The search for the Higgs boson at the Tevatron:

The ~10 years prior to the discovery

Ben Kilminster
University of Zürich

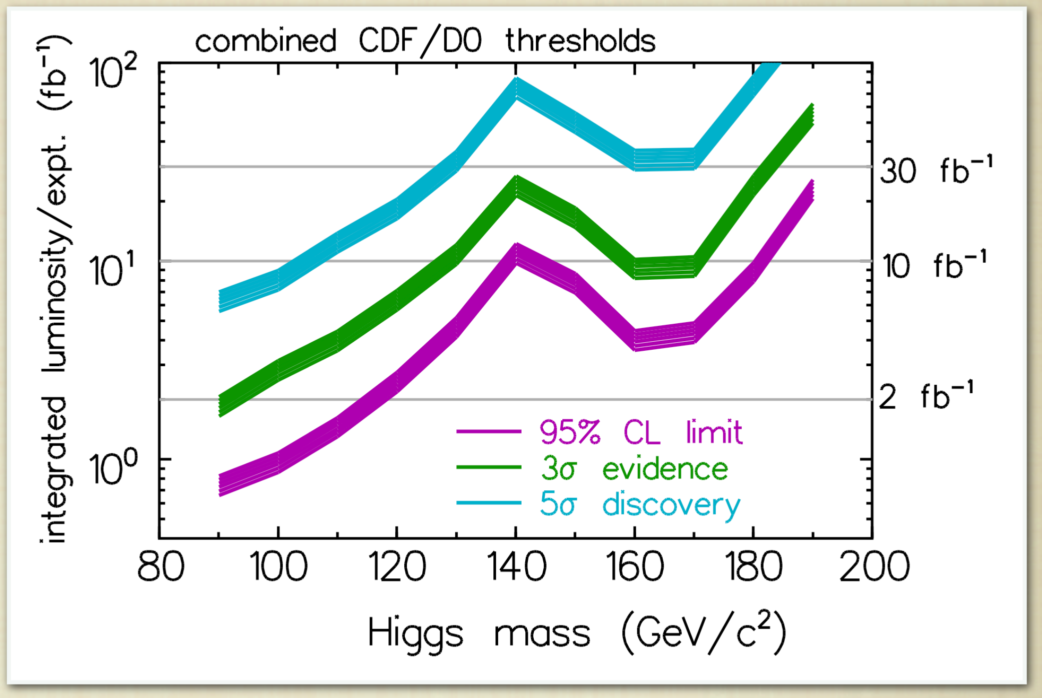
~July 4th, 2022

Story from my perspective starting as a 1st year grad student in 1998

1998 (as a 1st year grad student)

- **Tevatron (CDF/D0) had just discovered the top quark in 1995**
  - **Inspired many of us to join Tevatron Run 2**
    - **Colliding beams to be in 2000**
    - **Prospects of 20 fb^{-1} integrated luminosity**

Tevatron SUSY-Higgs report in 2000



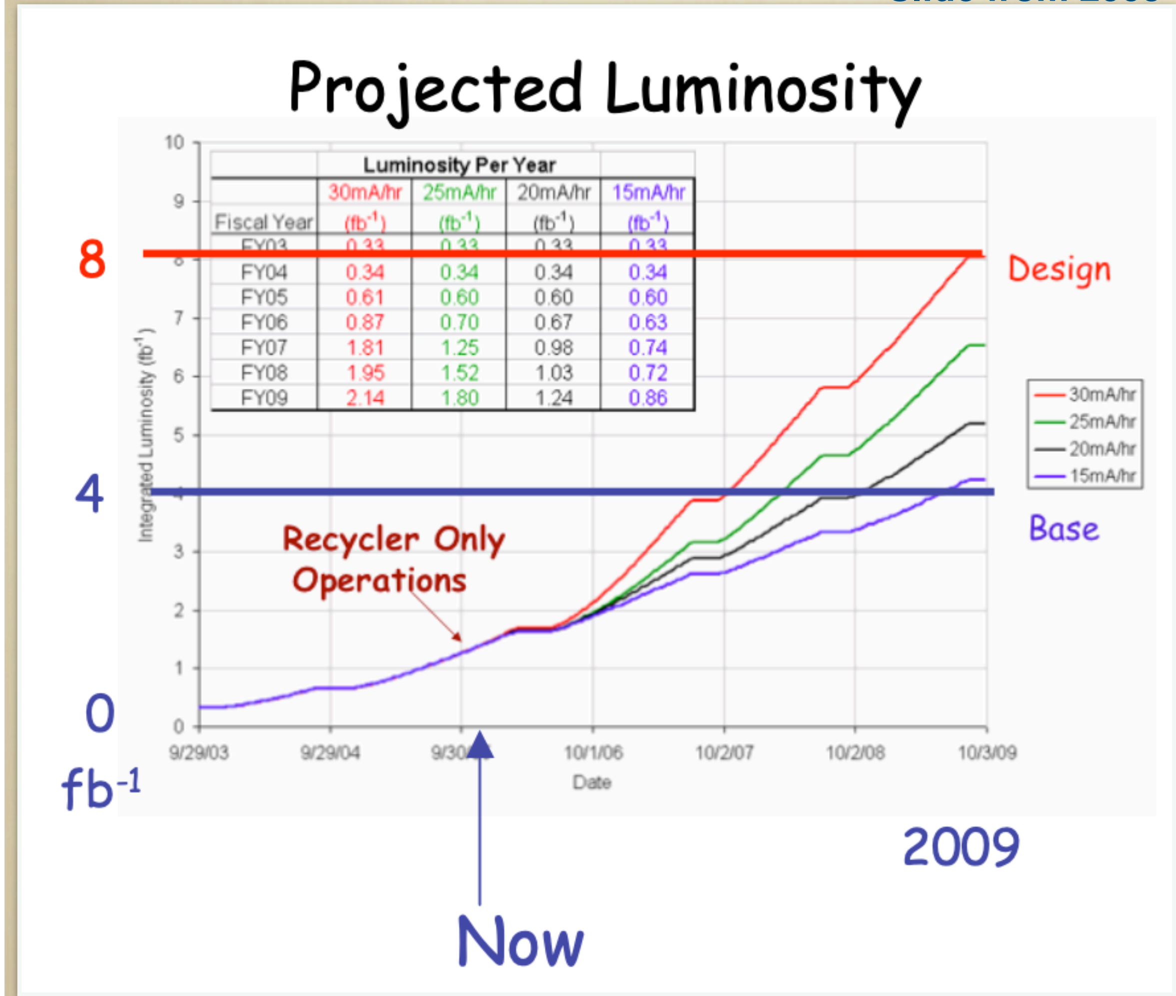
hep-ph/0010338

- **Joined SUSY-Higgs working group to help with Higgs sensitivity study**
- **2000 report results: With ~10 fb^{-1}, prospect of 3-Sigma evidence for a 125 GeV Higgs boson**

1998 - 2004

- **Slow start to Run 3, and realization that the Tevatron could not switch from 396 to 132 ns bunch crossings**

Slide from 2005



A large uncertainty in the expected integrated luminosity lay ahead

Design Lumi reduced to 8 fb^{-1}

Should we be optimistic or pragmatic ?

The optimists and pragmatists at D0/CDF started thinking of ways to use the extra time between bunches to upgrade the triggers and mitigate the pileup just in case we could reach design

So as a starting postdoc in 2004, I got to work on the upgrade of the CDF track trigger to 3D

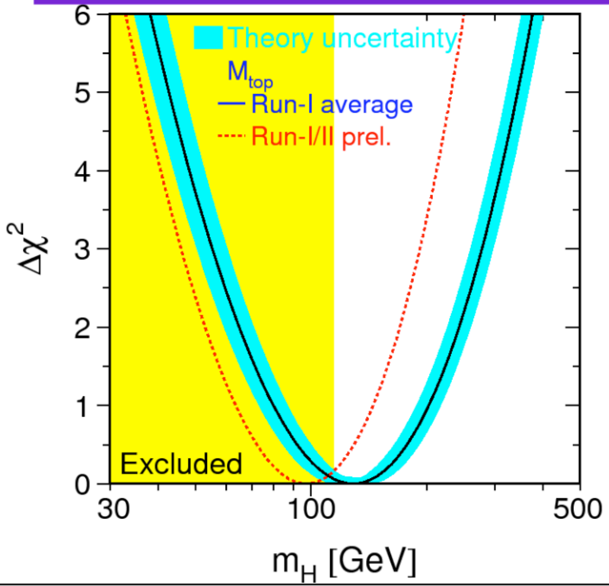
In 2005, with 1 fb^{-1} and hope … what were we looking for ?

Expected Higgs mass (& type=SM or MSSM)

SM: From electroweak fits with new CDF/D0 Run I/II top mass 172.7 + 2.9 GeV/c^2

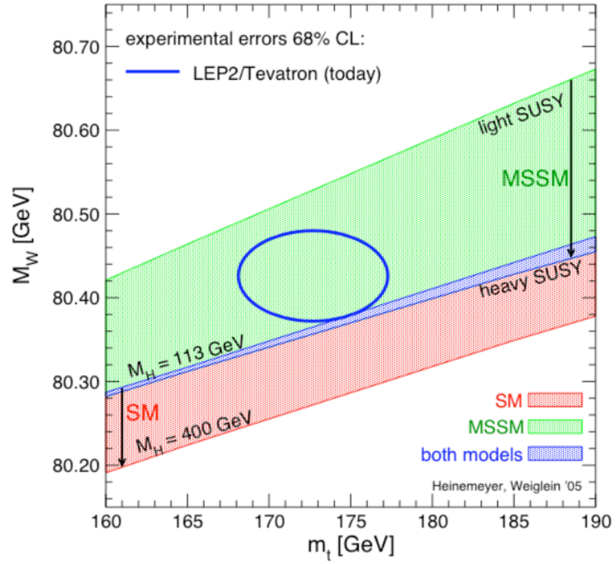
$$M_H = 91^{+45}_{-32}\,\mathrm{GeV/c^2}$$

$$M_H < 186\ \mathrm{GeV/c^2}\ @95\%\ \mathrm{C.L.}$$



Direct LEP $M_H > 114.4$ GeV @ 95% CL

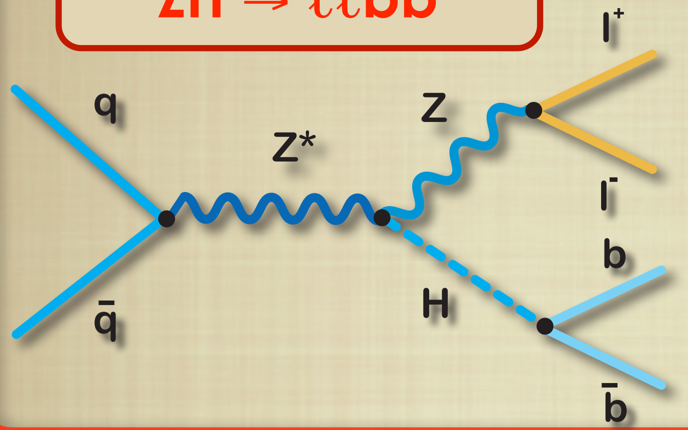
MSSM: top mass, W mass makes MSSM favorable



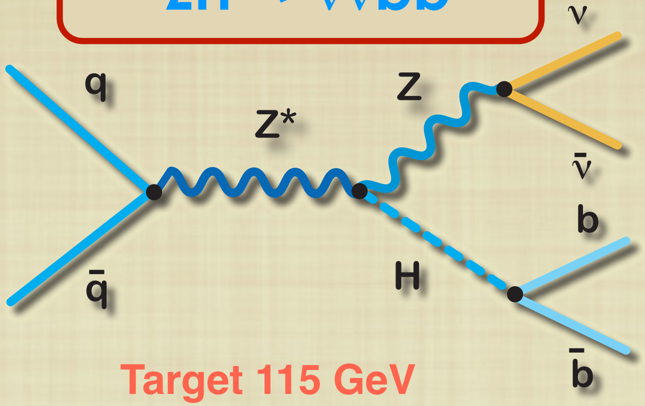
Ben Kilminster PANIC 2005: CDF SM & MSSM Higgs 24 Oct. 2005; p.4 of 13

Higgs at the Tevatron

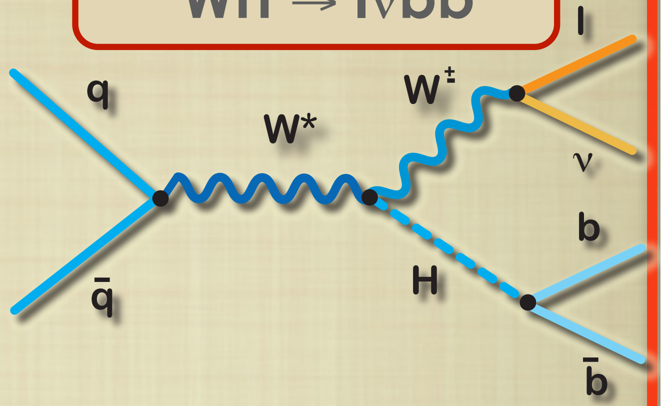
ZH → ℓℓbb



ZH → ννbb

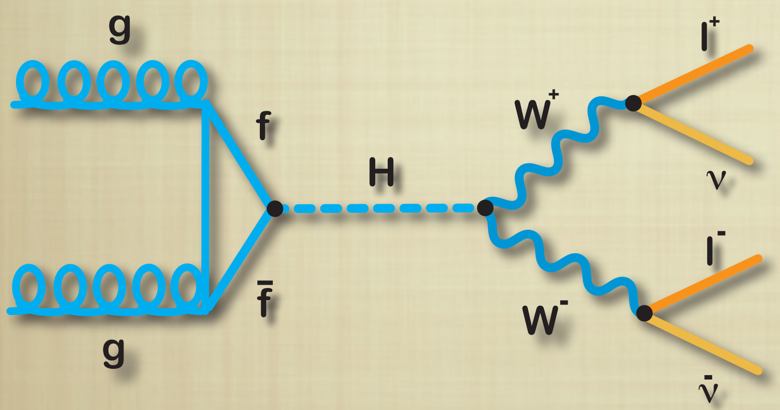


WH → lνbb

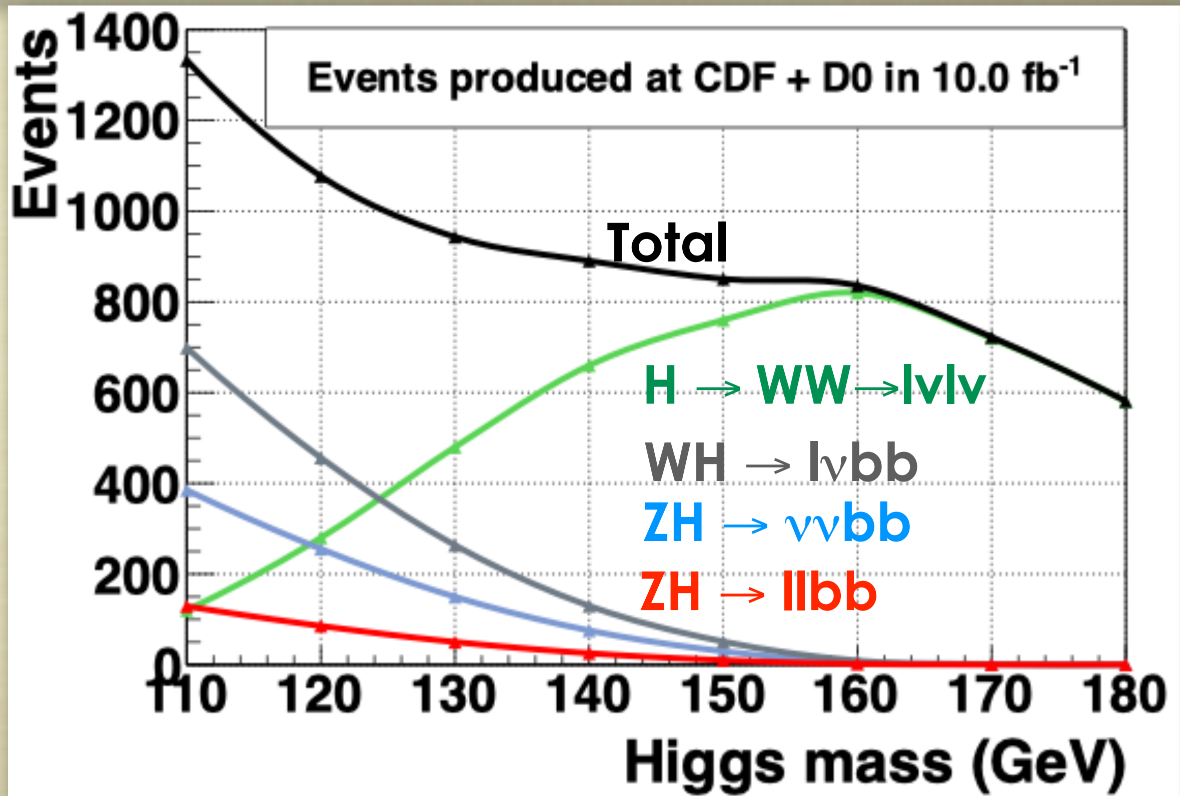


Target 115 GeV

H → WW → lνlν



Target 160 GeV

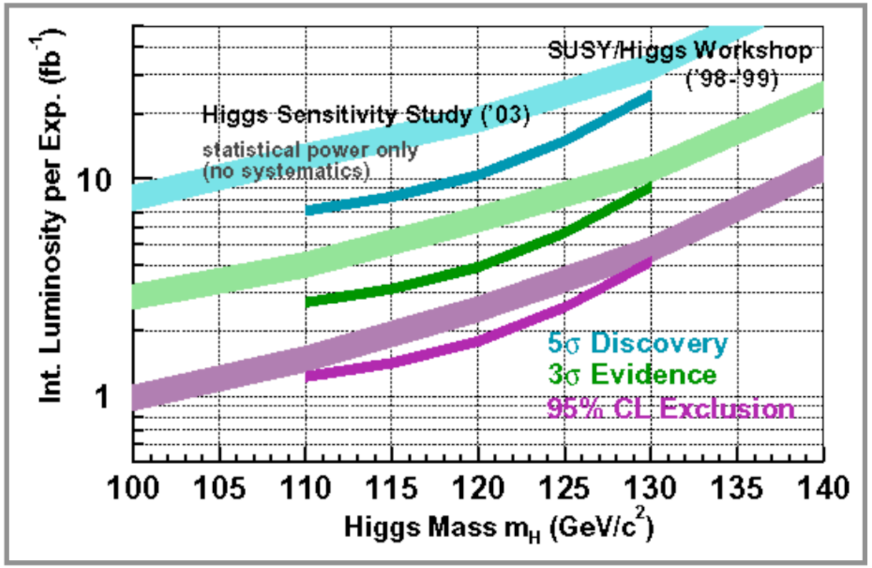


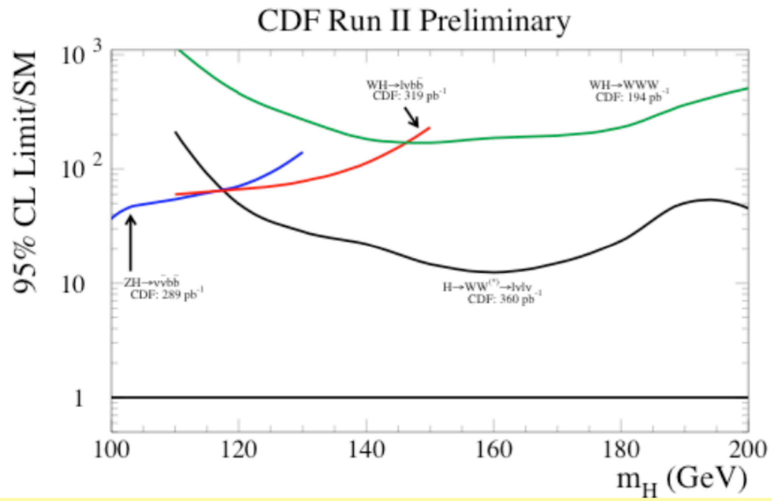
Slide from 2005

Summary of SM Higgs searches

THE OHIO STATE UNIVERSITY

CDF II





2003 Sensitivity Projections

- m_H = 115 GeV
  - ~ 2 fb^{-1} for exclusion (if not there)
  - ~ 4 fb^{-1} for m_H = 115 3σ evidence
- Assumes :
  - all Higgs channels combined at both CDF and D0
  - realistic data, no systematics
- 8 fb^{-1} by 2009 is design

2005 Status

- CDF preliminary results with 200 - 400 pb^{-1} data
  - channels not combined, some missing
  - need factor of 30-40
    - factor of ~20 from data up to 2009
    - factor of 2 from CDF/D0 combination
- Working on ways to improve sensitivity
  - Neural Nets for everyone ! (factor of ~1.7)
  - Improved jet resolution (1.1 for each 1%)
  - Improved lepton acceptance (> 1.5)

Ben Kilminster PANIC 2005: CDF SM & MSSM Higgs 24 Oct. 2005; p.10 of 13

Slide from 2005

So How Do We Get There??

Luminosity Equivalent $(s/\sqrt{b})^2$

Start with existing channels, add in ideas with latest knowledge of how well they work.

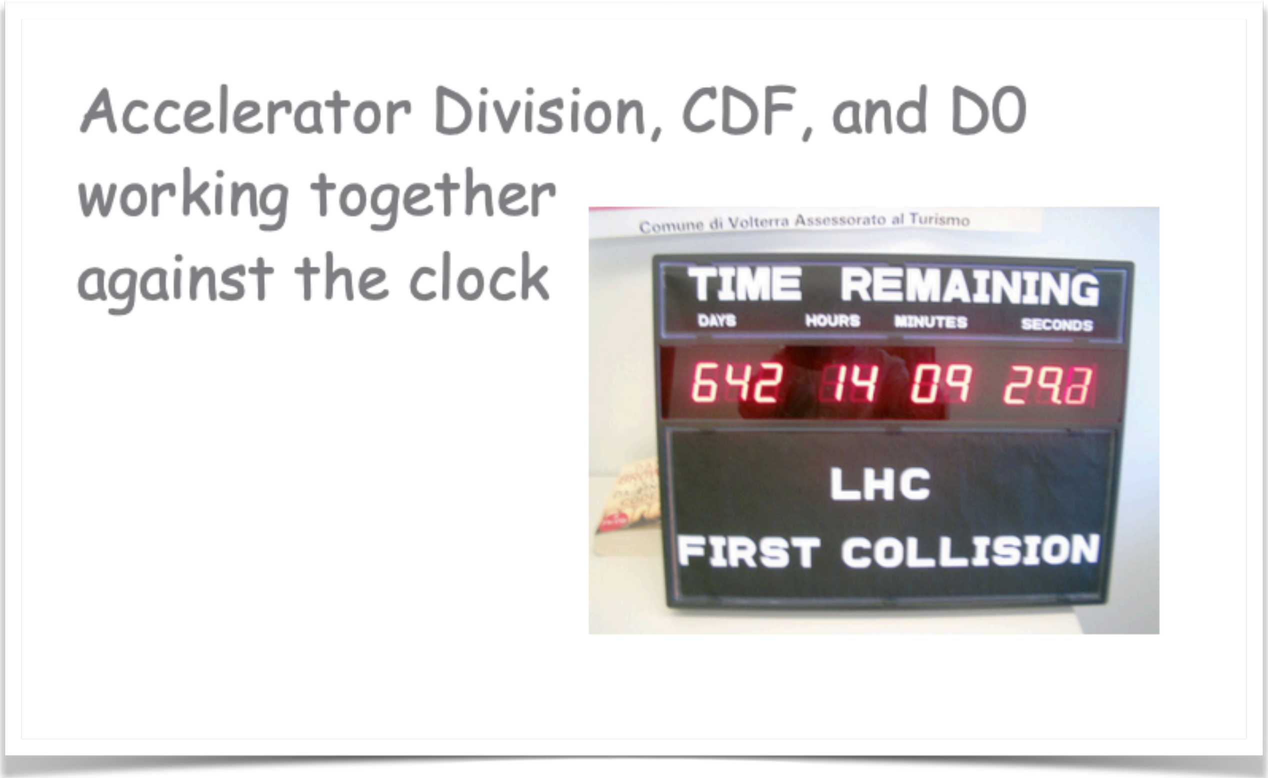
Improvement	WH→lνbb	ZH→ννbb	ZH→llbb
Mass resolution	1.7	1.7	1.7
Continuous b-tag (NN)	1.5	1.5	1.5
Forward b-tag	1.1	1.1	1.1
Forward leptons	1.3	1.0	1.6
Track-only leptons	1.4	1.0	1.6
NN Selection	1.75	1.75	1.0
WH signal in ZH	1.0	2.7	1.0
Product of above	8.9	13.3	7.2
CDF+DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

Expect a factor of ~10 luminosity improvement per channel, and a factor of 2 from CDF+DØ Combination

Ben Kilminster PANIC 2005: CDF SM & MSSM Higgs 24 Oct. 2005; p.16 of 13

This clock sat in Wilson Hall at Fermilab

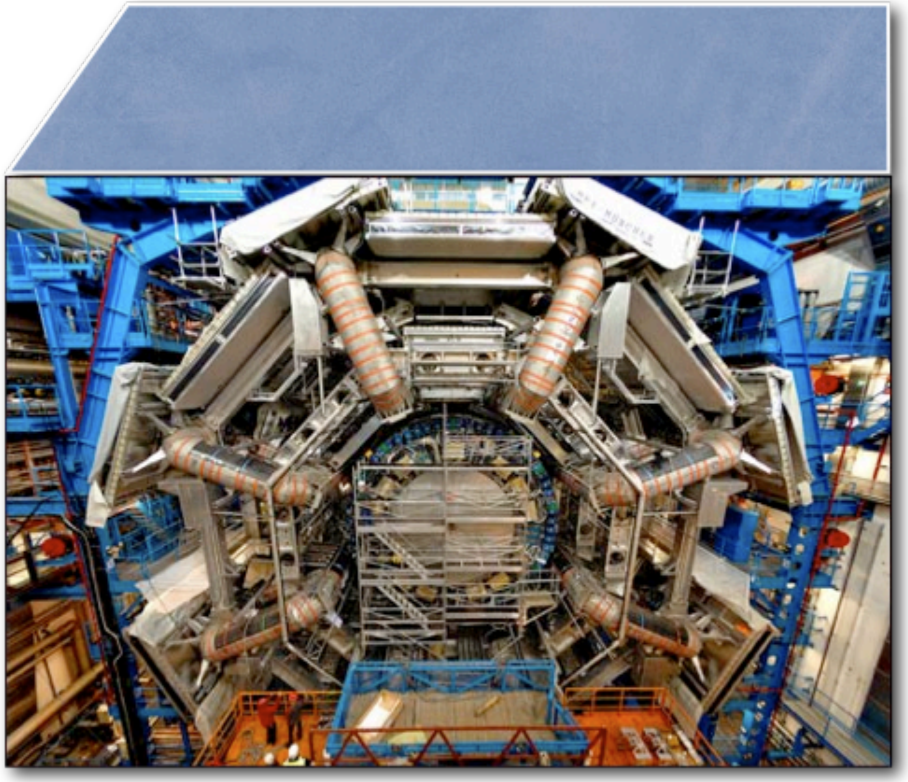
Slide from 2005



David vs. Goliath

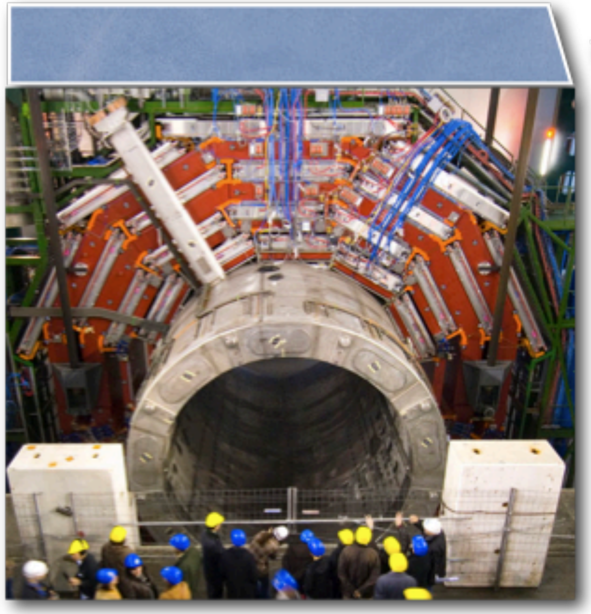
Slide from 2013

Diameter = 25 m
Length = 46 m



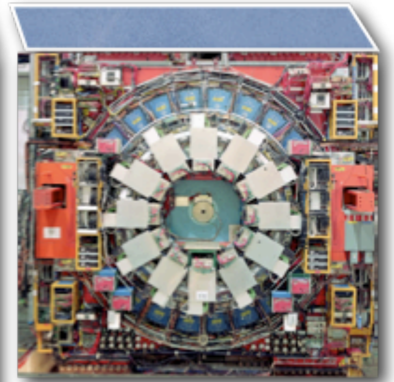
ATLAS

D = 16 m
L = 21 m



CMS

D = 12 m
L = 12 m



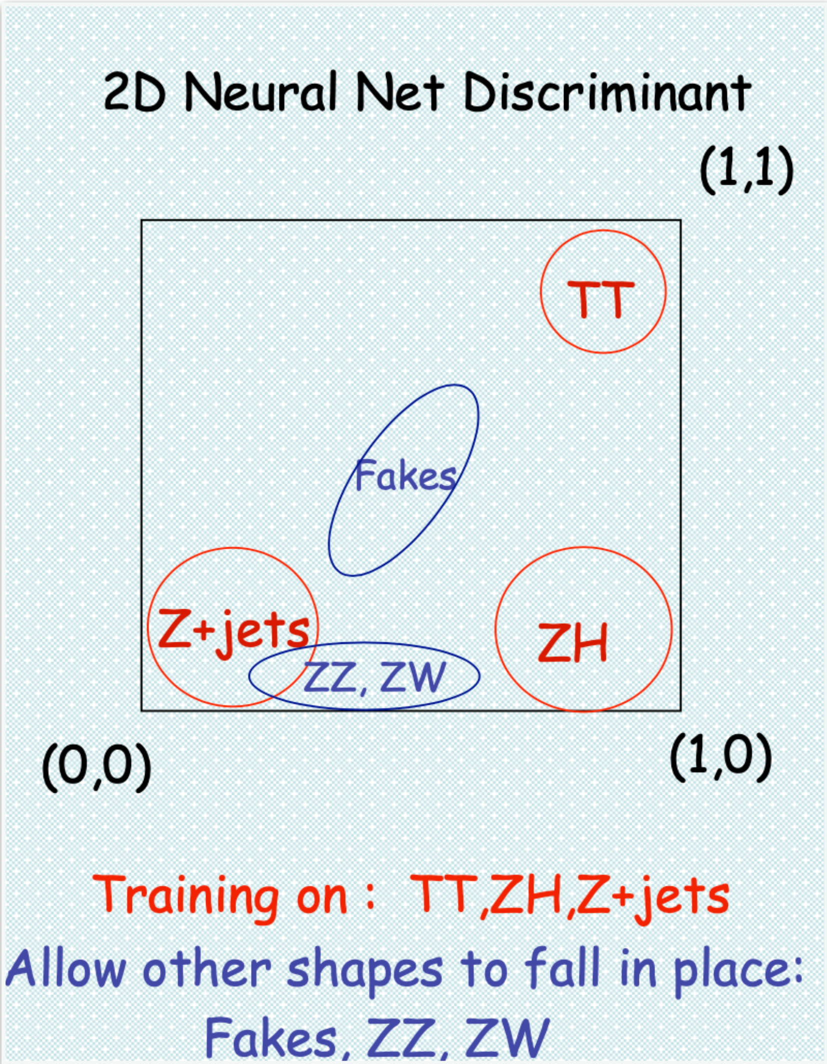
CDF

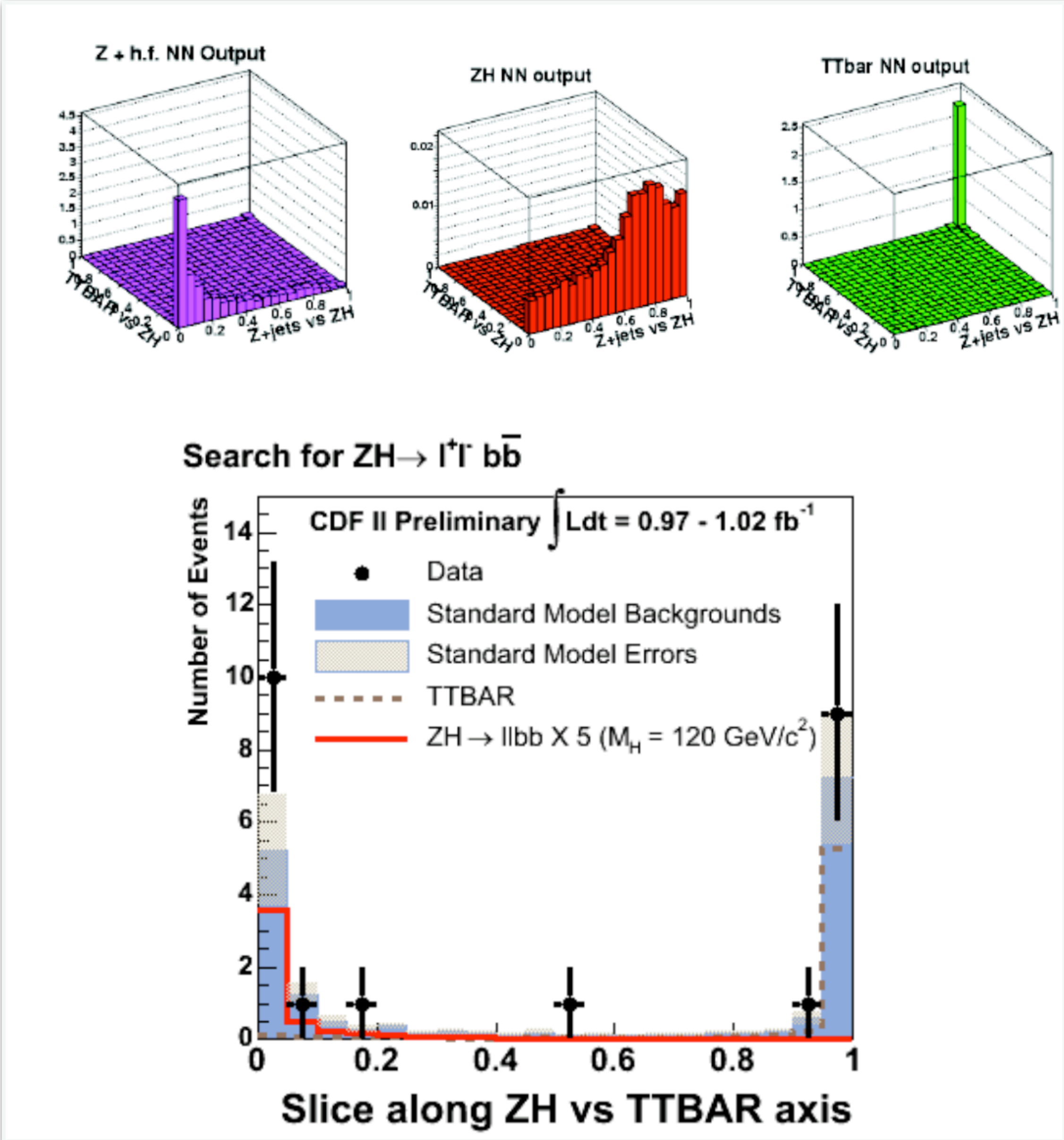
CDF & D0 needed to be resourceful with data

Multivariate signal discrimination

ZH → ℓℓbb

From 2006 slides



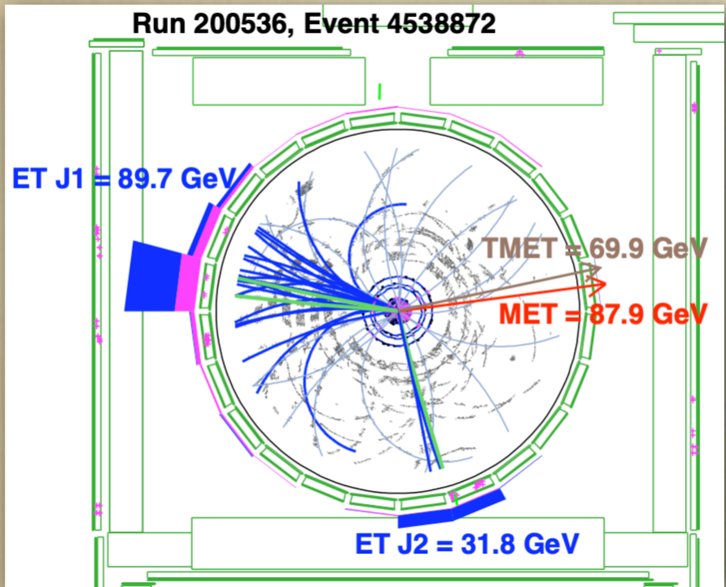


The invention of "trackMET"

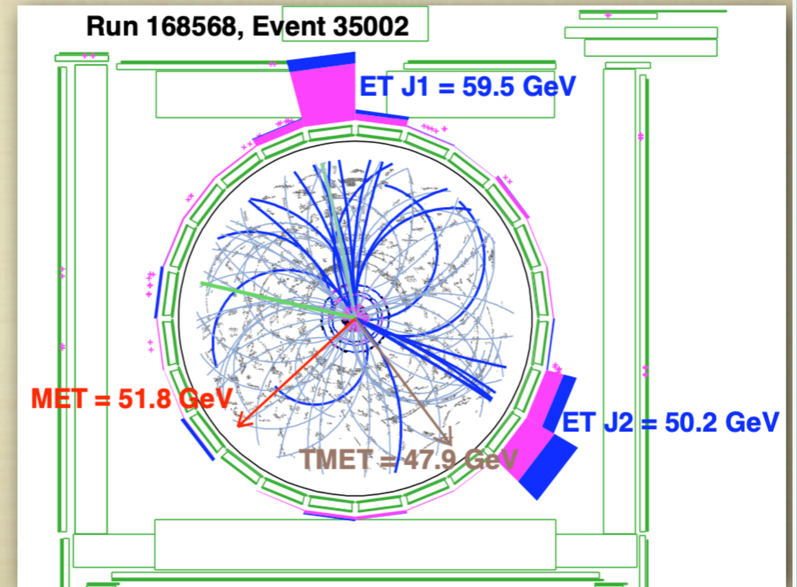
Slide from 2008

ZH → vvbb candidates in Data

- **Most Higgs-like event**
  - M_{jj}= 113 GeV
  - Track MET points toward MET
    - indicates real neutrinos
    - High NN Output (0.89)



- **QCD-like event**
  - M_{jj}= 156 GeV
  - Track MET points toward jet
    - indicates mismeasured jet
      - Low NN Output (0.003)



B. Kilminster, Tollestrup Award talk, June 2008

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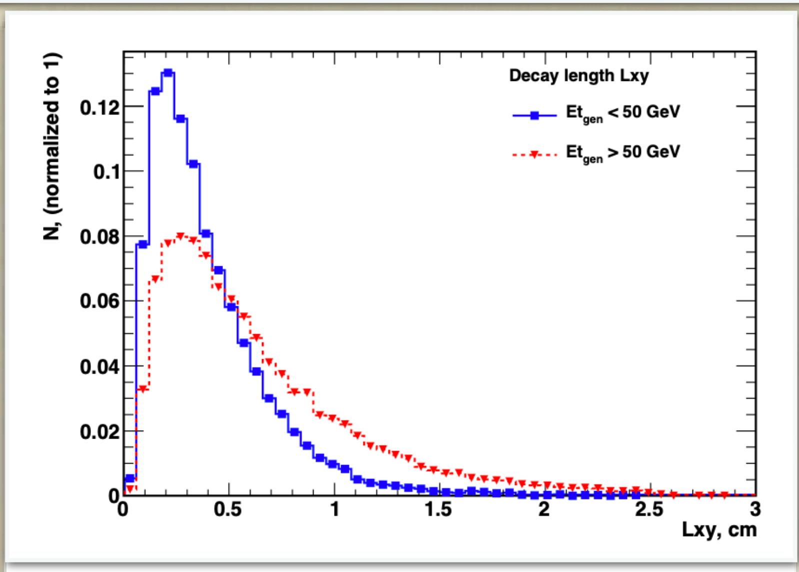
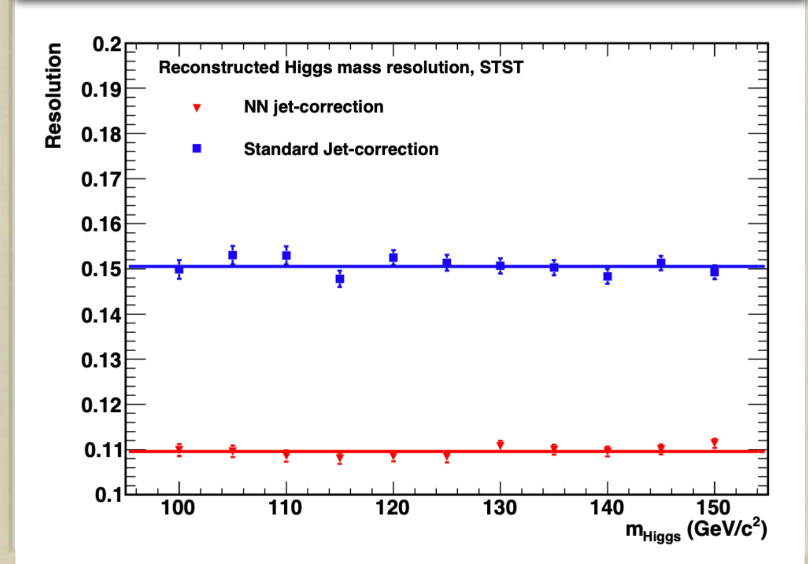
Used as part of a "trackMET NN" to correlate vertex, tracks, calorimeter towers

Jet energy resolution evolution

1. Calorimeter-based cone
2. Kinematic fit using MET to correct jet energy (ZH → $\ell\ell bb$)
3. H1-style algorithm (track PT from primary vertex replaces HCAL energy)
4. B-specific NN jet energy corrections (ie, impact parameter significance correlated to b-jet energy)
5. Addition of $\pi^0 \to \gamma\gamma$ measurements from Shower-max ECAL detector

Improved b-jet Energy Correction for $H \to b\bar{b}$ Searches at CDF

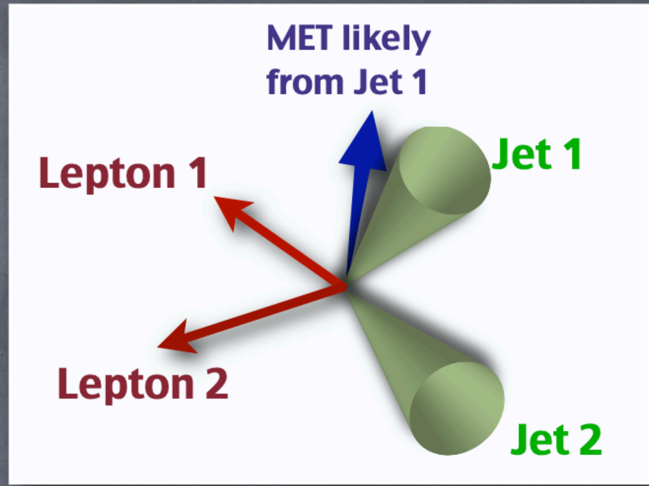


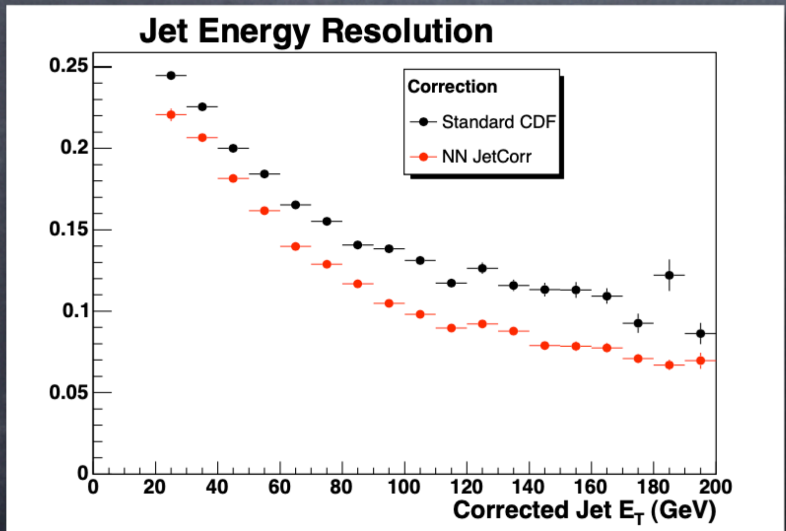


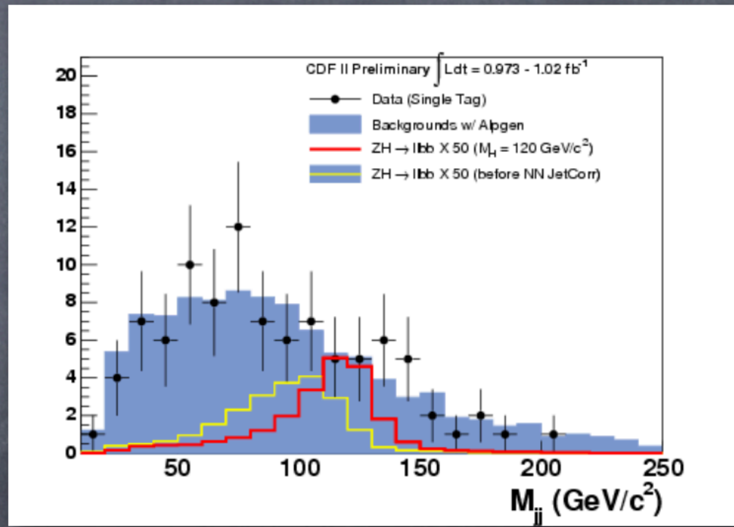
1107.3026 [hep-ex]

ZH → llbb

- Can improve Mjj resolution by correcting jets according to projection onto MET direction





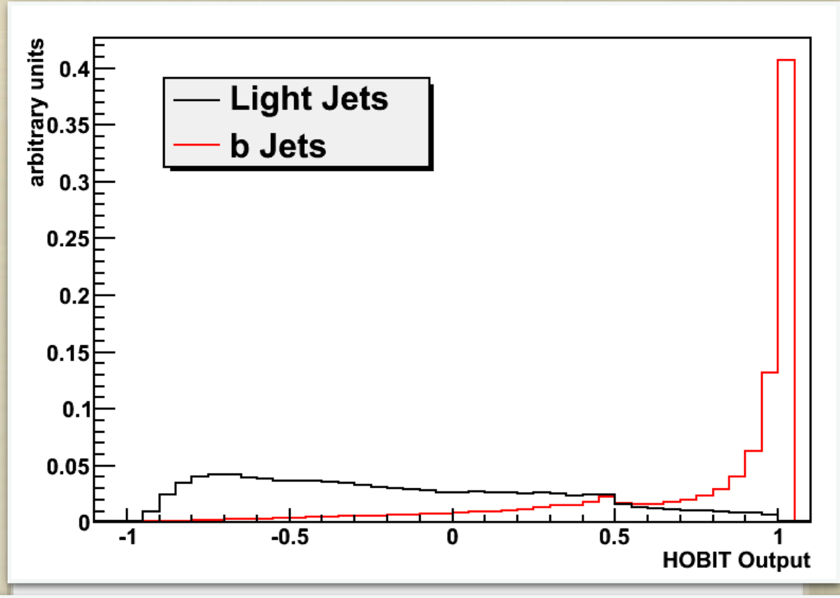


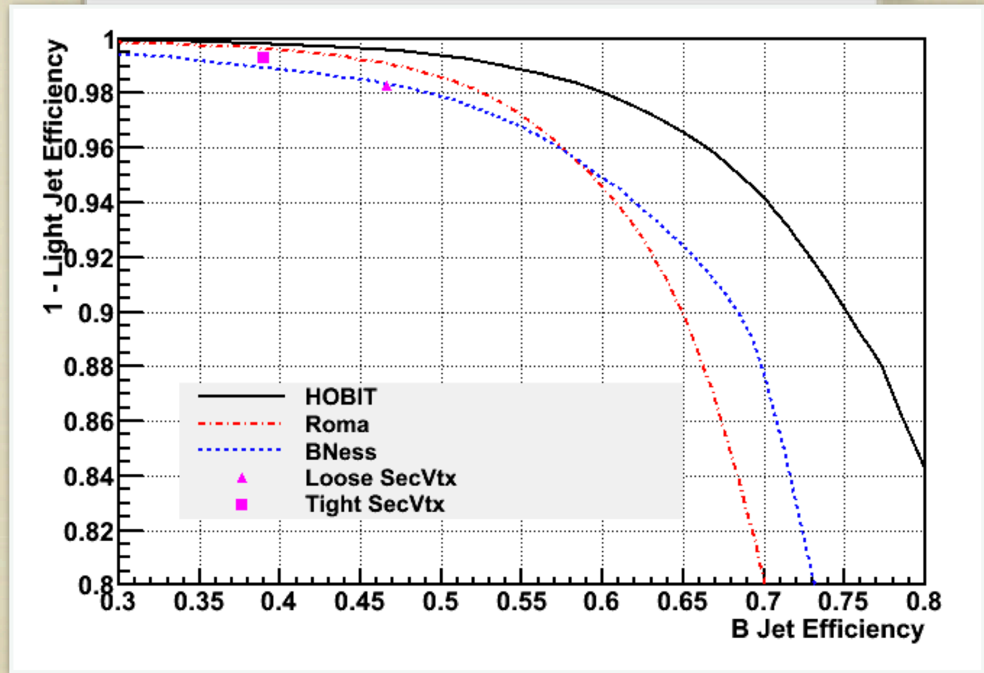
- For events w/ two b-tags, dijet mass resolution improves from 18% to 11%

B-tagging evolution

Higgs Optimized b Identification Tagger (HOBIT)

1. secondary vertex (SECVTX) algorithm
2. Tight and loose secvtx categories split purity
3. NN to classify b-jets as light, charm, B
4. additional category with impact-parameter b-tagger
5. NN combining multiple b-taggers & soft muon info





arXiv:1205.1812 [hep-ex]

Trigger & data usage evolution

1. single-object electron, muon, MET triggers (tracking at L1 at Tevatron)

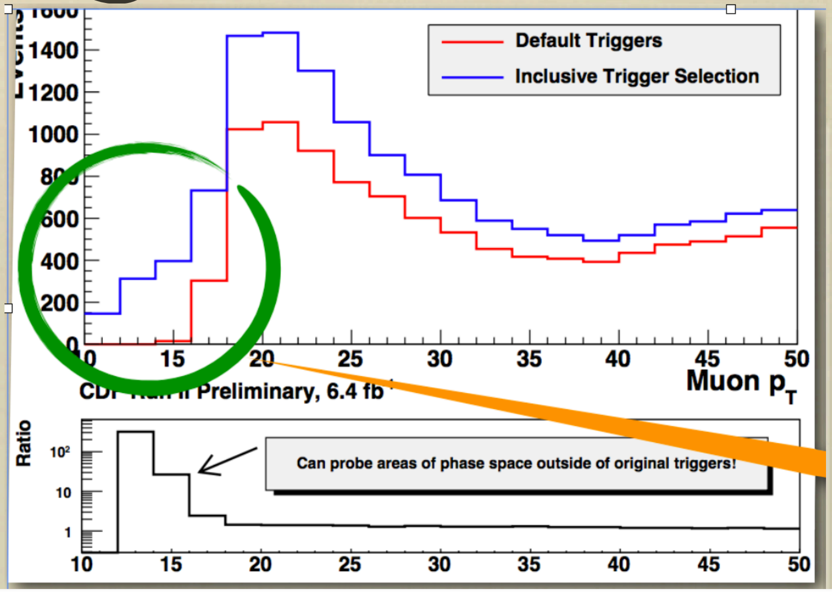
2. Upgrade L1 track triggers to 3D

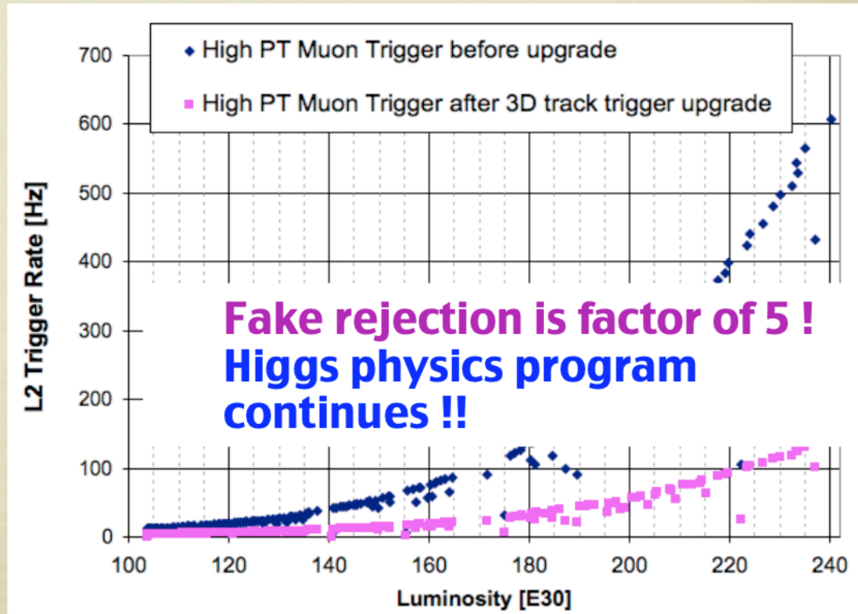
3. Add no-track triggers

4. Add triggers for multiple objects ($Z \rightarrow ee$ notrack trigger)

5. Consider every event coming in on any trigger, use NN regression to calculate efficiencies

6. Add back in data marked "bad" and parameterize inefficiency



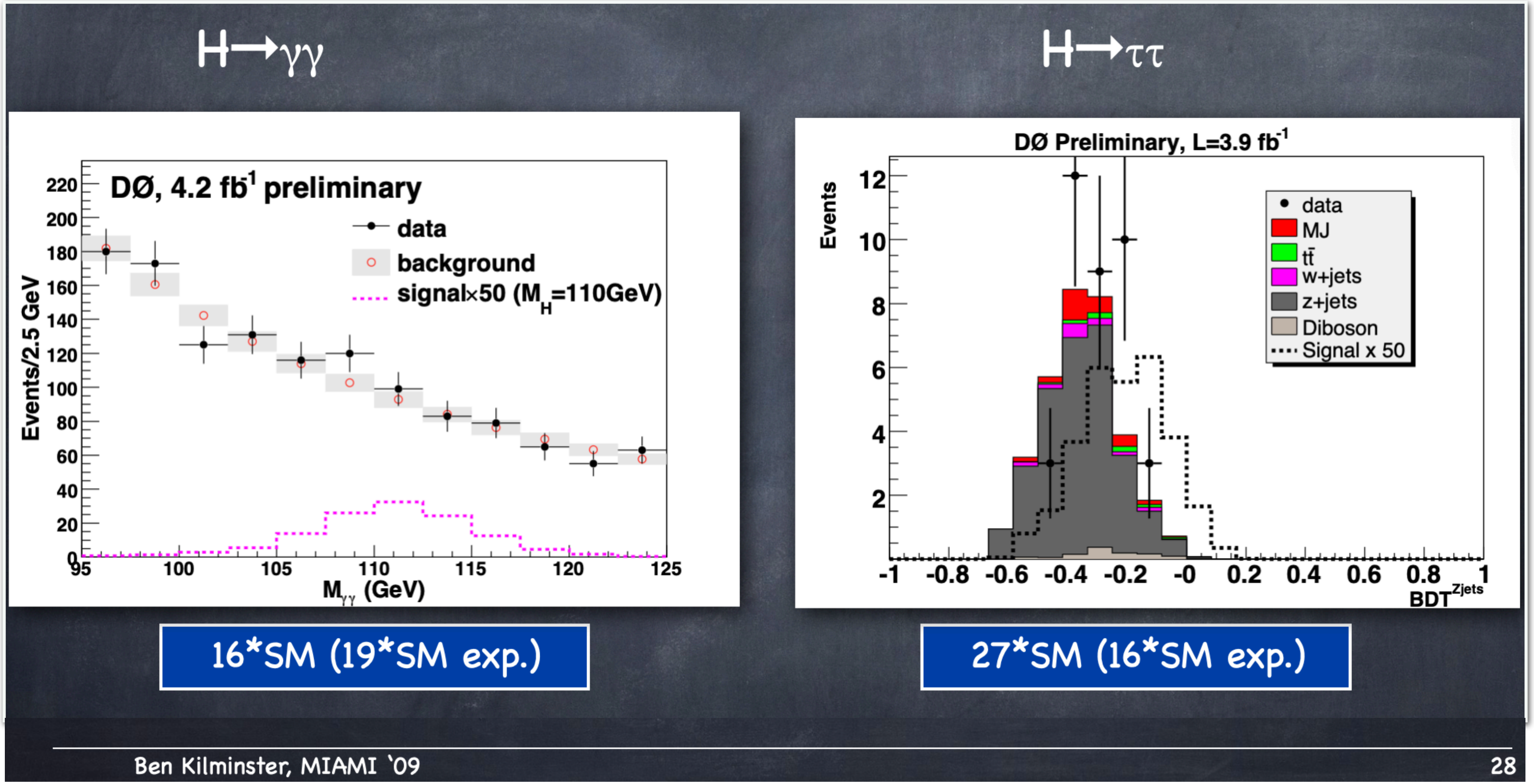


B. Kilminster, HEP seminar, Jan. 2008

Tevatron actually, achieved 400E30 $cm^{-2}\,s^{-1}$!!

Incorporate more channels !

Slide from 2009

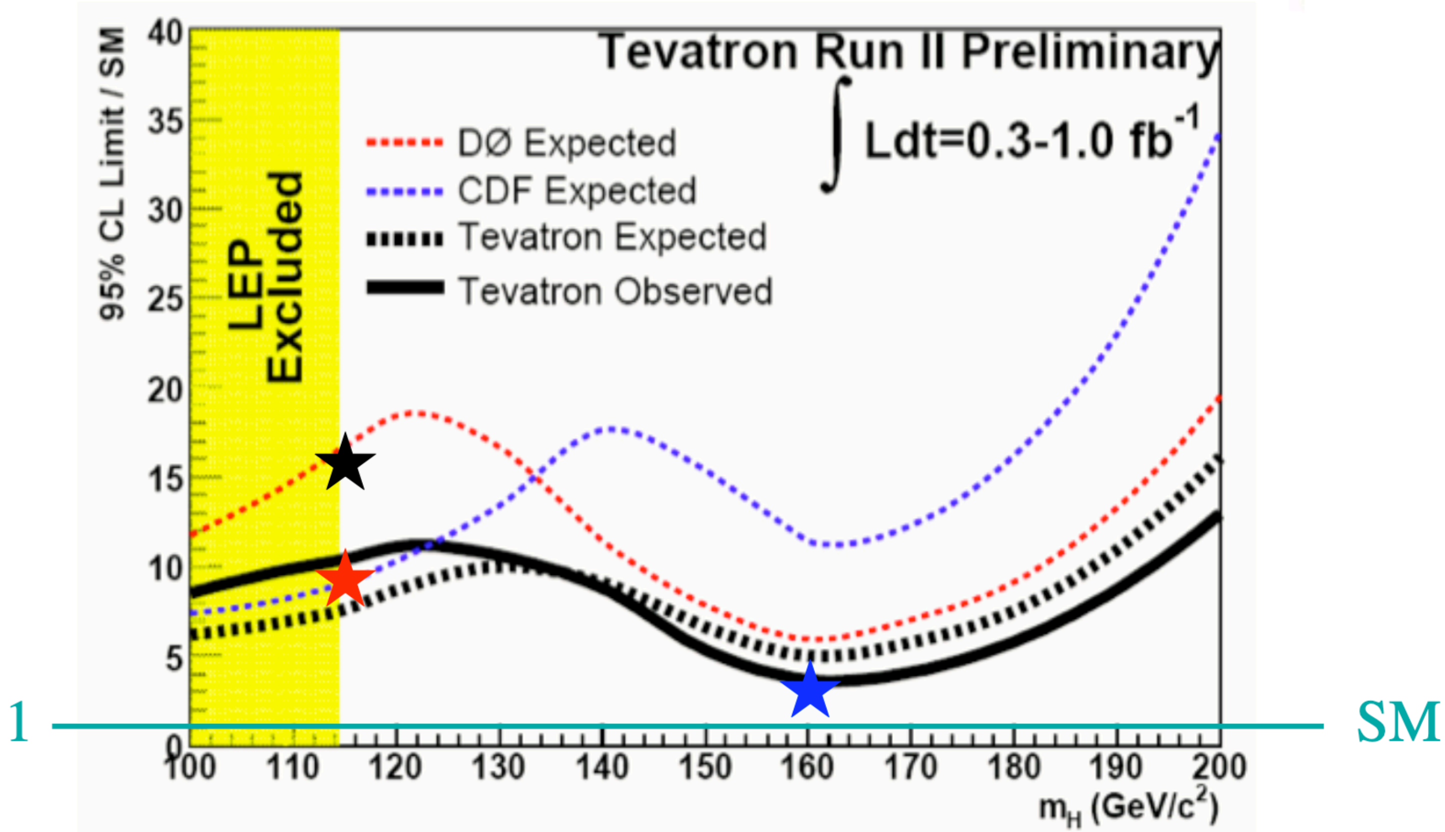


2006 : first CDF + D0 combination

Slide from 2007

Combinations

Ben Kilminster, OSU
Moriond QCD '07
p. 1

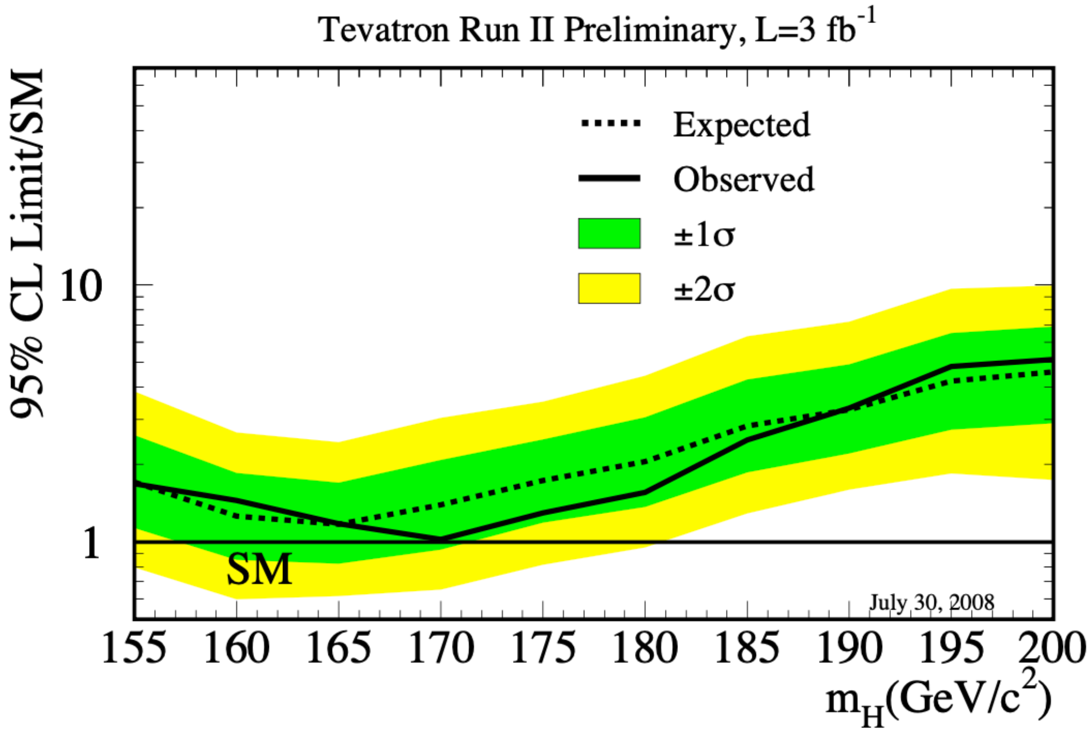


- The above limits do not include
  - new CDF ZH->llbb ★
  - new CDF H->WW results ★
  - **new D0 WH results** ★

H → WW contributes more at 135 as WH

2009 : first exclusion (m_H != 170 GeV)

Slide from 2009



CDF+D0 combined Higgs searches exclude m_H = 170 GeV

Look for these high mass exclusions to broaden over the next year

Ben Kilminster, CDF Collaboration meeting Jan 09

Slide from 2009

Much thanks to previous Higgs conveners !

- Matt Herndon
- Mark Kruse

Wear your hats proudly !

Ben Kilminster, CDF Collaboration meeting Jan 09

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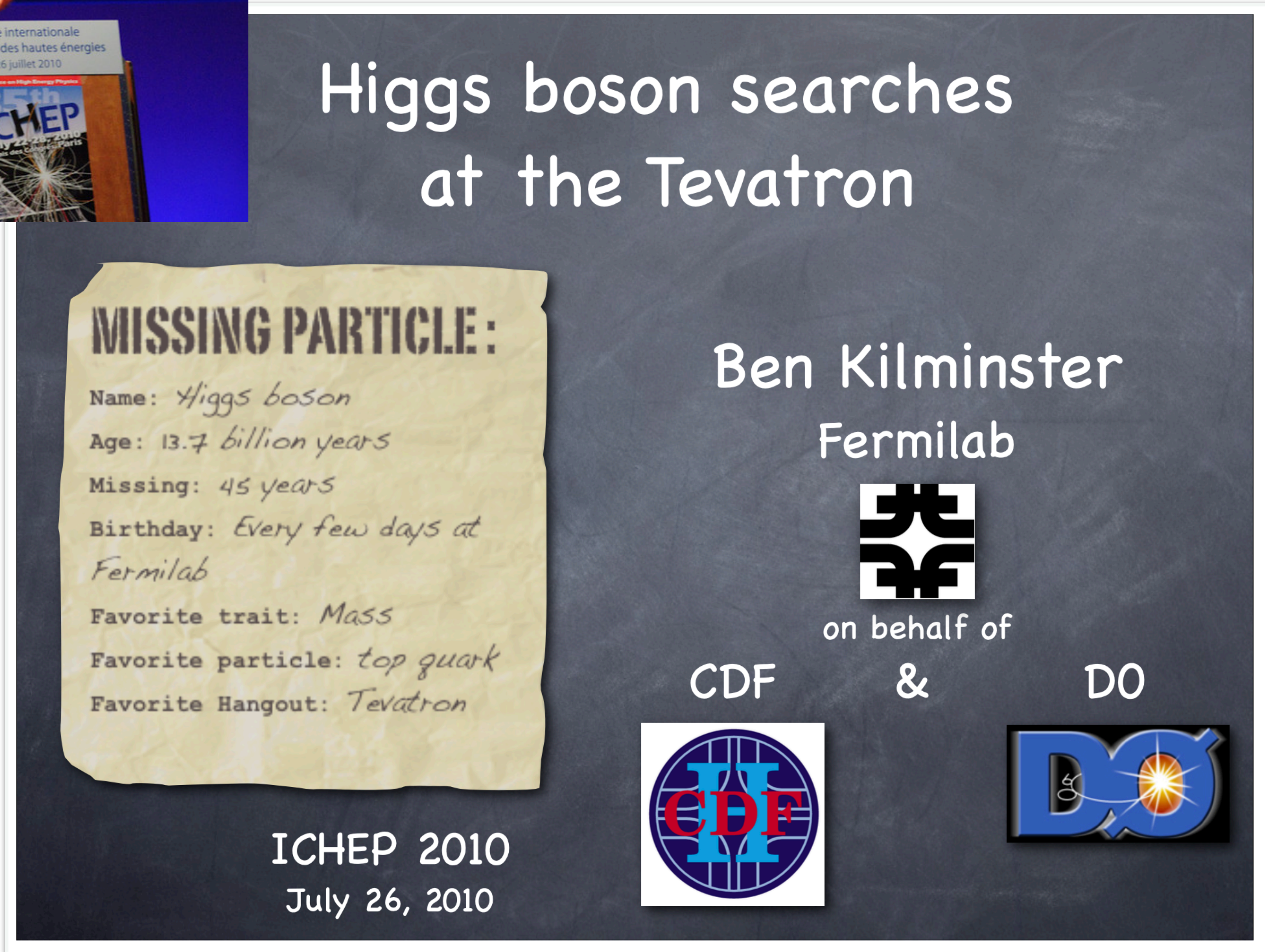
2010 was a big year for Tevatron Higgs

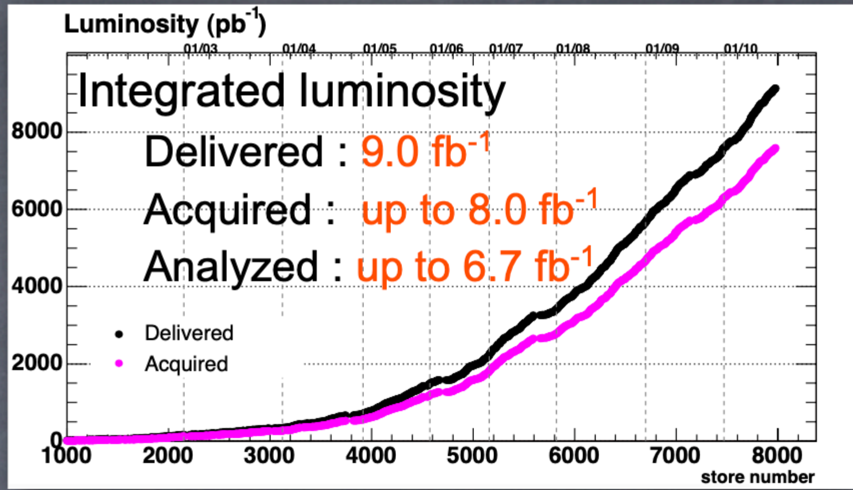
Slide from 2010



Slide from 2010

Tevatron

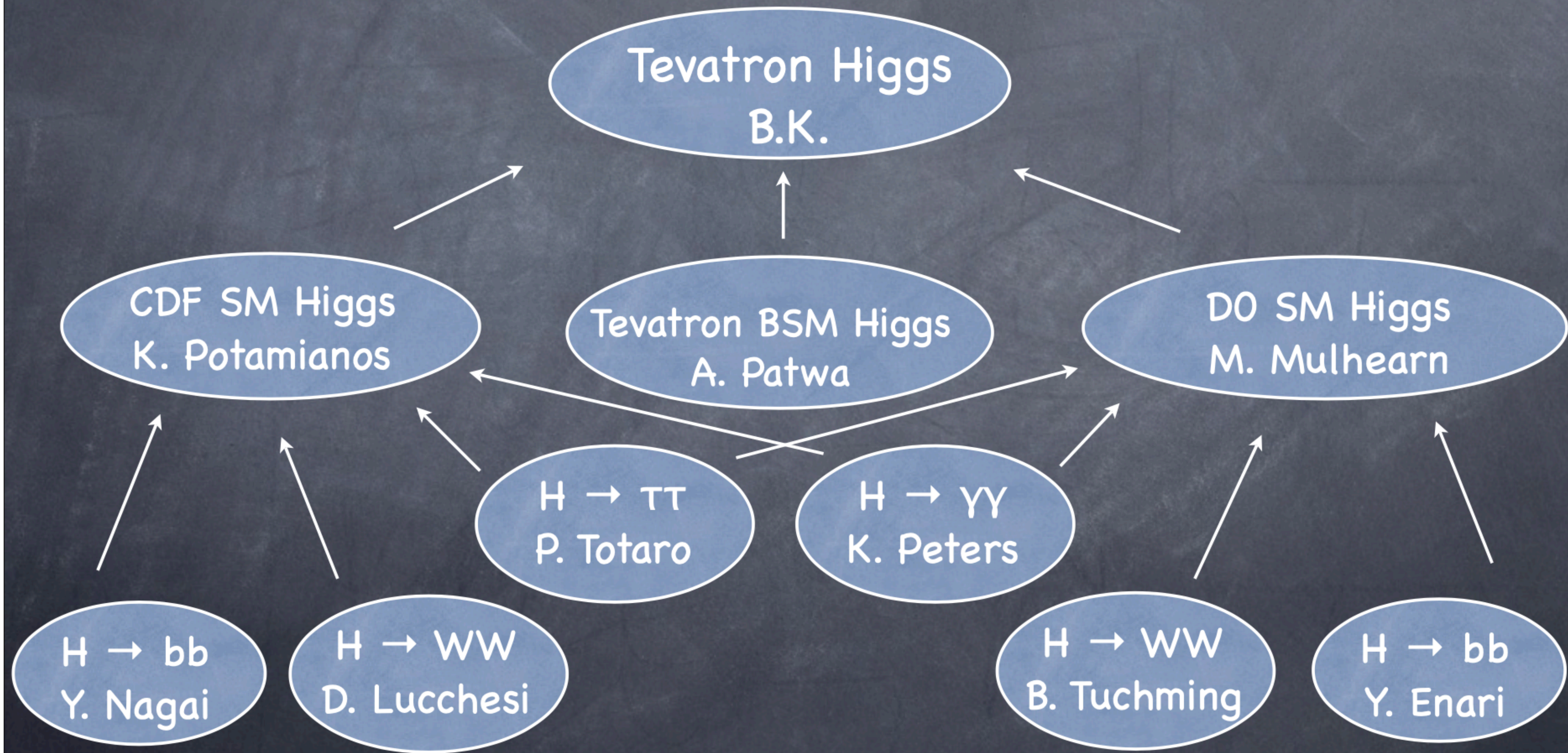
- $p\bar{p}$ collisions with $\sqrt{s}$ = 1.96 TeV
- Two collider experiments, CDF & D0



Ben Kilminster, ICHEP 2010 7

Slide from 2010

- ICHEP Tevatron Higgs talks
  - Covered variety of Higgs searches and analysis techniques



Slide from 2010

Tevatron Higgs storyline

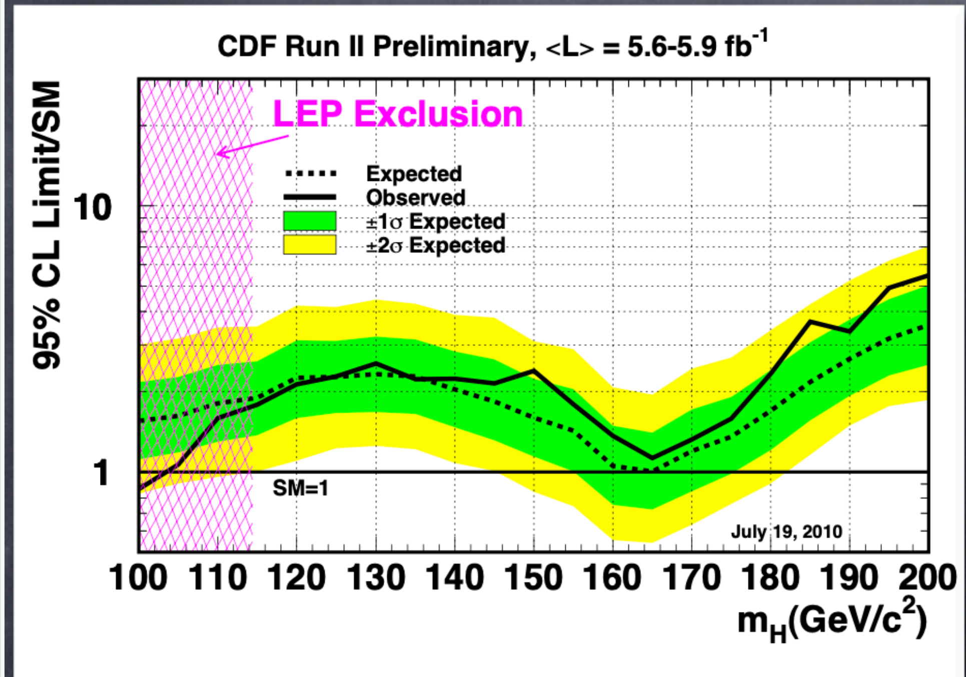
- How to build an advanced Higgs analysis program
  - Start with basic analysis for particular channel
  - Bootstrap special techniques to gain sensitivity
    - Improve acceptance
      - Loosen lepton ID & b-tag requirements
      - Add backup triggers
      - Relax kinematic selection
    - But... backgrounds increase & become more difficult to model
      - Incorporate specialized background rejection techniques
      - Don't cut, separate out events into categories with alike S/sqrt(B)
        - High S/sqrt(B) gives best signal sensitivity
        - Low S/sqrt(B) gives best background constraints
      - Use multivariate techniques to distinguish signal events from bkgd
      - Background modeling checks ! Data must stay well modeled !
- Repeat for each Higgs topology per grad student
- Combine modes taking into account uncertainties correlated between backgrounds

Ben Kilminster, ICHEP 2010 10

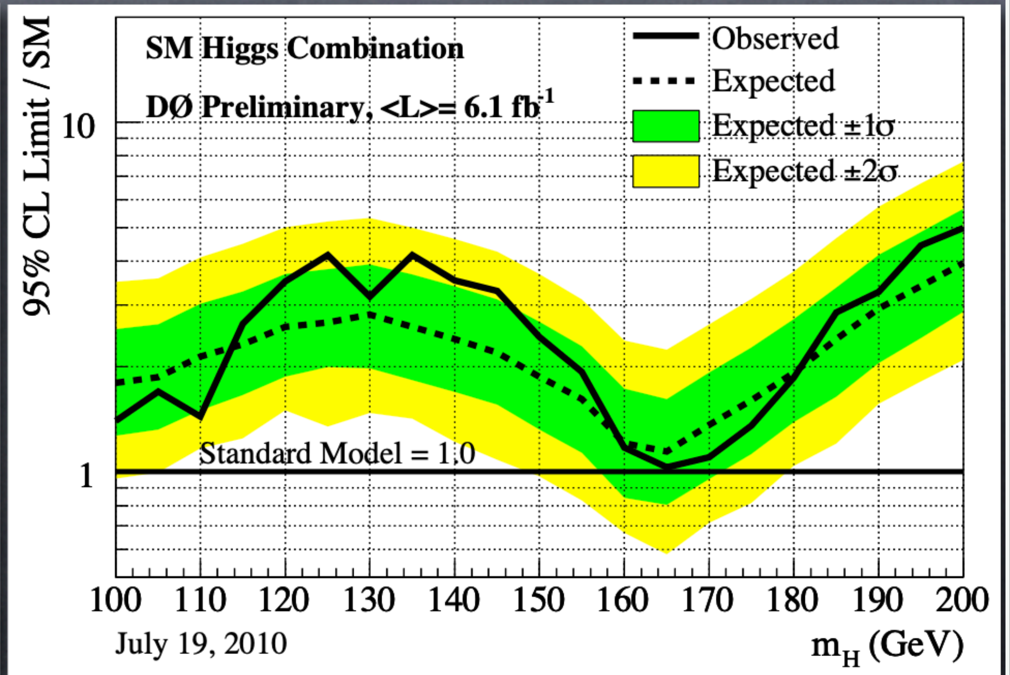
CDF & D0 combinations

Shown first on July 23, 2010

CDF's limits



D0's limits



CDF achieves expected exclusion at 165 GeV

D0 almost achieves observed exclusion at 165 GeV

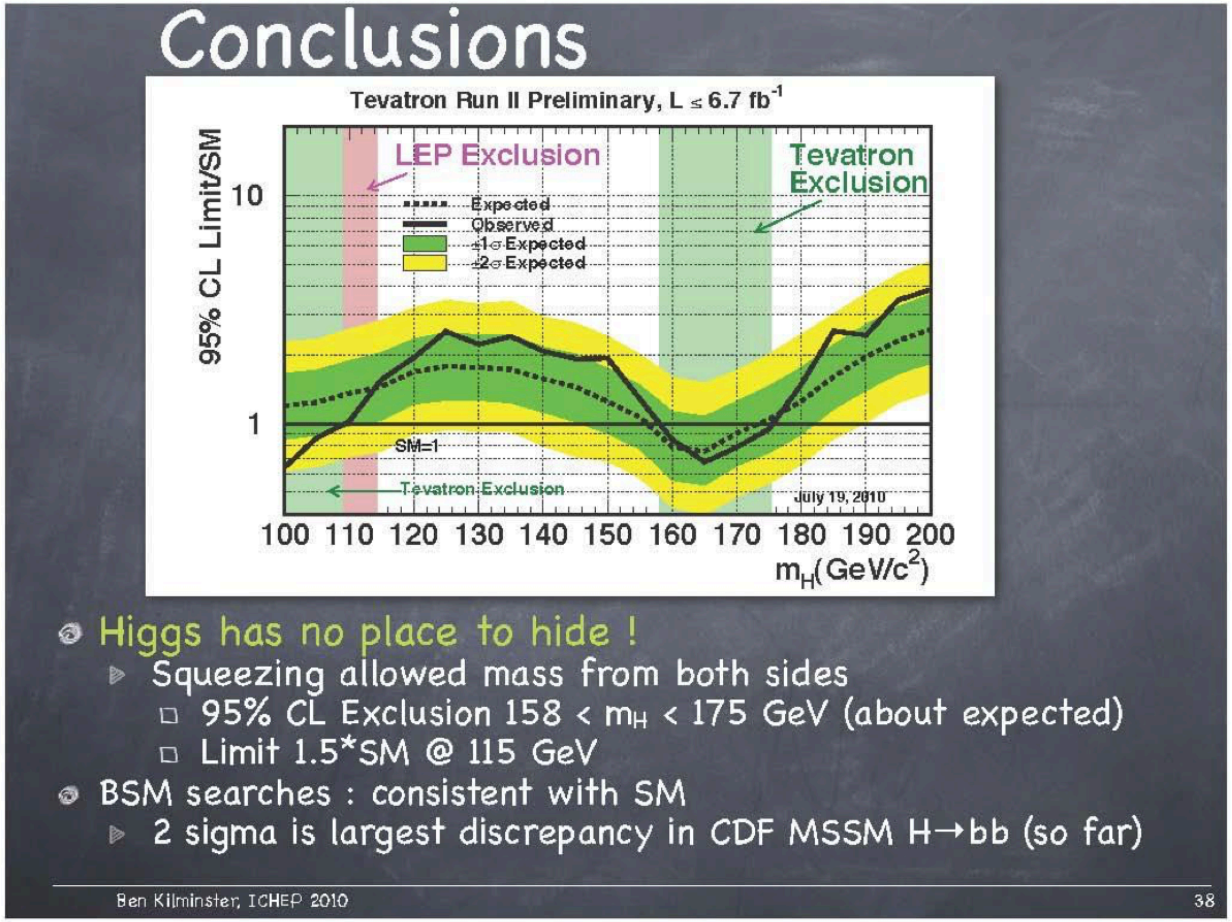
@ m_H = 100 GeV, both set observed limits below expected

Closing in on low mass LEP exclusion

Ben Kilminster, ICHEP 2010 23

Slide from 2010

Approaching the moment of truth



$\Delta\sigma$ th?

Michel Spiro - ICHEP 2010 Summary Talk
Paris, July 28th, 2010

Tevatron shuts down
Sept. 30, 2011
:(

D0 control room

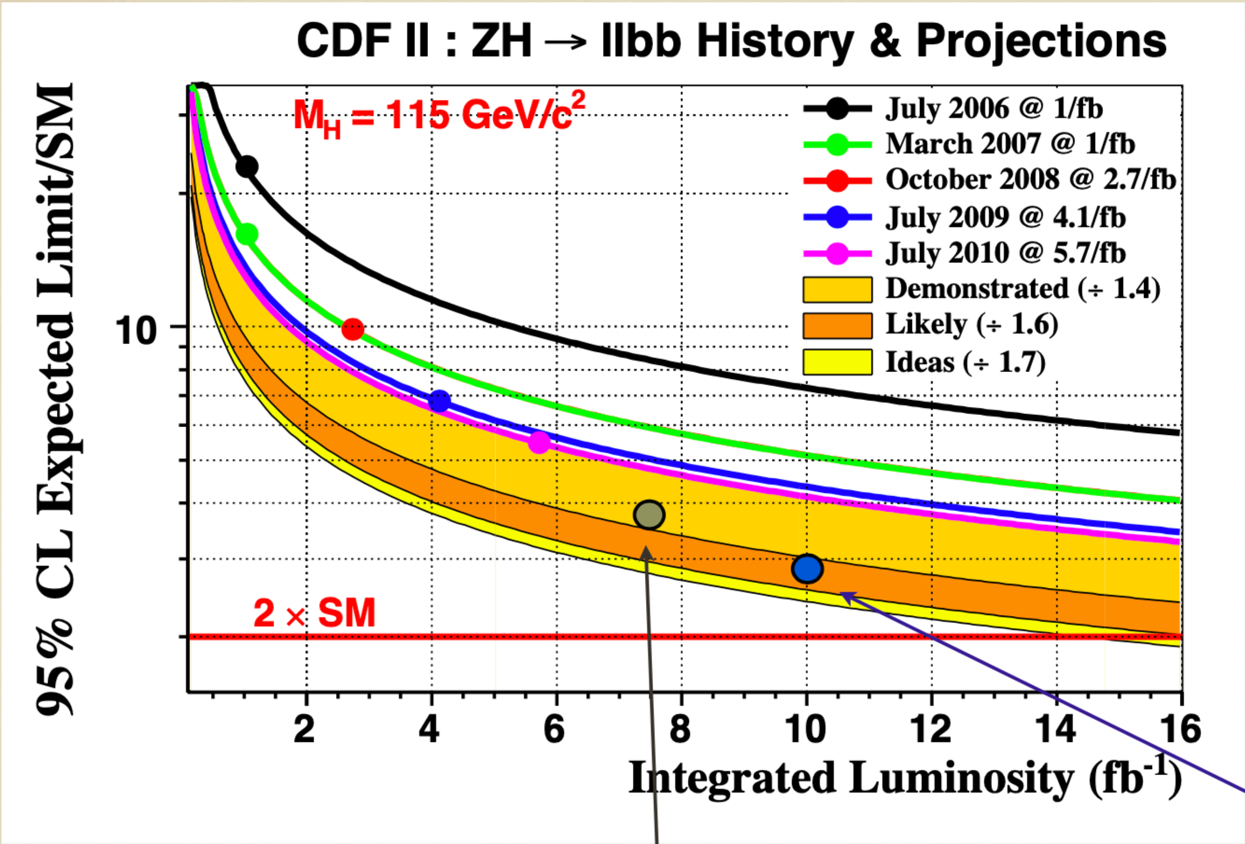
Tevatron control room

CDF control room

2011-2012 : The final push

Slide from 2011

Past improvements



Estimate for summer 2011
(next week's result)

Need to be here
by final result
2012

B. Kilminster, Higgs conveners update, July 2011

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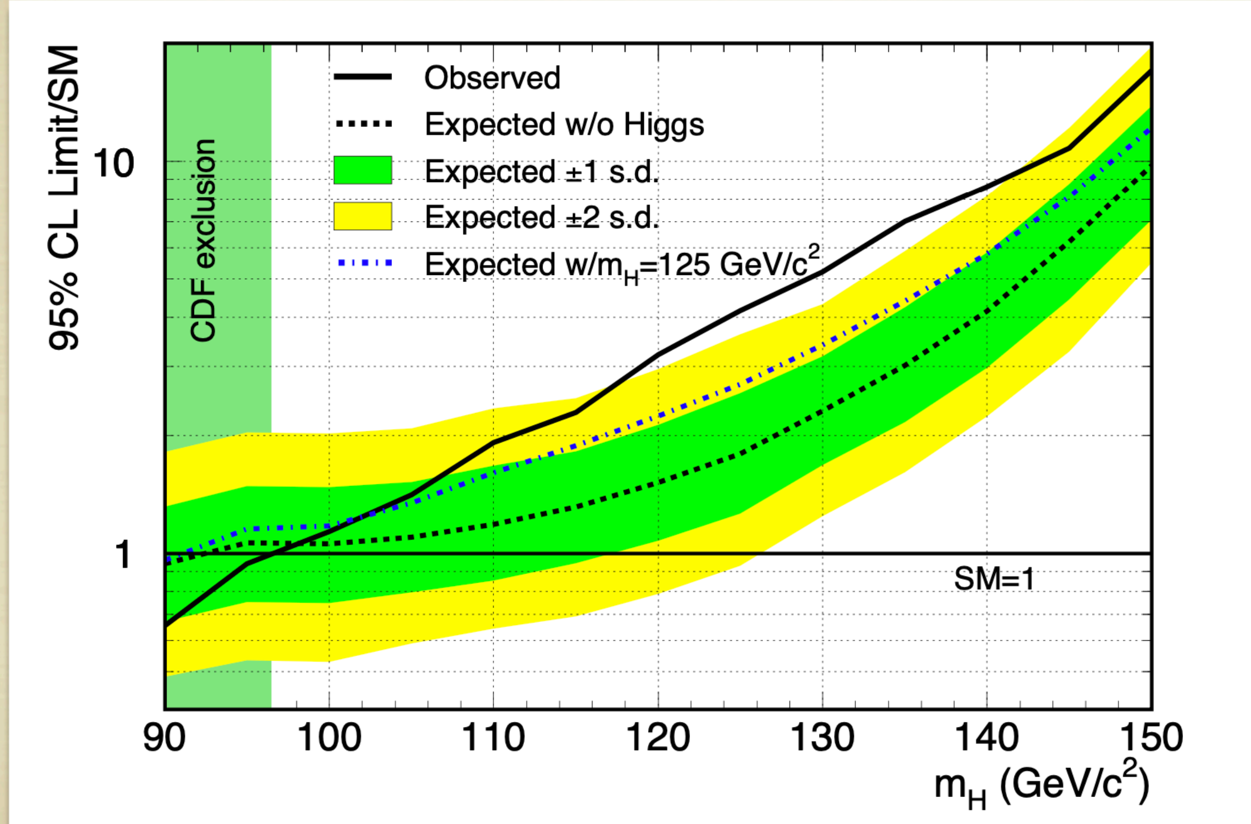
The exciting conclusion

July 3, 2012   with full Tevatron data

Slide from 2013

Combination of H→bb

- CDF

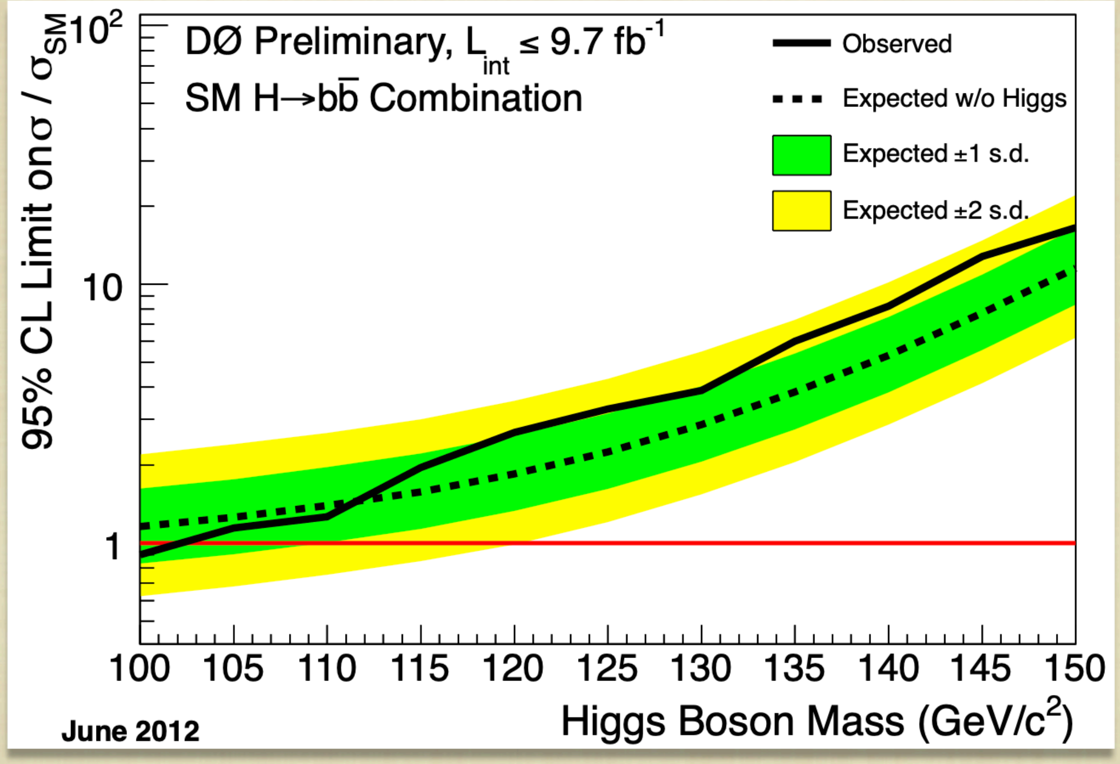


Excess 110 - 140 GeV

Slide from 2013

Combination of H→bb

- D0



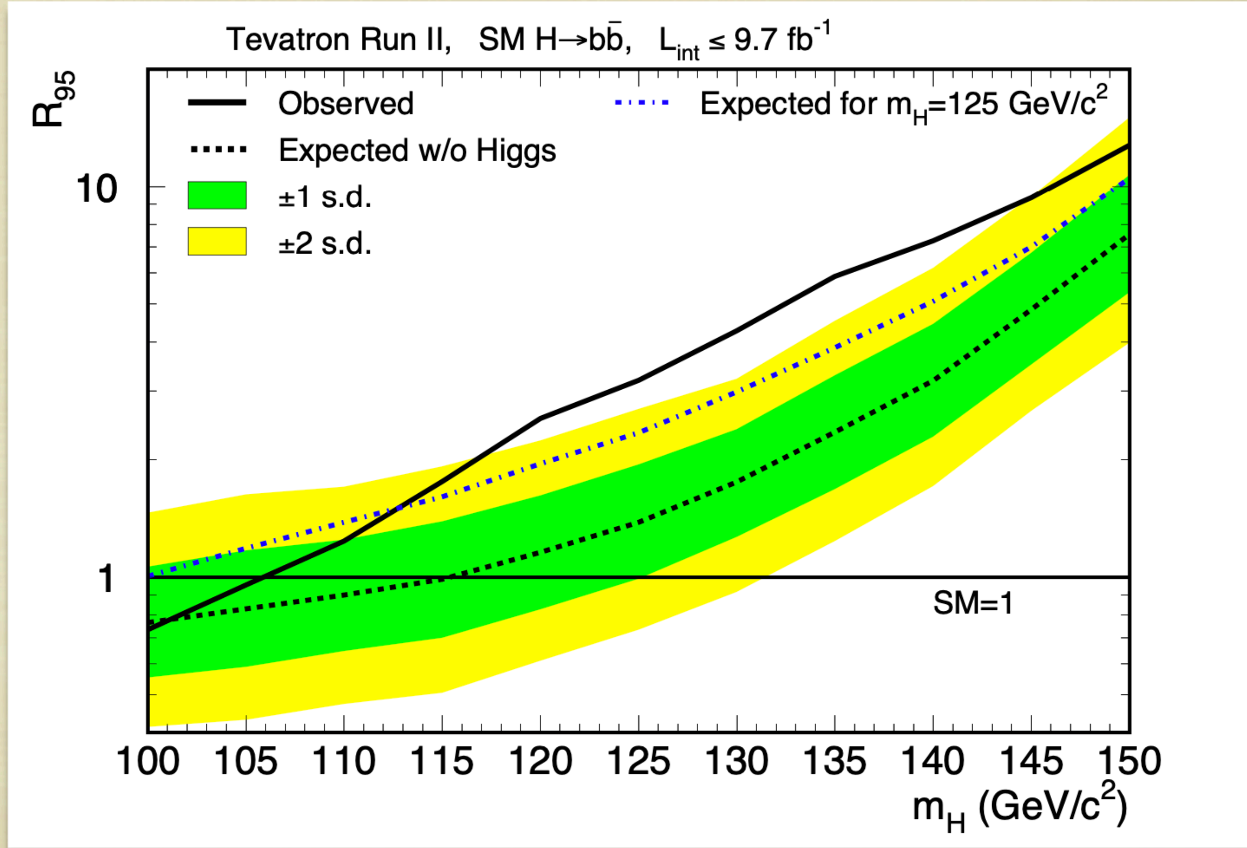
Excess smaller than CDF

B. Kilminster, DESY seminar, Jan. 2013 44

Slide from 2013

Tevatron H→bb combination

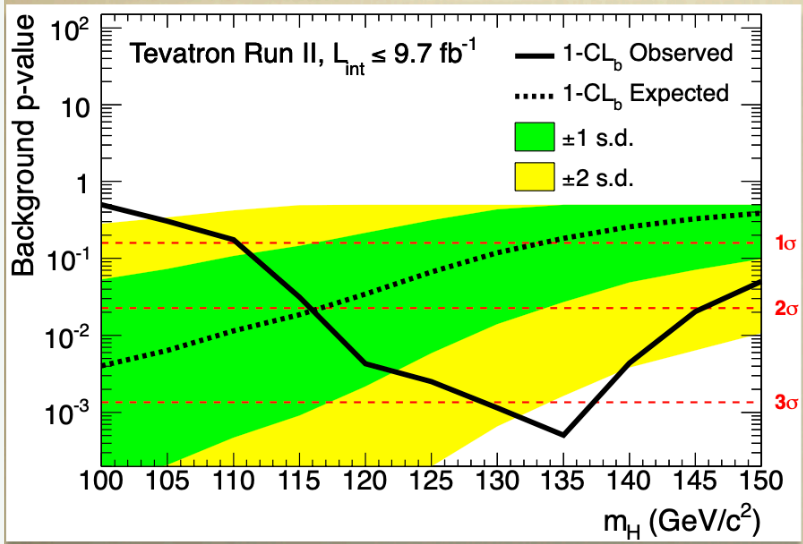
- Tevatron



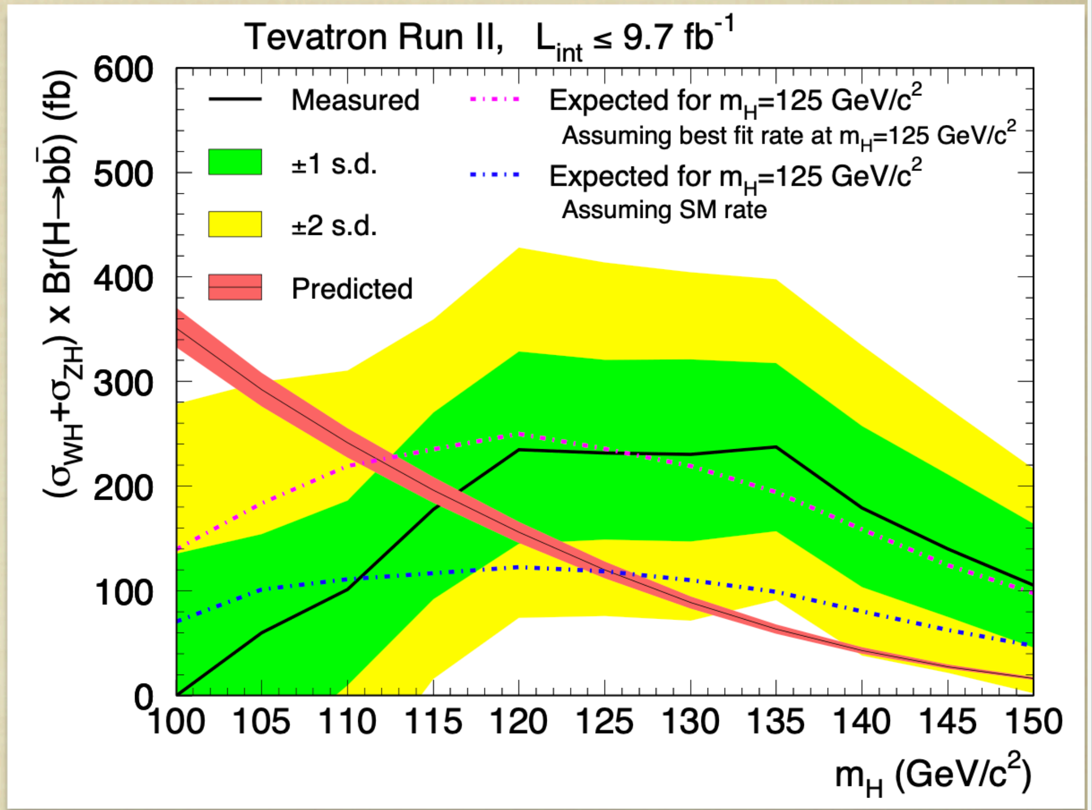
> 2 Sigma

B. Kilminster, DESY seminar, Jan. 2013 45

Analysis of excess



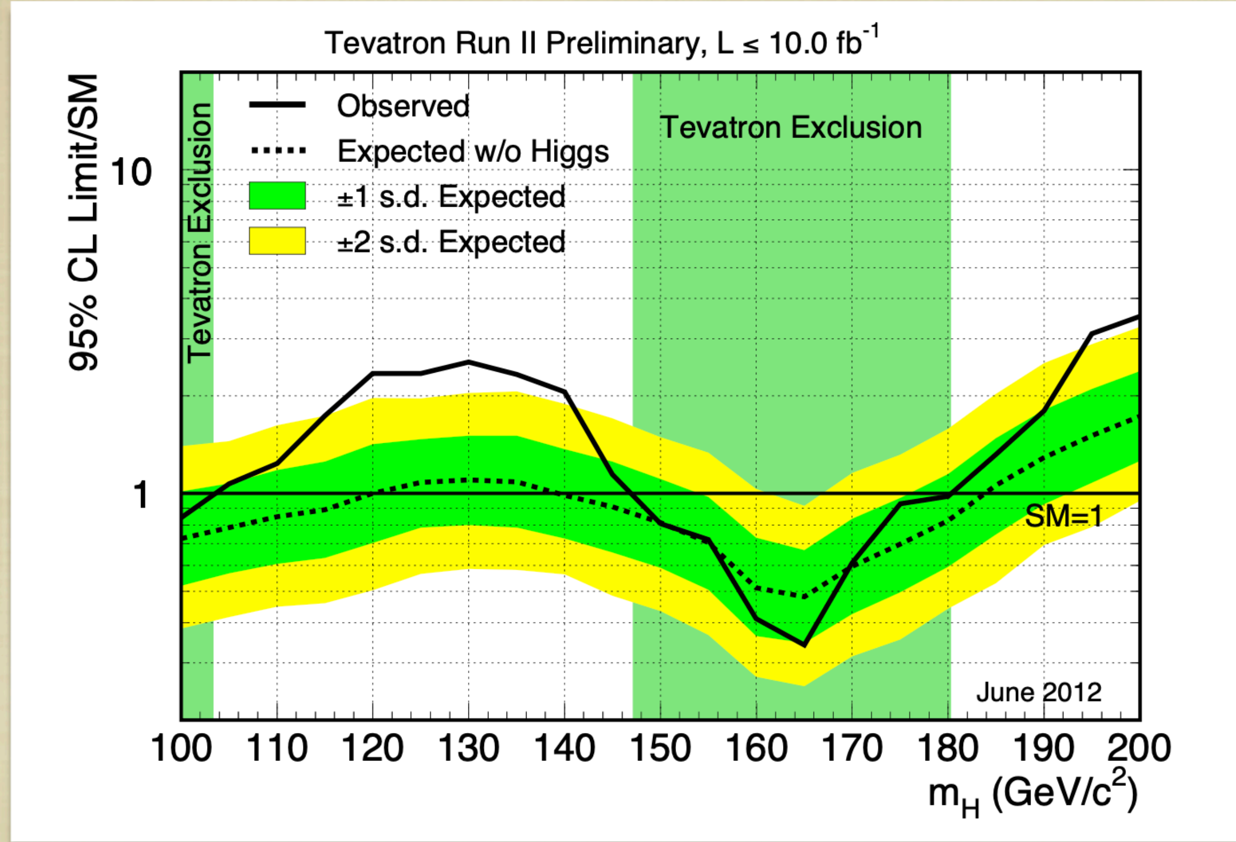
3.3 σ largest deviation



Injecting signal, comparing to prediction from SM

B. Kilminster, DESY seminar, Jan. 2013 46

Full Tevatron combination

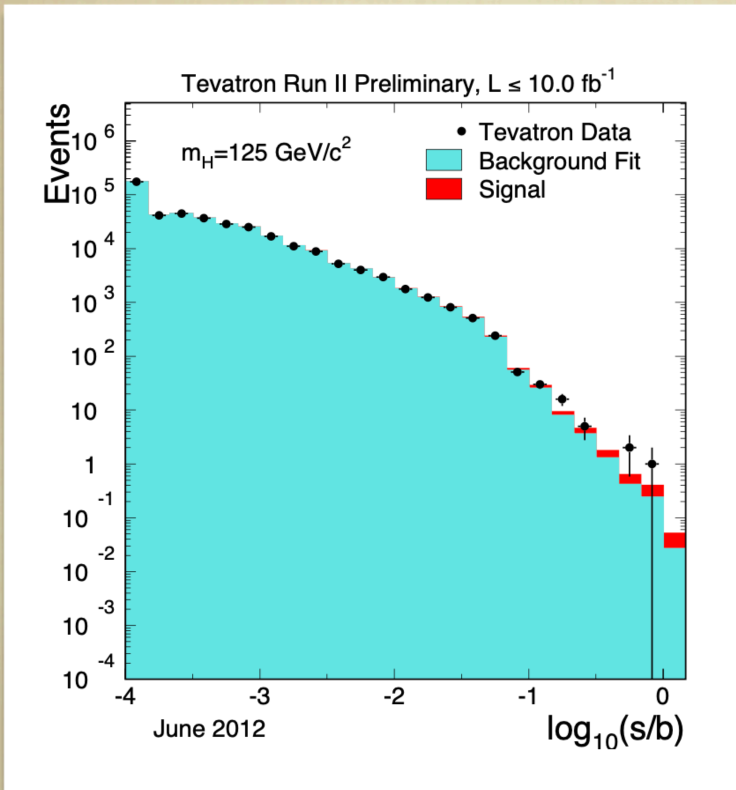


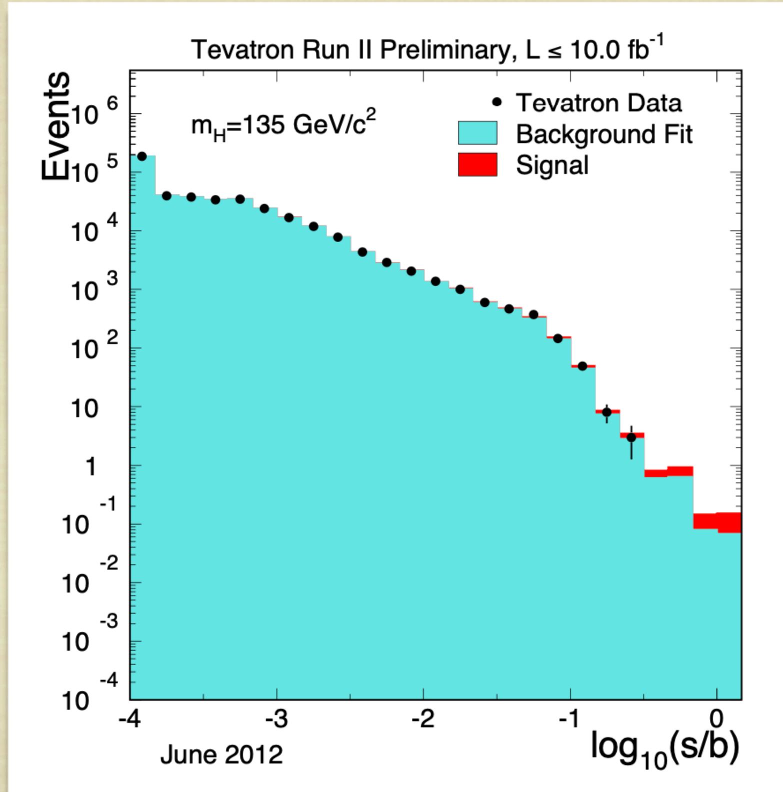
- **Expect to exclude < 120 GeV, excess means exclusion is <103 GeV**
- **High mass exclusion 147 - 180 GeV**
- **H→WW reduces excess from H→bb at high mass**

Slide from 2013

Combining all signal regions

- **Sorting all histogram bins from all searches by S/B**





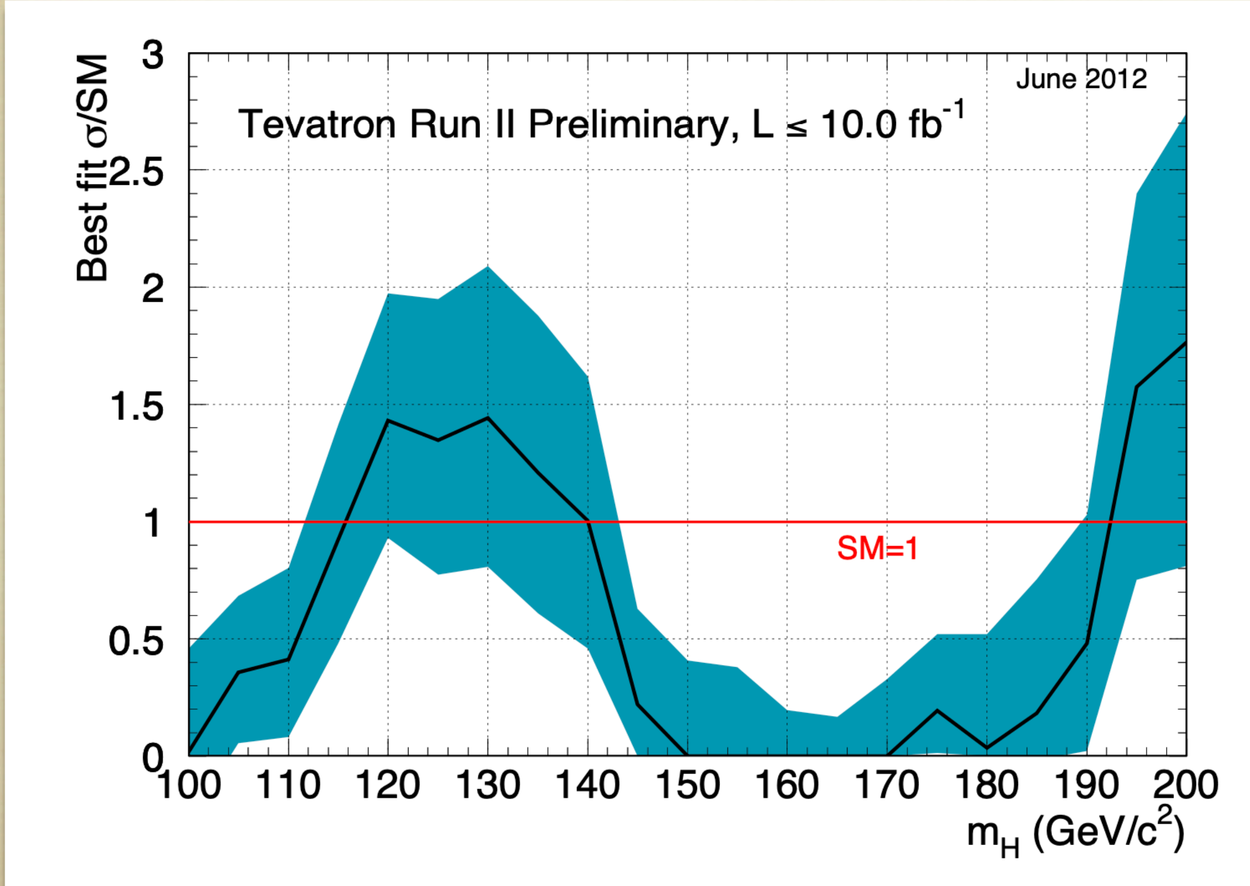
m_H = 125 GeV hypothesis

m_H = 135 GeV hypothesis

Slide from 2013

Best fit to Higgs X-section

- Likelihood fit of all searches for Higgs cross-section

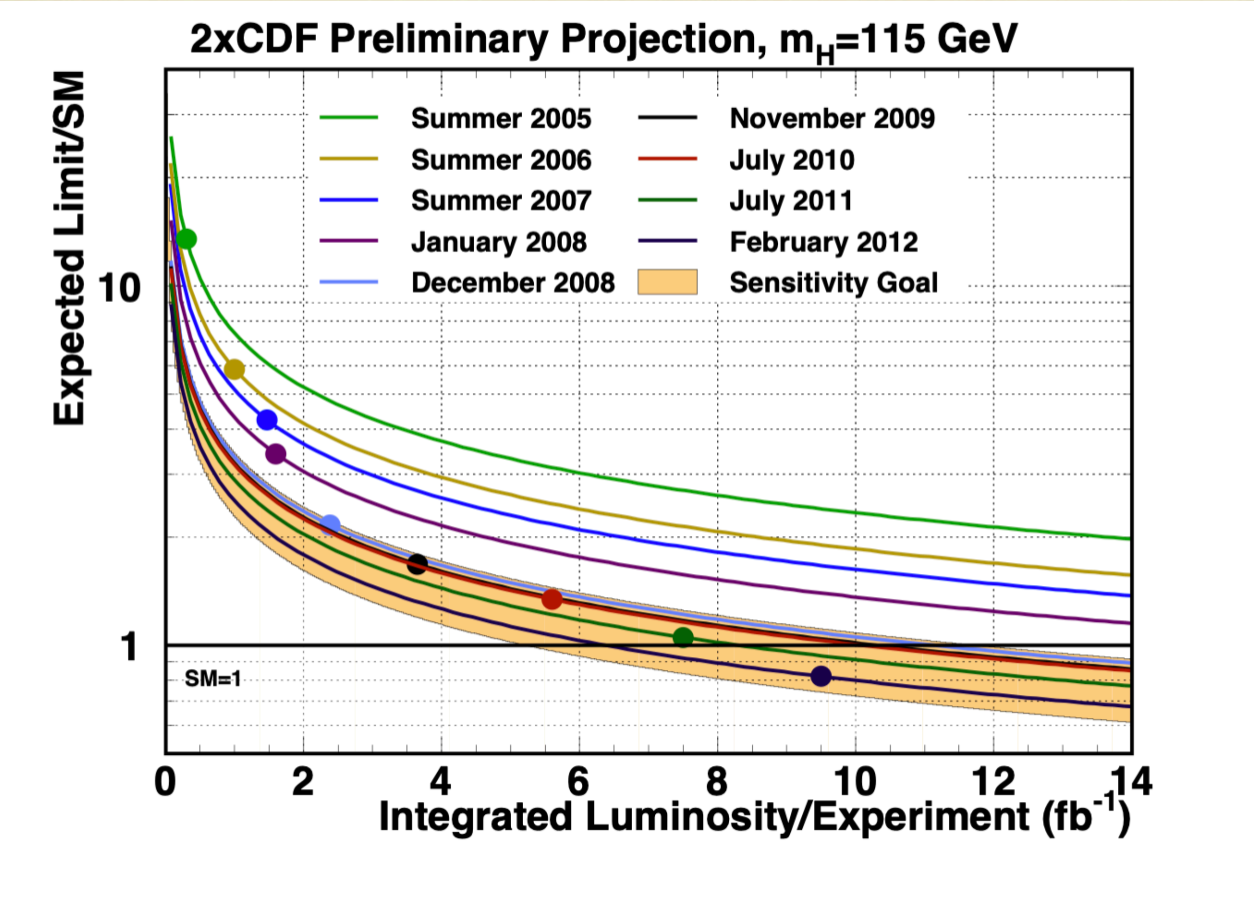


B. Kilminster, DESY seminar, Jan. 2013 54

Slide from 2013

Sensitivity gains in H→bb

- 2005 - 2012 improvements in analyses



B. Kilminster, DESY, Jan. 2013

Slide from 2013

July 4, 2012

Fermilab @ 2 AM on
American Independence Day

CERN

Half a million people tuned in
For Electroweak Independence Day !

Higgs was truly brought to the masses !

DESY

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B. Kilminster, DESY seminar, Jan. 2013

July 4, 2012

- **Published papers from CMS and ATLAS, Tevatron**

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

The CMS Collaboration*

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

The ATLAS Collaboration

Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron

Summary

- Many more Higgs boson results from the Tevatron skipped today (Higgs spin/parity, BSM Higgs, …)
- Results:
  - Evidence for Higgs boson from Tevatron
    - Consistent with what we know now
  - Exclusions of heavier Higgs bosons & much BSM
- Analysis approaches created at the Tevatron live on today in LHC searches and Higgs measurements
- The Higgs boson searches at the Tevatron brought out the best in CDF, D0, accelerator division scientists !