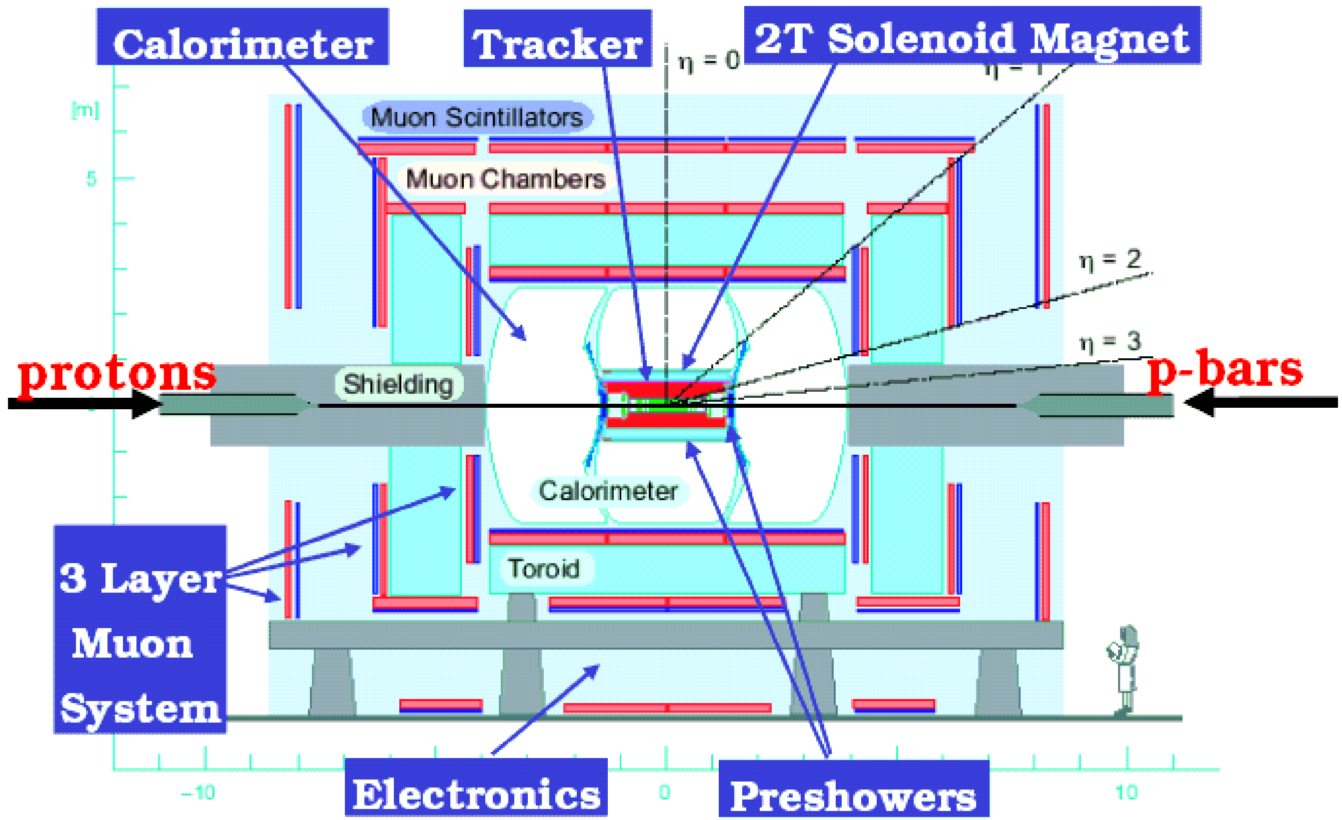


Figure 1: Left: $\Delta\chi^2$ as a function of M_H for the *complete fit*. The solid (dashed) lines give the results when including (ignoring) theoretical errors. The minimum $\Delta\chi^2$ of the fit including theoretical errors is used for both curves in each plot to obtain the offset-corrected $\Delta\chi^2$; Right: Contours of 68%, 95% and 99% CL obtained from scans of fits with fixed variable pairs M_W vs. m_t for three sets of fits explained in the main text. The horizontal bands indicate the 1σ regions of measurements (world averages).



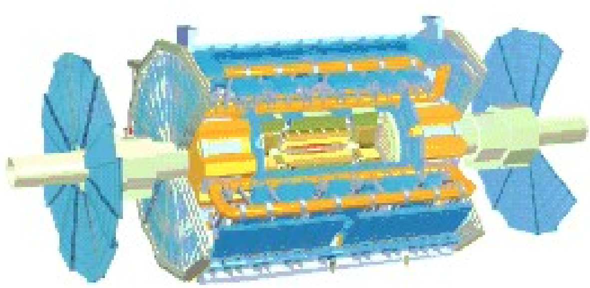
- Silicon microstrip vertex detector
- Scintillating fiber tracker
- Uranium / liquid argon calorimeter
- Wire chamber + scintillation counter muon detector system
- 2T solenoid magnet & 1.8T toroid magnet

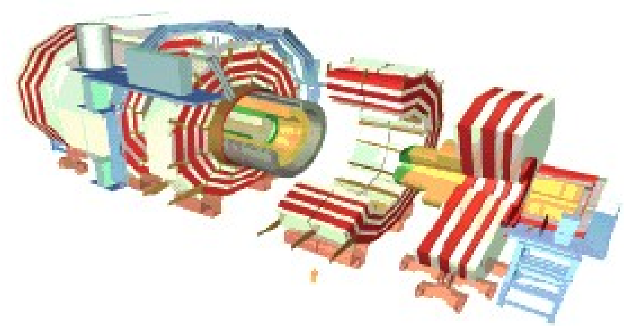
Angular Coverage	$\|\eta\|$
Muon ID	~2
Tracking	~2.5
EM / Jet ID	~4

- Angle_ljjbis : 3D angle between muon and dijet bisector
- AngleWj0higgs : 3D angle between jet0 and leptonic W in the Higgs CM frame
- Beta : $|p|/E$ for hadronic
- Centrality : sum of PT / sum of E for lepton and all good jets
- CMthetajj : 3D angle between selected dijet pair in the Higgs CM frame
- HTjjlepnu : sum of p_T for lepton, $\not{E}_T$, and all good jets
- Jet0leptonDR : ΔR(lepton,lead jet associated w/ hadronic W)
- Jet1leptonDR: ΔR(lepton,2nd jet associated w/ hadronic W)
- KTmax : $\Delta R(j1, j2) * E_T(j1)/(E_T(l) + \not{E}_T)$
- KTmin : $\Delta R(j1, j2) * E_T(j2)/(E_T(l) + \not{E}_T)$
- METbis : dot product of $\not{E}_T$ and dijet bisector
- PTrel : magnitude of jet1 p_T perpendicular to dijet system
- SphericityLepjj : Sphericity calculated from lepton and dijet pair
- WWbisDPhi : $\Delta\phi$ between leptonic W and dijet bisector
- WWmass : Mass of the WW pair

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 $\sigma/p_T \approx 5 \times 10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5 \times 10^{-4} p_T + 0.005$
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)





Why did we conceive and design ATLAS this way (also in comparison with CMS) ?

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3.8 \times 10^{-4}\ p_T \oplus 0.015$	Si pixels + strips Little particle identification B=4T $\sigma/p_T \sim 1.5 \times 10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 10$ % at 1 TeV standalone (~ 7% combined with tracker)	Fe → $\sigma/p_T \sim 15\text{-}30\%$ at 1 TeV standalone (5% with tracker)

SM Higgs searches at √s<14TeV

LHC will start working with center of mass energy lower than 14 TeV around 10 TeV

► Main Effect: cross section changes

Different energy of LHC has two effects:

- Cross section for signals (and background) goes down
- Signal (Higgs production) goes down faster: Higgs is mainly produced from gg and backgrounds from qq

Process	$\frac{\sigma_{\sqrt{s}=10TeV}}{\sigma_{\sqrt{s}=14TeV}}$	$\frac{\sigma_{\sqrt{s}=6TeV}}{\sigma_{\sqrt{s}=14TeV}}$
$t\bar{t}$	0.450	0.113
Wt	0.450	0.113
WW	0.650	0.320
WZ	0.650	0.320
ZZ	0.650	0.320
$Z \to \ell\ell$	0.681	0.371
$W \to \ell\nu$	0.681	0.371
$gg \to H$	0.540	0.190

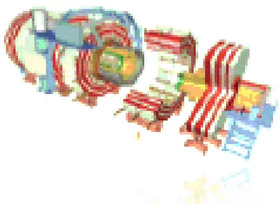
Efficiency and Acceptance:

- Higgs becomes relatively "heavier", i.e. decay products become relatively more central for smaller LHC energies

- Therefore, the corresponding second order correction is larger than 1 (scaling factor)

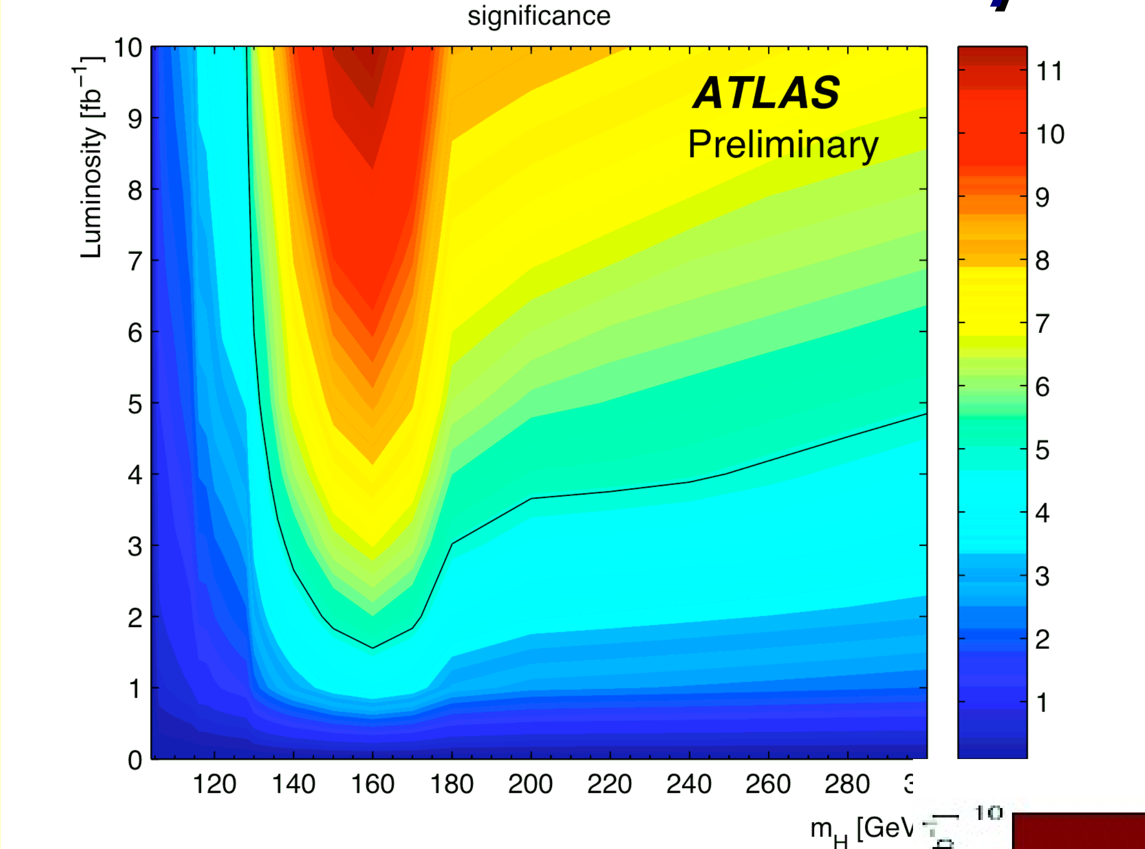
Example : HWW + HZZ combined

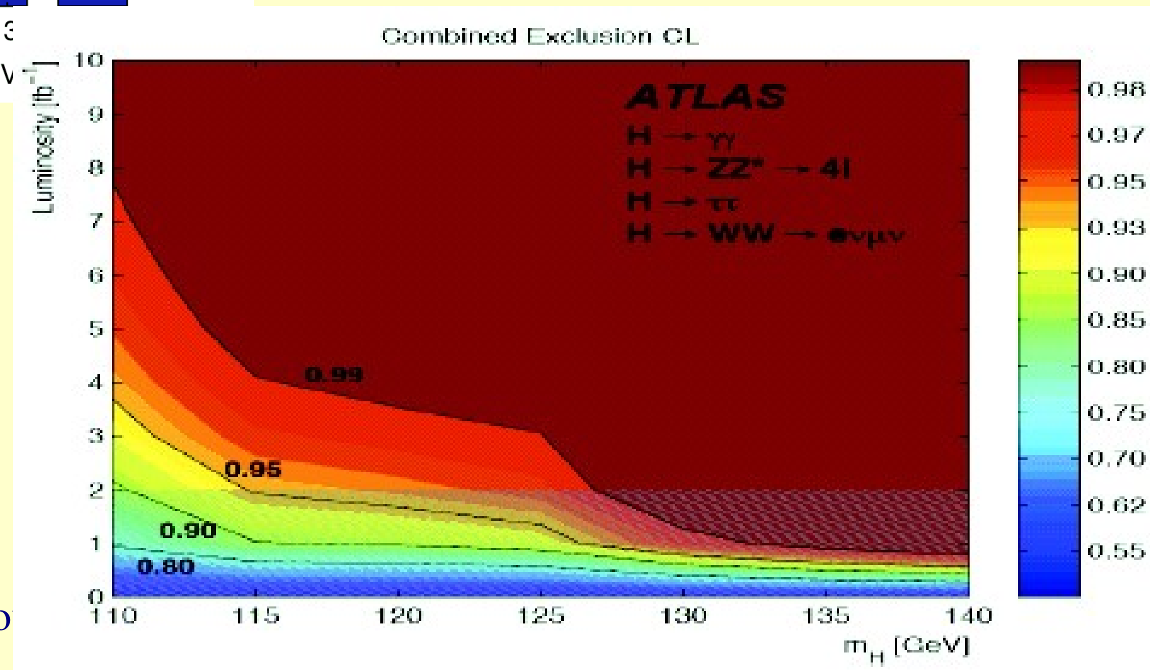
∫L for 5σ	14 TeV	10 TeV
m_H =200 GeV	0.6 fb-1	1.3 fb-1



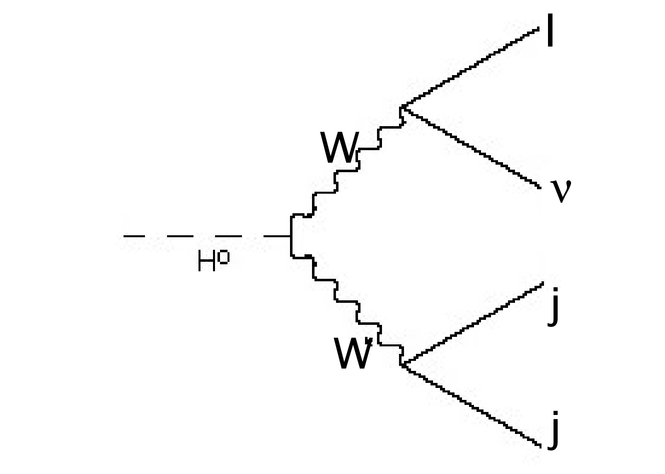
PYTHIA for HZZ (LO) and MCFM for HWW cross section calculations, standard CMS MC Samples used for estimate

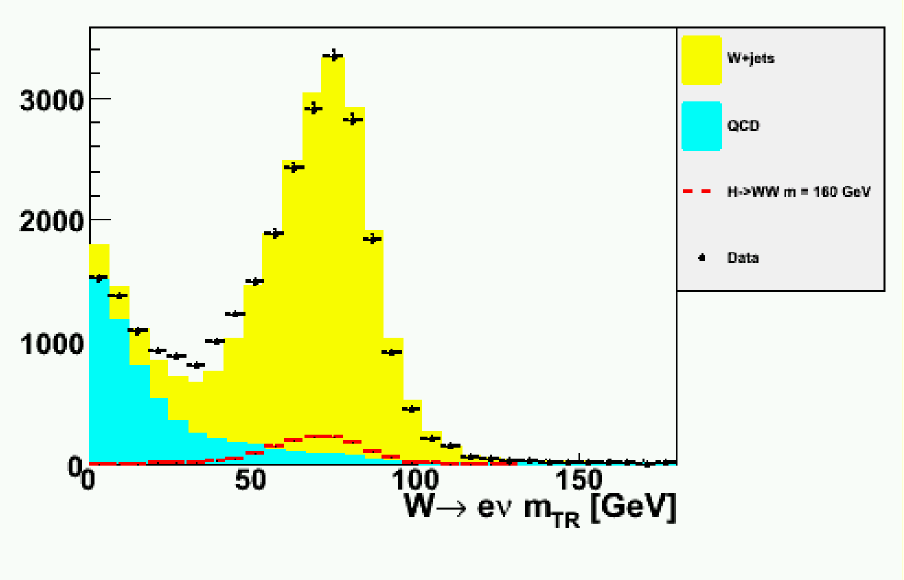
Atlas discovery and exclusion

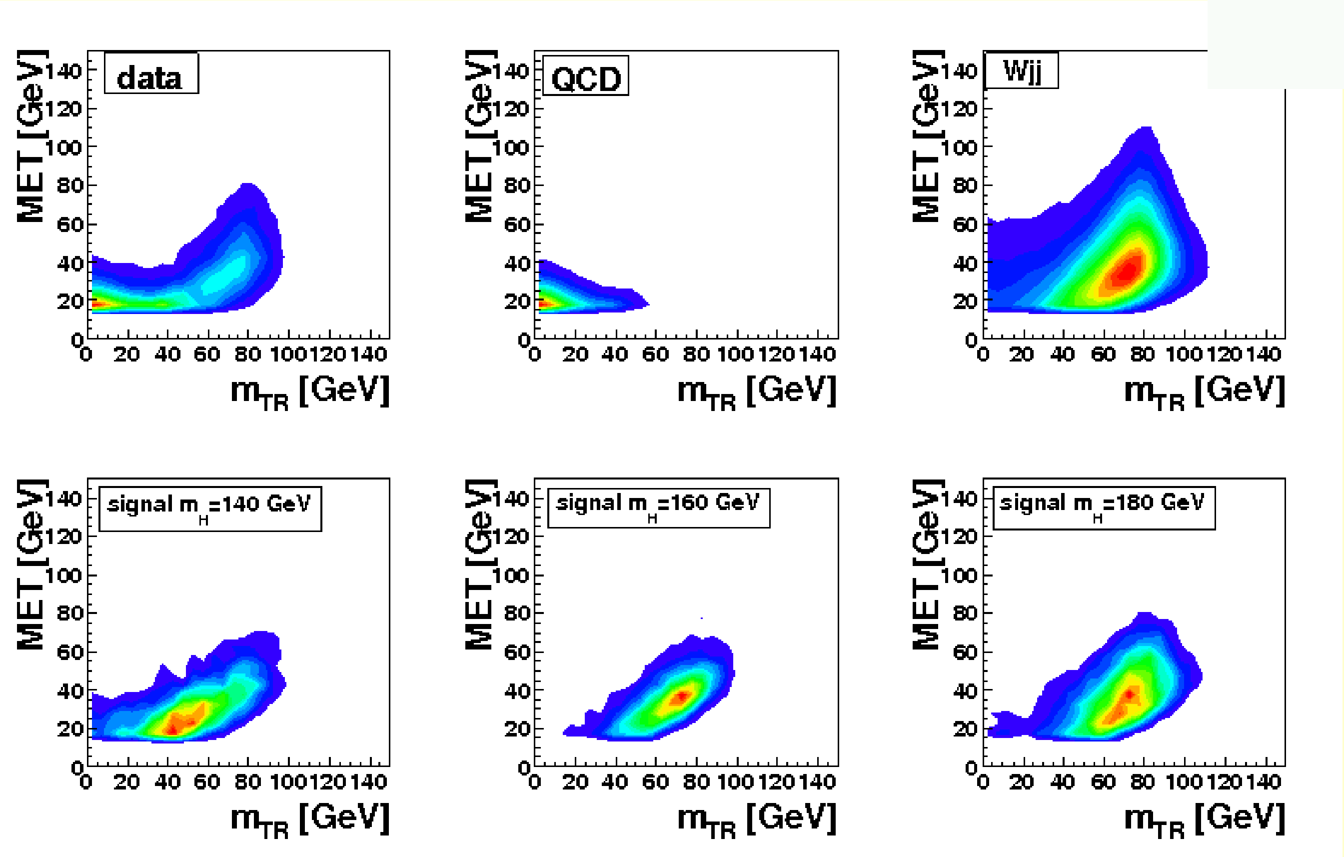




Event Selection

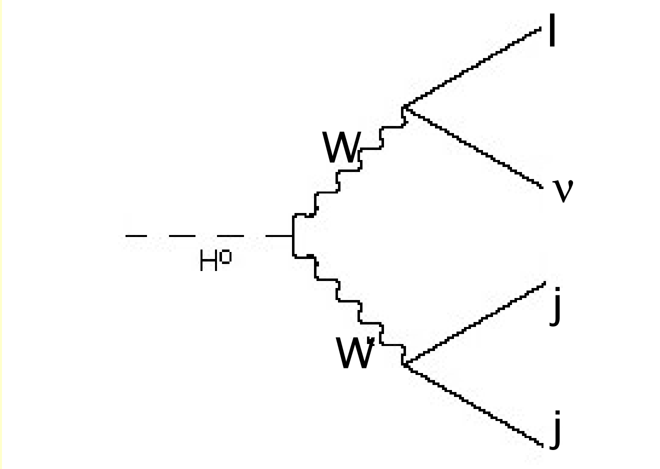


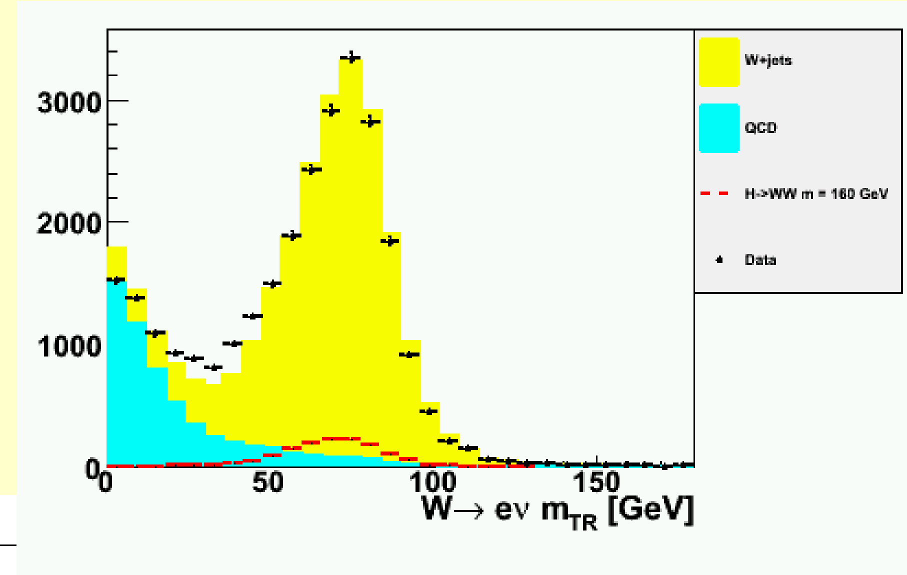


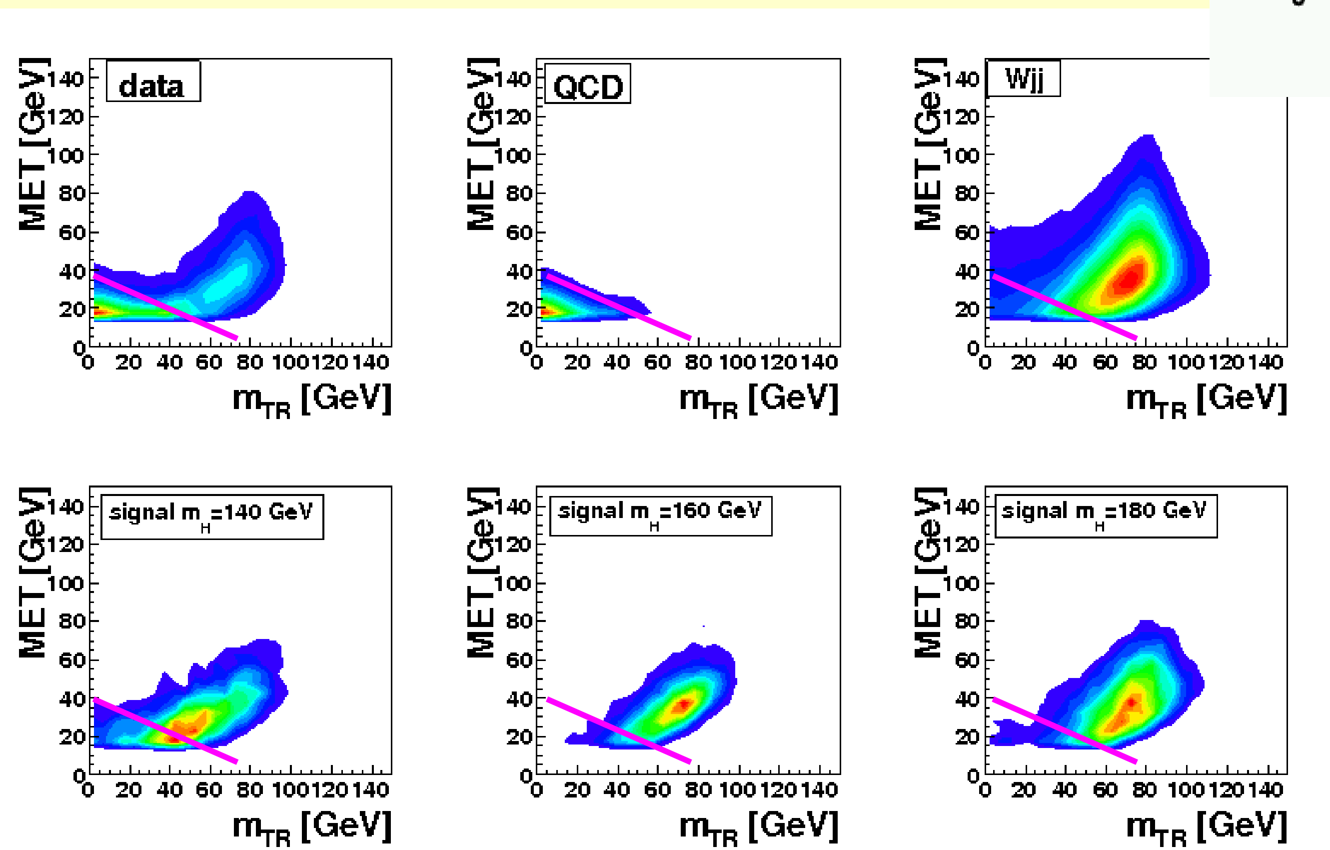


- QCD reduction
  - jet faking electron
  - missmeasured jet energies give MET

Event Selection

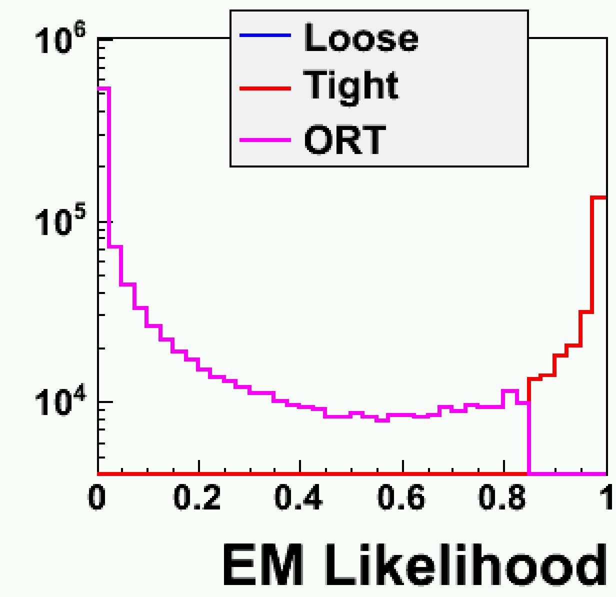


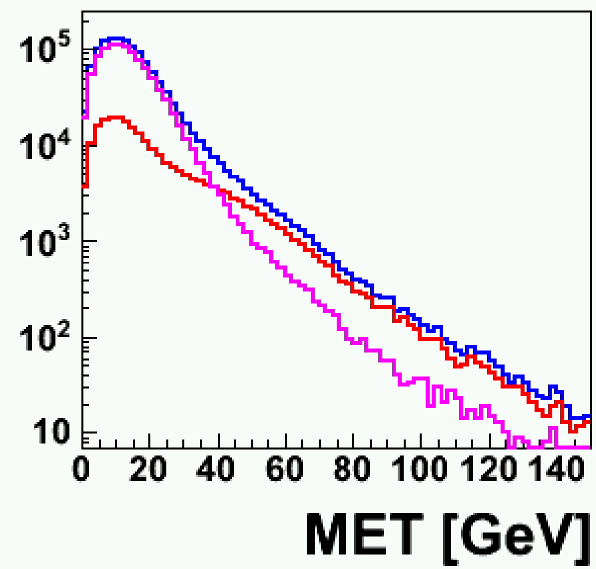


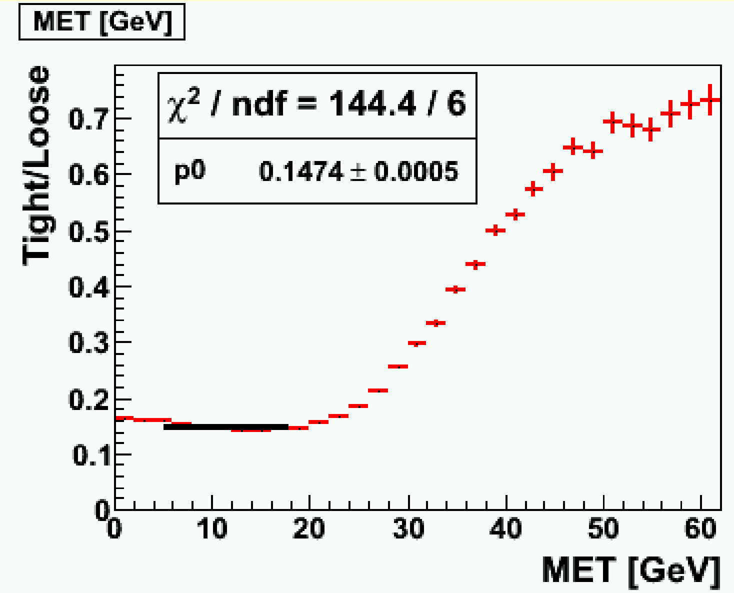


- QCD reduction
  - electron faking jet
  - missmeasured jet energies give MET
- Triangle cut between transverse mass and MET

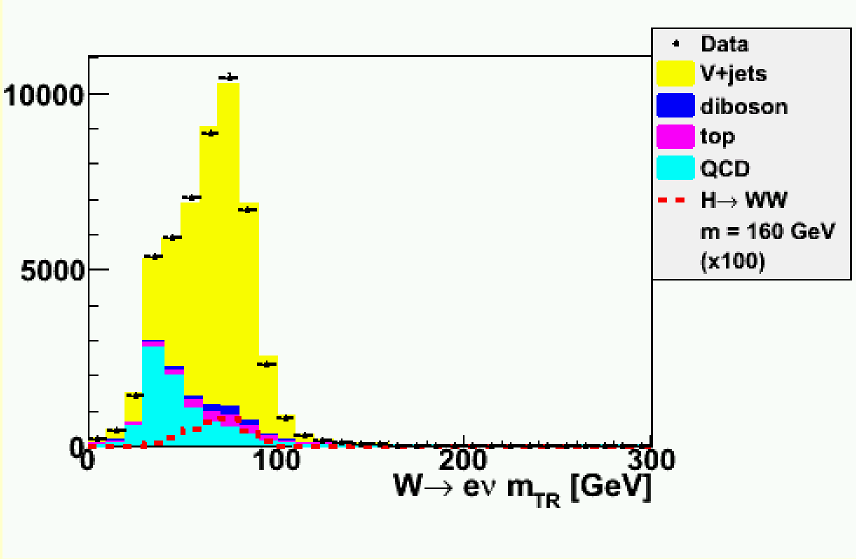
QCD estimation







- 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 shape
  - It may depend on the p_T of lepton



NLO pQCD calculations & MC Models

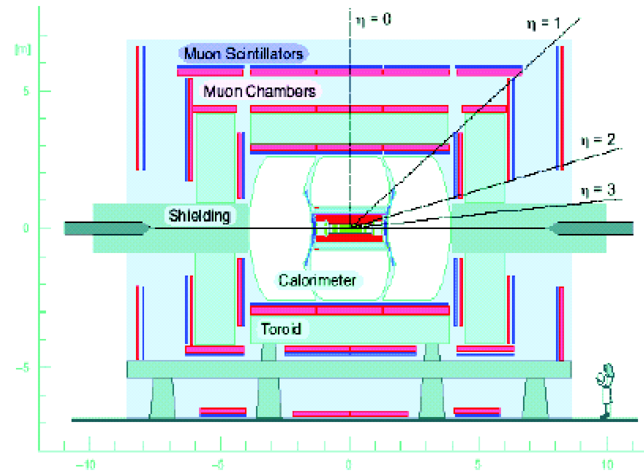
- pQCD predictions calculated with MCFM, JetPhoX
- Many LO MC programs on the market:
  - MEPS: Alpgen, Sherpa, Madgraph, Helac, Madevent, ...
  - PS: Pythia, Herwig, Ariadne, ...
- CKKW
  - the separation of ME and PS for different multijet processes is achieved through a kT-measure
  - undesirable 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

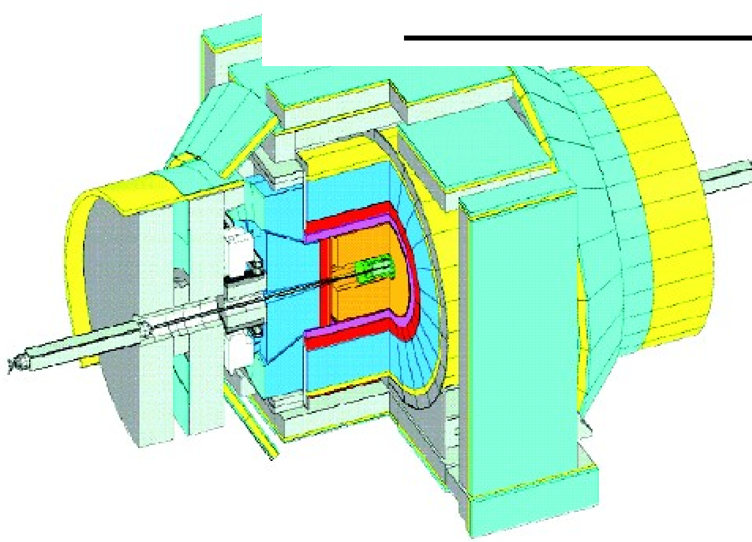


The CDF De

Tracking:
Silicon Vertex Tracker
Central Tracker
1.4 T Solenoid

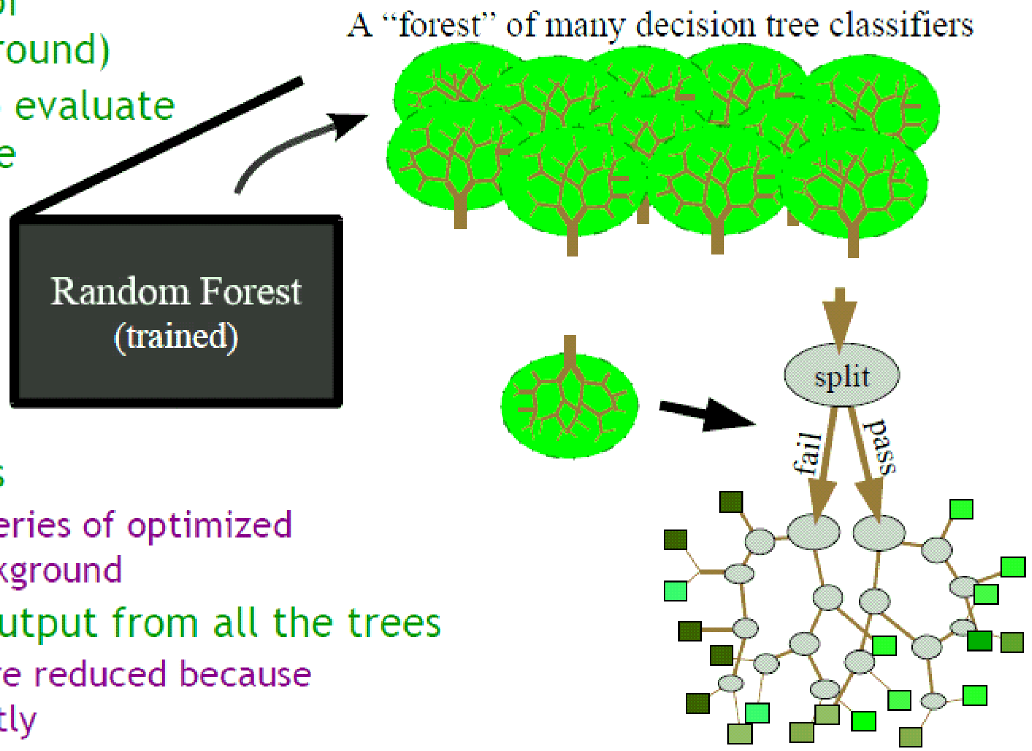
Calorimeter:
EM Calorimeter
(lead/scintillator)
HAD Calorimeter
(iron/scintillator)

Muon:
Drift Chambers
Scintillators

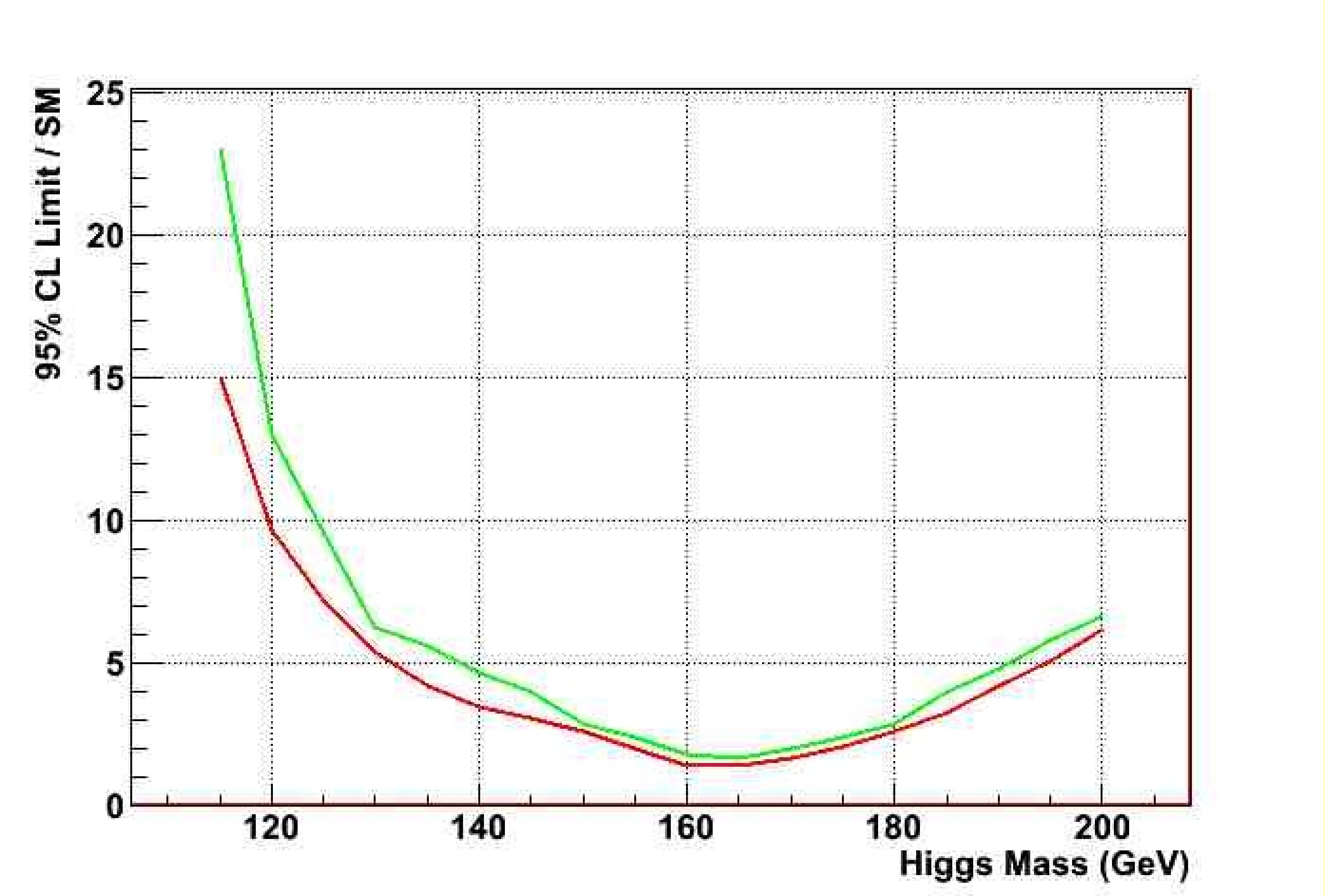


Multivariate Classification

- 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


95% CL Limit / SM
25
20
15
10
5
0
120
140
160
180
200
Higgs Mass (GeV)

Outline

- Motivation
- Current limits
- Current searches
- Future

- Plan:
  - intro 3-4
  - Tevatron, detectors 4
  - dataflow, DQ 2
  - Object id, MET 2
  - Low mass Higgs 3
  - High mass Higgs 2-3
  - My analysis 15
  - Stat. analysis 3-4
  - Future at LHC 4
  - Summary 1-2

```
centrality = (jet1.Pt()+jet2.Pt()+lep.Pt()) / (jet1.E()+jet2.E()+lep.E());
```