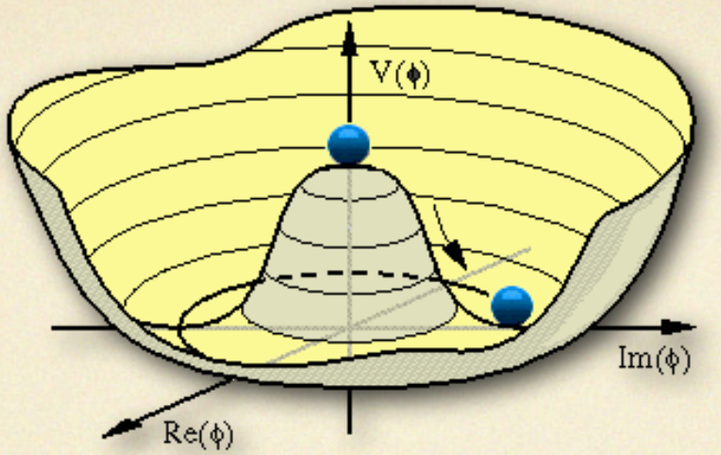



# Search for the SM Higgs Boson at the Tevatron

Brian L. Winer
The Ohio State University
for
The CDF and DO Collaborations

APS Meeting, St. Louis, April 12, 2008

# Standard Model Higgs

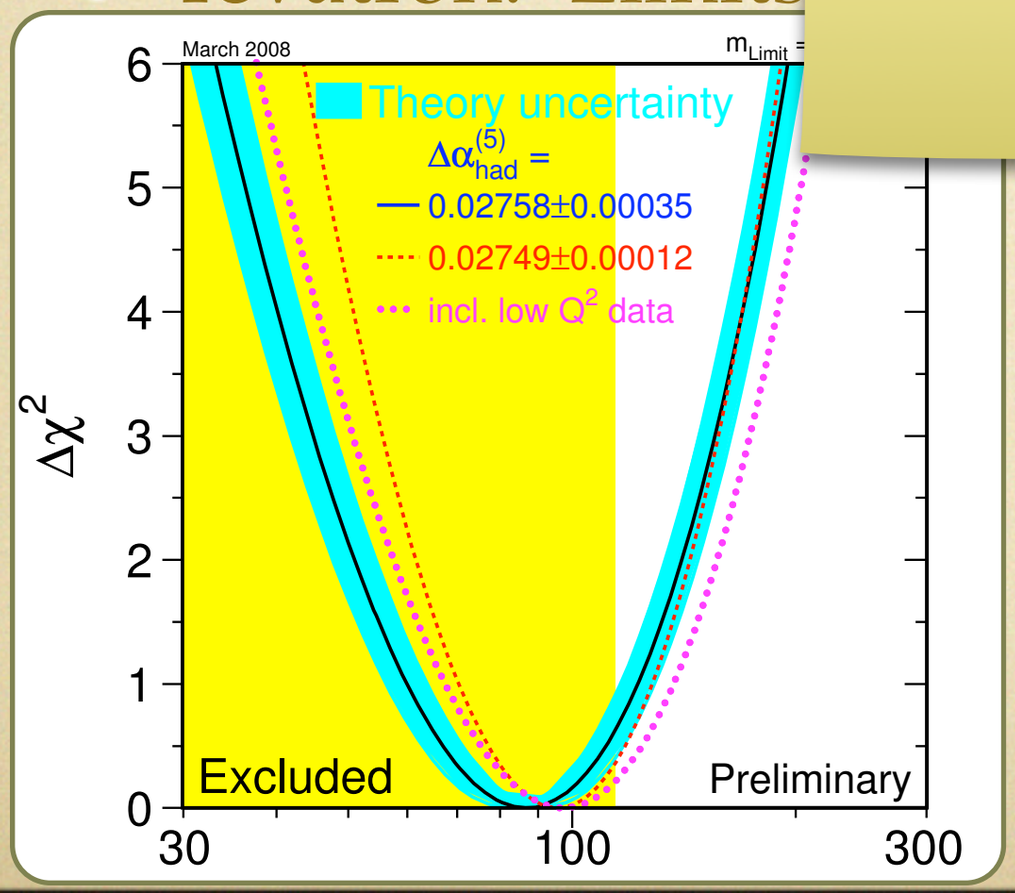
- SM Higgs is the simplest way to break EWK symmetry.
- Indirect Constraints (SM Parameters: $M_W$ , $M_t$ , etc)

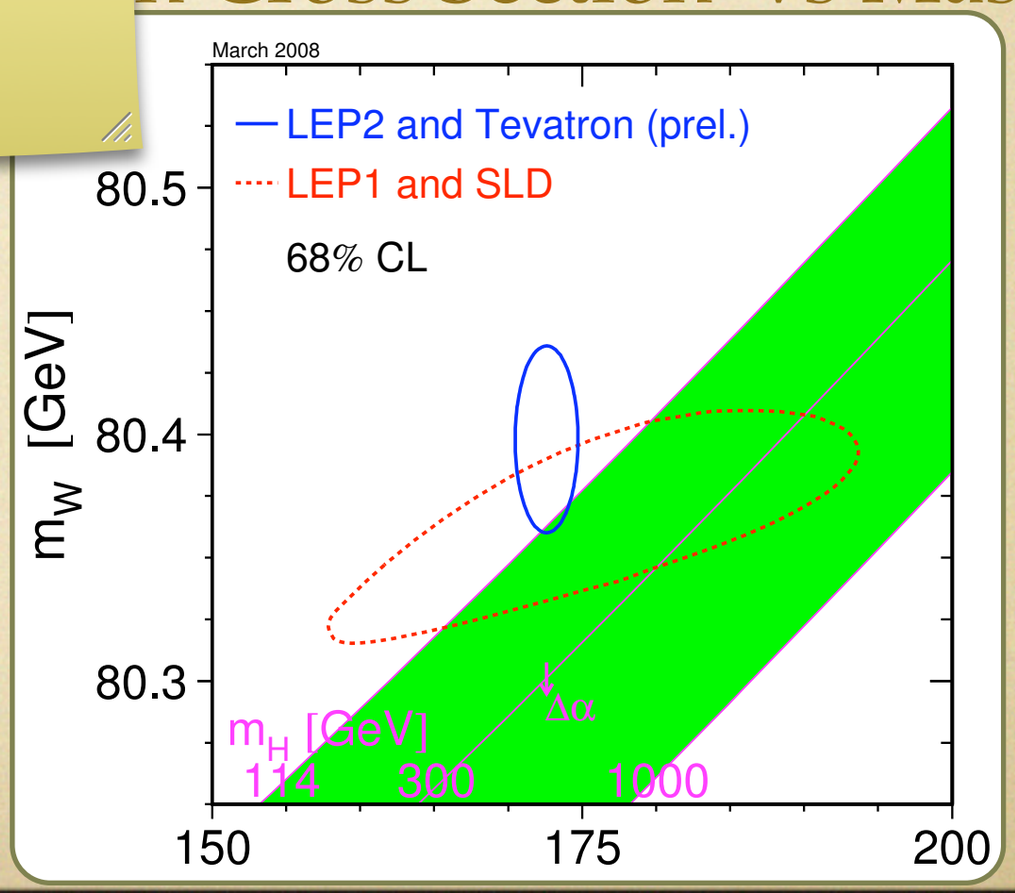
New 3/08

**$m_H = 87^{+36}_{-27}$ GeV/$c^2$**
**$m_H$ < 160 GeV/$c^2$ @ 95 % CL**

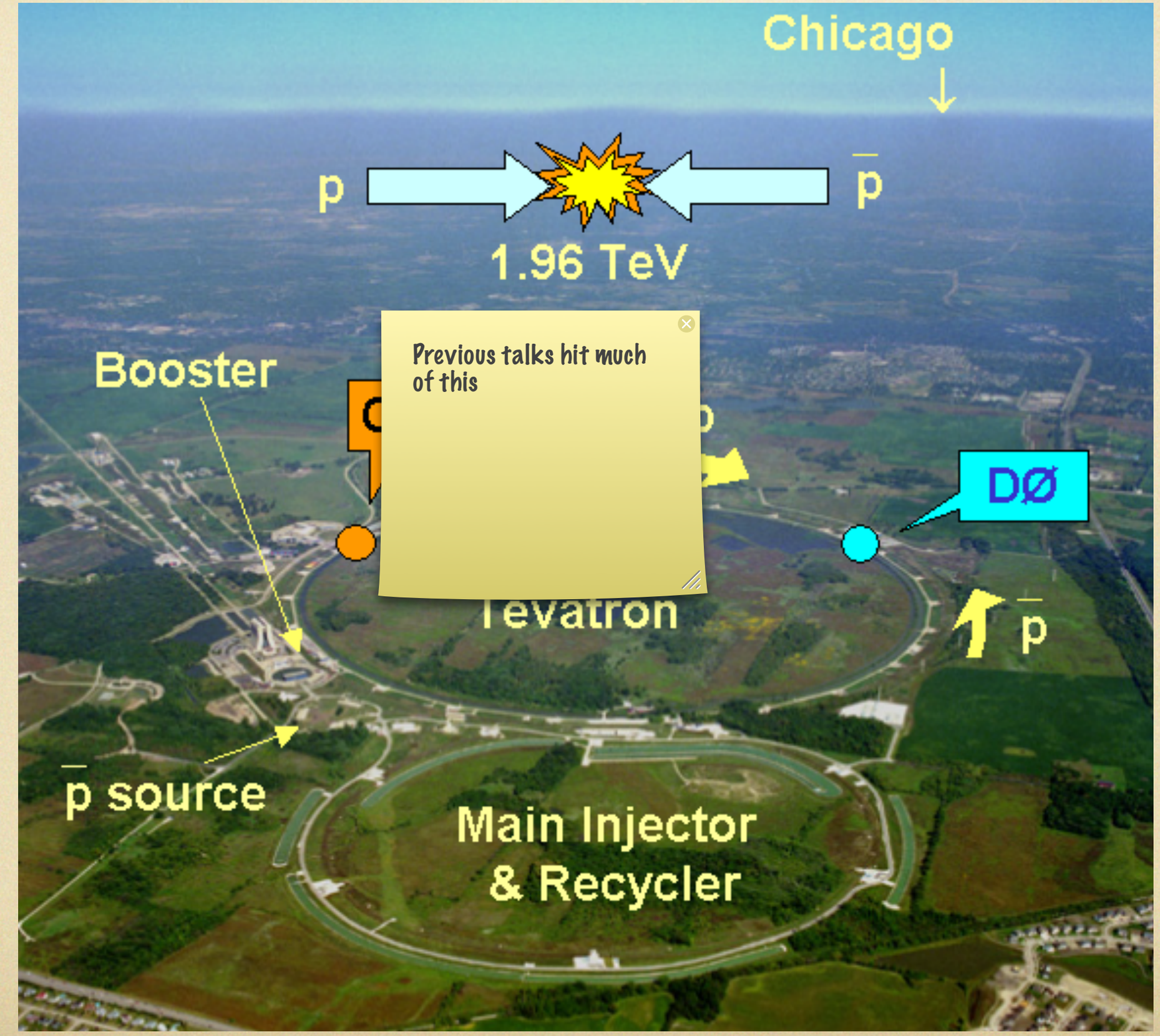
- Direct Searches
  - LEP: $m_H > 114$ G
  - Tevatron: Limits n Cross Section vs Mass.

Add limit with LEP Limit



# Tevatron and Experiments




Previous talks hit much of this

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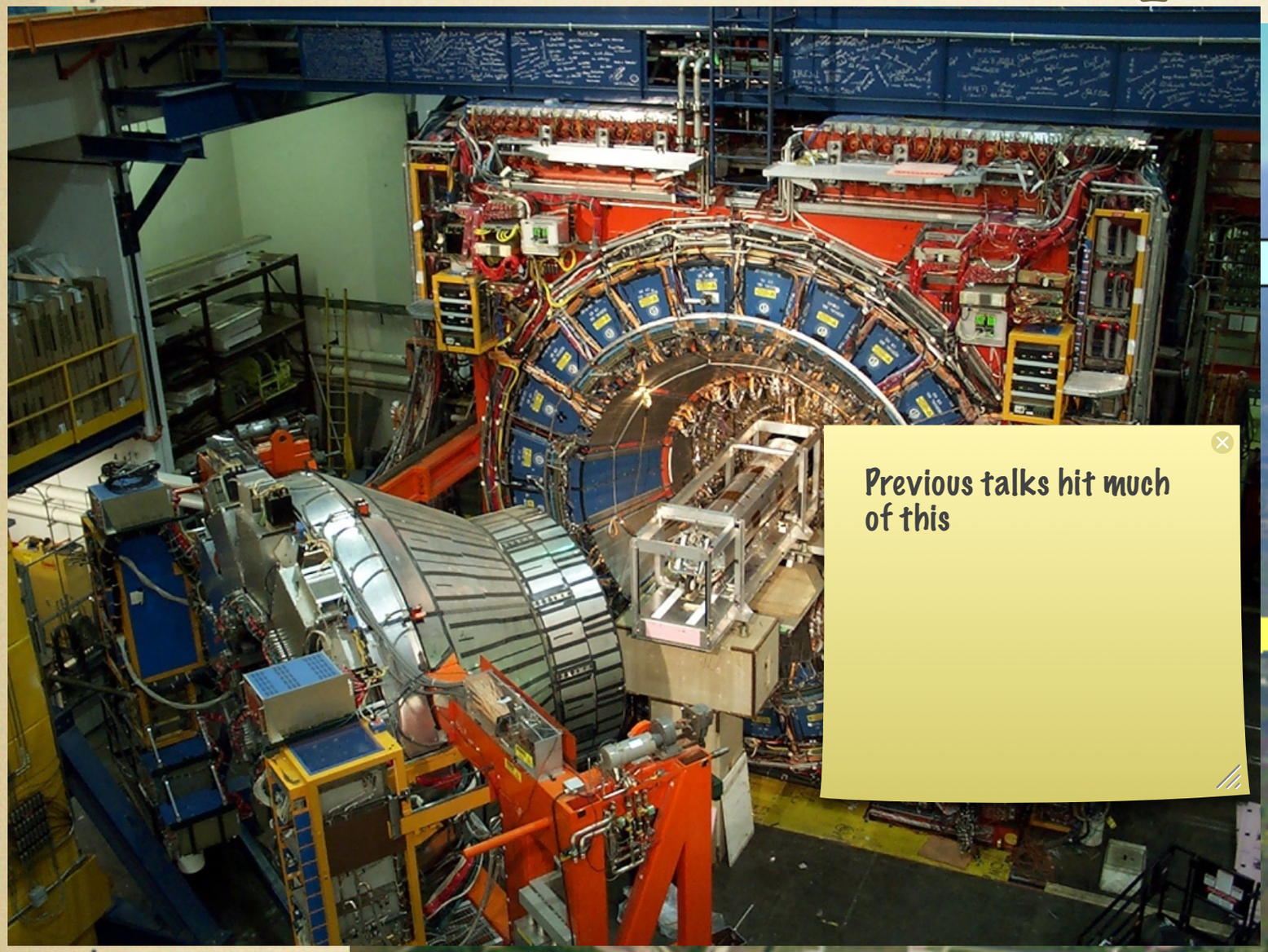

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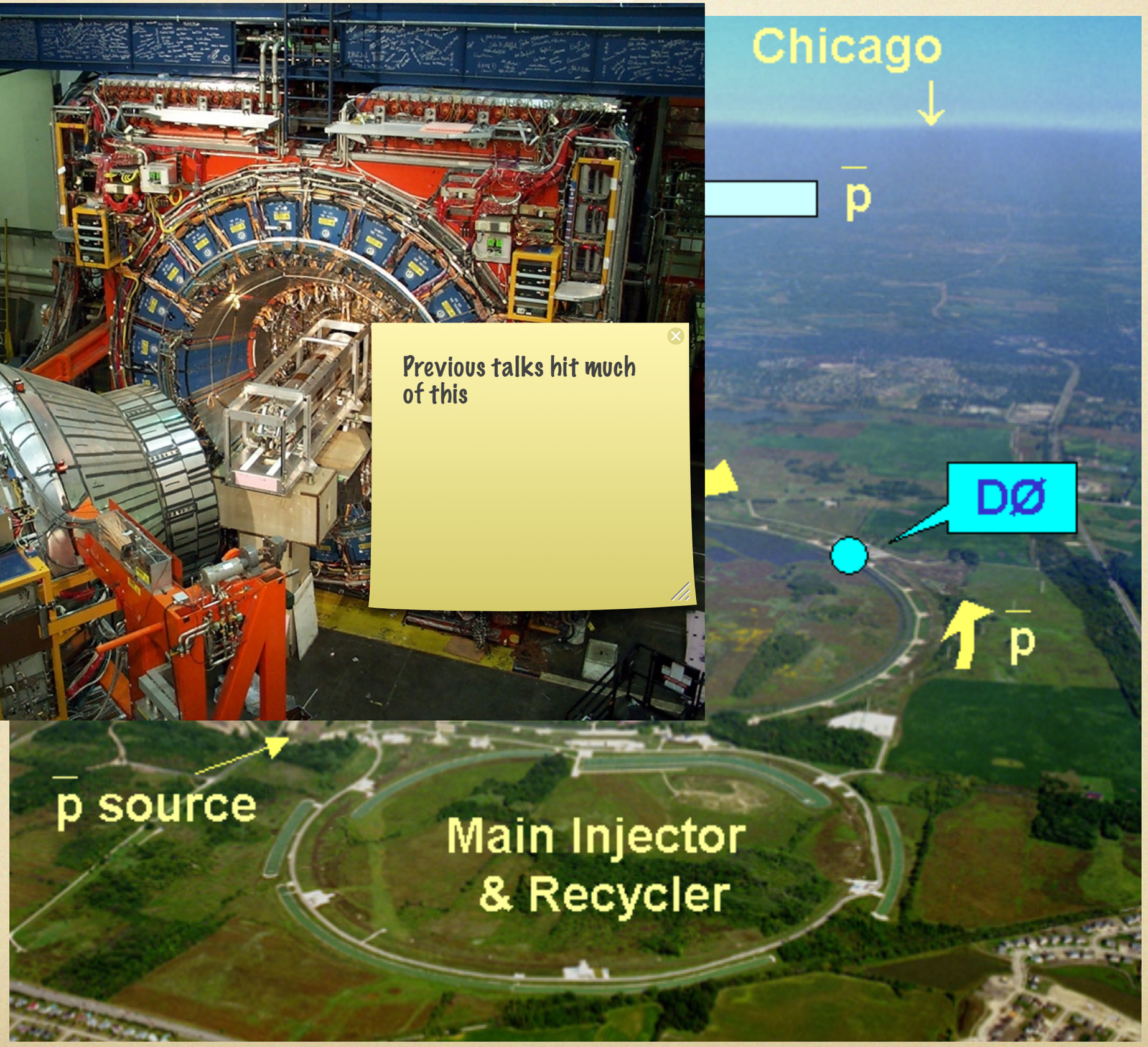

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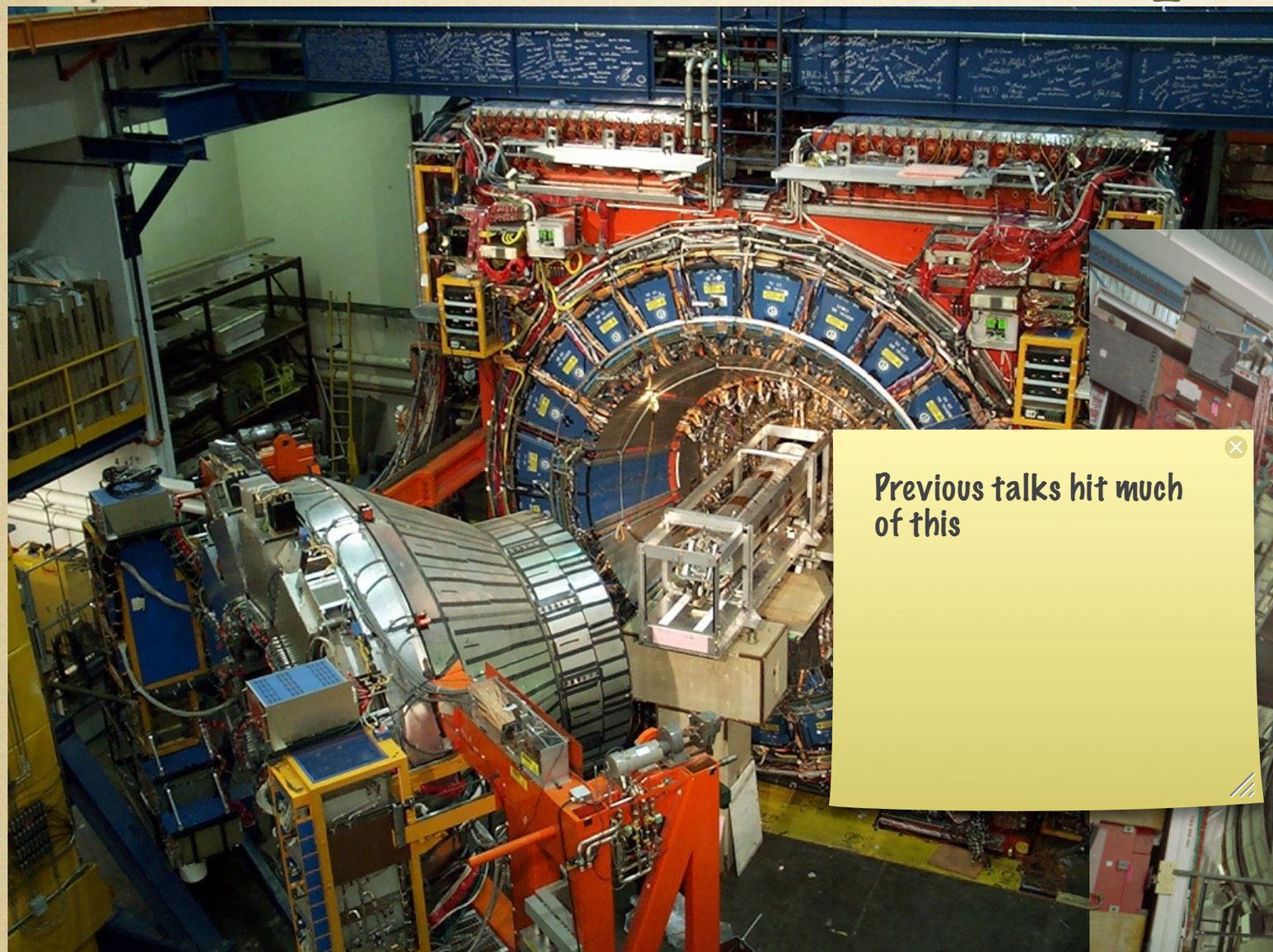

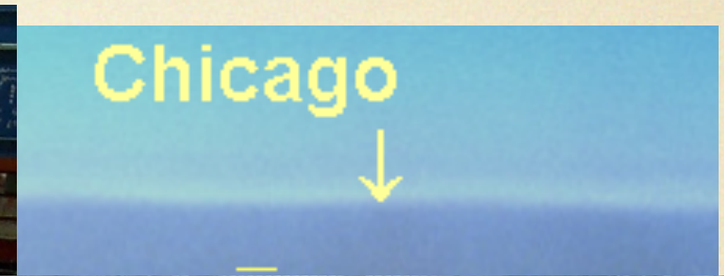


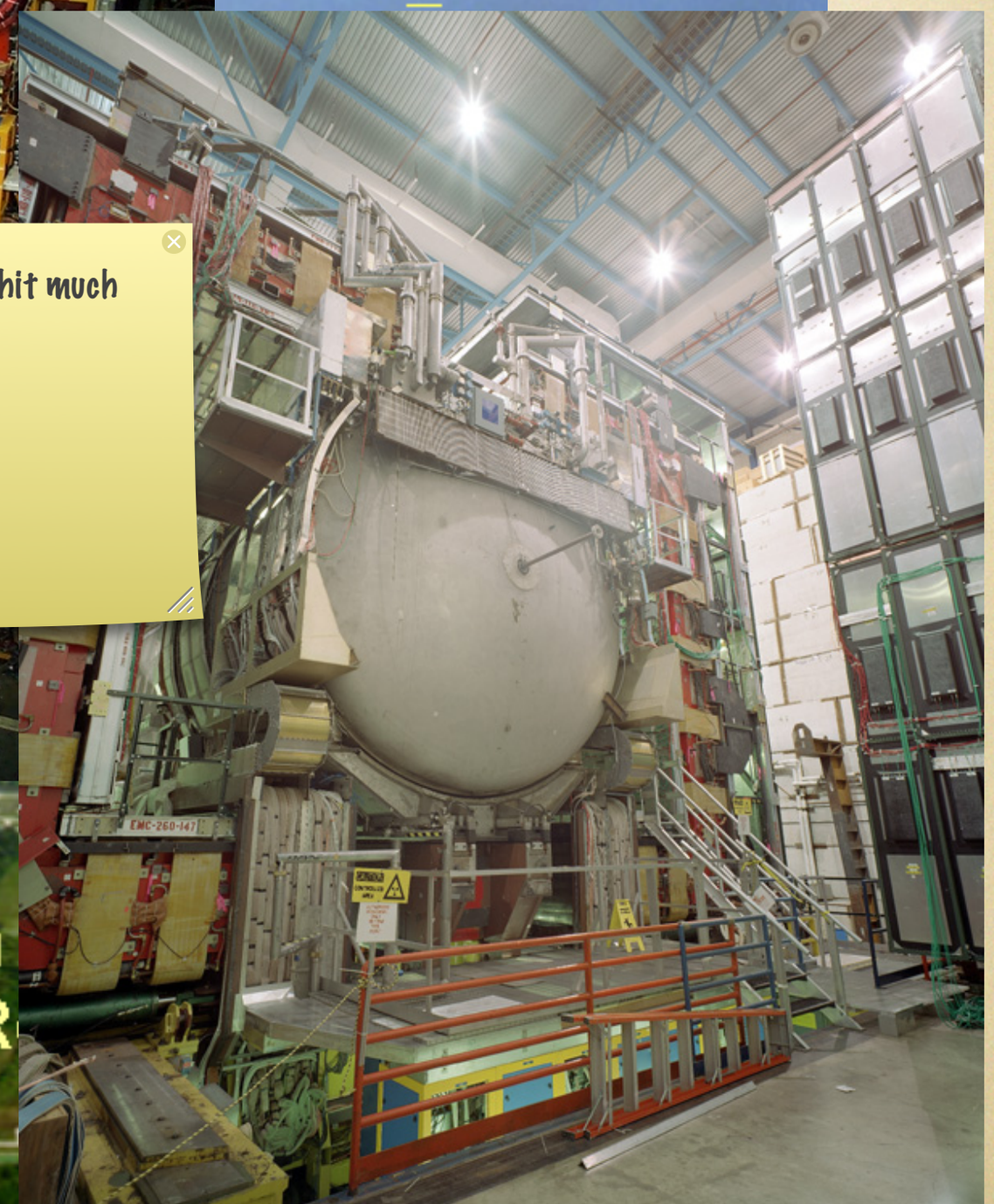

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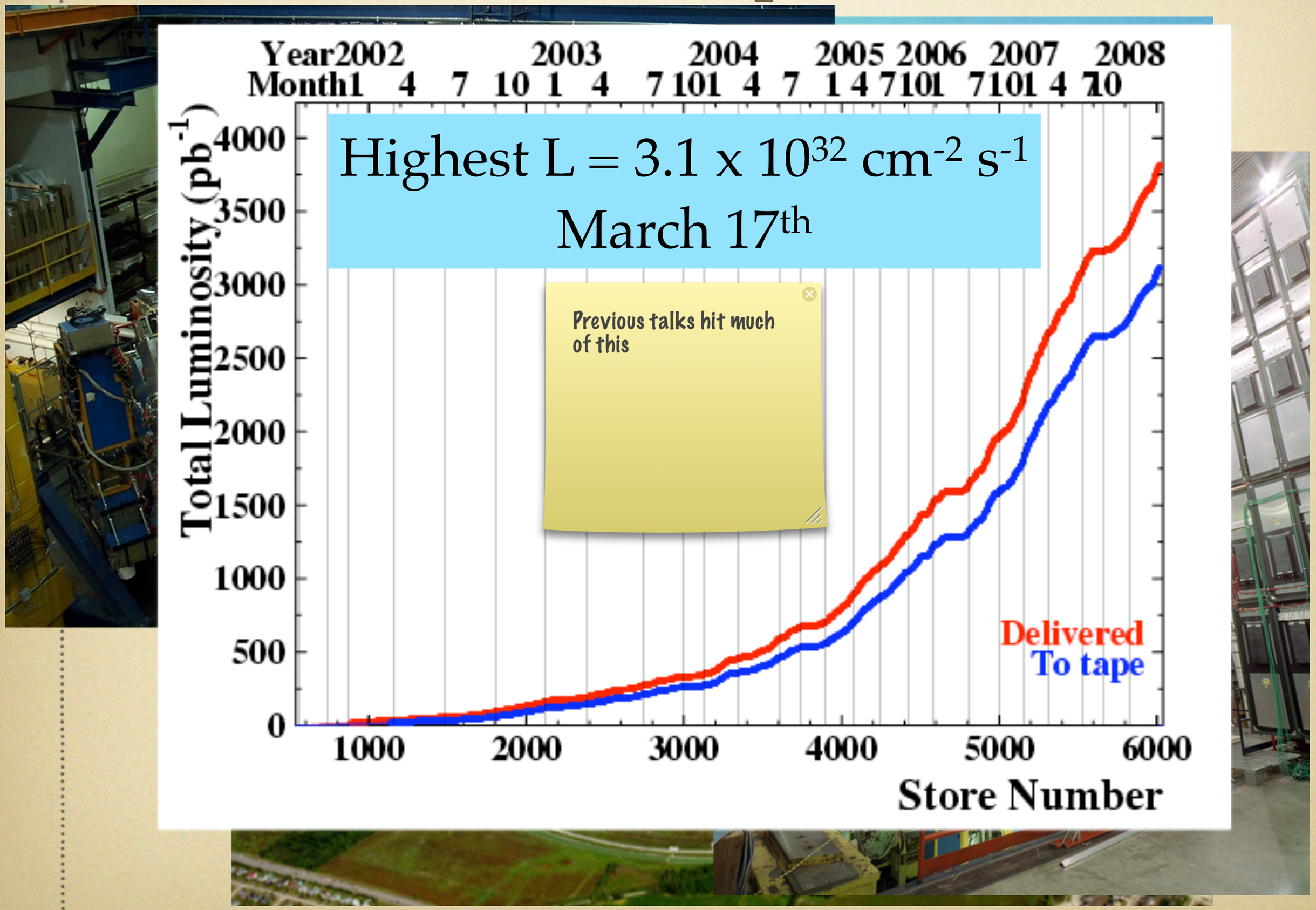

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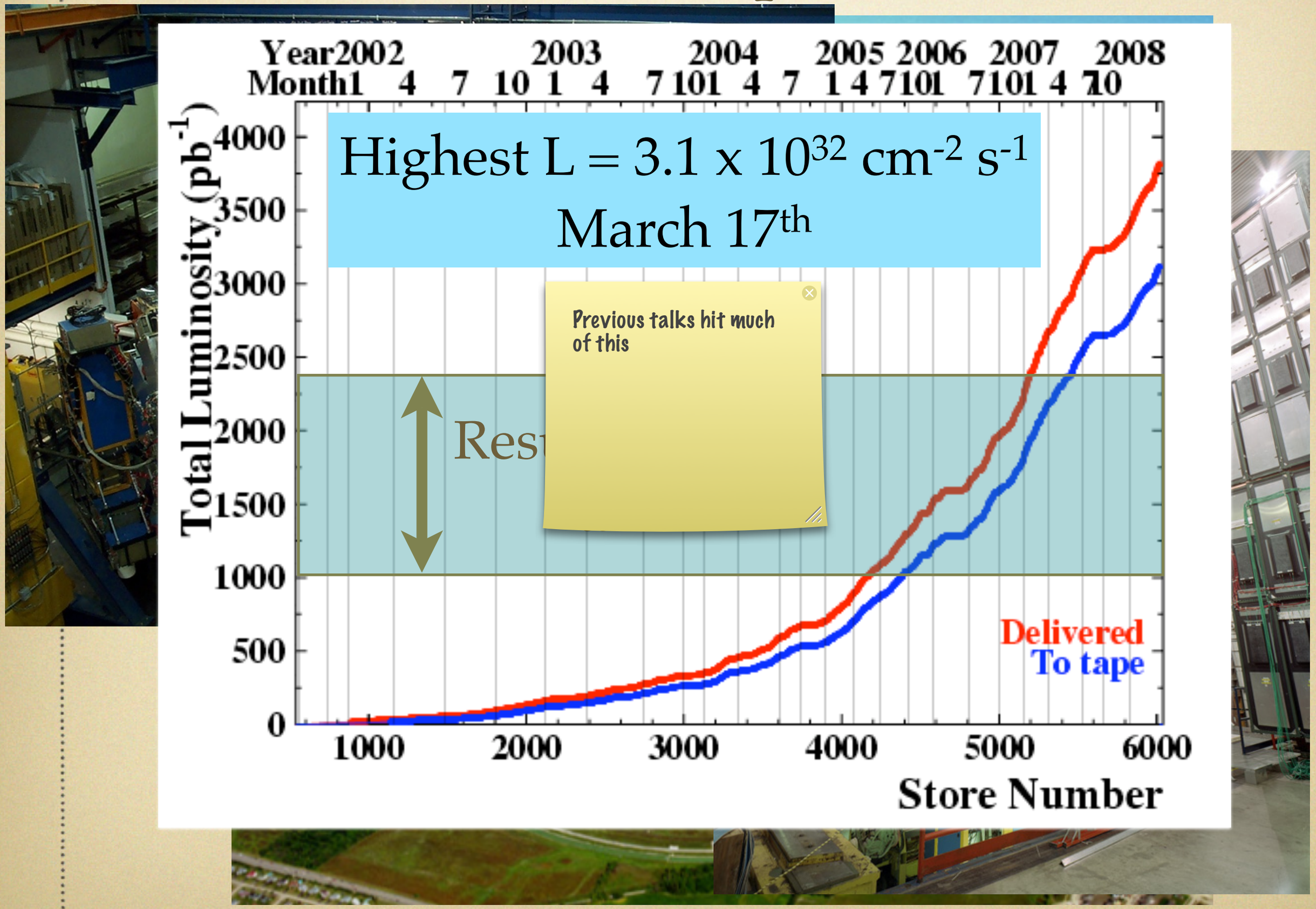
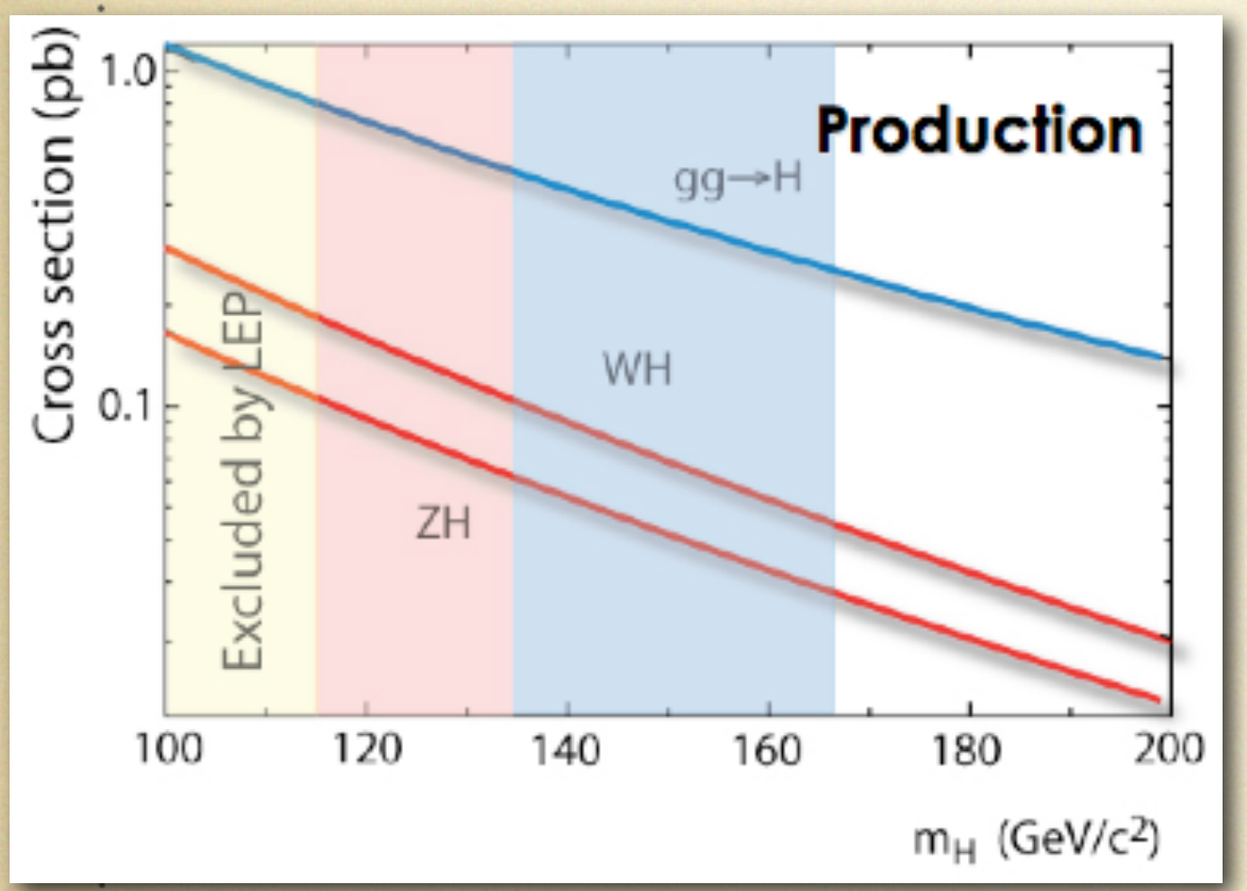
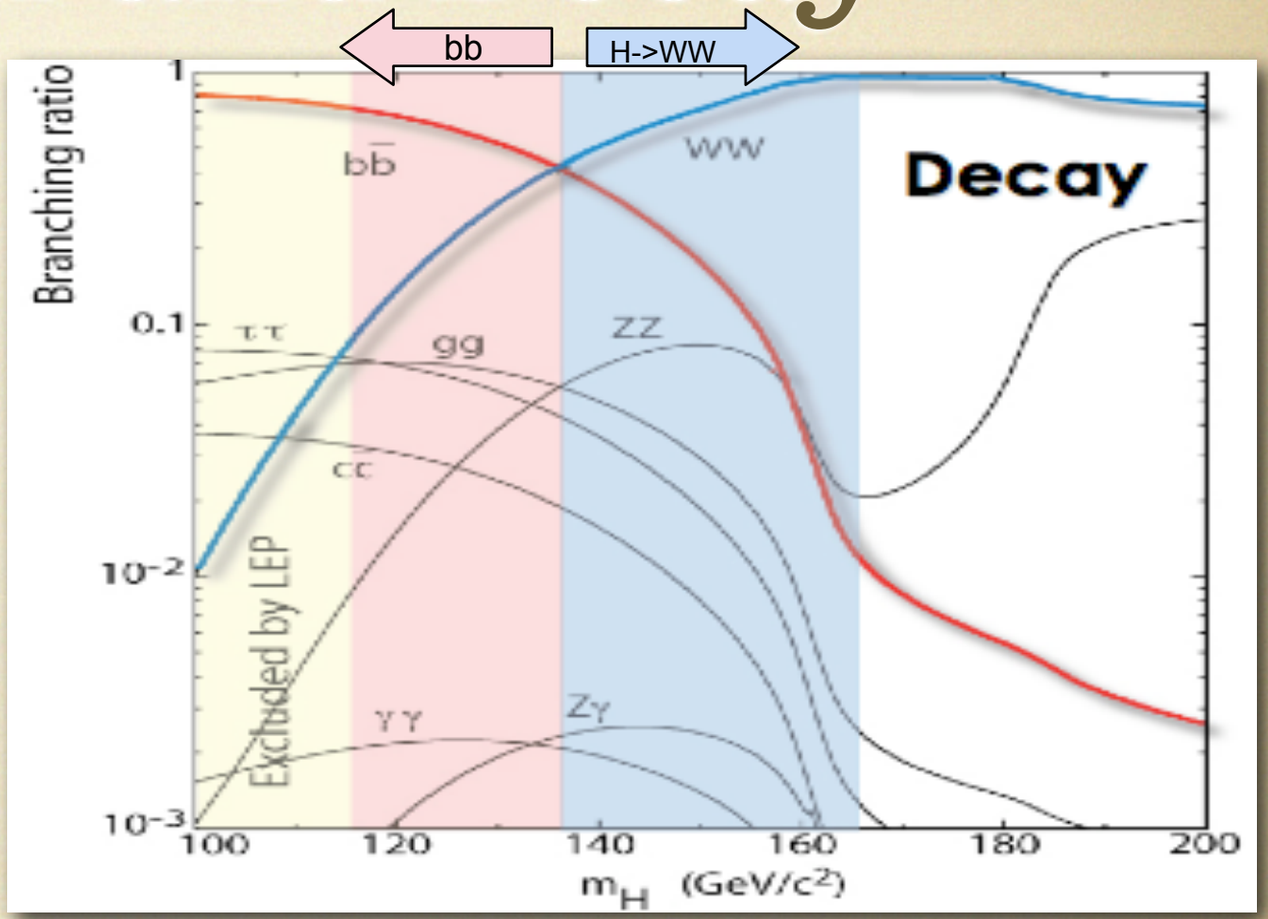


# Production and Decay



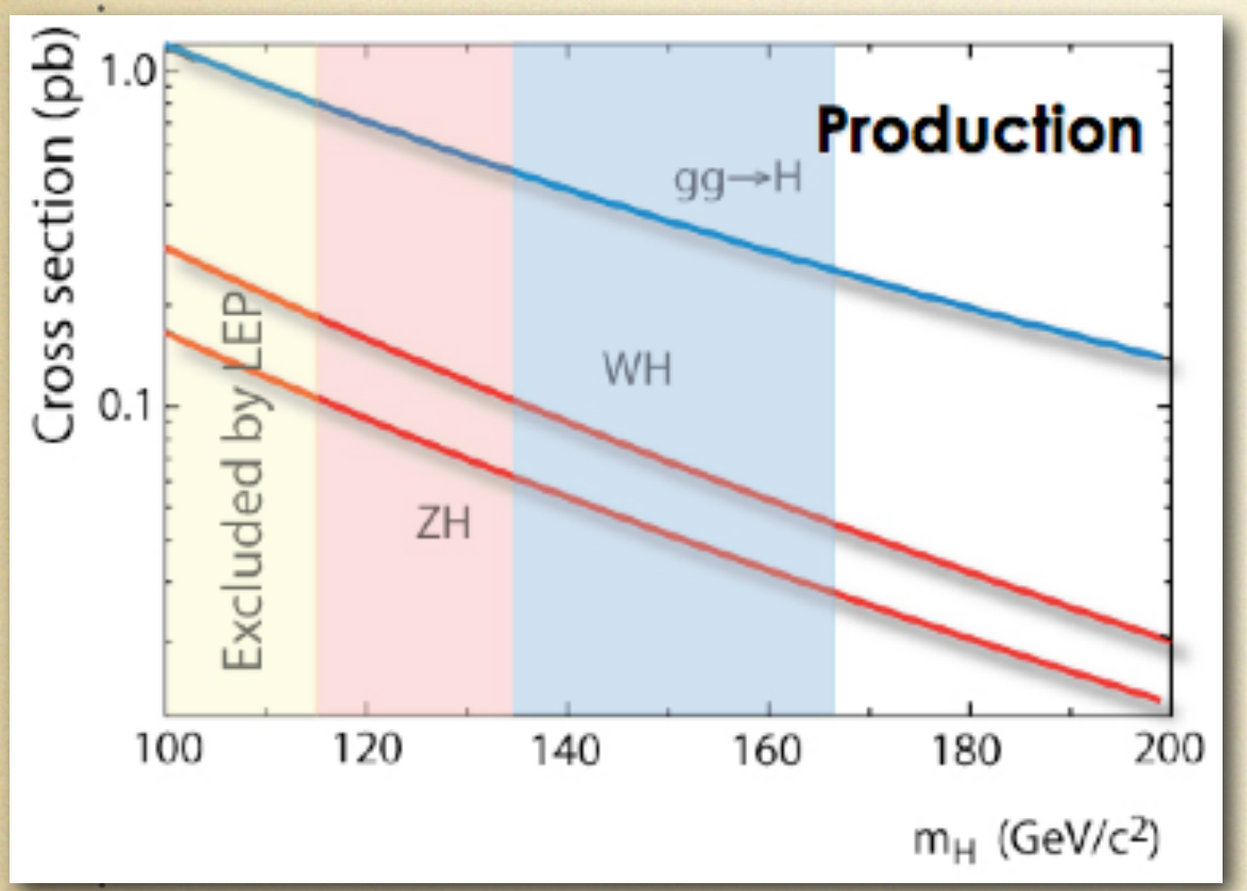



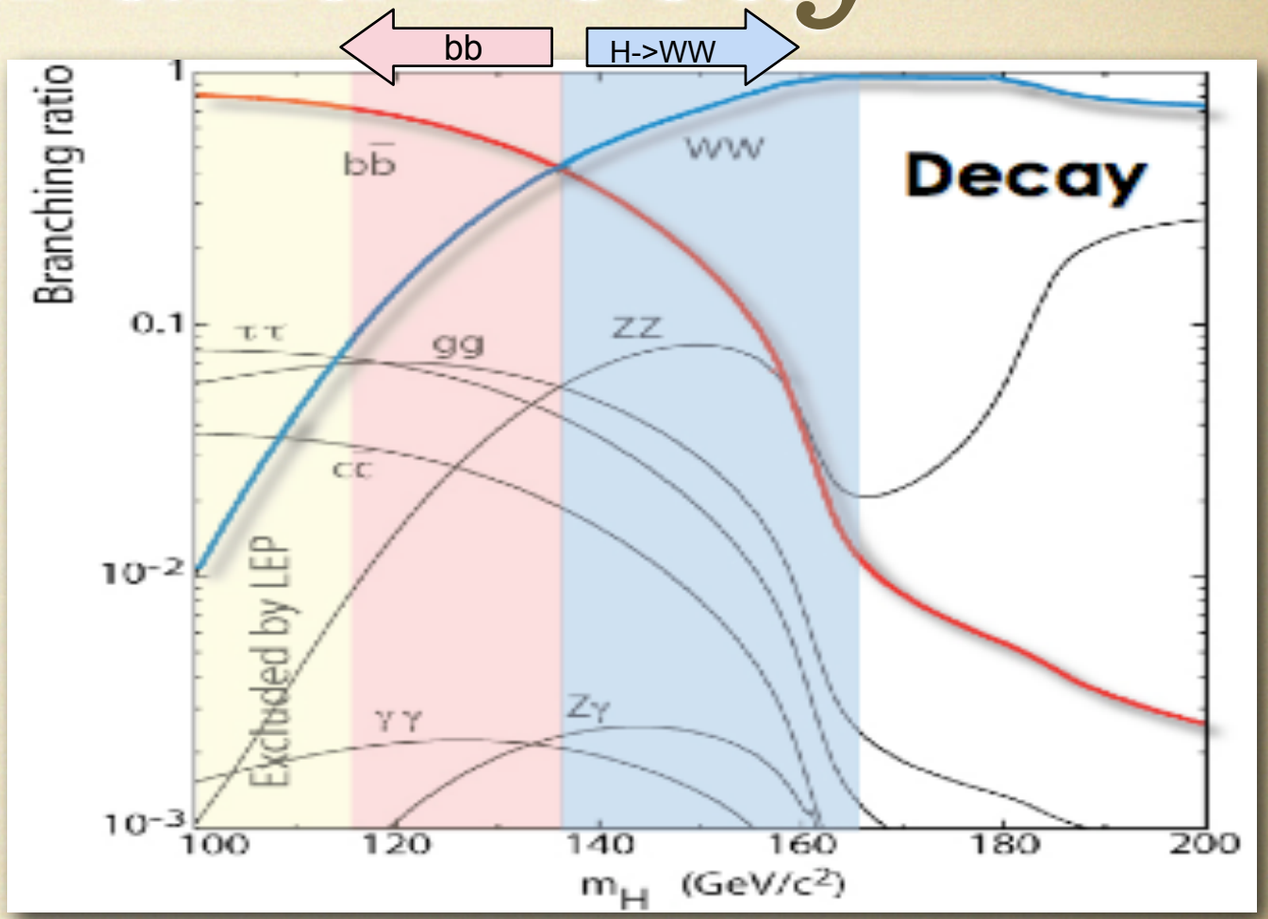

## Low Mass Final States

$$WH \to \ell\nu b\bar{b}$$
$$ZH \to \ell\ell b\bar{b}$$
$$ZH \to \nu\nu b\bar{b}$$
$$WH \to (\ell)\nu b\bar{b}$$

$$VH,\ VBF, H \to \tau\tau + 2j$$

# Production and Decay




## Low Mass Final States

$WH \to \ell\nu b\bar{b}$ → 1 High $P_T$ Lepton + $\not{E}_T$ + b jets

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

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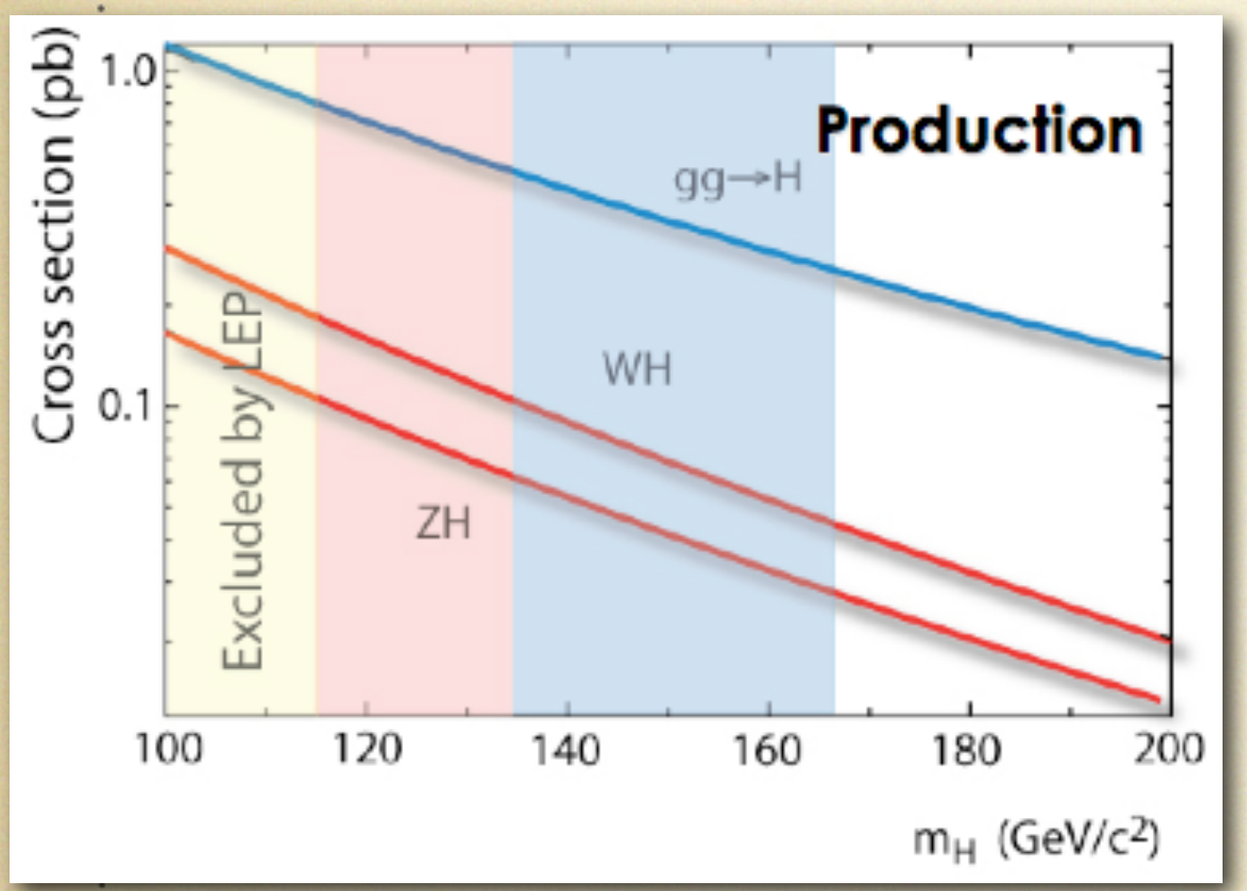


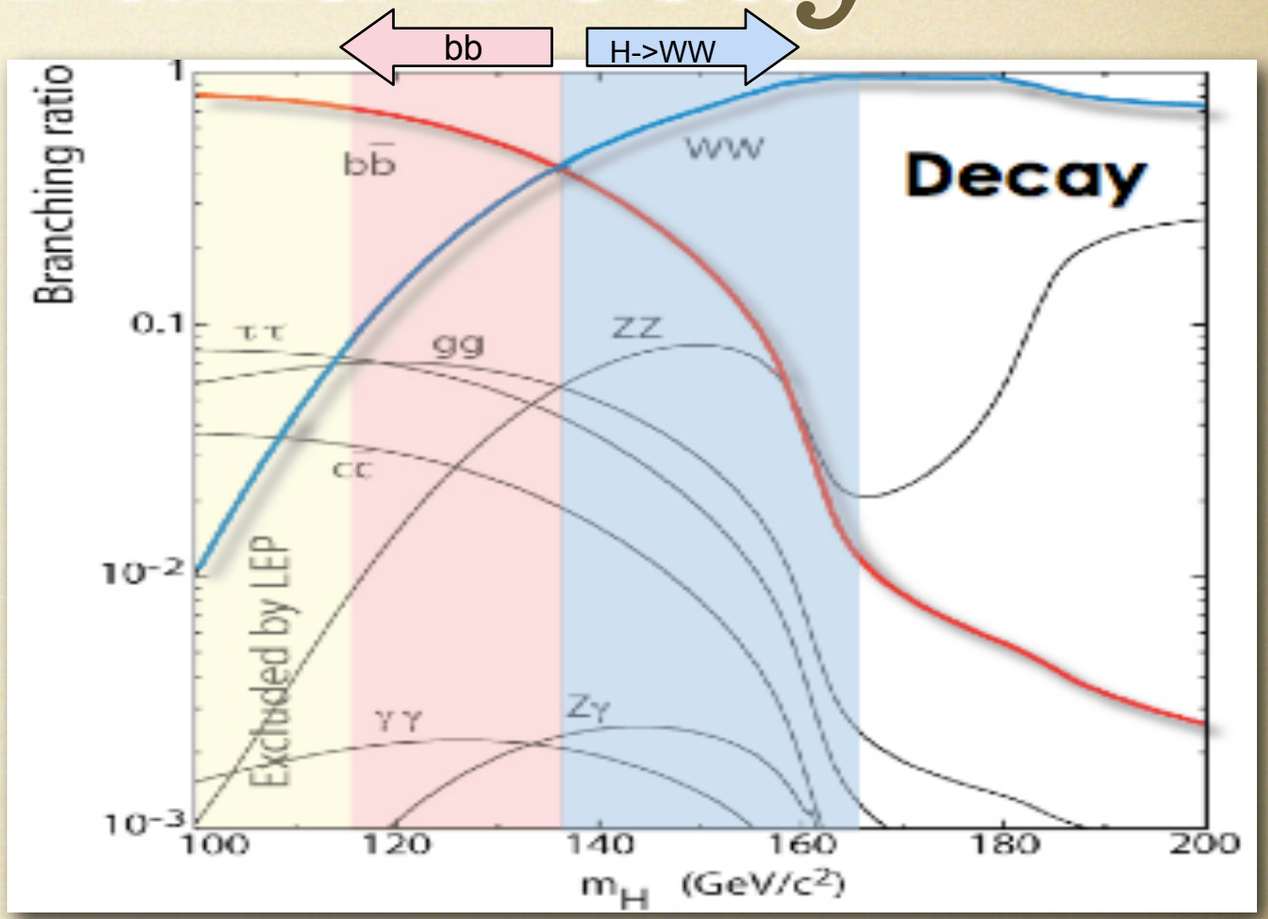


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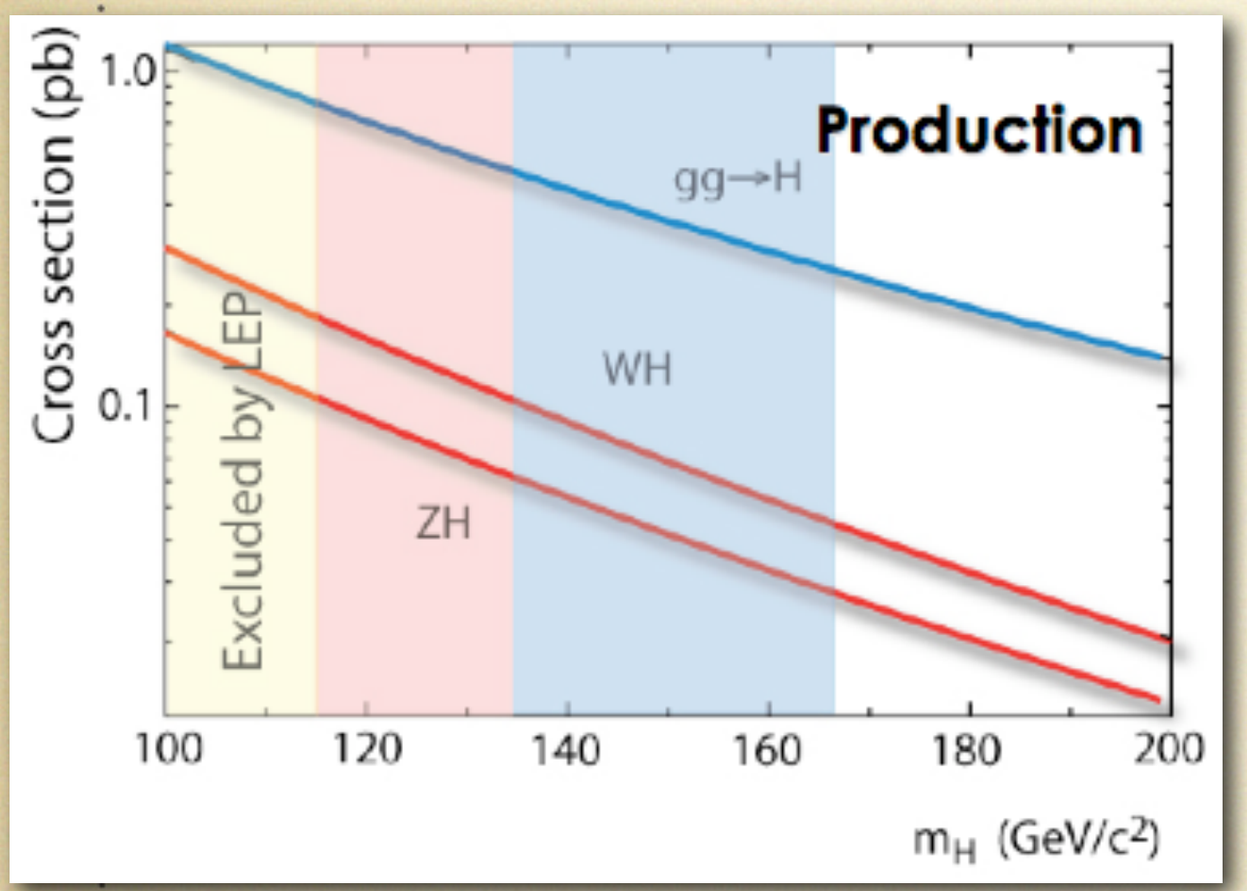


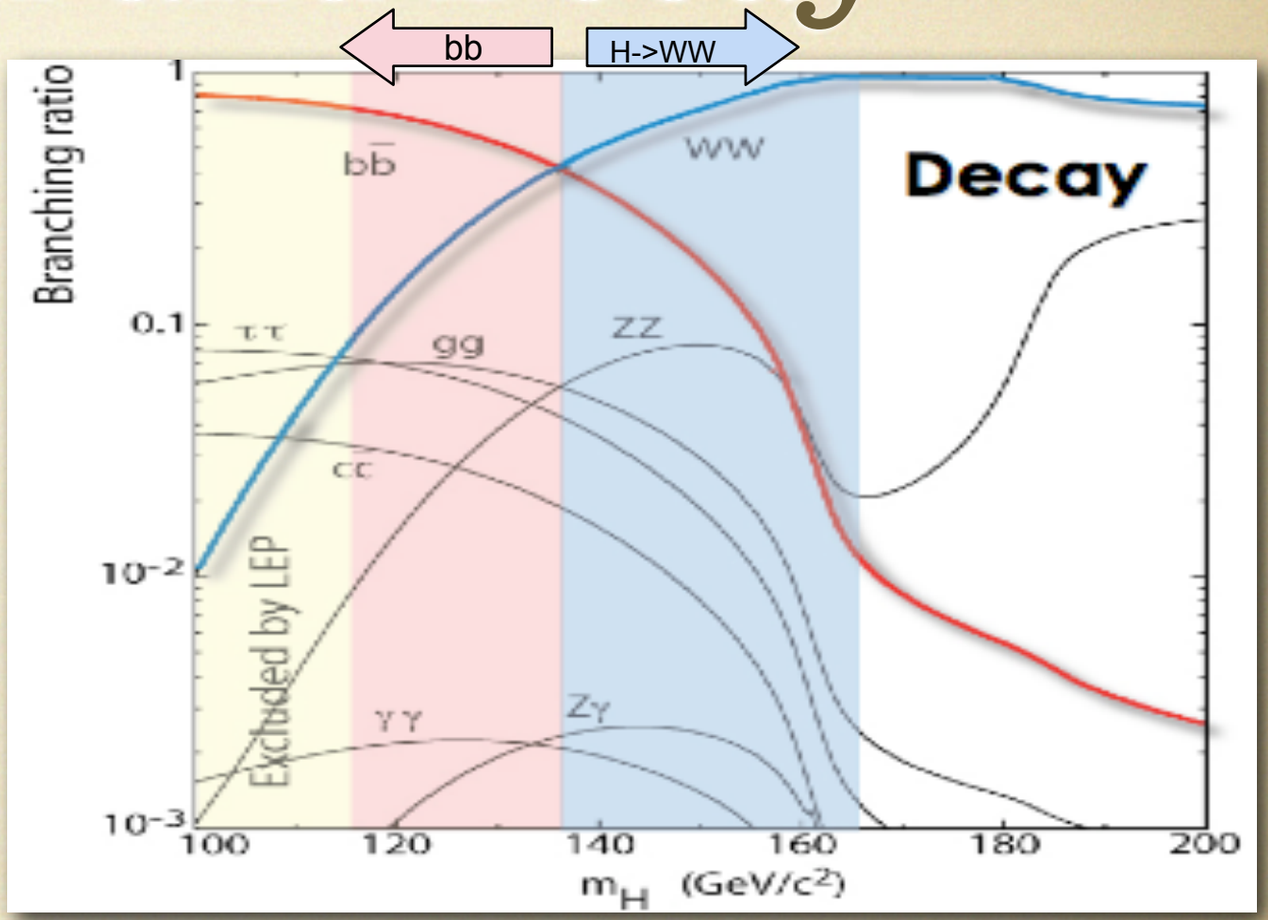


## Low Mass Final States

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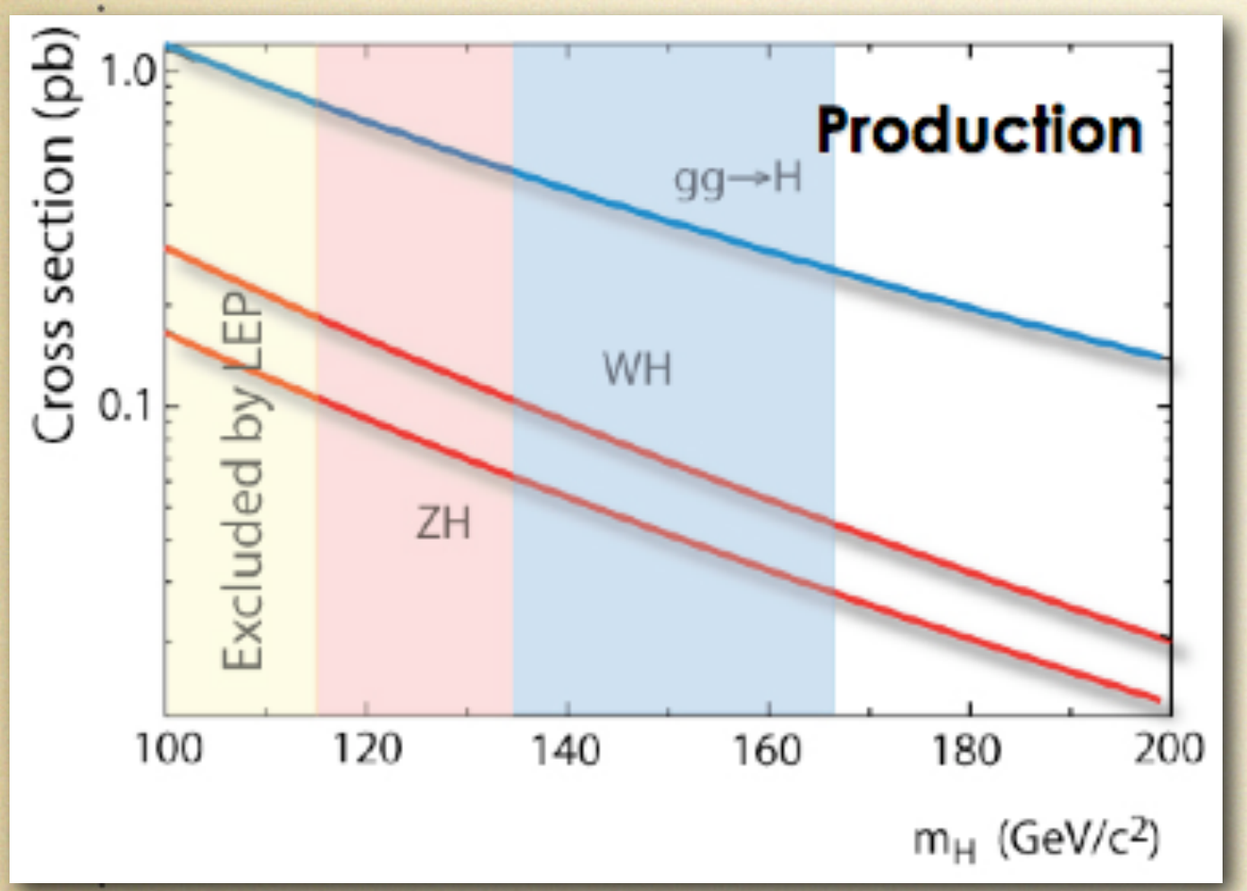
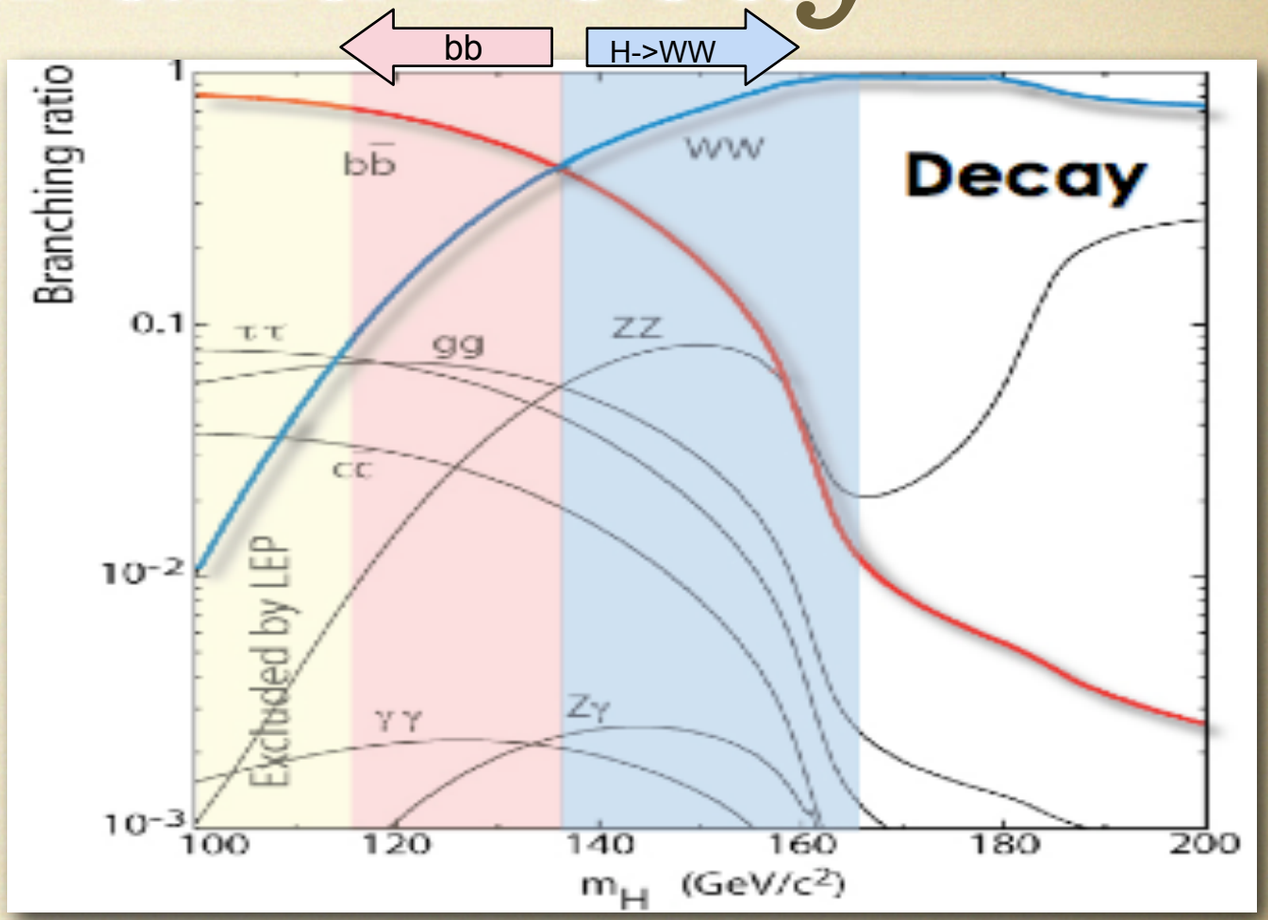
$ZH \rightarrow \nu\nu b\bar{b}$
$WH \rightarrow (\ell)\nu b\bar{b}$ → 0 High $P_T$ Leptons + $\not{E}_T$ + b jets

$VH,\ VBF, H \rightarrow \tau\tau + 2j$

# Production and Decay

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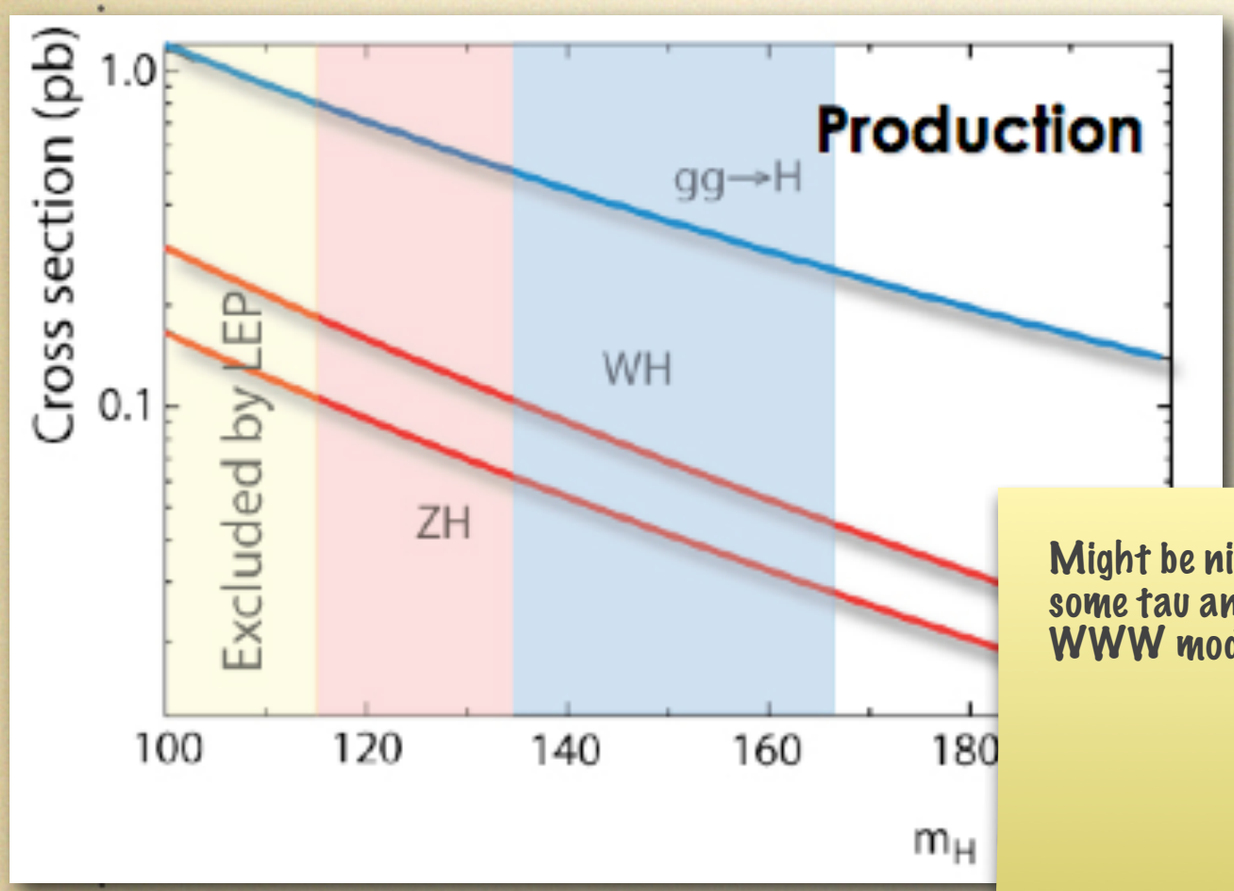
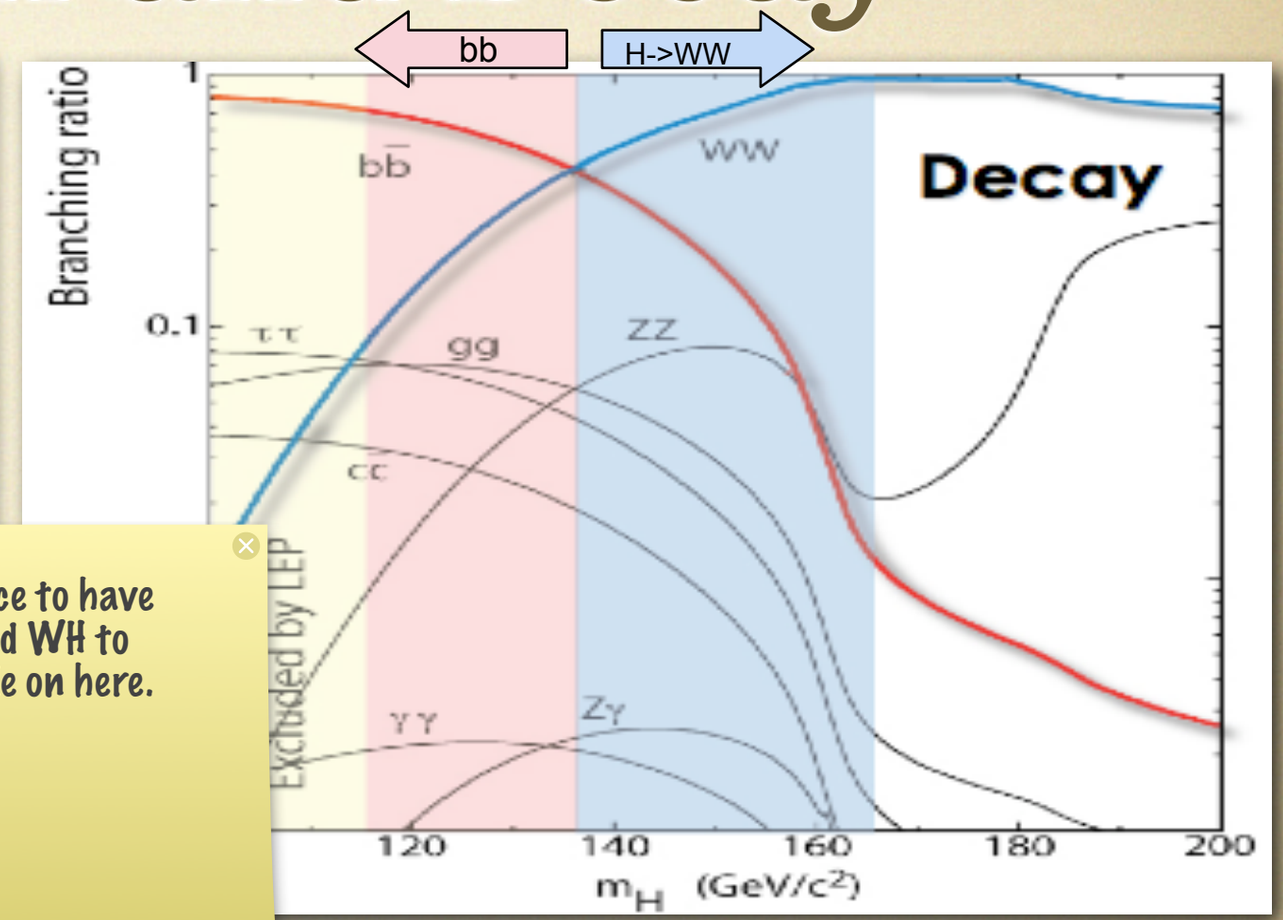
$VH,\ VBF, H \rightarrow \tau\tau + 2j$ → 1 Lepton + Trk(s)+ jets

# Production and Decay



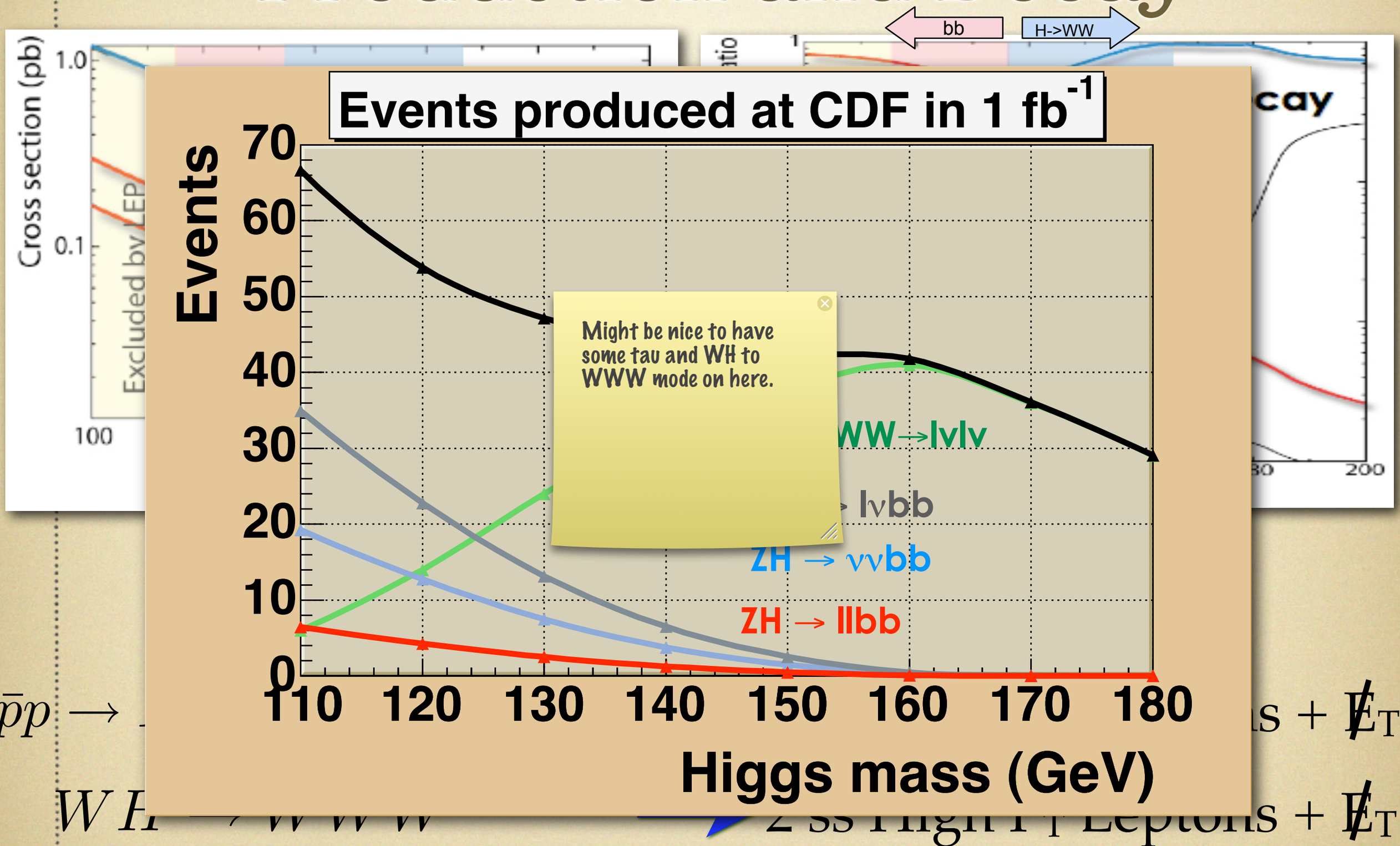

Might be nice to have some tau and WH to WWW mode on here.

## High Mass Final State

$\bar{p}p \rightarrow H \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$ → 2 High $P_T$ Leptons + $\not{E}_T$

$WH \rightarrow WWW^*$ → 2 ss High $P_T$ Leptons + $\not{E}_T$

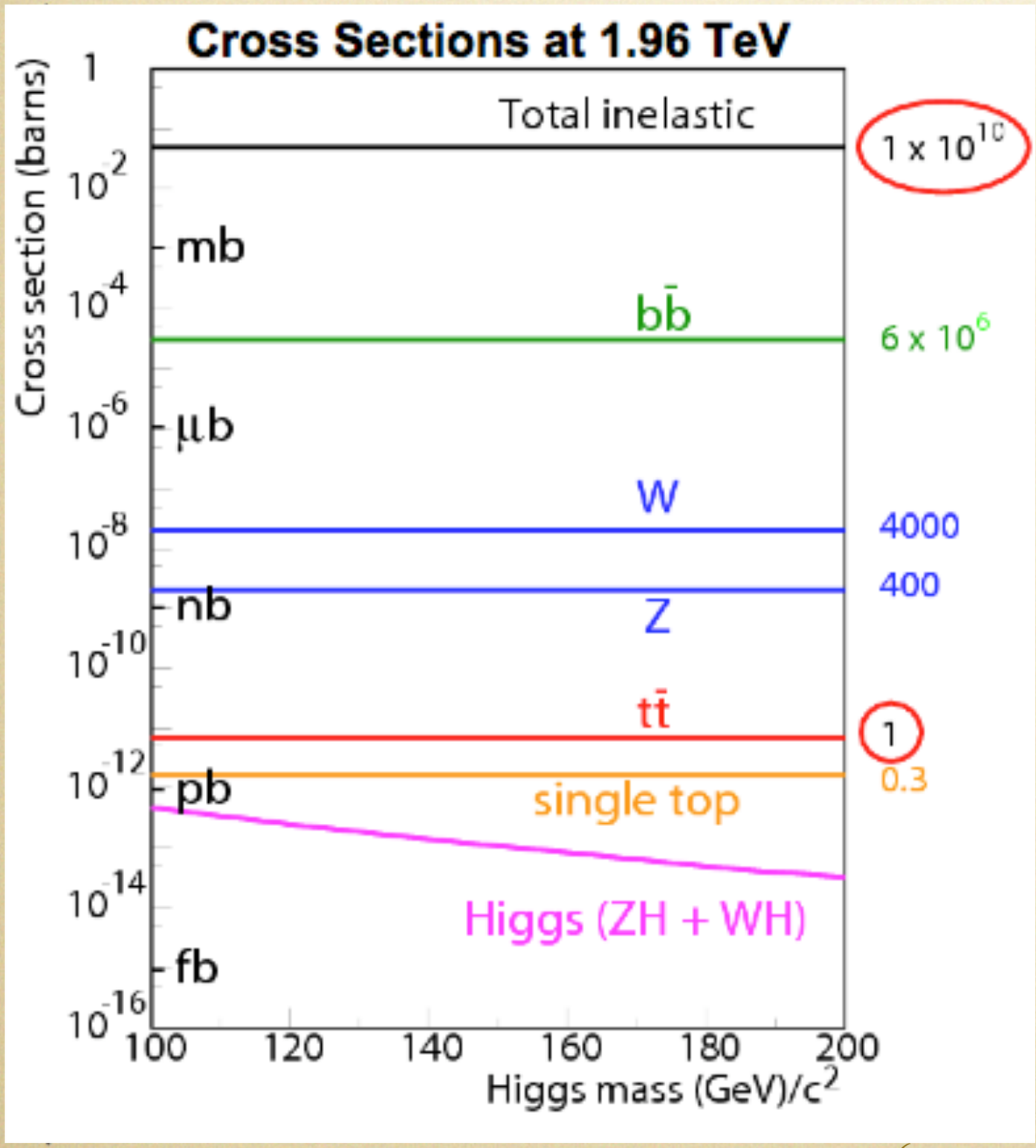
# Production and Decay




$\bar{p}p \rightarrow$ ... $+ \not{E}_T$

$WH \rightarrow WWW$ ... 2 ss High $P_T$ Leptons $+ \not{E}_T$

# The Challenge...




- Higgs Production is a low rate process at the Tevatron.
- Backgrounds are many orders of magnitude larger.
- Challenge: Separate Signal from Background

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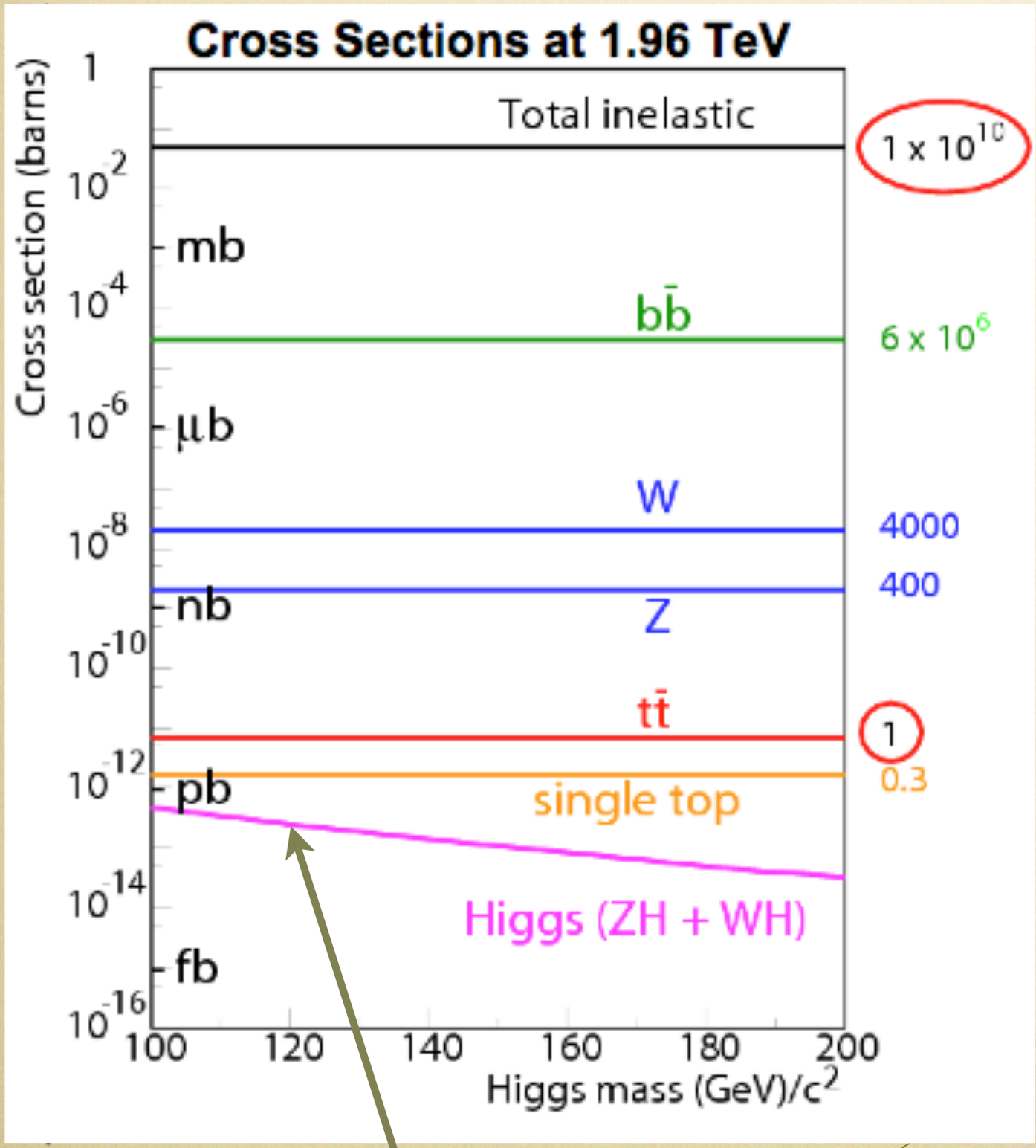



- Higgs Production is a low rate process at the Tevatron.
- Backgrounds are many orders of magnitude larger.
- Challenge: Separate Signal from Background

Before Anything
S:B ~ $1:10^{11}$

# First Step...

- Select High $P_T$ leptons (e,μ,τ).
- Select Events with Missing Energy (neutrino(s))
- Select Events with jets from b-quarks (low $M_H$)
- Details for each analysis slightly different

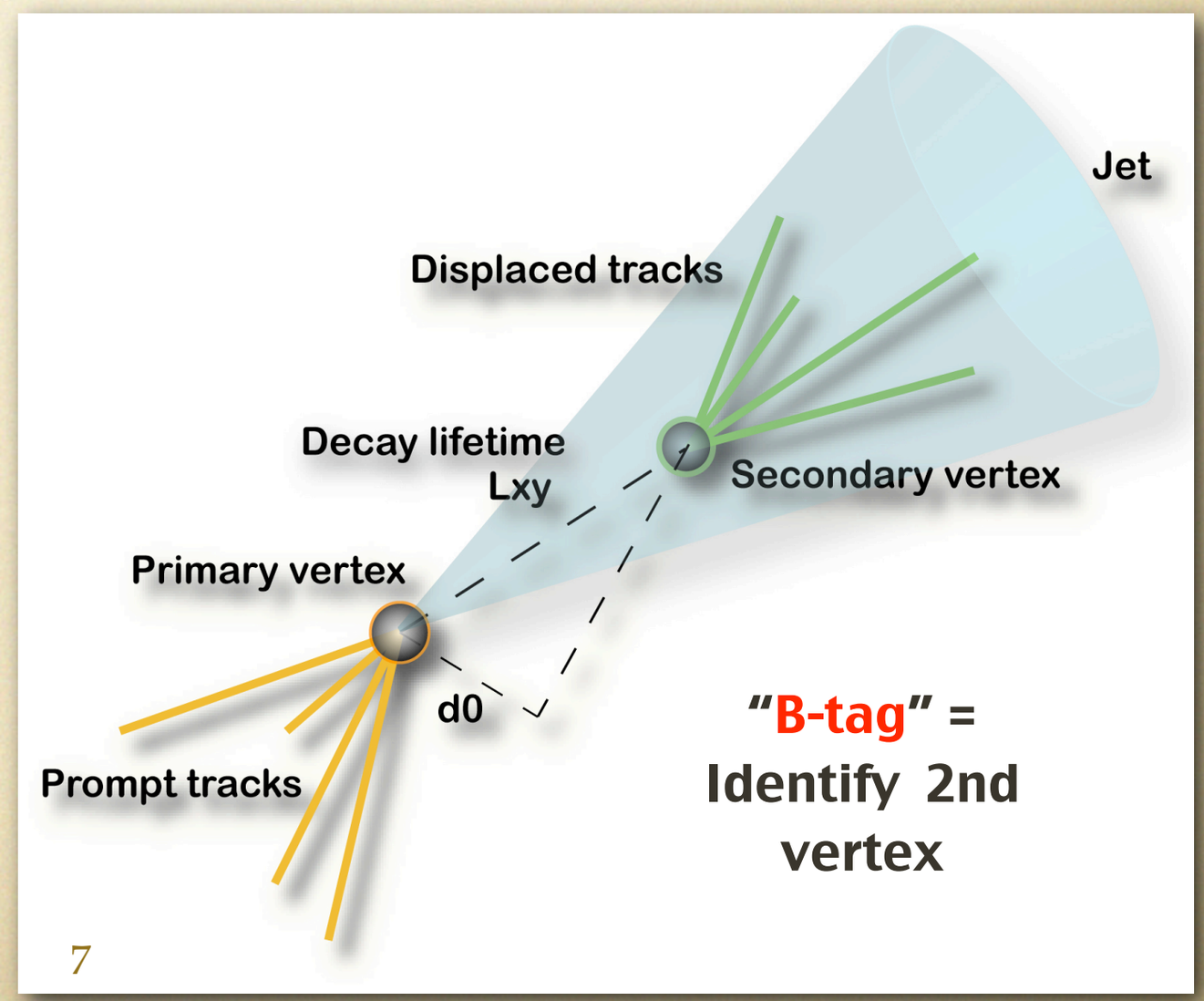
b-tagging is about ~50-70% efficient. Dependence on: $E_T$ and η of jet.

Now

$S:B_{1\text{-btag}} \sim 1:400$

$S:B_{2\text{-btag}} \sim 1:50\text{-}100$

WW ~ 1:50



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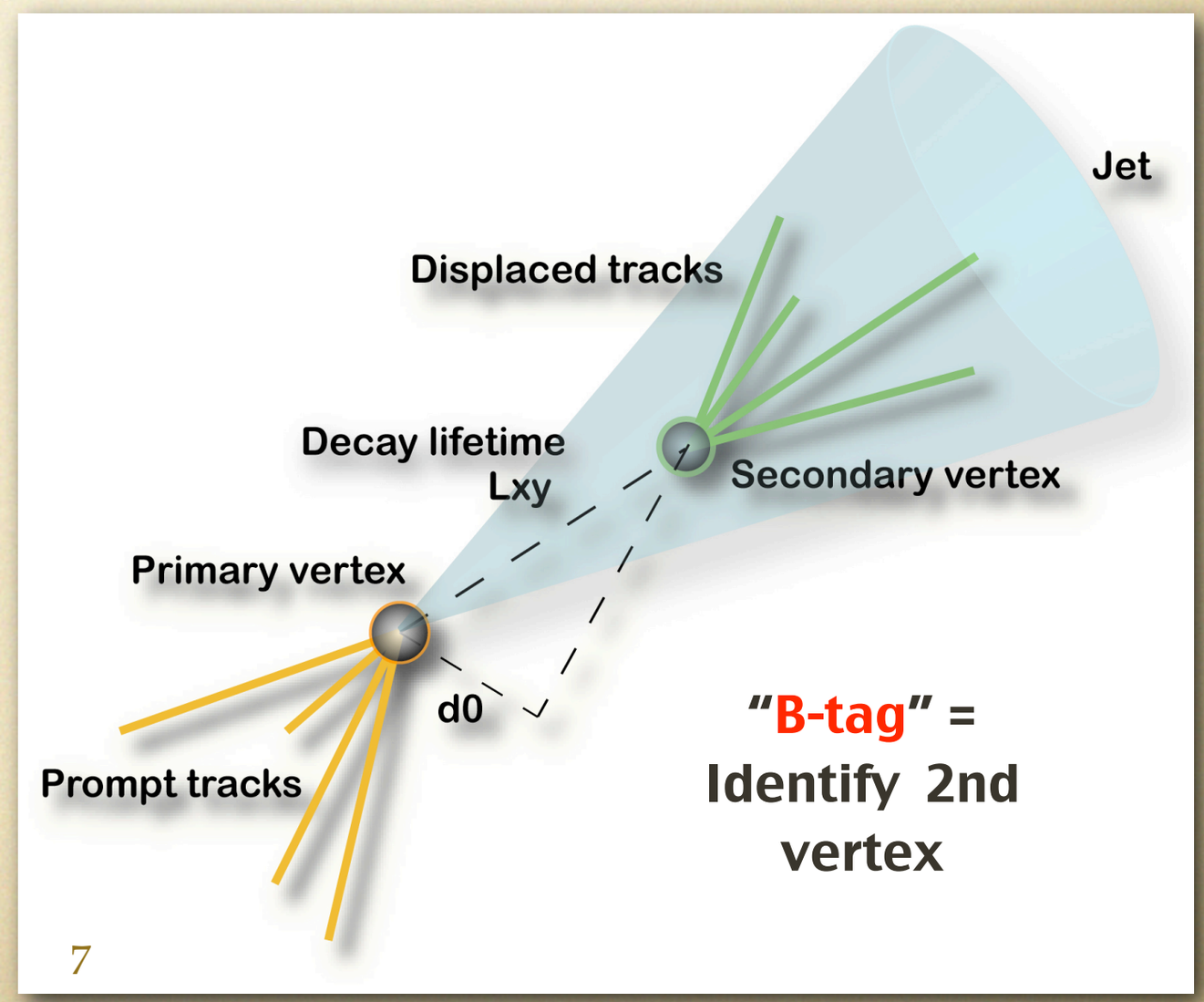
Now

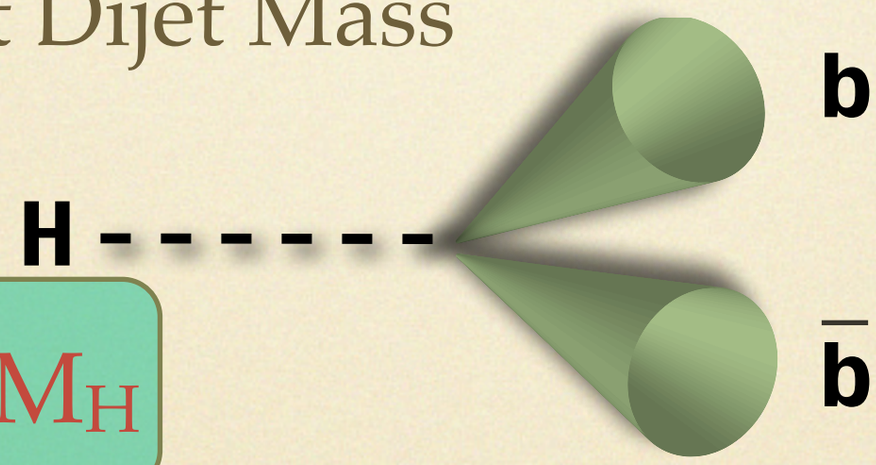
So the first factor of ~1 billion is "easy".

WW ~ 1:50

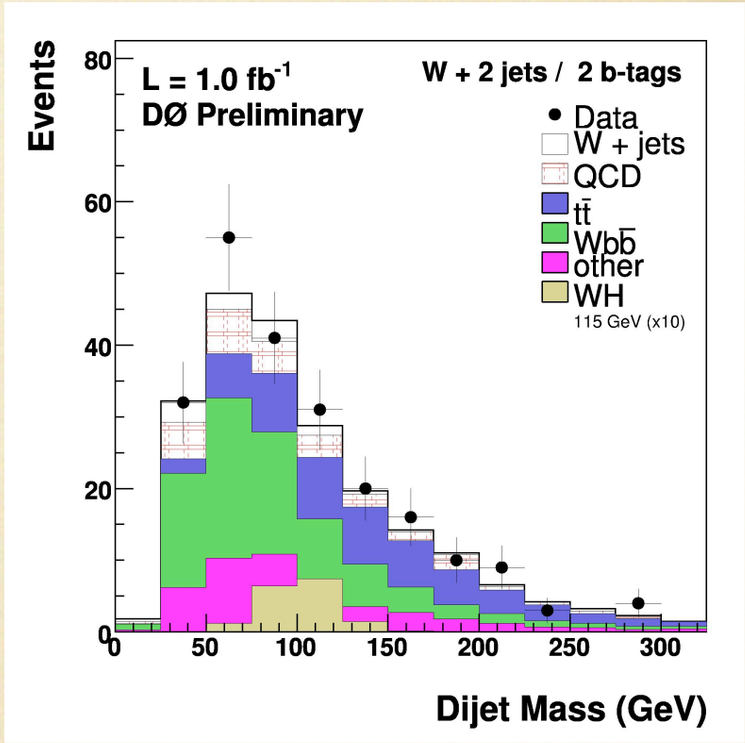


# Second Step...

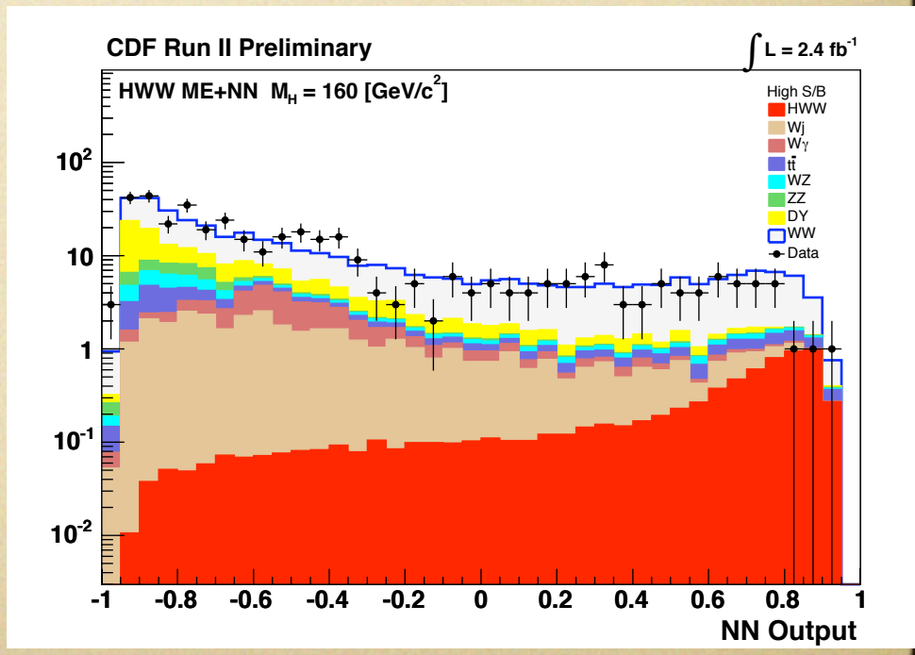
- Use other distinguishing features
- Simplest Approach: Fit a Kinematic Distribution
  - Low $M_H$: Fit Dijet Mass




$M_{bb} = M_H$




- More Sophisticated Approach:
  **Use multivariate approach.**
  - Artificial Neural Network
  - Matrix Element Approach
  - Other Discriminants



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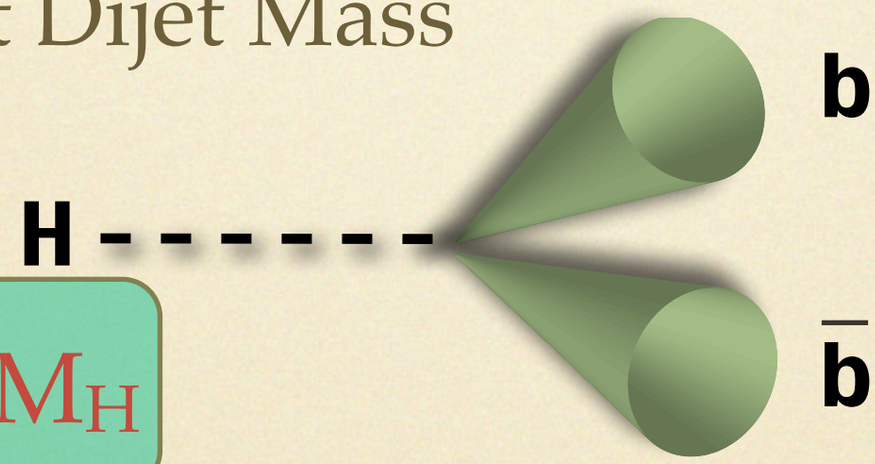


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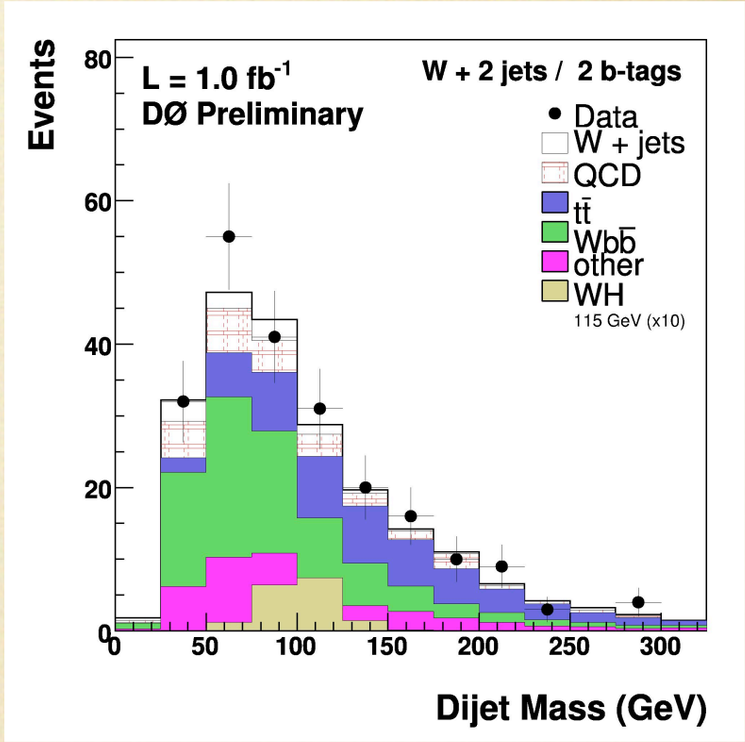


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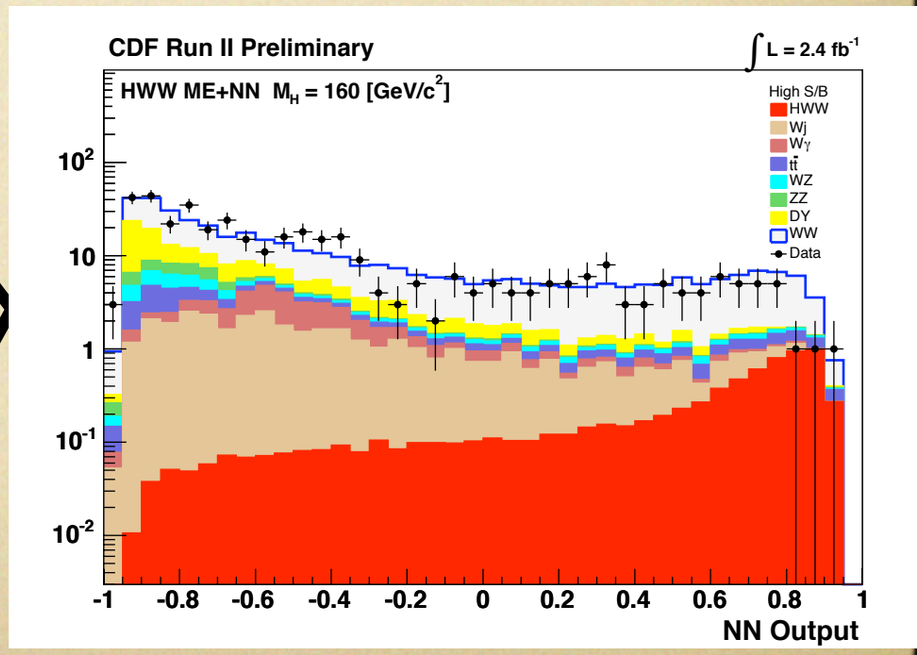


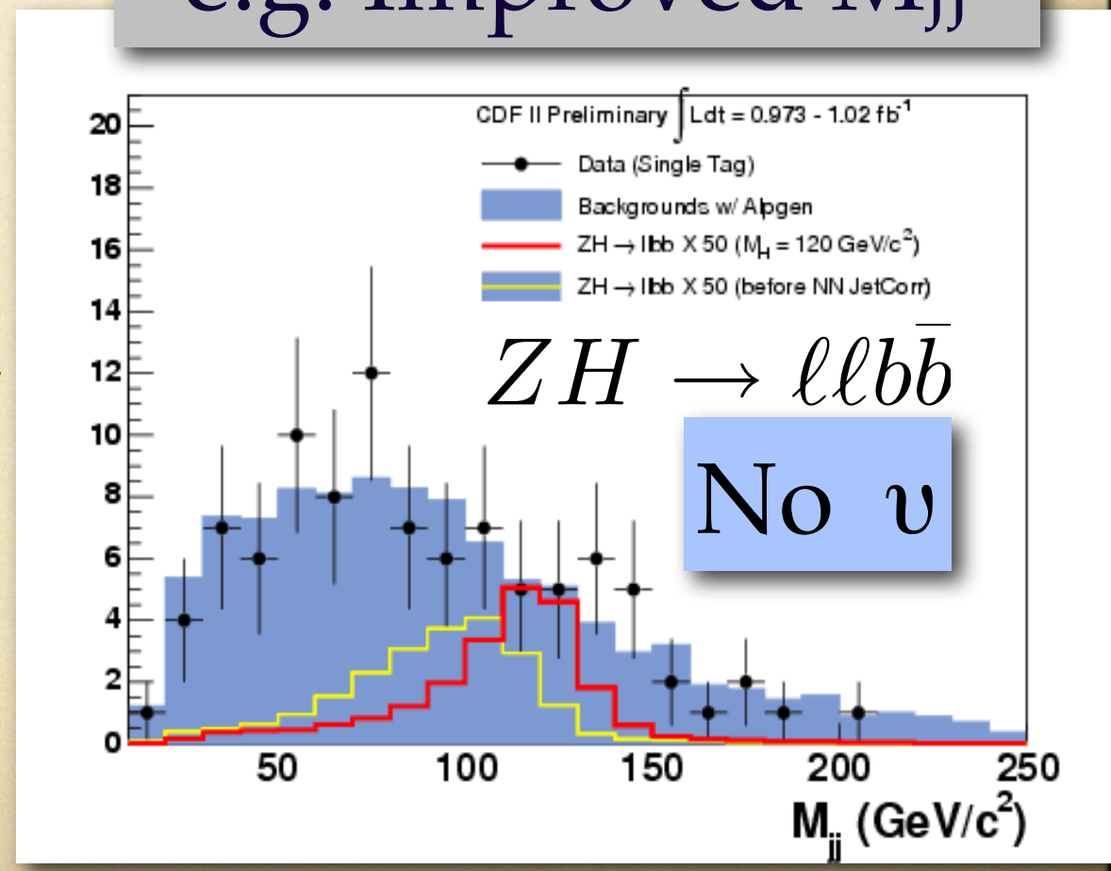

**All analyses now use these**

# Third Step...Optimization

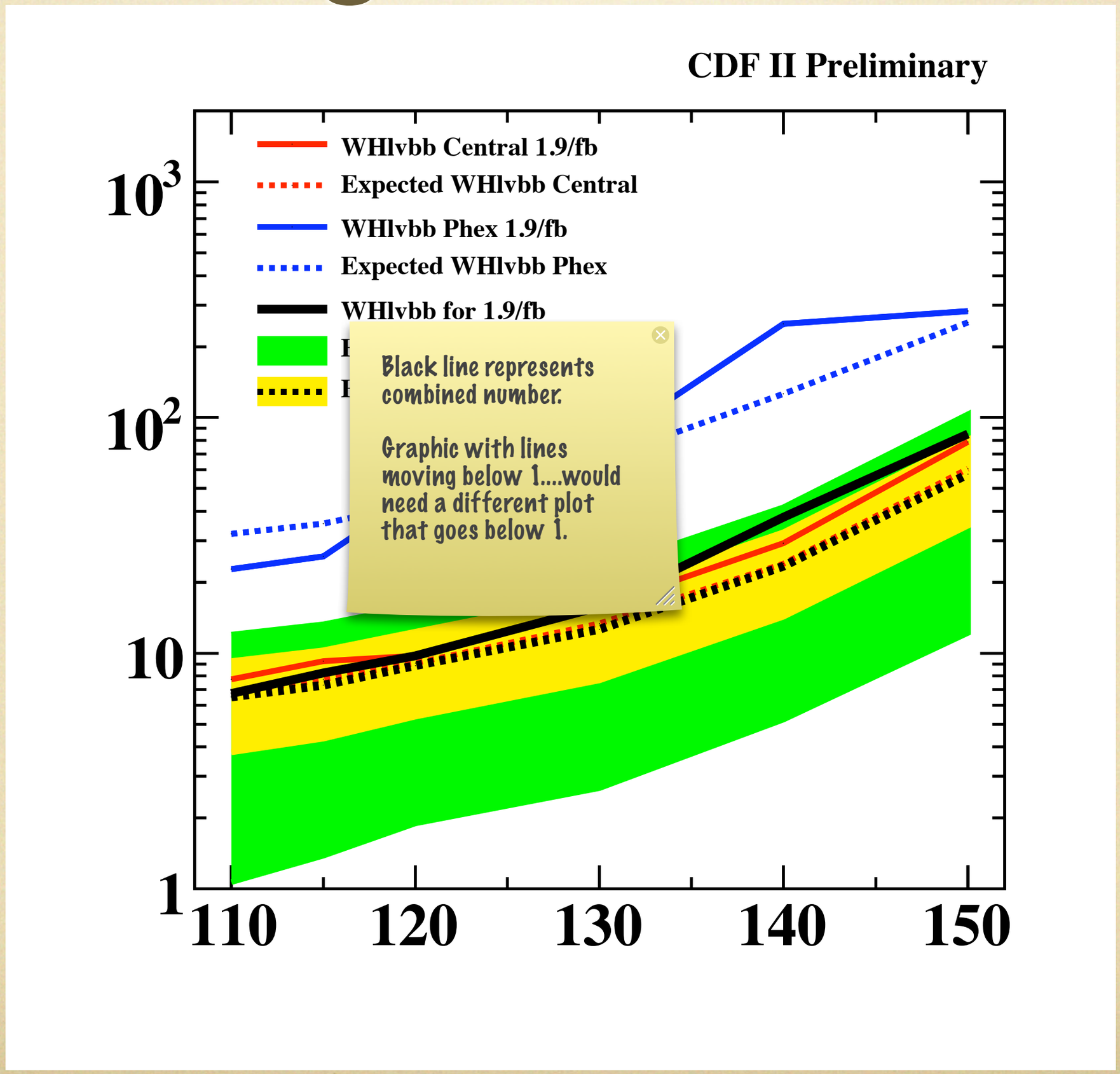
- **On-going** intense optimization efforts.
- Basic Selection:
  - Maximize Trigger Configurations
  - Identify as many high $P_T$ Leptons as possible
- B-tagging:
  - Various tagging requirements
  - **Neural Network Tagging**
- Background Rejection
- Missing $E_T$ and Jet Resolution
  - Critical for $M_{JJ}$ Resolution
  - Multivariate Inputs

**This is the hard work!**

e.g. Improved $M_{JJ}$



# Decoding Limit Plots 101



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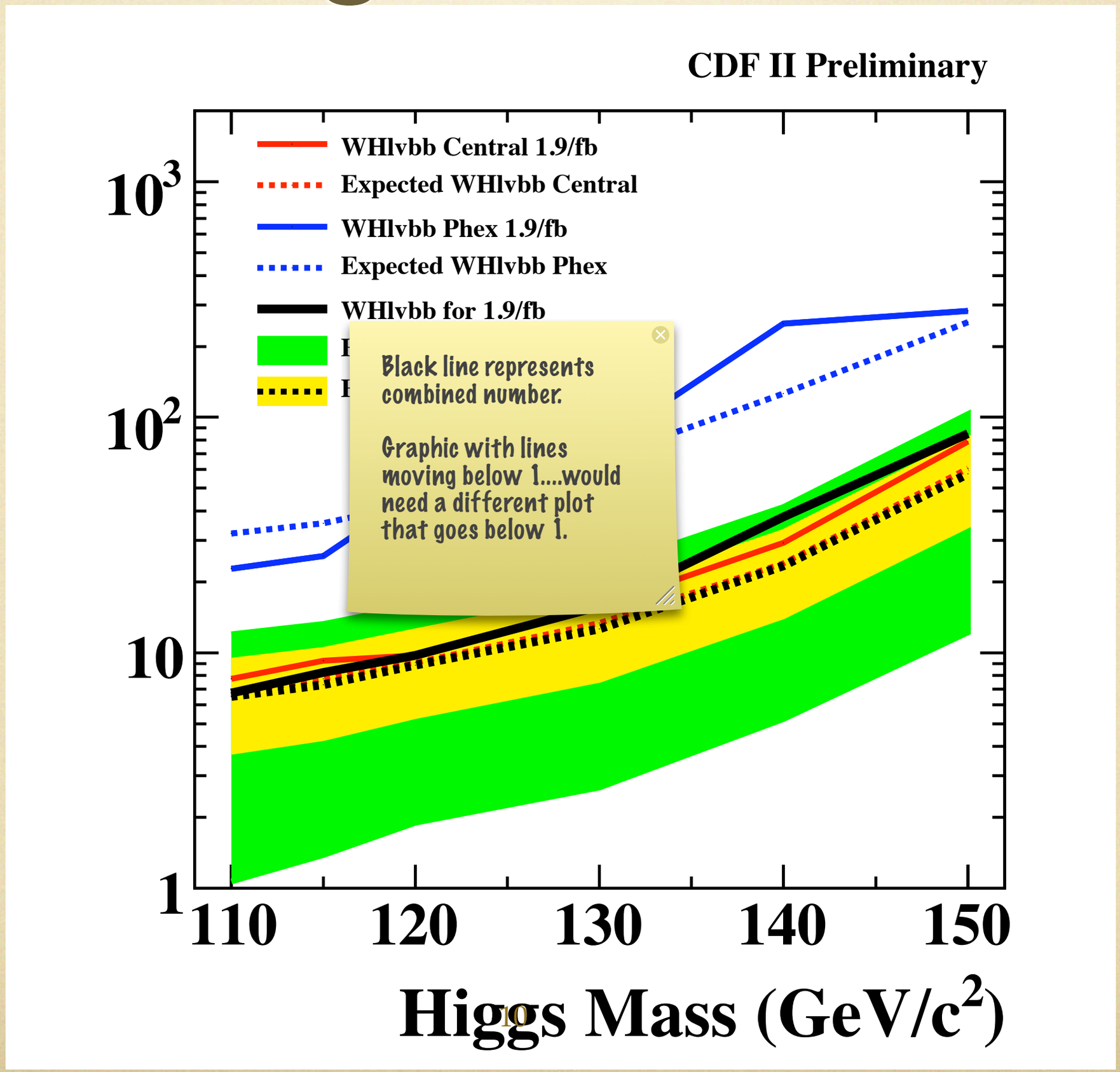


Black line represents combined number.

Graphic with lines moving below 1....would need a different plot that goes below 1.

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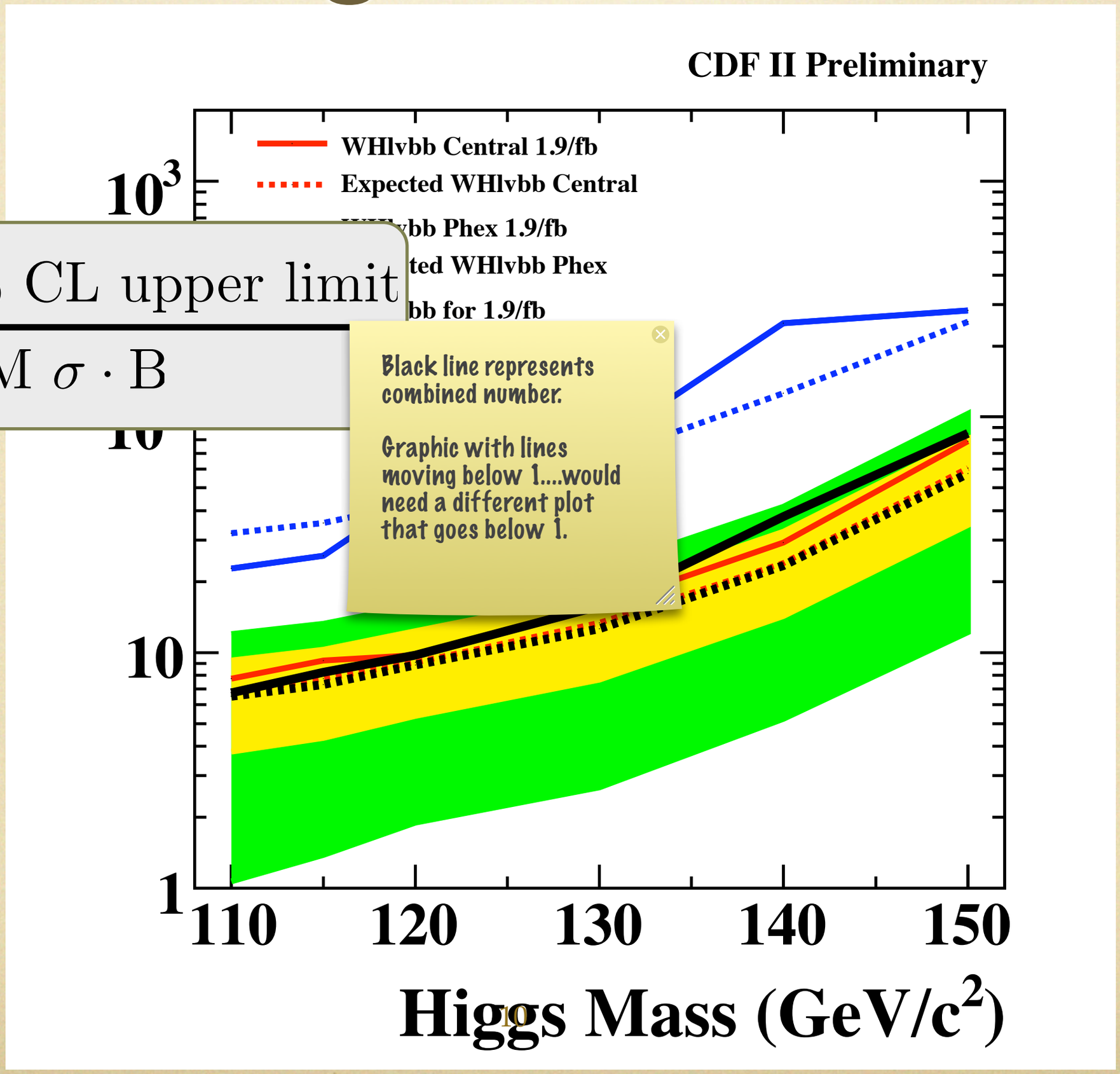


$$\frac{\sigma \cdot B \quad 95\% \text{ CL upper limit}}{\text{SM } \sigma \cdot \text{B}}$$

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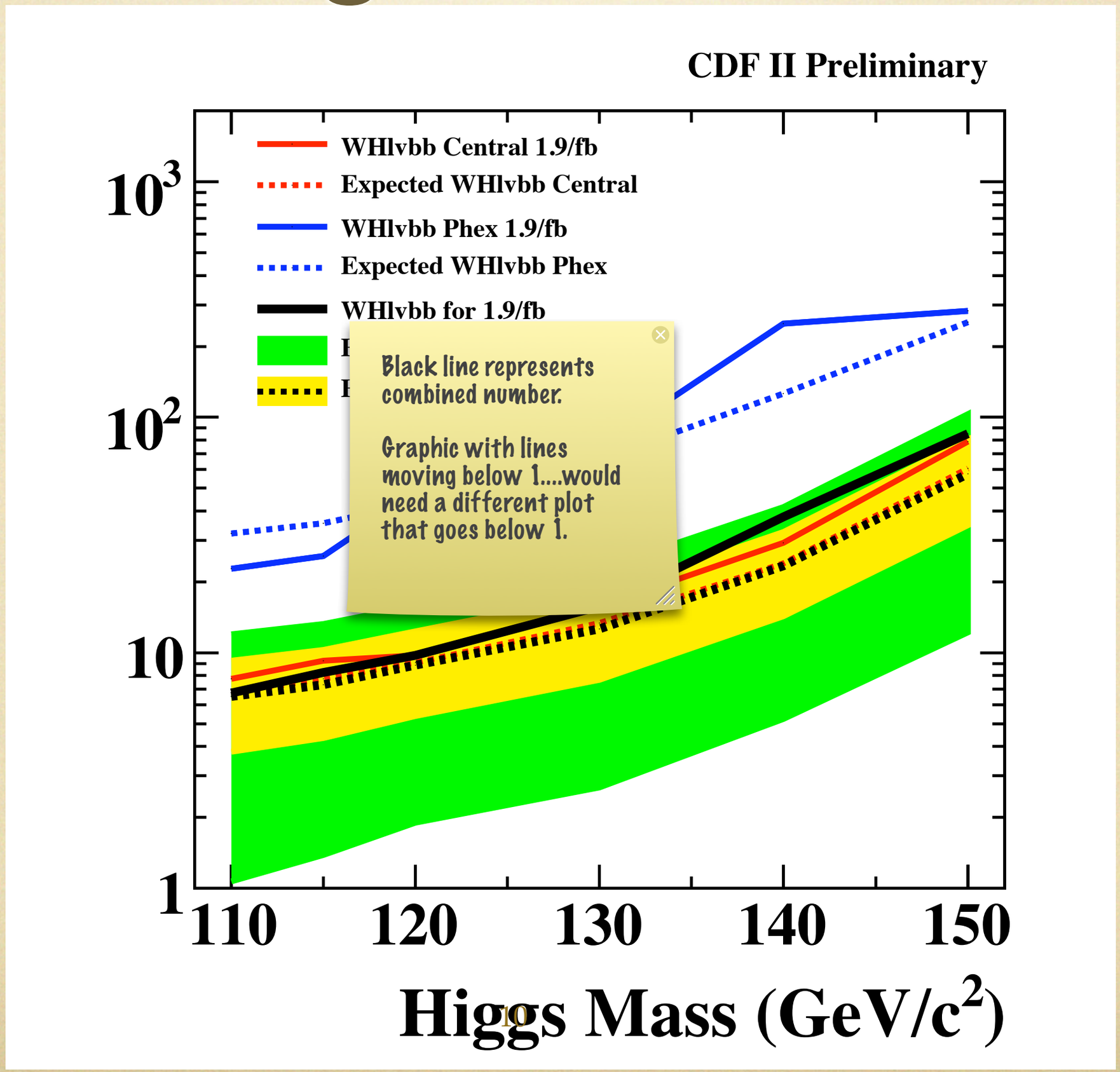


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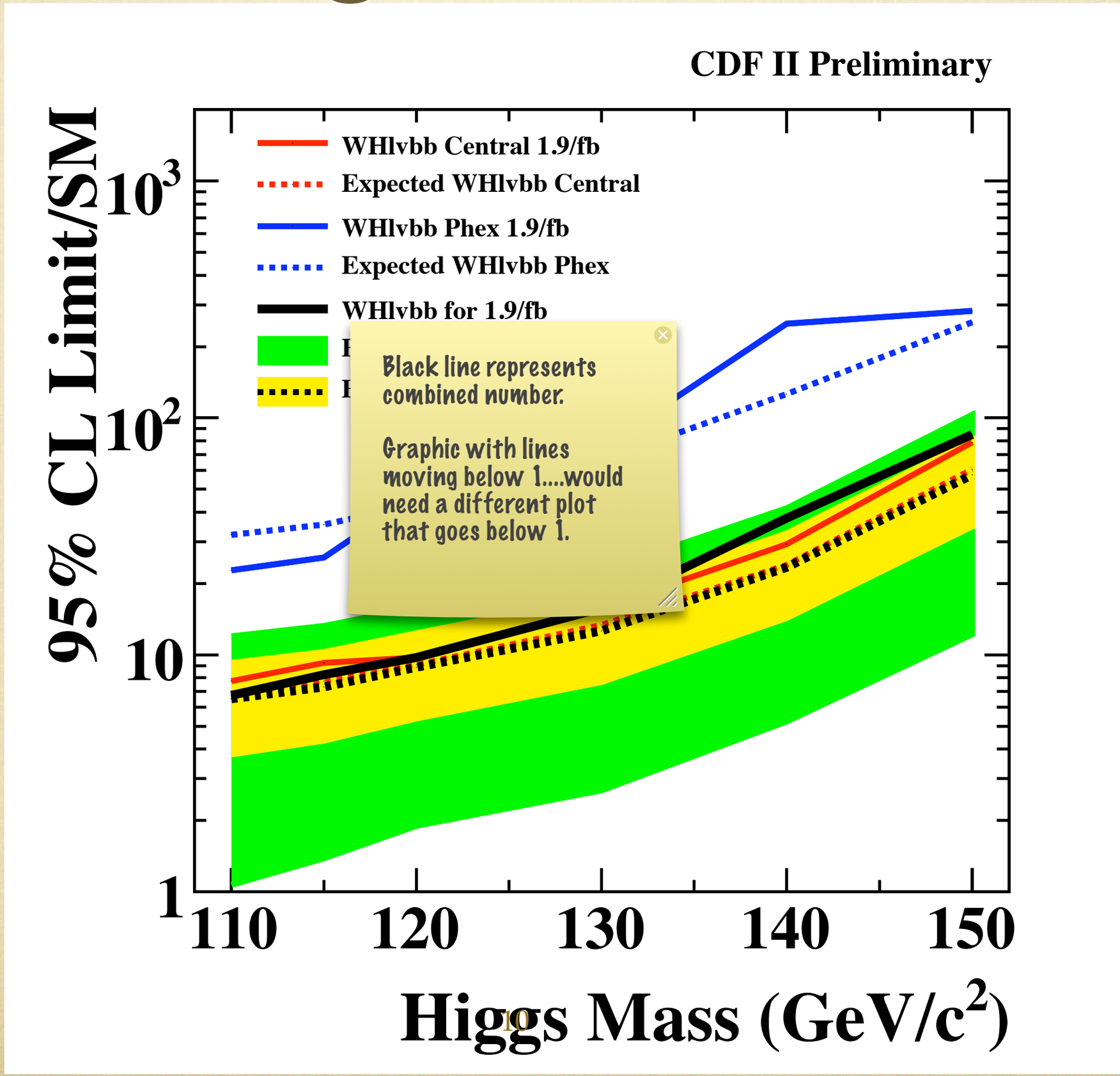


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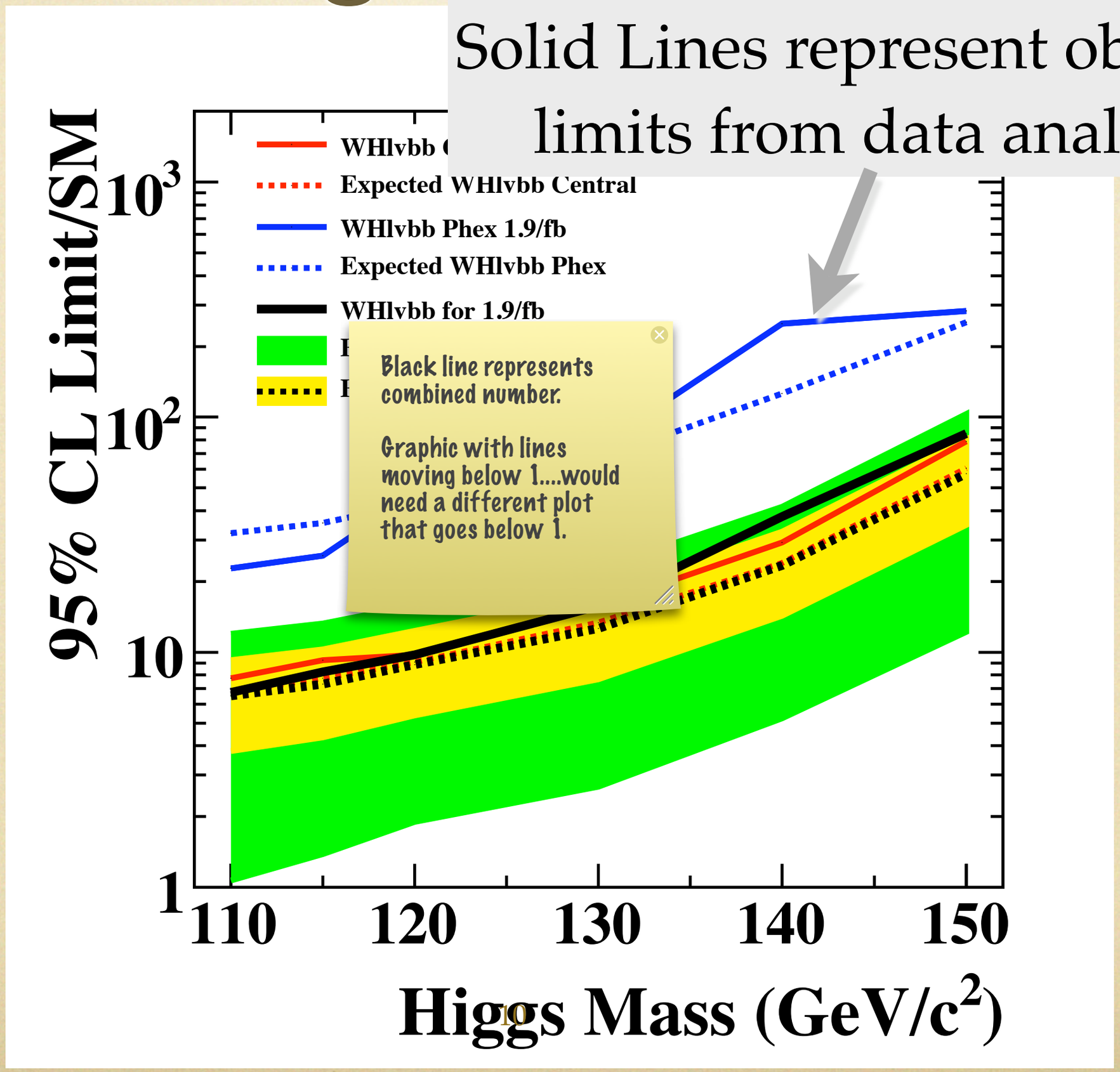
Solid Lines represent observed limits from data analysis.



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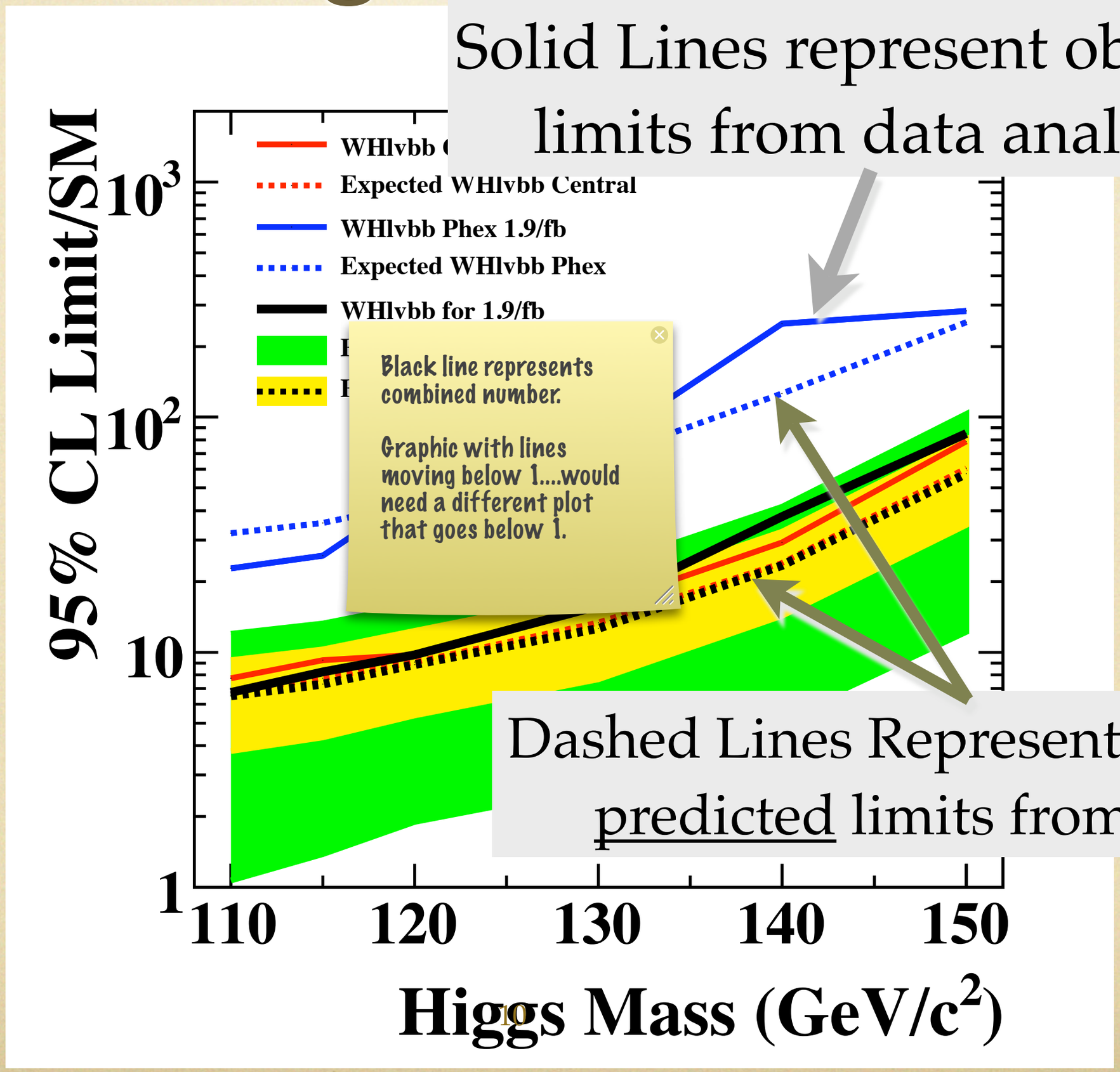
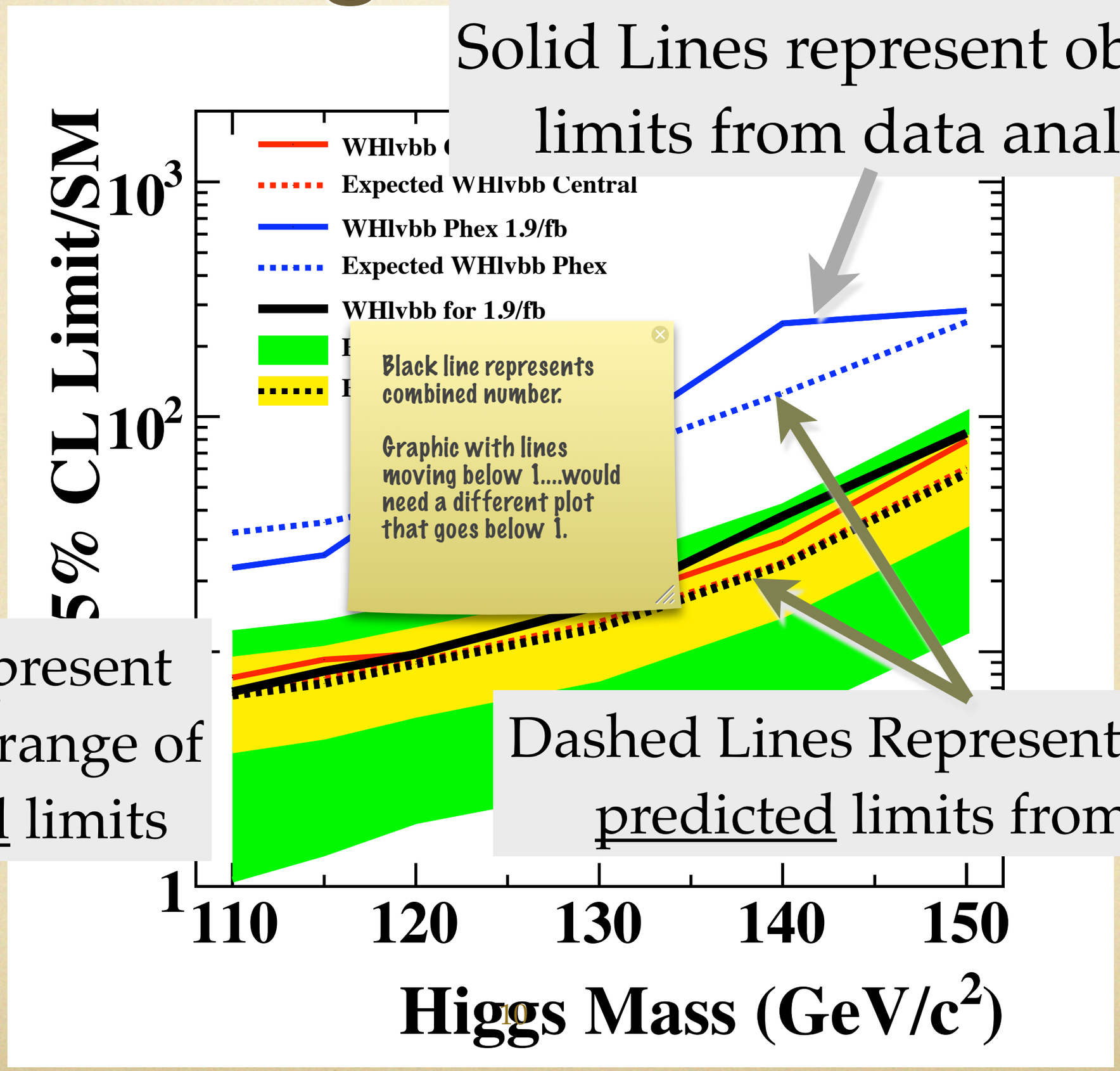



Dashed Lines Represent median predicted limits from MC

# Decoding Limit Plots 101

Solid Lines represent observed limits from data analysis.

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Bands represent 1σ and 2σ range of <u>predicted</u> limits

Dashed Lines Represent median <u>predicted</u> limits from MC

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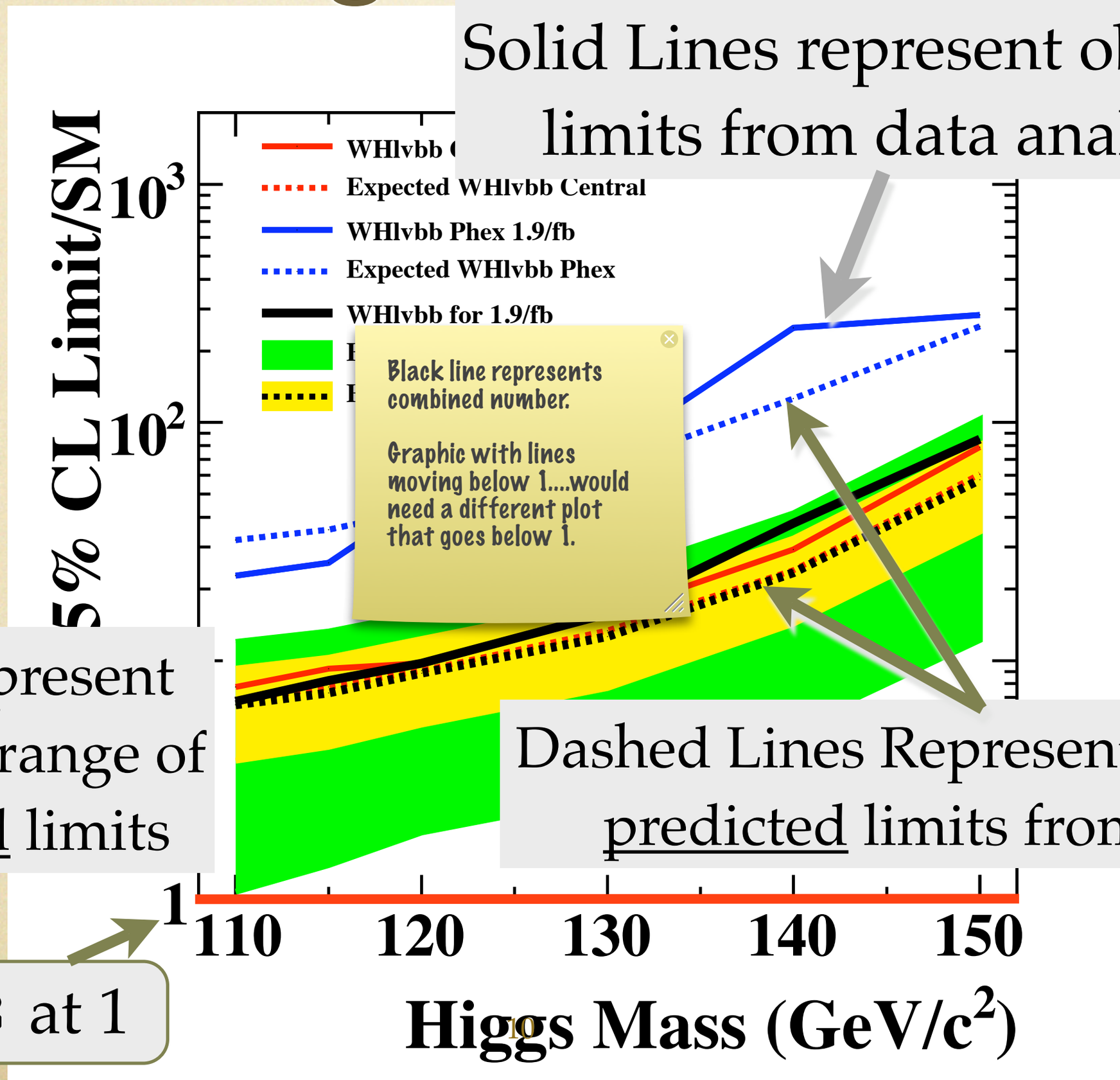


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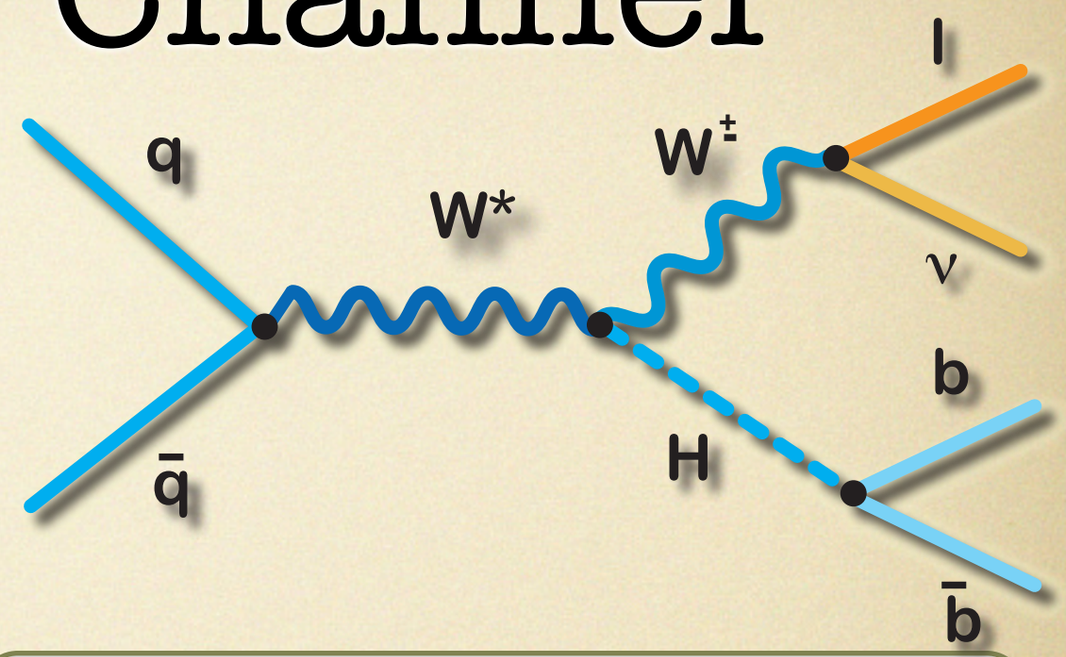
SM $\sigma \cdot$ B at 1

# Low Mass Signatures

# $WH \rightarrow \ell\nu b\bar{b}$ Channel




- High $P_T$ Lepton
- Missing $E_T$
- 2 jets
  - Split up 1 and 2 b-tags
- Examine "Figures of Merit"

**Features:**

1. Good Acceptance
2. Final state similar to single top prod.
3. ~2-3 evts/fb$^{-1}$

**Primary Backgrounds**

$Wb\bar{b}$, $Wc\bar{c}$, $Wqq'$

$t\bar{t}$

Single top

non − W QCD

$WZ$, $WW$

$Z \rightarrow \tau\tau$

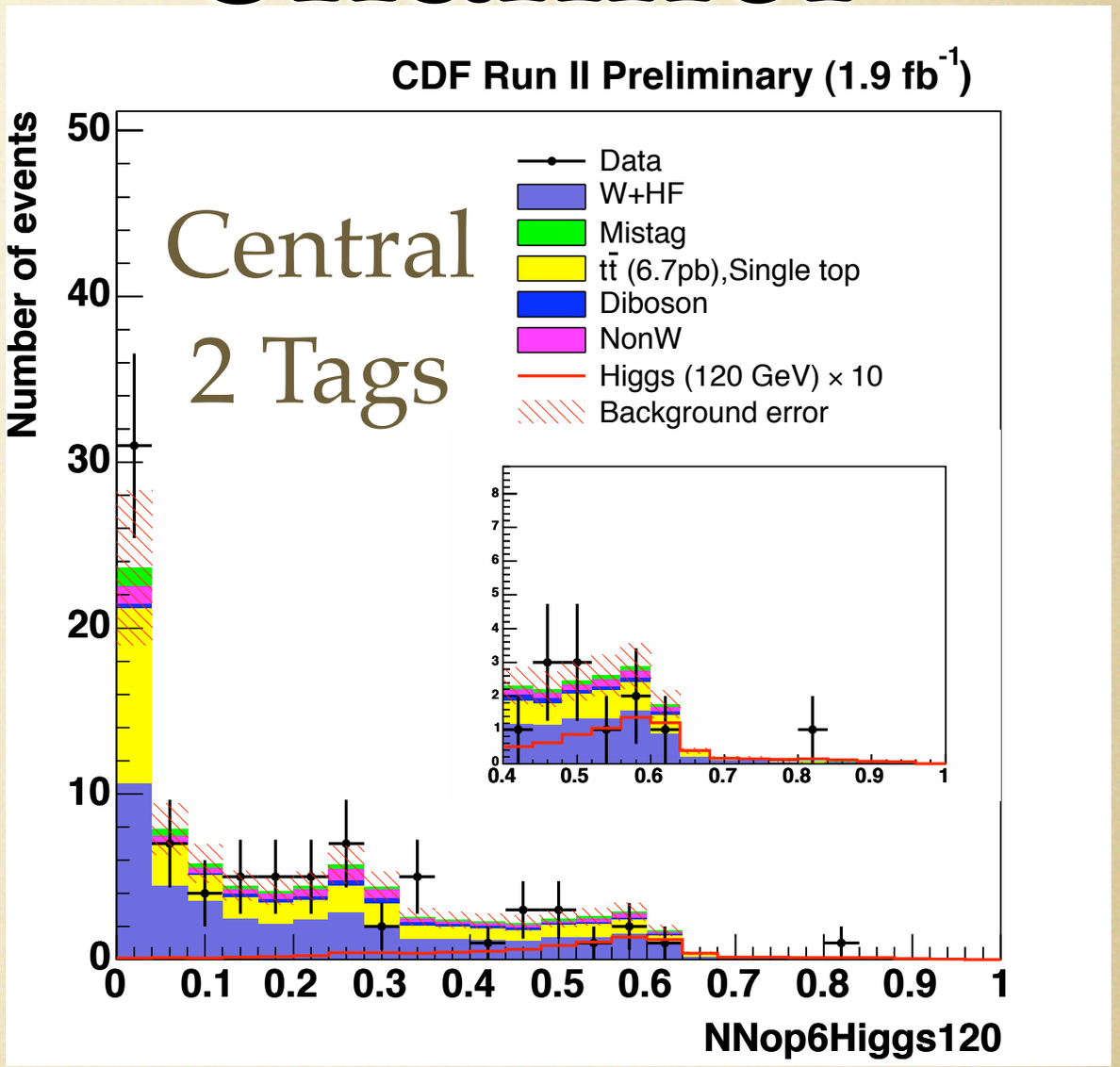
# $WH \rightarrow \ell\nu b\bar{b}$ Channel

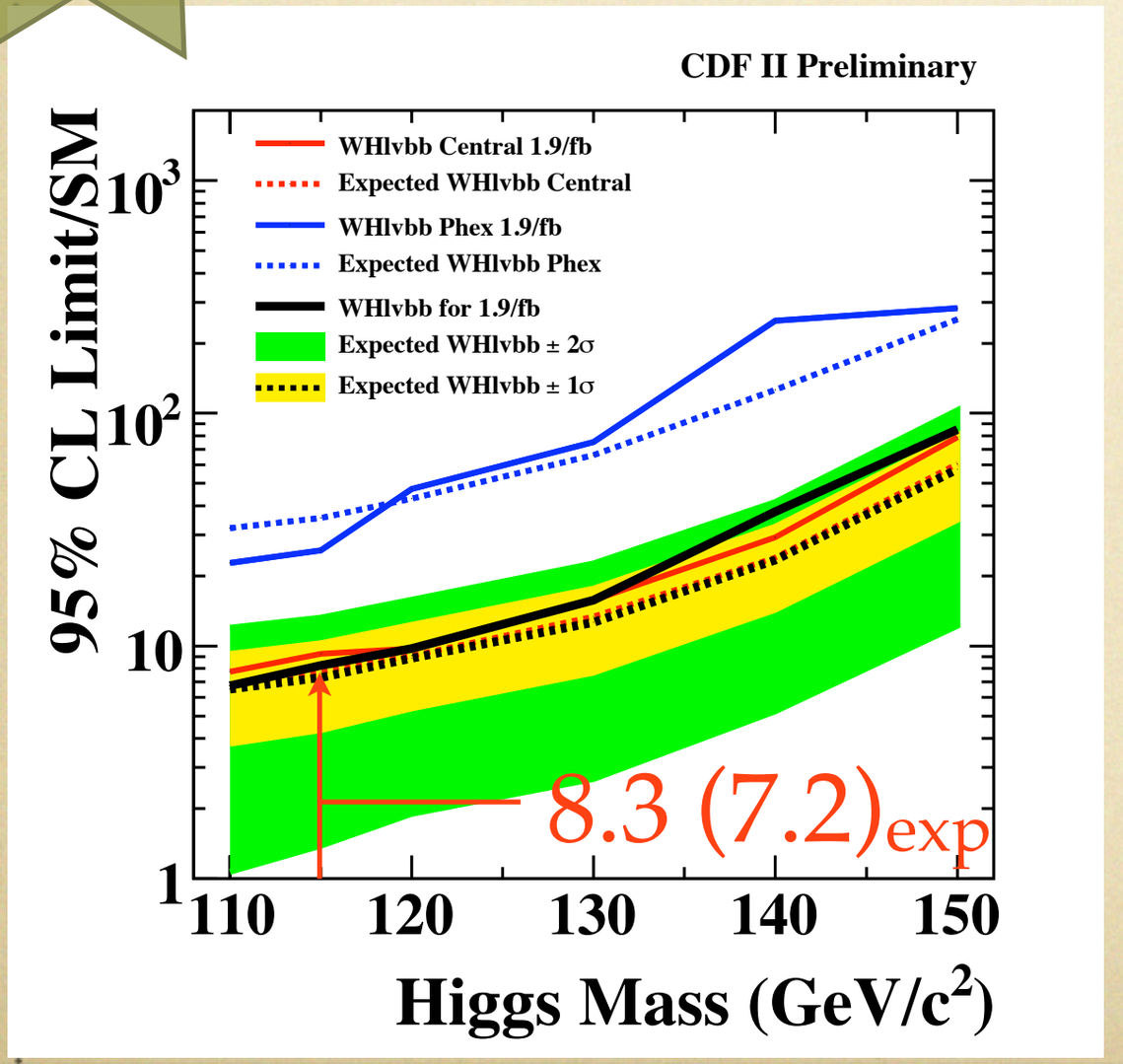
Figure of Merit: ANN

Inputs: $M_{jj}, P_T^{imb}, P_T^{sys},$

$M_{\ell\nu j}^{min}, \Delta R_{\ell\nu}, E_T^{jets}$

New ME




Classes: (6 Total)

Two Lepton: Central and Plug

Three b-Tagging: 2 double tag

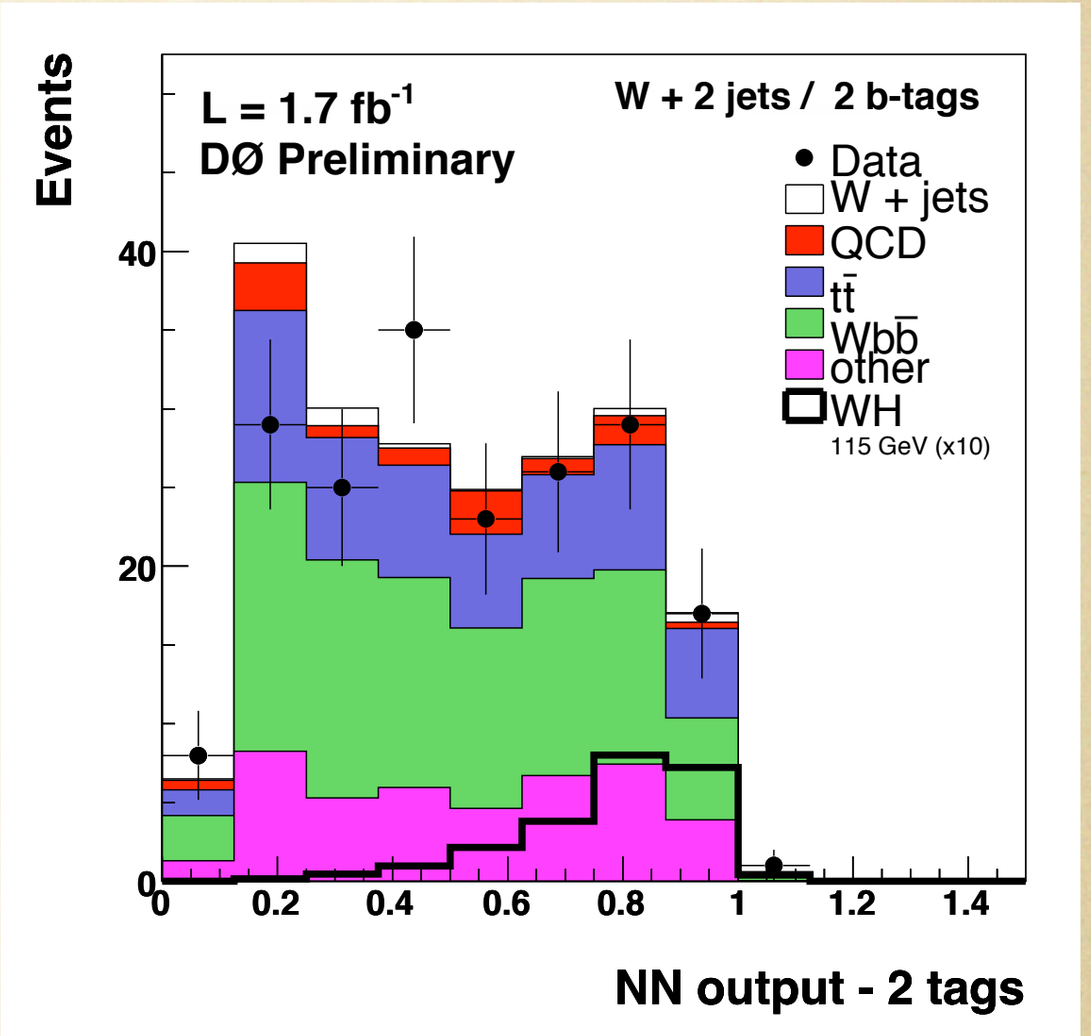
1 Single Tag

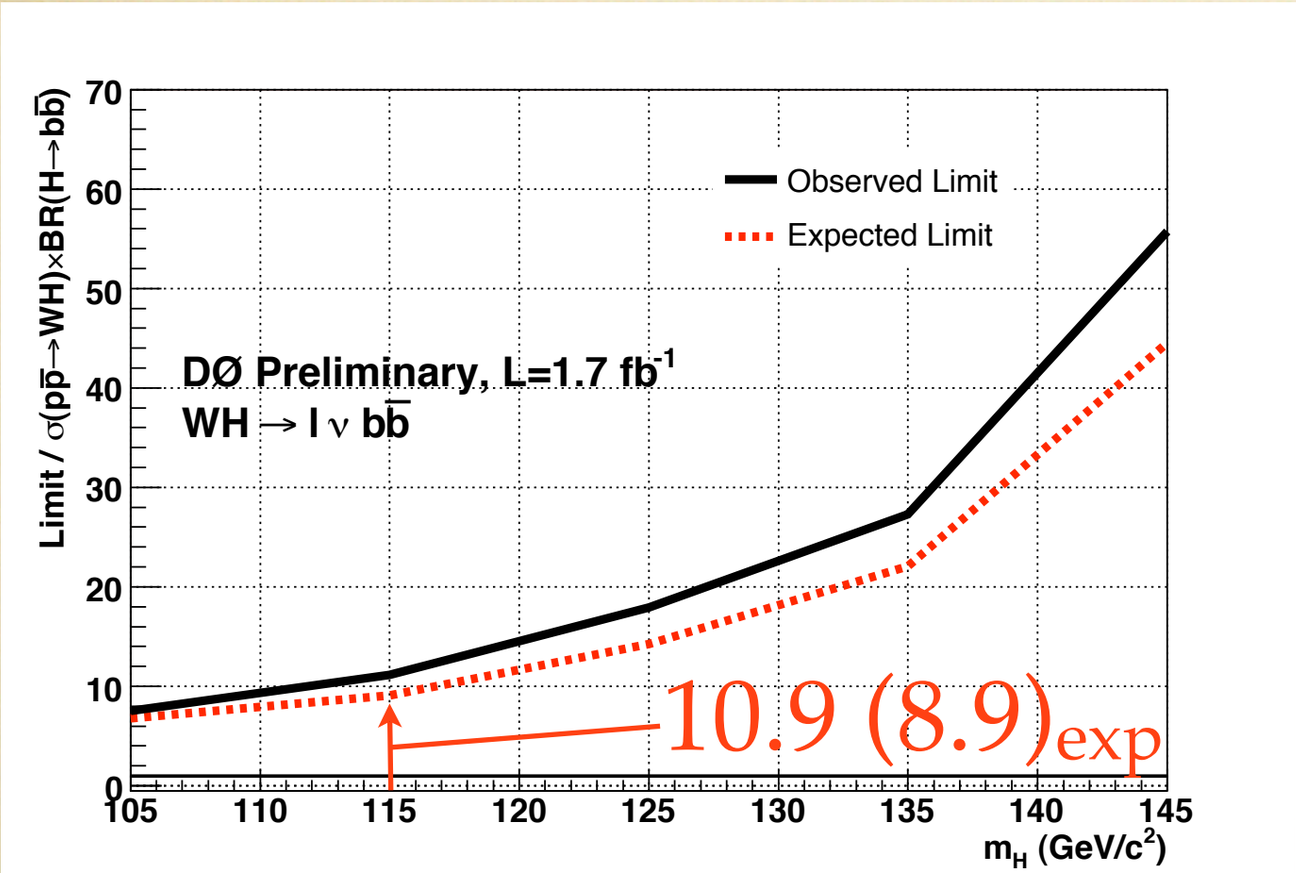
# $WH \rightarrow \ell\nu b\bar{b}$ Channel

Figure of Merit: ANN

Inputs:

$$P_T^{j1},\ P_T^{j2},\ \Delta R_{jj}, \Delta\phi_{jj},$$
$$P_T^{jj},\ M_{jj},\ P_T^{\ell-MET}$$




Classes: (8 Total)

Two Lepton: elec and muon

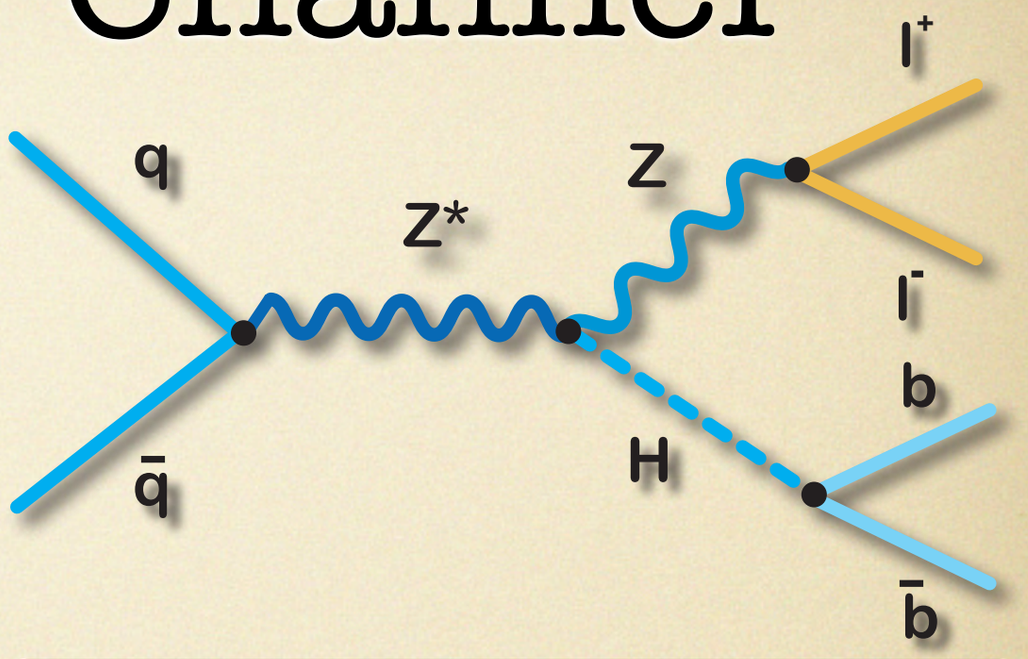
Two b-Tagging: 1 double tag

NN Tagger 1 single Tag

Two Data Periods

# $ZH \rightarrow \ell\ell b\bar{b}$ Channel

- Two High $P_T$ Leptons
- No (direct) Missing $E_T$
- 2 jets
  - Split up 1 and 2 b-tags




**Features:**

1. Small $\sigma \cdot BR$
2. Several tight constraints
   i. $M_{ll} \cong M_z$
   ii. "$\not{E}_T$" $\rightarrow$ improve jet resol.
3. ~1 evt/fb$^{-1}$

**Primary Backgrounds**

$Zb\bar{b}$, $Zc\bar{c}$, $Zqq'$

$t\bar{t}$

$WW + jj$, $WZ$, $ZZ$

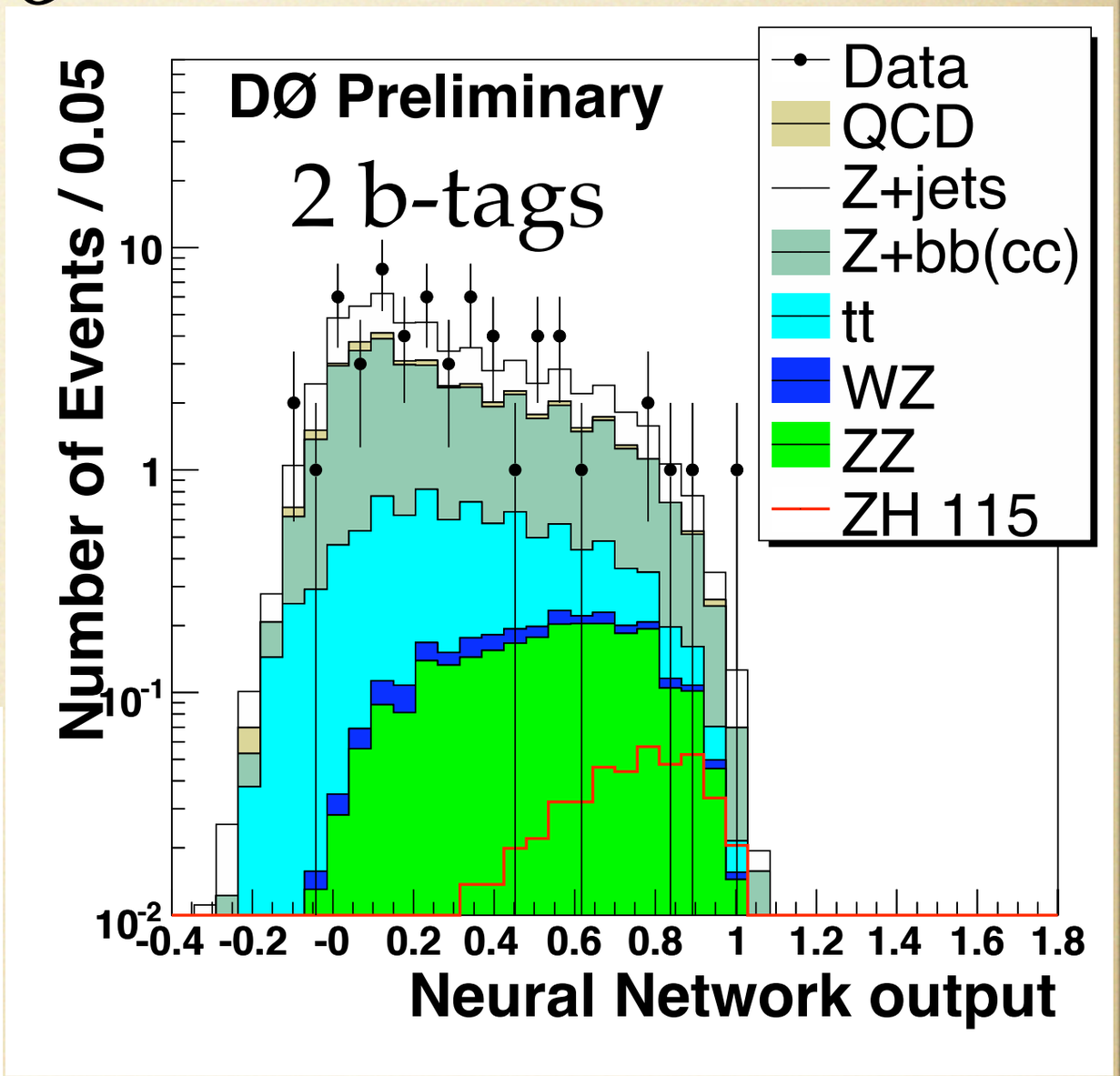
$Z \rightarrow \tau\tau$

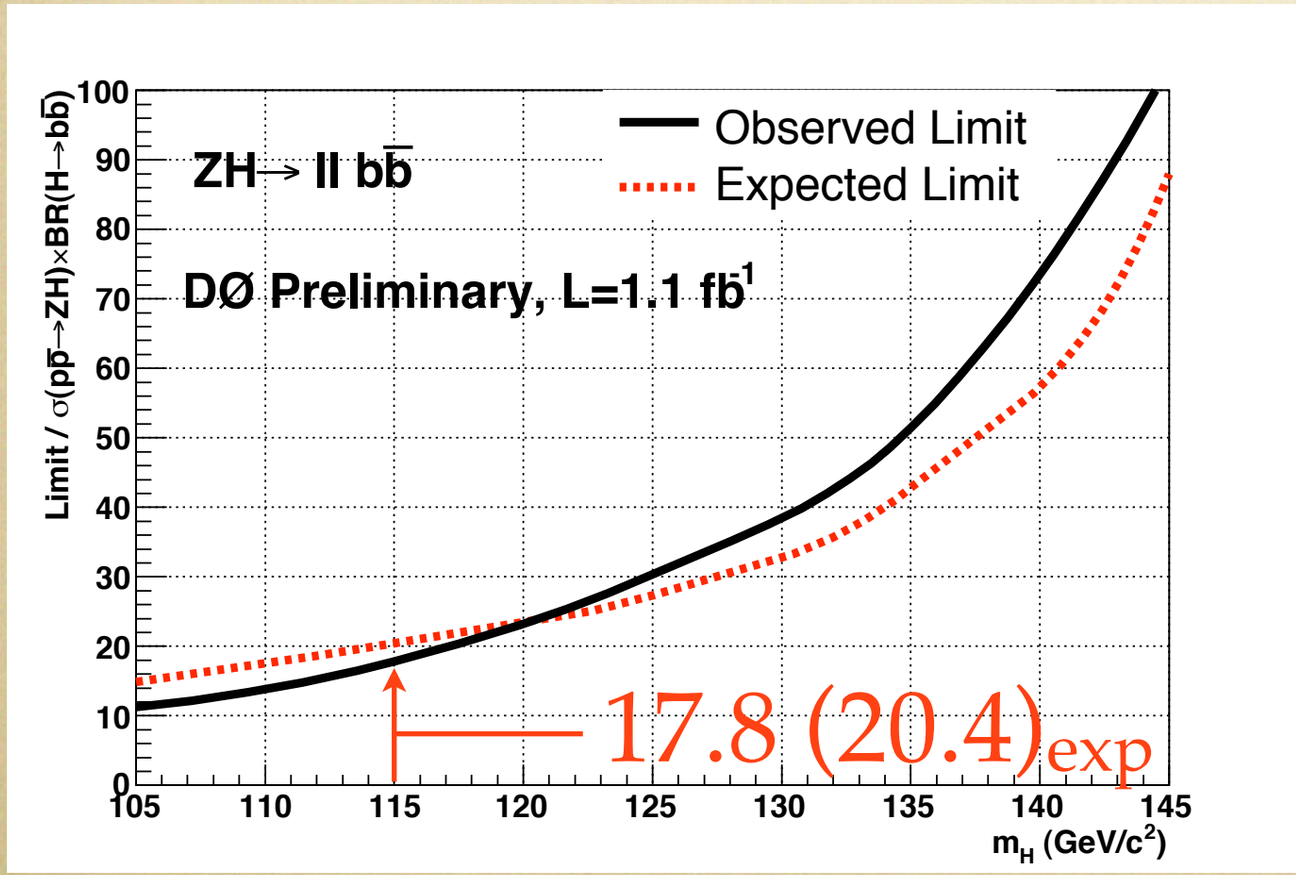
# $ZH \longrightarrow \ell\ell b\bar{b}$ Channel

Figure of Merit: ANN

Inputs:

$$M_{bb},\quad P_T^{j_1},\quad P_T^{j_2},\quad \Delta R_{\ell\ell},$$
$$|\Delta\eta_{jj}|,\quad |\Delta\phi_{jj}|,\quad \Delta R_{Z-j_1},$$
$$|\eta_Z|,\quad \mathrm{MET},\quad \Sigma E_T^i$$




Classes: (4 Total)

Two Lepton: ee and μμ

Two b-Tagging: 1 double tag

1 single Tag

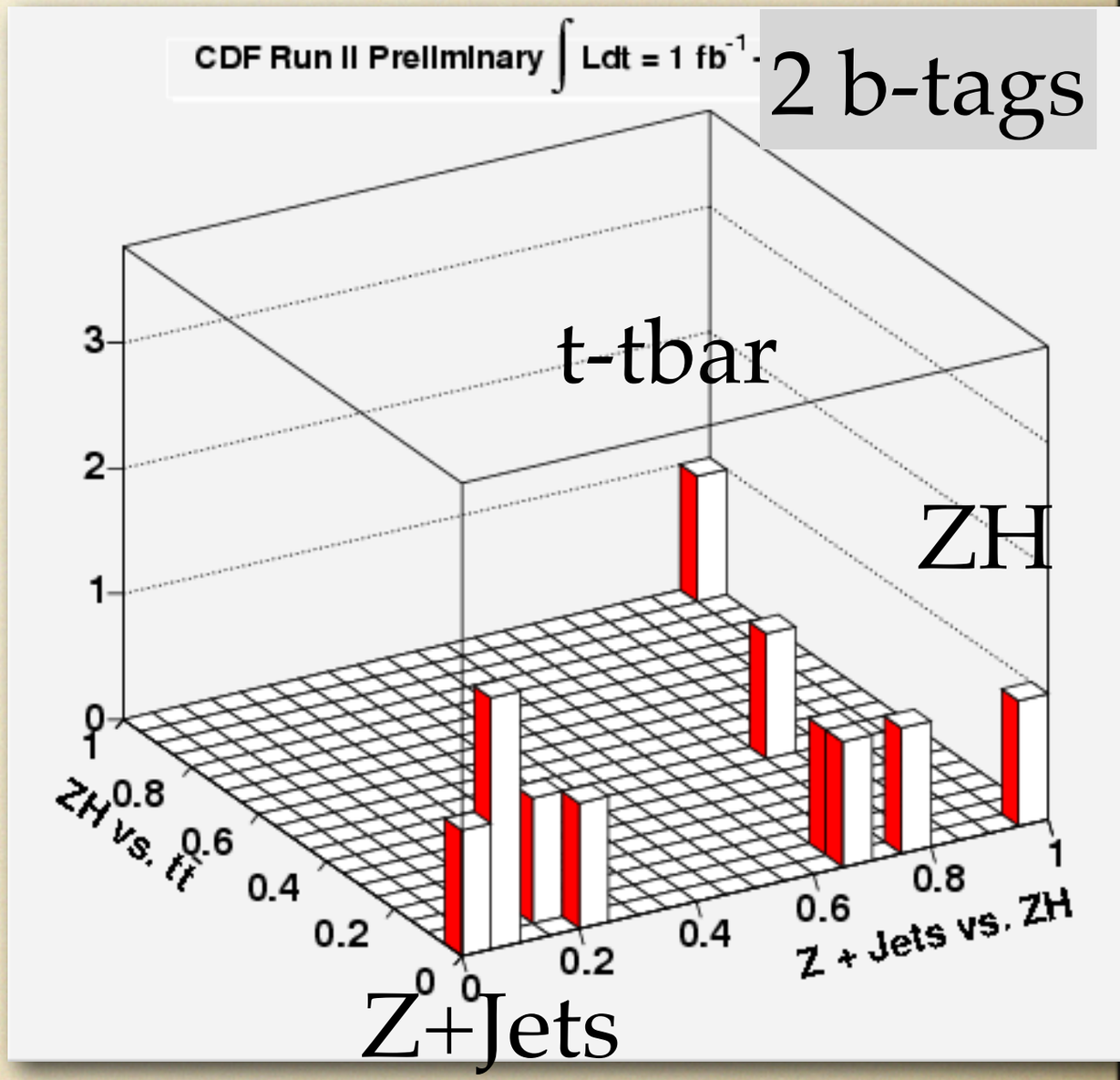
# $ZH \rightarrow \ell\ell b\bar{b}$ Channel

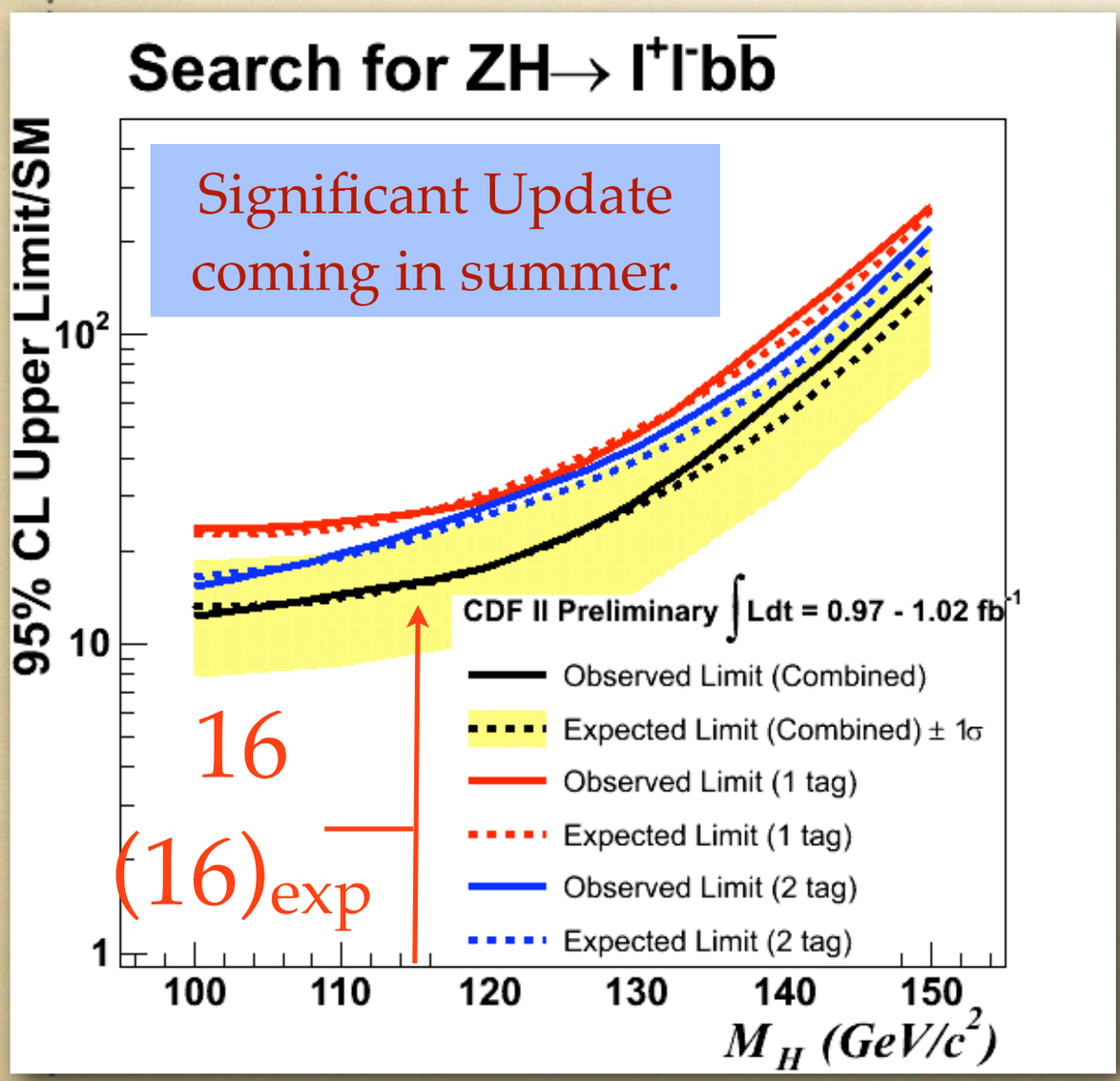
2-D ANN:

Z+Jets vs ZH vs t-tbar

Inputs: $\not{E}_T,\ H_T,\ M_{jj},\ Sph,\ \eta_{j_2}$

$\Delta R_{j_1,Z},\ \Delta R_{j_2,Z},\ \Delta R_{j_1,j_2}$




Tagging split into double tag and single Tag

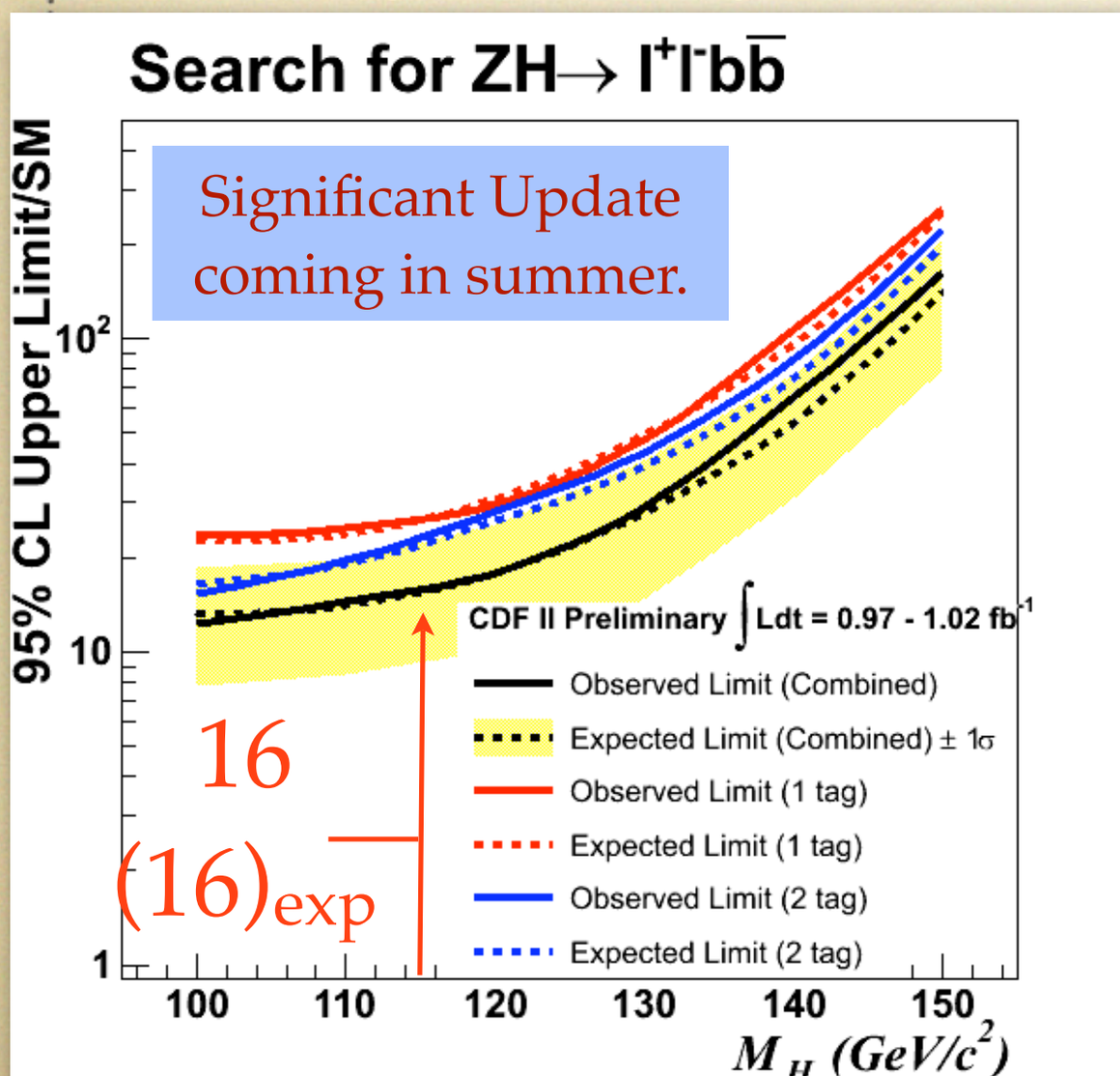
# $ZH \rightarrow \ell\ell b\bar{b}$ Channel

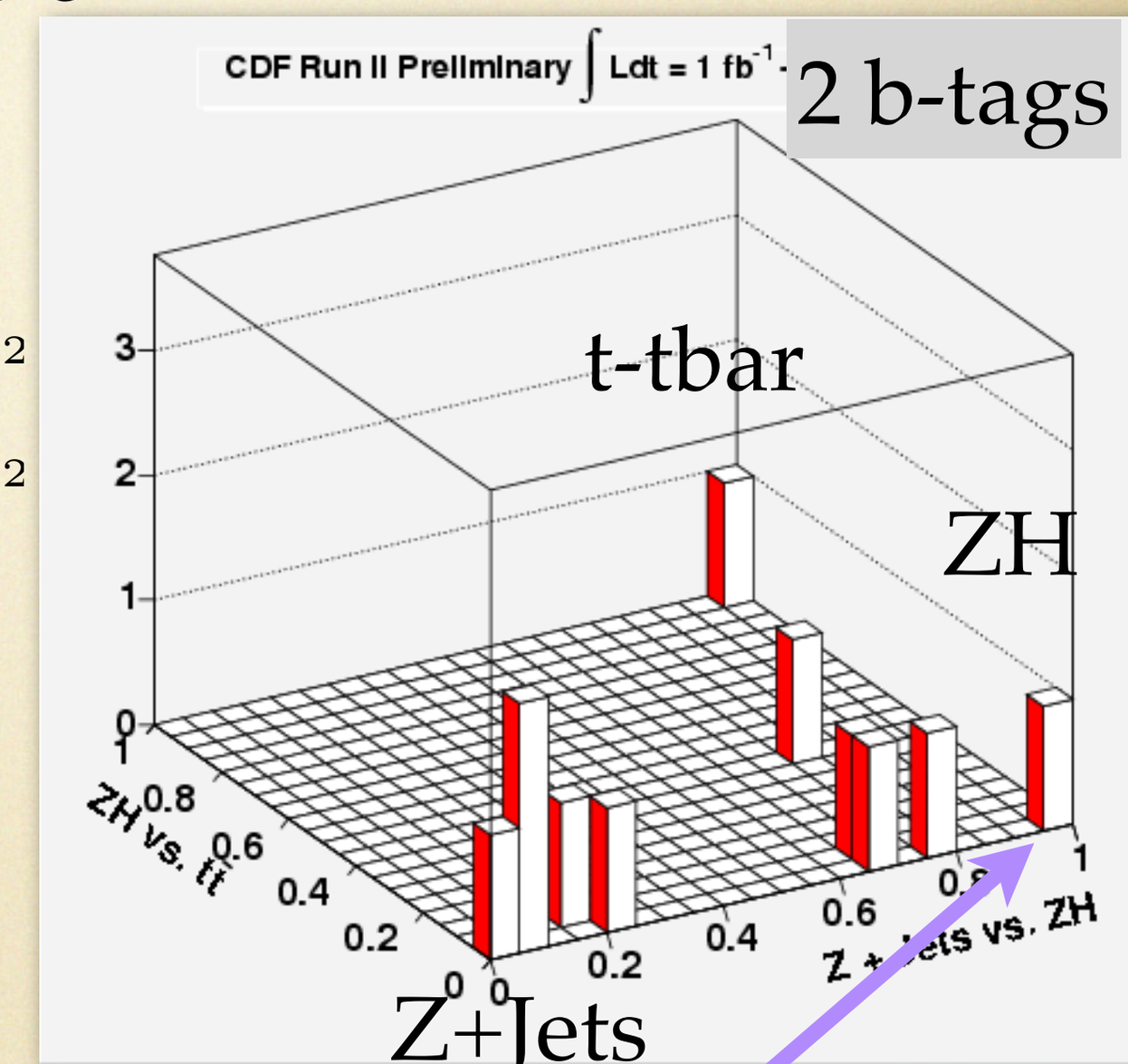
2-D ANN:

Z+Jets vs ZH vs t-tbar

Inputs: $\not{E}_T,\ H_T,\ M_{jj},\ Sph,\ \eta_{j_2}$

$\Delta R_{j_1,Z},\ \Delta R_{j_2,Z},\ \Delta R_{j_1,j_2}$



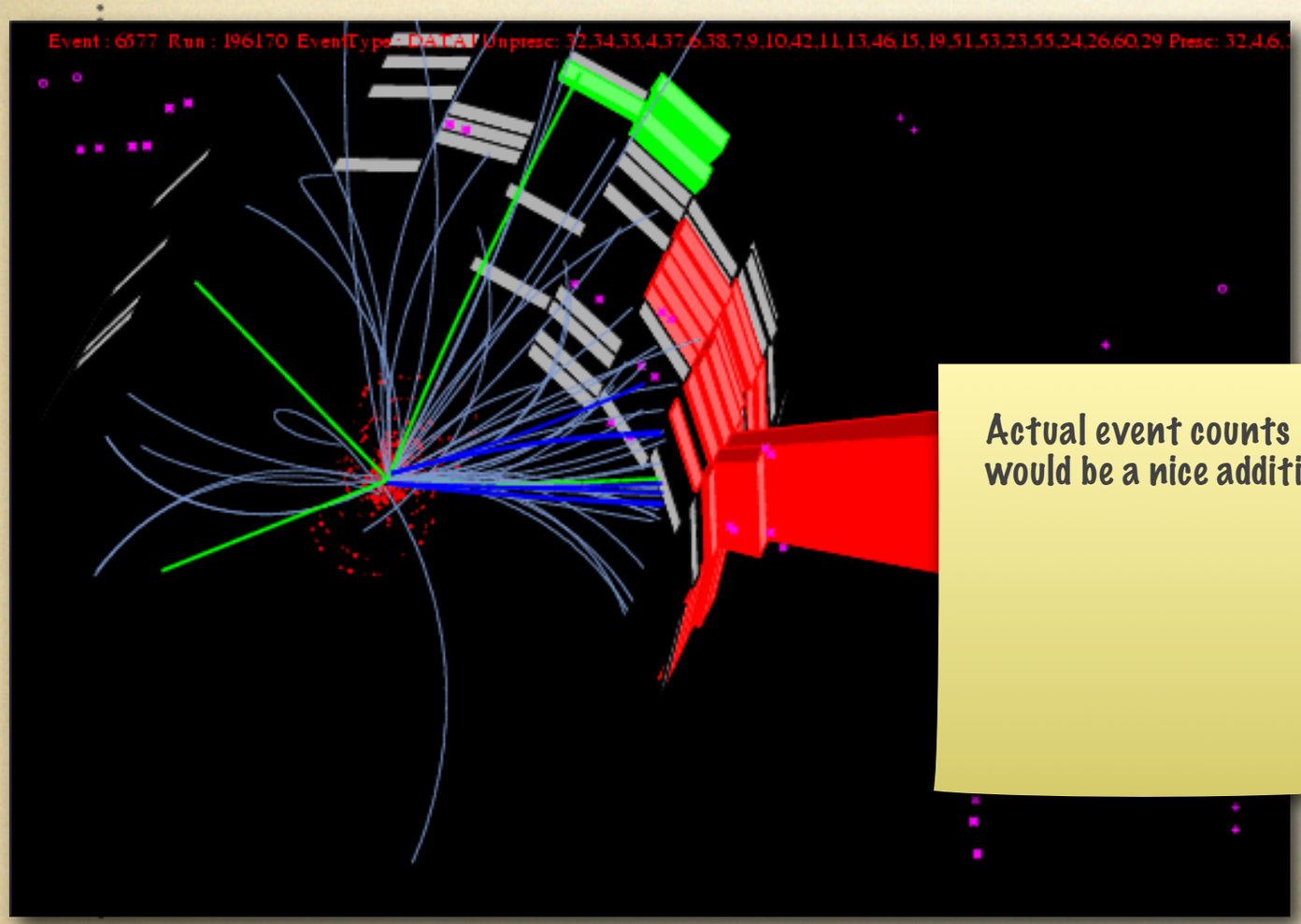




Interesting Event

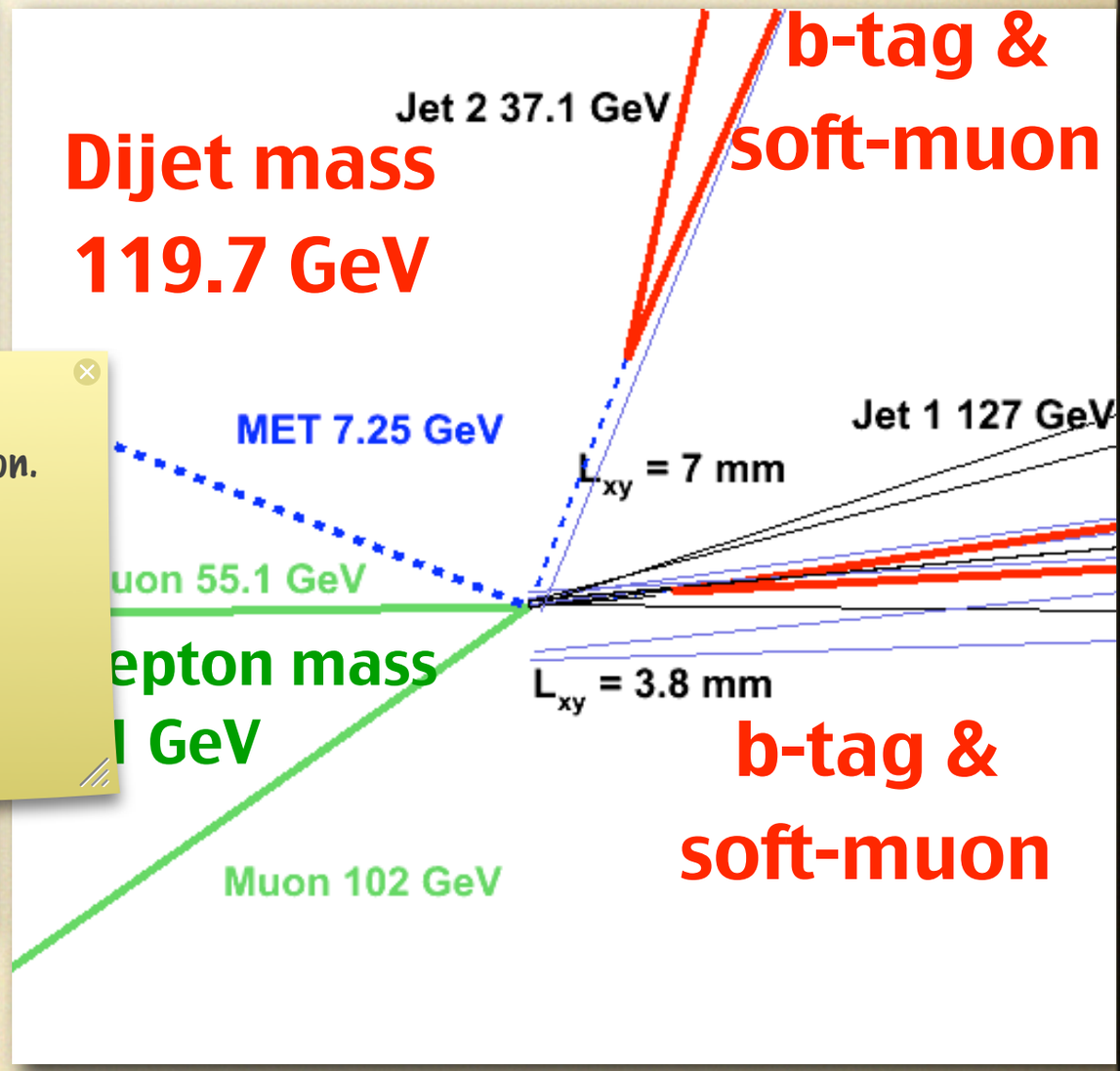
Tagging split into double tag and single Tag

# Most Higgs-like Event

## RUN 196170 EVENT 6577




Actual event counts would be a nice addition.




**Background in this bin**

60% Z+bb

11% tt

9% Z+cc

9% ZZ

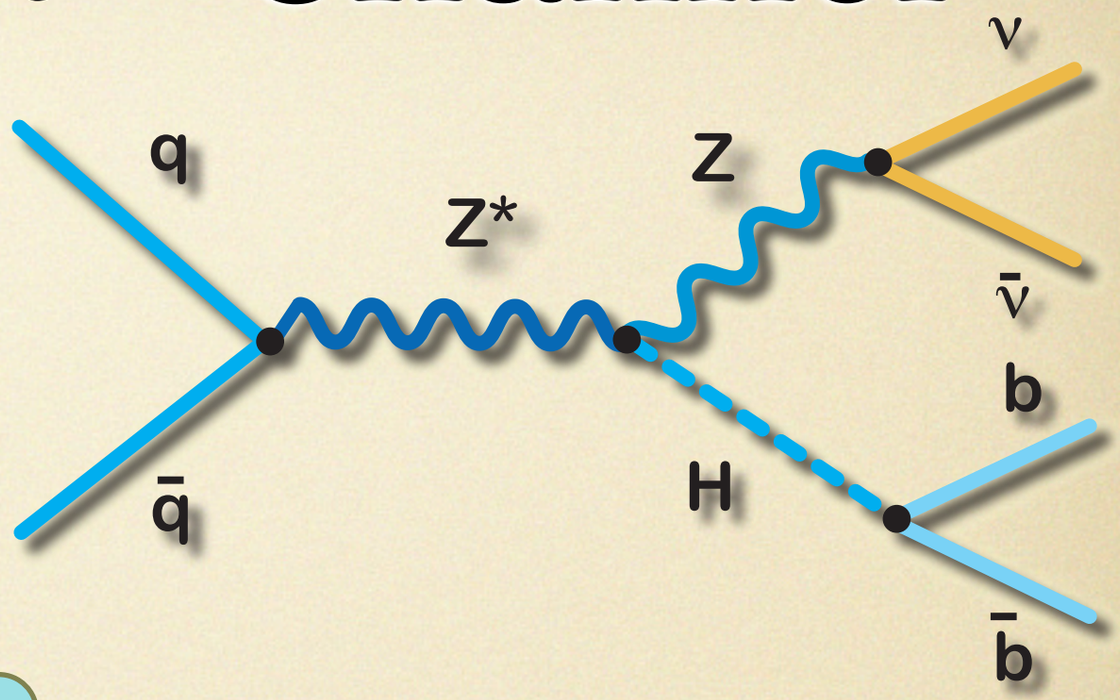
5% Z+qq (light)

**Higgs ~ 2 times tt**

**S:B ~ 1:4**

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

- No High $P_T$ Leptons
- Large Missing $E_T$
- 2 jets
  - Require 2 b-tags




Features:

1. Trigger is more challenging
2. Large QCD/Fake Bkgs
   i. Difficult to Simulate
   ii. Use data to est. bkgs
3. **Use tracks to help bkg identification.**
4. ~2-3 evts/$fb^{-1}$

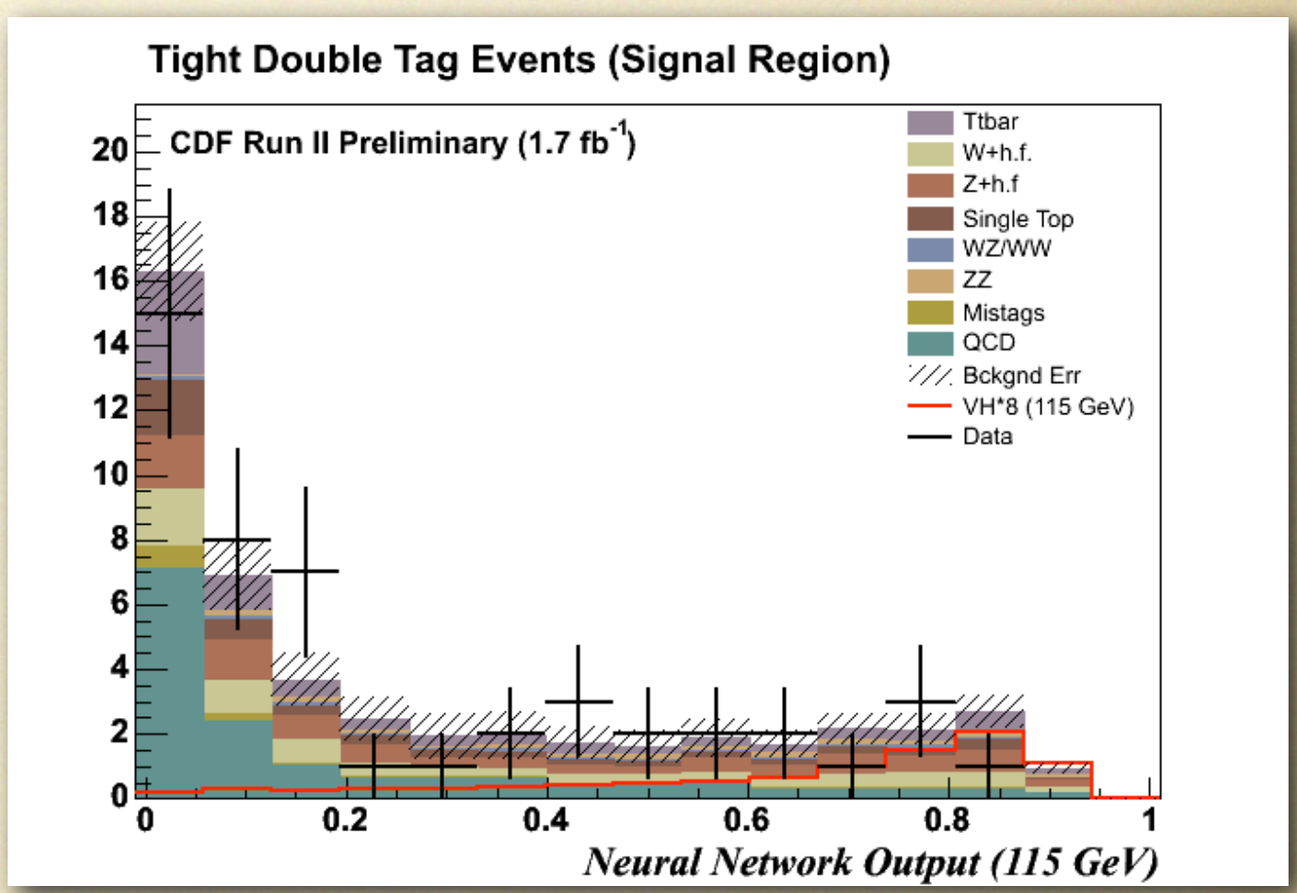
| Primary Backgrounds |
| --- |
| QCD Heavy Flavor, |
| $t\bar{t}$, $W/Z + b\bar{b}/c\bar{c}$, |
| Single Top, |
| $ZZ$, $WZ$, $WW$ |

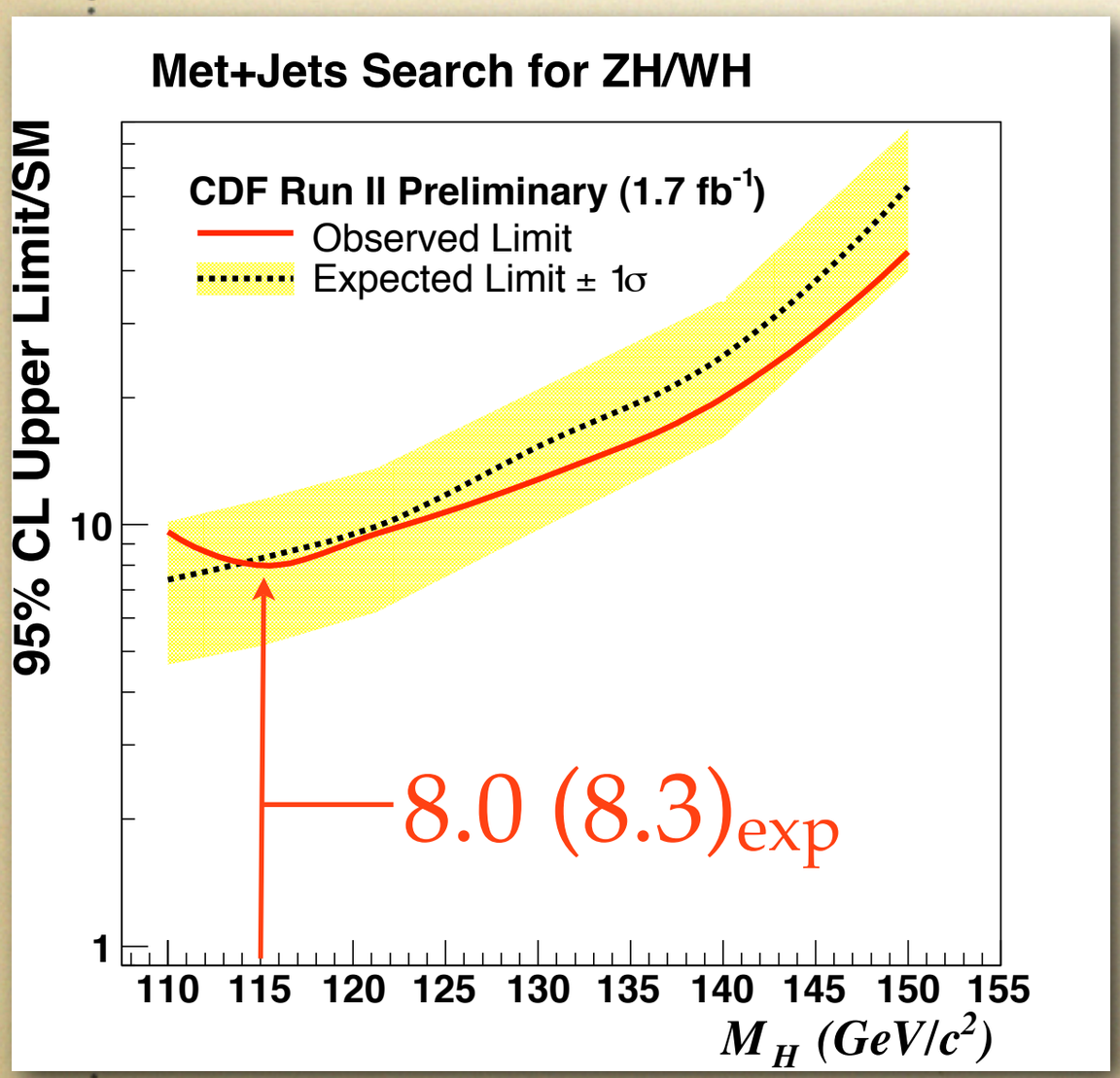
# $ZH \rightarrow \nu\nu b\bar{b}$ Channel

Figure of Merit: ANN

Inputs:

$$M_{bb},\ MET,\ \Delta R_{j_1-j_2},$$
$$MET_{cal} \cdot MET_{trk},\ Trk_{NN}$$




Classes: (2 Total)

Two b-Tagging:

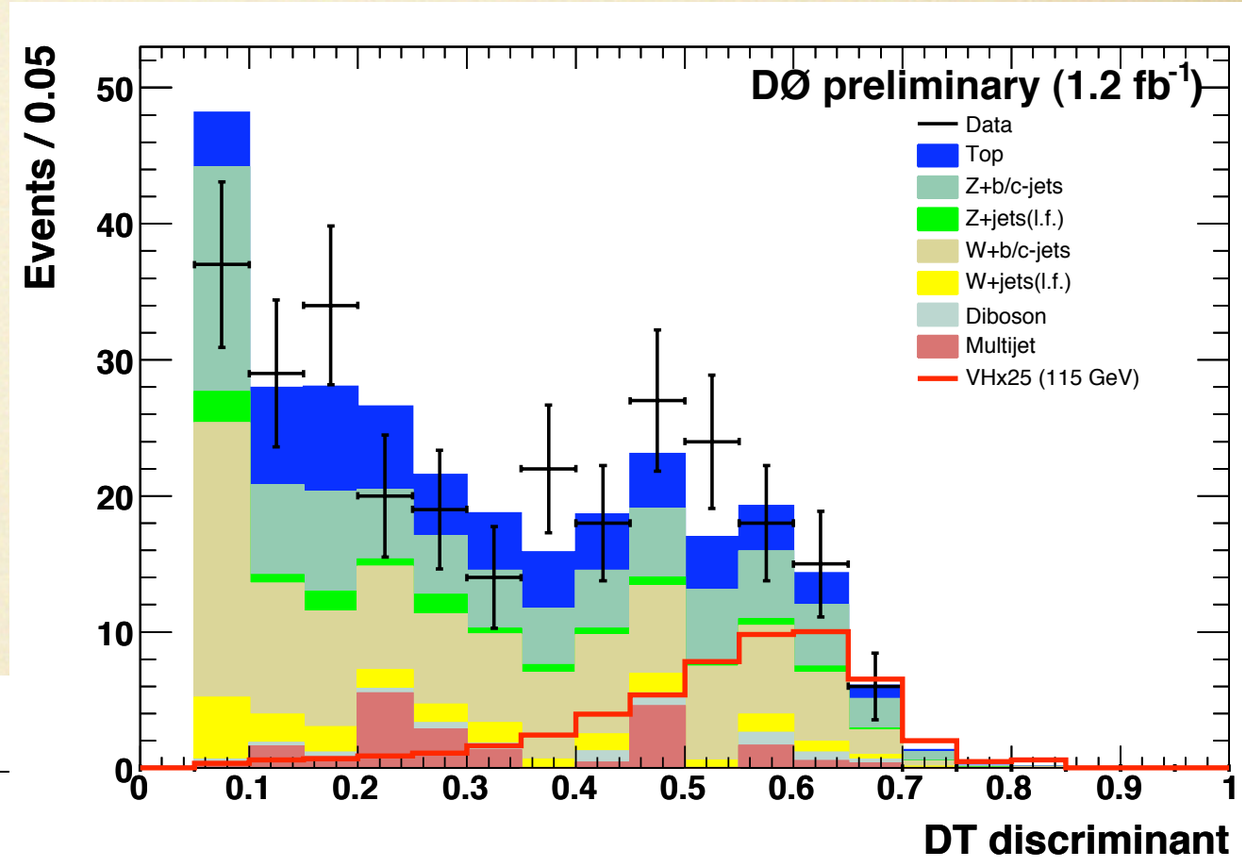
- double tight tag
- 1 tight + 1 loose tag

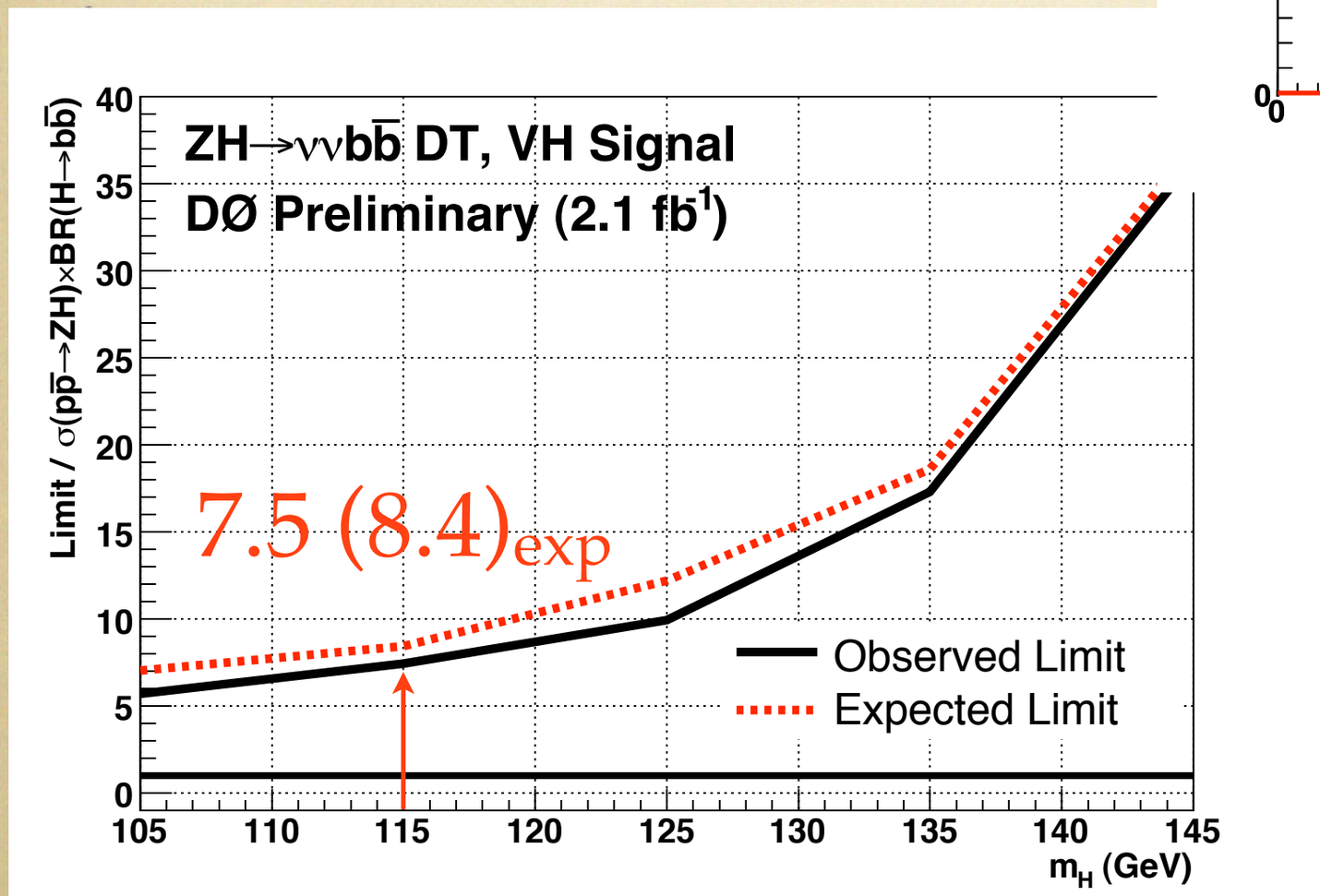
# $ZH \rightarrow \nu\nu b\bar{b}$ Channel

Figure of Merit:

Boosted Decision Tree

Inputs: 24 variables




Classes: (2 Total)

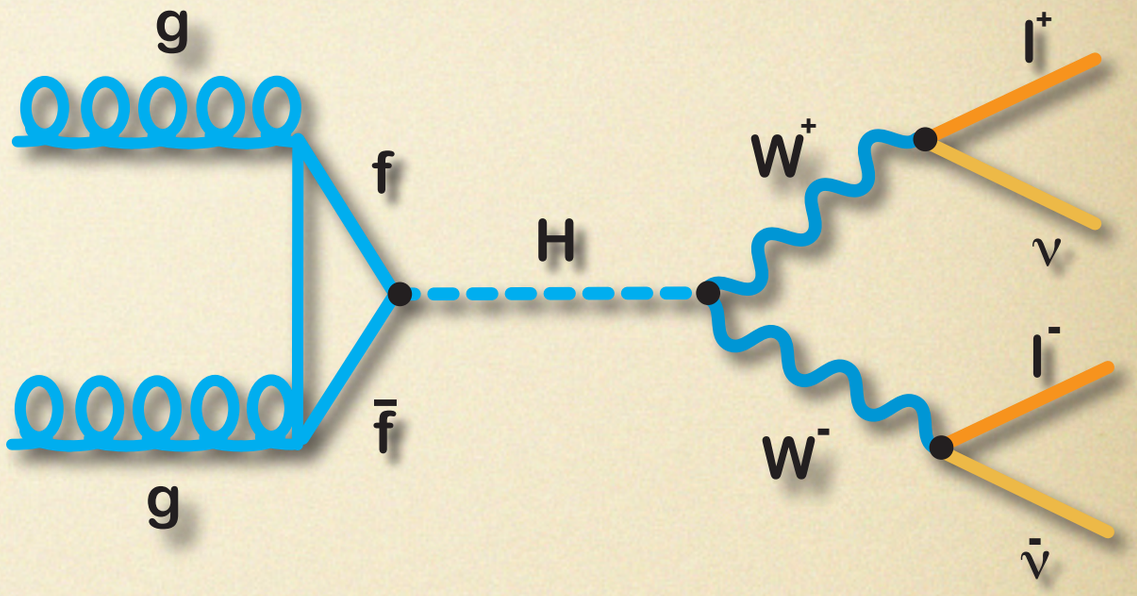
Two Data Periods

Double b-tagging required.

# High Mass Signature

# $\bar{p}p \to H \to WW^* \to \ell^+\nu\ell^-\bar{\nu}$ Channel

- Two High $P_T$ Leptons
- Large Missing $E_T$
- No significant jet activity




Features:

1. Most signif. for high mass
2. No kinematic mass peak
3. Higher production x-sec.
4. No b-tag eff. reduction.
5. Spin 0 Higgs → Ang. Corr.
6. ~2-4 evts/fb$^{-1}$

Primary Backgrounds

$WW$, $WZ$, $ZZ$,
$W + \text{jets}$, $t\bar{t}$,
$Z^{(*)} \to \ell\ell$

# $\bar{p}p \to H \to WW^* \to \ell^+\nu\ell^-\bar{\nu}$ Channel

Figure of Merit:

ANN w/ Matrix Elem.

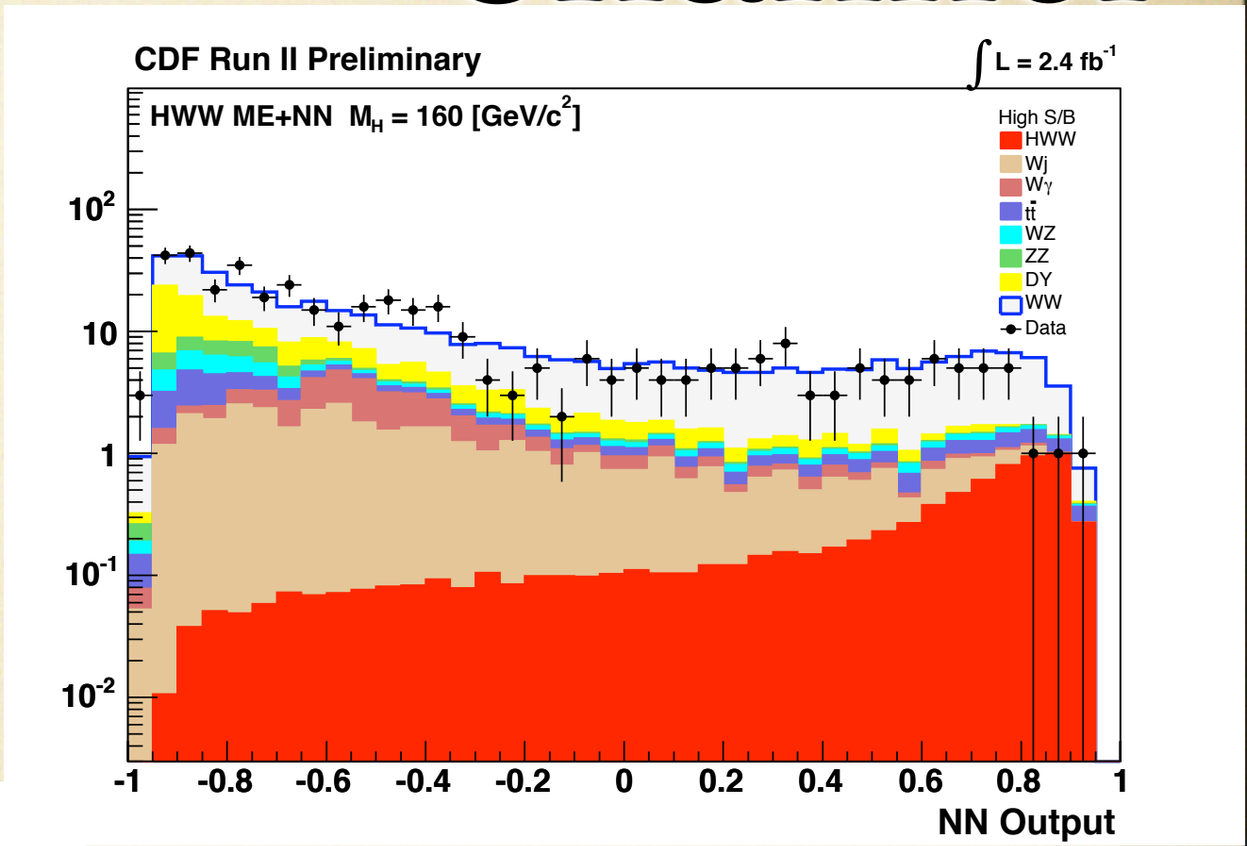
Inputs: $M_{\ell\ell},\ \Delta\phi_{\ell\ell},\ \Delta R_{\ell\ell},$

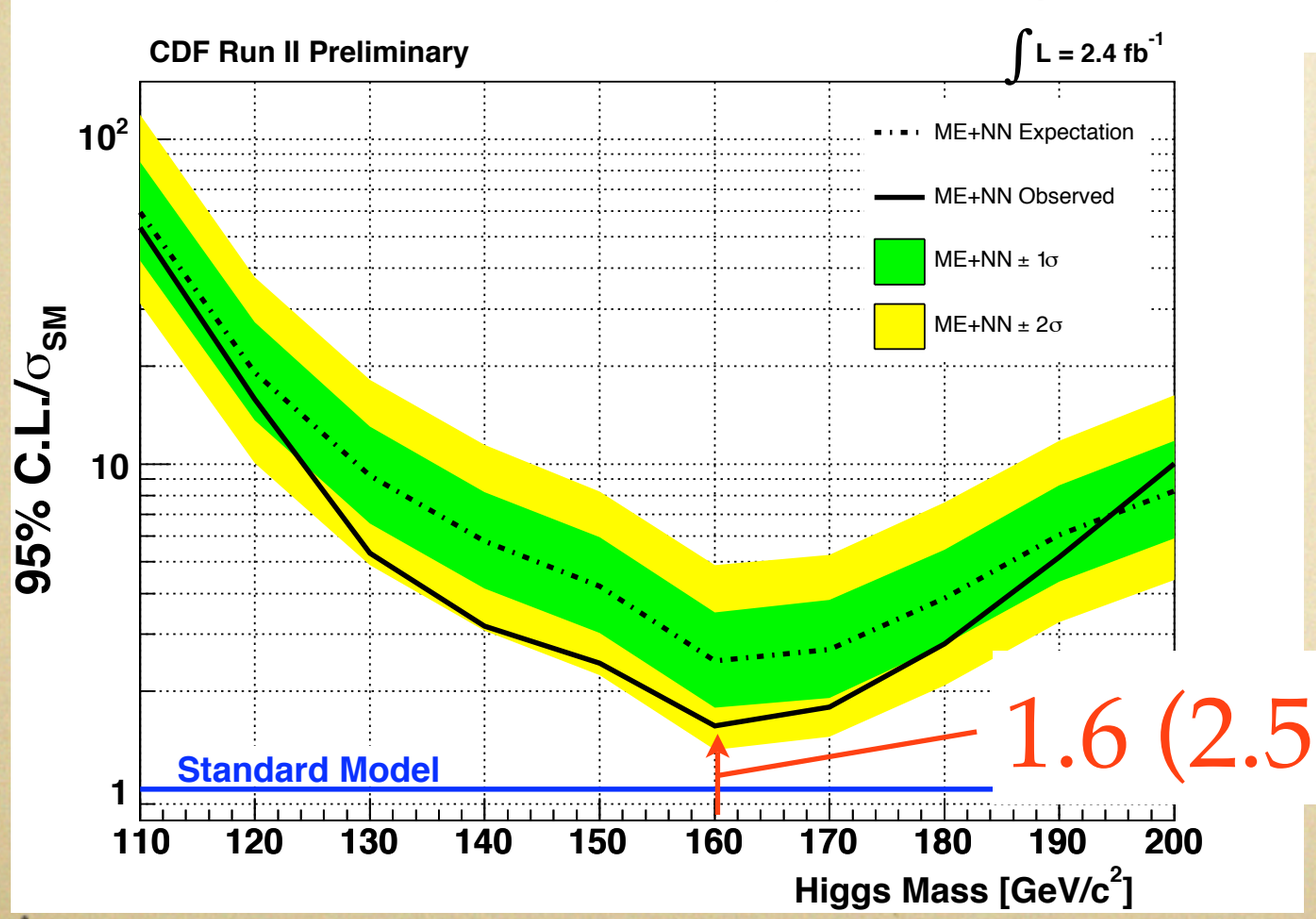
$\Delta\phi_{lj,MET},\ MET,\ MET_{\mathrm{Spec}},$

5 Likelihood Ratios :

$H \to WW^*,\ WW,$

$ZZ,\ W\gamma,\ W + jets$




$1.6\ (2.5)_{\mathrm{exp}}$

Classes: (2 Total)

Lepton Pairs:

ee, eμ, μμ,

e+trk, μ+trk

# $\bar{p}p \to H \to WW^* \to \ell^+\nu\ell^-\bar{\nu}$ Channel

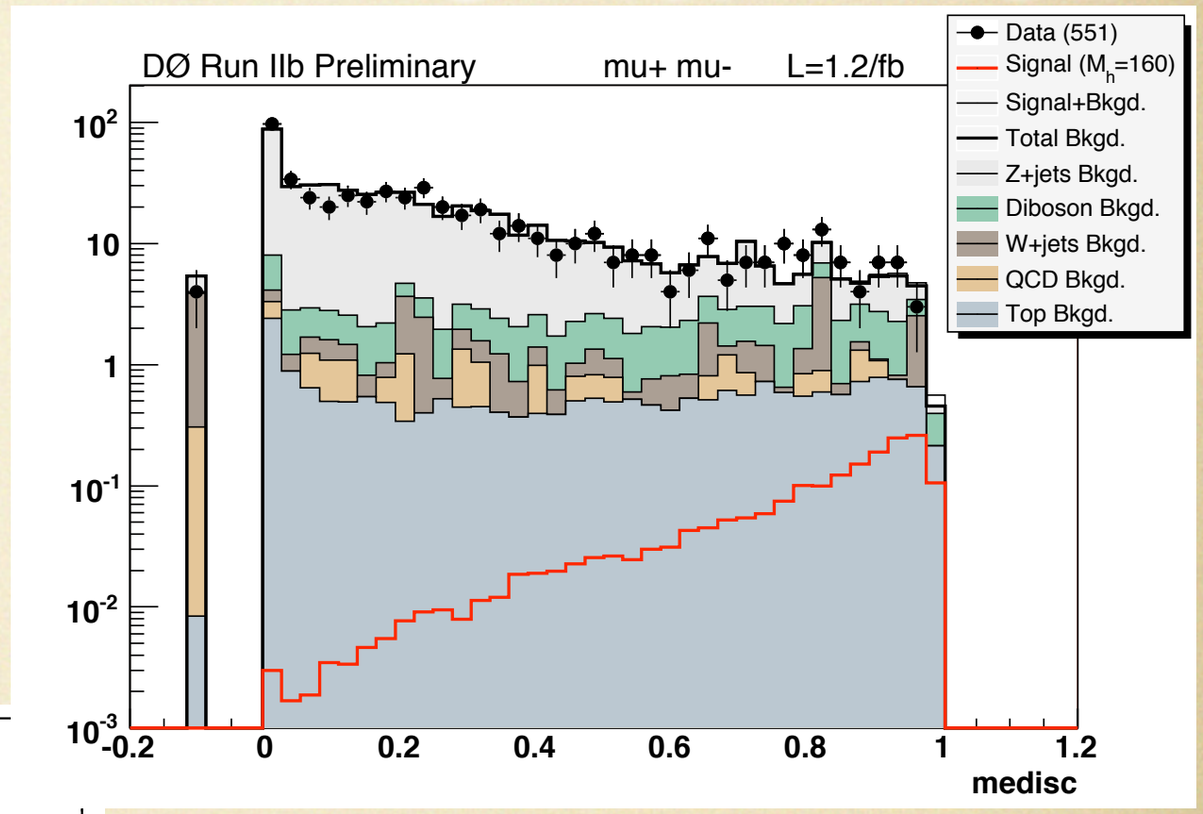
Figure of Merit:

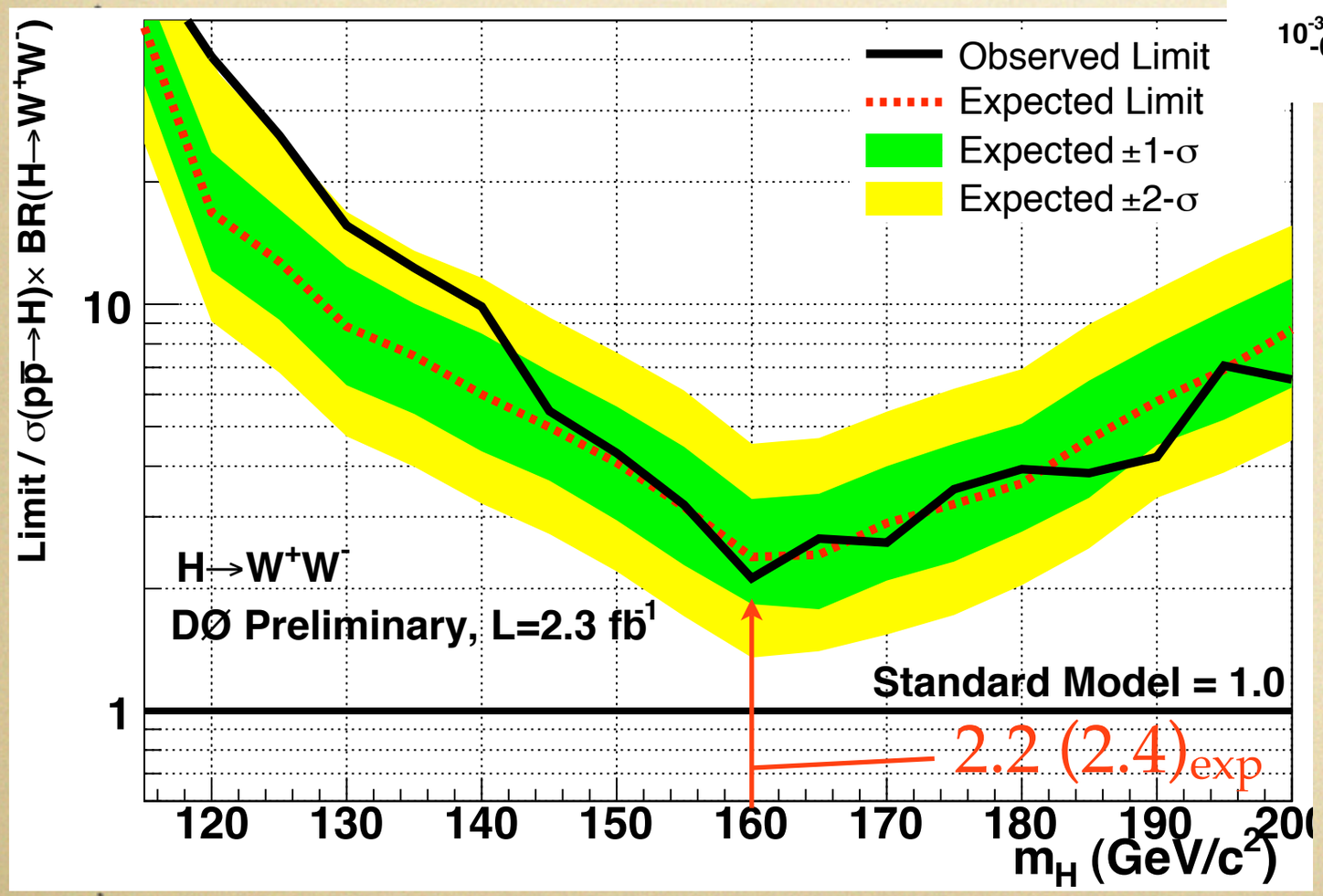
ANN w/ Matrix Elem.

Inputs: ee: 11 var + ME

eμ: 11 var

μμ: 14 var + ME




Classes: (3 Total)

Lepton Pairs:

ee, eμ, μμ

Backgrounds are very different.

# Other Channels...

- Other decay chains are also being considered
- IF the SM is correct, these are not as sensitive
- BUT, <u>every little bit helps</u> and <u>nature could be different</u>.

$t\bar{t}H \rightarrow \ell\nu qq' bbbb$

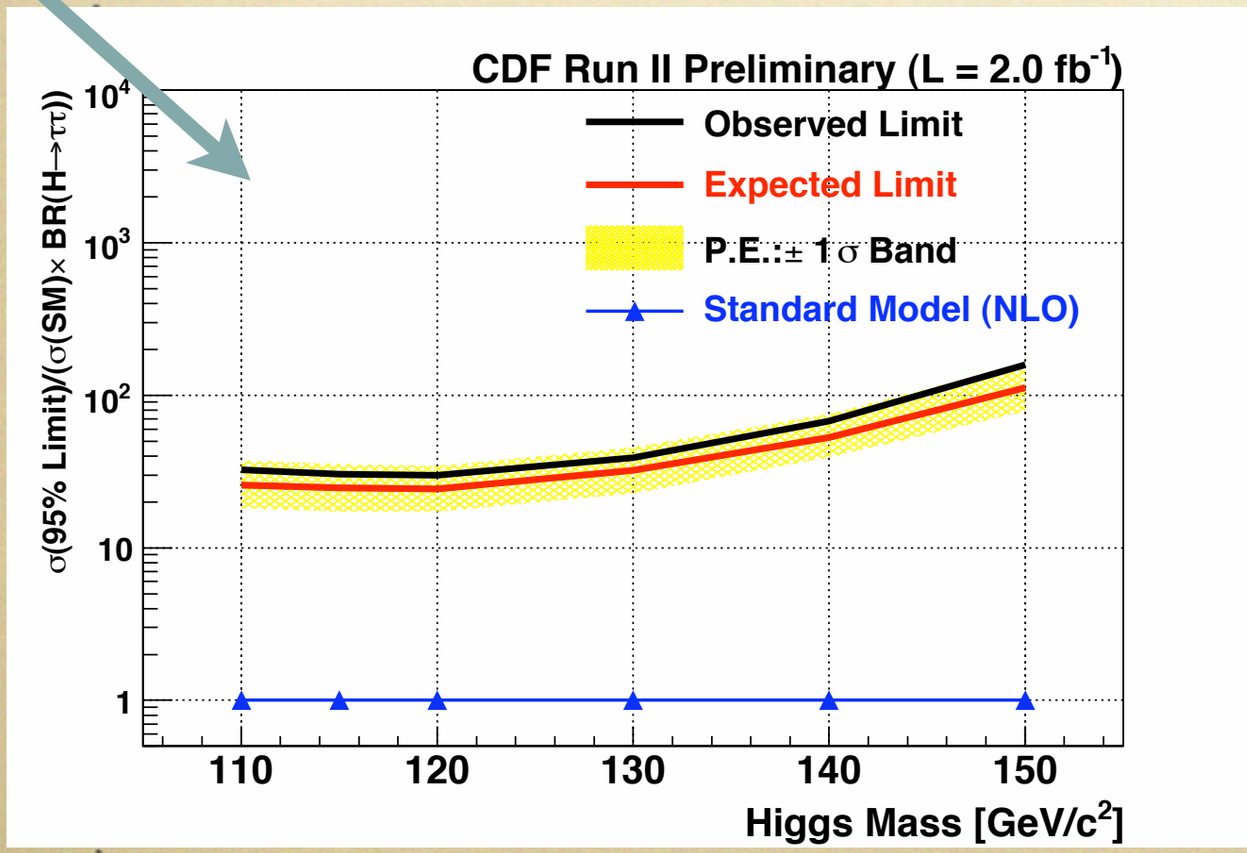
$WH \rightarrow WWW^*$

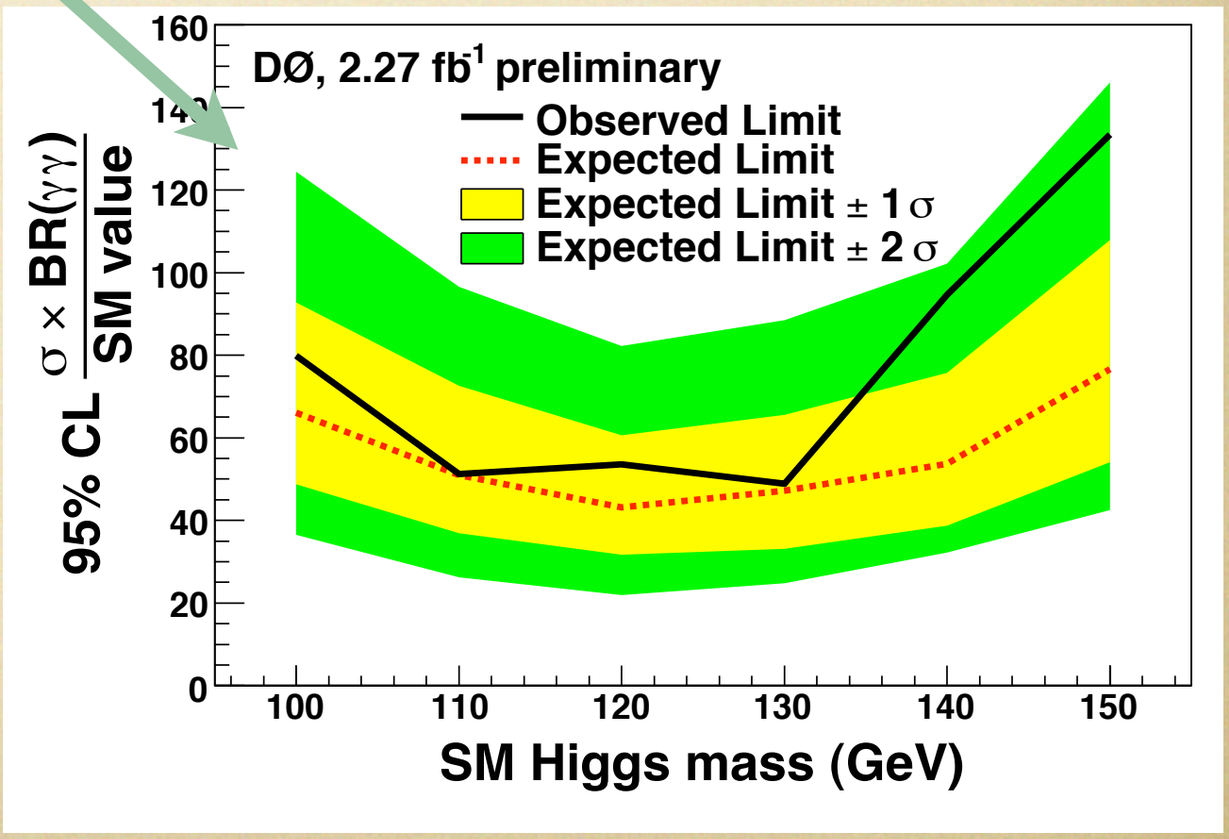
$VH,\ VBF, H \rightarrow \tau\tau + 2j$

$H \rightarrow \tau\tau$

$WH \rightarrow WWW^*$

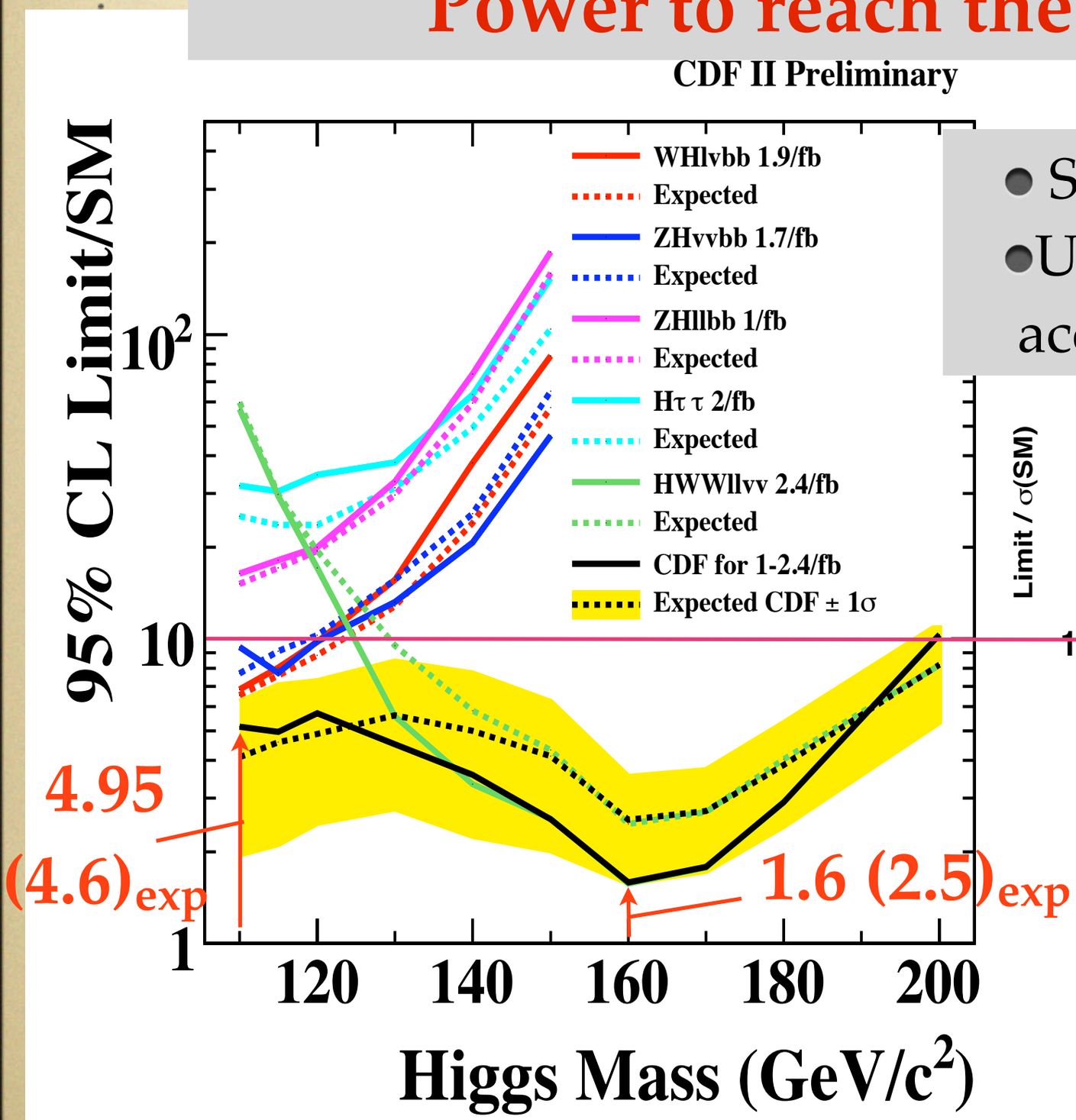
$\bar{p}p \rightarrow H \rightarrow \gamma\gamma$



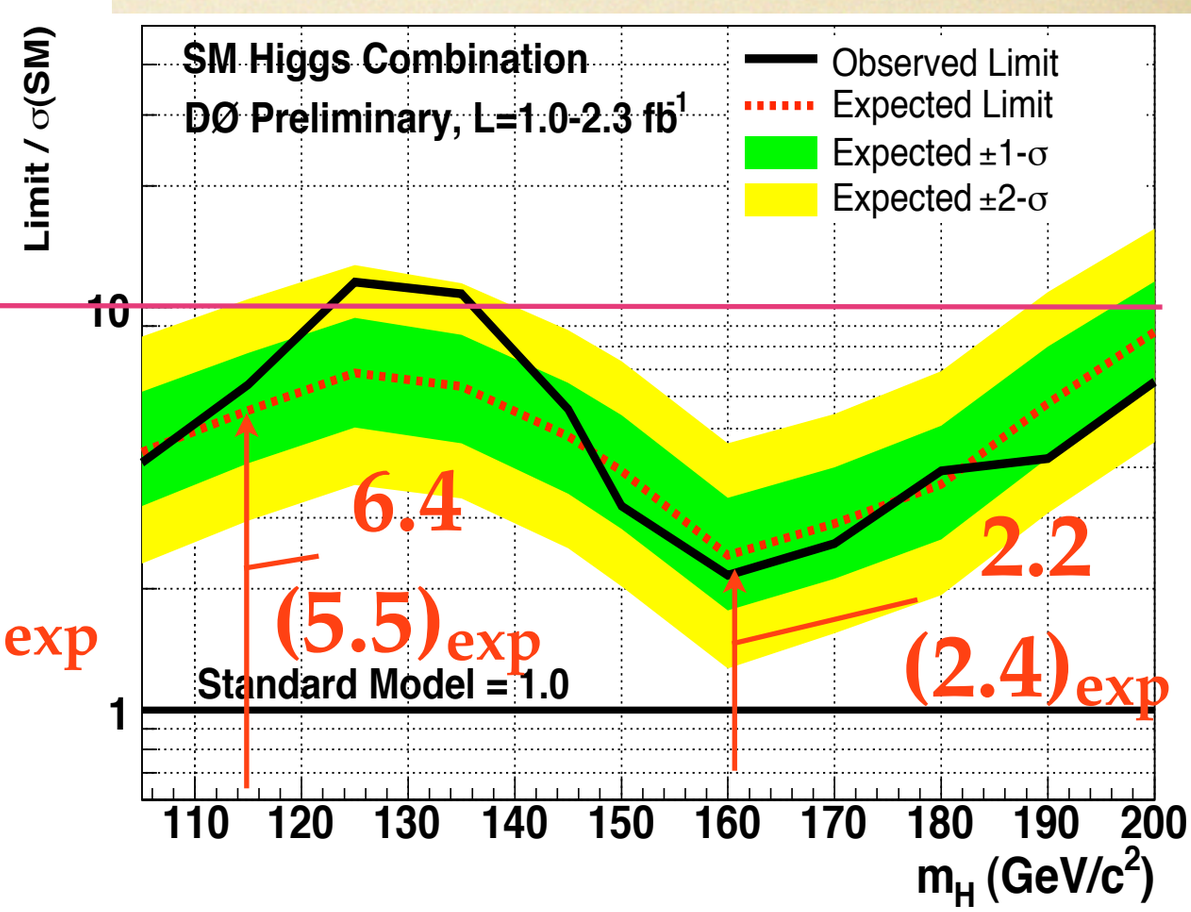



# 4th Step...Channel Combination

**No Single Decay Channel Has Sufficient Power to reach the SM prediction.**




- Statistically Combine Channels.
- Use a procedure to properly account for correlated uncertainties.



# 5th Step…Tevatron Combination

**Neither Experiment Has Sufficient Power to span the full mass range $M_H$ < ~200 GeV/c².**

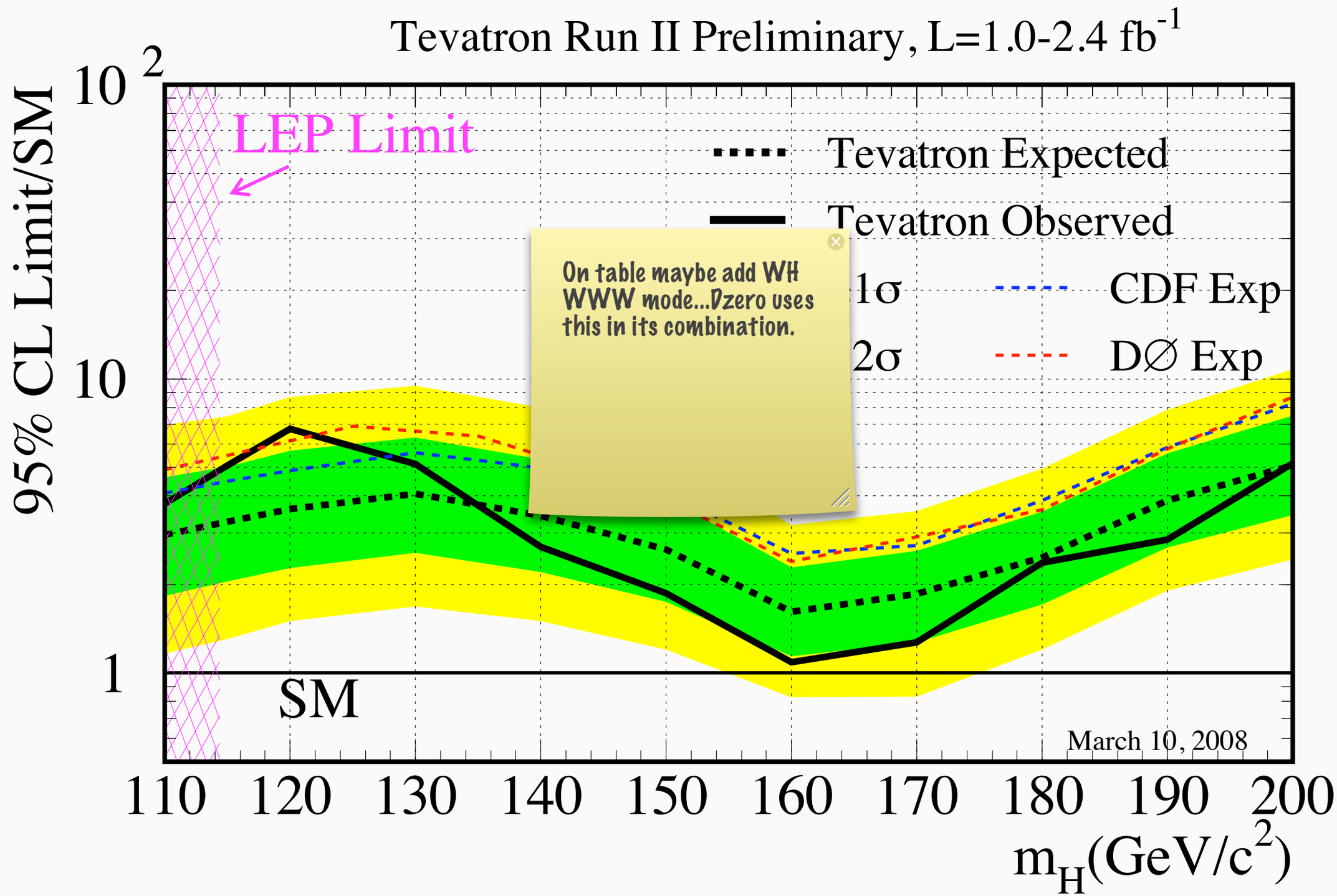
On table maybe add WH WWW mode…Dzero uses this in its combination.

| Channel | CDF Limits σxB/SM obs (exp) | DZero Limits σxB/SM obs (exp) |
|---|---|---|
| $WH \to \ell\nu b\bar{b}$ | [illegible] | 10.9 (8.9) |
| $ZH \to \ell\ell b\bar{b}$ | [illegible] | 17.8 (20.4) |
| $ZH \to \nu\nu b\bar{b}$ | 8.0 (8.3) | 7.5 (8.4) |
| $H \to \tau\tau$ adds 10% | 30.5 (24.8) | - |
| Combined | 4.95 (4.6) | 6.4 (5.5) |
| Tevatron Combined | **5.1 (3.3)** | |
| $H \to WW^*$ | 1.6 (2.55) | 2.2 (2.4) |
| Tevatron Combined | **1.1 (1.6)** | |

$M_H = 115\ \mathrm{GeV}/c^2$

$M_H = 160\ \mathrm{GeV}/c^2$

# 5th Step...Tevatron Combination

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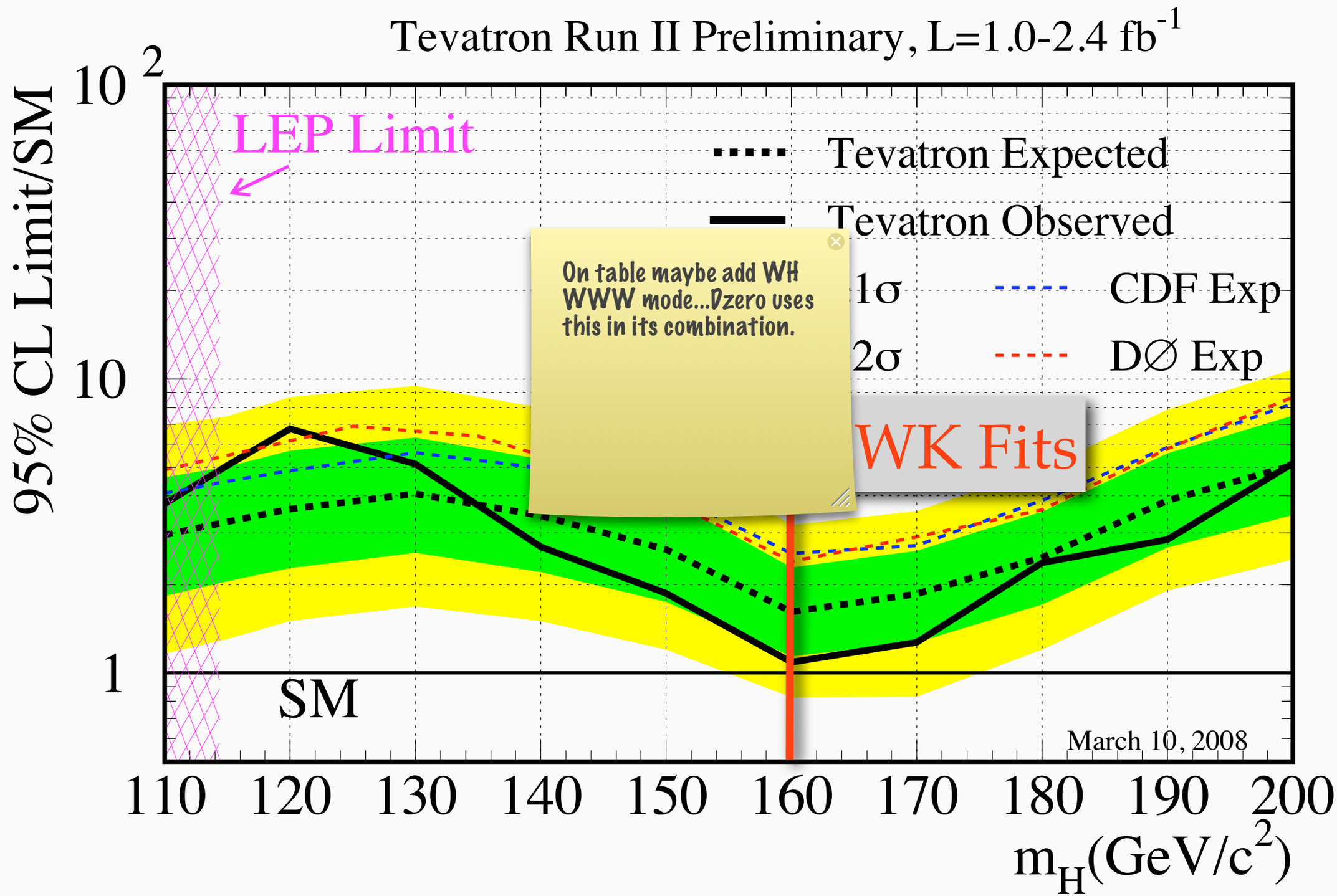
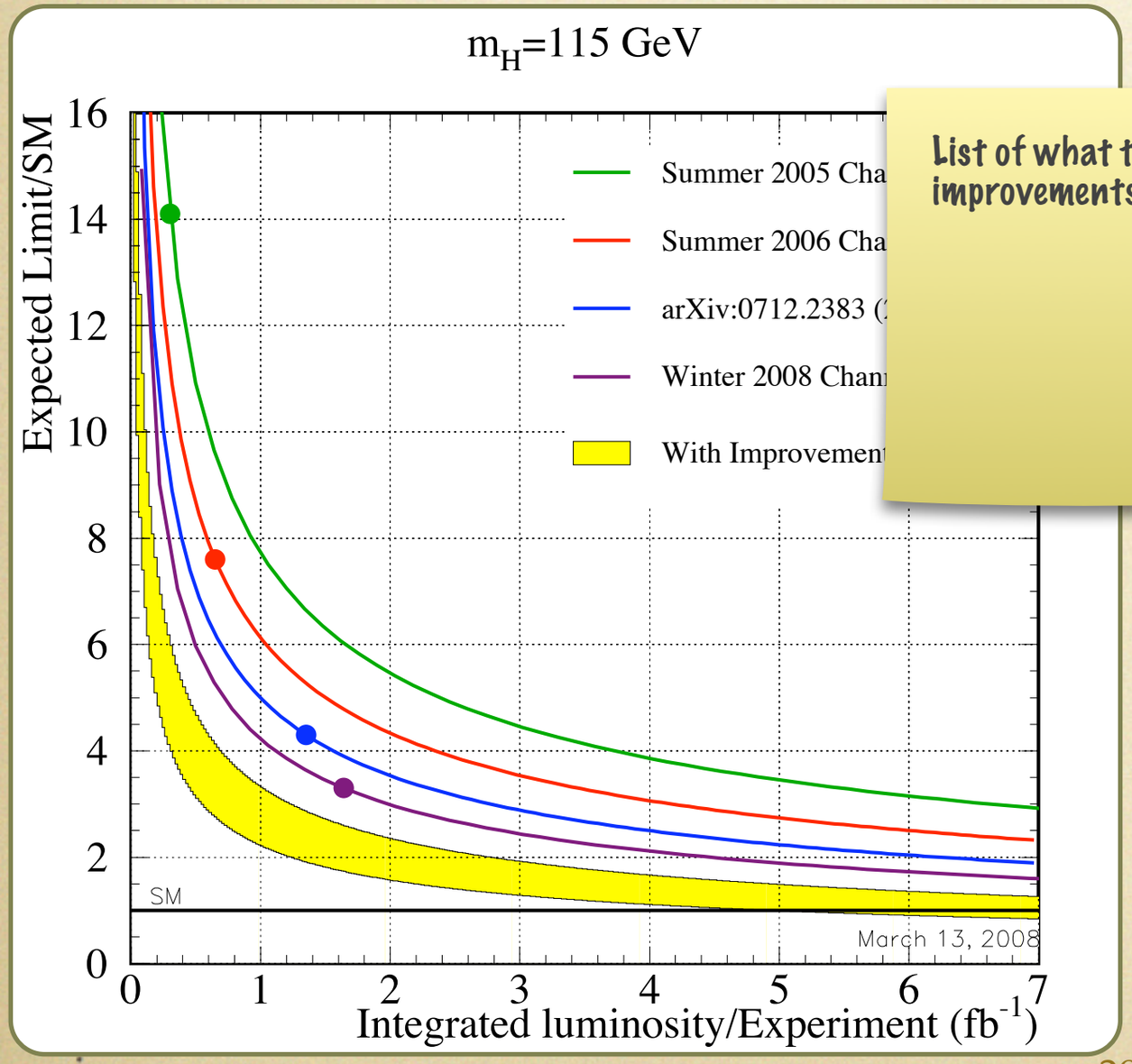


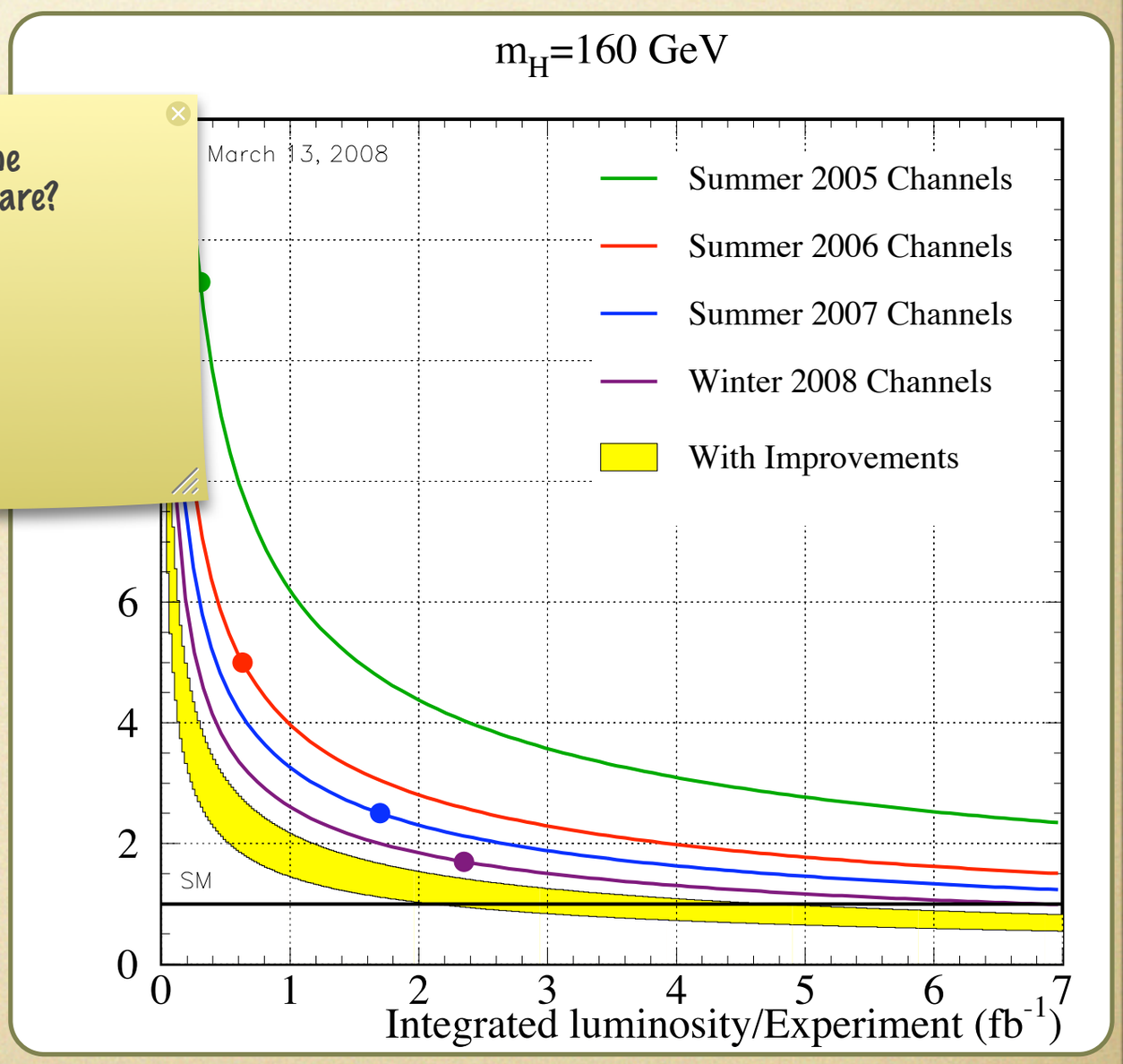

On table maybe add WH WWW mode...Dzero uses this in its combination.

WK Fits

# Future Prospects

- We can extrapolate into the future using either:
  - (1) The current analyses only adding more data.
  - (2) Extend the sensitivity for anticipated improvements




List of what the improvements are?

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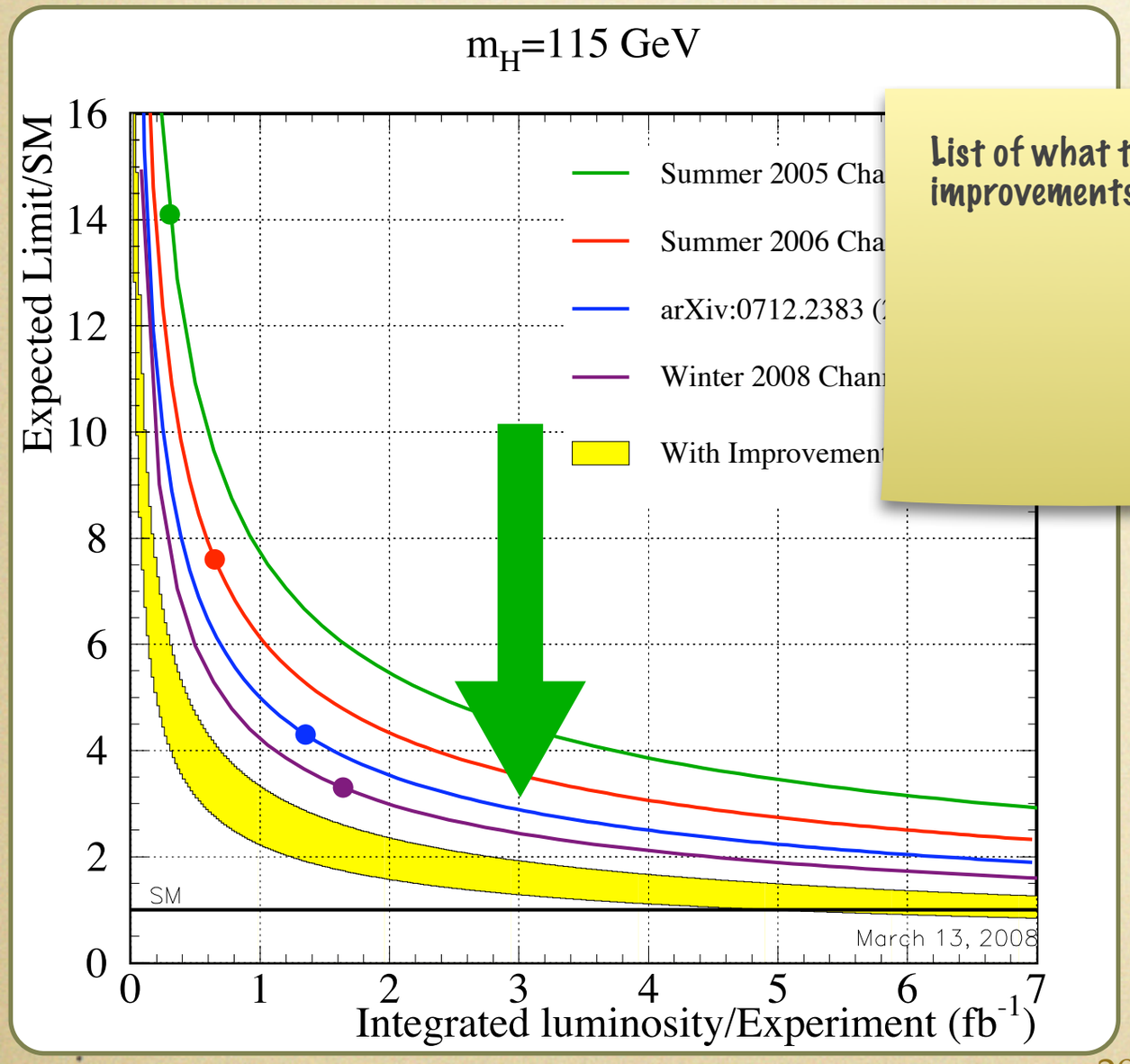


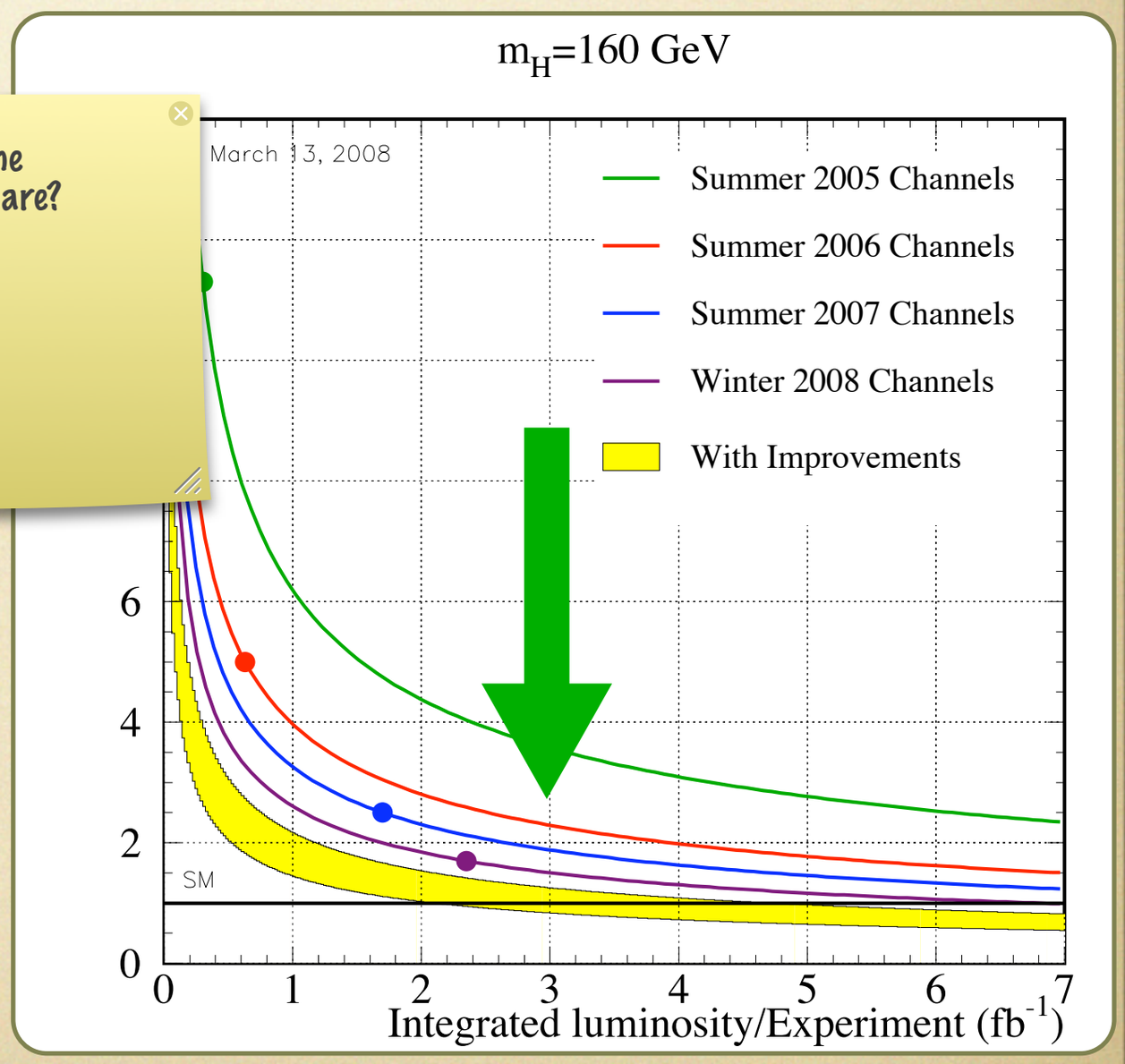


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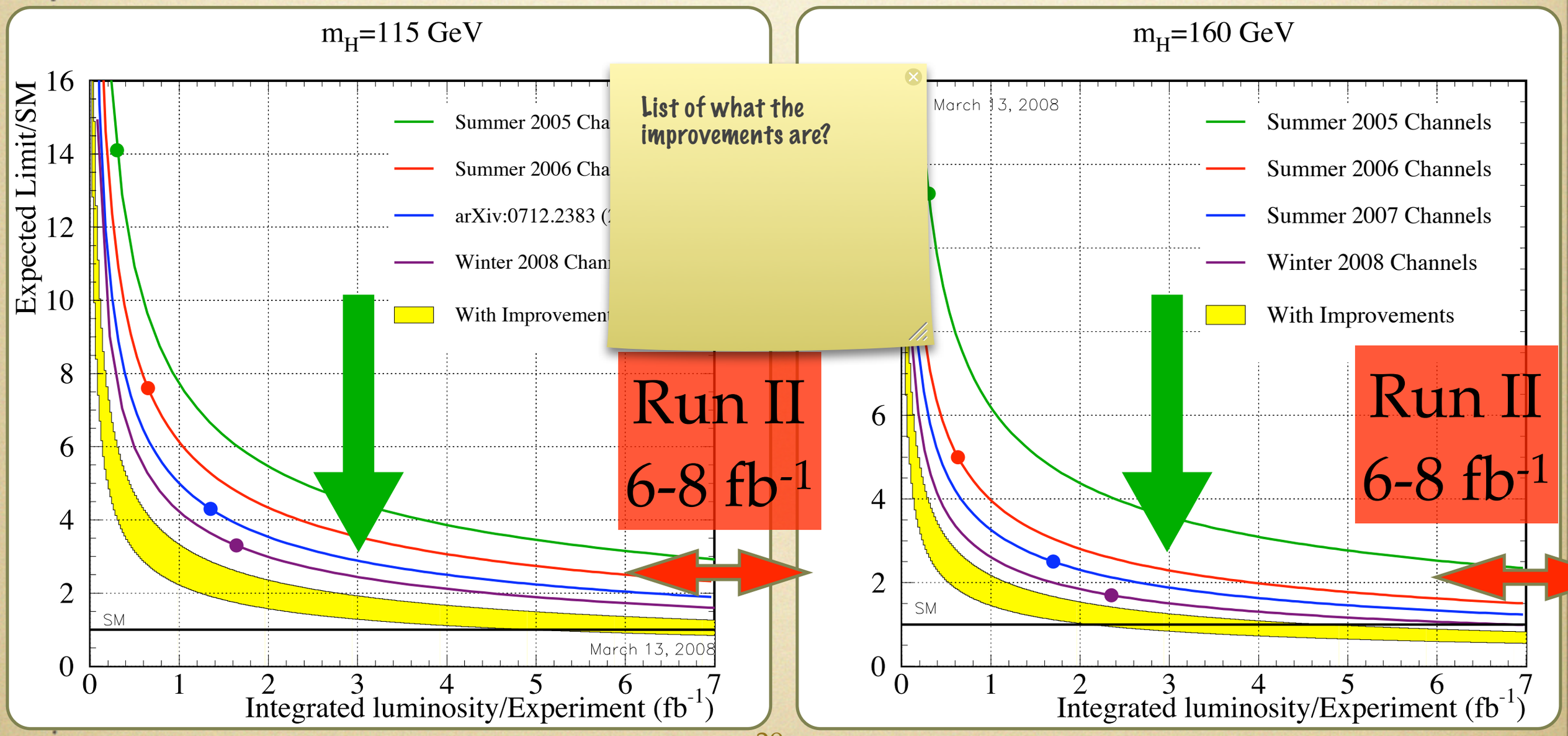

# Summary

- Higgs search at Fermilab has become mature.
- The collaborations are squeezing every last bit of sensitivity from all channels.
- Improvements continue to occur.
- With the additional data expected, there is still an excellent opportunity for the Tevatron to weigh in on the Higgs before the LHC takes over.
- Perhaps as early as this summer, the experiments will begin excluding masses around 160 GeV/$c^2$.

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- With the addit ed, there is still an excell the Tevatron to weigh in o ggs before the LHC takes over.
- Perhaps a early as this summer, the experiments will begin excluding masses around 160 GeV / $c^2$.

Stay Tuned!

# Higgs Sessions

**Sunday, April 13th: 1:30 - 3:00, 3:30 - 5:30**

"Search for Higgs Boson in WW* Decays" Penning

"Search for H Decays to WW* at CDF" Burke

"Search for WH to WWW Using Like Sign Dileptons at CDF" Wakisaka

"Search for Associated Production of W and Higgs Bosons in lnu bb Final States" Xu

"Search for SM Higgs Boson Produced in Association with a Z or a W Boson at CDF" Apresyan

"Evolutionary Neural Network Based Analysis of the ZH to ll bb Channel" : Shekhar

"Search for Higgs boson using matrix-element technique at CDF" Alvarez

"Search for Associated Production of W and Higgs Bosons in the All Hadronic Decay Mode" Clutter