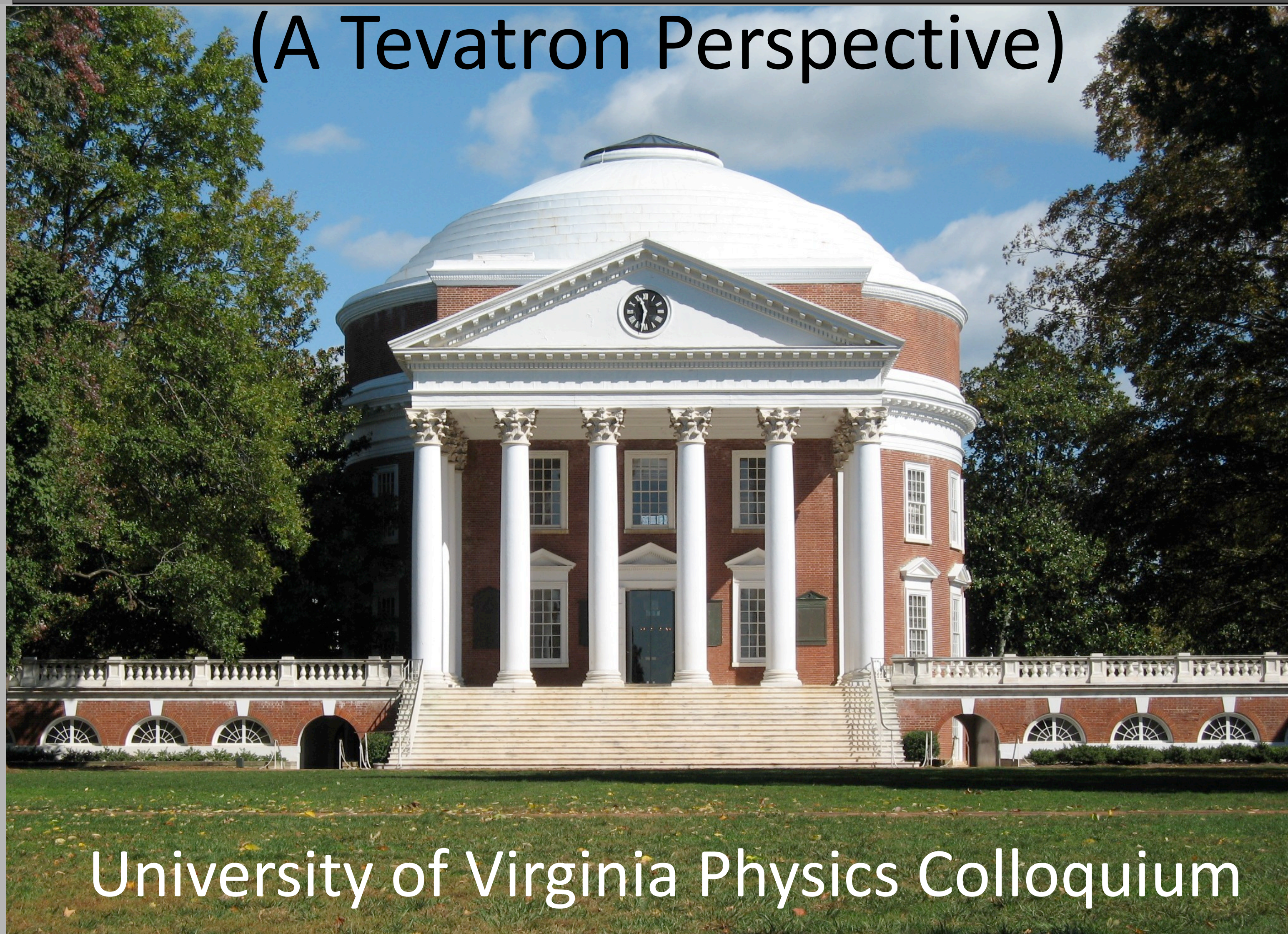
The Race for the Higgs Boson

(A Tevatron Perspective)



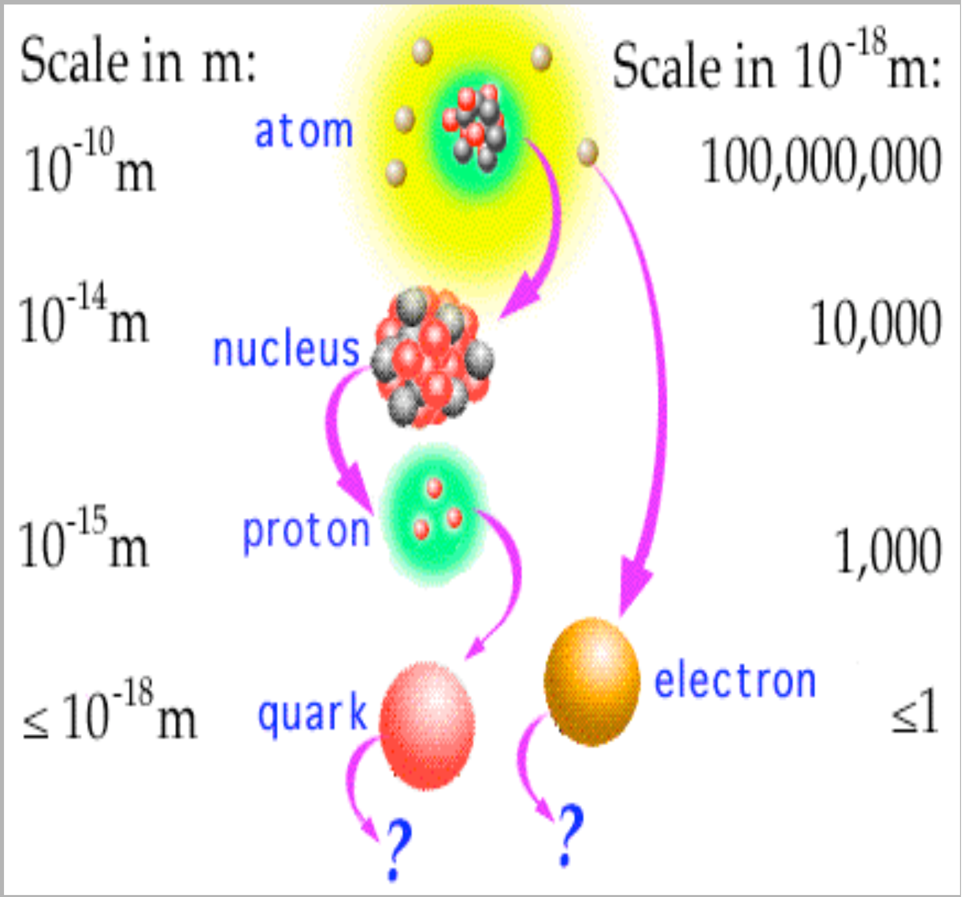
University of Virginia Physics Colloquium

Setting the Scale for Particle Physics

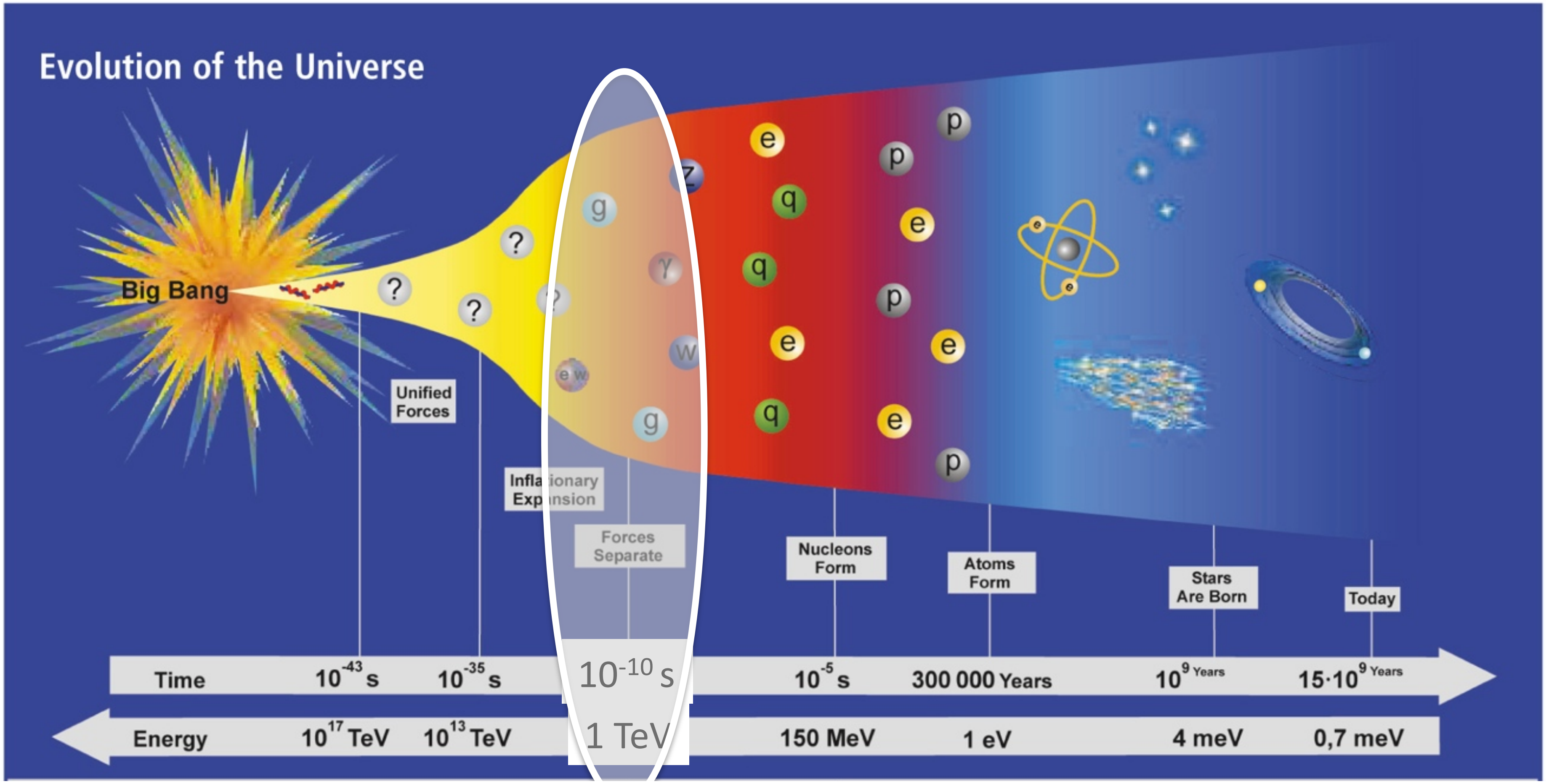
Particle physics is the study of the most basic building blocks of matter and their interactions

Why high energy?

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



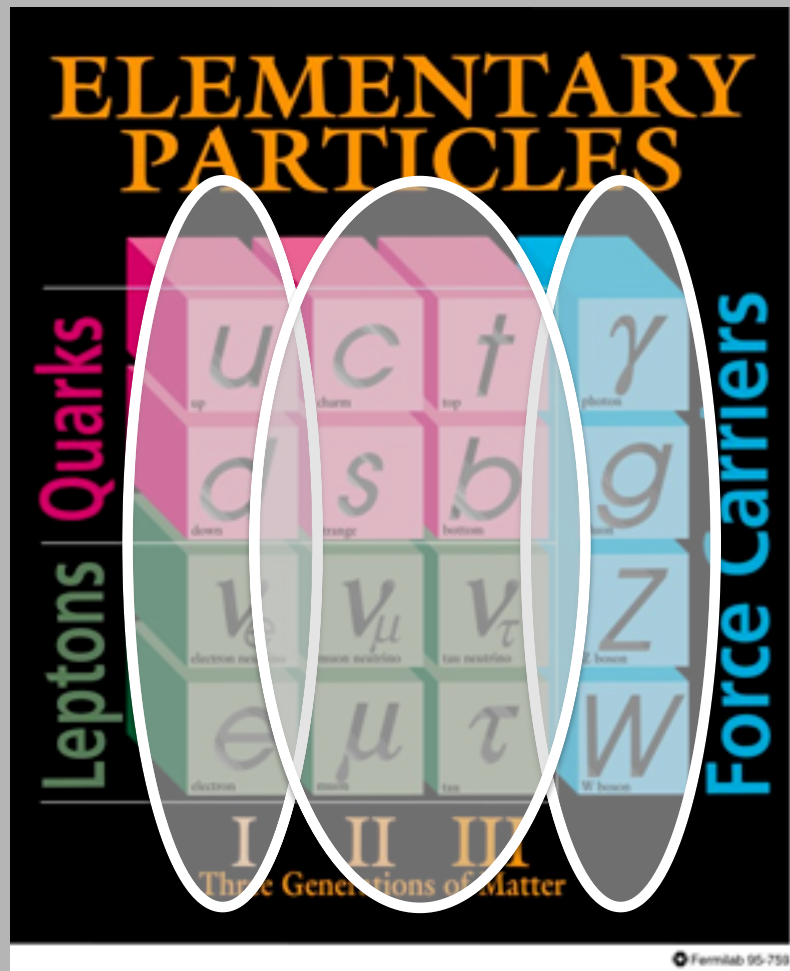
Evolution of the Universe



With TeV collisions we probe the universe
When it was only 10^{-10} s old!

Are there undiscovered fundamental particles?

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

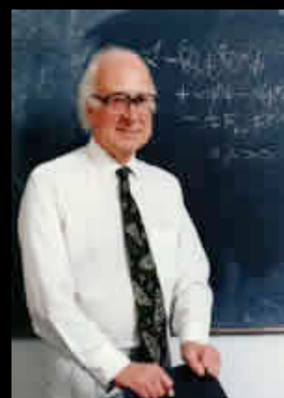
What is the origin of Electroweak Symmetry Breaking?

- Consider the Electromagnetic and the Weak Forces
- Coupling at low energy: EM: ~[?], Weak: ~[?]/($M_{W,Z}$)
2
  - Coupling strength governed by the same dimensionless constant
  - Difference due to the mass of the W and Z bosons
    - Electroweak symmetry: $M_\gamma = M_Z = M_W$
    - But photons massless and W and Z are massive?
- SM postulates a mechanism of electroweak symmetry breaking via the Higgs mechanism
  - Results in massive vector bosons and mass terms for the fermions
  - Theory predicts a massive new particle called the Higgs boson!

2010 Sakurai Prize

... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."






Englert Brout Higgs Guralnik Hagen Kibble

PRL 13, 321-323 (1964) PRL 13, 508-509 (1964) PRL 13, 585-587 (1964)

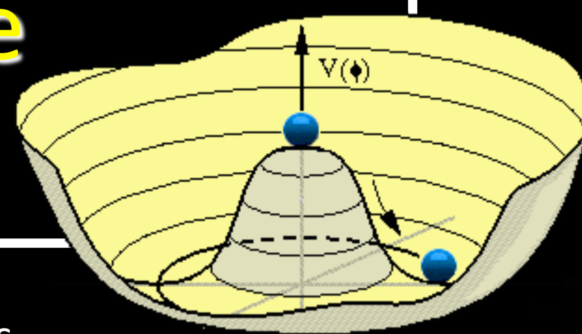
So in honor of their work ...

Brout-Englert-Higgs-Hagen-Guralnik-Kibble (BEHHGK) mechanism

[Pronounced "beck" mechanism; preserves author grouping, publication ordering,

- Ad
- Cle
  - his non-
- Fin

I will use "Higgs" and "BEHHGK" boson interchangeably in this talk, but will refer to the H particle



- Means BEHHGK field exists
  - Means we confirm our theory for the origin of mass

Higgs Analogy

- The BEHHGK field permeates the universe and the strength with which a particle interacts with it determines the observed mass of the particle

Mass = Popularity

Are there undiscovered fundamental particles?

The stand… this!

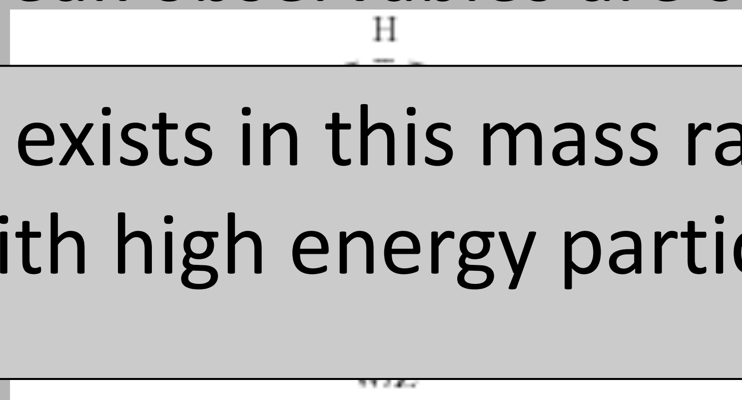
Discovery … shine light on the que… breaking

Constraints the Standard Model Higgs Boson

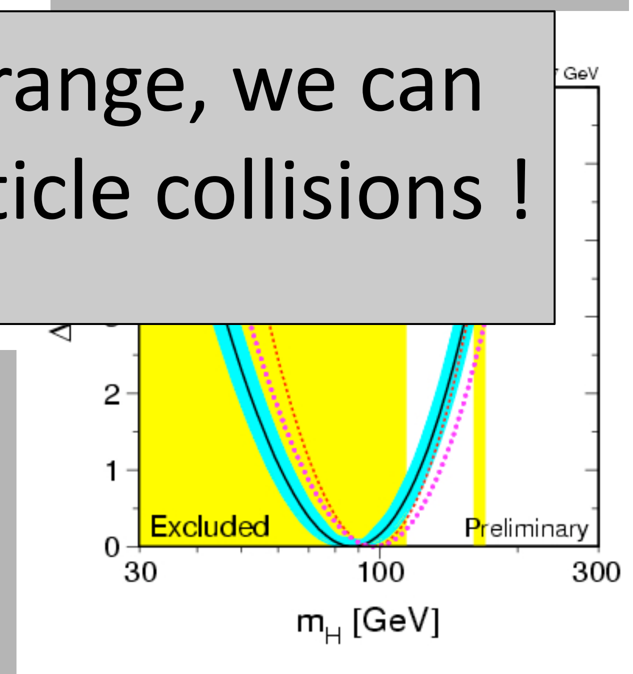
Higgs searches ongoing for 30 years!

- Direct searches from LEP:
  - Higgs mass > 114 GeV

Many Electroweak observables are sensitive to the Higgs boson:



If the Higgs exists in this mass range, we can produce it with high energy particle collisions !

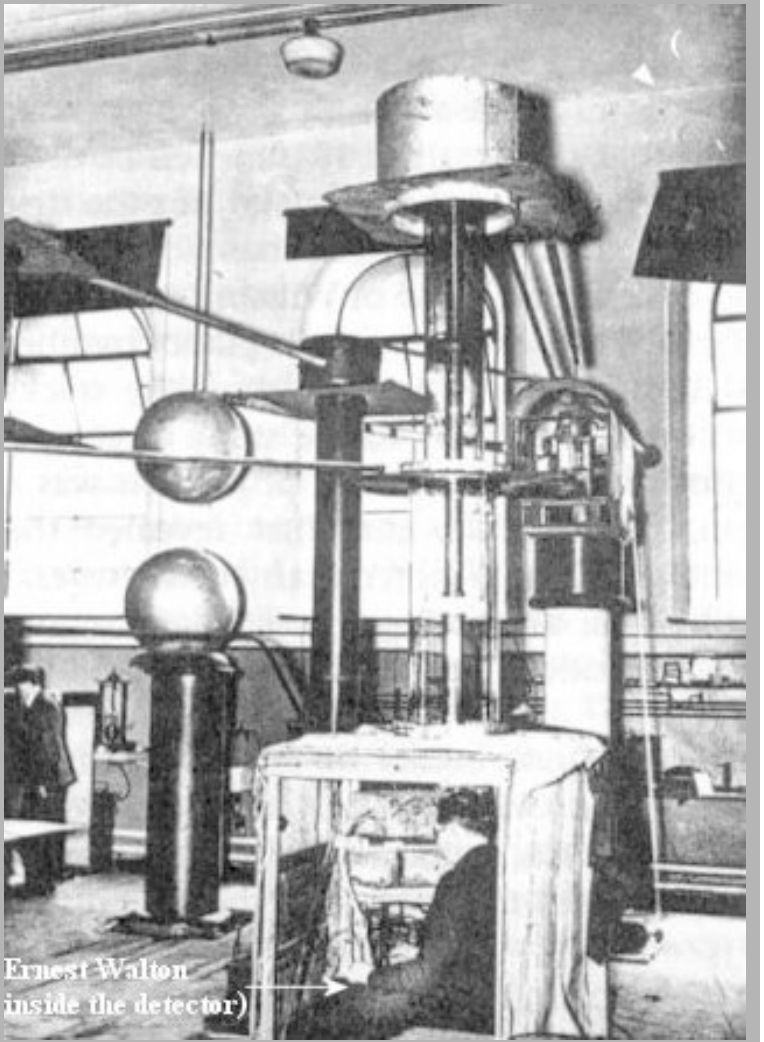


- Indirect EWK constraints:
  - Higgs mass < 157 GeV

Particle Accelerators

High energies are needed to:
→ probe small distances
→ produce heavy particles

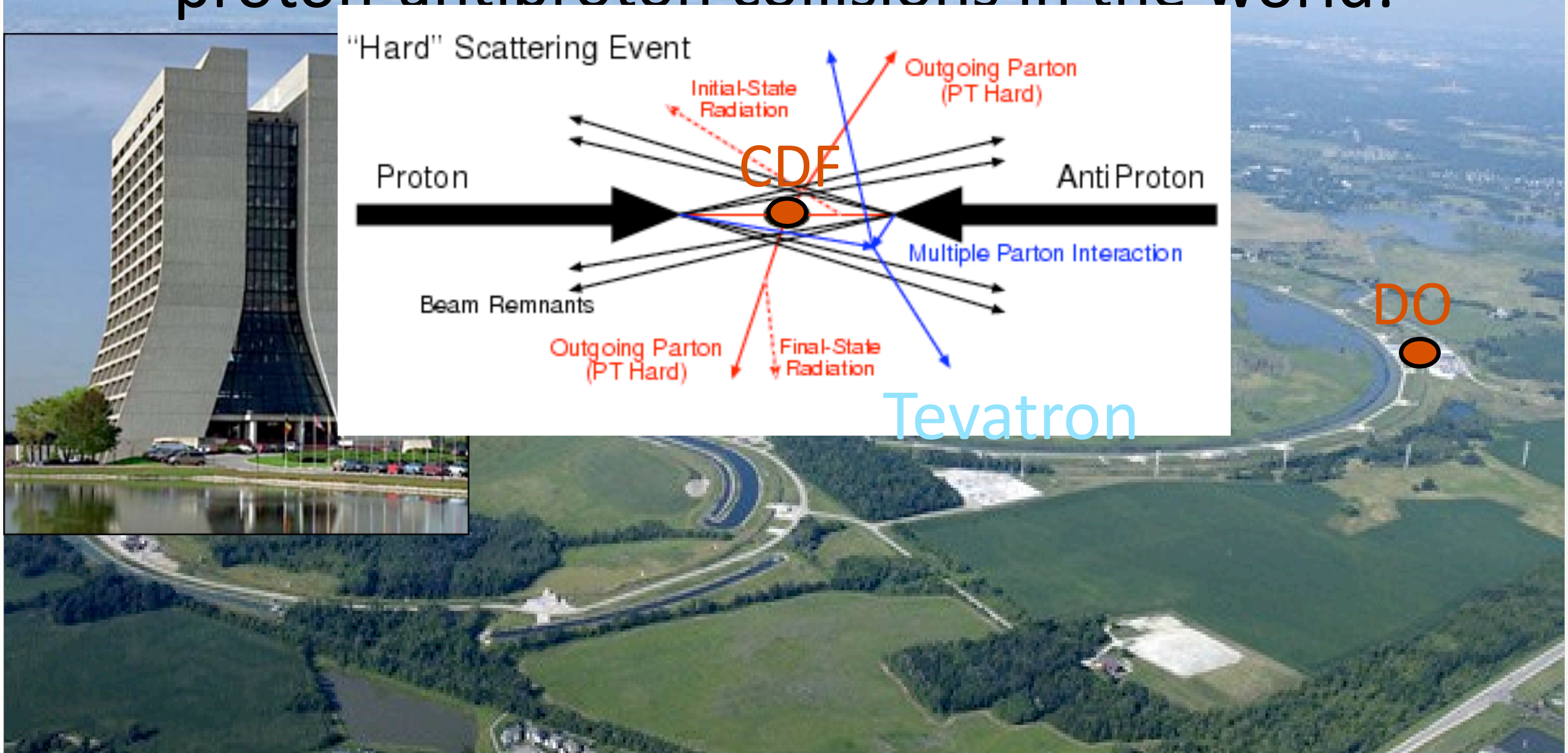
Image:
→ 1932, Cockroft-Walton accelerator
→First nuclear reaction instigated by artificially accelerated particles



Accelerators have come a long way…

The Tevatron at Fermilab

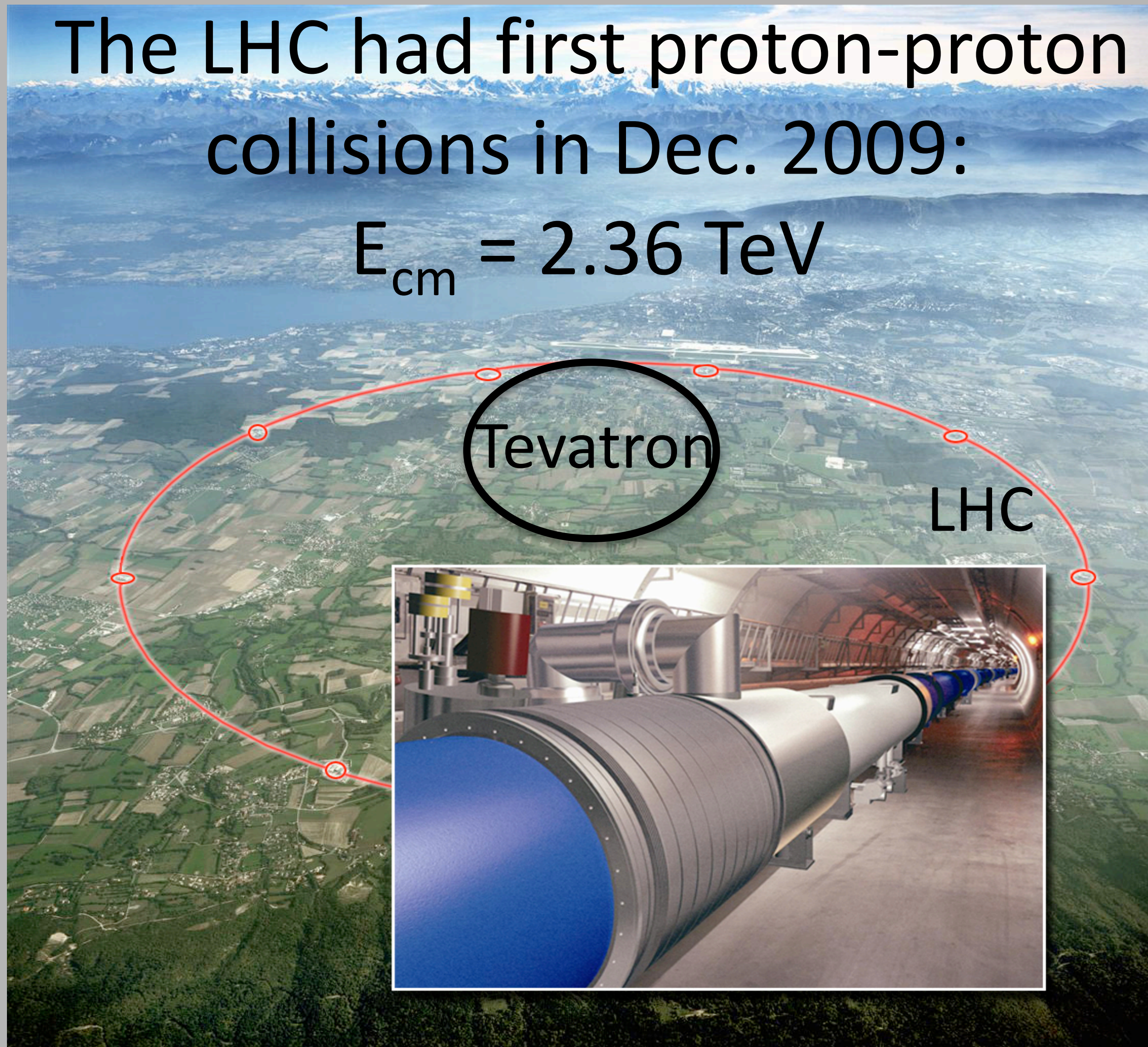
The Tevatron currently provides the highest energy proton-antiproton collisions in the world:



The LHC at CERN

The LHC had first proton-proton collisions in Dec. 2009:

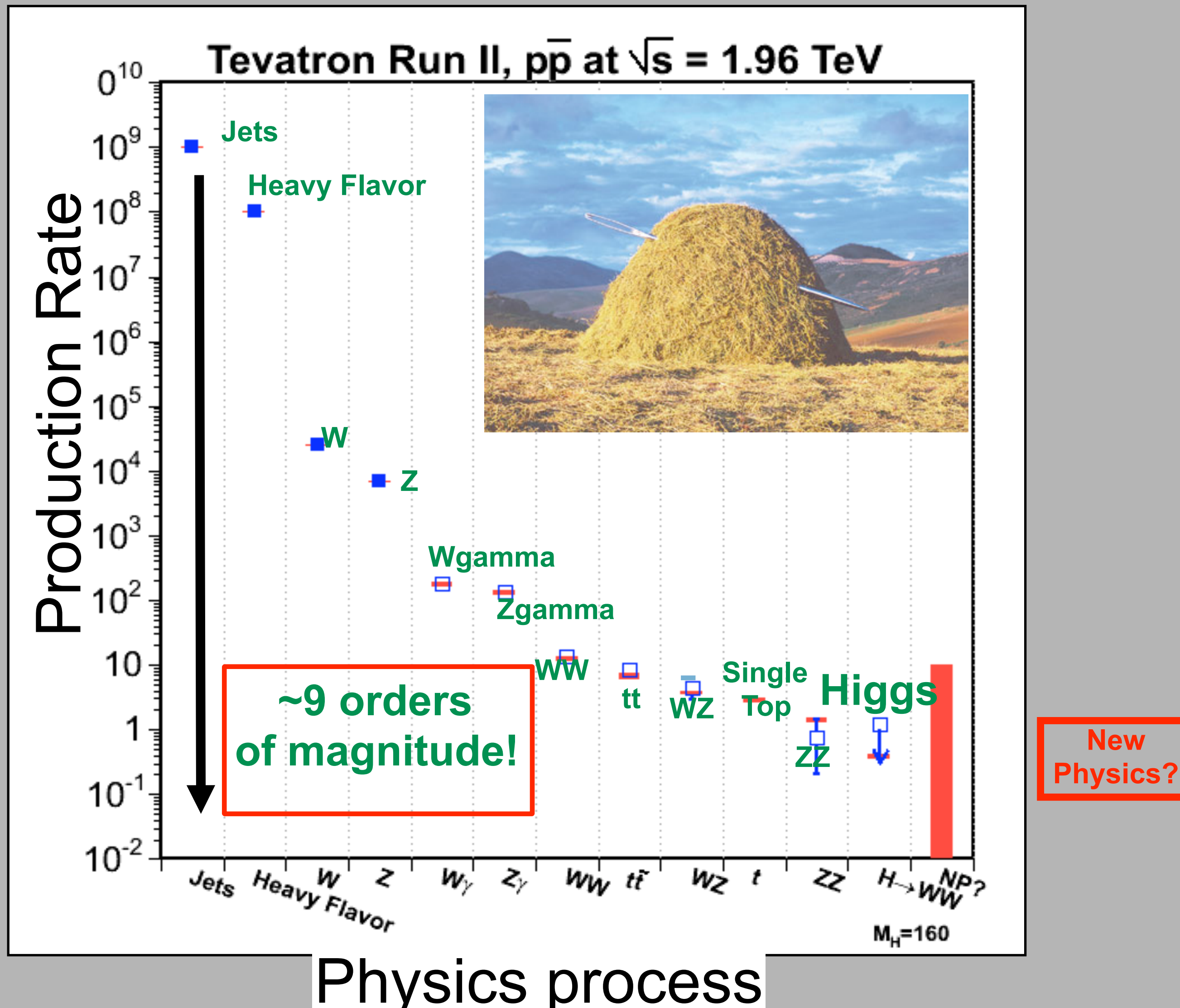
E_{cm} = 2.36 TeV



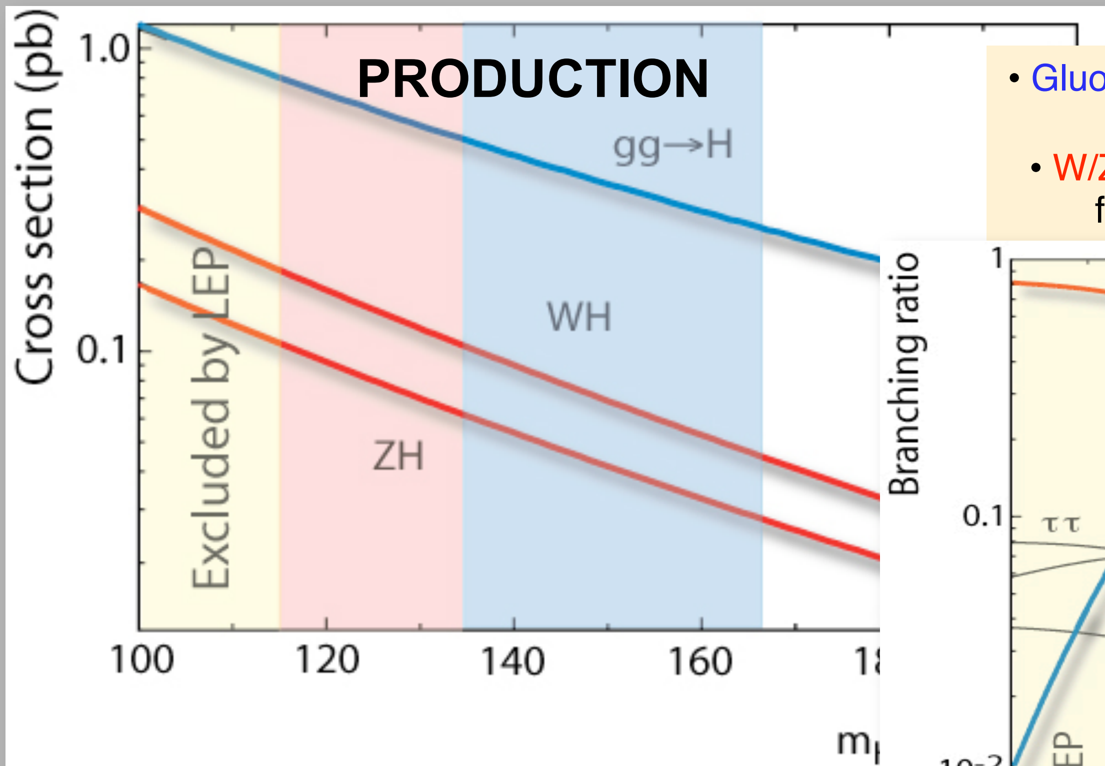
The Race Tracks: Tevatron v/s LHC

	The Tevatron	The LHC
Circumference	6.3 km	26.7 km
Beams	Proton-antiproton	Proton-proton
Collision Energy	1.96 TeV	7 (10) [14] TeV
Status	Taking Data since 2002 > 400 publications	First 7 TeV beam expected within the next few months

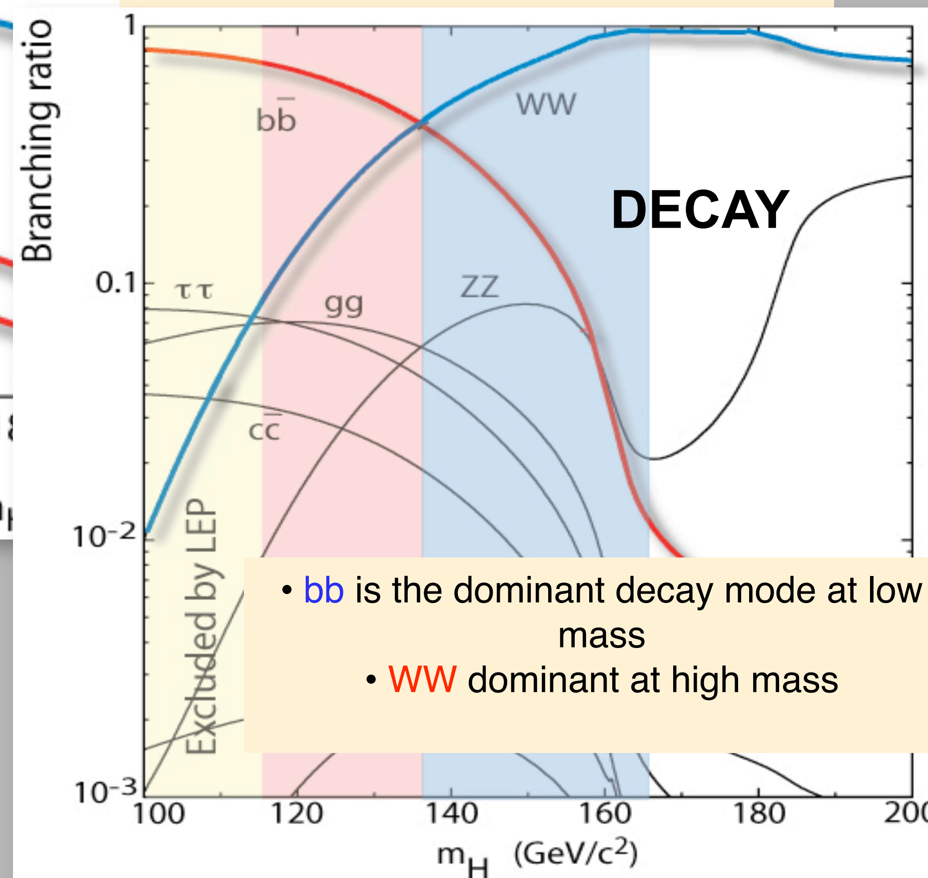
Rates of Physics Processes at the Tevatron



Higgs Production and Decay



- Gluon fusion is the dominant production mode: σ ~1.1-0.1 pb
- W/Z associated production next most frequent mode: σ ~0.2-0.01 pb

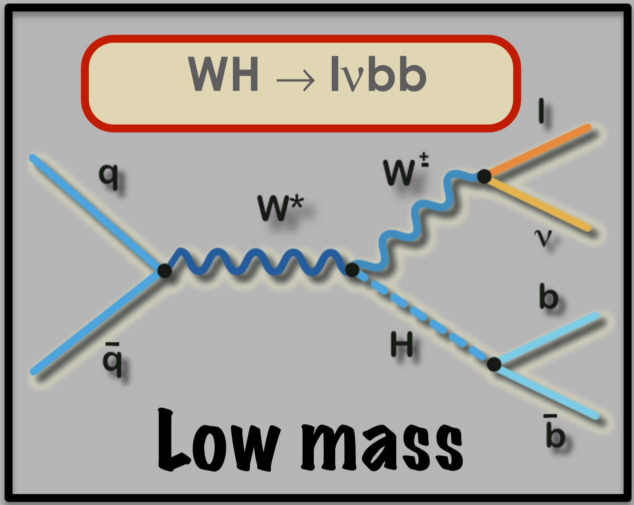


- bb is the dominant decay mode at low mass
- WW dominant at high mass

Low mass

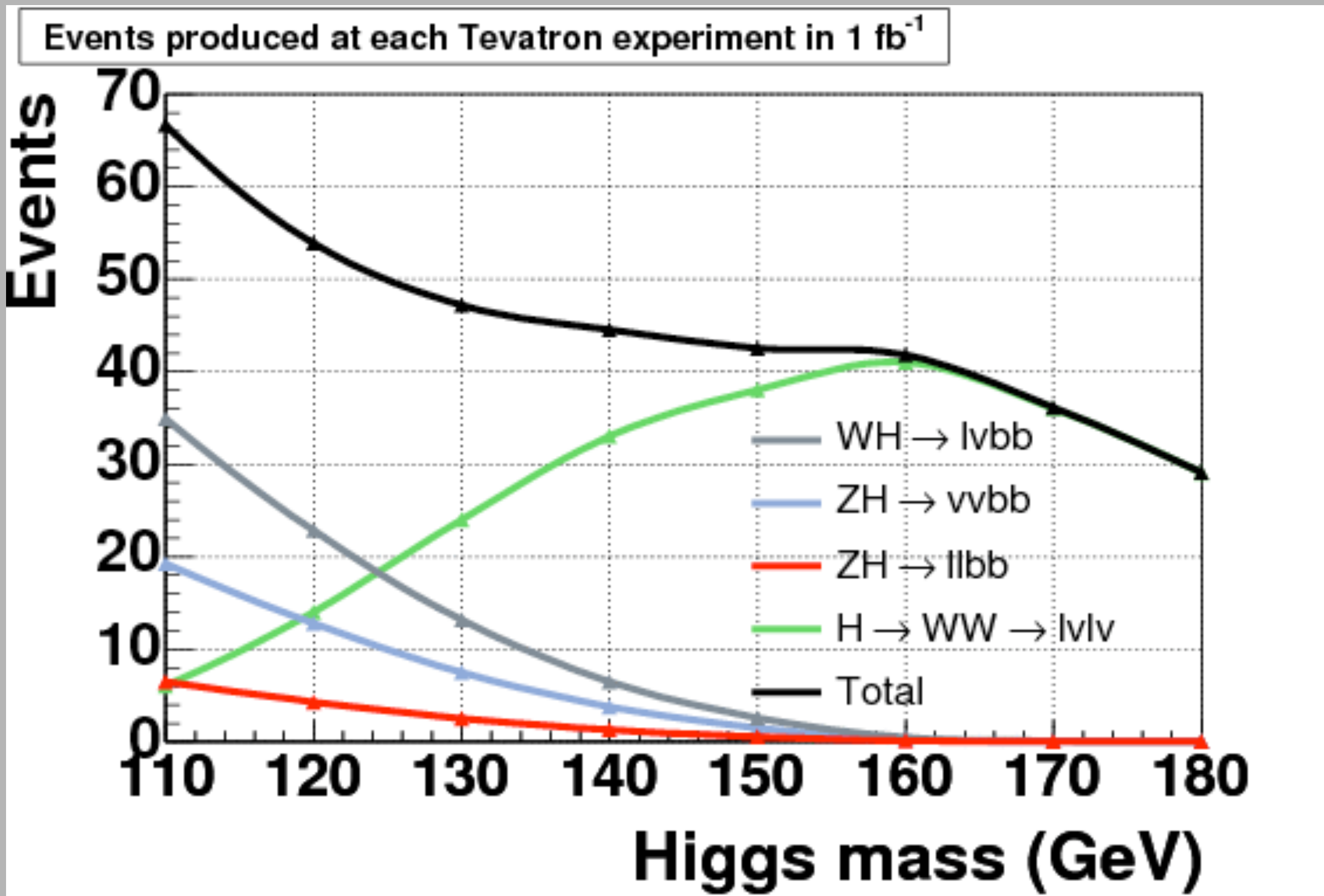
High mass

Main Search Channels



I will focus on low-mass and use the **WH → lνbb** analysis from CDF as an example

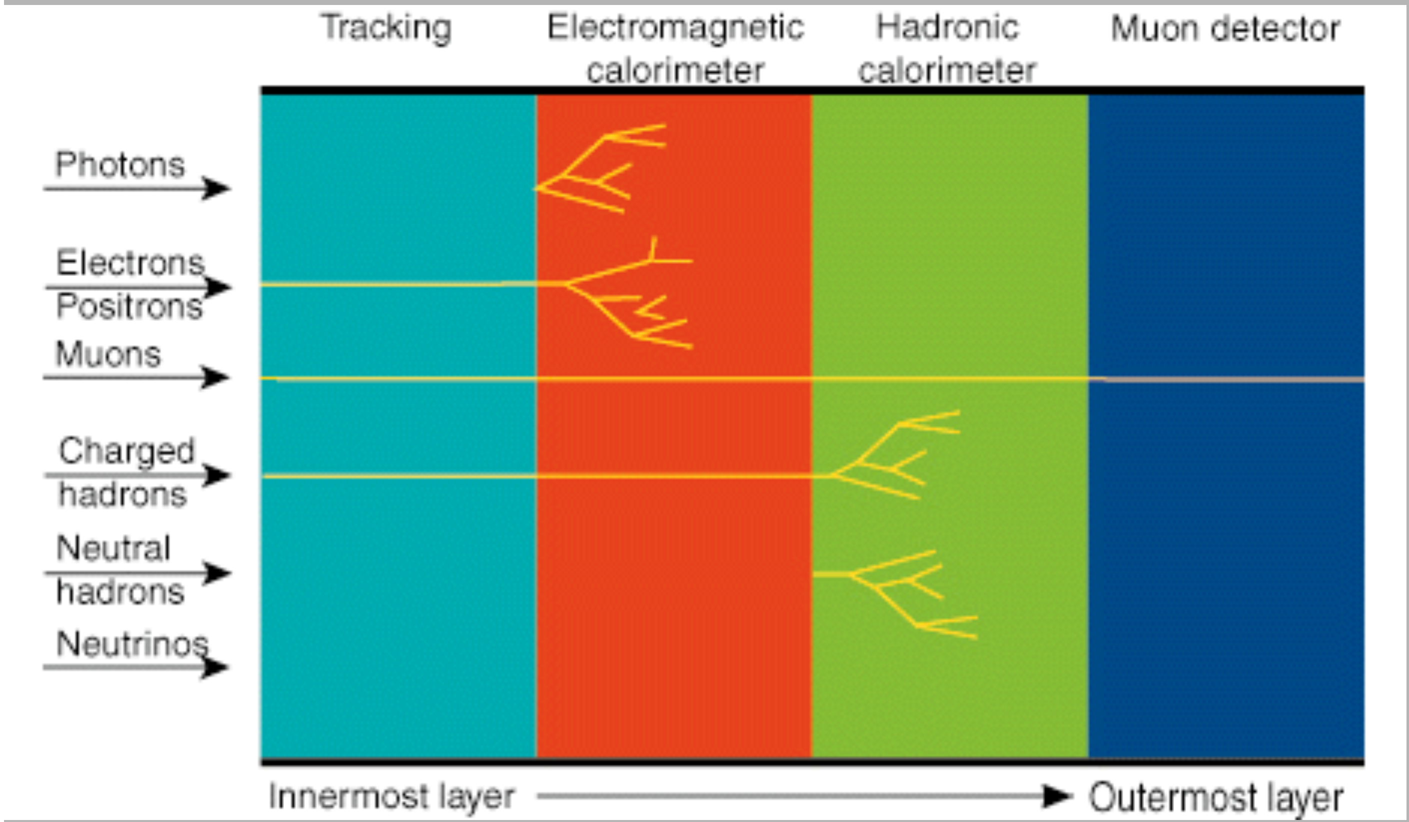
Higgs Production Rates



About 1000 Higgs events expected at the Tevatron in the with dataset (10 fb^-1)

Particle Identification

So, for **WH** $\rightarrow$ **lνbb** we need to identify event with a lepton, neutrino, and two b jets.



General purpose particle physics detectors

Tracking (large B field):
- Si chamber
  - Very good spatial resolution (b tags)
- Wire chambers

Sampling Calorimeters:
- EM Cal
- Hadronic Cal

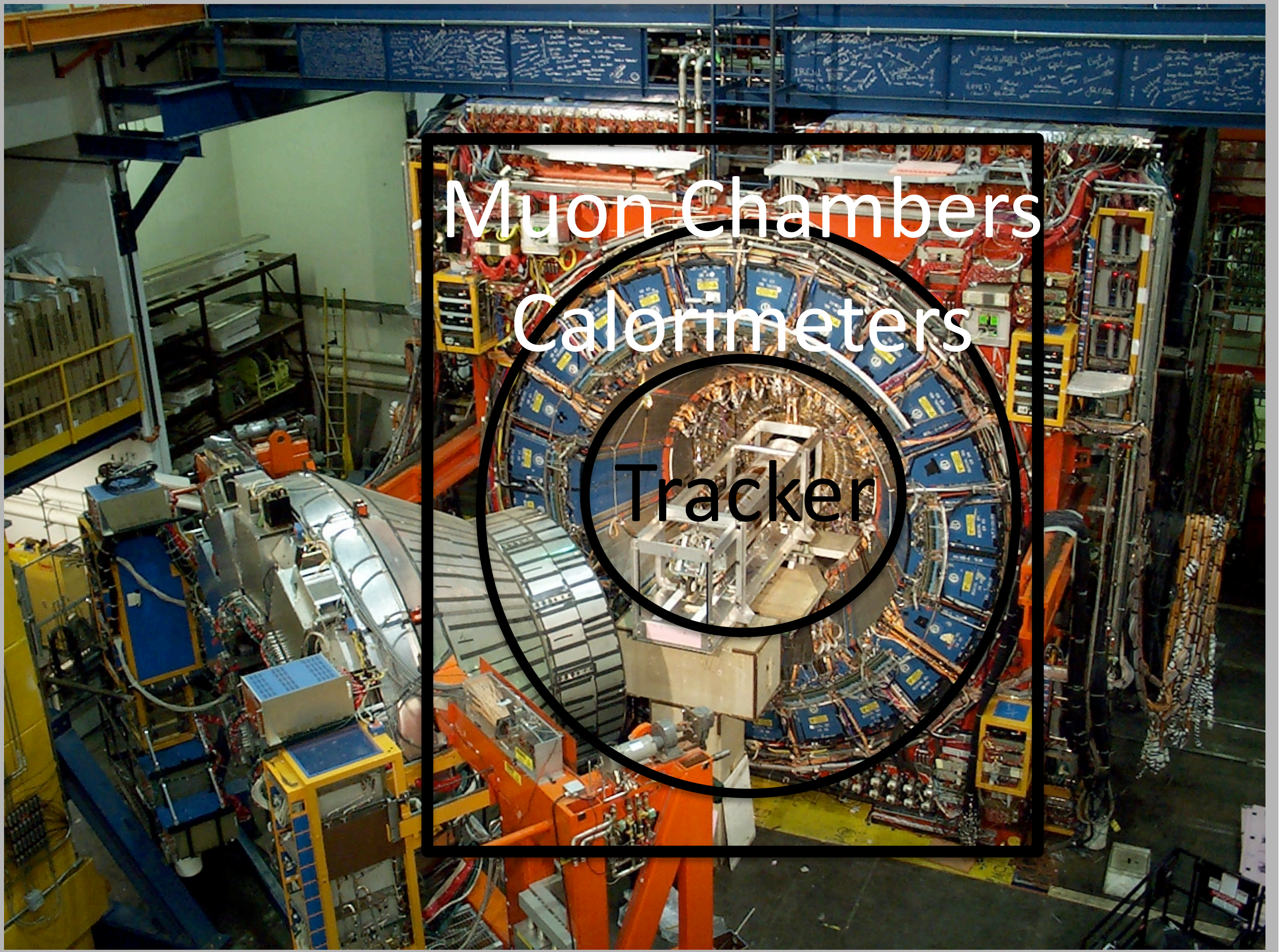
Muon Chambers:
- Drift Chambers
- Scintillators

The CDF Experiment at FNAL

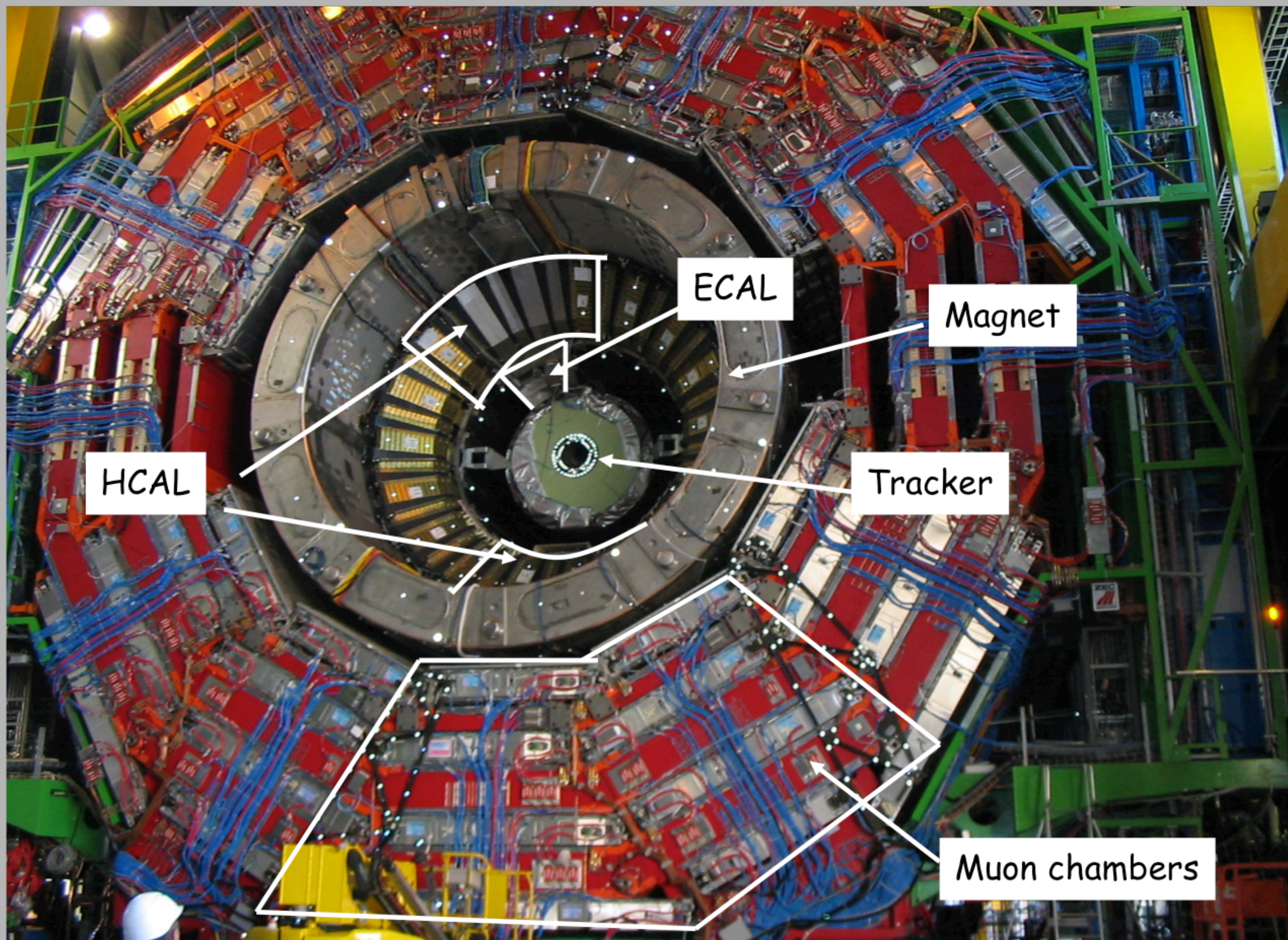
Collaboration

----

15 Countries
63 Institutions
602 Authors
~50 pubs/year



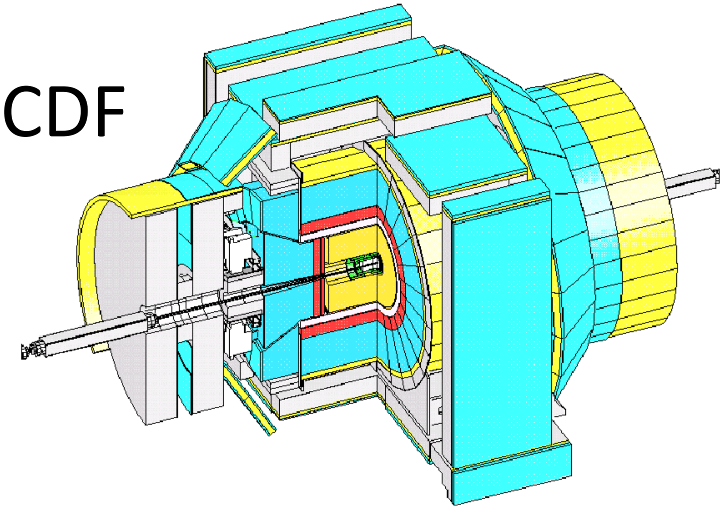
The CMS Experiment at the LHC

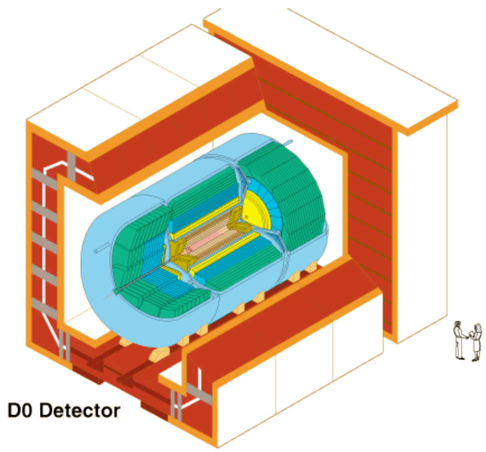


The Racers

Tevatron

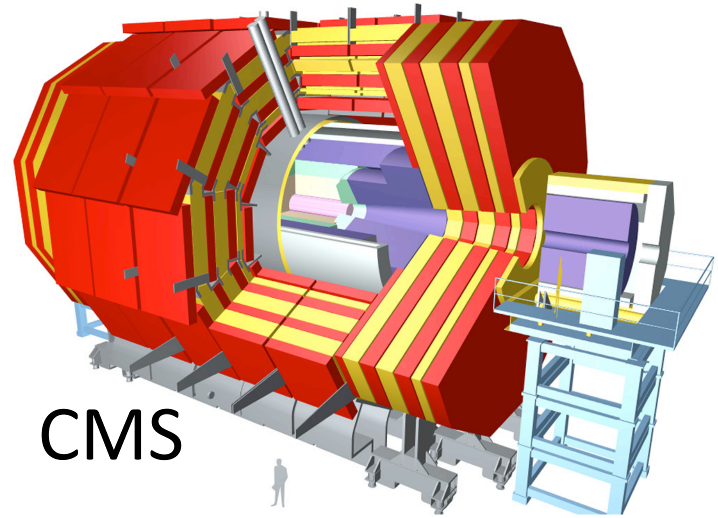
CDF



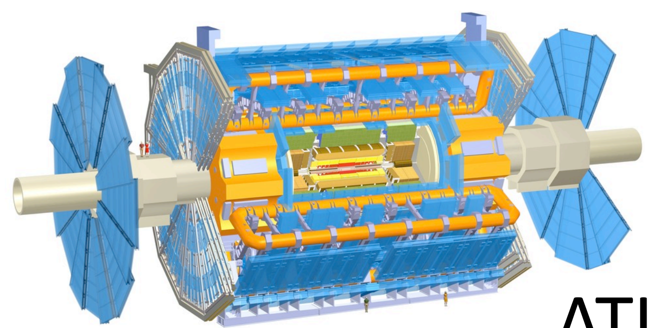


D0

The LHC



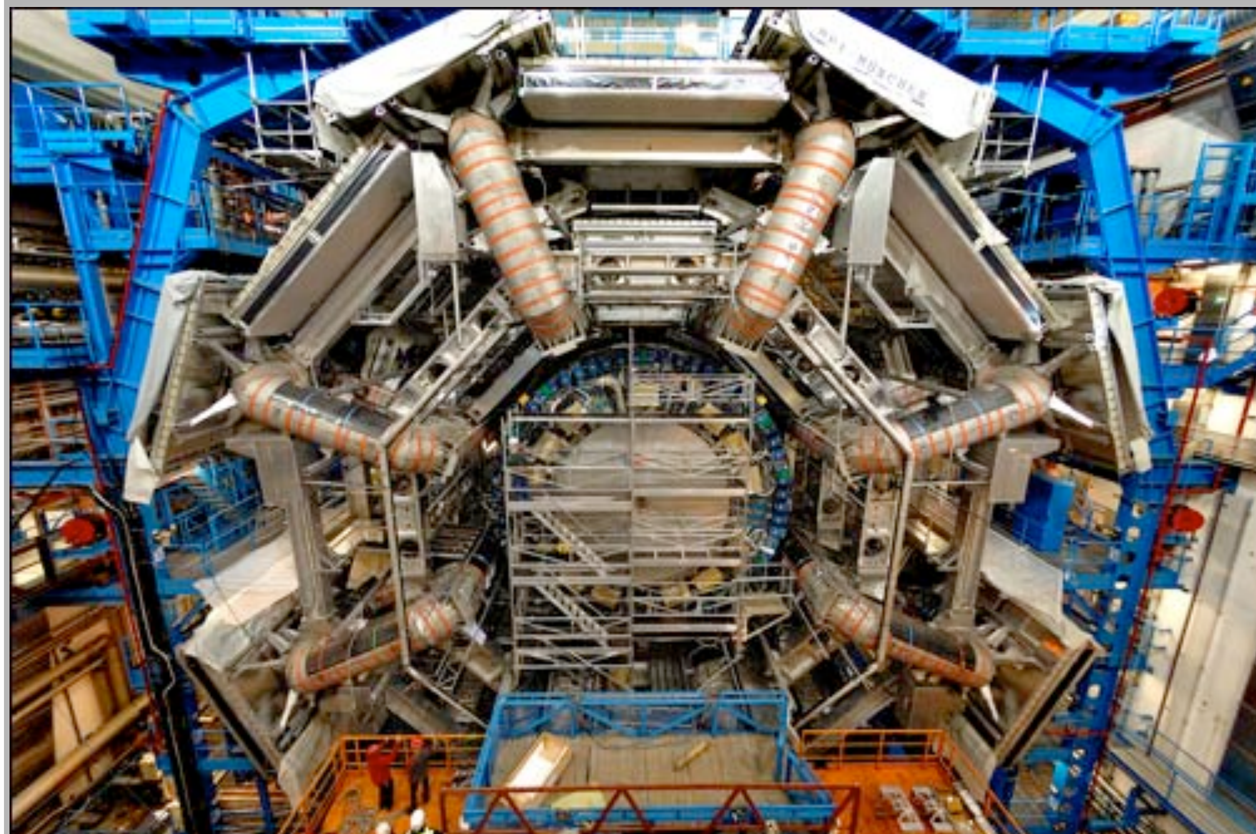
CMS



ATLAS

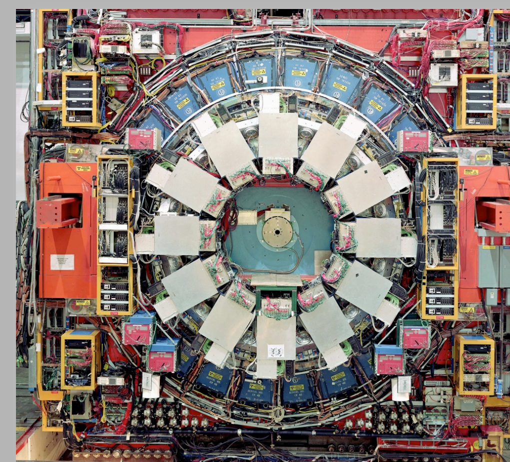
Detectors to Scale

diameter = 25 m
length = 46 m

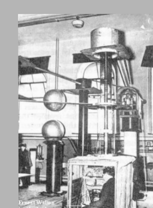


ATLAS

d = 12 m
l = 12 m



CDF



Cockroft-Walton
(Accelerator and Detector!)

Higgs Searches at the Tevatron

Triggers

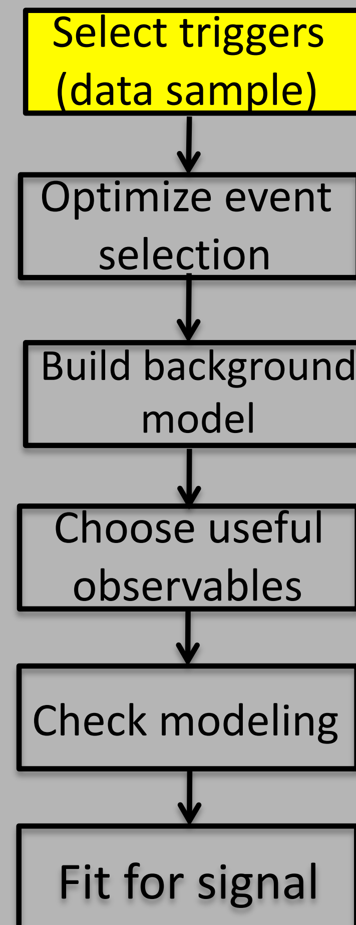
- *Collisions occur at a rate of ~ 2.5 MHz!*
  - → More than 99.9% jet events
  - → We can't (and don't want to) store all events
- We select (trigger) potentially useful events and throw the rest away!
- There are many different triggers to choose from:

  We can trigger on the lepton (*e or μ):*

  - *WH → ℓνbb*, *ZH → ℓℓbb, H → WW*

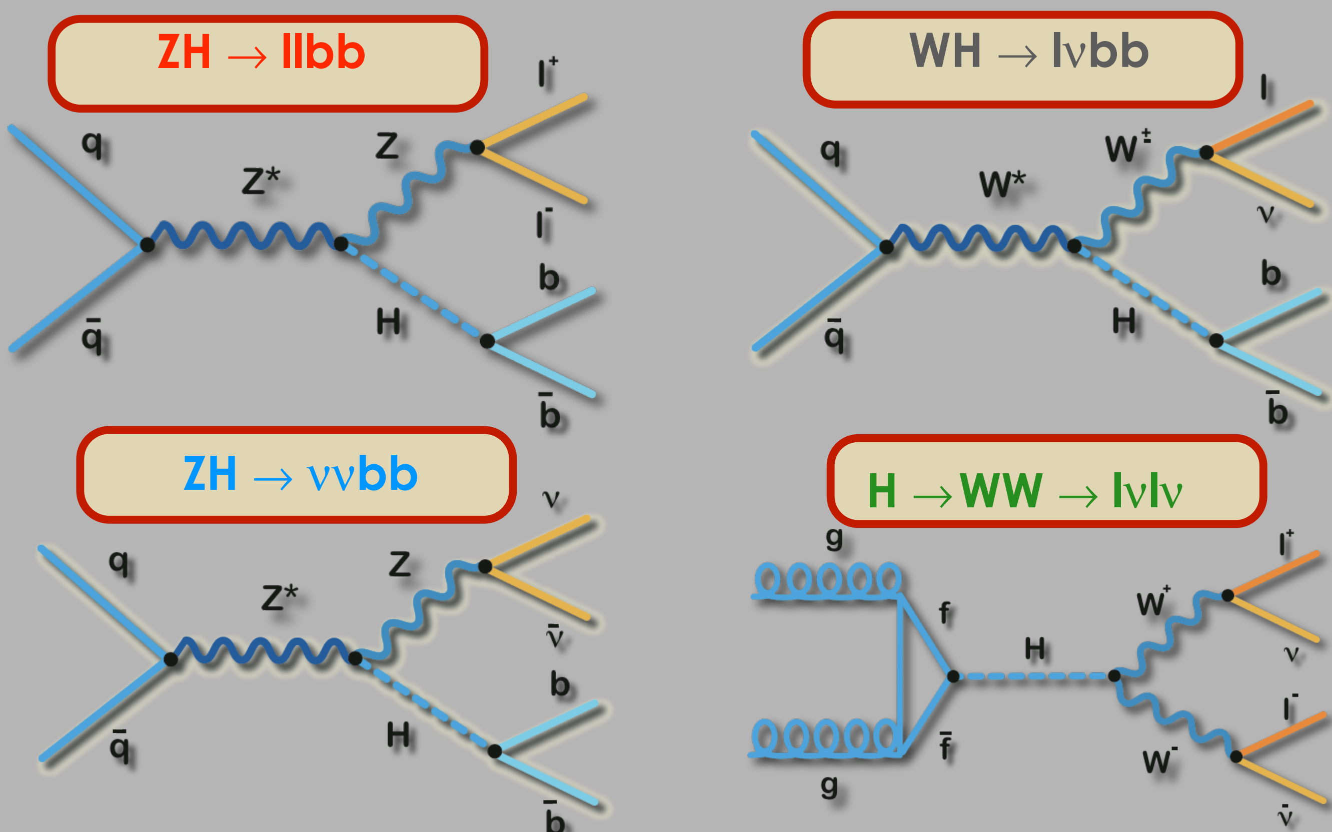
  Or, *MET + jets (MET= missing transverse energy):*

  - *WH → ℓνbb*, *ZH → ννbb*



Event Selection

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

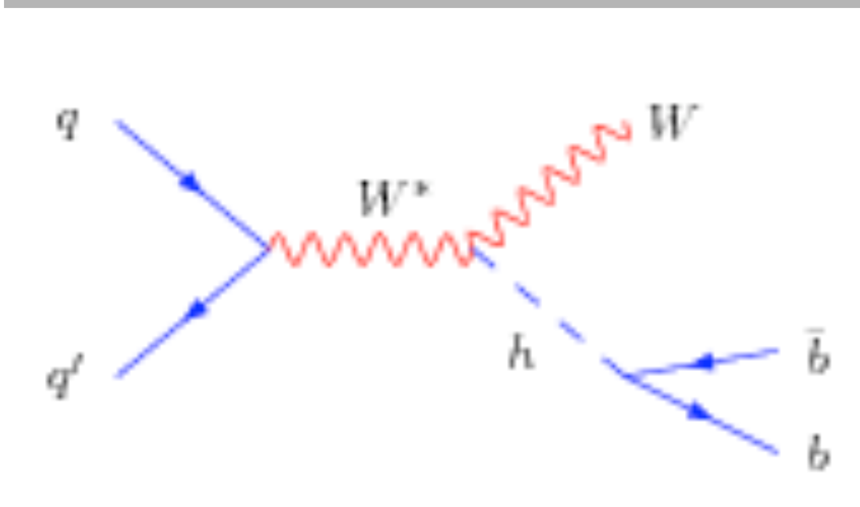


- Select triggers (data sample)
- ↓
- **Optimize event Selection**
- ↓
- Build background model
- ↓
- Choose useful observables
- ↓
- Check modeling
- ↓
- Fit for signal

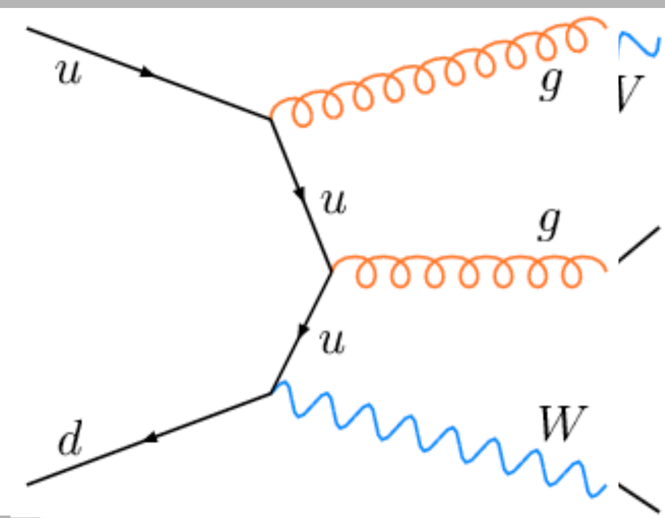
Backgrounds to the Higgs Boson Signal

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

Examples from WH → lνbb



Signal



Physics
Instrumental
Background

Other backgrounds from top, dibosons, …

Select triggers (data sample)

↓

Optimize event Selection

↓

Build background model

↓

Choose useful observables

↓

Check modeling

↓

Fit for signal

WH Background Estimate

Top/EWK (WW/WZ/Z→ττ, ttbar)

- MC normalized to theoretical cross-section
- Modeled by Pythia Monte Carlo

MC driven

W+HF jets (Wbb/Wcc/Wc)

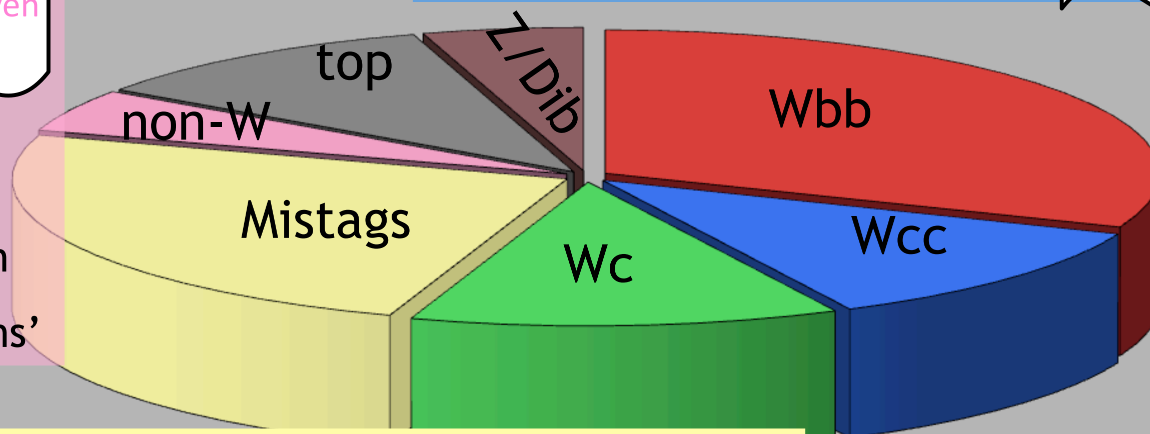
- W+jets normalization from data and heavy flavor (HF) fractions from ALPGEN Monte Carlo
- Modeled by Alpgen W+HF MC

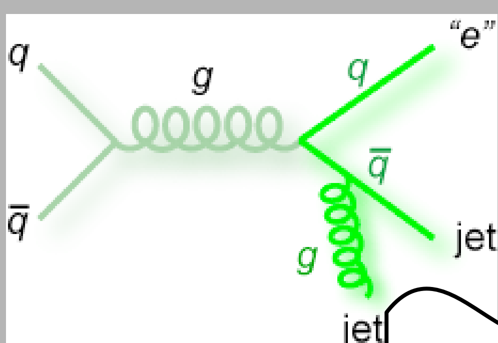
MC+ data driven

Non-*W (QCD)*

Data driven

- Multijet events with semileptonic *b*-decays or mismeasured jets
- Fit low MET data and extrapolate into signal region
- Modeled by 'Anti/Jet-electons'



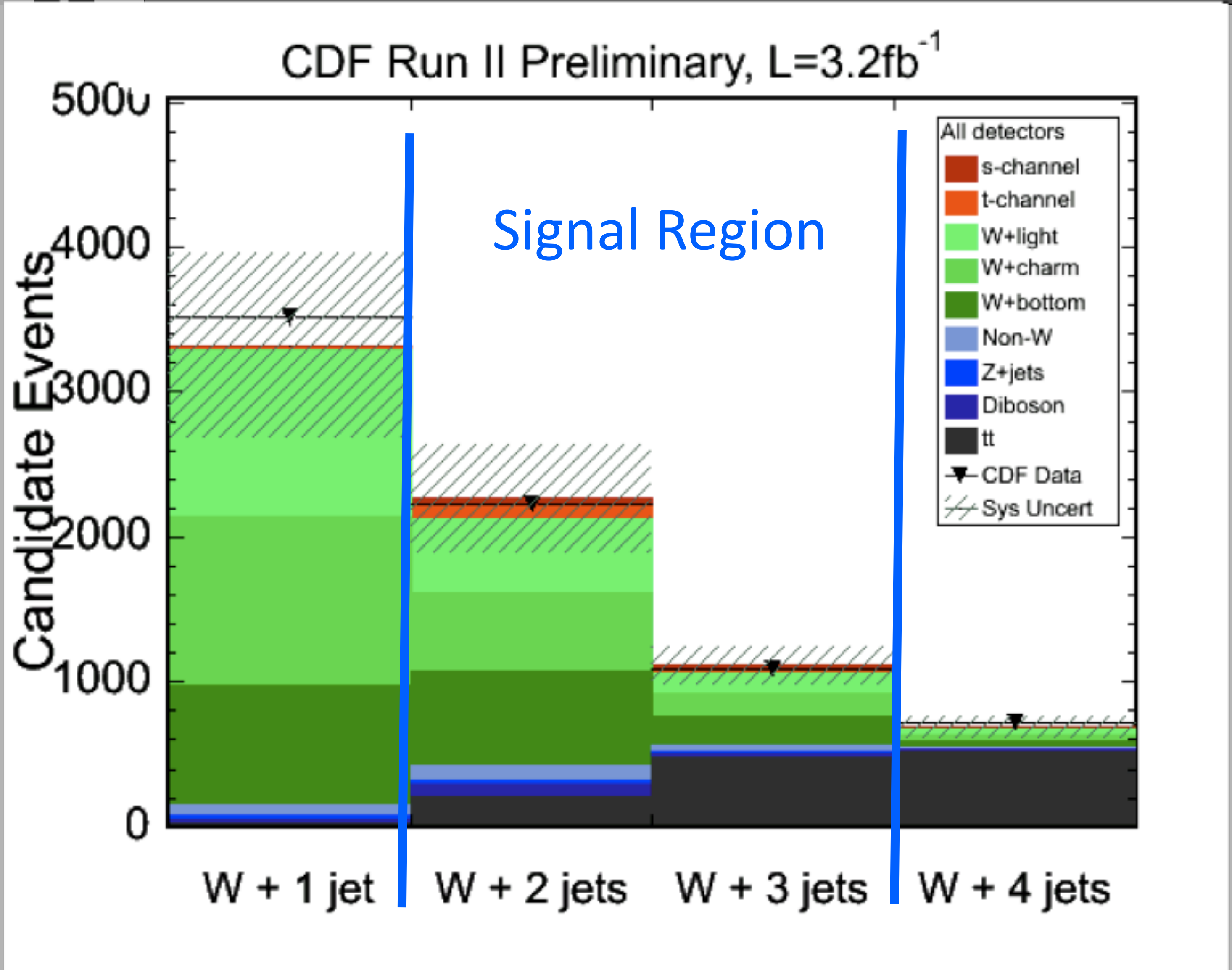


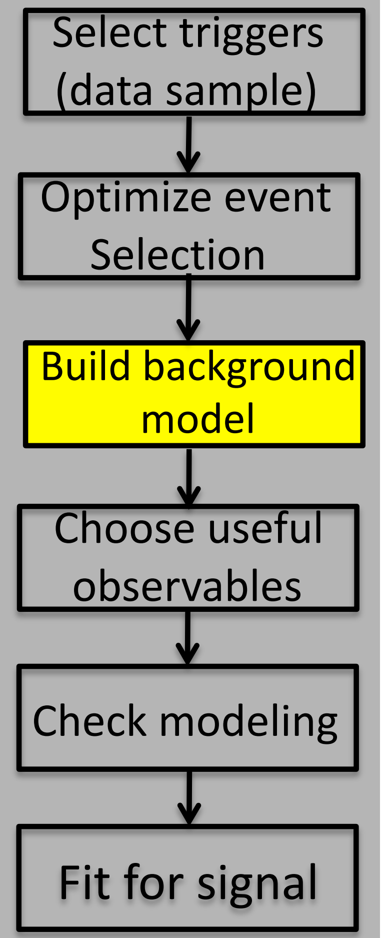
data driven

Mistags (W+2jets)

- Falsely tagged light quark or gluon jets
- Mistag probability parameterization obtained from inclusive jet data
- Apply mistag probability to generic W +jets sample

Background Estimate

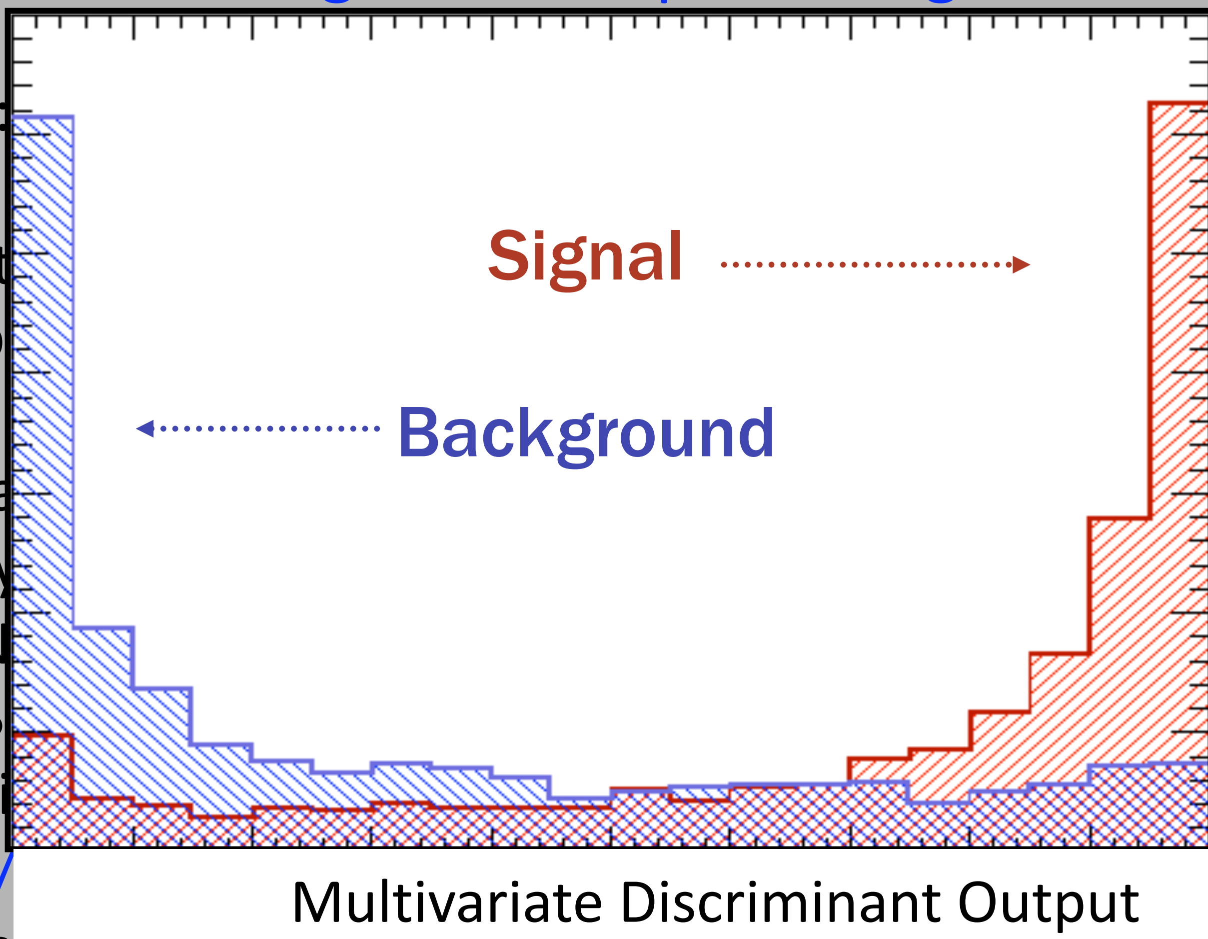


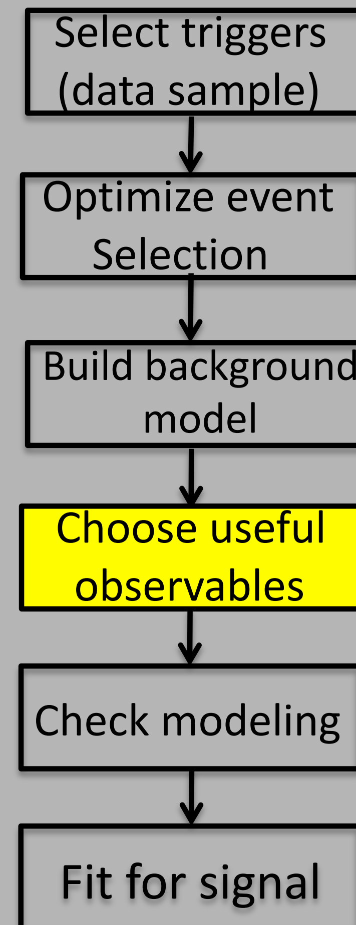


Multivariate Techniques

Uncertainties on background prediction are larger than expected signal !

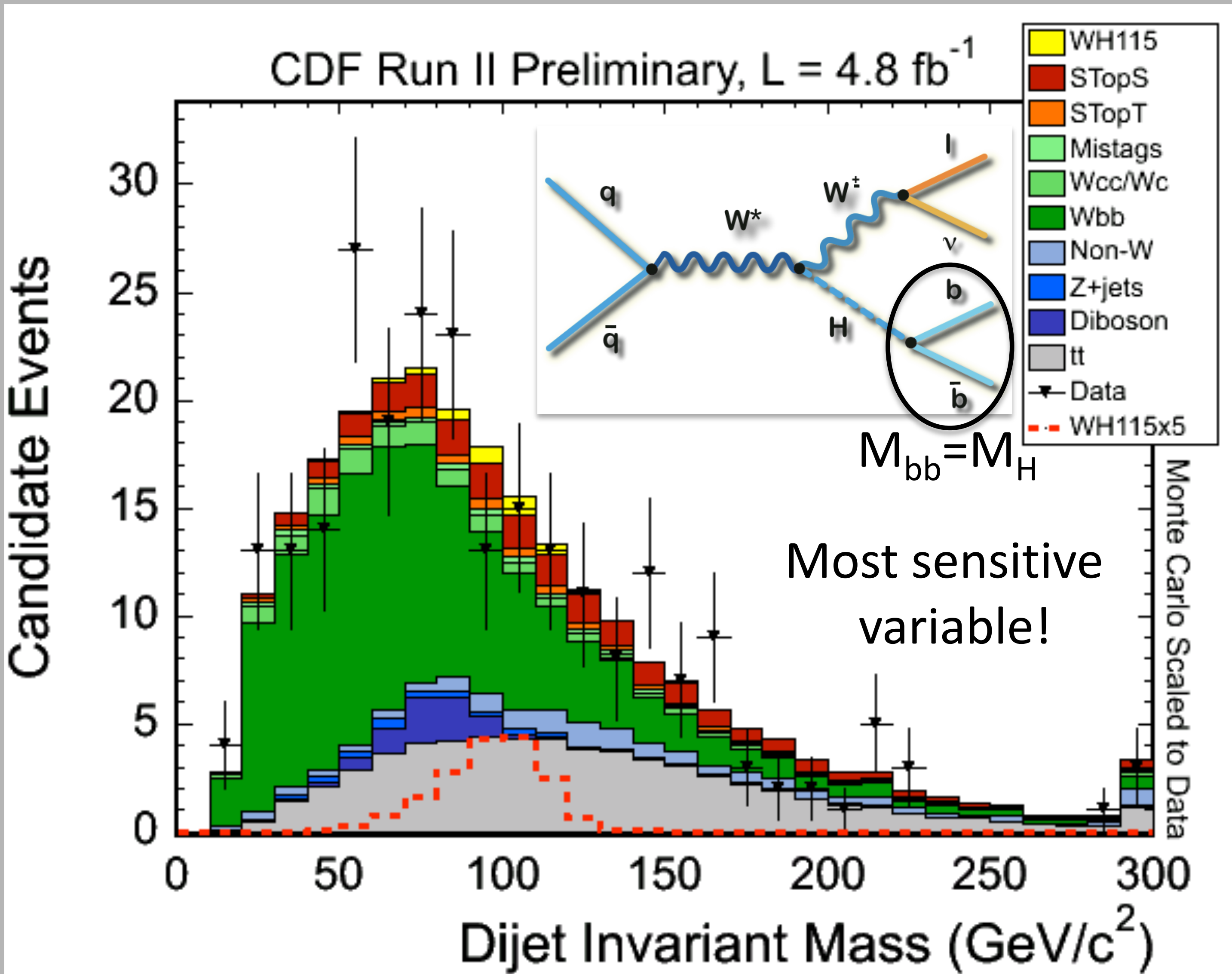
•Goal: ... ate
signal ...
•Input ...
•Outp ... ny
single ...
•Just a ...
•Many ...
•N ...
•B ...
•Li ...
•M ...





→ We use all of these in Higgs searches at the Tevatron!

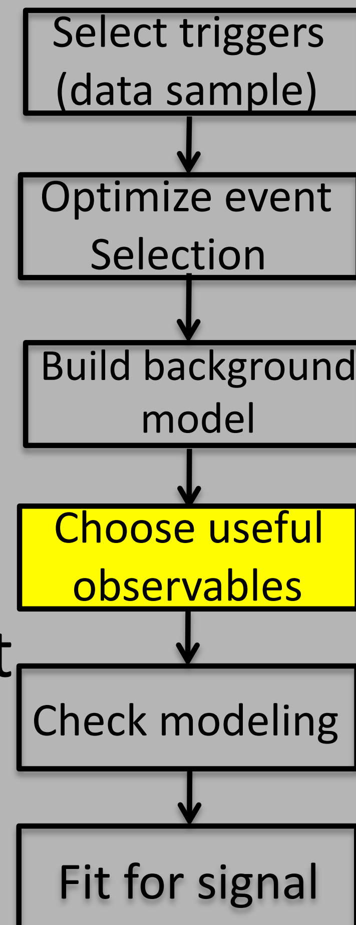
Variable Selection



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

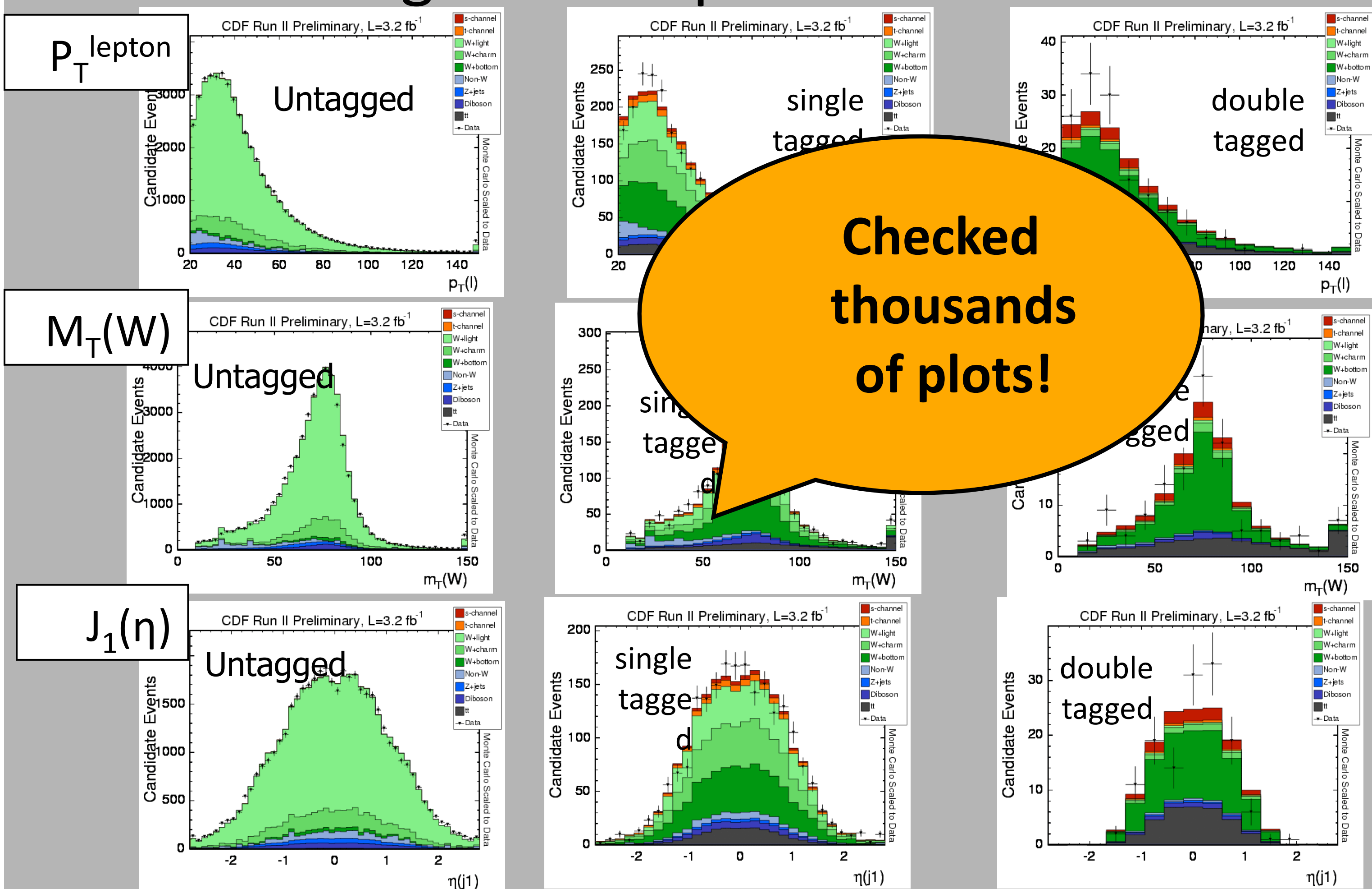
Other Variables

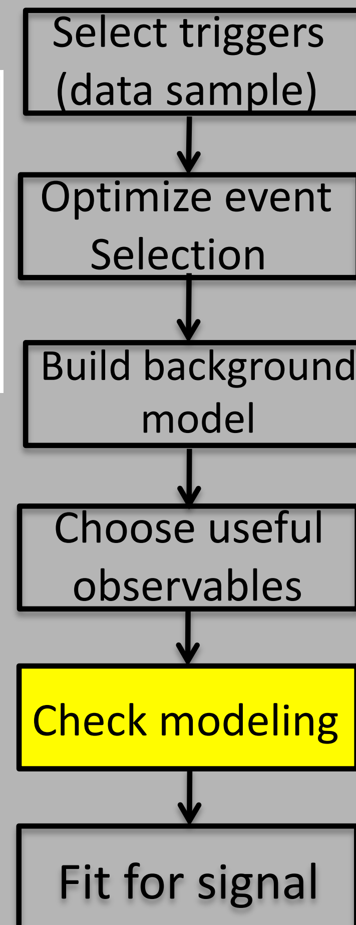
- M_{jj} is the most sensitive, but other variables can add separation power between signal and background
- Example: the matrix element method uses the final state 4-vectors reconstructed in each event to calculate the theoretical event probability
  - → Highly correlated with dijet mass
- For NN or BDT we carefully choose variables that have separation power for at least 1 background
- Using multivariate techniques improves sensitivity by ~25% for WH over just using M_{jj}



Check Background Modeling

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

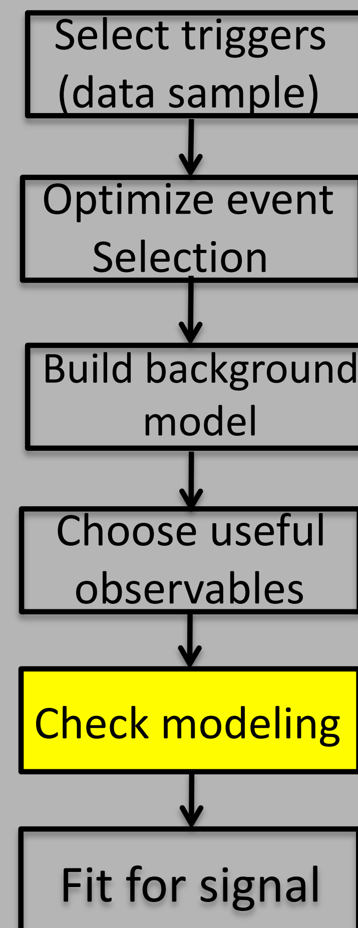




A Plethora of Cross Checks!

Most searches perform a “blind” analysis:

- The method is fixed before looking at multivariate discriminate in the signal region
- The background modeling is checked in control regions defined to isolate different backgrounds:
  - before *b-tag (W+jets)*
  - 4-jet (*tt)*
- Many additional “blind” checks performed
  - Correlations of input/output are well modeled
  - Many “slices” of phase space checked
- Systematic uncertainties cover modeling concerns...



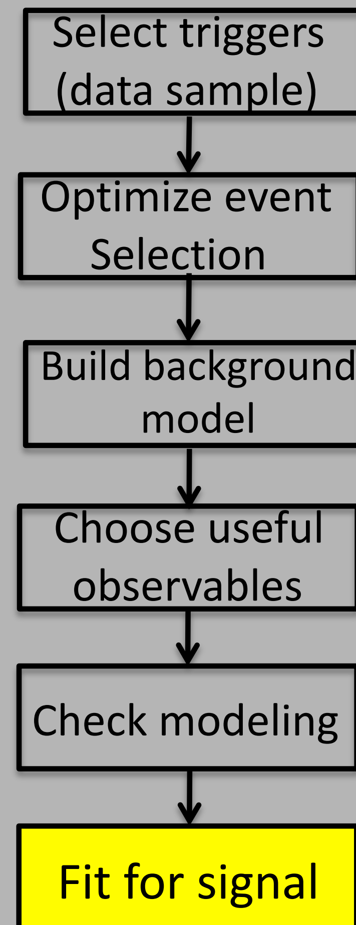
Fit For Signal (we wish!)

We don’t see evidence for the Higgs boson yet!

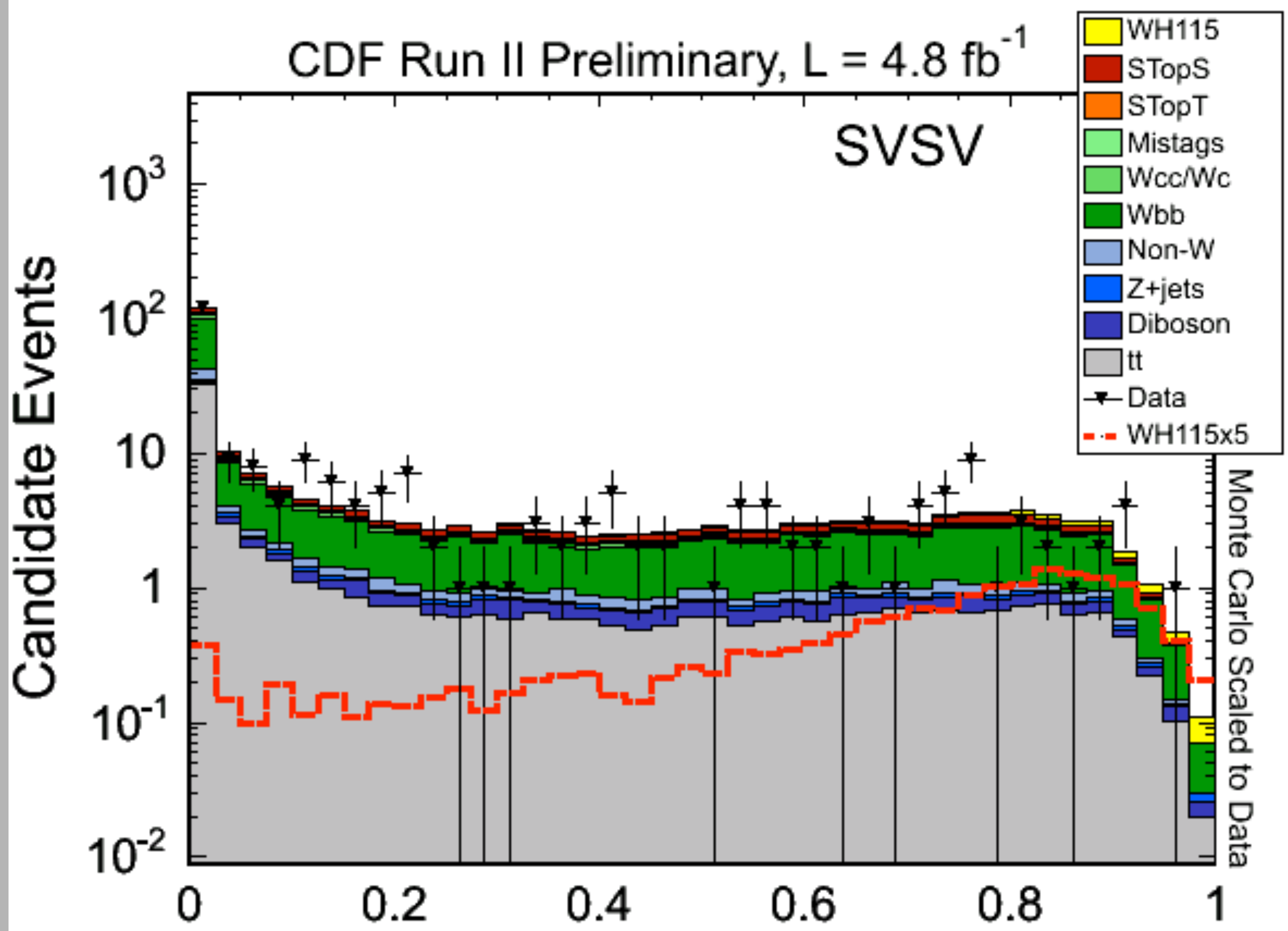
- For now, we set limits on its rate of production
- These limits say:

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

- We only get one real experiment ! ☺
- To study our sensitivity we make test experiments (called pseudo-experiments).
- These take statistical fluctuations and systematic uncertainties into account
- We often quote these limits in factors away from the standard model prediction



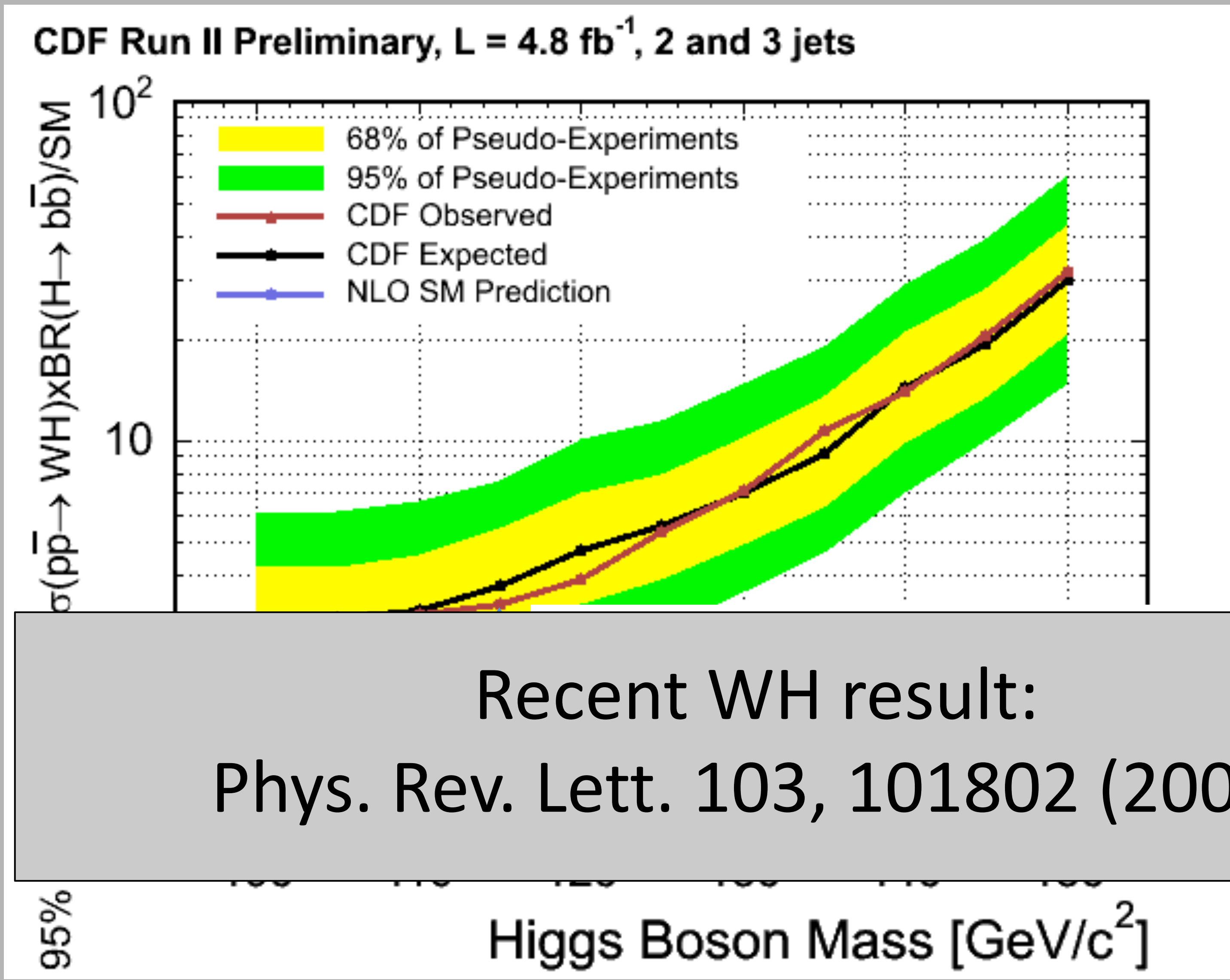
Fit For Signal (we wish!)

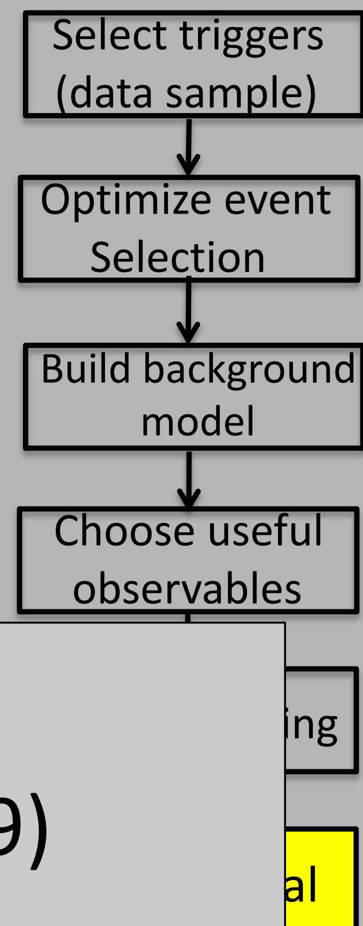


Matrix Element Discriminant used for WH

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

WH Limit Result





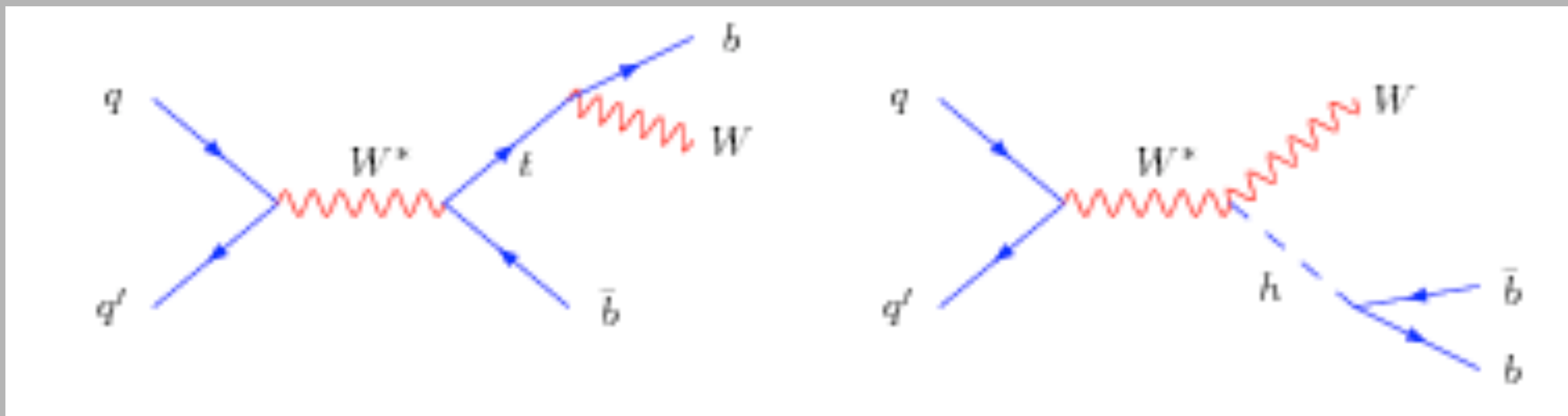
Recent WH result:

Phys. Rev. Lett. 103, 101802 (2009)

WH Proofs of Principle

Single Top Quark Production

Measuring single top quark production is a benchmark for WH!



CDF first observation of single top:

Phys. Rev. Lett. 103, 092002 (2009)

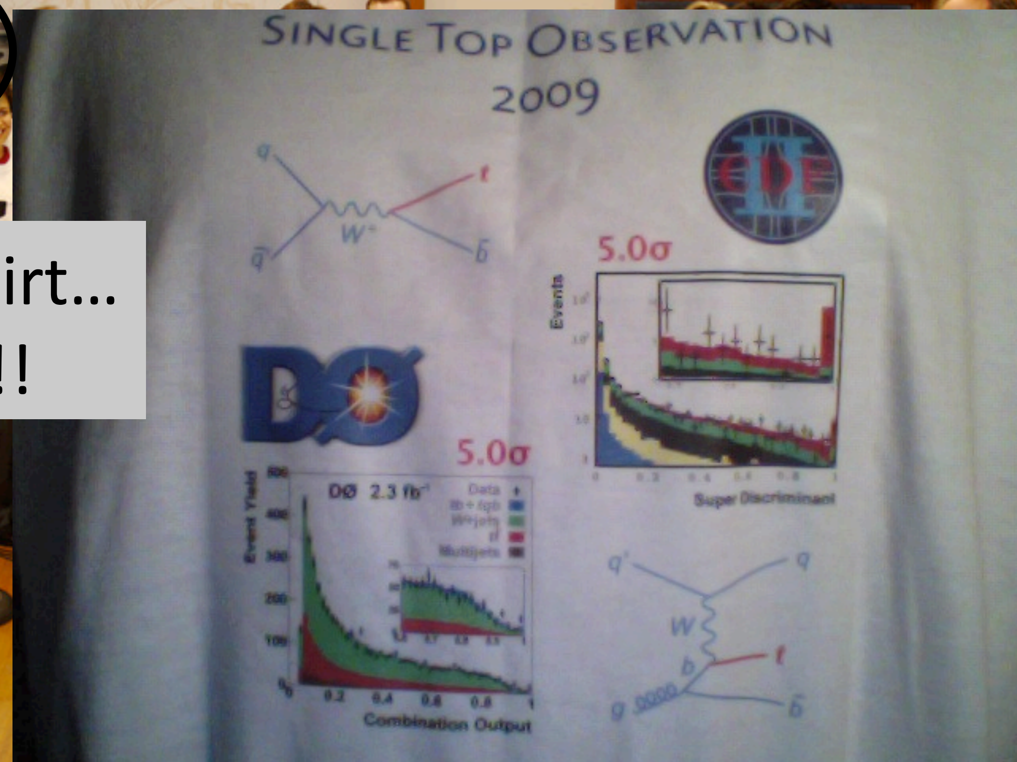
WH 1/10 Singletop

Single Top Celebration

Relieved Single Top Conveners!

The single top T-shirt…

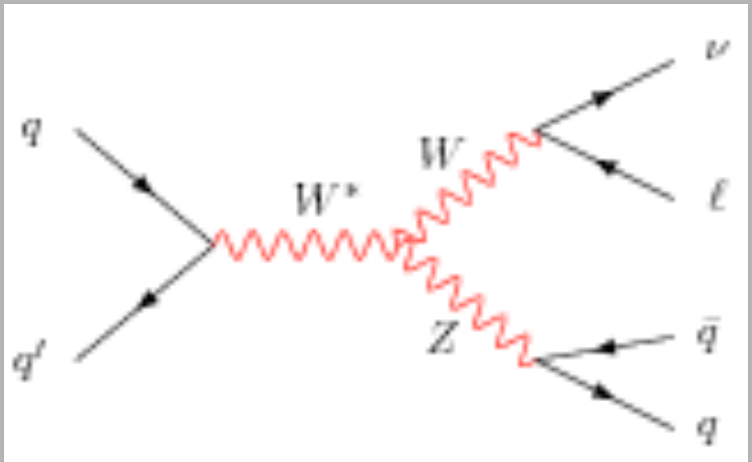
Get yours today!!

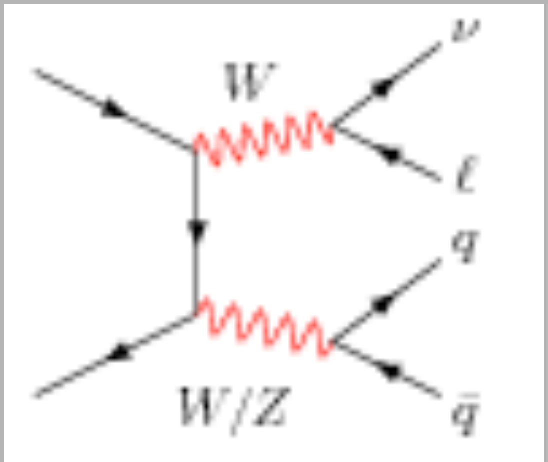


WH Proofs of Principle

Diboson Production (lvjj)

Measuring diboson production is a benchmark for WH!

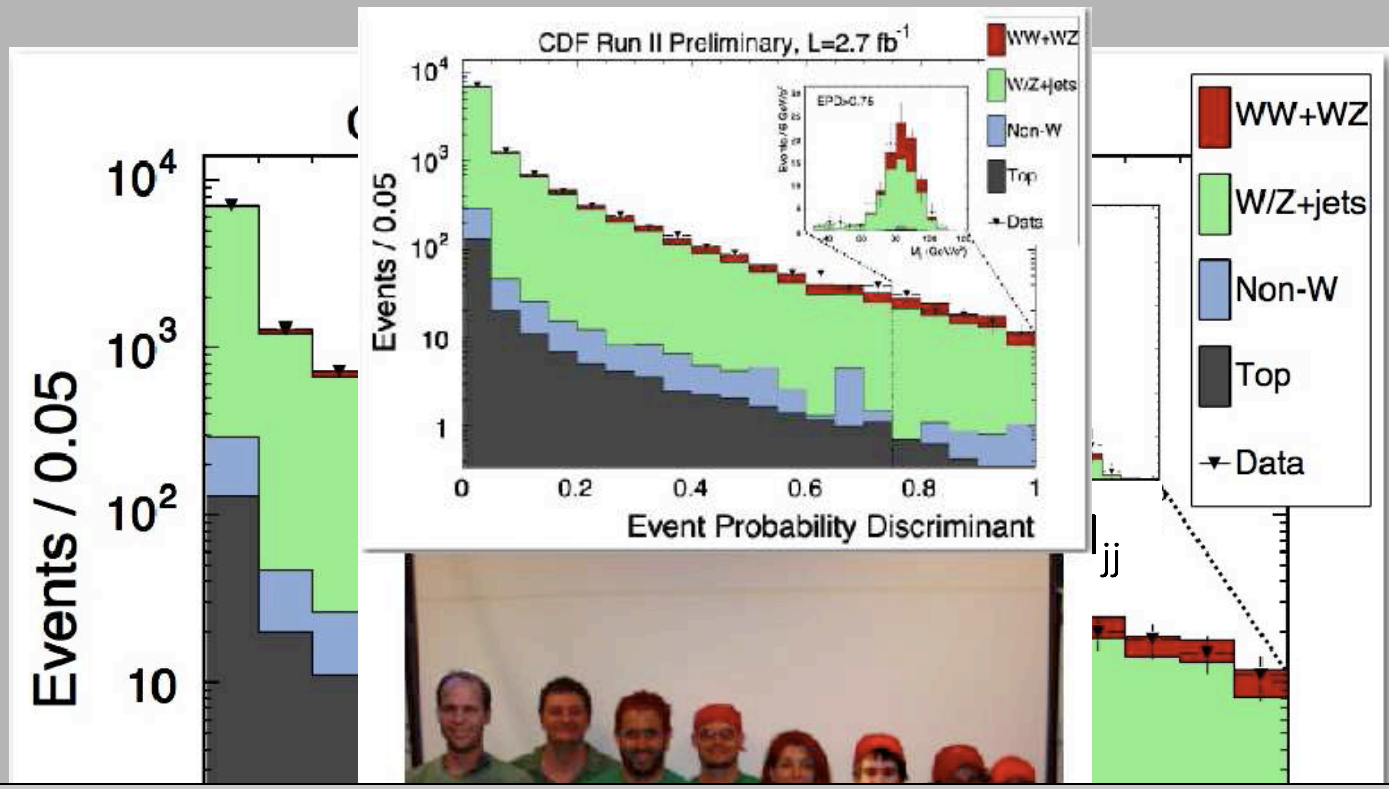




- *lvjj final state also very similar to Higgs*
- Small signal in large background
- Use same background method and analysis tools
- Dijet mass most sensitive variable

→also in low-mass Higgs searches!

WH Proofs of Principle



CDF first observation diboson (lvjj):
arXiv:0911.4449 (accepted by PRL)

CDF Results: All Channels

CDF limits at low mass (*M_H = 115 GeV/c^2*)

Channel	Limit x SM (expected)
WH → lνbb	3.8
ZH → ννbb	4.2
ZH → llbb	5.8
H → WW → lνlν	8.5 (@ 120 GeV)
ZH+WH → jjbb	19.9
H → ττ	26.1
H → ϒϒ (New!)	19.5 (@ 120 GeV)

CDF Results: All Channels

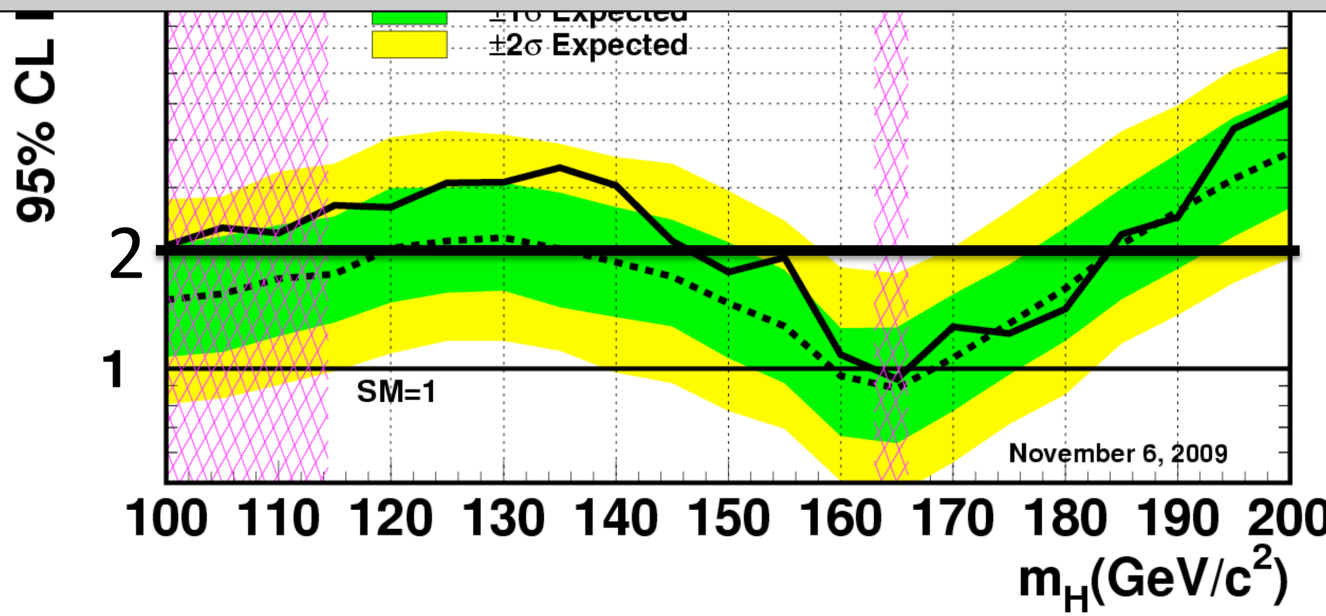
CDF limits at low mass ($M_H = 115\ GeV/c^2$)

Channel	Limit x SM (expected)
$WH \rightarrow l\nu bb$	3.8
$ZH \rightarrow \nu\nu bb$	4.2
$ZH \rightarrow llbb$	5.8
$H \rightarrow WW \rightarrow l\nu l\nu$	8.5 (@ 120 GeV)
$ZH+WH \rightarrow jjbb$	19.9
$H \rightarrow \tau\tau$	26.1
$H \rightarrow \Upsilon\Upsilon$ (New!)	19.5 (@ 120 GeV)
CDF combined	2.4

Latest Tevatron Combined Results

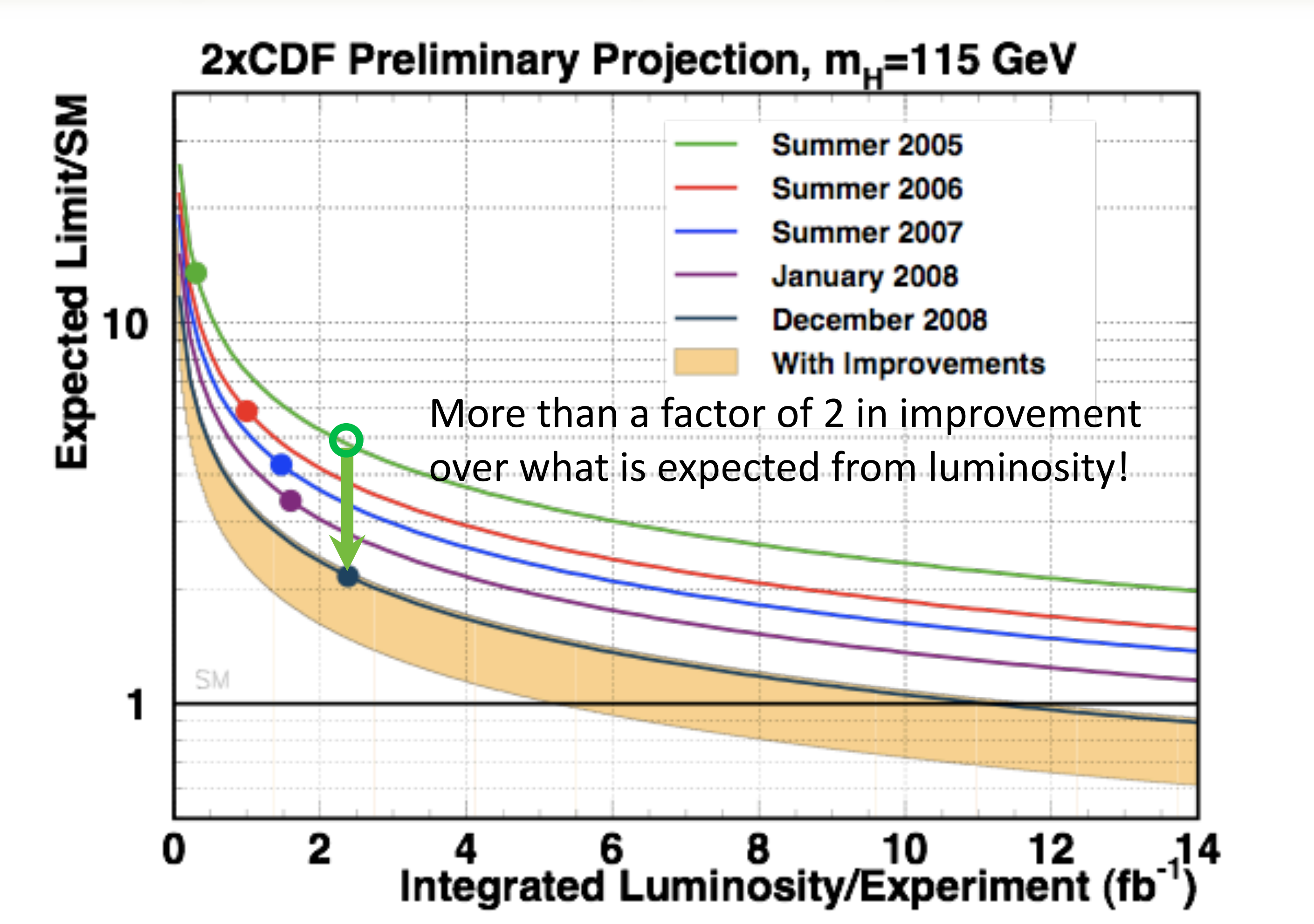
All channels combined from the CDF and D0 experiments

Within a factor of 2 of exclusion sensitivity to SM over the full interesting mass range!



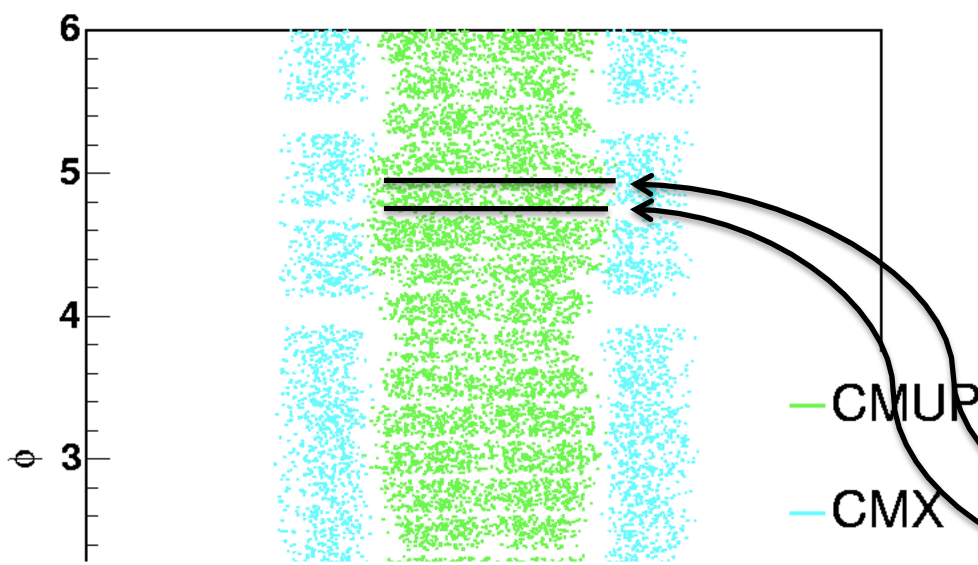
Higgs Search Progress

Orange band = 1.5 expected improvement factor

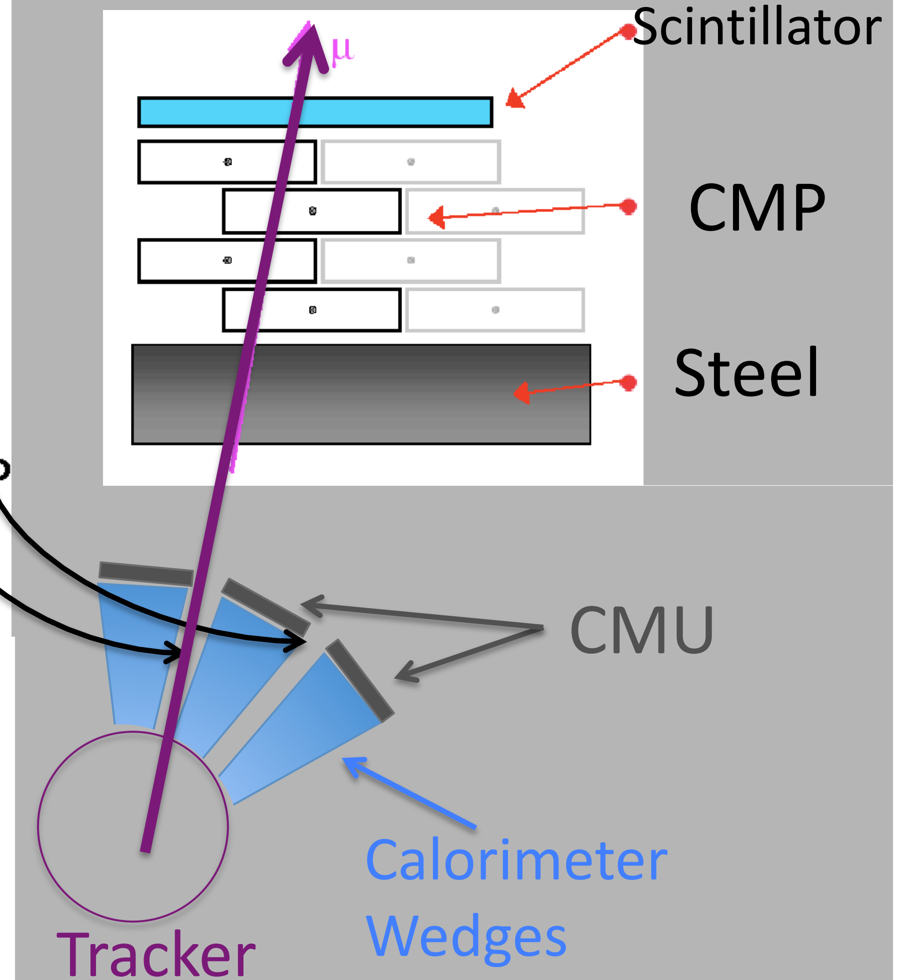


Improvement Example

Filling "gaps" in muon trigger coverage

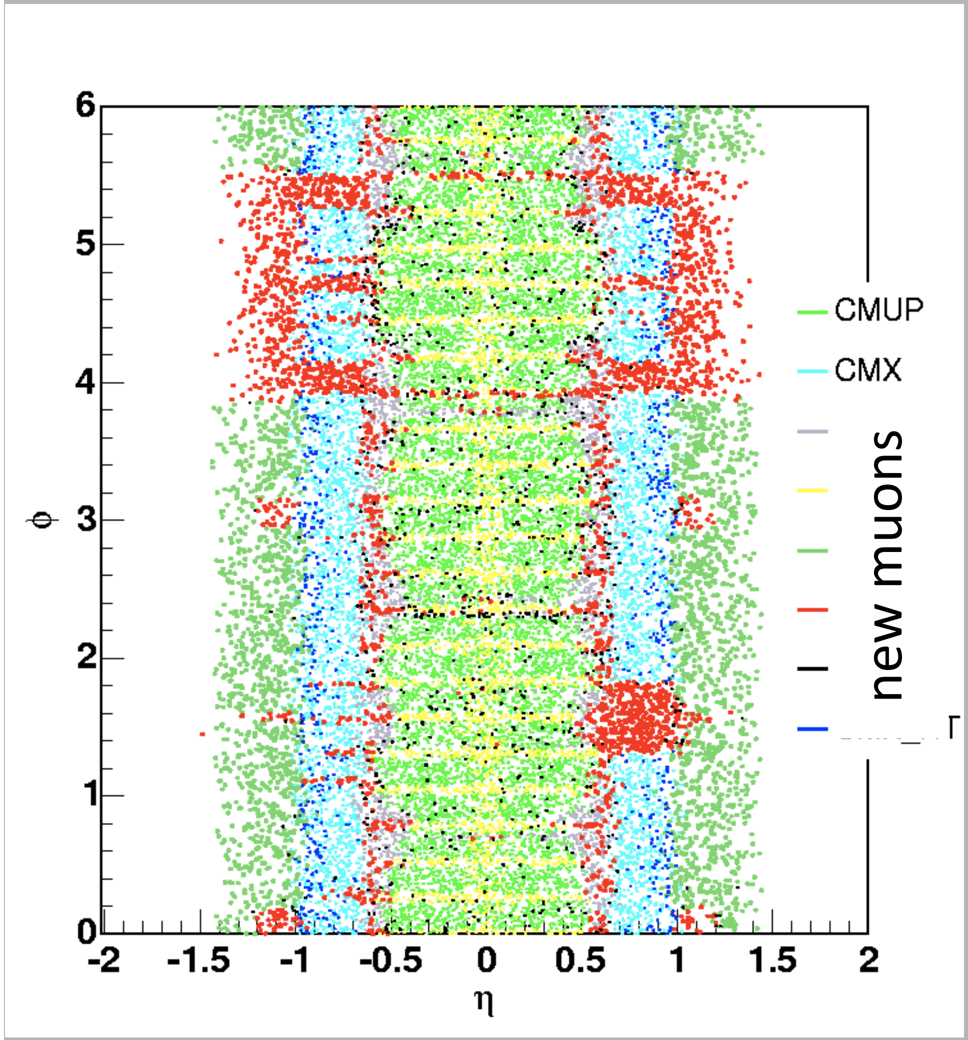


Added "gap" trigger for CMP-only muons
- Match tracks to cracks in CMU
- Matched hit in CMP to scintillator to reduce very high trigger rate
- Running trigger since 2007
- Unfortunately triggers are not retroactive!



Improvement Example

Filling "gaps" in muon trigger coverage



Also filled in gaps using triggers based on missing E_T +jets triggers:

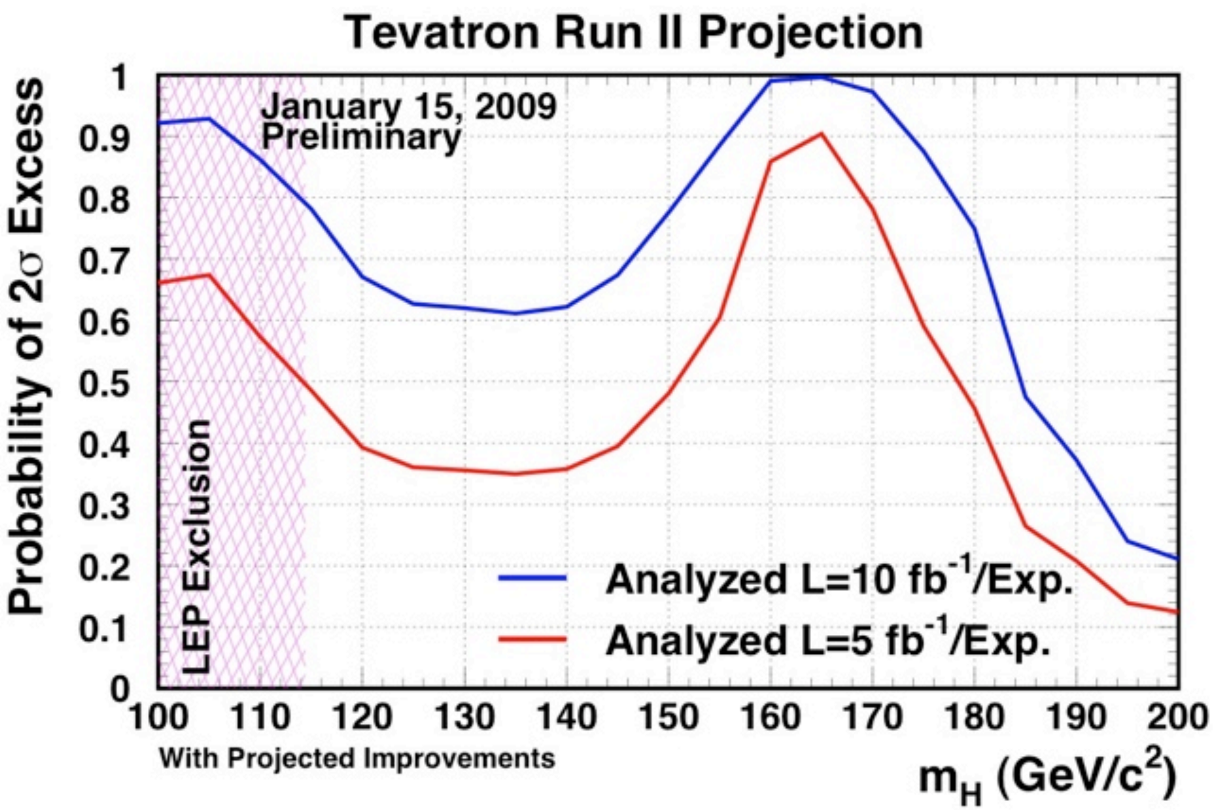
- MET+jet triggers in for full dataset
- Can fill in all "types" of muons
- Muons are minimum ionizing and contribute to MET in trigger

  → Improves efficiency
- Large increase in muon acceptance for WH!

Equivalent to having 20% more luminosity

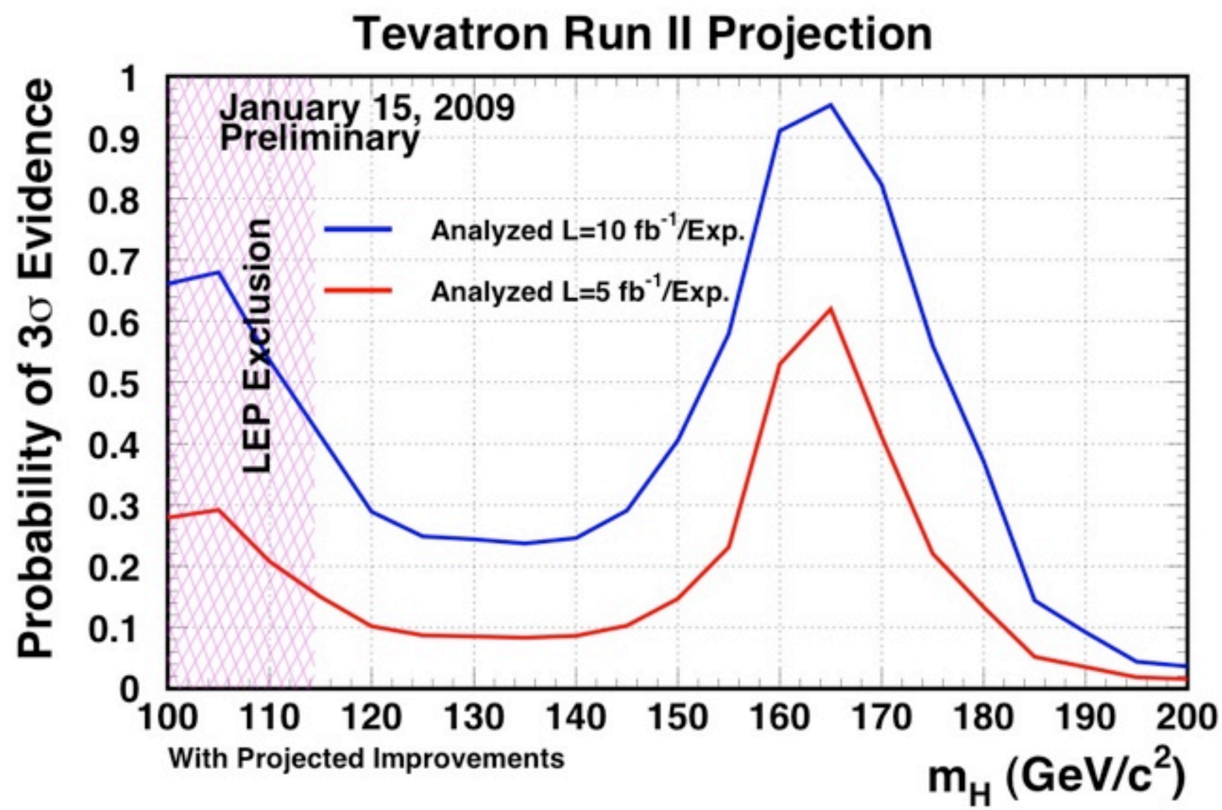
Higgs Outlook

2-sigma



Higgs Outlook

3-sigma



Tevatron Higgs Summary

- Datasets shown here should at least double
- Tevatron will have sensitivity to a low-mass Higgs boson!

-> Should be able to exclude at 95% confidence level over the entire mass range with 8-10 fb^{-1}

Or, we might just see something!

Higgs Searches at the LHC

Peter Higgs in the LHC tunnel
(First observation of Higgs at the LHC!)

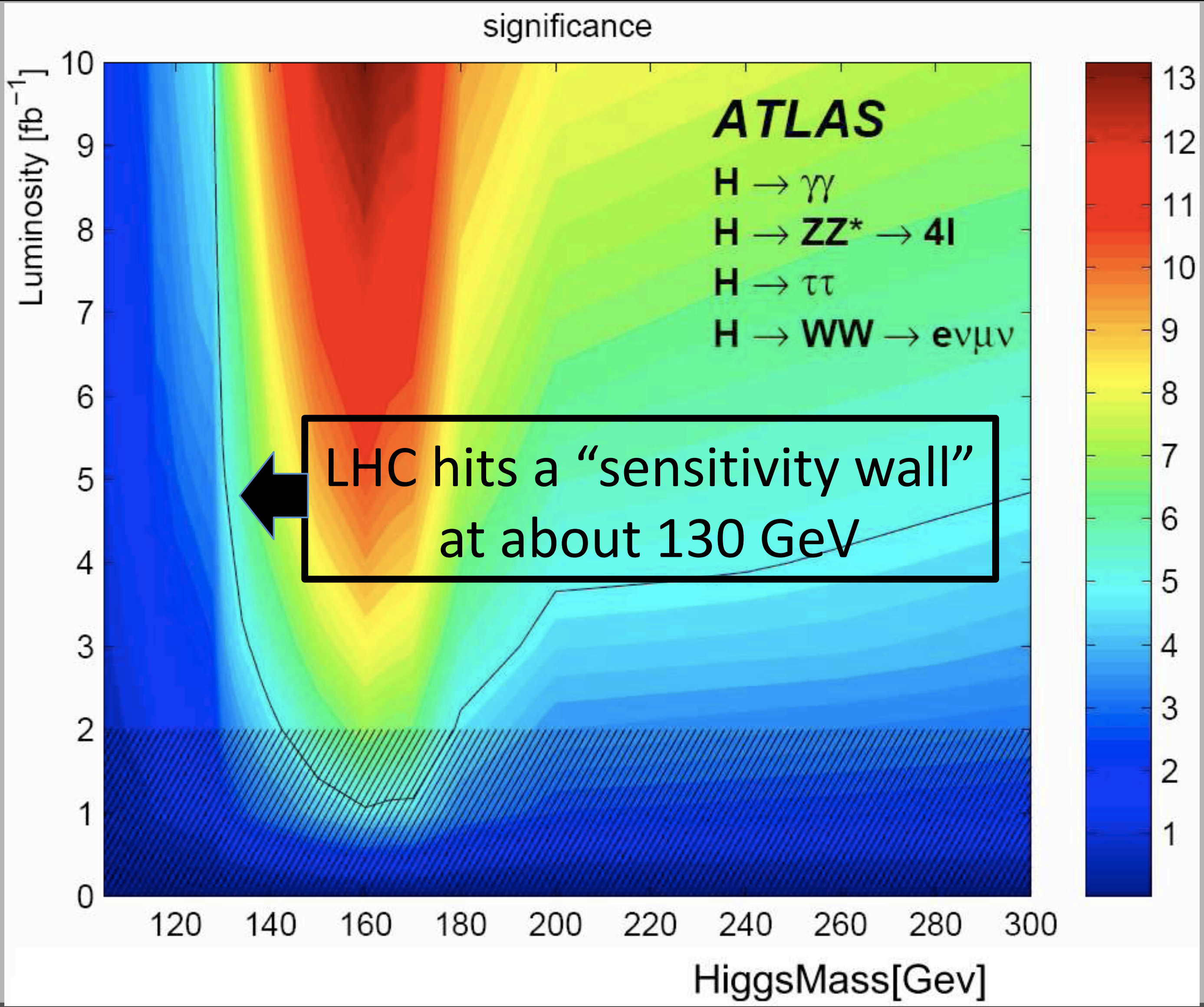
Higgs Searches at the LHC

- LHC very sensitive to high mass Higgs boson
  - Tevatron already excluding their "sweet spot"
- Low mass searches are also very challenging at LHC!
- LHC uses different production/decay channels:
  - $ttH \rightarrow ttbb$
  - $gg \rightarrow H \rightarrow \gamma\gamma$

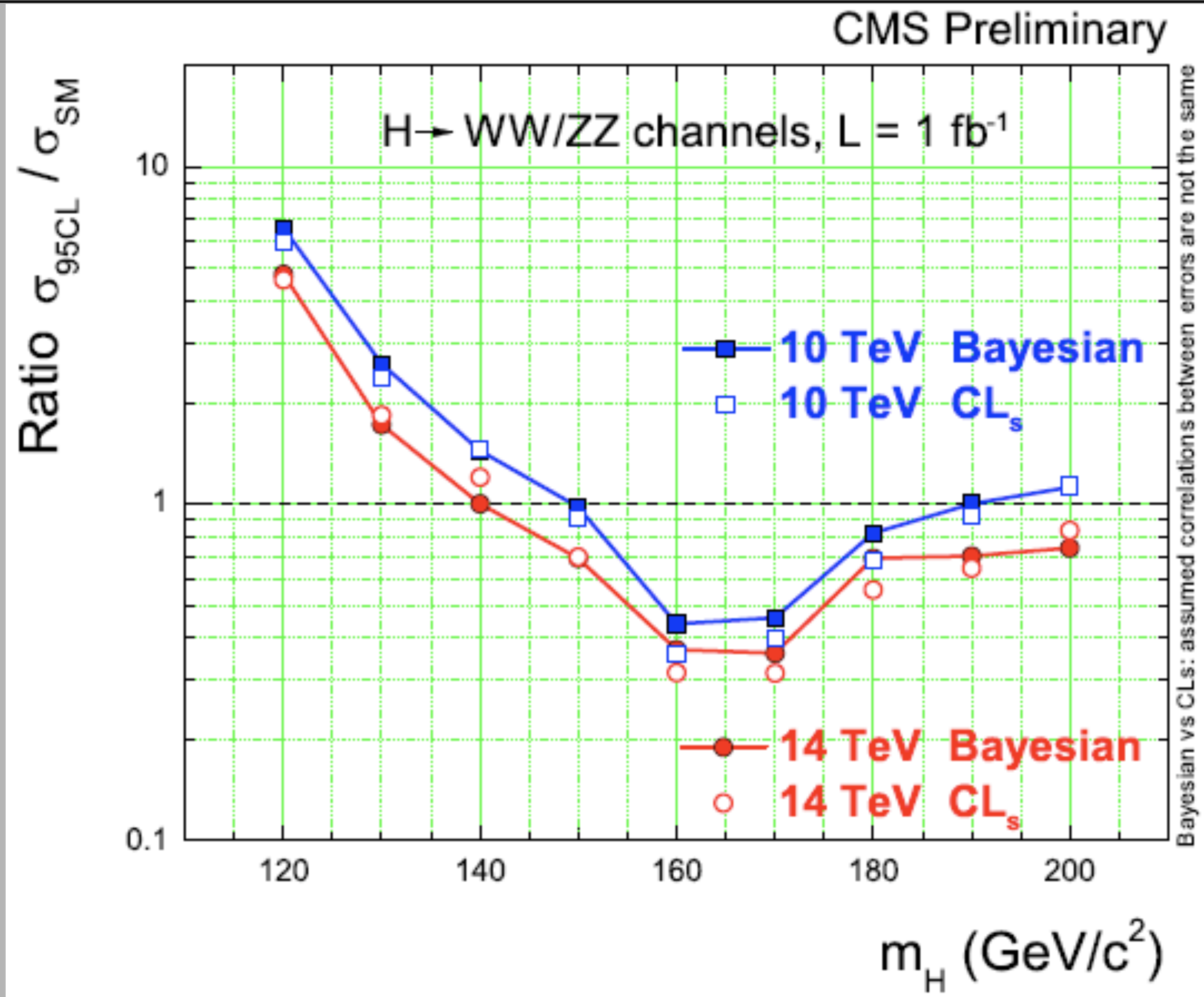
$\rightarrow$ Complimentary to Tevatron searches!

- Once observed, we need to measure as many of its production and decay modes as possible
- Tevatron data may be able to confirm or deny early evidence at LHC

Example: Atlas Sensitivity at 14 TeV



Example: 10 TeV v/s 14 TeV



The LHC Plan

- First collision data last year at about Tevatron energies
- First 7 TeV collisions in the next few months
  → New energy frontier!
- Run for about 2 years at 7 TeV
  → Goal to accumulate about ~1 fb^{-1} *of "good" data*
- Followed with shutdown for ≥ 1 year to prepare the magnets for 14 TeV

Once the LHC accelerator is working well,
luminosity will come quickly
(Don't have to make anti-protons!)

The race is on!

The Tevatron has begun to exclude the High mass region

→ This is the “sweet spot” for the LHC

Low mass is hard at the Tevatron and the LHC

→ Tevatron has a head start

Once LHC working well, data and sensitivity to the Higgs will come fast!

→ The Tevatron is still running steady

Tevatron

LHC

Acknowledgements

The WH Team:

Conveners: Craig Group and Weiming Yao

Students: B. Alvarez, A. Buzatu, B. Casal, P. Dong, M. Frank, J. Slaunwhite, T. Masubuchi, Y. Nagai, J. Kueng, T. Aaltonen, B. Wu, E. Pianori , F. Sforza

Post Docs: C. Group, N. Krumnac, H. Wolfe, E. Palencia, J. Vizan

Profs: F. Canelli, J. Cuevas, J. Dittmann, E. Eusebi, R. Hughes, K. Lannon, S. Kim, A. Ruiz, R. Wallny, B. Stelzer , C. Neu, T. Muller, R. Snihur, E. Thomson, A. Taffard, R. Vilar, A. Canepa, N. Lockyer , G. Chiarelli, B. Winer, W. Wagner, J. Wagner-kuhr, A. Warburton, Weiming Yao

Identifying b jets

- lifetimes for b hadrons are ~10^{-12} s
- travel a finite distance in the detector
  ~ 500 μm