Search for Higgs bosons at Tevatron

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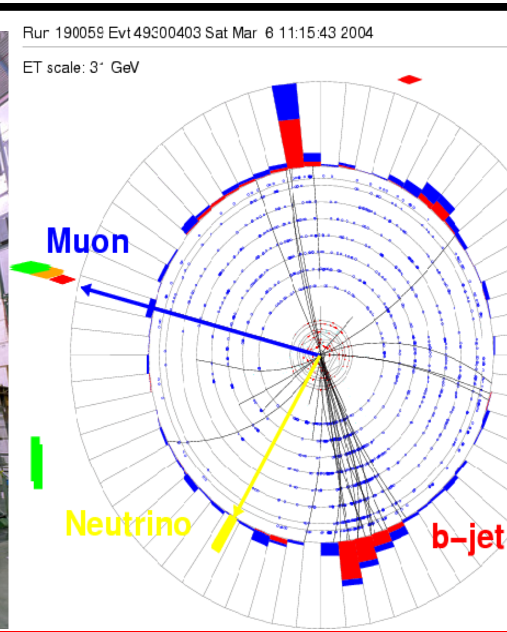
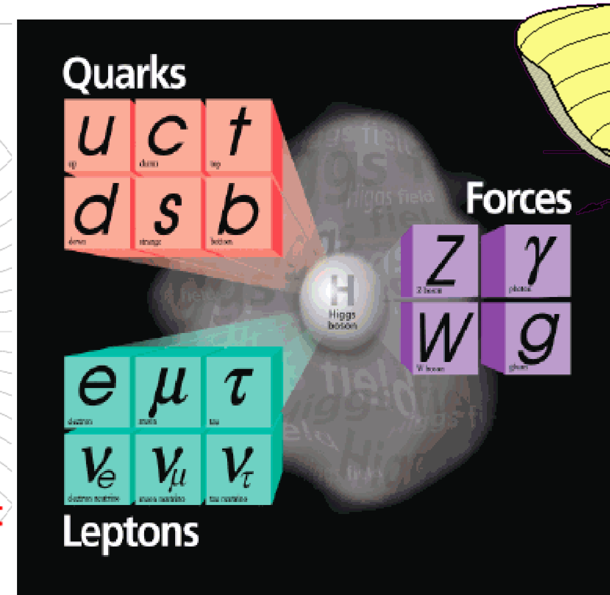
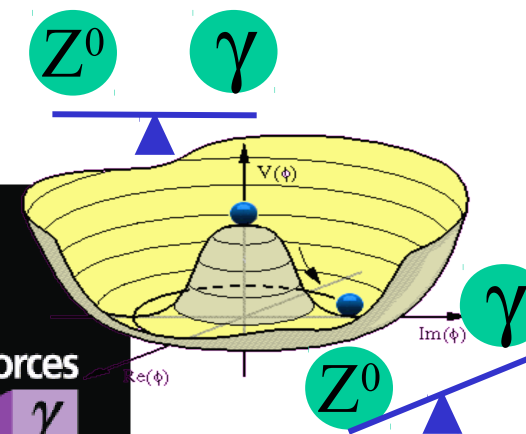
Outline :
- SM Higgs
  - channels
  - techniques
  - results

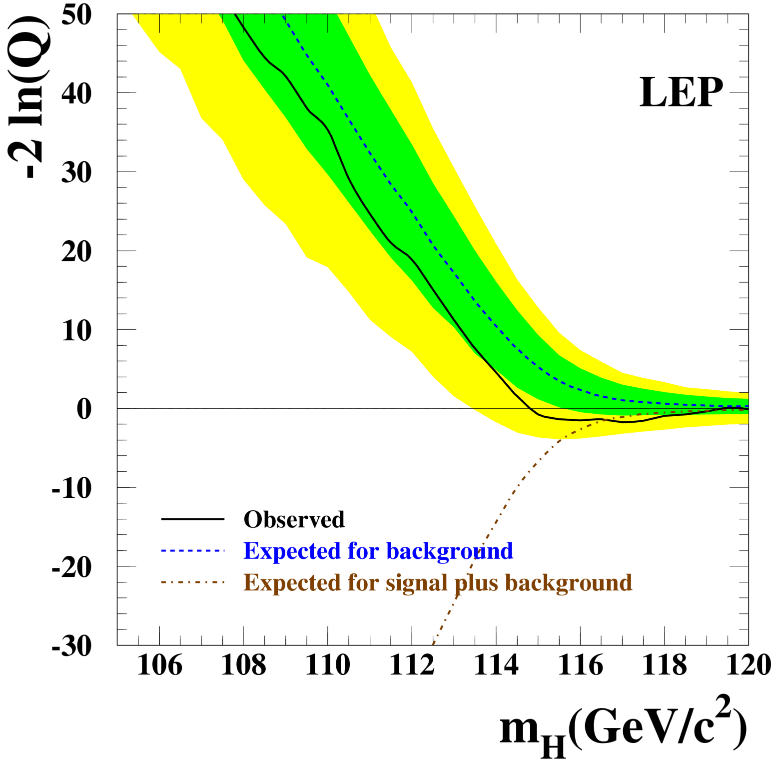




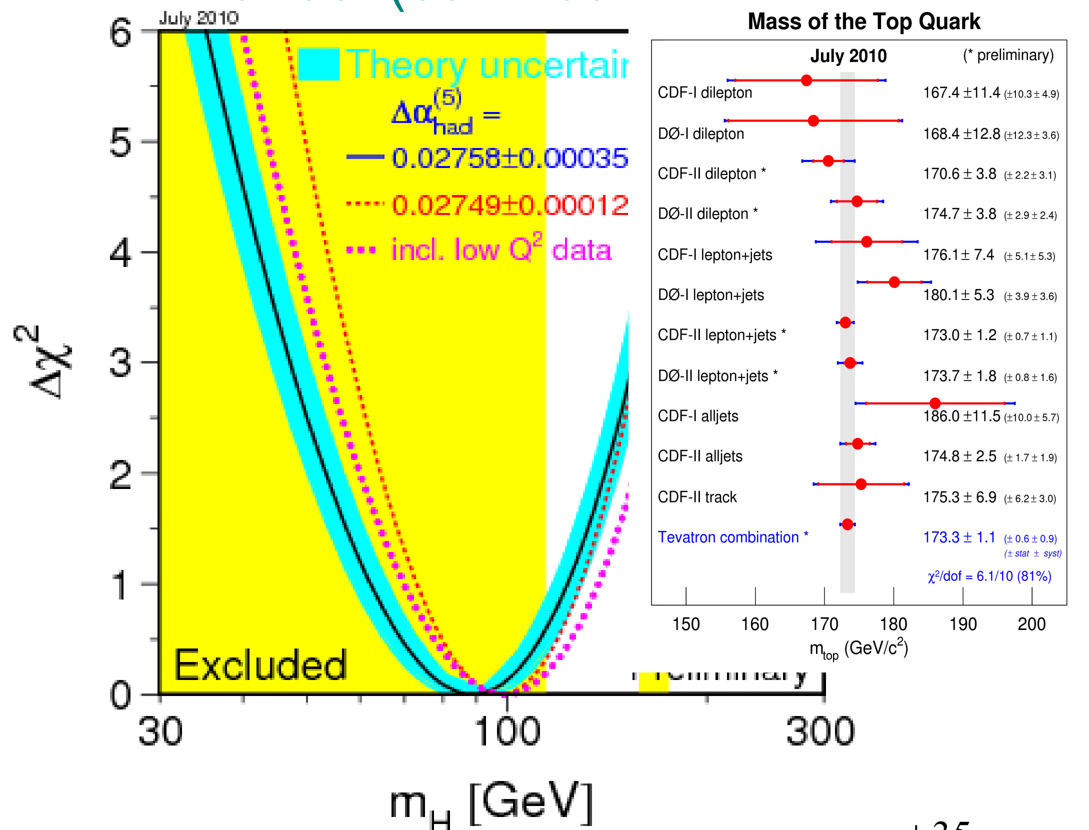


Before Tevatron direct searches what did we know about Higgs boson ?

Direct constraints from LEP



Indirect (contributions from Tevatron)



$$M_H = 89^{+35}_{-26}\, GeV$$

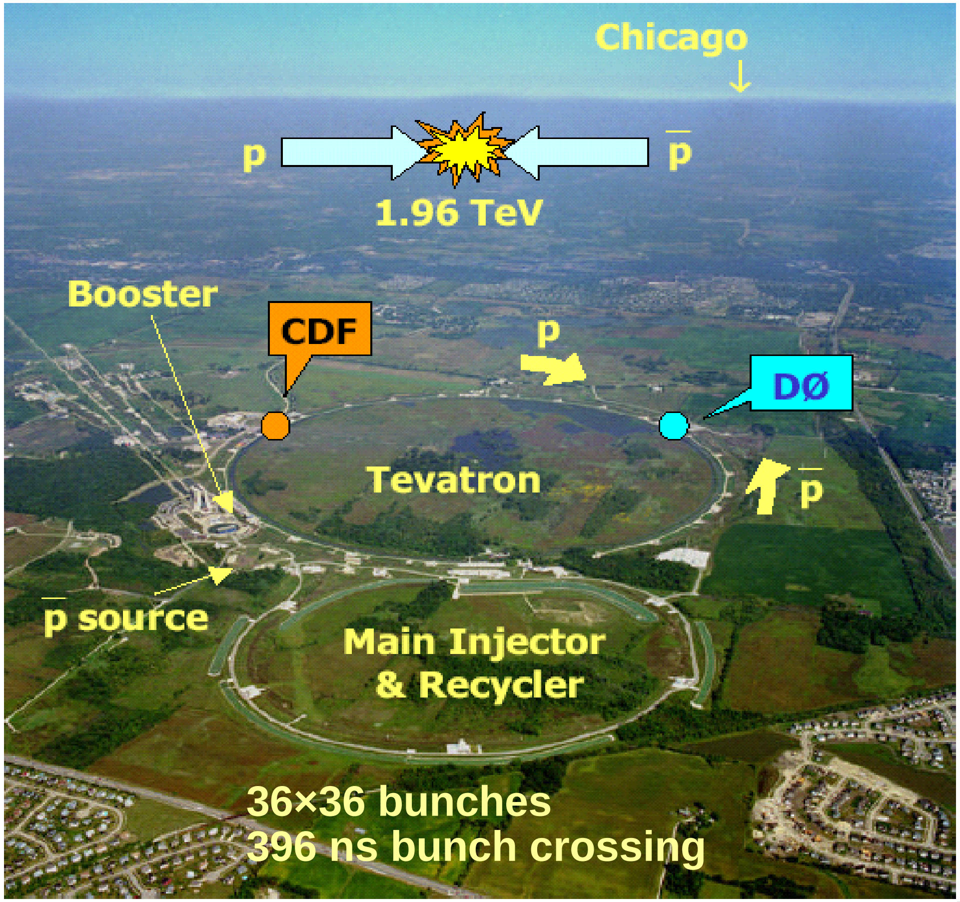
$M_H > 114.4$ GeV @95%

$M_H < 185$ GeV @95%

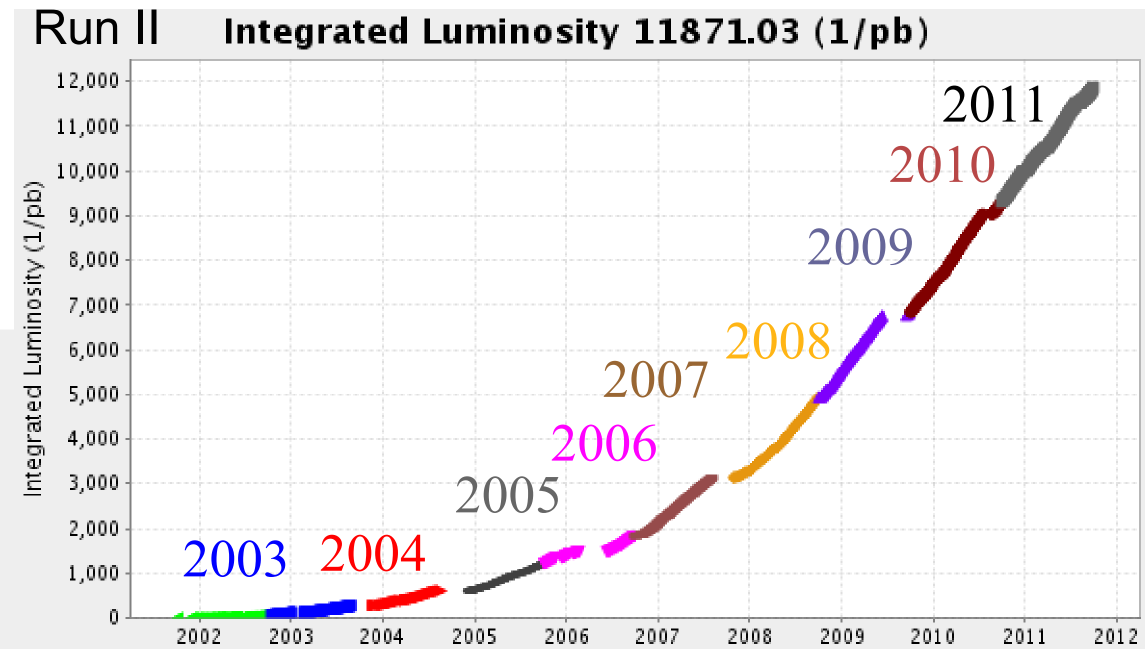
Light mass Higgs is favoured

- Region accessible to Tevatron

The Tevatron proton-antiproton collider



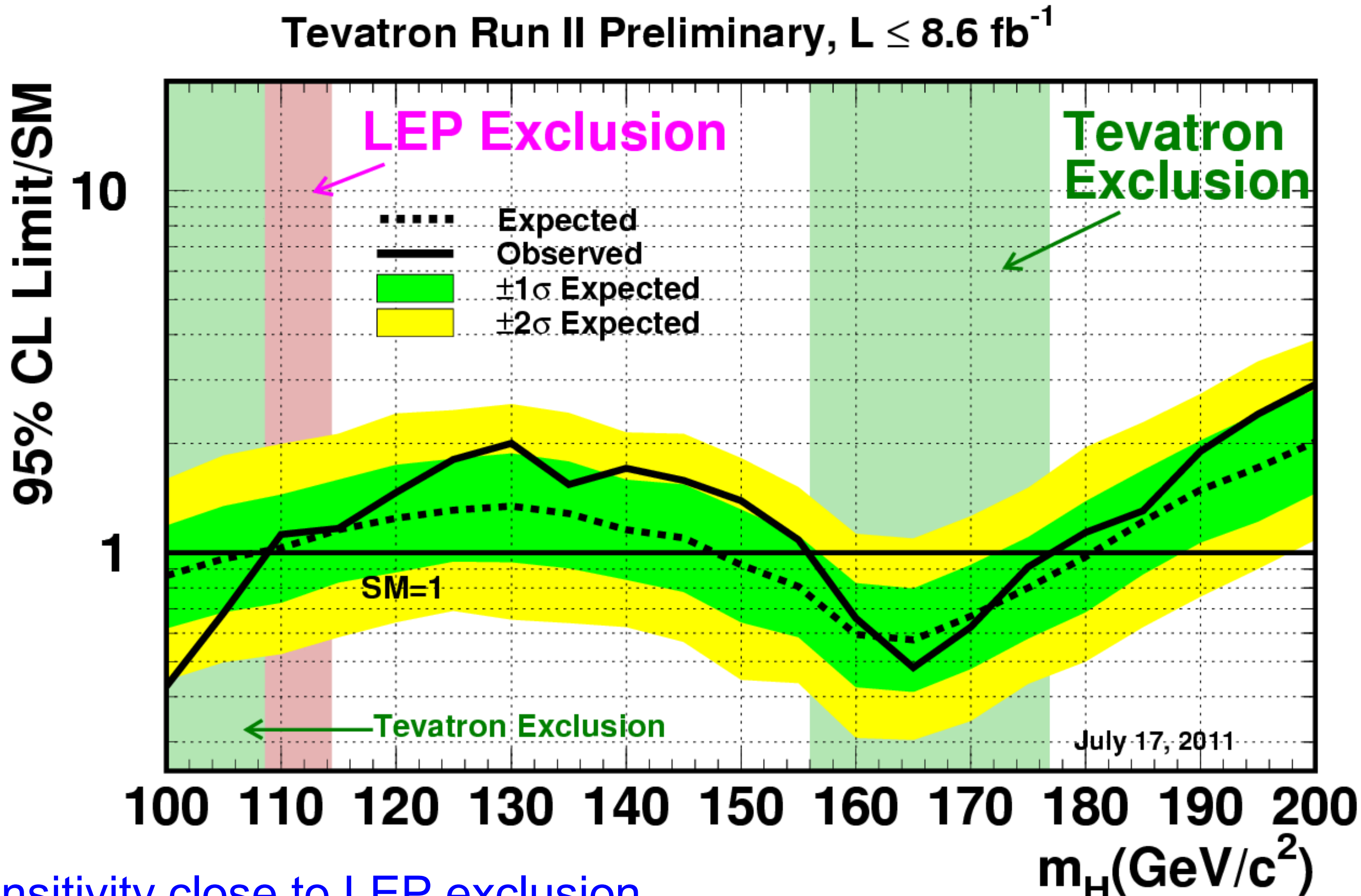
Run I (1993-1996)
~120 pb^{-1} per experiment-top quark discovery
Run II: (2002-2011)
- Shutdown 30 september 2011
- ~11.9 fb^{-1} delivered per experiment
- ~9.5 fb^{-1} for physics analysis



Most of the Higgs results today rely on: 5.3-8.6 fb^{-1}

Current exclusion results (summer 2011)

$100<m_H<109$ GeV is excluded
$158<m_H<175$ GeV is excluded
expected sensitivity
$100<m_H<108$ GeV
$148<m_H<181$ GeV



Low mass sensitivity close to LEP exclusion

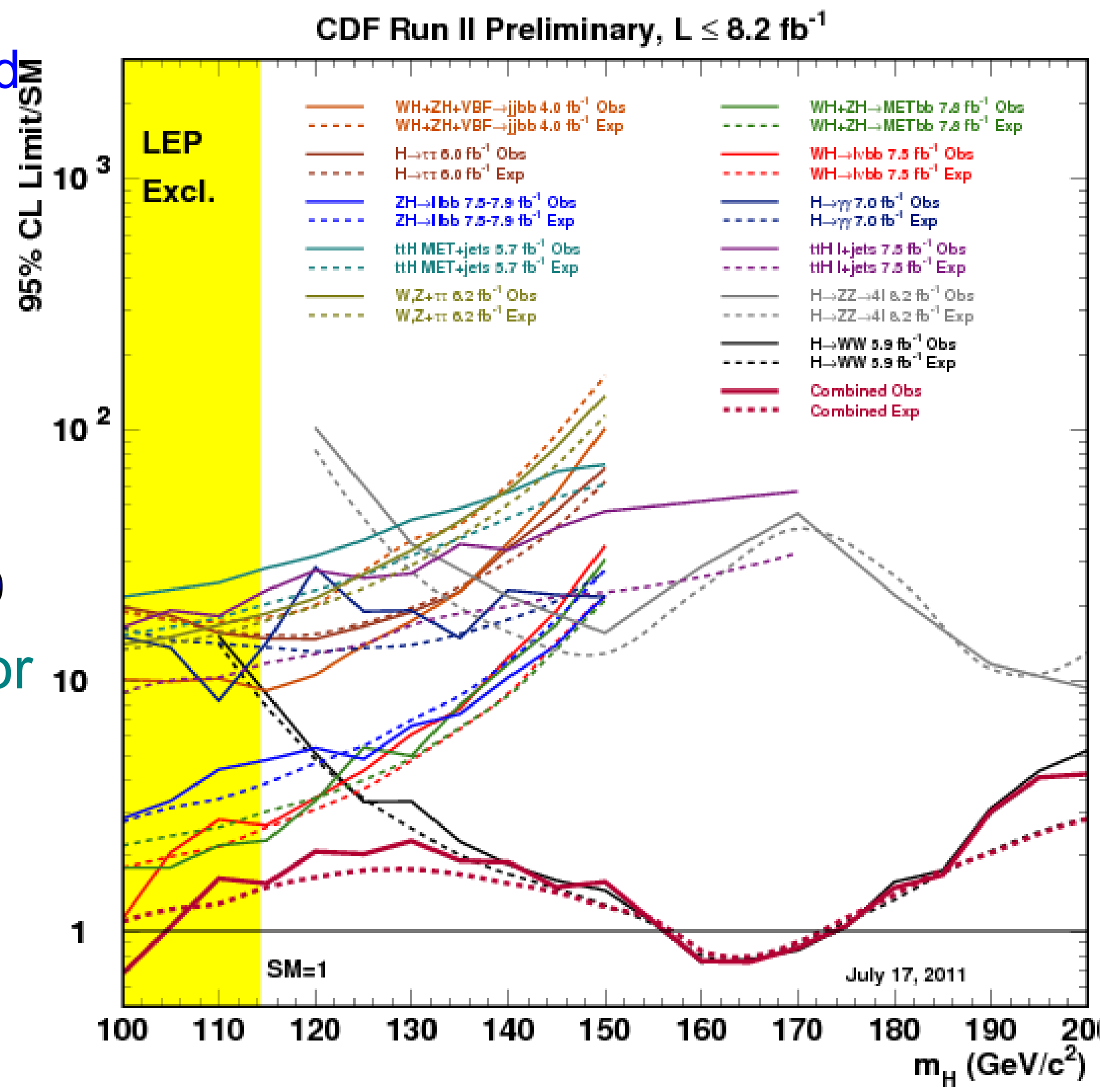
Limits For m_H=115 GeV $\sigma_{95}/\sigma(SM)$ =1.17 (1.16 expected)
Limits For m_H=130 GeV $\sigma_{95}/\sigma(SM)$ =2.0 (1.35 expected)

Results are the combination of many channels

How to combine:

- Channel 1 : limite1
- Channel 2 : limite2
- Good approximate of the combined sensitivity:

$$limite = \sqrt{\frac{1}{\frac{1}{limite_1^2} + \frac{1}{limite_2^2}}}$$



Therefore

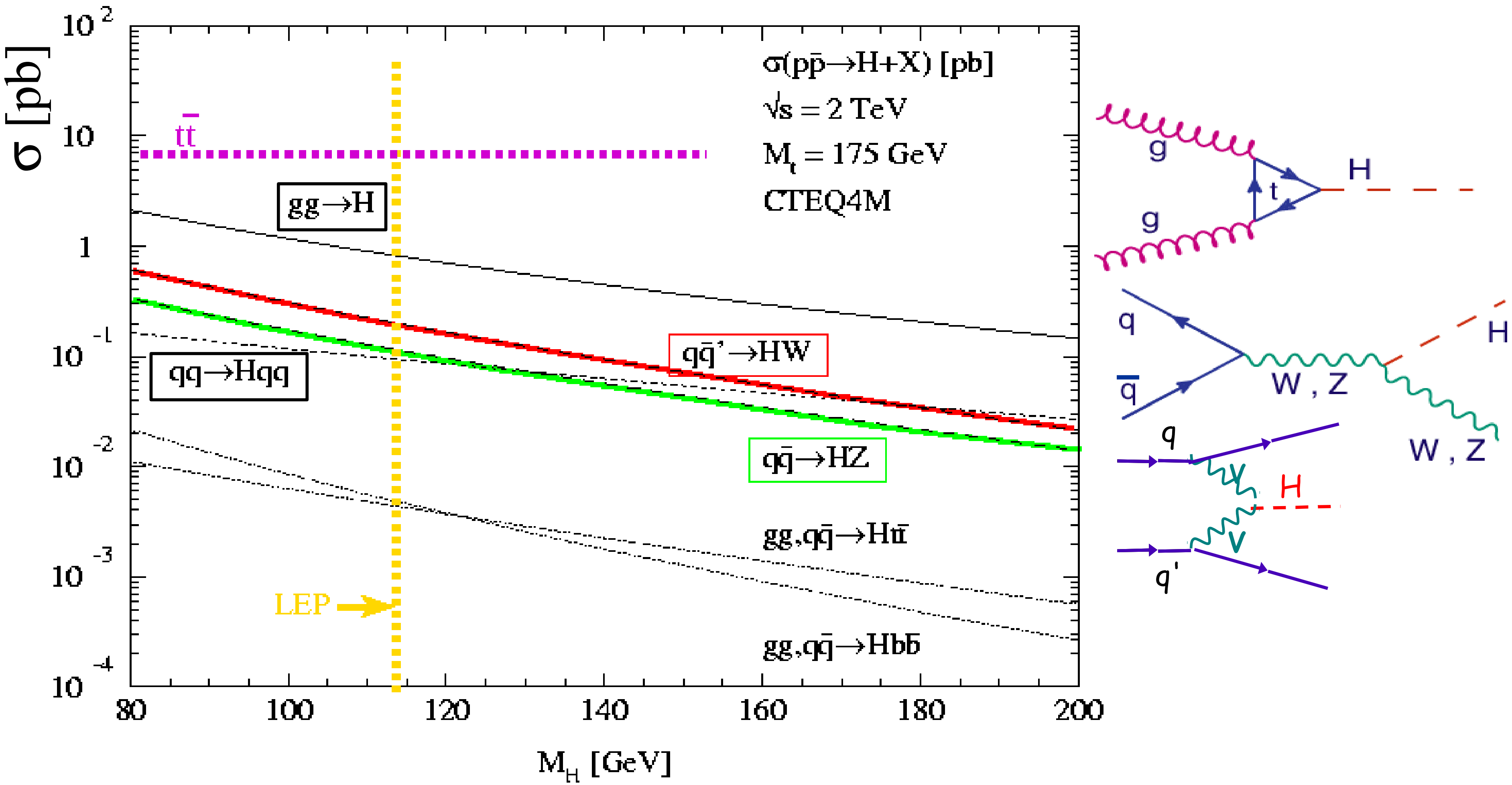
- channel with sensitivity $\sigma_{95}/\sigma(SM)\sim20$
- equivalent to 1% more luminosity or acceptance in channel with sensitivity $\sigma_{95}/\sigma(SM)\sim2$

- All possible channels contribute ?
  - Actually not really !!

Higgs production at the Tevatron

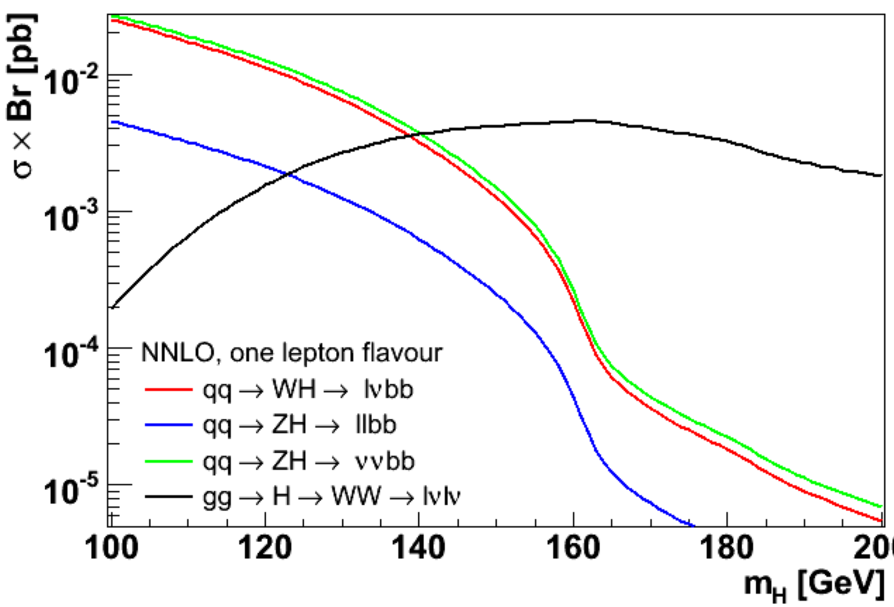
Production cross section (for $115 < m_H < 180$ GeV)

- in the 1.2-0.3 pb range for gluon fusion $gg \rightarrow H$
- In the 0.2-0.03 pb range for WH associated vector boson production
- In the 0.08-0.03 pb range for the vector boson fusion $qq \rightarrow Hqq$

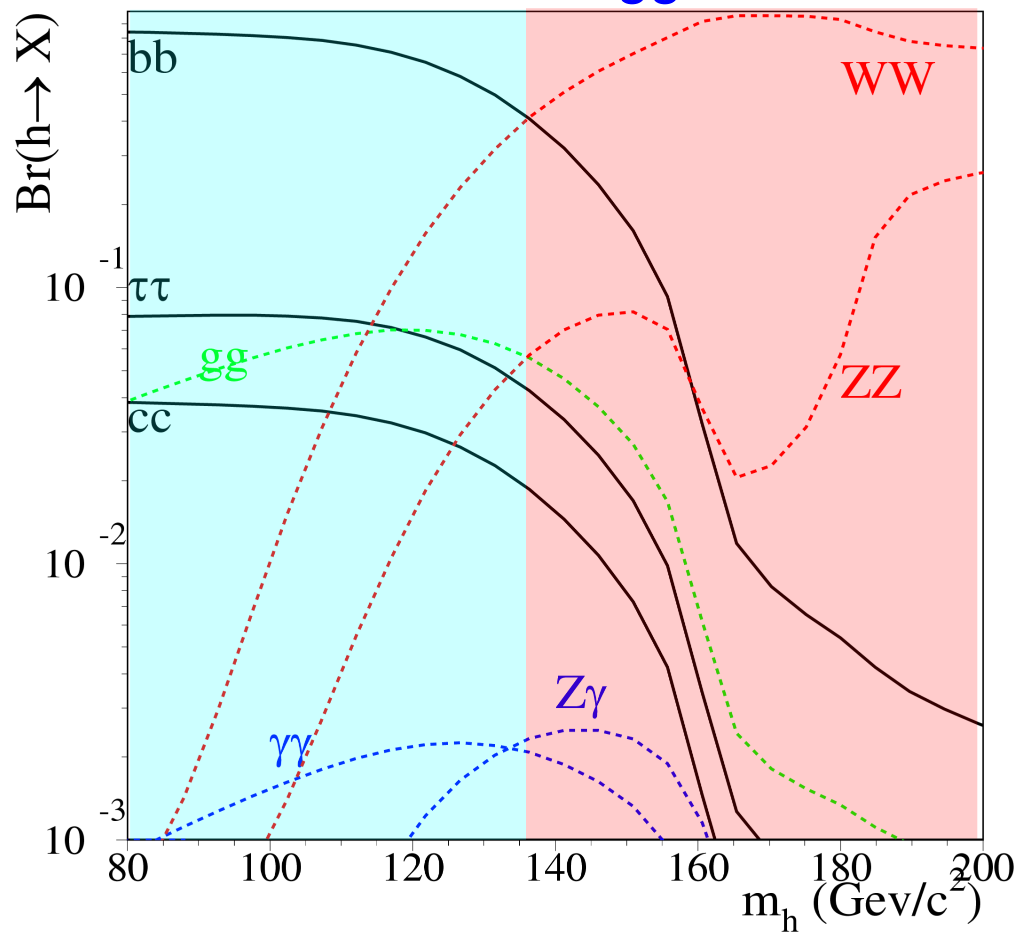


Low Mass vs High Mass

- Overwhelming QCD background in hadron colliders: Need for lepton and/or missing E_T signature
- At low mass:
  - b-quarks+ signature of Vector boson
- At high mass :
  - Look for W decay products
  - Peak sensitivity just above threshold M_H~165 GeV.



- Decay modes depend on the Standard Model Higgs mass



m_H<135 GeV

$H \rightarrow bb$

$H \rightarrow \tau\tau$

m_H>135 GeV

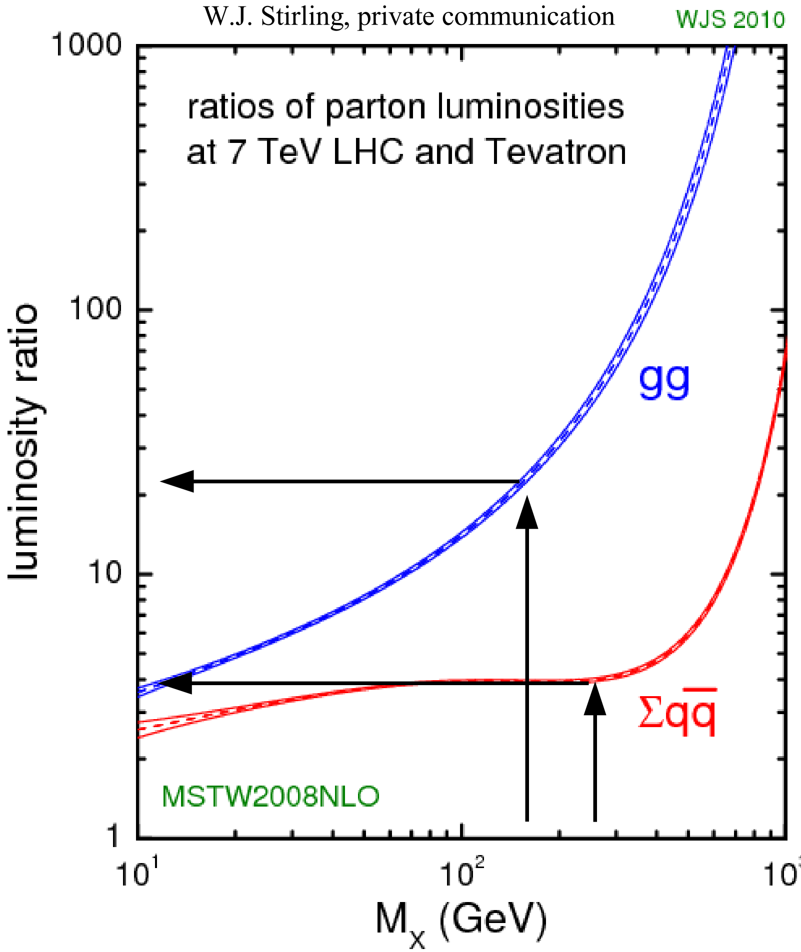
$H \rightarrow WW^*$

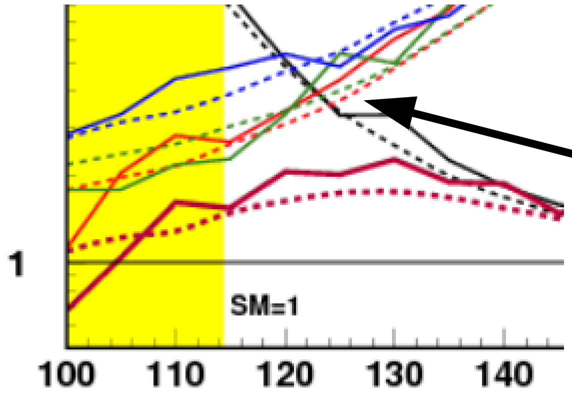
Tevatron vs LHC

- Two colliders, two energies
  - LHC: proton – proton 7 TeV
  - Tevatron: proton-antiproton 2 TeV

- for M~140 GeV
  - gg → H ~20 times larger @ LHC
  - qq → WH ~4 times larger @ LHC

- Beginning of LHC era BUT Tevatron has still competitive sensitivity in the low mass region





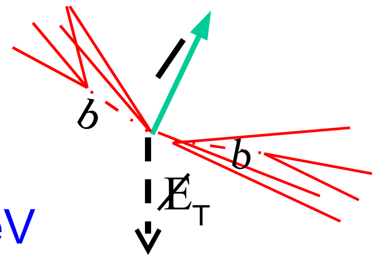
"High mass" channels contribute also down to 125 GeV

Channels at the Tevatron

For M_H < 130 GeV

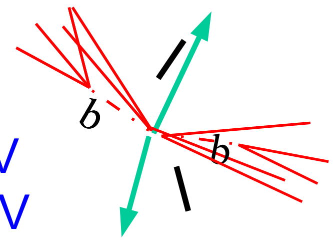
pp → WH → Wbb

- eν bb, μν bb:
  - 2 b-jets ~ 40 GeV
  - 1 lepton ~ 40 GeV
  - $\not{E}_T$ ~40 GeV

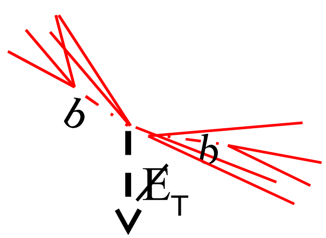


pp→ ZH → Zbb

- ee bb, μμ bb
  - 2 b-jets ~ 50 GeV
  - 2 leptons ~ 40GeV

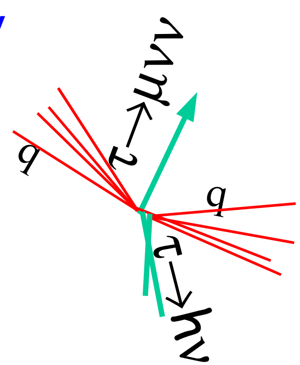


- νν bb:
  - 2 b-jets ~ 50 GeV
  - $\not{E}_T$ ~ 50 GeV



pp →H+ Z/V/X → jj ττ

- 2 jets ~ 30 GeV
- 1 leptonic tau
- 1 hadronic tau

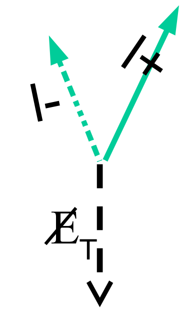


NB: Xsec normalized to NNLO

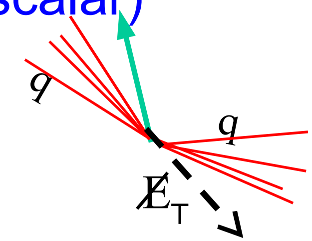
For M_H > 130 GeV

gg→H→WW*

- eνeν, μνμν, eνμν, τνμν
  - 2 leptons ~ 40 GeV
  - $\not{E}_T$ ~ 60 GeV
  - smallΔϕ(l+,l-) (H is scalar)



- eν jj, μν jj:
  - 1 leptons ~ 40 GeV
  - $\not{E}_T$ ~ 40 GeV
  - 2 jets ~ 40 GeV
  - $M_{jj}=M_{l,\not{E}T}$=80 GeV

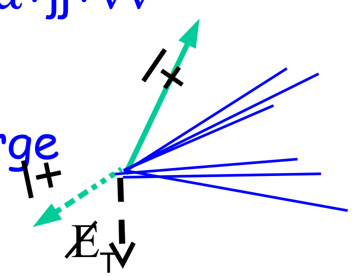


pp → WH→WWW*

ee+jj+νν,eμ+jj+νν, μμ+jj+νν

$\not{E}_T$ ~ 40 GeV

2 leptons of same charge



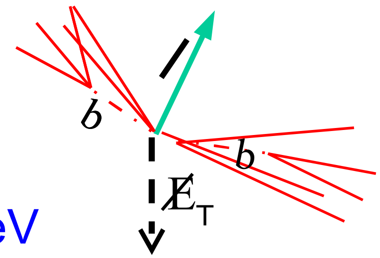
NB: Xsec normalized to NNLO+NNLL

Channels at the Tevatron

For M_H < 130 GeV

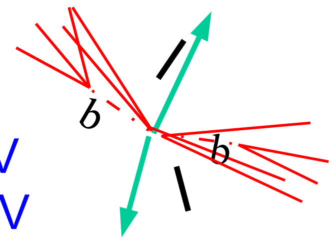
pp → WH → Wbb

- eν bb, μν bb:
  - 2 b-jets ~ 40 GeV
  - 1 lepton ~ 40 GeV
  - $\not{E}_T$ ~40 GeV

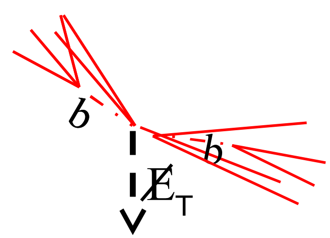


pp→ ZH → Zbb

- ee bb, μμ bb
  - 2 b-jets ~ 50 GeV
  - 2 leptons ~ 40GeV

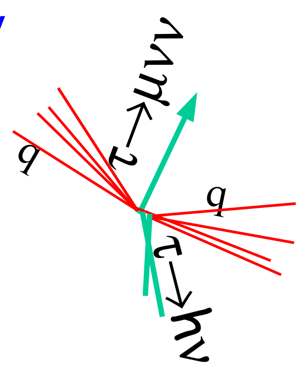


- νν bb:
  - 2 b-jets ~ 50 GeV
  - $\not{E}_T$ ~ 50 GeV



pp →H+ Z/V/X → jj ττ

2 jets ~ 30 GeV
1 leptonic tau
1 hadronic tau



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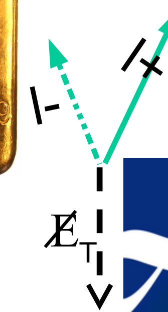
  - small Δφ(l+,l-) (H is scalar)



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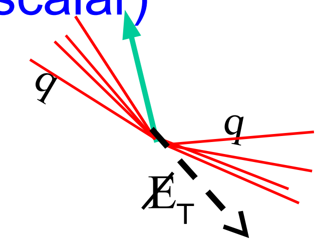
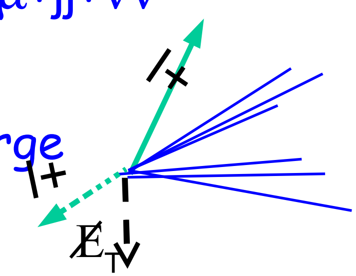


pp → WH→WWW*

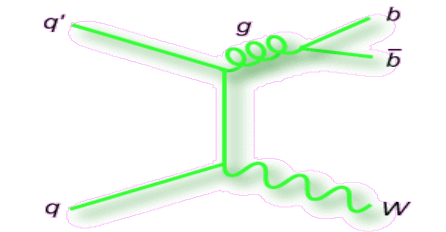
ee+jj+νν,eμ+jj+νν, μμ+jj+νν
$\not{E}_T$ ~ 40 GeV
2 leptons of same charge

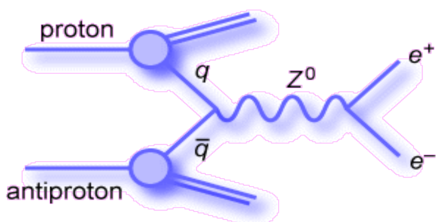


NB: Xsec normalized to NNLO

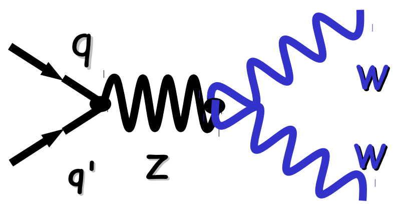
NB: Xsec normalized to NNLO+NNLL

Backgrounds to Higgs Searches

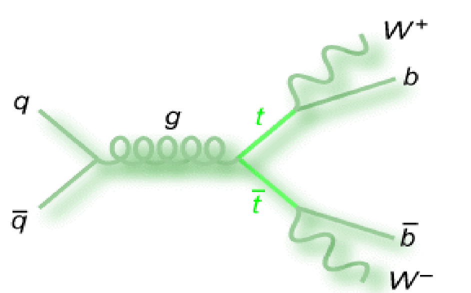


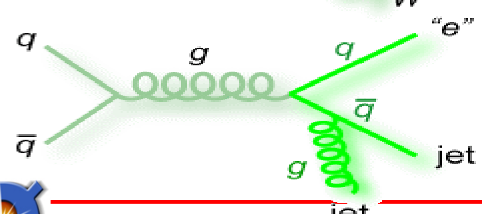


- W+jets, Z/γ +jets
  - Alpgen MC+ pythia showering, NNLO cross-sections, data-based corrections to model $p_T(W)$,$p_T(Z)$
  - background for all channels:
    - jets faking lepton
    - mismeasured jets or leptons MET
    - W+bb, Z+bb final states (mimic ZH, WH)



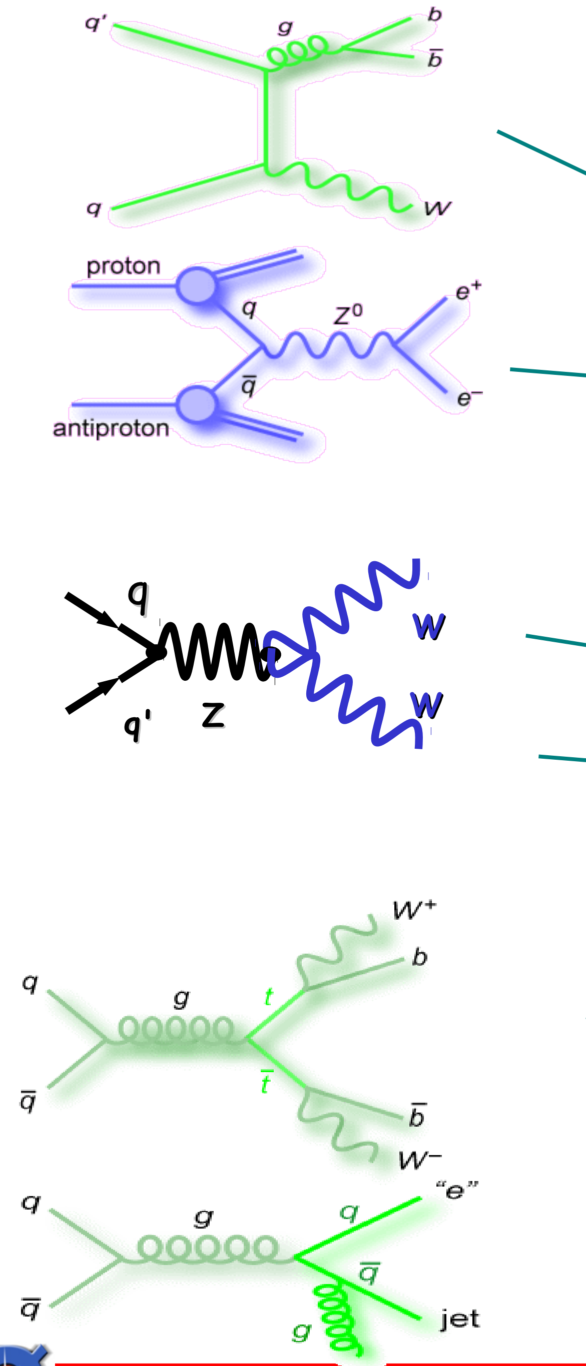
- Di-boson WW, WZ, ZZ
  - NLO calculation for cross-sections
  - for WW: NLO correction for p_T and di-lepton opening angle

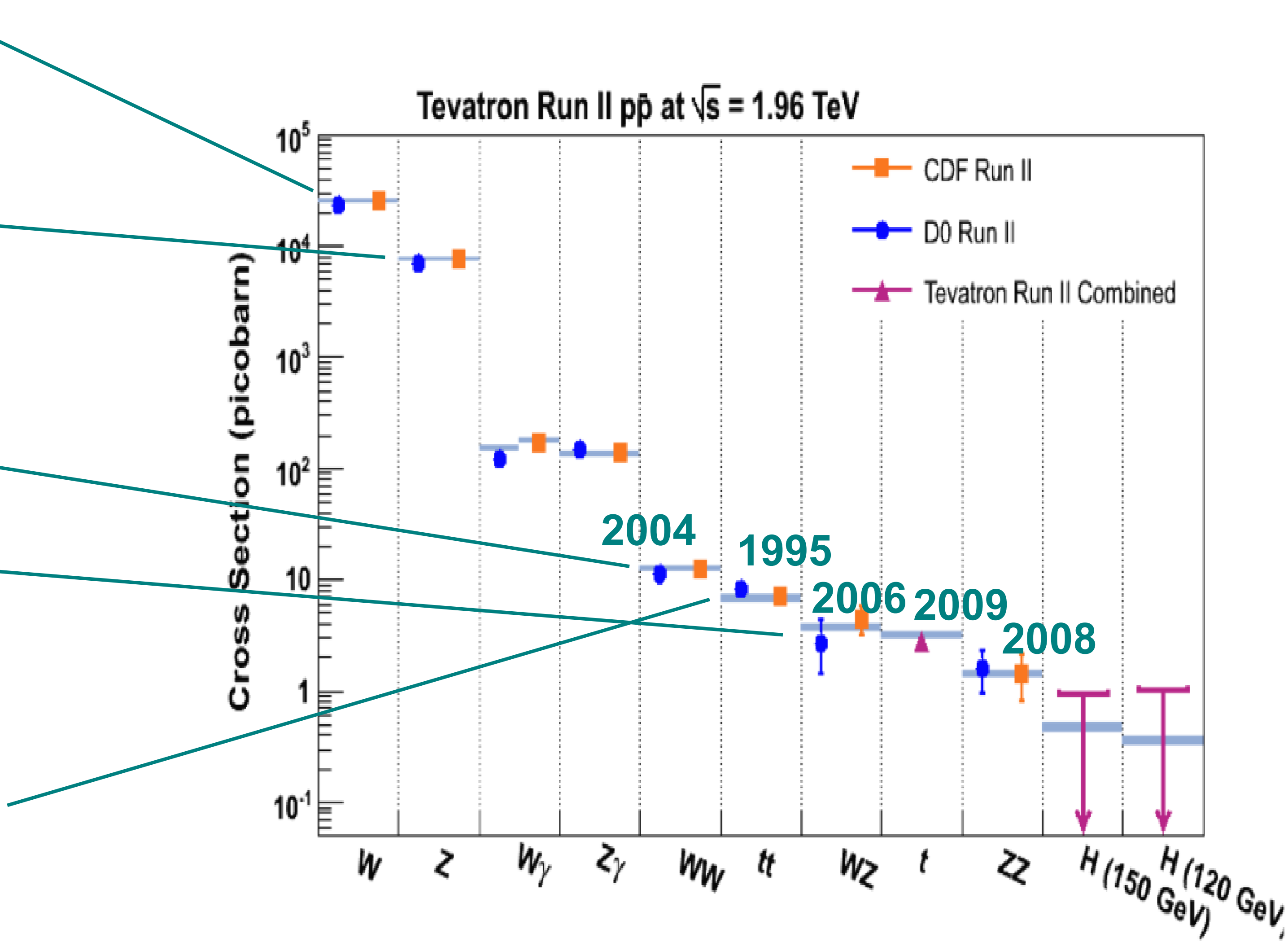




- Top pair and single top
  - cross-section normalized at NNLO
- QCD multijet events
  - jets faking leptons
  - mismeasured jets creating MET
  - data driven models

Backgrounds to Higgs Searches

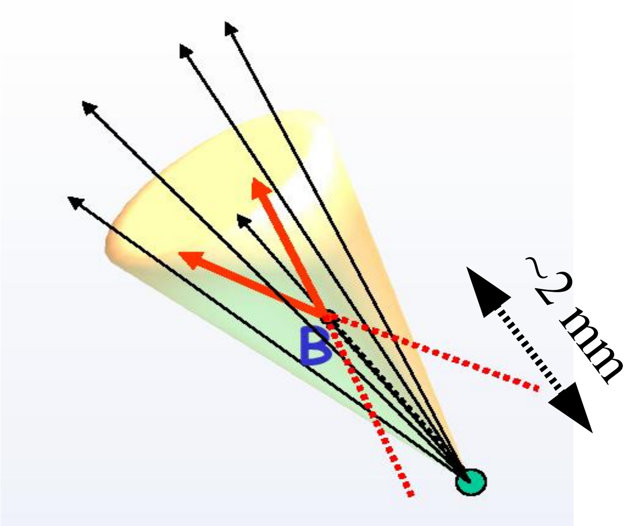




The Higgs signal is several order of magnitude below backgrounds

b jets tagging: essential for search at low mass

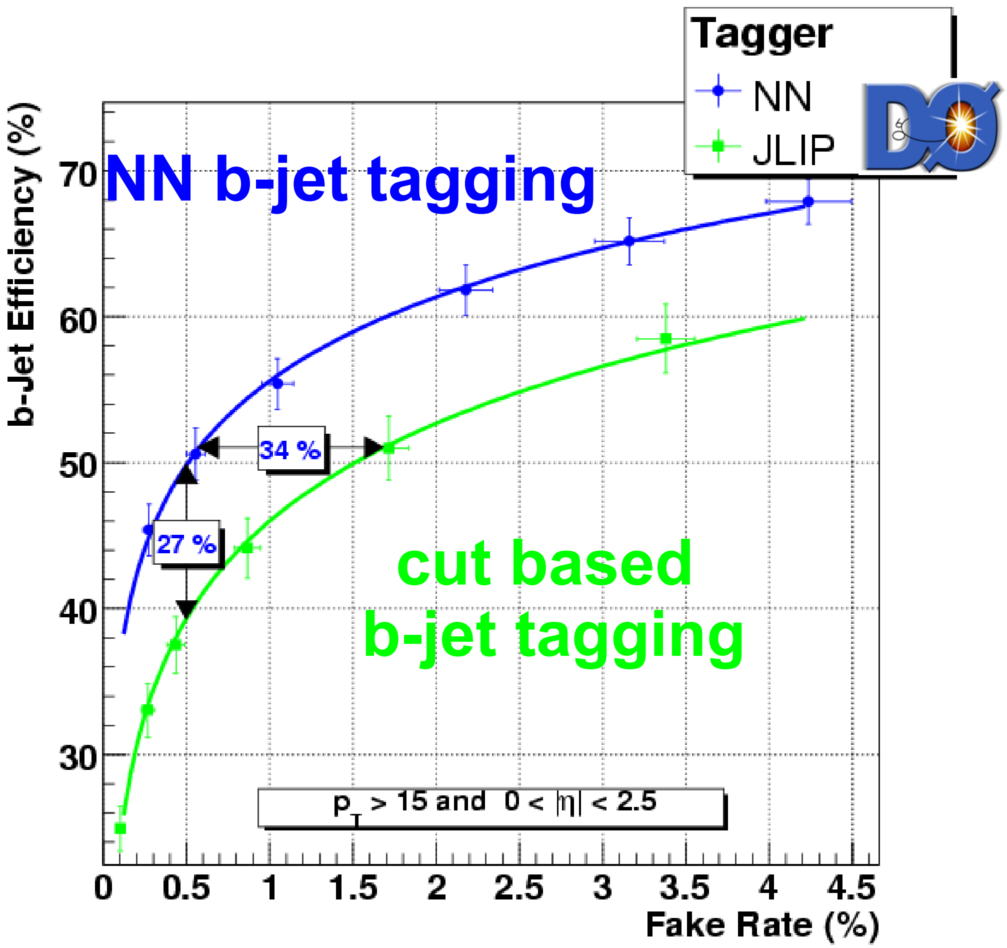
B-hadrons are long lived particles: $c\tau \sim 0.5$ mm.
B-hadrons can decay semi-leptonically: b->$\mu\nu$c

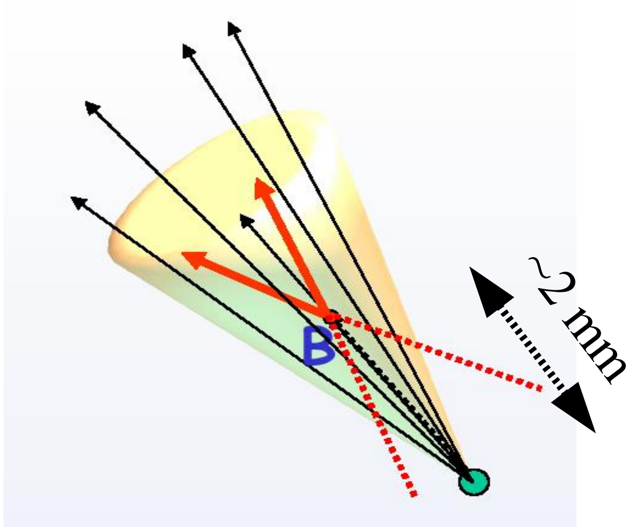


Can make use of:

- High impact parameter of tracks
  ==> light quark Jet Probability
- Secondary vertex reconstruction (SVX)
- Lepton tag
- b-jet kinematics (large B-hadron mass)
- Combination of above with multivariate techniques (eg Neural Network)

b jets tagging: essential for search at low mass

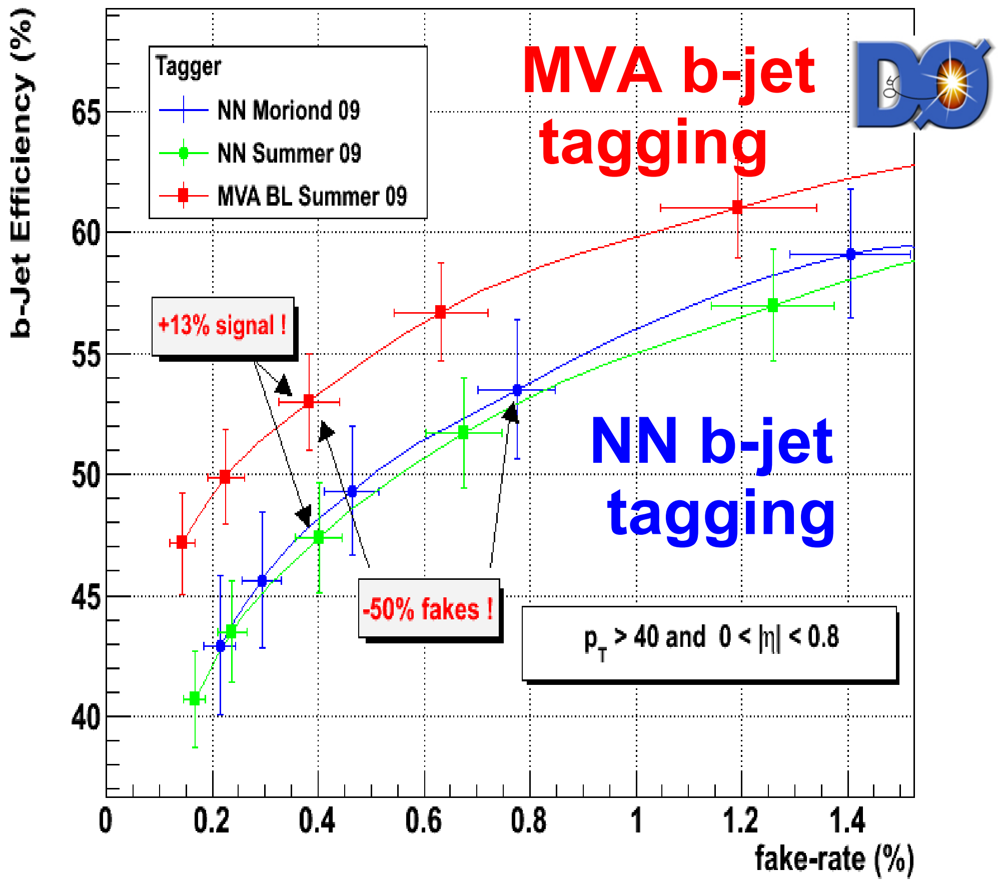


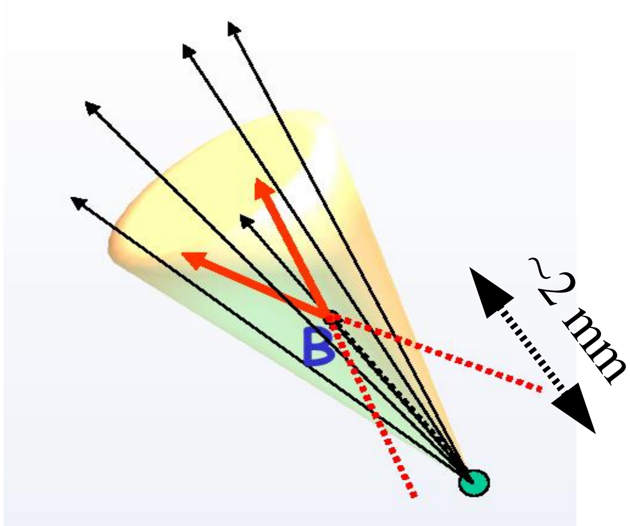


Eg: CDF 2nd vtx tag ε=50% for 2% mis-tag at η<1

Eg: D0 NN (2006) ε=60% for 1.5% mis-tag Pt=50 GeV (loose tag)

Improving acceptance with better b-tagging





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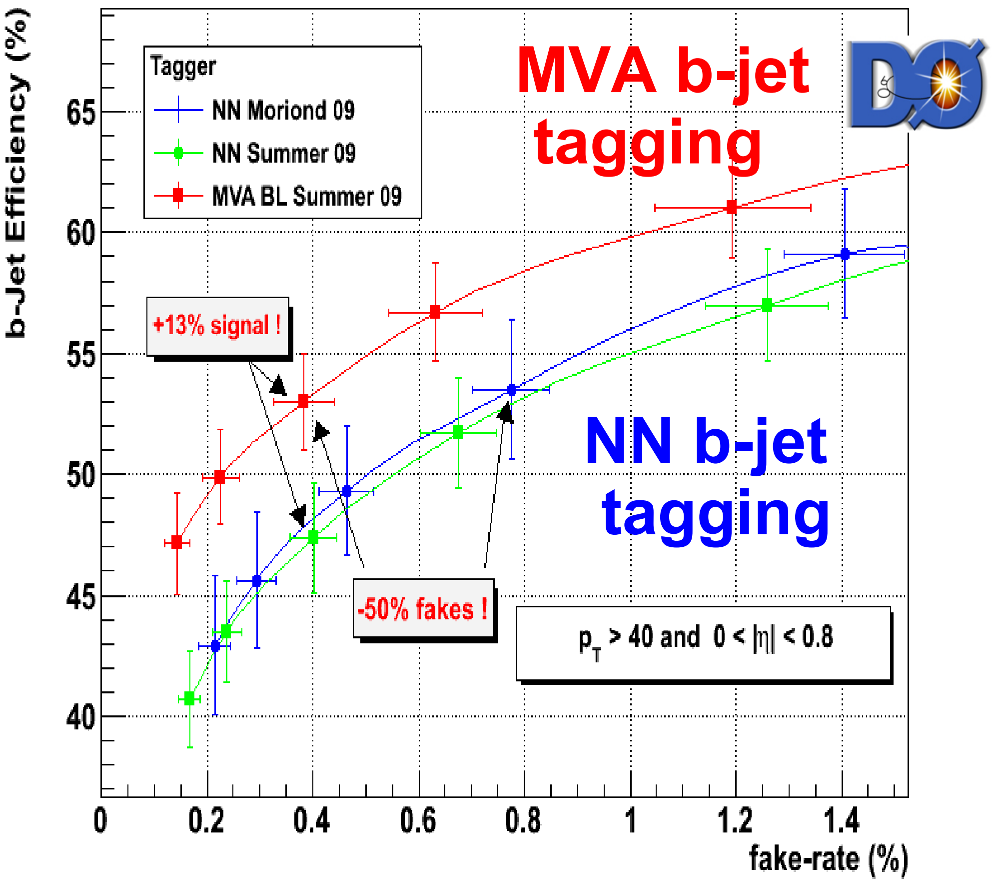
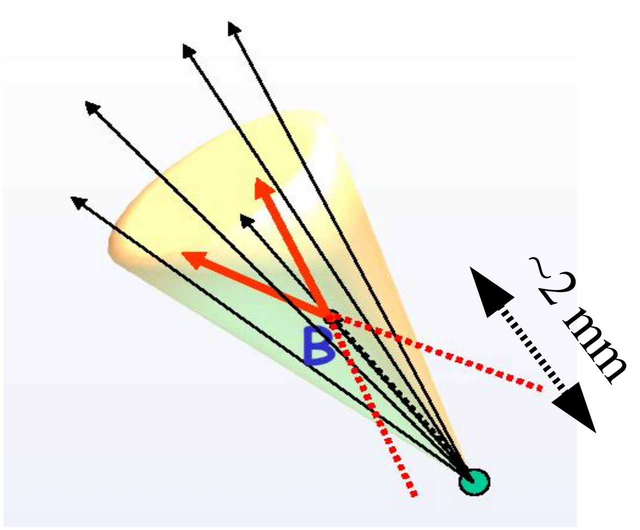




Further improvements expected soon

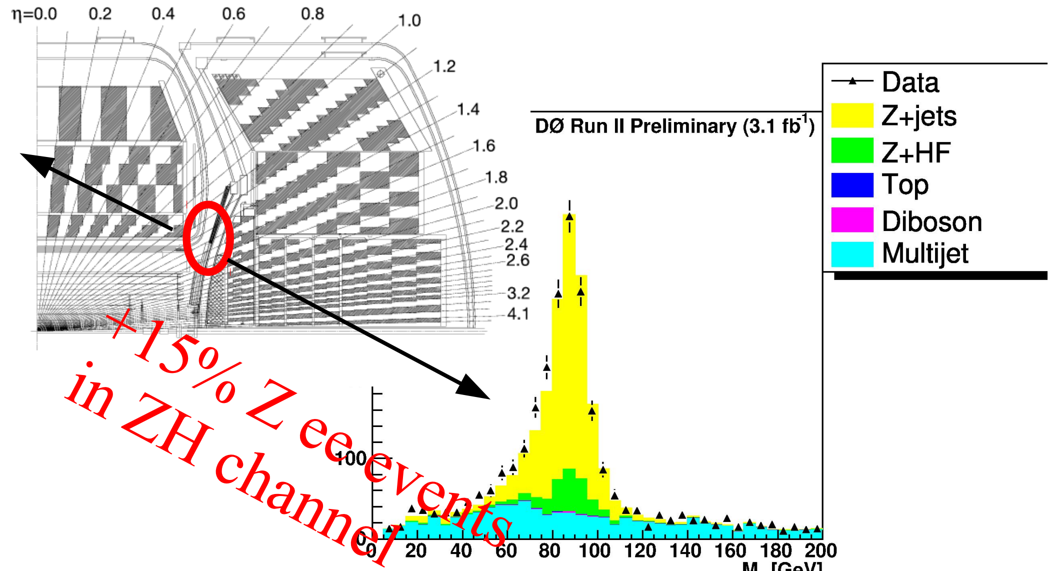
Eg: CDF 2^{nd} vtx tag — ε=50% for 2% mis-tag at η<1

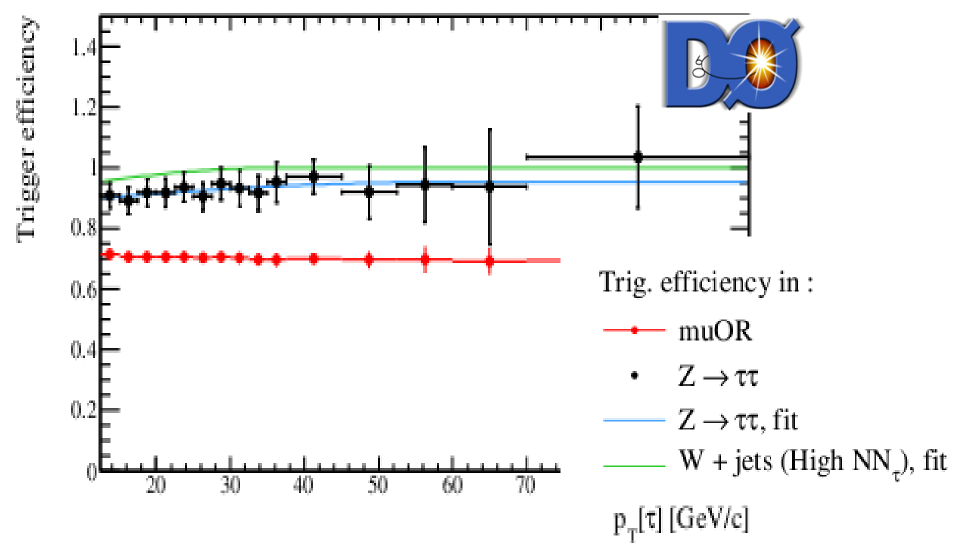
Eg: D0 NN (2006) — ε=60% for 1.5% mis-tag Pt=50 GeV (loose tag)

D0 MVA (2009) — ε=60% for 1% mis-tag Pt=50 GeV

Increasing number of Higgs candidate events

- D0
  - electrons in intercryostat region
  - isolated tracks without muon identification
- CDF
  - plug (forward) electrons
  - muon chamber extensions
- Both
  - modified isolation for nearby leptons
  - Inclusive triggering:
    - accept events from all possible triggers
    - compute acceptance correction from reference triggers

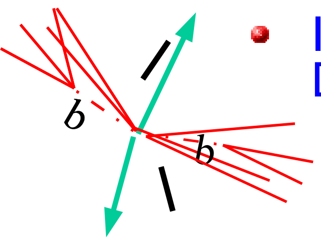


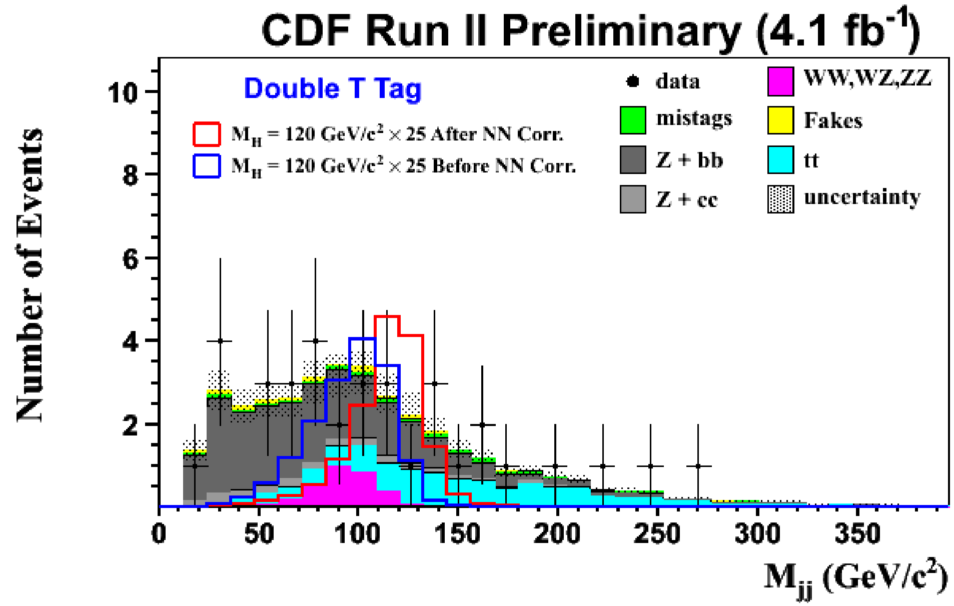


from R. Madar (Saclay) thesis

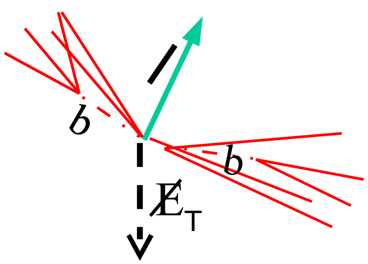
Jet energy resolution

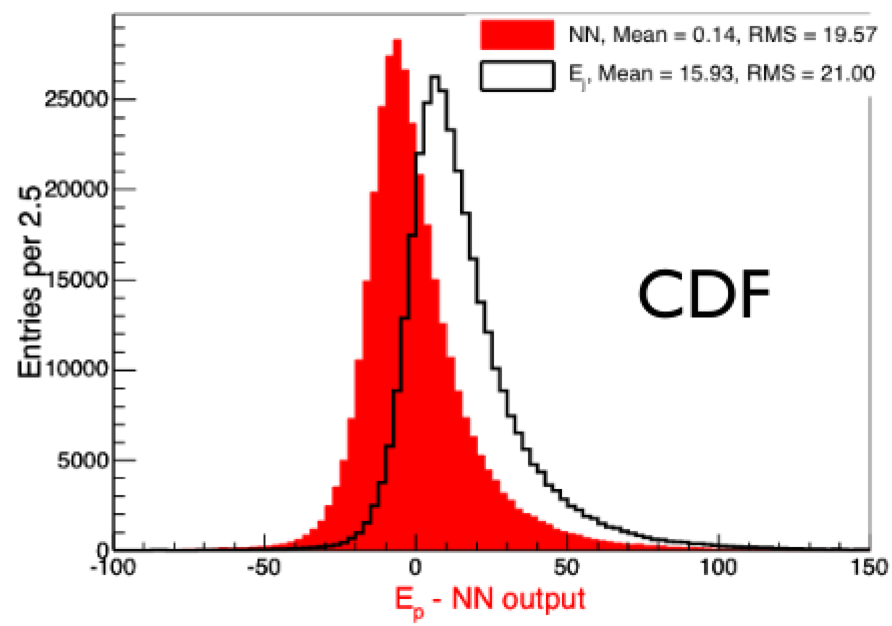
- ZH → ll bb :
  - $\not{E}_T$ ~0 as kinematical constraint
  - Improve dijet mass resolution at D0 and CDF





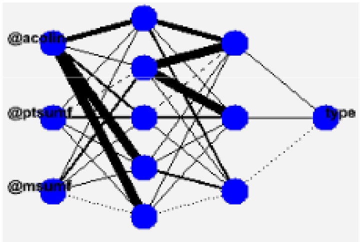
- WH → lν bb
  - Kinematics variable of (b) jets to bring energy closer to the initial parton energy
  - Gain of ~ 20-25% in relative resolution



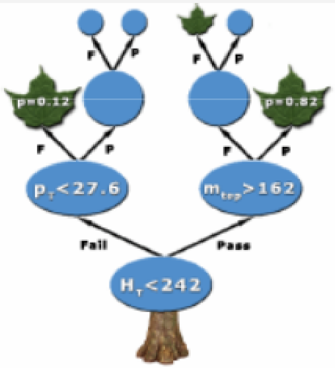


Multivariate techniques

- Extended use of :
  - Artificial Neural Network (NN)



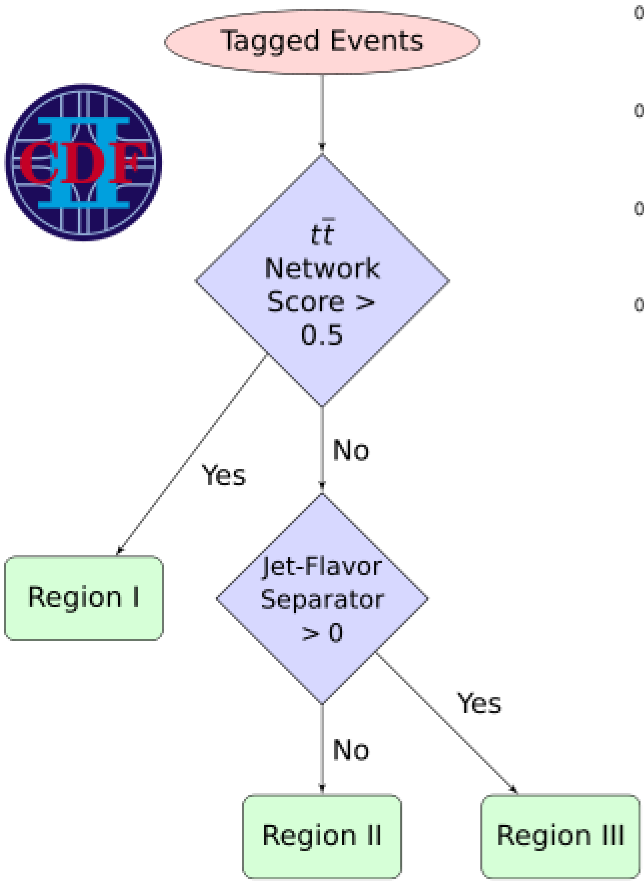
  - Boosted Decision Tree (BDT)
    - Easier and faster to train

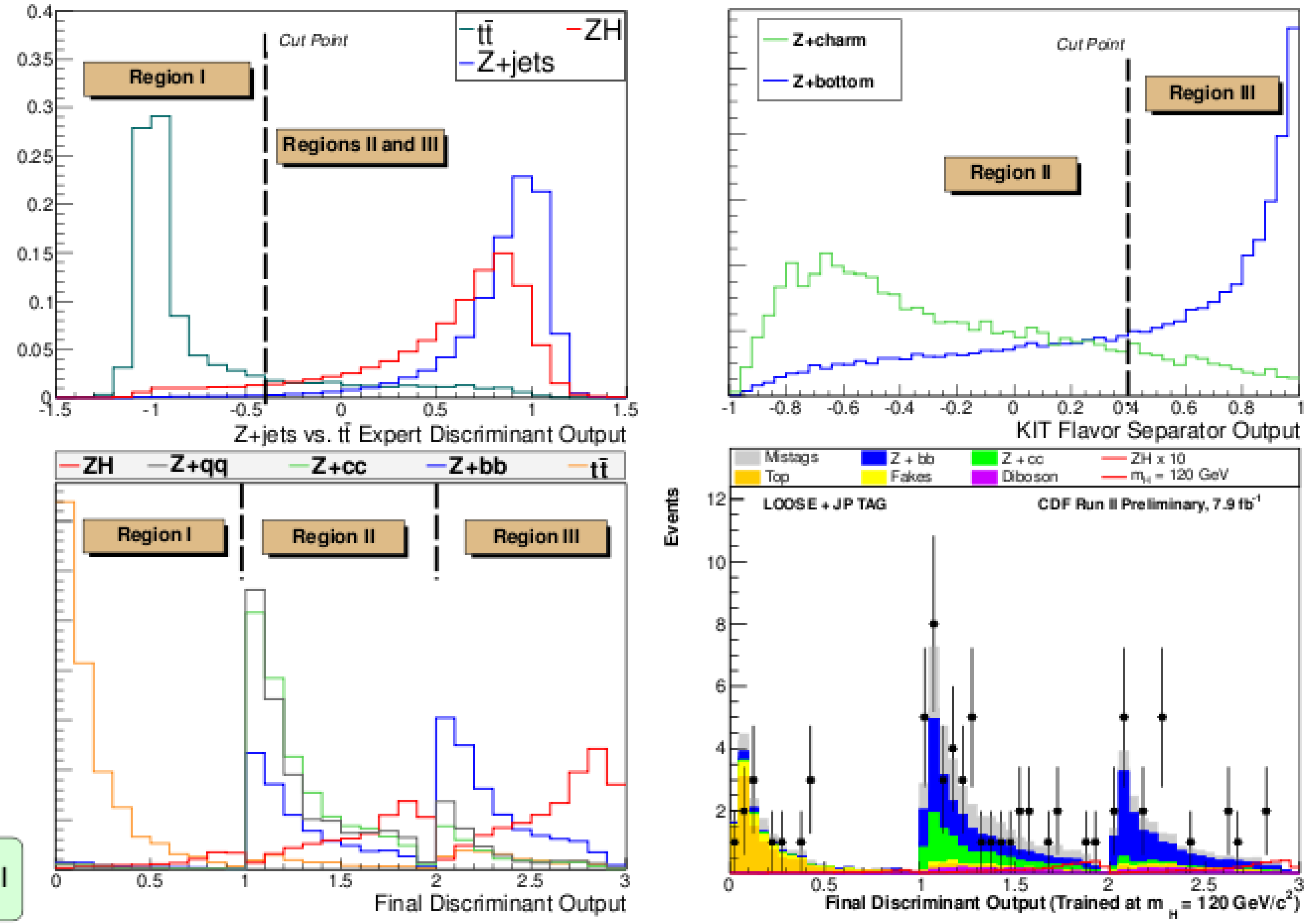


  - Matrix Element (ME)
    - computer intensive
    - Inputs are 4-vectors, and resolution functions

$$P_{\mathrm{WH}}(x) = \frac{1}{\sigma} \underbrace{\sum_{i,j}}_{\text{Flavor}} \int_y \underbrace{f_i(q_1) f_j(q_2)}_{\text{PDF}} \times \underbrace{\frac{d\sigma_{\mathrm{WH}}}{dy}}_{\text{ME}} \times \underbrace{W(x,y)}_{\text{Detector Responce}}$$

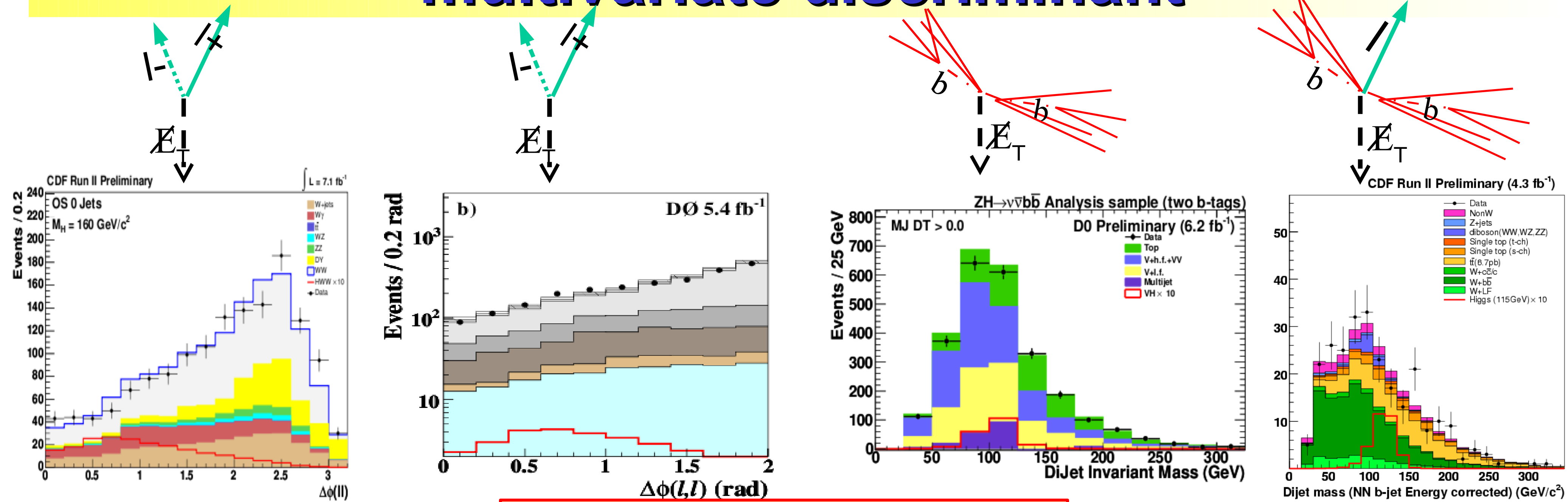
Smarter use of multivariate techniques





- Separating the *NN* output using $t\bar{t}$, light and heavy flavor score;
- Systematics on large backgrounds constrained by data in region I & II;
- 8% gain relative to the original discriminant network ($ZH \to \ell\ell b\bar{b}$);

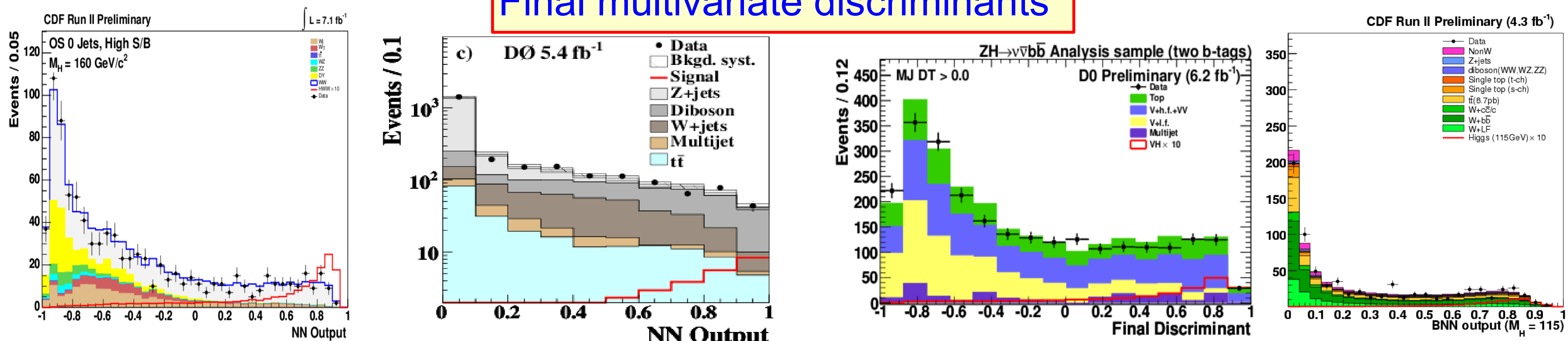
Each channel now uses (at least) one multivariate discriminant



Main discriminating variables

gain 20-30% in sensitivity

Final multivariate discriminants



Method validation

- Testing background model
  - use control region
- Testing sensitivity to Higgs
  - measure alike SM process cross-sections → di-boson
  - New in 2011: diboson with heavy flavor jets

WZ/ZZ → lνbb, lνcs

xsec=1.08$\pm_{0.40}^{0.26}$ x SM

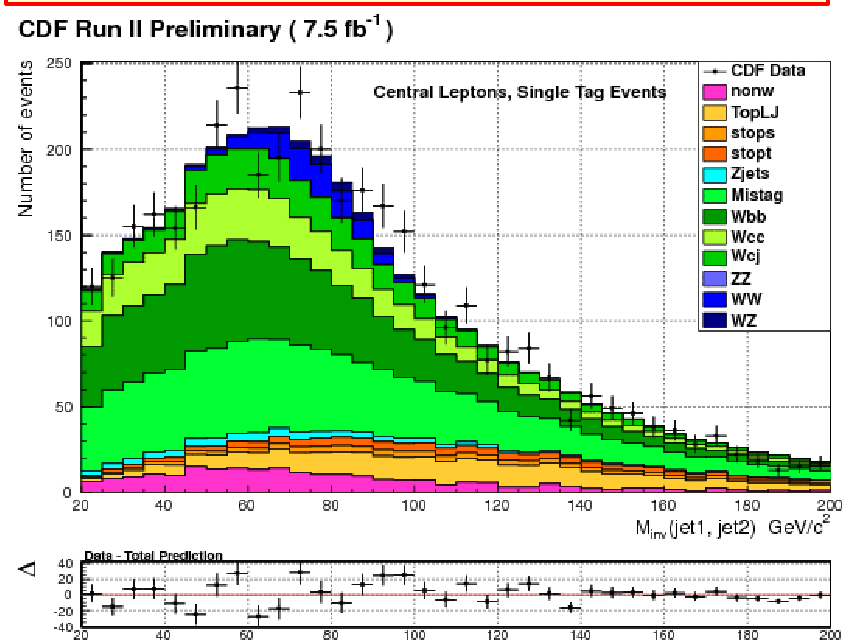
(3σ above bkg)

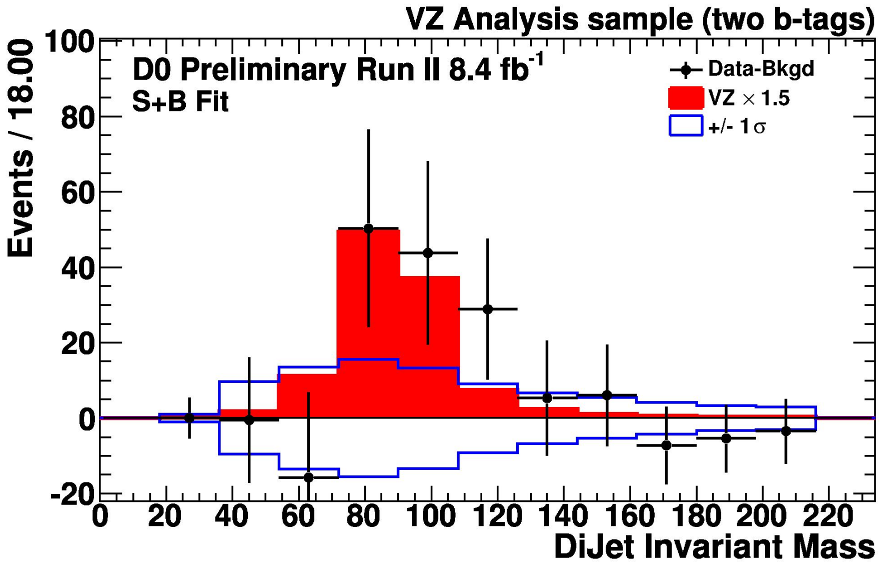
ZZ → ννbb

di-jet : 2.3σ above bkg

Multivariate : 2.8 σ above bkg

xsec=1.5±0.5xSM





Analysis method: Divide and Rule

Channels are split into subchannels: ~50 analysis to be combined

- Different bins in jet multiplicity
- Different b-tagging content
- Lepton flavour, lepton id criteria

Eg: llbb at D0 = 8 channels (ee, μμ, e+ICRe , μ+track)x(1 b-tag, 2 b-tag)

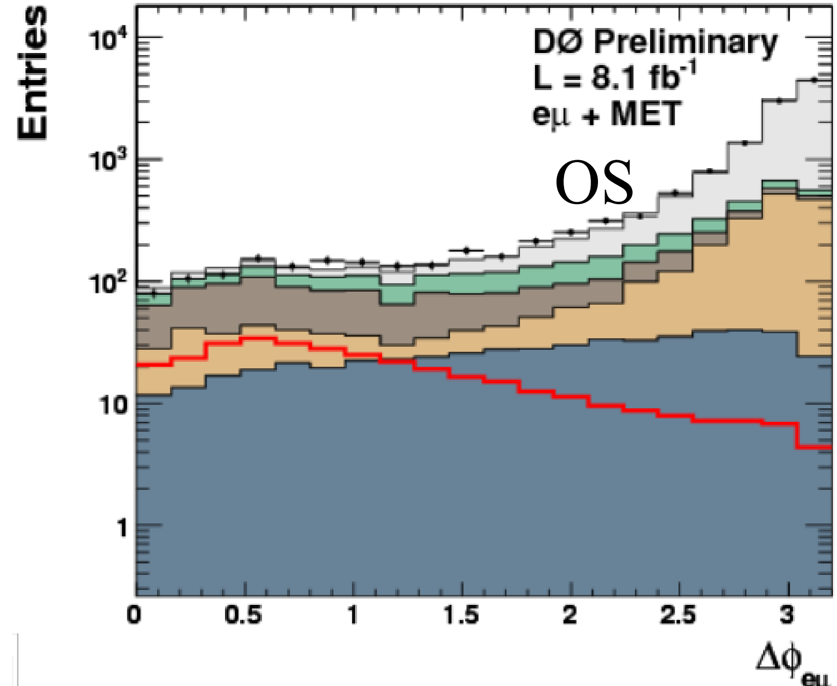
Goal is to maximize sensitiviy : each subchannel has its own S/B

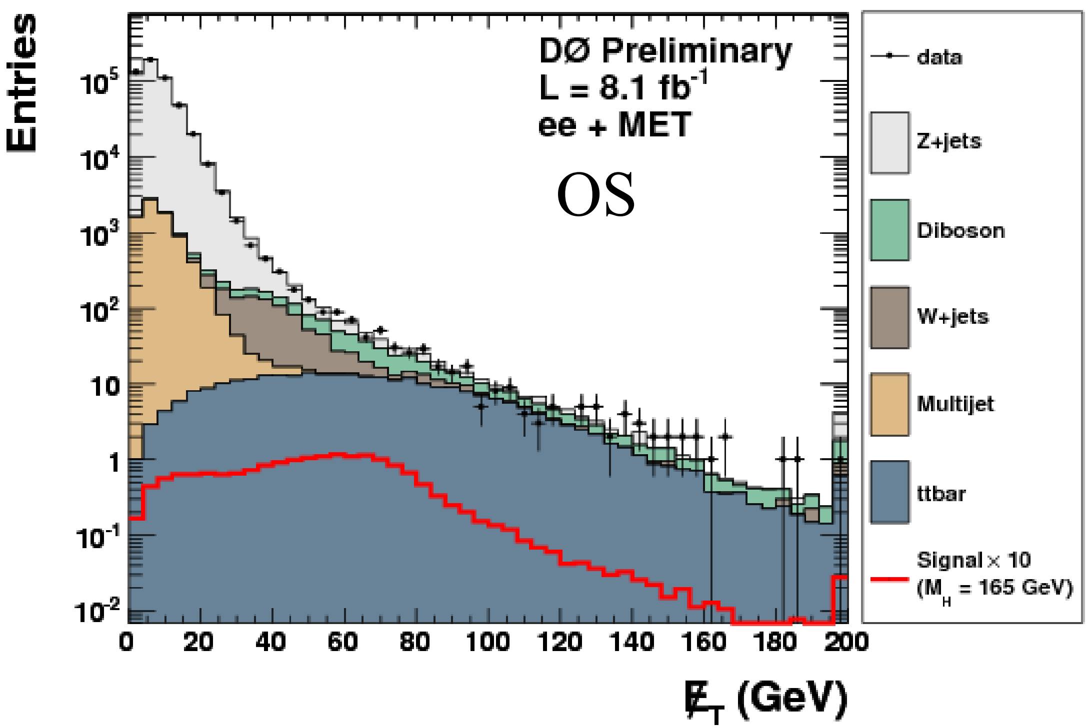
Eg WH, 2jets : 0-btag S/B~1:4000 , 1btag(only) S/B~1/400 2 b-tag S/B ~ 1/100

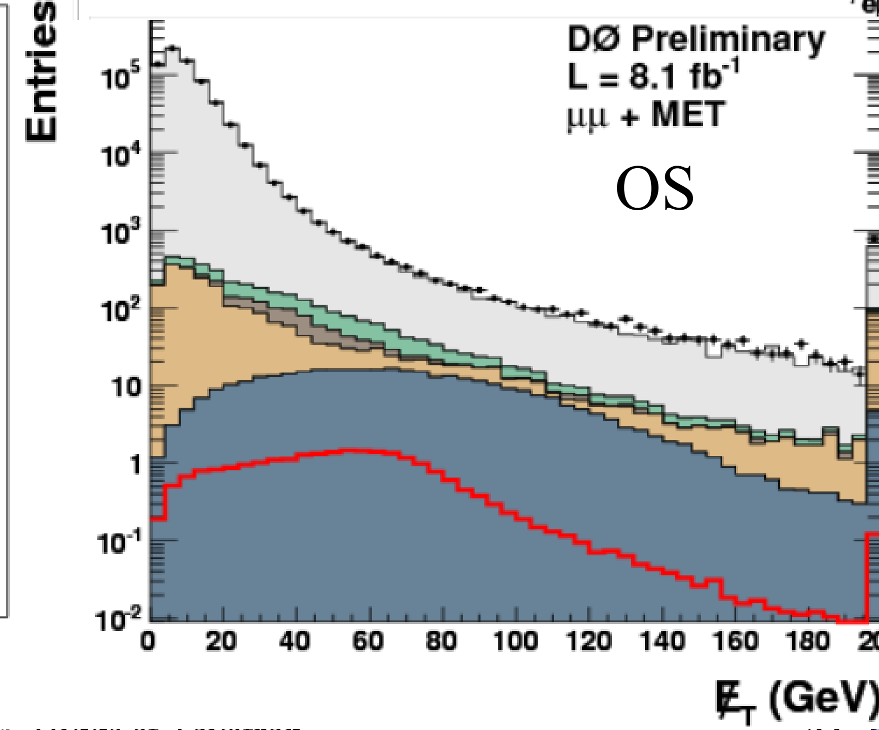
Examples : Di-lepton + $\not\!\!E_T$ Subchannels at D0

Split analysis according to :

- lepton flavor ee, eμ, μμ (D0)
- signal purity based on lepton quality (CDF),
- low (<16 GeV) di-lepton mass (OS channel at CDF)
  - Different instrumental (fake) background
  - Different lepton momentum resolution
    - typically 4% for electrons, 10% for muons at D0
  - Different background composition







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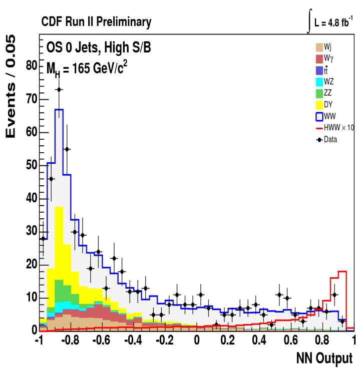
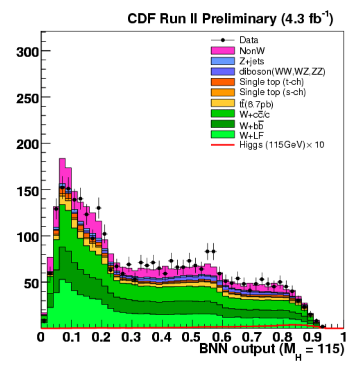
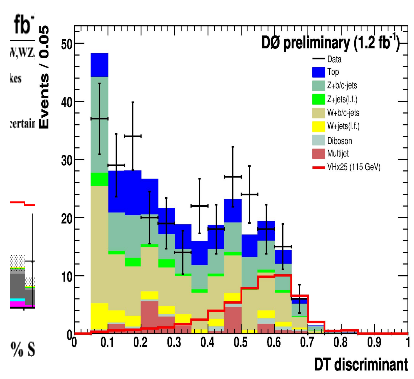
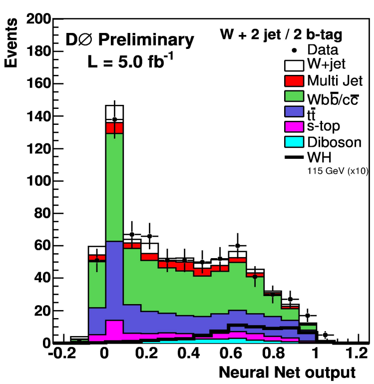
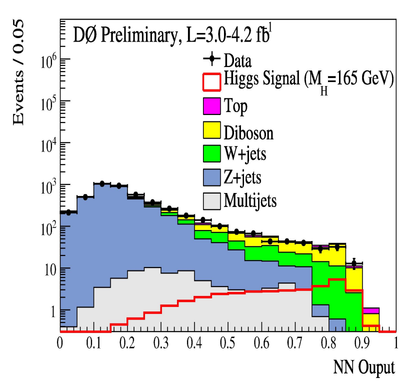
Build Likelihood based on multivariate discriminant distribution to test S and S+B hypothesis











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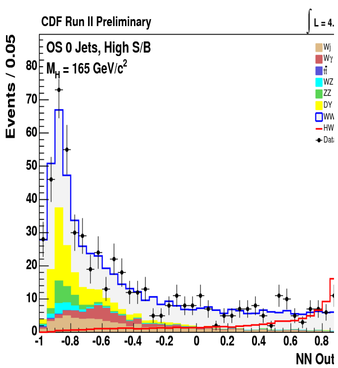
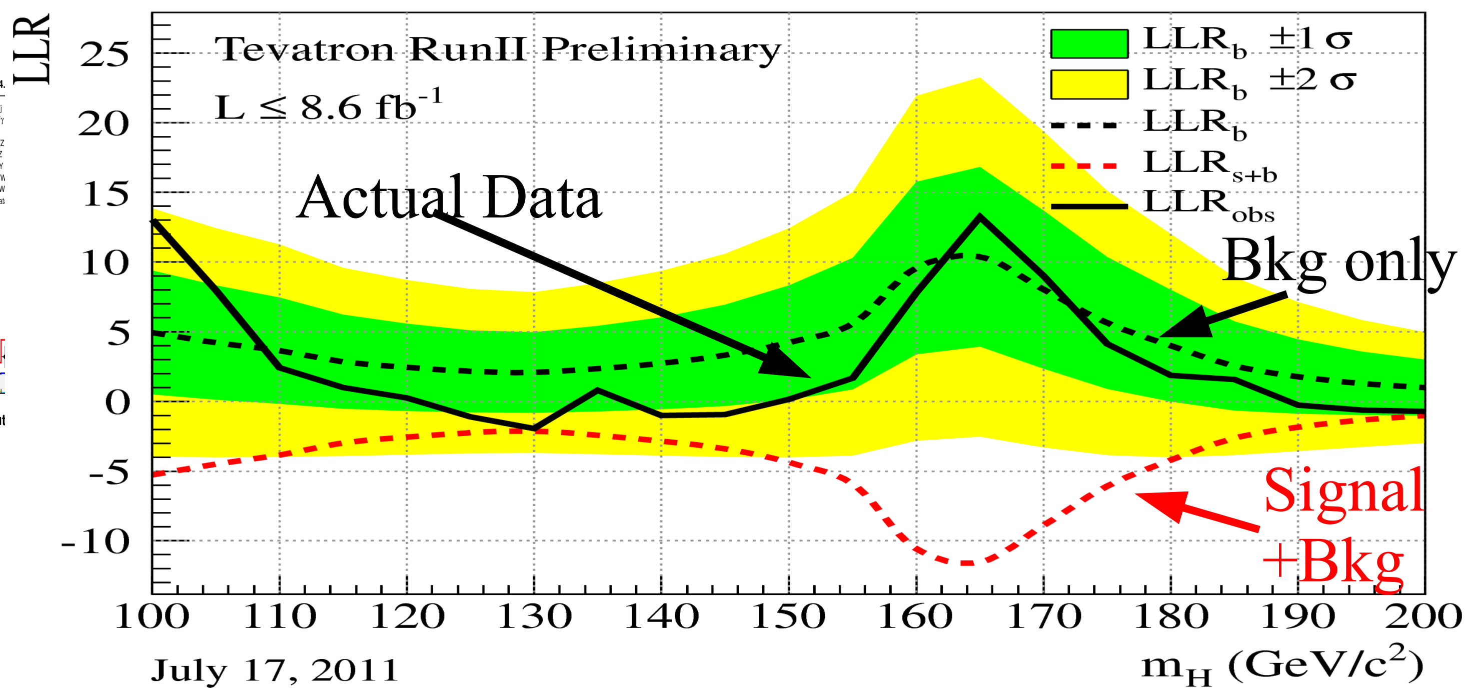
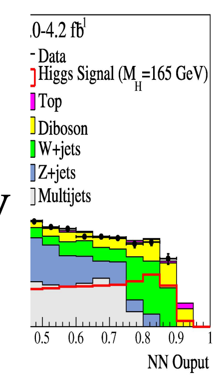
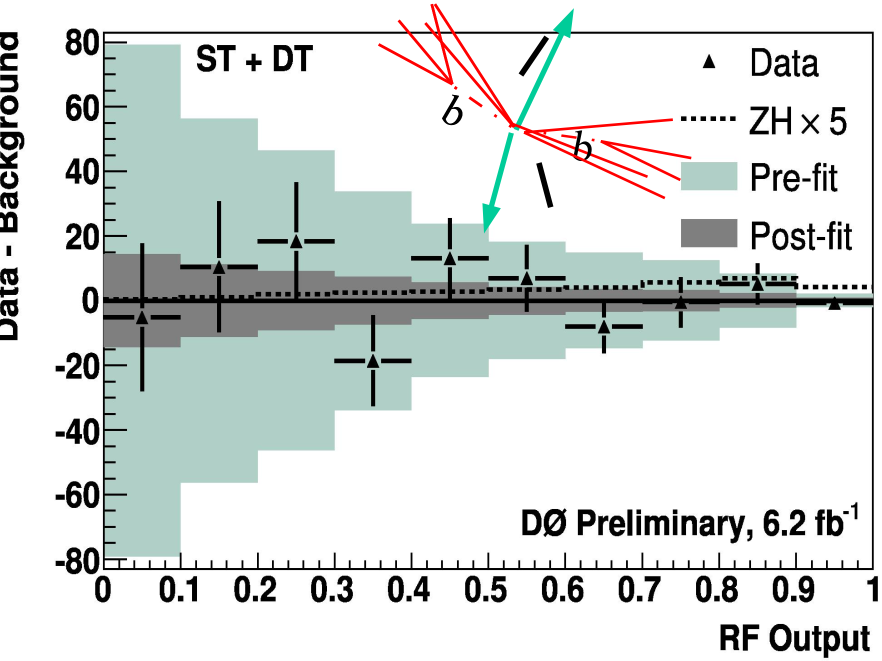






…

Systematics



Uncertainties have a sizable impact

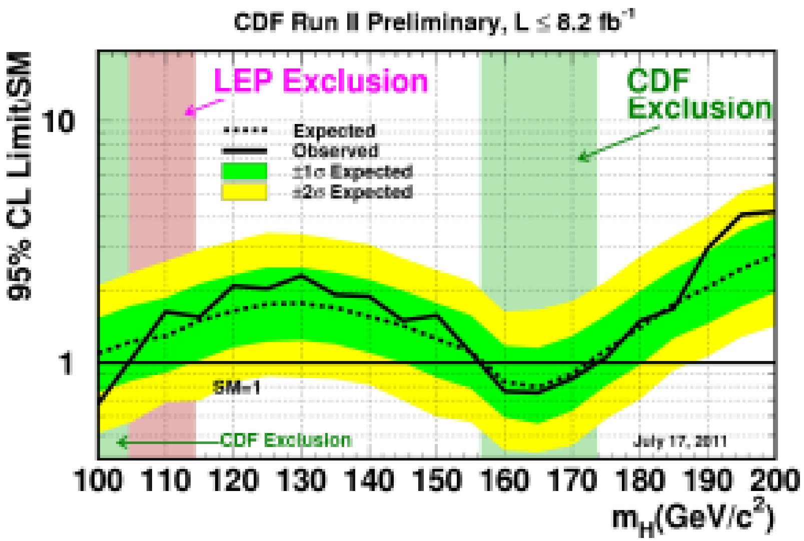
- Flat : affect overall normalization
- Shape: modify output of final discriminant
- Have to account of correlations among channels and experiments
- Impact is reduced thanks to constraints from background dominated region
- Degrade sensitivity by ~15-25%

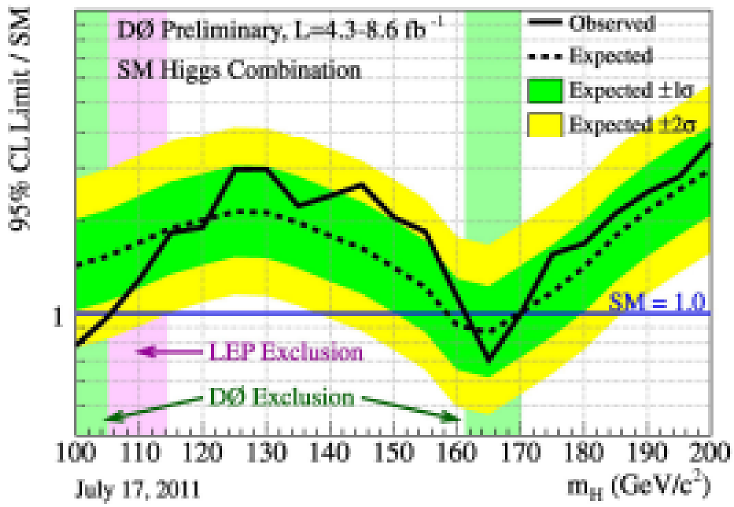
Goal to reduce uncertainties on background in particular to gain sensitivity for lower masses.

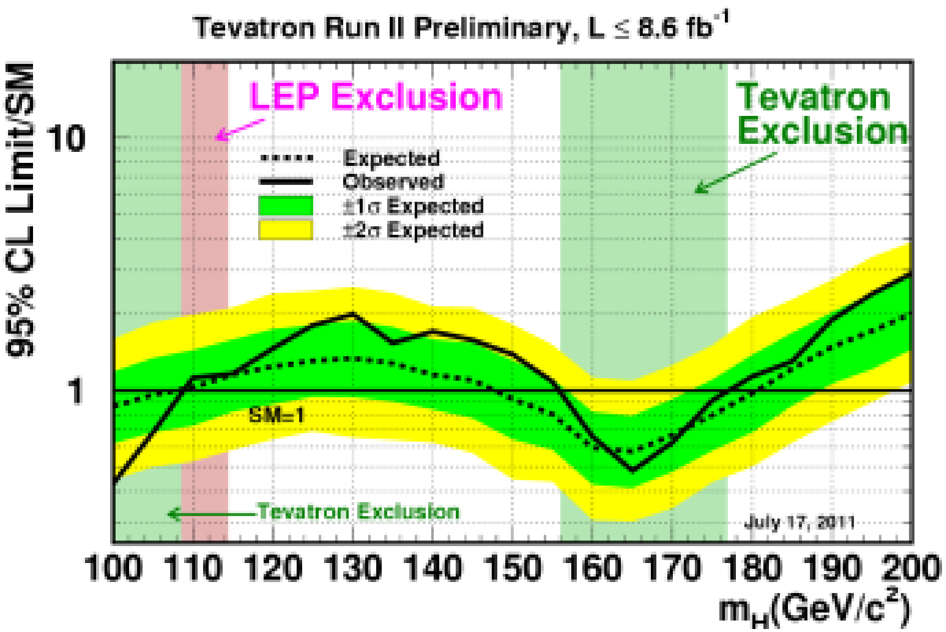
Main sources are:

- Luminosity and normalization
- Multijet background estimates
- Background cross-sections, K-factors for W/Z+ Heavy flavor
- Modeling of background differential distributions (shape)
- B-tagging efficiency
- Jet energy calibration
- Lepton identification
- Theoretical uncertainty for signal. Follow prescription of LHC Higgs working group

CDF/D0 achieve single experiment exclusion in 2011







Observed exclusion:
100-109 and 156-177 GeV

Expected exclusion:
100-108 and 148-181 GeV

Conclusion

All possible Higgs channels are scrutinized by both CDF and DØ

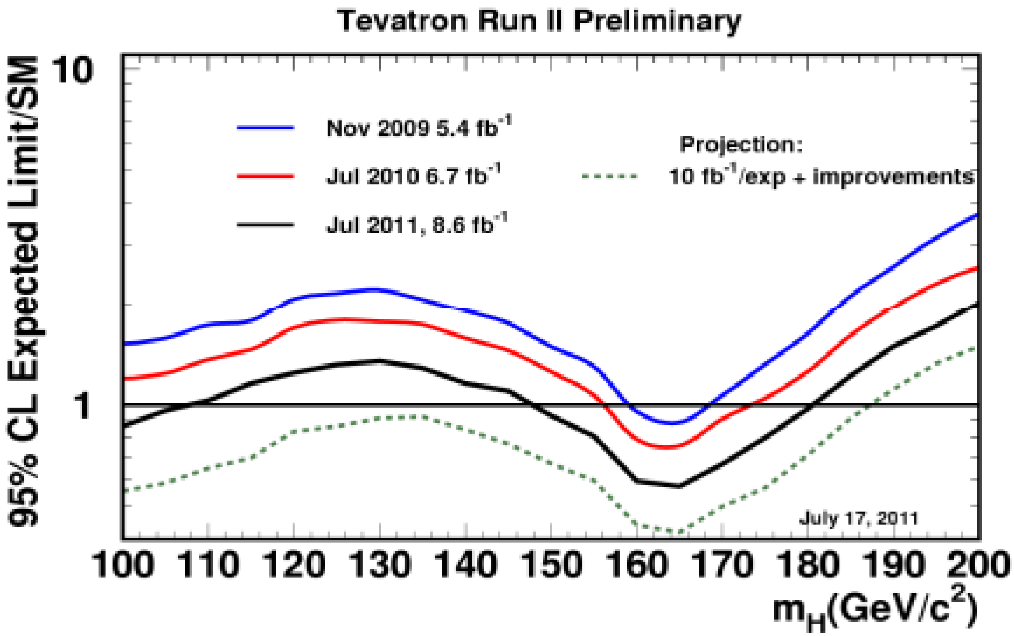
- Sensitivity to Higgs boson around 165 GeV is achieved by each single experiment since winter 2011
- Sensitivity to lower mass is in range

End of Data taking

- Tevatron has shut down in September
- LHC has now better sensitivity at high mass

Have to focus on analysis improvements at low masses

- Still room to improvements:
  - for low mass analysis: WH, ZH
  - High mass channels also have a role to play down to ~125 GeV.
- More acceptance
- Better background modeling
- Reduced systematic uncertainties
- Challenge: have all of this in time because LHC is very fast nowadays



Backup

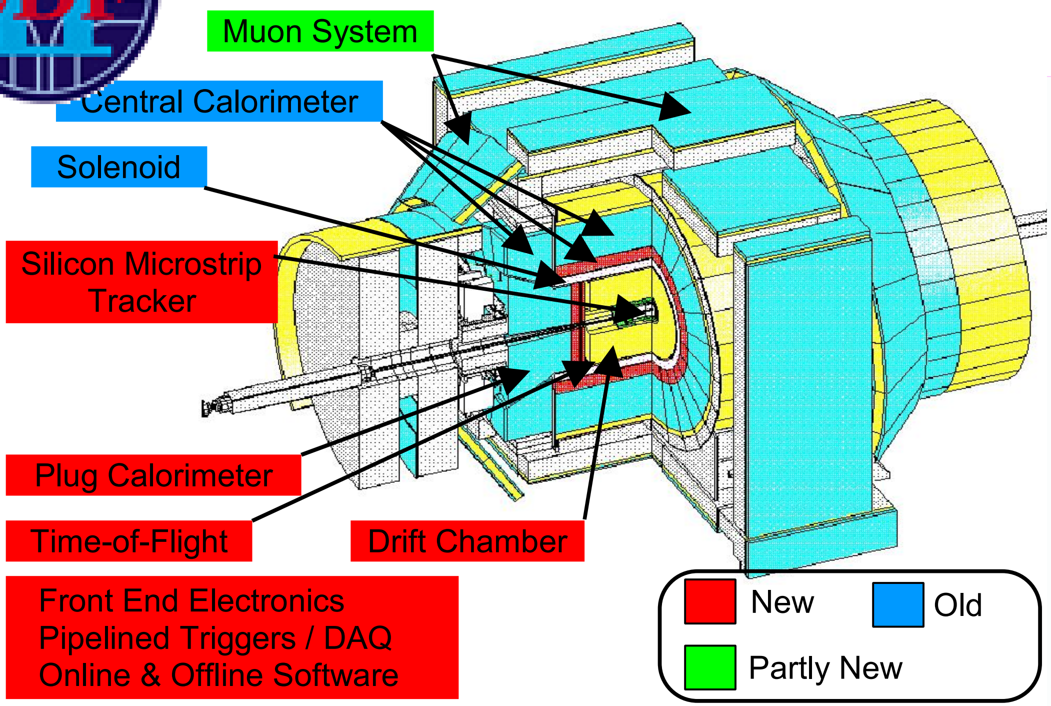
Challenge

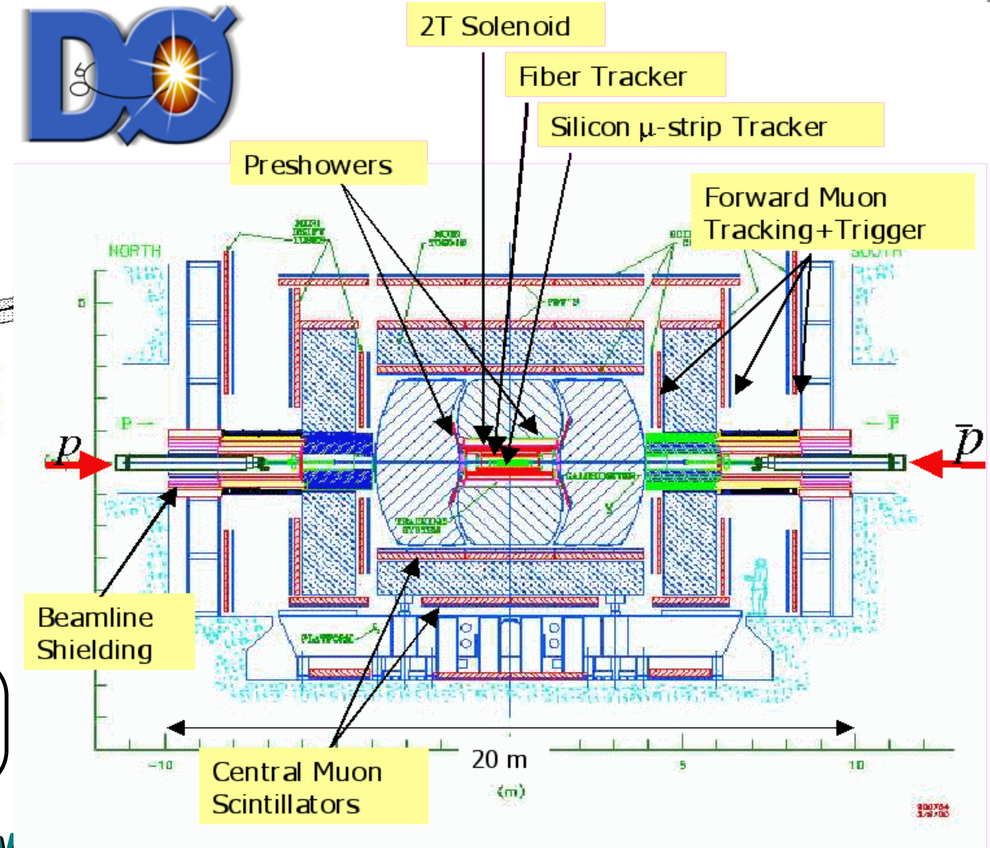
Expected number of events per fb^{-1} per experiment

Higgs Mass (GeV/c^2)	$WH \to l\nu bb$	$ZH \to \nu\nu bb$	$ZH \to llbb$	$H \to WW \to l\nu l\nu$
120	25	12	4	13
135	10	5	2	26
150	3	2	1	32

reconstruction/selection/tagging efficiencies ~ 10% in $H \to bb$ channels and ~25% in $H \to WW$ channels

Tevatron Experiments at RunII





New

- silicon detector
- Drift chamber
- TOF PID system

Upgraded

- Calorimeter
- DAQ/trigger
- displaced-vertex trigger

New

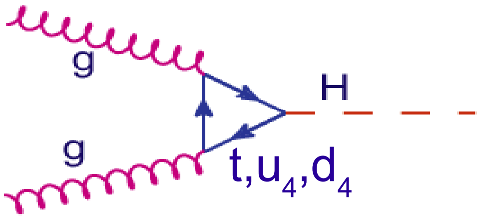
- Tracking in B-field
- Silicon detector
- fiber tracker

Upgraded

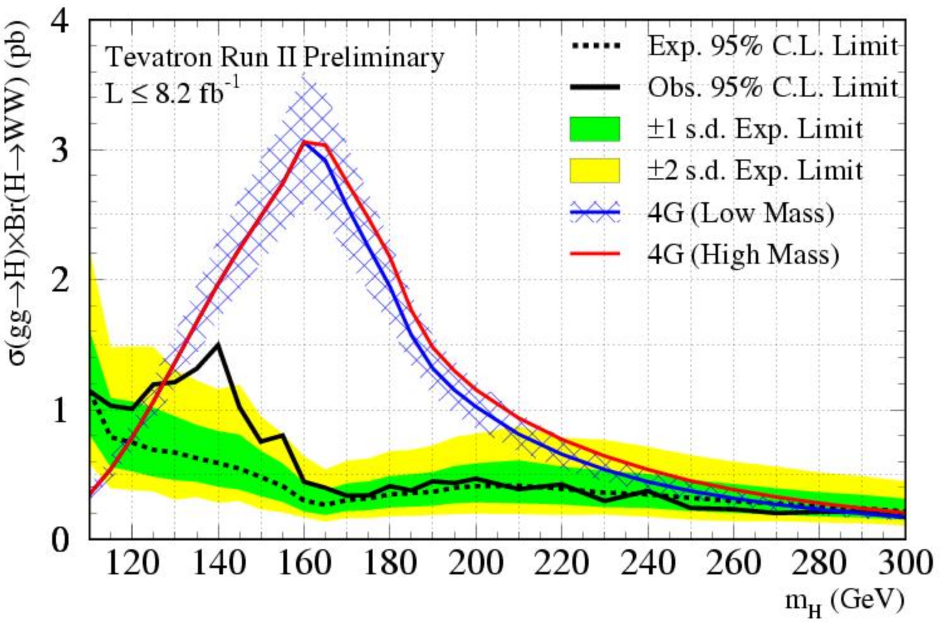
- Calorimeter, muon system
- DAQ/trigger
- RunIIb: Silicon layer 0, Cal Trigger

Higgs search within 4th generation model

- New heavy generation of quarks
  - ggH coupling is multiplied by 3 compared to SM
  - Production is enhanced by 9

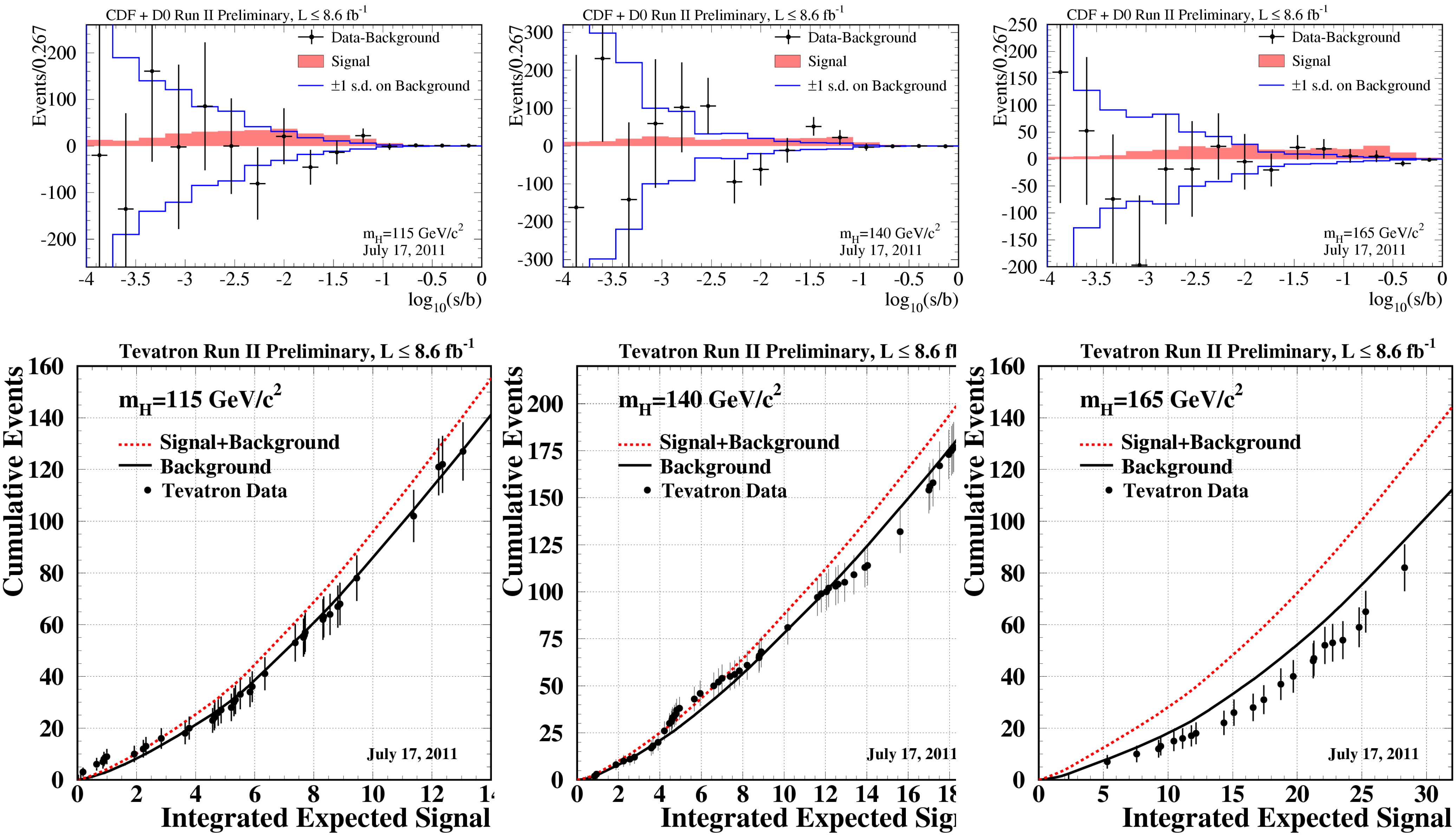


- Search in di-lepton +MET channel can be recycled
  - Some analysis tuning required because of extended mass reach (eg $\Delta\phi(l,l)$ cut not applicable when W's are boosted)



CDF only	8.2 fb^{-1}	(summer 11)	$123<m_H<215$ GeV @95%CL
DØ only	8.1 fb^{-1}	(summer 11)	$140<m_H<240$ GeV @95%CL
Combination			$124<m_H<286$ GeV @95%CL

Another way of viewing results



Results from both experiments

CDF and DØ achieved single experiment sensitivity in winter 2011

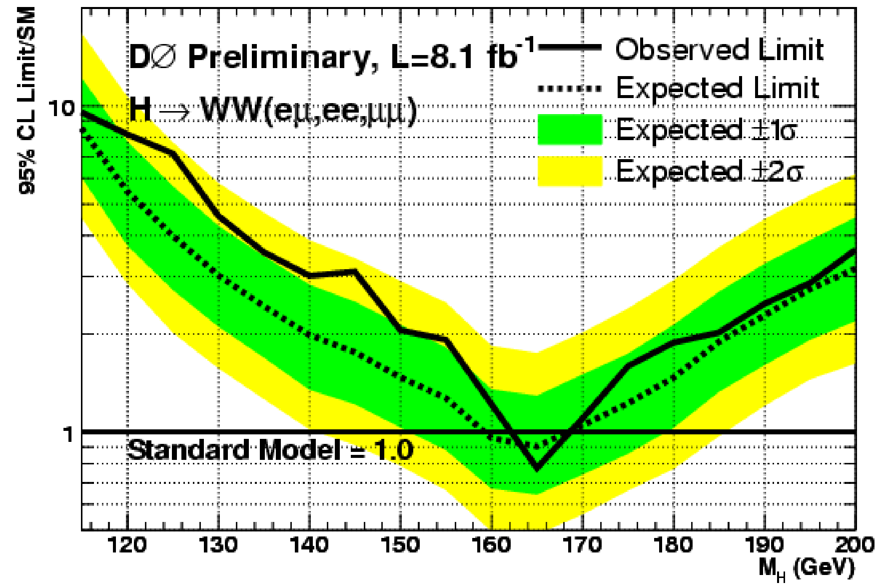
- DØ, 8.1 fb^{-1}, OS di-lepton

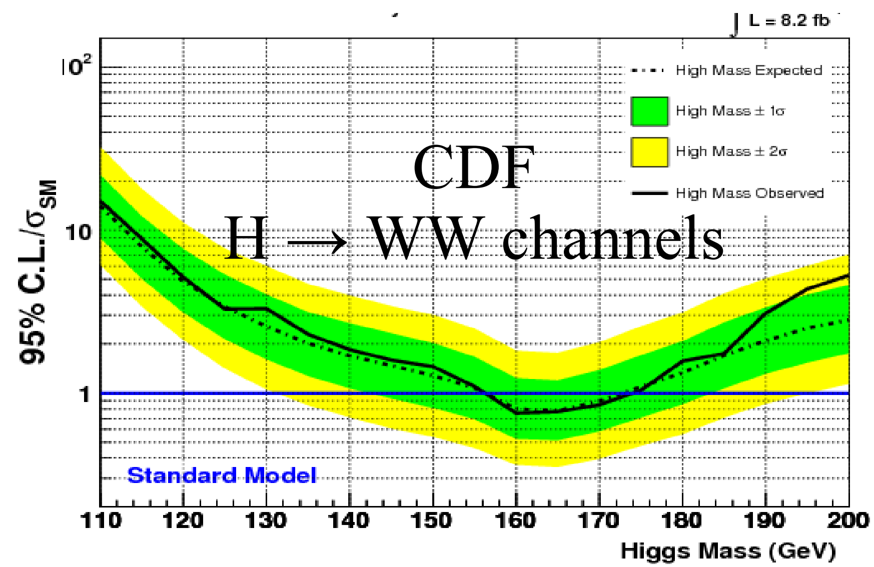
95% CL expected sensitivity range	
Winter 11	Summer 11
[~162,~165] GeV	[~159,~169] GeV

- CDF all WW channels

95% CL expected sensitivity range	
Winter 11	Summer 11
7.1 fb^{-1}	8.2 fb^{-1}
[~160,~167] GeV	[~156,~173] GeV

- Sensitivity continue to increase faster than just by adding more data.





Limit for m_H=165 GeV

DØ OS di-lepton 8.1 fb^{-1} : $\sigma_{95}/\sigma(SM)$ =0.78 (0.90 expected (0.97 in winter))

CDF $H \to WW$ 8.2 fb^{-1} : $\sigma_{95}/\sigma(SM)$ =0.77 (0.78 expected (0.93 in winter))

examples of ystematic uncertainties $H \to WW$

Main systematics	Signal	Bkg
Lepton id +trigger	2-5%	2-5%
Lepton/jet fakes	-	14-50%
charge mis-id		20-40%
Luminosity	5.9%	6.1%
Jet calibration	5-17%	3-30%
$\not{E}_T$ modeling	~20%	~20%
pT(Z) pT(W) pT(WW)pT(H)	1.5%	1-5%
Cross-sections	(VBF,VH) 5-10%	6-10%
$gg \to H$ production Scale PDF	(jet dependent) 7-33% 7.6-30%	-

Uncertainties have a sizable impact

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- Shape: modify output of final discriminant
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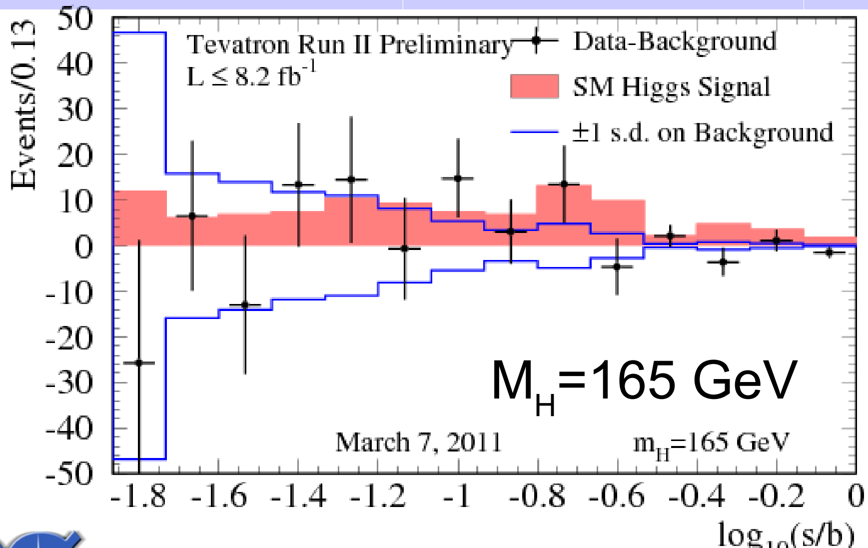

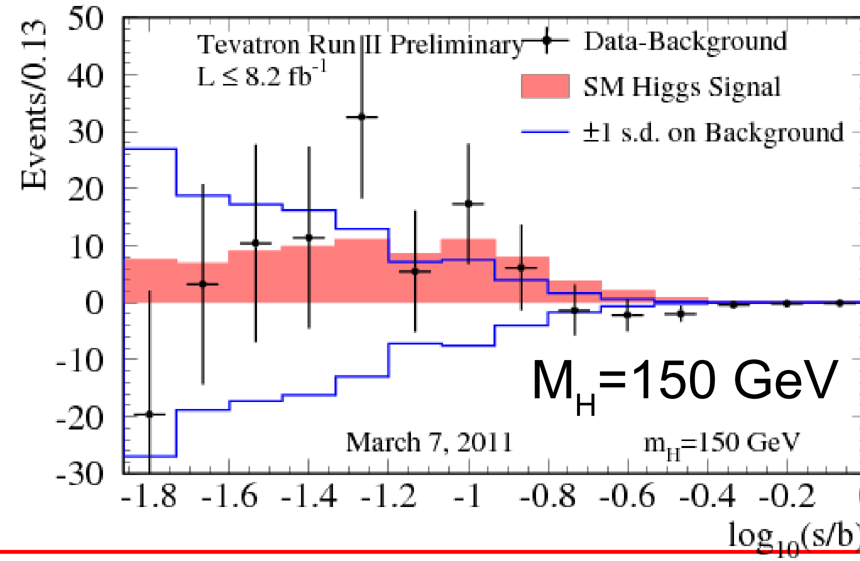

Conclusion

H → WW di-lepton channels are scrutinized by both CDF and DØ

- Sensitivity to Higgs boson around 165 GeV is achieved by each single experiment since winter 2011
- Sensitivity is still increasing faster than luminosity thanks to analysis improvements
- Able to probe 4th generation models

Have to focus on analysis improvements

- Tevatron will shut down in September
  - Cannot just « wait and see » new data
- More acceptance, more channels, reduced systematic uncertainties
- Goal to increase H → WW reach at lower masses ~130 GeV
- H → WW will help covering "low mass" ranges for the Higgs Searches

Di-lepton modes are part of the combined CDF/DØ results

- See next talk for the contributions of other decay modes
- See forthcoming parallel and plenary talks for combined results

$gg \rightarrow H$ (μ_R,μ_F) scale uncertainties

- Vary independently ggH +0jet, ggH+1jet, ggH+2jets scale uncertainties (s0, s1,s2).
- Account for migration between jet multiplicity bin.

	s0	s1	s2
0 jet	0.134	-0.230	0.0
1 jet	0.0	0.35	-0.127
2+jet	0.0	0.0	0.33

Scale Variations (μ_R & μ_F)

- Is our treatment of assessing cross section uncertainties due to scale variations reasonable?

- We obtain our gluon fusion production cross sections from:

  D. de Florian, M. Grazzini, Phys. Lett. **B674**, 291-294 (2009). [arXiv:0901.2427 [hep-ph]].

  C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].

- We use a scale variation of a factor of 2 from the central value ($\mu=m_H/2$) to estimate the magnitude of potential contributions from higher-order processes

- The authors confirmed that higher order corrections to these cross sections are small and that the standard $\kappa=2$ scale variations are perfectly reasonable for assigning uncertainties

- Another recent, independent publication argues for even smaller scale uncertainties than those being currently assigned in our searches:

  V. Ahrens, T. Becher, M. Neubert *et al.*, Eur. Phys. J. **C62**, 333-353 (2009). [arXiv:0809.4283 [hep-ph]];

  V. Ahrens, T. Becher, M. Neubert *et al.*, [arXiv:1008.3162 [hep-ph]].

- **Yes, our treatment is sufficient and supported by the theoretical community**

Borrowed from: Marc Buehler, on behalf of TeVNPHWG, La Thuile 2011

Additional Theoretical Uncertainties

- Should there be an additional theoretical uncertainty assigned to our gluon fusion cross sections coming from the effective field theory (EFT) approach used to integrate electroweak contributions from heavy and light loop particles?
- Such an uncertainty is already included:

  C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].

- Uncertainties on the gluon fusion cross section used in Tevatron Higgs searches incorporate a ~2% level component to account for this effect
- The same authors find that when they entirely remove corrections from light quark diagrams (clearly too conservative), the total cross section changes by less than 4%
- **Our current treatment of EFT effects is on solid ground**

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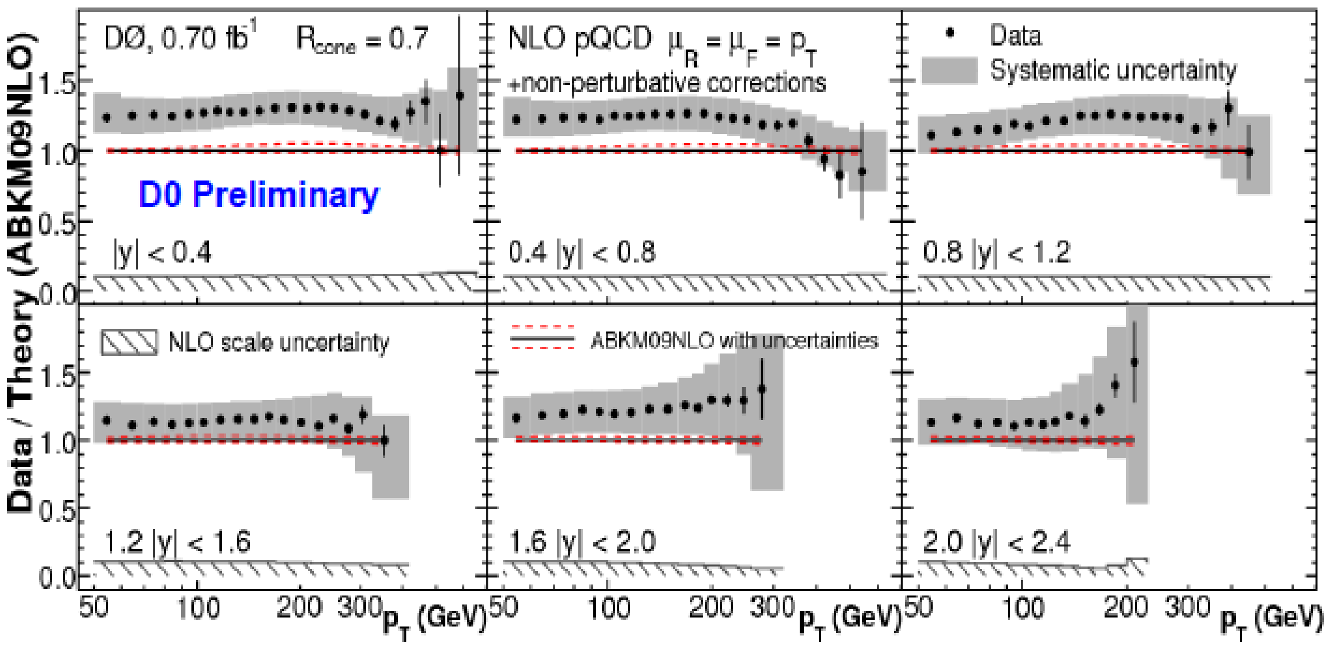
PDF Uncertainties

- Should our PDF uncertainties account for observed differences in cross sections obtained using our default MSTW model and ABKM/HERAPDF models?
- See Juan Rojo's talk on "Recent Developments and Open Problems in Parton Distributions" in the Tuesday afternoon session
- ABKM09 & HERAPDFs do not include Tevatron data, which provide the best constraints on the relevant high-x gluon distributions at Tevatron energies
- A comparison of high E_T Tevatron data with ABKM09 & HERAPDF shows large disagreement:

ABKM09 at the Tevatron:
Ratio of D0 High-ET jet cross-section to ABKM09 prediction (Data vs central PDF value)

(→ Uncertainty on ABKM Prediction)



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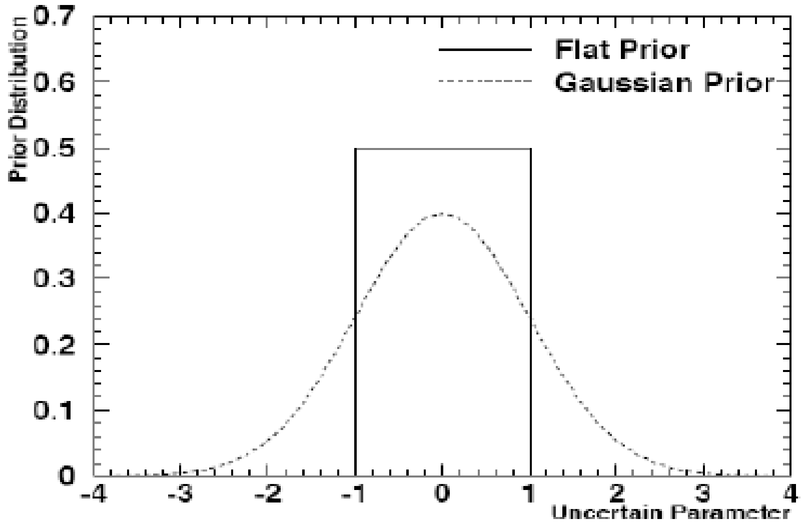
Treatment of Theoretical Uncertainties

- Most theoretical uncertainties are rather loosely stated. They are interpreted in terms of a maximum range of variations (*flat prior*)
- We treat theoretical uncertainties as gaussian (*gaussian prior*)
- Are we underestimating our uncertainties?
- We use the maximum bound as 1σ. This means we allow even larger variations than the given bounds. (See figure)
- We also tested the flat prior approach and found no significant change in our limits
- **We are not underestimating our uncertainties**



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Emulation of Tevatron Limit Calculation

- Care needs to be taken when trying to emulate Tevatron limits
- Correlations between different input channels need to be properly taken into account:
    - Our limit calculation uses these correlations to constrain the backgrounds
    - Our backgrounds are better constrained by the data, as compared to the theory. This can be viewed as a measurement of the true rate and the a posteriori uncertainty is an experimental determination of the true error.
- An estimation of the sensitivity increase due to MVA is not straightforward:
    - Our pre-selection cuts are kept as loose as possible to maximize signal acceptance and cannot be interpreted as an optimized cut-based analysis
    - MVAs are used to separate signal from background
    - To estimate MVA sensitivity gains: compare fully optimized cut-based results with MVA results
    - MVAs typically improve limits by ~30% over optimized cut-based
- Impact of theoretical uncertainties:
    - Theoretical uncertainties are statistically accounted for together with other systematics
    - Increasing theoretical cross section uncertainties is not equivalent to decreasing the central prediction

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