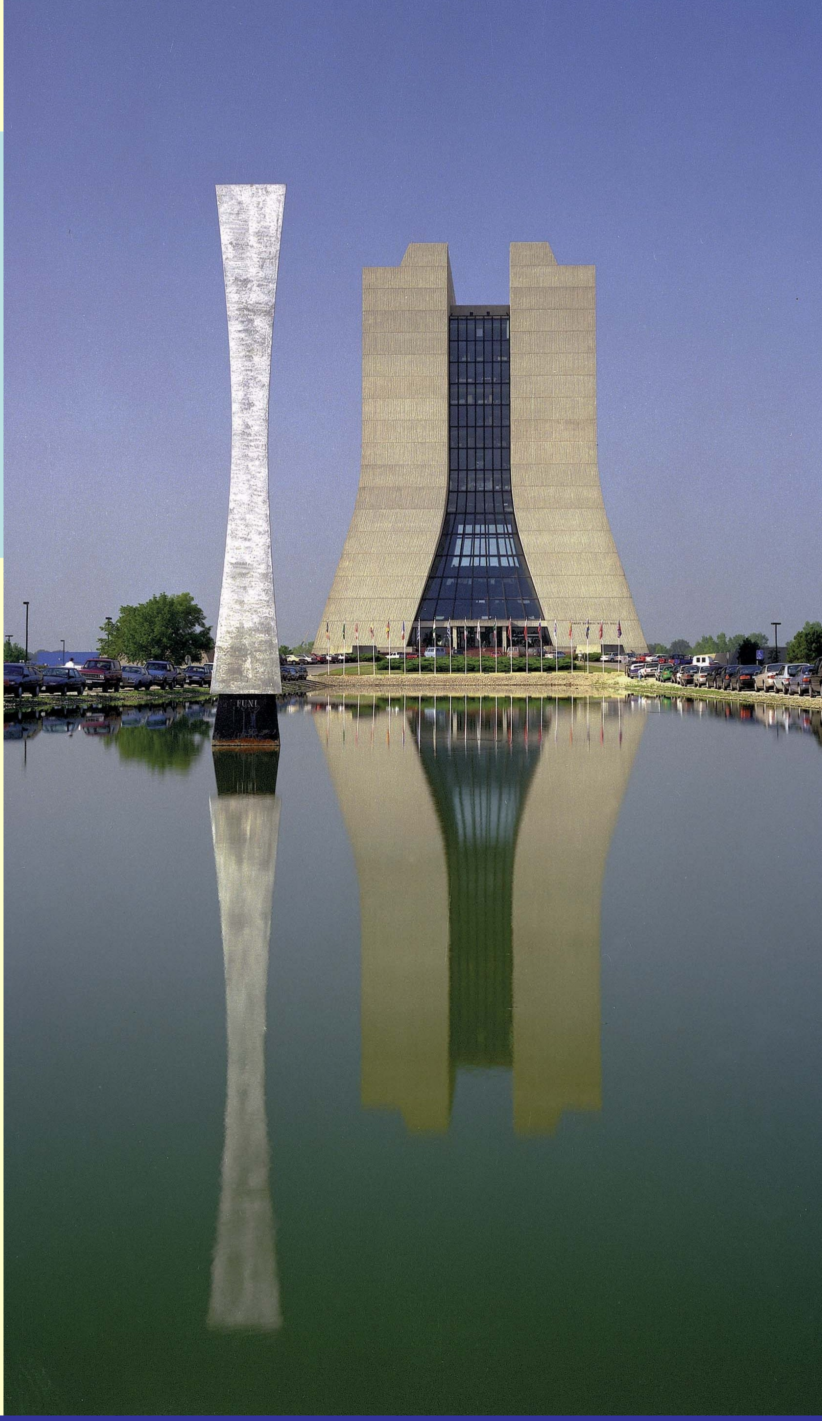
The Standard Model Higgs Search at the Tevatron

Wade Fisher, Fermilab

On behalf of the DØ Collaboration

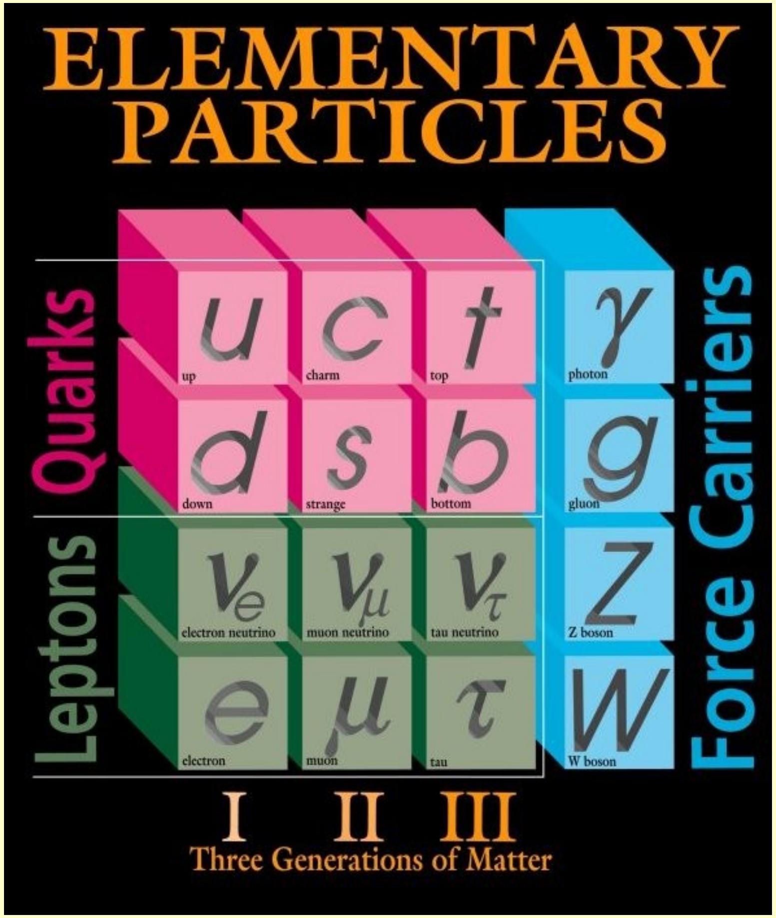
On behalf of the Tevatron Higgs Working Group



Michigan State University **September 25th 2007**

The Case for the Higgs

✗ Many years of work have led to our current description of matter and its interactions: ***the Standard Model***



Cast of characters includes

- Matter particles (fermions): quarks and leptons
- Force carriers (bosons): photon, gluon, $W^{\pm}/Z^0$

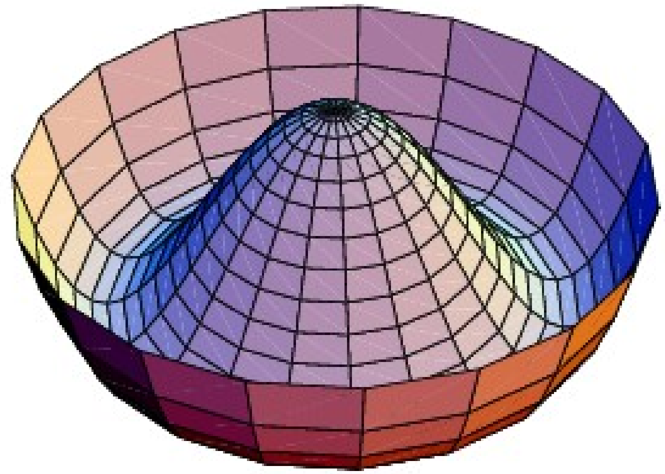
Highly successful predictive model

- *But there's a problem!! No explanation for particle masses*

The Case for the Higgs

- Electroweak model is very powerful
  - $SU(2)_L \times U(1)_Y$ well-tested at collider experiments
  - *But it is not a symmetry of our vacuum* – otherwise gauge bosons would be massless
- Higgs mechanism provides a natural solution
  - Add one complex doublet of scalar fields in a Φ^4 potential
- Symmetric solution unstable: broken EW symmetry creates non-zero vacuum expectation value
  - $W^{\pm}/Z^0$ longitudinal polarizations absorb three degrees of freedom, remaining one becomes neutral scalar (Higgs boson)
  - Ground state VEV parameterizes W/Z masses
  - *Higgs mass not predicted:* $m_H \propto \mu$

$$V_{Higgs} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



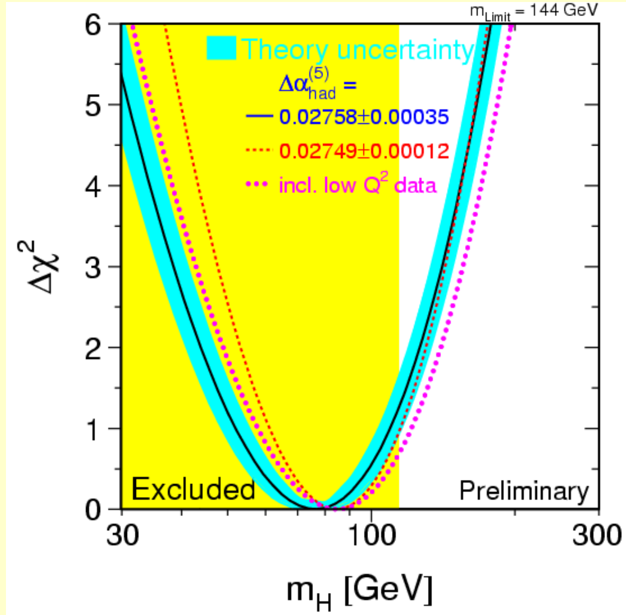
$$\phi_0 = \pm \sqrt{-\mu^2 / 2\lambda}$$

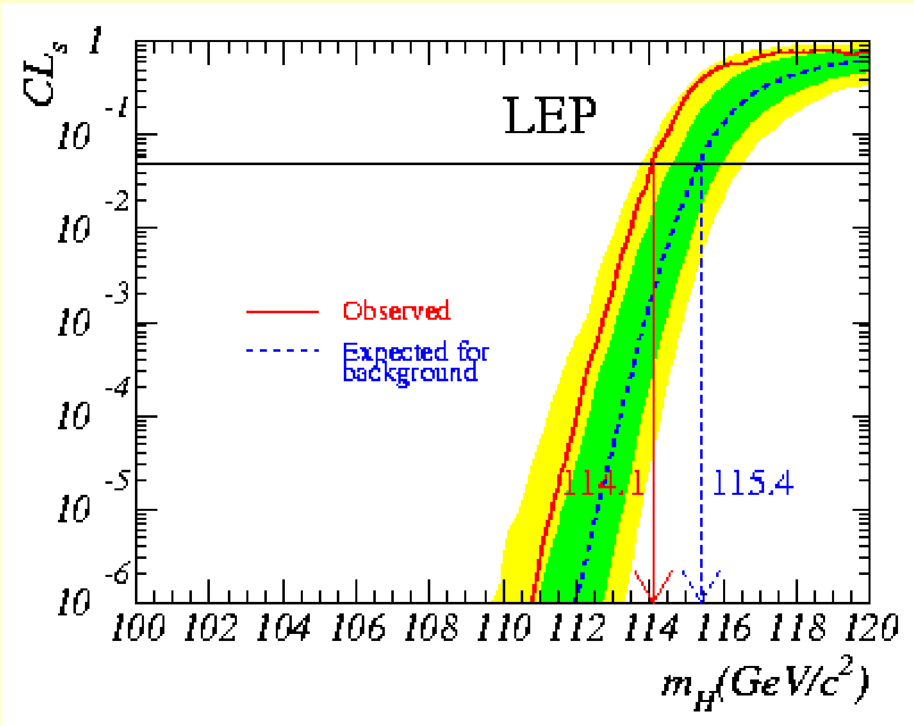
An Aside:

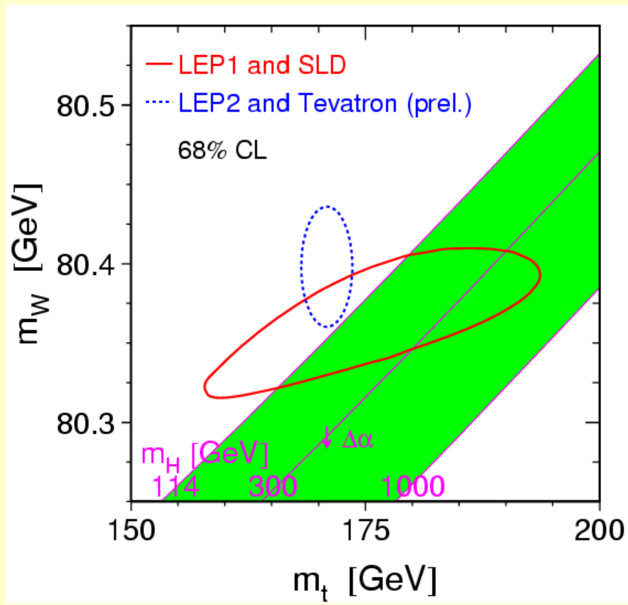
Quark and lepton masses must be added "by hand" via Yukawa-type terms in the Lagrangian. The Higgs mechanism is convenient, but may not be the complete picture.

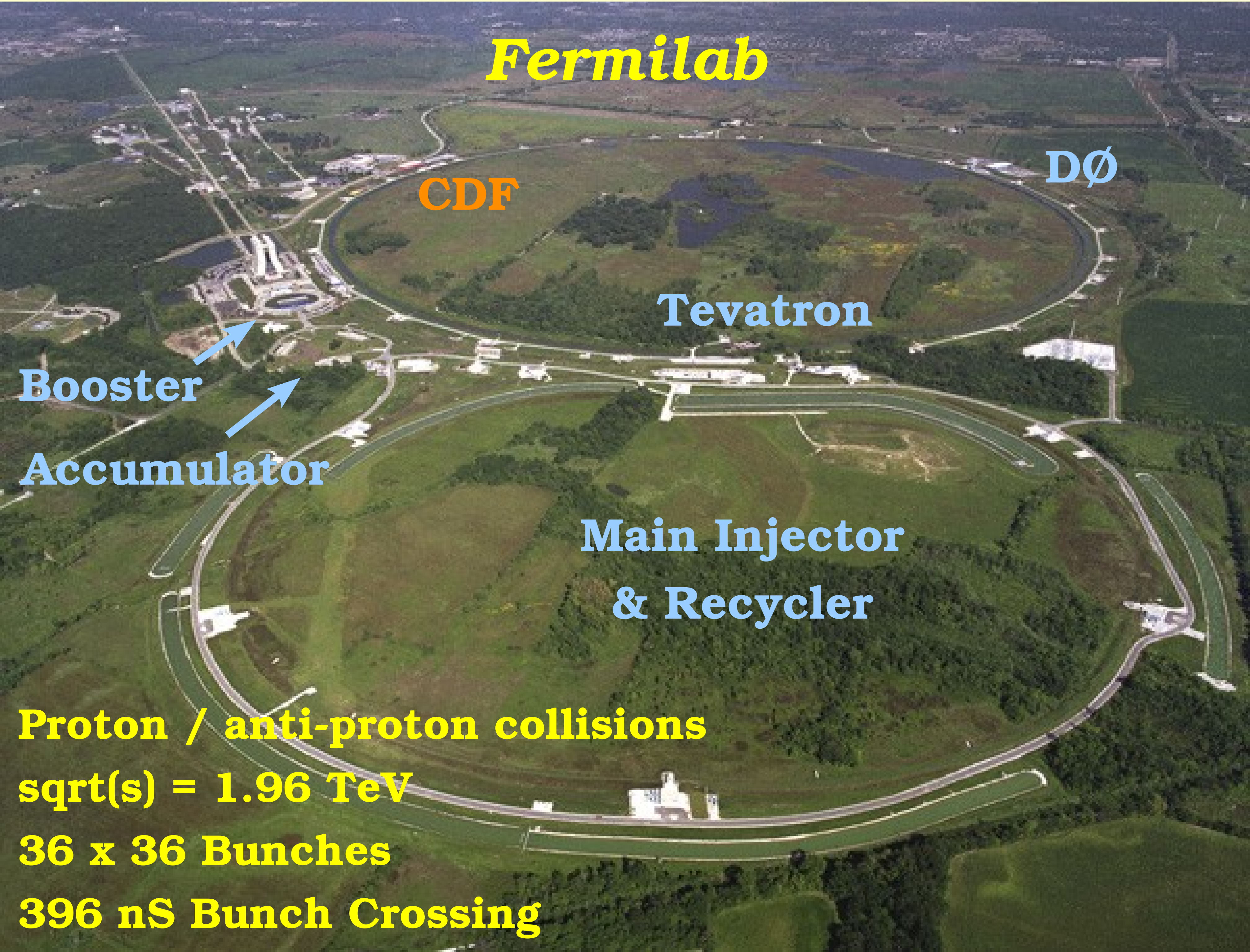
Evidence for the Higgs

- ✗ Direct searches and indirect evidence have restricted possible phase space
  - LEP II direct search: mH >114.4 GeV (95% CL)
  - Continuous refinements of top-quark and W-boson masses at the Tevatron
  - Fit of precision electroweak data: mH < 144 GeV at 95% CL *(mH<182 GeV including LEP II limit)*

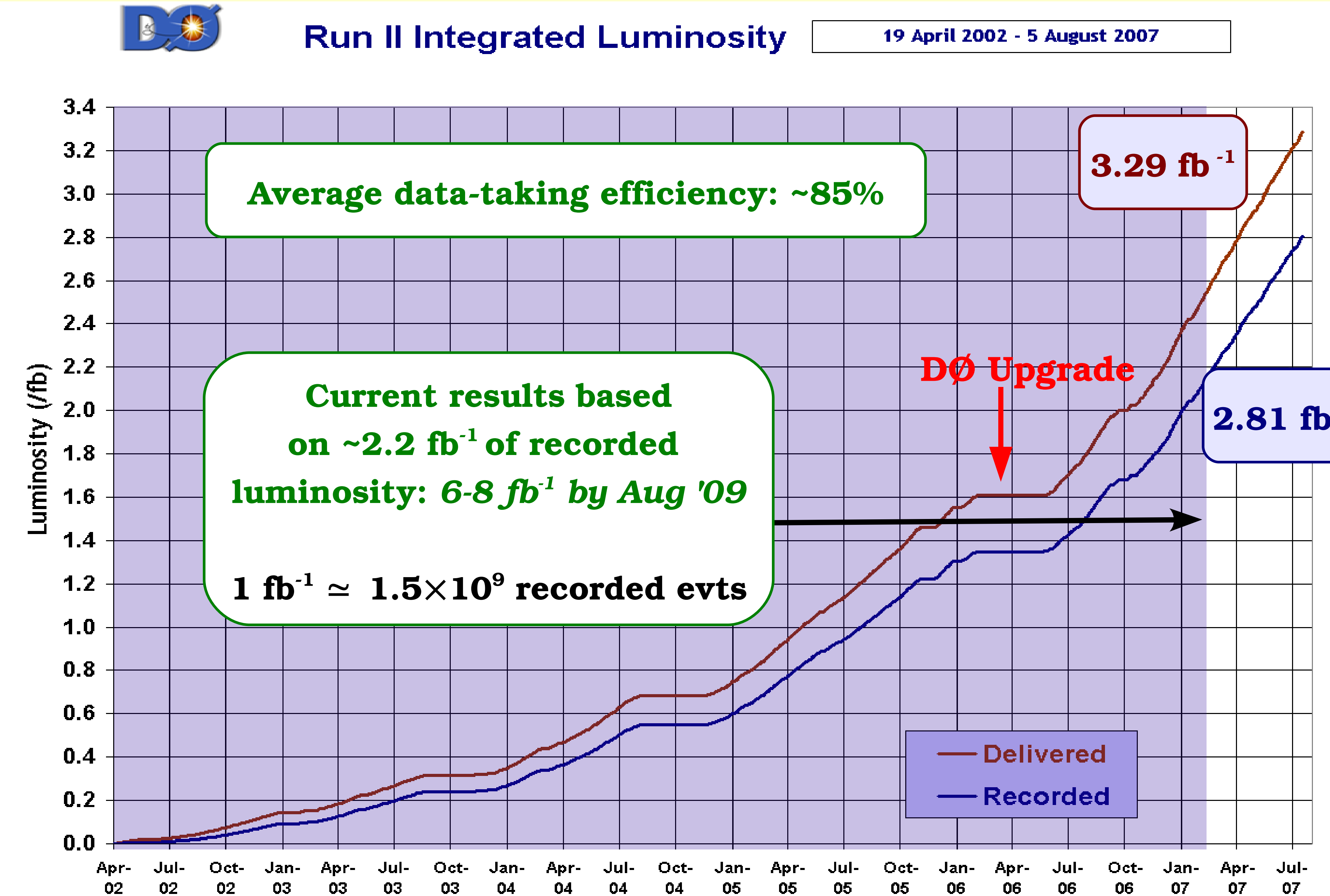




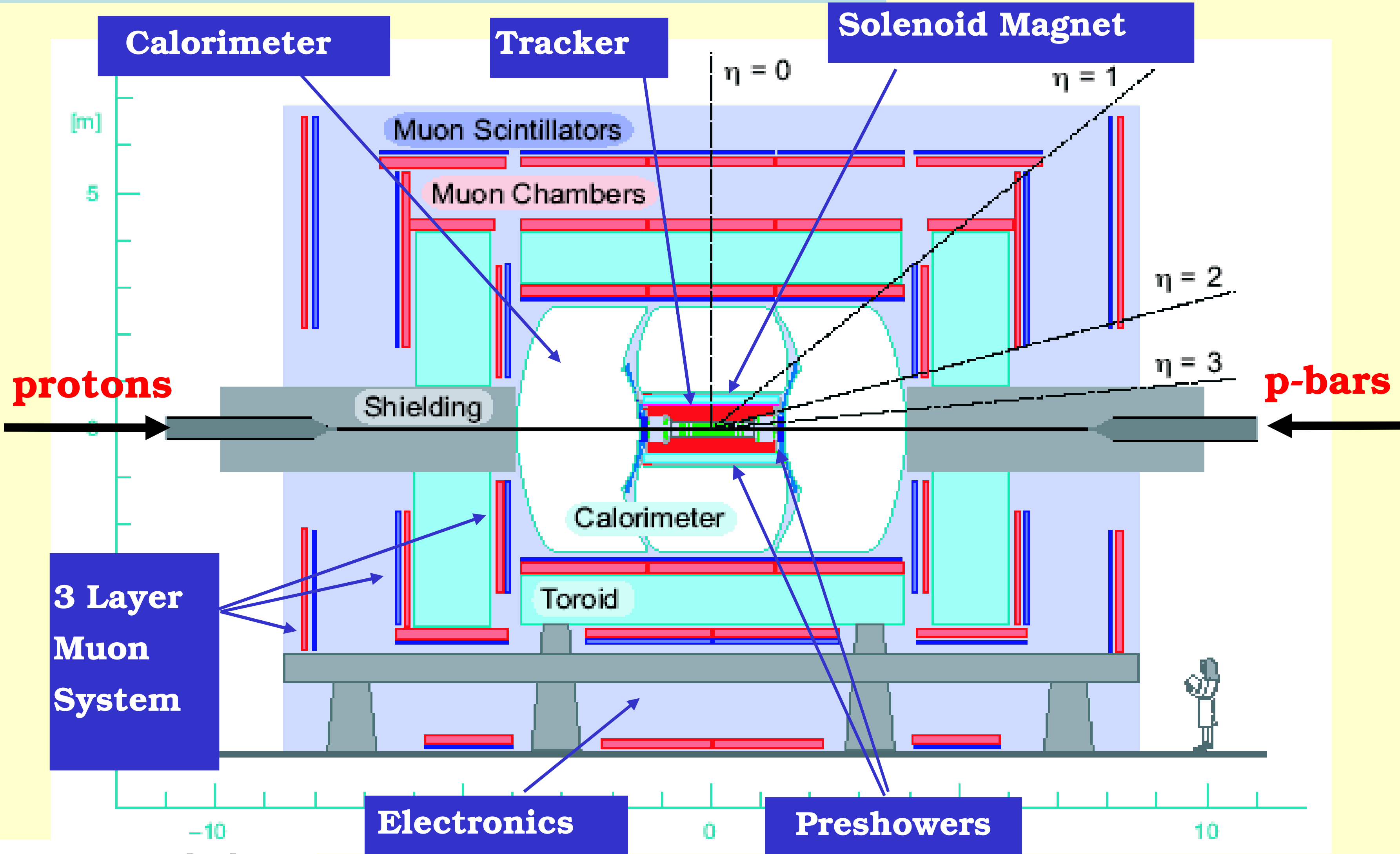



Fermilab
CDF
DØ
Tevatron
Booster
Accumulator
Main Injector
& Recycler
Proton / anti-proton collisions
sqrt(s) = 1.96 TeV
36 x 36 Bunches
396 nS Bunch Crossing

Dataset


Run II Integrated Luminosity
19 April 2002 - 5 August 2007
Average data-taking efficiency: ~85%
Current results based on ~2.2 fb^{-1} of recorded luminosity: *6-8 fb^{-1} by Aug '09*
1 fb^{-1} $\simeq$ 1.5×10^9 recorded evts
DØ Upgrade
3.29 fb^{-1}
2.81 fb^{-1}
Luminosity (/fb)
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
Apr-07
Jul-07
Delivered
Recorded

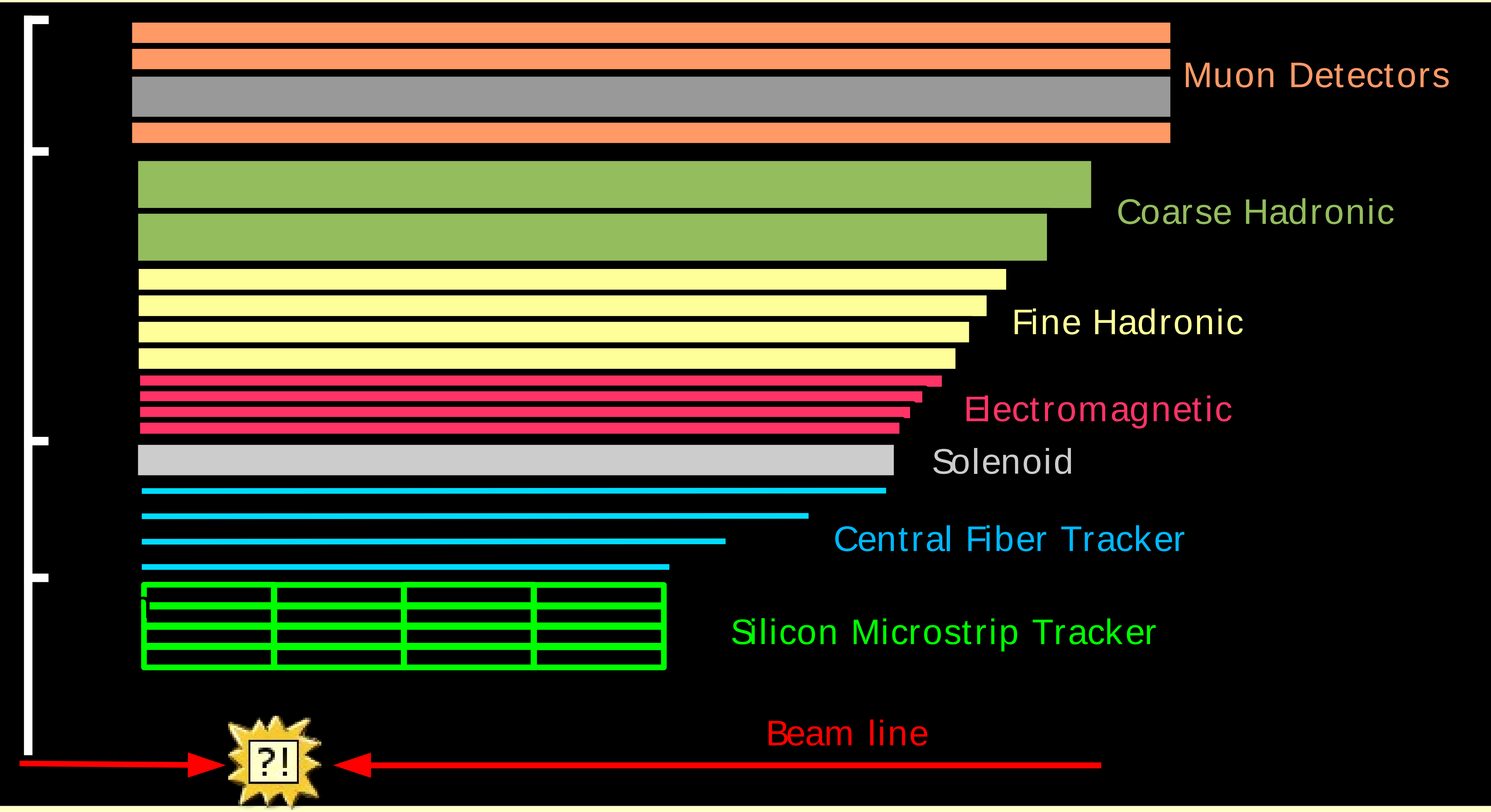
The DØ Detector



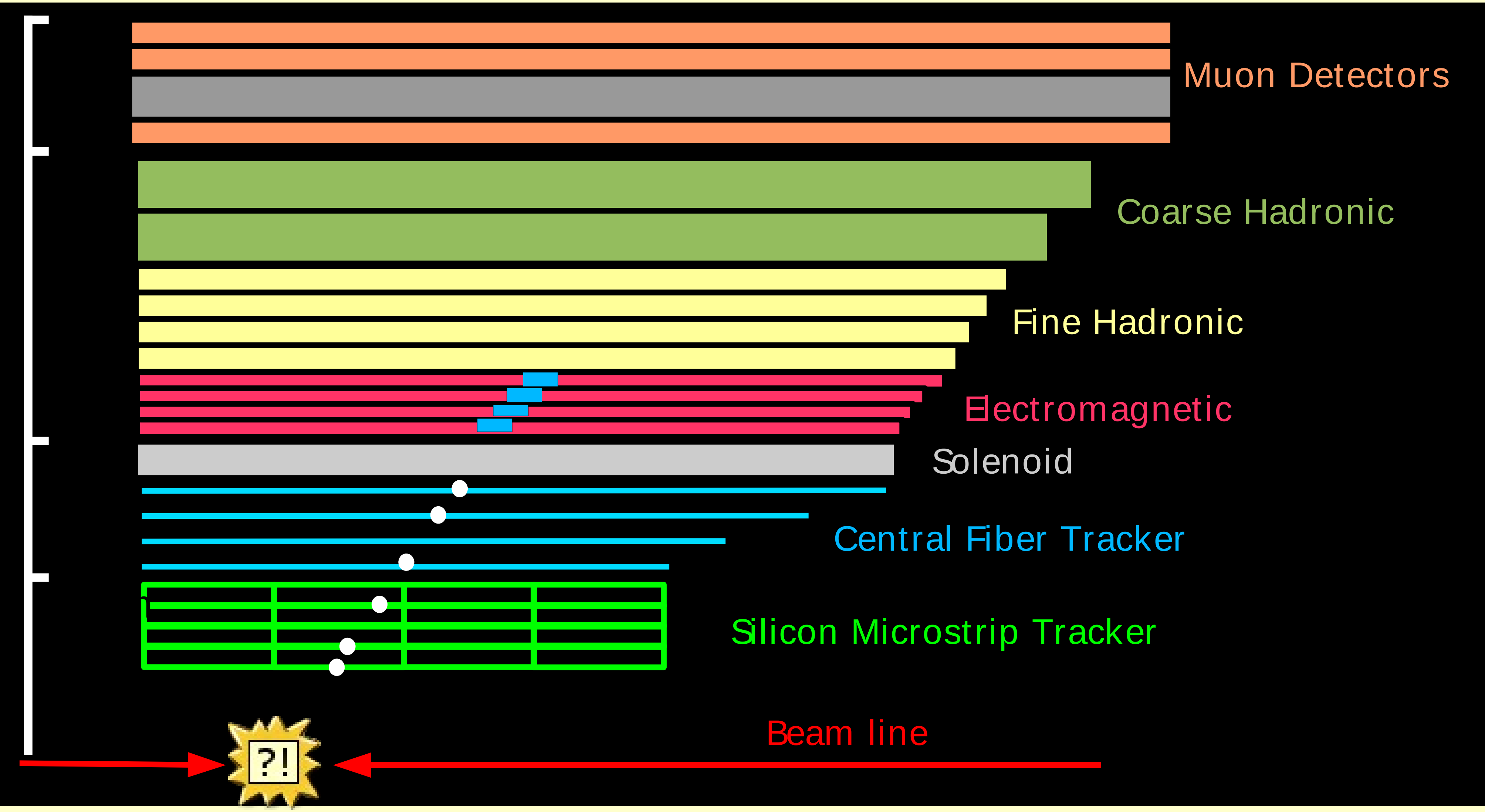
	$\|\eta\|$
Muon ID	**~2**
Tracking	**~2.5**
EM / Jets	**~4**

The CDF detector has similar features of detector design

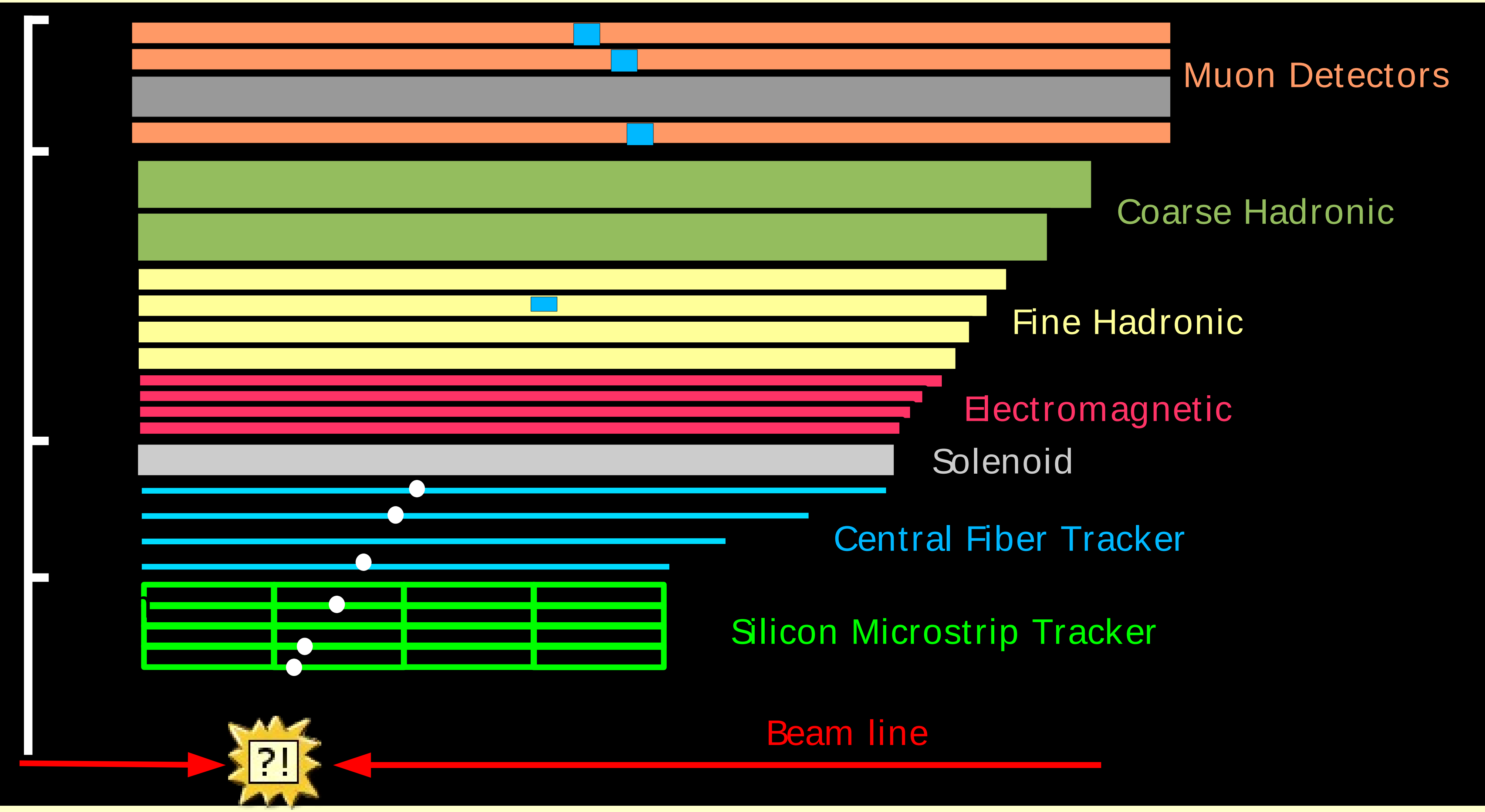
Particle Detection



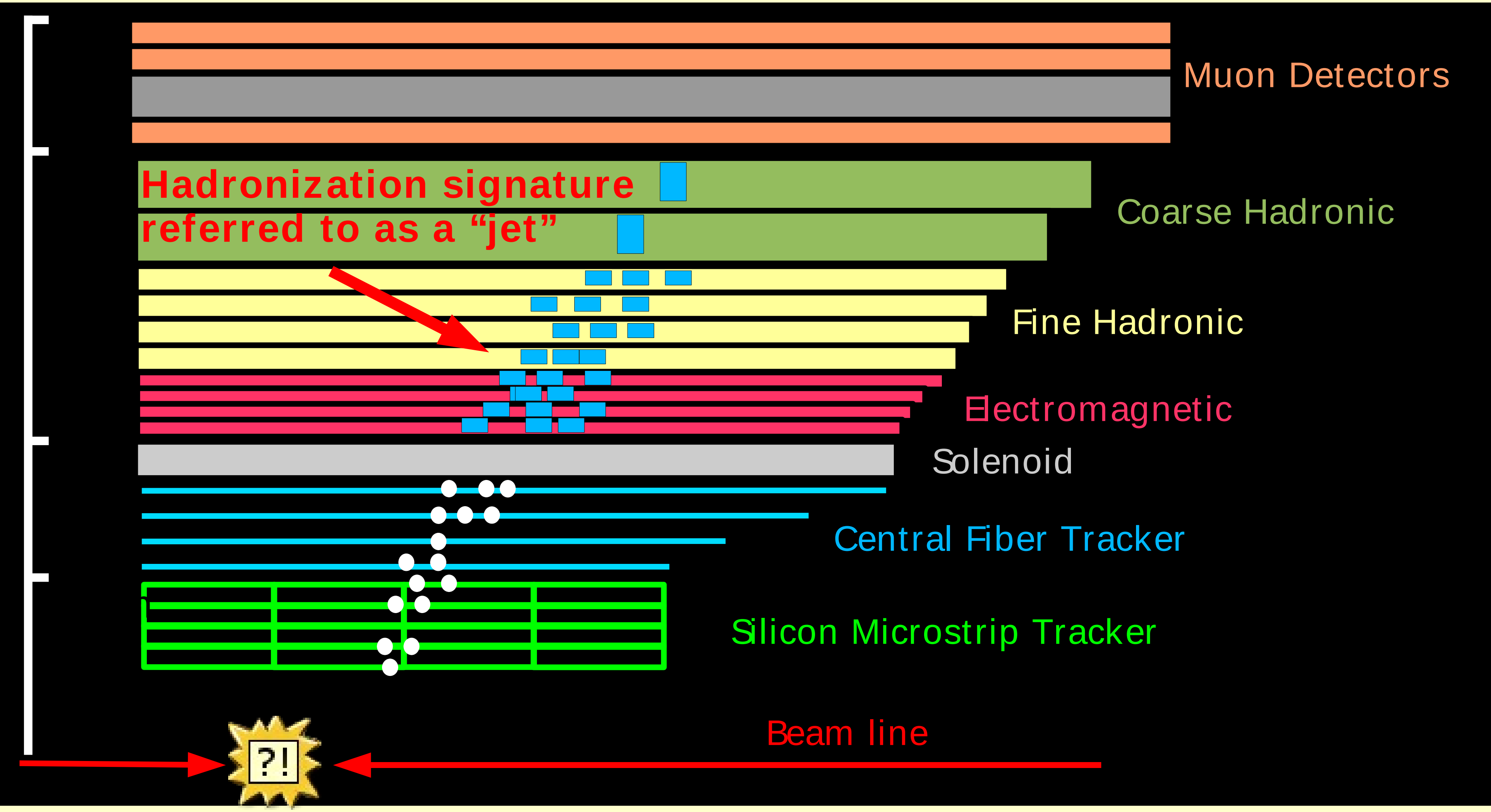
Particle Detection: Electrons



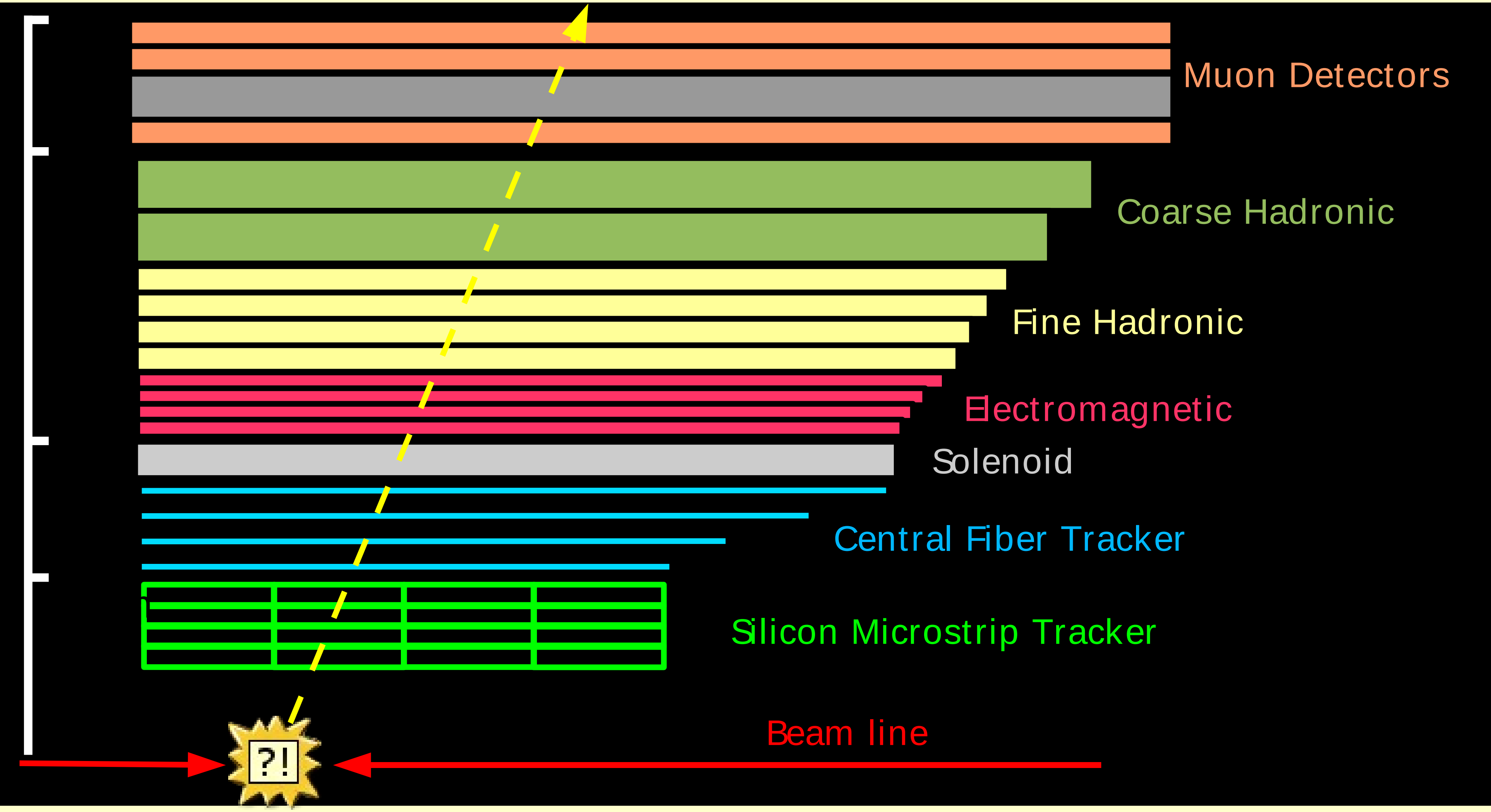
Particle Detection: Muons



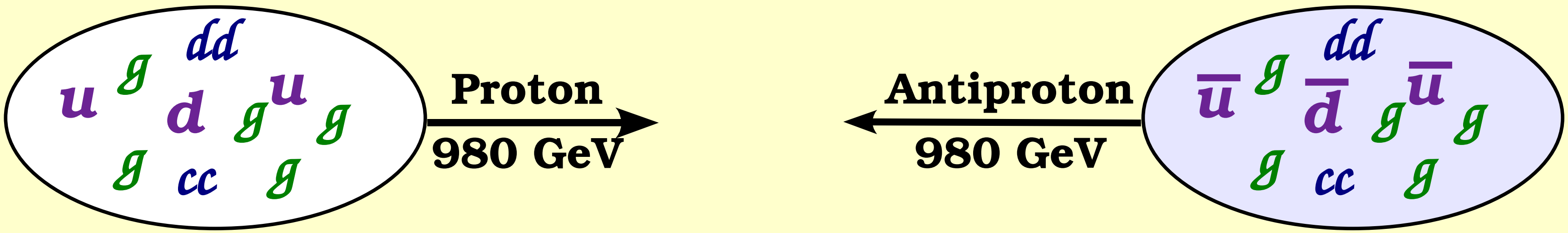
Particle Detection: Quarks & Gluons



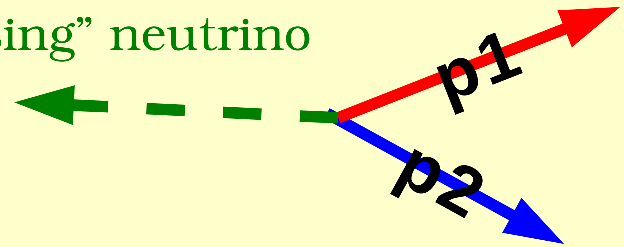
Particle Detection: Neutrinos



Proton-Antiproton Collisions



Transverse Variables



$$MET = \sqrt{\left|\sum \vec{P}x\right|^2 + \left|\sum \vec{P}y\right|^2}$$

- ✗ Summation performed over calorimeter & muon energies
  - Signature of non-interacting neutrinos
- ✗ Capitalize on momentum balance in transverse plane
  - "Transerverse momentum", pT

Coordinate Systems

- ✗ Based on relativistic invariance
  - Allows for consistent description of z-boosted events
- ✗ Azimuthal angle ϕ is manifestly invariant under boosts, but θ isn't.
- ✗ Introduce invariant "rapidity" and zero-mass limit "pseudo-rapidity"

$$Rapidity = \frac{1}{2}\frac{\ln(E+Pz)}{\ln(E-Pz)}$$

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

SM Higgs at the Tevatron

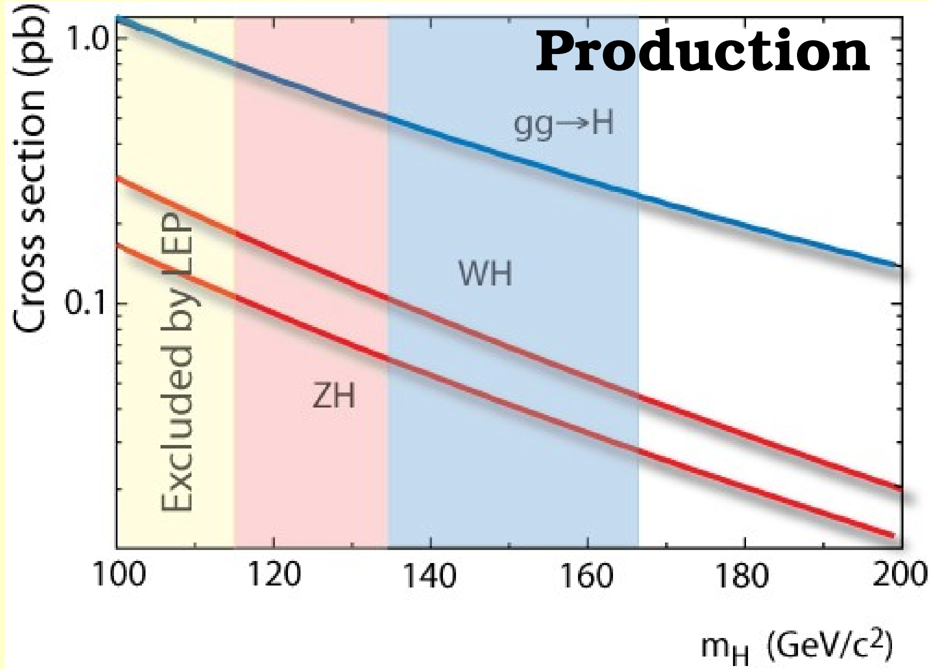
MSU HEP Seminar
Sept 25th, 2007

Gluon fusion dominant at hadron colliders

- Large backgrounds restrict many useful Higgs decay channels

Next largest is associated production of W/Z + Higgs

- Leptonic decays of W/Z bosons provide tag for trigger and analysis

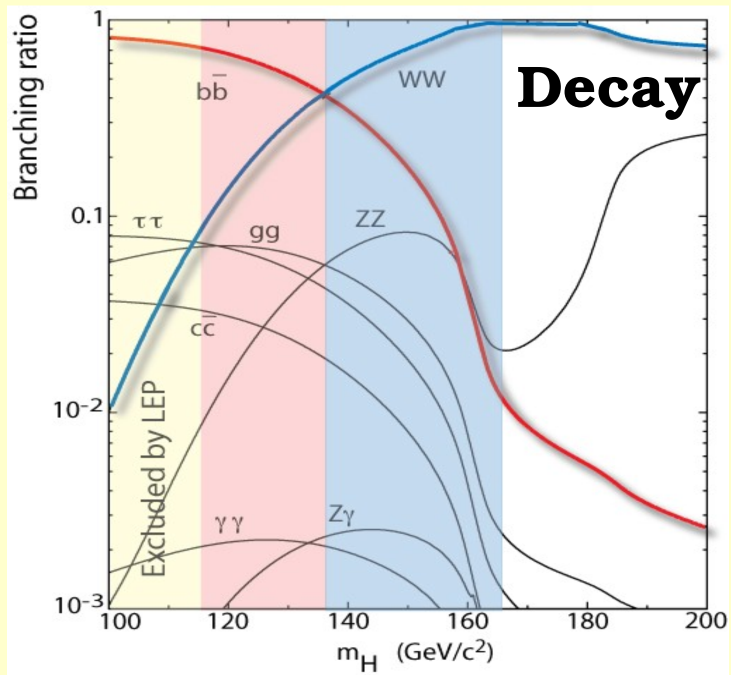


Low-mass Higgs (m_H<135 GeV) prefers to decay to bottom-quark pairs

- Need efficient identification of bottom quarks to reduce backgrounds

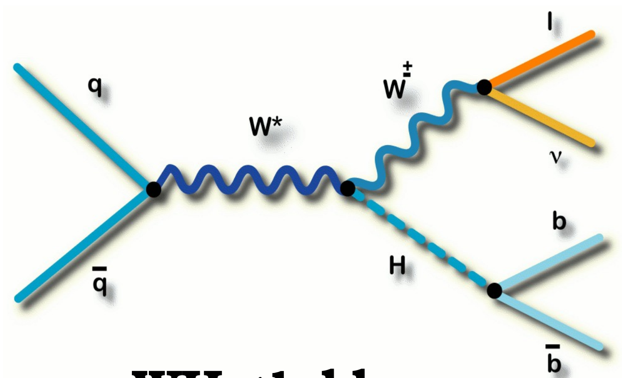
At high mass (m_H>135 GeV), search for $H \rightarrow WW^*$

- Off-shell W boson allows off-resonance production

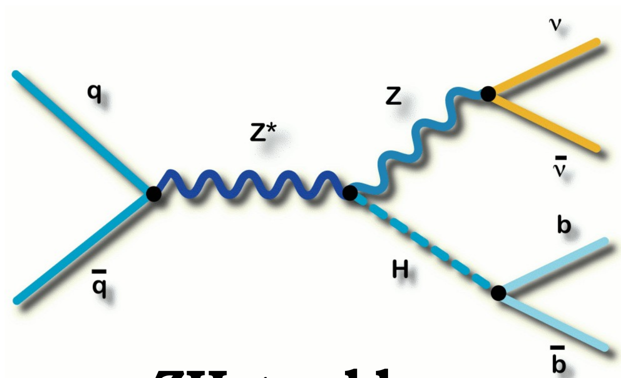


Search Channels

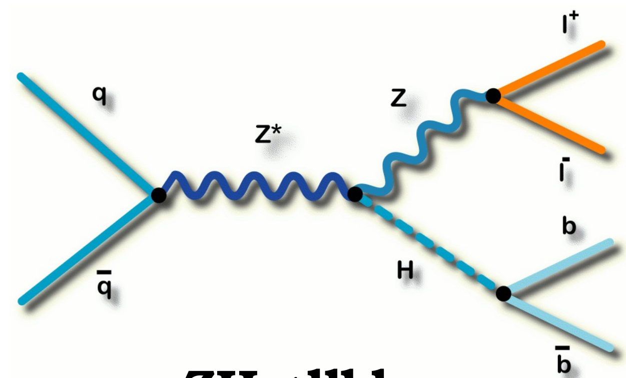
<u>Associated Production:</u> Low mass only, 3 final states



WH→lνbb

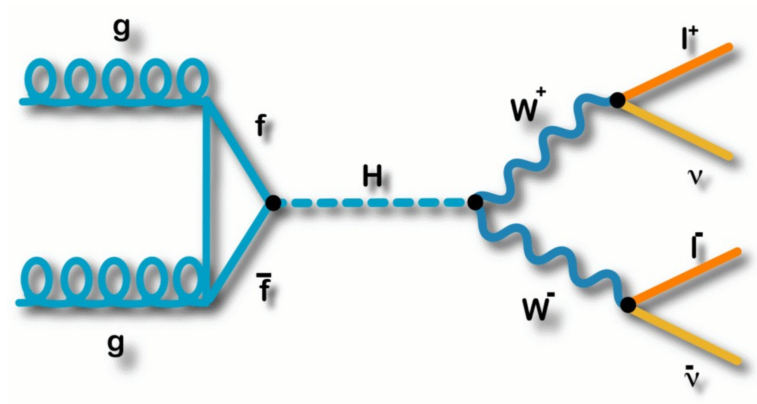


ZH→ννbb

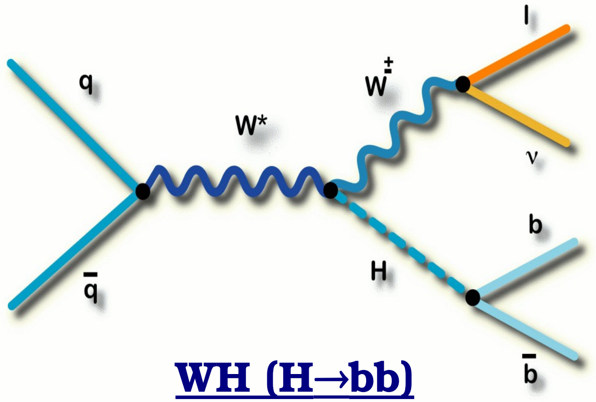


ZH→llbb

<u>Gluon Fusion Production:</u>
Maximum sensitivity at high mass, also useful at low mass

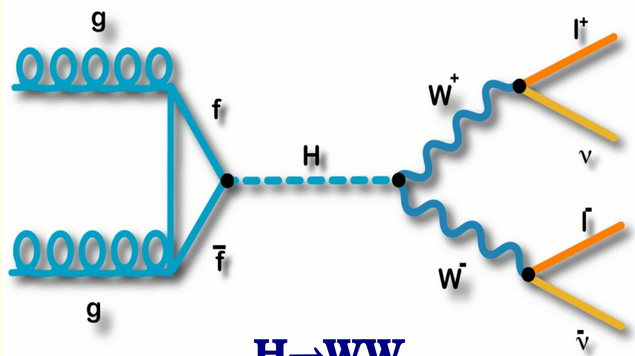


Backgrounds & Rates



WH (H→bb)

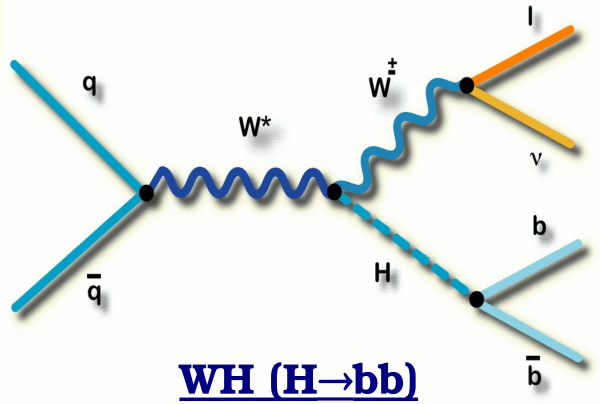
$\sigma \times$BR = 130 fb @ mH=115



H→WW

$\sigma \times$BR = 380 fb @ mH=160

Backgrounds & Rates



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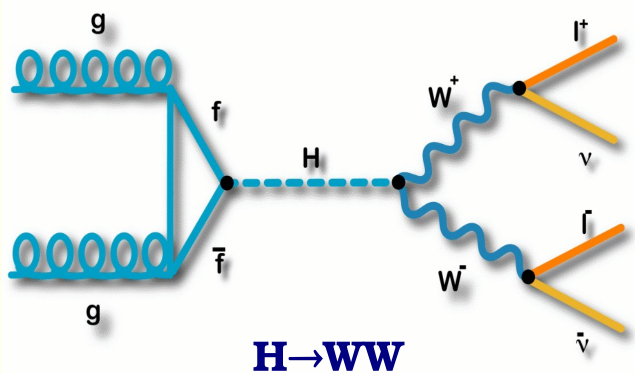

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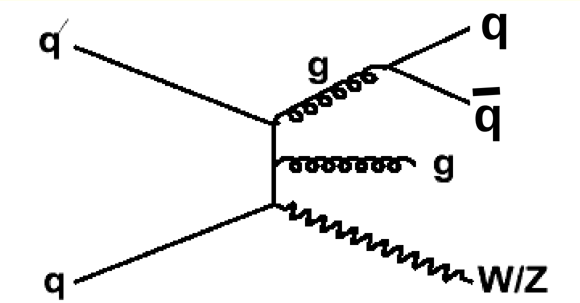


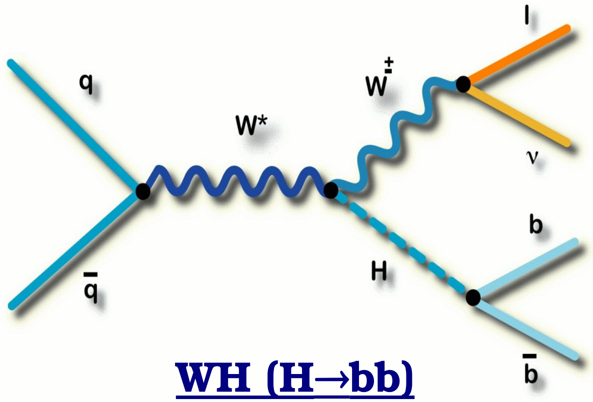
W+qq or "Gluon Splitting"

W+bb: σ×BR = 4×10^4 fb

W+cc: σ×BR = 1×10^5 fb

W+qq: σ×BR = 2×10^6 fb

Backgrounds & Rates



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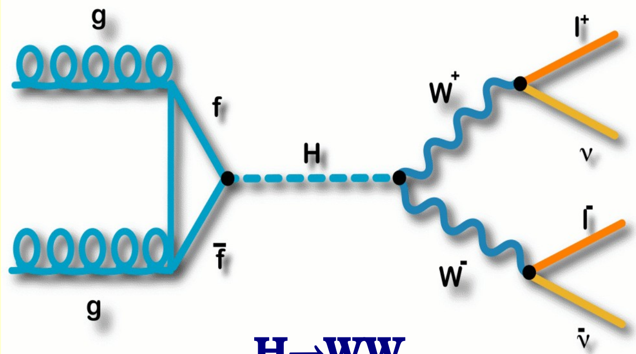

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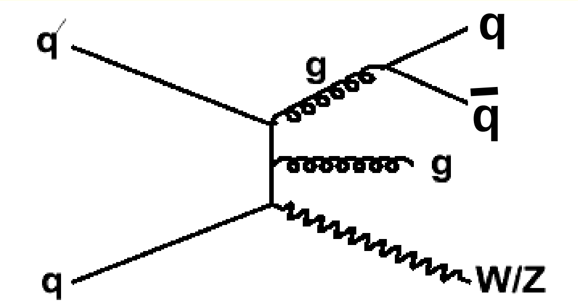

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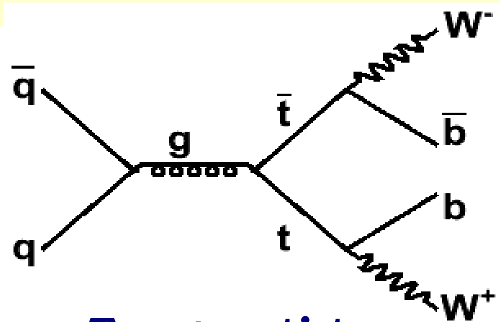
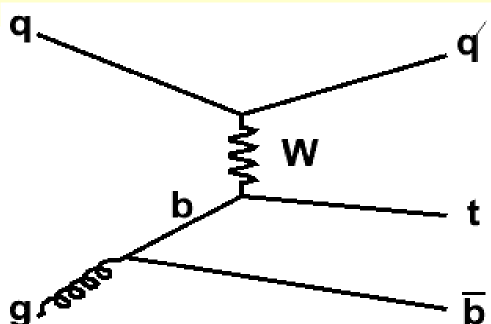


Top + anti-top

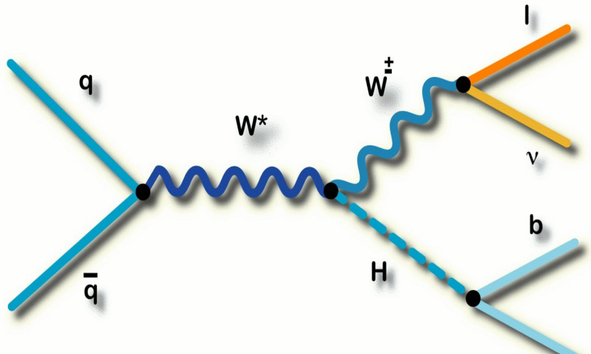
$\sigma \times BR$ = 6800 fb



Single top

$\sigma \times BR$ = 3000 fb

Backgrounds & Rates



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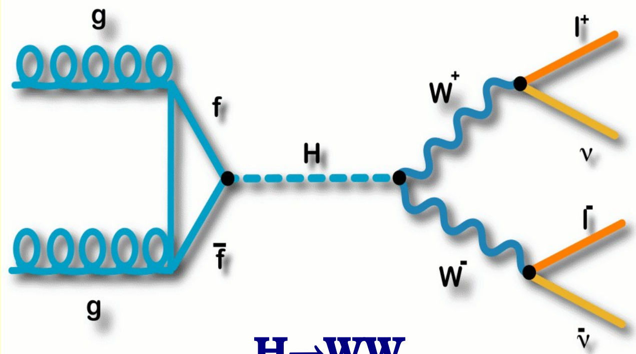

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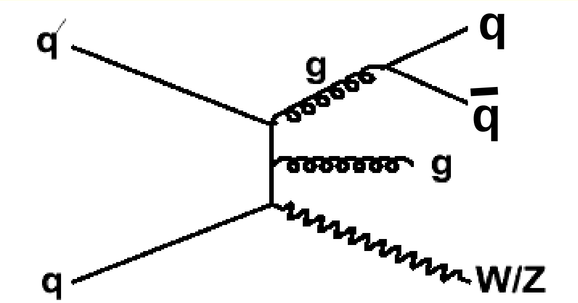

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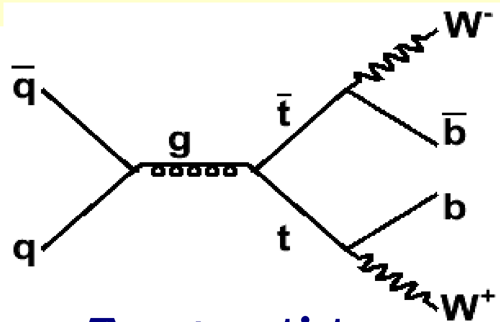

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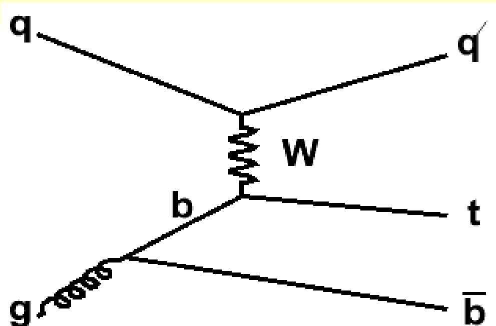
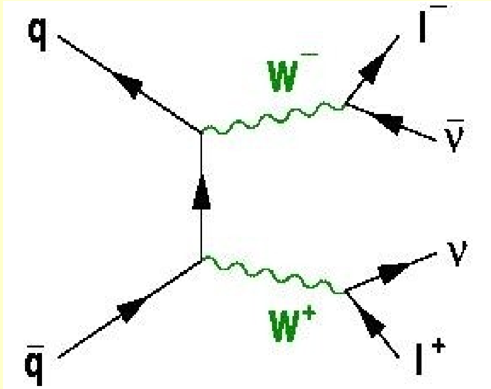


Single top

$\sigma \times BR$ = 3000 fb



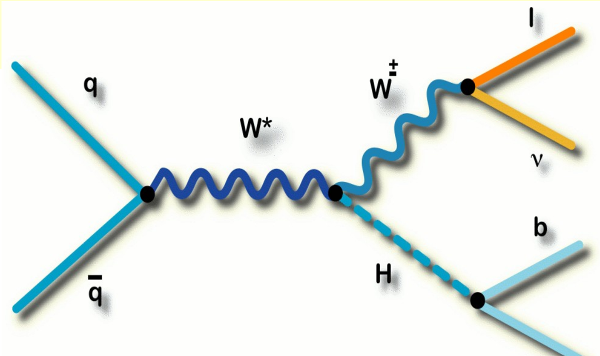
Diboson

WW: $\sigma \times BR$ = 13000 fb

WZ: $\sigma \times BR$ = 4000 fb

ZZ: $\sigma \times BR$ = 1500 fb

Backgrounds & Rates



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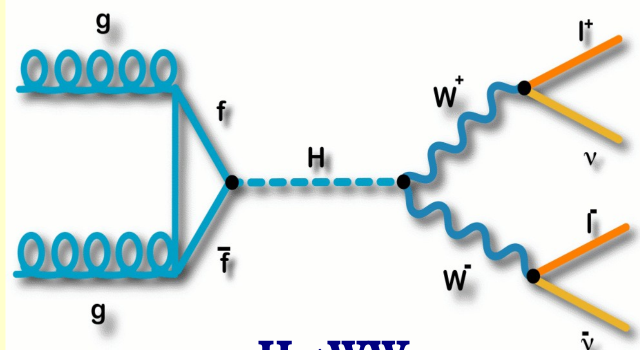

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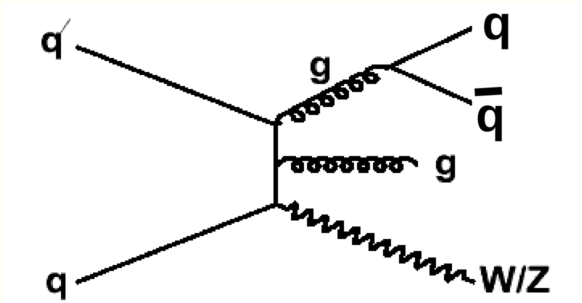

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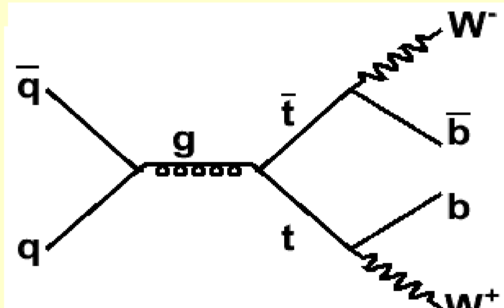

Top + anti-top

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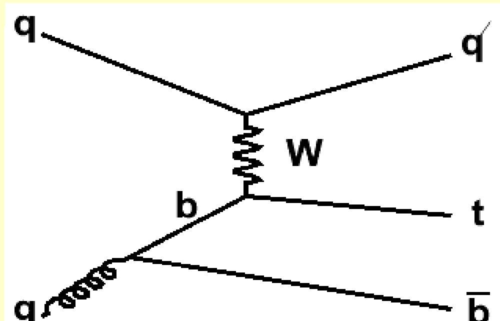

Single top

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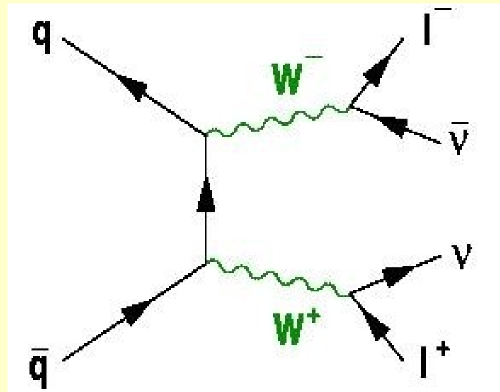


Diboson

WW: $\sigma \times BR$ = 13000 fb

WZ: $\sigma \times BR$ = 4000 fb

ZZ: $\sigma \times BR$ = 1500 fb

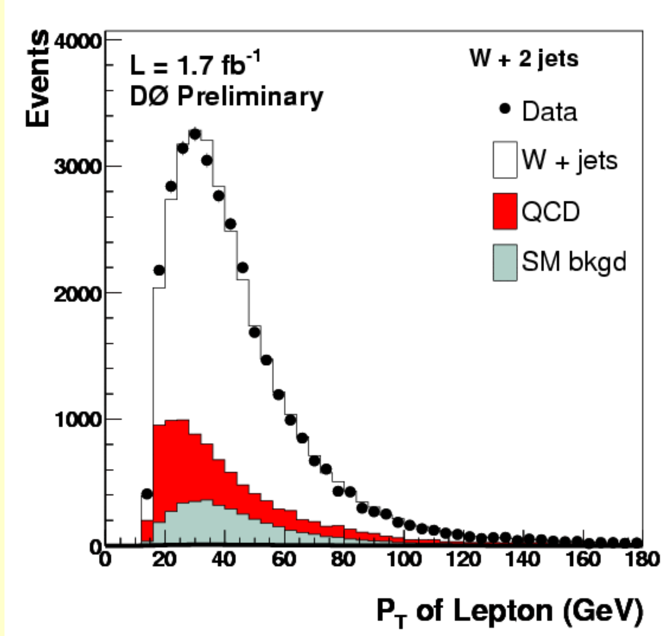
Large rate of QCD multi-jet production
("fake" lepton + neutrino)

Simulations notoriously poor

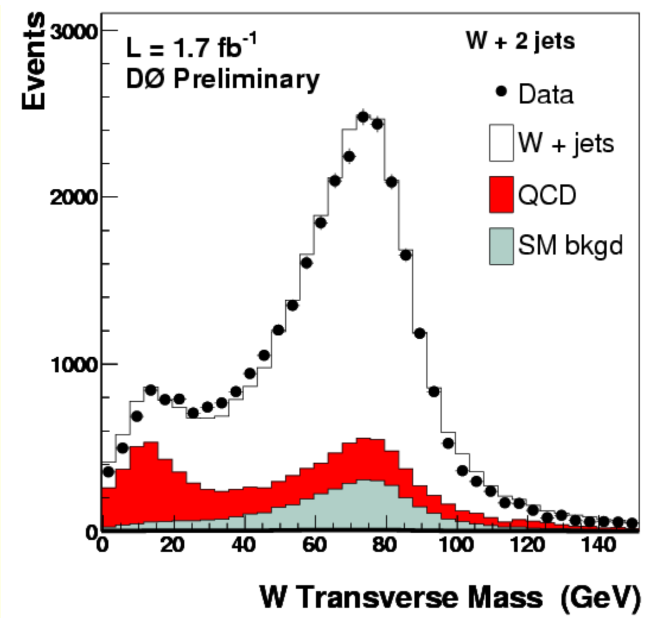
⇒ Measured in data

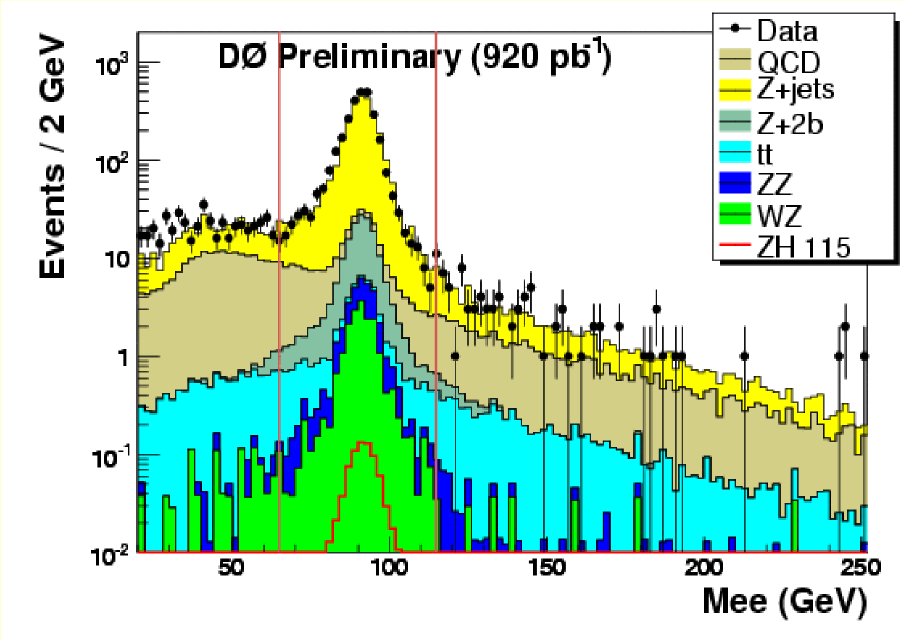
Searching for H→bb

- Rely on **W→lν** and **Z→ll** provide handle to reduce backgrounds
  - Start with high-pT leptons: pT > **20** (**15**) GeV
  - Neutrinos manifest as missing transverse energy
    - **WH→lνbb:** MET > 20 GeV
    - **ZH→llbb:** MET *should be small!!*
  - Vector boson resonant mass is very important

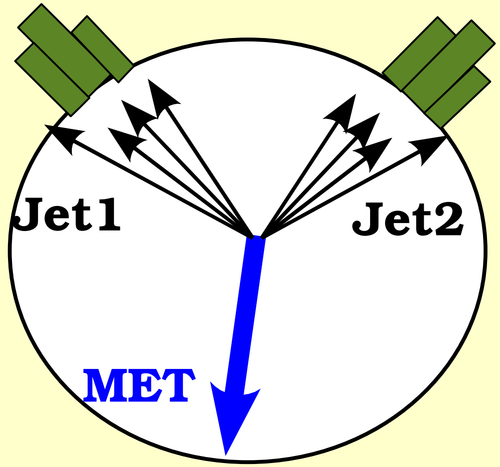


$$M_W^{trans} = \sqrt{2 p_T^l ME_T (1 - \cos(\Delta\phi))}$$

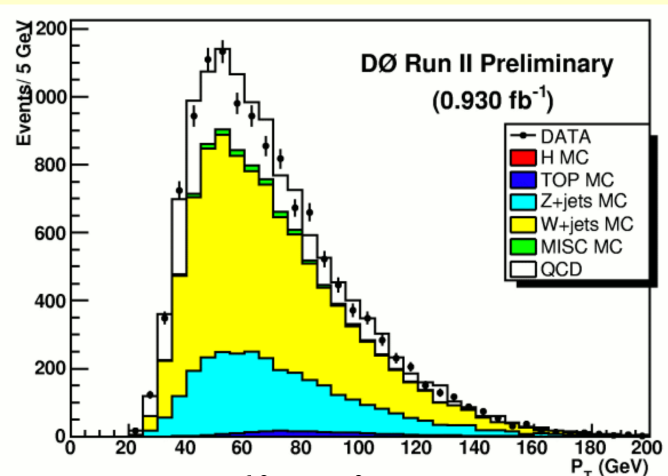




Searching for H→bb

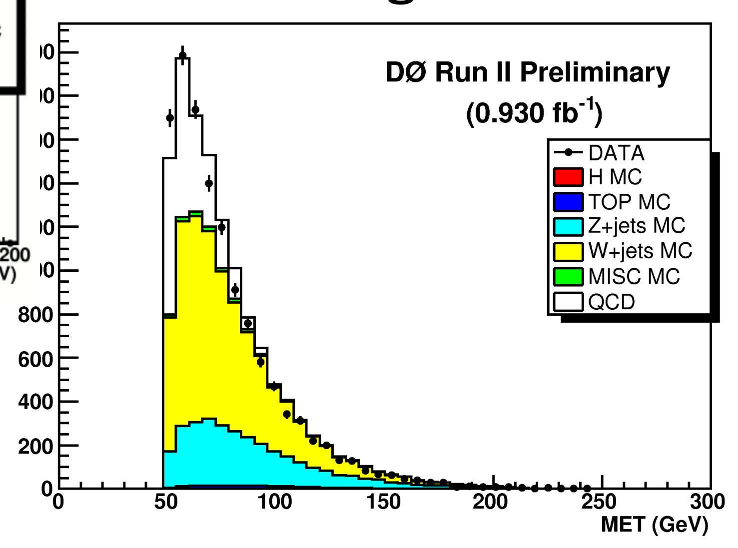


- ✗ For ZH→ννbb the search is more difficult: no charged leptons!
  - Rely on large MET (neutrinos!)
  - <u>"Physics" Bkgd:</u> Z+jets, W+jets, top-pair, ZZ, WZ
  - <u>"Instrumental" Bkgd:</u> QCD multijets with mismeasured jets
  - ⇒ Asymmetry between MET and jet recoil isolates QCD



Leading jet pT

Missing ET

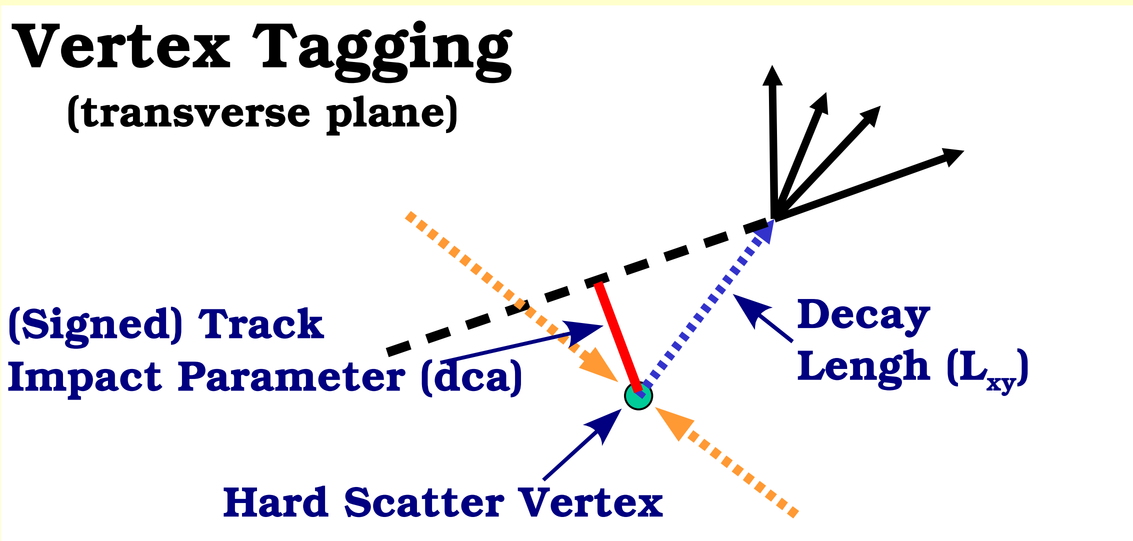


- ✗ **Background reduction:**
  - Trigger on large missing HT (vector sum of jet ET), select large MET:>50 GeV
  - Select two high-pT jets to define final state (pT>20 GeV, |η|<2.5)
  - Veto back-to-back jets: $\Delta\phi$ <165°

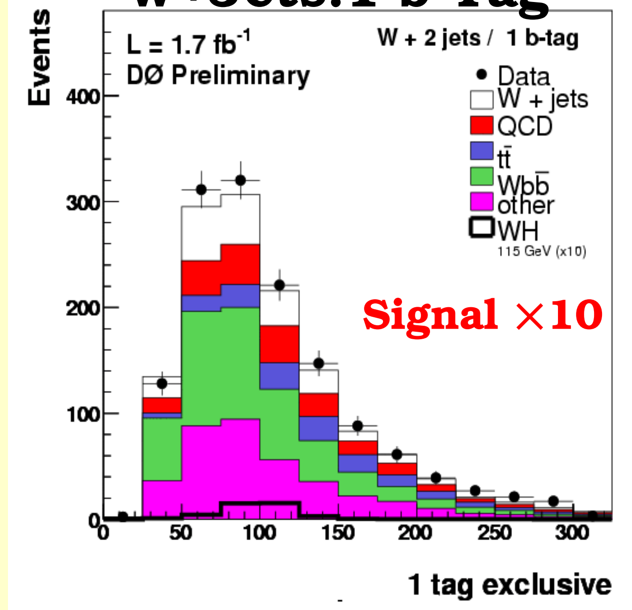
Searching for H→bb

MSU HEP Seminar
Sept 25th, 2007

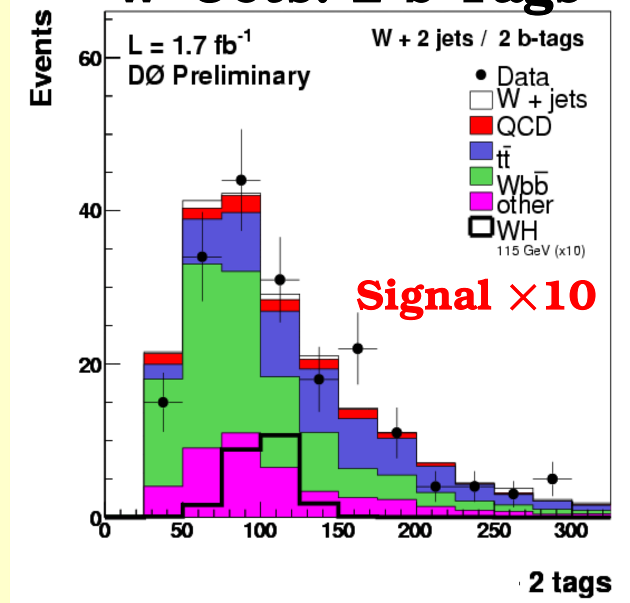
- ✗ Select quark-jets consistent with Higgs decays
  - At least two high-pT jets (pT>20-25 GeV)
  - Angular separation consistent with scalar particle
  - Dijet invariant mass provides great discrimination
- ✗ Remove light-flavor jets via heavy-flavor "tagging"
  - Identify via displaced vertex due to b-meson lifetime
- ✗ Two main categories
  - Impact parameter based
  - Secondary vertex based



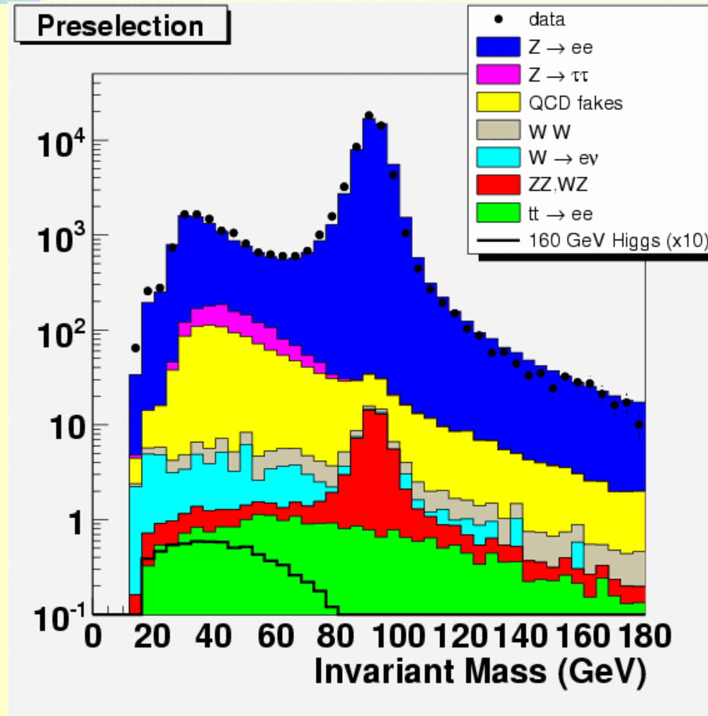
W+Jets:1 b-Tag



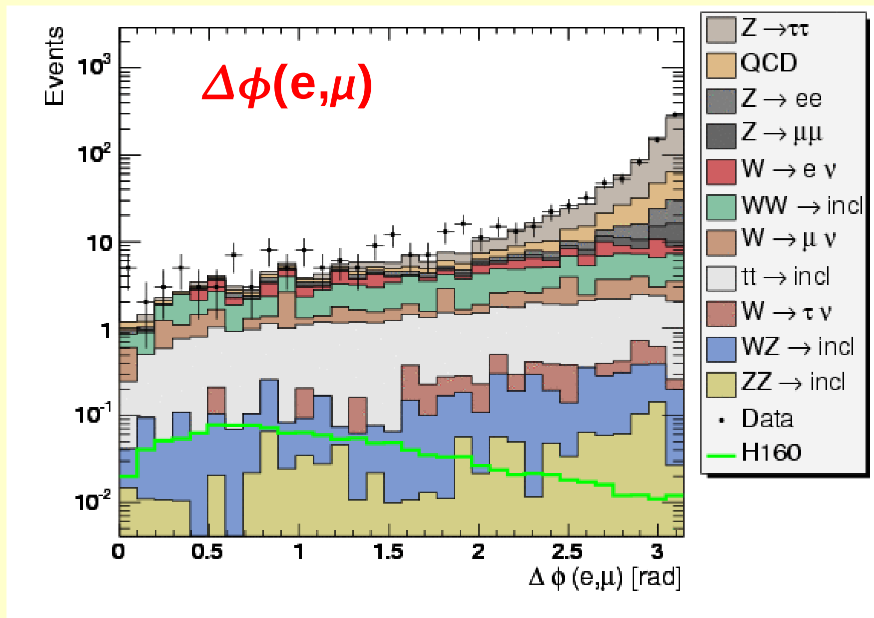
W+Jets: 2 b-Tags



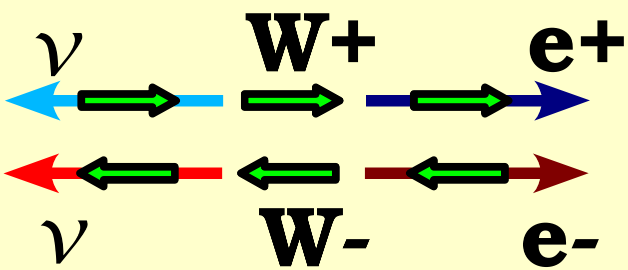
Searching for H→W^+W^-



- ✗ Select only leptonic W-boson decays
  - Select high-pT leptons (electrons & muons)
  - Use Z-peak for normalization (ee/$\mu\mu$), veto region near peak
  - Require large missing transverse energy signature from neutrinos, restrict sum of MET + lepton pT (scalar and vector)
  - Preselection removes W/Z+jets, but Standard Model W^+W^- production remains

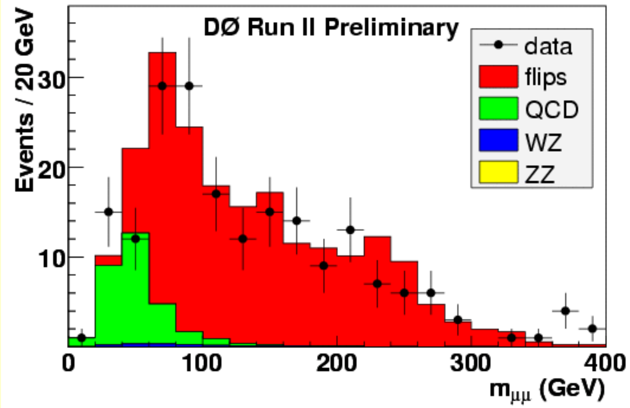


- ✗ Scalar higgs (spin-0) provides natural discrimination due to spin correlation
  - Leptons prefer to be collinear

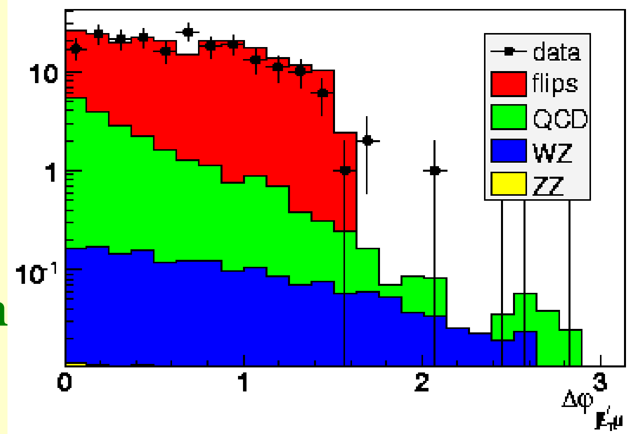


Searching for WH→WW⁺W⁻

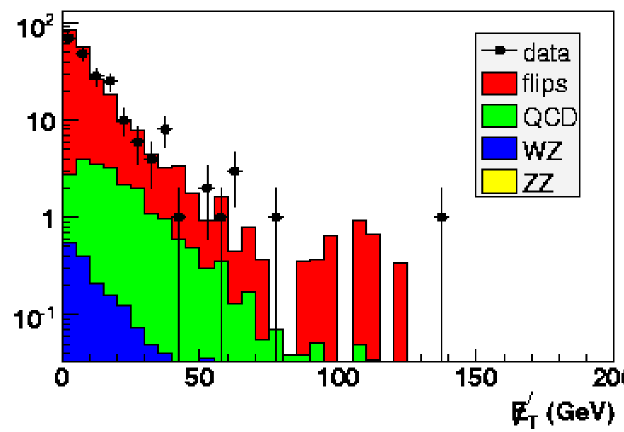
- ✗ Very rich spectrum in leptons
  - Three W-bosons give 1-,2-,3-lepton final states
  - First version of analysis reduces backgrounds by selecting same-signed lepton final states
  - Di-lepton mass, angles, MET all good discriminators



- ✗ $WH \to l^{\pm}l^{\pm}+X$ has few backgrounds
  - Physics Bkgds: WZ, ZZ, W+jets (*fake lepton*)
  - Instrumental Bkgds: QCD (*fake leptons*), charge-sign "flips"

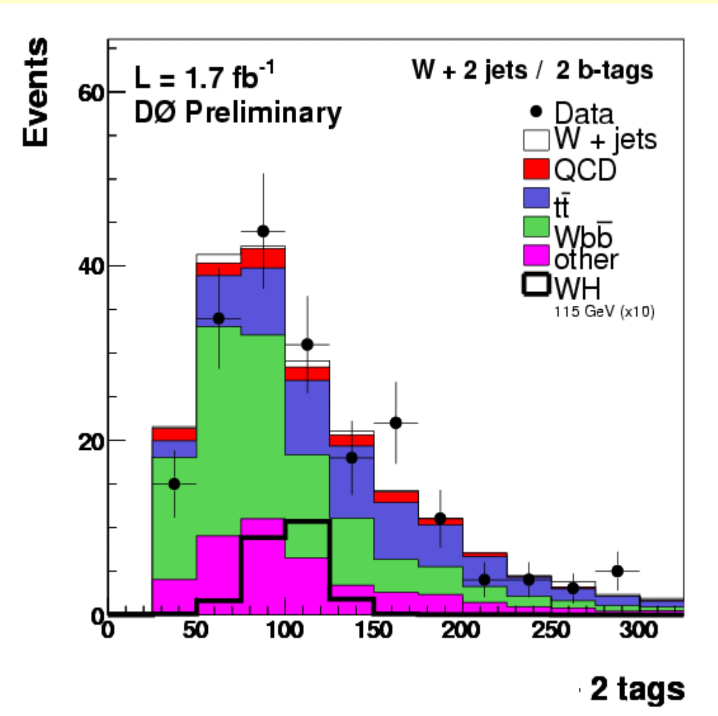


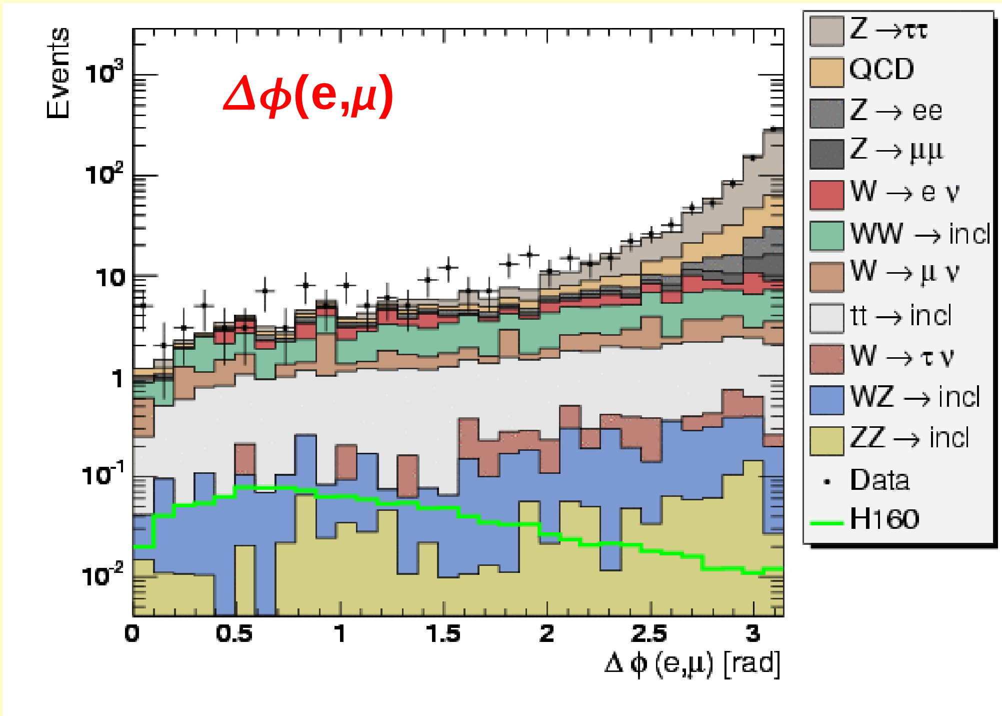
- ✗ Instrumental backgrounds carefully measured
  - Flips: Use multiple sign measurements for orthogonal "non-Z" events. Diagonalize matrix of Same-Same, Opposite-Same, & Opposite-Opposite events



Final Variables

- In the past, analysis challenges forced analyses to estimate search sensitivity from single kinematic variables
  - Data/MC agreement, sample statistics, background uncertainties
- Significant reduction in potential search power
  - Low mass: Dijet invariant mass
  - High mass: Dilepton angular separation

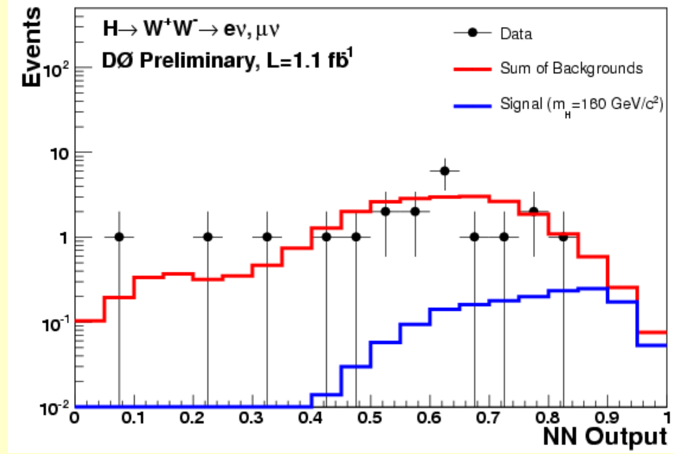




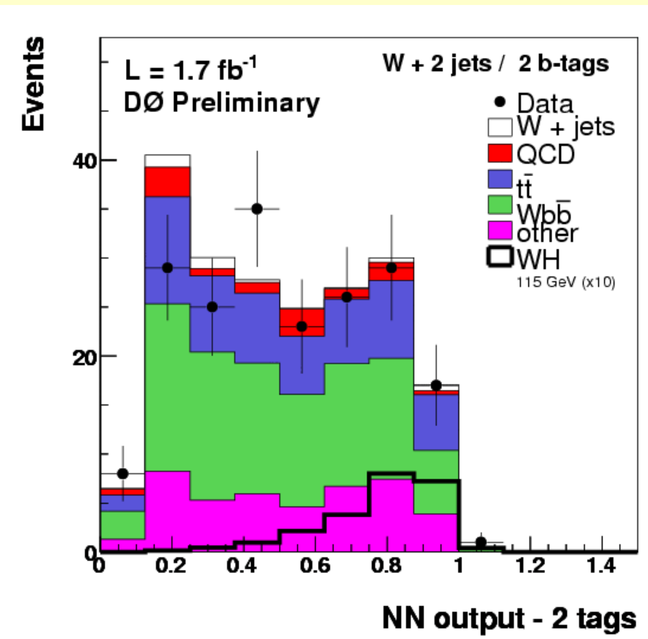
Advanced Analysis Techniques

- ✗ Several multivariate approaches have emerged
  - Neural networks, likelihood discriminants, Matrix Element discriminants
  - Techniques demonstrate 20-50% improvement in signal isolation
    - *Analysis refinement & optimization still ongoing*

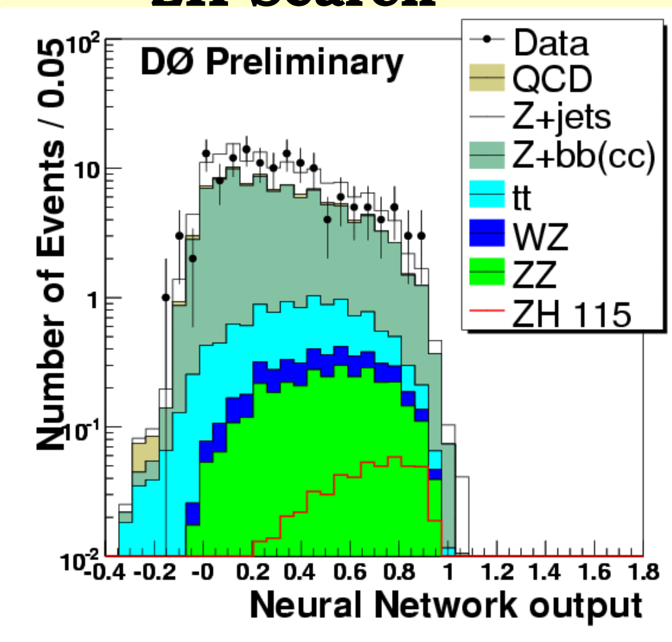
H→WW Search



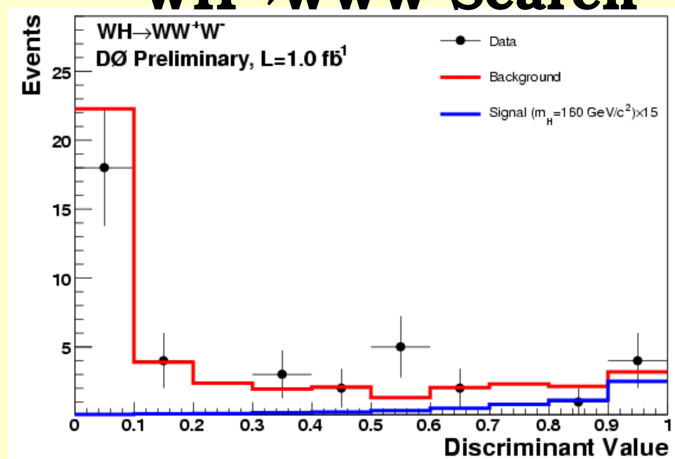
WH Search



ZH Search

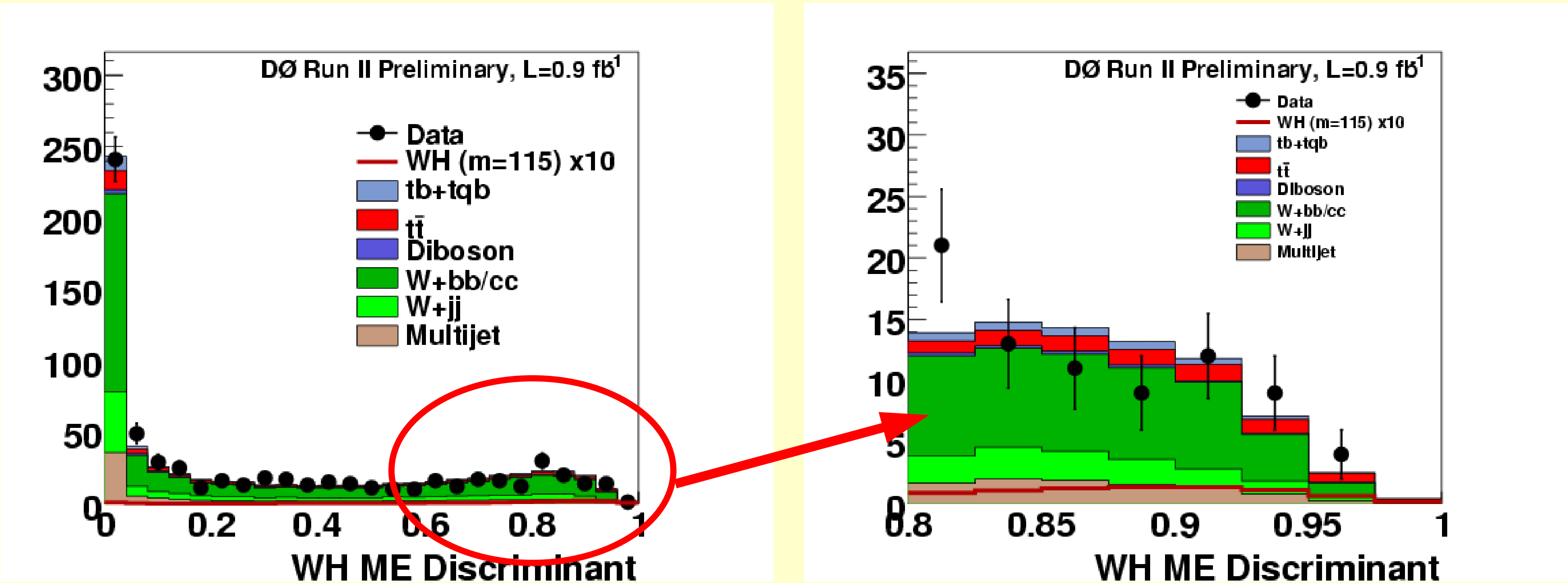


WH→WWW Search



Advanced Analysis Techniques

- “Matrix Element” analysis technique
  - Developed in Tevatron top-quark search/measurements
    - *Utilized in both CDF, DZero single top quark & Higgs analyses as well*
  - Use signal/bkgd production Matrix Elements (tree-level) to form likelihood discriminant: *over 35% improvement in sensitivity*!
  - Can be combined with complementary analysis techniques



Summary of Analyses

- ✗ WH→lvbb: ev, mv, single-tag, double-tag
  - RunIIA+RunIIB: 1.7 fb^{-1} (4 analyses)
- ✗ ZH→vvbb: ZH and WH(missing lepton) signals
  - RunIIA: 0.95 fb^{-1} (1 analysis)
- ✗ ZH→llbb: ee + mm, single-tag, double-tag
  - RunIIA: 1.1 fb^{-1} (4 analyses)
- ✗ H→WW: ee, em, mm
  - RunIIA+RunIIB: 1.7 fb^{-1} (3 analyses)
- ✗ WH→WWW: ee, em, mm
  - RunIIA: 1.0 fb^{-1} (3 analyses)

15 analysis channels, 11 Higgs decays!

Testing the Higgs Hypothesis

- ✗ Assuming we've assembled all the pieces properly, proceed to test our two hypotheses: **H0** and **H1**
- ✗ Tevatron ⇨ utilize both Bayesian and as-Frequentist-as-possible treatments
  - Uncertainty on nuisance parameters generally only has a Bayesian interpretation
  - Access to the subsidiary measurement isn't guaranteed, generally nuisance parameters are some number for which we apply a non-Frequentist belief distribution
- ✗ Bayesian treatment: choose an appropriate prior and integrate likelihoods over nuisance parameters
  - Choice of prior: flat in non-negative number of expected signal events (Heaviside step function / Jeffrey's Prior)
- ✗ Semi-Frequentist approach (CLs): use likelihood ratio as a test statistic and simulate pseudoexperiments to populate distributions for **H0** and **H1**
  - Vary nuisance parameters according to their Bayesian credibility distributions in the pseudoexperiments to obtain the "prior predictive ensemble"

We find CLs usually gives slightly better sensitivity, and fewer coverage issues

The CLs Approach

- ✗ Adopt Bayes-type definition of confidence levels
  - This normalization can help remove ambiguity of poorly modeled bkgds

$$CL_s = 1 - \frac{CL_{s+b}}{CL_b}$$

Not a discovery tool!

- ✗ Use likelihood ratio for search test statistic
  - Distributions of simulated outcomes are populated via Poisson trial with mean values given by b-only or s+b
  - Systematics are sampled for each Poisson trial, correlations propagated

$$Q(\vec{s}, \vec{b}, n_{cand}^{\rightarrow}) = \prod_{i=0}^{N_{Channels}} \prod_{j=0}^{N_{bins}} \frac{(s+b)_{ij}^{n_{ij}} e^{(s+b)_{ij}}}{n_{ij}!} / \frac{b_{ij}^{n_{ij}} e^{b_{ij}}}{n_{ij}!}$$

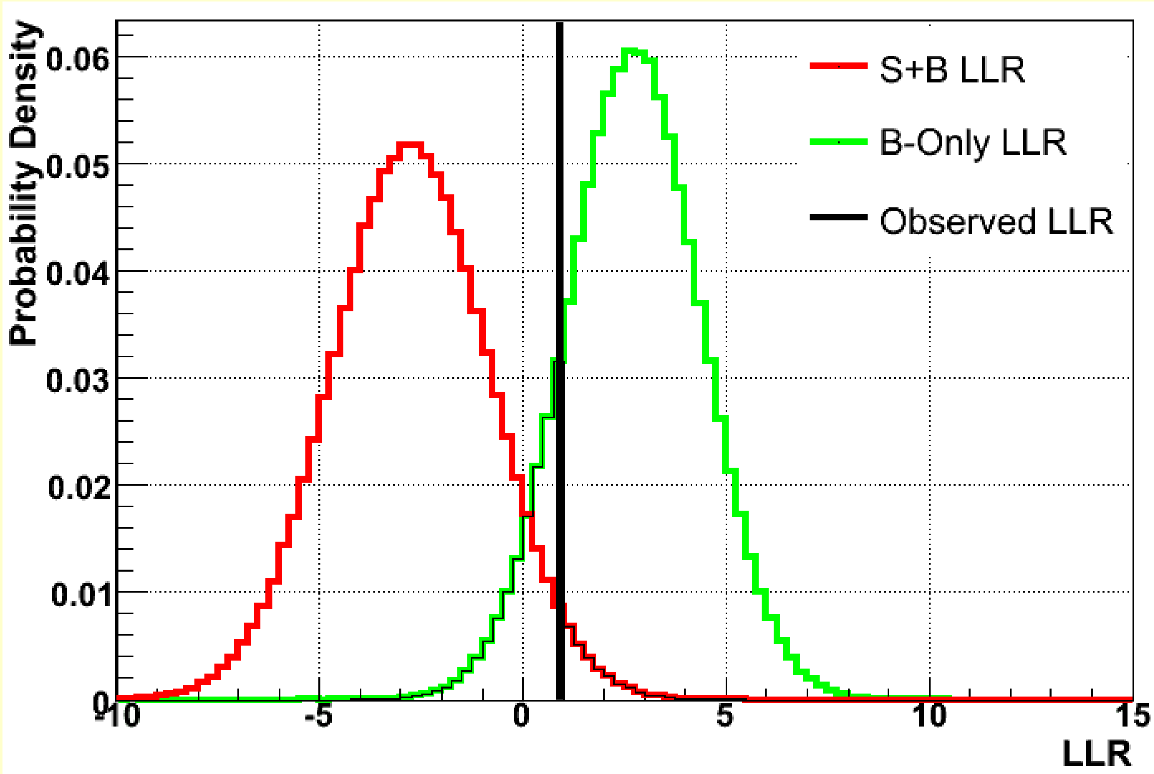
  - Log likelihood ratio monotonic in number of candidate events

$$-2\ln(Q) = 2s_{tot} - 2 \sum_{i=0}^{N_{Channels}} \sum_{j=0}^{N_{bins}} n_{ij} \ln\left(1 + \frac{s_{ij}}{b_{ij}}\right)$$

CLs in Pictures

- ✗ Model repeated outcomes of the experiment via Poisson distribution
  - Simulate Signal+Bkgd and Bkgd-Only outcomes based on predictions
  - Uncertainties on nuisance parameters folded in via Gaussian smearing

- ✗ **Black line: Observed LLR value (LLR_{obs})**
  - **Determined by data**
- ✗ **Green: Bkgd-only hypothesis**
  - **CL_b is region to right of LLR_{obs}**
  - **Equals ~50% for good bkgd/data agreement**
- ✗ **Red: Signal+bkgd hypothesis**
  - **CL_{s+b} is region to right of LLR_{obs}**



CLs in Pictures

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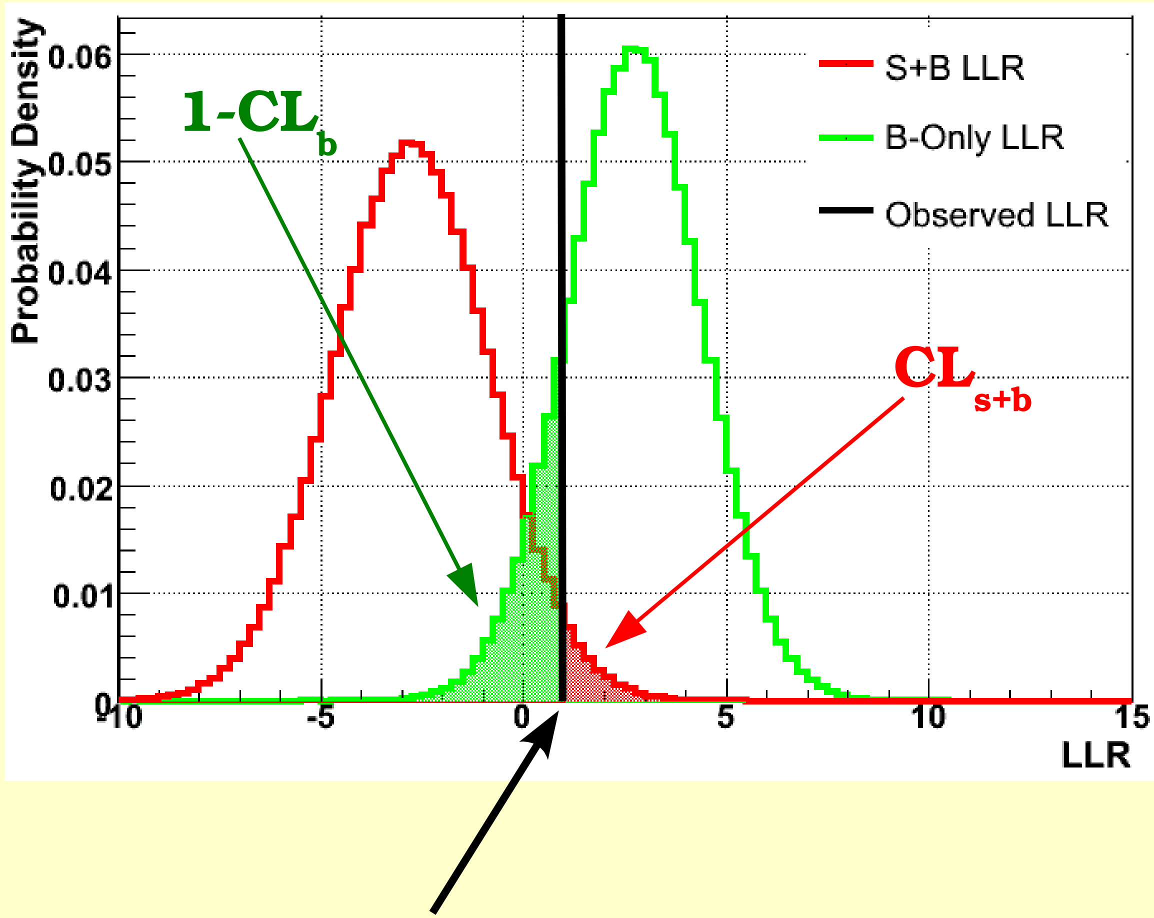


"Data excess" scenario

Profile Likelihood

- Now we can get serious about systematics and limits
  - First define the best fit of our MC model to data
    - **Assume background transforms as:** $\hat{X}_i = X_i \prod_k (1+\sigma_i^k S_k)$
    - **Where S_k has a mean of 0 and width of 1 (*unit Gaussian*)**
  - Our "*educated guesses*" to size of uncertainties must be taken into consideration along with data/MC shapes
    - These can (should) be limited via our previous discussion
    - Need to change our estimator to penalize departures from input distributions
  - Minimize estimator by varying S_k values!
  - Likelihood now a function of nuisance parameters

$$\chi^2 = 2\sum_i (\hat{X}_i - D_i) - D_i \ln\left(\frac{\hat{X}_i}{D_i}\right) + \sum_k S_k^2$$

Sidebands in CLs

- The CLs approach does not have sideband constraints *a priori*
  - But we'd still like to benefit, otherwise significance can be severely degraded via marginalization
  - Several solutions exist in statistical literature, we choose to maximize likelihoods over nuisance parameters:

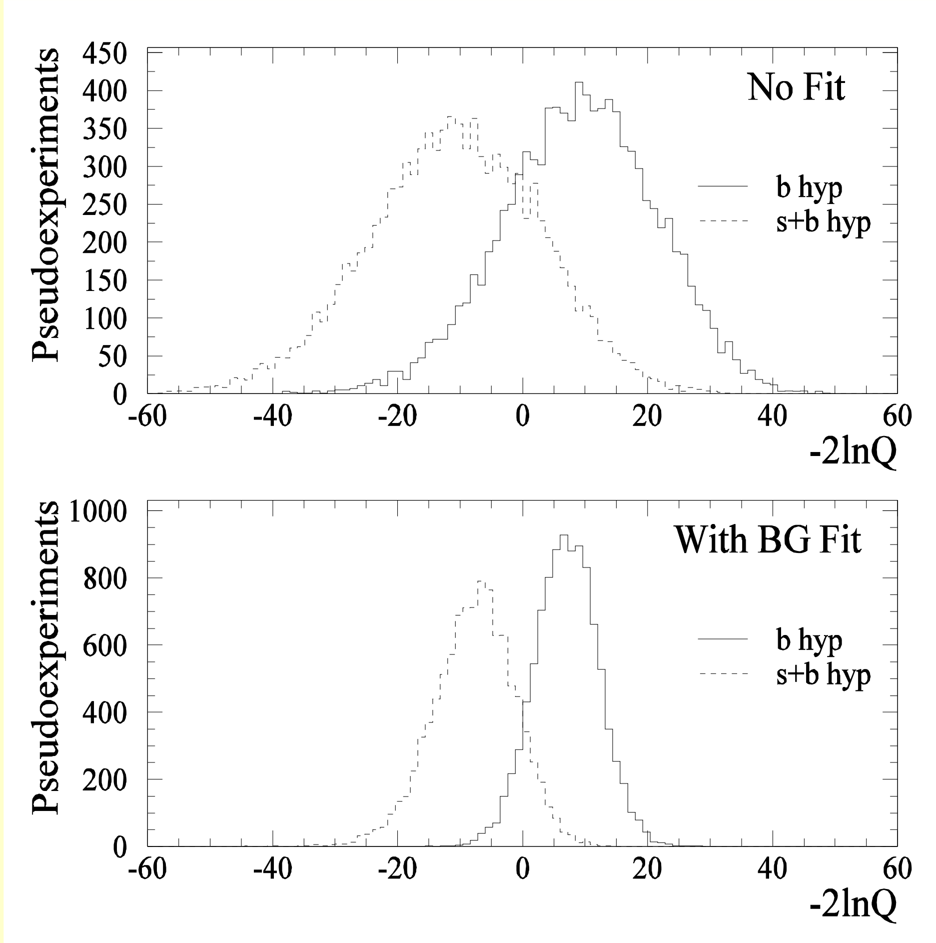
$$Q = \frac{L(x|\theta_{R1}, \hat{\theta}_S)}{L(x|\theta_{R0}, \hat{\hat{\theta}}_S)}$$

Two maximizations performed independent of physics parameters, once for each pseudoexperiment

- θ_{R1} : Physics parameters in **H1**, θ_{R0} : Physics parameters in **H0**
- $\hat{\theta}_S$: Nuisance parameters which maximize L for **H1**
- $\hat{\hat{\theta}}_S$: Nuisance parameters which maximize L for **H0**
  - If sidebands are unambiguous, optionally maximize just once per pseudoexperiment – introduces bias in sideband selection

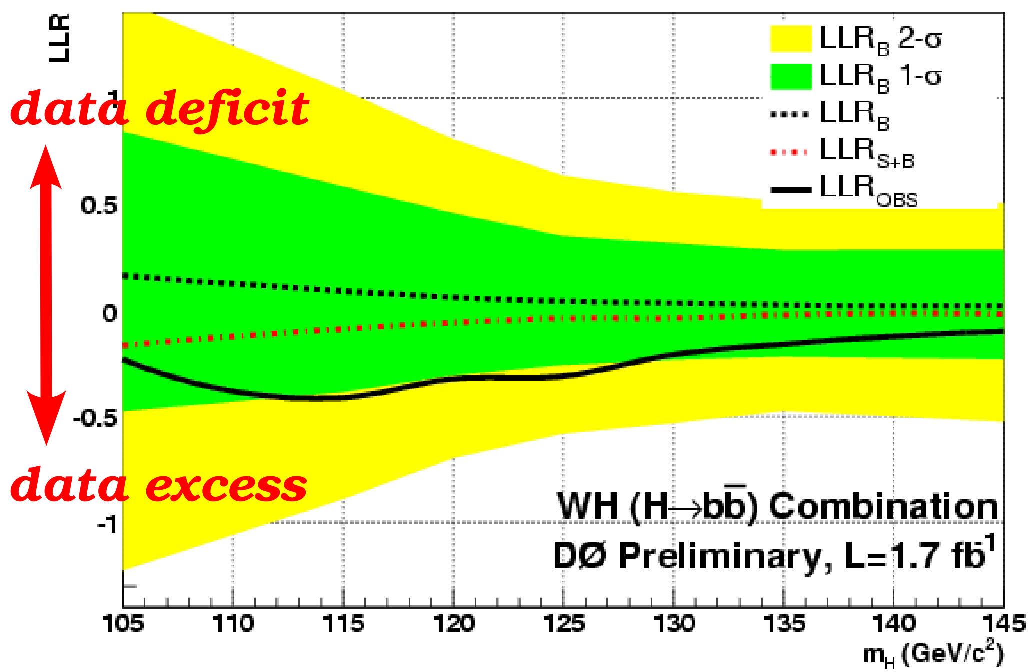
Maximum Likelihood Fits

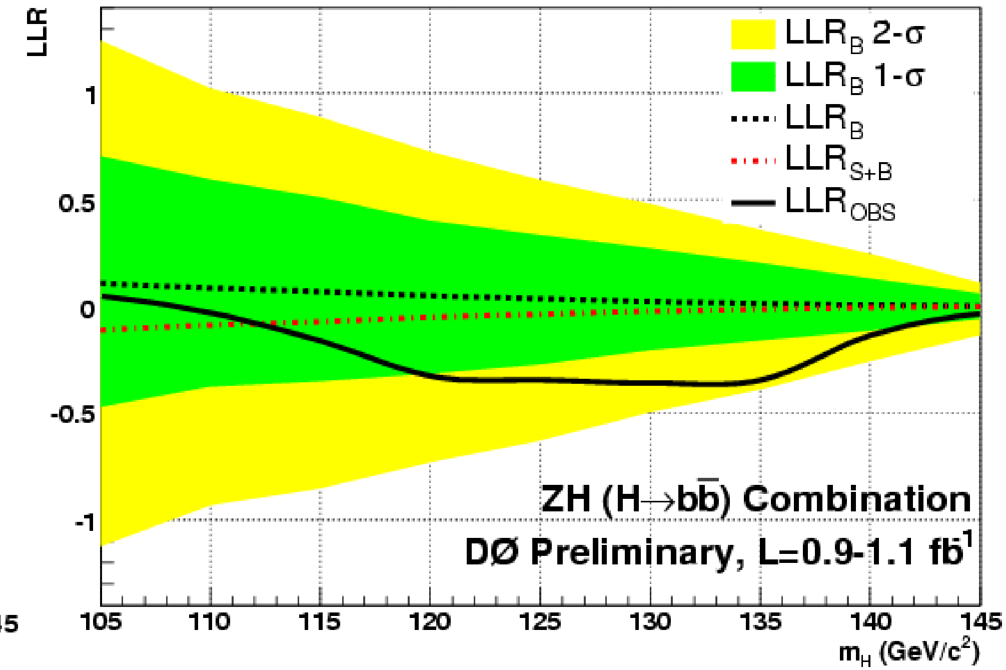
- Nominally, finding best fit for nuisance parameters makes both **H1** and **H0** match the data better
- In practice, improves separation of **H1** and **H0** in -2lnQ distributions: effective constraint on size of nuisance parameter uncertainty
  - We rely on MINUIT for fitting, assume same answer for identical problems

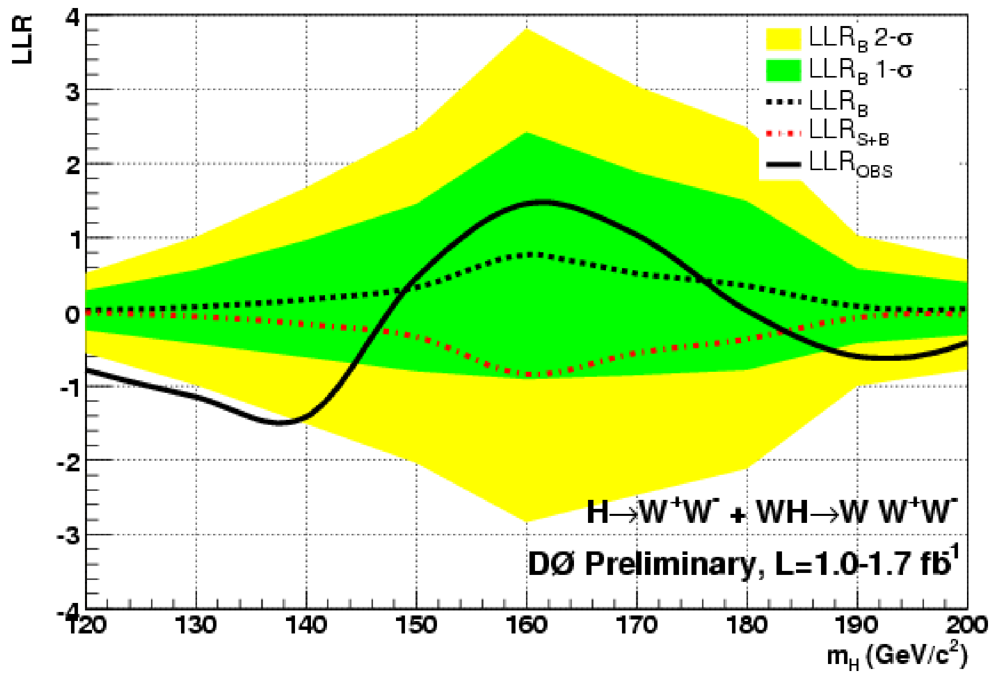


- Question: Doesn't this mean your uncertainties are overestimated?
- Answer: In many cases this is true, but subsidiary experiments for constraint are often unavailable.

Individual Channel Results

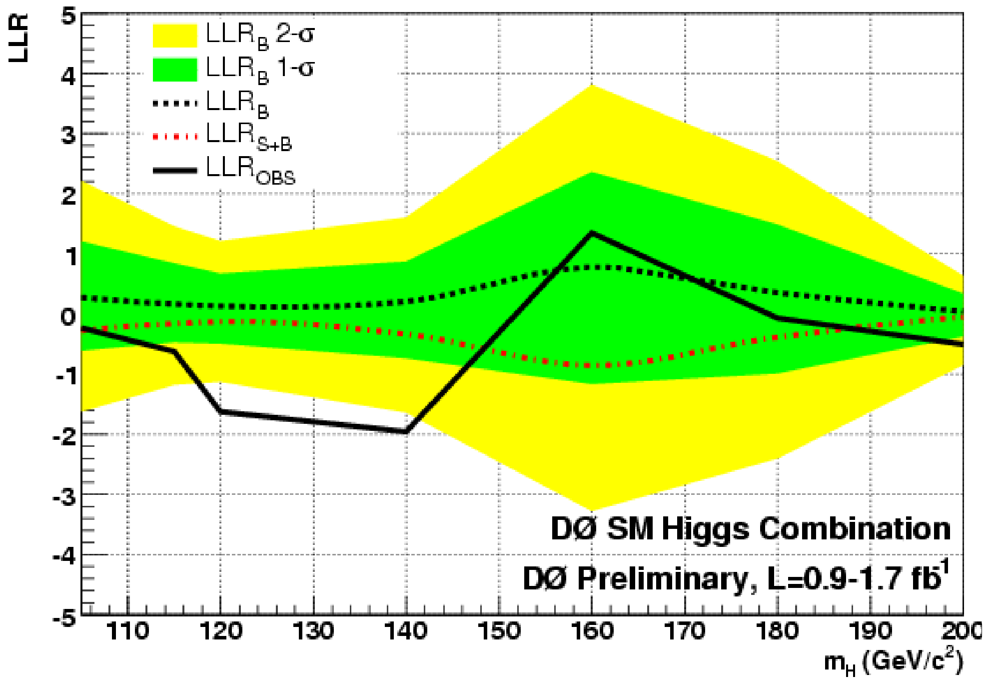


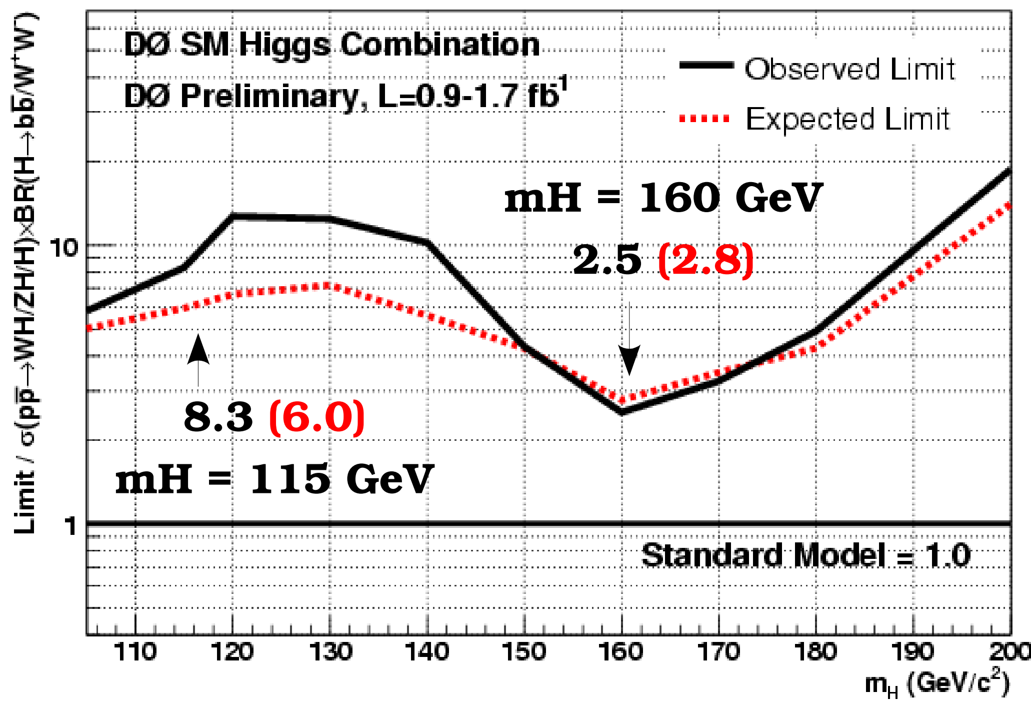




- LLR profile vs Higgs mass
  - Dashed lines show **S+B** and **B-Only** mean value
  - Shaded bands indicate 1- and 2-σ variation of B-only distribution
  - Solid black line indicates **data observation**

Limits on Higgs Production





Combined results for 15 analysis channels covering 0.9-1.7 fb^{-1}

Results reported as ratio of 95% CL limit on σ×BR to standard model expectation ⇒ Sensitivity to SM achieved when R≤1.0

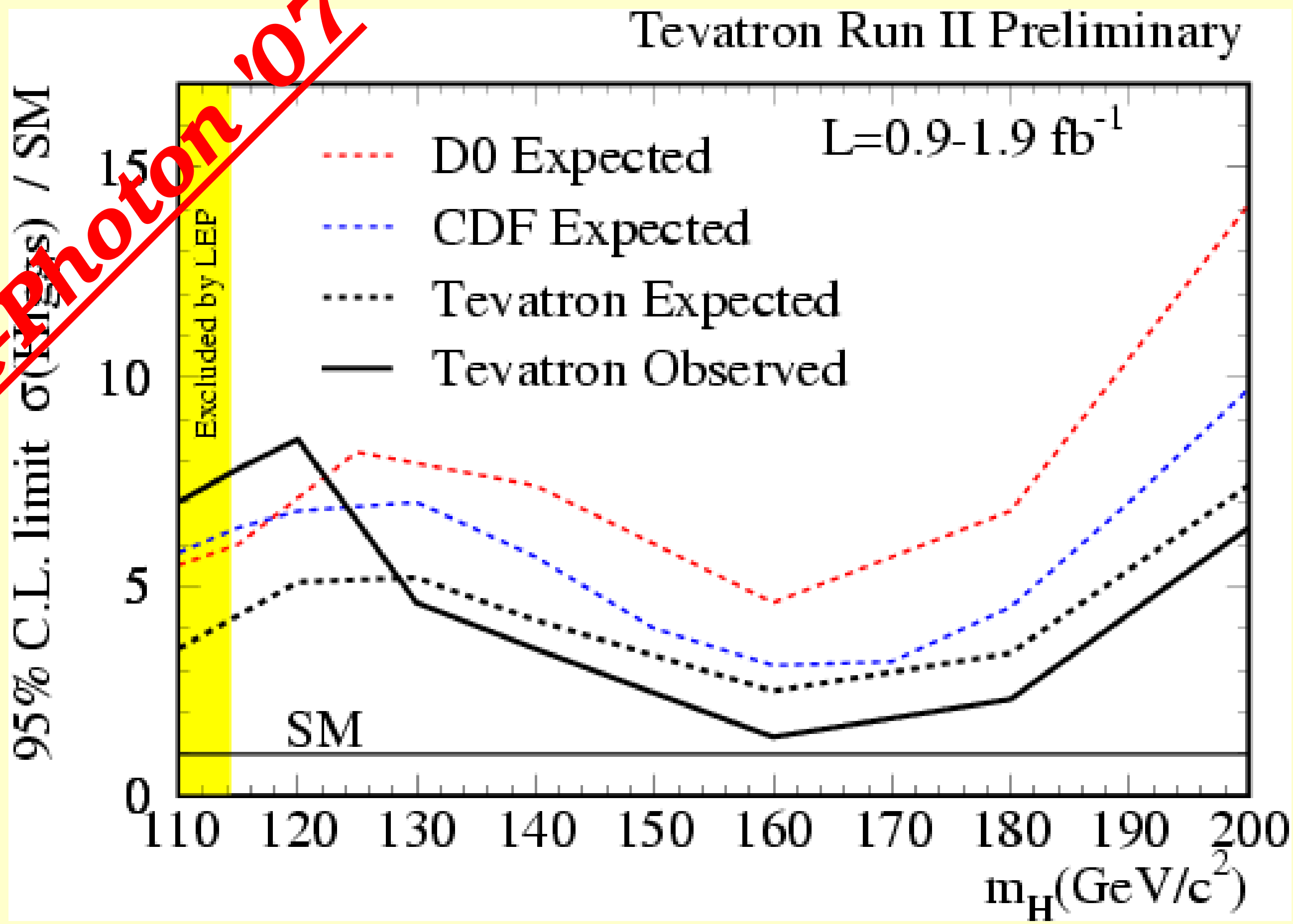
Analyzed luminosity depends on analysis channel & understanding of bkgds

Combined Tevatron Limits

CDF+DZero combination evaluated by the *Tevatron Higgs Working Group*

- CDF adds similar search sensitivity in all analysis channels
- Total luminosity per channel varies between experiments: "snapshot" of progress

Lepton-Photon '07



Obs (exp) = 7.8 (4.3) @ mH = 115 GeV

Obs (exp) = 1.4 (2.5) @ mH = 160 GeV

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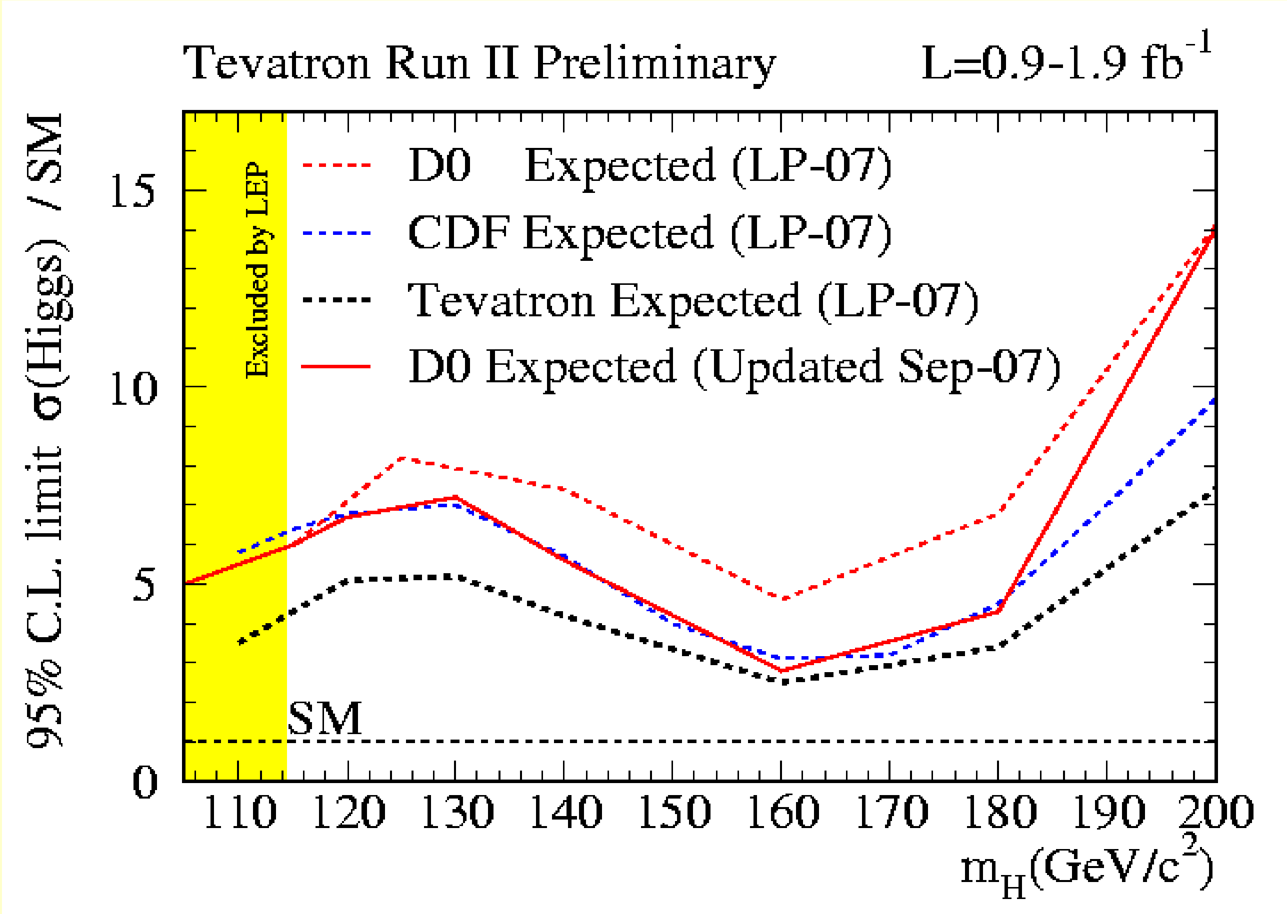


Obs (exp) = 7.8 (4.3) @ mH = 115 GeV

Obs (exp) = 1.4 (2.5) @ mH = 160 GeV

Missing Pieces

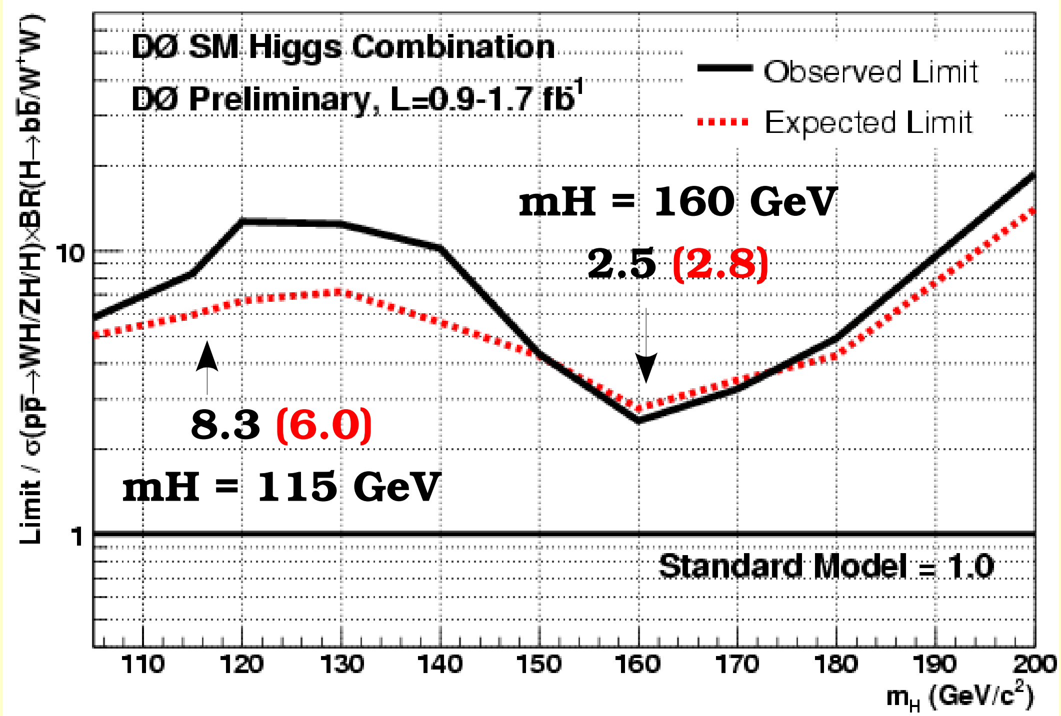
General Issues

Many channels systematics-limited: growing dataset reduces uncertainties

More powerful analysis techniques become feasible with growing dataset

Currently have only ~55% of desired branching fraction

Recovery of efficiency via fiducial volume



Low Mass Higgs (H→bb)

Dijet mass resolution drives sensitivity

ZH→ννbb: Only using 0.9 fb^{-1}, updated analysis in approval process

WH→τνbb: Analysis under development

High Mass Higgs (H→WW)

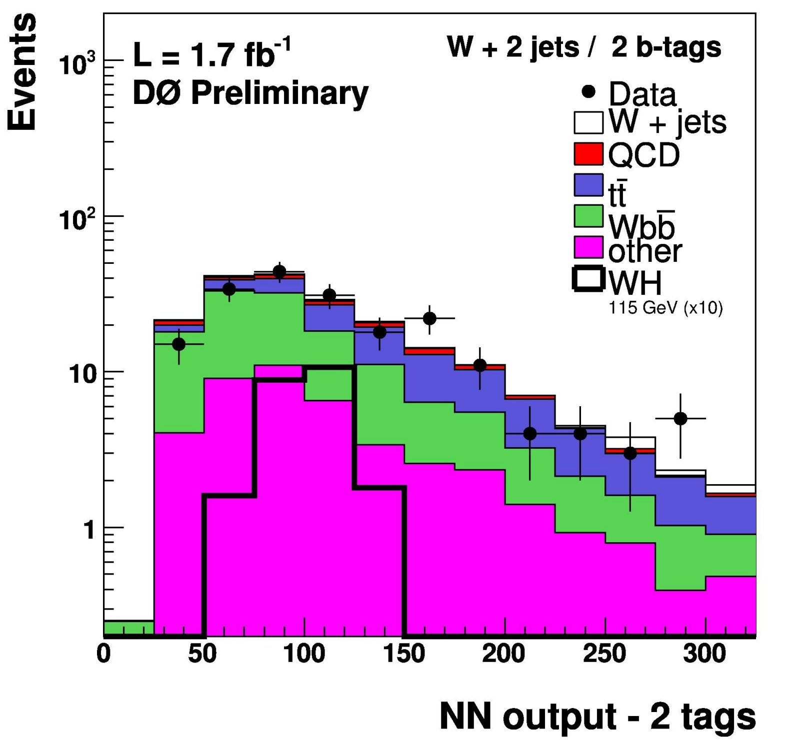
Initial neural network treatment suboptimal

Tau channels and hadronic W decay analyses under development

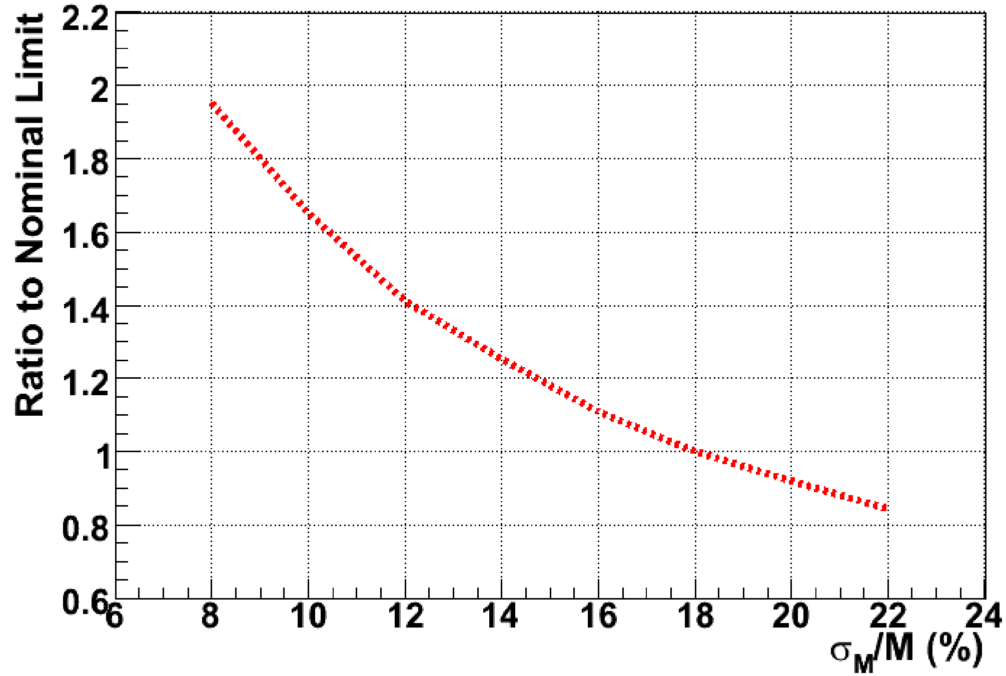
Major Challenges

- ✗ Low mass: dijet mass resolution
  - Still dominant variable in NN & ME analysis techniques
- ✗ Currently at ~18% ⇒ goal closer to 10%
  - Studies indicate ~14% is achievable soon
    - *Largely determined by calibration of calorimeter*

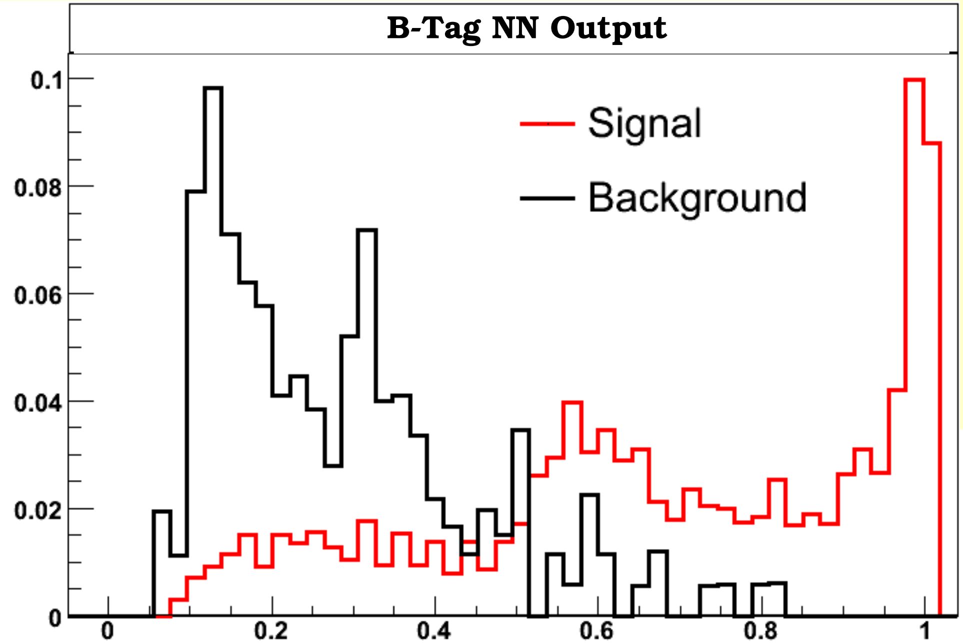
NN-Weighted Dijet Mass



Effective Lumi

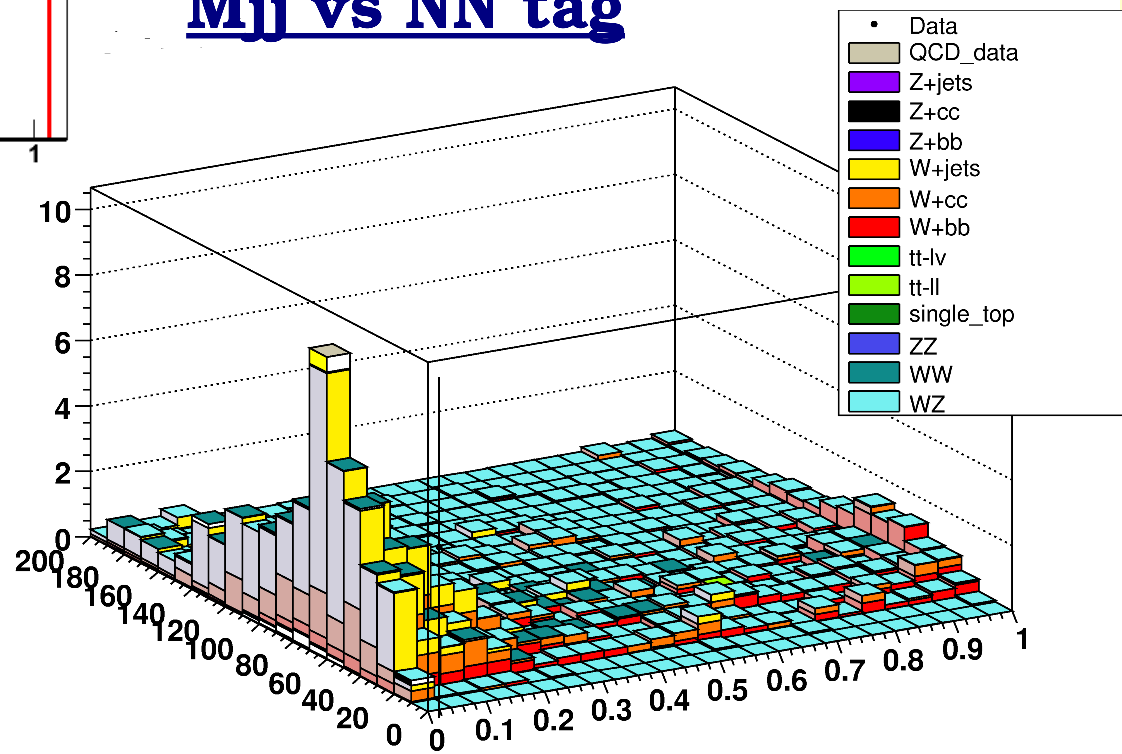


Major Challenges



✗ Low mass: b-Tagging

Mjj vs NN tag

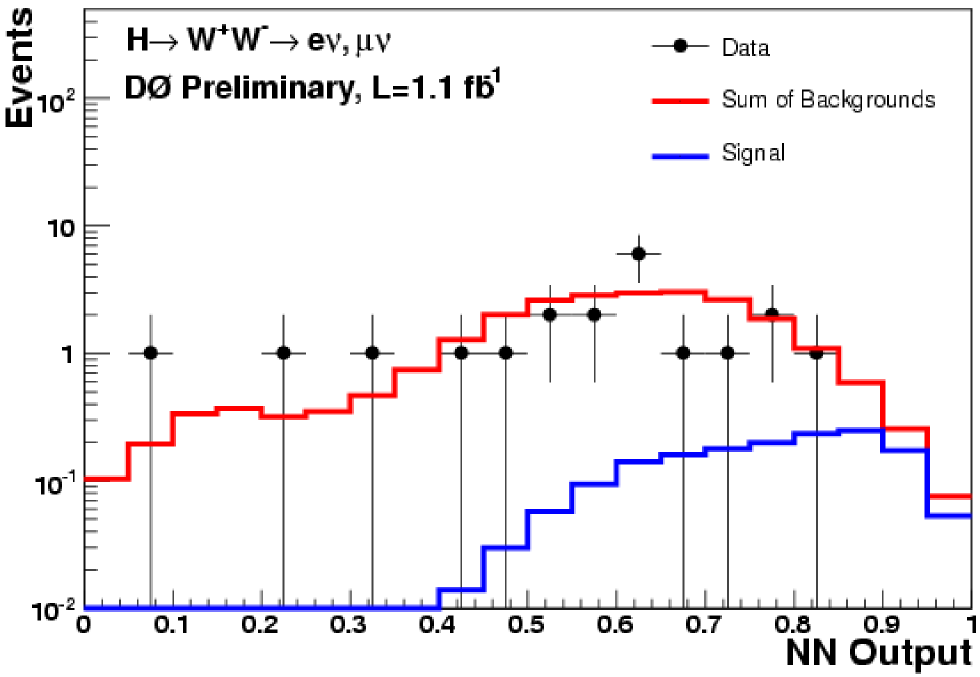


✗ Current b-Tag algorithm is NN based
- NN shape not used in analyses due to modeling of tracking
- Studies show ~30% improvement in sensitivity possible

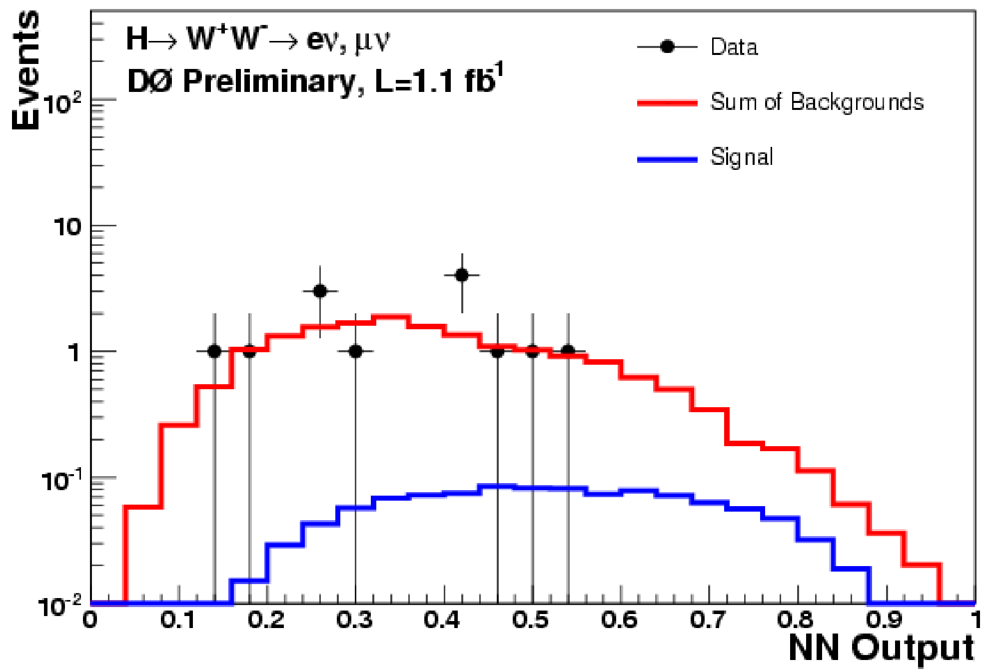
Major Challenges

- ✗ High Mass: uniform background reduction
  - Signal kinematics change significantly over $100<m_H<200$ GeV
  - Dominant background(s) change as a function of mass
  - More data statistics needed for careful optimization
- ✗ Studies indicate 20% improvement possible for $100<m_H<140$ GeV

mH=160 GeV



mH=140 GeV



Sensitivity Projections

Can project sensitivity as a function of analyzed luminosity

Analyzed luminosity = ~80% of delivered luminosity

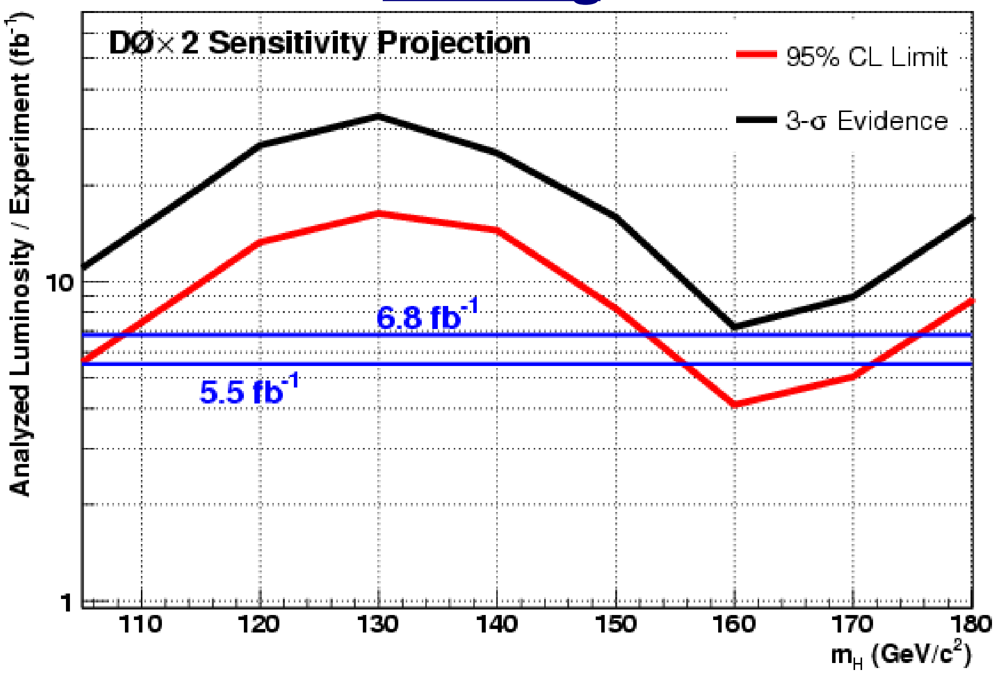
5.5 fb^{-1} = ~7 fb^{-1} delivered in 2009; 6.8 fb^{-1} = ~8.5 fb^{-1} delivered in 2010 *(if funded…)*

Two benchmark scenarios:

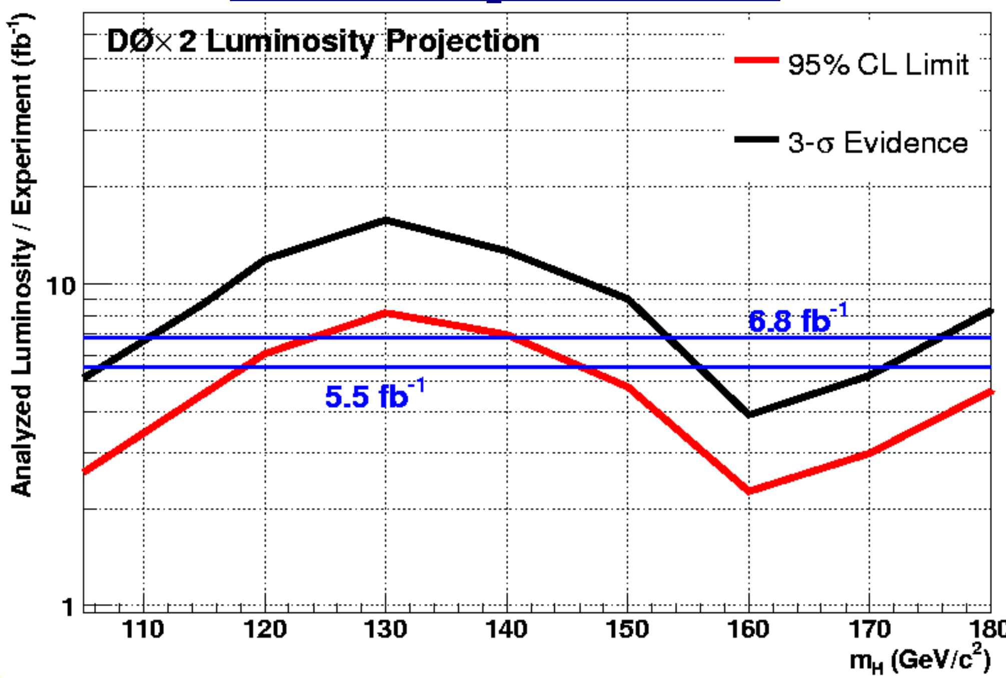
Coasting: no improvements beyond what we have TODAY

Known improvements: achieving potential for known sources of improvement

Coasting



Known Improvements



Sensitivity Projections

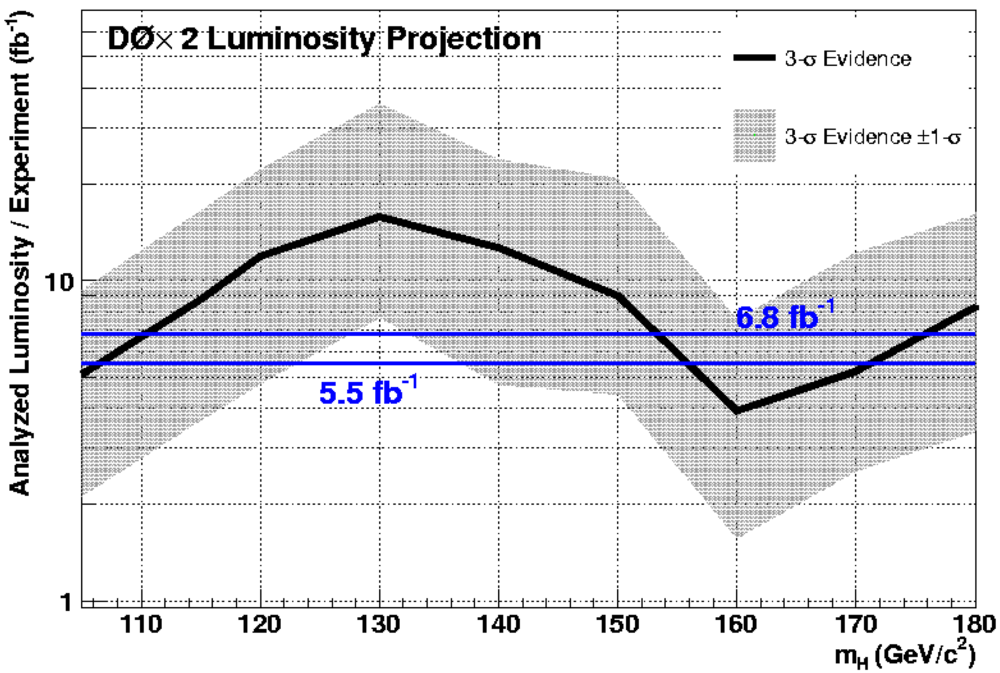
What if we're lucky (*or unlucky*)?

Shaded bands indicate regions enclosing 68% of simulated data outcomes

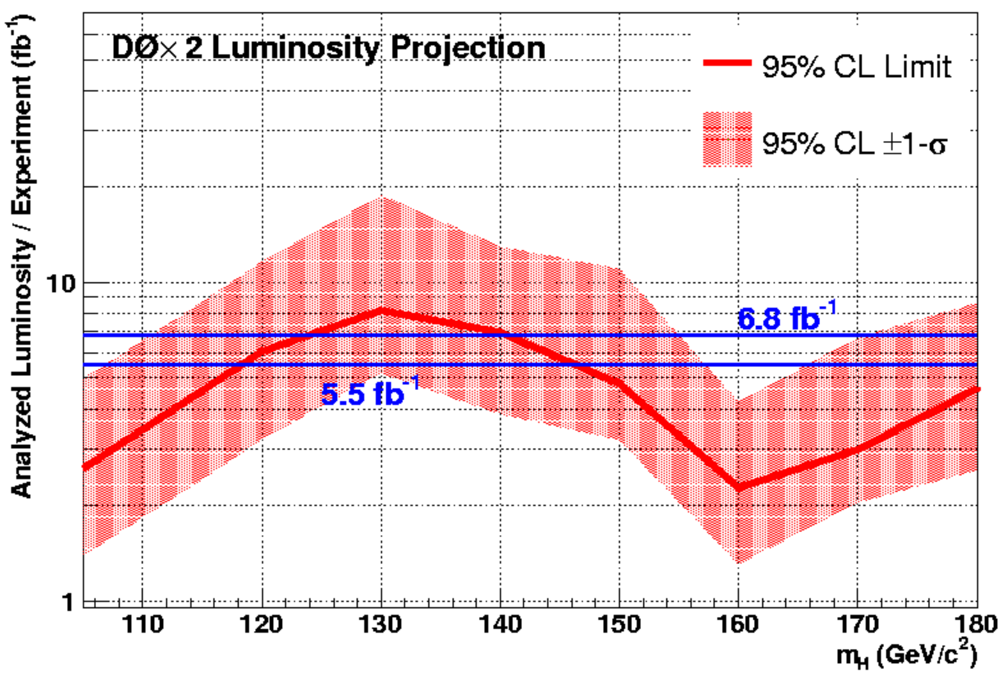
As expected, depends strongly on what we observe!

Region near mH=130 GeV still difficult…

3-Sigma Evidence



95% CL Exclusion



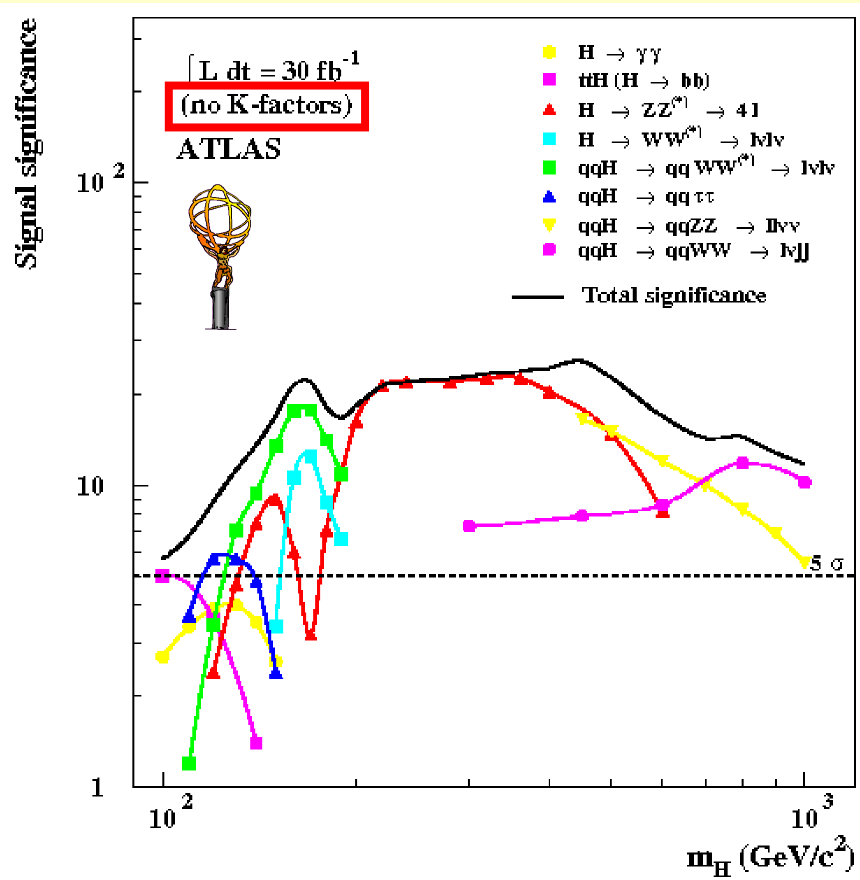
LHC Timescale

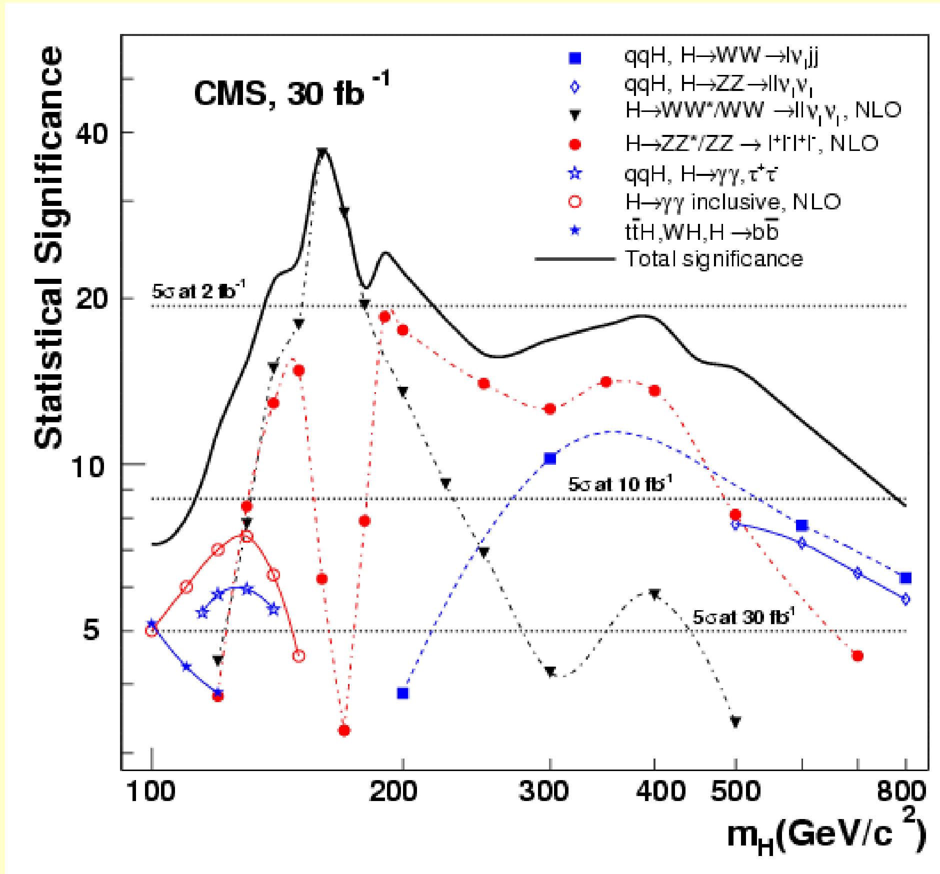
LHC predictions show broad discovery potential in 10 fb^{-1} (exclusion requires less)

Low mass Higgs is particularly challenging at LHC

First LHC Higgs search results should be available by summer to fall 2009

Tevatron search will be very mature at this point





Conclusions

- The Tevatron experiments have demonstrated a robust Higgs program in their first 2 fb^{-1} of recorded data
  - DZero Only: Observed limits at a ratio of **8.3** **(2.5)** to the SM at mH= **115** **(160)** GeV
  - Tevatron combined: Observed limits at a ratio of **7.8** **(1.4)** to the SM at mH= **115** **(160)** GeV
  - Expect 7-8 fb^{-1} by August 2009, more if 2010 running approved
  - Working to demonstrate "faster-than-lumi" increases in sensitivity

- New analyses and improvements frequently available
  - CDF & DØ will soon update low mass analyses, DØ will update at high mass, CDF will deliver $WH \rightarrow WWW$

- Higgs physics in Run II of the Tevatron is very exciting
  - Timing of first data from the LHC will make this an interesting race