From Collisions to Publication
A Higgs Story

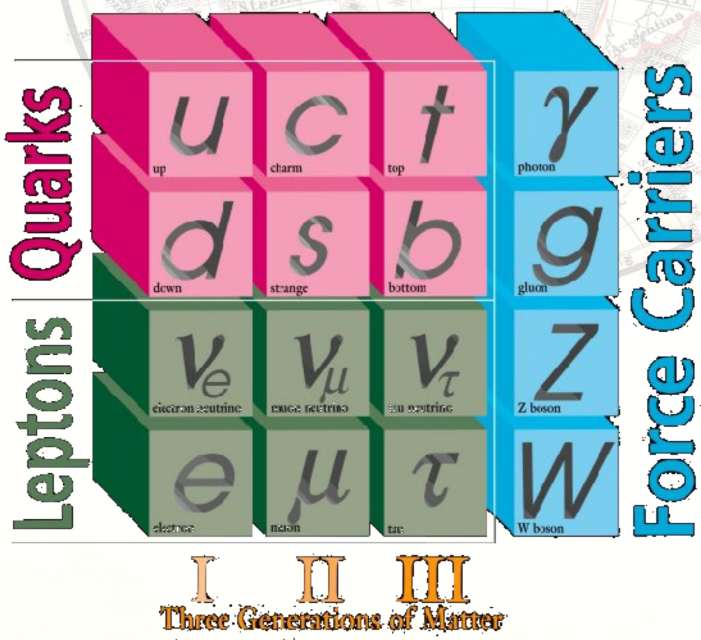
Vadim Rusu

Fermilab

- What we have
- What we want
- What can we use
- How do we get it
- How far along are we

Terra Firma

- Standard Model of Particle Physics
  - 3 generations of fermions
    - Leptons and quarks
  - Force carriers
    - EWK – gamma,W,Z
    - Strong – gluons
  - Very good fit to the experimental data so far



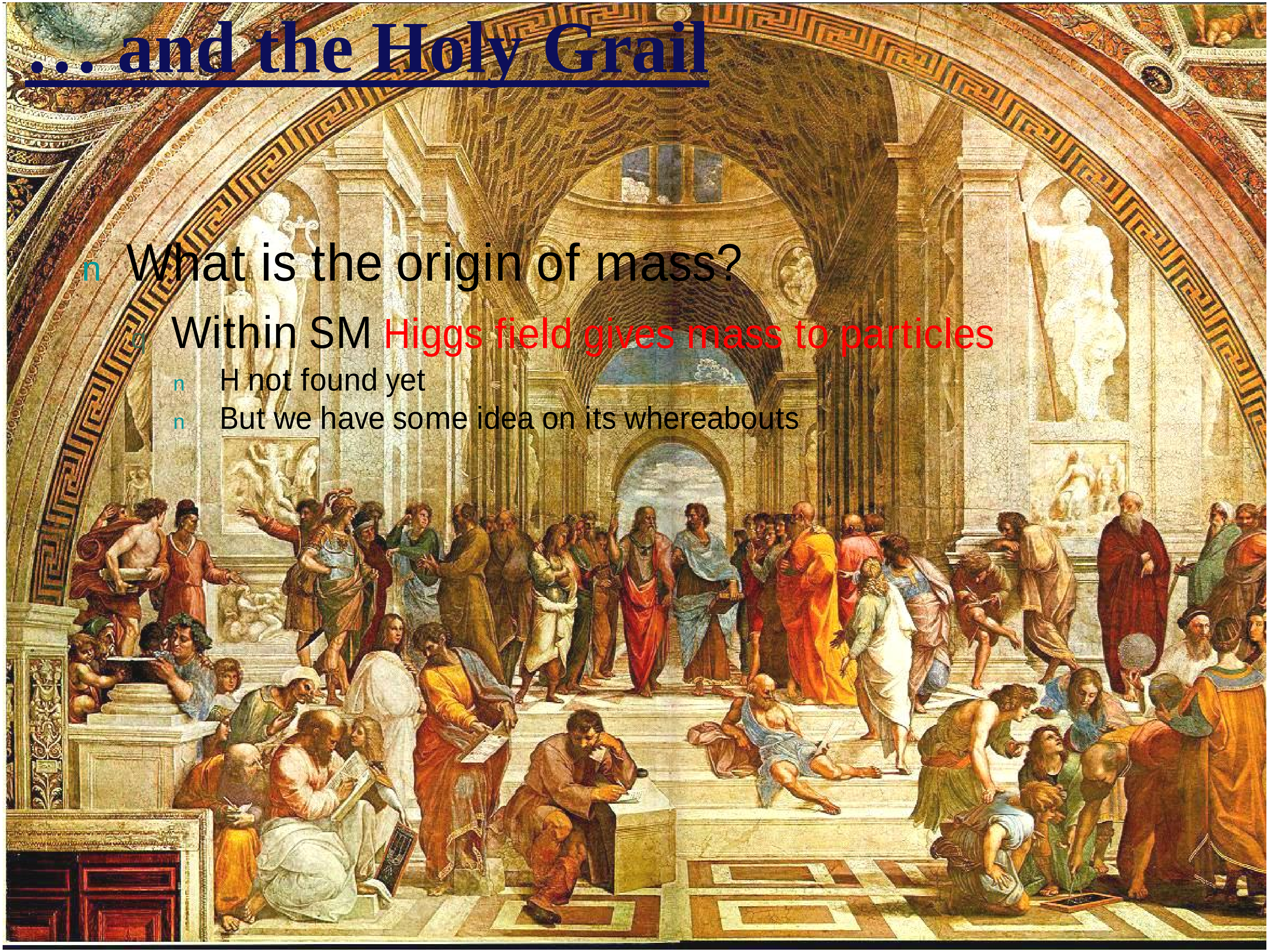
CDF: 80.413+/- 0.048 GeV

Terra Incognita

- What is Dark Matter / Dark Energy
- Why 3 families?
- Why 4 fundamental forces?
- Why are neutrinos so light?
- …

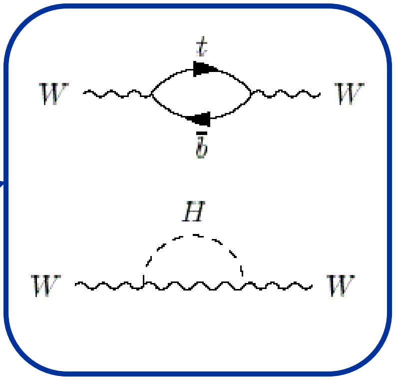
… and the Holy Grail

- What is the origin of mass?
  - Within SM Higgs field gives mass to particles
    - H not found yet
    - But we have some idea on its whereabouts



Experimental constraints on Higgs

- Direct search at LEP
  - $m_H > 114$ GeV at 95%CL
- Indirect searches
  - Loop effects
  - $m_t = 172.6 \pm 1.4$ GeV
  - $m_W = 80.398 \pm 0.025$ GeV



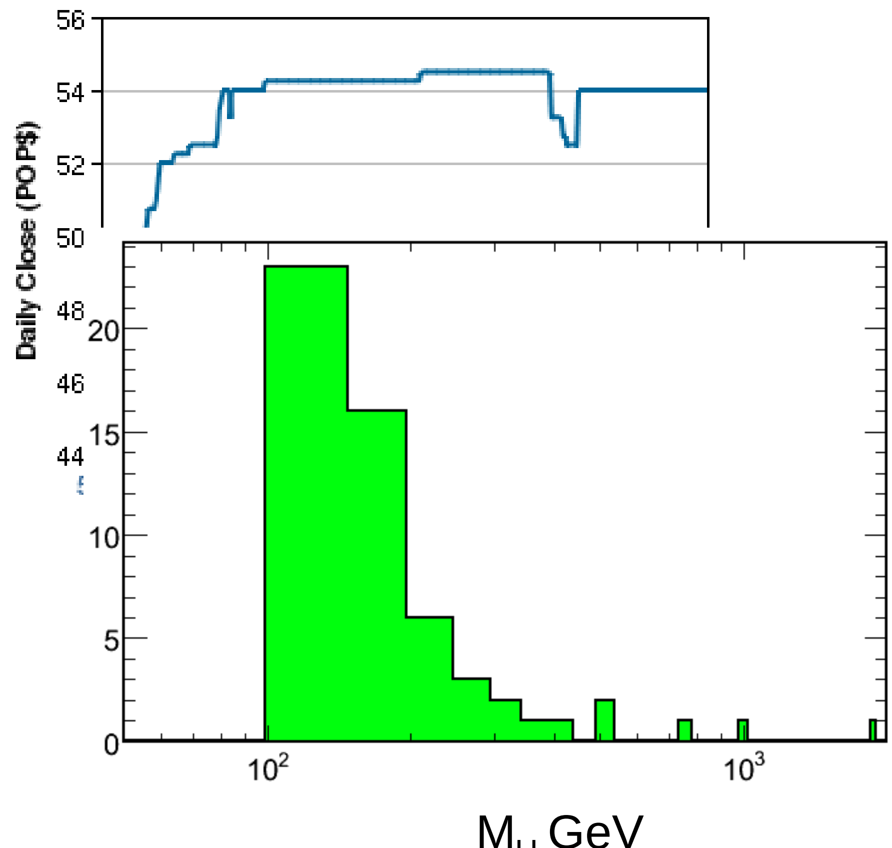
$m_H = 87 \pm_{36}^{27}$ GeV,
$m_H < 160$ GeV @ 95% CL

What else we (think) know about it?

- Chaos, Solitons & Fractals Volume 30, Issue 2, October 2006 (E-infinity theory)
  - Higgs mass is 161.8033989 GeV

Financial derivatives at ppx.popsci.com pricing the discovery of Higgs at Tevatron

T. Schucker compiled a list of Higgs predictions (58) at arXiv:0708:3344



Disclaimer

- We have not found the Higgs (yet)
  - If we did, you would have heard it already from blogs
- The road is more interesting than the destination
- There will be no limits in this talk
  - For an experimental physicist the data tells more stories than an abstract plot
  - Not to mention that I'd rather talk about the detector and the data than try to explain how arcane models were excluded or not
- I will concentrate on the SM Higgs
  - Most of the final states are similar

Tevatron at Fermilab

- Tevatron circulates protons (p’s) and anti-protons (pbar’s)
  - **Not** fundamental particles!
  - All the work is in making the pbar's
- Particle beams collide at experiment sites (CDF, DØ)
  - Energy in C.O.M.: 2 TeV
- Tevatron is ***Energy Frontier*** right now

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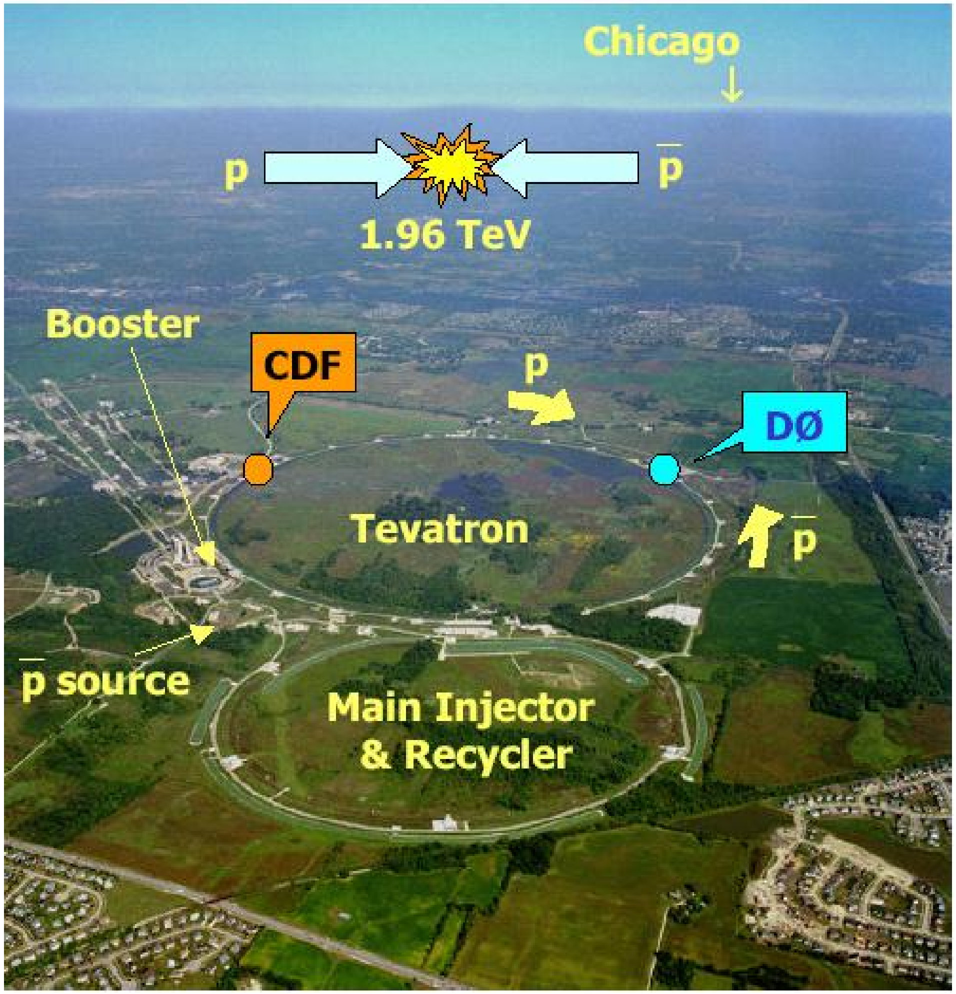
TIFF (Uncompressed) decompressor
are needed to see this picture.



Record inst. Luminosity:

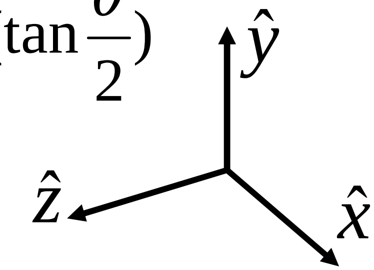
3.15×10^{32} $cm^{-2}s^{-1}$

Record weekly integrated luminosity:

46.5 pb^{-1}

CDF detector

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

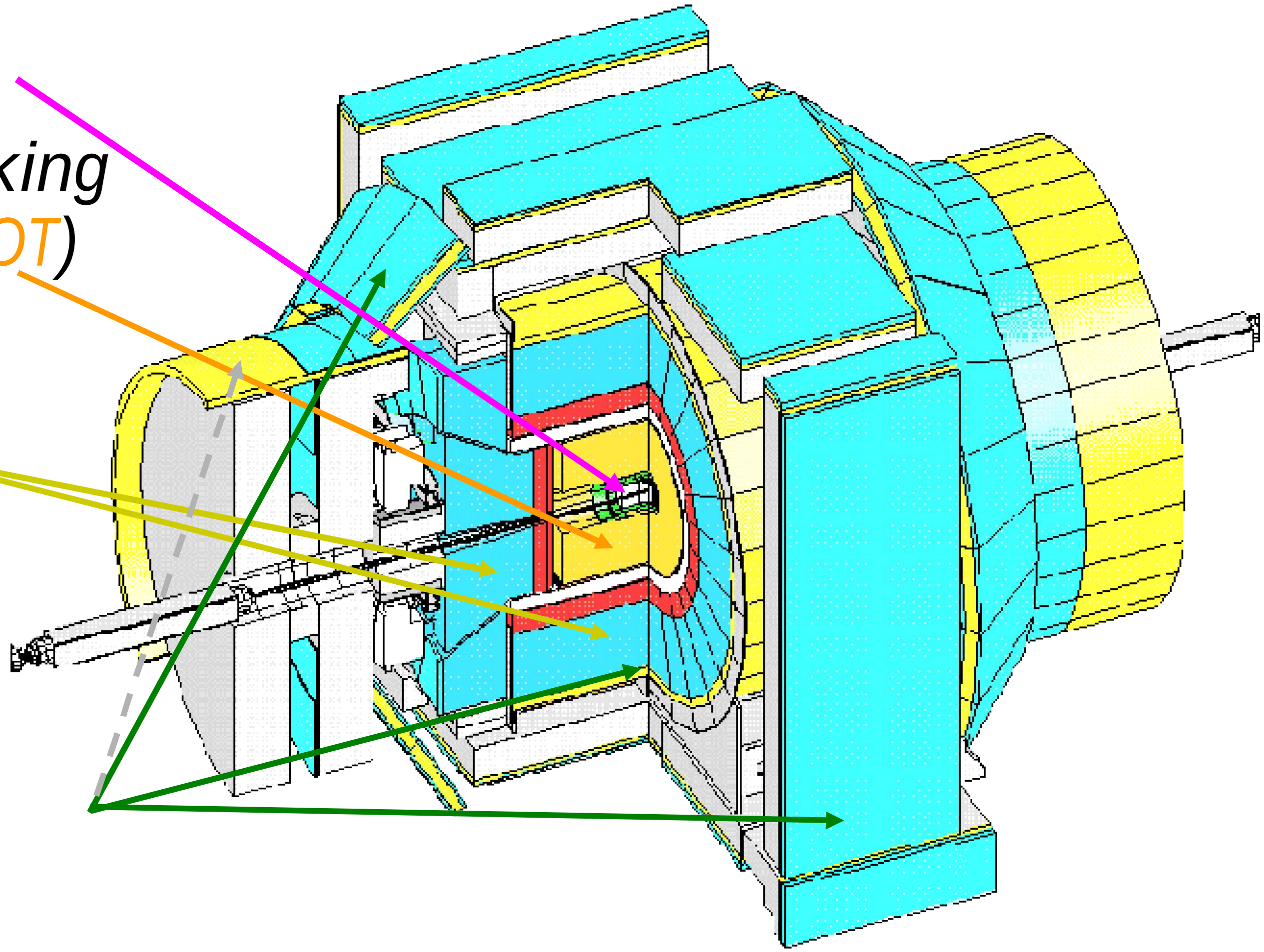


General, multi-purpose detector

•Focus on charged-particle tracking

Features:

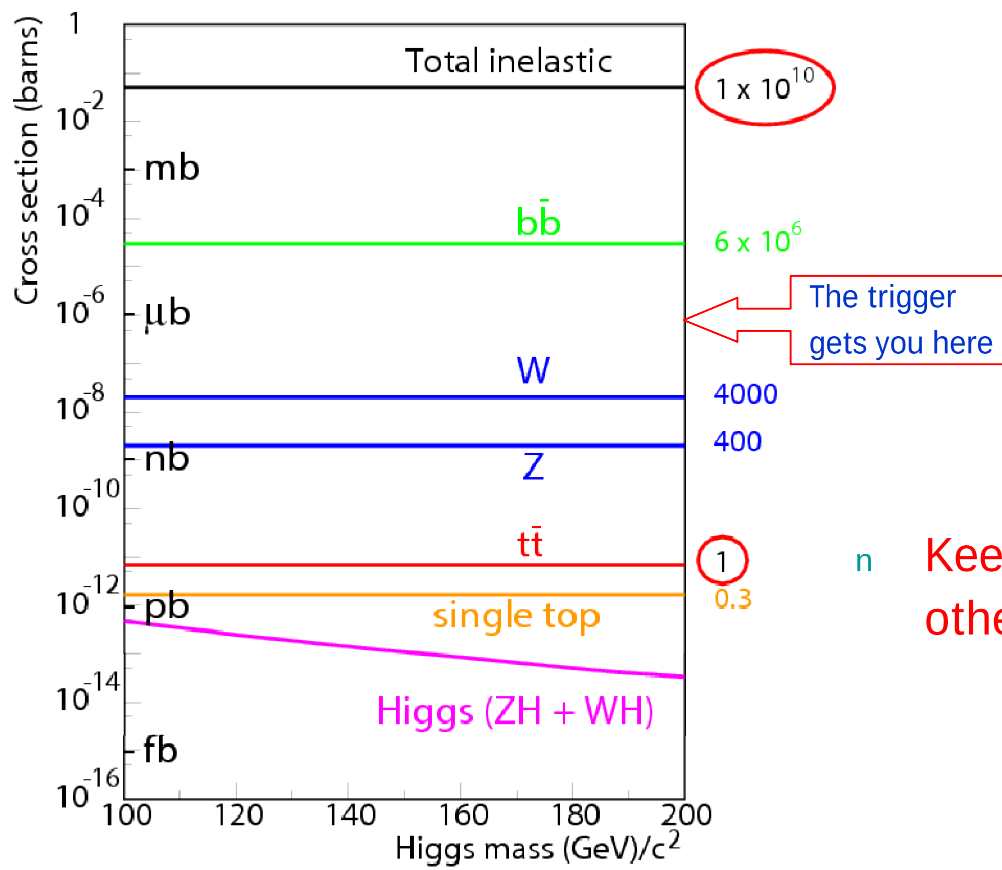
- *Silicon tracker*
- *large radius tracking wire chamber (COT)*
- *Magnet (1.4T)*
- *Calorimeter*
  - *($|\eta| < 3.6$)*
- *muon chambers*
  - *($|\eta| < 1$)*



Triggering at hadron colliders

1.7MHz→100Hz

- The physics cross sections span 12 orders of magnitude



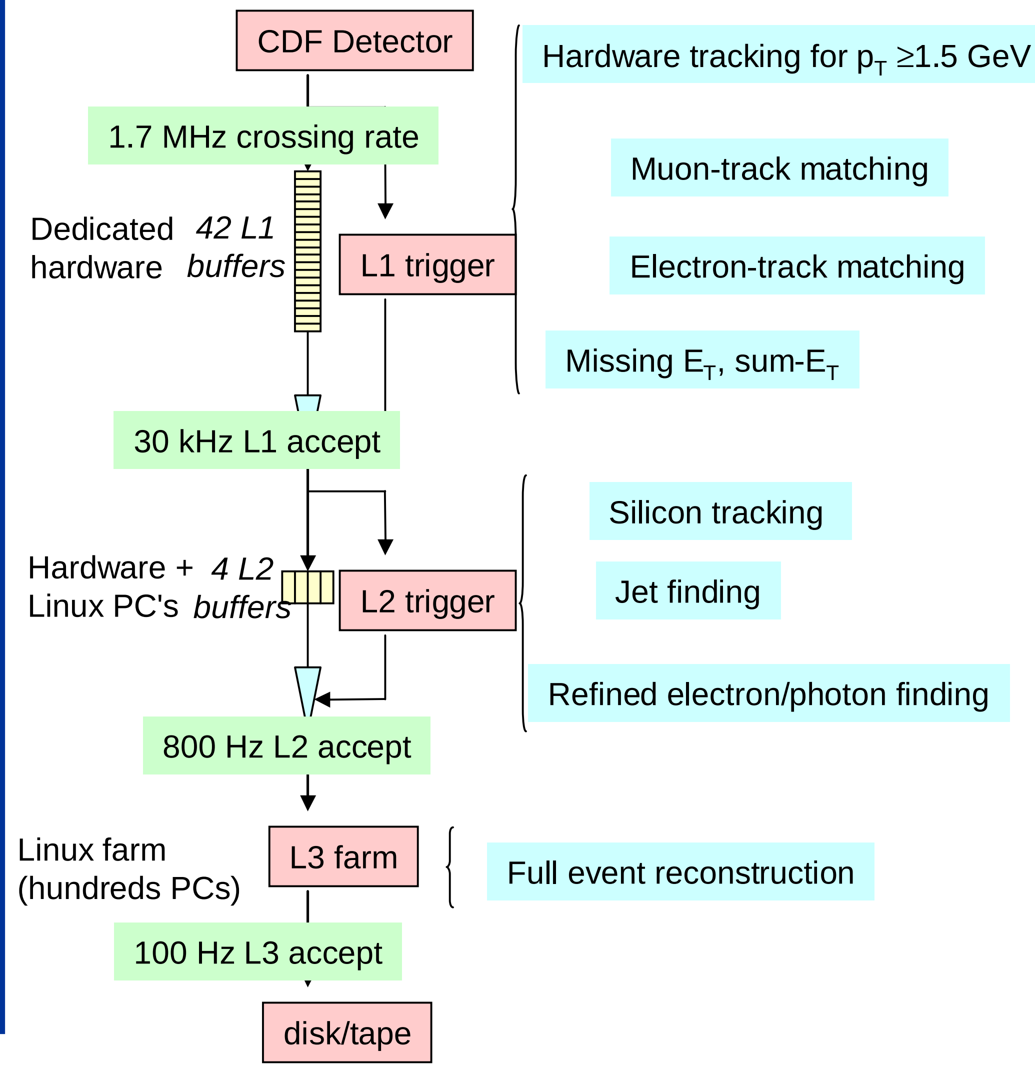
- Interesting events are rare

Process	At 100E30 every
Inelastic ppbar	100ns
b and anti b quark	20μs
W	1 s
t and anti t quark	half hour
Higgs	~6 hours

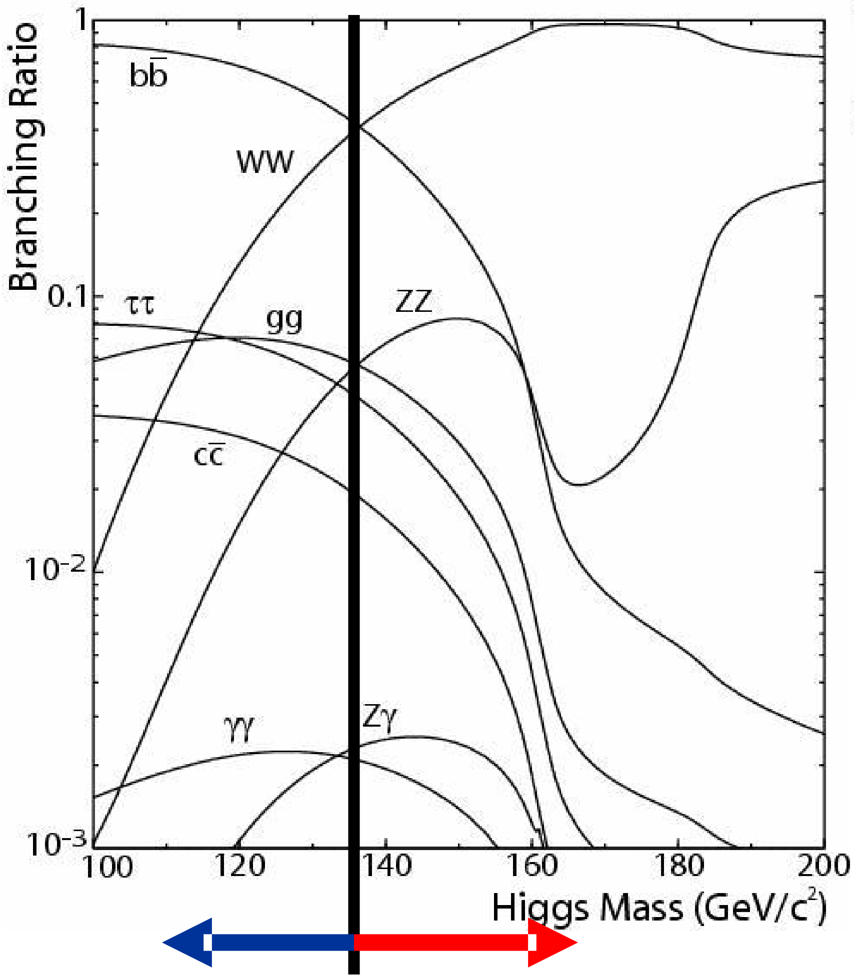
- Keeping the rare events while rejecting the others is the job of the trigger

The CDF trigger system

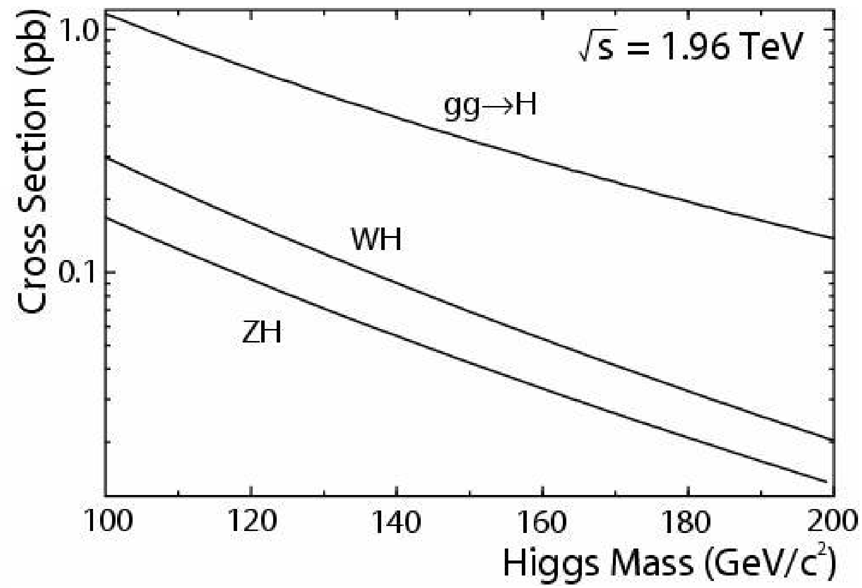
- Hierarchical trigger system
  - 3 Levels of increasing sophistication in algorithms
  - Combination of custom build hardware and commodity PCs
- Premium on inclusive triggers
  - CDF can trigger on any event with a lepton (e or μ) above 20GeV
  - This allows broad open searches



Road to the Higgs



H→bb H→WW



- gg→H
  - H→WW (high mass)
    - Easy signal
    - small(er) x section
  - H→bb (low mass)
    - Tough signal
    - Larg(er) x-section
    - Associative prod
- W/ZH
  - striking signatures
  - low production

H→WW

- Basic Selection
  - Two leptons
  - MET from ν
  - MET=missing E_T
- Trigger:
  - High P_T leptons
  - MET

- Backgrounds:
  - Drell-Yan
  - WW

Angle between leptons provides good separation

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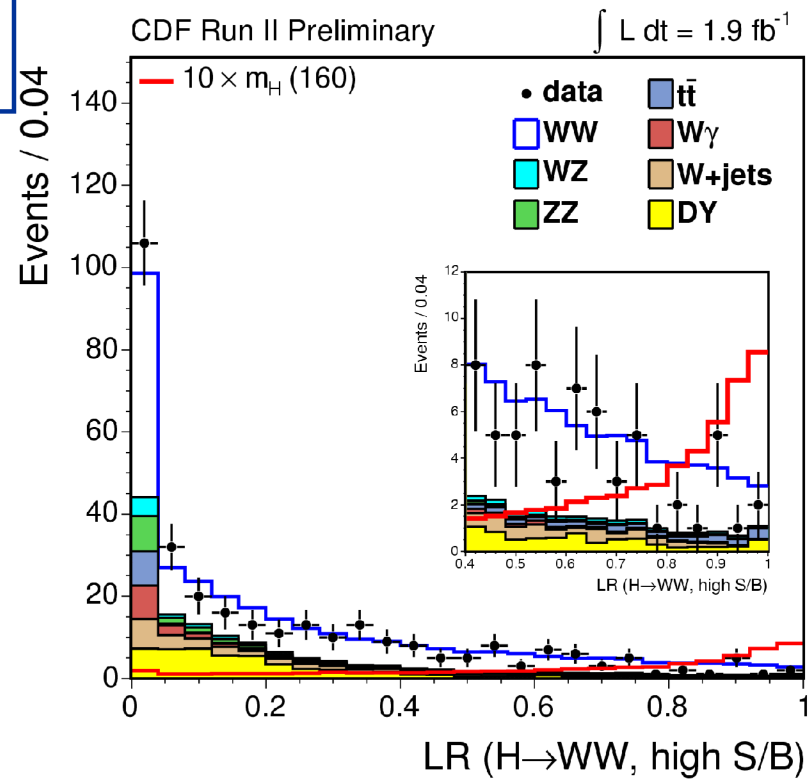
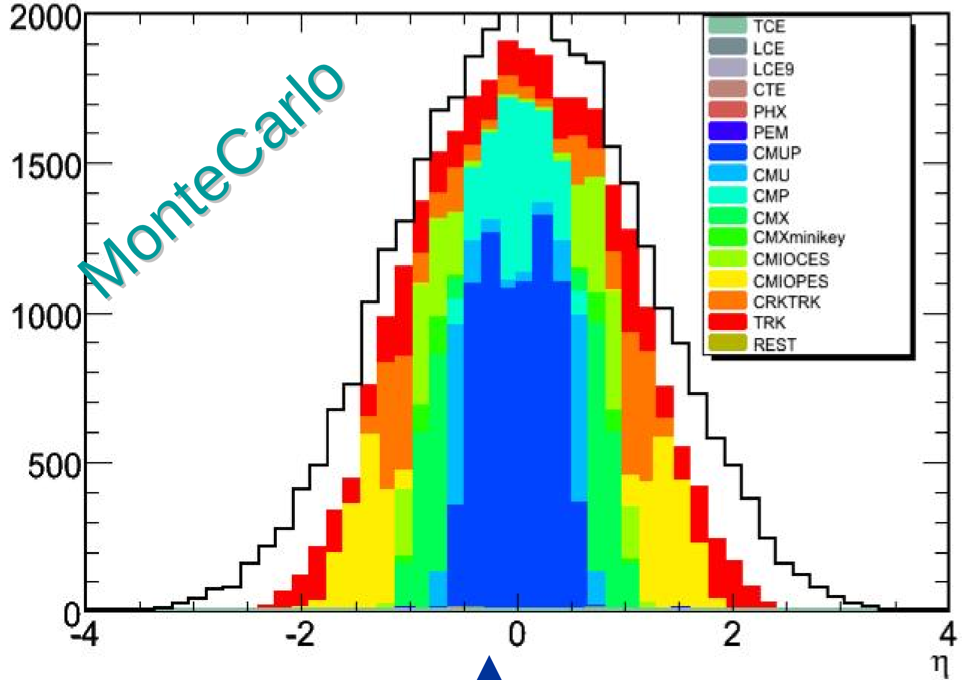


Stats is name of the game

Increase lepton acceptance

Identifying leptons

- Leptons at CDF
  - Electrons - EM deposition (plus track)
  - Muons - Tracks with associated hits in muon chambers (MIPs in calorimeter)
- The complication come from detector nonuniformity
  - Lots of subdetectors in fact



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- Not all can be used in analysis (det. backg.)
- The trigger is not folded in

More leptons for H->WW

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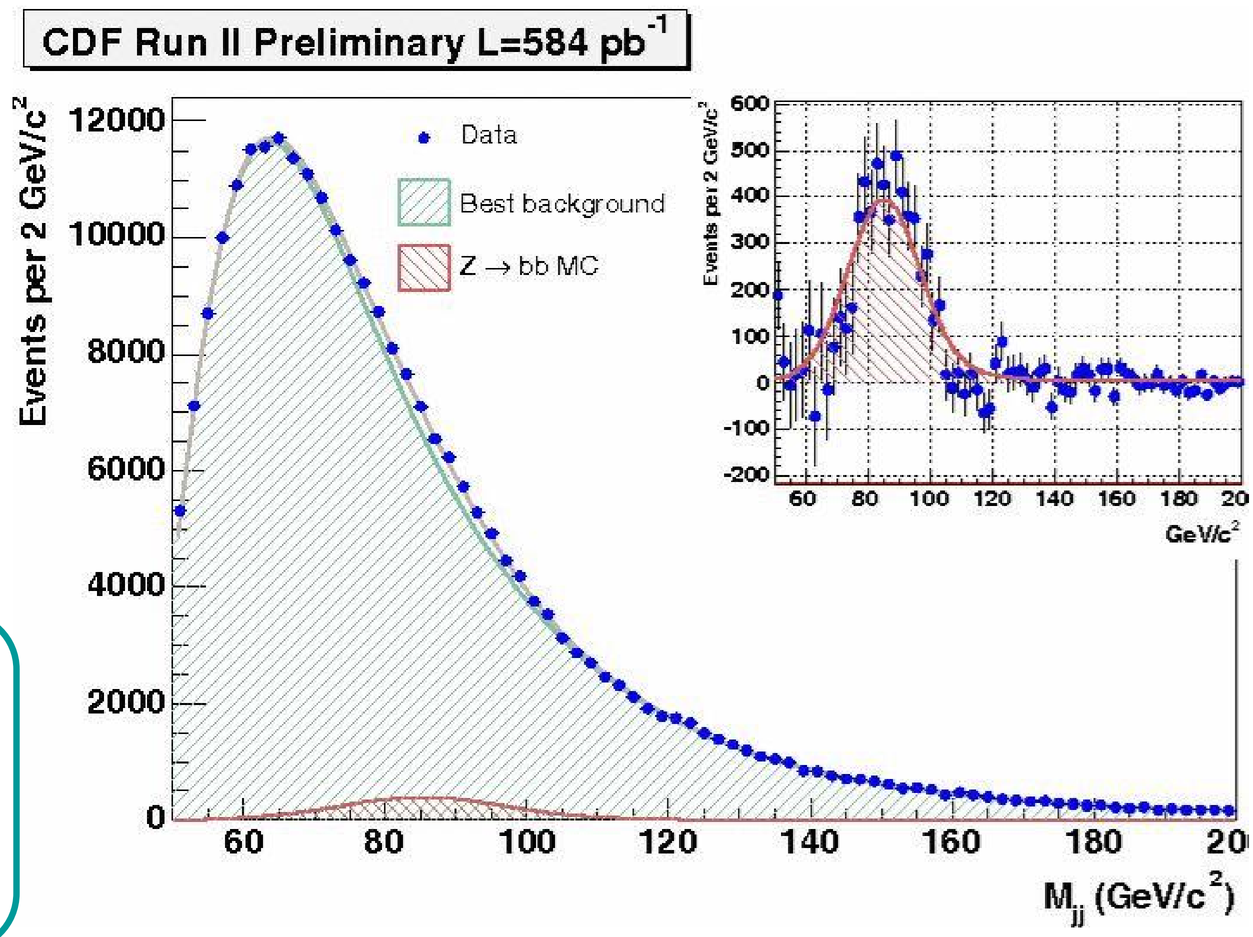
- Project the cylindrical detector geometry
  - Pseudorapidity (η) and azimuth (φ)
  - Different colors represent different muon candidates reconstructed in different muon chambers and/or different algo

$H \to b\bar{b}$

- $\sigma_Z \bullet BR(Z \to b\bar{b})$ = 1129 ± 22 pb
- The $Z \to b\bar{b}$ process will set the scale of the problem

Background shape is determined from sidebands



Selection:
- Two jets E_T>22GeV
- $|\eta|$ < 1
- Jets IDed as b

Associated production

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2 b jets + MET
Largest expected signal

2 leptons+2 b jets
Cleanest signal

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Lepton+MET+2 b jets
Highest x-section

$ZH \to \nu\nu b\bar{b}$

- Signal selection
  - MET+2 jets (one identified as coming from b)
- Trigger selection
  - MET>35GeV
  - 2 jets E_T>15 GeV
  - MET is difficult to trigger on
    - qq->qq dominant
    - $E_q = E_{jet} + E_{mismeasured}$
    - $\sum E_{mismeasured}$ = MET
    - MET(trigger) != MET(offline)

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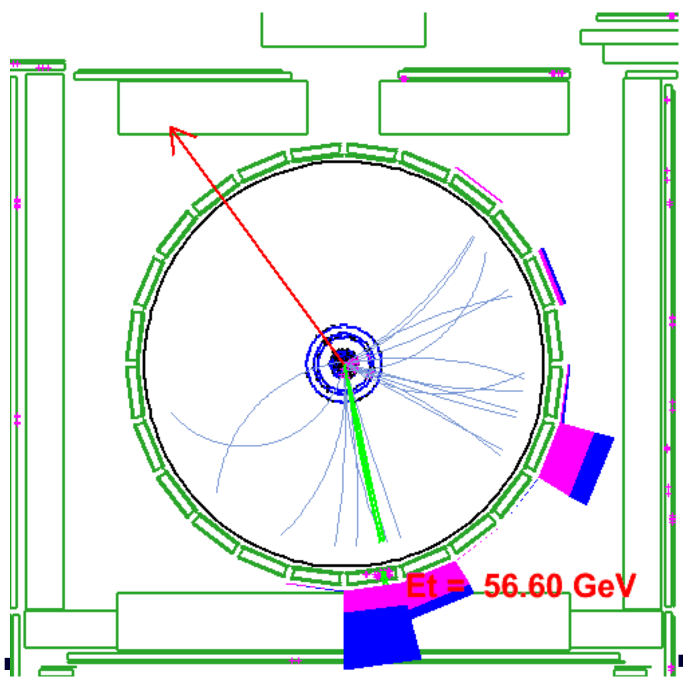
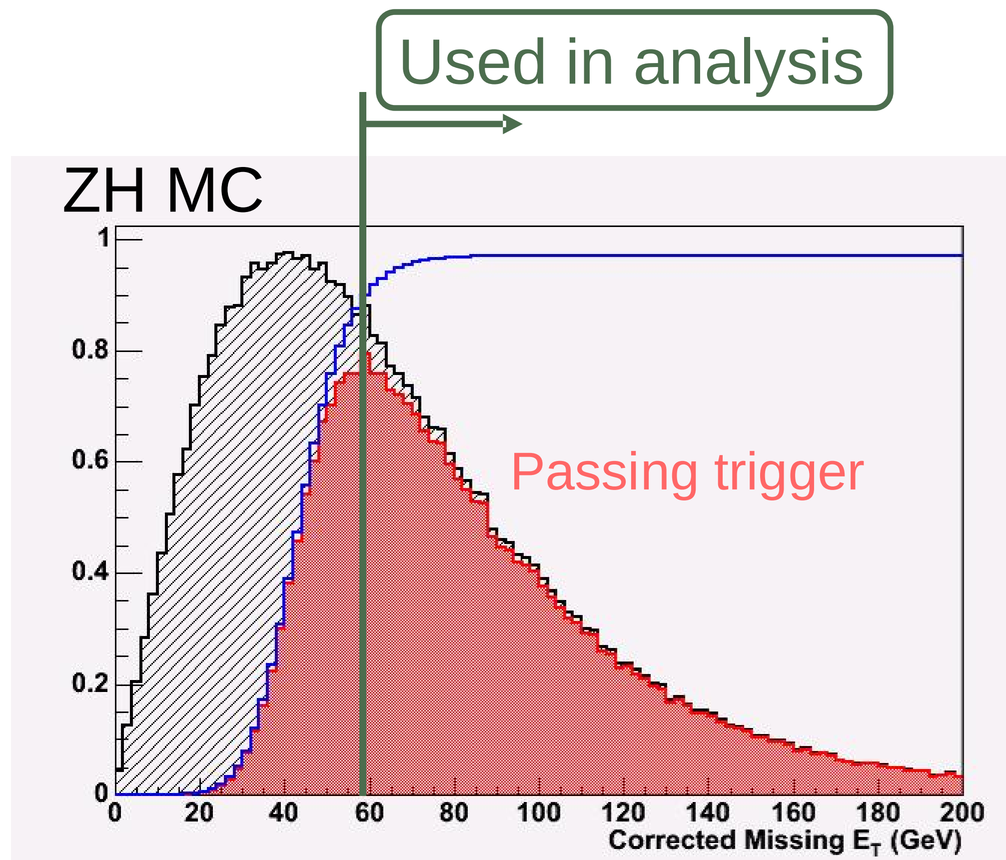
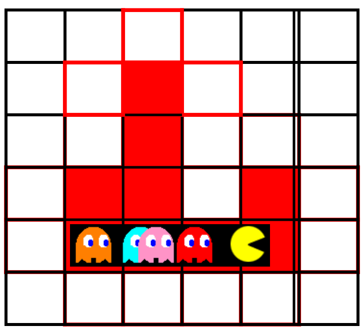


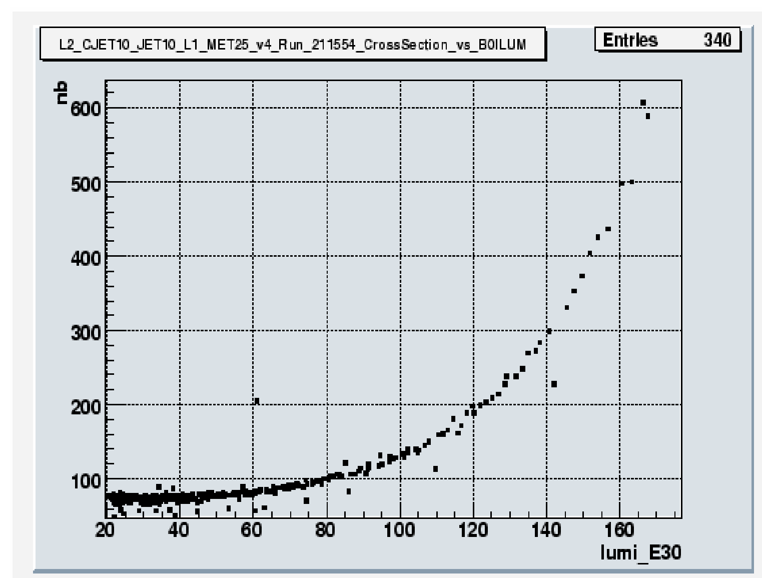


Jet clustering in the trigger

- Jet clustering implemented in hardware using Run I algorithm
  - The calorimeter is viewed by the trigger on 24x24 η-φ map
  - The algorithm finds a seed (threshold 3GeV), then attaches any tower above the shoulder threshold (1 GeV) which touches any other tower in the cluster
    - “Cone clustering” offline



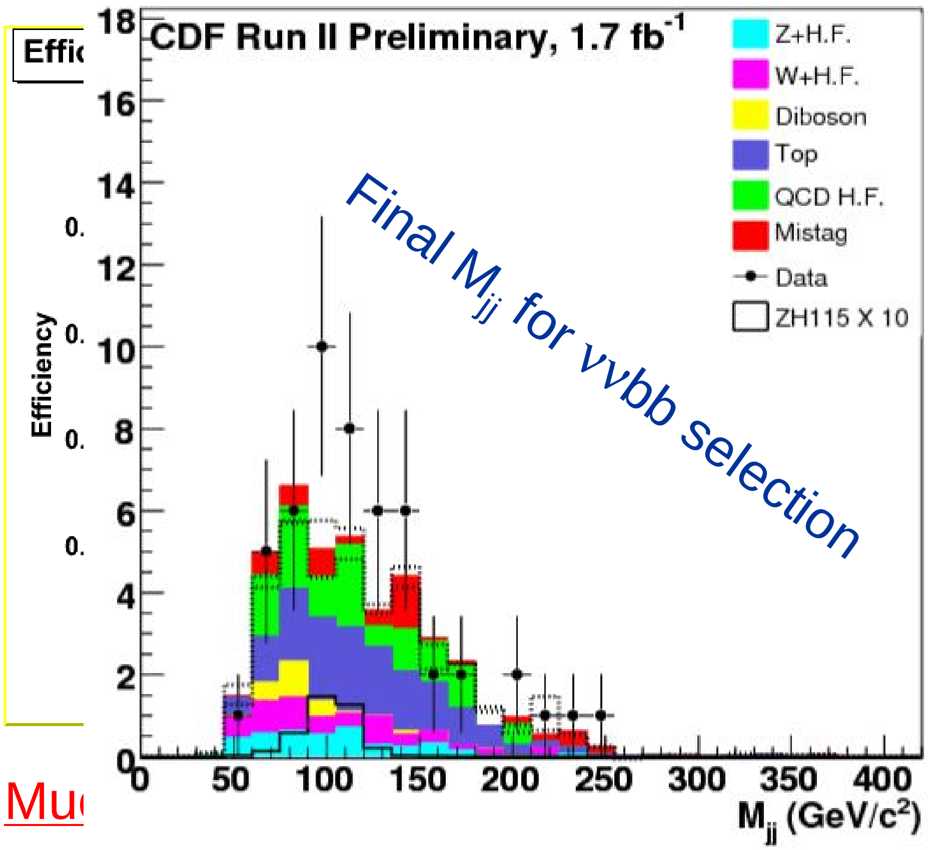
“Pac-Man”



Trigger rate grows to untenable values at high instantaneous luminosity

New calorimeter trigger

- Take advantage of modern technologies to implement “cone clustering” in hardware
  - In operation since last summer



Mu

ZH→llb $\bar{b}$

- Cleanest signature
  - 2 leptons from Z
  - 2 jets (IDed as b)
- Main background:
  - Z+jets

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Use the well identified Z→ll as tag

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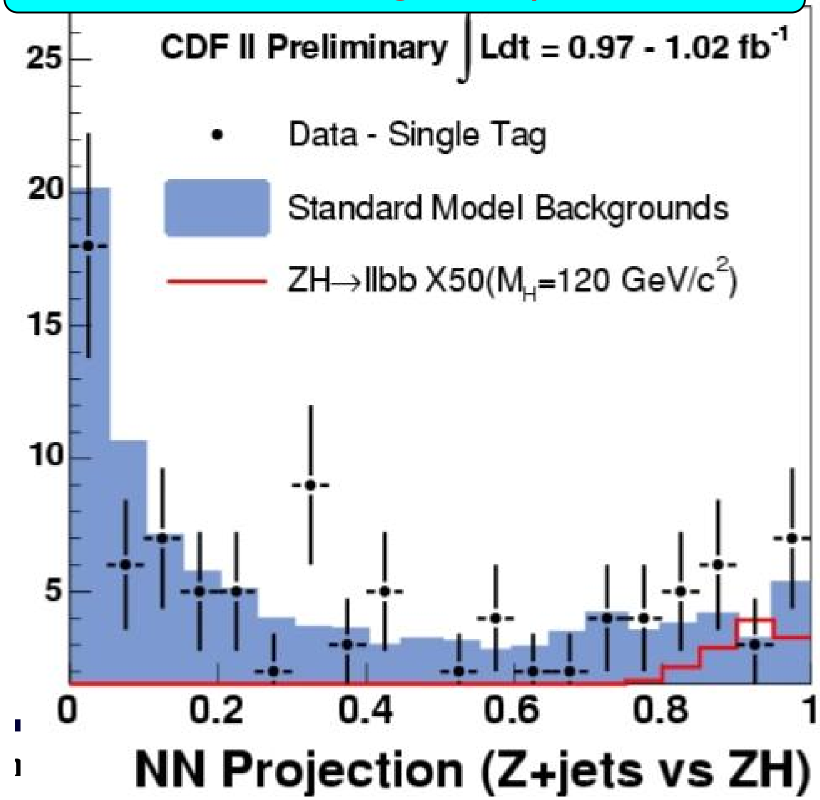
NN selection using multiple variables



ZZ as a road mark

- Same signature ($llb\bar{b}$)
- σ_{ZZ} = 1.5pb
  - B.R. $Z\to b\bar{b}$ = 20%
- Can we find this first?
- Pre-road mark
  - $ZZ\to 4$ leptons

$\sigma(p\bar{p} \to ZZ)$=1.4+0.7-0.6 pb

Combined with the $ll\nu\nu$ channel

Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	**2**	**1**

$WH \to l\nu b\bar{b}$

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- Basic selection:
  - High Pt lepton
  - 2 high Et jets (b ID)
  - Large MET
- Backgrounds difficult
  - W+HF

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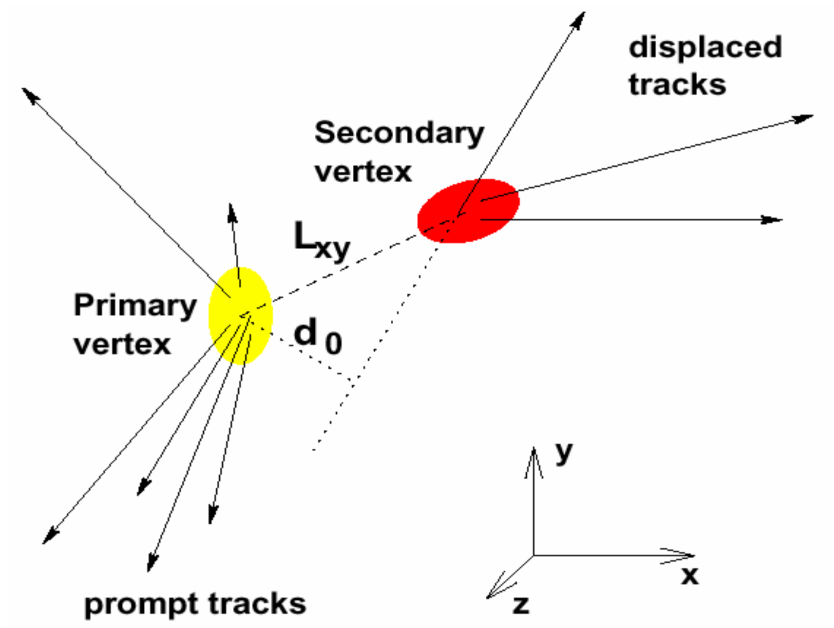
are needed to see this picture.

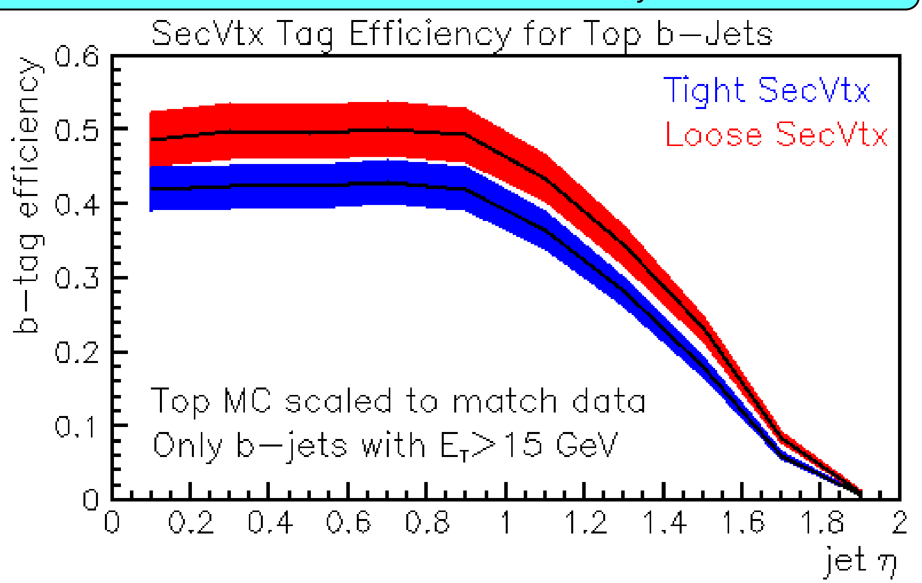
b tagging an important ingredient

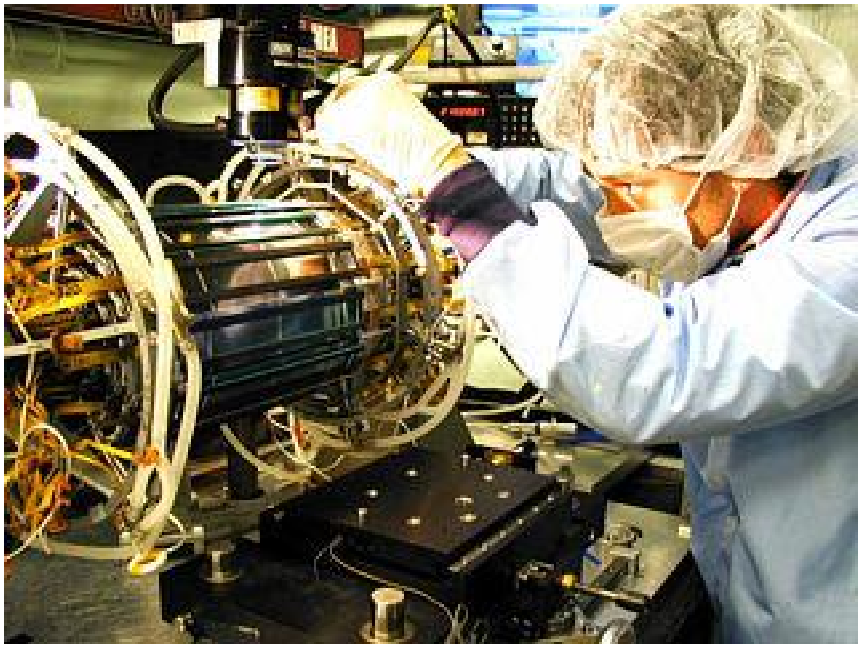
How to find a b

- Are b's different than other quarks?
  - Long lifetime $c\tau$ = 450 um
    - Displaced vertices
  - Large hadron mass - opening angle for decays
    - High impact parameter for tracks in b jets
    - 40-60 μm resolution for SVX (30 μm from beam width)
  - Semileptonic decays (high momentum lepton)



Fit displaced tracks and cut on L_{xy} significance





Findings those b's better

- There is a wealth of information in b decays.
  - Complex and complicated by detector effects
  - Synthesizing all this information is the name of the game

QuickTime™ and a
TIFF (Uncompressed) decompressor
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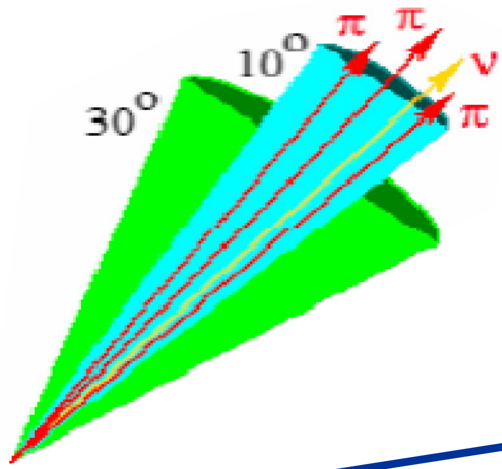
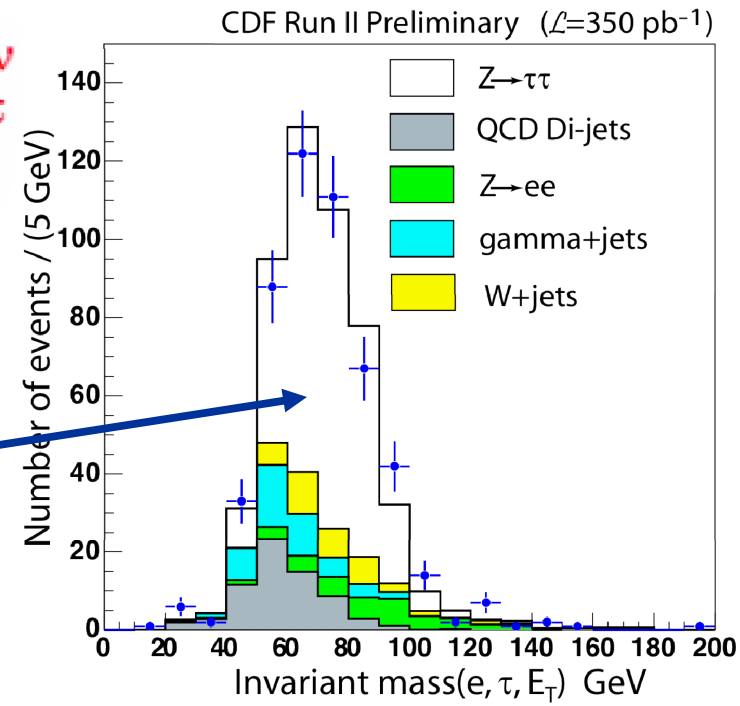
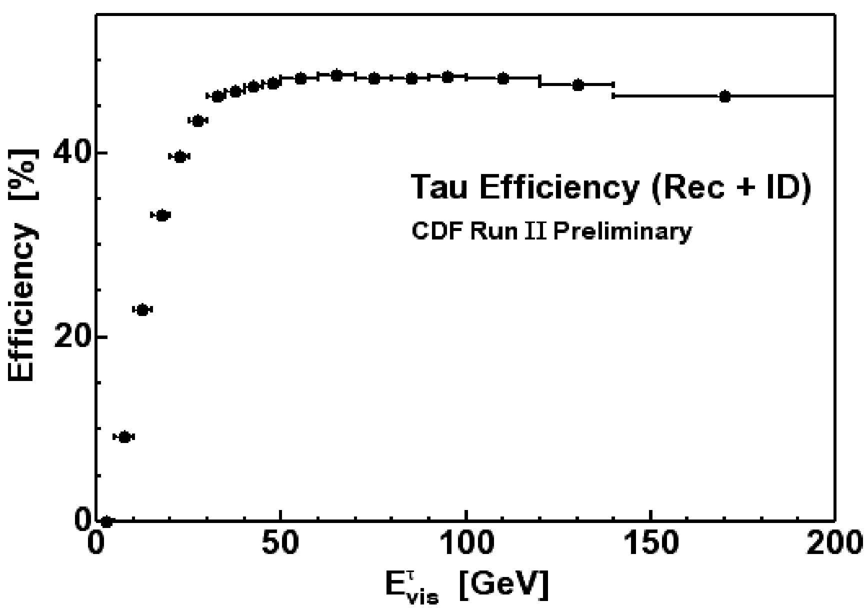
Combine multiple variable in a neural network and set the NN cut to a comfortable S/B

H→ττ

- Tough by itself
  - BR down by x10
- Associative production?
  - Lower BR
  - Taus are better than b
    - We actually have a Z→ττ
  - Don't have to rely so hard on W/Z purity
    - (τ τ jet jet) final states



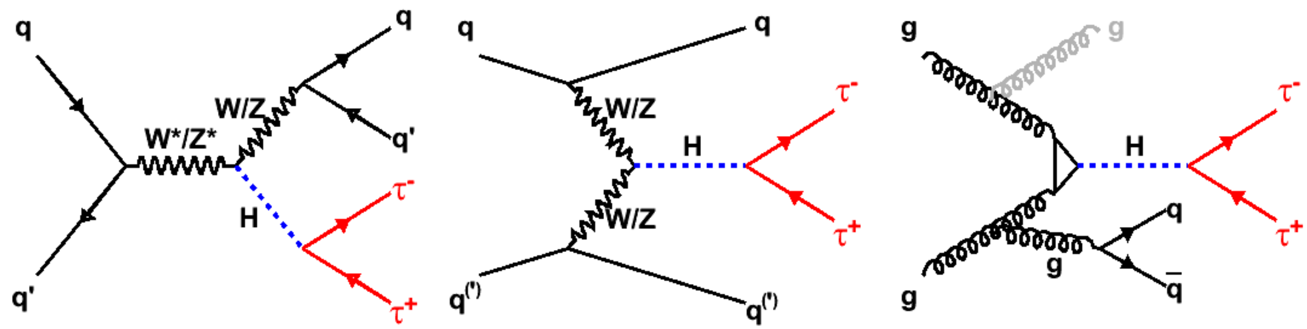




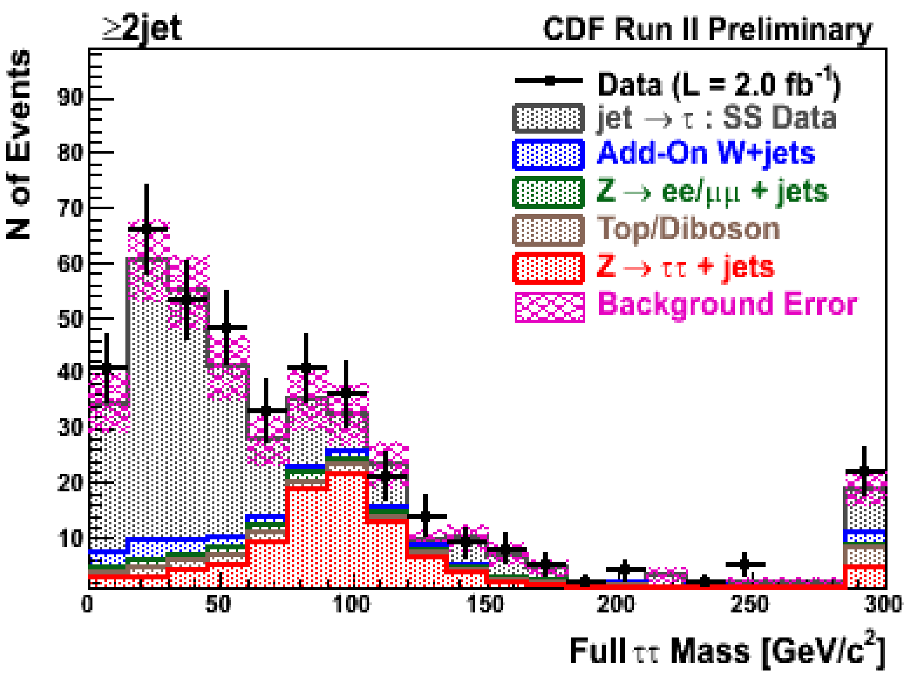
- Combination of one leptonic and one hadronic decaying tau

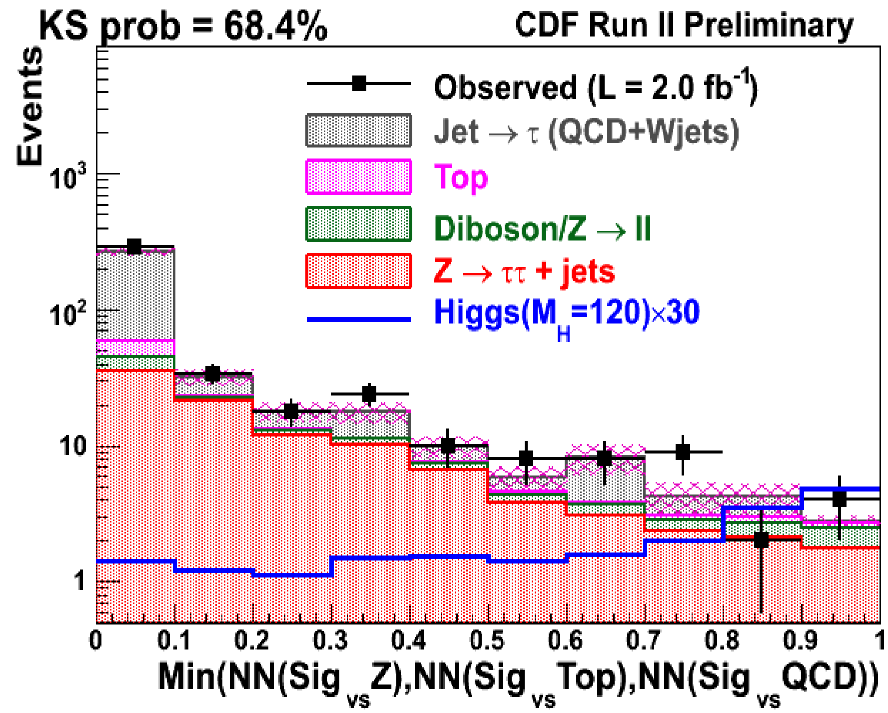
- Efficiency about the same as for b, but <0.5% fake rate

ττ+2jets



- Consider all possible channels
  - WH+ZH+VBF+ggH

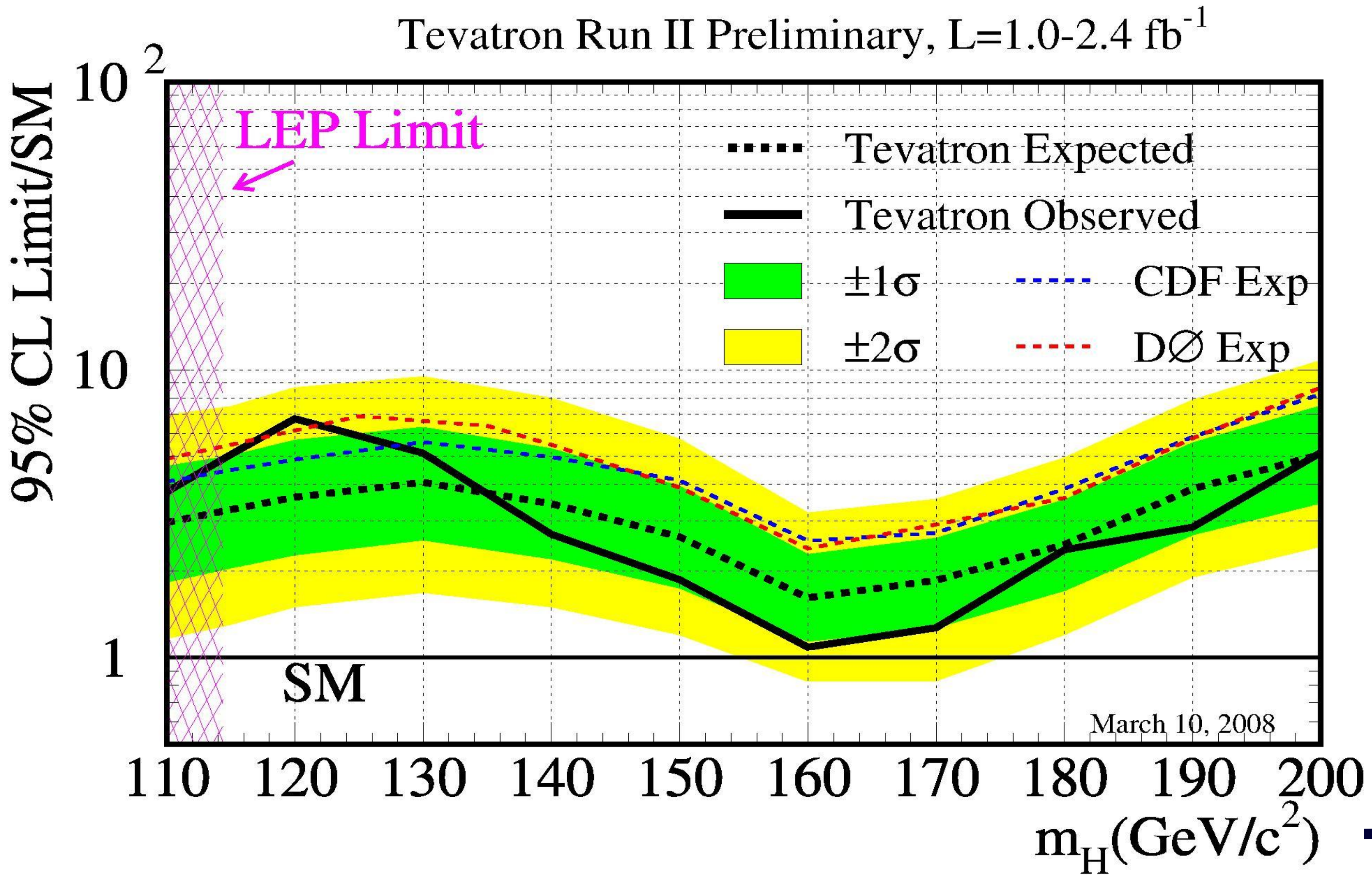




Lots of kinematics to separate signal from background

A final combination

- Though I have tried, I could not escape showing a limit plot



Conclusions

- CDF is way on its way towards the Higgs
- Detector improvements and new analysis techniques are the lifeline of any experimental physics endeavor
- There are many interesting BSM searches which I have not had time to go into
- Right now, the Tevatron and CDF are the high energy frontier of the world
- It will be a challenge to get to the Higgs but where is the fun without the challenge?
- “I haven't a clue as to how my story will end. But that's all right. When you set out on a journey and night covers the road, you don't conclude that the road has vanished. And how else could we discover the stars?”

MSSM Higgs

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are needed to see this picture.

- MSSM is a SUSY model with 2 Higgs doublets
- 5 Higgs bosons: h, H, A, H+, H-
- 2 parameters MA and tanbeta describes the MSSM Higgs sector

Production cross section enhanced by ~tan2   with respect to SM Higgs

• Braching ratio neutral Higgs:

• 8% tau pairs

• 90% b pairs

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TIFF (Uncompressed) decompressor
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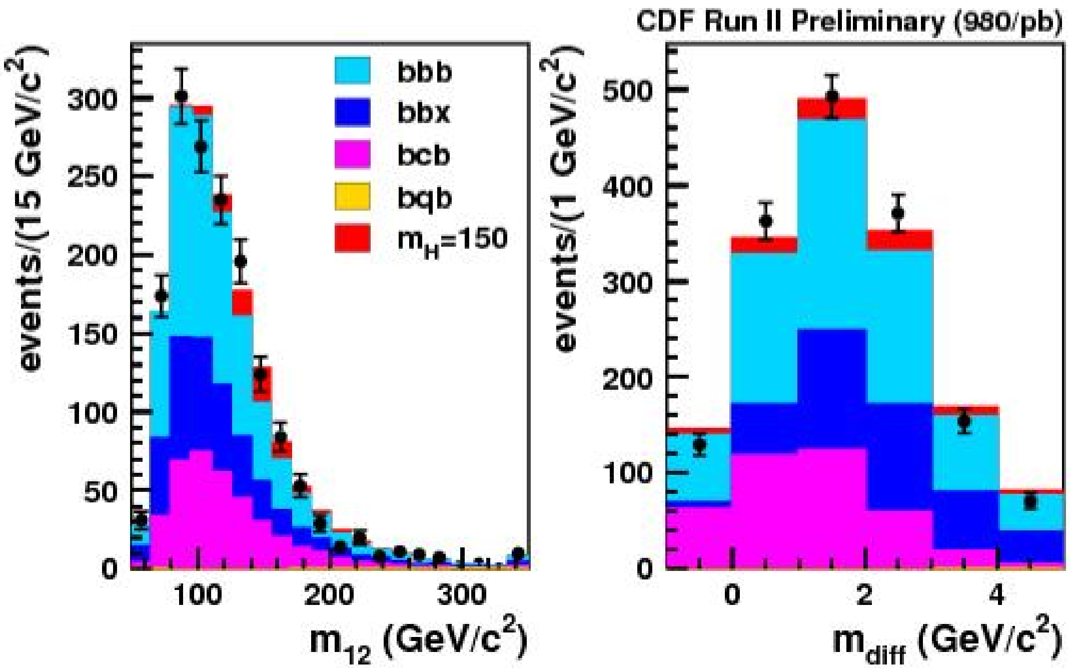
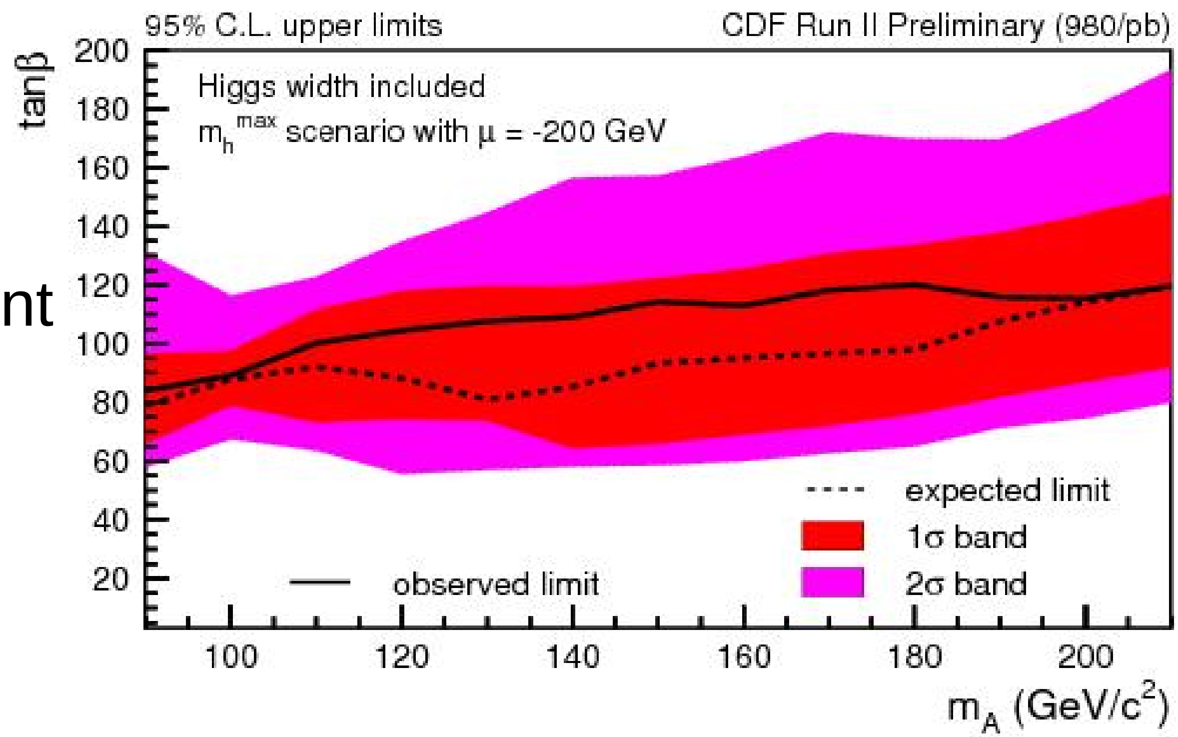
gg->H->bbb(b)

- Use data to obtain normalizations and templates for different heavy flavor production backgrounds
- Use three b tagged jets
- Fit using several variables interest

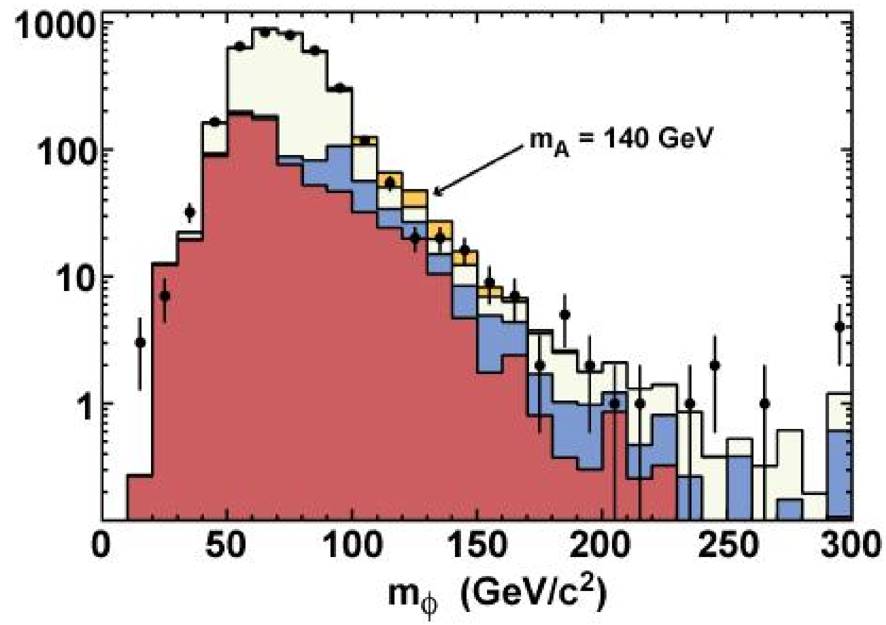
Limit is model dependent

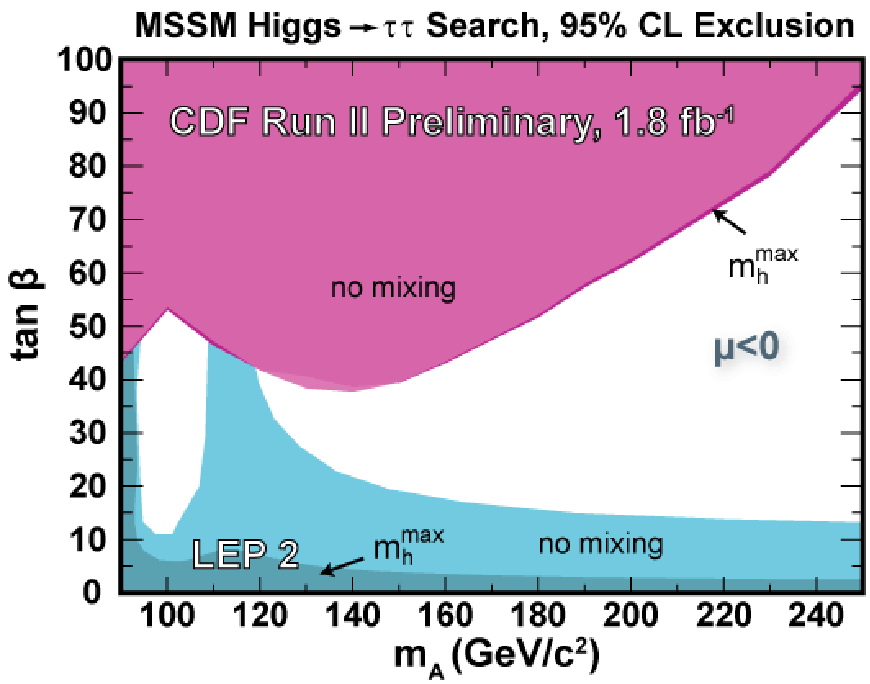




gg/bb->H->tautau

- Selection:
  - 1 leptonic tau
  - 1 had tau
- QCD background form the data
- EWK from MC
- Background and signal templates fit to data





QCD flavor production mechanisms

Experimental constraints on Higgs

- Direct search at LEP
  - m_H>114 GeV at 95%CL
- Indirect searches
  - M_t=170.9 ± 1.8 GeV
  - m_W=80.398 ± 0.025 GeV

QuickTime™ and a
TIFF (Uncompressed) decompressor
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m_H = 76 +33 -24 GeV,
m_H < 144 GeV @ 95% CL