Searching for the Higgs at the Tevatron

Krisztian Peters
University of Manchester

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Outline

Introduction

The challenges and analysis strategies

Low mass SM Higgs searches

High mass SM Higgs searches

Combined Tevatron result

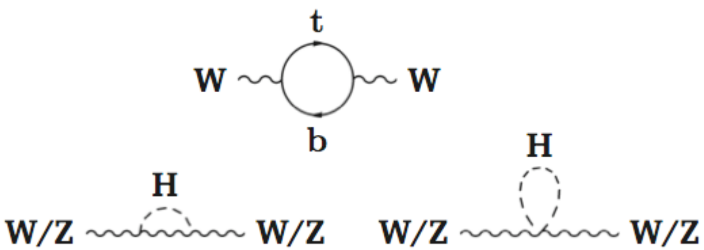
MSSM Higgs searches

Conclusions

Stalking the Higgs

Lower mass bound from direct searches at LEP:
114.4 GeV @ 95%CL

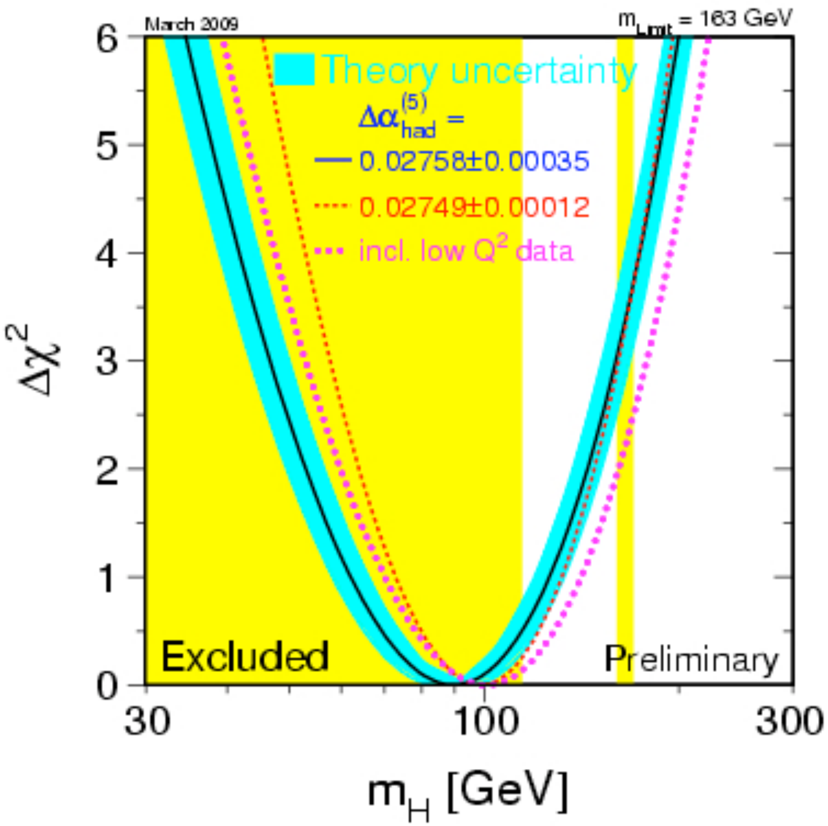
The SM relates m_H, m_t, m_W via radiative corrections:



Indirect constraints on the Higgs boson mass from global EW fits:

$m_H < 191$ GeV @95%CL

New precision measurements on the top and *W* mass from the Tevatron



Stalking the Higgs

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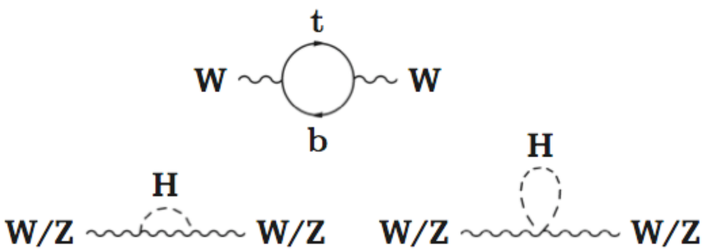

Indirect constraints on the Higgs boson mass from global EW fits:

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A light Higgs boson might be around the corner (if the SM is correct)!

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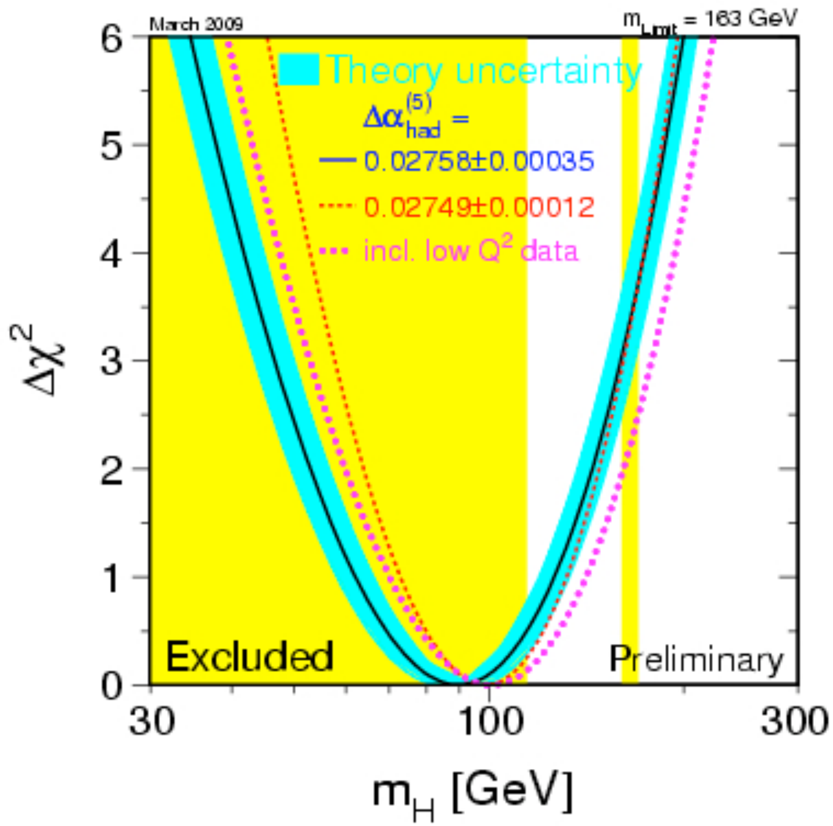
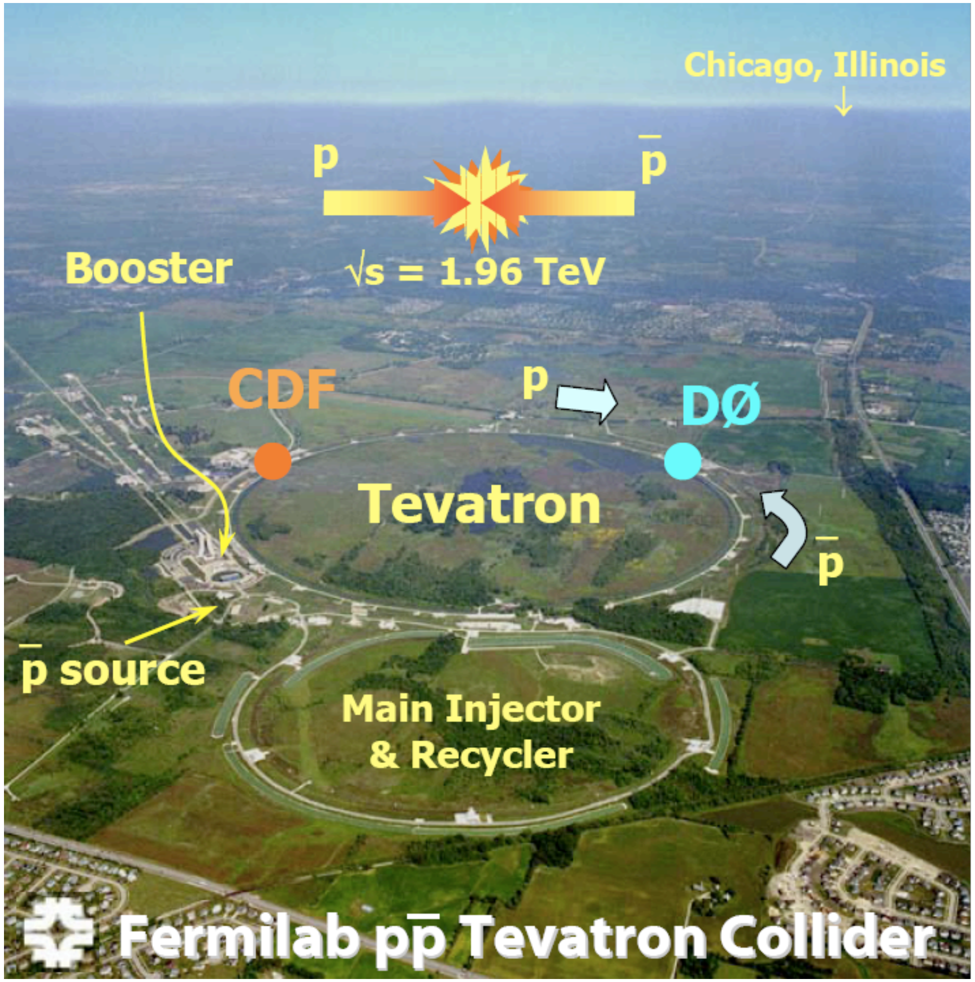
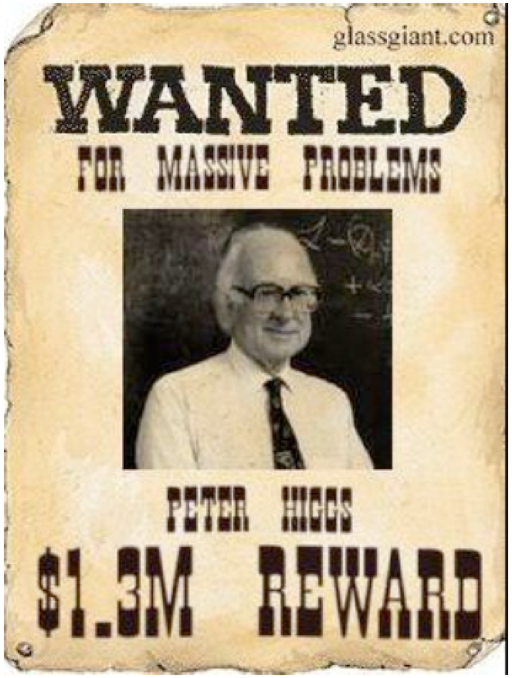


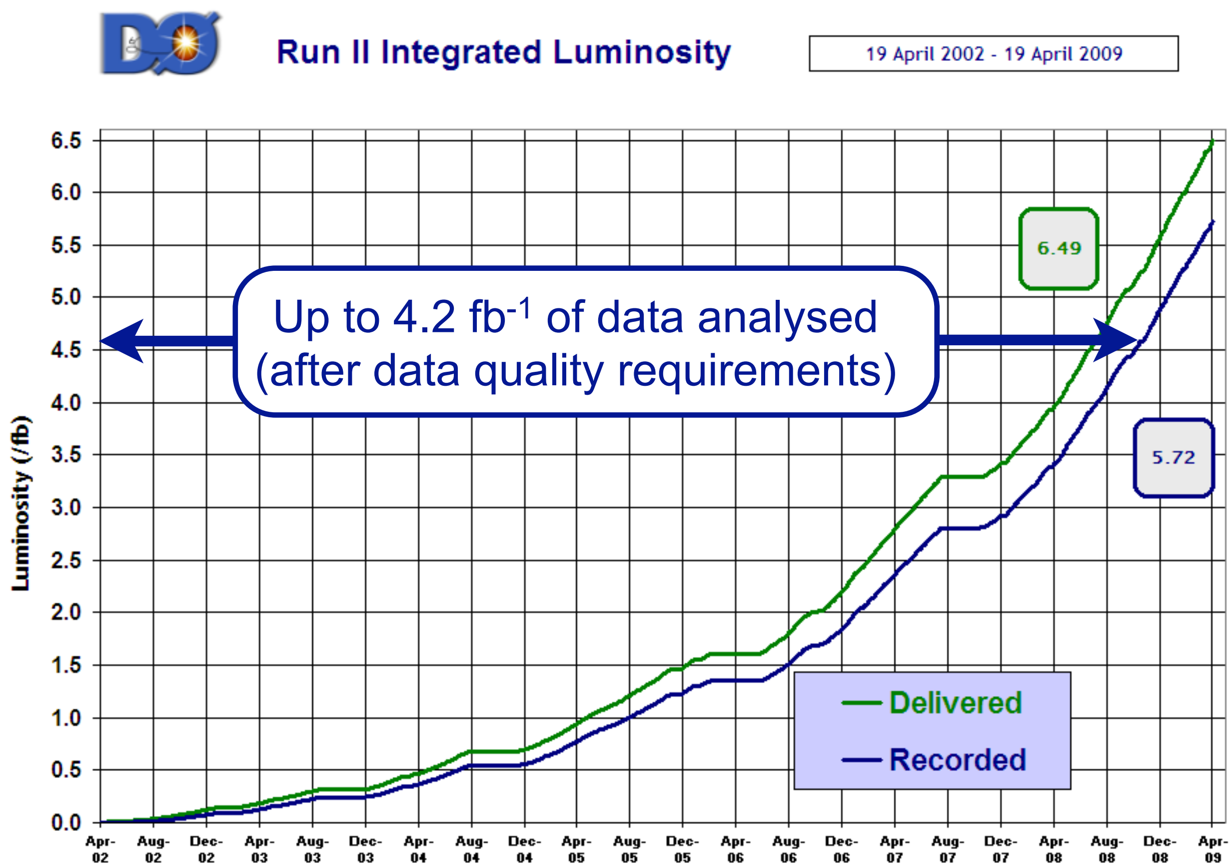
Tevatron collider in Run II





Data set

Tevatron delivers a data set equal to Run I (~100 pb^{-1}) every 2 weeks
+ Well understood detectors with data taking efficiencies of ~90%

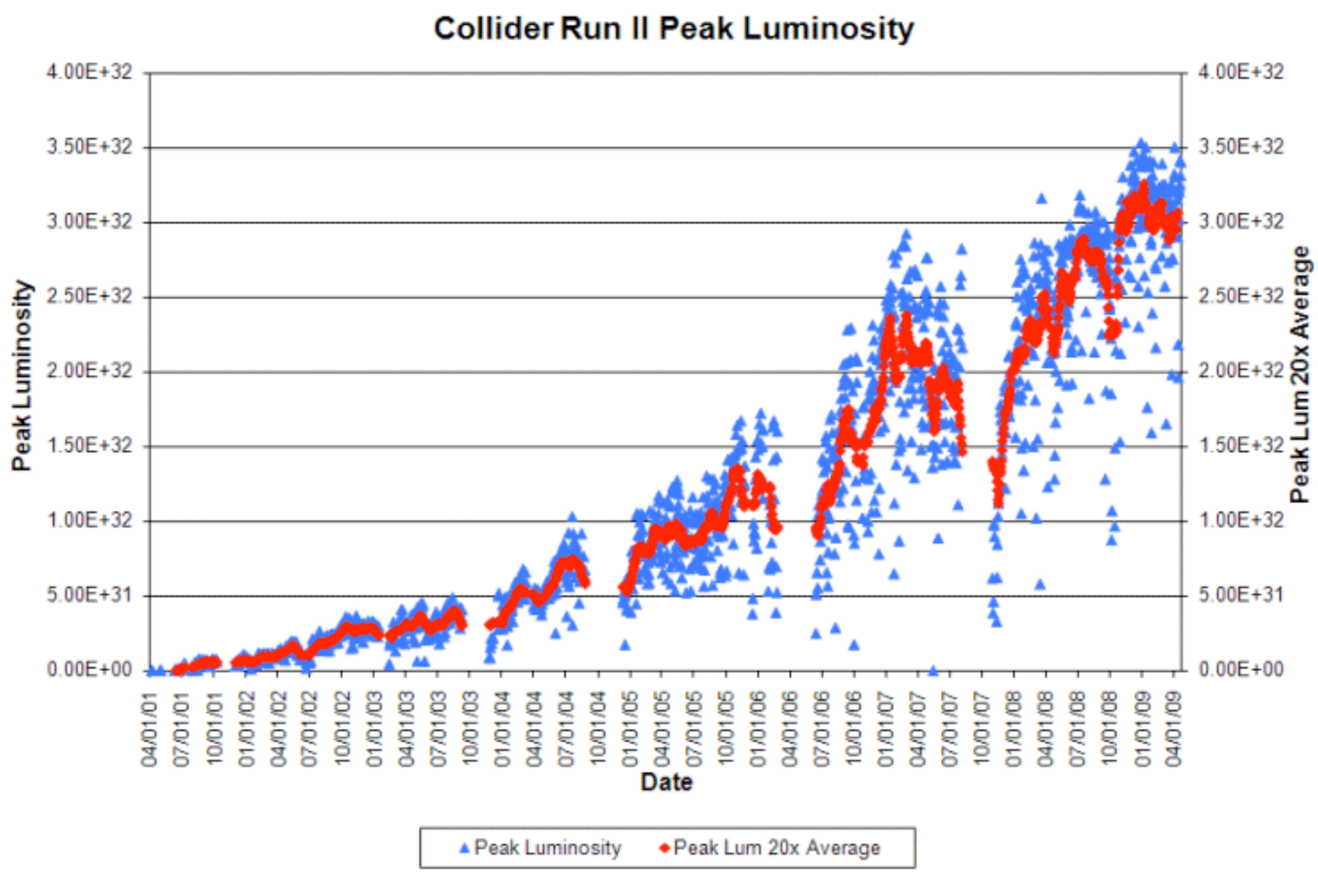


Similar for CDF

Expected to ~double this data set by the end of RunII

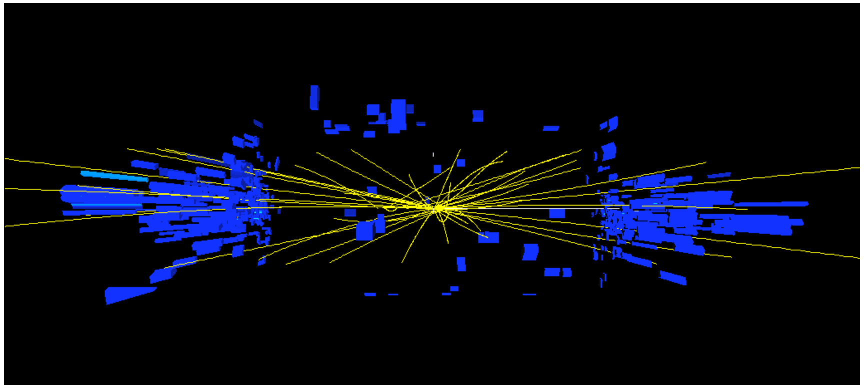
Tevatron performance

More data with higher instantaneous luminosities

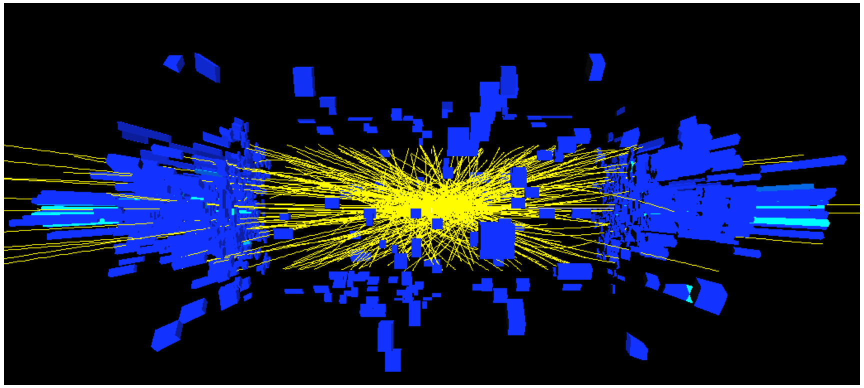


Challenges with high luminosity

A zero bias event @ 60E30 cm^2s^{-1}



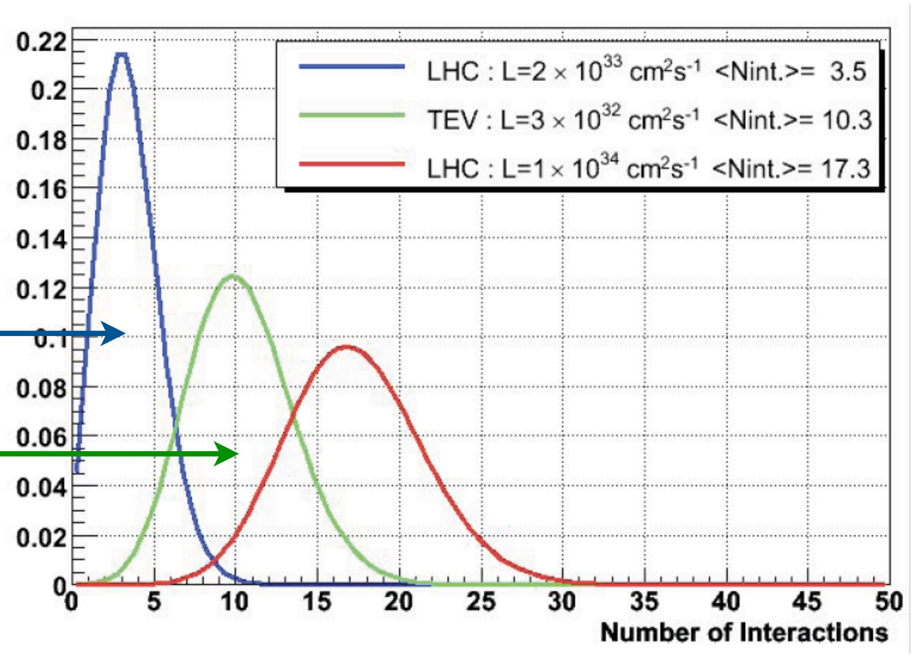
... and @ 240E30 cm^2s^{-1}



Average number of interactions:

LHC: initial "low" lumi run
(L=2000E30 cm^2s^{-1}): <N>=3.5

TeV: (L=300E30 cm^2s^{-1}): <N>=10



Challenges with high luminosity

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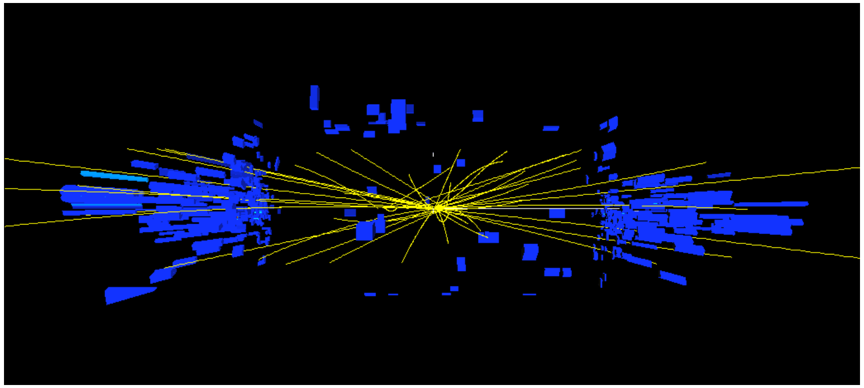

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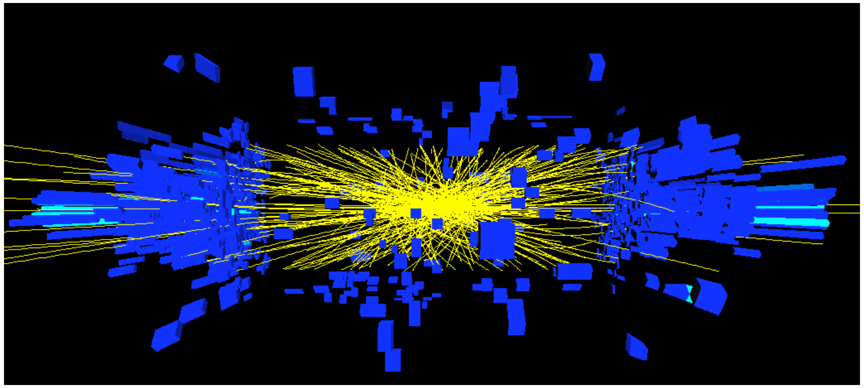

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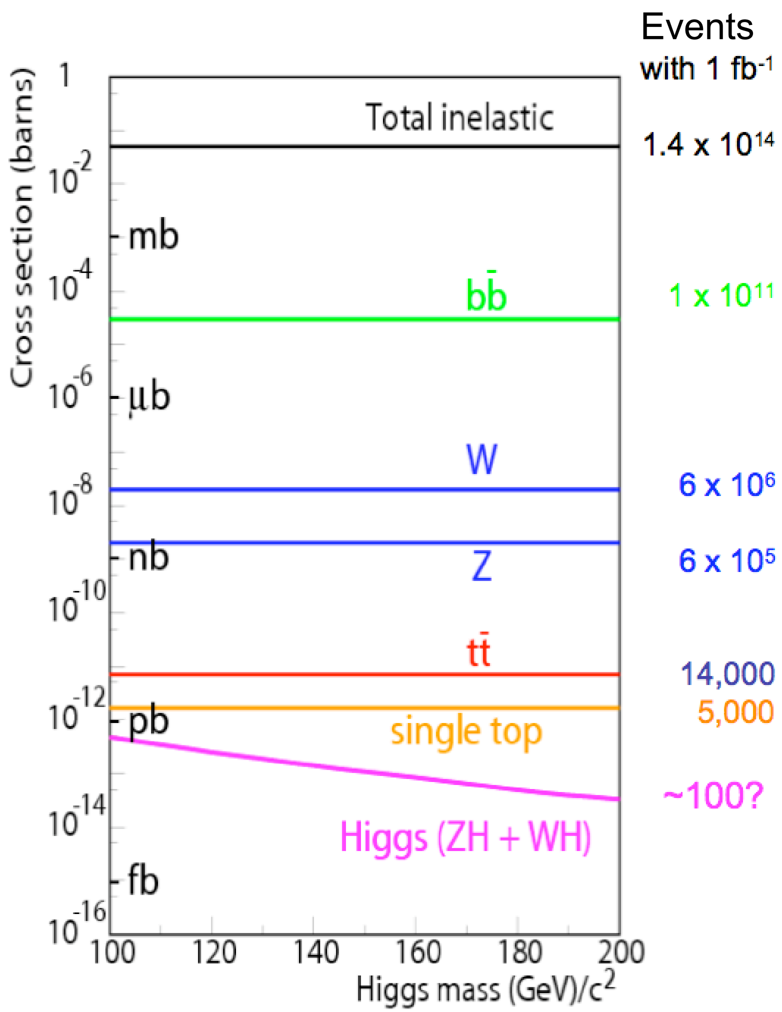
To cope with high luminosities:

New techniques to improve calibration

Improve / redesign algorithms for electron, photon, jet, tau and missing transverse momentum reconstruction

Higgs production at the Tevatron



only one in ~10^{12} events
will be a Higgs boson

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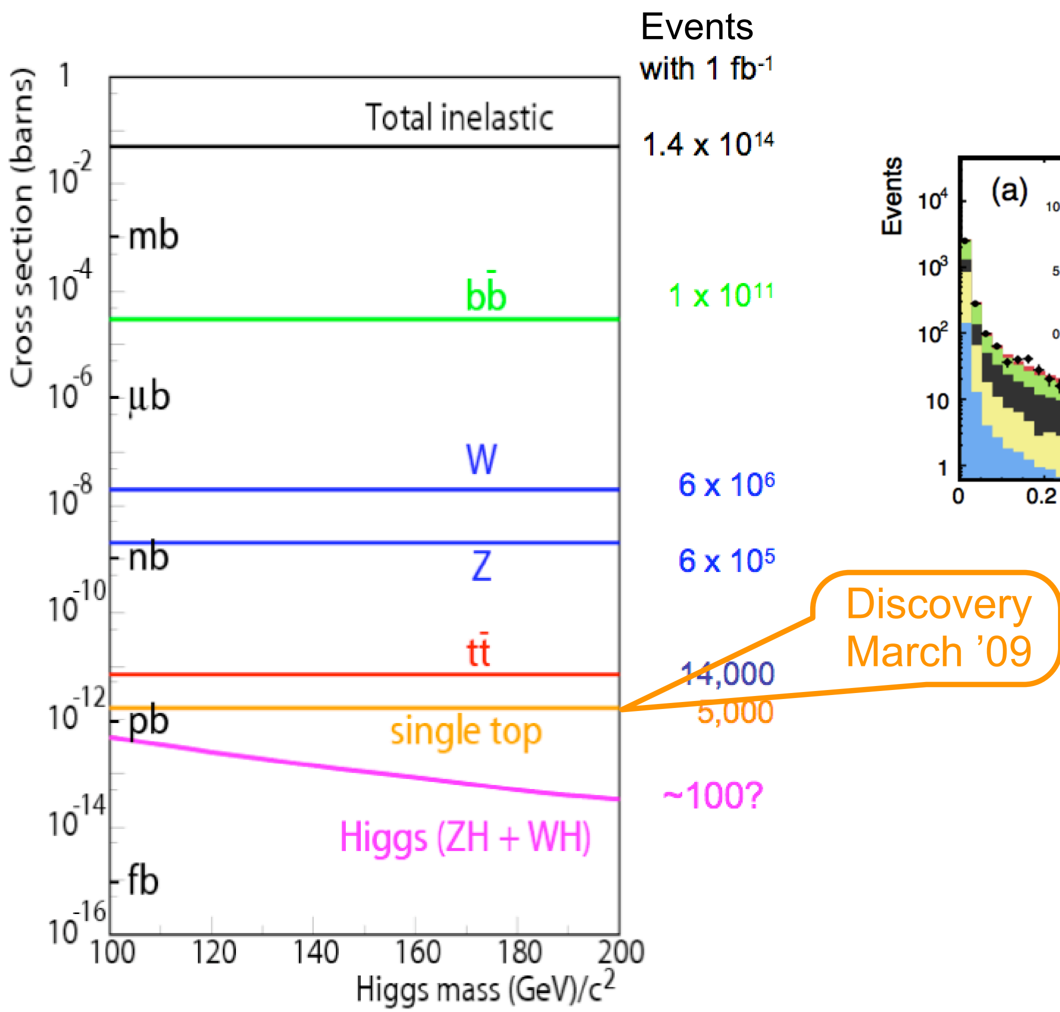

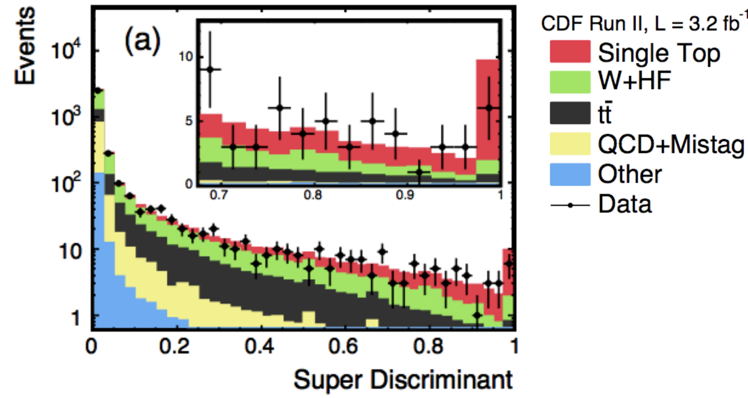

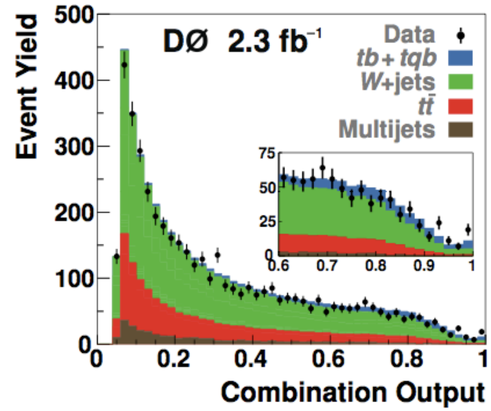

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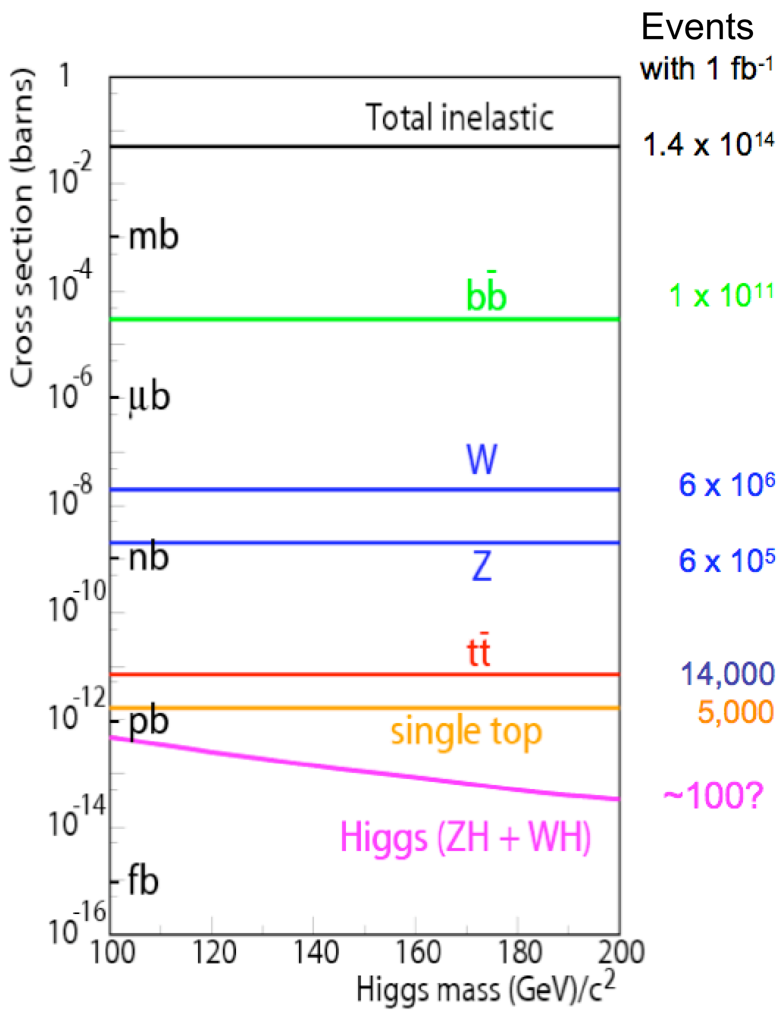

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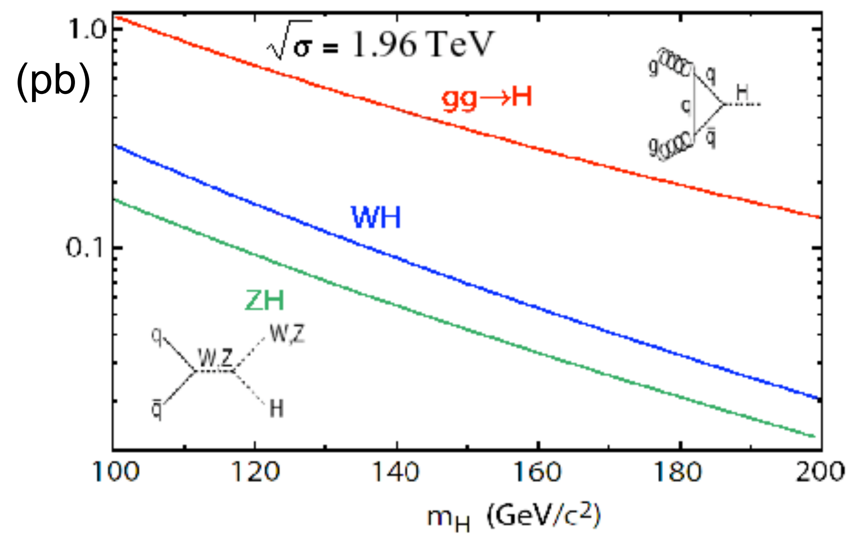
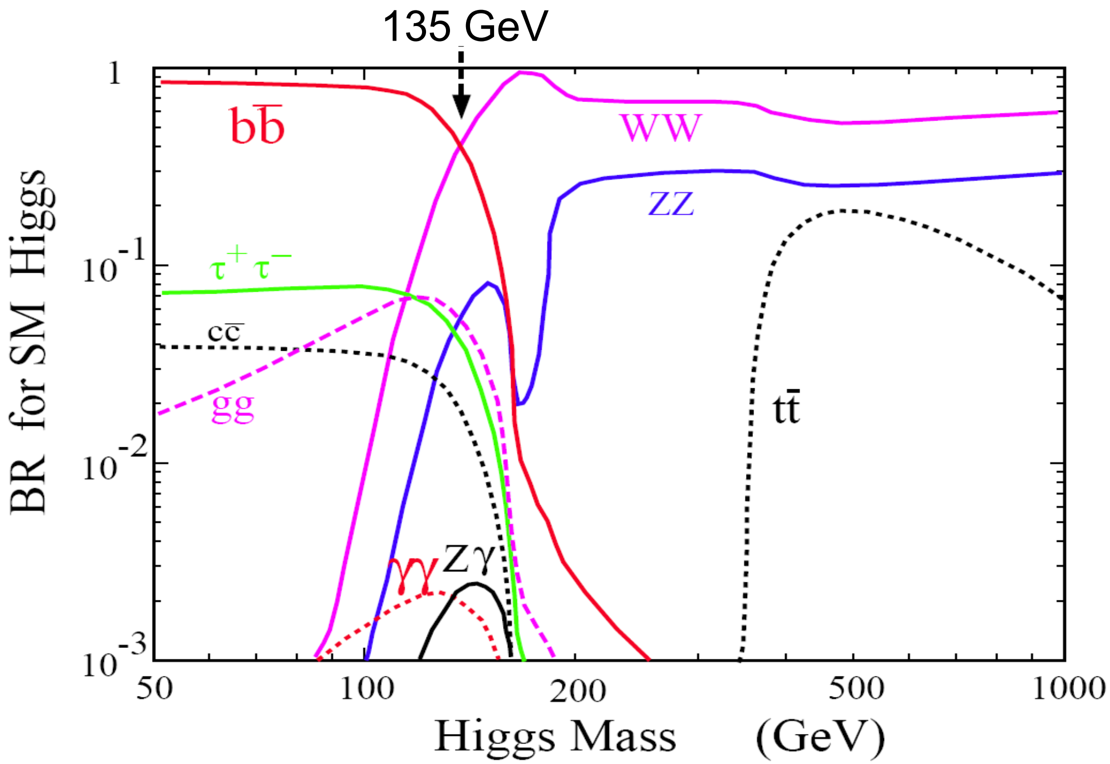


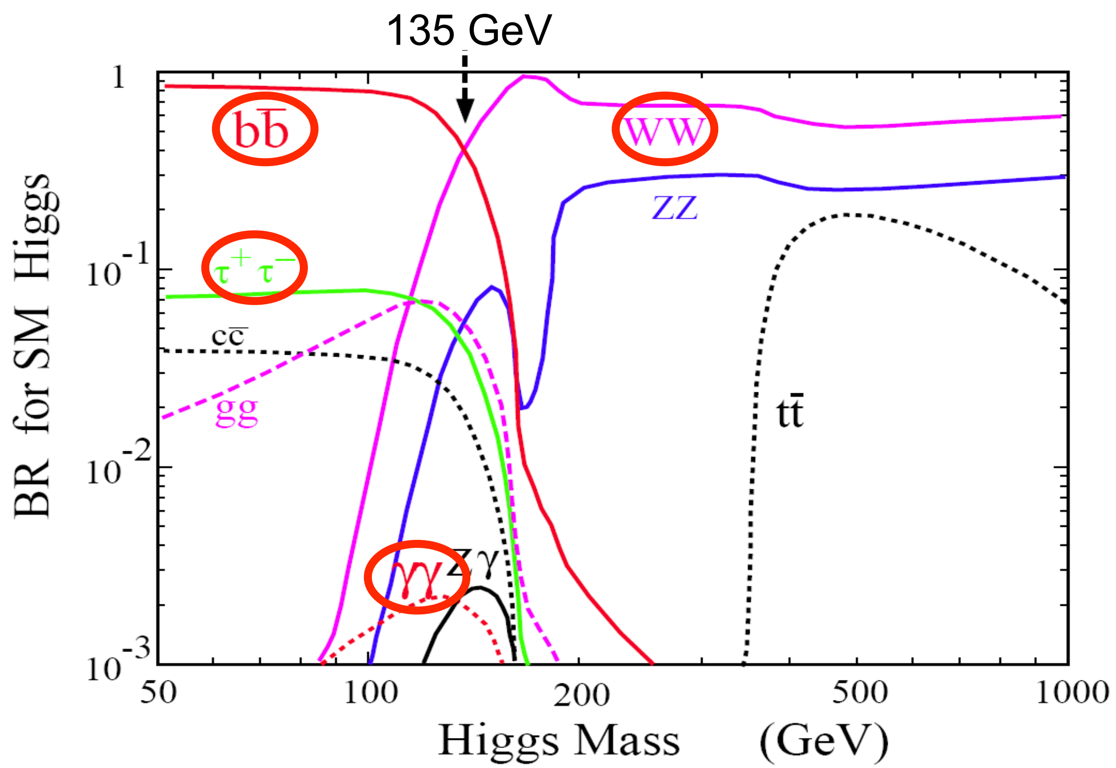
Higgs production cross sections are small: 0.1-1 pb depending on m_H

Dominant production mode is gluon fusion

Higgs decays



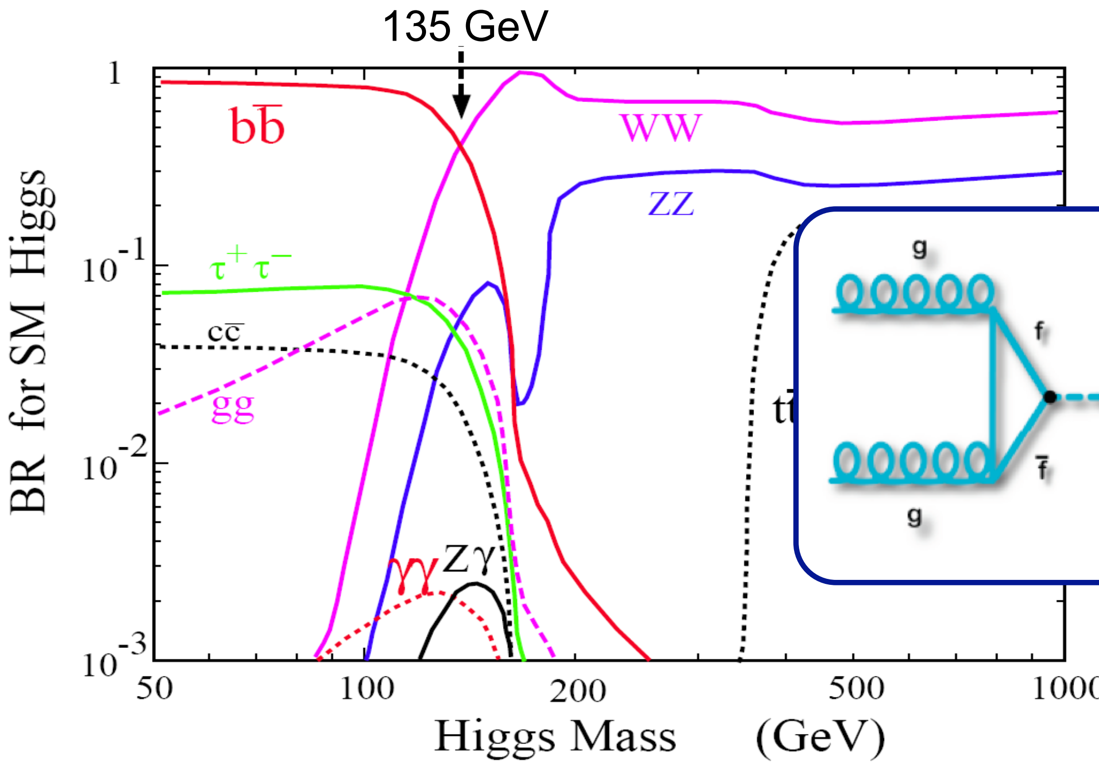
Search strategy at the Tevatron

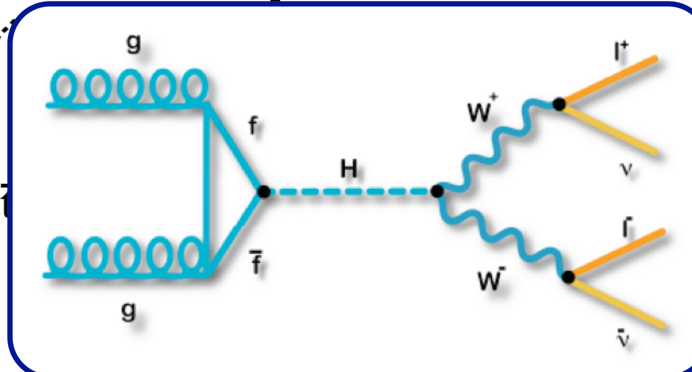


Investigate different production mechanisms and a large number of final states

→ Focus on the main search channels in this talk

Search strategy at the Tevatron





m_H > 135 GeV:

gg→H production with decay to WW

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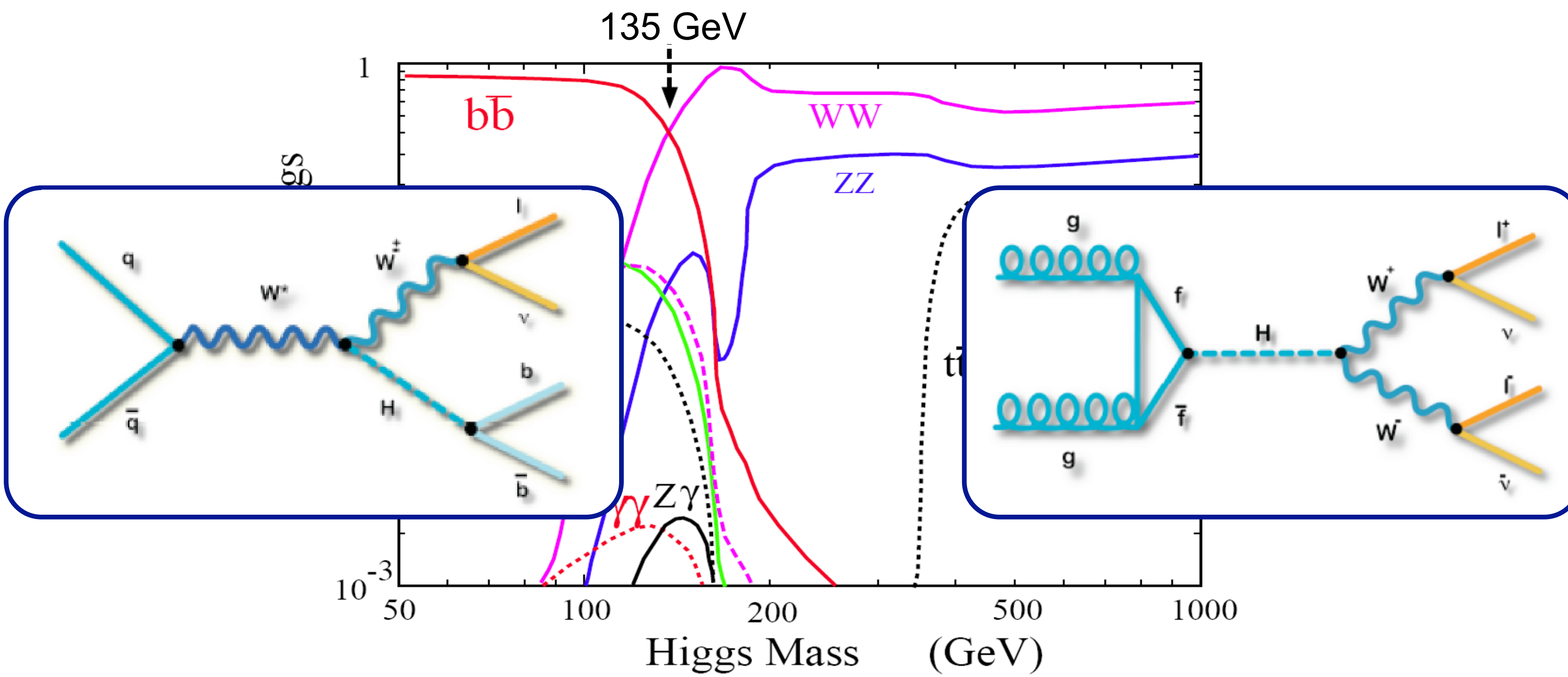


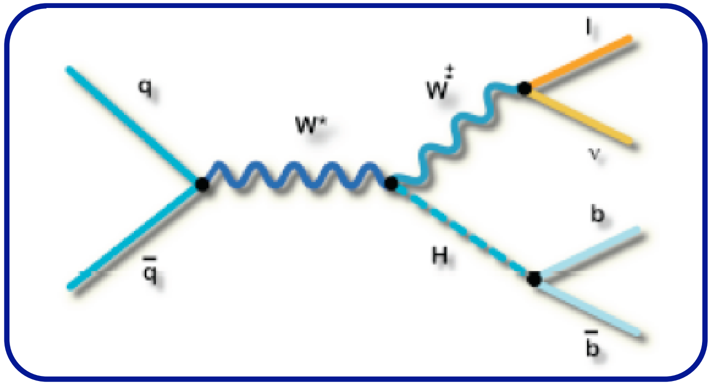
$m_H < 135$ GeV:

Associated production WH and ZH with H→bb decay

$m_H > 135$ GeV:

gg→H production with decay to WW

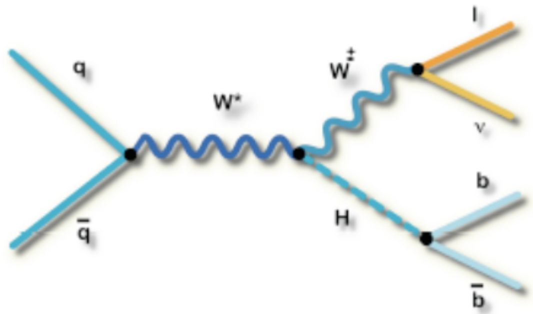
Searches for a low mass Higgs



$m_H < 135$ GeV:

Associated production WH and ZH with H→bb decay

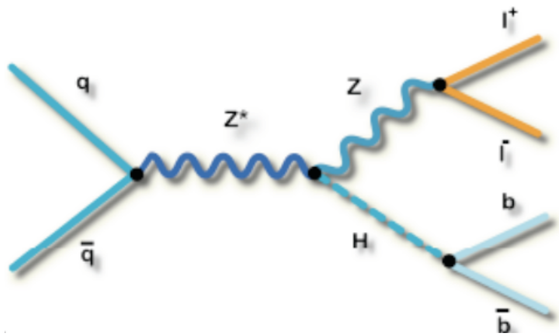
Main low mass search channels



MET+l+bb: $WH \rightarrow l\nu bb$

Largest *VH* production cross section

More backgrounds than $ZH \rightarrow llbb$

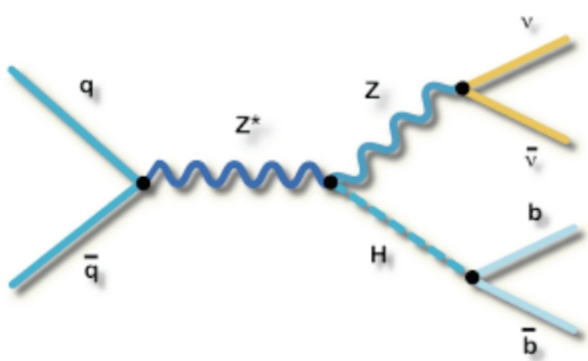


ll+bb: $ZH \rightarrow llbb$

Less backgrounds

Fully constrained

Smallest Higgs signal



MET+bb: $ZH \rightarrow \nu\nu bb$

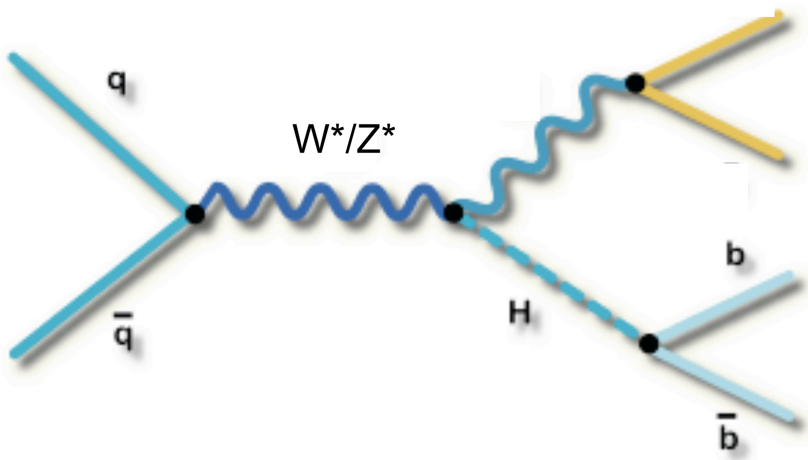
3x more signal than $ZH \rightarrow llbb$

(+$WH \rightarrow l\nu bb$ when lepton missing)

Large backgrounds which are difficult to handle

Signal and backgrounds

Experimental signature:



Missing transverse energy and/or isolated leptons

Two high p_T jets, acoplanar, b-tagged

Main backgrounds:

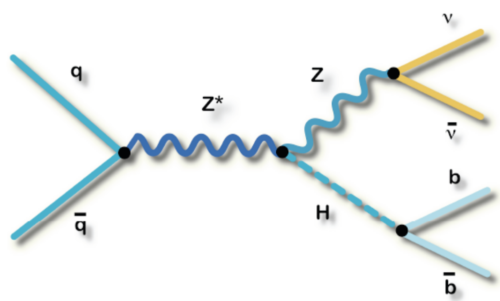
- Physics (from MCs): W/Z+jets, diboson, $t\bar{t}$ and single top
- Instrumental (from Data): Multijet events with mismeasured missing E_T or jets faking leptons

➡ Constrain and test background modelling in sideband regions

Searches for low mass Higgs

A three step approach

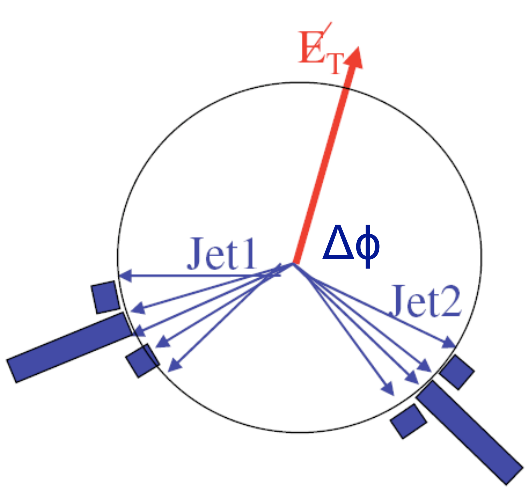
Example: $ZH \rightarrow \nu\nu bb$

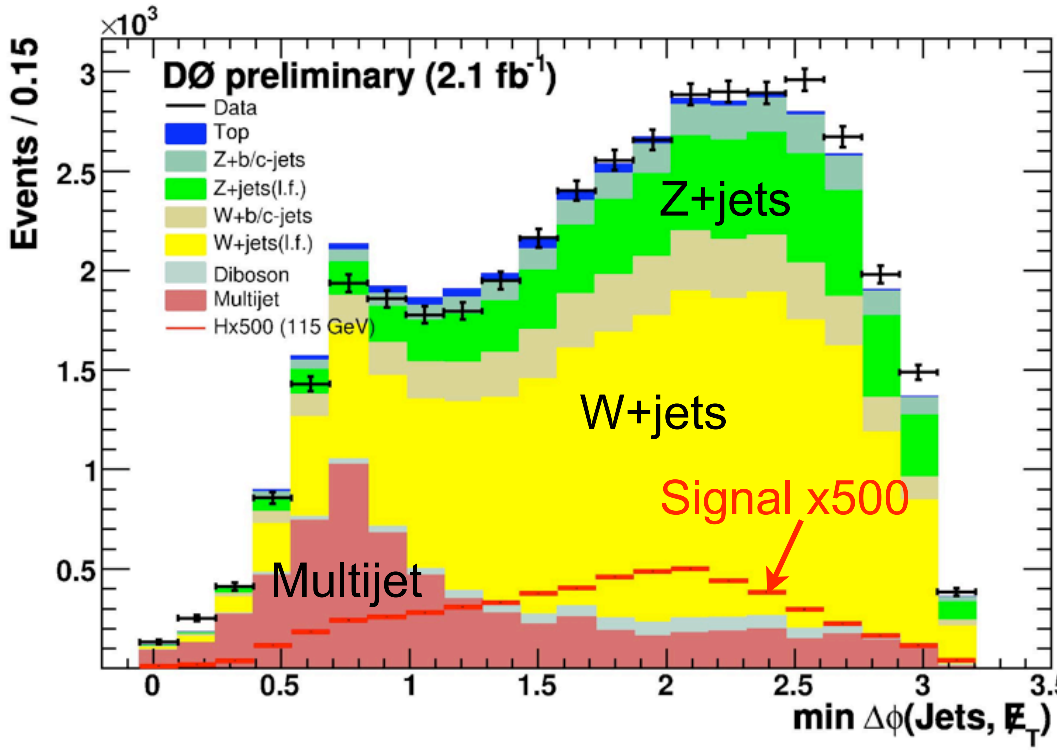


large MET

2 high p_T b-jets

First step: select events consistent with W/Z and 2 jets

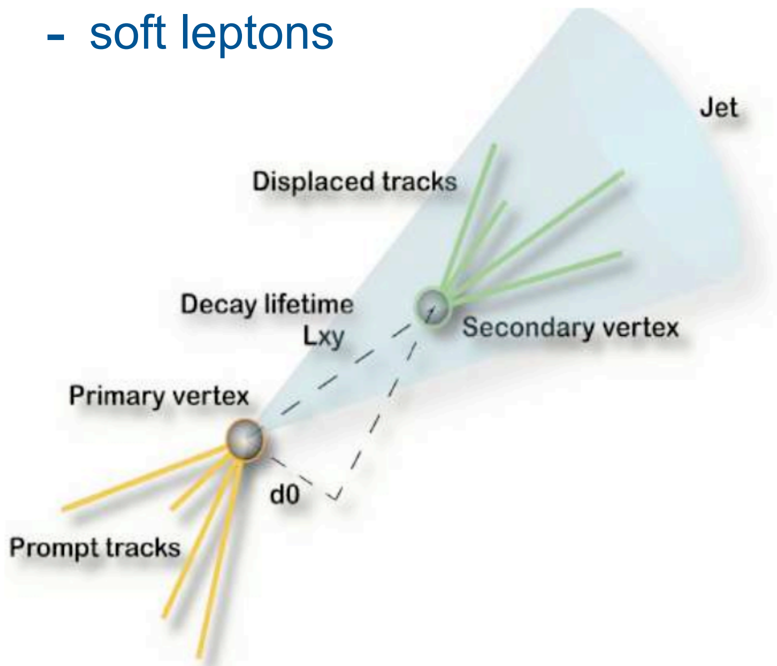


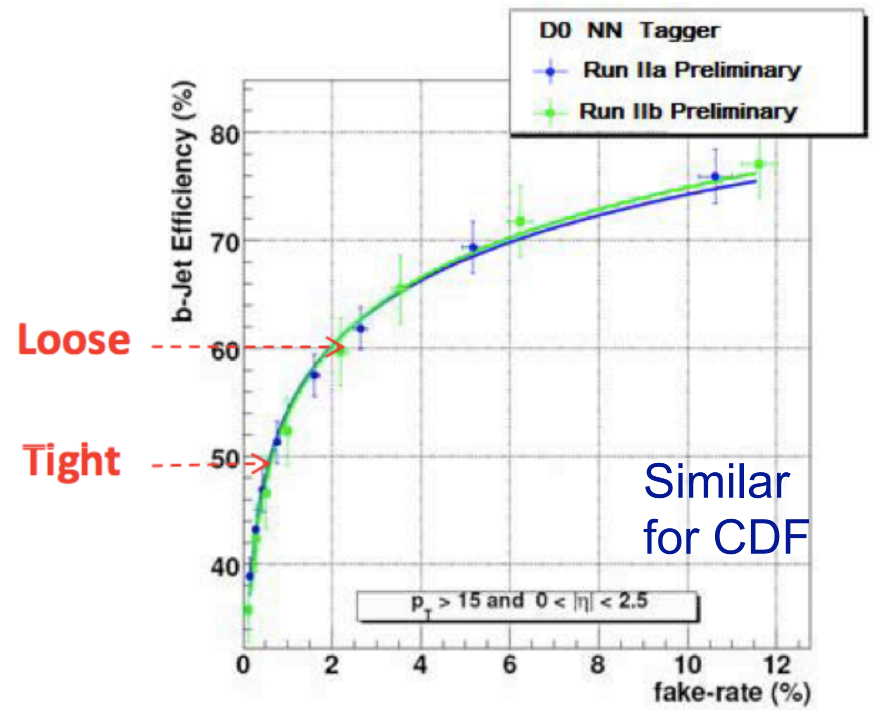


Searches for low mass Higgs

Second step: b-tagging

- Exploit B meson lifetime, mass, fragmentation and decay modes to separate b from light-quark jets
    - secondary vertex
    - tracks impact parameter
    - vertex track multiplicity
    - vertex mass
    - soft leptons





Similar for CDF

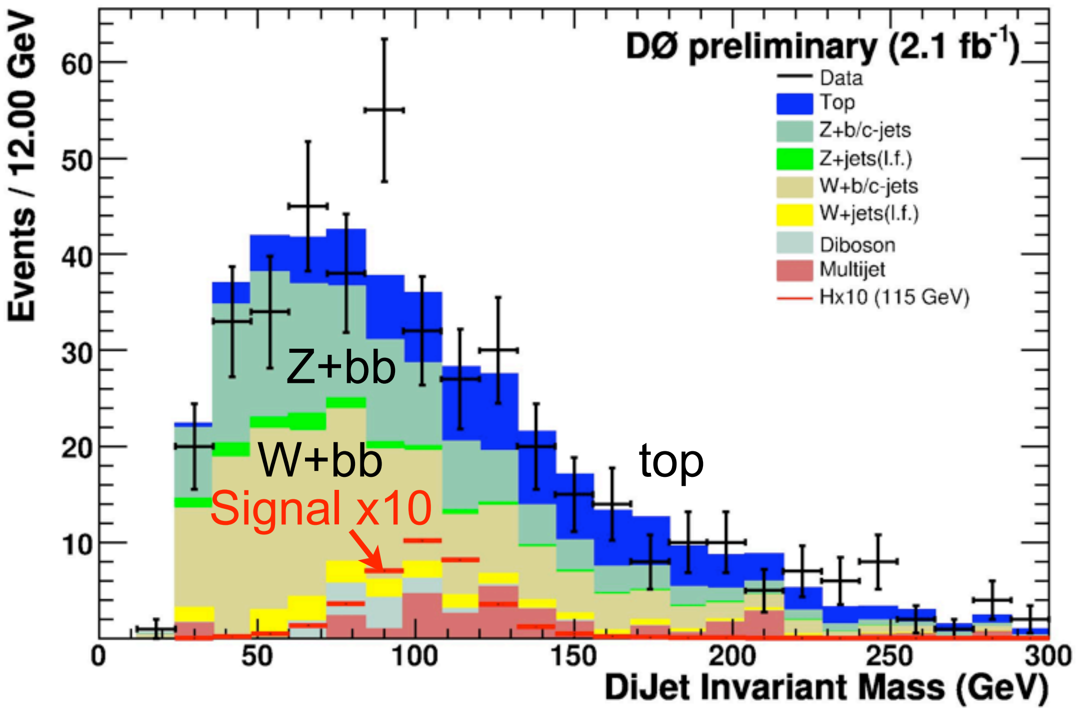
- Use neural networks for optimal combination of tagging information

Searches for low mass Higgs

After b-tagging

Backgrounds dominated by: W/Z+bb and top

Most discriminating quantity: dijet invariant mass



Searches for low mass Higgs

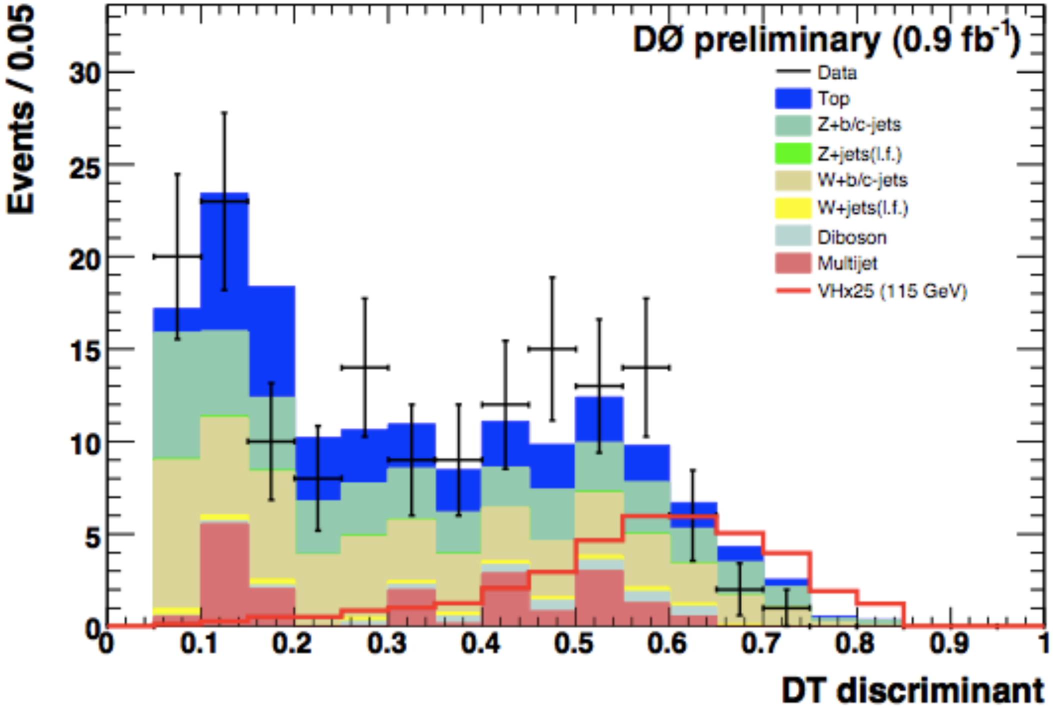
Third step: Optimise separation power with multivariate discrimination

Most common techniques:

Neural Network, Decision Tree and Matrix Element

- Exploit information from several final state variables and correlations among them

Decision Tree discriminant

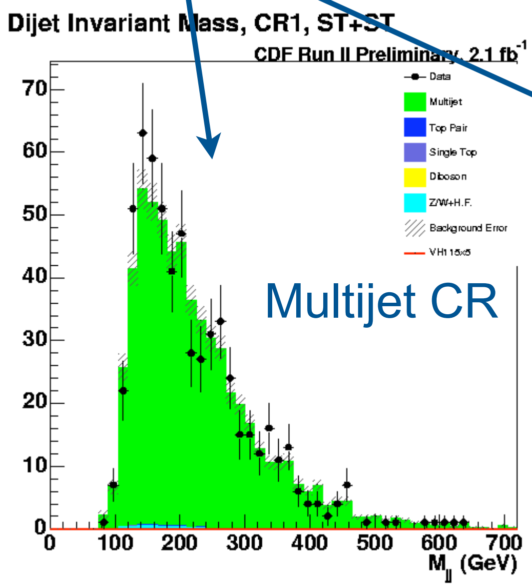


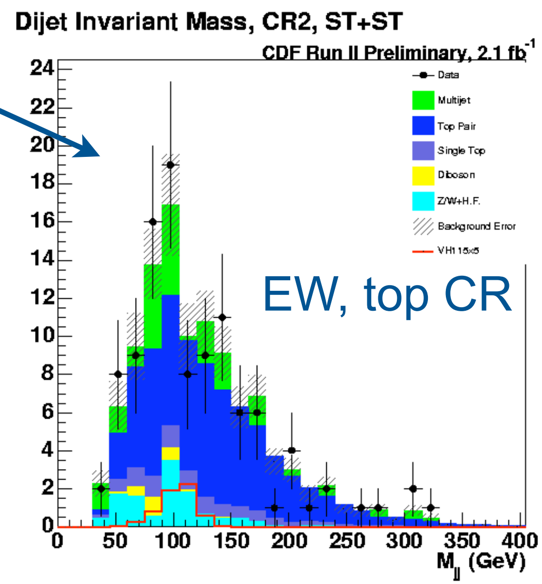
Control regions

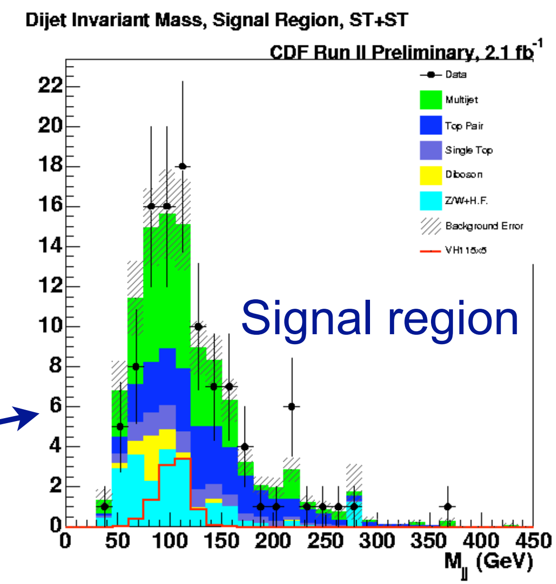
Understand modelling of main backgrounds in control regions:

Example: $ZH \rightarrow \nu\nu bb$

- Multijet enhanced: MET aligned with jets
- EW, top enhanced: require isolated lepton







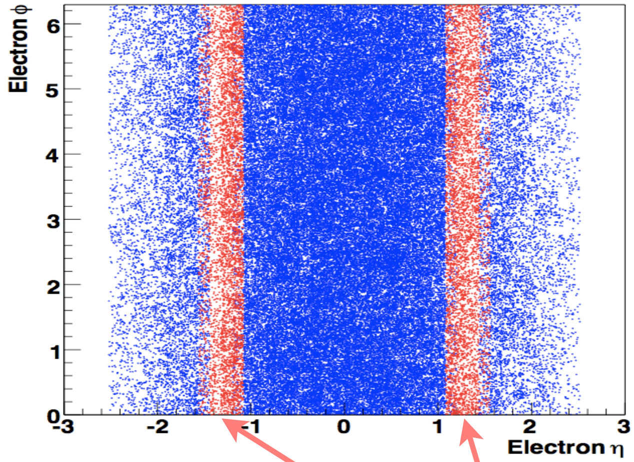
Once control regions well understood,
"open the box" perform search in signal region

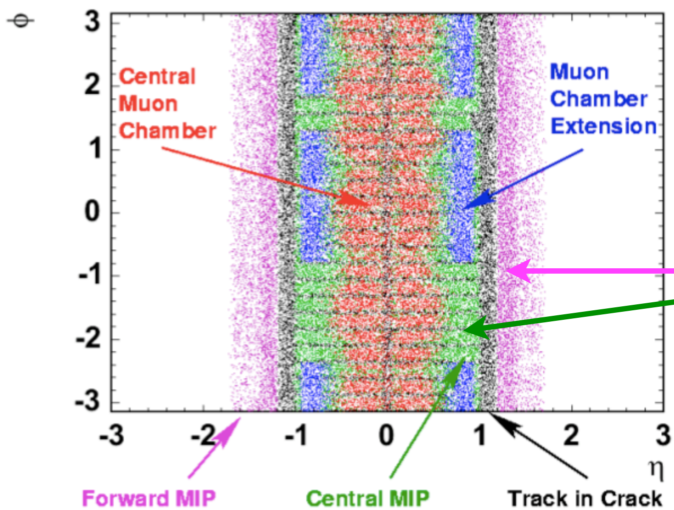
Signal acceptance

Increase signal acceptance with looser lepton identification criteria

Example: $ZH \rightarrow llbb$

- Selection of lepton pairs consistent with Z mass gives handle against backgrounds





Lepton+track selection

DØ: electrons in inter-cryostat region

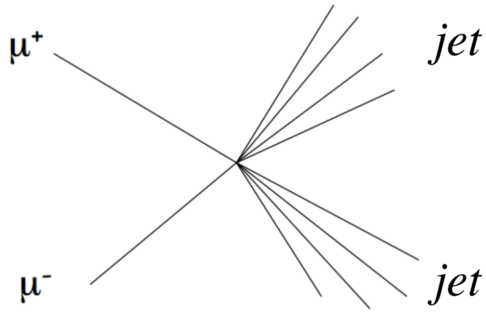
CDF: MIP's without hit in muon chambers

Up to 15-30% increase in signal yields

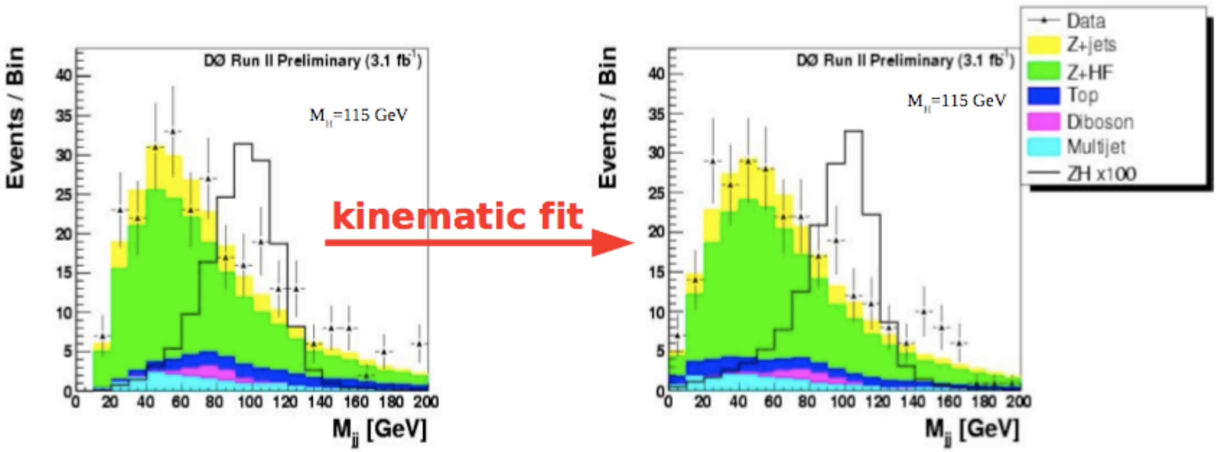
Dijet mass resolution (I)

Example: $ZH \rightarrow llbb$ fully reconstructed, no intrinsic missing E_T

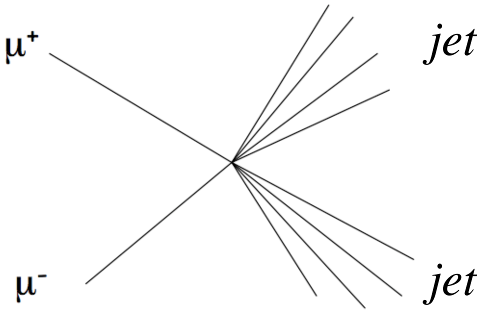
➡ use constraints to improve di-jet mass resolution



Gives up to ~10% improvement in the limits



Dijet mass resolution (II)



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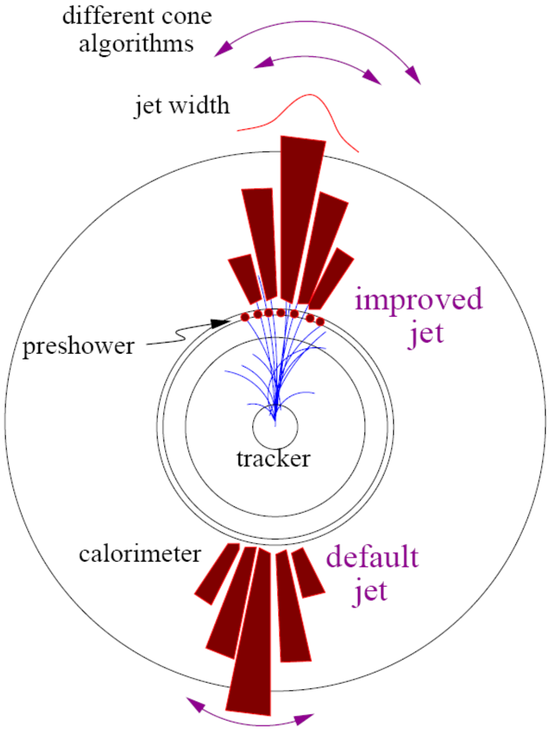


Example: $ZH \rightarrow \nu\nu bb$ (CDF)

Improve dijet mass resolution with information from the tracker

Up to ~10% improvement in the limits

Lot of efforts ongoing to achieve further mass resolution improvements

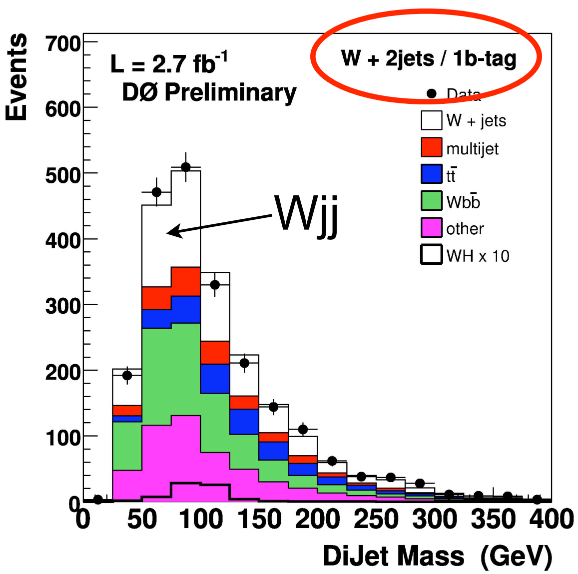
Maximise benefit from S/B variations

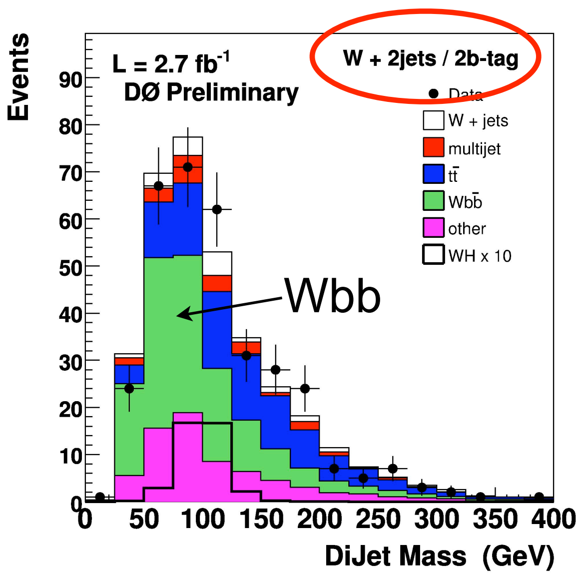
Split data into several sub-samples with different S/B to increase sensitivity

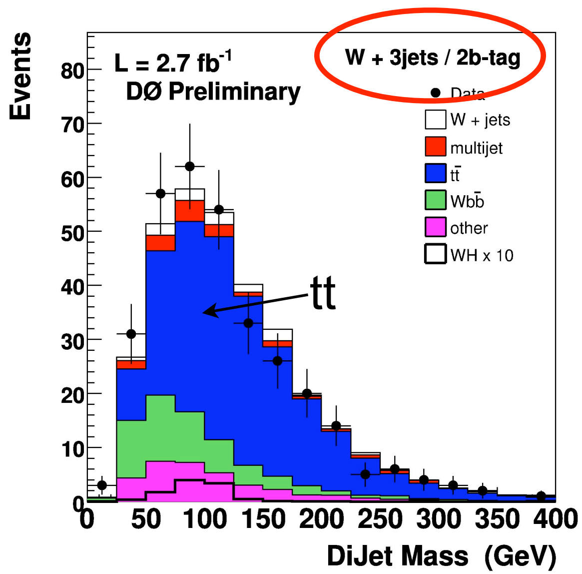
- Tight/loose lepton definitions
- Number of jets
- Number of tagged jets
- b-tagging operating point

➡ Different sample compositions increase multivariate discrimination

Example: $WH \rightarrow l\nu bb$







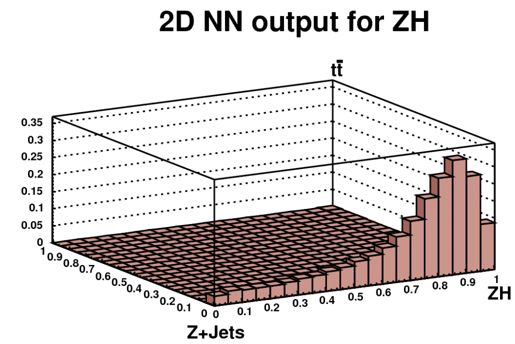
Multivariate techniques

Final discrimination with multivariate techniques

- Boosted decision trees
- Neural Networks
- Matrix Element Likelihood

➡ Combination of several methods for further sensitivity increase

Example: $ZH \to llbb$



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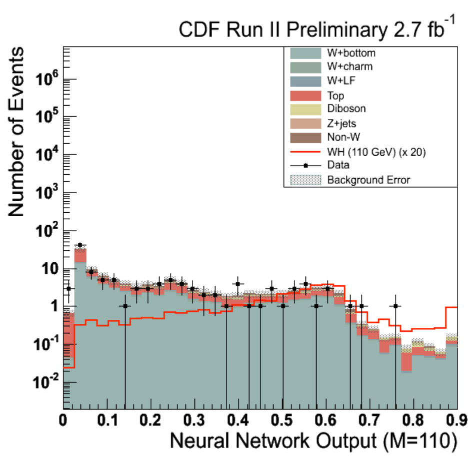
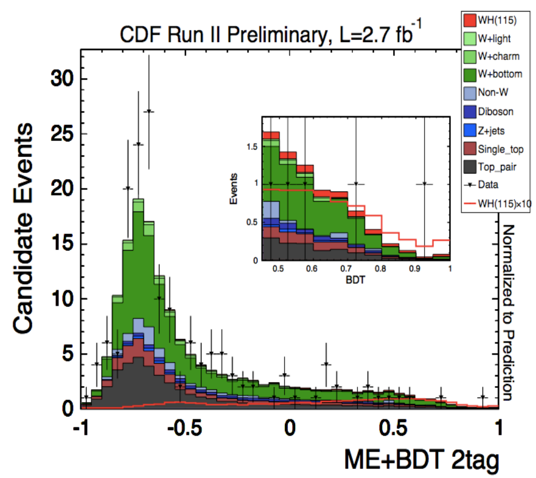
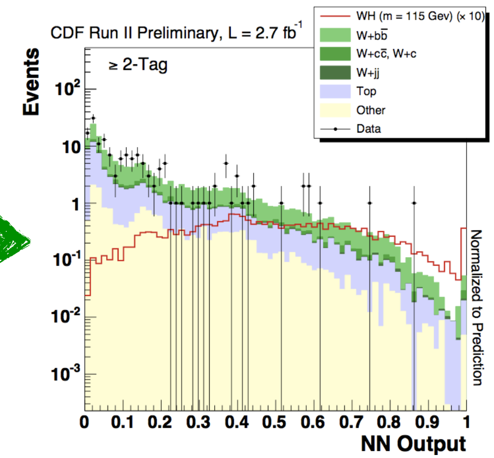






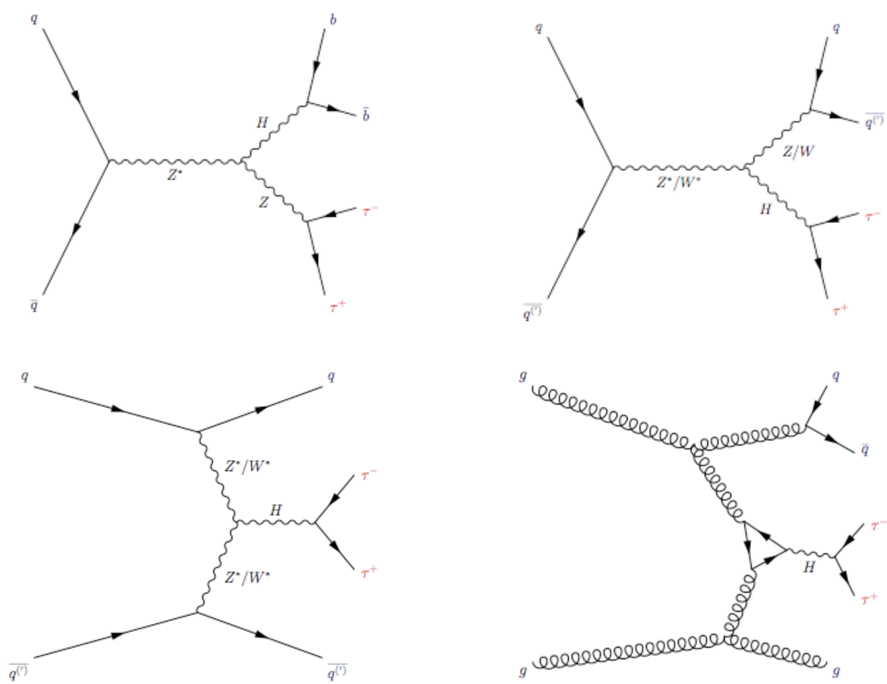
Typical sensitivity gain compared to single variable is 15-20%
Additional sensitivity gains from smart combinations typically 5-10%

Final states with taus

Increase overall sensitivity with additional channels

$H \rightarrow \tau\tau$: second largest BR in low mass region

Example: $\tau\tau jj$ final state. Sensitive to ZH ($Z \rightarrow \tau\tau$, $H \rightarrow bb$), VH ($V \rightarrow jj$, $H \rightarrow \tau\tau$) and vector boson/gluon fusion with $H \rightarrow \tau\tau$



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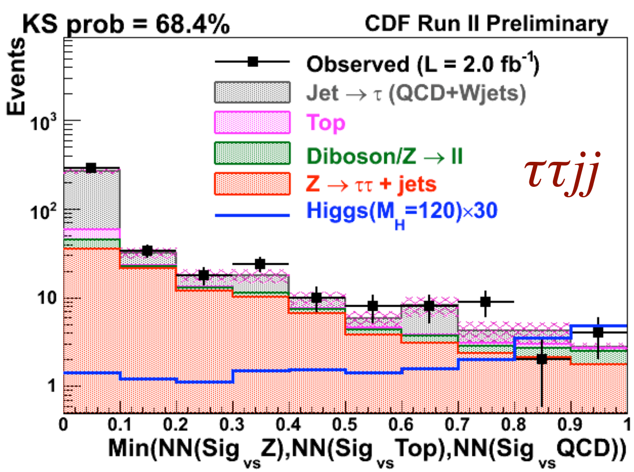
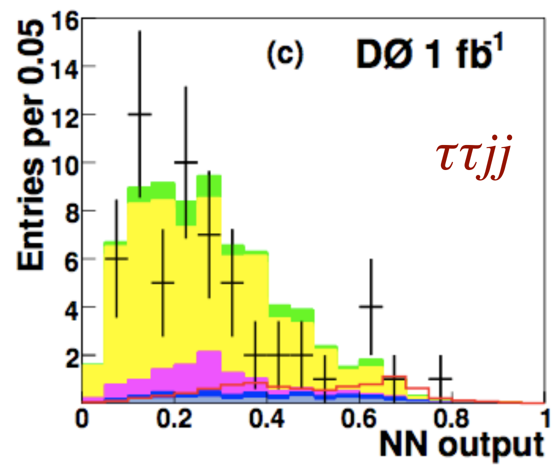
Combination of several NNs trained for different backgrounds and signals





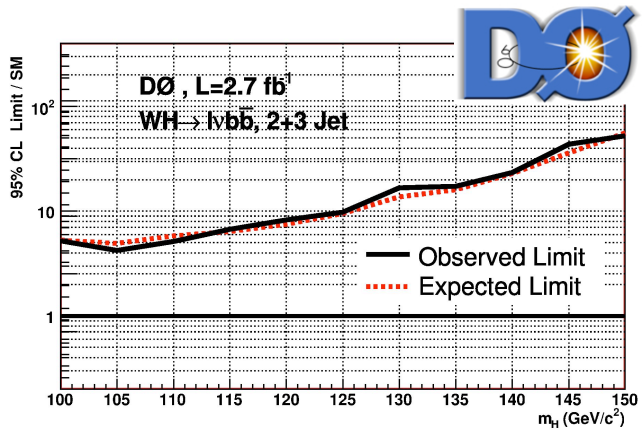
5-10% additional sensitivity from tau final states

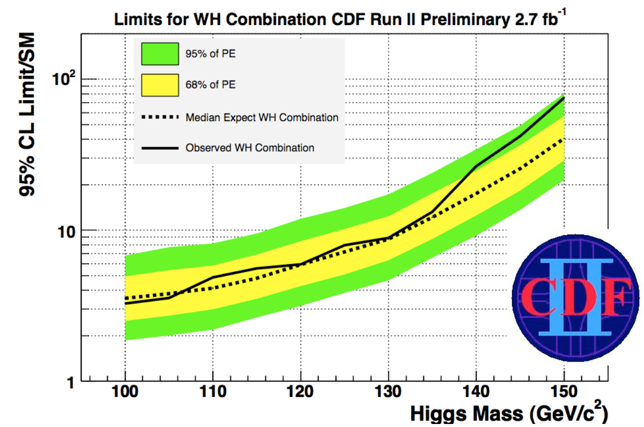
Individual low mass results

Limits on individual channels a factor of 5-10 away from SM cross section at m_H=115 GeV

- Combination of all contributing channels crucial

Single channel limit example:
$WH \rightarrow l\nu bb$



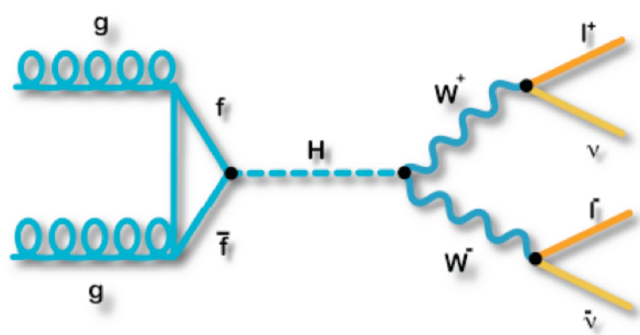


Main systematic uncertainties for low mass channels:

- Signal (total 15%): cross section, b-tagging, ID efficiencies
- Background (total 25-30%): normalisation of W/Z+jets heavy flavour samples, modelling of multijet and W/Z+jets background, b-tagging

At high discriminant values S/B typically 1/10 - 1/20 for the most sensitive low mass channels

Searches for a high mass Higgs



m_H > 135 GeV:

gg→H production with decay to WW

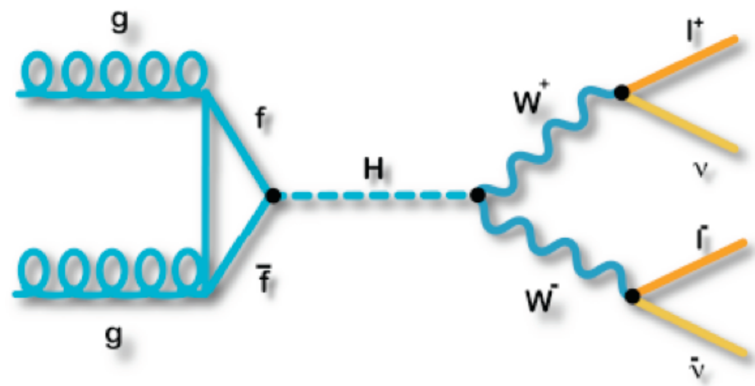
$H+X \rightarrow l^+l^-$ + missing E_T

Dominant decay for m_H>135 GeV: $H \rightarrow W^*W$

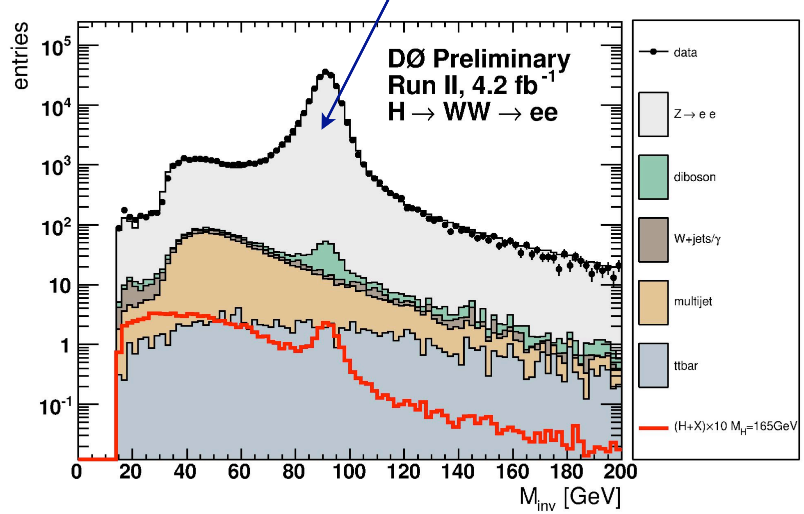
Clean environment can take advantage of $gg \rightarrow H$ production

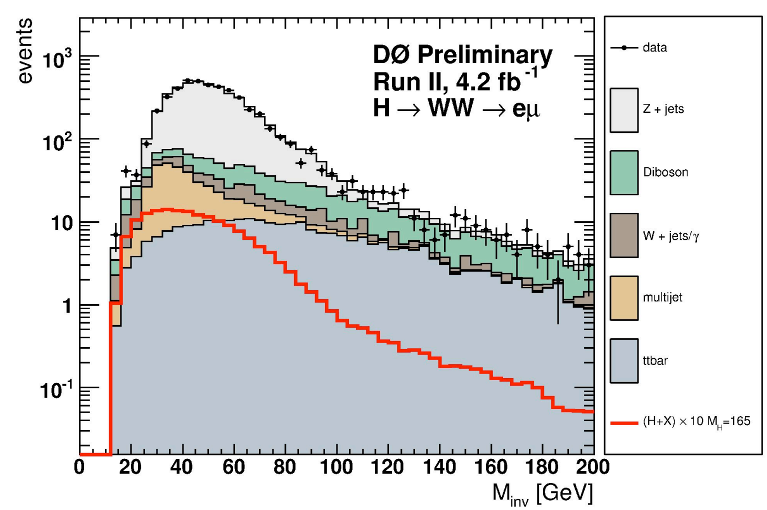
Signal contribution also from $W/Z+H$, qqH production

➡ Consider all sources of opposite sign di-lepton + missing E_T



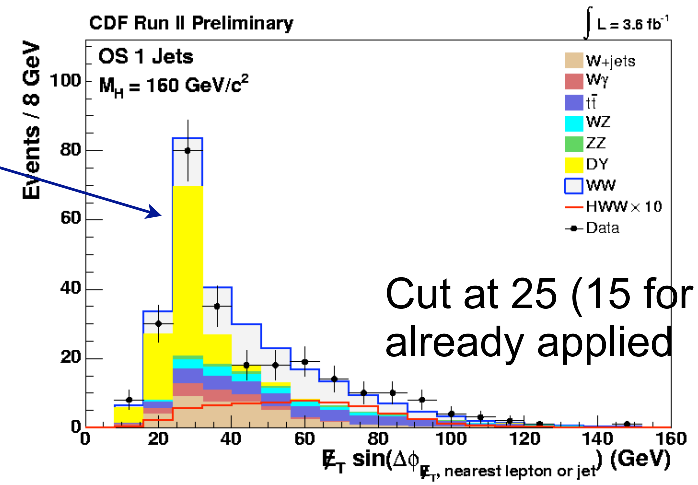
Backgrounds: Drell-Yan production, diboson, tt, W+jets/γ , multijet



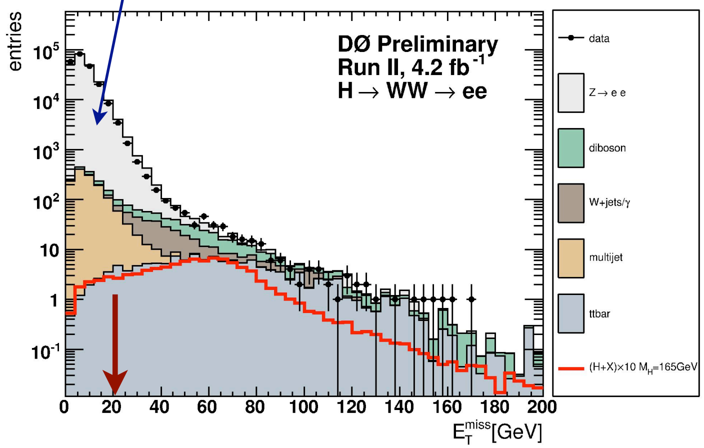


$H+X \rightarrow l^+l^-$ + missing E_T

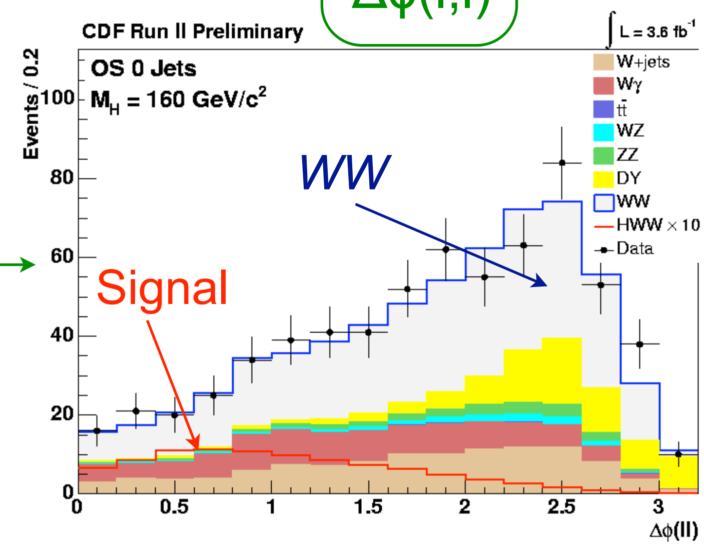
Dominant background of Drell-Yan production reduced with cuts on missing E_T and its significance



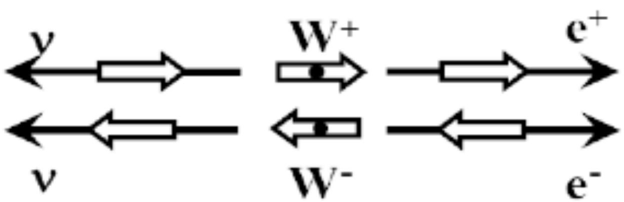
Cut at 25 (15 for eμ) already applied



$\Delta\phi(l,l)$



Spin correlation gives main discrimination against irreducible background from non-resonant SM *W* pair production

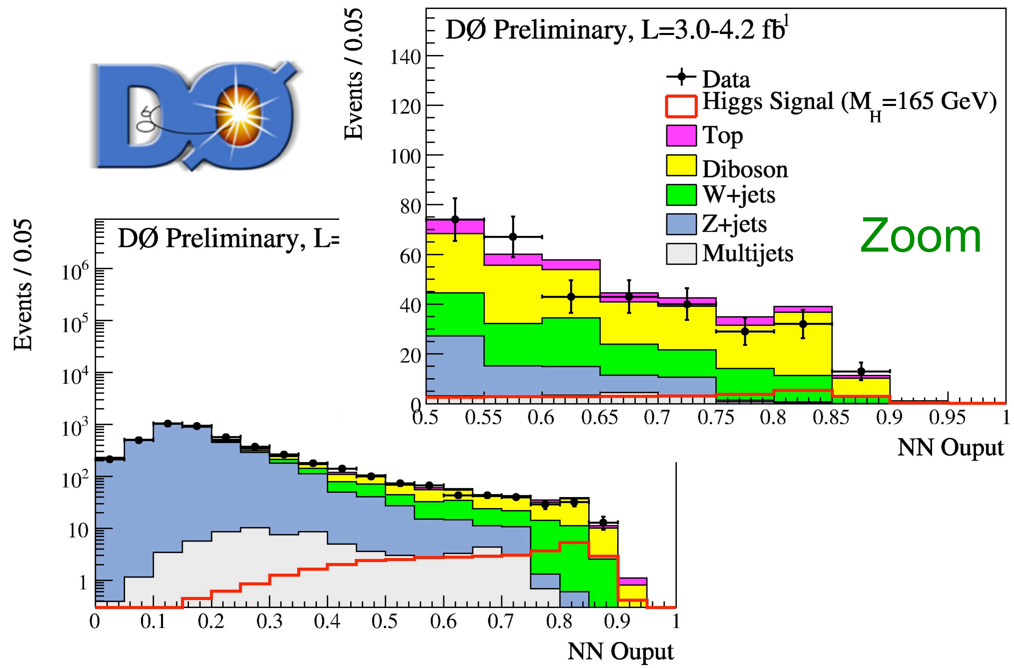


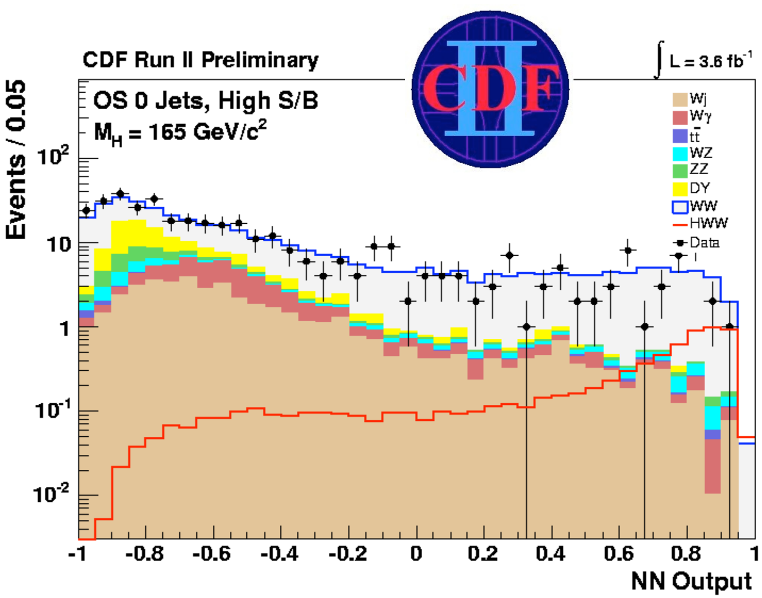
$H+X \rightarrow l^+l^-$ + missing E_T

To increase sensitivity:

DØ: Split the samples according to lepton flavour and combine result

Neural Network with 11 kinematic and topological input variables



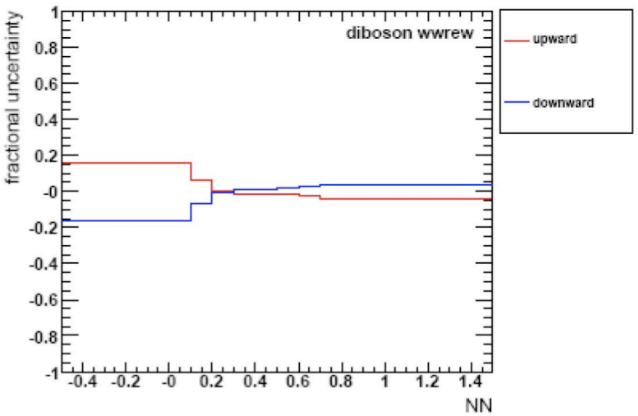


CDF: Split samples into jet multiplicity and lepton ID criteria: different signal and background composition

Veto events with tight b-tagged jet

Neural Network with additional ME input for the 0-jet NN

Systematic uncertainties



Change of NN when p_T(WW) changes

Main systematic uncertainties:

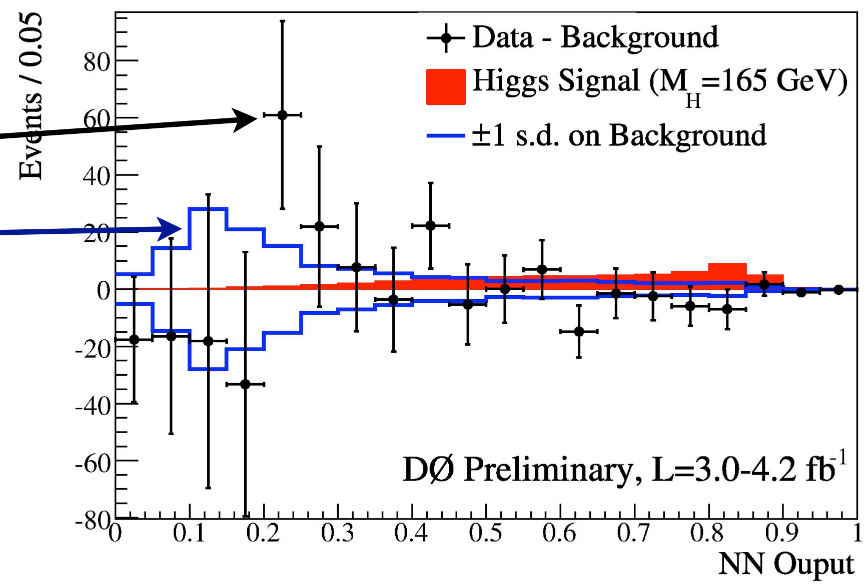
- Signal (total 10%): cross section, lepton ID/ trigger
- Background (total 13%): cross sections, jet→lepton fake rate, jet ID/resolution/calibration

Systematic uncertainties change rate and shape of the signal and background predictions

SM signal expectation and data after background subtraction

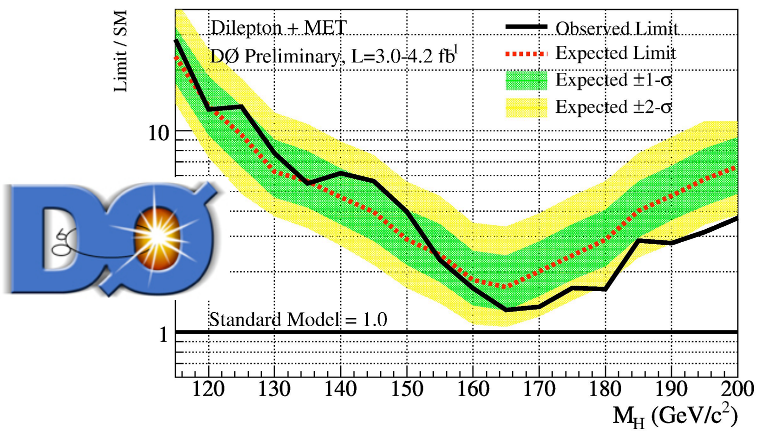
Constrained total systematic uncertainty

Expected 165 GeV SM Higgs signal would be visible over background uncertainty

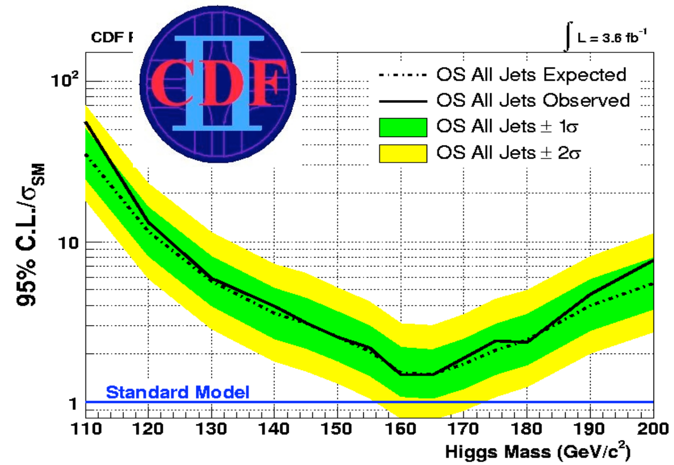


$H+X \rightarrow l^+l^-$ + missing E_T

Exclusion limits per experiment:



mH=165 GeV
Exp(Obs): 1.7(1.3) x σ_{SM}



mH=165 GeV
Exp(Obs): 1.4(1.5) x σ_{SM}

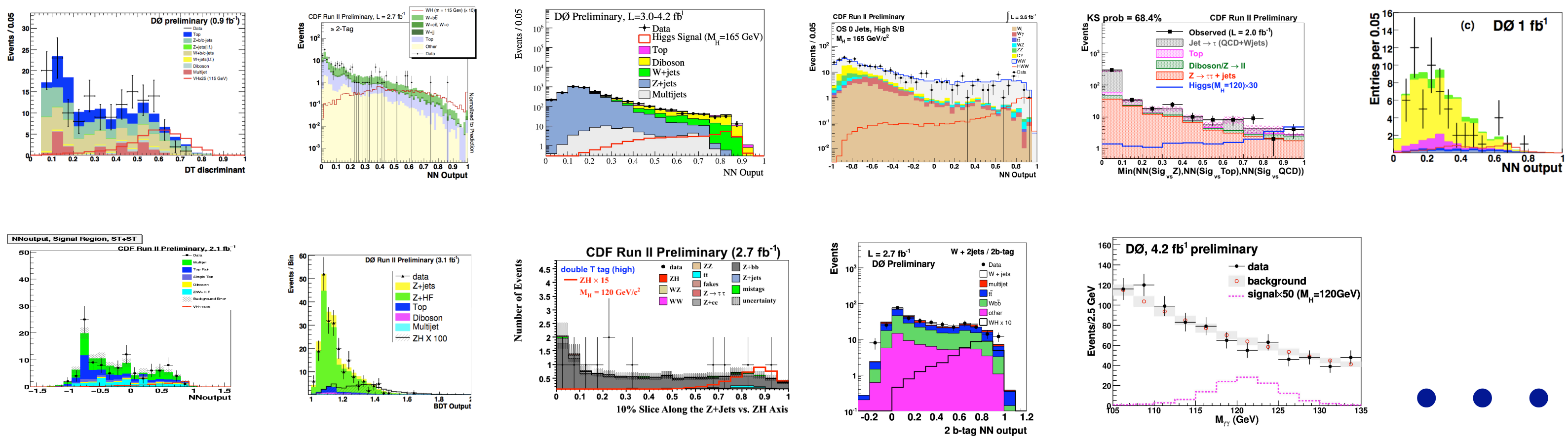
At high Neural Network values S/B at the order of 1

With additional luminosity and improvements (e.g. additional channels) expect single experiment exclusion around m_H = 165 GeV in the near future

Limit setting

Full combination of all channels from CDF and DØ for best sensitivity

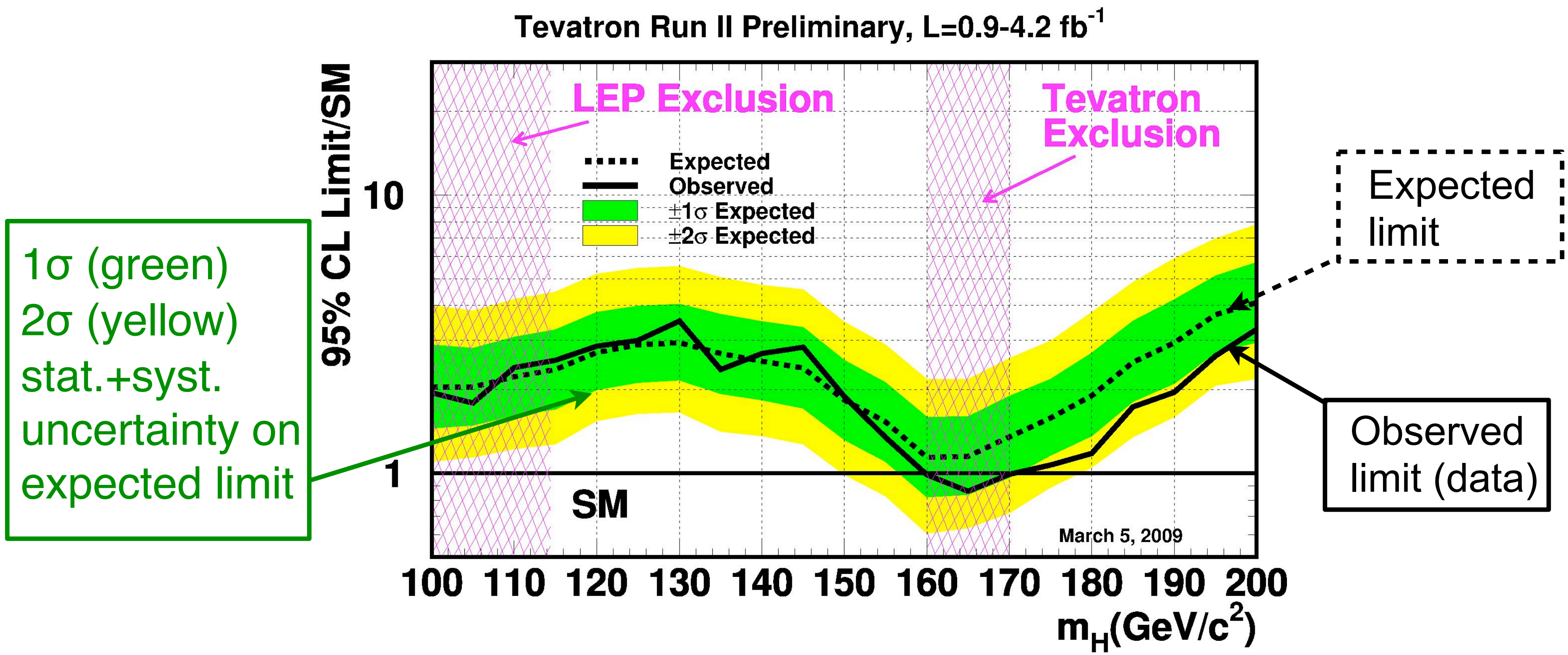
- Combining more than 30 different channels per experiment



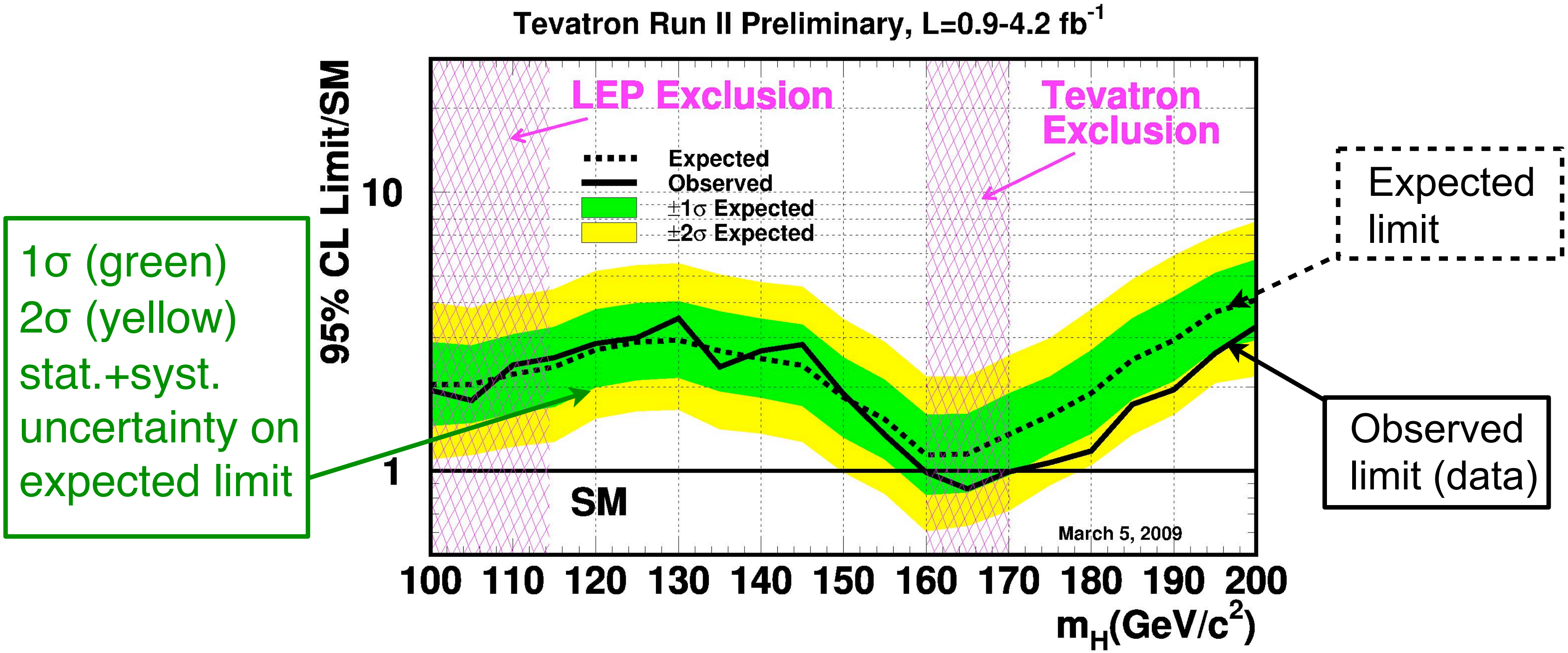
More than 50 different sources of systematic uncertainties are considered, and constrained in sidebands

Use different techniques to cross check calculations (Bayesian, modified frequentist) → Results agree within 5%

Combined Tevatron limits



Combined Tevatron limits



The Tevatron experiments reached sensitivity to the SM Higgs boson around the mass region of 160−170 GeV. First direct exclusion since LEP!

At m_H=115 GeV Exp(Obs): 2.4(2.5) x σ_{SM}

Effective luminosity for current analyses in CDF+DØ combination at the low mass region: 2.55 fb^{-1}

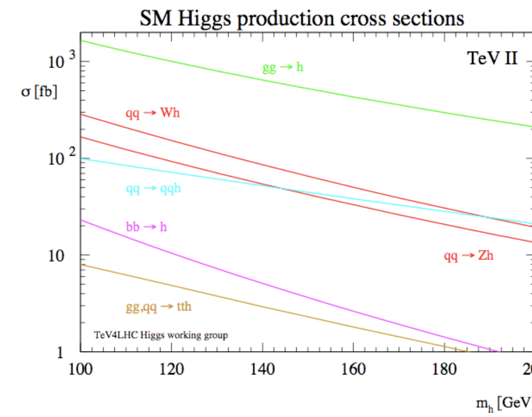
SUSY Higgs sector

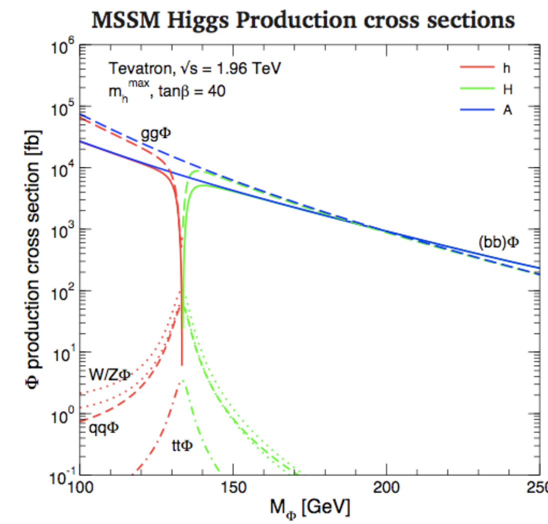
2 Higgs doublets and 5 physical Higgs bosons
- 3 Neutral (A,H,h)→ϕ and two charged $H^{\pm}$

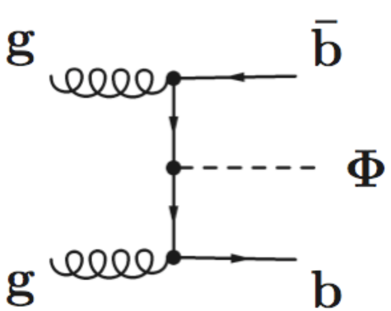
Coupling of neutral Higgs to *b*-quarks enhanced by tan*β*
- Large cross-sections for Higgs production at high tan*β*

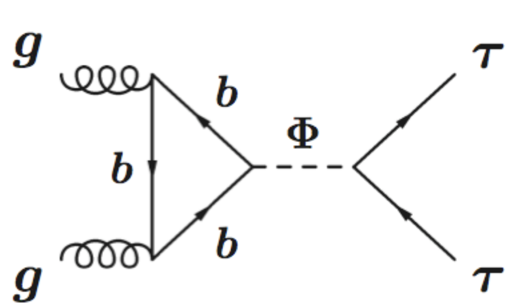
Neutral MSSM Higgs decay:
- *bb* ~ 90% (Large backgrounds)
- *ττ* ~ 10% (More distinct signature)

Main search channels at the Tevatron:
- Associated production with *b(b)* with ϕ → *bb*,*ττ*
- Enhanced gluon fusion cross section: $gg \rightarrow \phi \rightarrow \tau\tau$









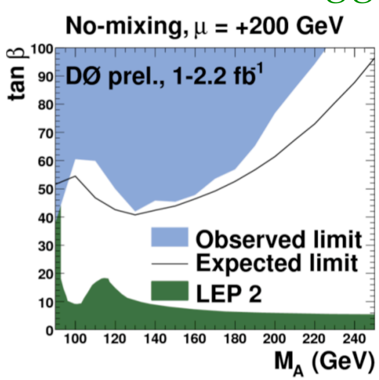
SUSY Higgs searches

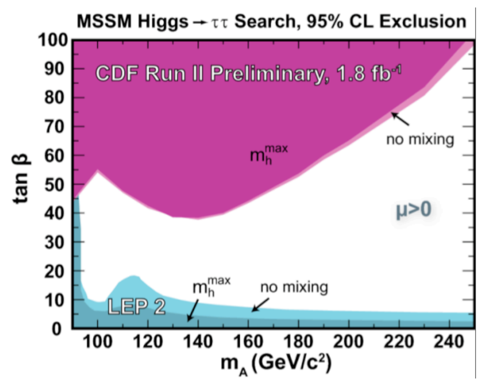
Visible mass or dijet invariant mass most discriminating quantity

Interpretation within MSSM: limits on tanβ as a function of m_A

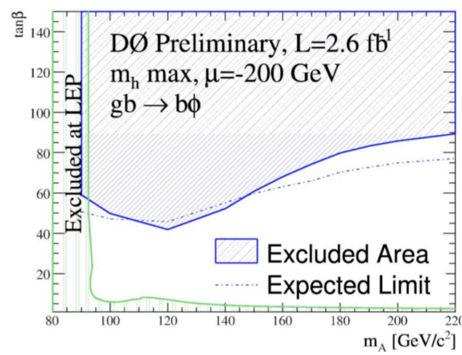
- In the region 90 < m_A < 200 GeV, tanβ values down to 40 are excluded for the no-mixing and the m_h^{max} benchmark scenarios

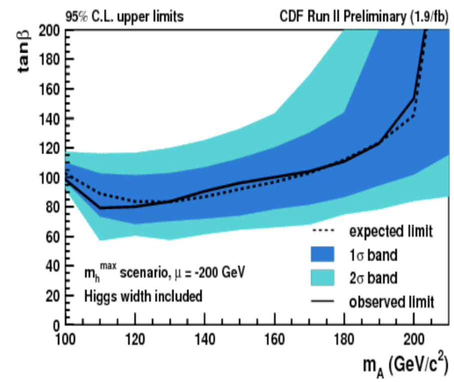
$gg \rightarrow \phi \rightarrow \tau\tau$



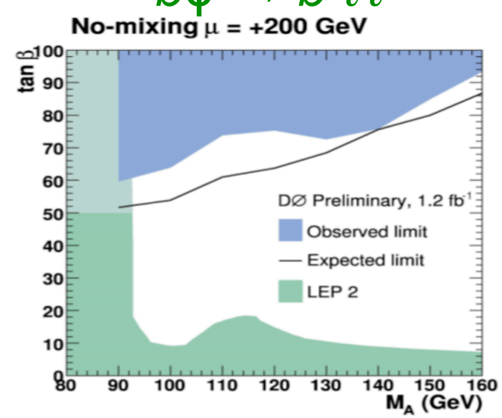


$b\phi \rightarrow b\phi \rightarrow bbb$





$b\phi \rightarrow b\,\tau\tau$



Tevatron MSSM combination underway

Expect to reach sensitivity to tanβ ≈ 20 with full RunII dataset

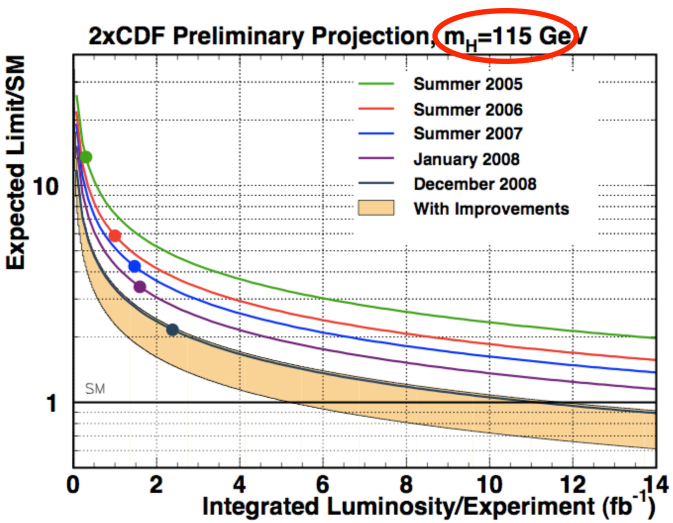
+ Many other BSM searches not presented here…

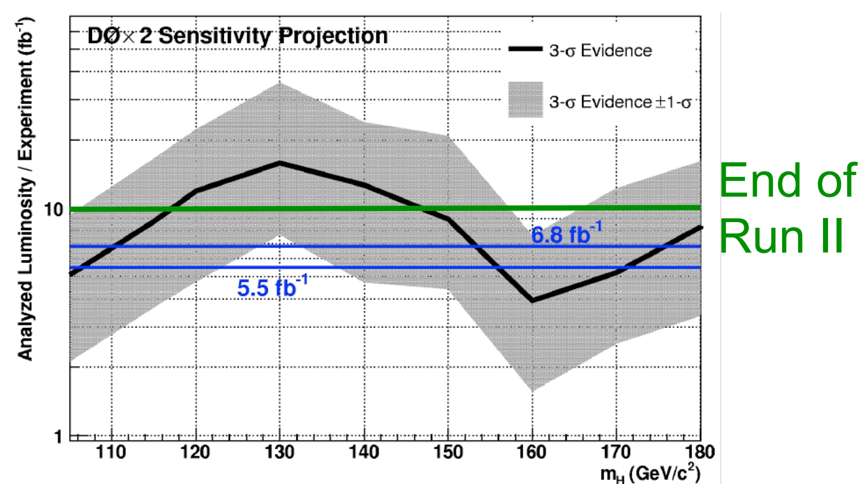
Conclusions

The Tevatron experiments have achieved sensitivity to the SM Higgs boson production cross section

- Started to exclude the Higgs at LHC's most sensitive mass region (~160 GeV), reach of sensitivity will be expanded greatly
- Higgs mass range below ~130 GeV difficult also for the LHC experiments and the decay to *bb* will provide complementary information to LHC results

With additional improvements and luminosity will be sensitive for the Higgs over the entire mass range preferred by EW fits

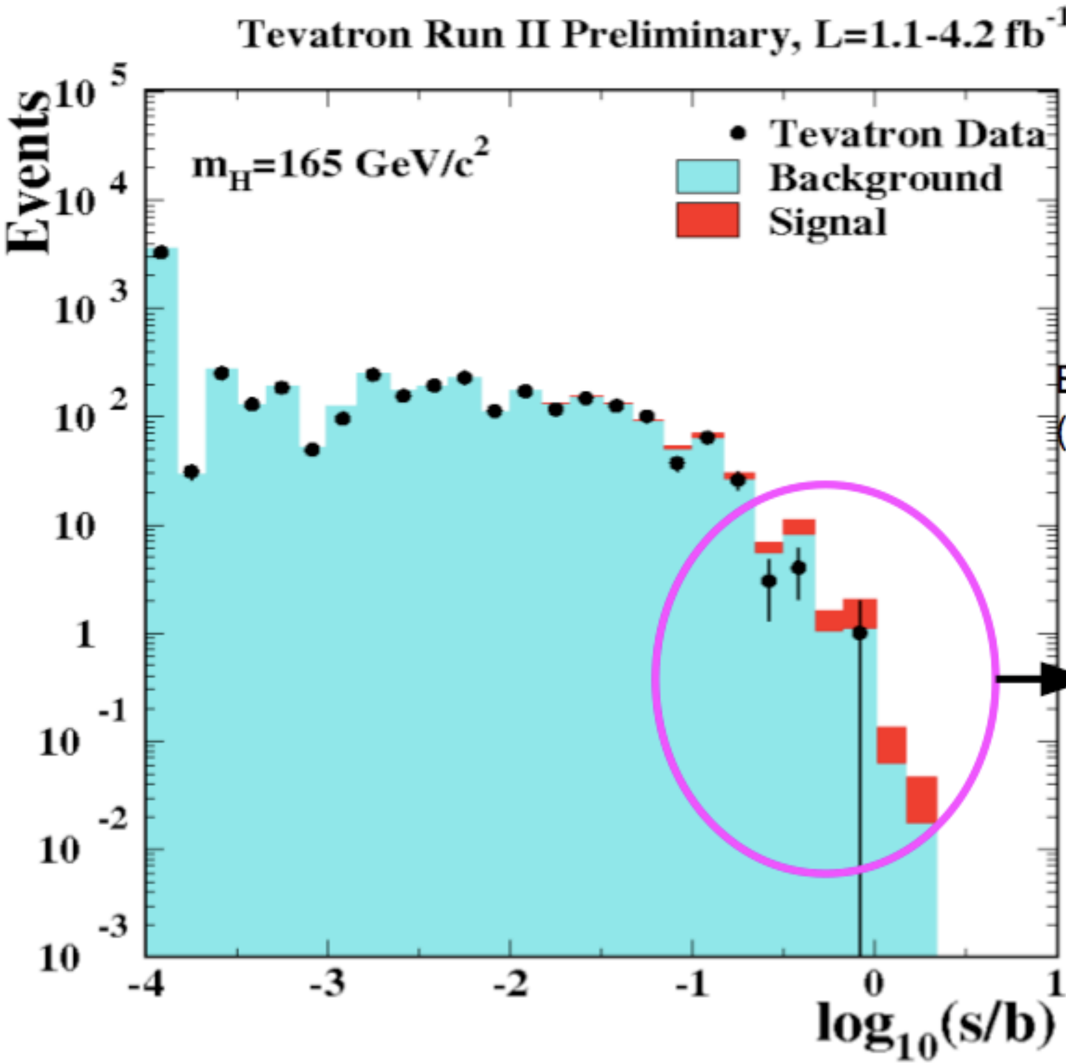




➡ Very exiting times ahead at the Tevatron in the next 1-2 years!

Backup slides

Tevatron sensitivity at m_H = 165 GeV



Bin Center (log10(s/b))	Signal	Bkgd	S/B	Observed Data
-0.583	1.38	5.38	0.26	3
-0.417	3.14	7.84	0.40	4
-0.250	0.60	0.99	0.61	0
-0.083	0.92	1.07	0.86	1
0.083	0.073	0.060	1.22	0
0.250	0.028	0.017	1.66	0

S/B ranges ~ 1:4 to ~ 1.6 : 1
last 6 bins
(most sensitive for limit)

Cross section calculations

Using up-to-date cross section calculations (arXiv:hep-ph/0607308 except where noted):

- **gg→H:** NNLL QCD, b quark contribution at NLO, 2 loop ewk corrections, changed since last Summer (arXiv:0901.2427 [hep-ph]), newer PDF set, consistent choice of α_s, 10% uncertainty
  - +12% at M_H=100 GeV
  - -8% at M_H=200 GeV
  - -4% at M_H=170 GeV
- **WH/ZH:** NNLO in QCD, NLO ewk, 5% uncertainty
- **Vector boson fusion:** NLO QCD, 10% uncertainty

CDF and DØ using common values (and correlated uncertainties) for cross sections of background processes: tt and single top (10%), diboson production (6%)

W/Z+jets(heavy flavour): considered uncorrelated (constrainted from data)

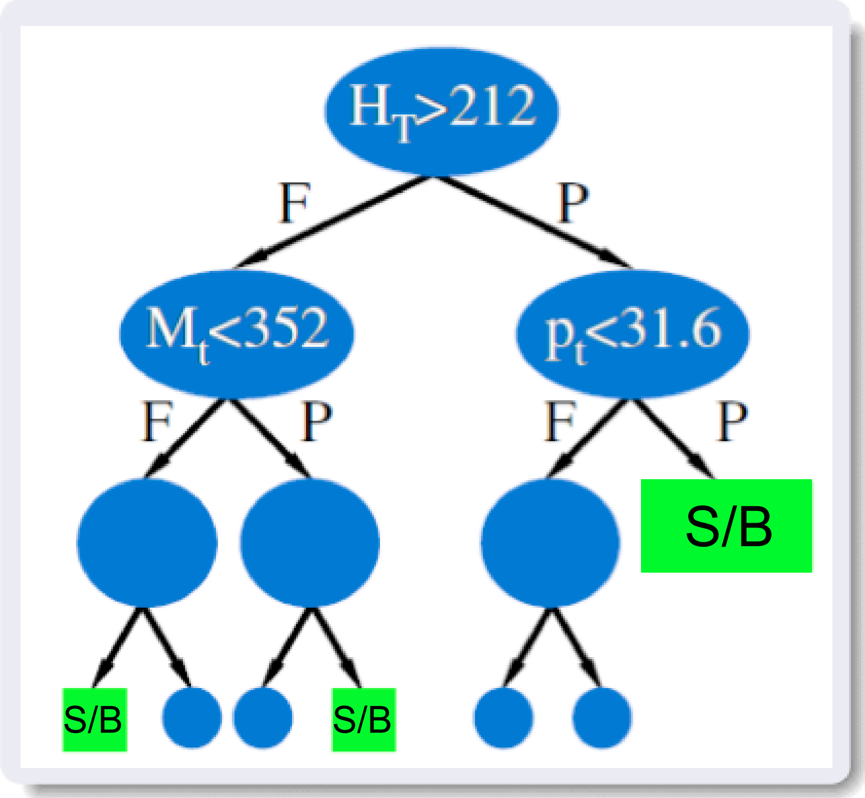
Multijet background: estimated from data (uncorrelated)

Decision Trees

Train

- Start with all events (first node)
- For each variable, find the splitting value with best separation between children (best cut).
- select best variable and cut and produce Failed and Passed branches
- Repeat recursively on each node
- Stop when improvement stops or when too few events left. Terminal node = leaf.

Idea: recover events that fail criteria in cut-based analysis



Matrix elements

- Use the 4–vectors of all reconstructed leptons and jets
- Use matrix elements of main signal and background diagrams to compute an event probability density for signal and background hypotheses.
- Goal: calculate a discriminant:

$$D_s(\vec{x}) = P(S|\vec{x}) = \frac{P_{Signal}(\vec{x})}{P_{Signal}(\vec{x}) + P_{Background}(\vec{x})}$$

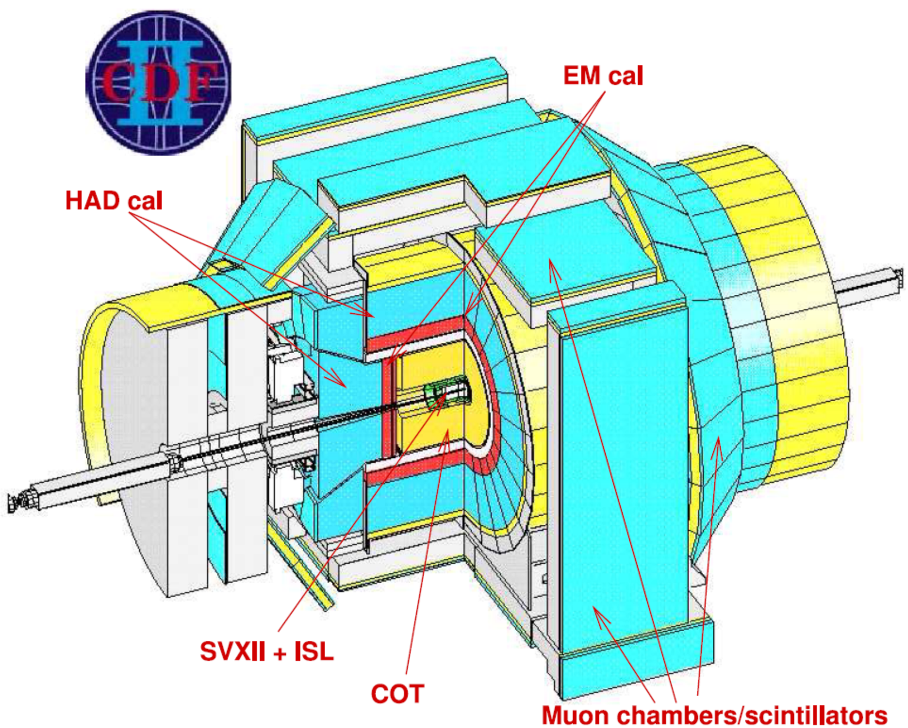
- Define P_{Signal} as properly normalized differential cross section

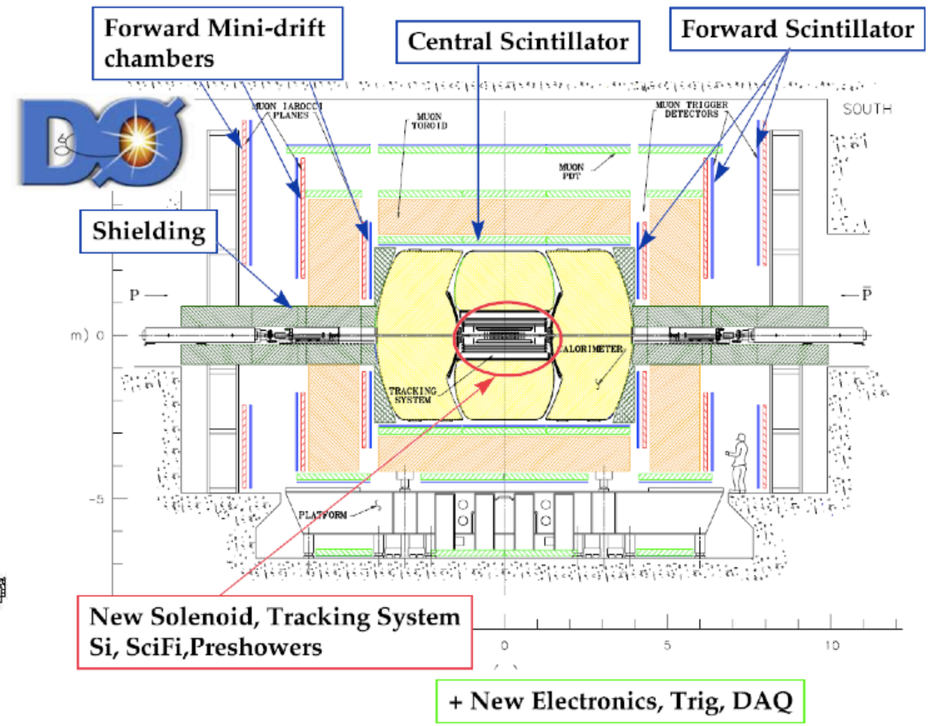
$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

CDF and DØ experiments in Run II

Two General-Purpose Detectors:

Precision tracking
Hermetic calorimeter
Muon system





Both detectors are highly upgraded in Run II

Well understood, stable operation and efficient data taking