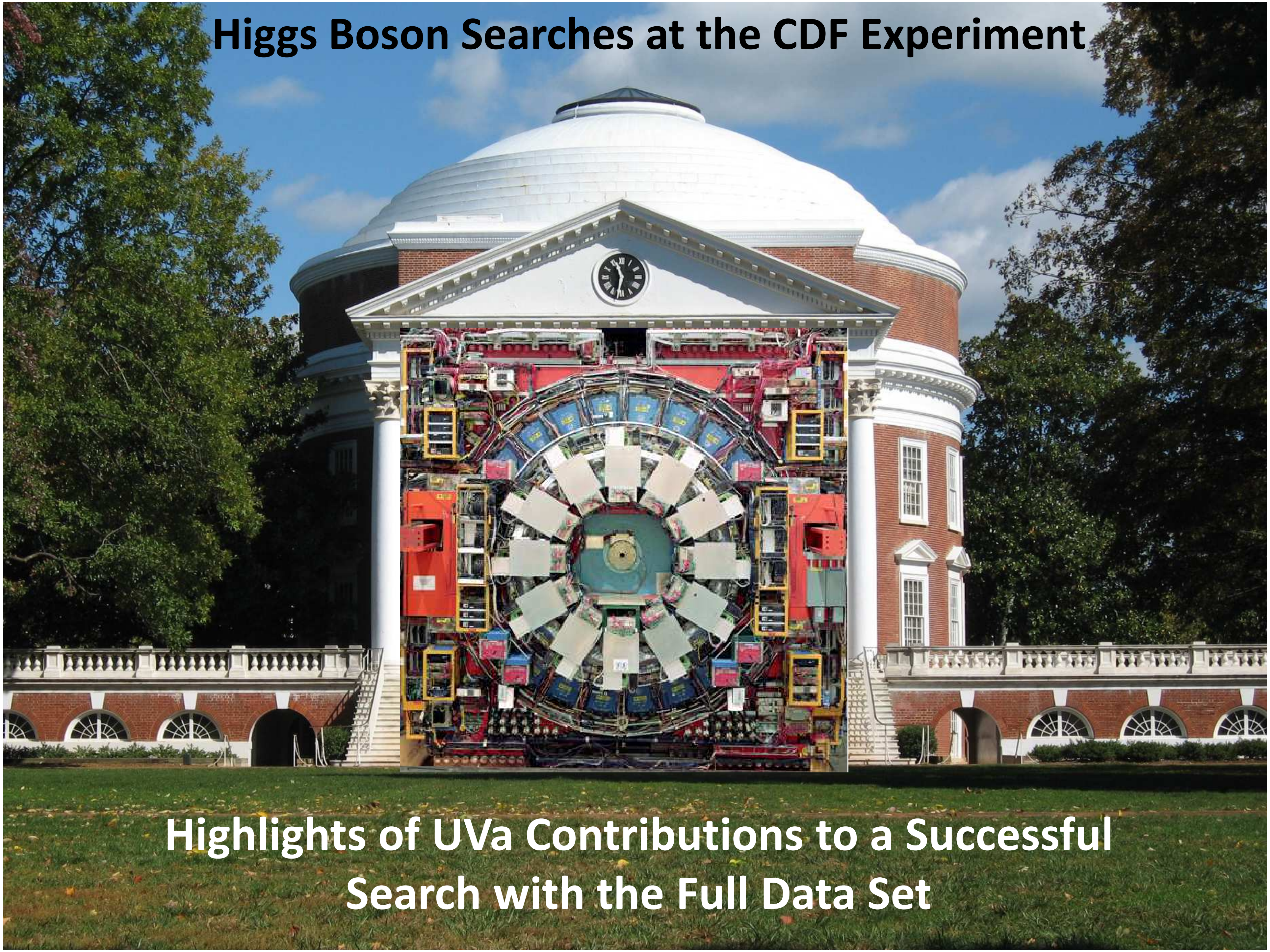

Higgs Boson Searches at the CDF Experiment
Highlights of UVa Contributions to a Successful
Search with the Full Data Set

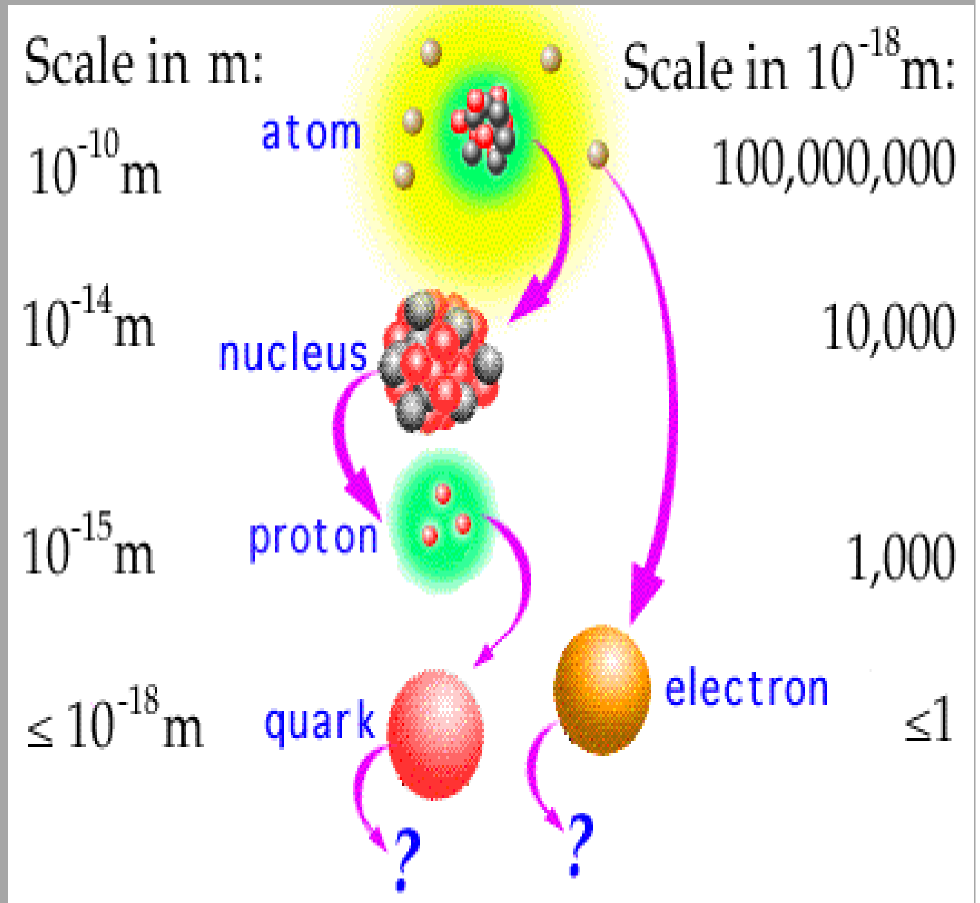
Introduction

Setting the Scale for Particle Physics

Particle physics is the study of the most basic building blocks of matter and their interactions

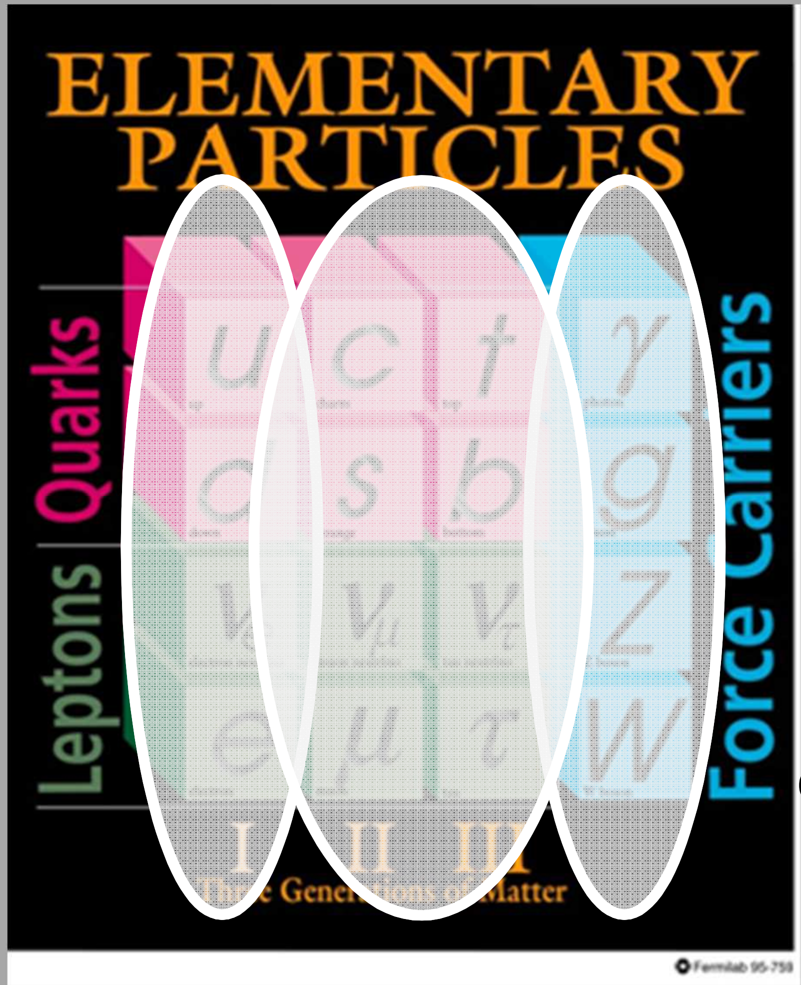
Why high energy?

- Small distances and high energies: λ = h/p
- Optical resolution proportional to λ
- So, we need high energy/momentum to probe the fundamental building blocks of nature



The "Standard Model" of Particle Physics

Make up all
"regular" matter
In the Universe



Force
Carriers

Unstable matter
created in high-energy
collisions

Standard Model (SM) of particle physics includes these experimentally observed particles and their interactions

What is the origin of Electroweak Symmetry Breaking?

- Consider the Electromagnetic and the Weak Forces
- Coupling at low energy: EM: ~α, Weak: ~$\alpha/(M_{W,Z})^2$
  - Coupling strength governed by the same dimensionless constant
  - Difference due to the mass of the W and Z bosons
    - Electroweak symmetry: $M_Y = M_Z = M_W$
    - But photons massless and W and Z are massive?
- SM postulates a mechanism of electroweak symmetry breaking via the Higgs mechanism

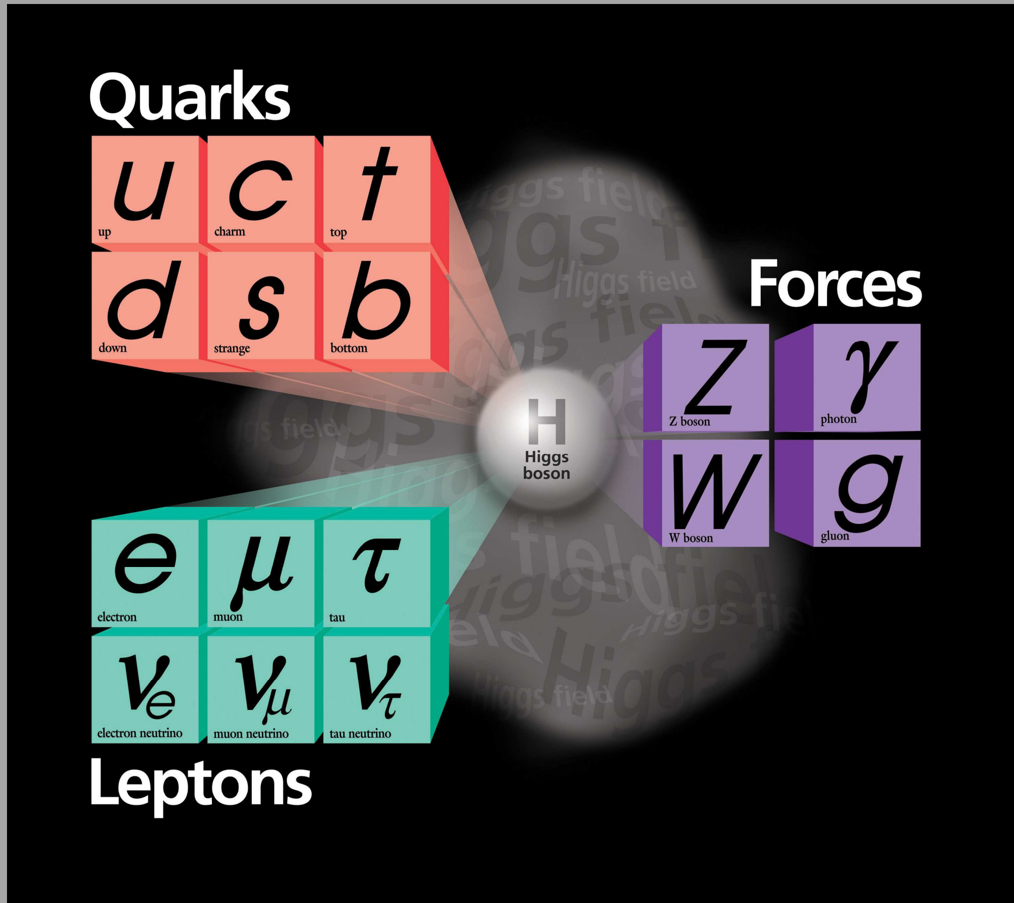
→massive vector bosons and mass terms for the fermions

→Theory predicts a massive new particle called the Higgs boson!

→Higgs mass not predicted by theory

Are there undiscovered fundamental particles?

The standard model really looks more like this!



Discovery (or exclusion) of the Higgs boson, will shine light on the question of the origin of EWK symmetry breaking

We have a discovery!

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

Phys. Lett. B 716, 1 (2012)

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

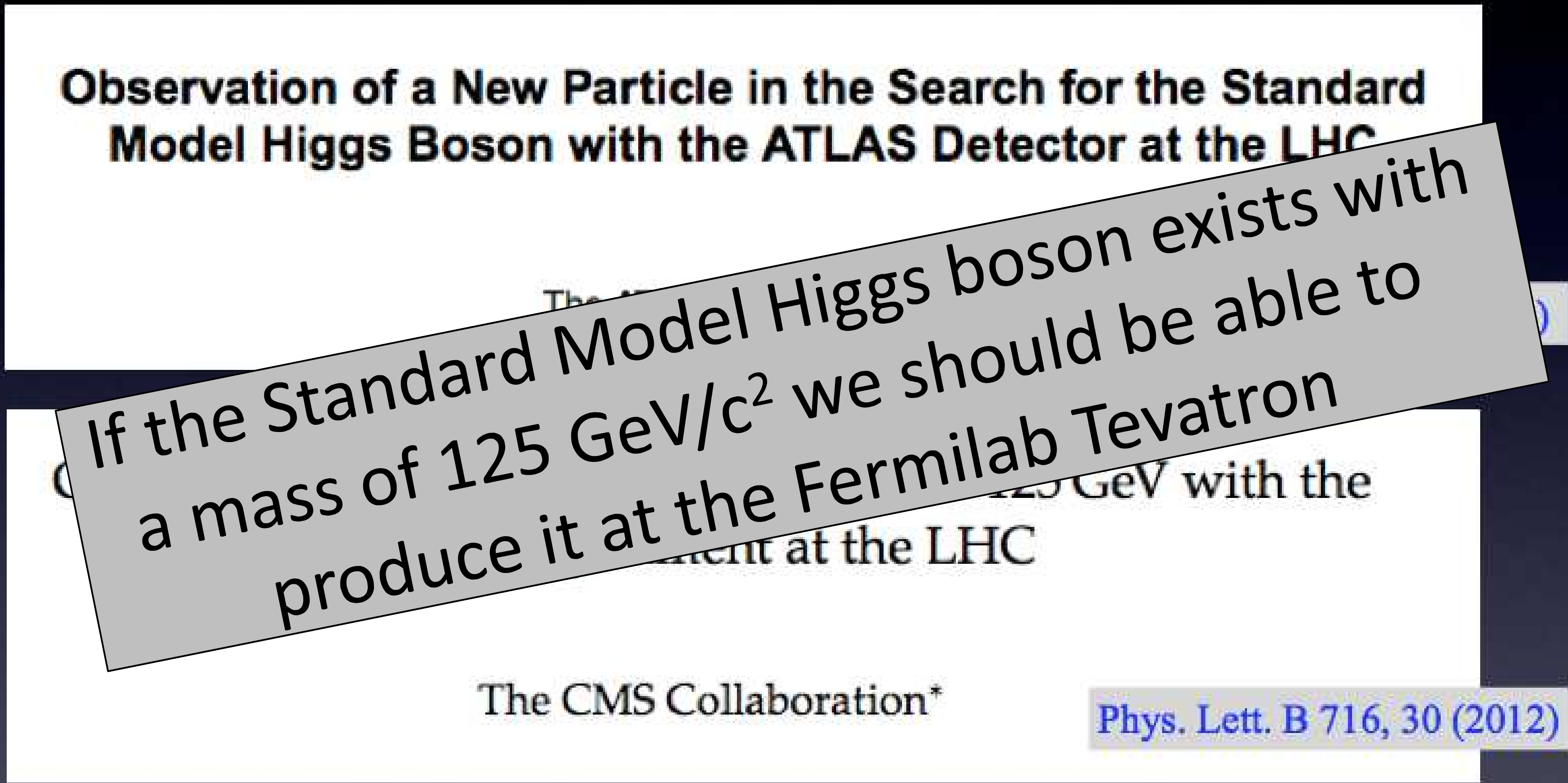
Phys. Lett. B 716, 30 (2012)

Congratulations to ATLAS and CMS on this fantastic discovery!

3 am Higgs Announcement Party

3 am Higgs Announcement Party

We have a discovery!


Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

GeV with the

at the LHC

The CMS Collaboration*

Phys. Lett. B 716, 30 (2012)

If the Standard Model Higgs boson exists with a mass of 125 GeV/c^2 we should be able to produce it at the Fermilab Tevatron

But, what exactly has been discovered?

The Tevatron at Fermilab

The Tevatron provided the World's highest energy proton-antiproton collisions:

E_{cm} = 1.96 TeV

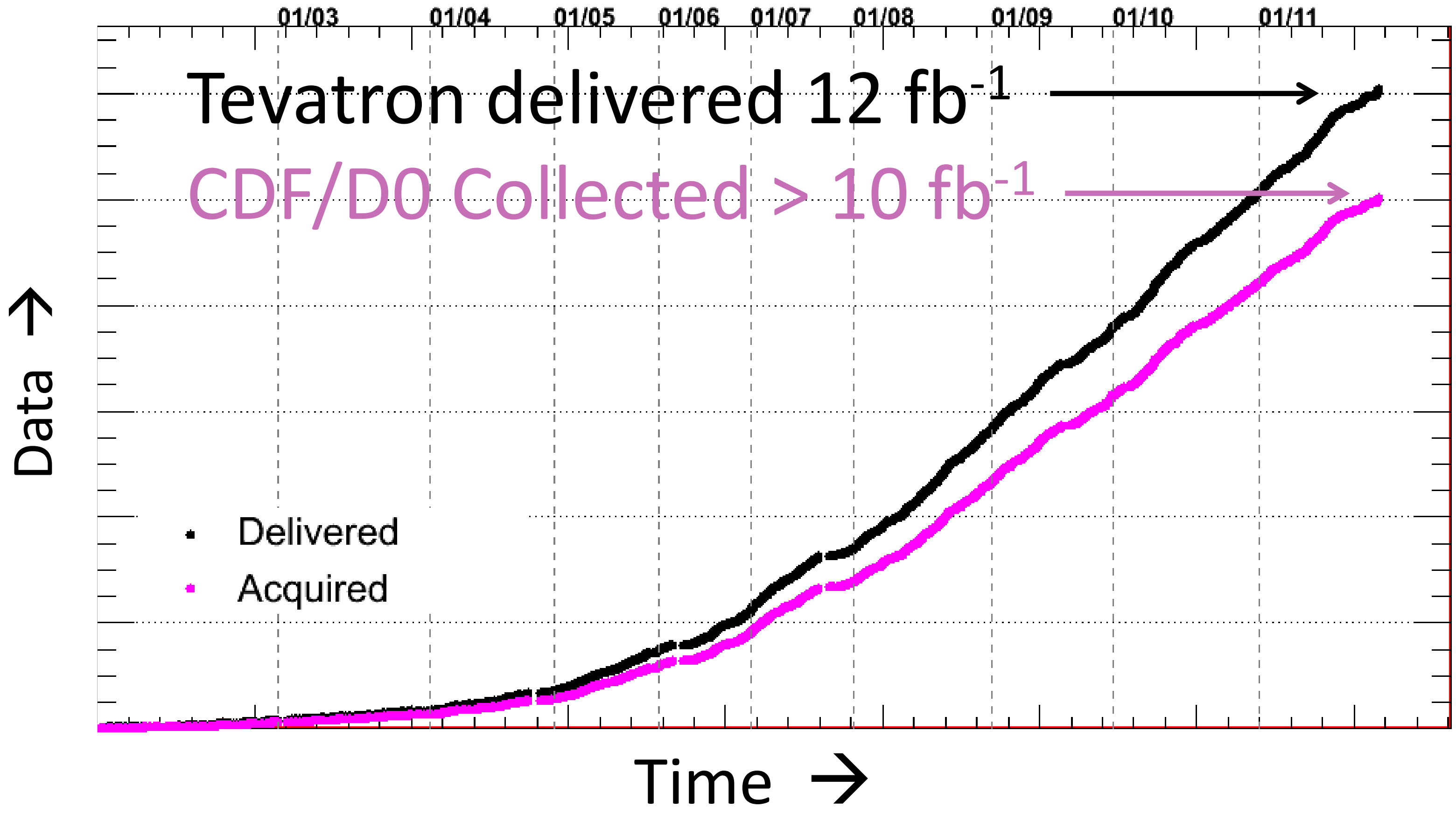
After a 26 year career, the Tevatron took its last collision on Sept. 30th 2011 !

D0

Tevatron

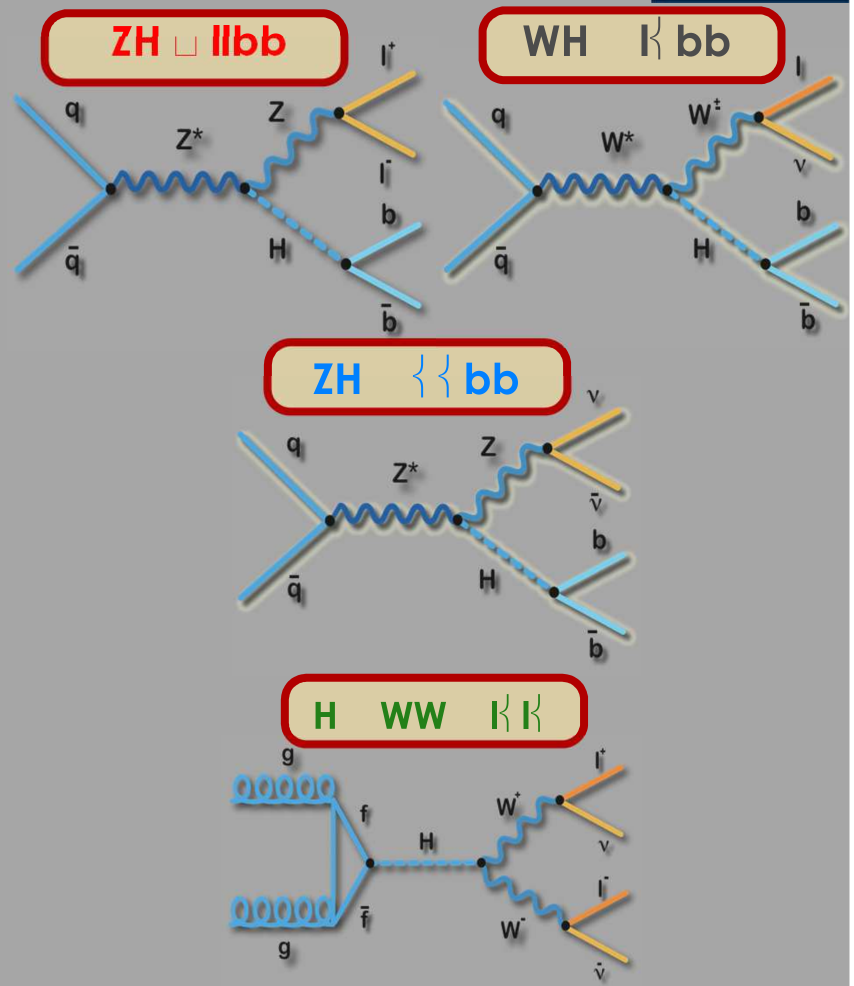
Tevatron Performance

An enormous thanks to the Fermilab Accelerator Division for an outstanding performance!



Higgs Searches: The basics

	Low Mass	High Mass
Primary Production:	WH, ZH	gg->H
Decay:	H -> bb	H -> WW
Main modes:	bb+lν bb+νν bb+ll	ll+νν
Important features:	• B-tagging • Dijet resolution	• Lepton acceptance • Angular correlations



Note: These are the most sensitive channels but all non-negligible production and decay modes are considered.

Higgs Searches: The basics

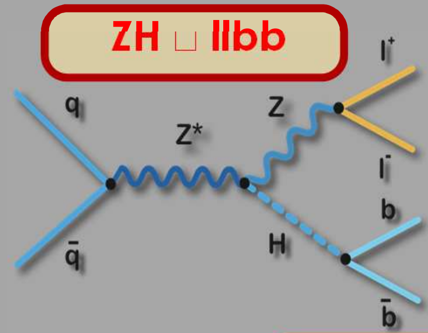
<u>Complementary to the LHC:
ATLAS and CMS</u>

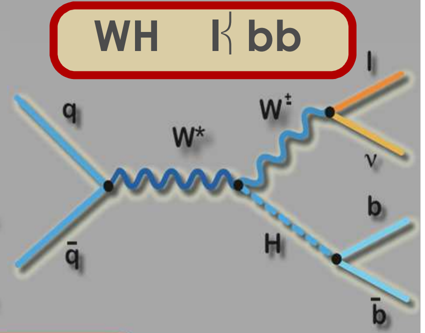
Strong evidence in diphoton channel (H-γγ)

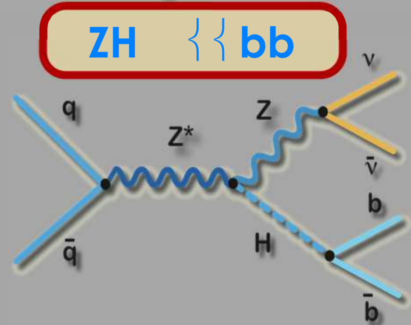
Evidence of H – ZZ

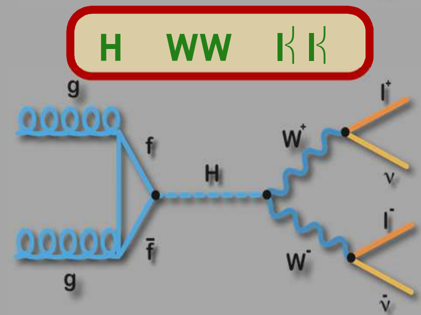
Weak Evidence of H- WW

No evidence so far of fermionic decays (Tau channels are data deficit)









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Important features:	• B-tagging • Dijet resolution	• Lepton acceptance • Angular correlations

WH lν bb

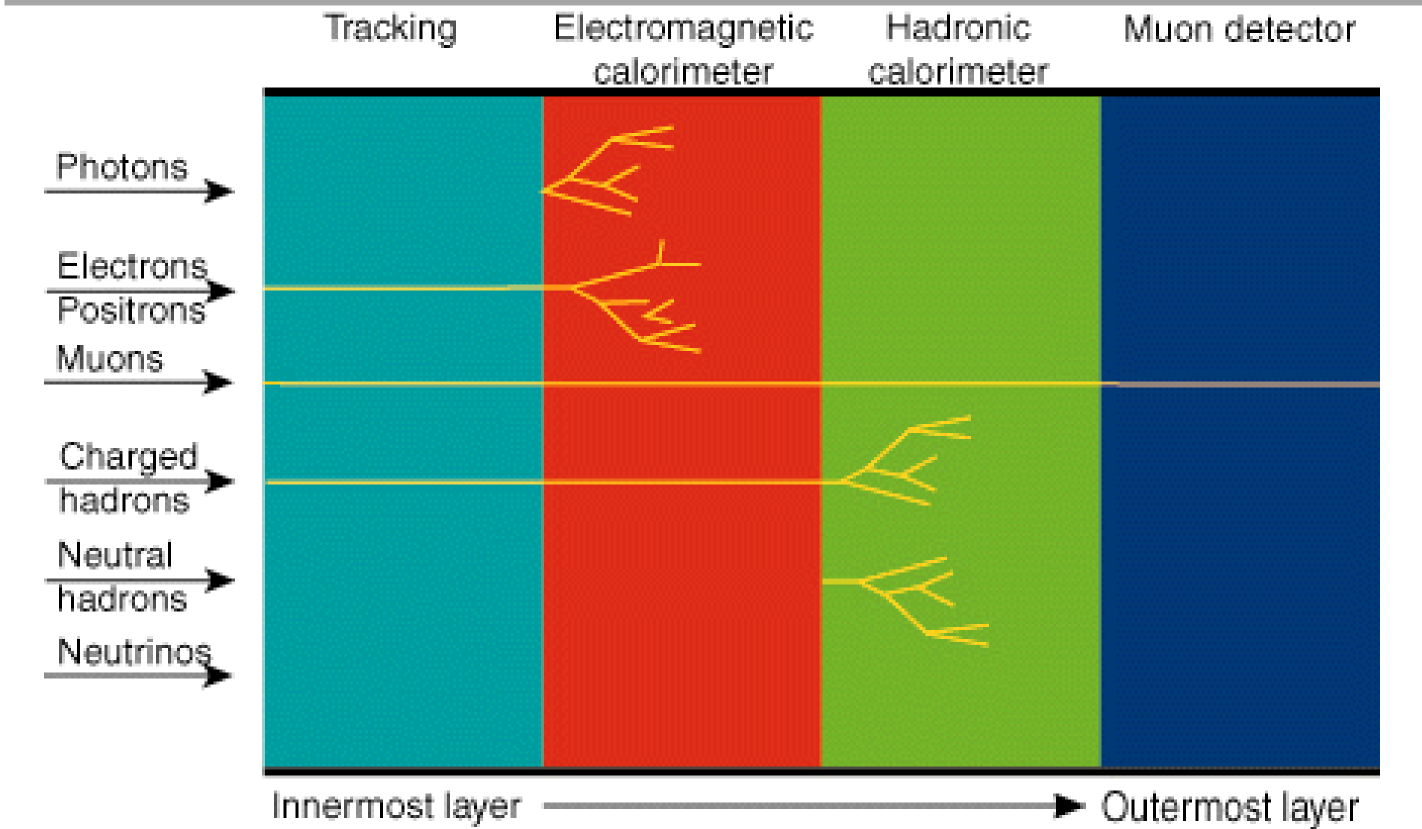
Our UVA effort focused mostly on this channel so I will use it for examples.

WH-lvbb at CDF is the most sensitive Tevatron channel for 125 GeV Higgs.

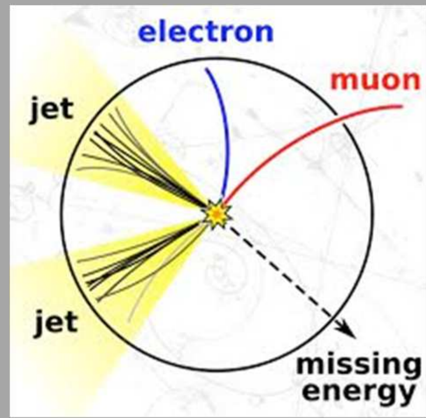
For WH-lvbb we need to identify leptons, neutrinos, and b-quarks.

Particle Identification

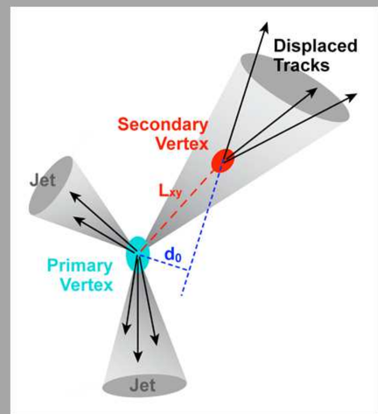
So, for **WH** → **ℓν bb** we need to identify event with a lepton, neutrino, and two b jets:



Quarks and gluons "hadronize" to form "jets" of clusters of particles in our detector.



b-jets are special:



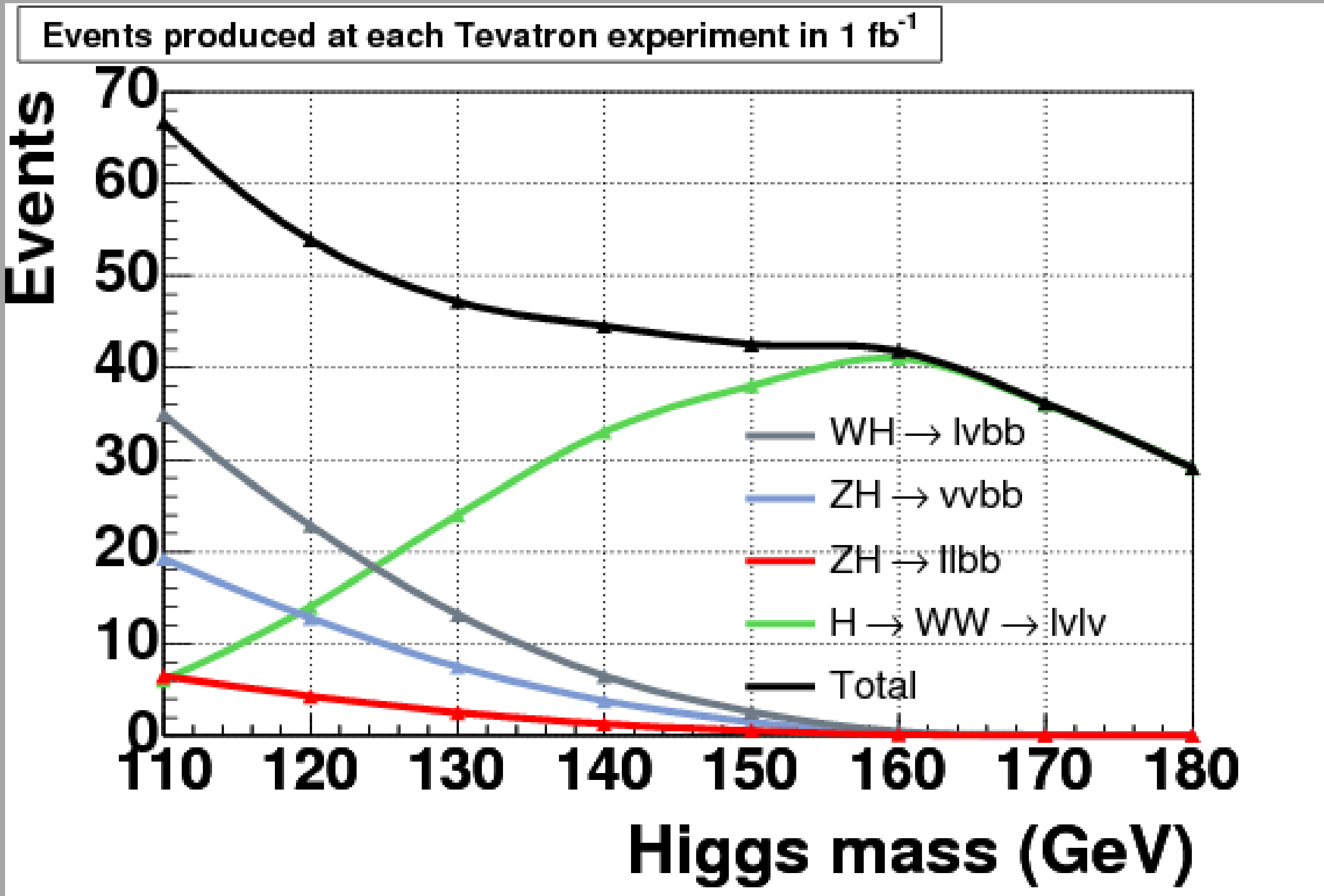
The CDF Experiment at FNAL

Our UVa effort joined the CDF experiment in October 2010!

Collaboration
----
15 Countries
~~56~~ 57 Institutions
475 Authors
~50 pubs/year

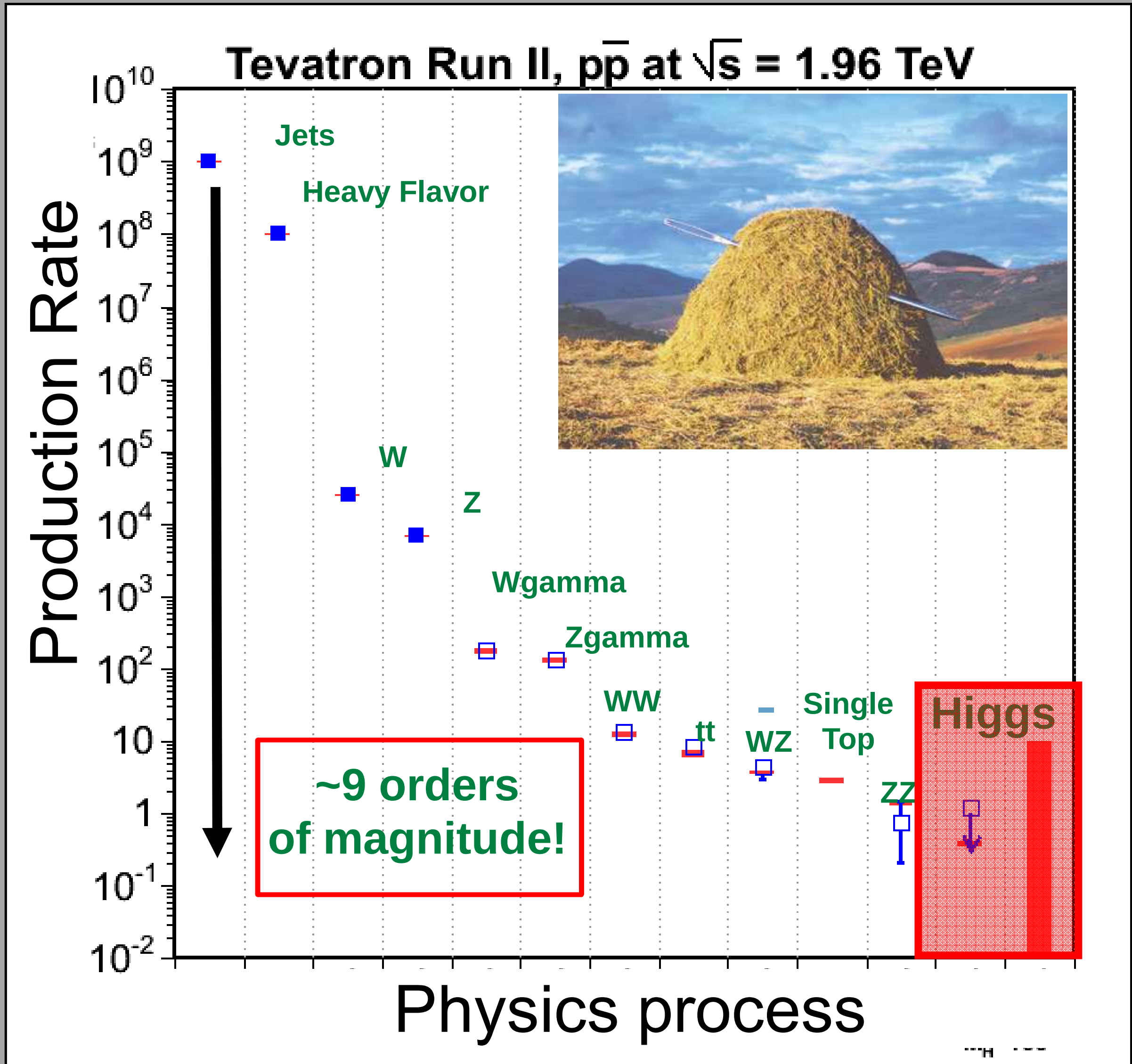
CDF @ UVa

Higgs Production Rates



About 1000 Higgs events expected in the main search channels with the full Tevatron dataset (10 fb^-1)

Rates of Physics Processes at the Tevatron



Analysis Flow

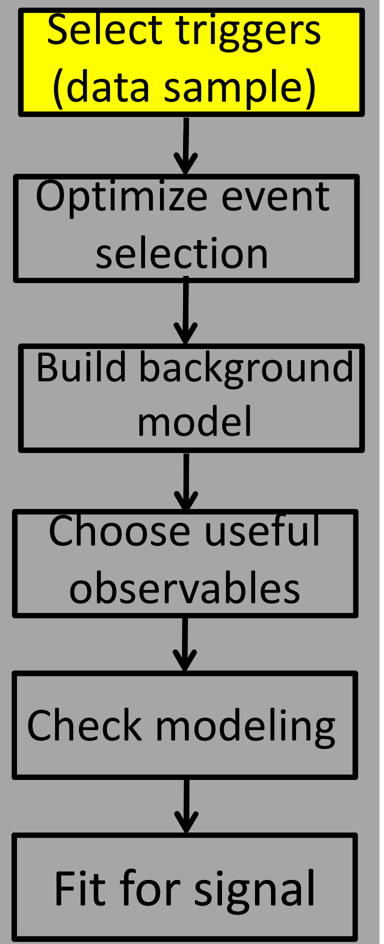
Triggers

- *Collisions occur at a rate of ~2.5 MHz!*
  → More than 99.9% jet events

- We select (trigger) potentially useful events and throw the rest away!

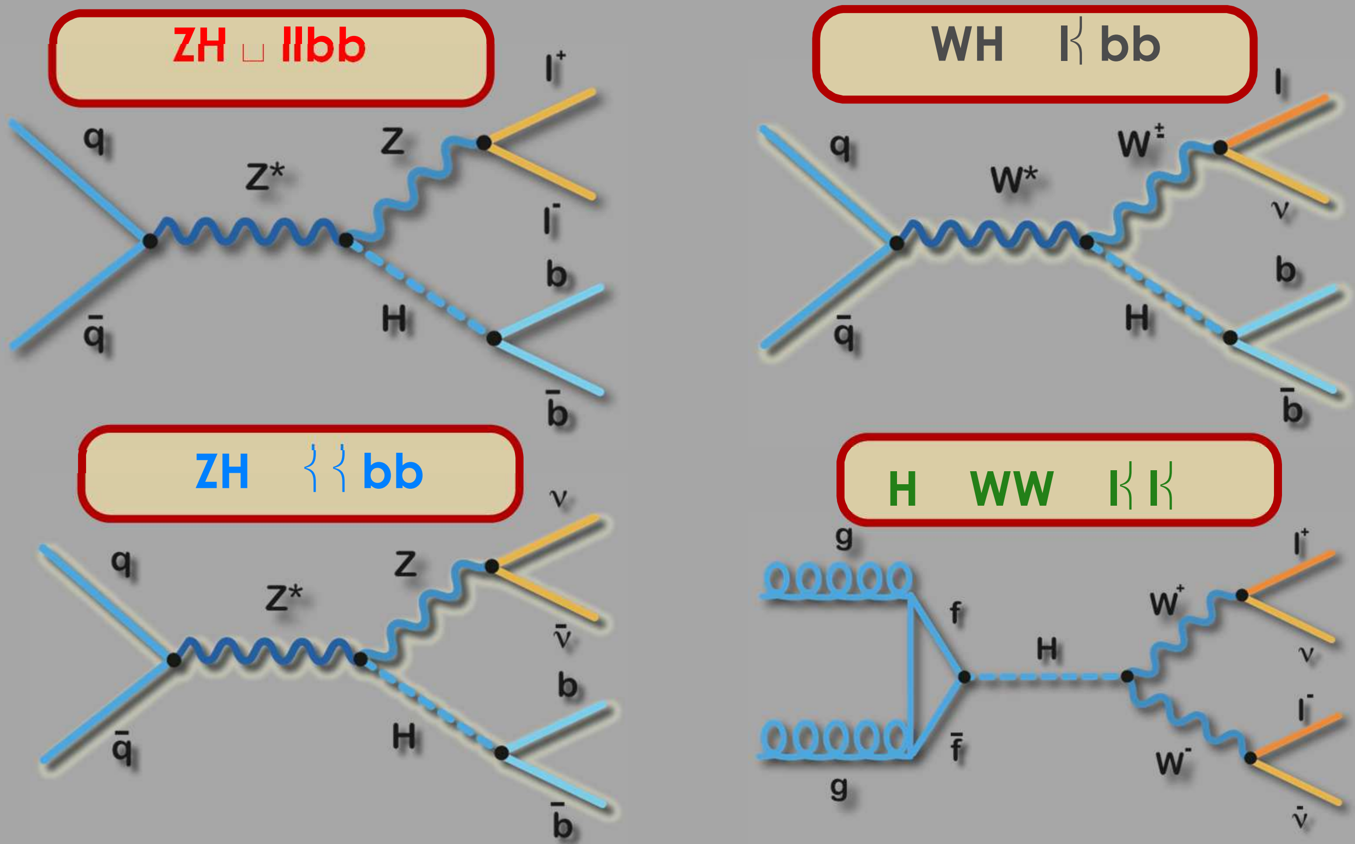
- There are many triggers to choose from:
  We can trigger on the lepton (*e or μ):*
  - *$WH \rightarrow \ell\nu bb$, $ZH \rightarrow \ell\ell bb$, $H \rightarrow WW$*

  Or, *MET + jets (MET= missing transverse energy):*
  - *$WH \rightarrow \ell\nu bb$, $ZH \rightarrow \nu\nu bb$*



Event Selection

Based on the final state content, event selection is optimized to maximize signal acceptance and sample purity

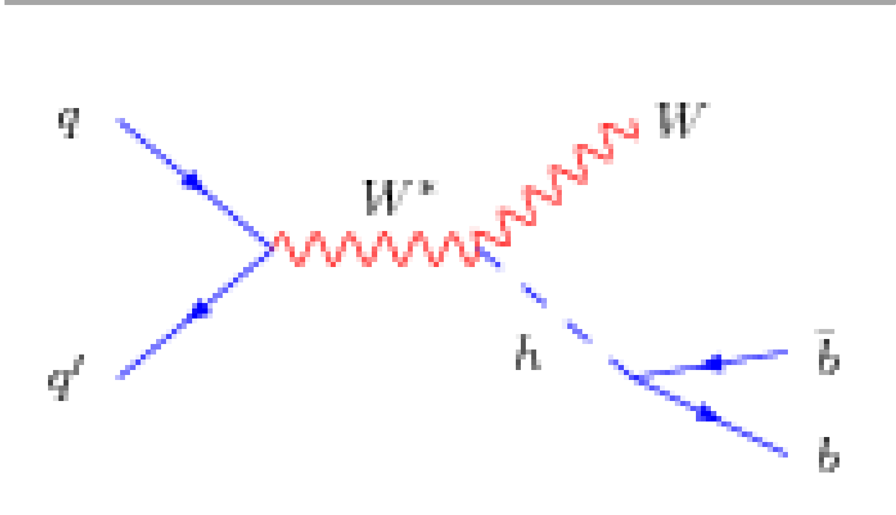


- Select triggers (data sample)
- Optimize event Selection
- Build background model
- Choose useful observables
- Check modeling
- Fit for signal

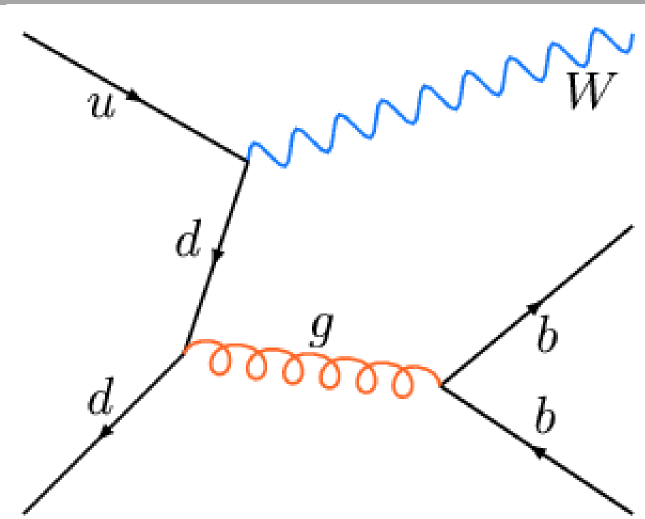
Backgrounds to the Higgs Boson Signal

Backgrounds are events from other processes that pass Higgs event selection.

Examples from WH → bb



Signal



Physics Background

- Select triggers (data sample)
- ↓ Optimize event Selection
- ↓ **Build background model**
- ↓ Choose useful observables
- ↓ Check modeling
- ↓ Fit for signal

Other backgrounds from top, dibosons, …

Backgrounds to the Higgs Boson Signal

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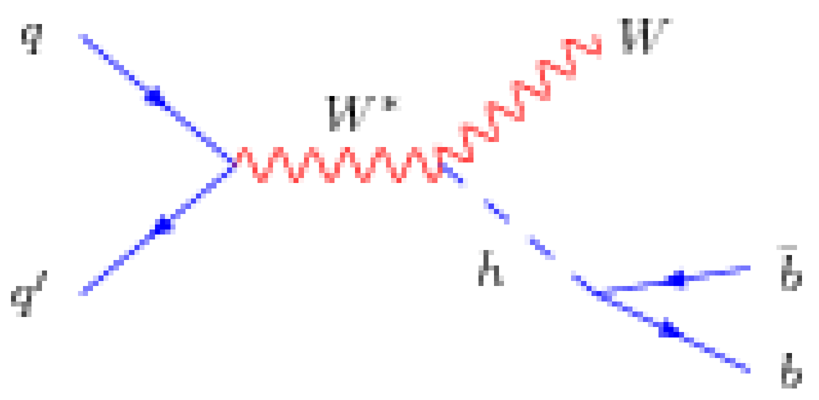
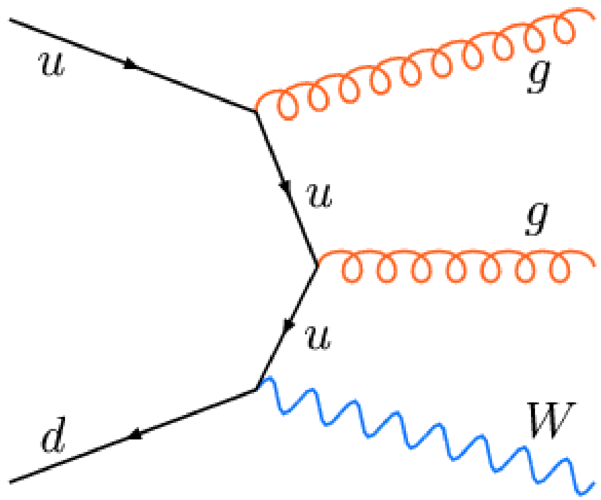
Examples from WH → bb



Signal



Instrumental Background

- Select triggers (data sample)
- Optimize event Selection
- Build background model
- Choose useful observables
- Check modeling
- Fit for signal

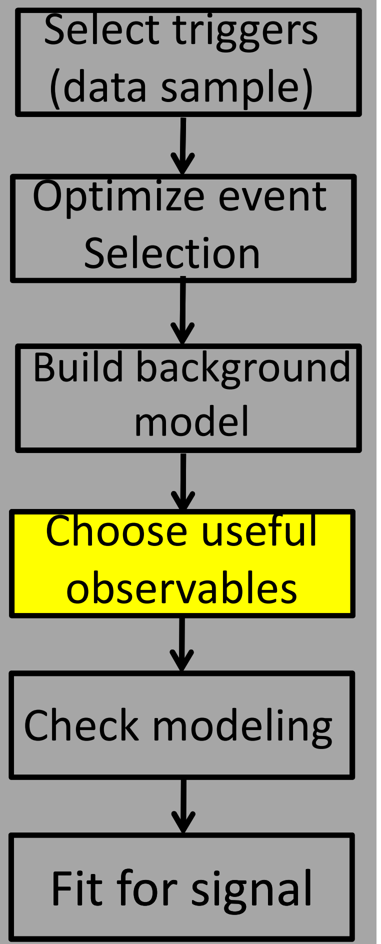
Other backgrounds from top, dibosons, …

Variable Selection

Uncertainties on background are larger than expected signal

Simple counting experiment won't work!

Need to use shape information…



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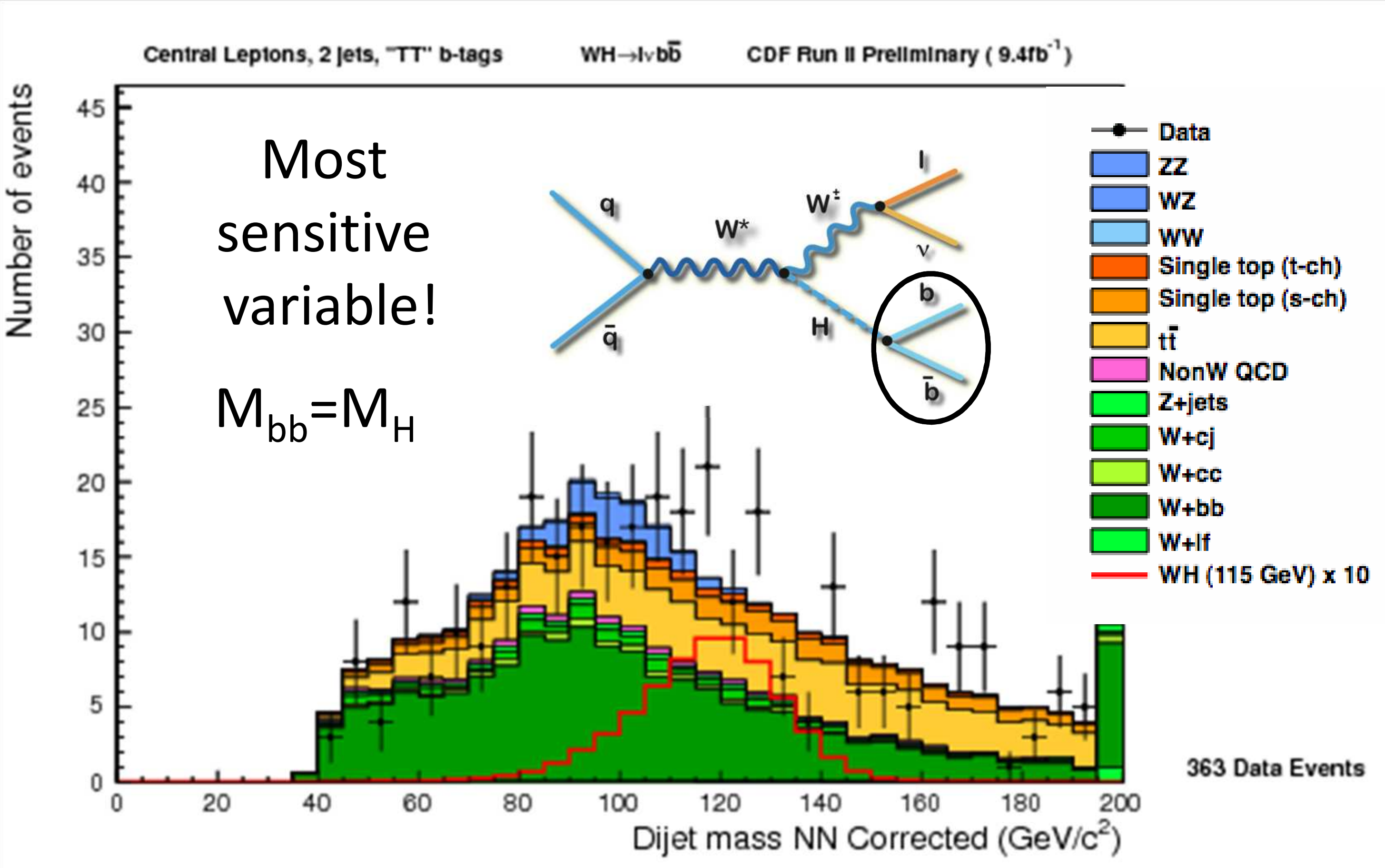
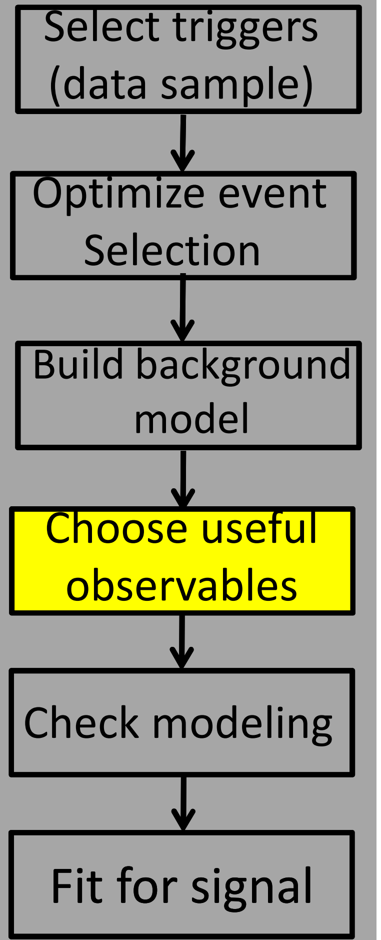


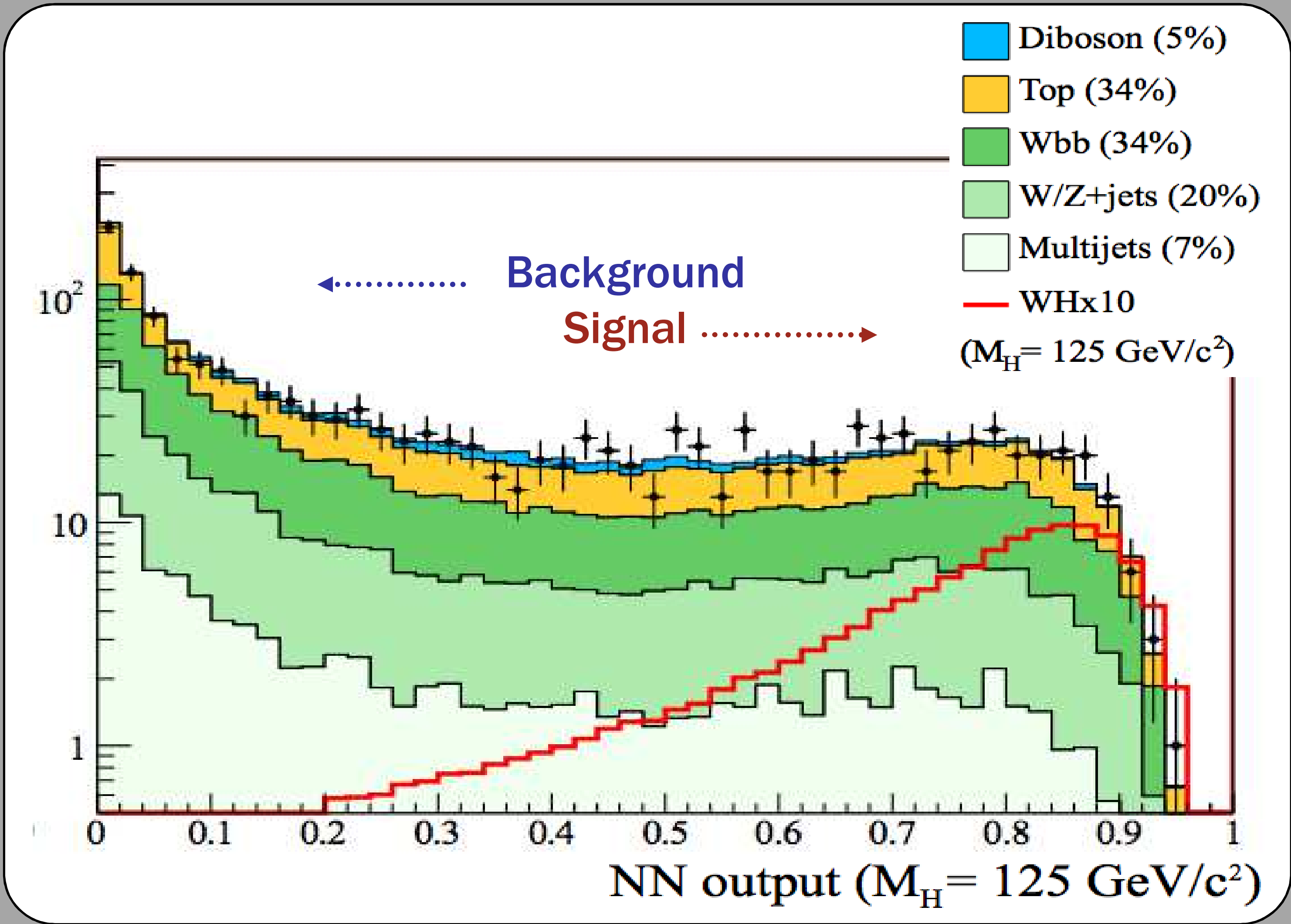
Select triggers (data sample)
↓
Optimize event Selection
↓
Build background model
↓
Choose useful observables
↓
Check modeling
↓
Fit for signal

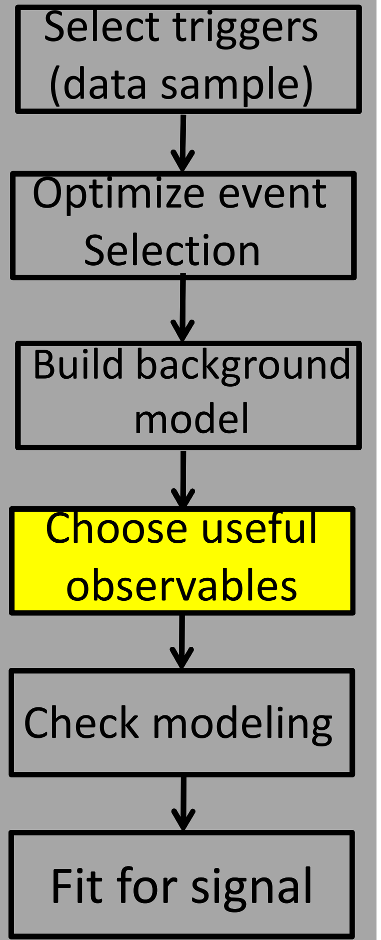
Other Variables

- For low-mass Higgs searches, M_{jj} is the most sensitive, but other variables can add separation power between signal and background
- Multivariate discriminant: Just a function with multiple parameters optimized to discriminate signal from background
- Using multivariate techniques improves sensitivity by ~25% over just using M_{jj}!



Multivariate Techniques





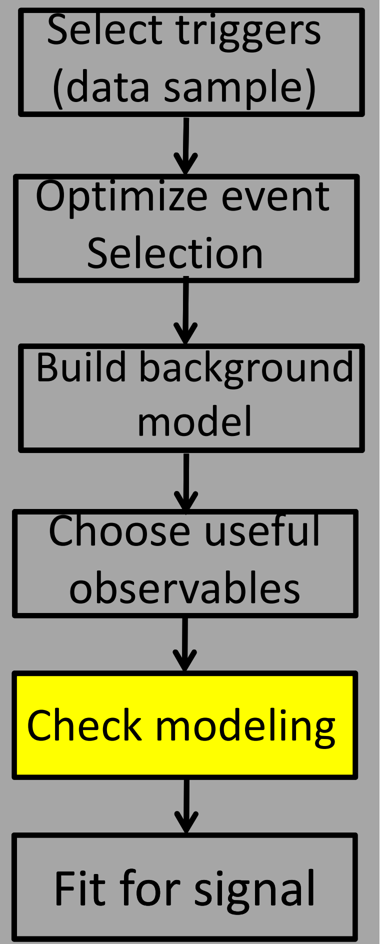
Example from WH-lvbb at CDF

Check Background Modeling

Multivariate techniques are only as good as the modeling of the input variables…

We check our background model in many ways:

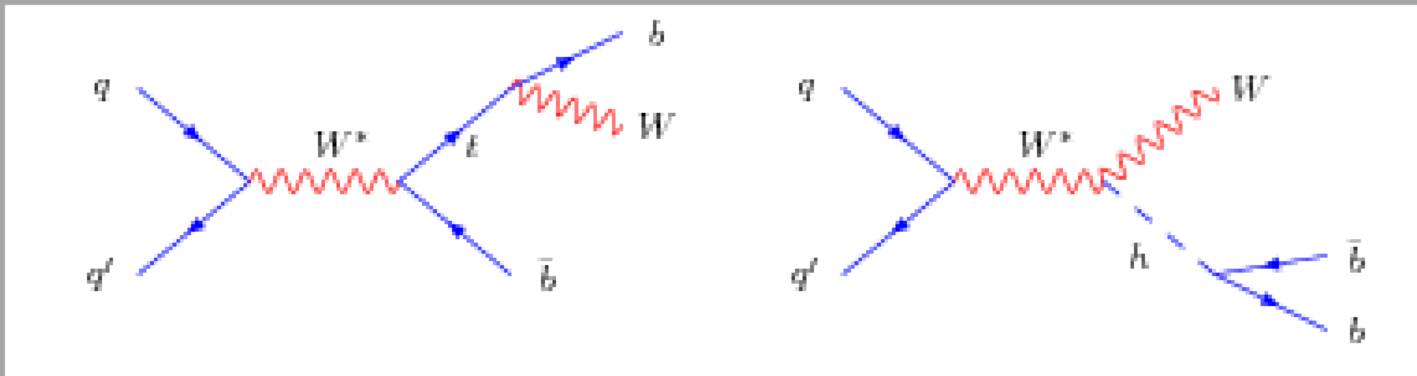
- Compare input variables and MVA output with data in control regions and signal regions
- Build confidence in the robustness of techniques and background model by successful measurements of other processes in similar final states.
  - Examples:
    - Single top production
    - Diboson production



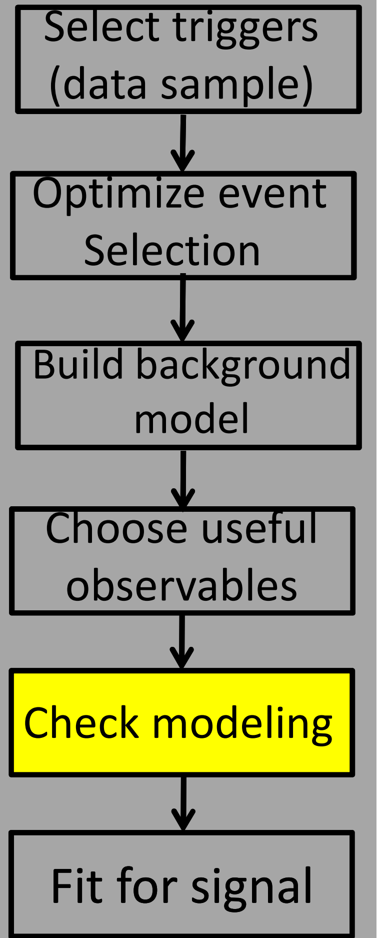
Check Background Modeling

Single Top Example

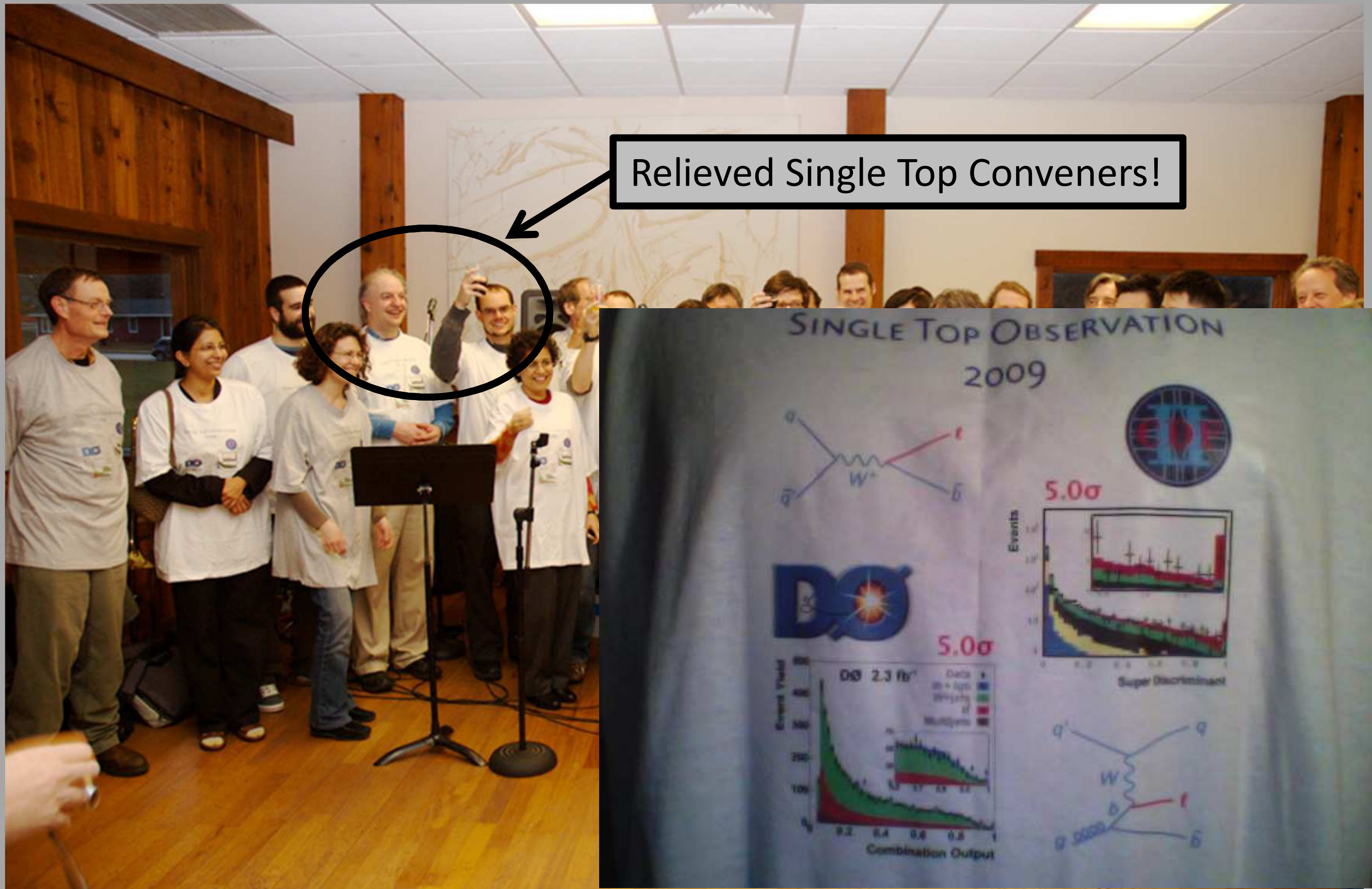
- Measuring single top quark production is a benchmark for WH-lvbb!



- Same final states, and therefore same analysis strategy, modulo different definitions of signal.
- Same tools and techniques
- Single top is a background for WH
- $\sigma_{WH} \sim 1/10\ \sigma_{Singletop}$



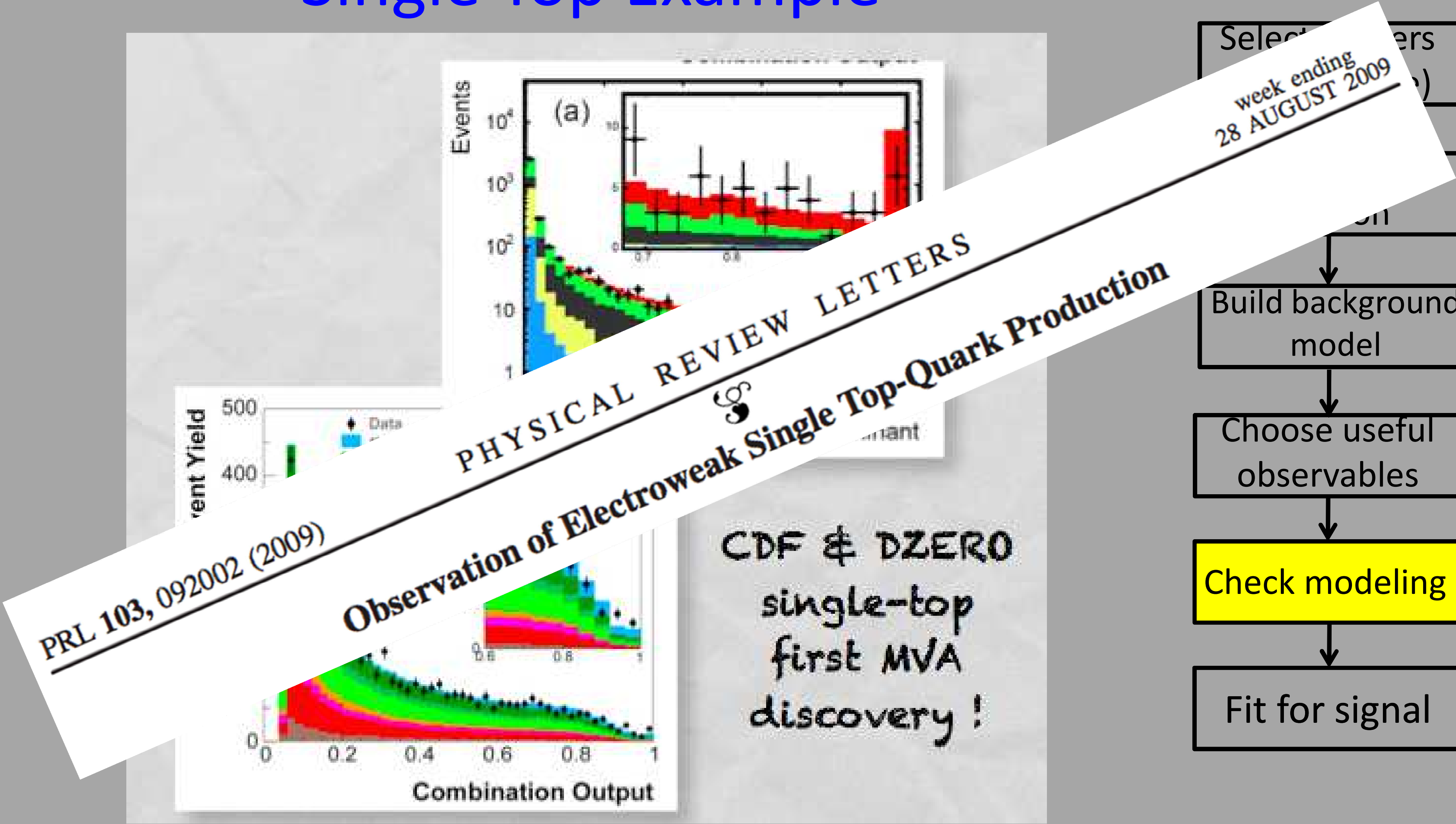
Single Top Celebration



We all got T-shirts.

Check Background Modeling

Single Top Example

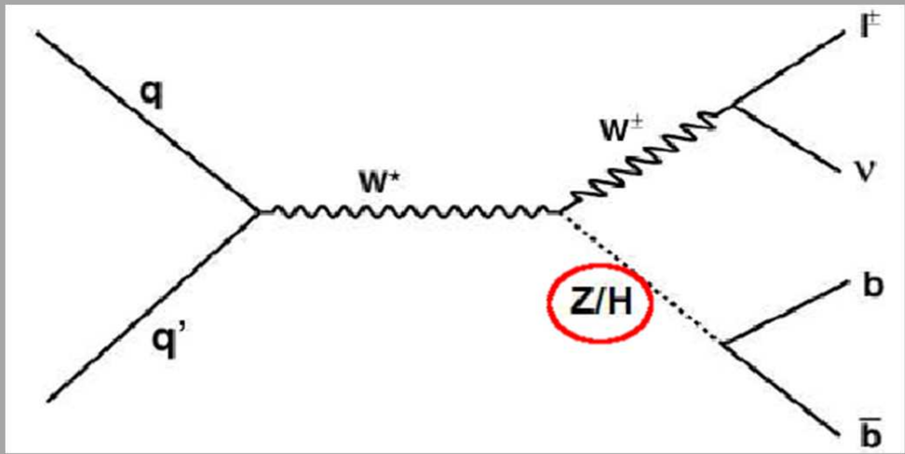


- Build background model
- Choose useful observables
- **Check modeling**
- Fit for signal

Check Background Modeling

Diboson Example

- Feynman diagrams are topologically equivalent to Higgs channels

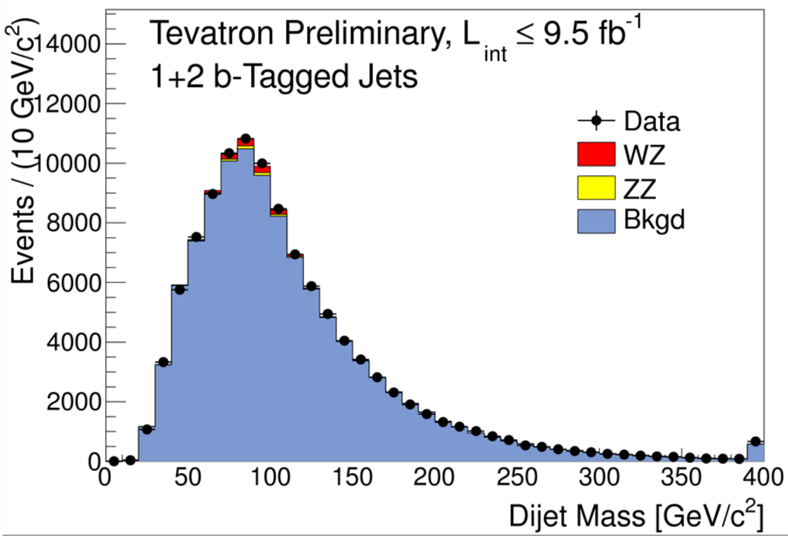


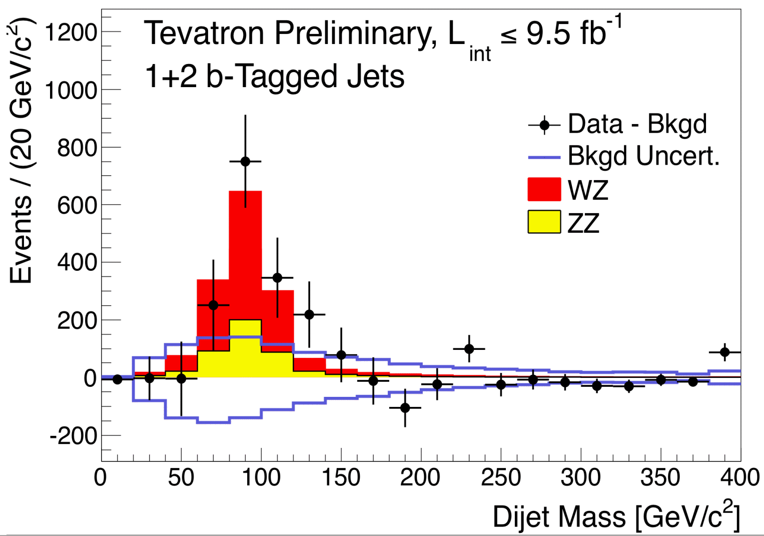
- Same final states, and therefore same analysis strategy, modulo different definitions of signal.
- We combine the main Higgs search channels retraining MVA discriminants for dibosons
- $\sigma_{WH} \sim 1/4\ \sigma_{WZ\text{-}l\nu bb}$

Select triggers (data sample) → Optimize event Selection → Build background model → Choose useful observables → **Check modeling** → Fit for signal

Check Background Modeling

Diboson Example





Select triggers (data sample)
↓
Optimize event Selection
↓
Build background model
↓
Choose useful observables
↓
Check modeling
↓
Fit for signal

σ(WZ+ZZ)= 3.9 ± 0.6(stat) ± 0.7 (syst) pb

(SM Prediction = 4.4 ± 0.3 pb)

(Note: MVA outputs used for cross section fit)

Fit For Signal

- We set limits on the Higgs boson production rate
- Use a combined binned likelihood fit:

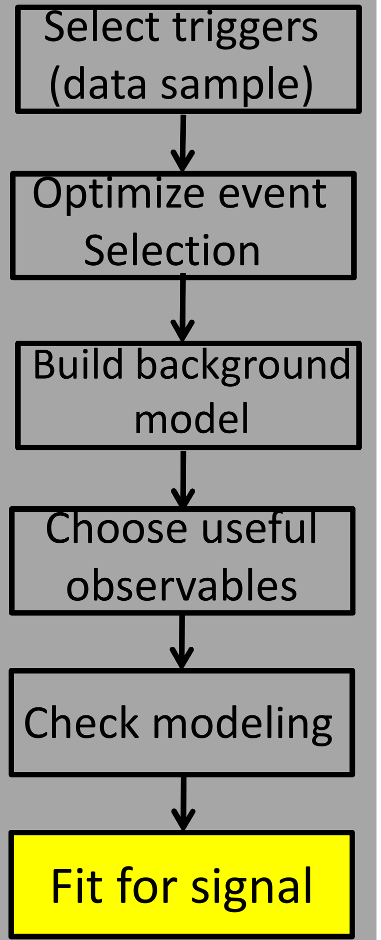
$$L(R, \vec{s}, \vec{b} | \vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

- Uncertainties incorporated as nuisance parameters

  -shape and normalization of background and signal

- These 95% C.L. limits say:

If the true Higgs production rate was at the limit value, we would see evidence of the Higgs signal more significant than what we observed in 95 % of experiments



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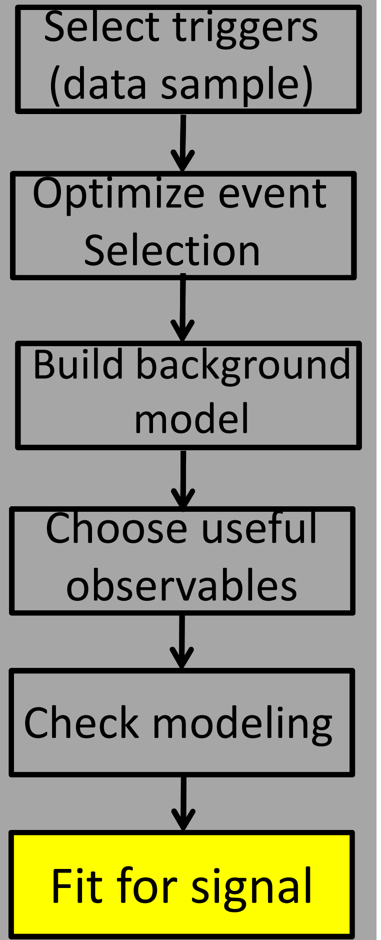


Combining All Channels

Low-Mass Channels	Sensitivity (m_H = 125 GeV)	
	CDF [SM]	D0 [SM]
WH → lν bb	2.8	4.7
VH → MET + bb	3.6	3.9
ZH → ll + bb	3.6	5.1
H → γγ	9.9	8.2
VH→eμ + X	-	5.9
VH→ eeμ/μμe/ττμ + X	-	7.1
VH, VBF, ggH → 1/2 jet + ττ	12	-

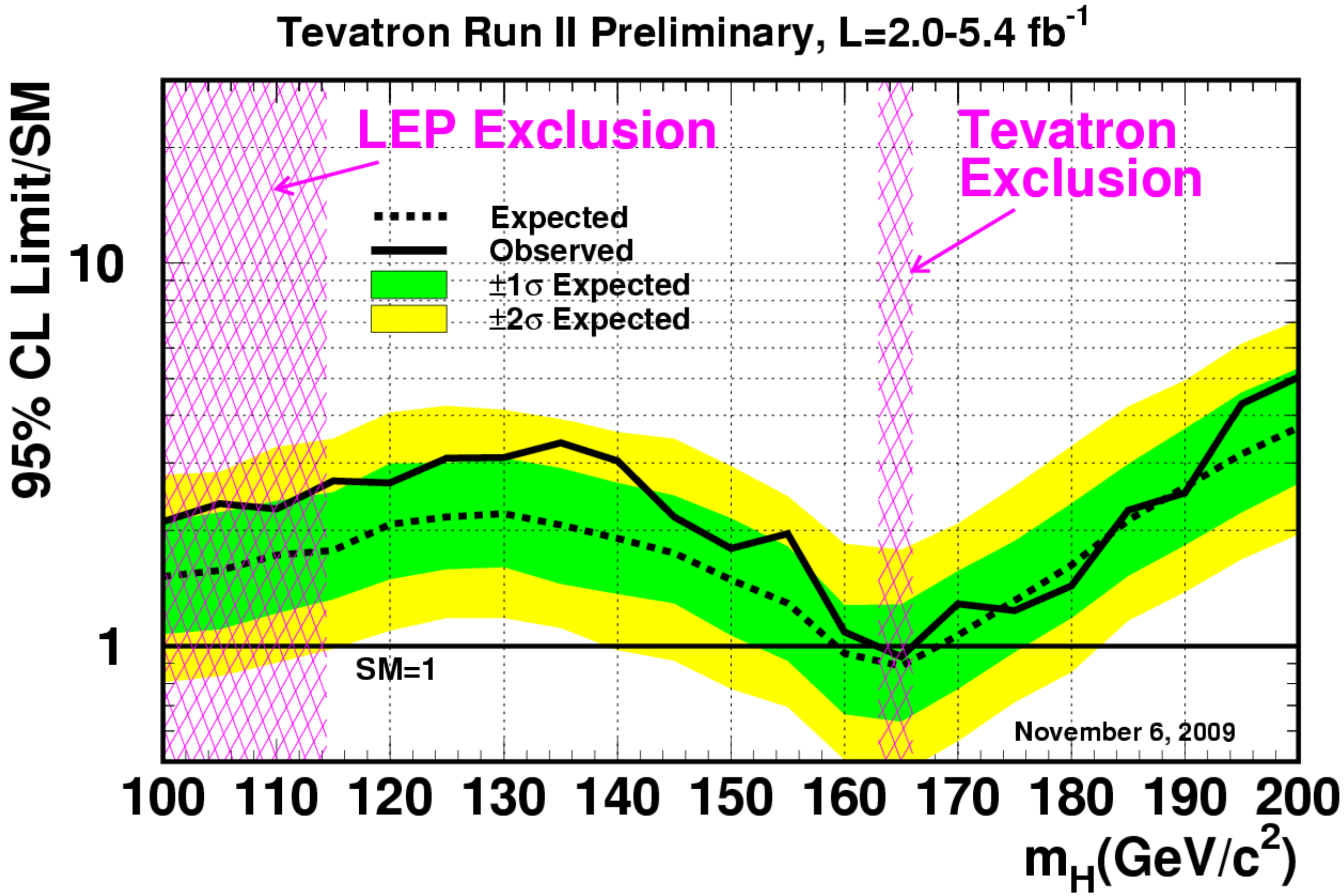
etc.

High-Mass Channels	Sensitivity (m_H = 165 GeV)	
	CDF [SM]	D0 [SM]
gg → H → WW → lνlν	0.7	0.8
H→WW→lνqq'	-	5.2
H→ZZ→ llll	20	-

etc.

Fall 2009 Tevatron Results

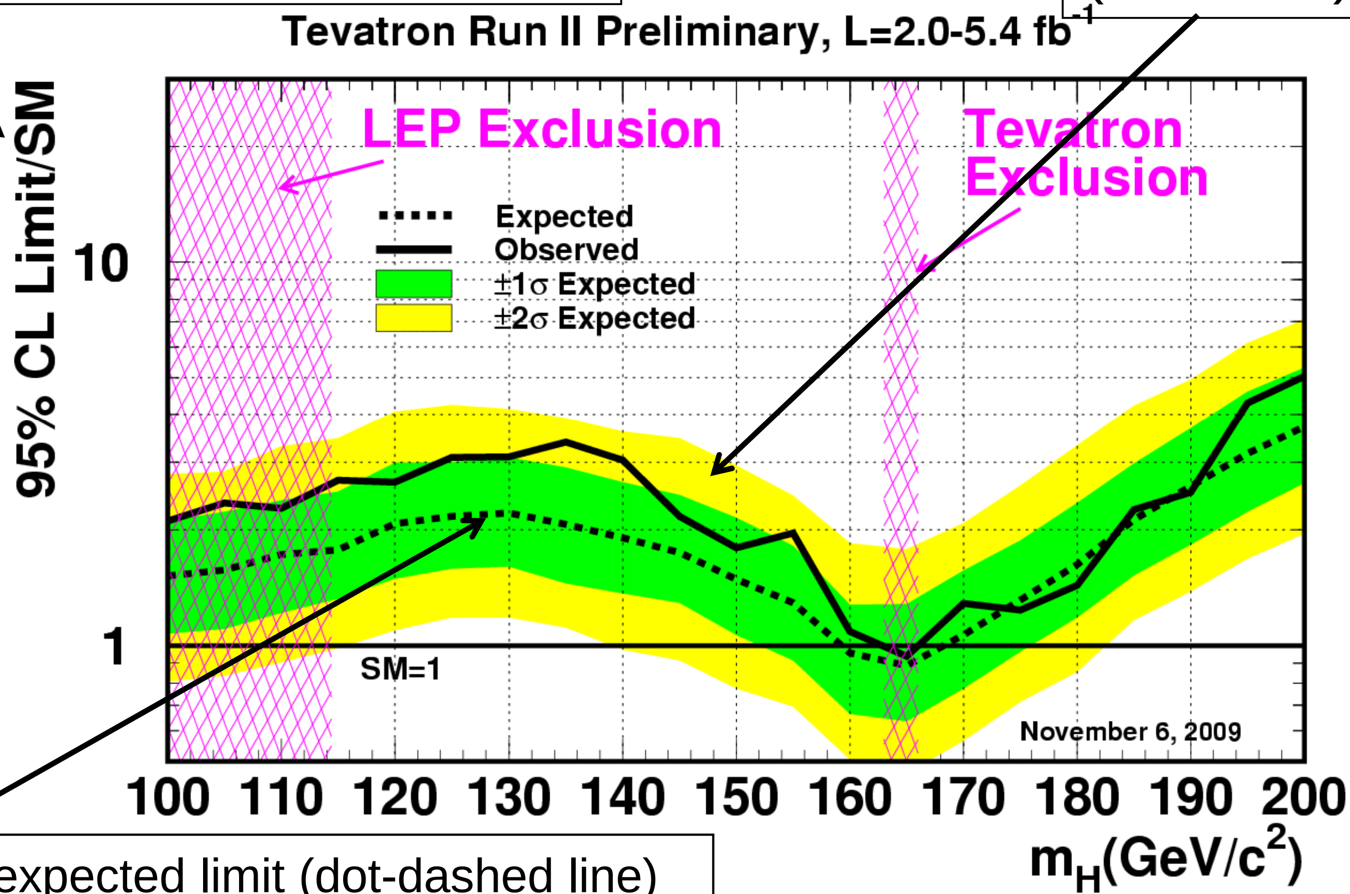
(The result that I showed at my interview in early 2010)



Fall 2009 Tevatron Results

1. Upper cross section limit for Higgs production relative to SM prediction

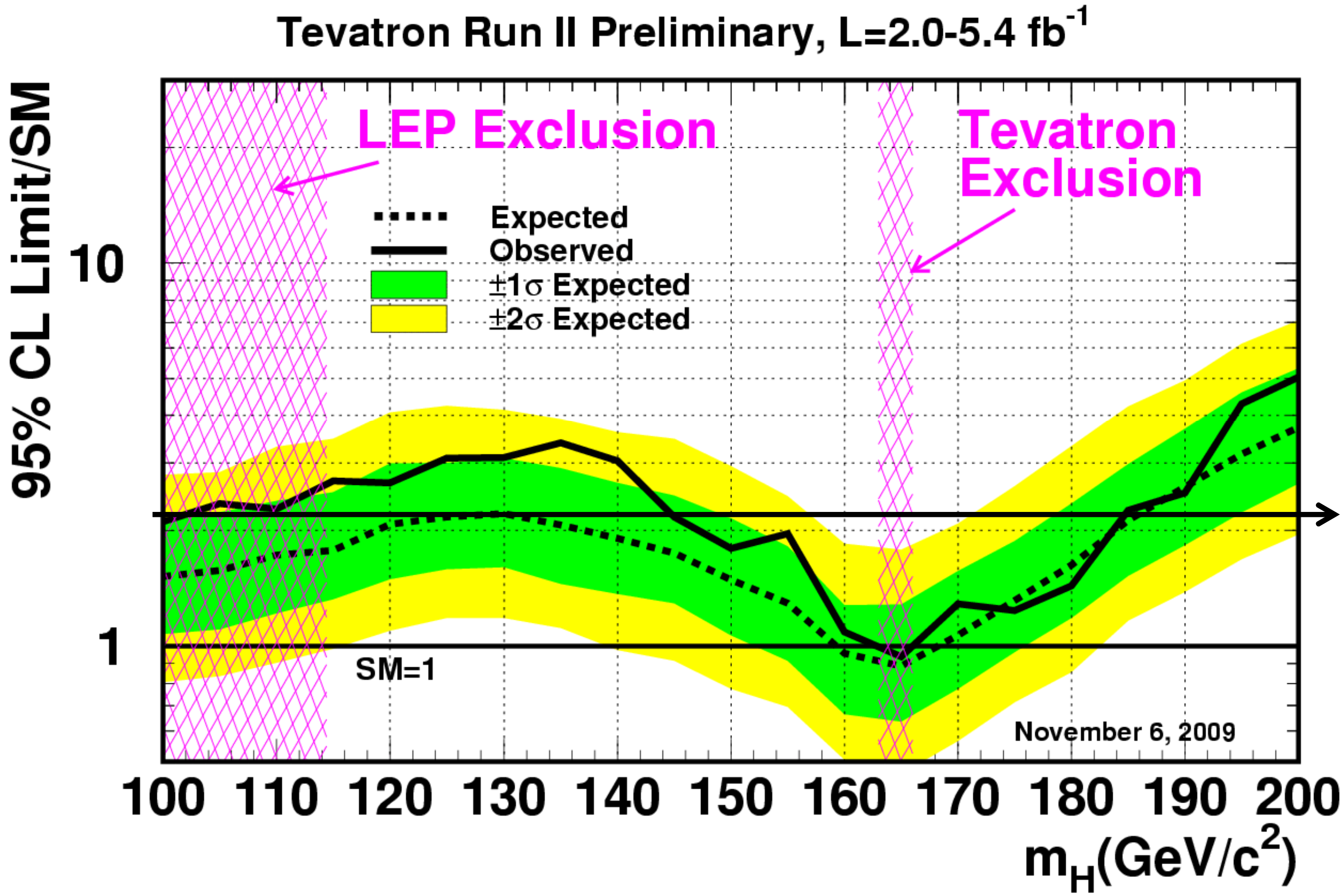
2. Observed limit (solid line) from data



3. Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

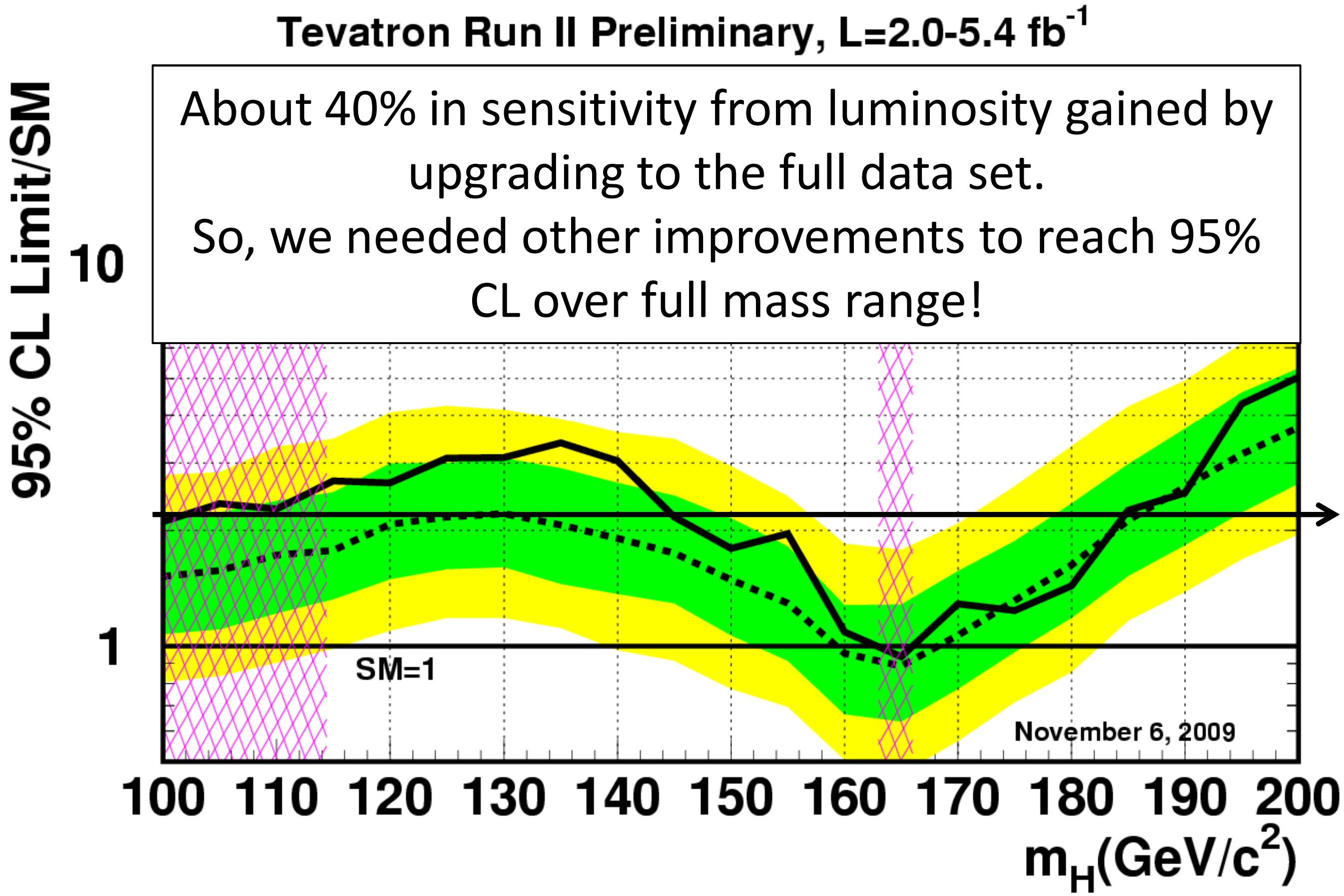
4. Analysis repeated using different signal templates for each m_H between 110 and 200 GeV in 5 GeV steps

Fall 2009 Tevatron Results



< ~2xSM sensitivity everywhere

Fall 2009 Tevatron Results



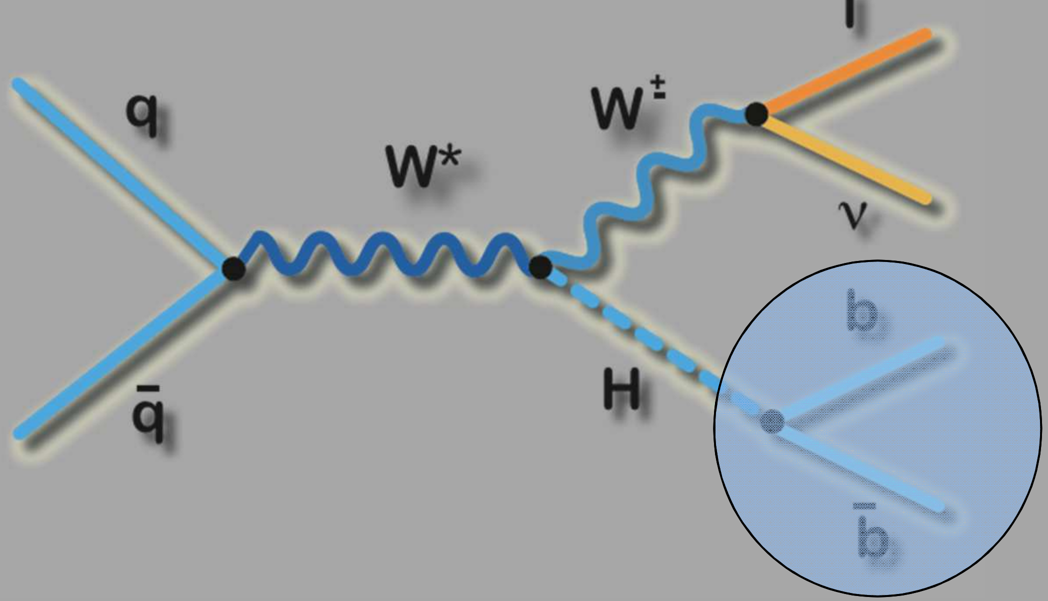
About 40% in sensitivity from luminosity gained by upgrading to the full data set.
So, we needed other improvements to reach 95% CL over full mass range!

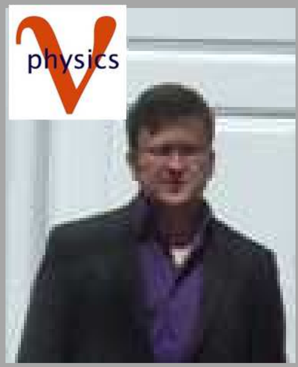
< ~2xSM sensitivity everywhere

UVA Improvements

Improvement Examples

Gain sensitivity by improving b-jet ID efficiency gains.
(applies to all h-bb channels)



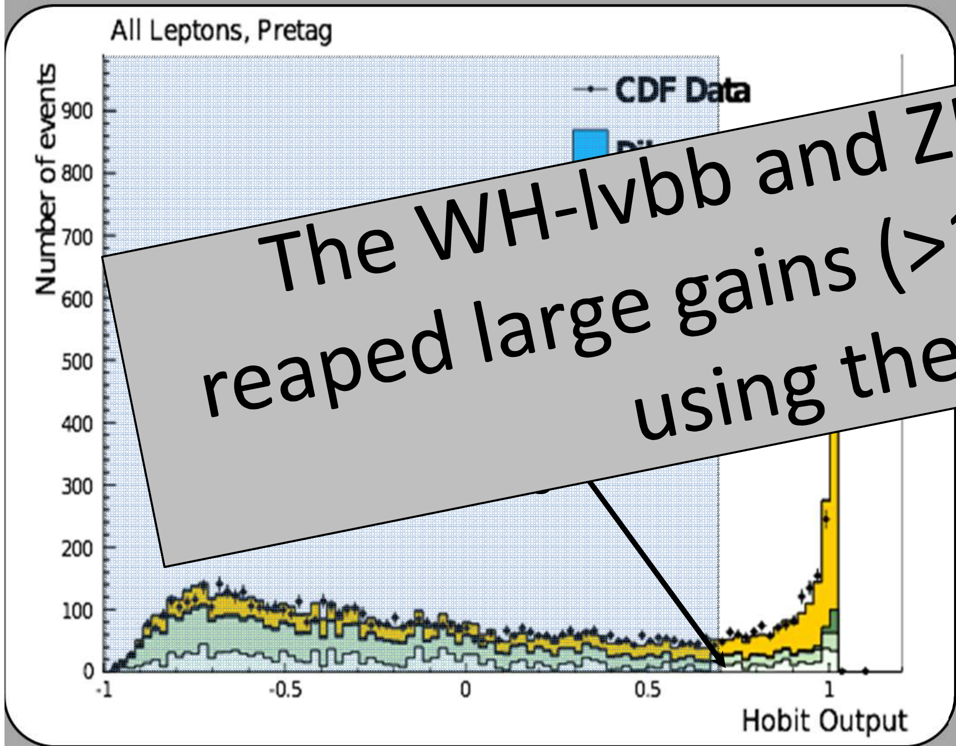


Yuri Oksuzian

Improved b-quark identification strategy for the low mass Higgs searches at CDF

New b-tagger at CDF

- By 2010 CDF had at least 5 types of b-taggers
- We incorporate the knowledge from previous taggers into:
  - The Higgs-Optimized b-Identification Tagger (HOBIT) - multivariate b-jet tagger



The WH-lvbb and ZH-llbb analyses have reaped large gains (>12%) in sensitivity from using the new tagger.

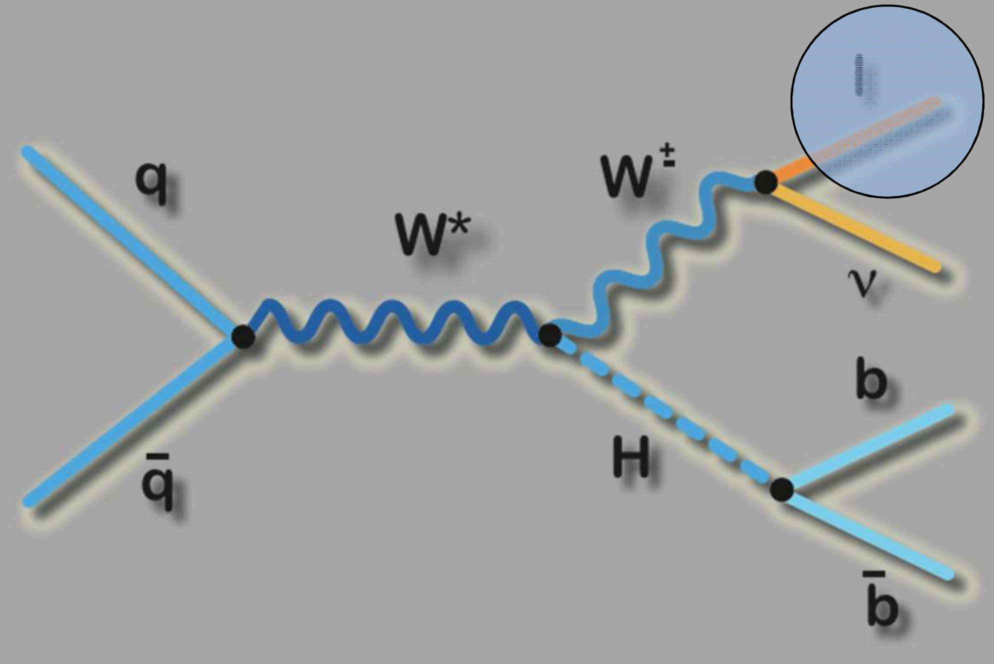
		(new tagger)
	39%	54%
~3%	47%	59%

Operating Point	mistag rate*	b-tag efficiency*
Tight	~1%	54%
Loose	~9%	70%

Form 5 orthogonal tagging categories: TT, TL, T, LL, L

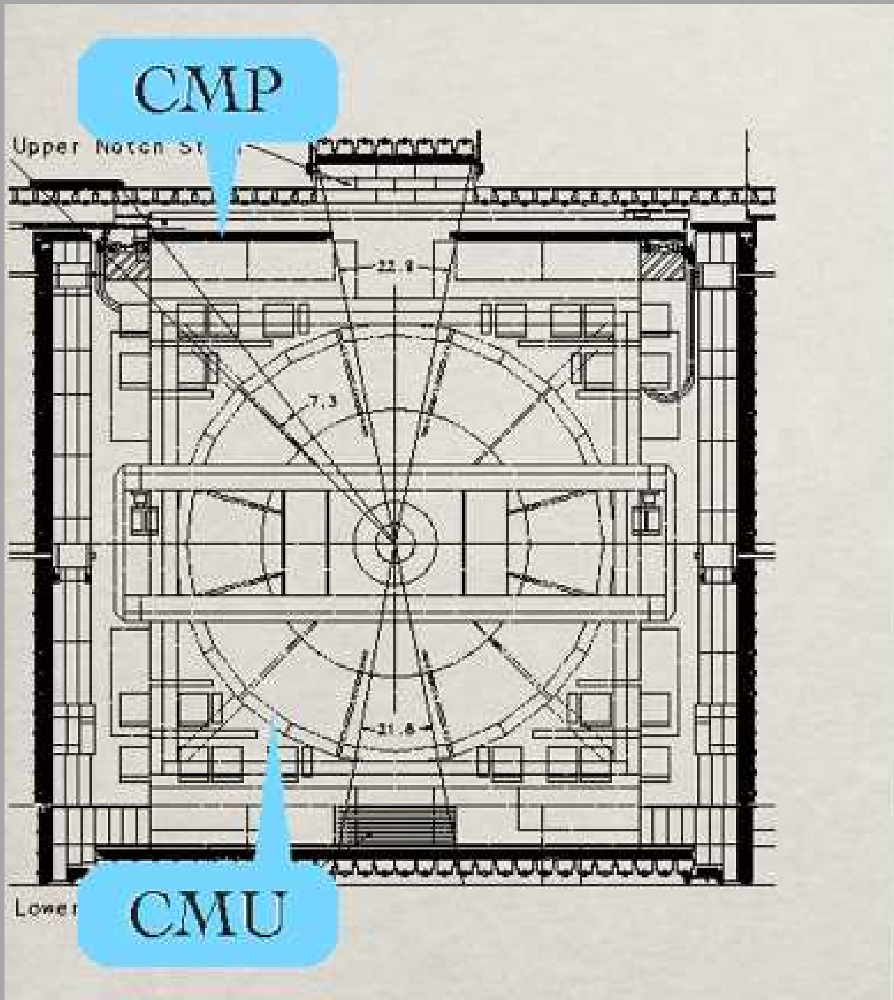
Improvement Examples

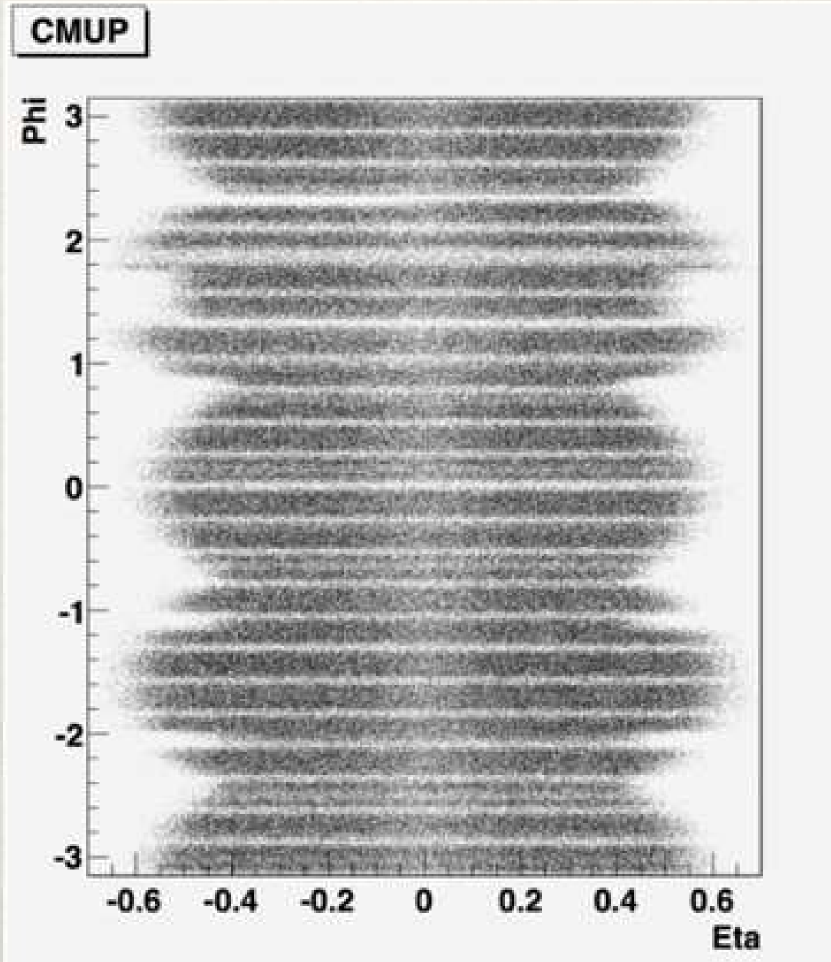
Gain sensitivity by improving lepton trigger acceptance.



Hao Liu
Improving the Trigger Efficiency for the WH-lvbb analysis at the CDF experiment

Muon Trigger Improvement



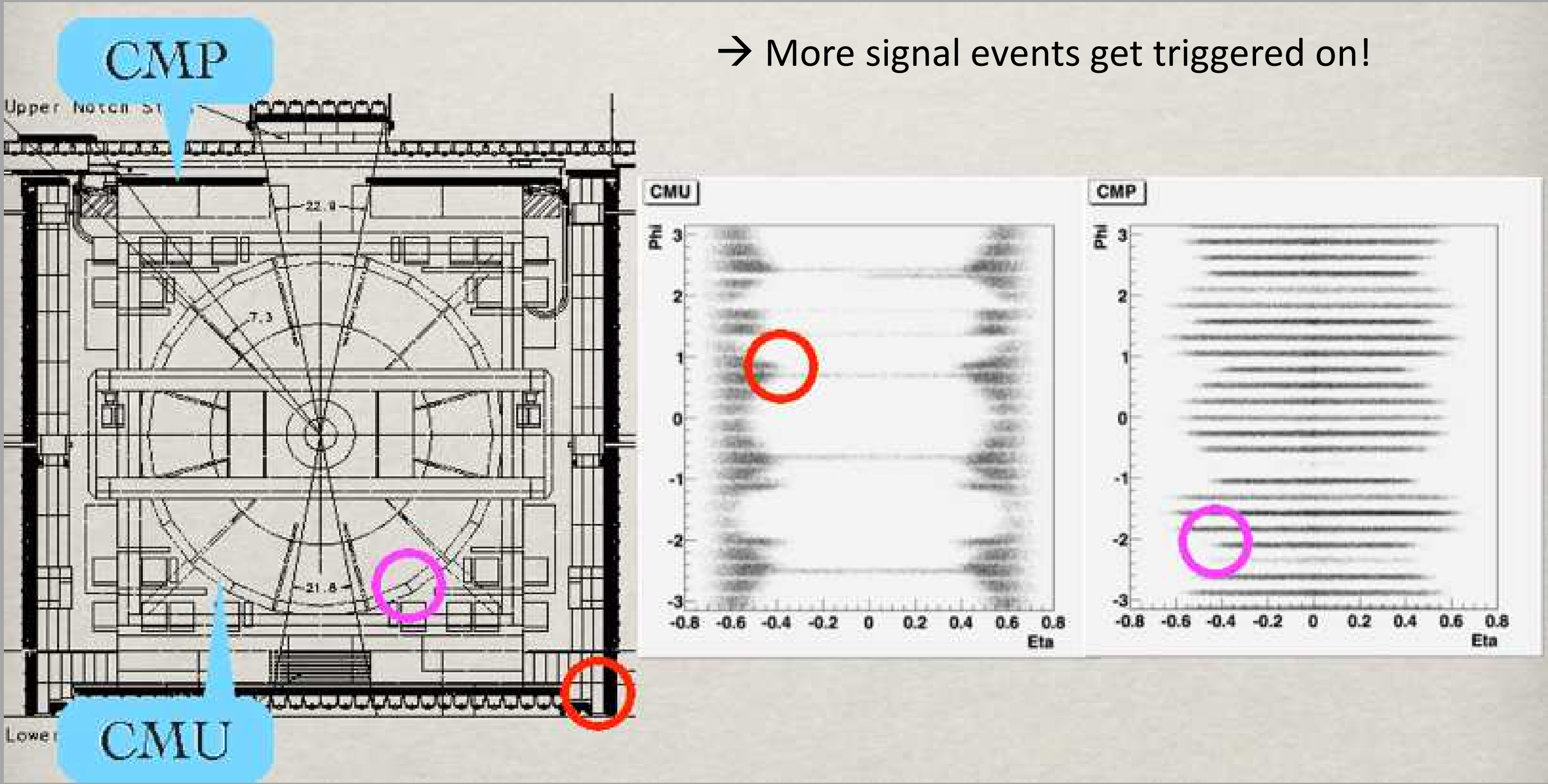


The primary muon trigger required ‘hits’ in both muon chambers (CMU && CMP) leaving many cracks in the trigger coverage.

Muon Trigger Improvement

In 2007 I created triggers based on CMU-only and CMP-only to improve trigger acceptance.

→ More signal events get triggered on!



In 2011 Hao Liu added these extra events to the CDF WH-lvbb Higgs search.
Hao also added an “inclusive” method to measure efficiency for a suite of triggers

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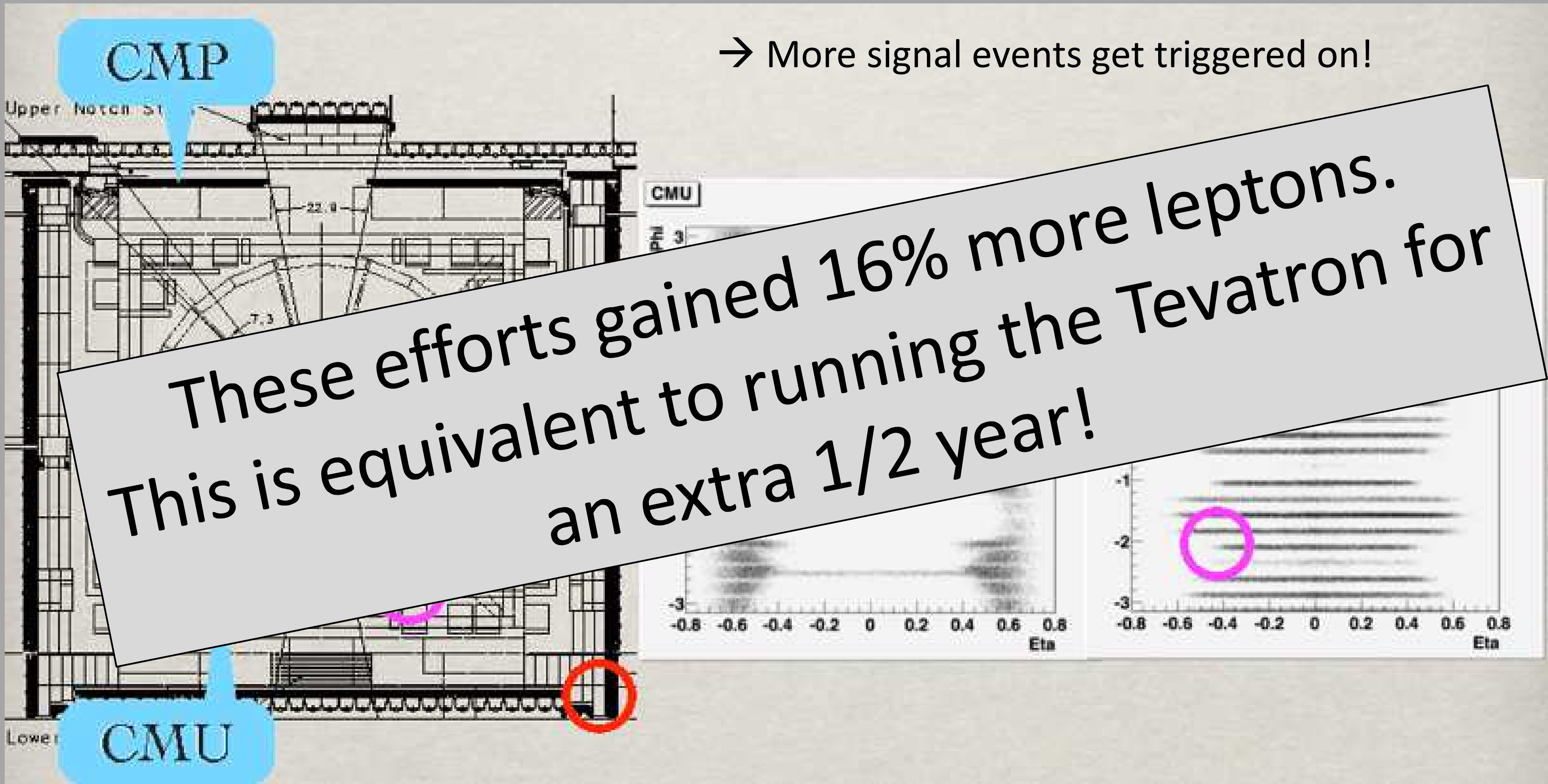

These efforts gained 16% more leptons.
This is equivalent to running the Tevatron for an extra 1/2 year!

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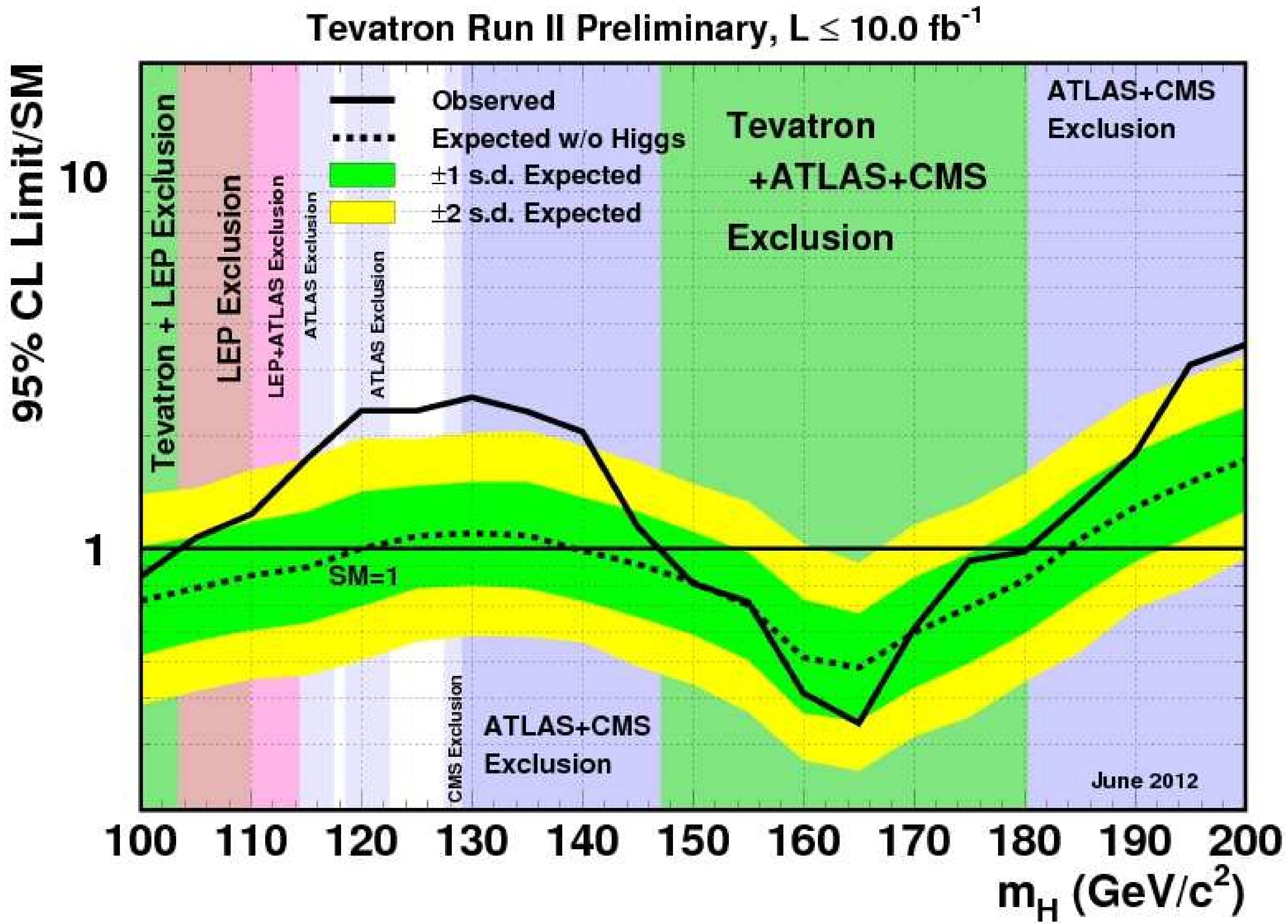
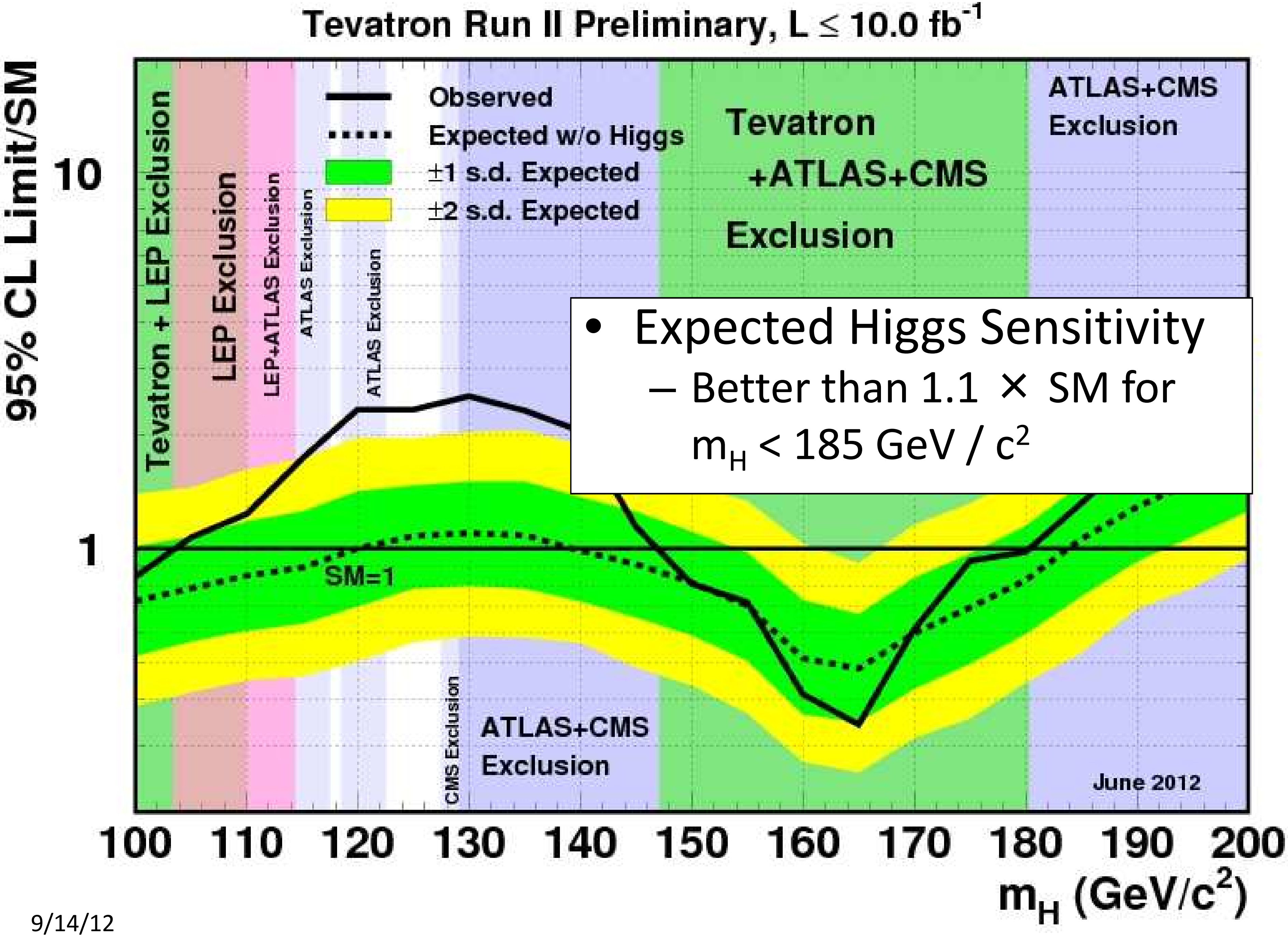
The 10 Million Dollar Man!

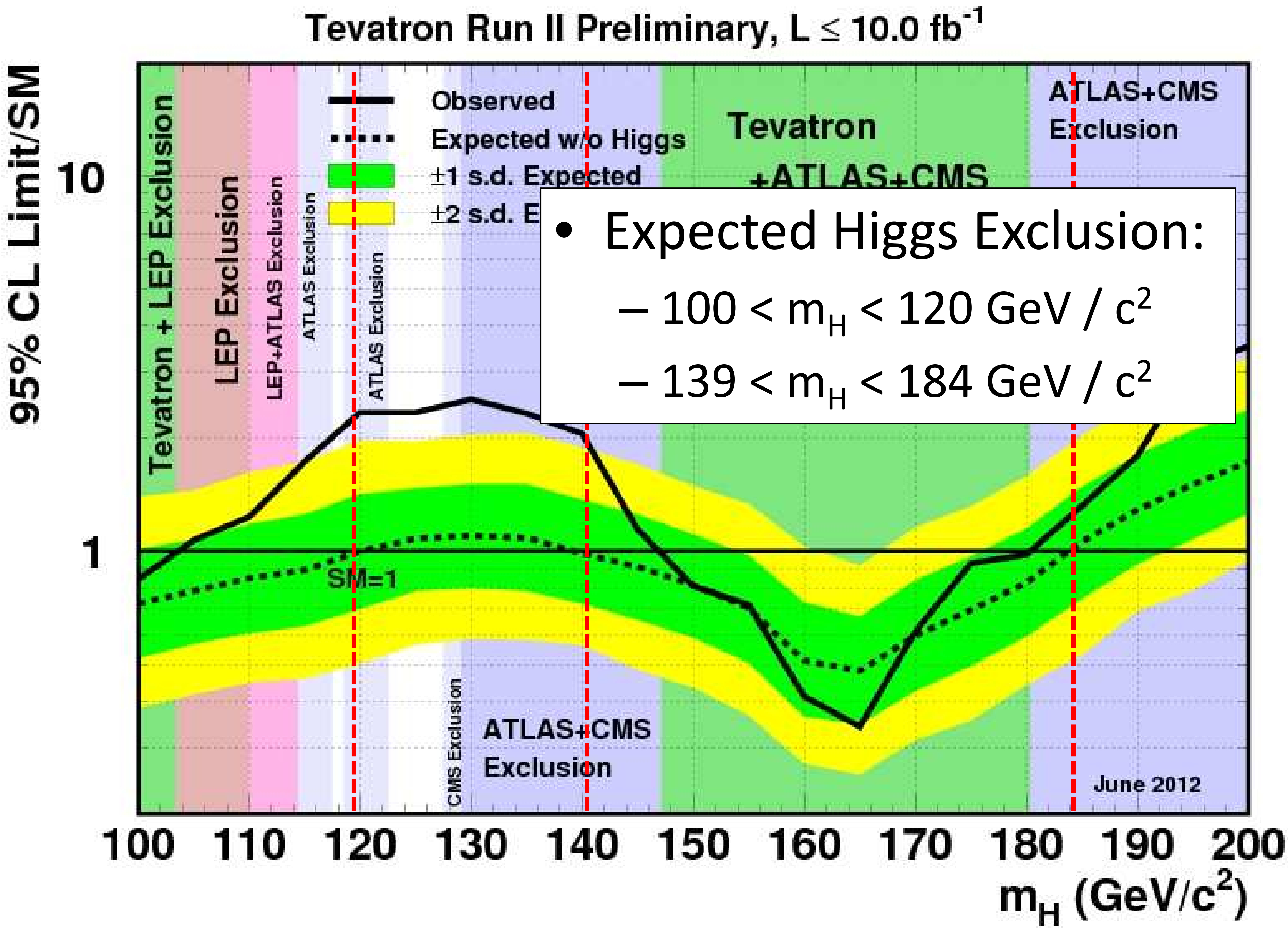
Results



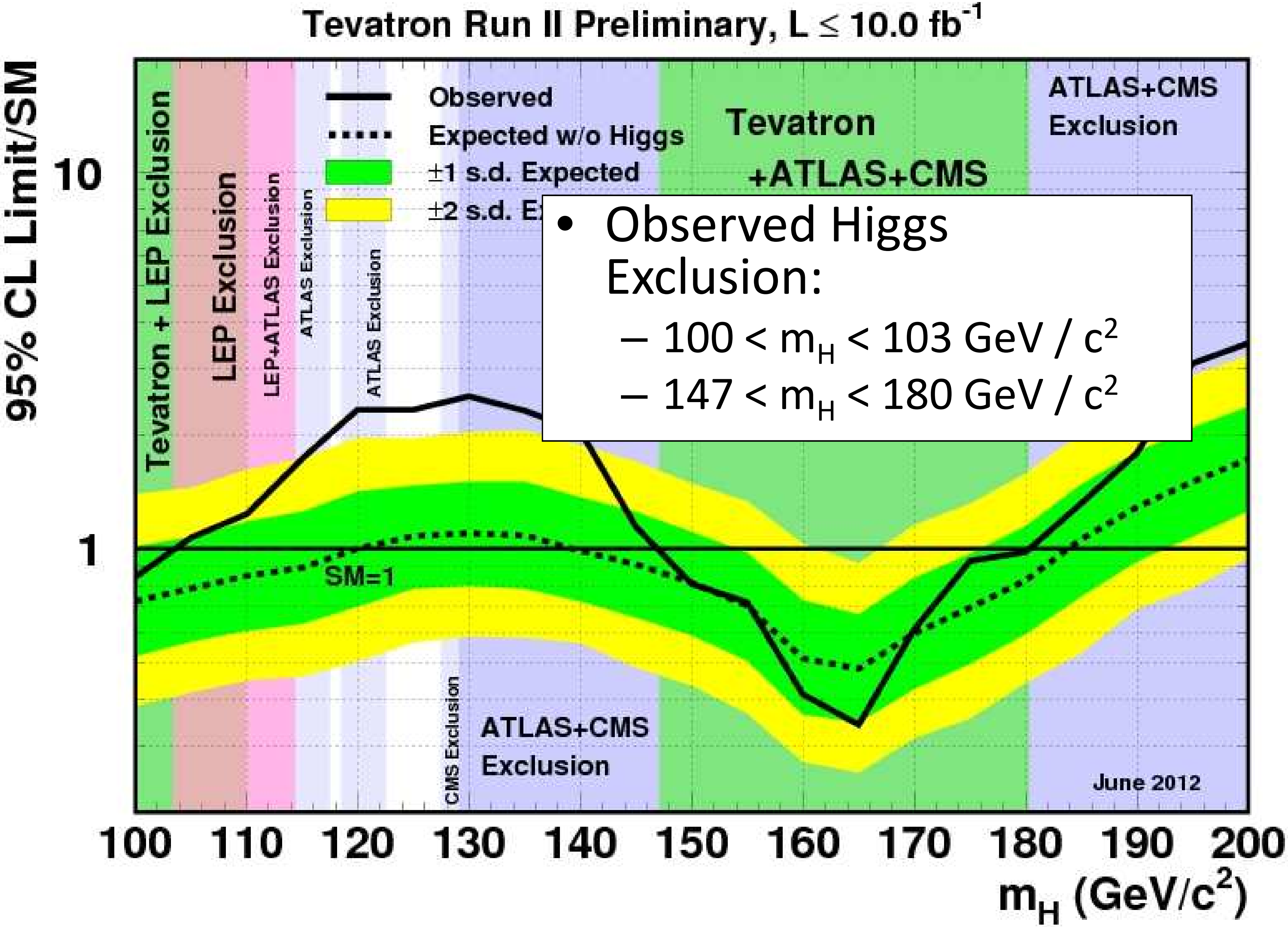
Tevatron Run II Preliminary, L ≤ 10.0 fb-1
95% CL Limit/SM
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expected
Tevatron + LEP Exclusion
LEP Exclusion
LEP+ATLAS Exclusion
ATLAS Exclusion
ATLAS Exclusion
CMS Exclusion
ATLAS+CMS Exclusion
Tevatron +ATLAS+CMS Exclusion
ATLAS+CMS Exclusion
SM=1
June 2012
10
1
100
110
120
130
140
150
160
170
180
190
200
mH (GeV/c2)



- Expected Higgs Sensitivity
  - Better than 1.1 × SM for m_H < 185 GeV / c^2



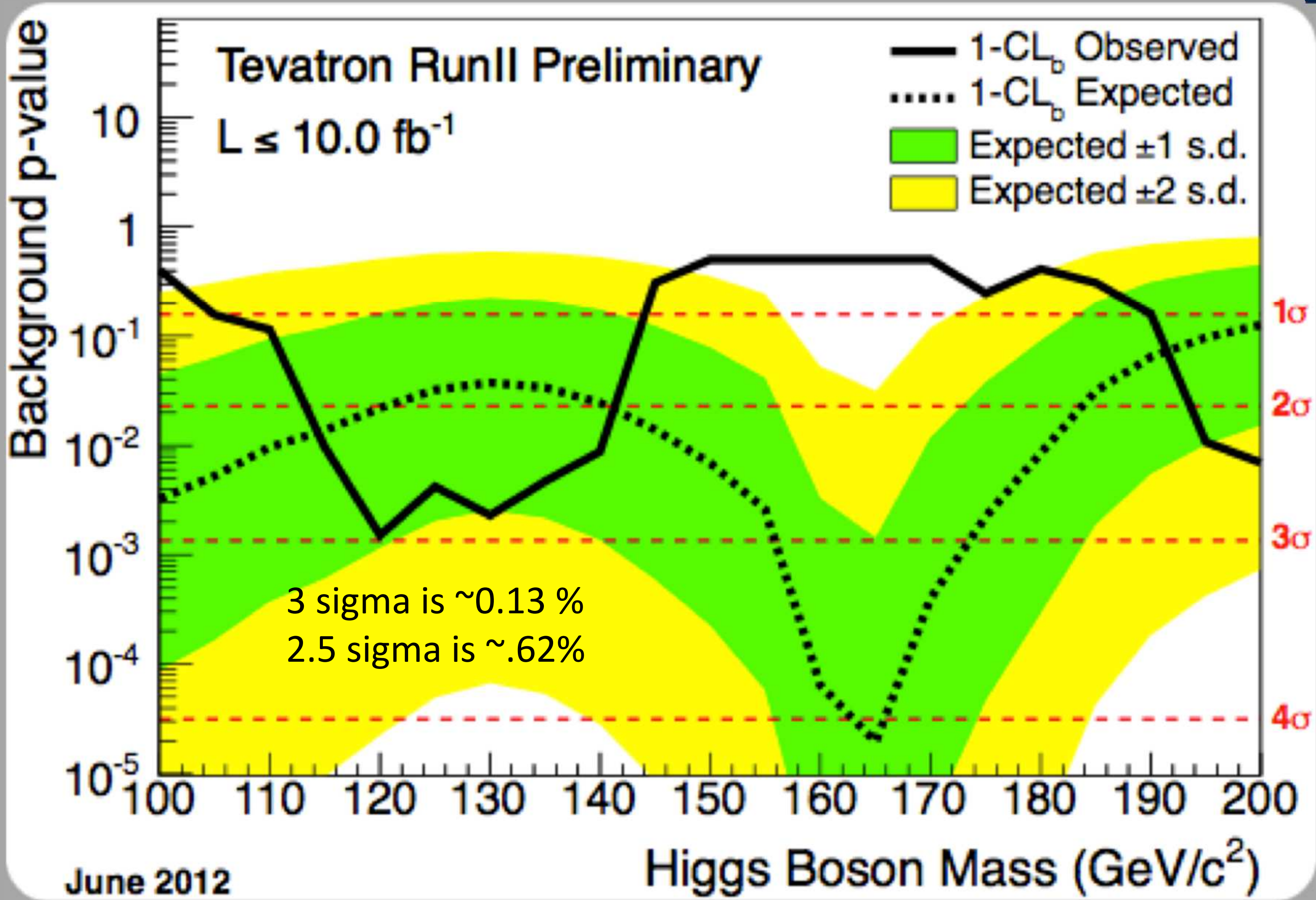
- Expected Higgs Exclusion:
  - $100 < m_H < 120$ GeV / c^2
  - $139 < m_H < 184$ GeV / c^2



- Observed Higgs Exclusion:
  - $100 < m_H < 103$ GeV / c^2
  - $147 < m_H < 180$ GeV / c^2

The Excess

Is it consistent with background only?

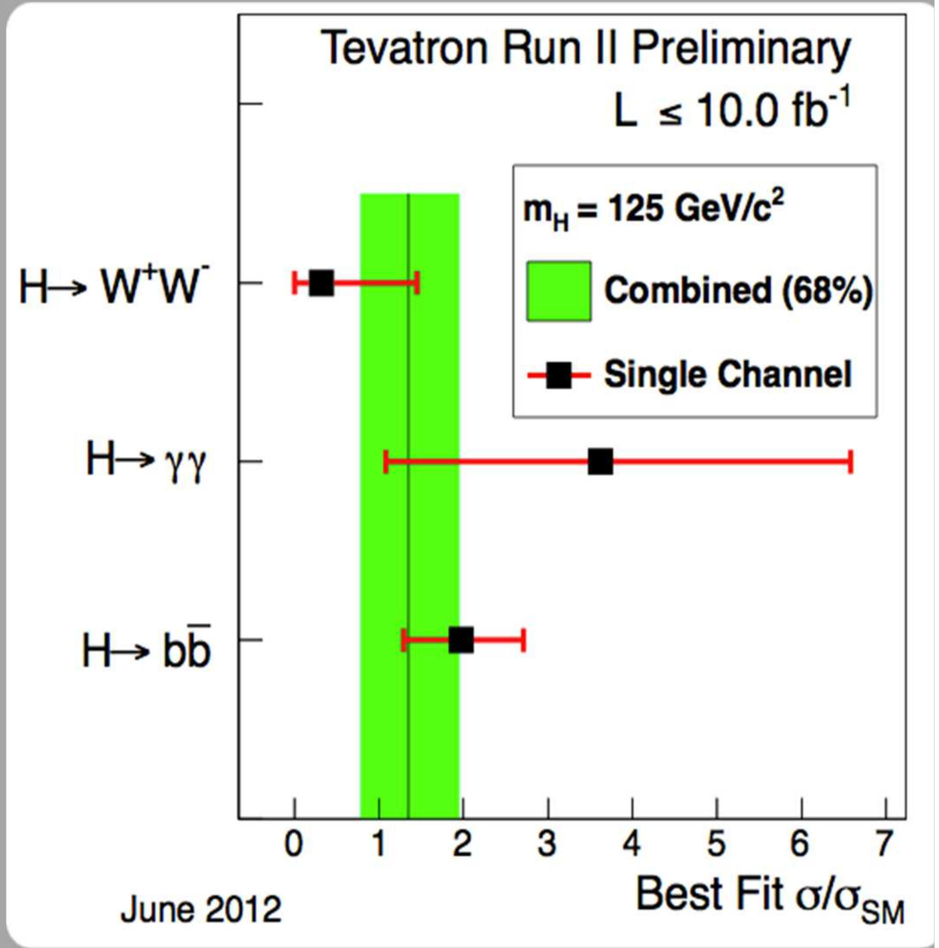


Local: 3.0 sigma → Global: 2.5 sigma (LEE of 4 for the region 100-200 GeV/c^2)

Is it consistent with SM Higgs signal?

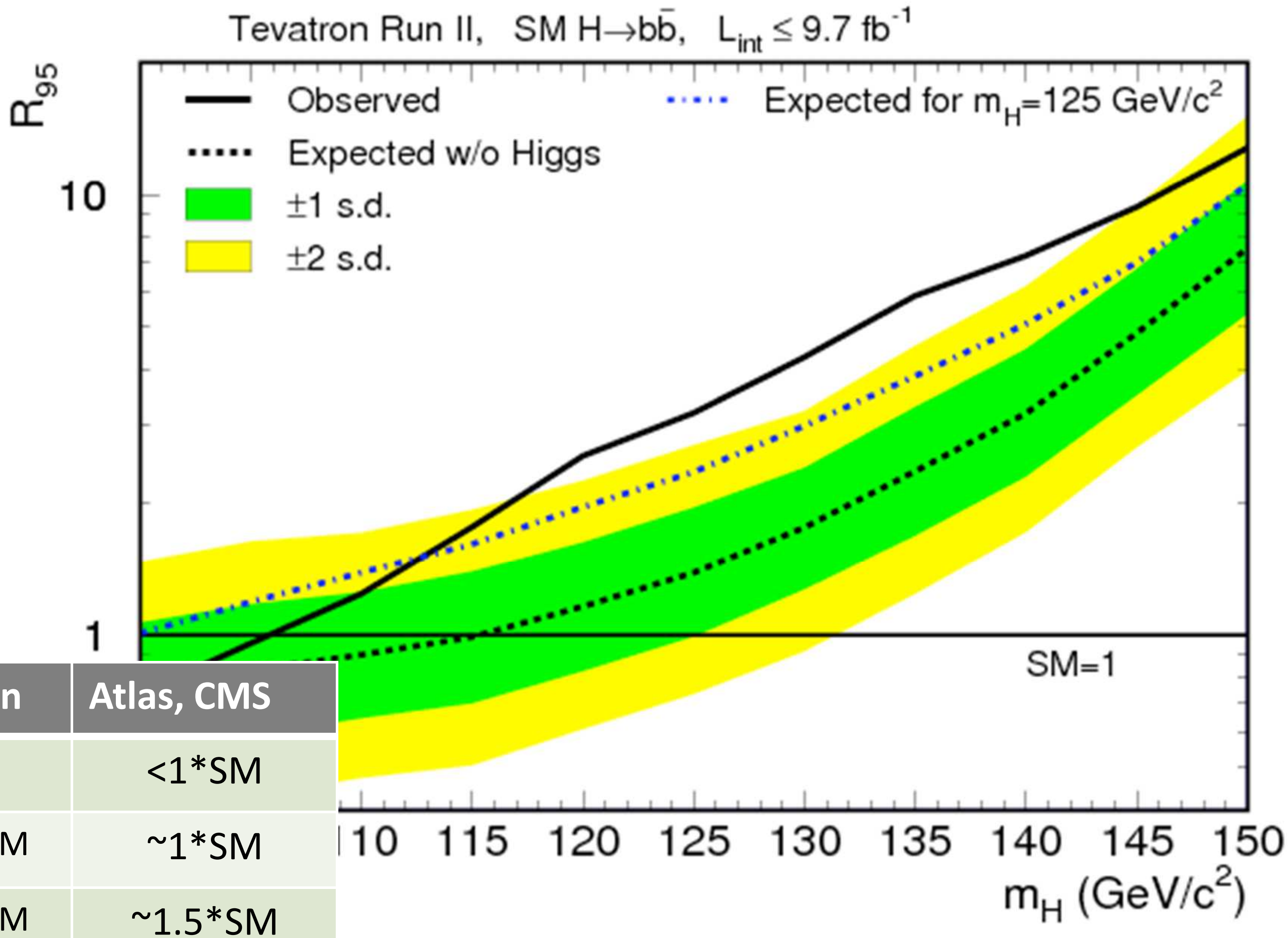
Perform fit of S+B model to data

Compare combined best fit Higgs production cross section to result from individual production modes



Consistent with SM values within the uncertainties

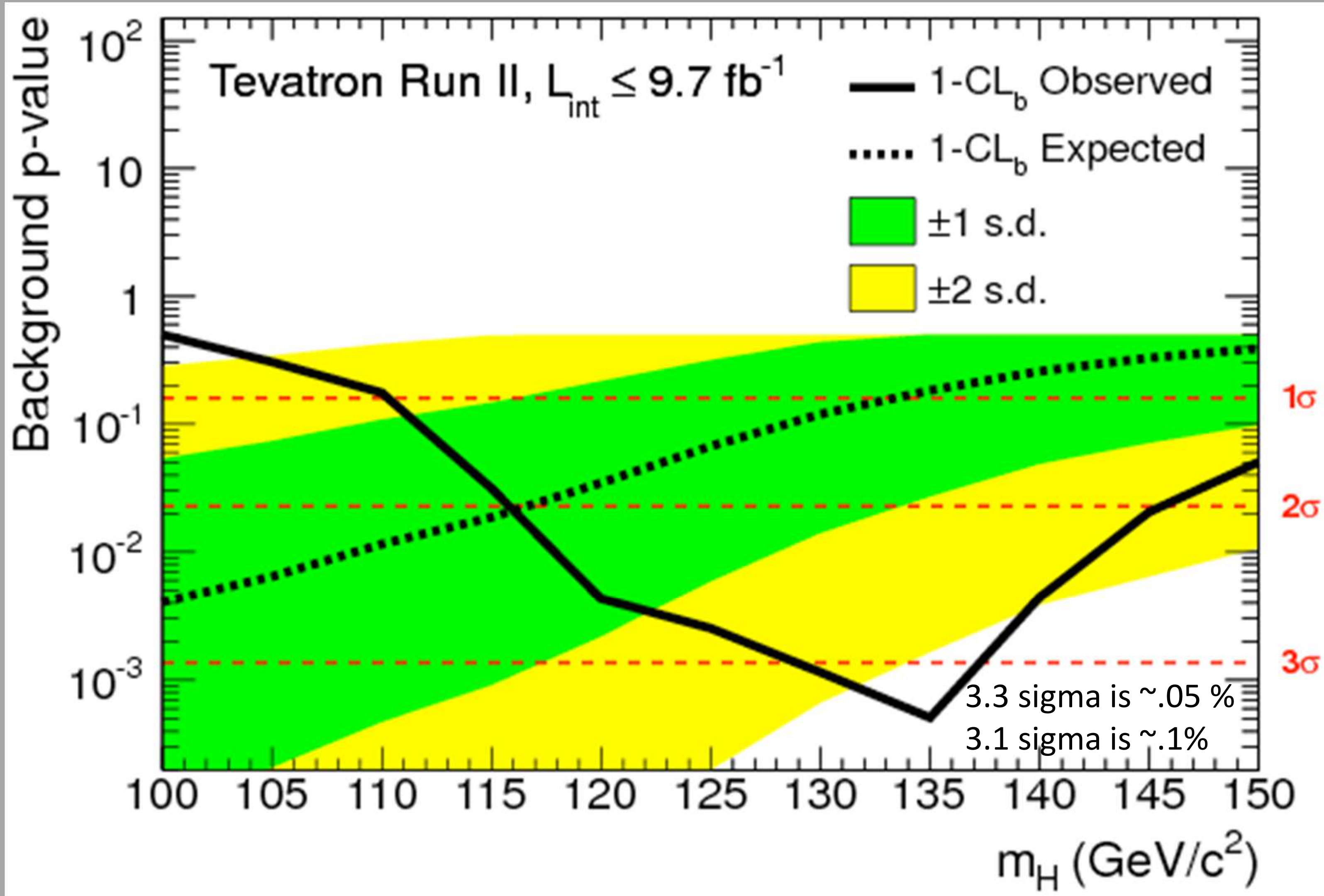
Strength of Tevatron is H→bb



Expected Limits at M_H=125 GeV:

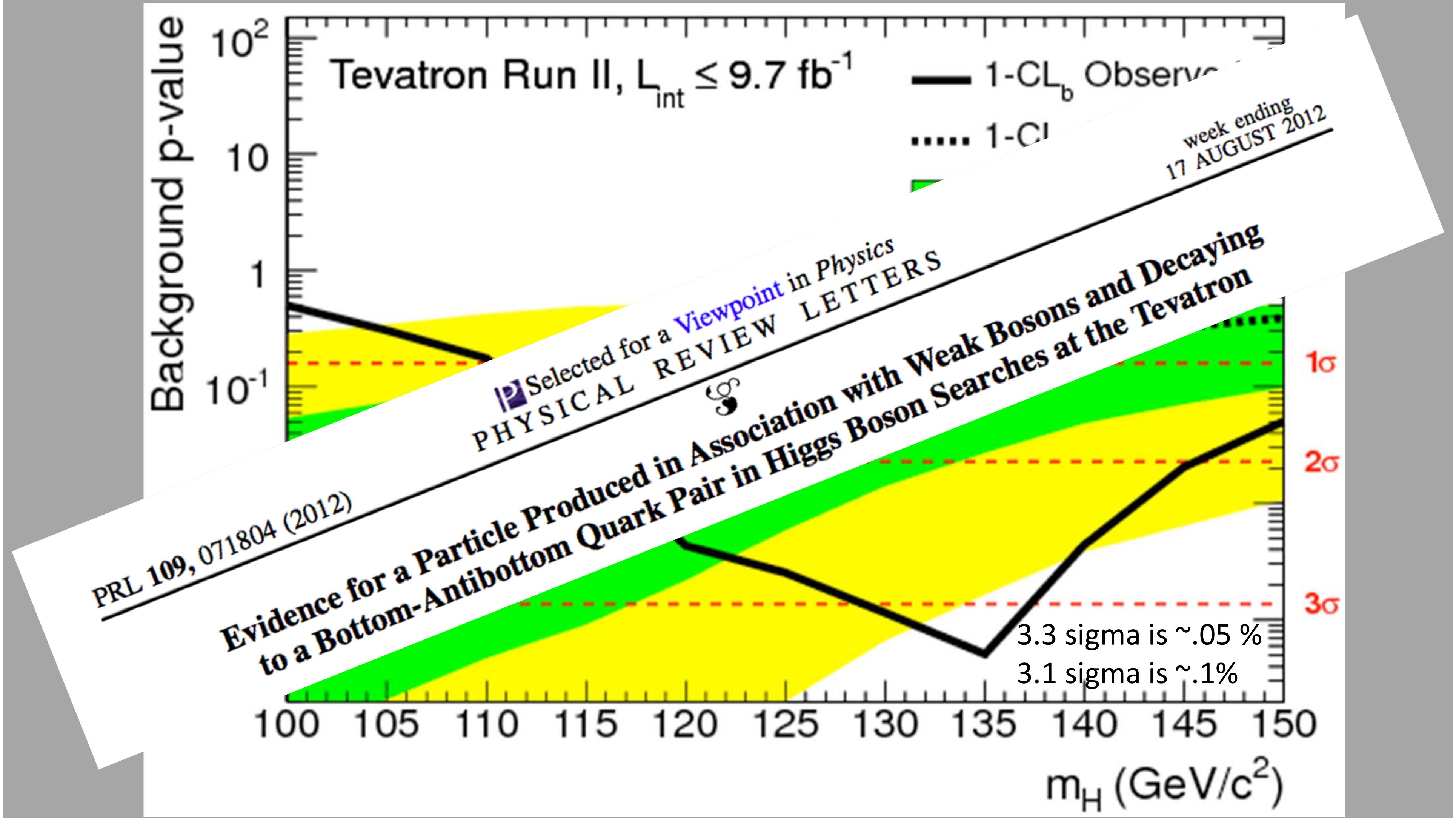
	Tevatron	Atlas, CMS
H→γγ	<10*SM	<1*SM
H→WW	~3.5*SM	~1*SM
H→bb	~1.5*SM	~1.5*SM

Strength of Tevatron is H→bb



Local: 3.3 sigma → Global: 3.1 sigma (LEE of 2 for the region 100-150 GeV/c^2)

Strength of Tevatron is H→bb



Local: 3.3 sigma → Global: 3.1 sigma (LEE of 2 for the region 100-150 GeV/c^2)

Higgs Summary

- Excluded values of M_H @ 95% CL

Expected	Observed
100-120 GeV	100-103 GeV
139-184 GeV	147-180 GeV

- Significance of observed excess :

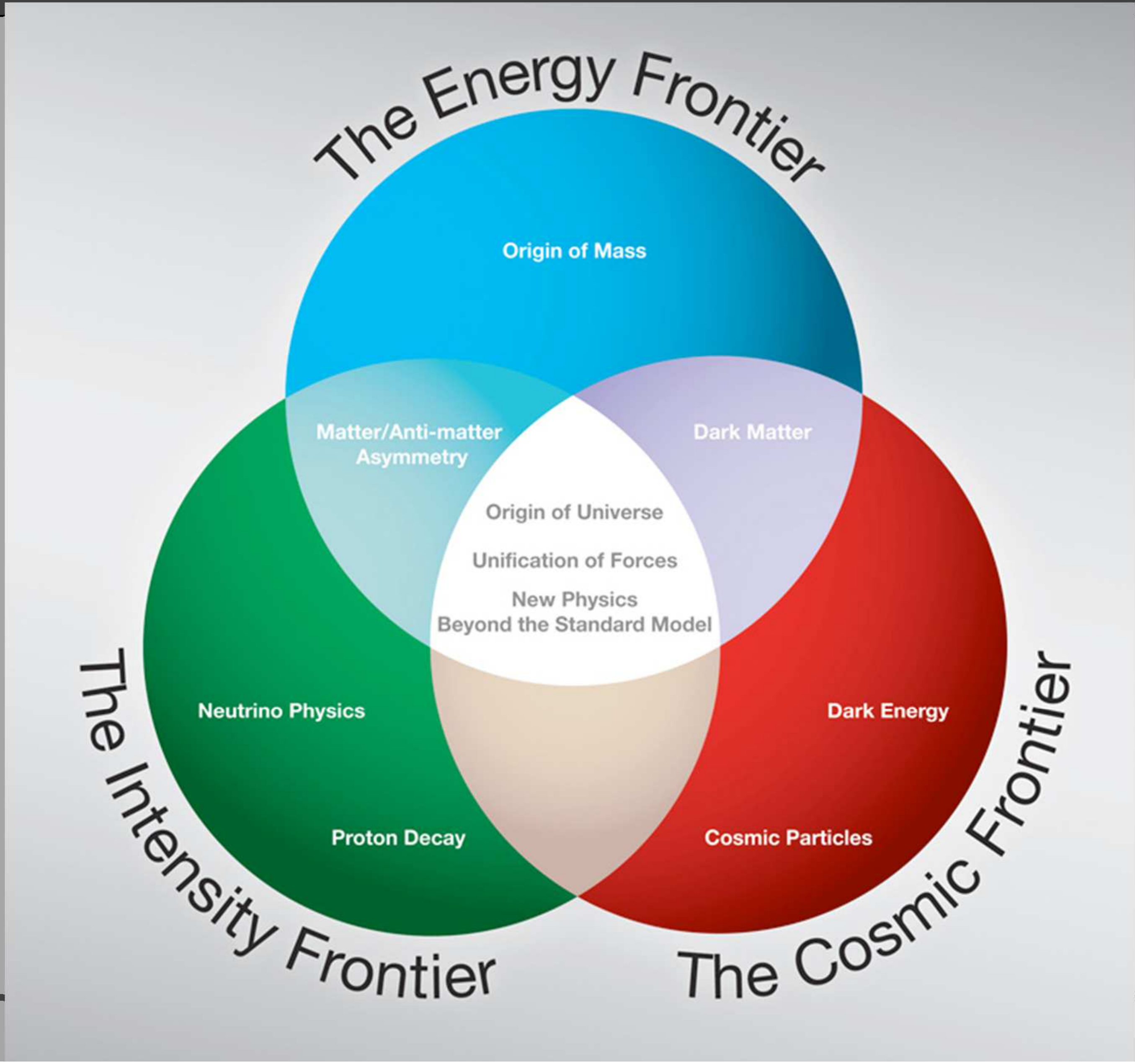
Channels	Local	Global
All Tevatron	3 σ	2.5 σ
$H \rightarrow bb$	3.3 σ	3.1 σ

Higgs Conclusion

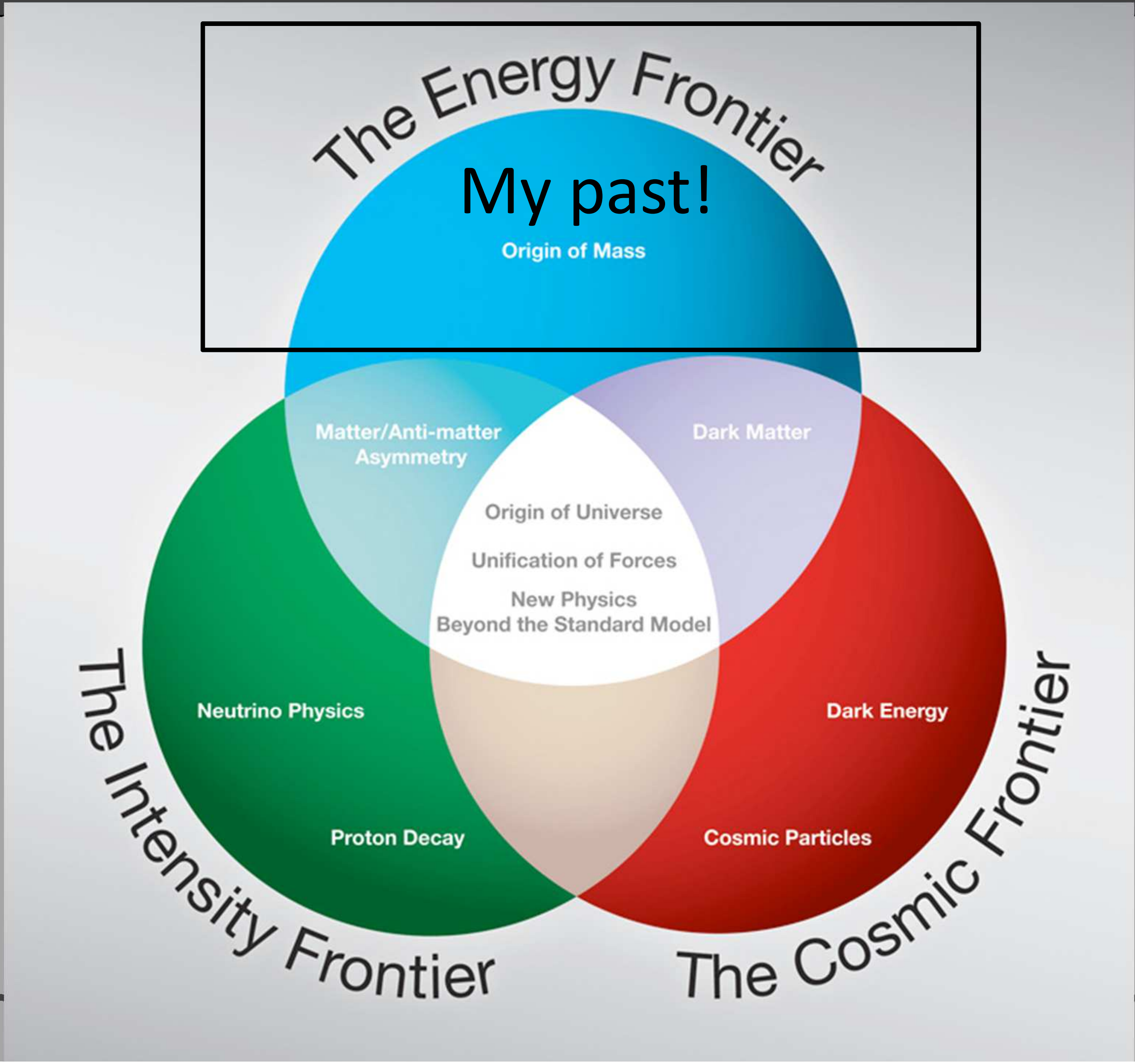
- We have incorporated the full Tevatron dataset into most of the major search channels .
- The UVA group made major contributions and improvements to the CDF Higgs search.
- There is a broad excess in the data that is inconsistent with the background only hypothesis at greater than the 2-sigma level.
- Significant excesses in complimentary channels to those present at the LHC.
- This is the year of the Higgs boson!

The Future

Research at Fermilab in 3 Frontiers

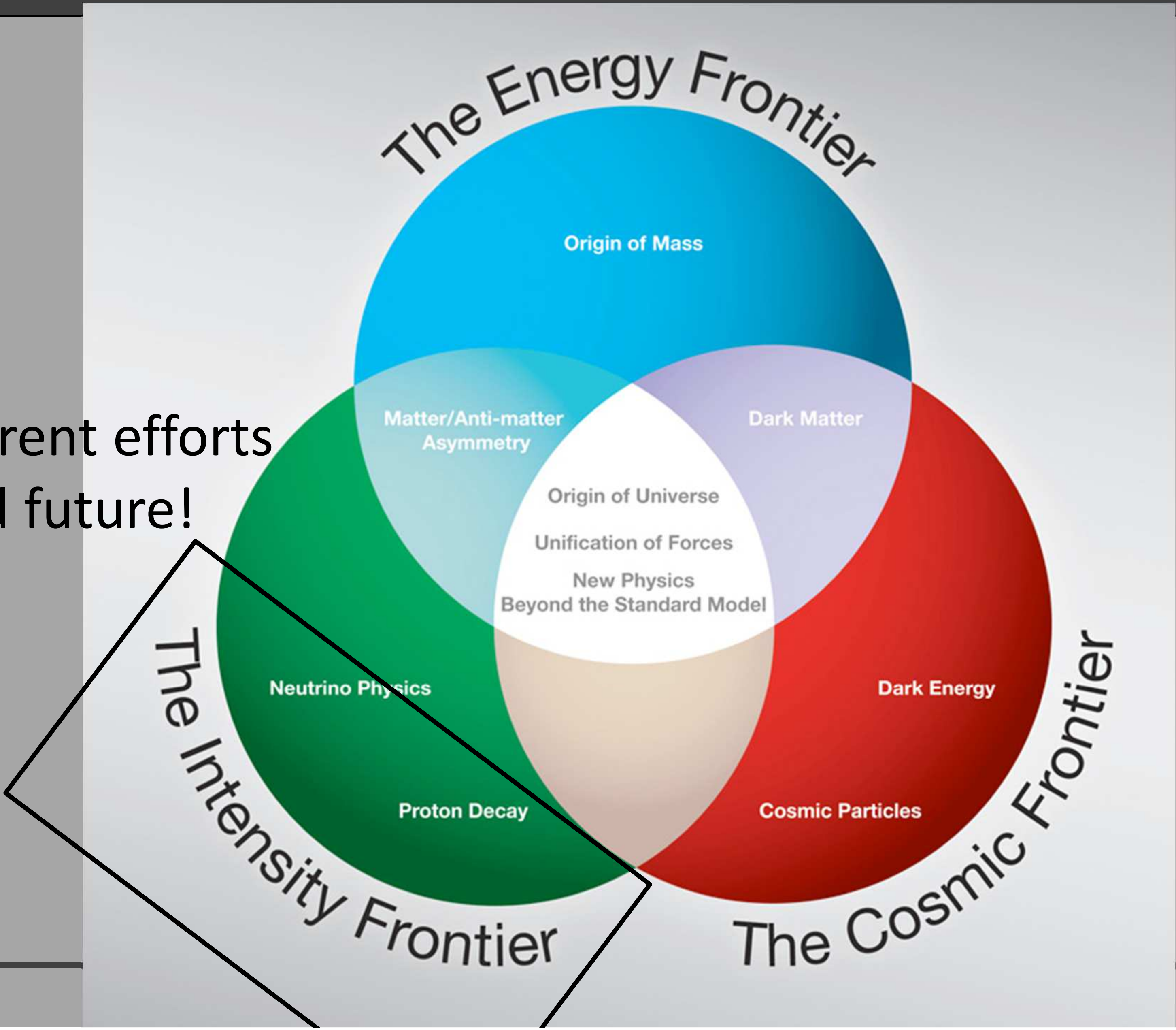


Research at Fermilab in 3 Frontiers



Research at Fermilab in 3 Frontiers

My current efforts and future!



The Intensity Frontier

- One can probe the properties of the universe by looking for extremely rare processes.
- Looking for rare processes using intense beams is an alternative to using higher energies.
  - The Intensity Frontier! (The future of Fermilab)
- The medium term future of particle physics on US soil is dedicated to the intensity frontier:
  - Rare decays (Mu2e for example)
  - Neutrino experiments (NOvA for example)

Mu2e

- Goals: Search for: $\mu^- N \to e^- N$
  - Measure ratio:

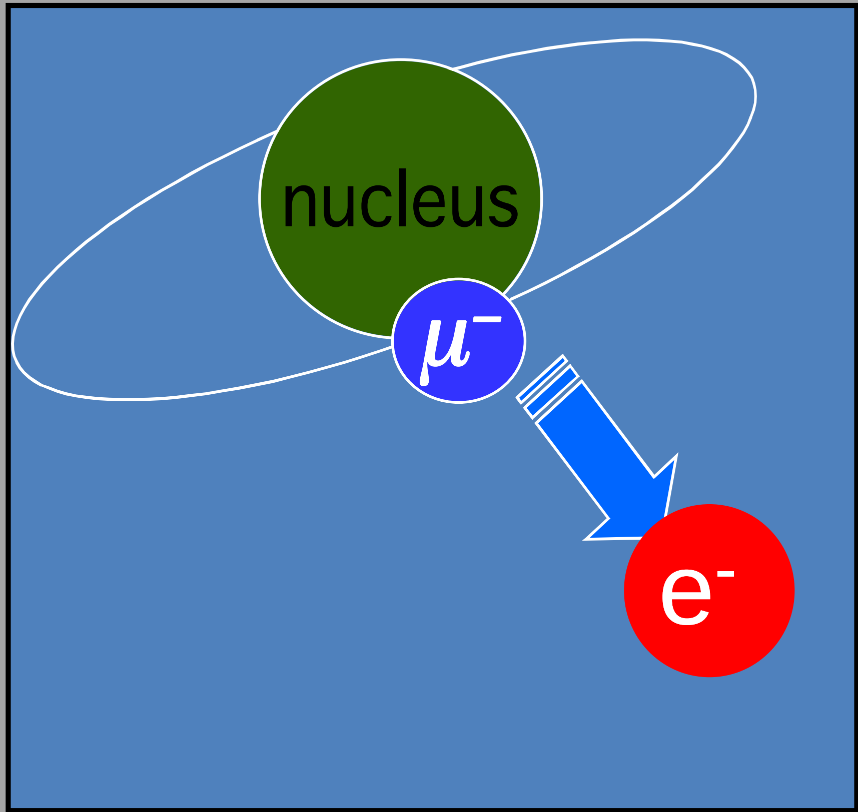
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

  - With sensitivity to R<10^{-17}
    - → 3 orders of magnitude better than the competition
    - →Need more than 10^{18} mouns!
      - →How to make muons? More than 10^{21} protons on target!
    - →Also need very small background
- UVa is the largest University group on Mu2e
  - → Particle Physics and Nuclear Experimentalists!

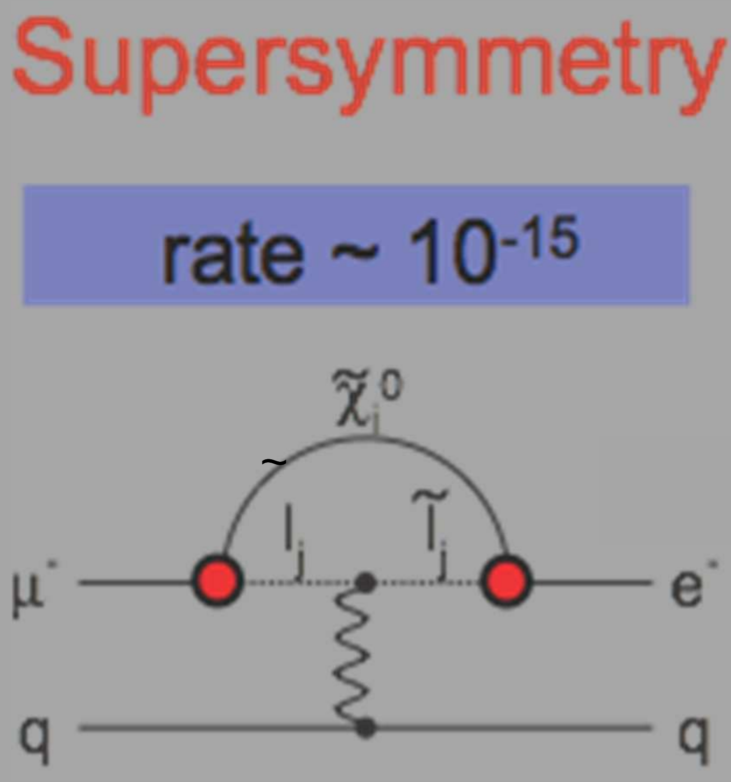
Experimental Signature

$$\mu^- N \rightarrow e^- N$$

- Signal: Single Monoenergetic Electron
- If N = Al, E_e = 105. MeV
  - Electron E depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup



CLFV from SUSY



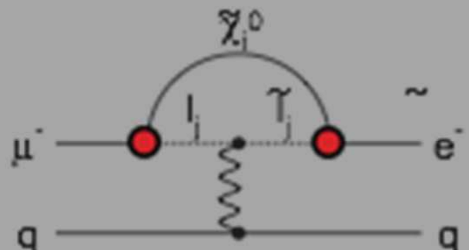
Access SUSY through loops:

Signal of Terascale at LHC implies ~40 event signal and only 0.4 bkg in this experiment

Other "new physics" probed at Mu2e

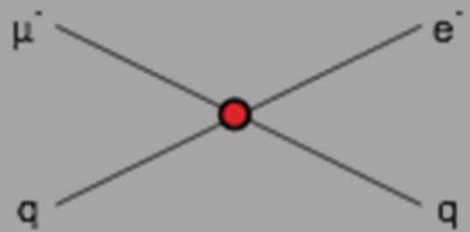
Supersymmetry

rate ~ 10^{-15}



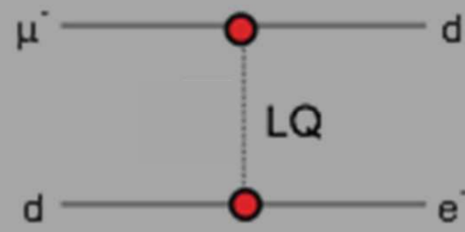
Compositeness

$\Lambda_c \sim 3000$ TeV



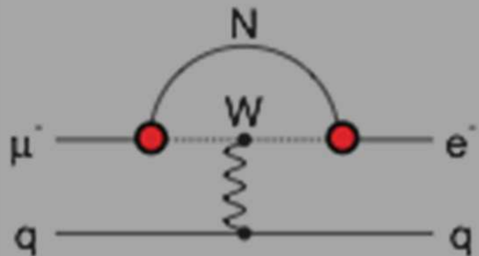
Leptoquark

$M_{LQ} = 3000\,(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



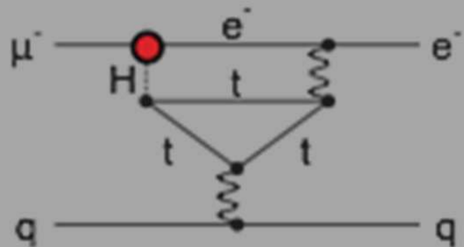
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

$M_{Z'} = 3000$ TeV/c^2

Cosmic Ray Background to Mu2e

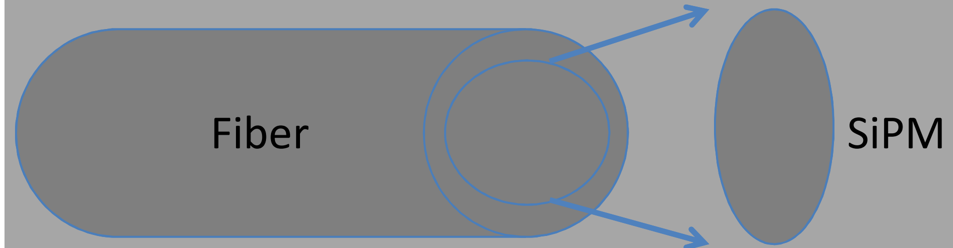
- In order to obtain single-event sensitivity we need to keep background well below one event.
- One dangerous background is from cosmic rays producing electrons in the Mu2e detector.
- Simulation shows that we need about 99.99% veto efficiency to keep this background to a negligible level.

UVA Goal: Design and build a cosmic ray veto (CRV) system that can obtain this level of efficiency.

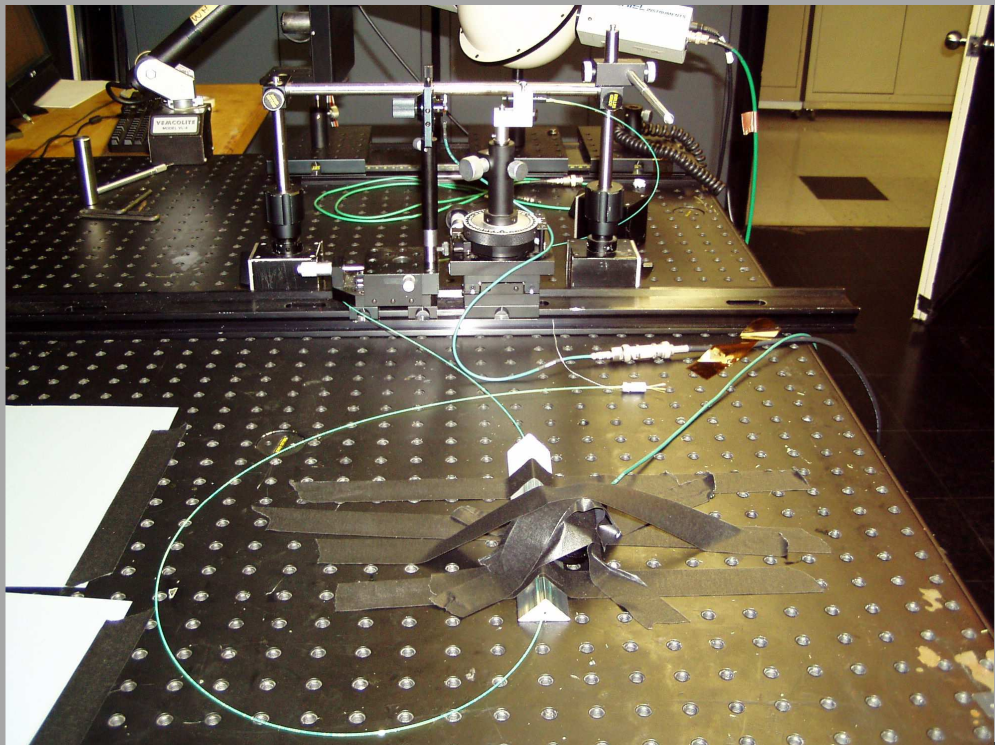
(~ 5M $ project)

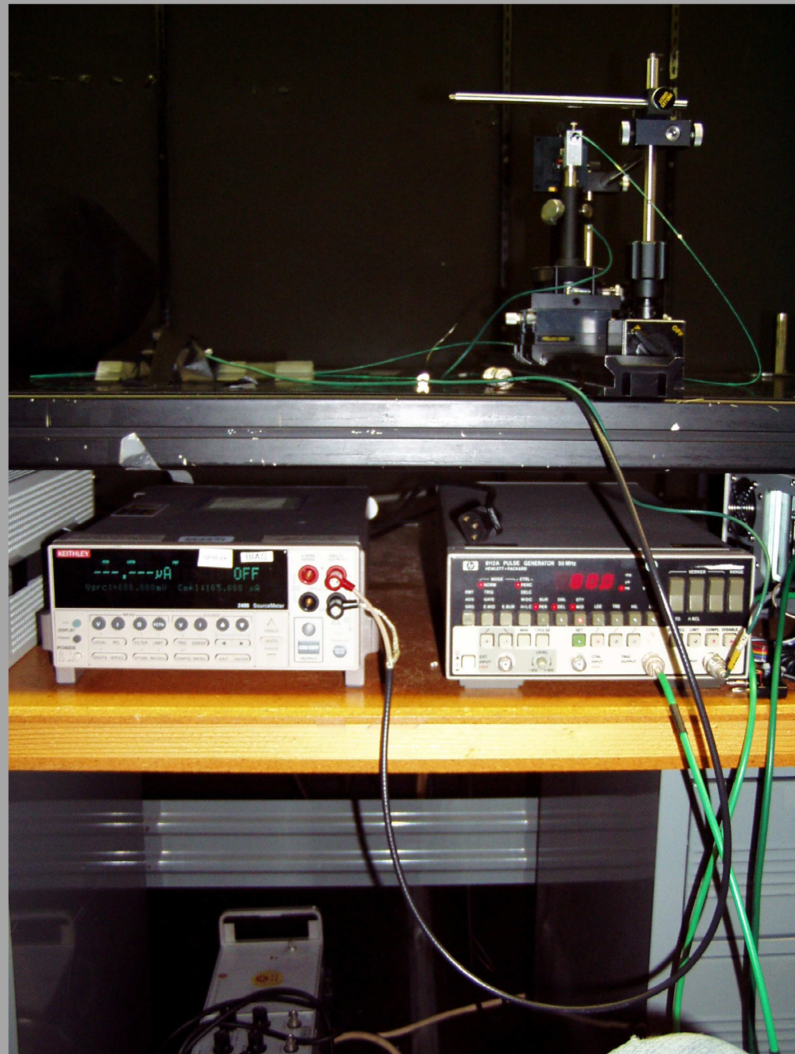
CRV prototype R&D efforts

More R&D (fibers)



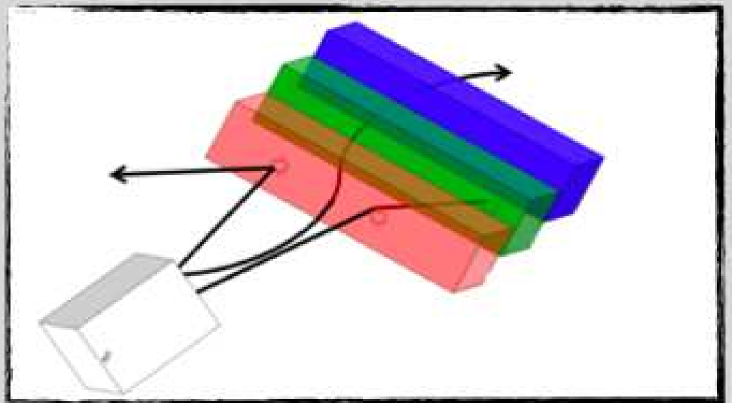
The idea is to study the angular (radial?) distribution
Of light leaving the fiber to optimize the light yield.

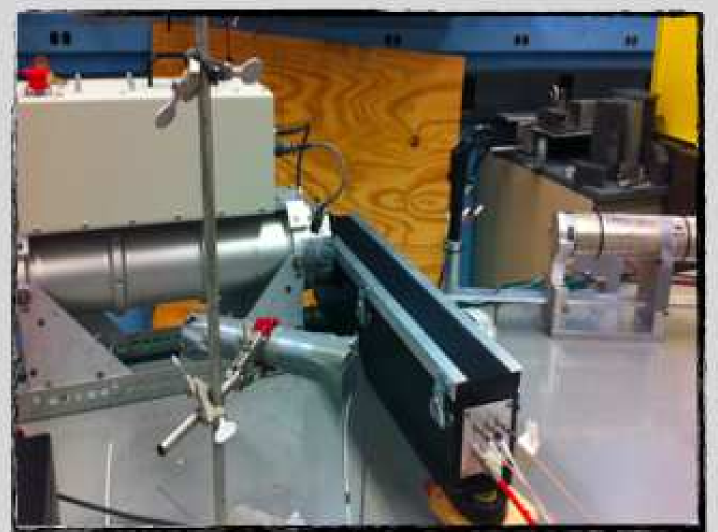




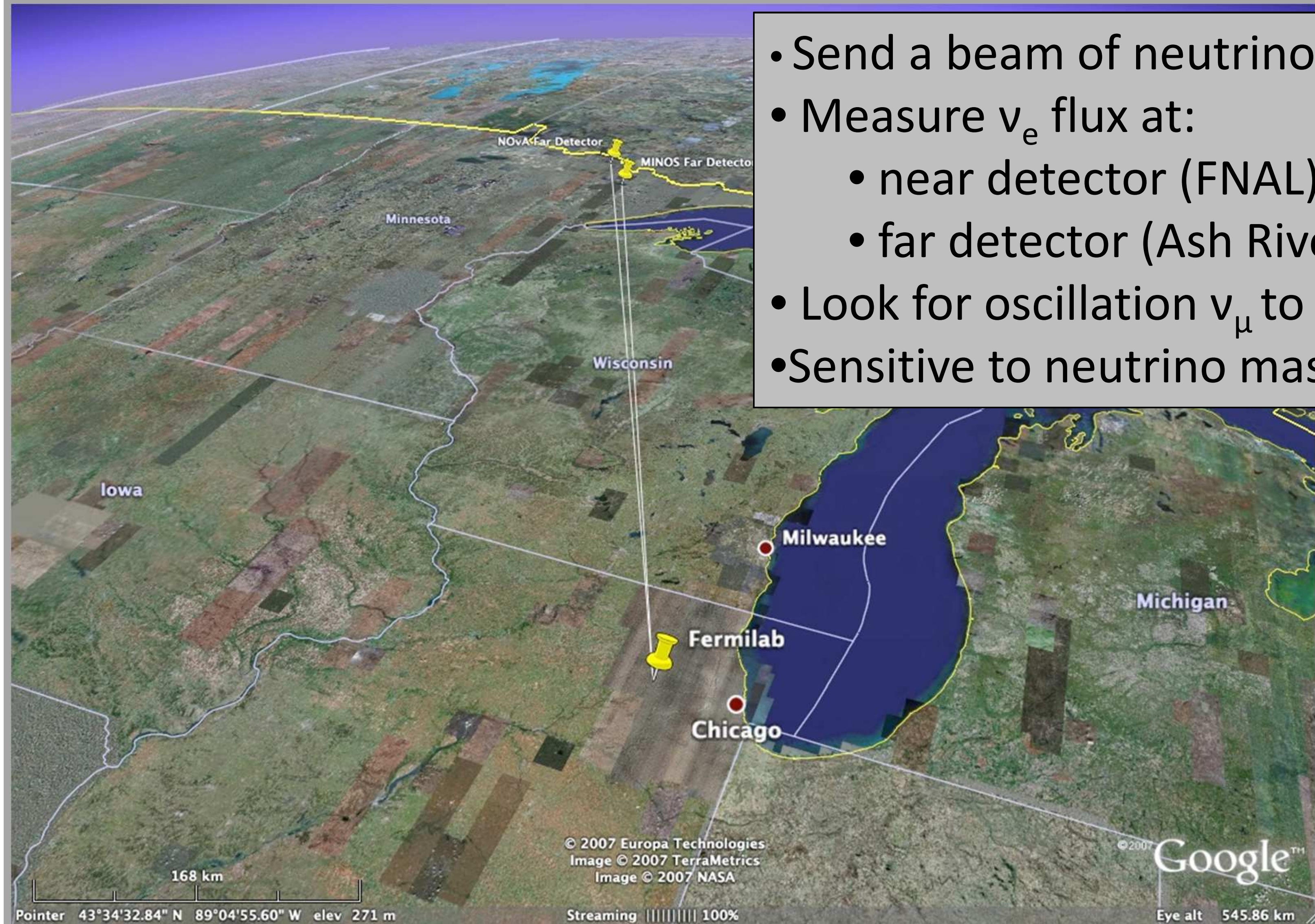
More R&D (neutrons)

- What?
  - Estimate the CRV efficiency to neutrons
- How?
  - Direct measuring the response of the CRV scintillator to neutron flux
  - Estimation from MCNP simulation
- So…?:
  - Data from neutron gun at UChicago
  - MCNP samples simulating our setup with neutrons energies 2.8MeV, 10, 20 MeV





NOvA



- Send a beam of neutrinos 810 km
- Measure ν_e flux at:
  - near detector (FNAL)
  - far detector (Ash River MN)
- Look for oscillation ν_μ to ν_e
- Sensitive to neutrino mass hierarchy!

NOvA will be enormous!

1st block was installed this week!

NOvA plan

- Far detector being installed now!
- UVa playing a major role in design, construction and commissioning of both detectors and will contribute to physics analysis and operation.
- CG joined NOvA in early 2012 and currently convening computing effort to prepare the collaboration for data analysis.

Intensity Frontier Conclusion

Mu2e Experiment: Actively contributing already to design and fabrication plan for cosmic ray veto system.

NOvA Experiment: Leading the computing effort to prepare for data analysis. The far detector is being constructed and analysis will start within the next year.

The Group Group