Search for the Standard Model Higgs Boson Produced in Association with a W boson Using the Collider Detector at Fermilab

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Seminar Talk

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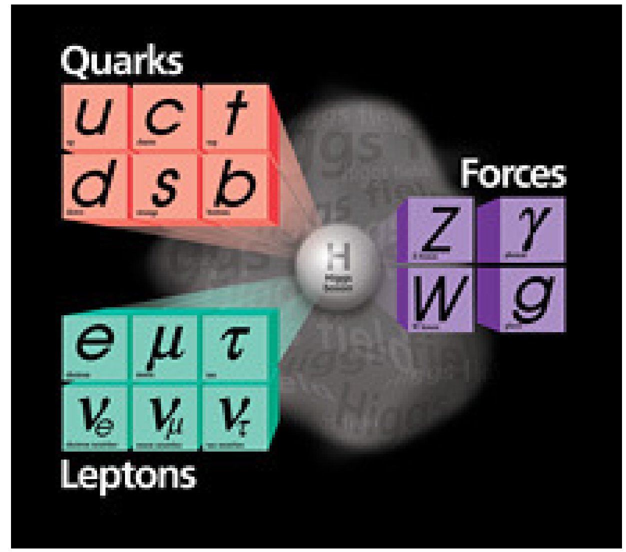
Talk Outline

- **Motivation**
  - Standard Model & Higgs Mechanism
  - Low Mass Higgs Boson & WH search
- **Analysis Description**
  - Analysis Strategy
  - Isolated-Track Charged Lepton Candidates
  - Novel Method to Combine Triggers
  - Event Selection, Discriminants and Limit Calculation
- **Results and Discussion**
  - Upper Limits on SM Higgs Boson
  - Future Plans
  - Conclusion

The Standard Model

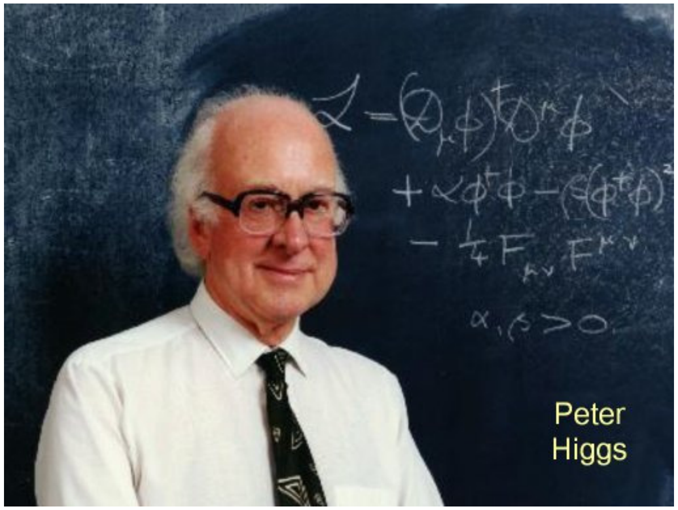
- **Describes the elementary particles and interactions**
  - Most precise human theory
  - Fermions and gauge bosons
  - One element is still missing



- **The origin of mass**
  - Photon is massless, Z^0 is massive
  - Massive W boson and fermions
  - Origin of electroweak spontaneous symmetry breaking?
- **The Higgs mechanism – the simplest solution**
  - Introduced in 1964 by Peter Higgs and others
  - Prediction: A scalar Higgs field and a scalar Higgs particle

The Higgs Boson

- Not yet discovered or refuted
- Characterized only by its mass
- Interaction couplings
  - with elementary particles proportional with their mass



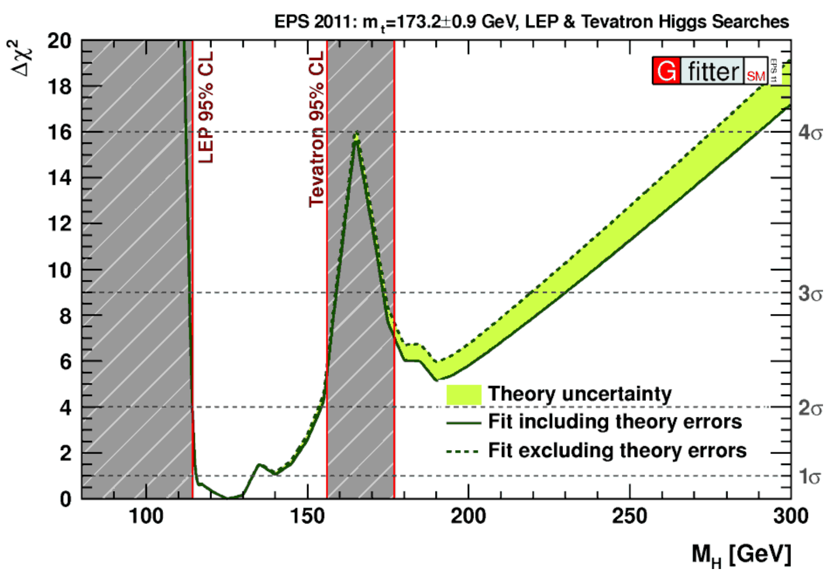
- Decay
  - Branching ratios depend only on Higgs boson mass
- Production
  - Cross sections decrease with Higgs boson mass
  - Also depend on experiment (centre-of-mass energy)
- Higgs Hunting
  - Ongoing since 1970s, but finally we are within reach!

Low Mass Higgs Motivation

McGill

- Higgs boson characterized only by its mass (in GeV/c^2)
- Direct and indirect searches excluded at 95% CL
  - Direct LEP: [0,114.4] and Tevatron: [100.0 -104.5] & [156.7-173.8]
  - Indirect Electroweak Fits from GFitter collaboration
    - Most probable value: 125+8-19 GeV/c^2
    - Upper bound at 154 GeV/c^2

Numbers from Lepton-Photon 2011!



  - Direct ATLAS: [146-232] & [256-282] & [296-466]
  - Direct CMS: [145-216] & [226-488] & [310-400]
    - ATLAS and CMS not included in GFitter yet

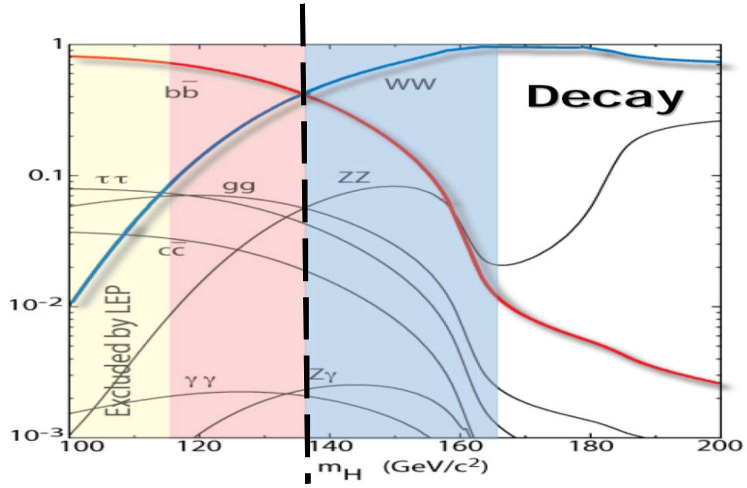
- All these point to a very low mass Higgs boson (if any)

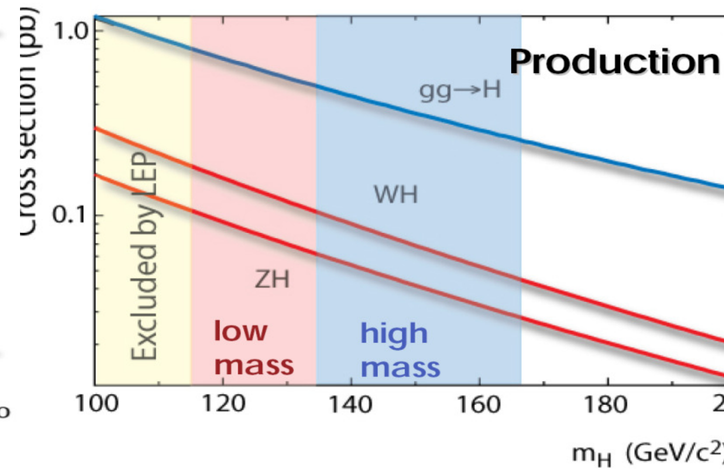
WH Search

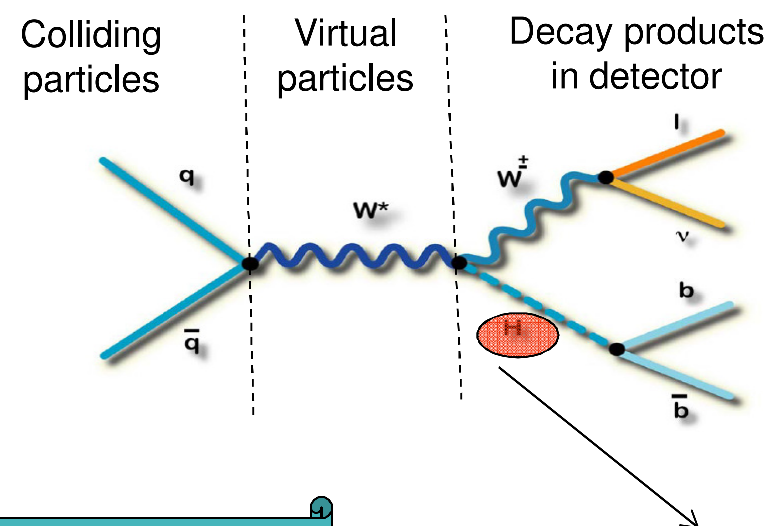
Low Mass Higgs

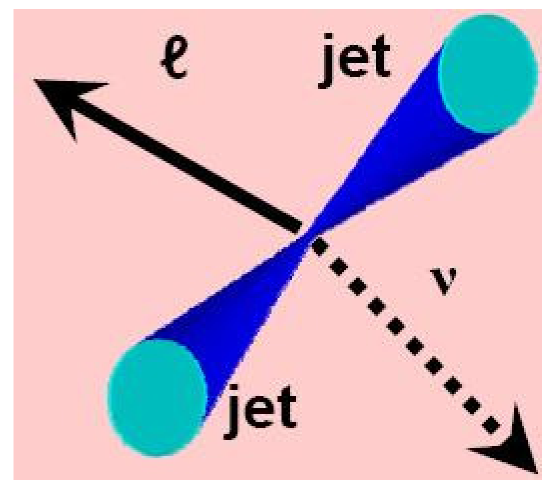
Higgs decay to bottom quark pairs

WH Associated Production







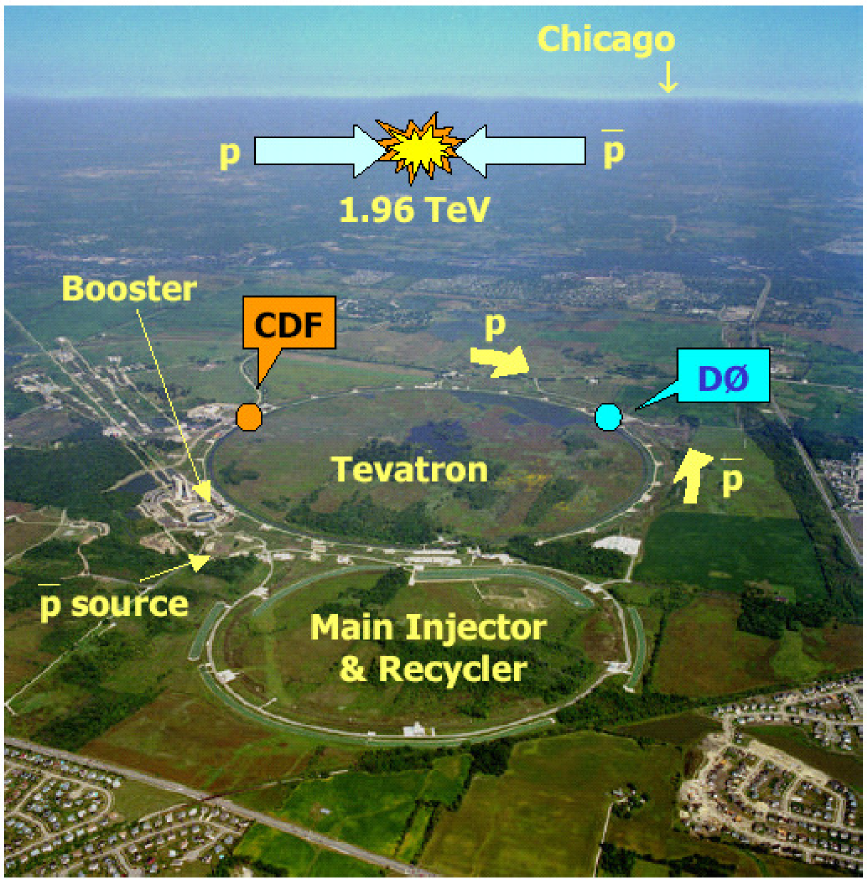


Also ZH ⟶ llbb where one charged lepton is lost

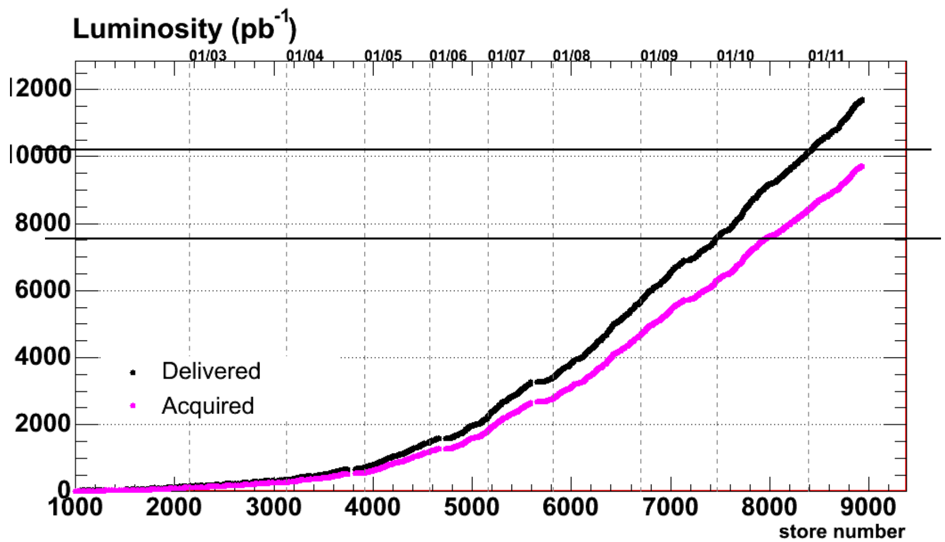
Higgs Particle (H)
Elementary particle as massive as heavy atoms

Tevatron Collider

- Each second: 2.5 million collisions; ~ 100 get saved
- Performed admirably for 25 years; will stop on 30 Sept 2011

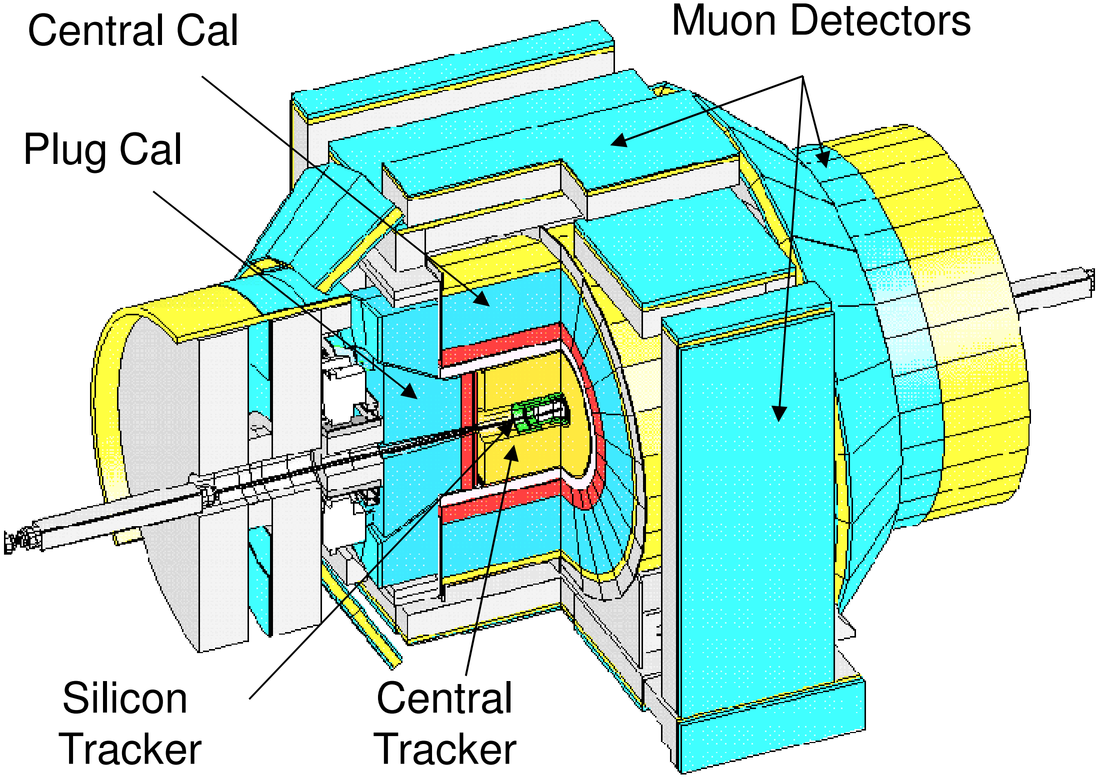


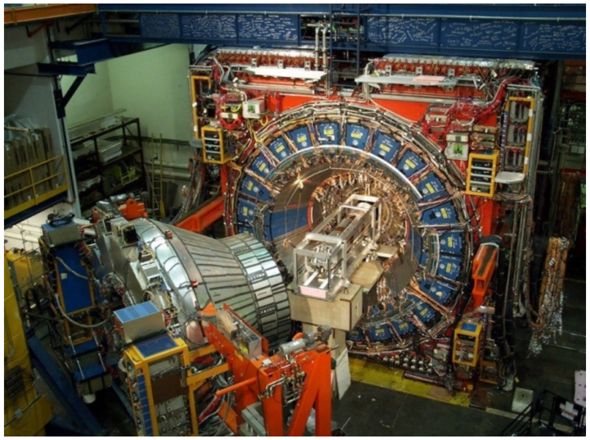
- This talk: July 2011: 7.5 fb^{-1}
- Final Dataset: Sept 2011 ~ 10 fb^{-1}



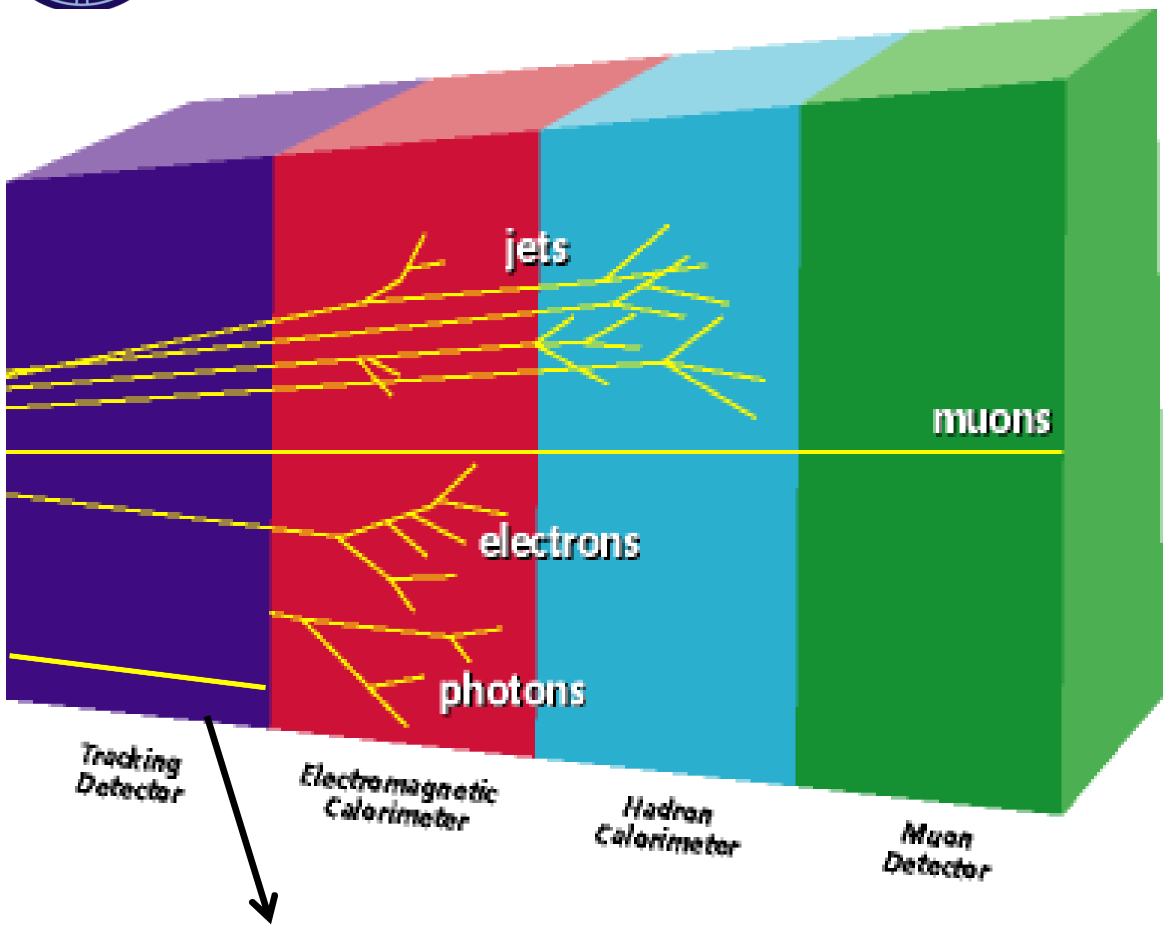
Collider Detector at Fermilab

- General purpose particle detector
- Azimuthal symmetry (cylindrical): central barrel and two forward plugs
- Layers of subdetectors (tracking, calorimeters, muon)



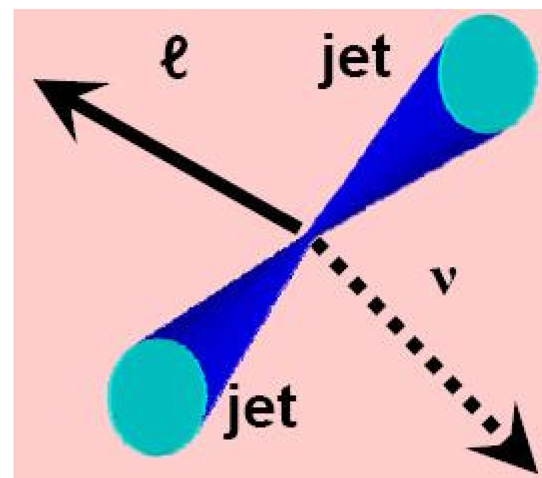


Particle Reconstruction



Isolated-Track Charge Lepton (my own contribution)

- One charged lepton (electron, muon or isolated track)
- Missing transverse energy
- 2 jets originating from bottom quarks

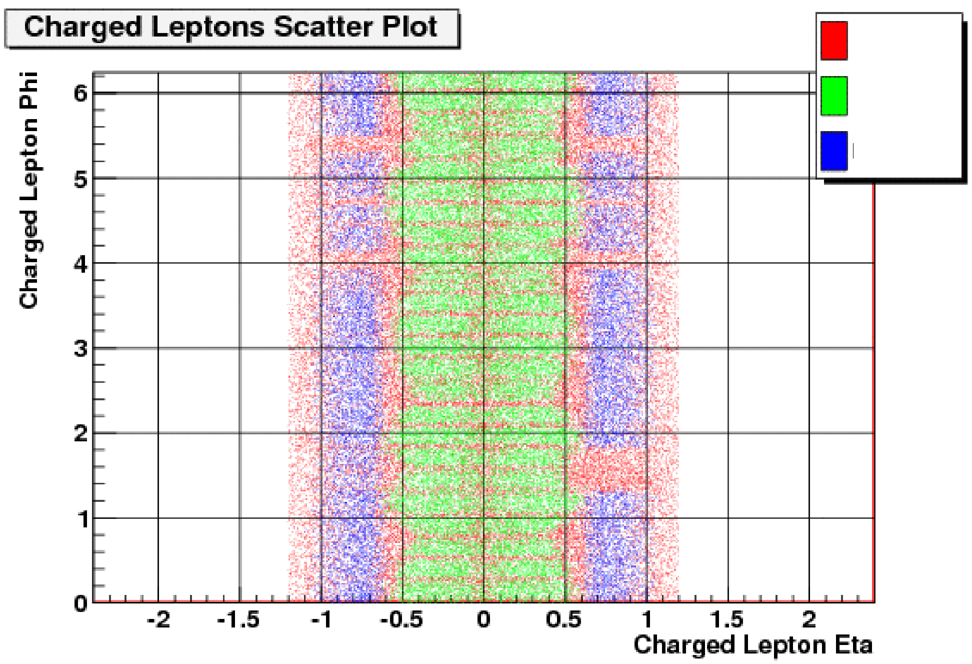


Isolated-Track Charge Lepton

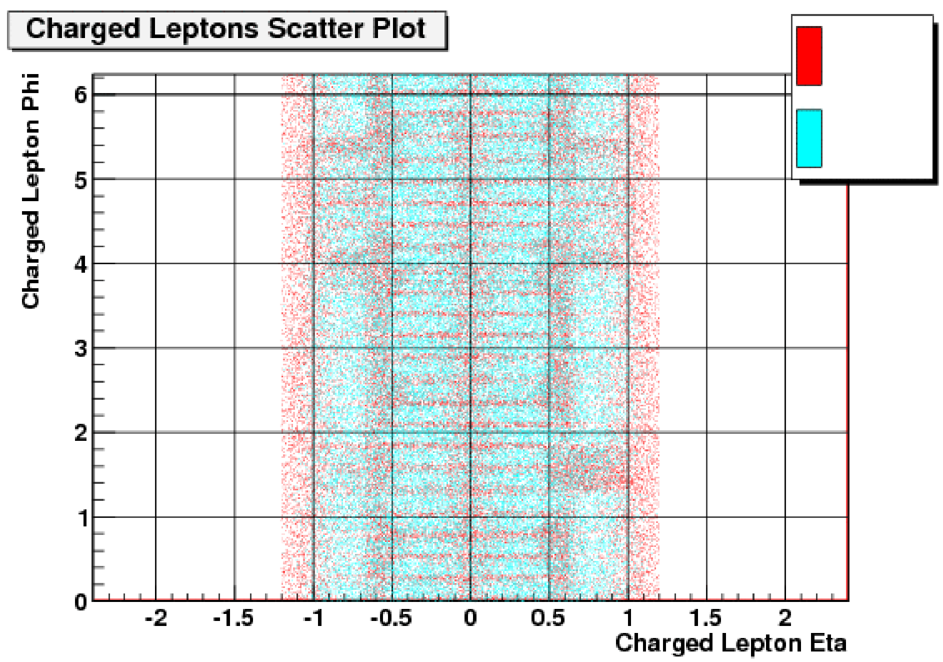
- High-p_T good-quality track isolated from other activity in the tracking
- Not required to match a calorimeter cluster (as for an electron)
- Not required to match a muon detector energy deposit (as for a muon)
- Orthogonal to the central tight electron and muon category

Isolated-Track Candidates (red)

Muon Candidates (blue, green)

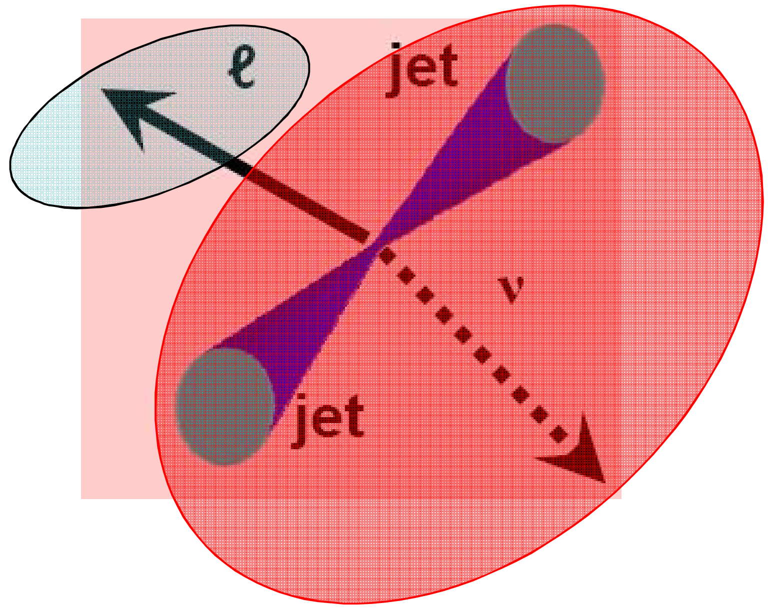


Electron Candidates (blue)



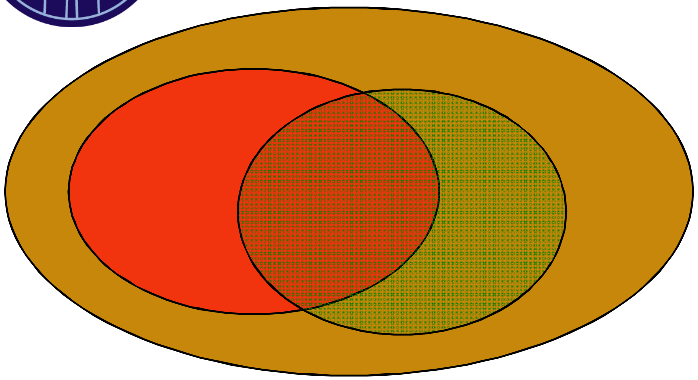
Triggers for Isolated Tracks

- Central tight electron (muon) candidates are selected with the inclusive electron (muon) trigger



- Isolated-track candidates use the remaining high level objects in the event (three triggers based on missing transverse energy – MET - and jets)
- How to combine them optimally?

Three MET+Jets Triggers



Avoid OR Trigger Combination Method
Systematic uncertainty has larger value and is harder to compute

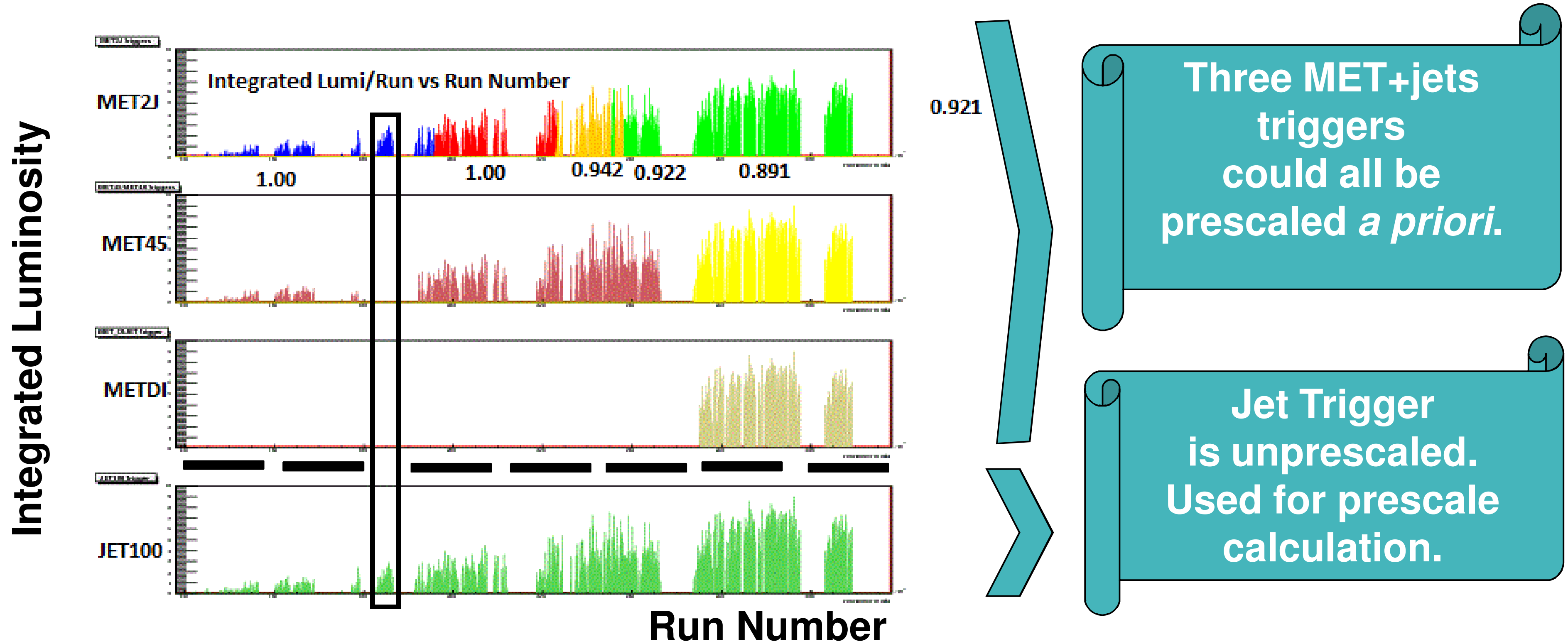
Old ways!

Traditional non-OR Trigger Combination Method
Divide kinematic phase space in orthogonal regions
Choose only one trigger to each kinematic region
Evaluate the trigger efficiency in that region
All these must be done before the analysis event loop!

- MET
  - ET_1>20 GeV, ET_2>20 GeV, $|\eta_1|<2.0$ or $|\eta_2|<2.0$
- MET + 2 Jets
  - ET_1>25 GeV, ET_2>25 GeV, dR_{12} > 1.0, $|\eta_1|<0.9$ or $|\eta_2|<0.9$
- MET + 2 Jets
  - ET_1>40 GeV, ET_2>25 GeV, $|\eta_1|<2.0$ or $|\eta_2|<2.0$

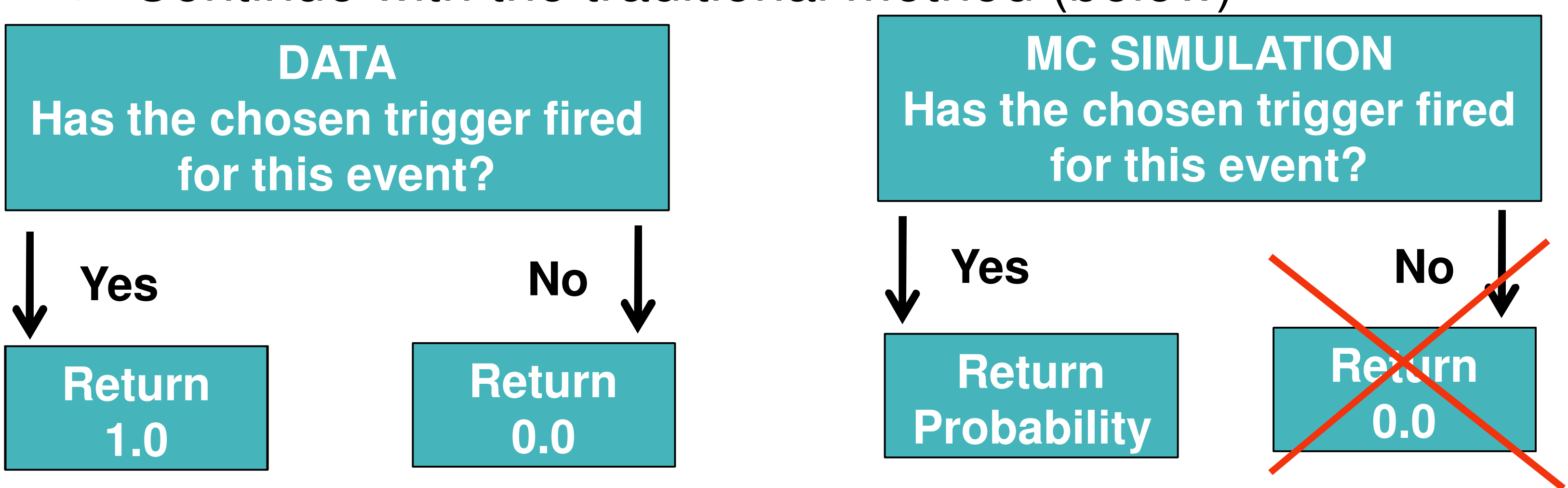
Additional Challenges

- Not all triggers are defined for all runs
  - (if bugs, must pretend not defined)
- One trigger is increasingly prescaled for later runs
- **We invented a general method to combine triggers**
  - Covers all these situations and more



In Situ Trigger Combination

- Generalize the standard non-OR combination method
- **Each event is its own orthogonal kinematic region**
- On an event-by-event basis (*in situ*) **New way!**
  - For each trigger evaluate ***a priori* a probability** that it fires
    - Details on the next slide
  - Assign to the event only the trigger with largest probability
  - Continue with the traditional method (below)

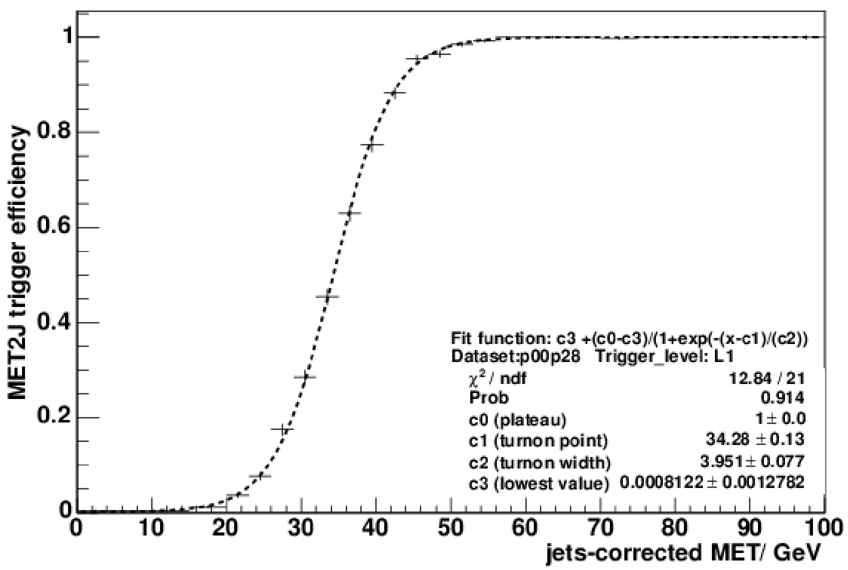


A priori Trigger Probability

- Computed *in situ* by multiplication of

Efficiency at Level 1	Efficiency at Level 2	Efficiency at Level 3	Prescale	Is Defined	Jet Selection

Parameterize trigger efficiency turnon curves at each trigger level as a function of MET



For MC simulated events throw **a random number** uniformly distributed between 0 and 1 to simulate in what interval of integrated luminosity the event is, thus picking the correct value of prescale and whether the trigger is considered defined

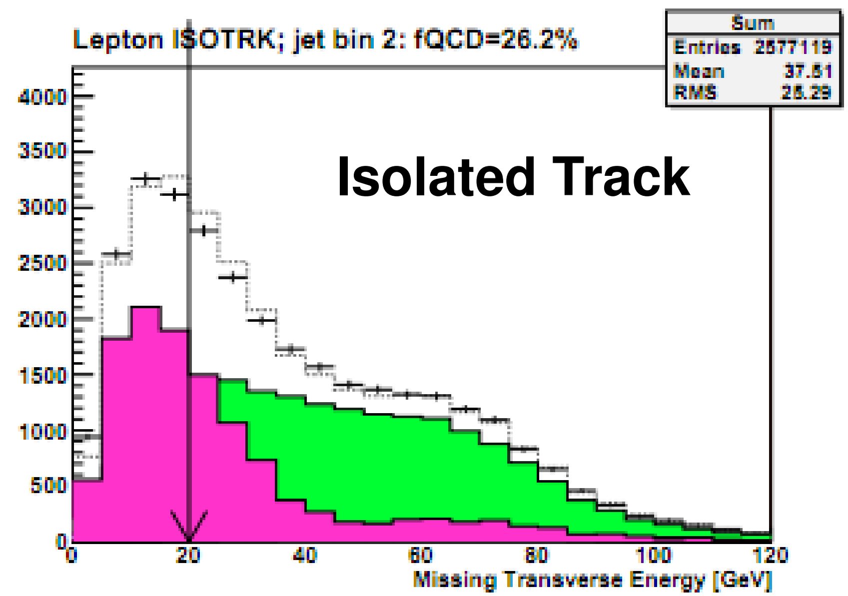
See Slide 13

Event Selection

- ❑ With small exceptions, 20 GeV cut on all objects
  - ➢ one charged lepton, MET, 2 or 3 jets
- ❑ 4 charged lepton categories
  - ➢ Tight central electron + Tight central muons
  - ➢ Isolated Track (central: 85% loose muons, 6% electrons, 7% tau)
  - ➢ Tight forward electron
  - ➢ Loose central electron
- ❑ Non-W (QCD) veto
  - ➢ Multivariate technique (SVM)
- ❑ Pretag selection
  - ➢ used as control sample

Non-W (QCD)

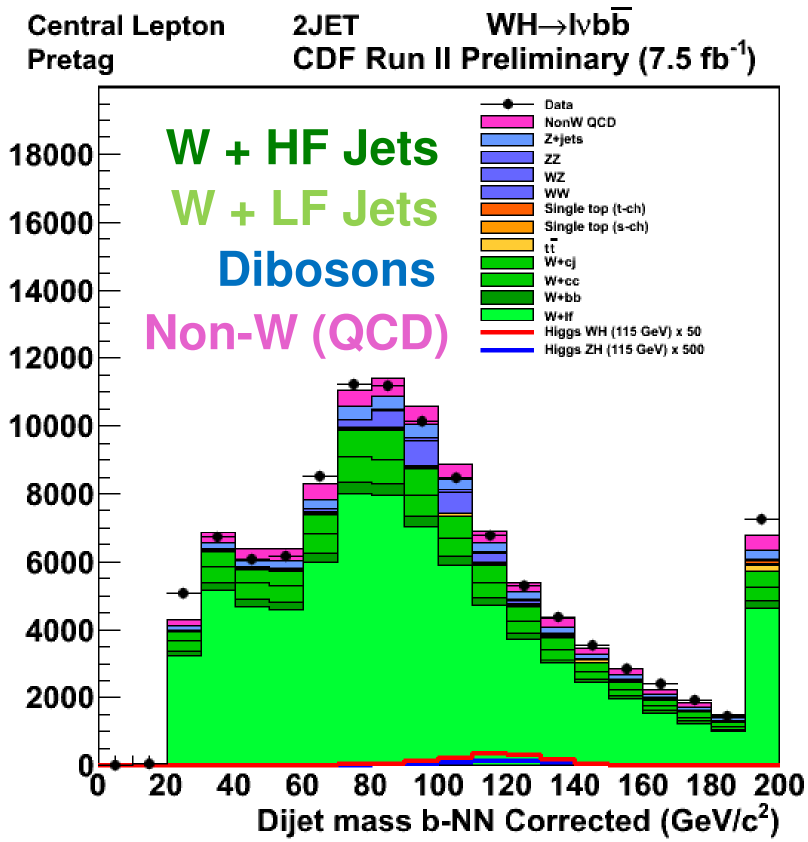
W+jets



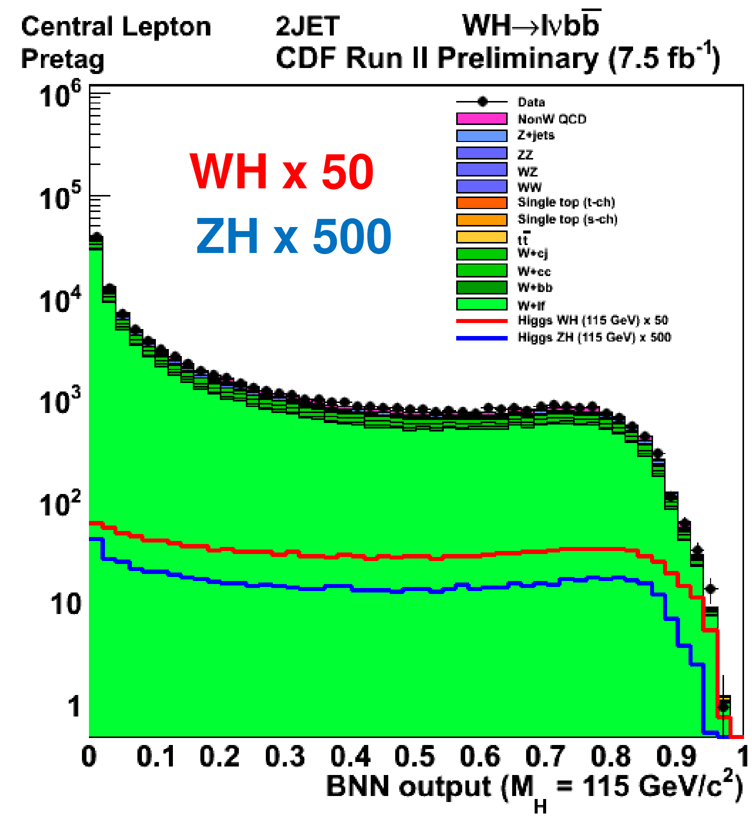
MET (GeV)

Pretag: Final Discriminant

- We train an artificial neural network using several inputs
  - Dijet invariant mass (corrected for jets with another NN)
  - Other kinematic quantities in the event
- One output with backgrounds (signal) peaking towards 0 (1)

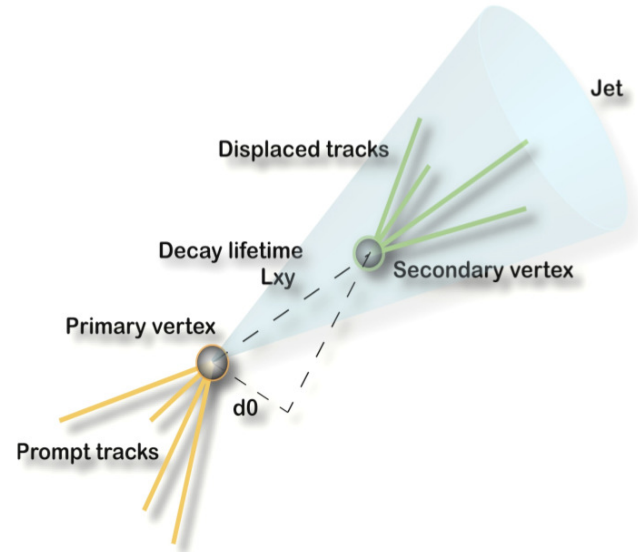


+ other kinematic quantities →



b-Tagging Algorithms

- Signature contains 2 jets that originate from bottom quarks
- Apply b-tagging to remove backgrounds with light jets
  - Gluons and u, d, s quarks
- 3 b-tagging algorithms

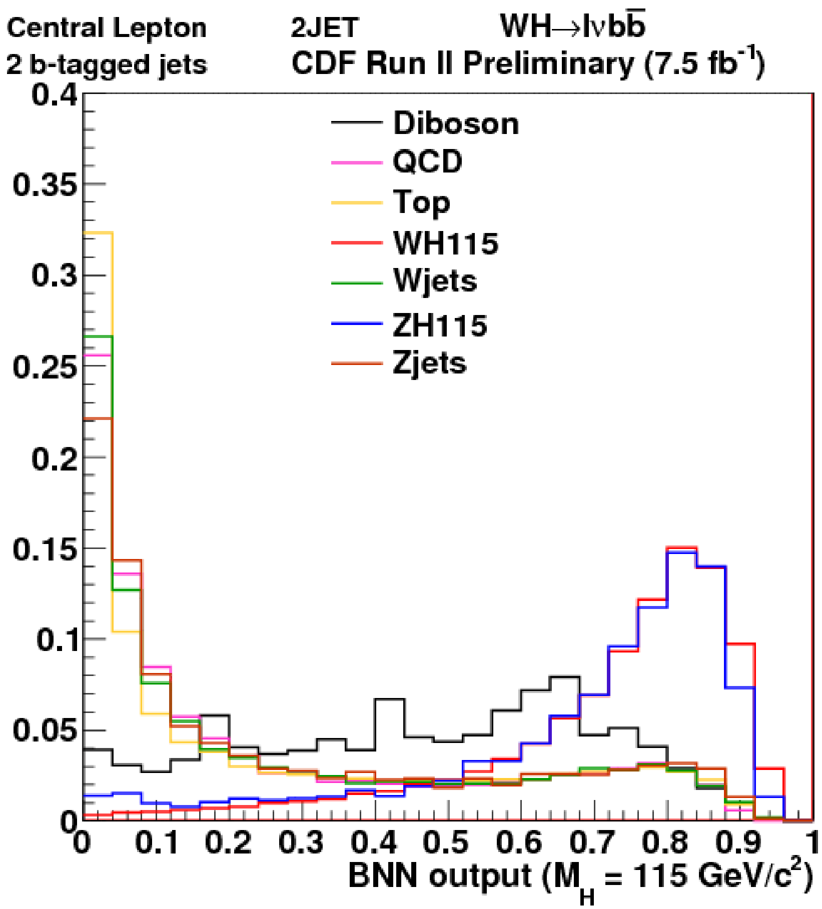


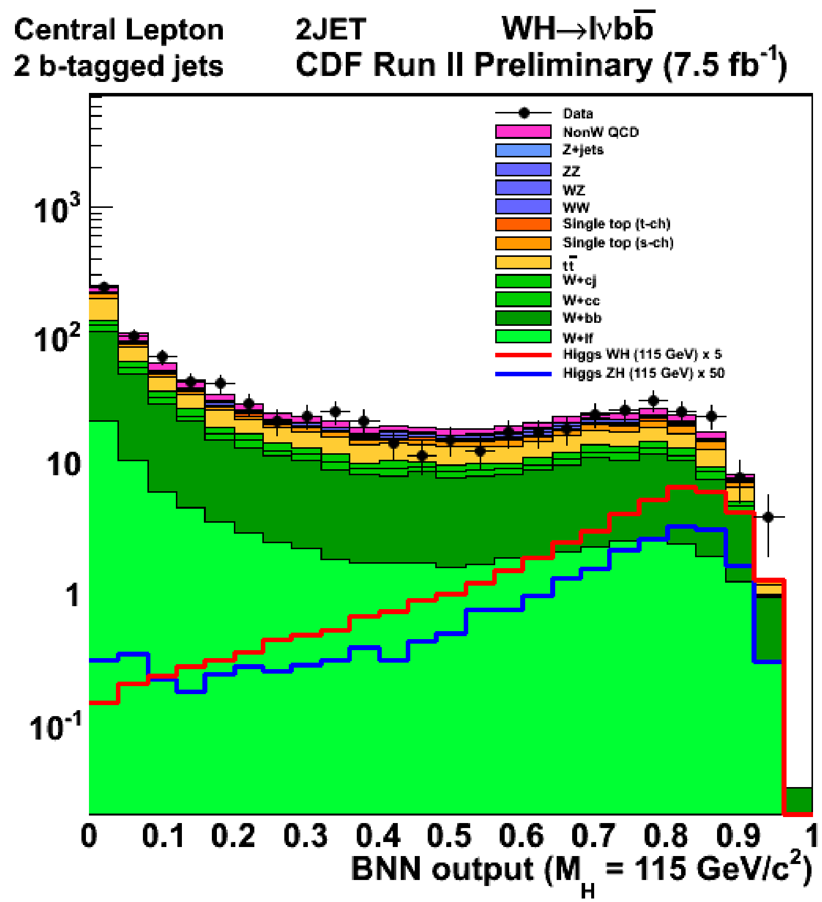
ST	• Reconstruct a secondary vertex
JP	• Track impact parameter distribution
NN	• Neural network tagger

- 4 orthogonal b-tagging categories as signal regions
  - ST+ST, ST+JP, ST+NN, 1-ST

Tag: Final Discriminant

- Three double-tag categories combined
- Central tight electron and muon candidates combined



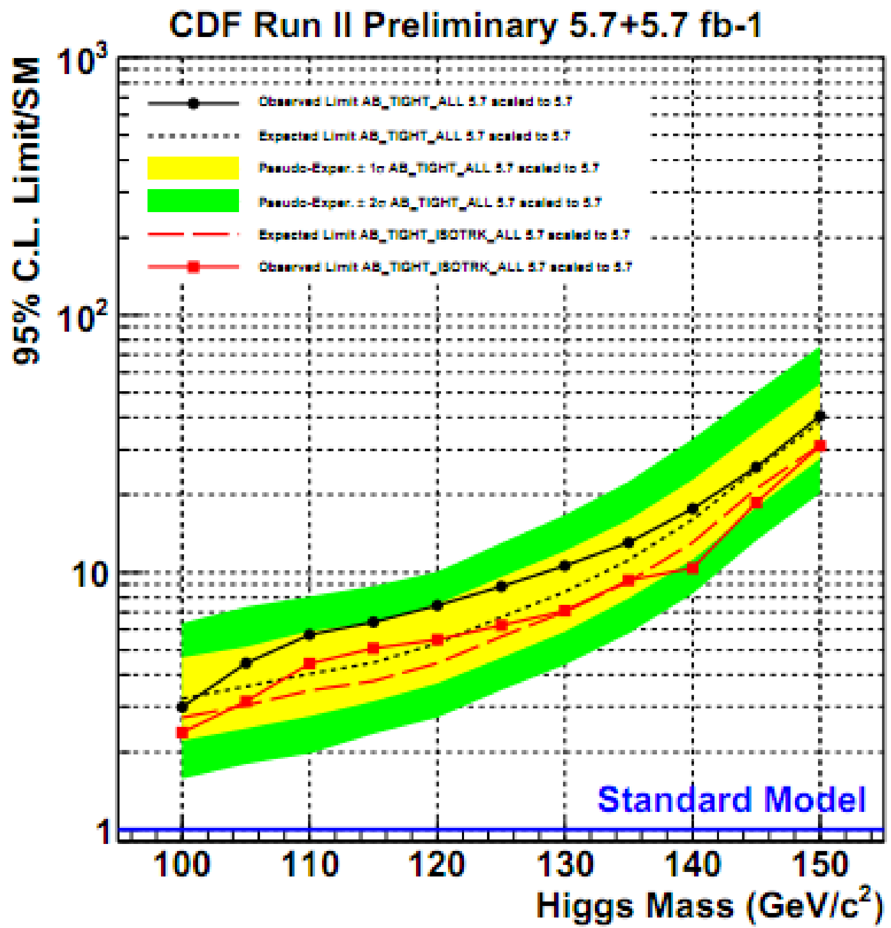


Limit Setting Procedure & Systematic Uncertainties

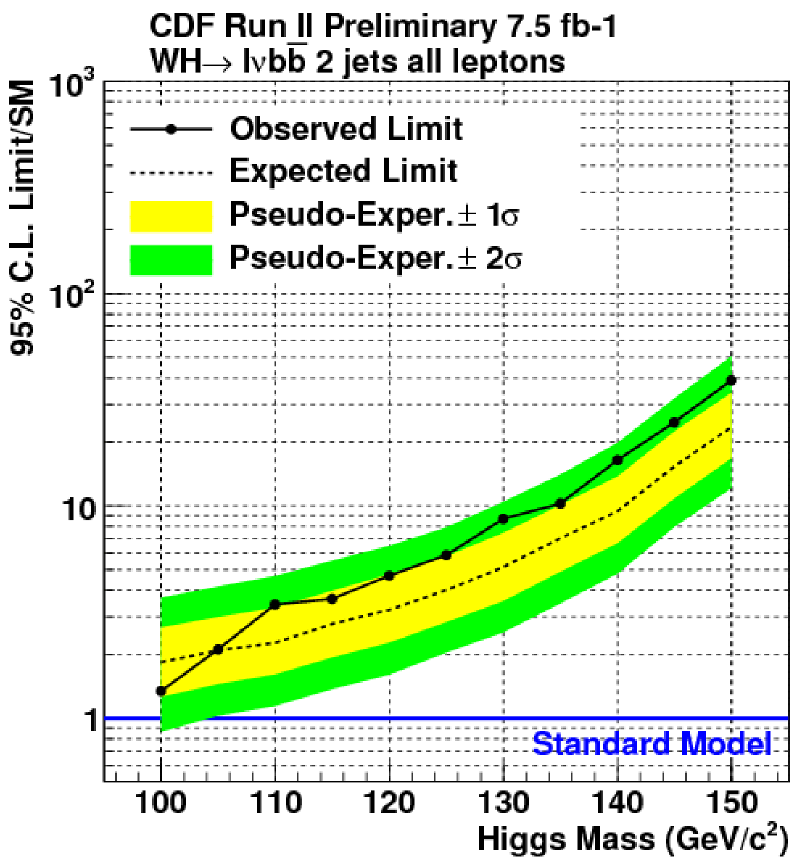
- **Bayesian** approach with **flat priors**
- **Poisson** statistics
- Rate and shape systematic uncertainties are introduced as **nuisance parameters**
- **Rate**: uncertainty on the total normalizations
- **Shape**: uncertainty on bin-by-bin normalizations
  - Use full discriminant shapes to extract the most information
- **Examples** of systematic uncertainties
  - Charged lepton, trigger, b-tagging efficiencies
  - Luminosity, background & signal cross sections
  - Fake object identification (ex: jets faking electrons and MET)
  - Data-driven background modelling

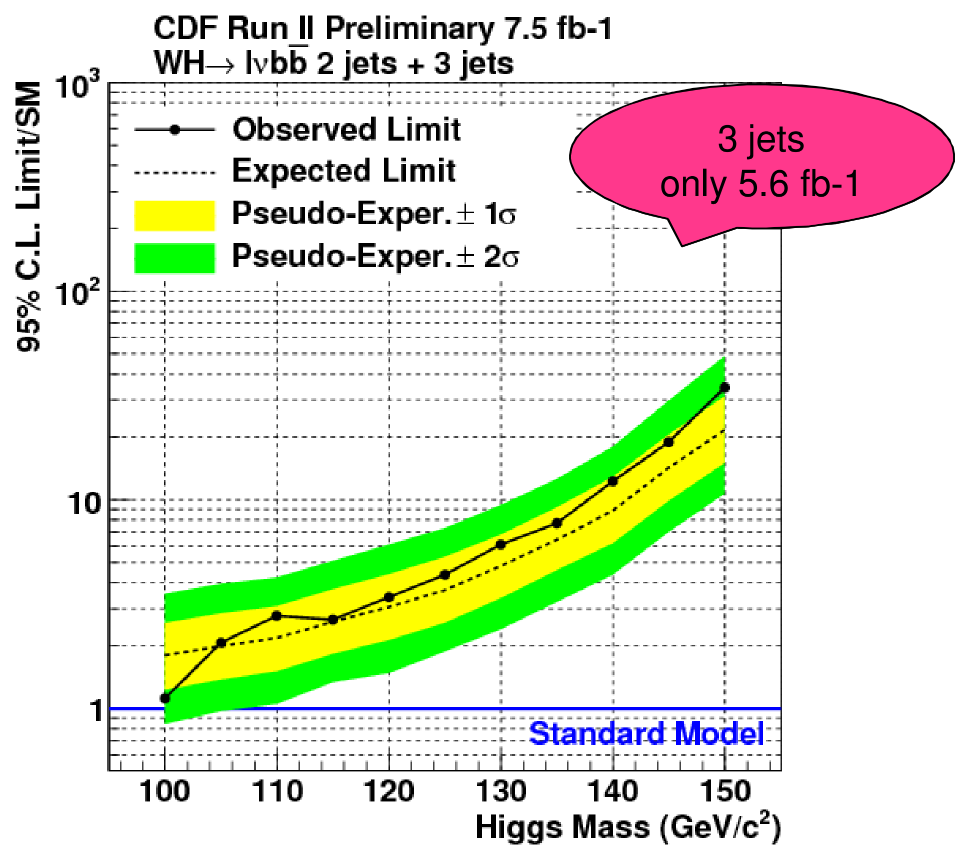
WH Upper Limits 1/2

- **Adding ISOTRK** brings 33% more signal and 17% more sensitivity (95% CL expected limits) over **TIGHT alone** at 5.7 fb^{-1}



WH Upper Limits 2/2





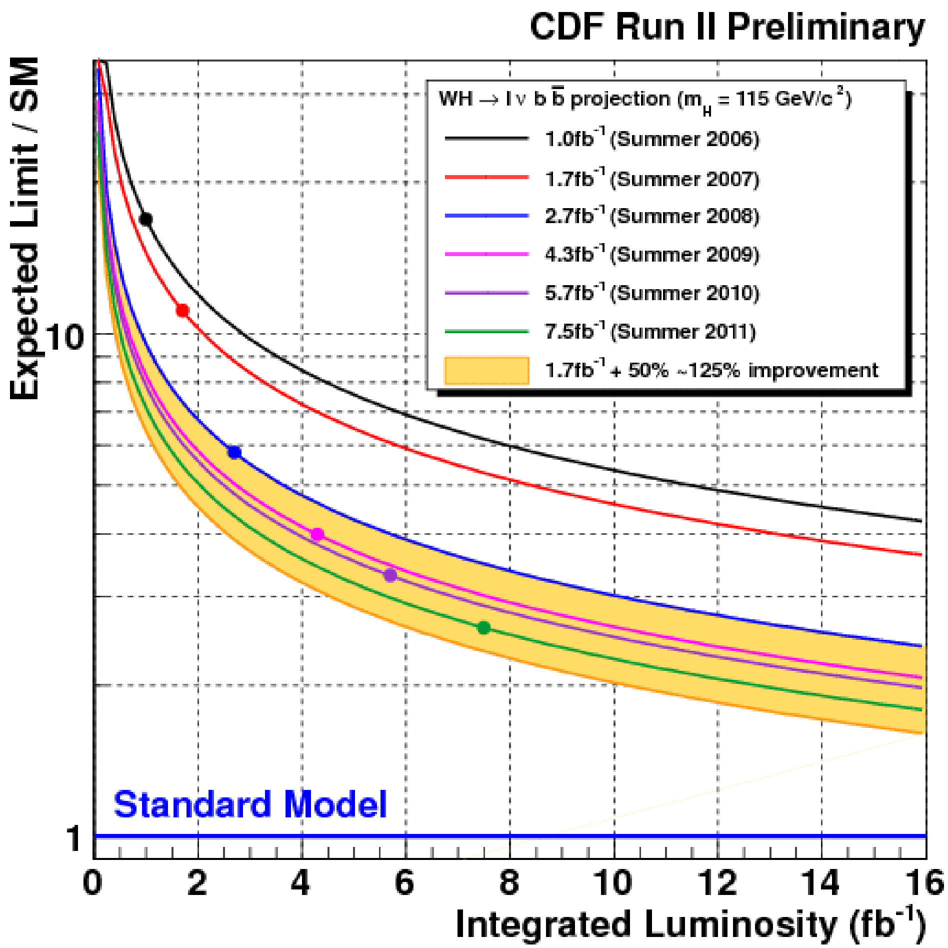
115 GeV/c^2: observed (expected) upper limits at 95% CL

3.64 (2.78) x SM 2.65 (2.60) x SM

Most sensitive analysis in the world for [115-125] GeV/c^2 Higgs

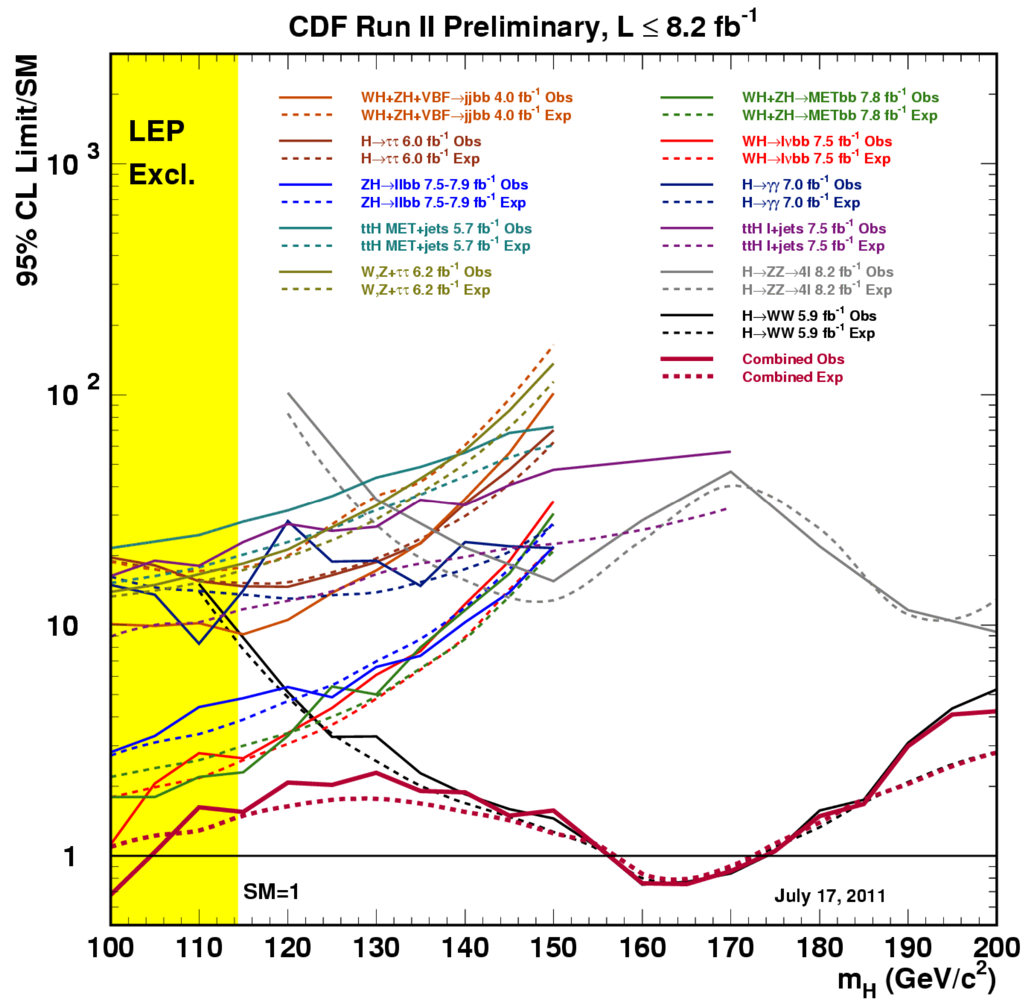
WH Search Projection

- Always improved more than just by adding luminosity
- Band: conservative and optimistic improvement plan in 2007



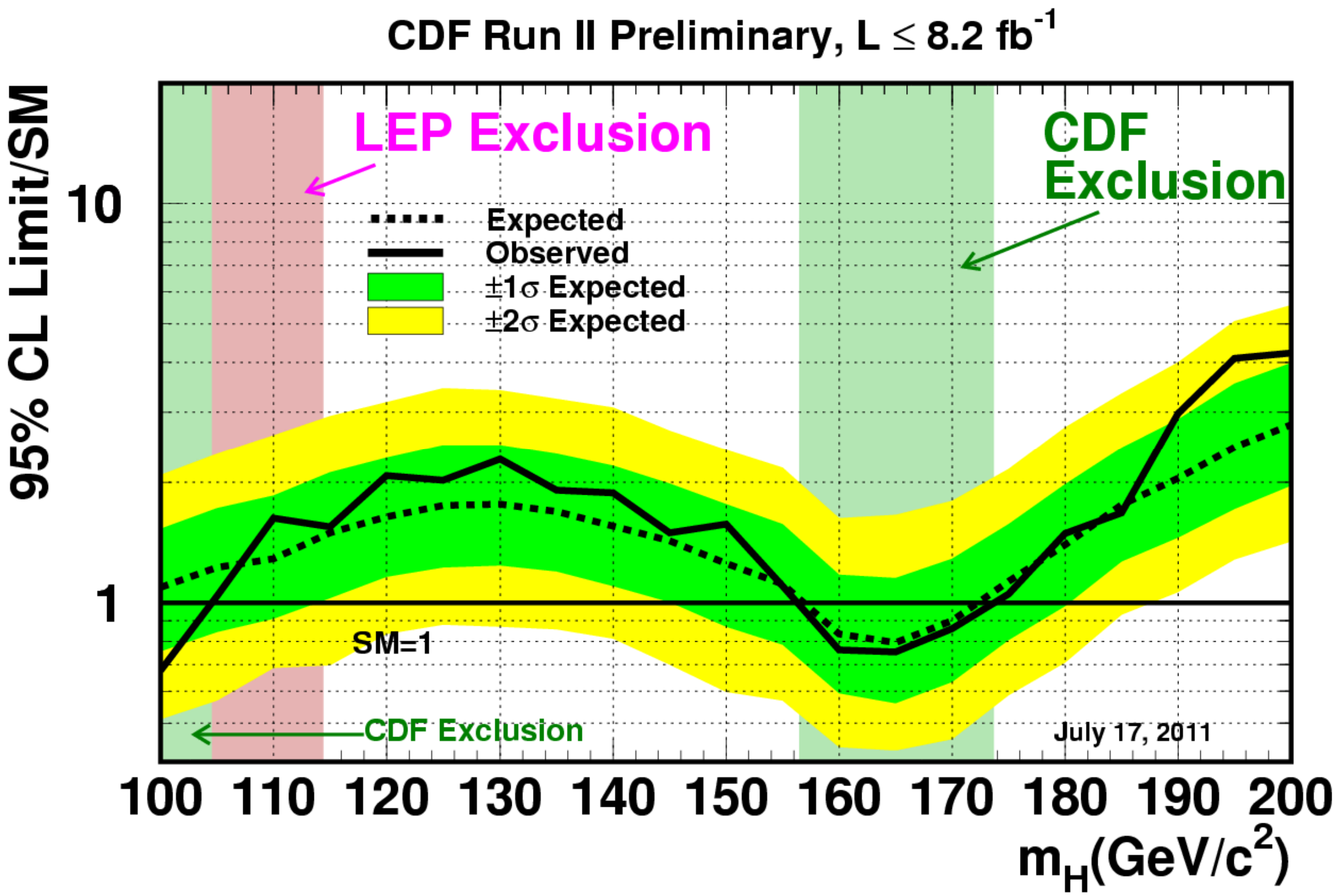
CDF Combination Limits 1/2

- http://www-cdf.fnal.gov/physics/new/hdg/Results.html



CDF Combination Limits 2/2

- Exclude at 95% CL: [100.0 -104.5] & [156.7-173.8] GeV/c^2
- Expect to exclude at 95% CL: [156.5-173.7] GeV/c^2



Future Plans

- As a general rule, try to increase the signal as much as possible, as the Higgs searches are statistically limited

- Improved b-tagging
  - 2-tag events have better sensitivity than 1-tag events
- Add new triggers
  - Loose muon dedicated triggers
- Improve the 3-jet bin
  - Train a new discriminant
  - Update to the latest luminosity (now only 5.6 fb^{-1})
- Recover part of the “bad” runs
  - Example: If bad for electrons, can still be used for muons

Conclusions

- Performed a WH associated production search at CDF
  - Motivated both theoretically and by the latest experimental results from Tevatron and LHC
- The most sensitive analysis in the world
  - Range 115-125 GeV/c^2
- Part of this improvement was due to my contributions
  - A novel charged lepton category with loose requirements
  - A novel general trigger combination method
- These improvements are used in other analyses
  - For the same signature at CDF (technicolor, WZ, single top, ttH) due to a software framework I co-authored and a trigger efficiency package I wrote
  - CDF continues to improve all Higgs analysis for the winter conferences, but mostly the low mass Higgs ones

Acknowledgements

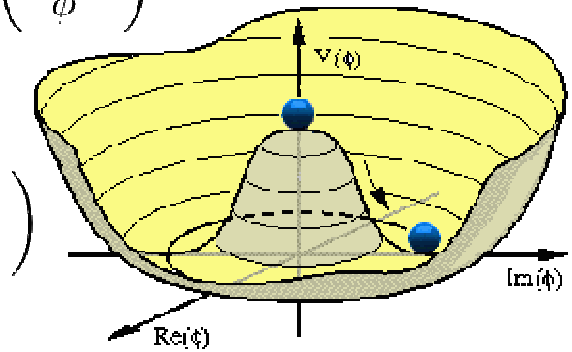
- The Tevatron accelerator operators
- The CDF collaborators and in particular the WH group
- My supervisor, Andreas Warburton
- The McGill staff, professors and colleagues

- Funding:
  - NSERC
  - McGill
  - URA

Backup Slides

The Higgs Mechanism

- **Simplest solution: a scalar Higgs field**
  - one doublet of scalar complex fields $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$
  - Potential $V(\Phi^\dagger, \Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda^2 (\Phi^\dagger \Phi)^2$
  - Non-zero expectation value
  - Radial perturbation $\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \eta(x) \end{pmatrix}$
  - Added to the electroweak Lagrangian



- **Acquire mass: Z^0, W^+, W^-, Higgs bosons**

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Electroweak}} \\ &= \left[\frac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \frac{1}{2}(\sqrt{2}\mu)^2 \eta^2\right] - \frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} - \frac{1}{4} f_{\mu\nu} f^{\mu\nu} \\ &\quad + \frac{1}{2}\left(\frac{gv}{2}\right)^2 (|W^{(+)}_\mu|^2 + |W^{(-)}_\mu|^2) + \frac{1}{2}\left(\frac{gv}{2\cos\theta_W}\right)^2 |Z_\mu|^2 \end{aligned}$$

W boson mass — Higgs mass — Z boson mass

Cross Sect. & Branch. Ratios

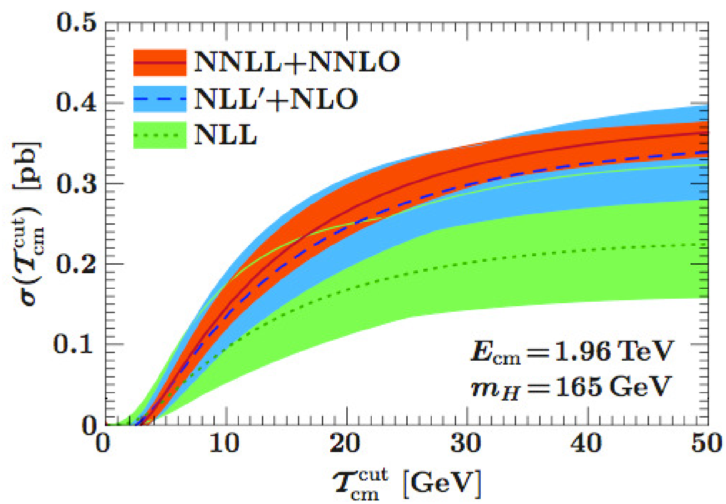
m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$\sigma_{t\bar{t}H}$ (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to \tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to \gamma\gamma)$ (%)
100	1821.8	291.90	169.8	97.2	8.000	79.1	3.68	8.36	1.11	0.113	0.159
105	1584.7	248.40	145.9	89.7	7.062	77.3	3.59	8.25	2.43	0.215	0.178
110	1385.0	212.00	125.7	82.7	6.233	74.5	3.46	8.03	4.82	0.439	0.197
115	1215.9	174.50	103.9	76.4	5.502	70.5	3.27	7.65	8.67	0.873	0.213
120	1072.3	150.10	90.2	70.7	4.857	64.9	3.01	7.11	14.3	1.60	0.225
125	949.3	129.50	78.5	65.3	4.279	57.8	2.68	6.37	21.6	2.67	0.230
130	842.9	112.00	68.5	60.4	3.769	49.4	2.29	5.49	30.5	4.02	0.226
135	750.8	97.20	60.0	55.9	3.320	40.4	1.87	4.52	40.3	5.51	0.214
140	670.6	84.60	52.7	51.8	2.925	31.4	1.46	3.54	50.4	6.92	0.194
145	600.6	73.70	46.3	48.1	2.593	23.1	1.07	2.62	60.3	7.96	0.168
150	539.1	64.40	40.8	44.6	2.298	15.7	0.725	1.79	69.9	8.28	0.137
155	484.0	56.20	35.9	41.2	2.037	9.18	0.425	1.06	79.6	7.36	0.100
160	432.3	48.50	31.4	38.2	1.806	3.44	0.159	0.397	90.9	4.16	0.0533
165	383.7	43.60	28.4	36.0	1.607	1.19	0.0549	0.138	96.0	2.22	0.0230
170	344.0	38.50	25.3	33.4	1.430	0.787	0.0364	0.0920	96.5	2.36	0.0158
175	309.7	34.00	22.5	31.0	1.272	0.612	0.0283	0.0719	95.8	3.23	0.0123
180	279.2	30.10	20.0	28.8	1.132	0.497	0.0230	0.0587	93.2	6.02	0.0102
185	252.1	26.90	17.9	26.9	1.004	0.385	0.0178	0.0457	84.4	15.0	0.00809
190	228.0	24.00	16.1	25.0	0.890	0.315	0.0146	0.0376	78.6	20.9	0.00674
195	207.2	21.40	14.4	23.3	0.789	0.270	0.0125	0.0324	75.7	23.9	0.00589
200	189.1	19.10	13.0	21.6	0.700	0.238	0.0110	0.0287	74.1	25.6	0.00526

The Higgs Boson

- Motivation
  - The only elementary particle predicted by the Standard Model not yet observed or refuted
  - Predicted by the Higgs mechanism in 1964, which explains
    - the spontaneous symmetry breaking
    - the masses of the electroweak bosons, the masses of fermions
- The Higgs boson characterized only by its mass
  - LEP direct searches
    - exclude masses < 114.4 GeV/c^2 at 95% CL
  - Previous Tevatron direct searches
    - exclude masses in [158-173] GeV/c^2 at 95% CL
  - Indirect electroweak fits
    - exclude masses > 185 GeV/c^2 at 95% CL
- Higgs production is a very rare process

More on Uncertainties

- Most up-to-date cross sections, branching ratios, and their uncertainties
- Consider three independent scale variations for gluon fusion Higgs production
  - Beam, soft and hard
  - Berger, Marcantonini, Stewart,
  - Tackmann, Waaleweijn
  - http://arxiv.org/abs/arXiv:1012.4480
  - Stewart and Tackmann, arXiv:1107.2117
  - Current prescription - BNL accord



- Branching ratio uncertainties
  - From α_s, and masses of bottom and charm quarks
  - Baglio and Djouadi, JHEP 1103:055 (2011)

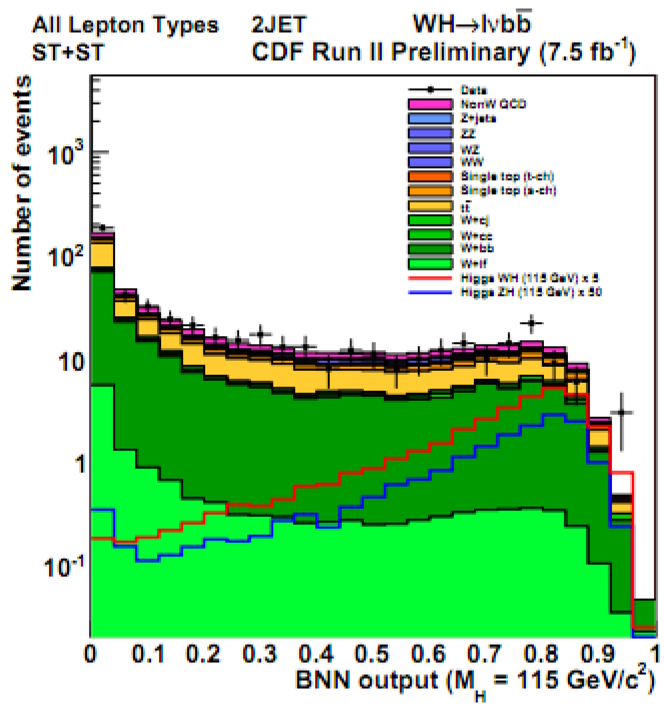
Scale Uncertainty Prescription

- Theory gives cross section uncertainties
  - Higgs + >= 0 jets: 7.05% (Grazzini, de Florian)
  - Higgs + >= 1 jets: 25.5% (MCFM)
  - Higgs + >= 2 jets: 33% (Campbell, Ellis, Williams)
- We use: 0 jet, 1 jet, >=2 jets

Jet bin	s0	s1	s2
0 jet	13.4%	-23.0%	0
1 jet	0	35%	-12.7%
>= 2 jets	0	0	33%

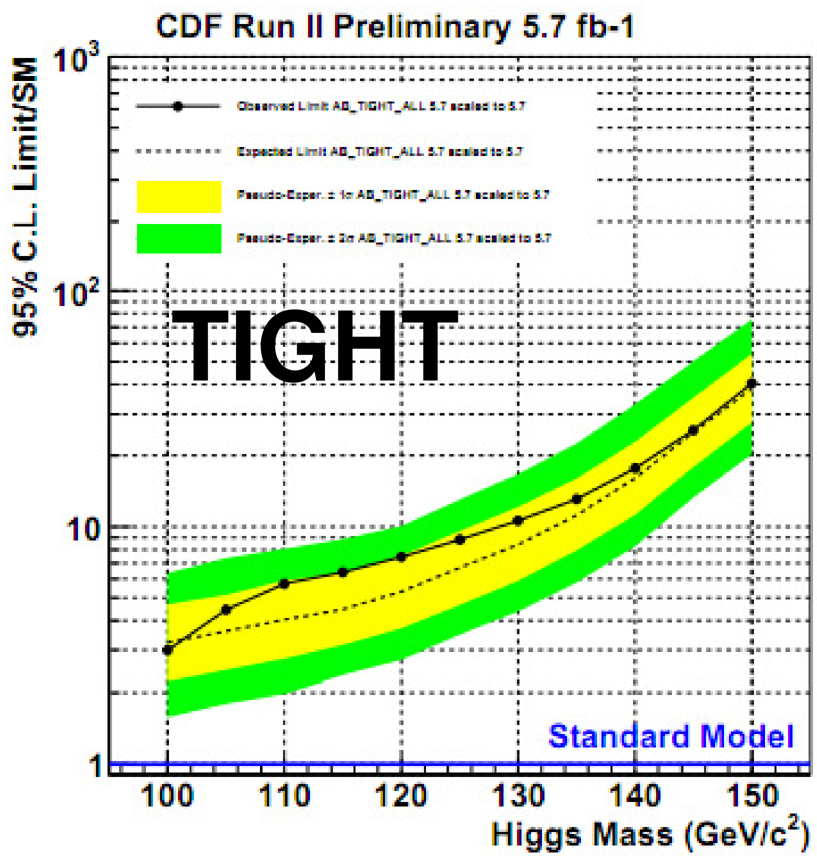
Example of Discriminant

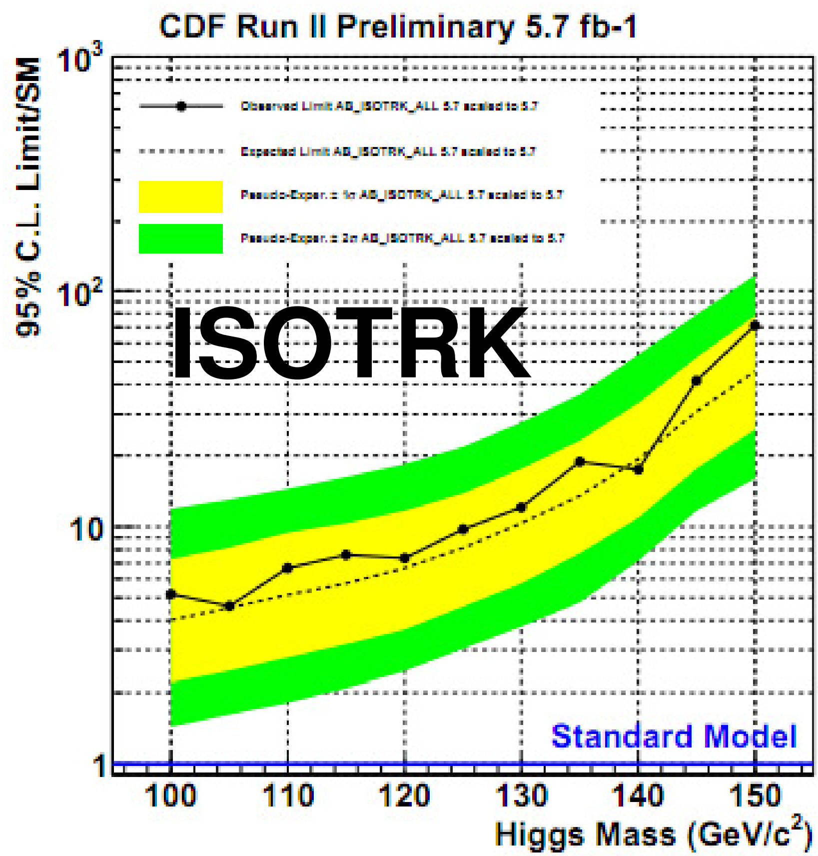
- WH →lvbb search 2jet b-tagging category with best s/b ratio; all charged leptons combined
- Artificial neural network as final discriminant trained for a Higgs boson mass of 115 GeV/c^2



Upper Limits 1/2

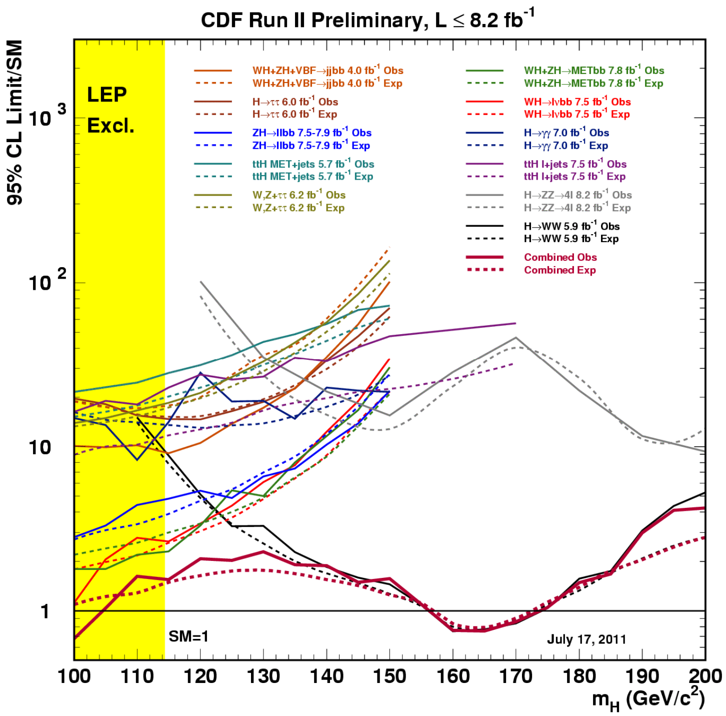
- Set 95% CL upper limits on Higgs boson cross section
- ISOTRK brings 33% extra signal on TIGHT alone

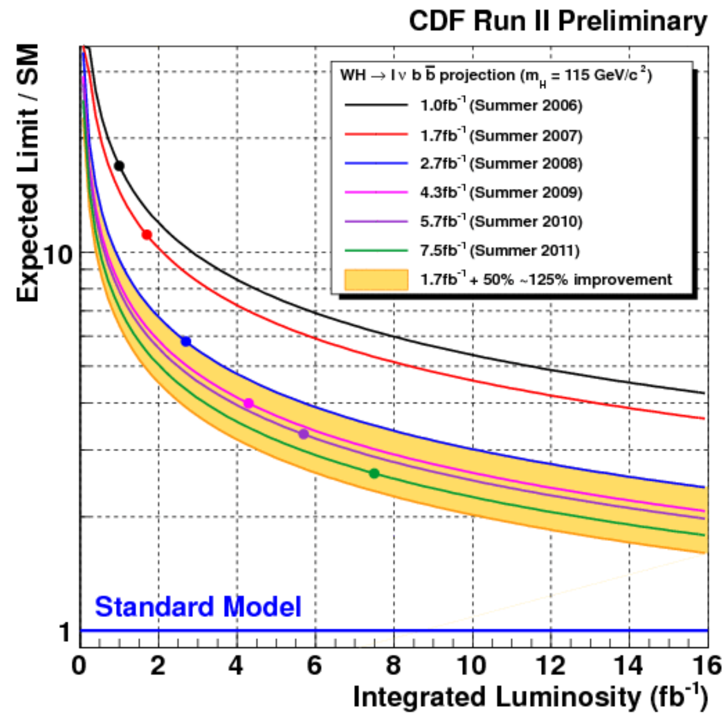




New Result (July 2011)

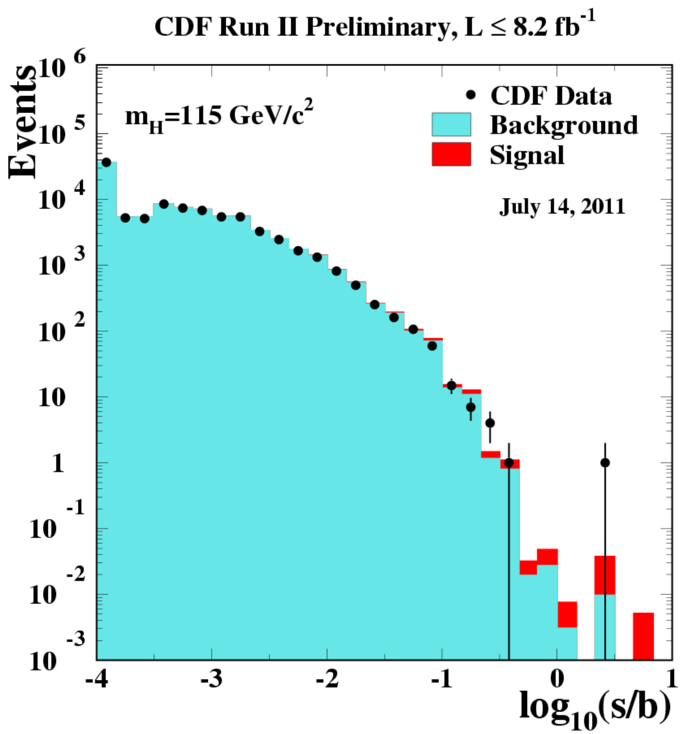
- Presented at EPS-HEP 2011 and Higgs Hunting 2011
  - Added several analysis improvements; also 5.7 → 7.5 fb^{-1}
- **Most sensitive analysis in the world at very low mass**
  - WH at CDF always improved more than with integrated luminosity
  - Improvement prediction made in 2007 (band in right plot)

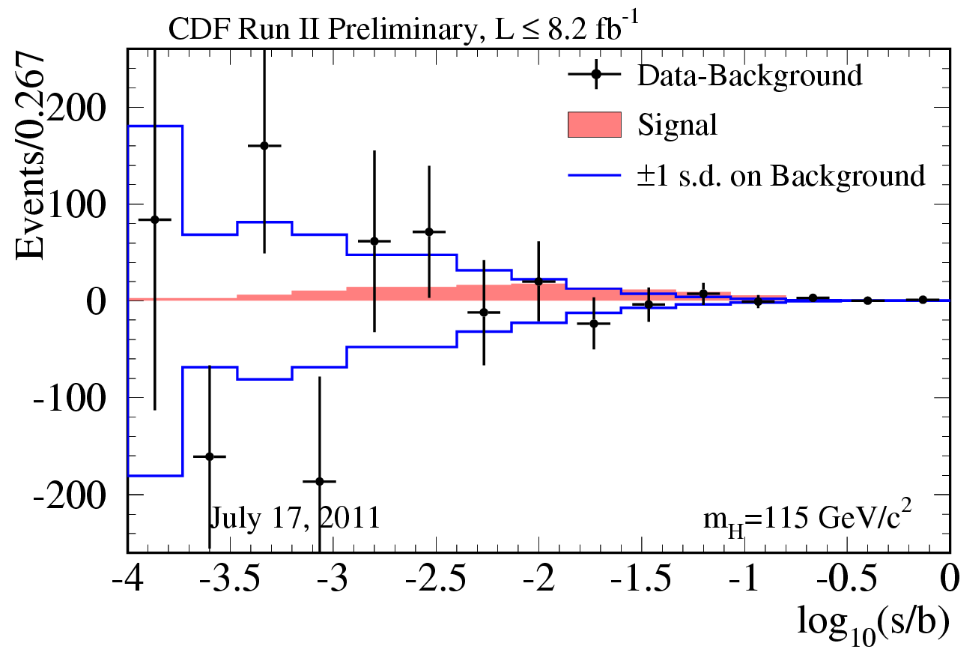




CDF Combination S/B Ratio

- Sum final discriminants after rebin in log(s/b)
  - Sum all independent channels
- Then subtract backgrounds from data
- No excess above backgrounds, so we set limits





Statistical Approach

Bayesian Posterior Probability

$$p(R|\vec{n}) = \frac{\int\int d\vec{s}d\vec{b}L(R,\vec{s},\vec{b}|\vec{n})\pi(R,\vec{s},\vec{b})}{\int\int\int dRd\vec{s}d\vec{b}L(R,\vec{s},\vec{b}|\vec{n})\pi(R,\vec{s},\vec{b})} \Rightarrow \int_0^{R_{0.95}} p(R|\vec{n})dR = 0.95$$

$R = (\sigma \times BR)/(\sigma_{SM} \times BR_{SM}),\ R_{0.95}$: 95% Credible Level Upper Limit

$\vec{s},\vec{b},\vec{n} = s_{ij}, b_{ij}, n_{ij}$ (# of signal, background and observed events in j-th bin for i-th channel)

π : Bayes' prior density

Combined Binned Poisson Likelihood

$$L(R,\vec{s},\vec{b}|\vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

Principle of ignorance

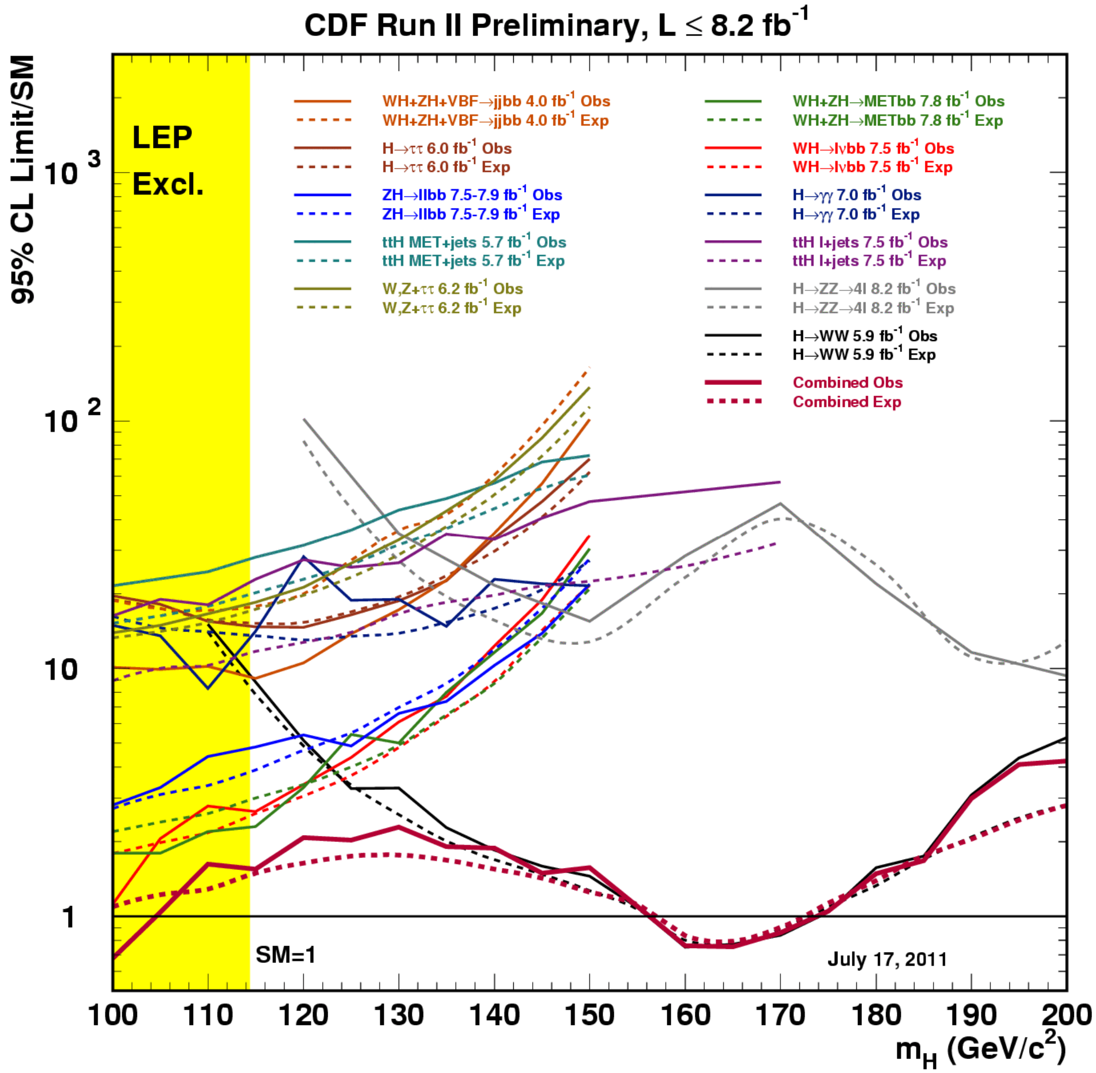
- for the number of higgs events (instead of higgs Xsec)

$$\pi(R,\vec{s},\vec{b}) = \pi(R)\pi(\vec{s})\pi(\vec{b}) = s_{tot}\theta(Rs_{tot})\pi(\vec{s})\pi(\vec{b})$$

$s_{tot} = \Sigma_{i,j} s_{ij}$: Total number of signal prediction

$\pi(x) = G(x|\hat{x}, \sigma_x)\quad (x = s, b)$ $\quad\hat{x}$: expected mean, σ_x: total uncertainty

CDF Combination Limits - 1



CDF Combination Limits - 2

McGill

- ❑Exclude at 95% CL: [100.0 -104.5] & [156.7-173.8] GeV/c^2
- ❑Expect to exclude at 95% CL: [156.5-173.7] GeV/c^2