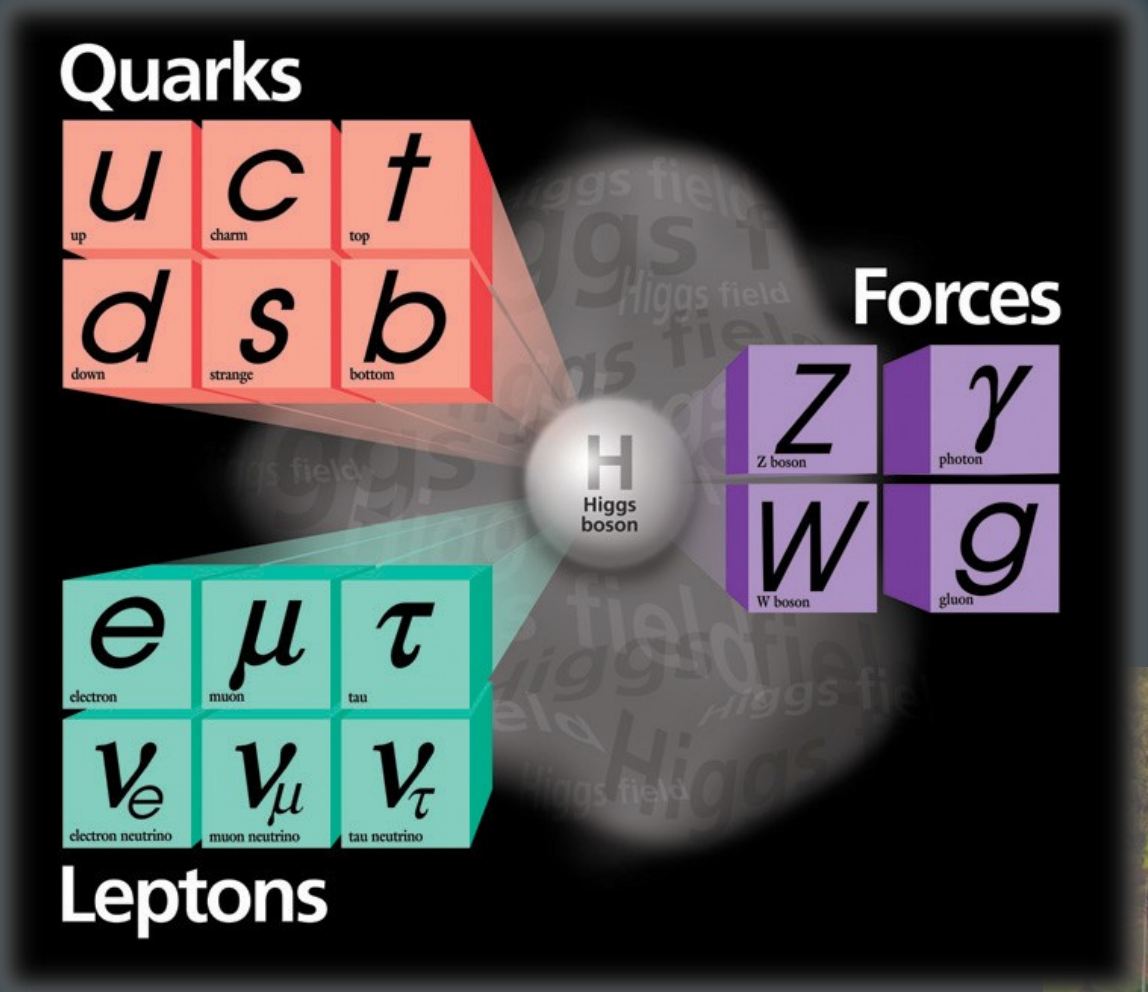
# Higgs Searches at the Tevatron

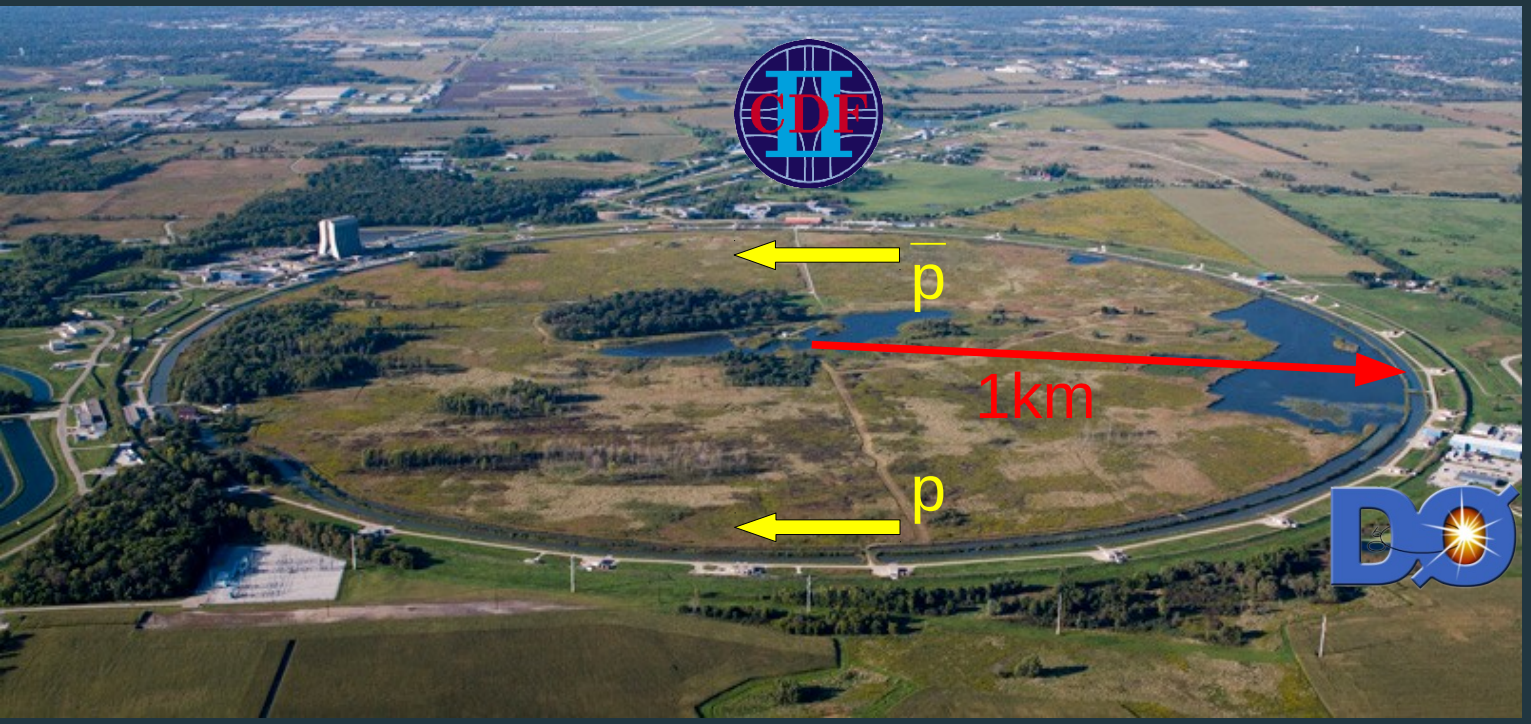




**Bob Hirosky**

**University of Virginia**


# Tevatron Accelerator and Experiments

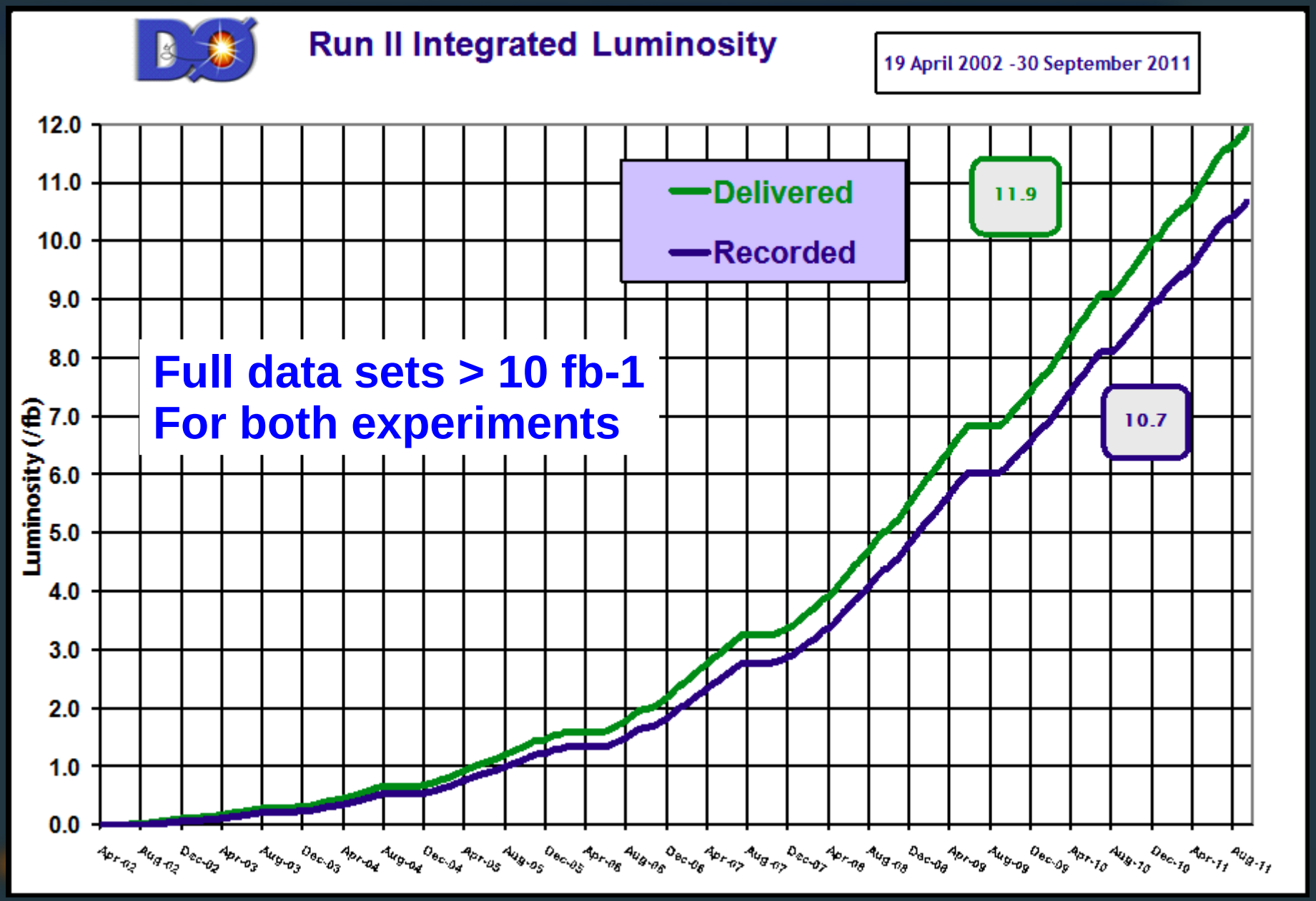



$p\bar{p}$ collisions
C.M. Energy 1.96 TeV

Tevatron Run 2 data collection completed Sept. 30 2011
~ 10 year program of data collection at highest $p\bar{p}$ collisions energies

~33 billion events recorded (D0) + similar for CDF

# Enormous debt of gratitude to Fermilab Accelerator Division for outstanding performance



# Good accelerator performance introduces its own challenges

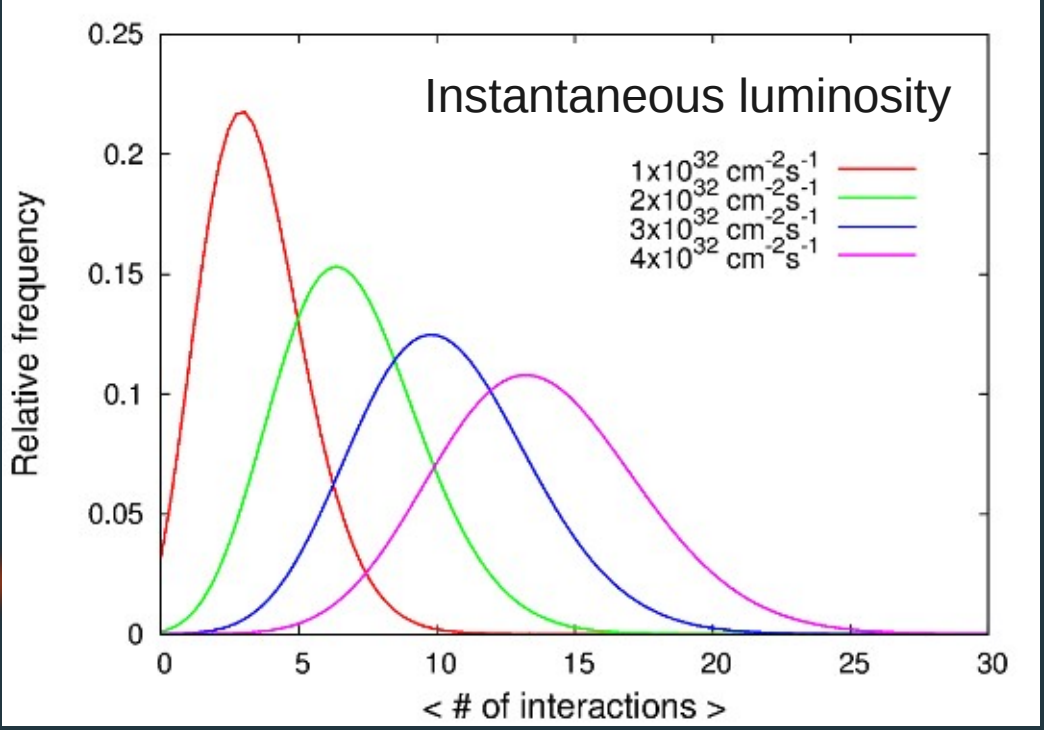
The good: >10 $fb^{-1}$ recorded per experiment
~ 60 $pb^{-1}$/week

The challenge: Peak luminosity to up $4x10^{32}$ $cm^{-1}s^{-1}$

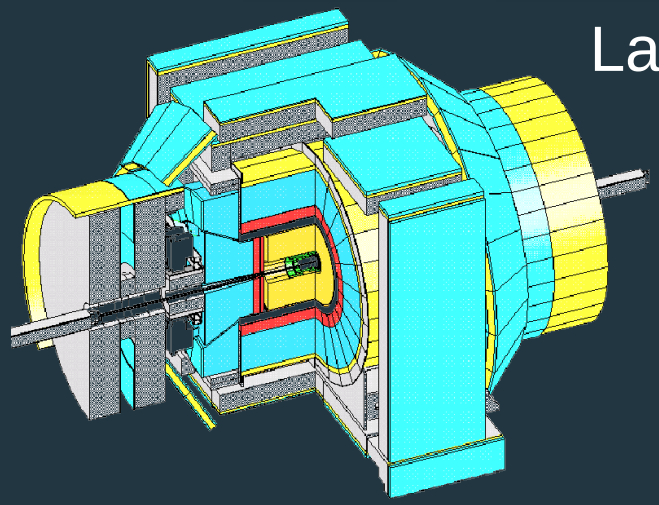
Brings all the expected (and often unexpected) complexities from multiple $p\bar{p}$ interactions / beam crossing.

Increasing challenges in:

- Triggers
- Object reconstruction and ID
- Efficiency measurements
- MC modeling
- ...

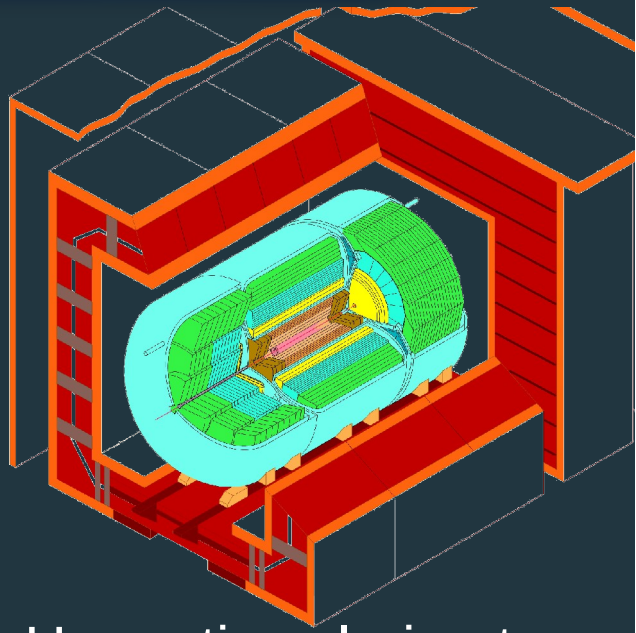


# CDF and DØ Detectors



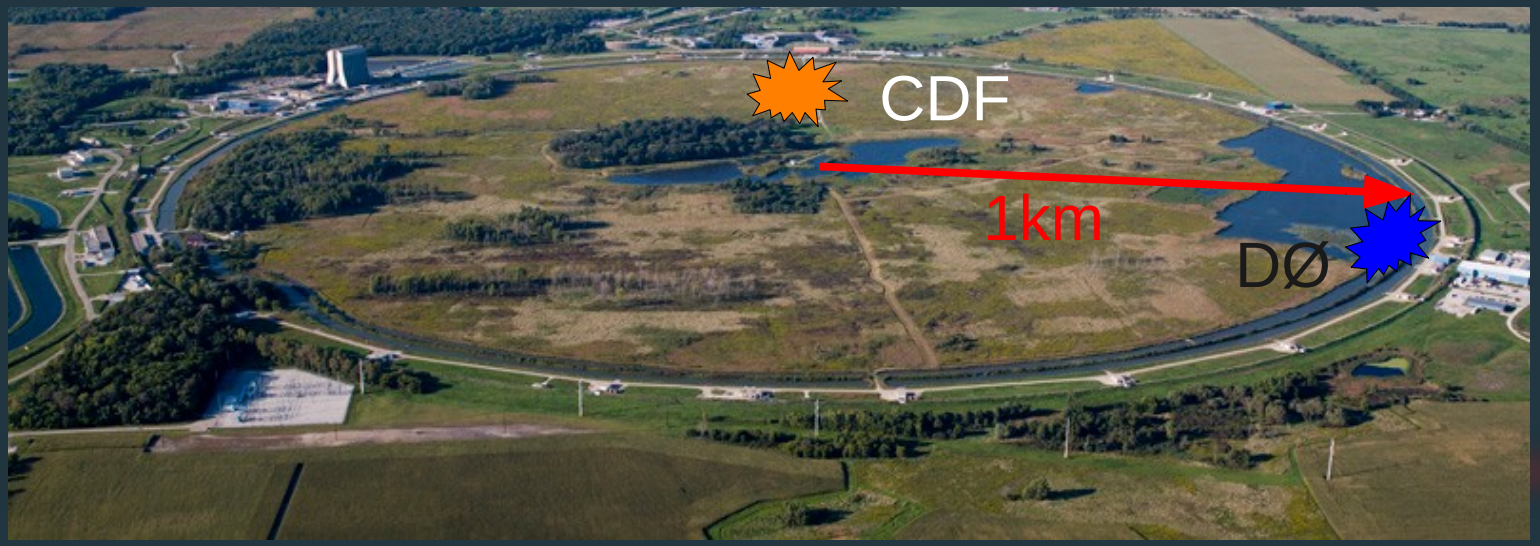
Large, multipurpose detectors

* Tracking
* Calorimetry
* Muon detection
* Missing ET → infer ν's



Large tracking volume

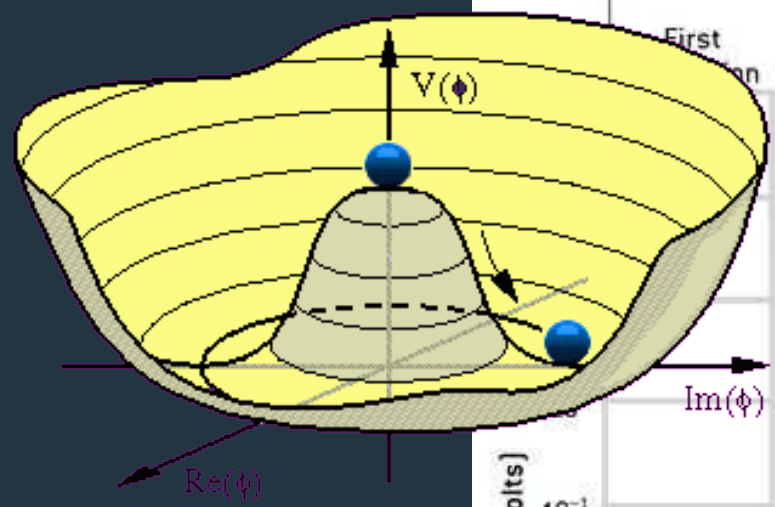
Hermetic calorimetry, μ coverage

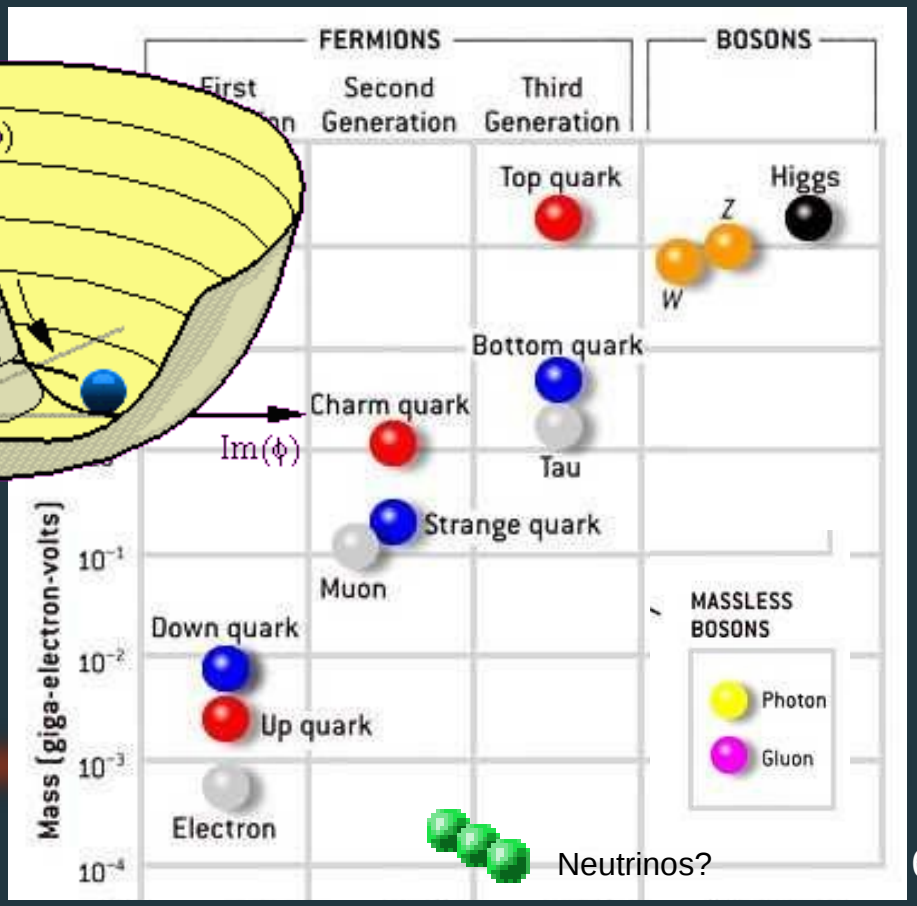


# Predictions for Higgs Mechanism

We have a theory that has captured the imaginations and interests of physicists and the general public.

Getting a handle on the origin of (any) elementary particle masses, is an exciting prospect for physics!



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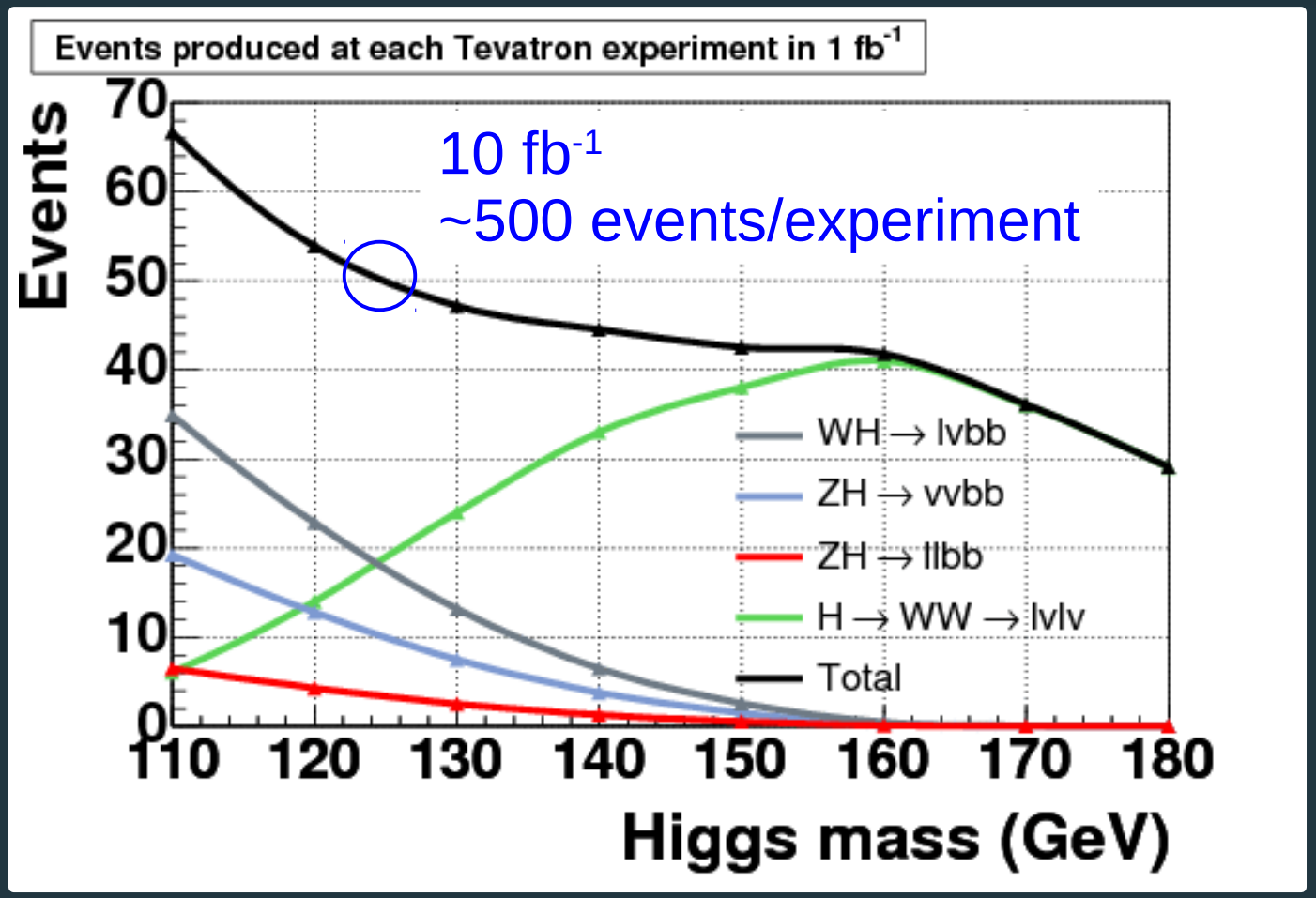
Leading contributions to

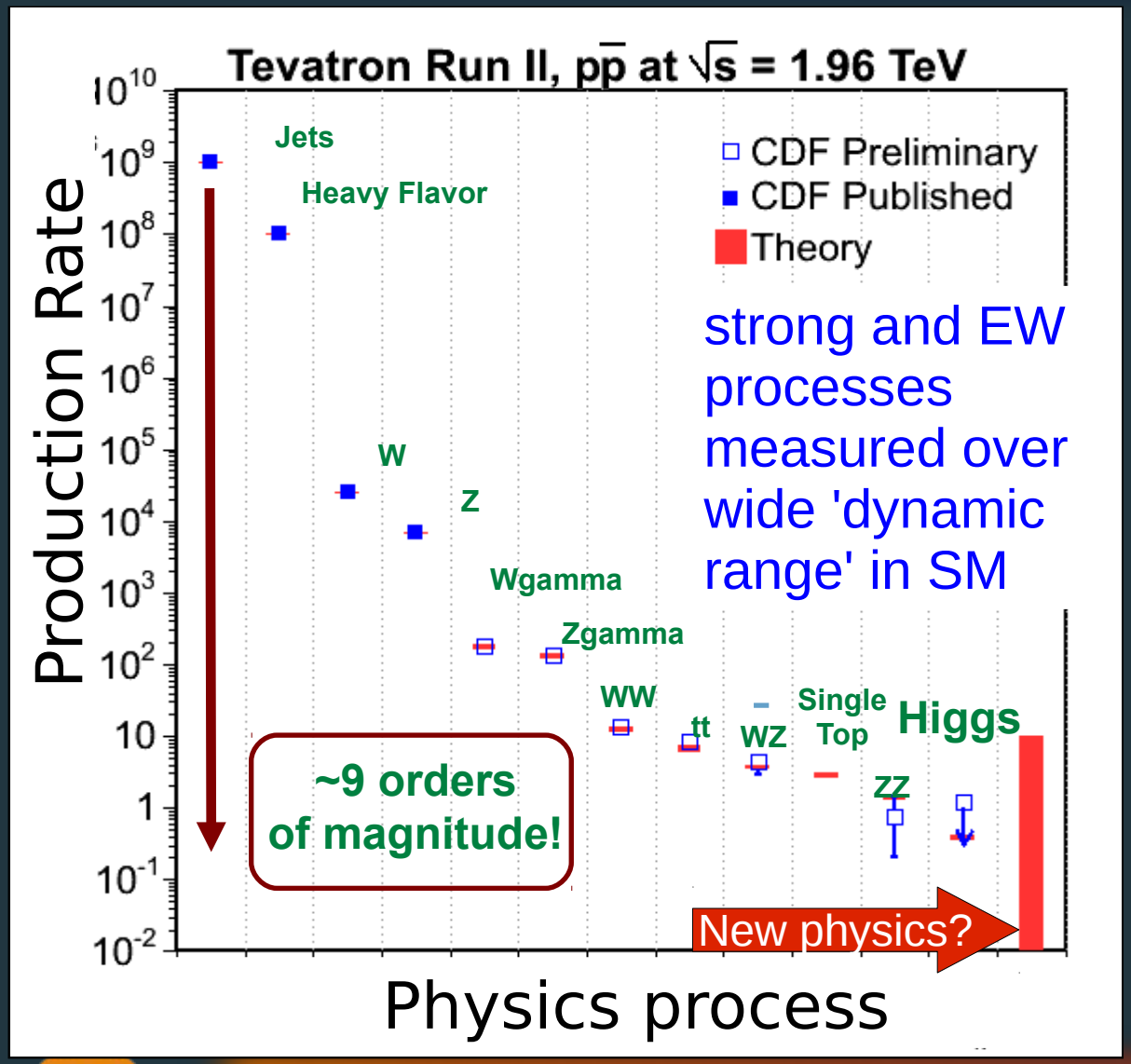
# Higgs Boson Production Rates

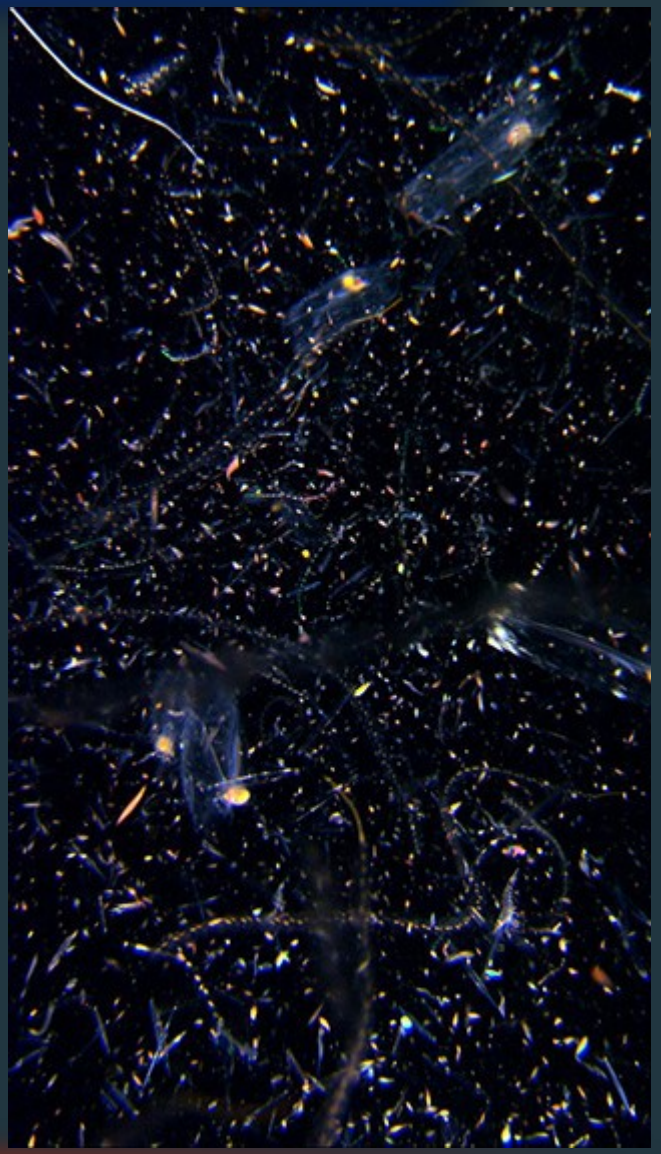



Multiple channels contribute in region of interest

Major challenge of

# Standard Model Physics Processes



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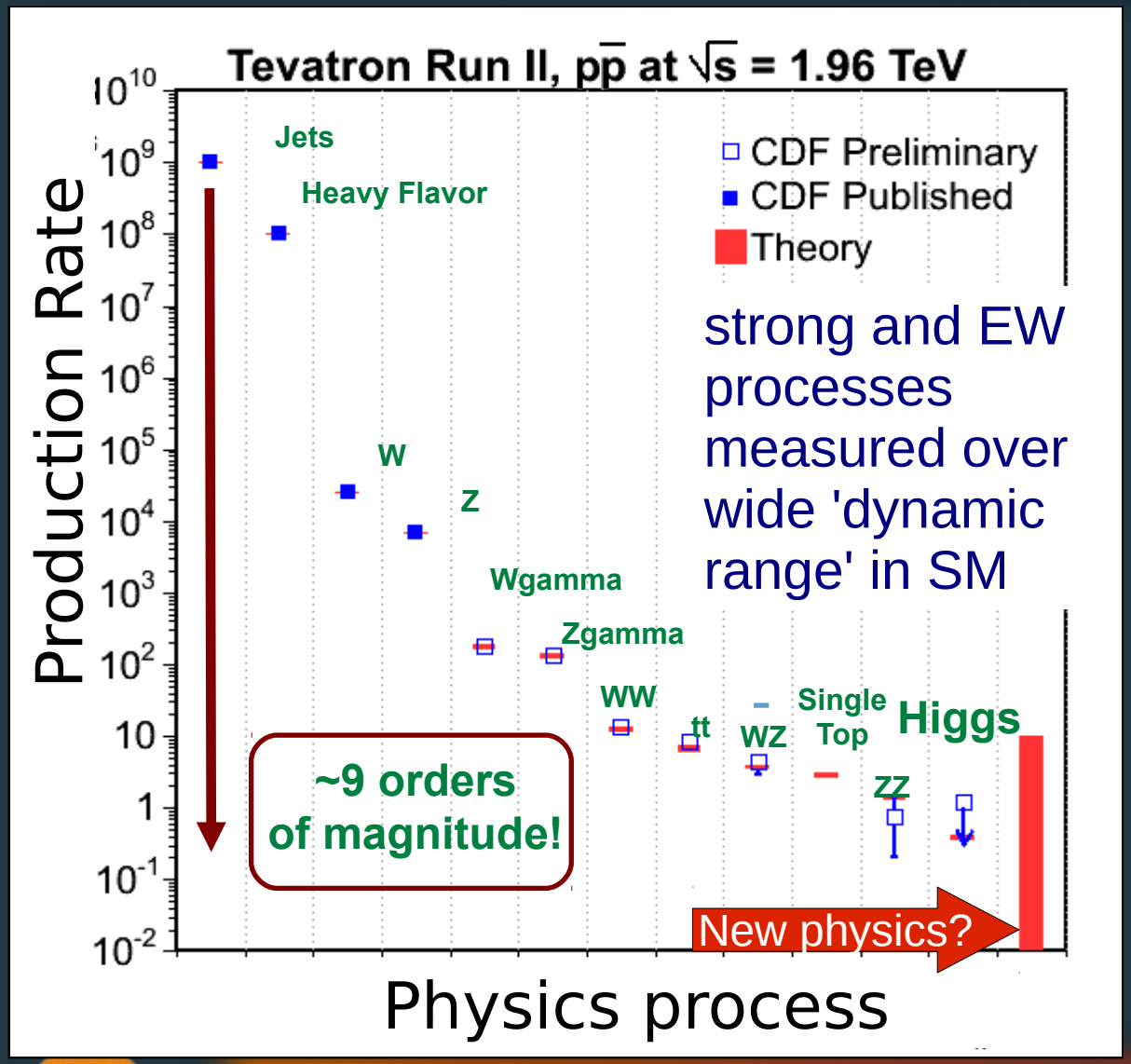
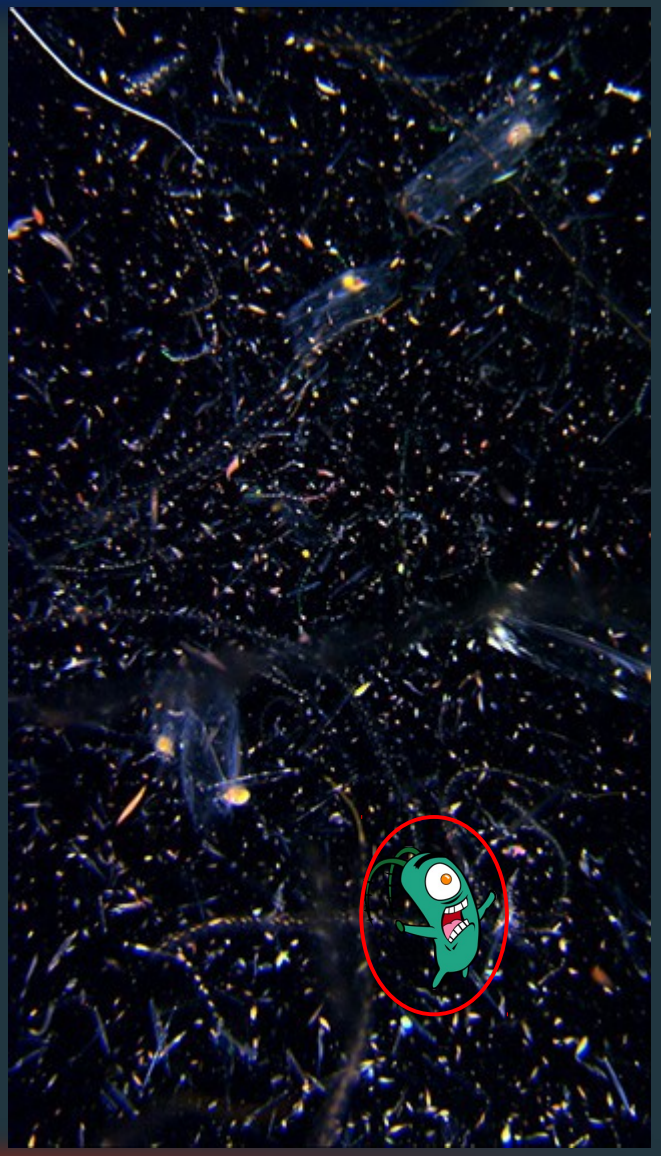
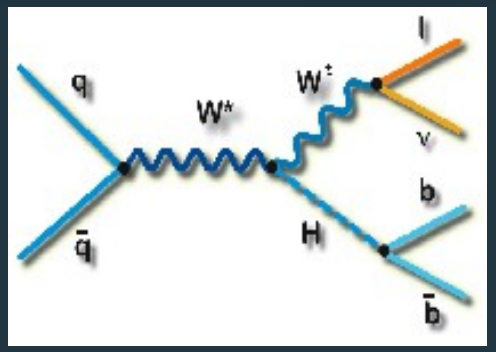
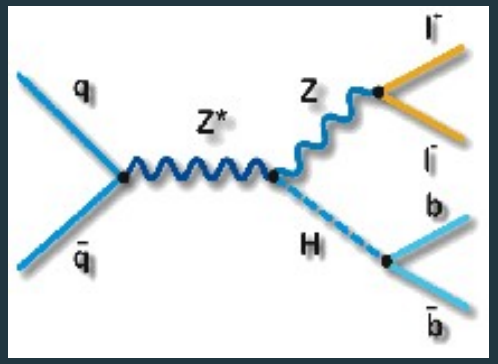


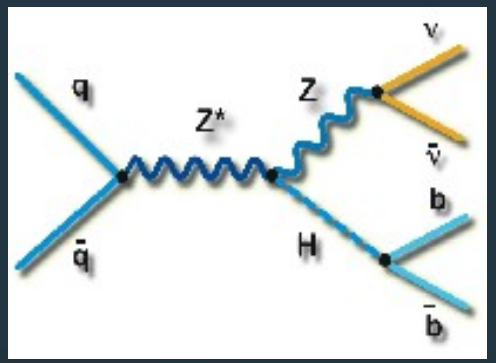



# Primary Search Channels

| | Low Mass | High Mass |
|---|---|---|
| | $qq \rightarrow WH, ZH$ | $gg \rightarrow H$ |
| | ↓ | ↓ |
| Decay: | $H \rightarrow bb$ | $H \rightarrow WW$ |
| Favored modes: | $bb+l\nu$ | |
| | $bb+\nu\nu$ | $l\nu+l\nu$ |
| | $bb+ll$ | |
| Detection: | lepton acceptance | |
| | b-tagging | angular |
| | dijet resol. | correlations |
| | Missing $E_T$ | |



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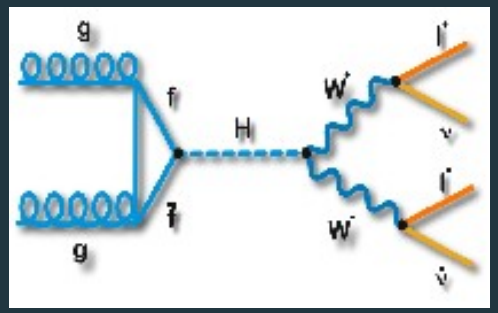

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| | b-tagging | angular |
| | dijet resol. | correlations |
| | Missing $E_T$ | |

Actively pursuing improvements in all non-negligible channels to complete results with full 10 $fb^{-1}$ data set.

# Background Reduction

Uncertainties on background are larger than expected signal

- Need to go beyond simple counting experiment in searches
- Use shape information (kinematic and topological variables)
- Construct multivariate discriminants to improve S/B
- Improve resolutions, purity – while preserving acceptance

# Background Reduction

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Dependent on <u>modeling of input variables</u>

- Validate input variables and MVA output with data in control regions and signal regions
- Validate robustness of techniques and background model by successful measurements of other processes in similar final states

Examples: Single top discovery, diboson production measurements

See talk by D. Price

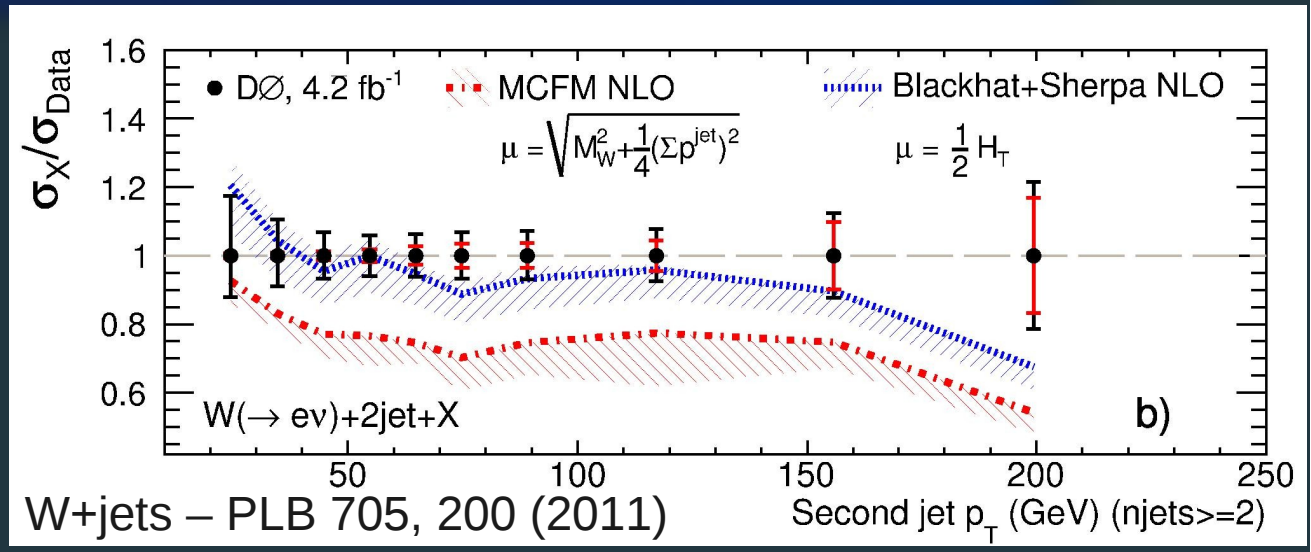
# Background Modeling

Depend on Monte Carlo event generators to model W/Z+jets

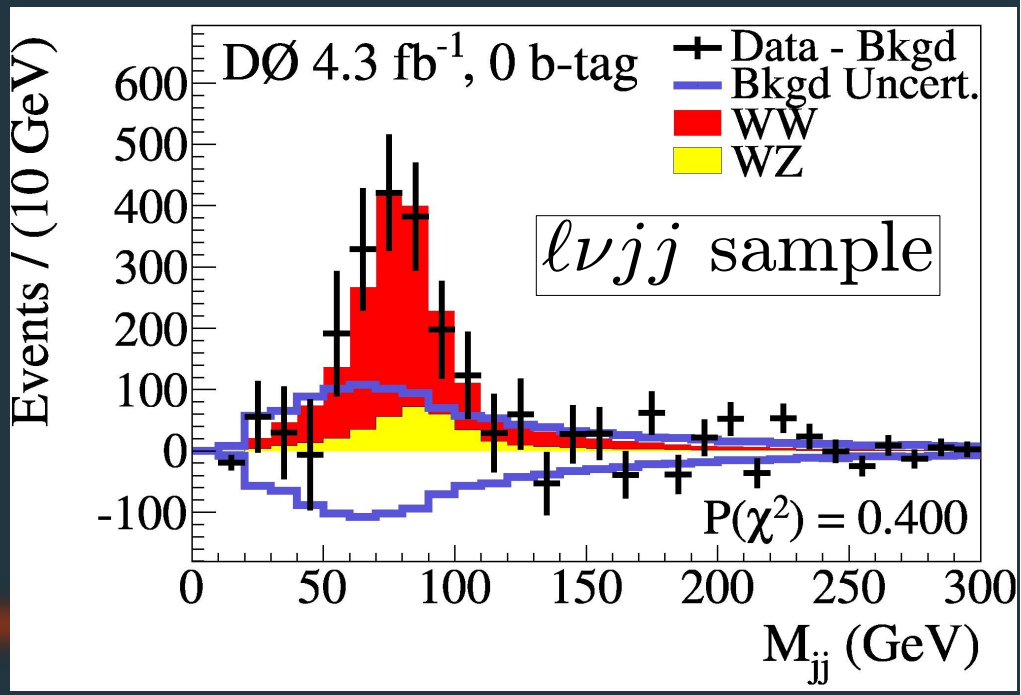
Perform detailed studies to understand quality of modeling

Avoid washing out a signal or creating false positives

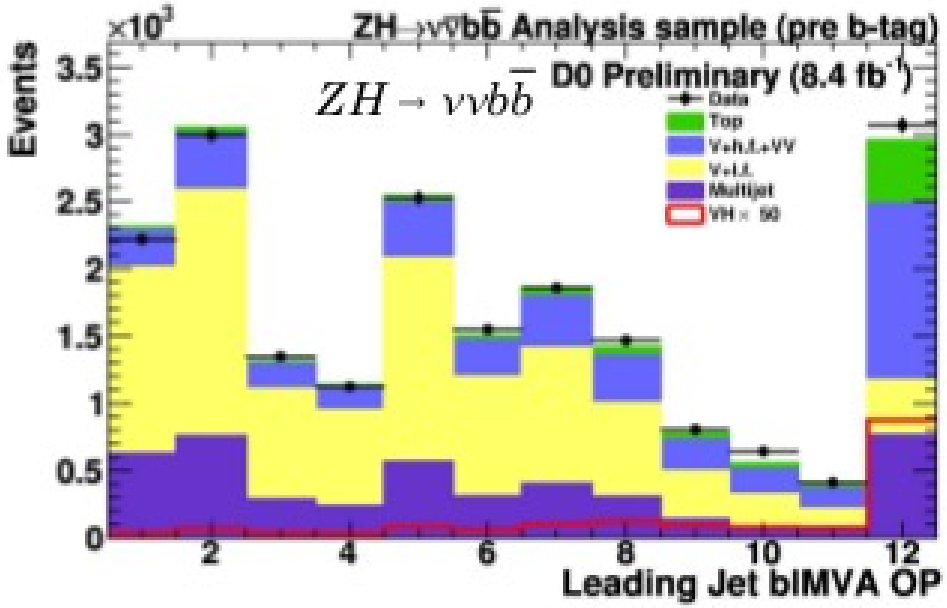
Cross check against dedicated measurements with known signals

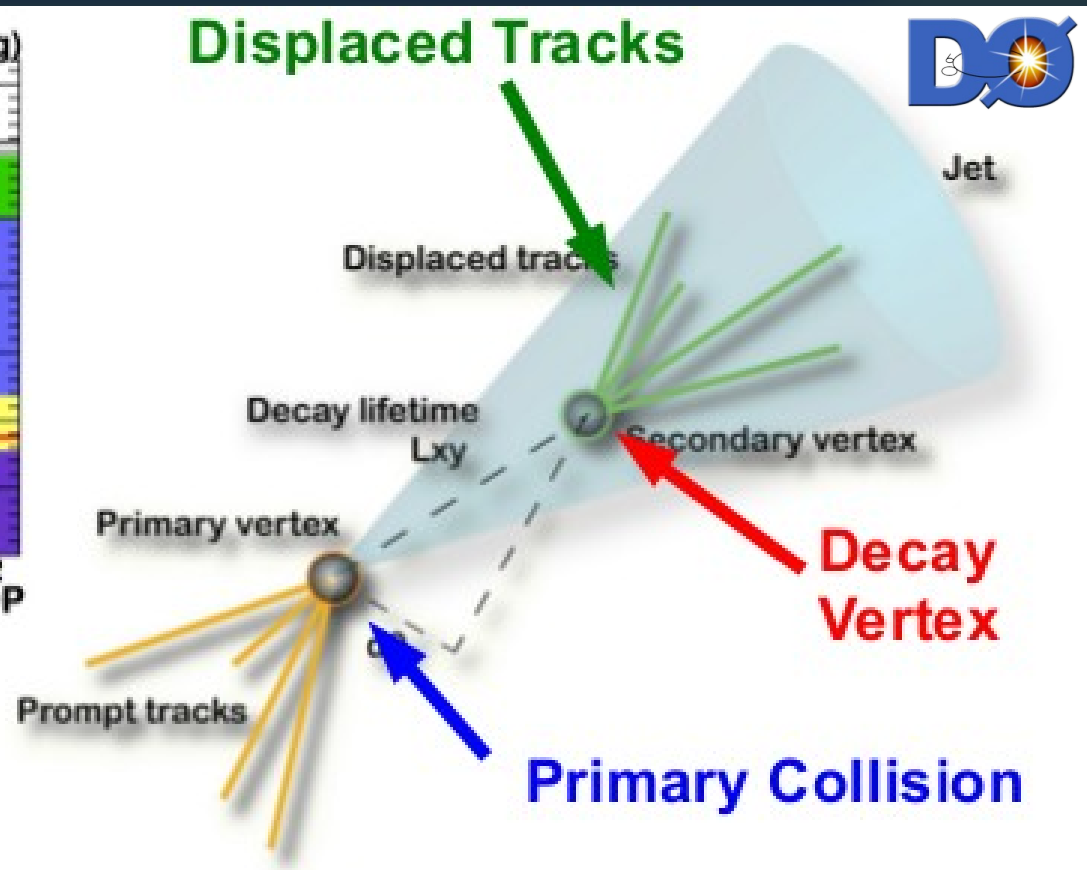



W+jets – PLB 705, 200 (2011)



# b-tagging



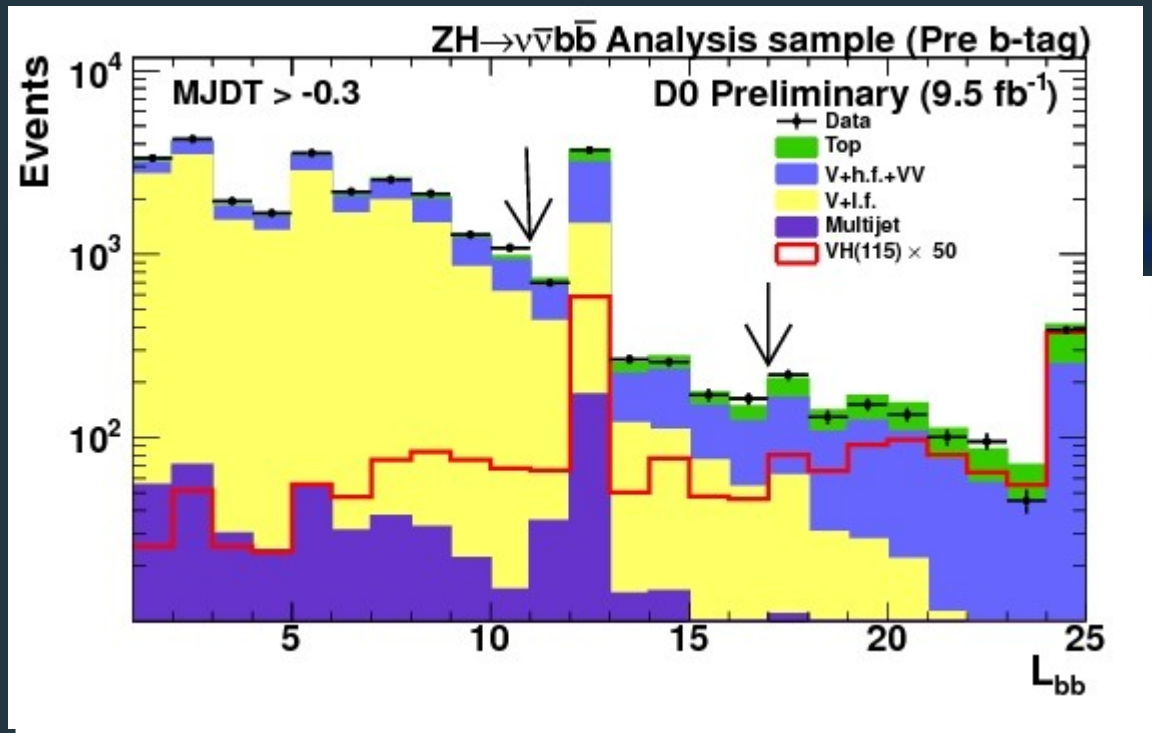



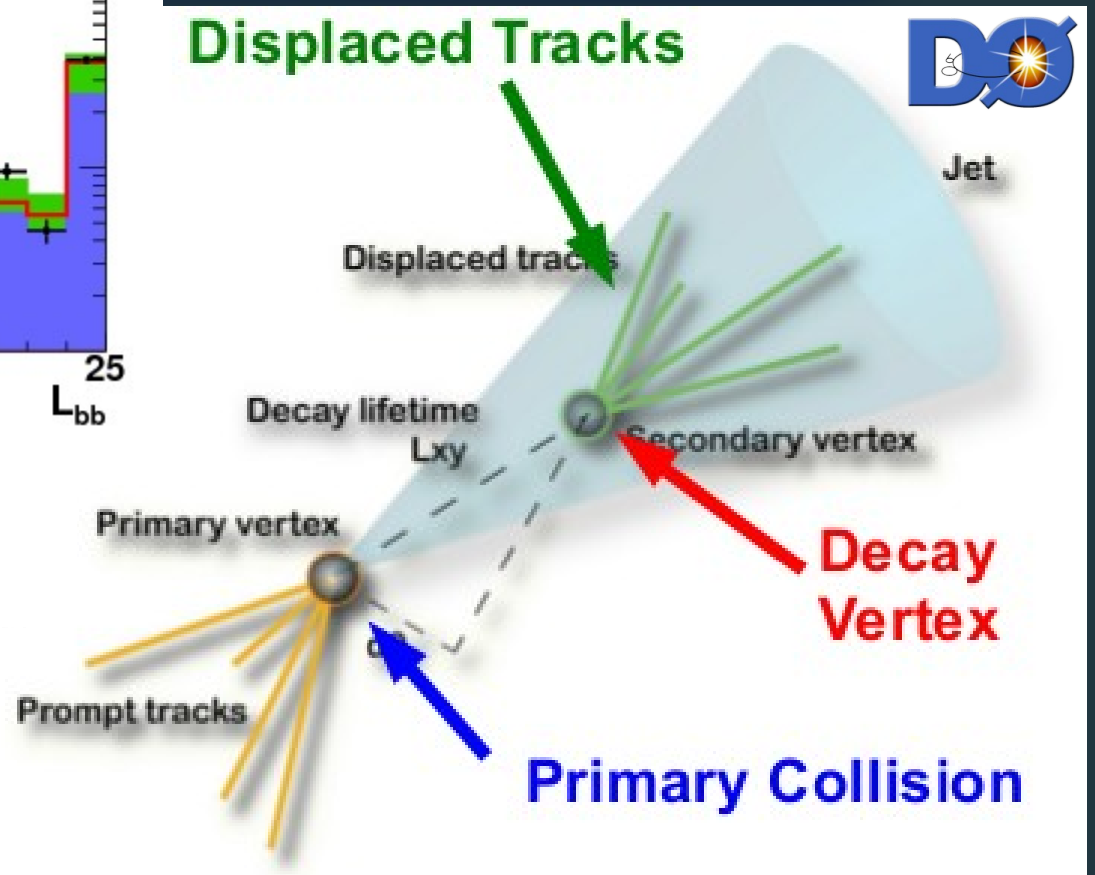

| | Efficiency |
|---|---|
| b-jets | 50%-70% |
| light jets | 0.5%-4.5% |

**Combine information with a multivariate b-tagger**

S. Desai FNAL W&C 03/12

# b-tagging



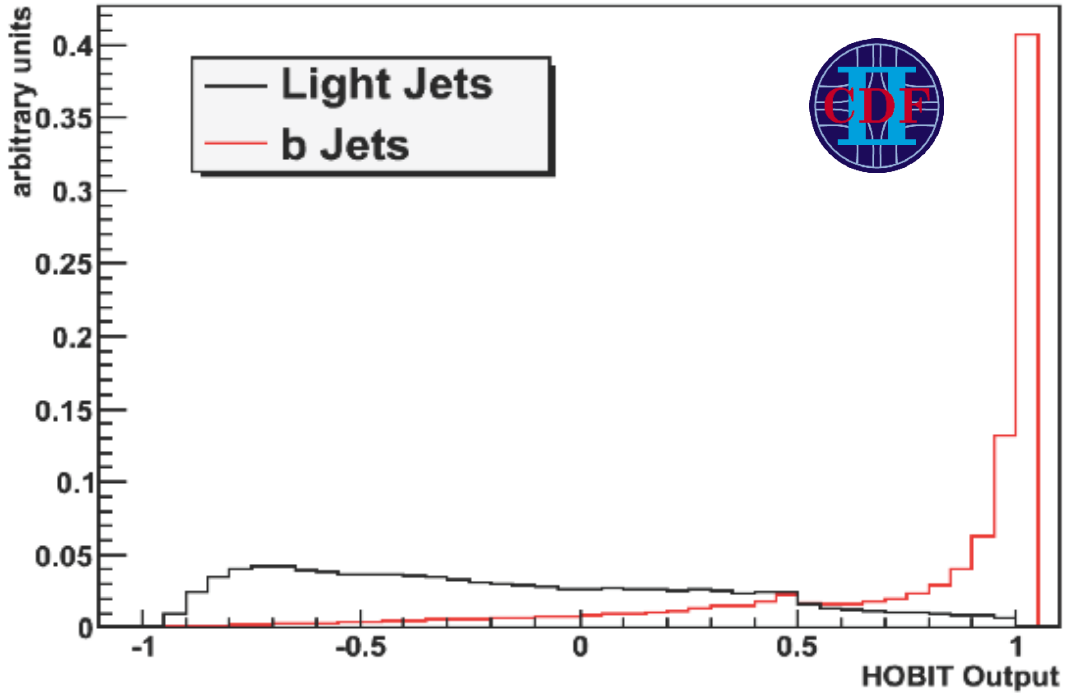

Extend to "event-level" btagging

Consider sum of btag outputs for $b\bar{b}$ signals

**Combine information with a multivariate b-tagger**

S. Desai FNAL W&C 03/12

# b-tagging



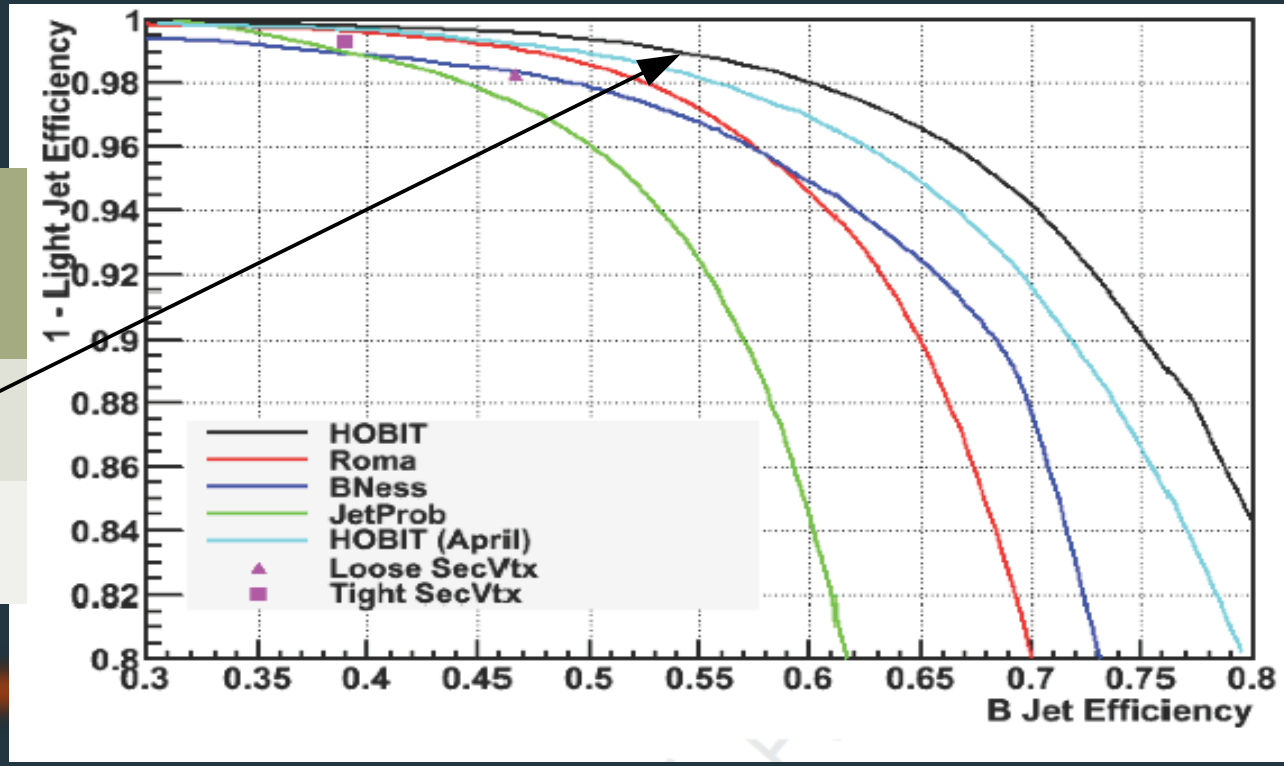

CDF Higgs Optimized b Identification Tagger (HOBIT)

25-input vars, trained for $H \rightarrow b\bar{b}$

See talk by M. Kirby

M. Stancari FNAL W&C 03/12

| mistag rate | SecVtx efficiency | HOBIT efficiency |
|---|---|---|
| ~1% | 39% | 54% |
| ~2% | 47% | 59% |



# HOBIT WH->lνbb

| OLD – Multiple Taggers<br>Tagging Category | S/√B |
|---|---|
| SecVtx+SecVtx | 0.228 |
| SecVtx+JetProb | 0.160 |
| SecVtx+Roma | 0.103 |
| Single SecVtx | 0.146 |
| **Sum** | **0.331** |

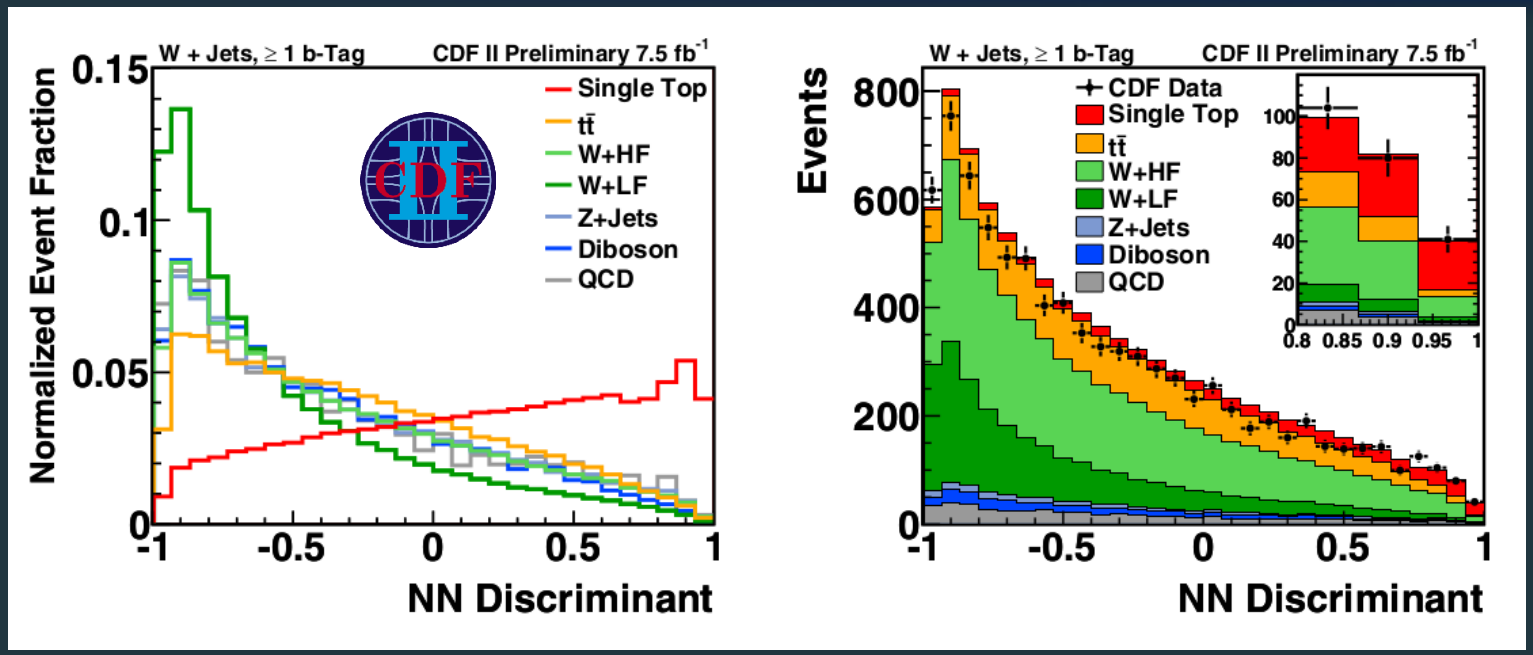
| New Hobbit<br>Tagging Category | S/√B |
|---|---|
| Tight-Tight | 0.266 |
| Tight-Loose | 0.200 |
| Single Tight | 0.143 |
| Loose-Loose | 0.053 |
| Single Loose | 0.044 |
| **Sum** | **0.369** |

Significant effort to optimize tagging categories and thresholds for loose/tight HOBIT selections

11% gain in S/√B ==> direct increase in overall search sensitivity

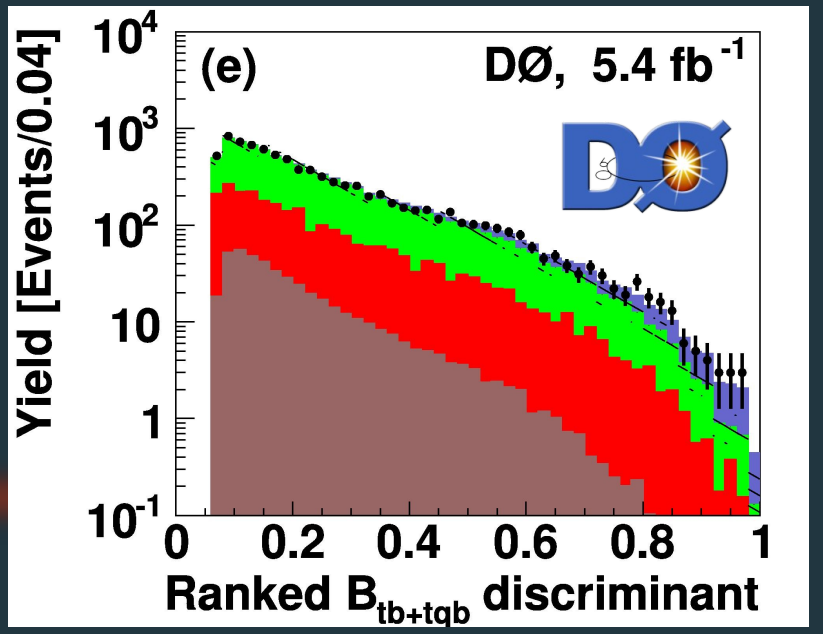
M. Stancari FNAL W&C 03/12

# Validation of MVA Techniques




D0 and CDF single top quark

MVA-based discovery!



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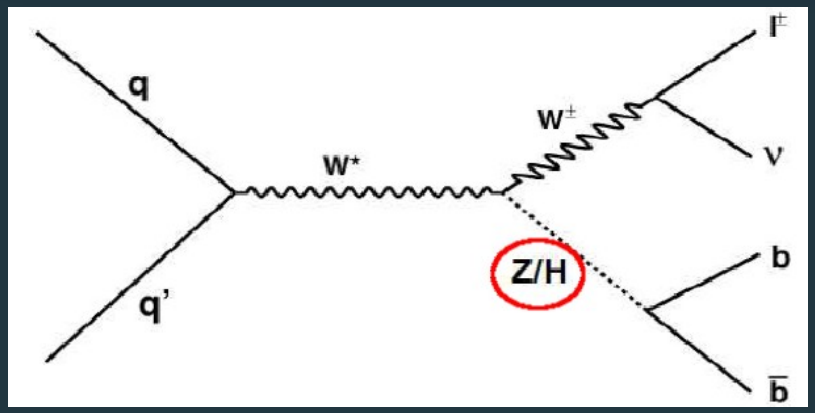
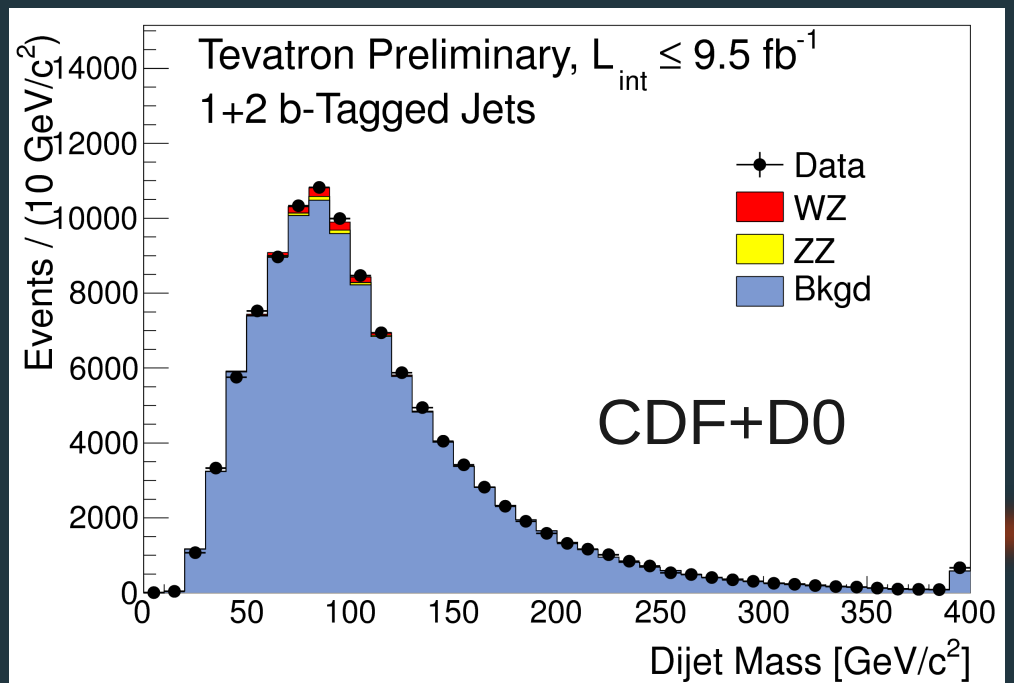
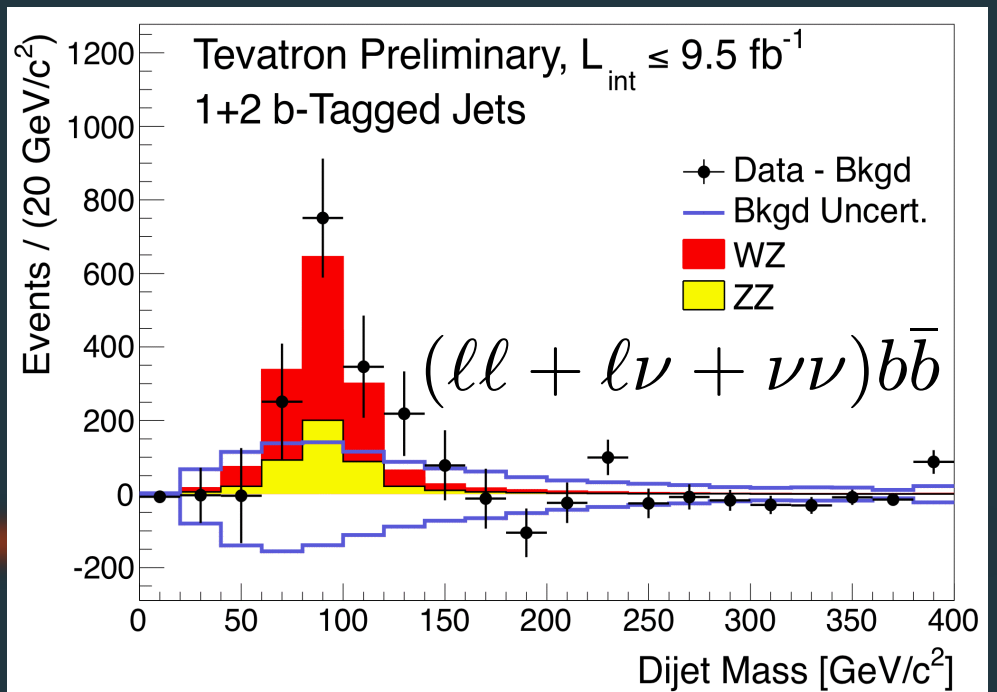



Dibosons V+Z, (Z->$b\bar{b}$) topologically similar to Higgs signal

Same final states and analysis strategy with different signal definitions.

Combine primary low-mass higgs search channels with MVAs retuned for diboson search

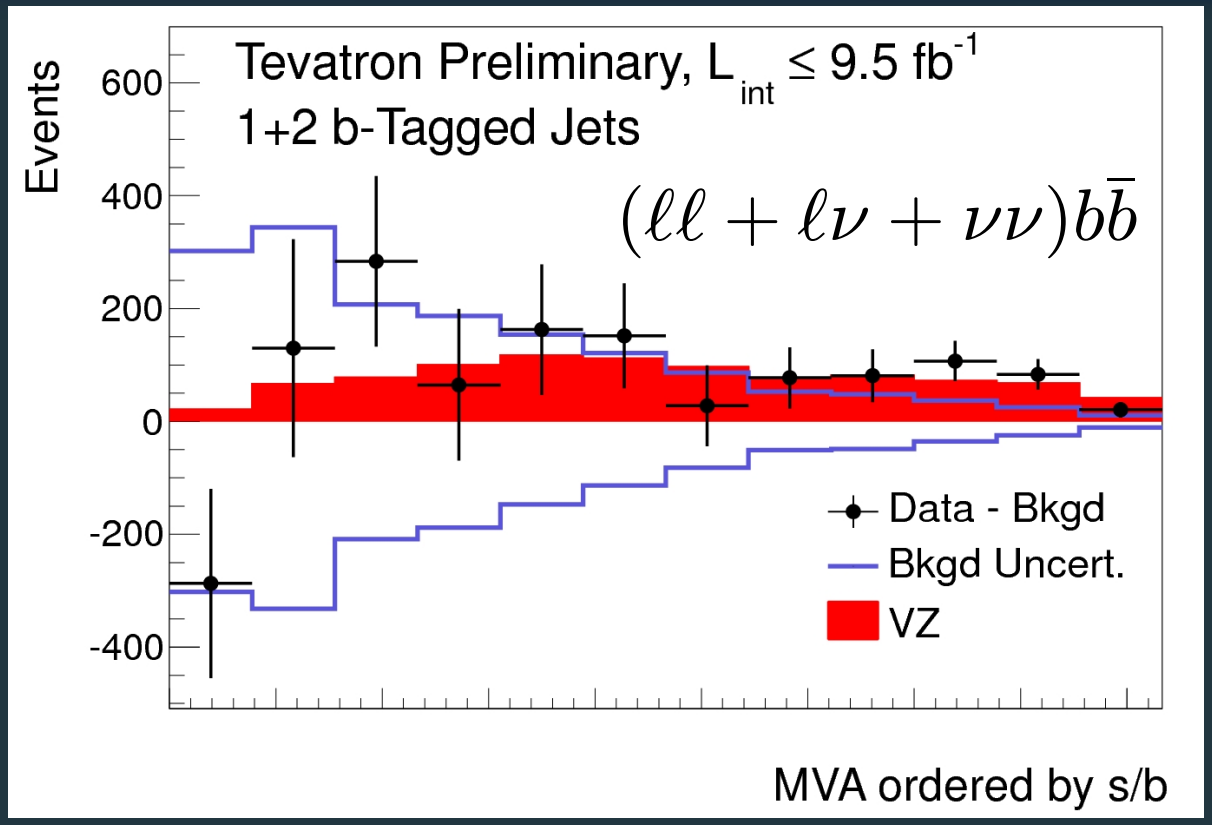


See talk by A. Askew

# Validation of MVA Techniques

MVA outputs used to extract cross section




σ(WZ+ZZ)= 4.47 ± 0.64 (stat) ± 0.73 (syst) pb

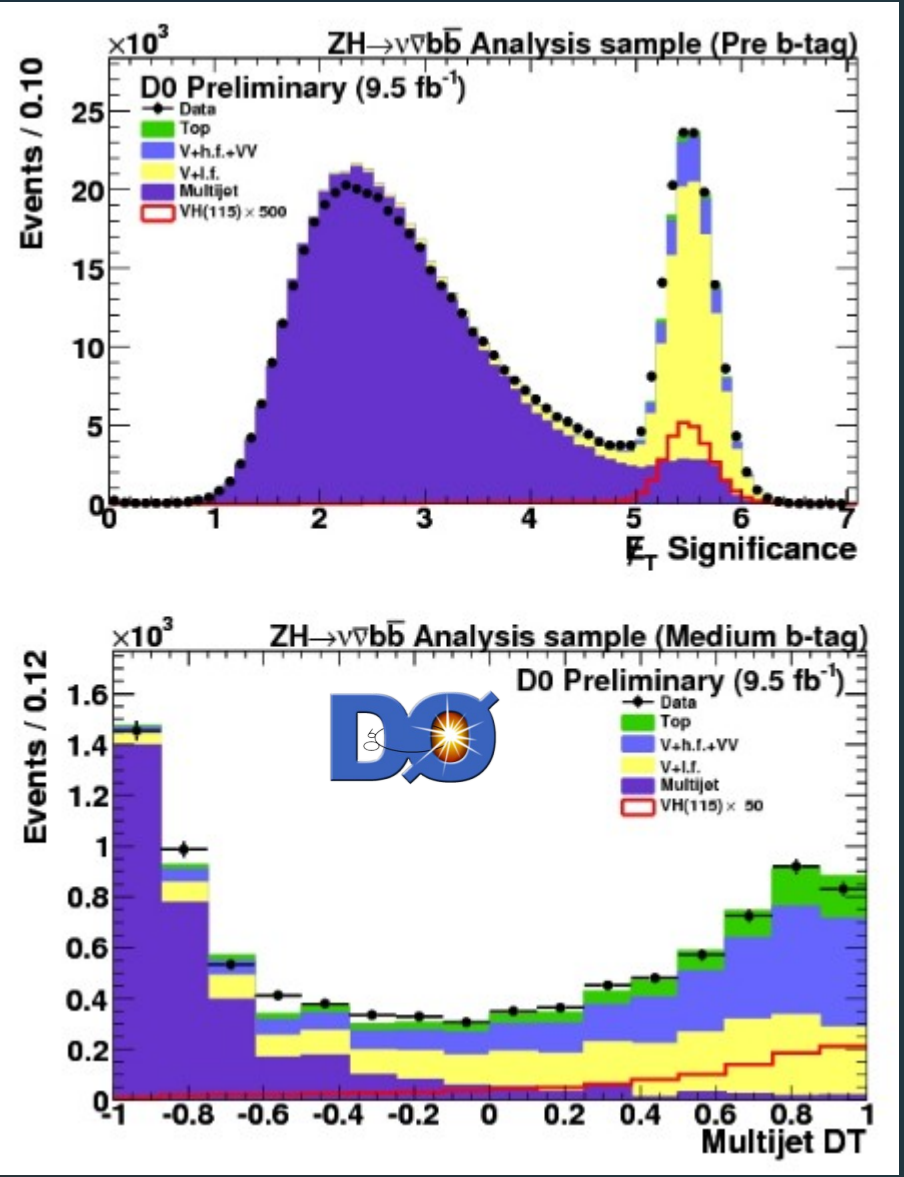
(SM Prediction = 4.4 ± 0.3 pb)

# MVA Improvements

Consider QCD bkgds in MET + bb

Suppressed with selection criteria:
Large MET
- MET should not align with jet
- Jets should not be back-to-back

Remaining QCD background suppressed with BDT, based on:
- MET
- MET significance
- Track Missing pT
- Angular Variables
- etc



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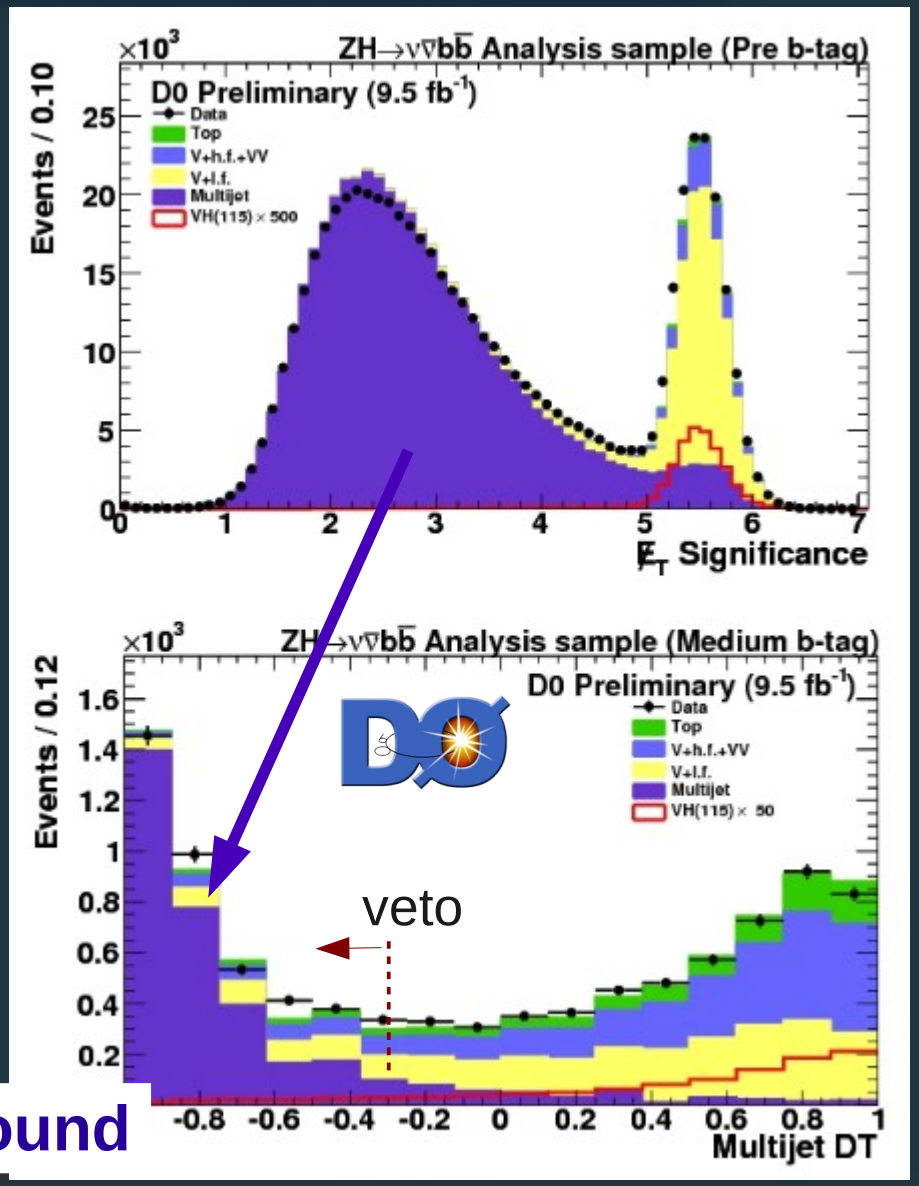
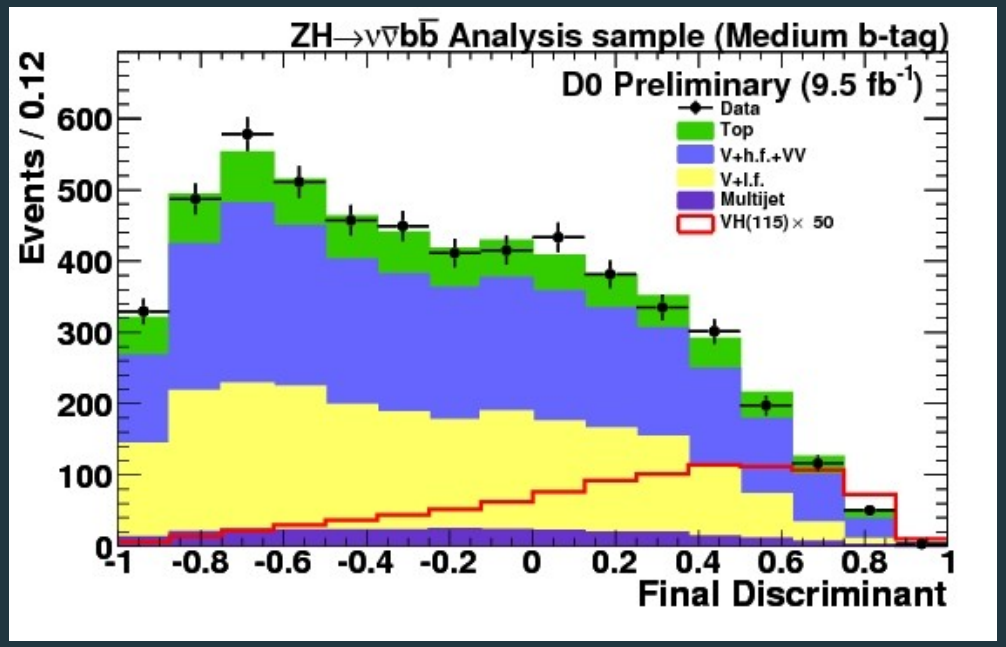


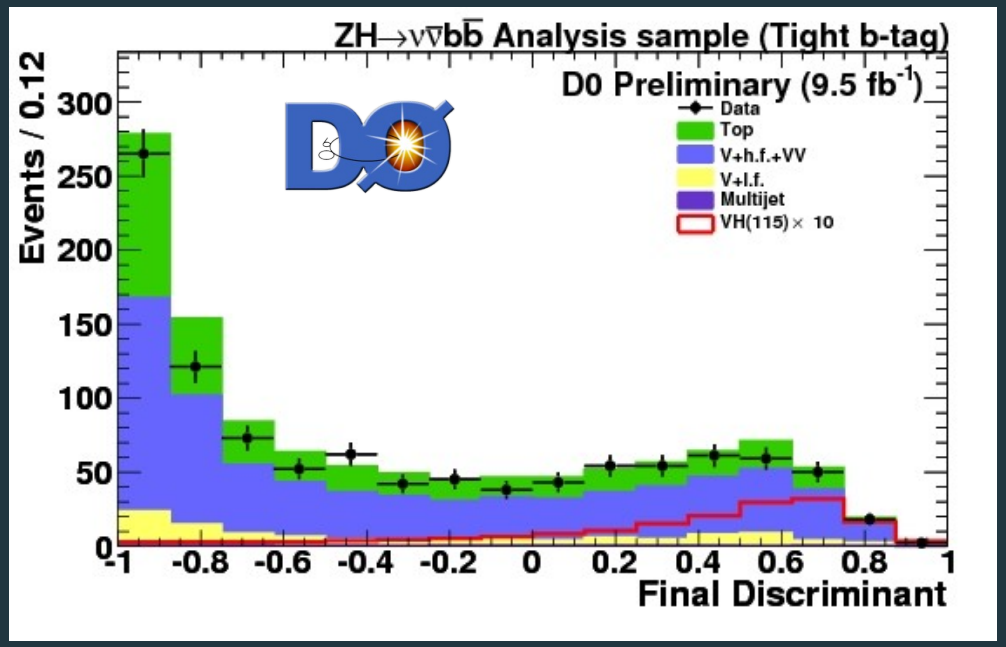

**MVA tuned for specific background**

# MVA Improvements

One final discriminant to separate signal and the remaining background after multijet veto



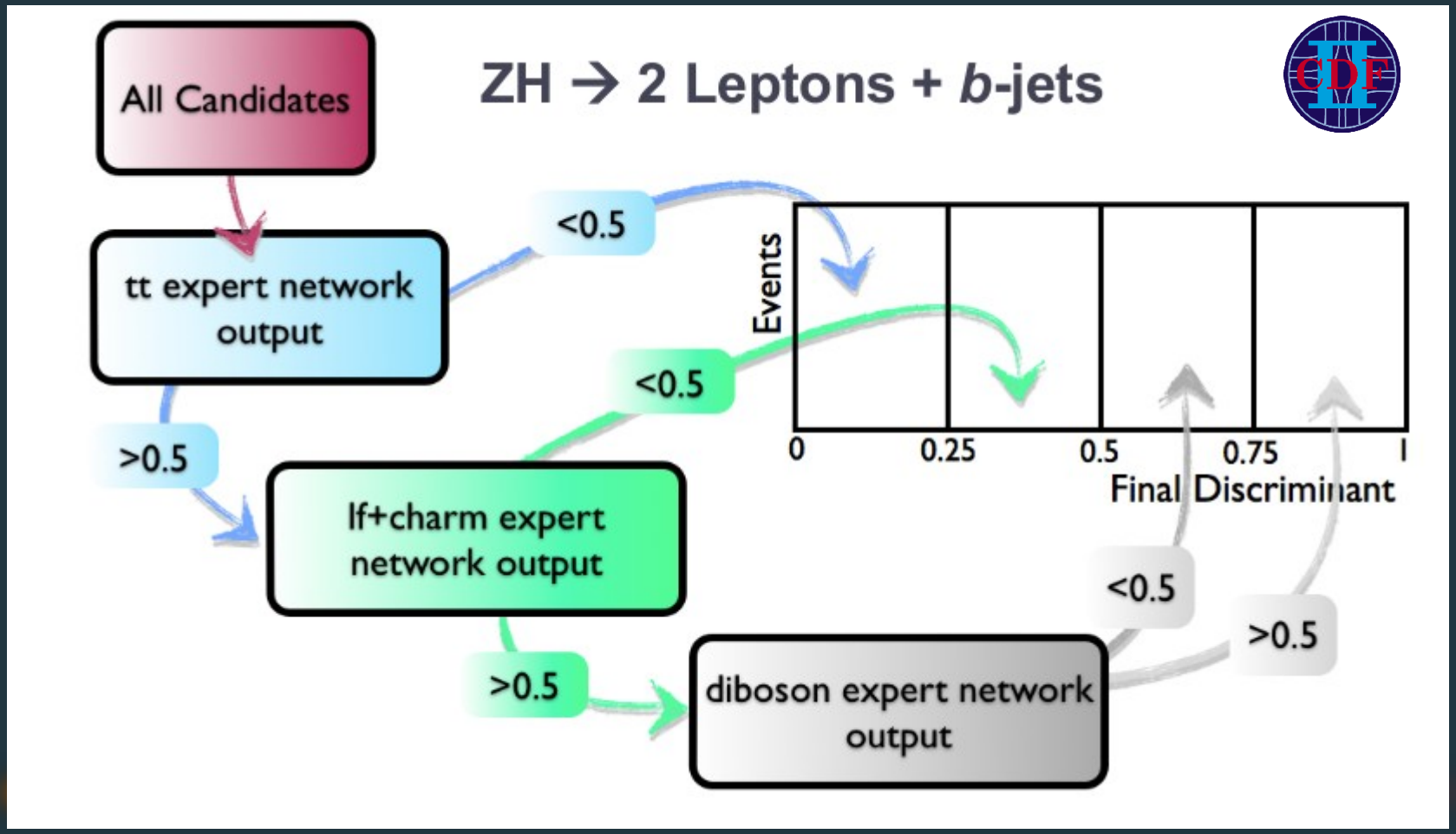

Medium tag sample




Tight tag sample

# MVA Improvements

Reorganize events based on majority background regions
Discard nothing, but seek regions with enhanced S/B



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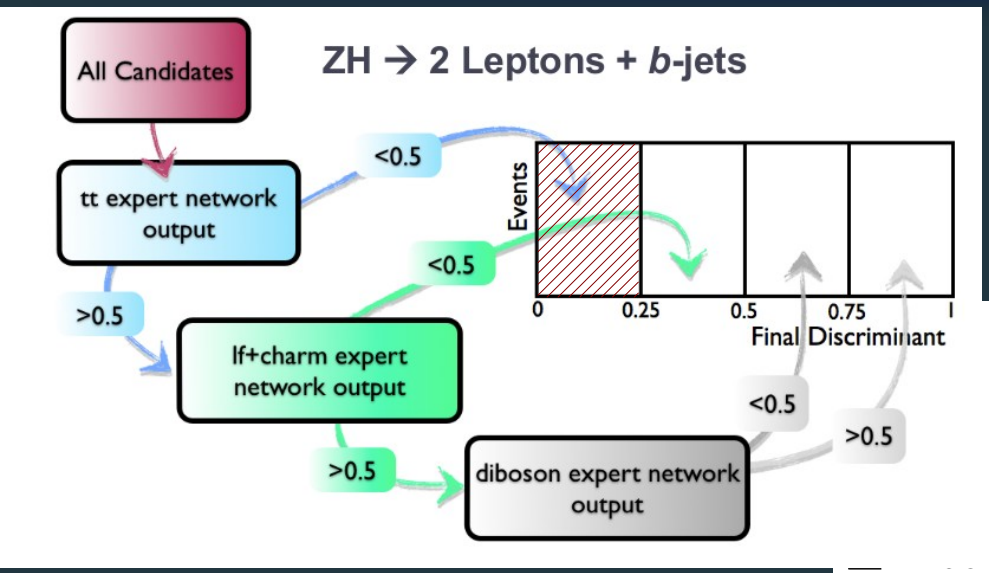


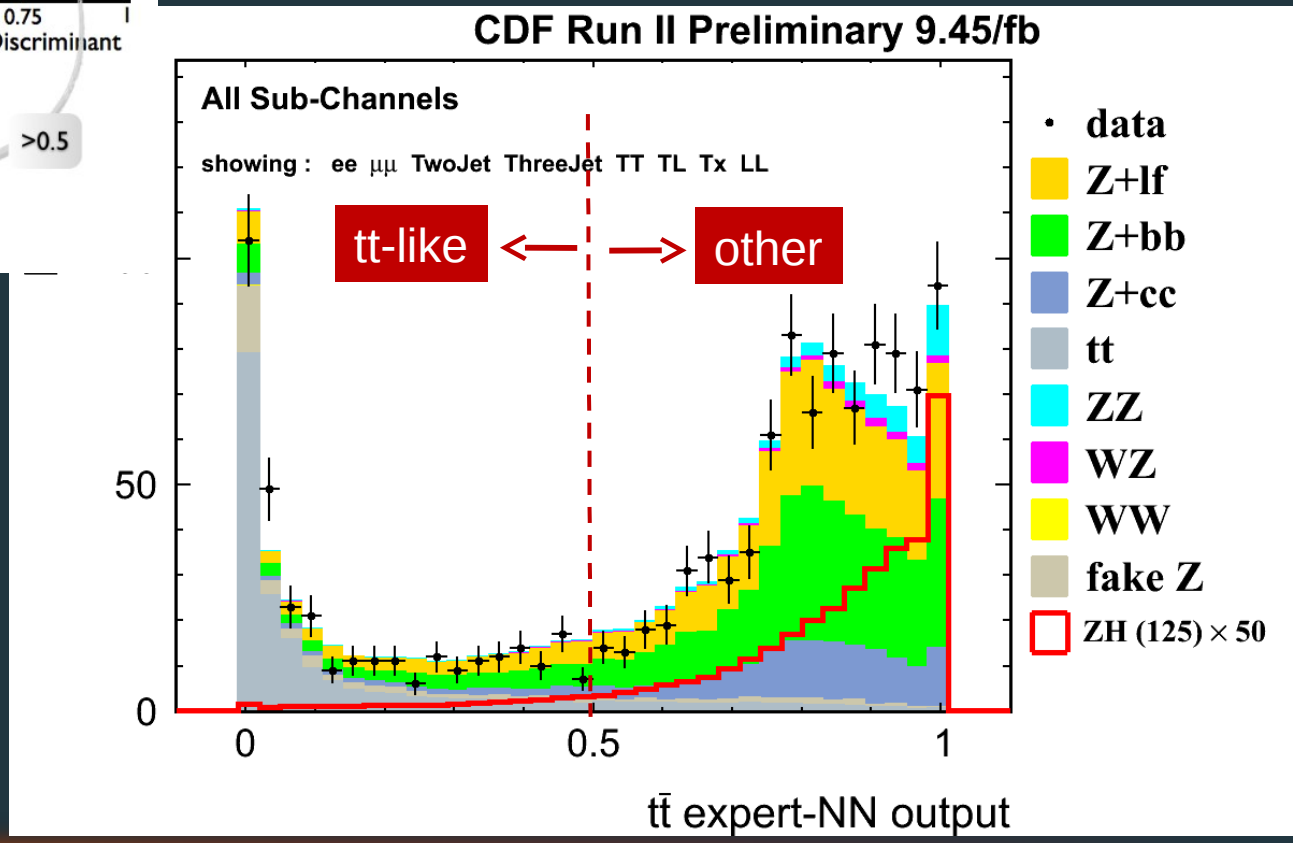

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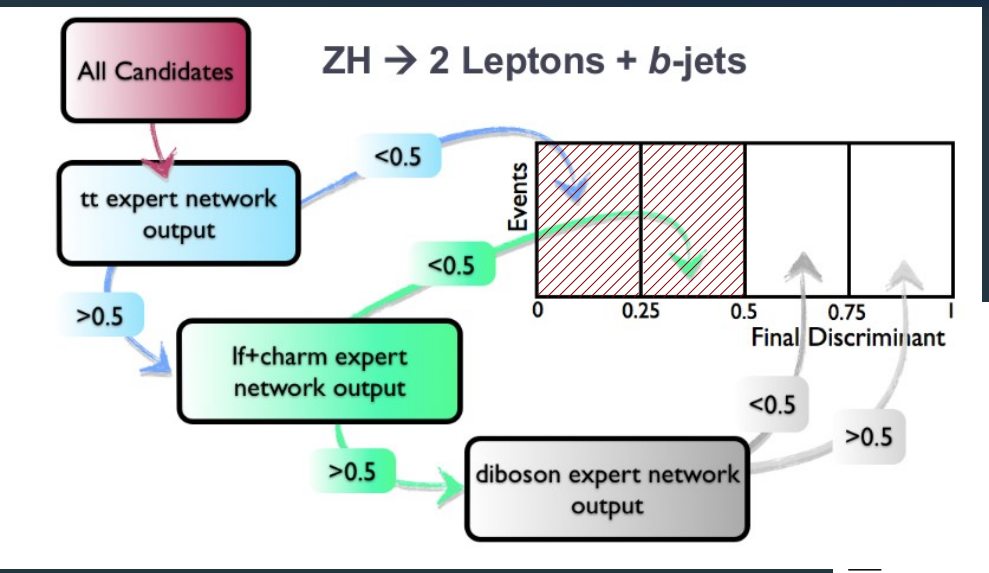


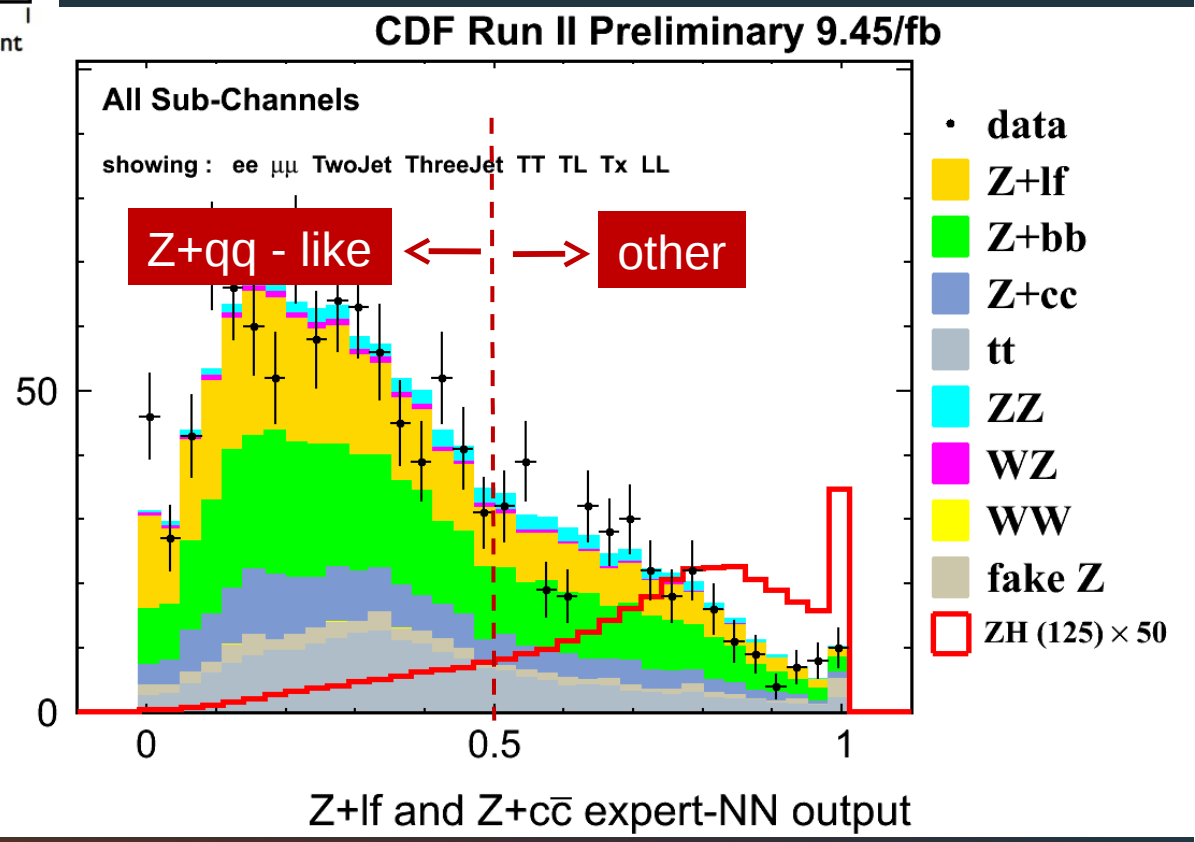

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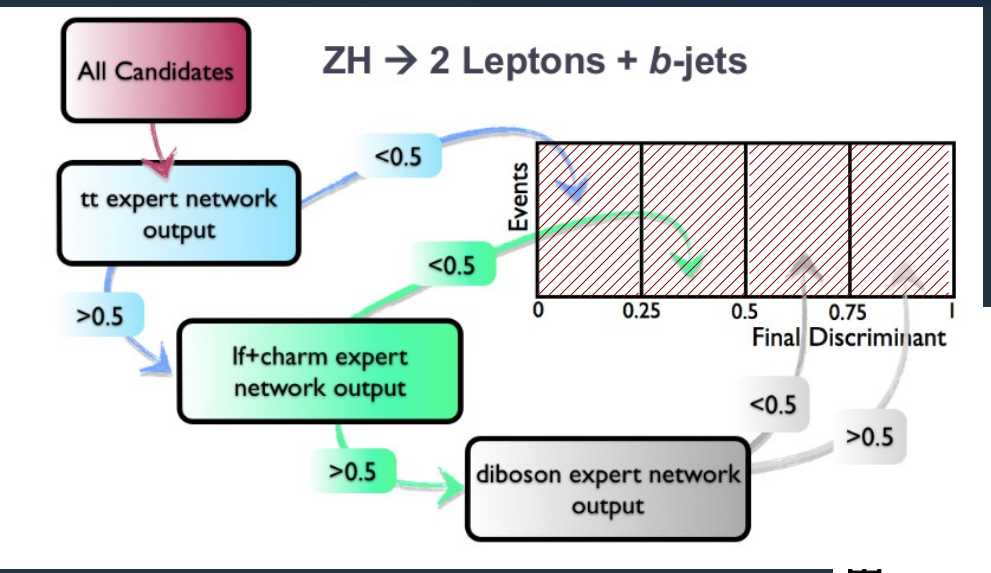
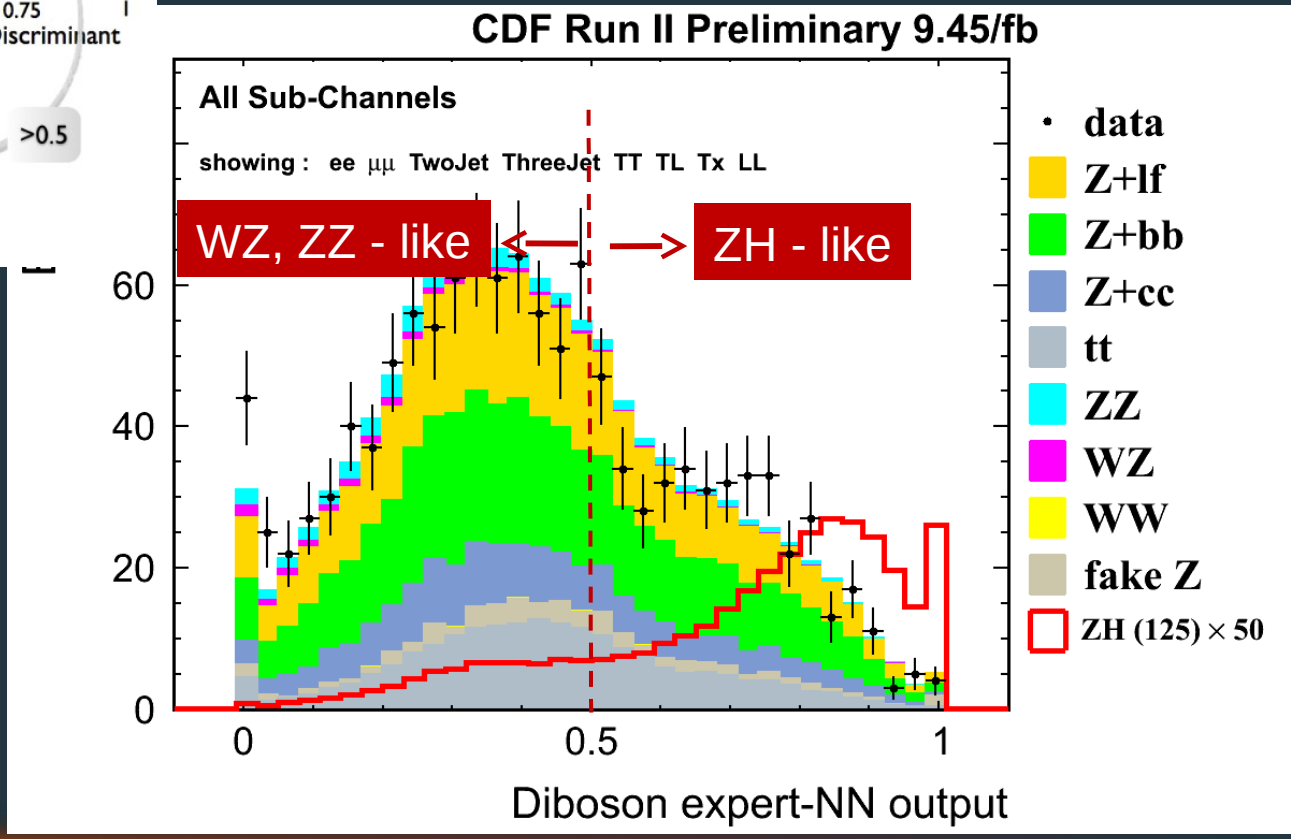
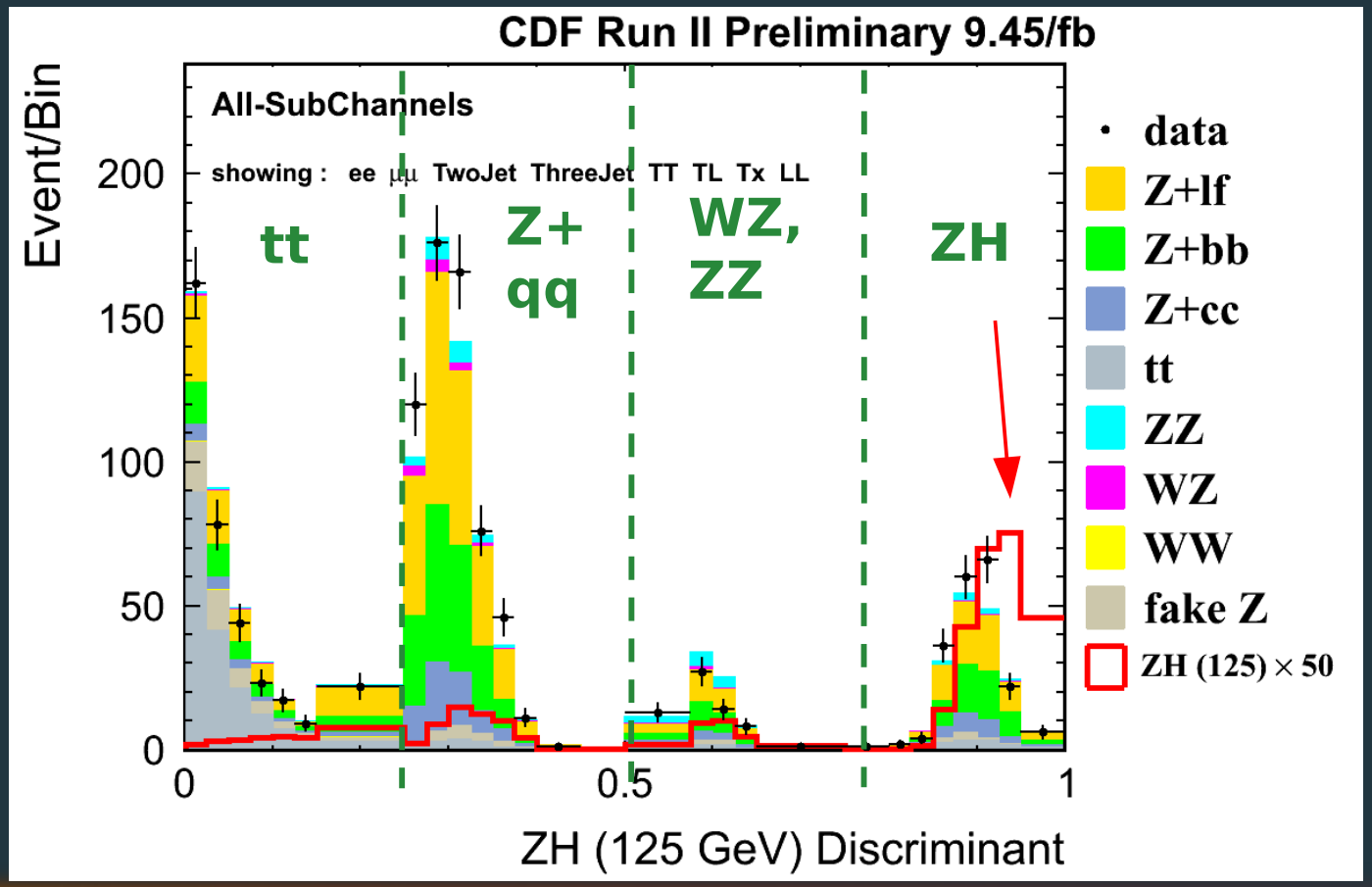


# MVA Improvements

Reorganize events based on majority background regions

Discard nothing, but seek regions with enhanced S/B



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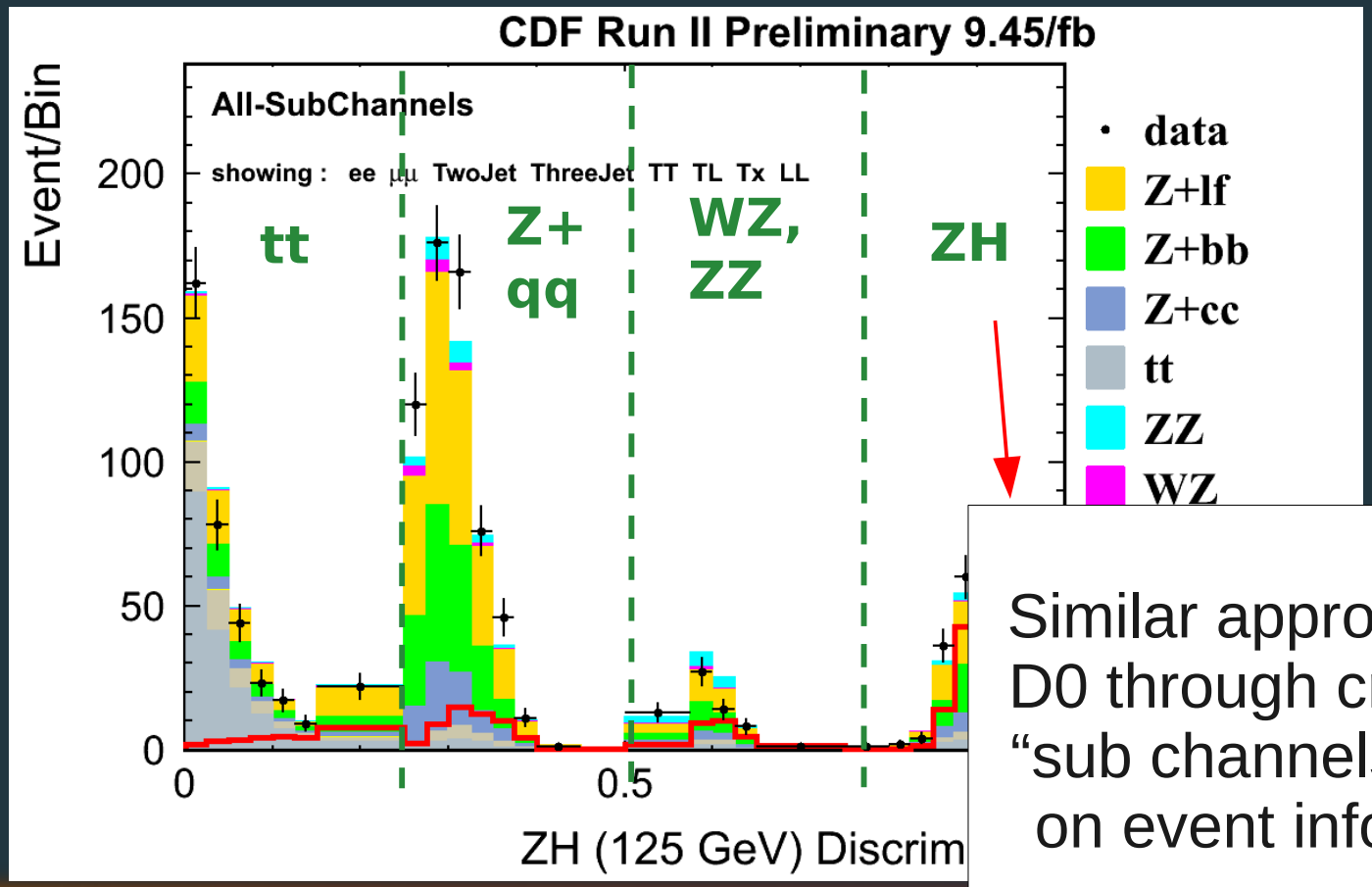
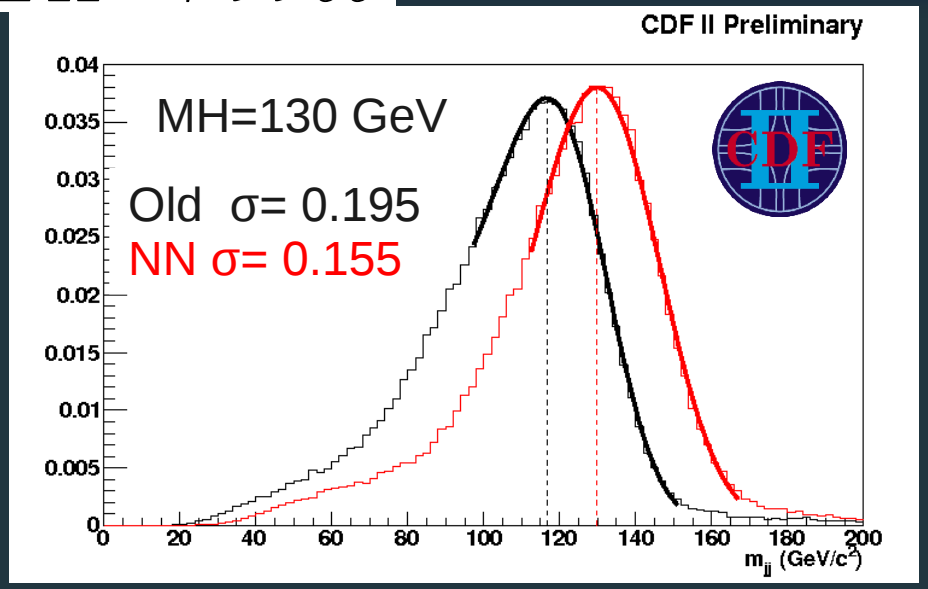



Similar approaches on D0 through creation of "sub channels" based on event information

# Other Improvements

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




NN-based jet energy correction

Use most probable jet energy based on bottom quark hypothesis

ex. improvement in mean/width of dijet mass for H->$b\bar{b}$ (MH=130 GeV)

Various improvements by experiments include:

- Increase acceptance/efficiency for leptons
- New multivariate electron identification (D0)
- More optimized b-tag categories

( future c-jet discrimination D0 )

Latest limits calculated via CLs technique

# Tevatron Limits on SM Higgs

Begin with combined likelihood calculations for (S+B and B-only) models

Expected events

$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}_i}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}}$$

Observed events

Latest limits calculated via CLs technique

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$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}_i}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_{np}} e^{-\theta_k^2/2}$$

Nuisance parameters

Observed events

Syst. uncertainties included as nuisance parameters affecting μ's

Determine best-fit nuisance-parameters by maximizing likelihood

Latest limits calculated via CLs technique

# Tevatron Limits on SM Higgs

Begin with combined likelihood calculations for (S+B and B-only) models

Expected events

$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}_i}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_n p} e^{-\theta_k^2/2}$$

Nuisance parameters

Observed events

Syst. uncertainties included as nuisance parameters affecting μ's

Determine best-fit nuisance-parameters by maximizing likelihood

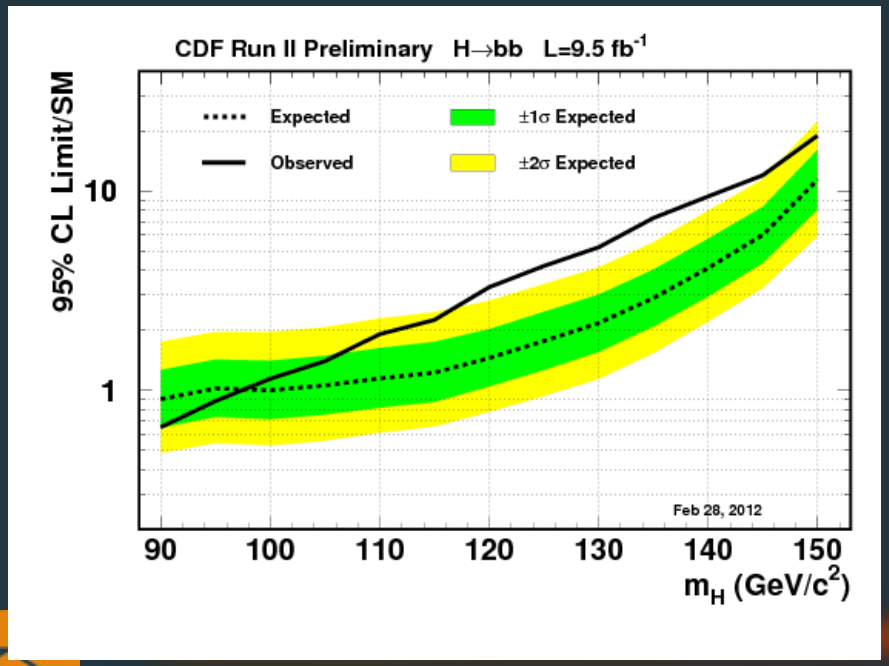
Test statistic based on log-likelihood ratio of hypotheses

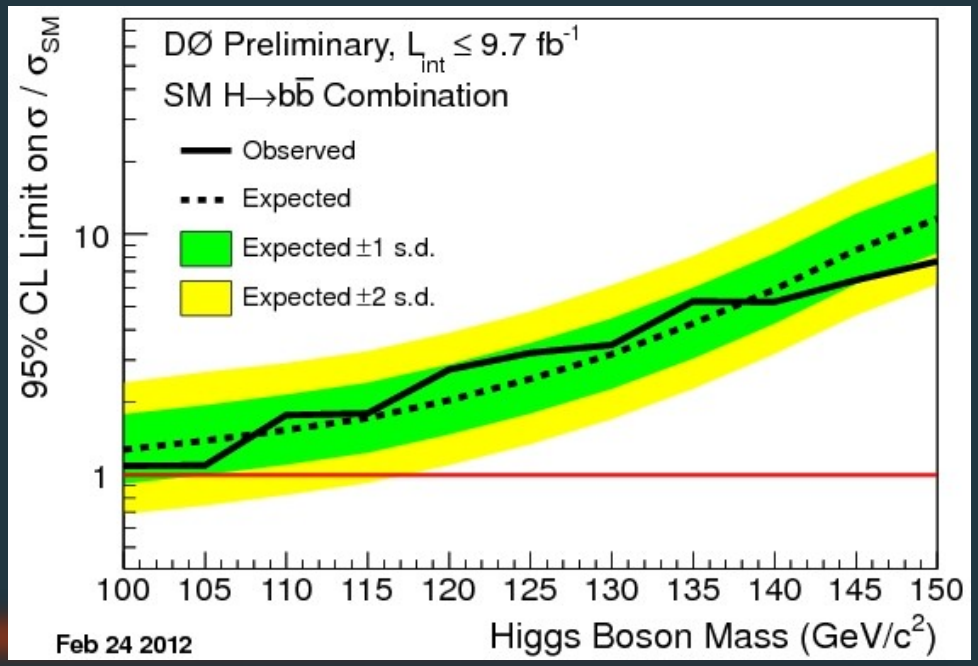
Good agreement with Bayesian method

$$LLR = -2ln\frac{p(data|S+B)}{p(data|B)}$$

# Limits on H->bb

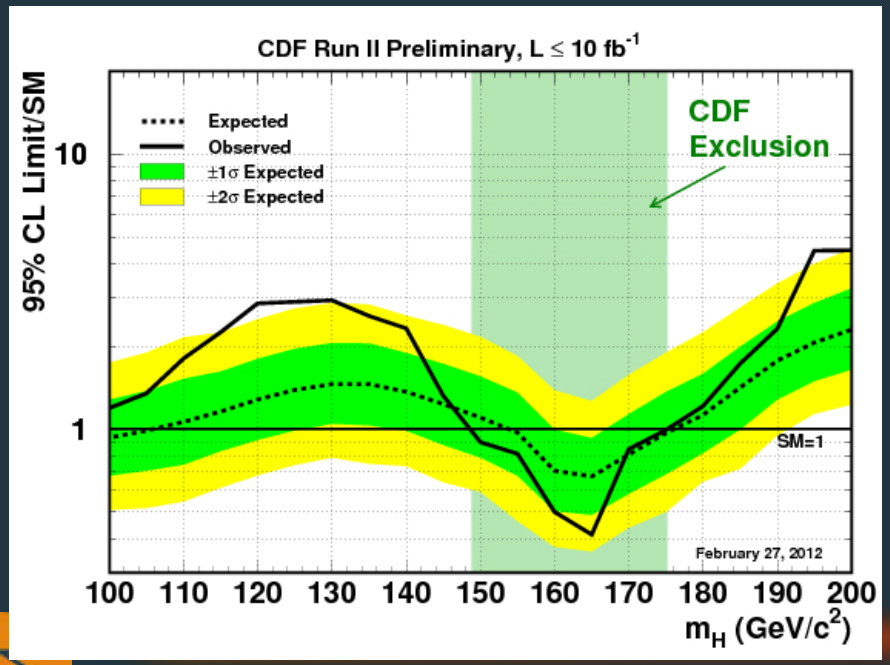
| | Sensitivity $M_H$=125 GeV | |
|---|---|---|
| Low Mass States | CDF | D0 |
| WH->lnubb | 2.8 | 3.9 |
| VH->MET+bb | 3.6 | 4.3 |
| ZH->llbb | 3.6 | 5.9 |

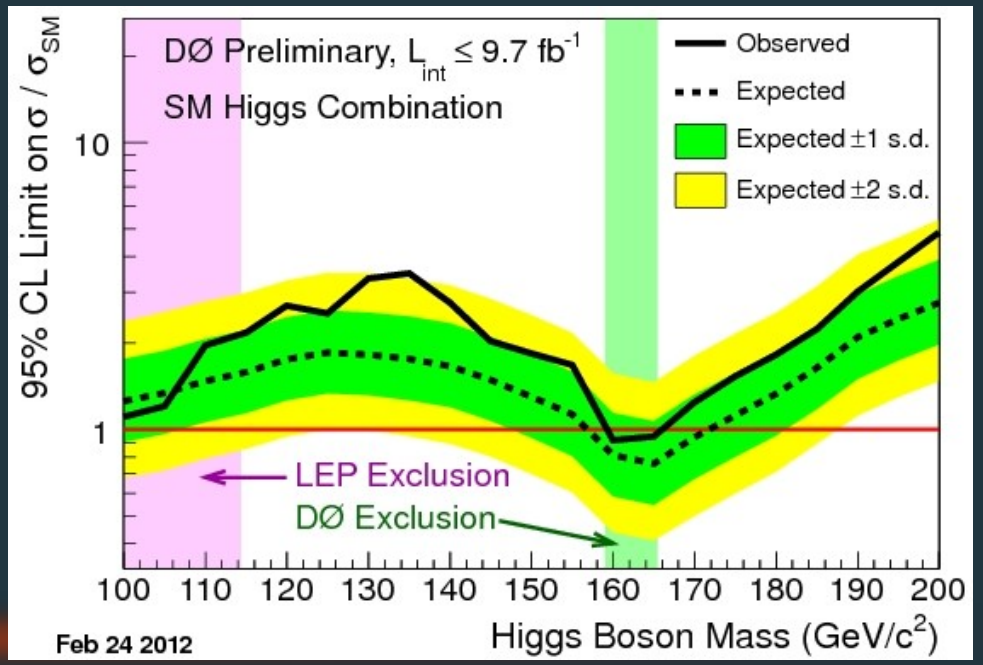


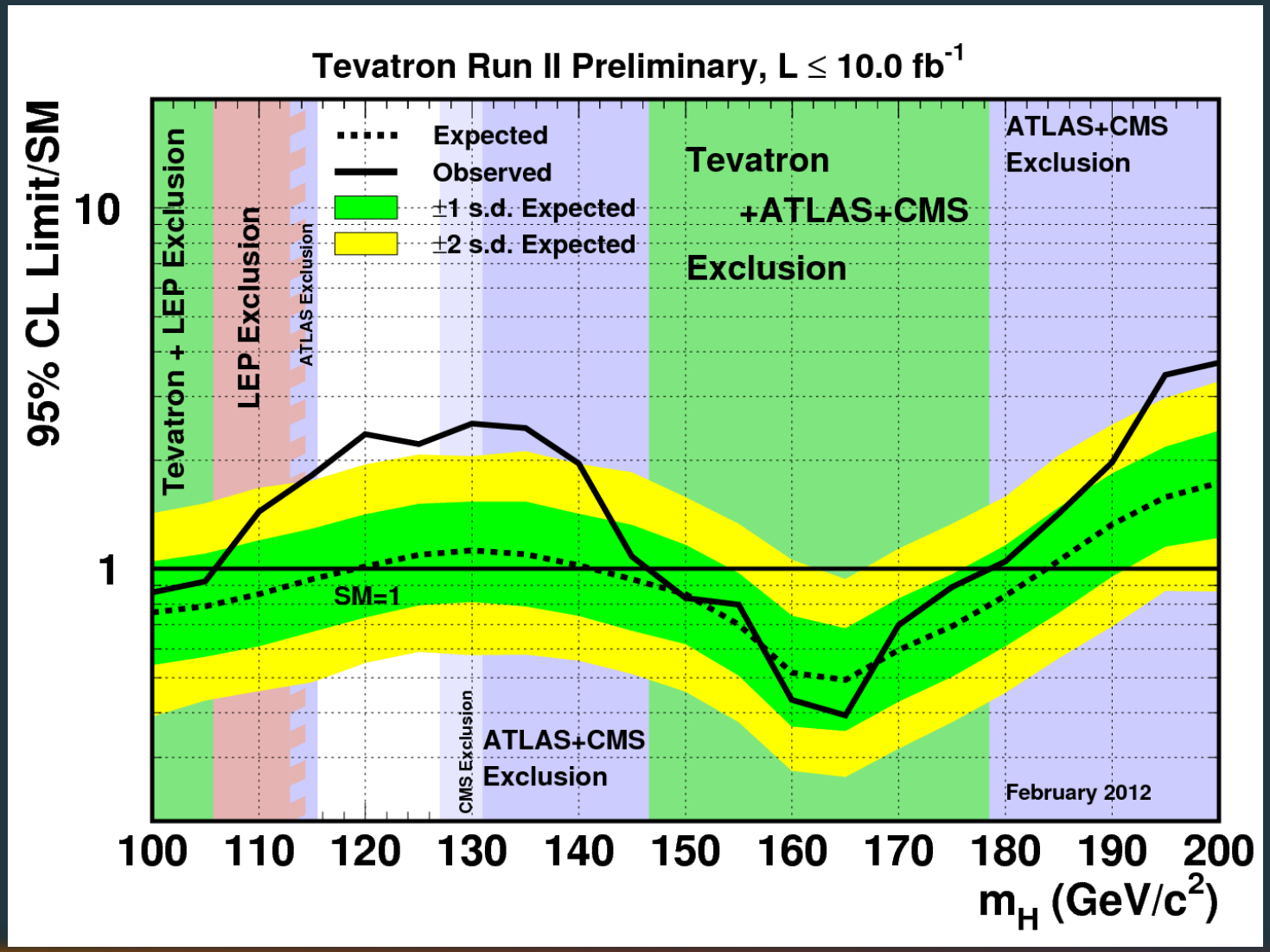
# Limits on All Channels

| MH | CDF | | D0 | |
|---|---|---|---|---|
| | Expected | Observed | Expected | Observed |
| 120 | 1.28 | 2.86 | 1.75 | 2.69 |
| 125 | 1.39 | 2.89 | 1.85 | 2.53 |
| 130 | 1.46 | 2.94 | 1.82 | 3.35 |

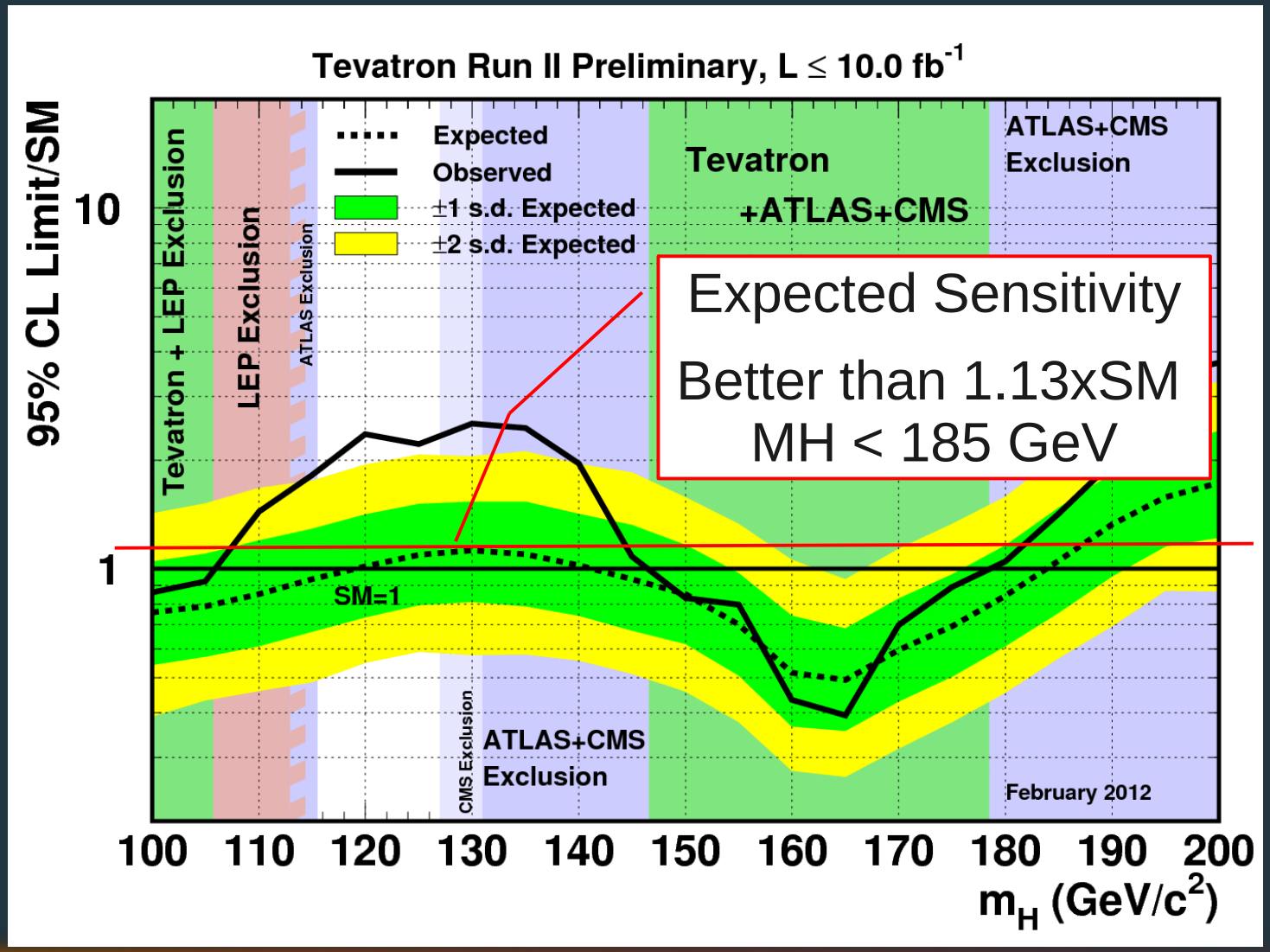


# Tevatron Combined Limits



# Tevatron Combined Limits



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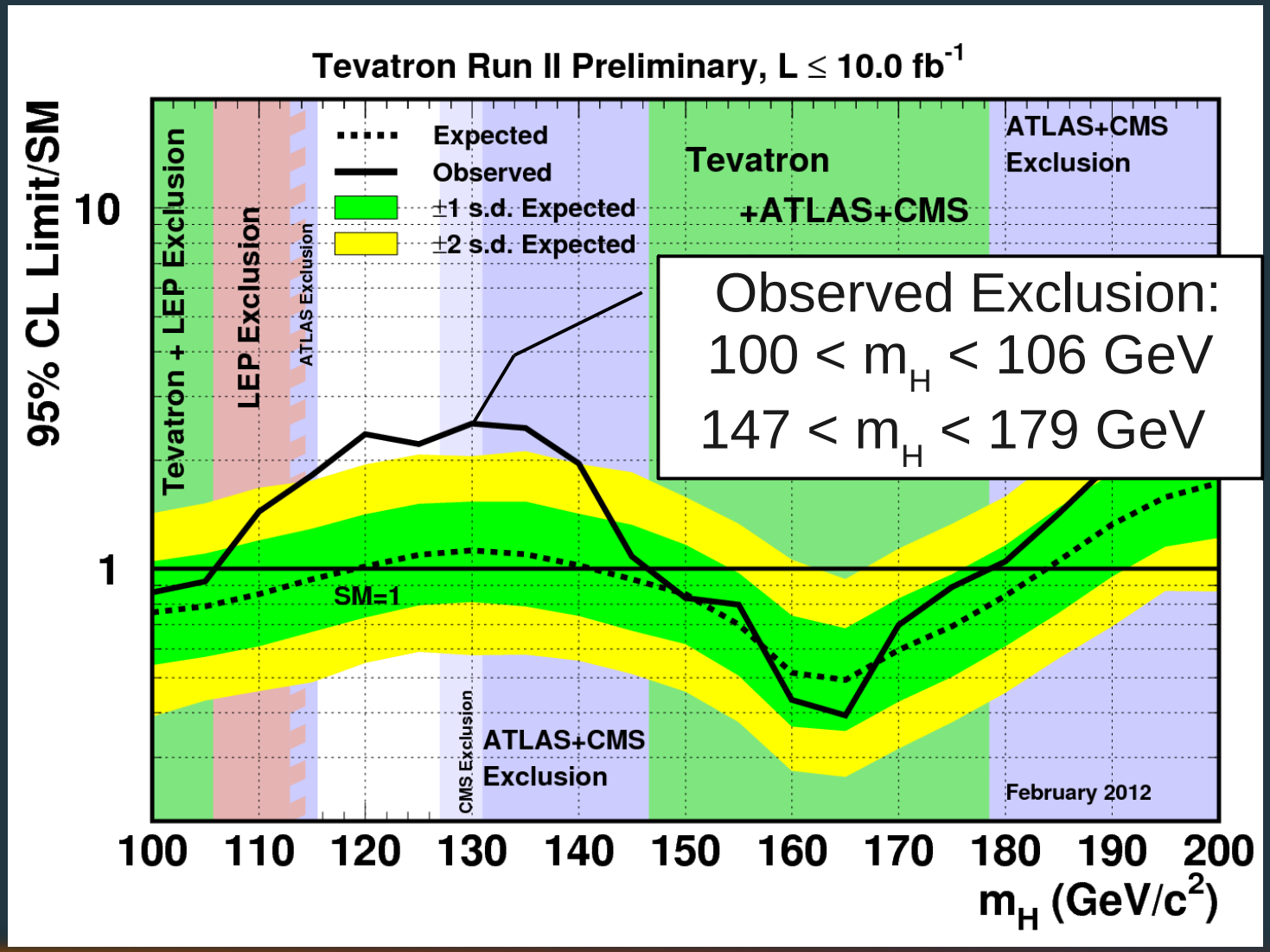
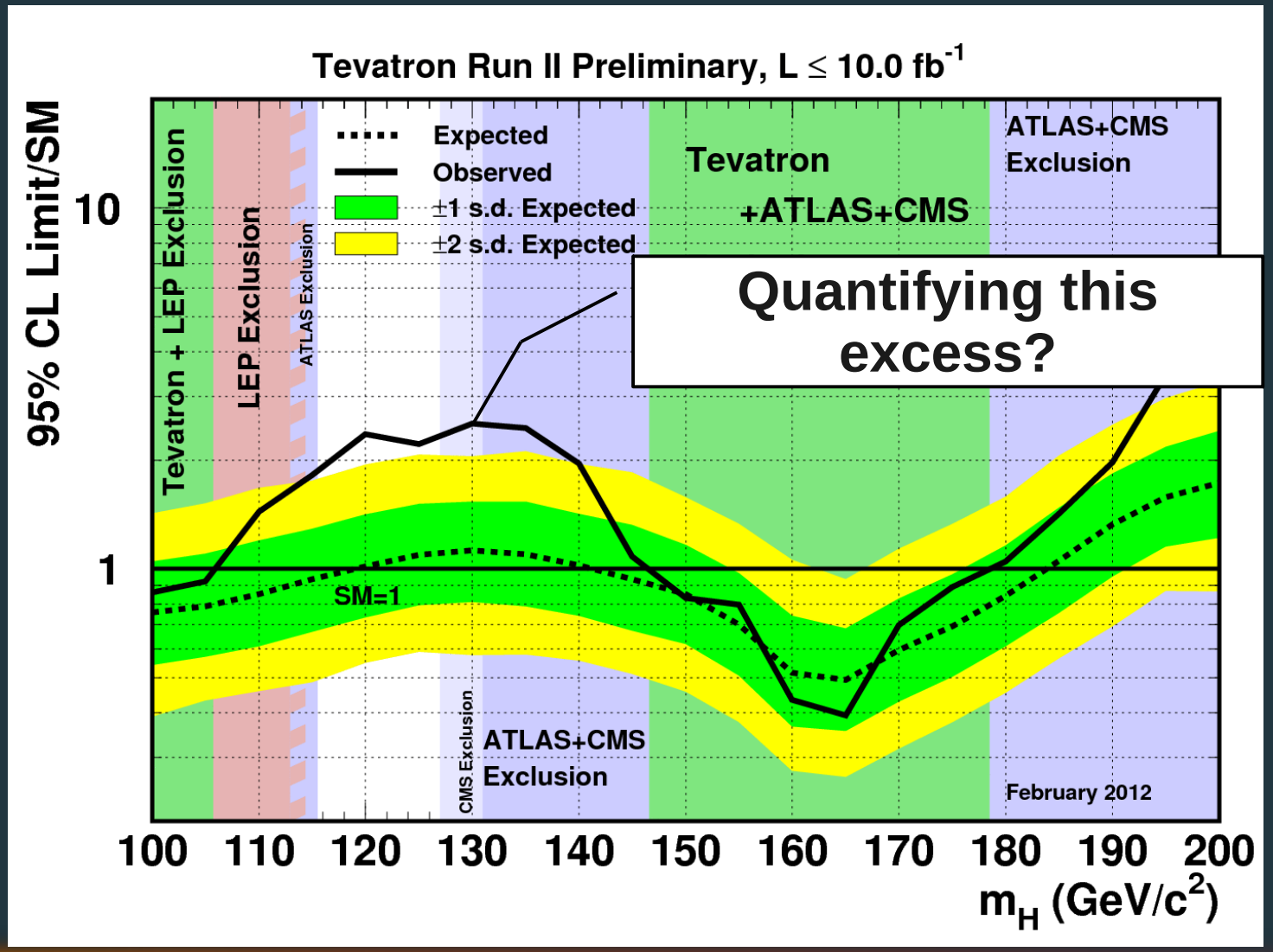



Observed Exclusion:
$100 < m_H < 106$ GeV
$147 < m_H < 179$ GeV

# Tevatron Combined Limits

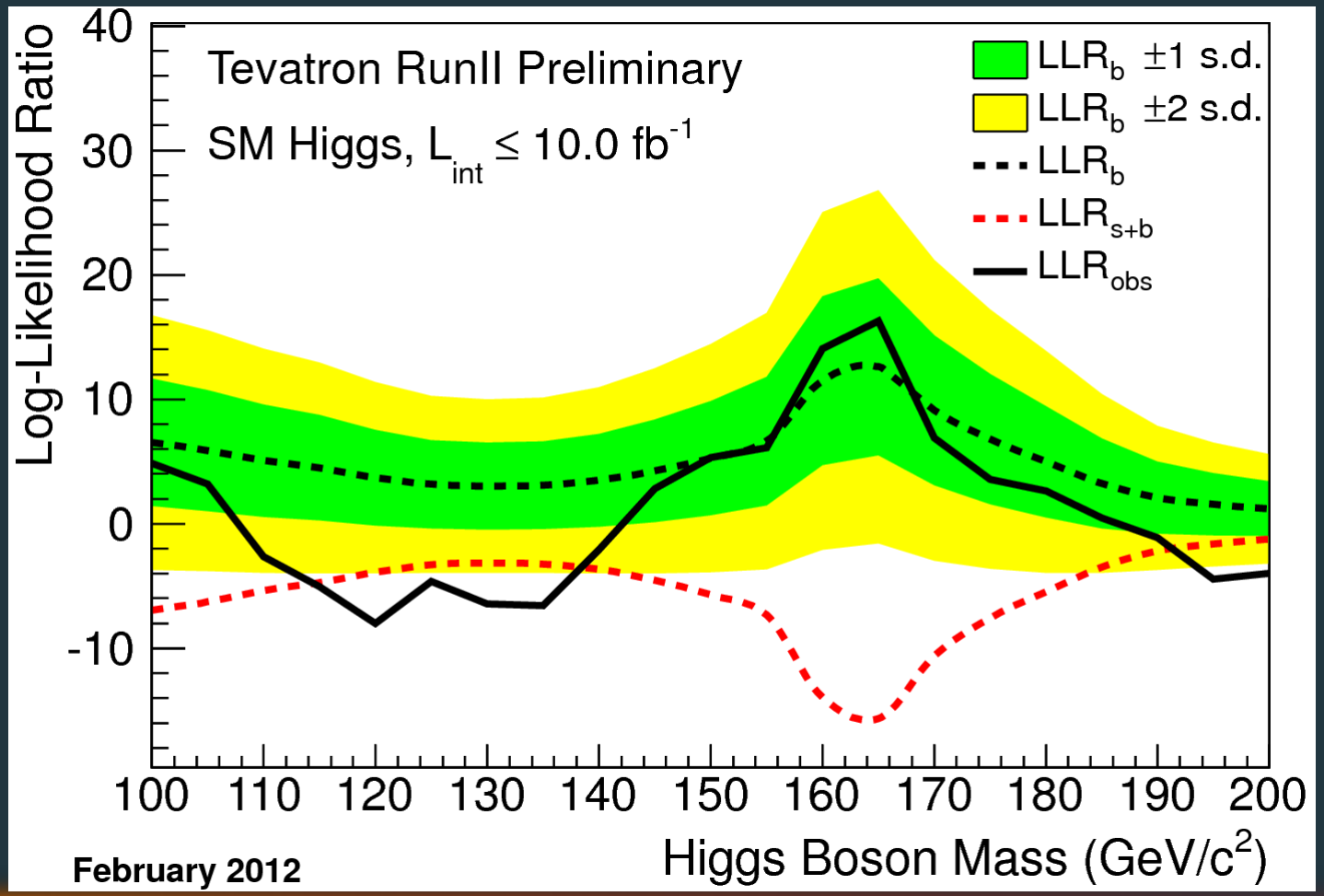



**Quantifying this excess?**

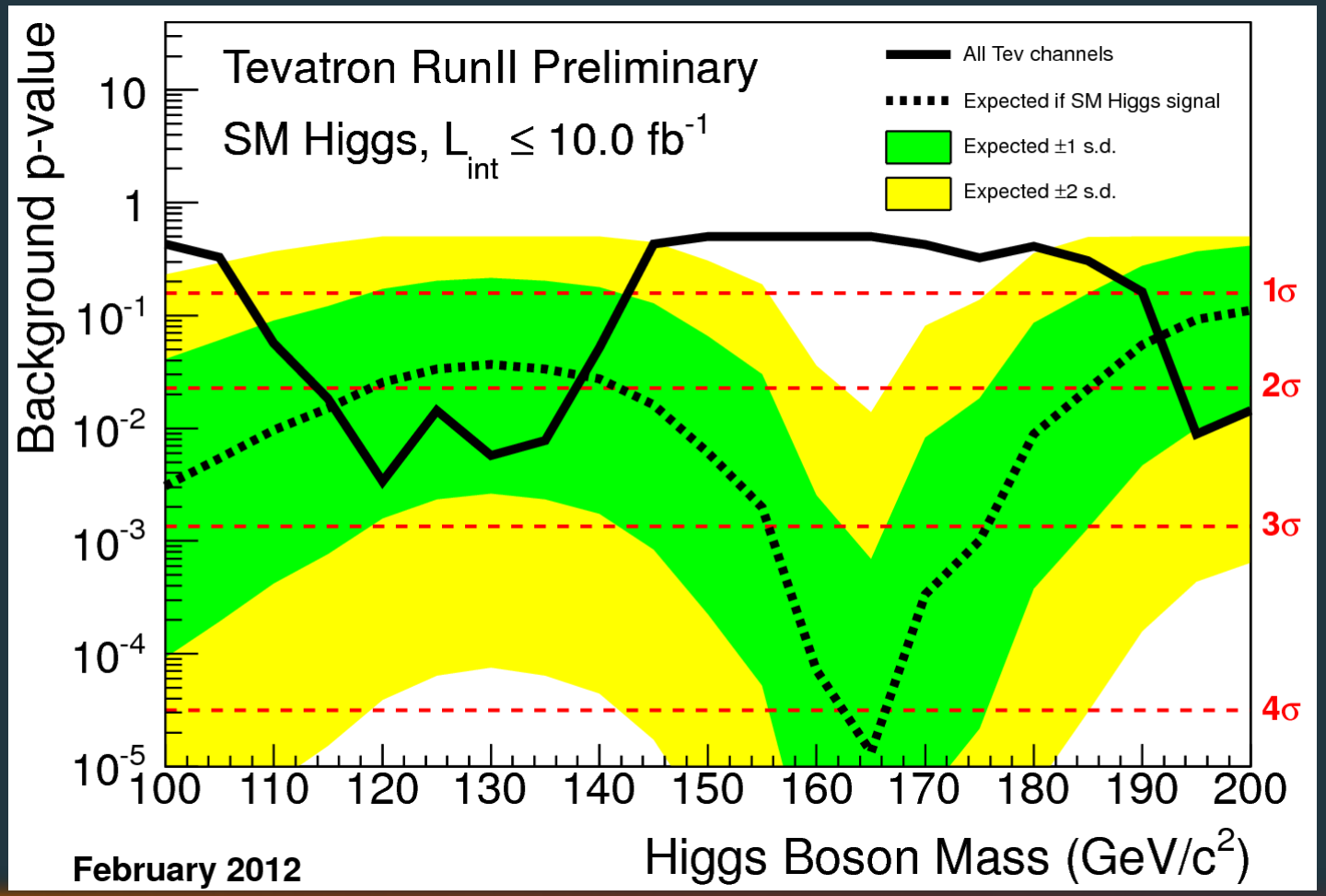
# LLR of Tevatron Combination

Compare to signal expectation

$$LLR = -2ln\frac{p(data|S+B)}{p(data|B)}$$

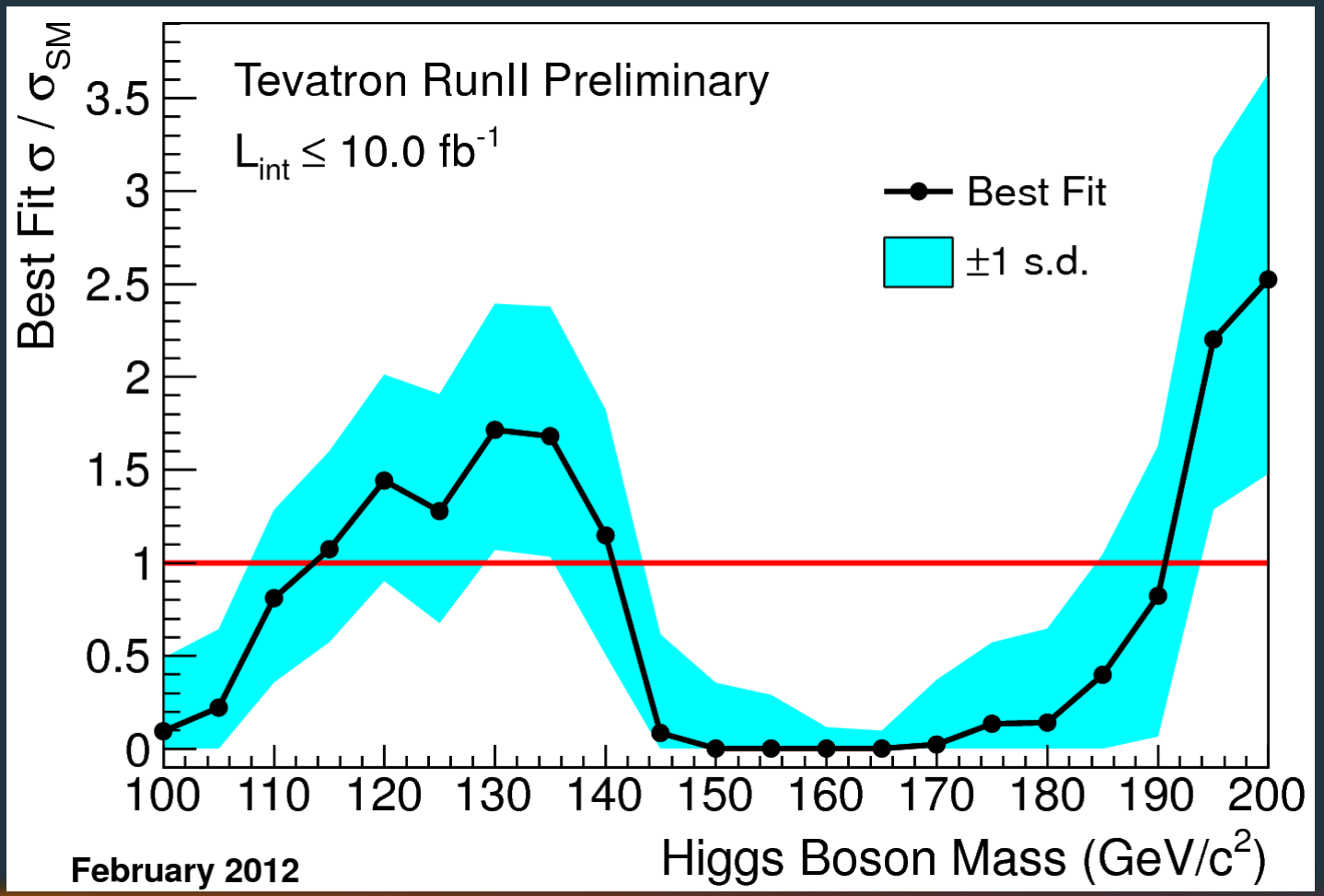


# p-value of Tevatron Combination

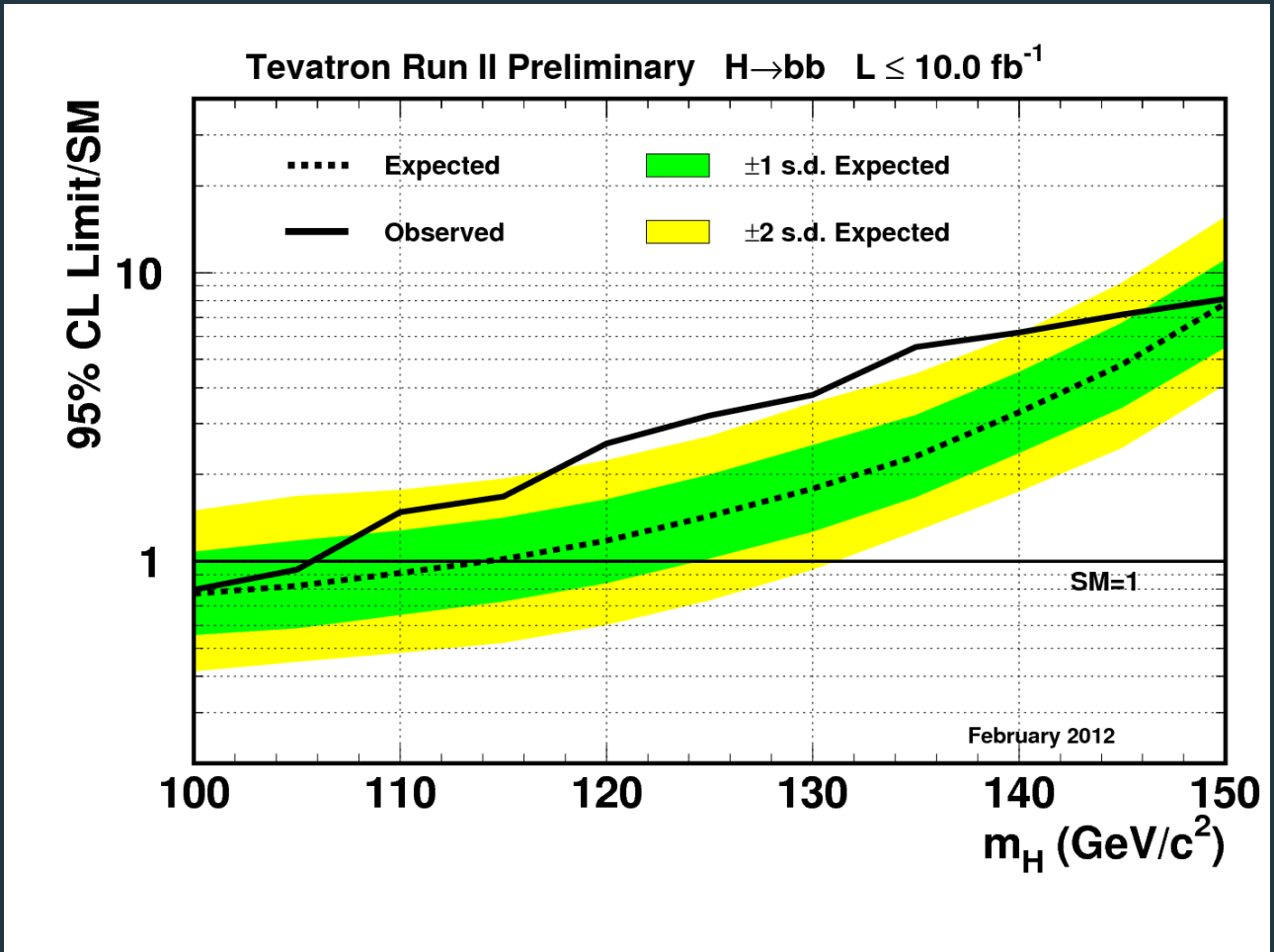


# Best Fit to Signal Model

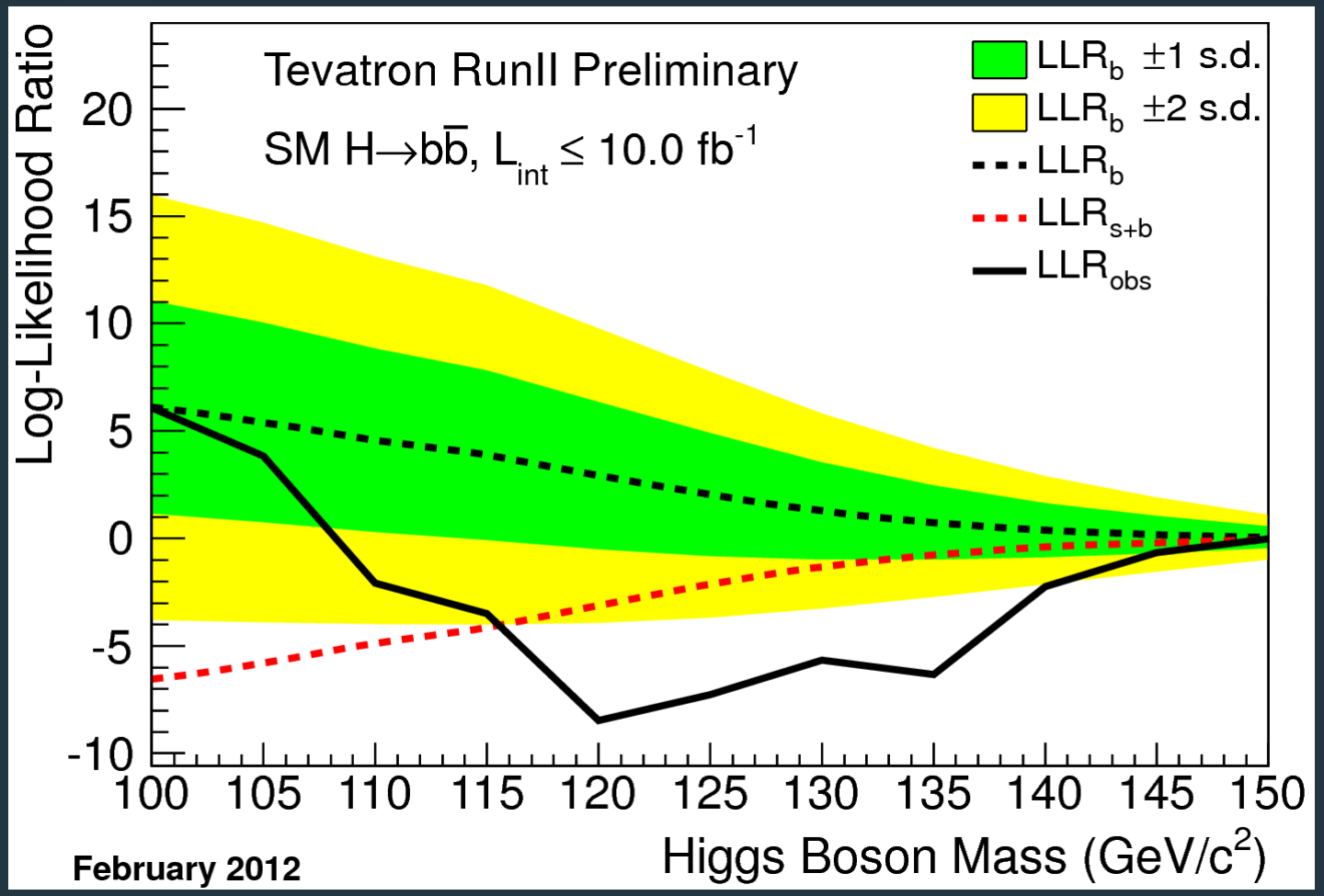
$$\sigma_H \times BR(H \to X)/SM$$



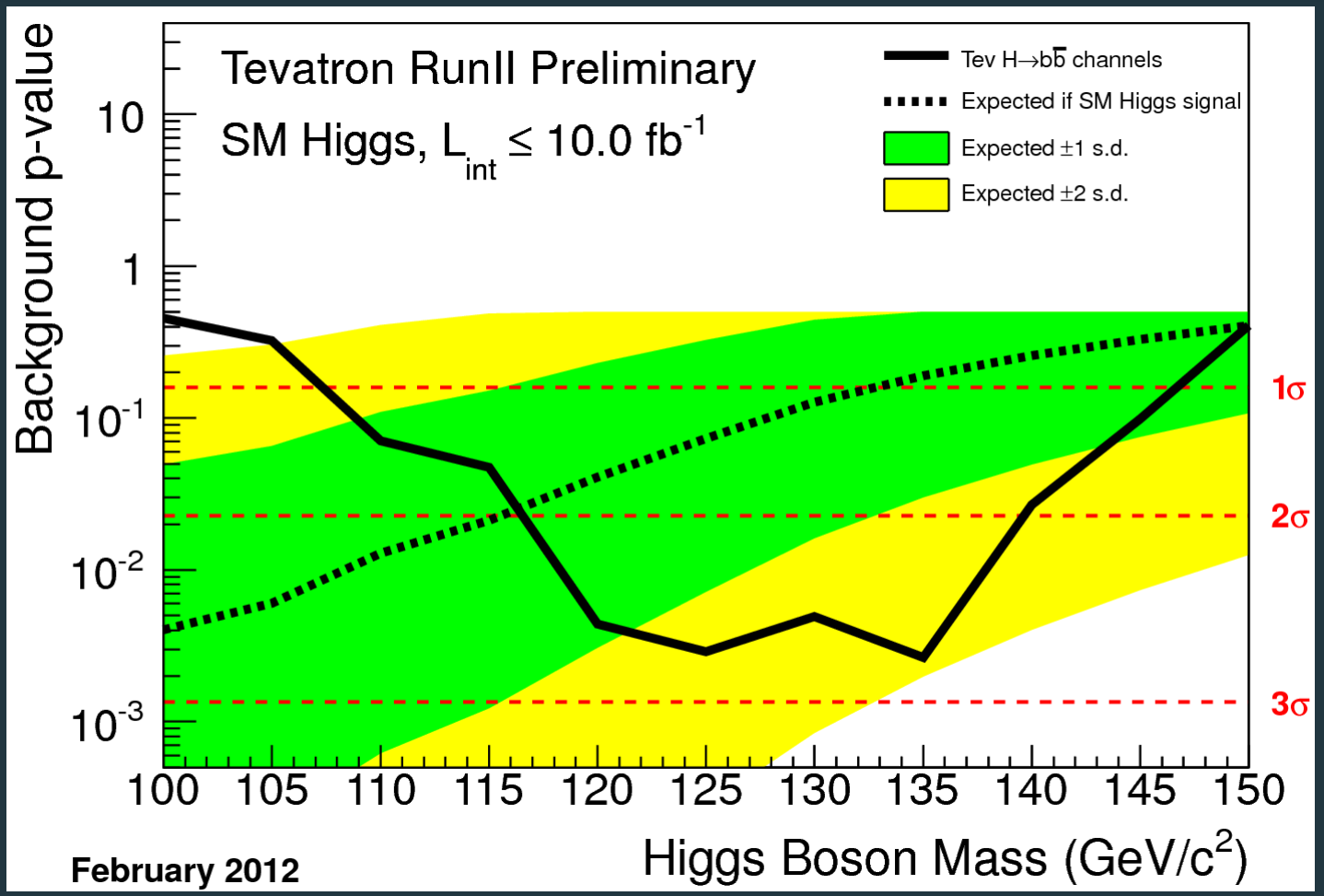
# H->bb Limits for Tevatron Combination



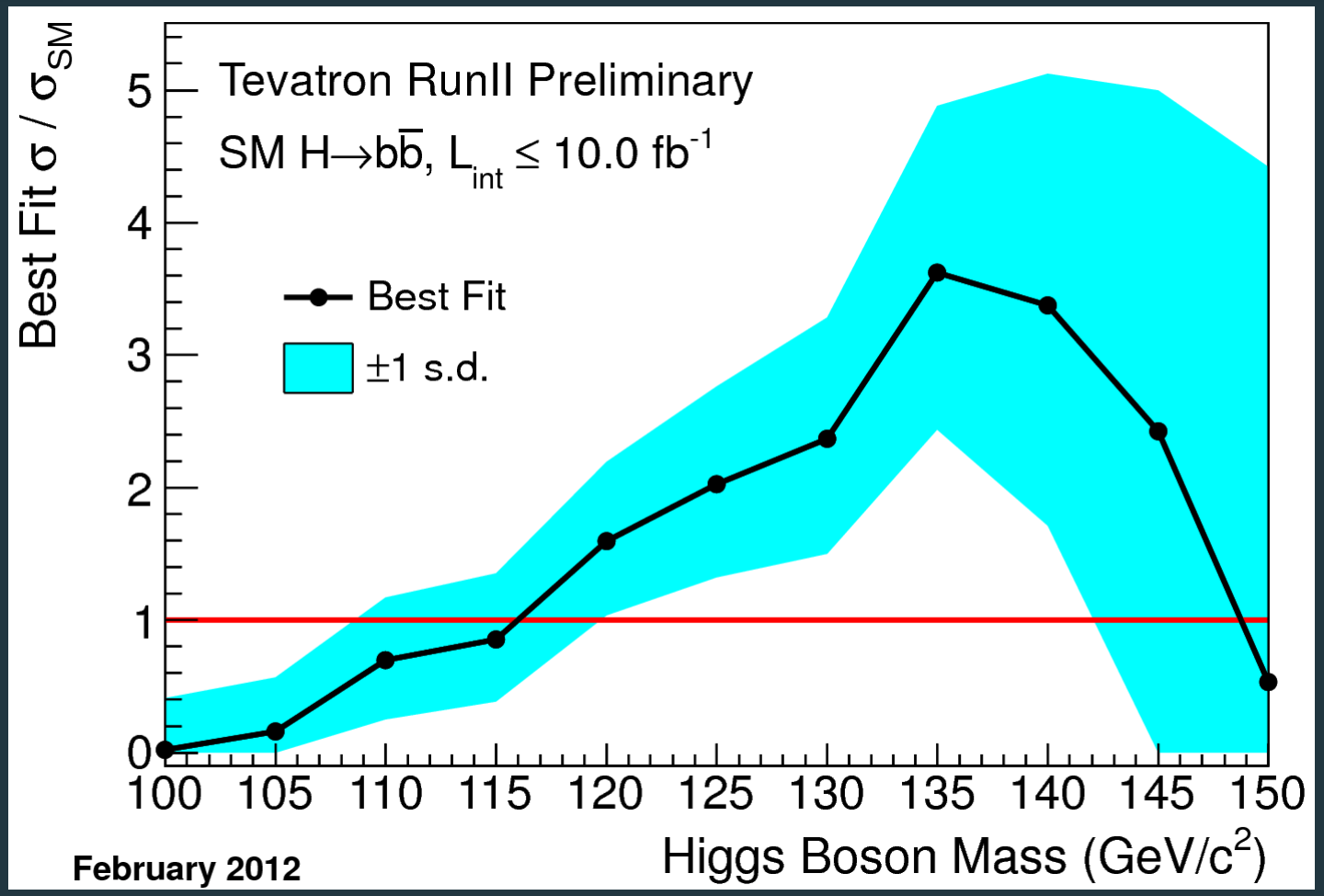
# H->bb LLR for Tevatron Combination



# H->bb p-value for Tevatron Combination



# H->bb Fit for Tevatron Combination



# Significance of Excess

Significance of a local excess is diluted by look-elsewhere effect

From studies of mass resolution, assume 4 independent search regions in $100 < m_H < 200$ GeV

Global p-value ≈ 4 × minimum local p-value

| | Local Significance | Global Significance |
|---|---|---|
| CDF | 2.6 σ | 2.1 σ |
| D0 | 2.2 σ | 1.5 σ |
| Tevatron | 2.7 σ | 2.2 σ |

Similar-sized excesses in complementary searches at the LHC and Tevatron

# Conclusions

Analysis improvements implemented in CDF and D0 to improve Higgs sensitivity to better than 1.13×SM for mH < 185 GeV

Broad excess in observed data relative to background-only hypothesis in $105 < m_H < 145$ GeV

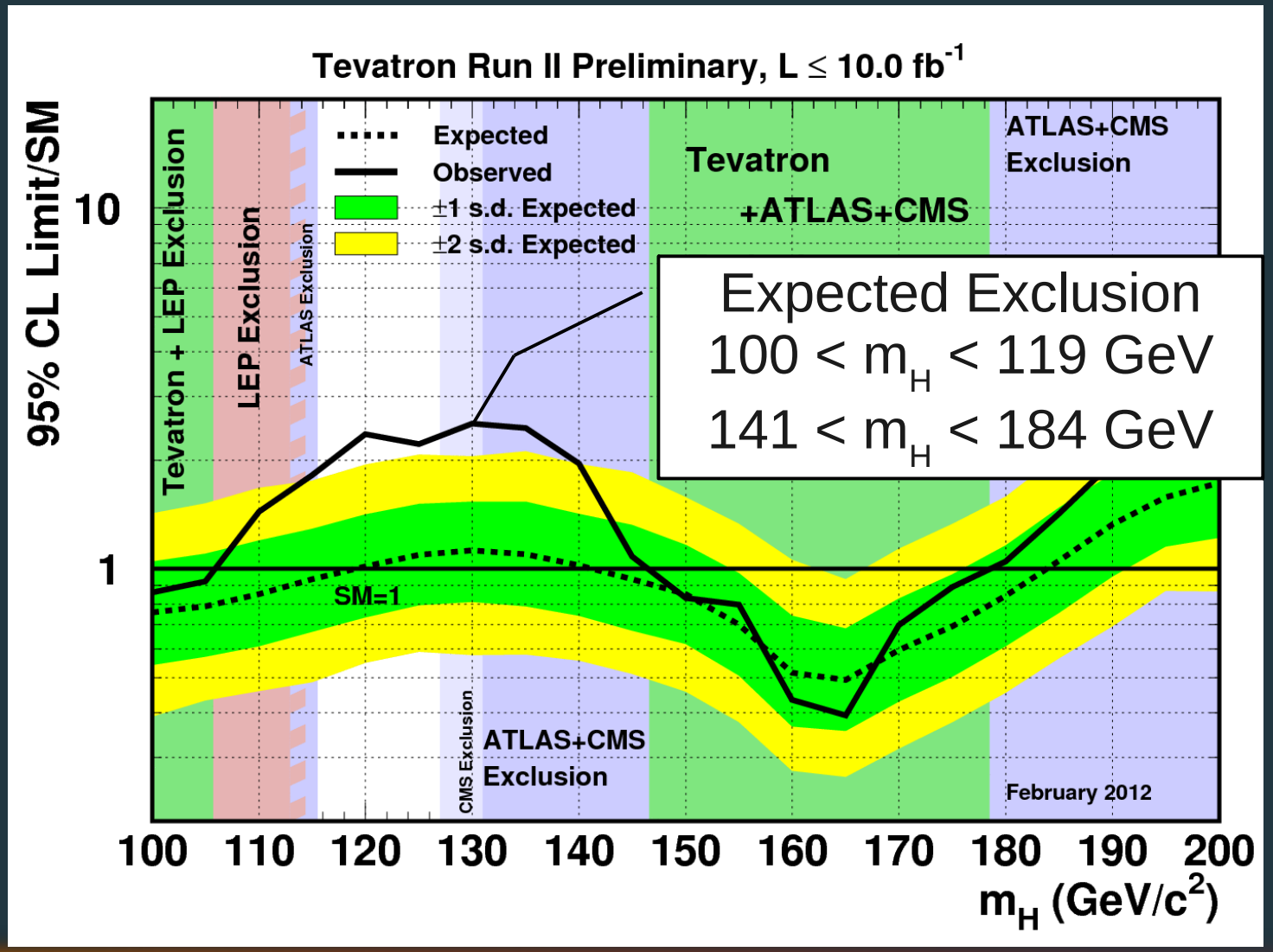
Global significance of excesses of all channels is 2.2 σ

Latest Tevatron combination is underway:

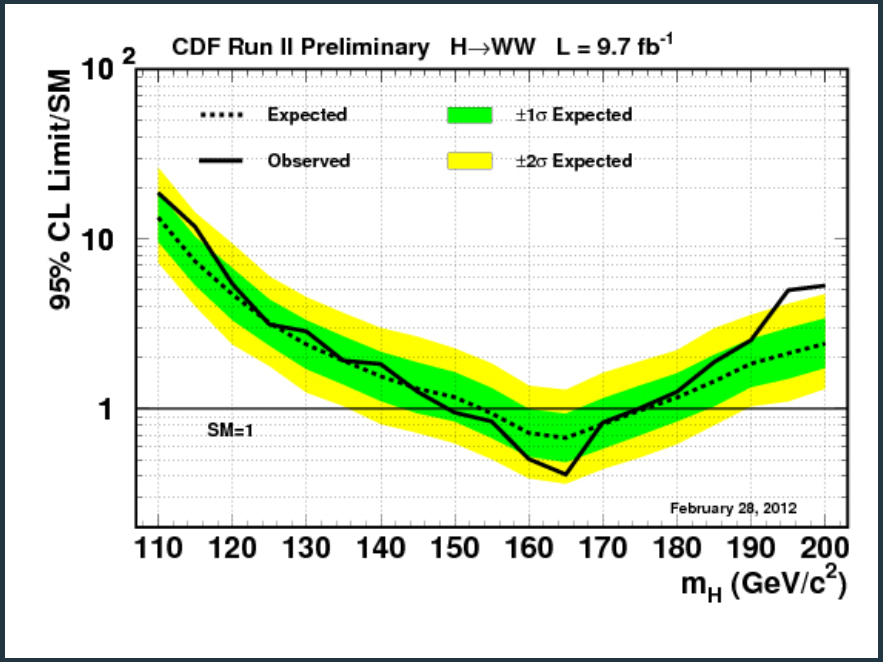
- Significant updates from all D0 analyses
- Inclusion of improved b-tagging in CDF MET + b-jets

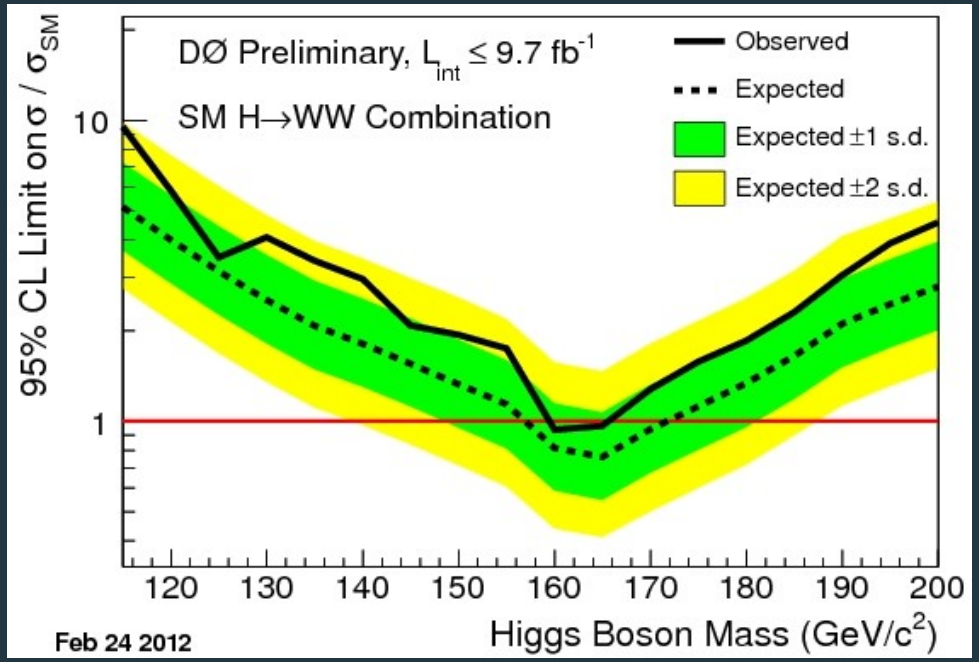
# Backup Slides

# Tevatron Combined Limits



# Limits on H->WW



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|---|---|---|
| CDF | 2.6 σ | 2.1 σ |
| D0 | 2.2 σ | 1.5 σ |
| Tevatron | 2.7 σ | 2.2 σ |
| | | |
| ATLAS | 3.5 σ | 2.2 σ |
| CMS | 2.8 σ | 2.1 σ |

# List of Channels (CDF)

| Channel | Luminosity ($fb^{-1}$) | $m_H$ range ($GeV/c^2$) |
|---|---|---|
| $WH \to \ell\nu bb$ 2-jet channels 4×(TT,TL,Tx,LL,Lx) | 9.45 | 100-150 |
| $WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(TT,TL) | 9.45 | 100-150 |
| $ZH \to \nu\bar{\nu}b\bar{b}$ (SS,SJ,1S) | 9.45 | 100-150 |
| $ZH \to \ell^+\ell^-b\bar{b}$ 2-jet channels 2×(TT,TL,Tx,LL) | 9.45 | 100-150 |
| $ZH \to \ell^+\ell^-b\bar{b}$ 3-jet channels 2×(TT,TL,Tx,LL) | 9.45 | 100-150 |
| $H \to W^+W^-$ 2×(0 jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$) | 9.7 | 110-200 |
| $H \to W^+W^-$ ($e$-$\tau_{\rm had}$)+($\mu$-$\tau_{\rm had}$) | 9.7 | 130-200 |
| $WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons) | 9.7 | 110-200 |
| $WH \to WW^+W^-$ tri-leptons with 1 $\tau_{\rm had}$ | 9.7 | 130-200 |
| $ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets) | 9.7 | 110-200 |
| $H \to ZZ$ four leptons | 9.7 | 120-200 |
| $H + X \to \tau^+\tau^-$ (1 jet)+(2 jets) | 8.3 | 100-150 |
| $WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ $\ell$-$\tau_{\rm had}$-$\tau_{\rm had}$ | 6.2 | 100-150 |
| $WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ($\ell$-$\ell$-$\tau_{\rm had}$)+($e$-$\mu$-$\tau_{\rm had}$) | 6.2 | 100-125 |
| $WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ $\ell$-$\ell$-$\ell$ | 6.2 | 100-105 |
| $ZH \to \ell^+\ell^-\tau^+\tau^-$ four leptons including $\tau_{\rm had}$ candidates | 6.2 | 100-115 |
| $WH + ZH \to jjb\bar{b}$ (SS,SJ) | 9.45 | 100-150 |
| $H \to \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv) | 10.0 | 100-150 |
| $t\bar{t}H \to WWb\bar{b}b\bar{b}$ (lepton) (4jet,5jet,≥6jet)×(SSS,SSJ,SJJ,SS,SJ) | 9.45 | 100-150 |
| $t\bar{t}H \to WWb\bar{b}b\bar{b}$ (no lepton) (low met,high met)×(2 tags,3 or more tags) | 5.7 | 100-150 |

# List of Channels (D0)

| Channel | Luminosity ($fb^{-1}$) | $m_H$ range ($GeV/c^2$) |
|---|---|---|
| $WH \to \ell\nu b\bar{b}$ (TST,LDT,TDT)×(2,3 jet) | 9.7 | 100-150 |
| $ZH \to \nu\bar{\nu}b\bar{b}$ (MS,TS) | 9.5 | 100-150 |
| $ZH \to \ell^+\ell^- b\bar{b}$ (TST,TLDT)×($ee$,$\mu\mu$,$ee_{ICR}$,$\mu\mu_{trk}$) | 9.7 | 100-150 |
| $H+X \to \ell^\pm \tau^\mp_{\rm had} jj$ | 4.3-6.2 | 105-200 |
| $VH \to e^\pm\mu^\pm + X$ | 9.7 | 115-200 |
| $H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ (0,1,2+ jet) | 8.6-9.7 | 115-200 |
| $H \to W^+W^- \to \mu\nu\tau_{\rm had}\nu$ | 7.3 | 115-200 |
| $H \to W^+W^- \to \ell\bar{\nu}jj$ | 5.4 | 130-200 |
| $VH \to \ell\ell\ell + X$ | 9.7 | 100-200 |
| $VH \to \tau\tau\mu + X$ | 7.0 | 115-200 |
| $H \to \gamma\gamma$ | 9.7 | 100-150 |