

Tests of BSM Higgs J/CP



For the CDF & DØ
collaborations

Wade Fisher
Michigan State University

Tevatron (1983-2011)

proton - antiproton collider

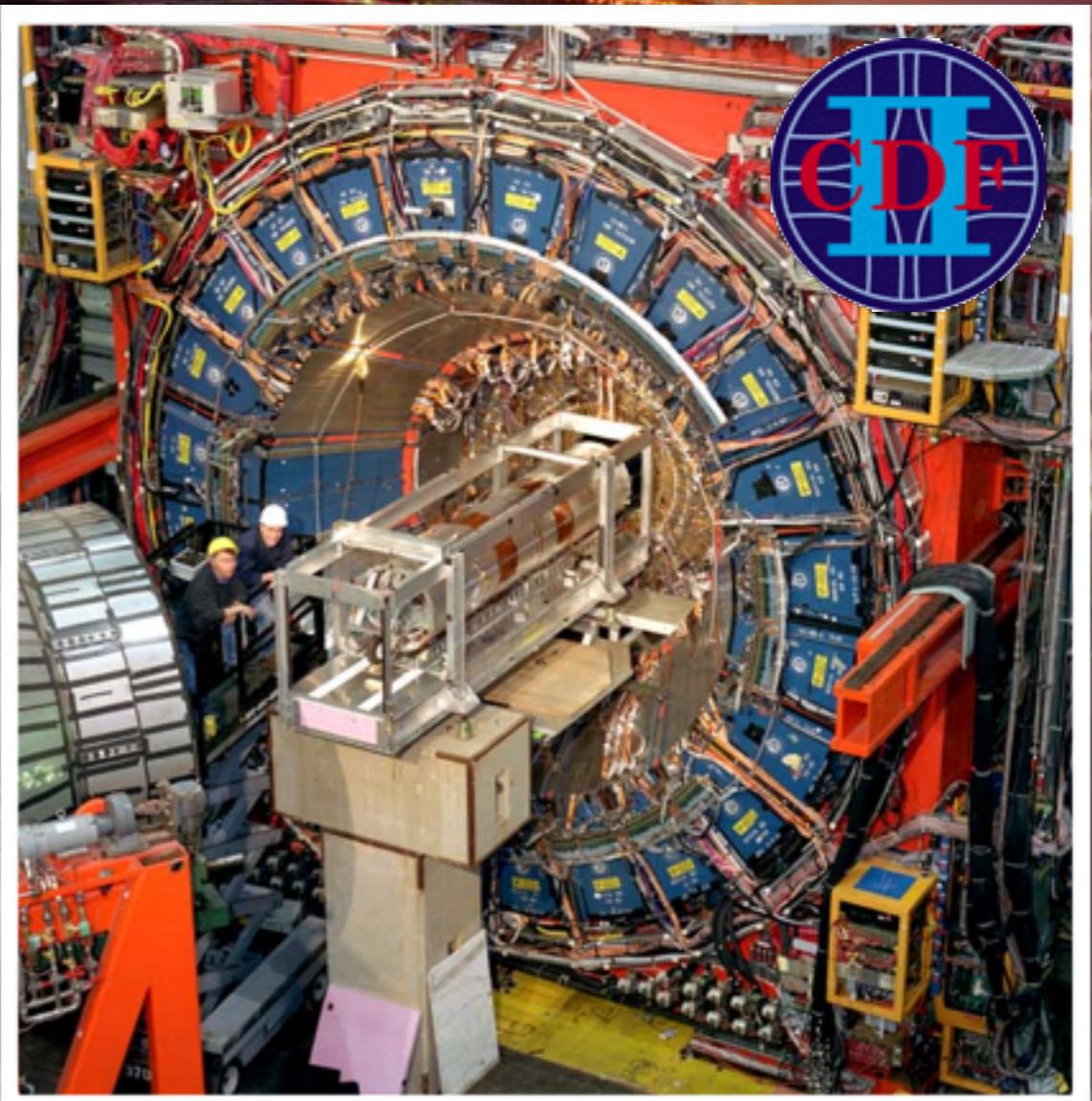
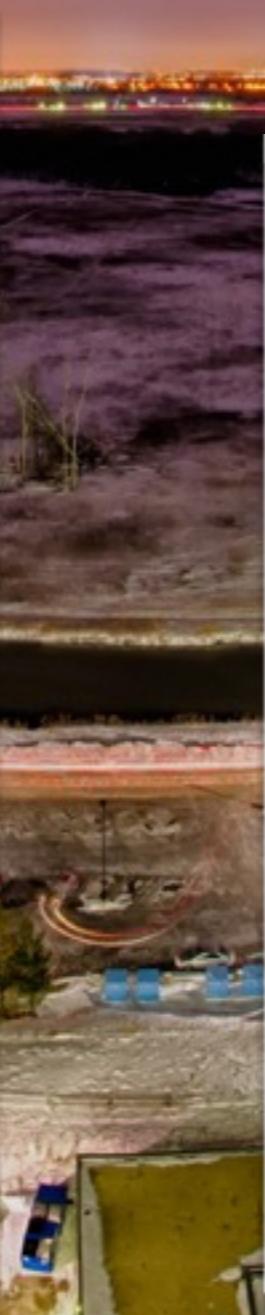
collision energy = 1.96 TeV



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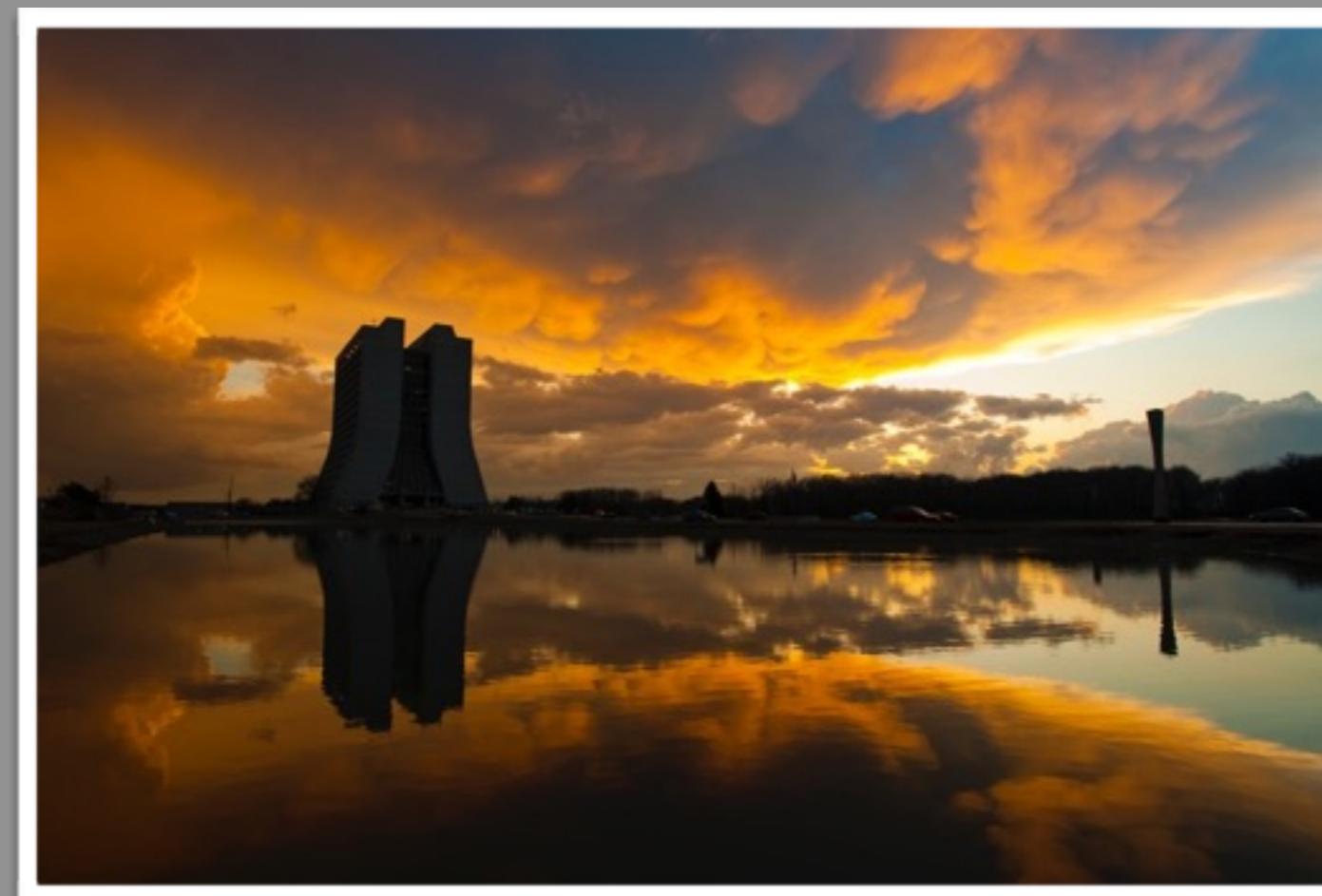
The Tevatron's Higgs Legacy

Higgs searches at the Tevatron

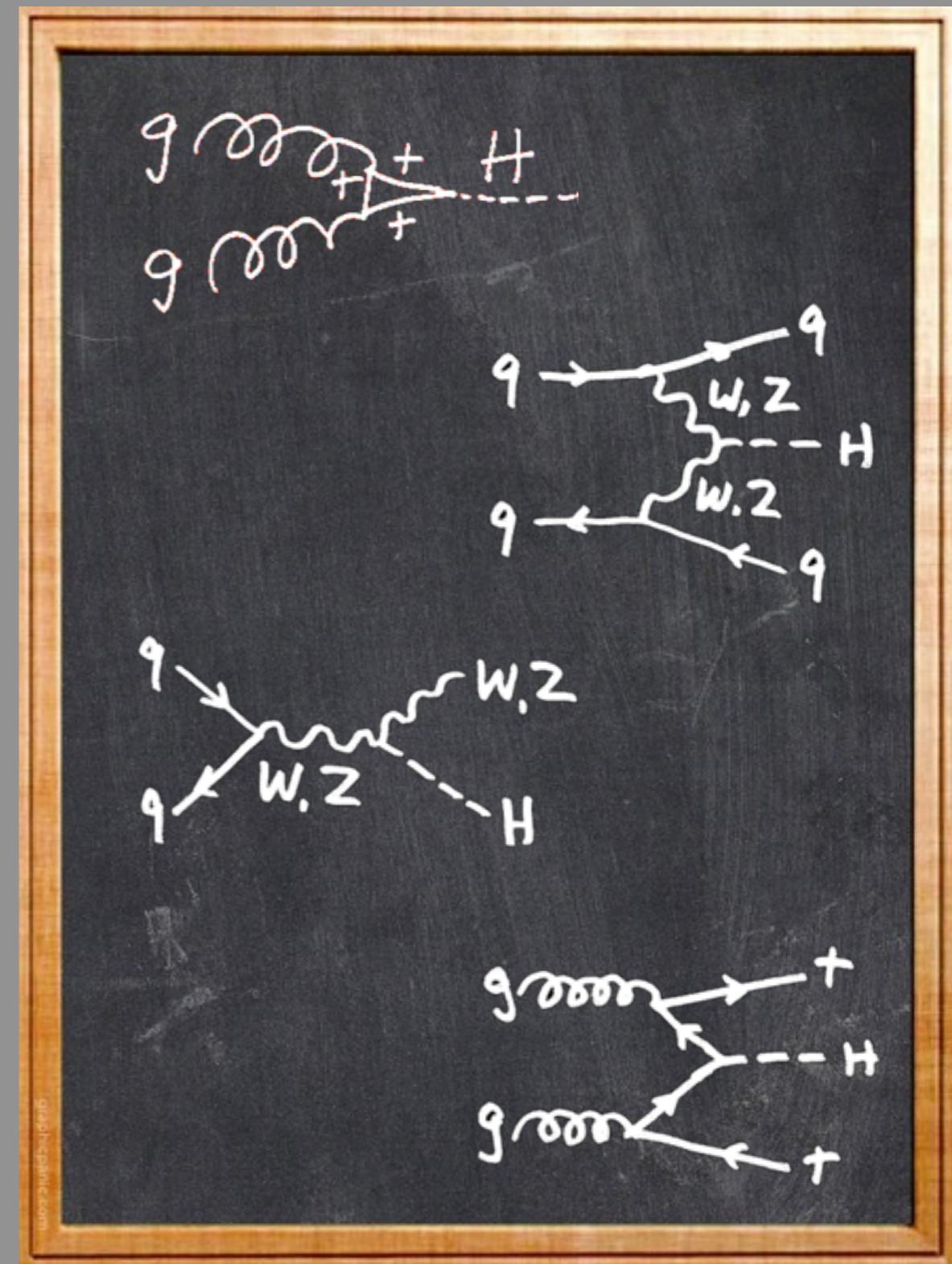
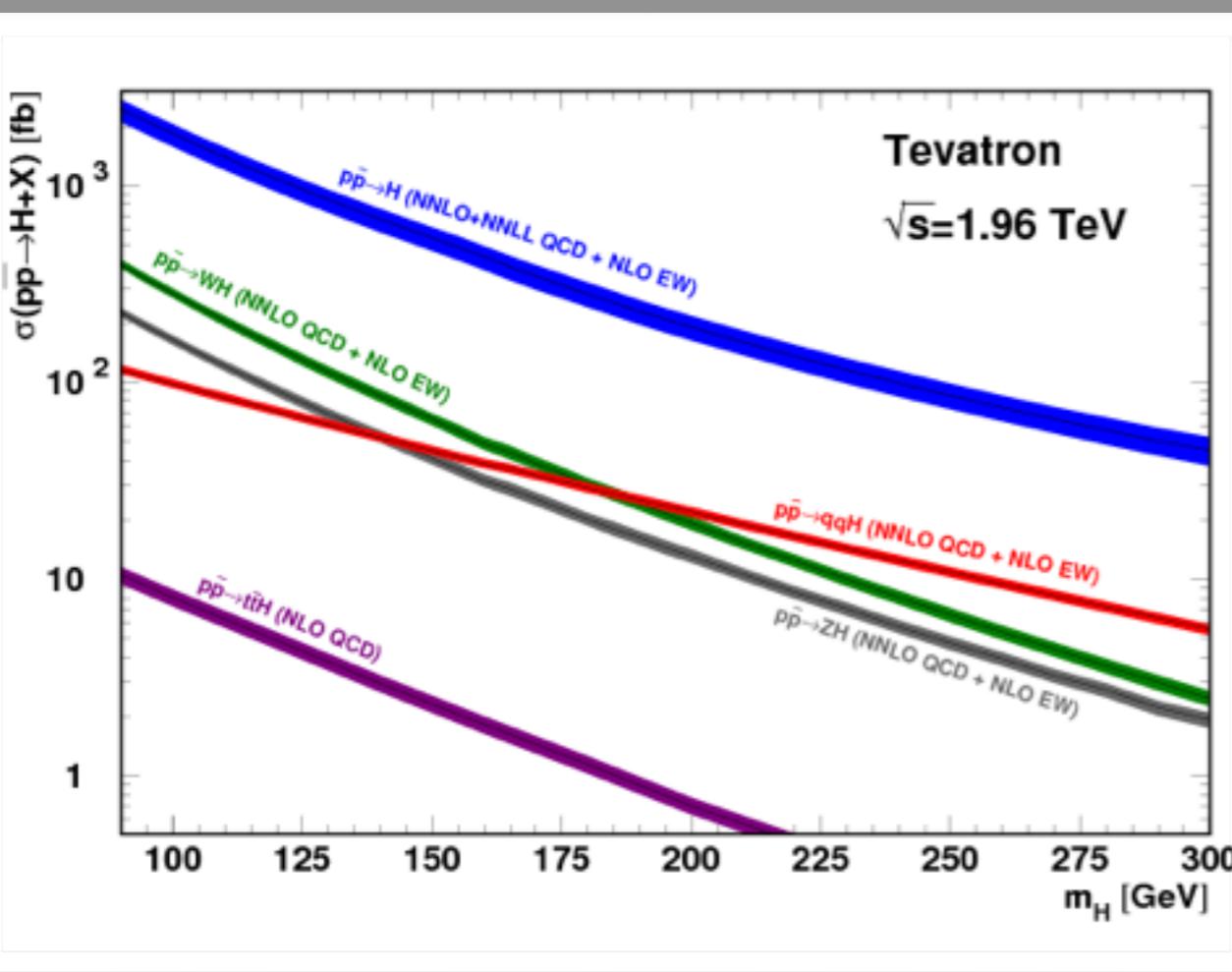
- ◆ Production and decay modes
- ◆ Search strategies

Studies of Higgs production
at $M_H=125$ GeV

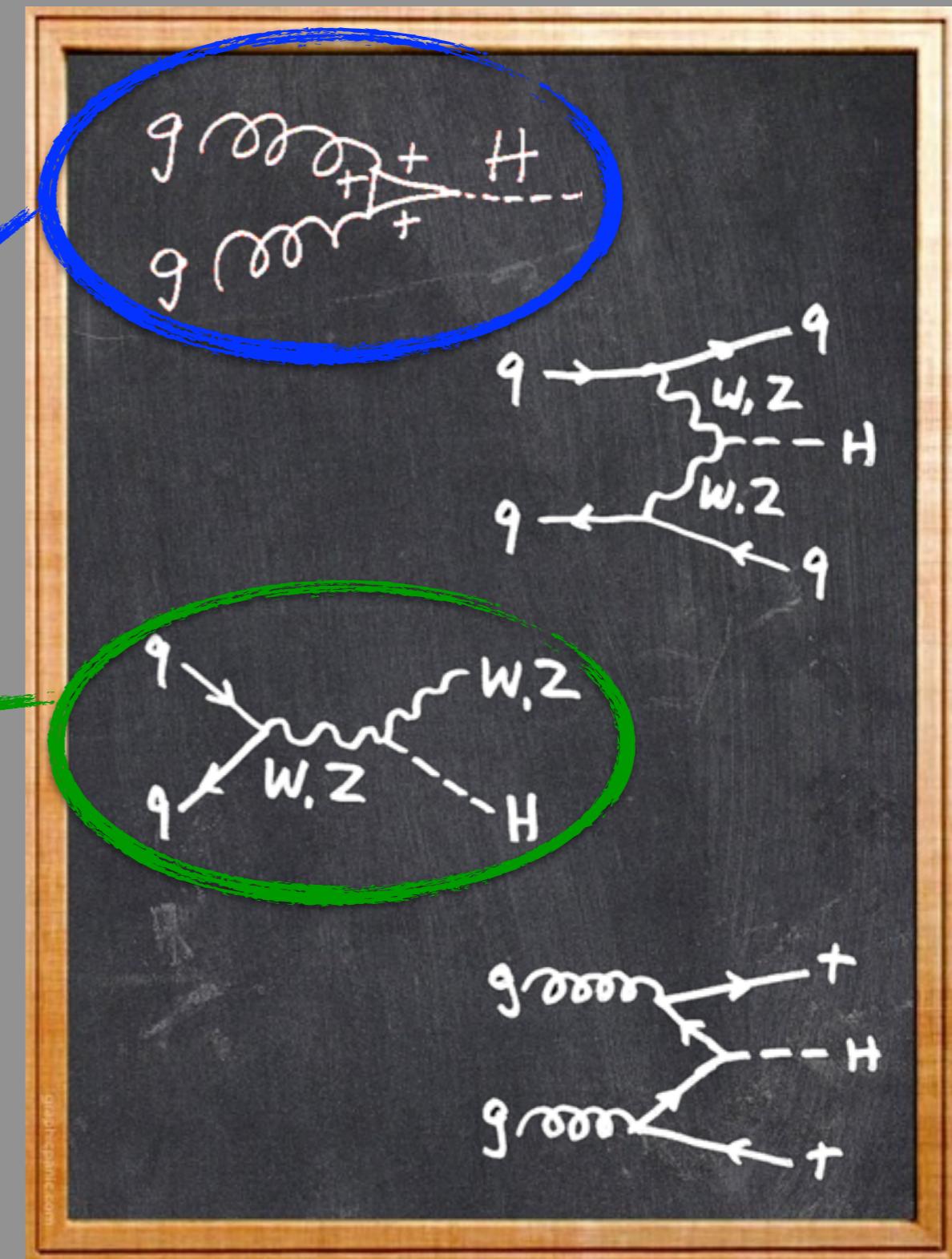
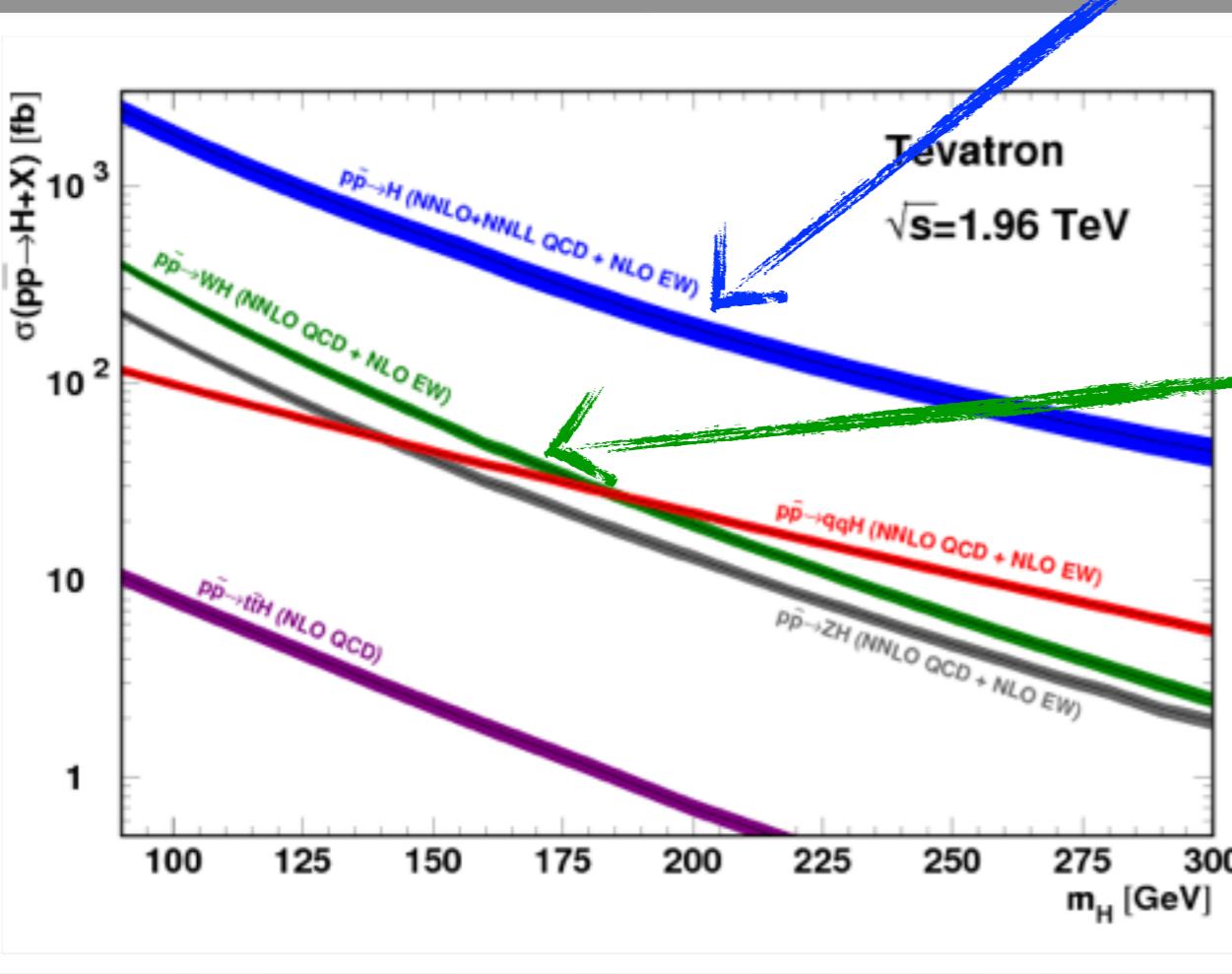
- ◆ Signal significance
- ◆ Probes of BSM Higgs J/CP



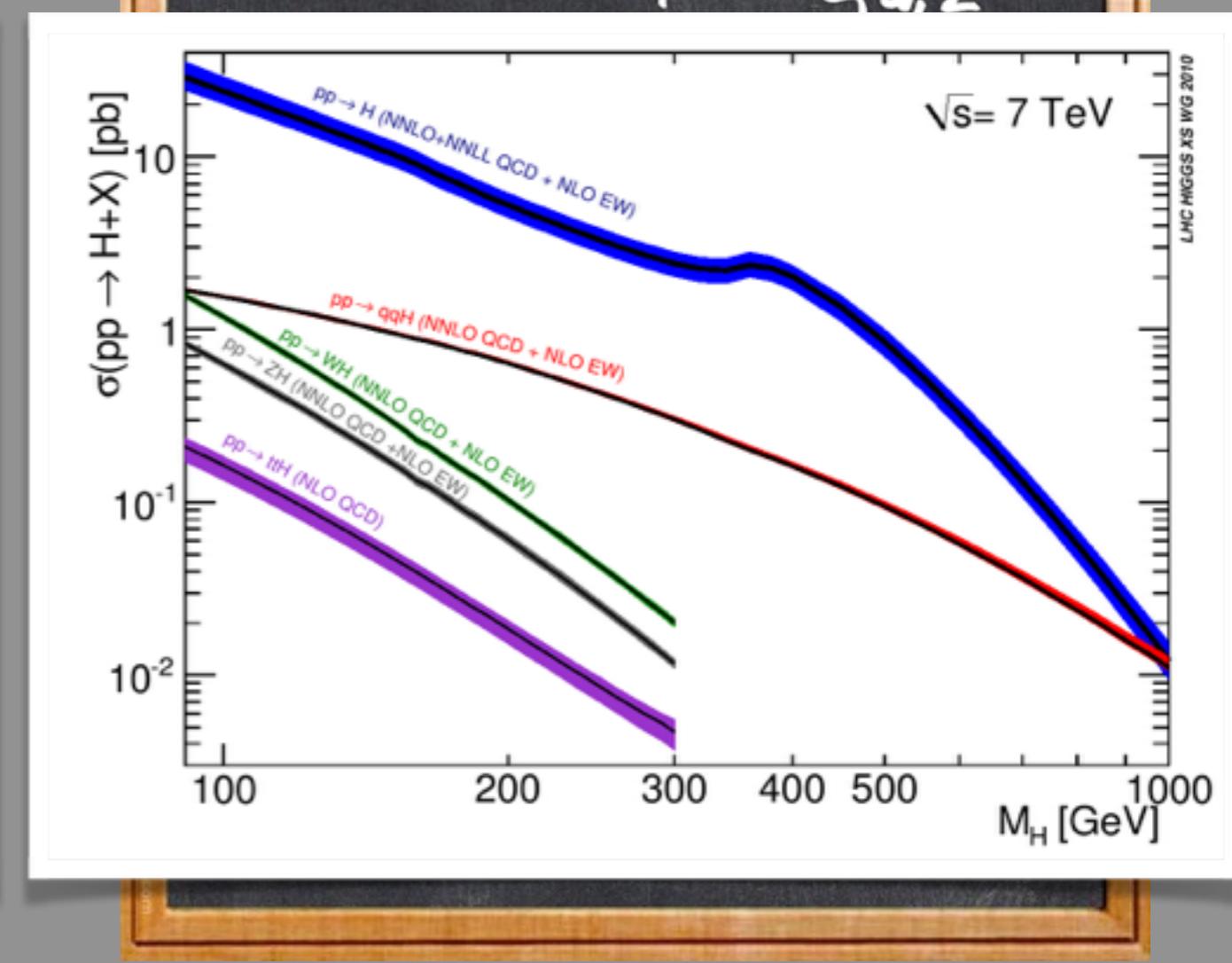
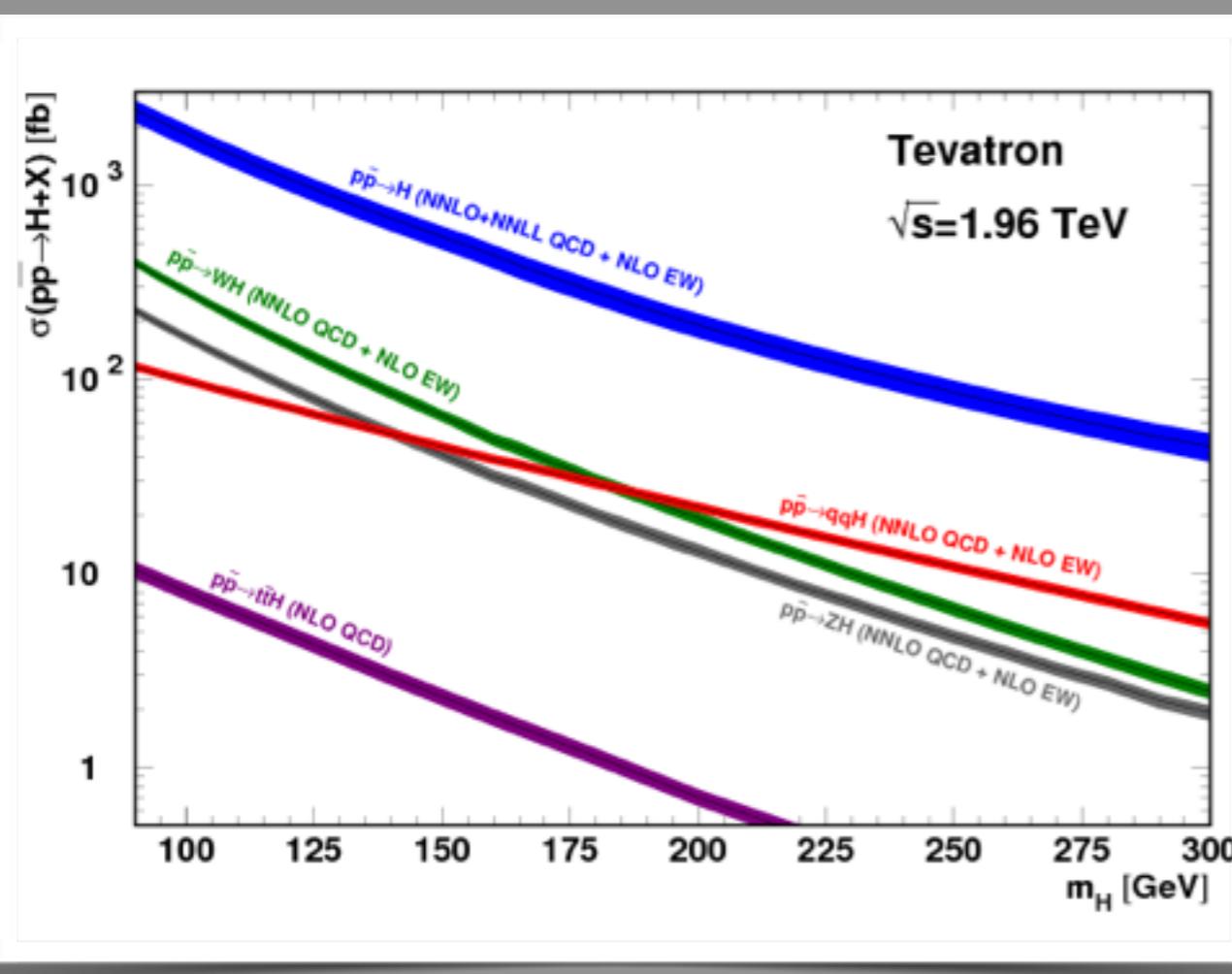
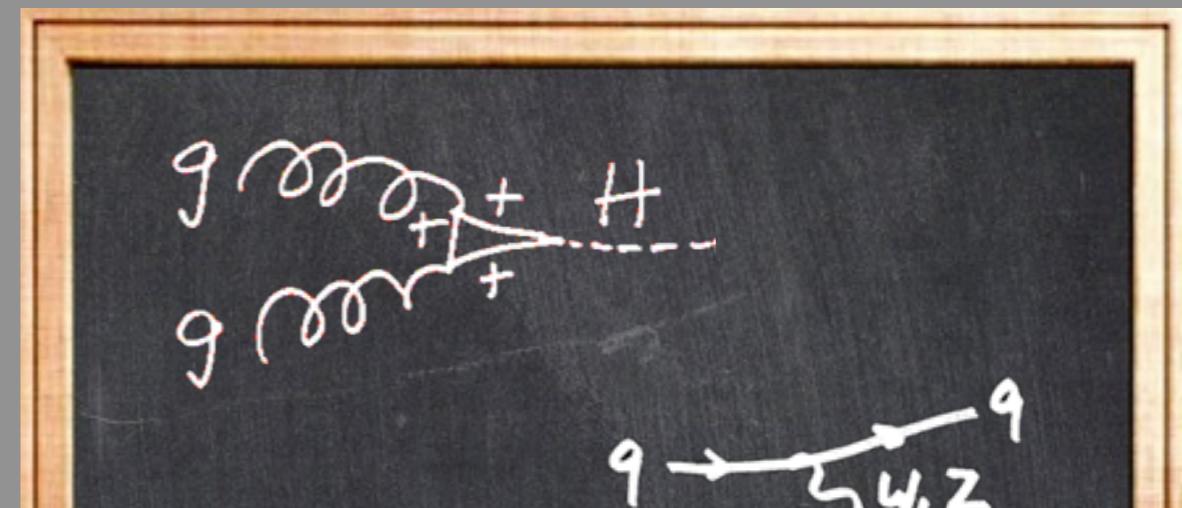
Producing Higgs at the Tevatron



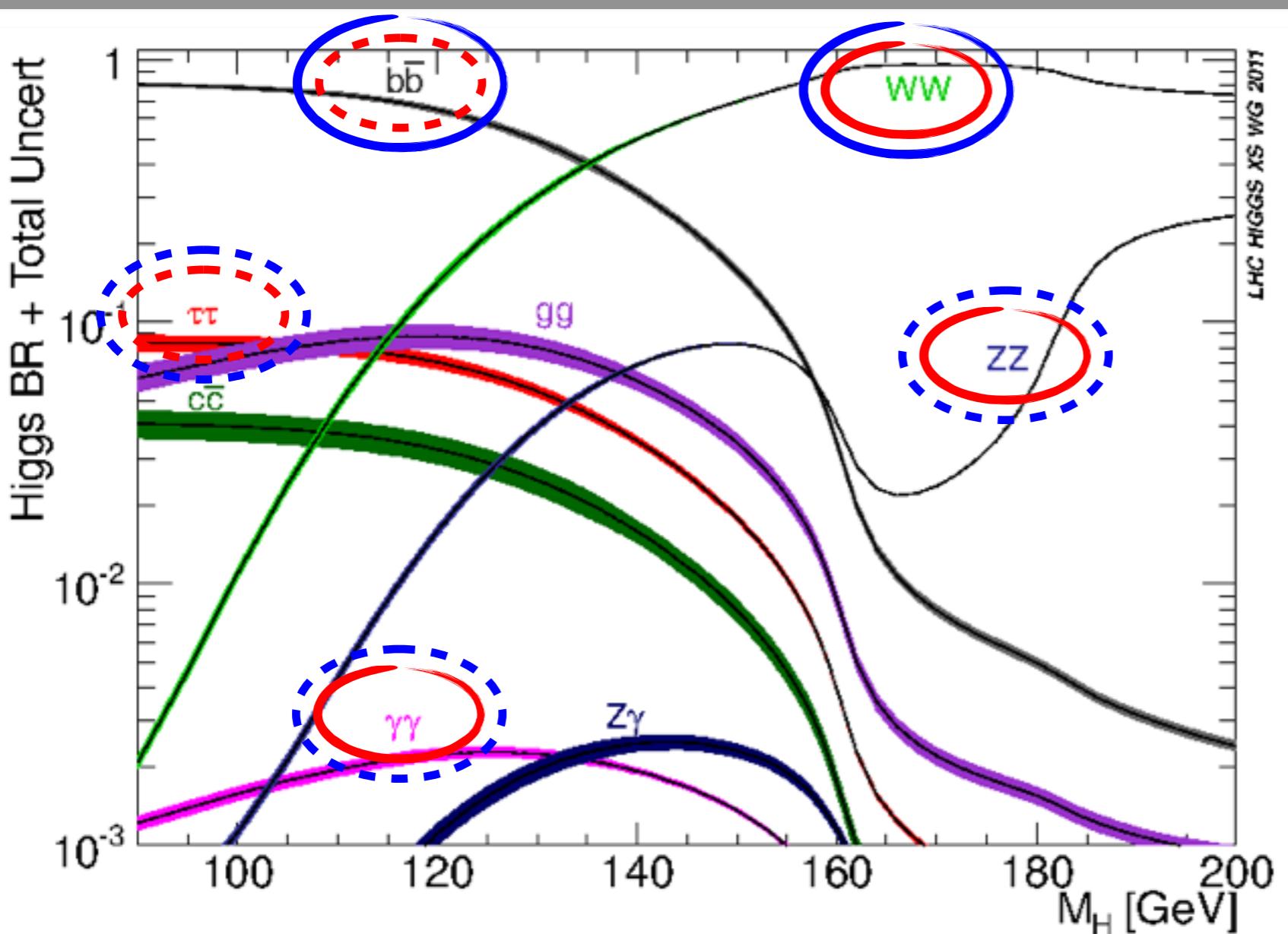
Producing Higgs at the Tevatron



Producing Higgs at the Tevatron

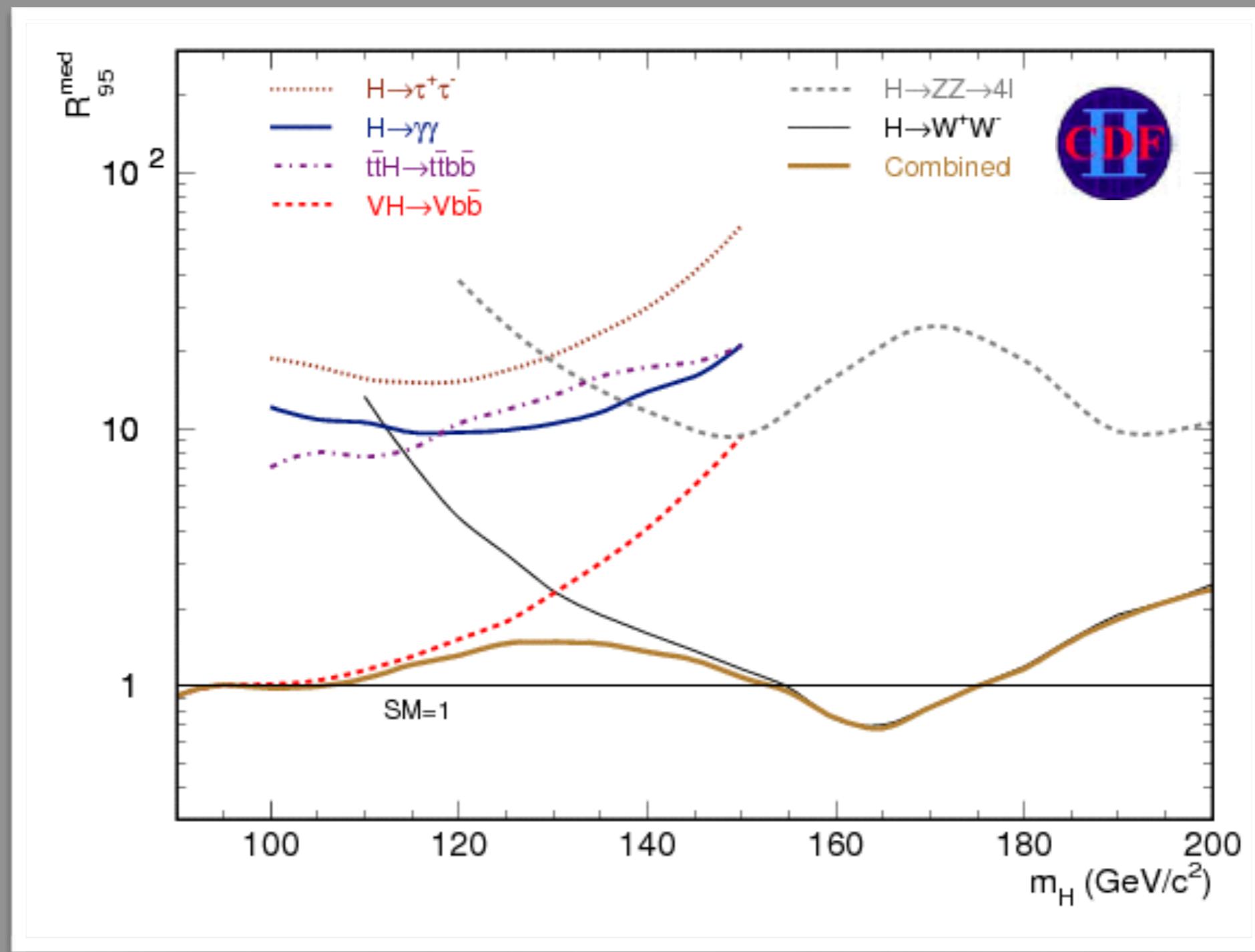


Focusing the Search

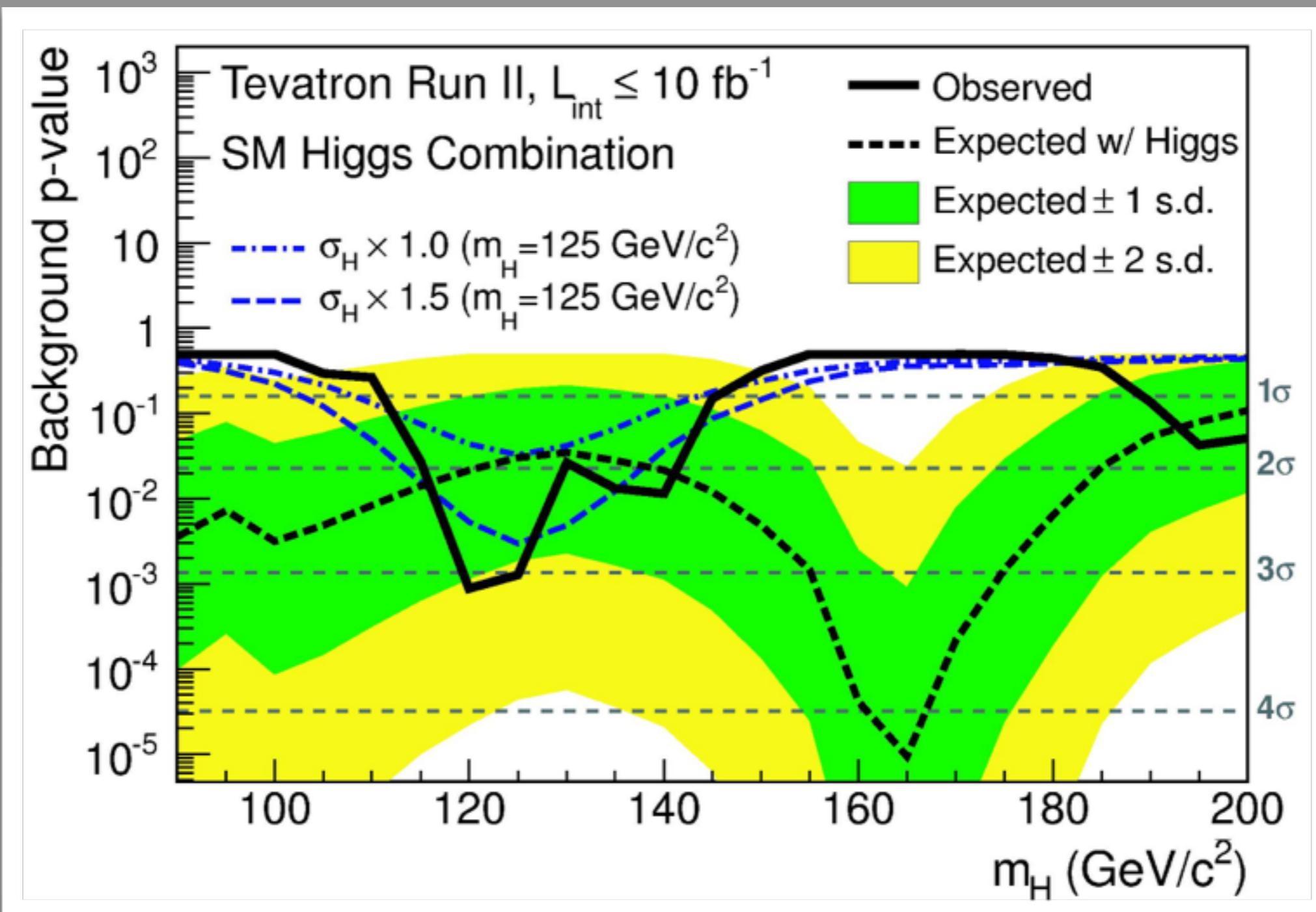


— Main mode
- - - Supporting mode
LHC Tevatron

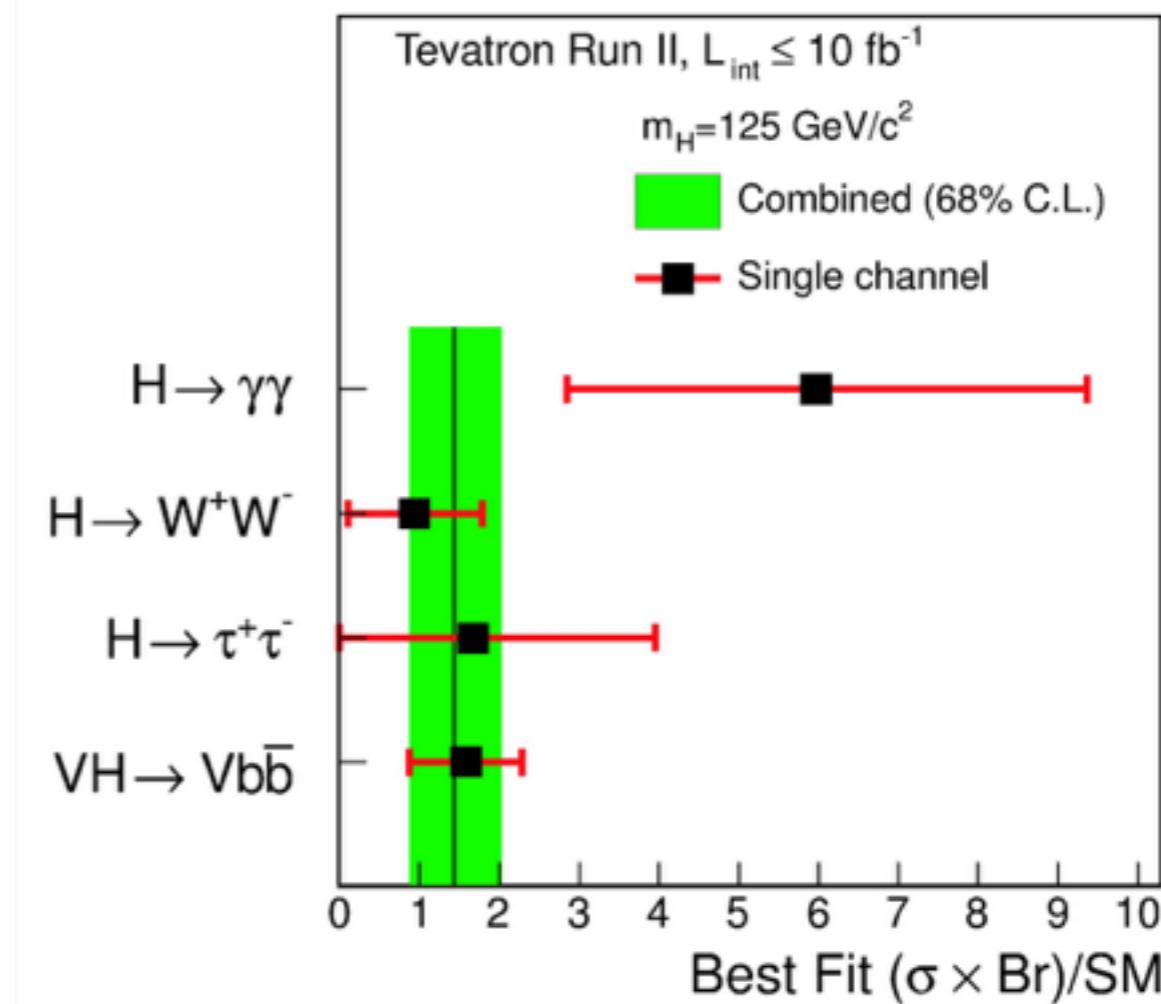
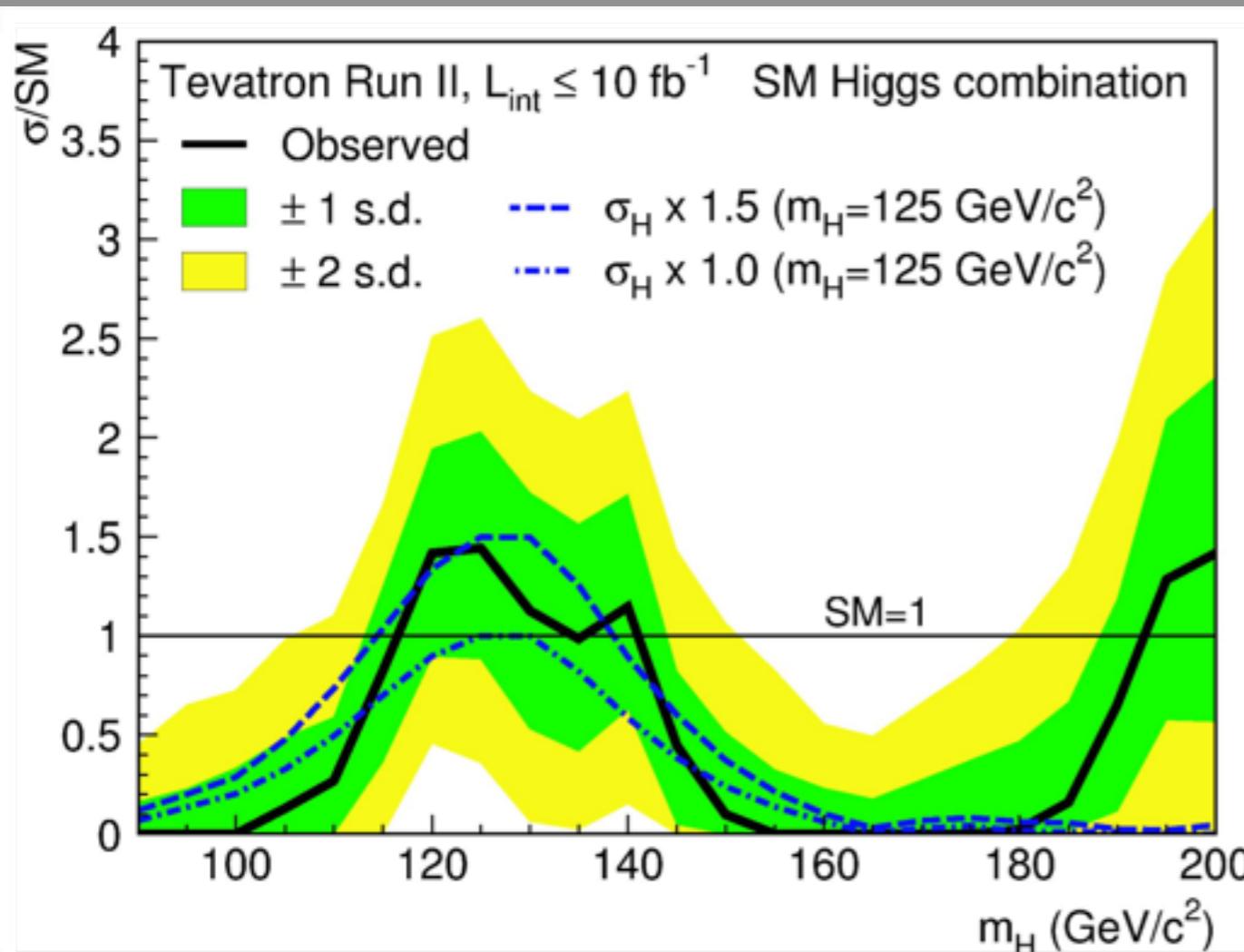
A Combination of Many Searches



p-values: Spring 2013



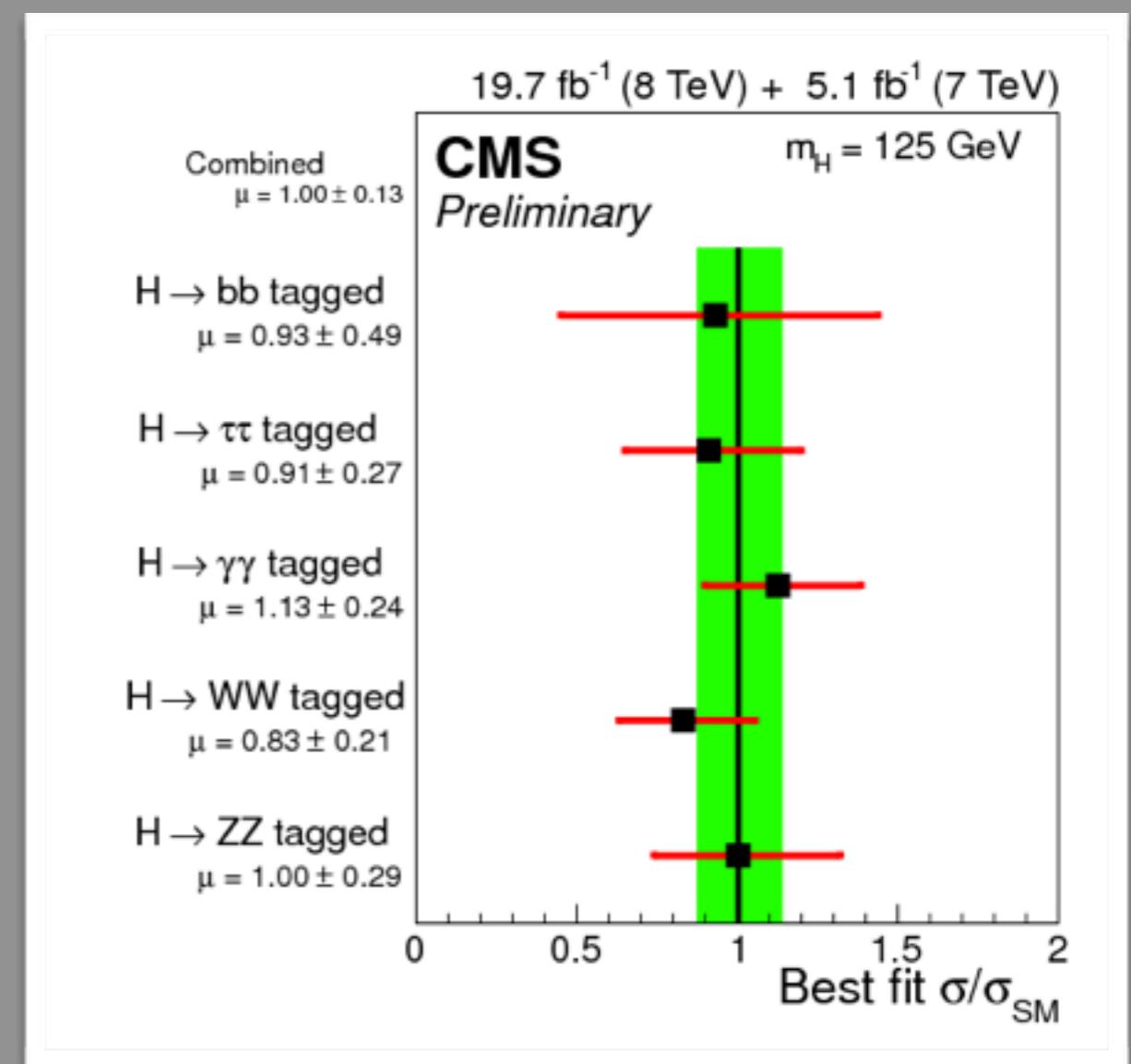
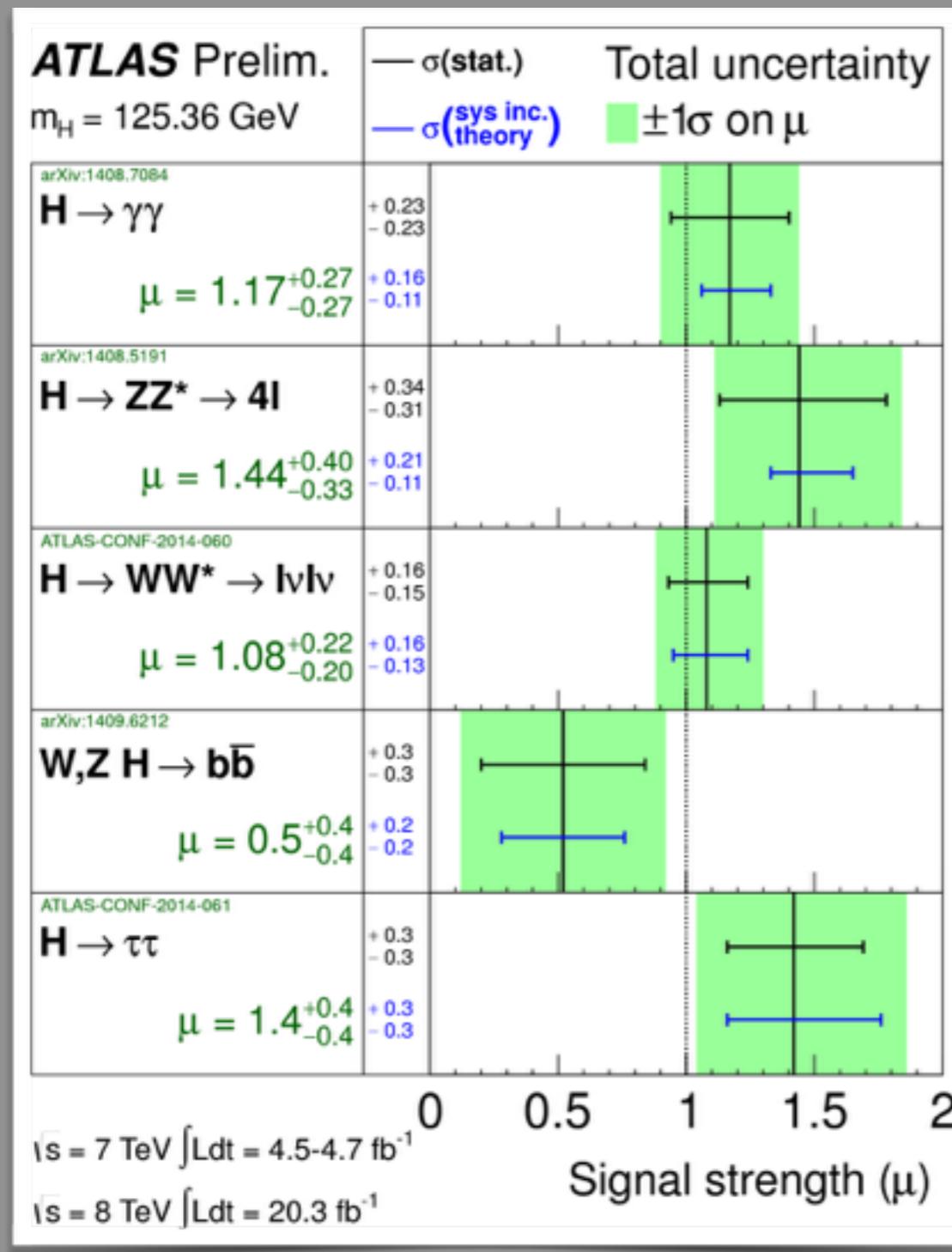
Production Rates



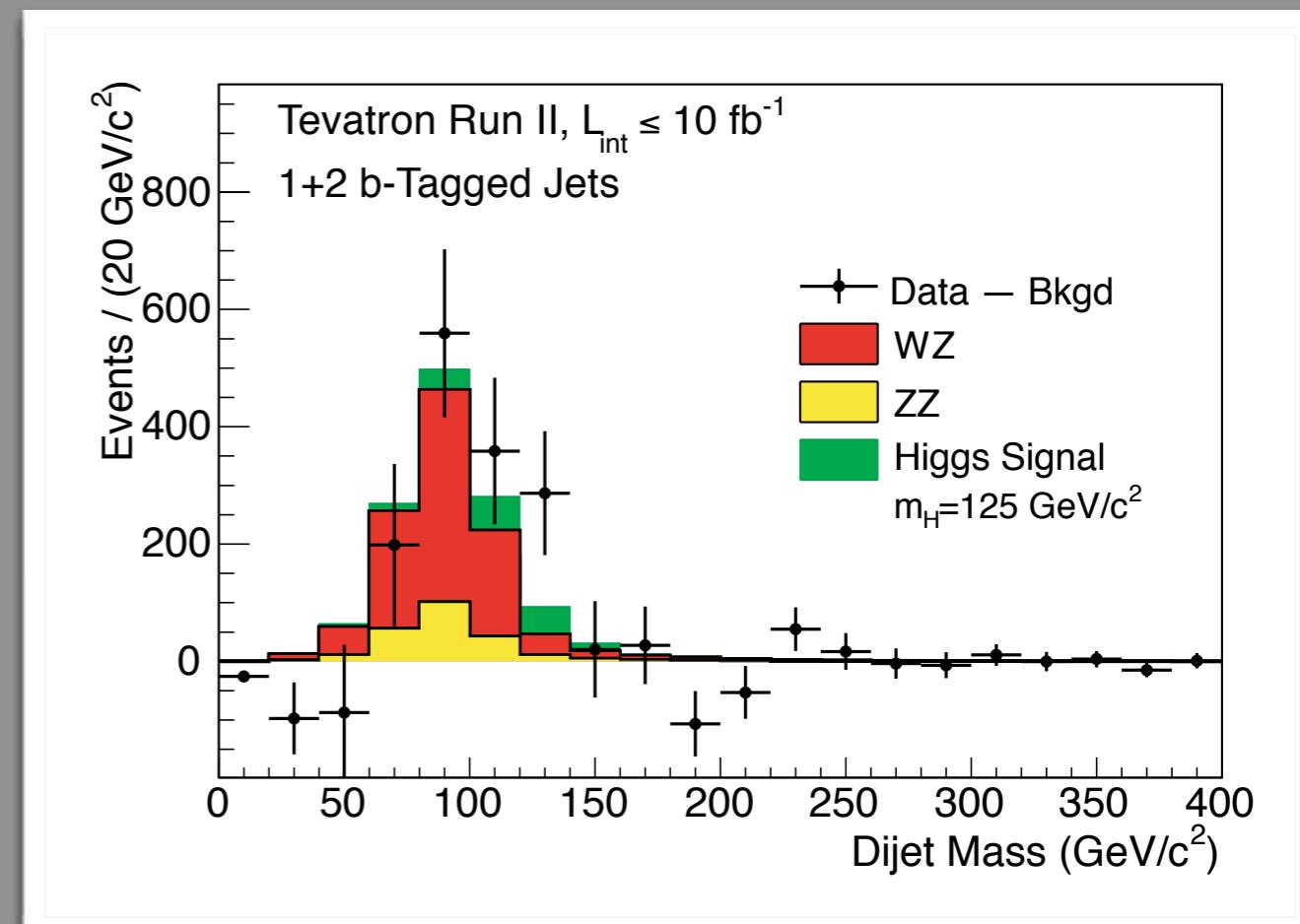
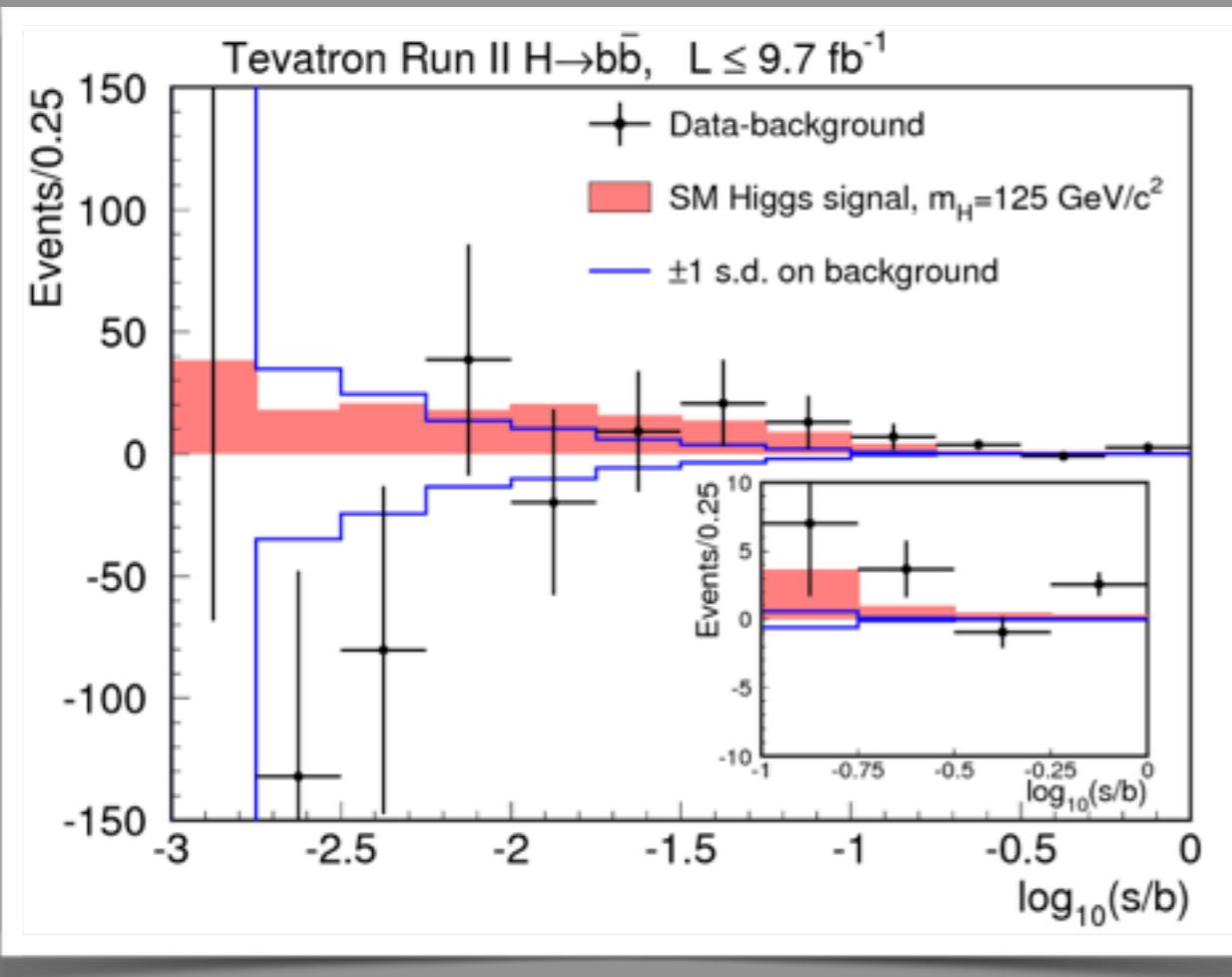
$$\mu_{125 \text{ GeV}} = 1.44^{+0.59}_{-0.56}$$

$$\mu_{H \rightarrow b\bar{b}} = 1.59^{+0.69}_{-0.72}$$

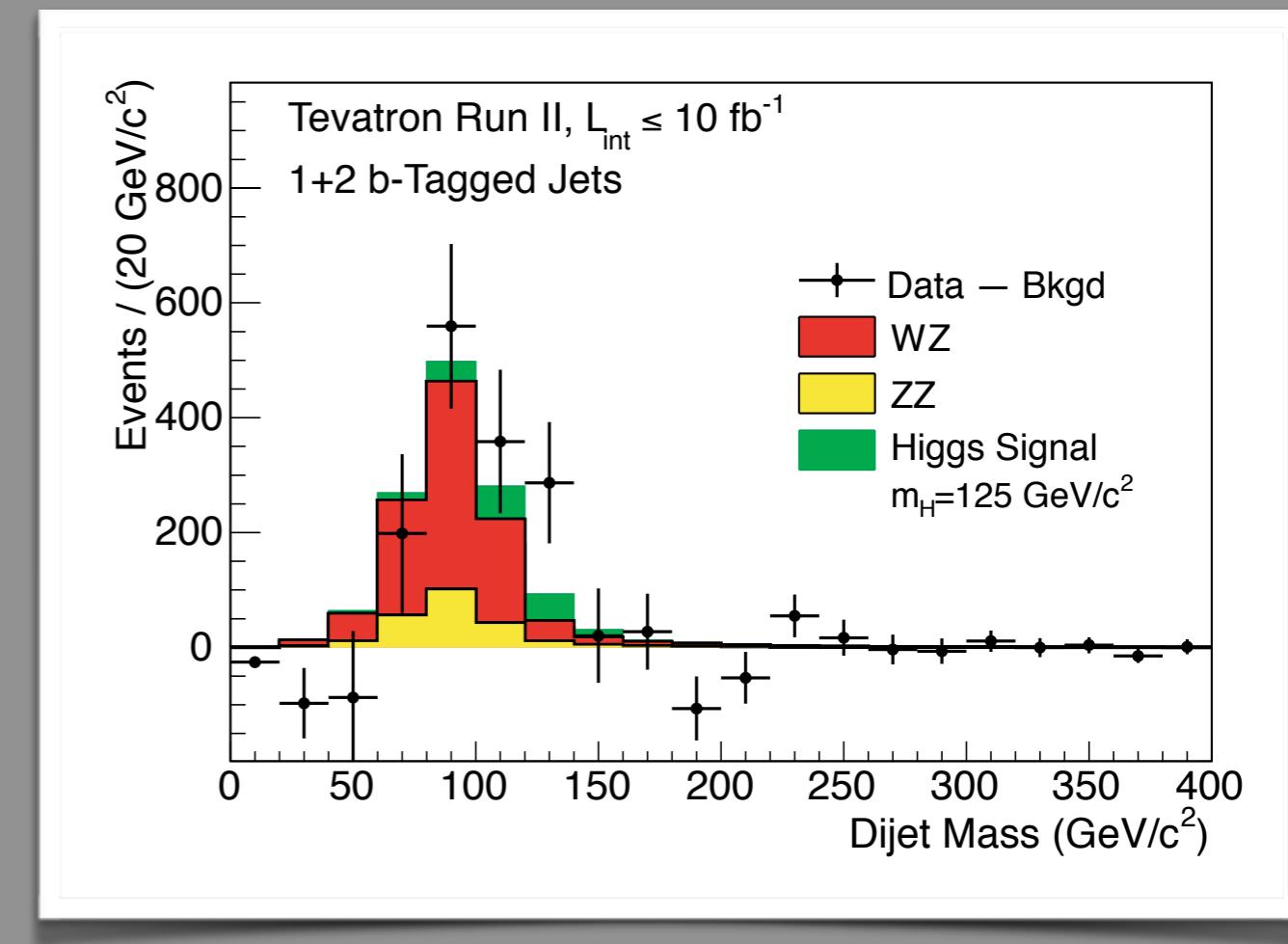
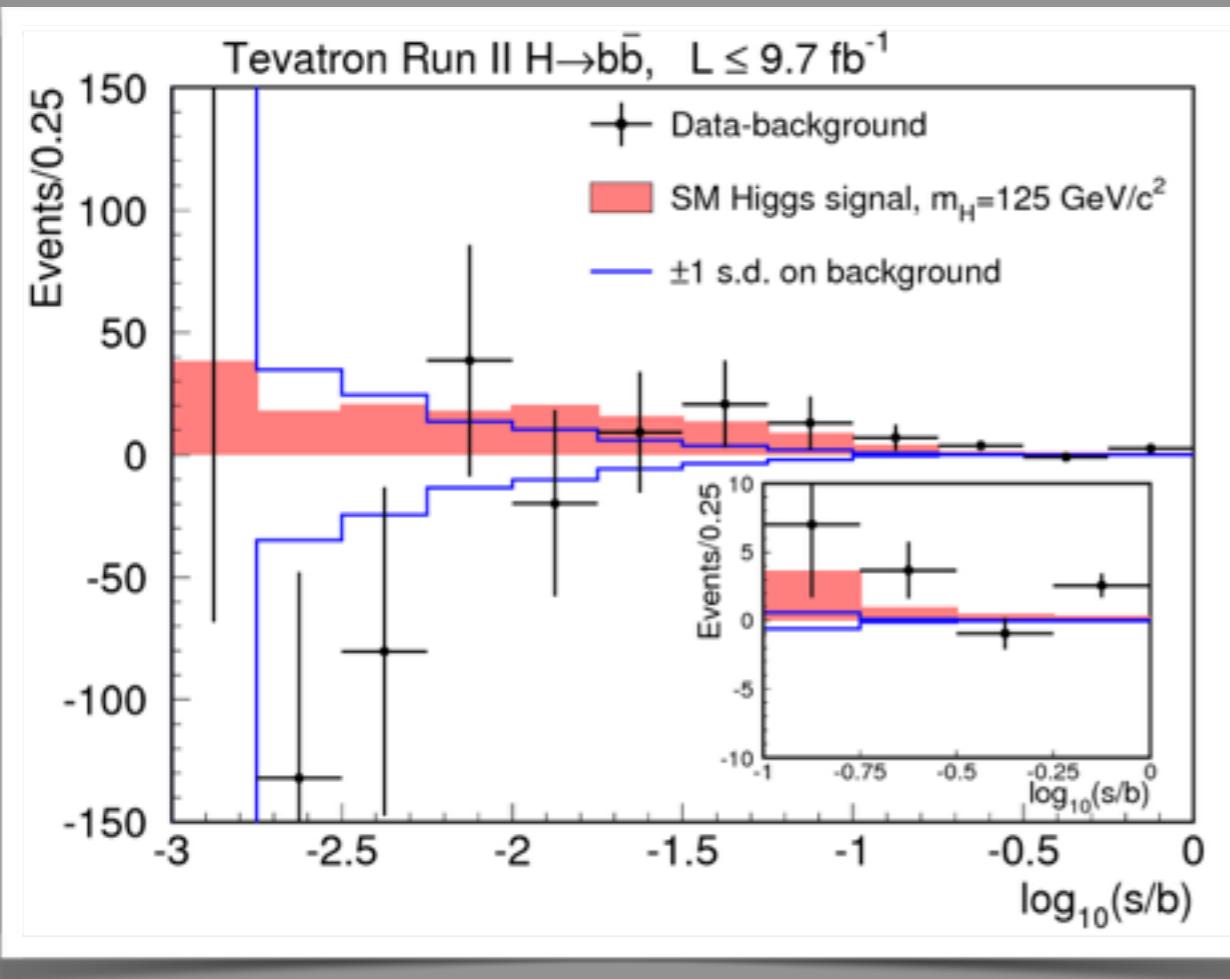
Consistent with LHC observation?



Tevatron excess in $H \rightarrow b\bar{b}$ decays



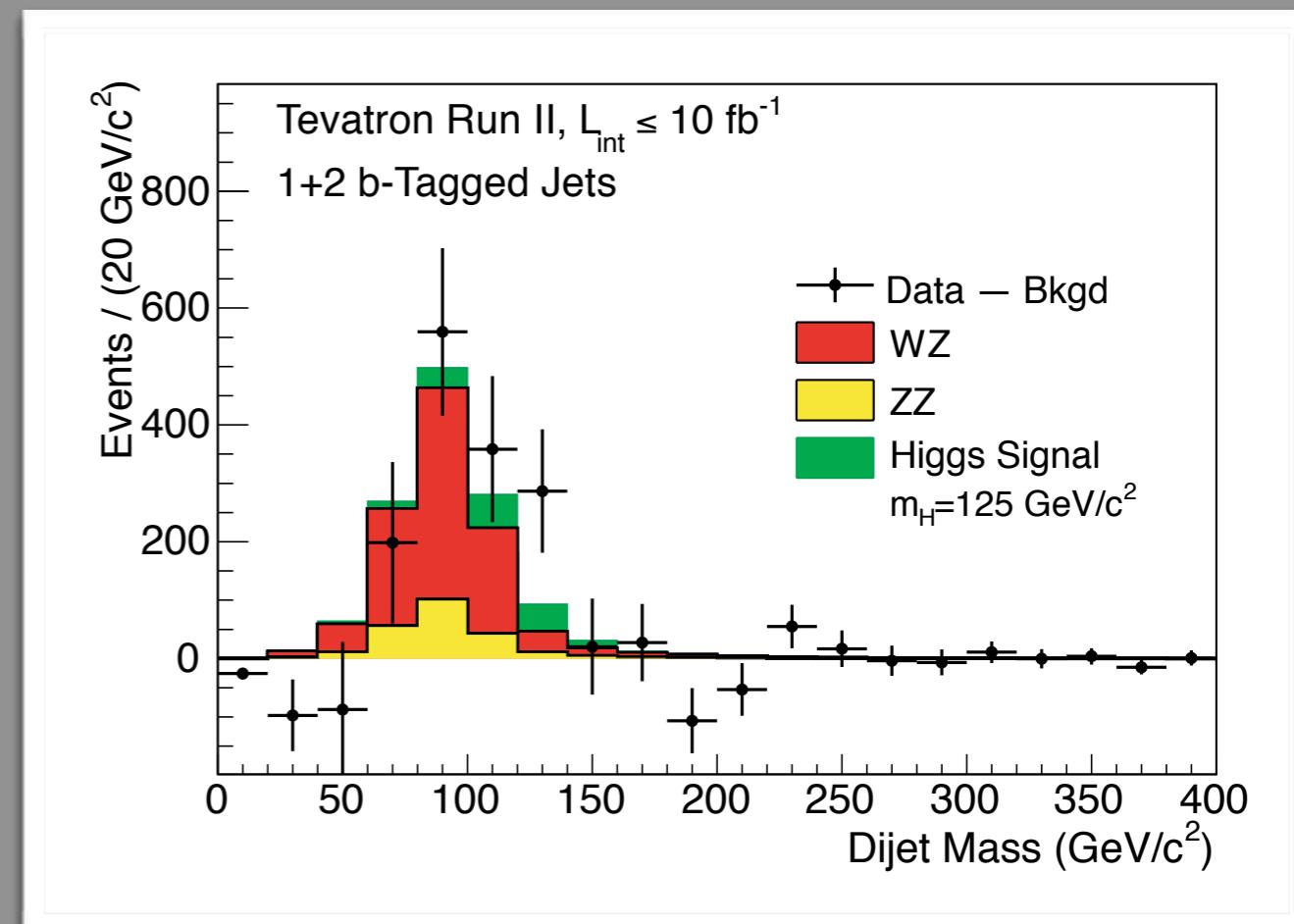
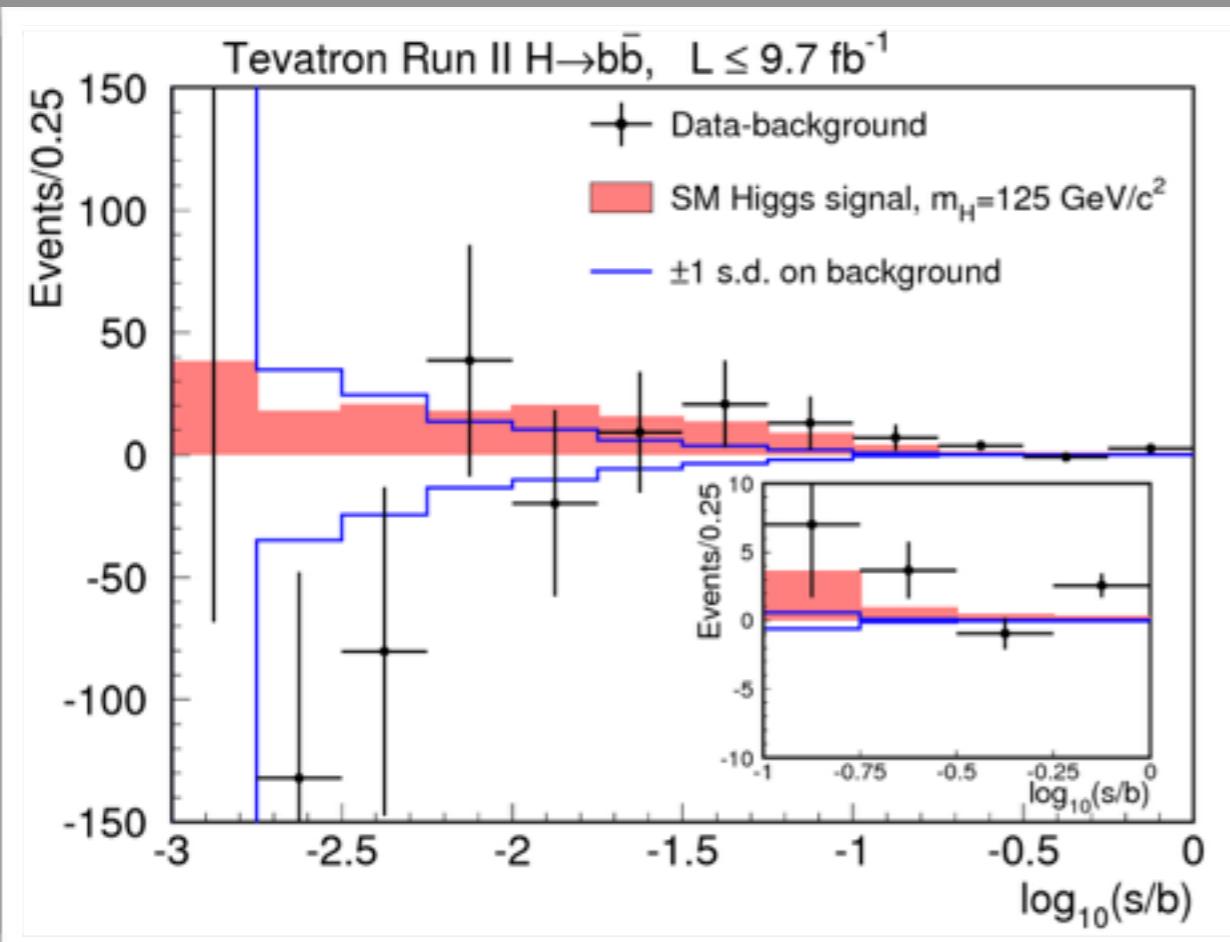
Tevatron excess in $H \rightarrow b\bar{b}$ decays



Consistent
with LHC?

~✓ Mass
~✓ Rate
?? Properties

Tevatron excess in $H \rightarrow b\bar{b}$ decays



Consistent
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Opportunity
to probe for
BSM J^P

JP

Class

Comments

 0^+

SM Higgs

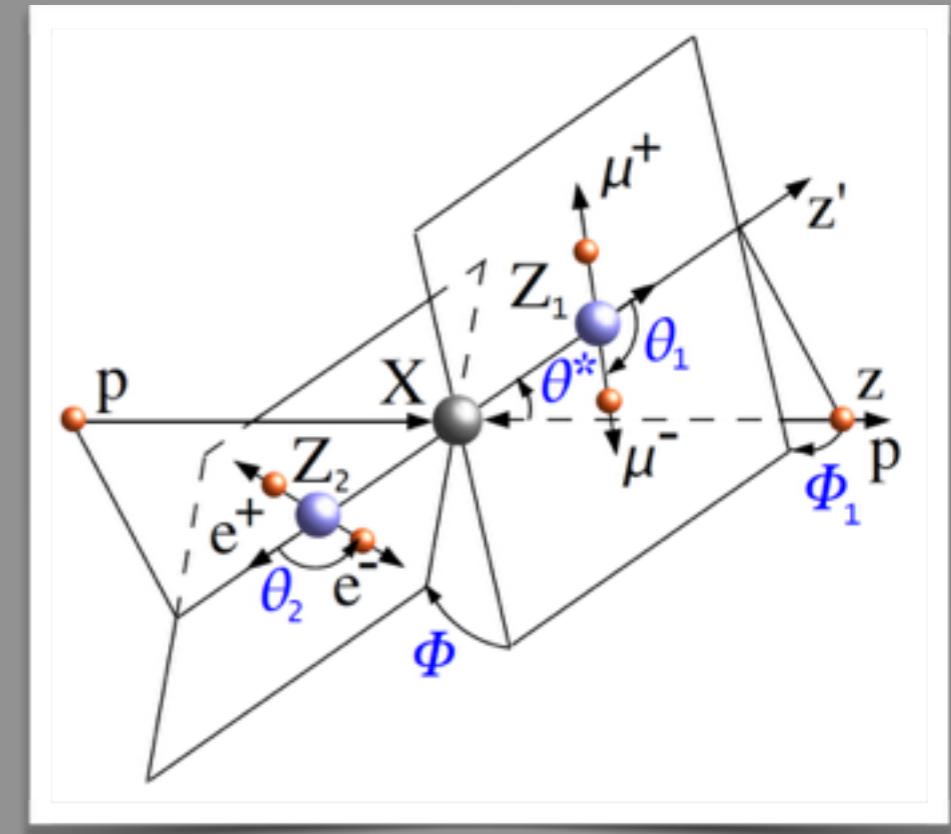
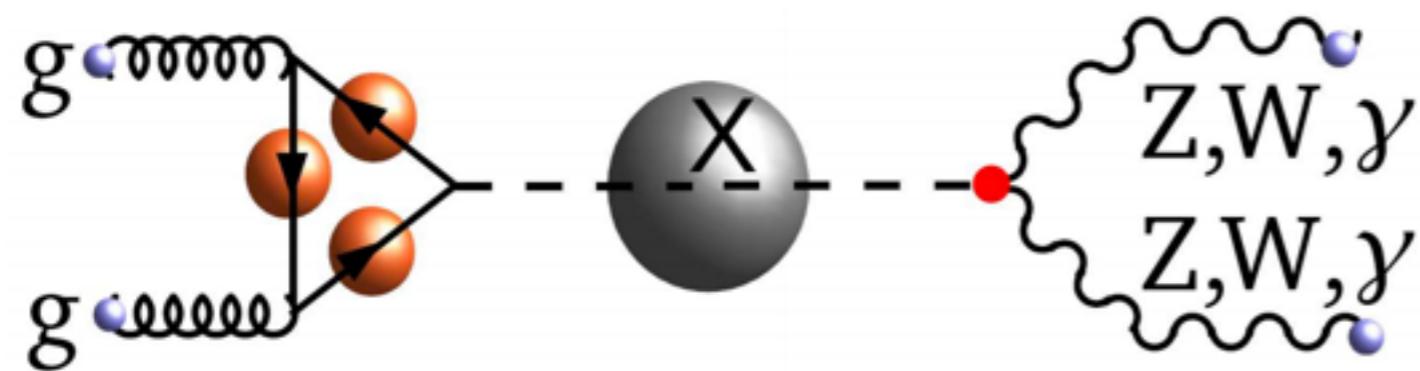
 $P = C = +$ 0^-

Pseudo-scalar

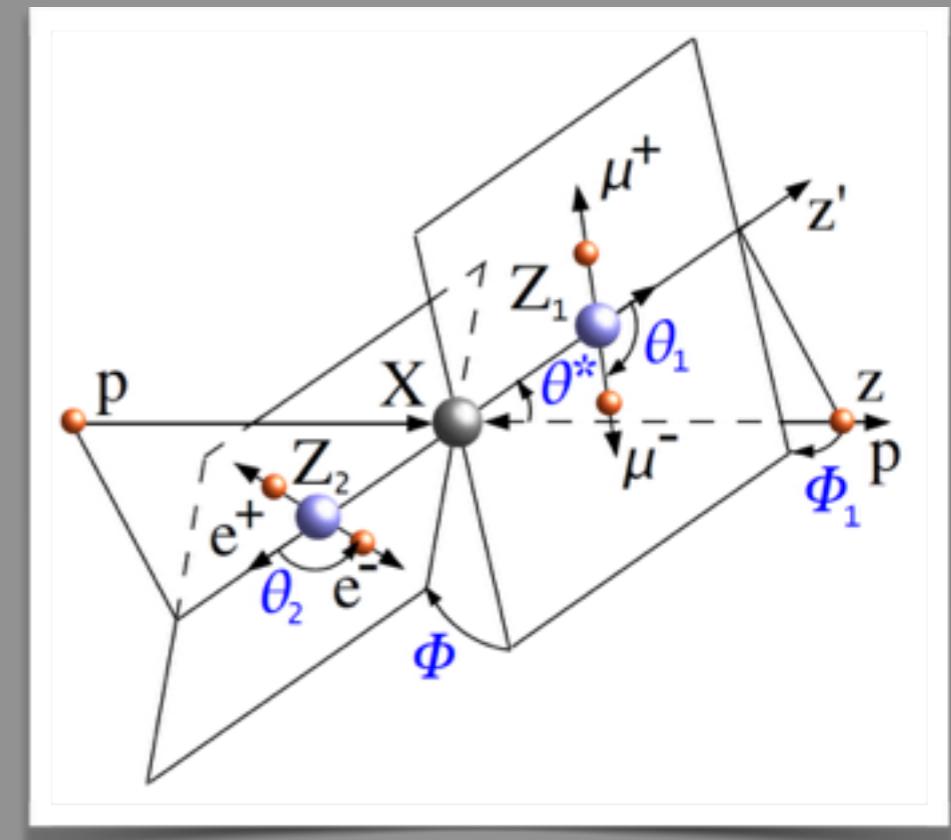
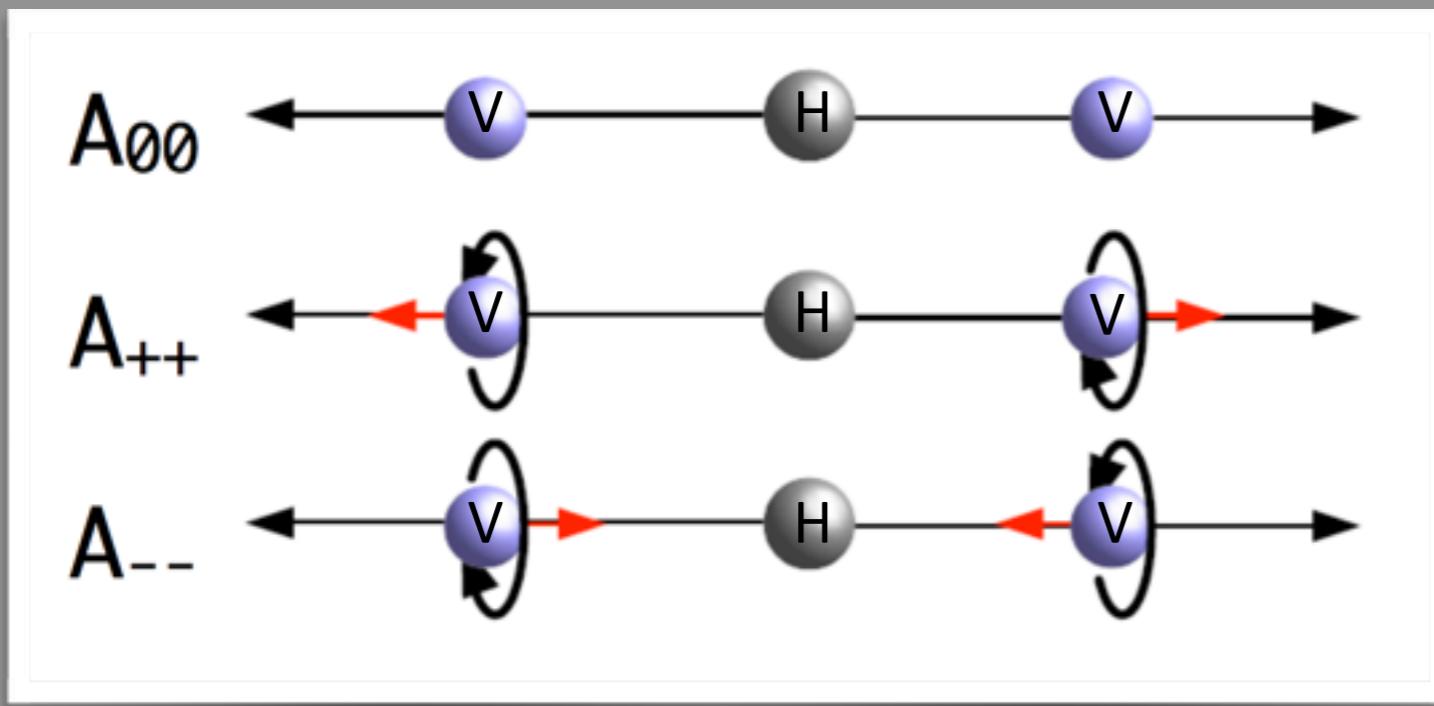
2HDMs, SUSY, etc

 1^- Composite
Higgs, KKQuark production
only. 1^+ modes of ED.
Strong SB (rho
analog - QCD).Forbidden by
Landau-Yang? 2^+ Graviton-like
tensor, or
pseudo-tensorMany assumptions
to be made,
depending on the
model constructed 2^-

At the LHC, the angles are key



At the LHC, the angles are key



$$A_{00} = -\frac{M_x^2}{v} (a_1 \chi + a_2 \eta (\chi^2 - 1))$$

$$A_{\pm\pm} = \frac{M_x^2}{v} (a_1 \pm i a_3 \eta \sqrt{\chi^2 - 1})$$

**Vector boson
helicity
amplitudes**

At the Tevatron, the threshold is important



$$A_{00} = -a_1 E_Z / M_Z$$

$$A_{10} = -a_1 \quad J^P: 0^+$$

$$A_{00} = 0 \quad J^P: 0^-$$

$$A_{10} = -ia_1 \beta s$$

$$\beta = 2p/\sqrt{s} \sim \sqrt{s - (M_H + M_Z)^2}$$

$$\sigma(V^\star \rightarrow VH) \propto \beta \sum_{ij} |A_{ij}|^2$$

At the Tevatron, the threshold is important



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$$A_{10} = -ia_1 \beta s$$

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} = \frac{3}{4A_{\text{Tot}}^2} (\sin^2 \theta [|A_{00}|^2 + 2|A_{11}|^2] + (1 + \cos^2 \theta) [|A_{01}|^2 + |A_{10}|^2 + |A_{12}|^2])$$

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$J^P: 0^+$

Isotropic near
threshold

At the Tevatron, the threshold is important



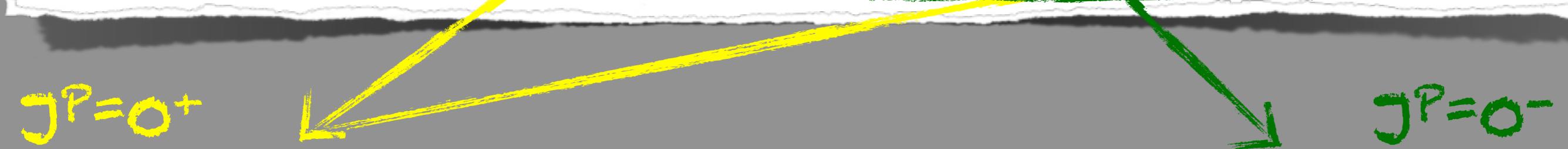
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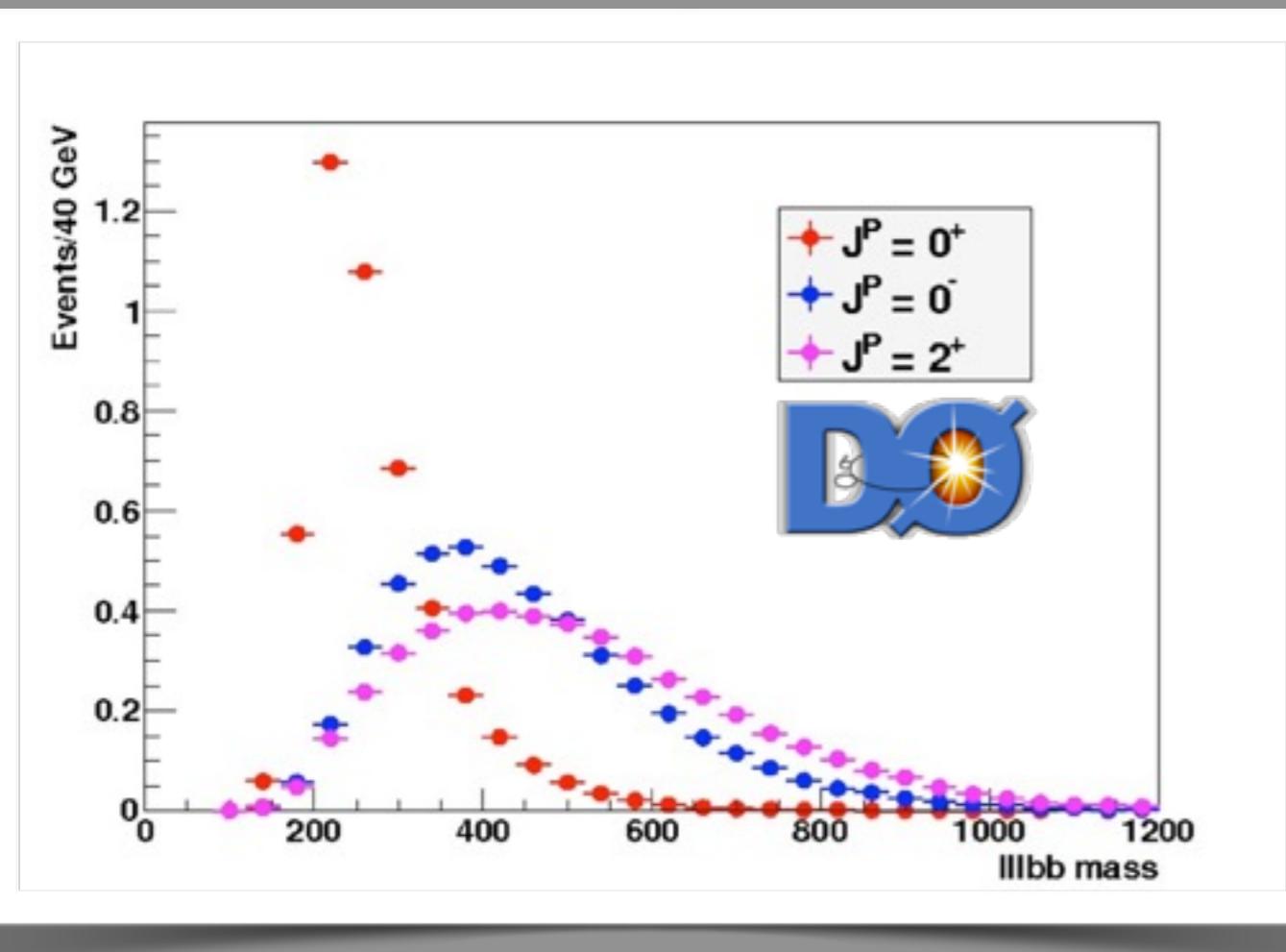


$J^P=0^+$
Isotropic near threshold

$J^P=0^-$
Strong angular dependence

Threshold V+H production goes as:

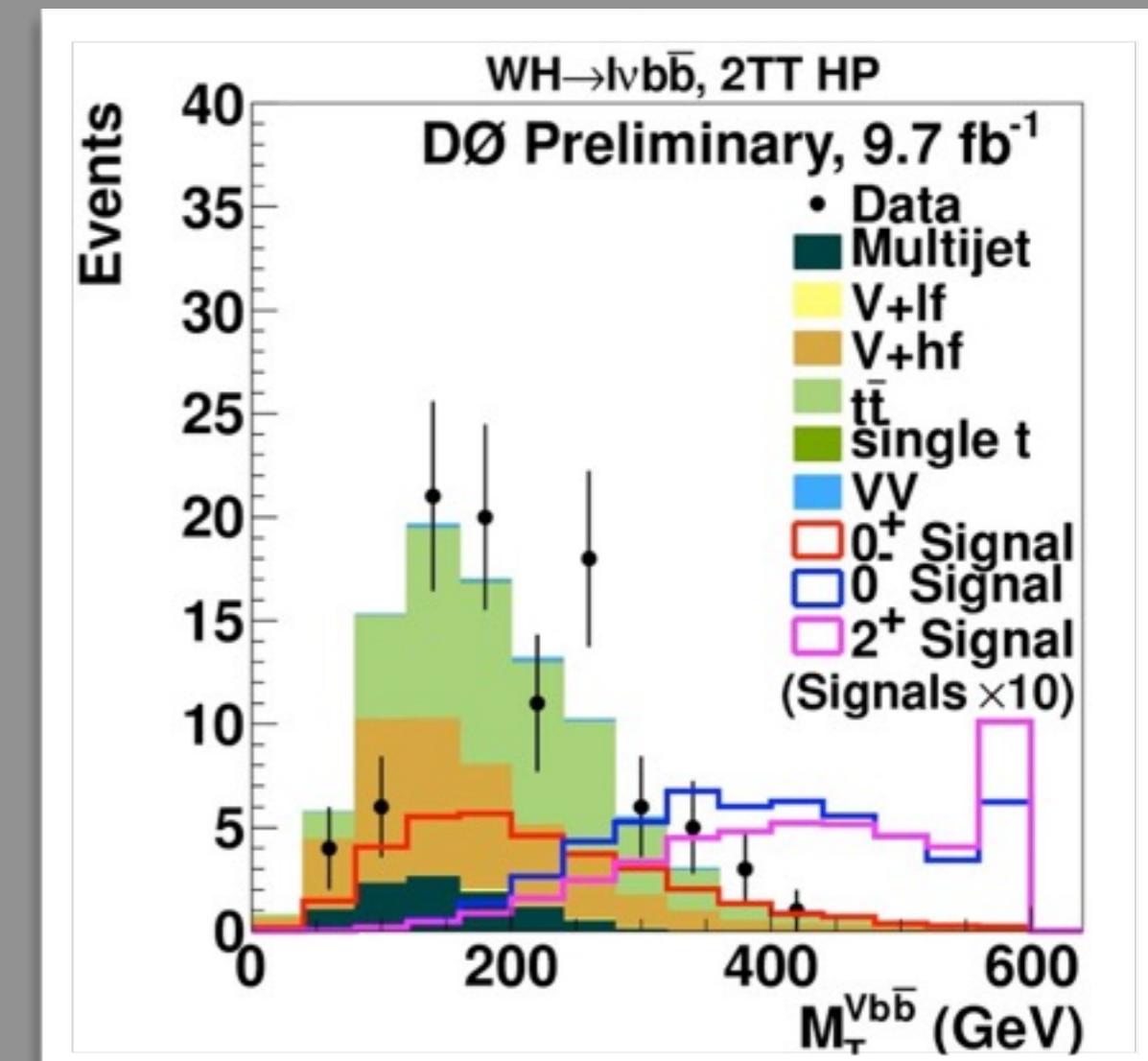
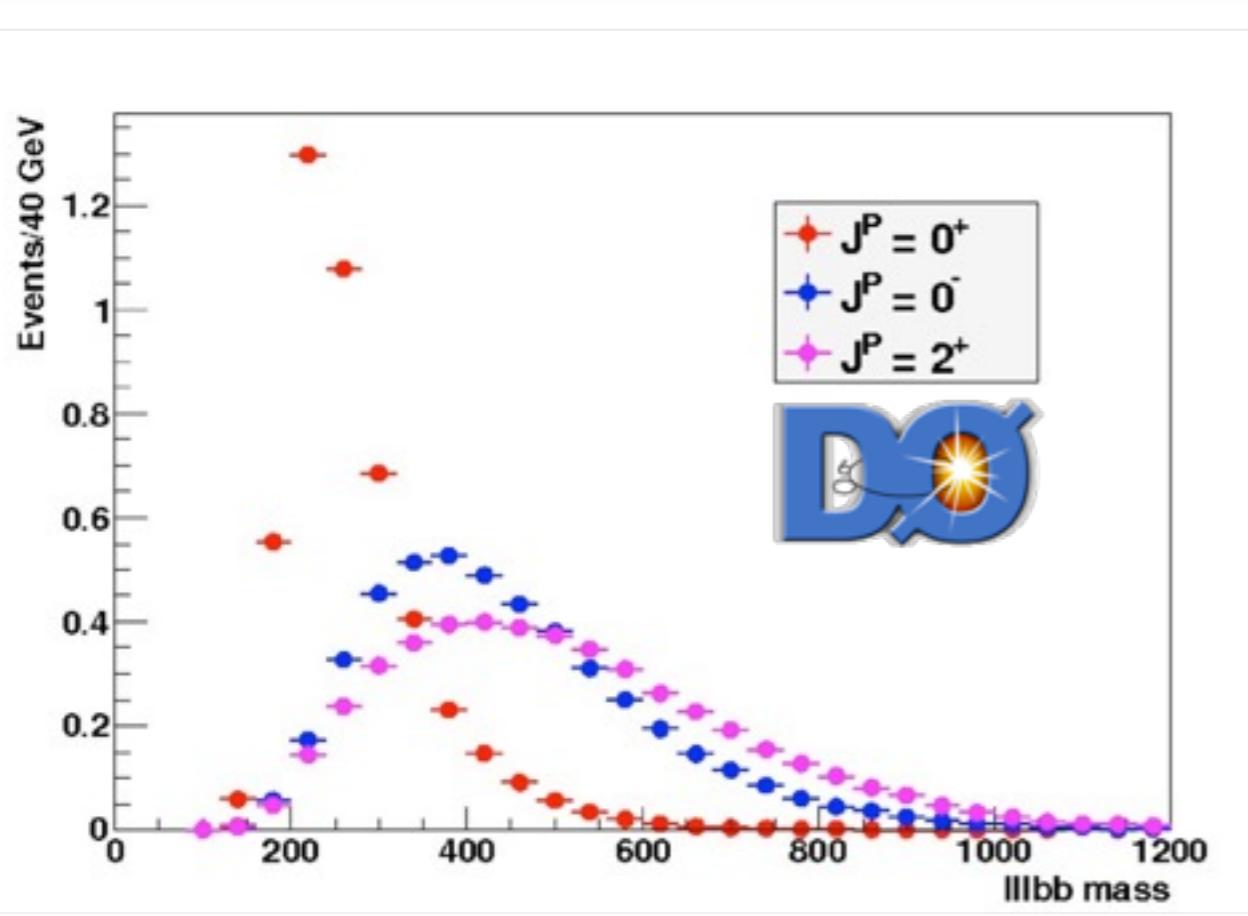
- β for $J^P=0^+$ (s-wave)
- β^3 for $J^P=0^-$ (p-wave)
- β^5 for $J^P=2^+$ (d-wave)



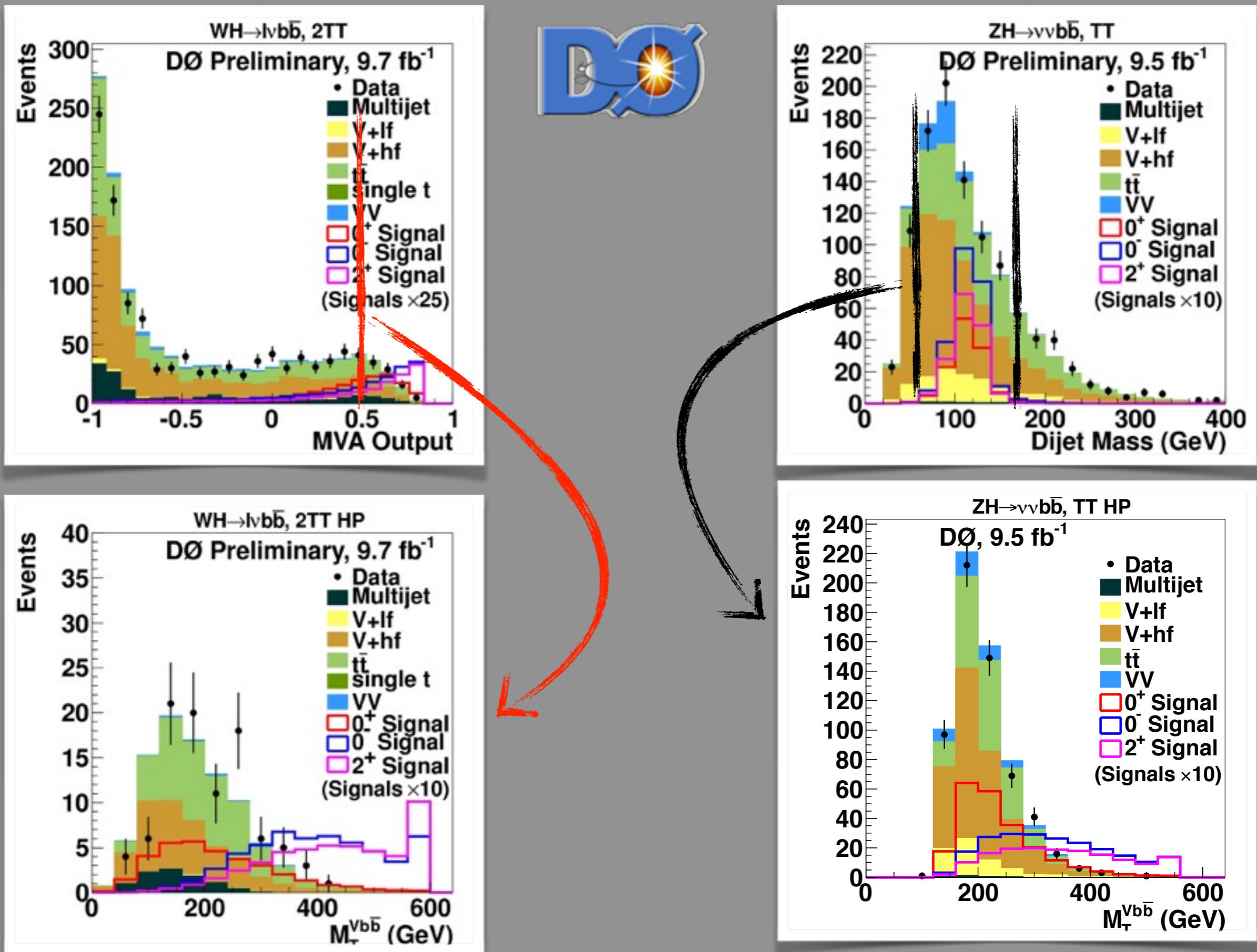
- J. Ellis, V. Sanz, and T. You, arXiv:1303.0208, (2013).
- J. Ellis, D. S. Hwang, V. Sanz, and T. You, J. High Energy Phys. 2012, 134 (2012).
- D. Miller, S. Choi, B. Eberle, M. Muhlleitner, and P. Zerwas, Phys. Lett. B 505, 149 (2001).

Threshold V+H production goes as:

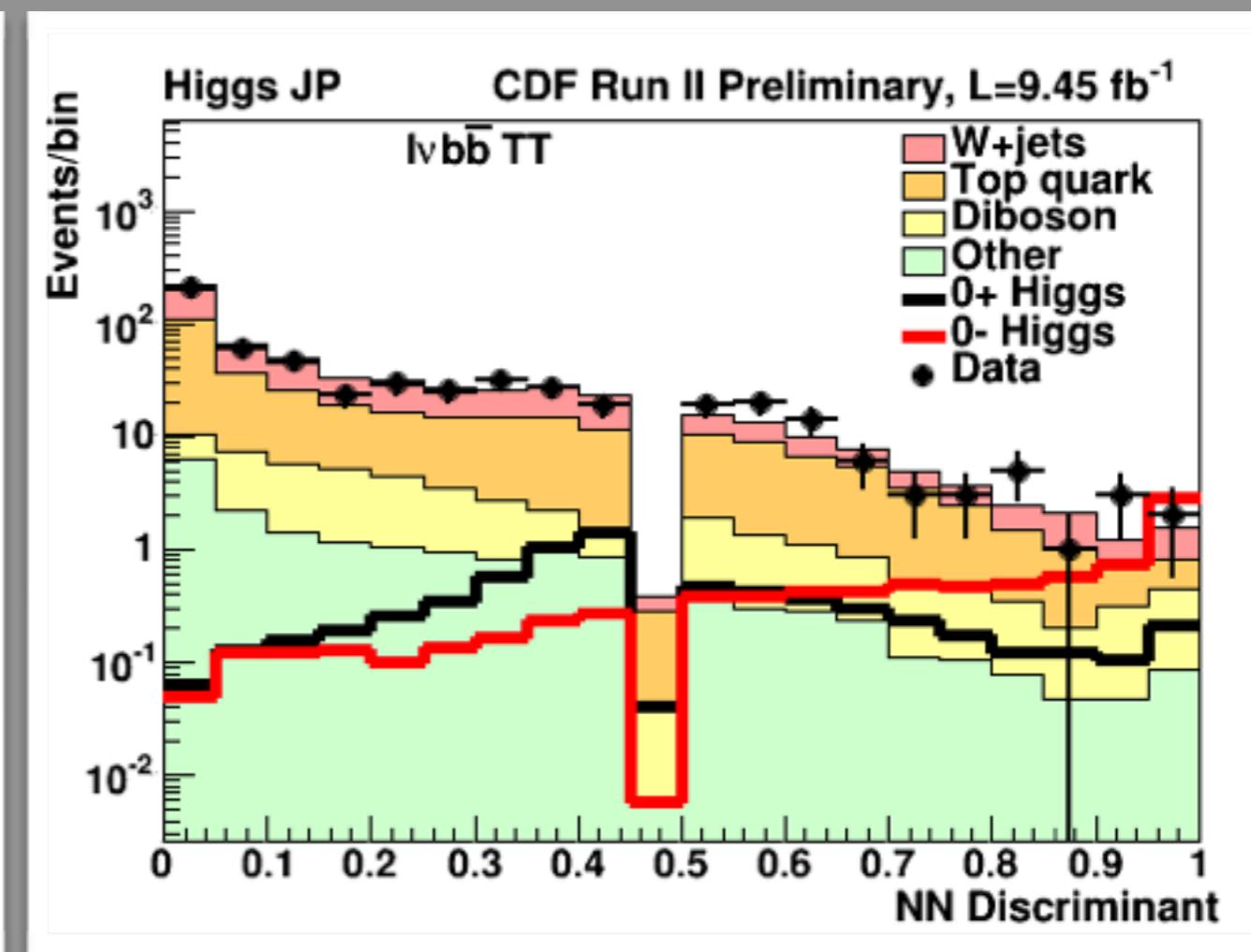
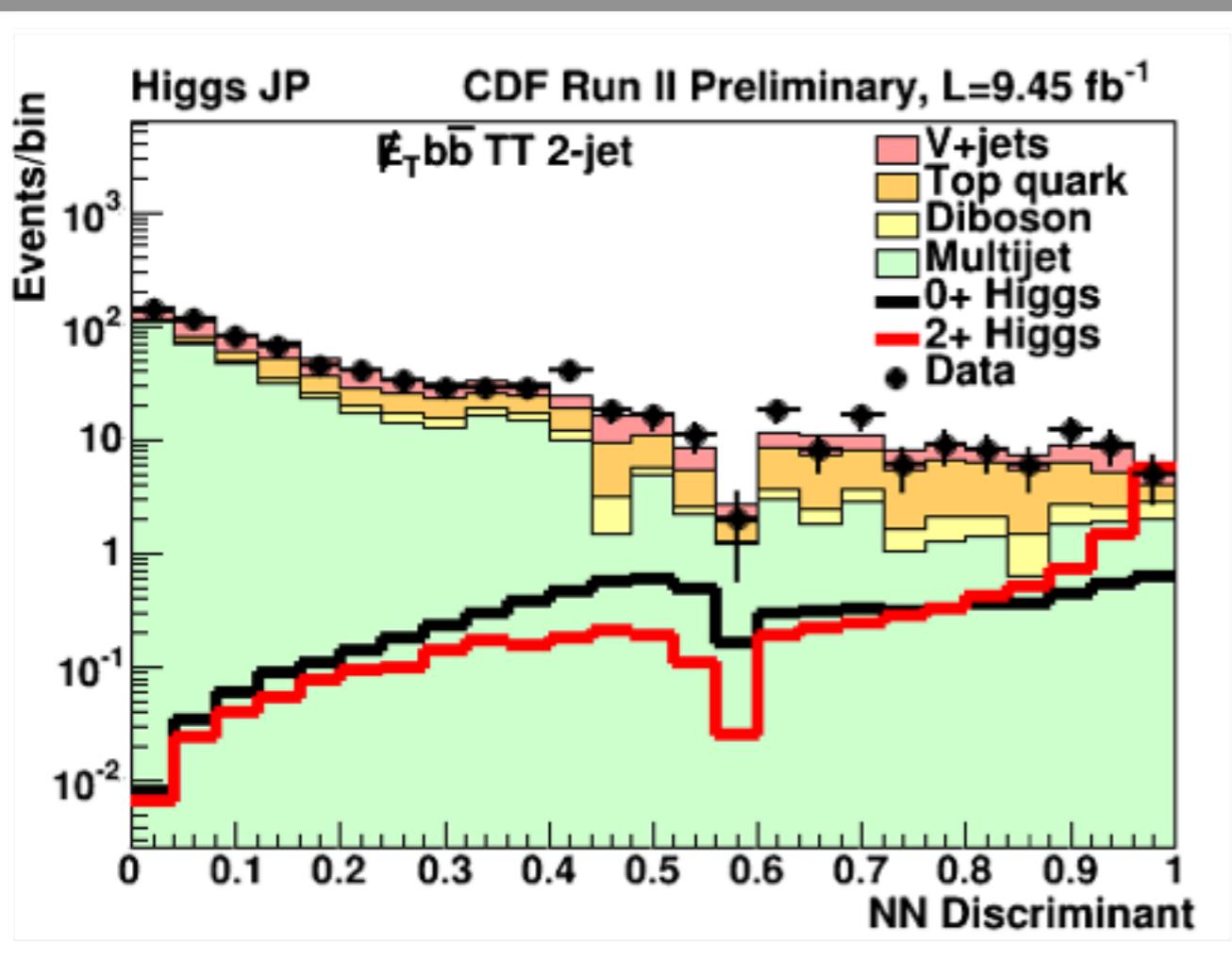
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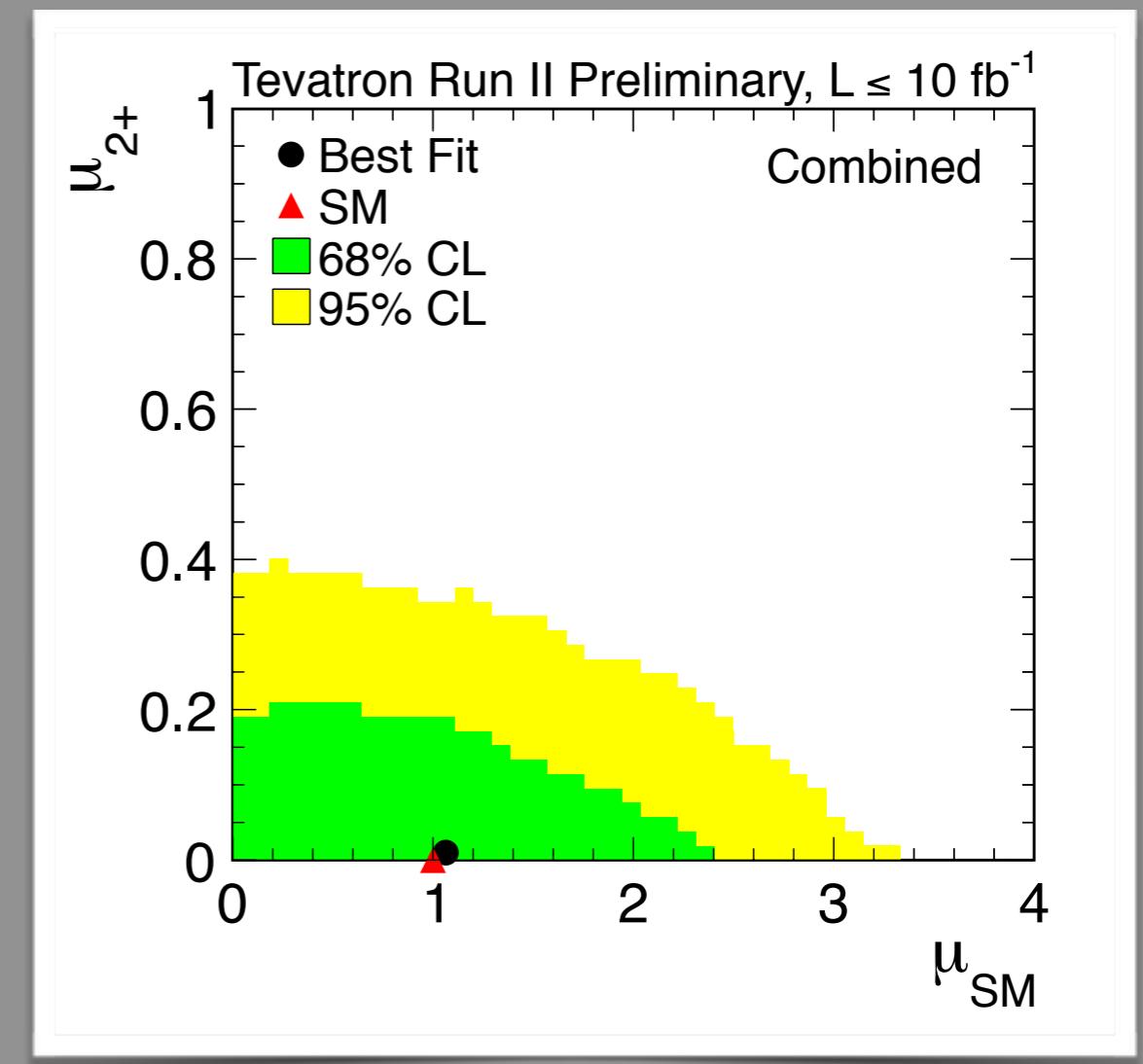
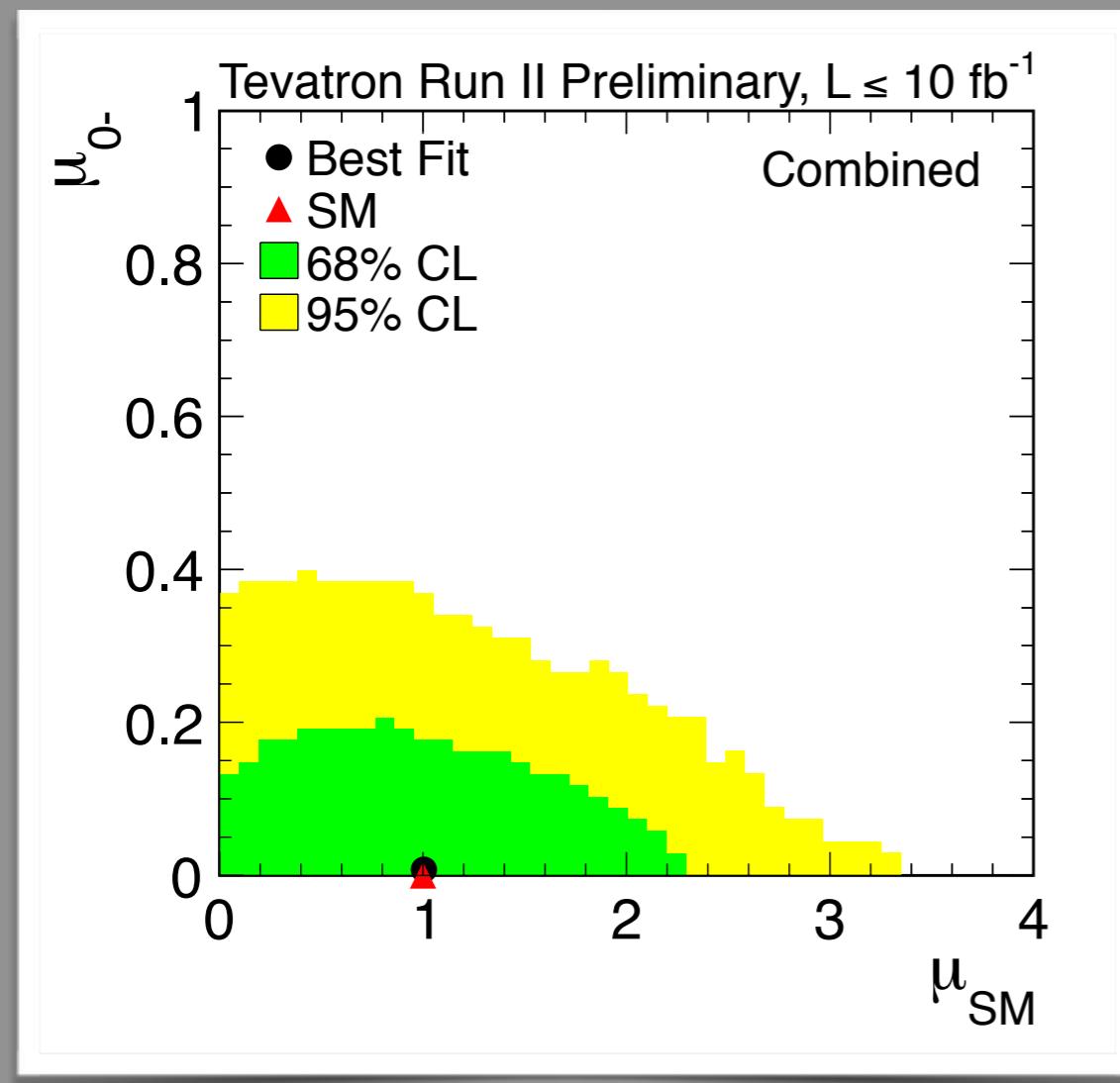
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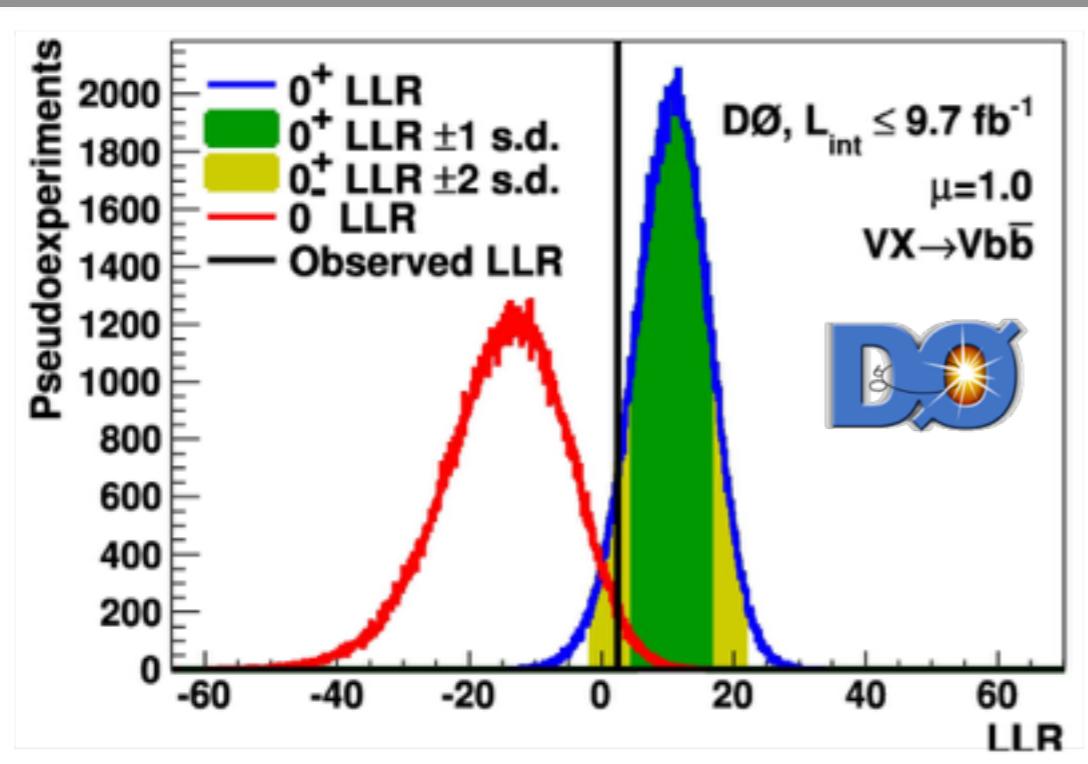


CDF uses full kinematic information in MVA

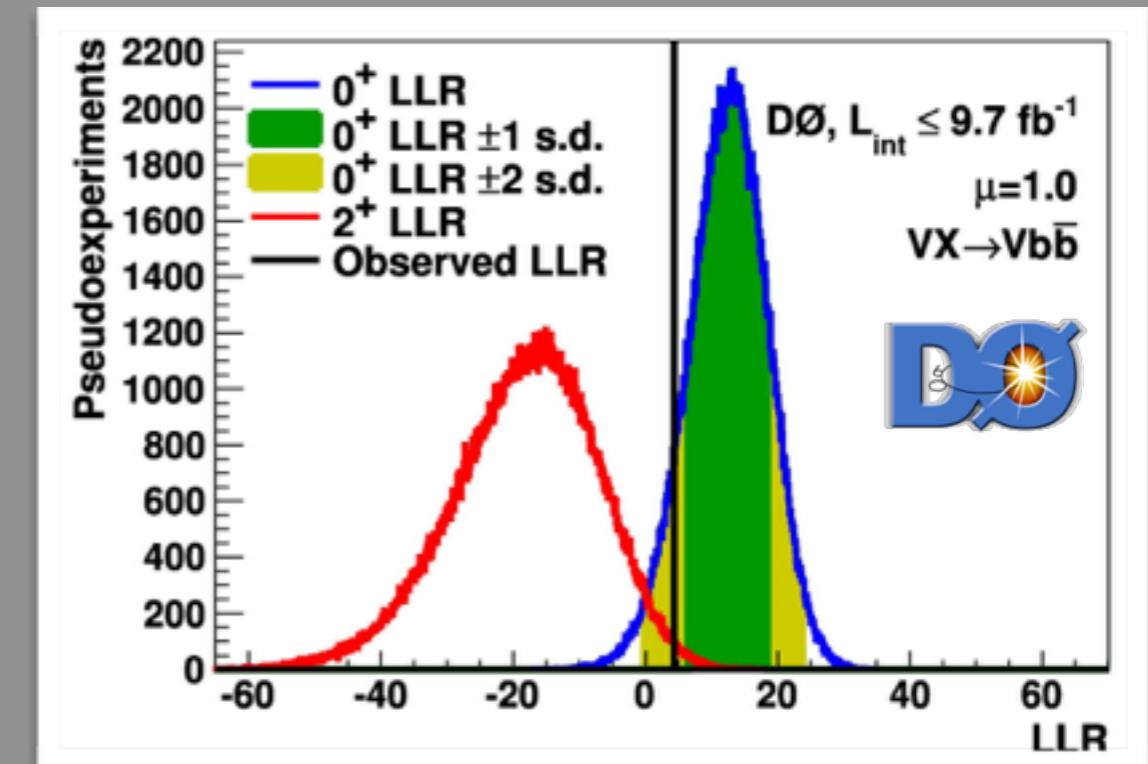


Probes of BSM vs SM rates

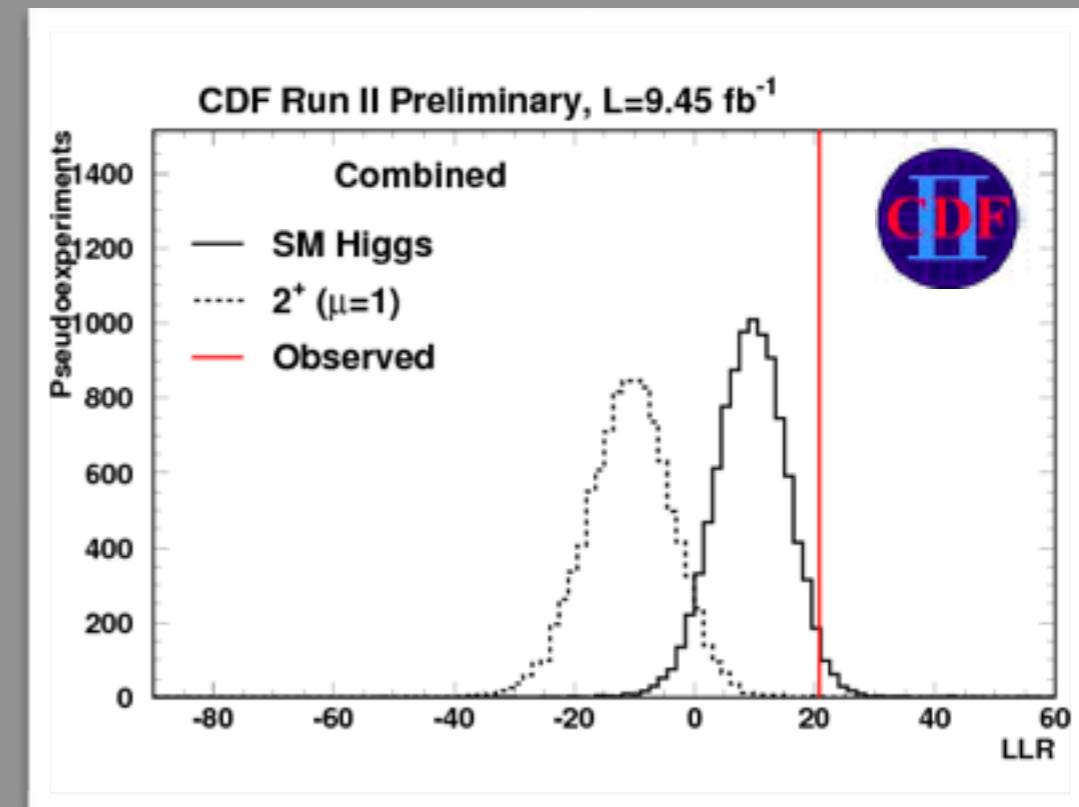
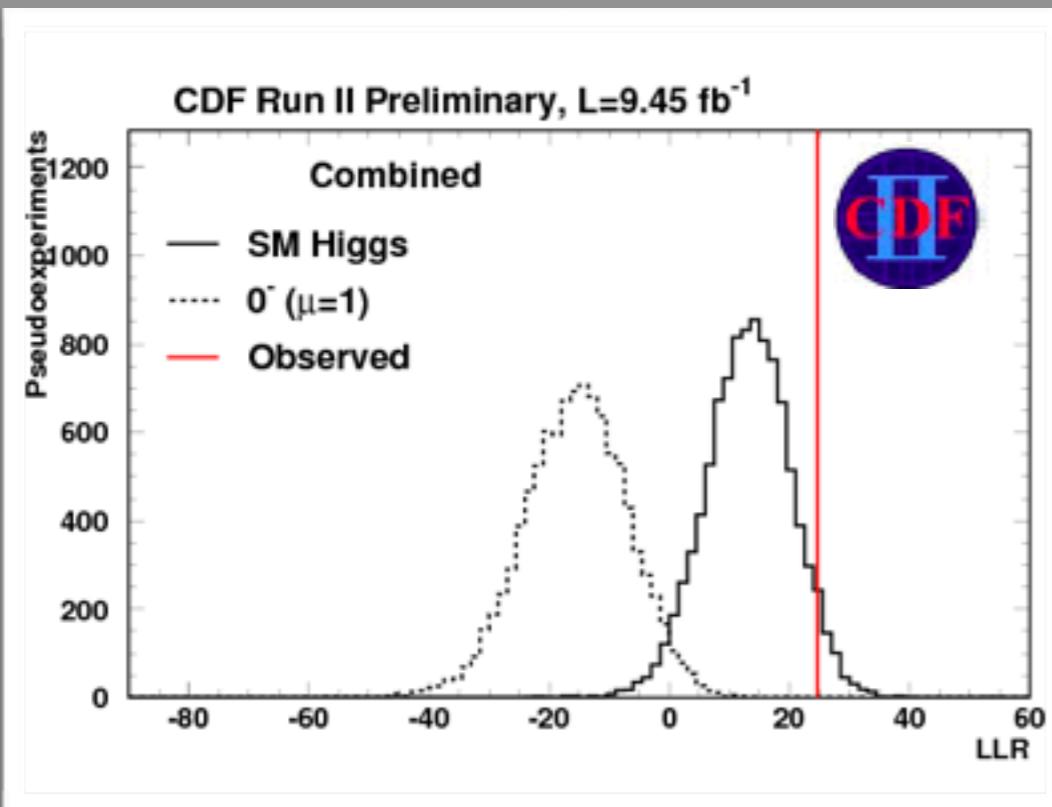




$J_P:0^-$



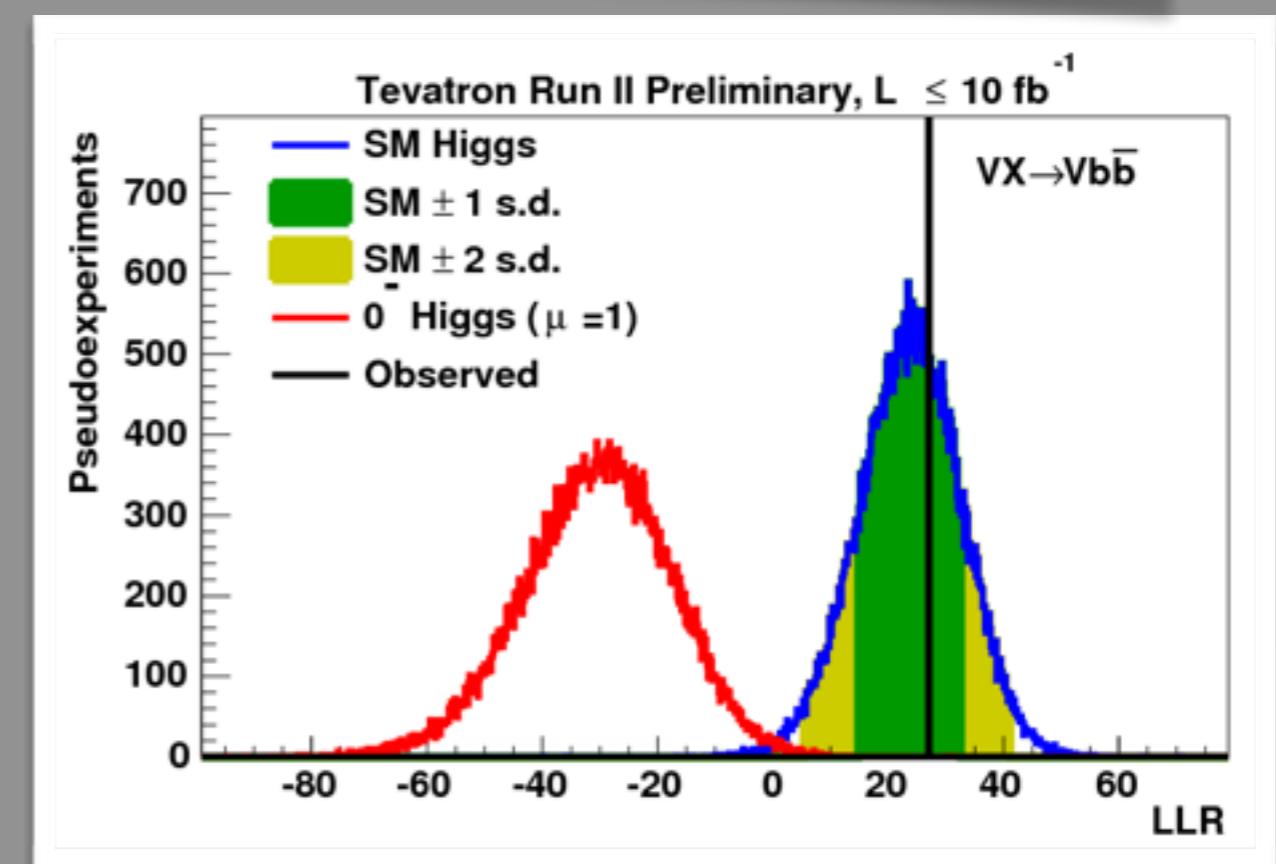
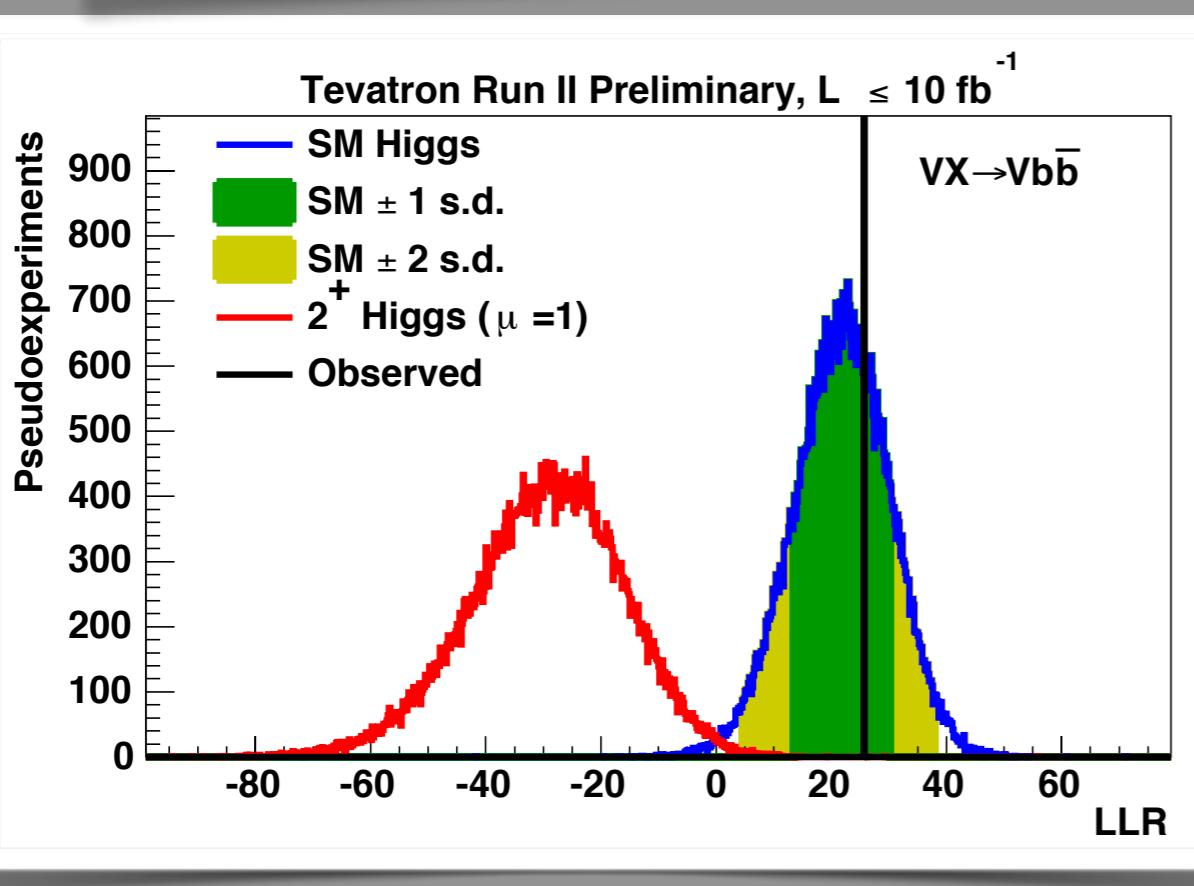
$J_P:2^+$



BSM J^P models constrained using $H \rightarrow b\bar{b}$ decays

- $J^P=0^-$ excluded at **5.0** std. dev.
- $J^P=2^+$ excluded at **4.9** std dev.

$$\sigma_{\text{BSM}}/\sigma_{\text{SM}} = 1$$

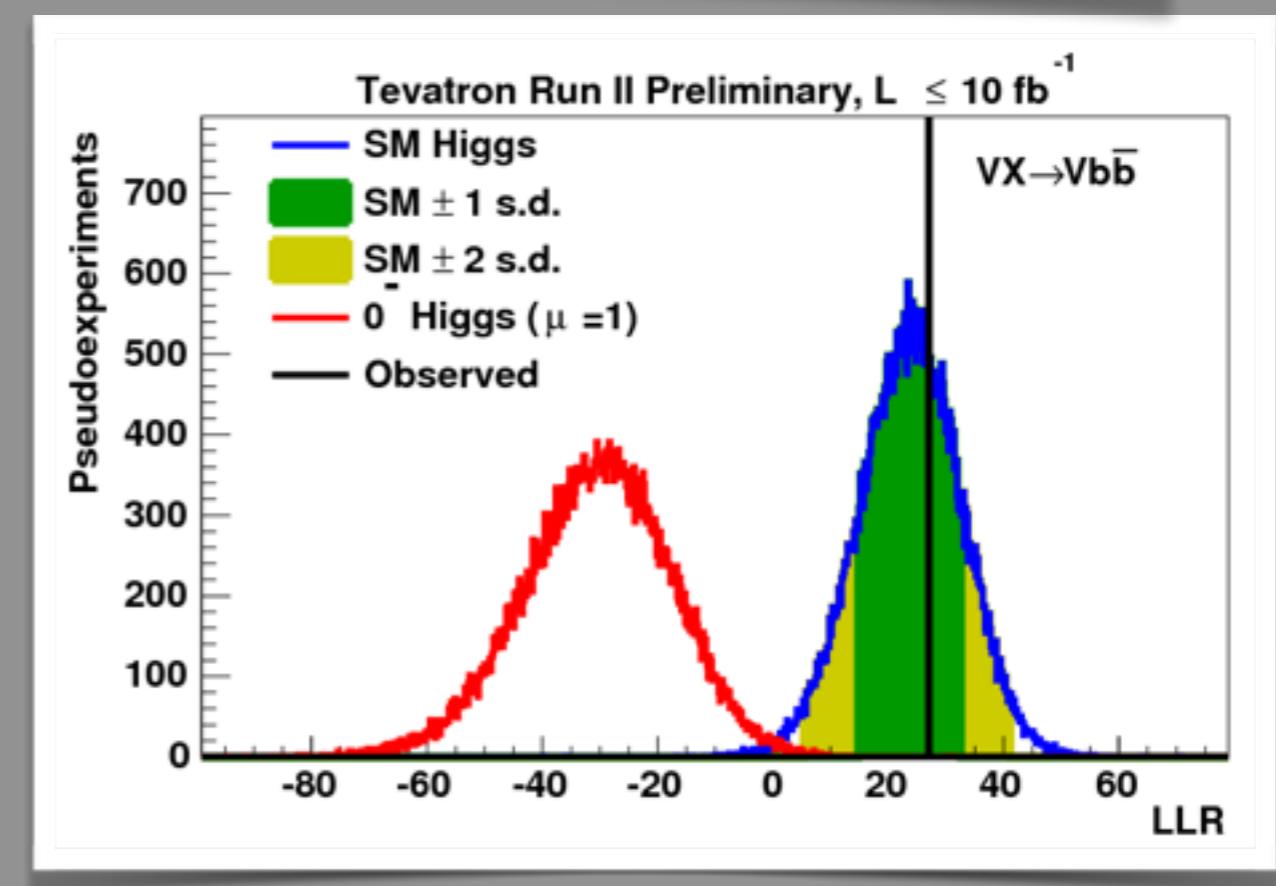
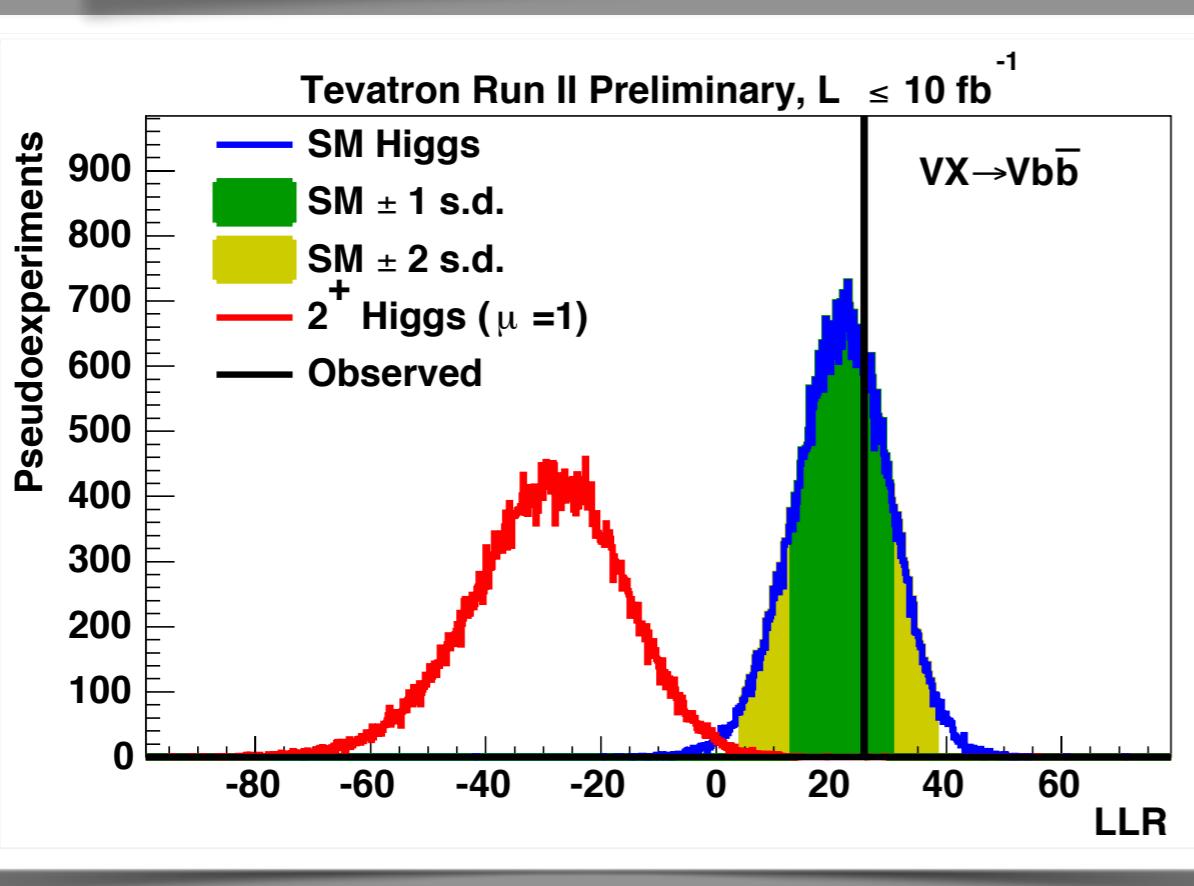


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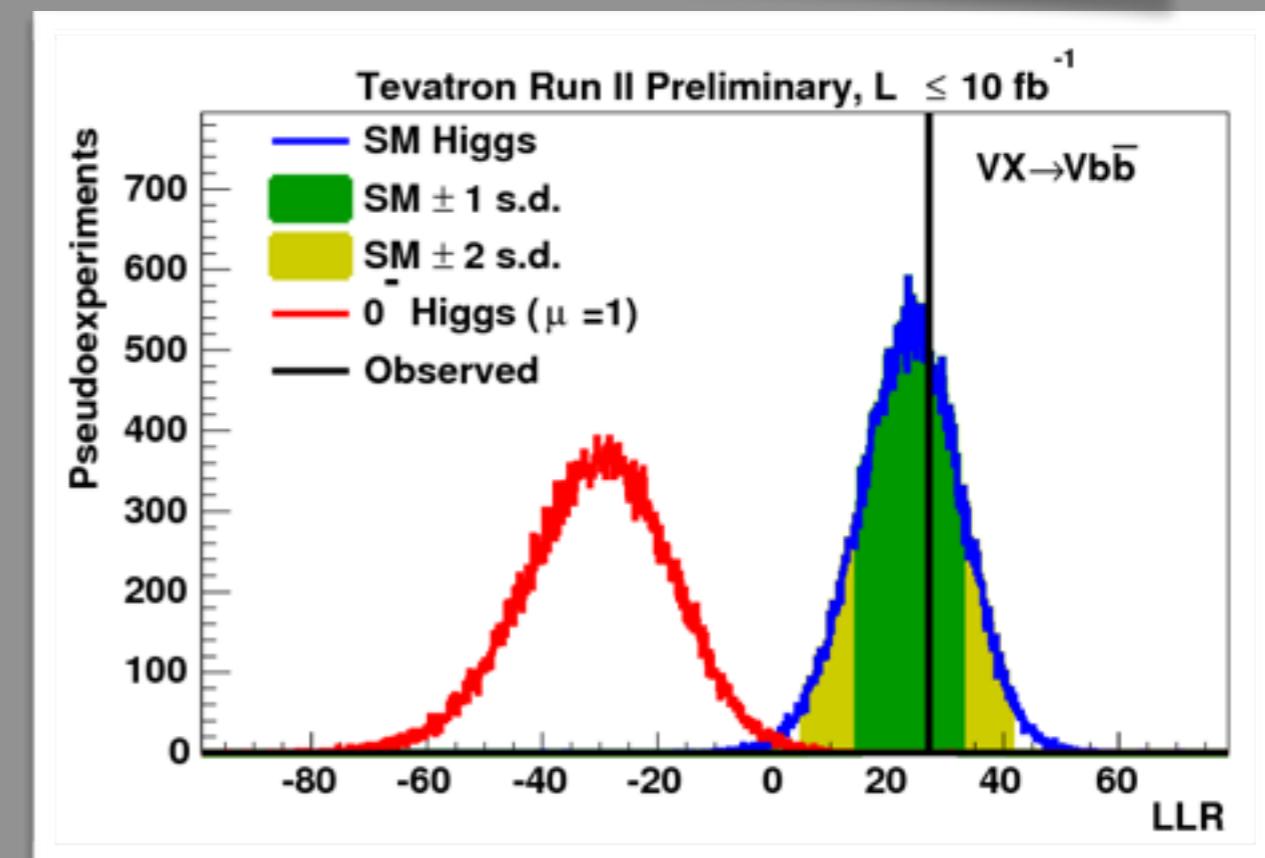
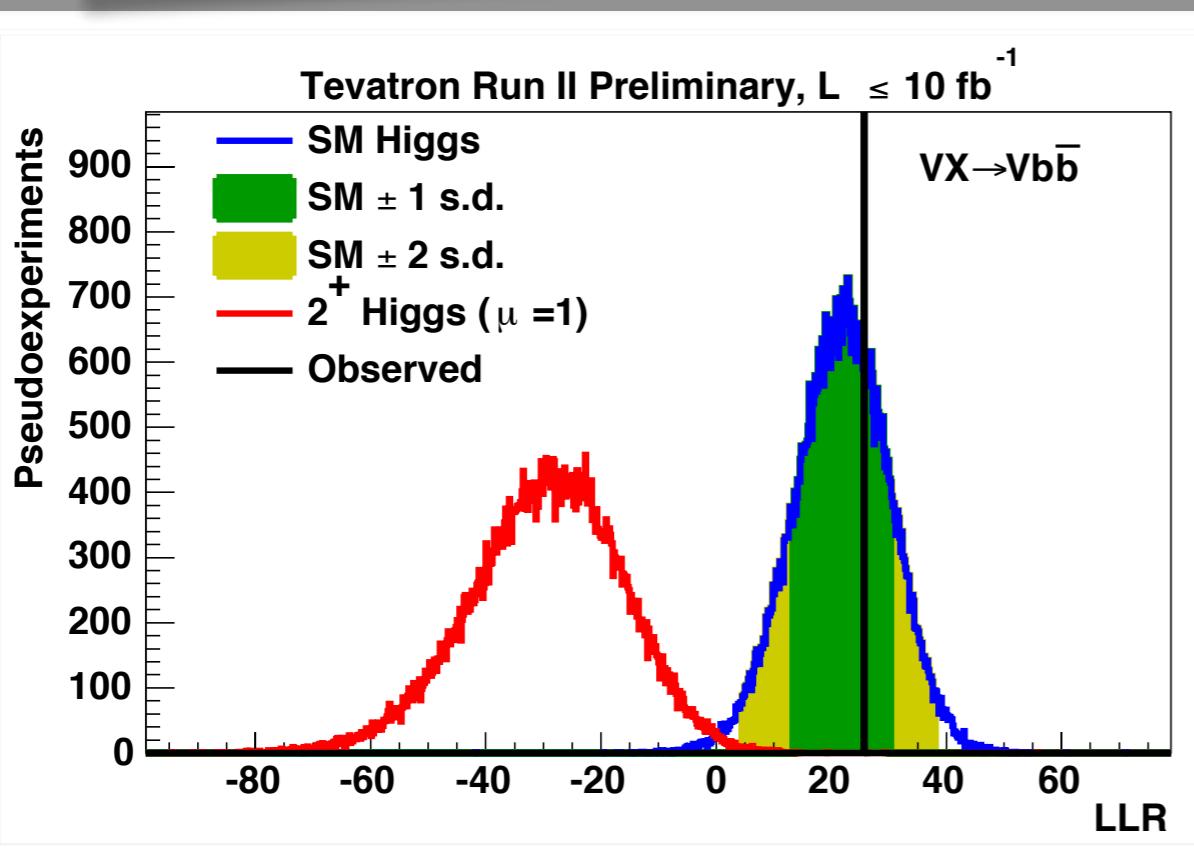
95% CL Upper Limit

- $\sigma(J^P=0^-)$ excluded above **0.36** σ_{SM}
- $\sigma(J^P=2^+)$ excluded above **0.36** σ_{SM}

BSM J^P models constrained using $H \rightarrow b\bar{b}$ decays

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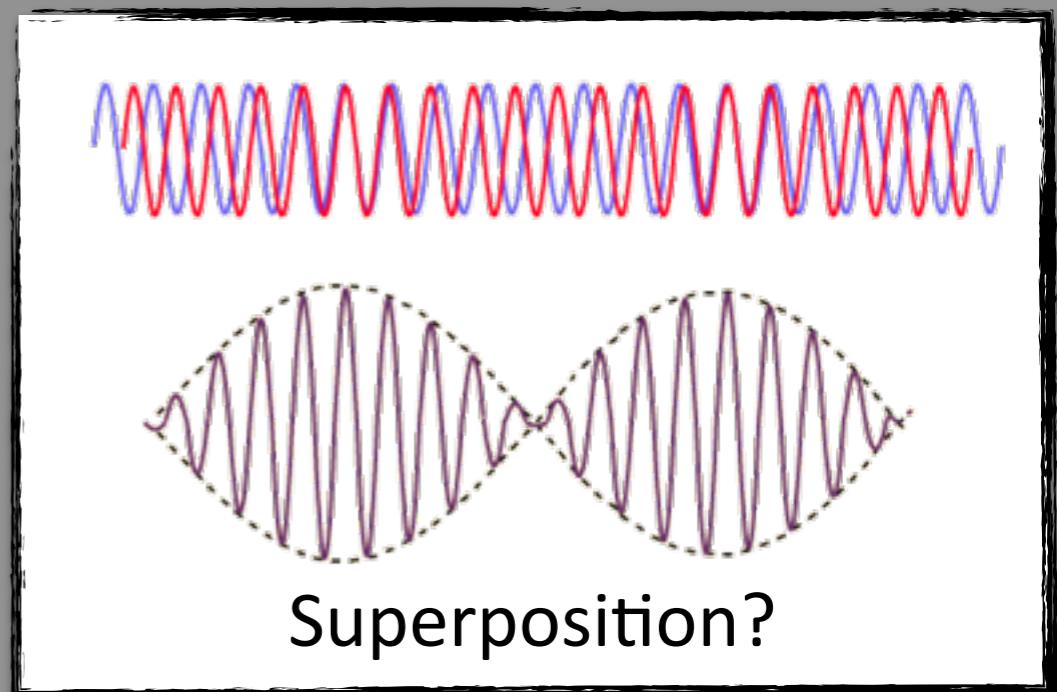
95% CL Upper Limit

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Assuming SM
Higgs Background

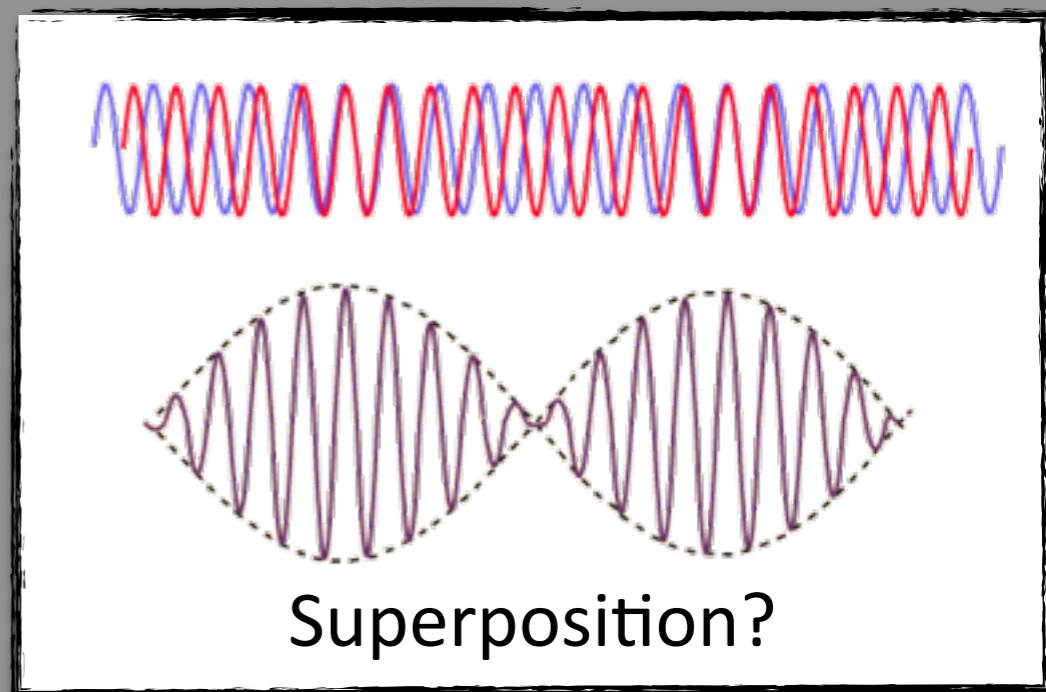
$$\begin{aligned}\sigma(J^P=0^-) &> 0.29 \sigma_{\text{SM}} \\ \sigma(J^P=2^+) &> 0.31 \sigma_{\text{SM}}\end{aligned}$$

Is nature more complicated?



Is nature more complicated?

$$\phi = \cos \alpha H + \sin \alpha A$$



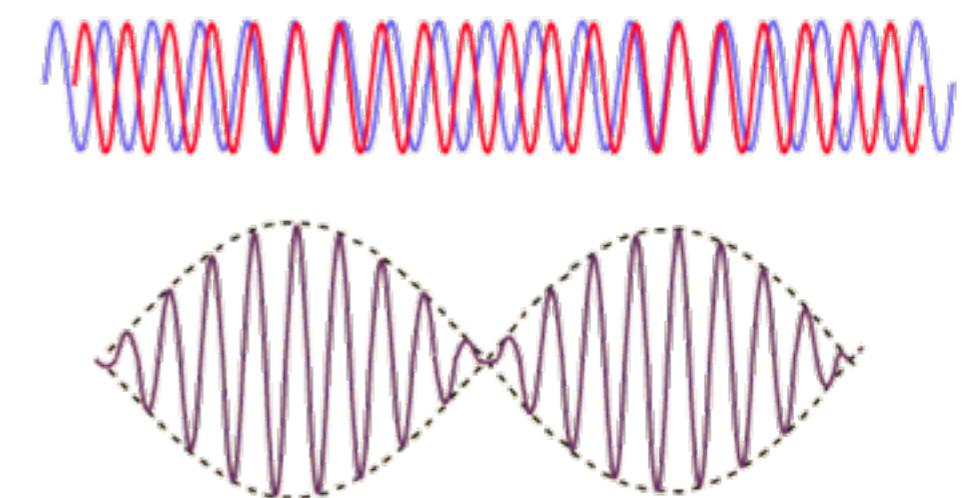
Eg, Two Higgs Doublet Model

Is nature more complicated?

$$\phi = \cos c H + \sin c A$$

CP-Even

CP-Odd



Superposition?

Eg, Two Higgs Doublet Model

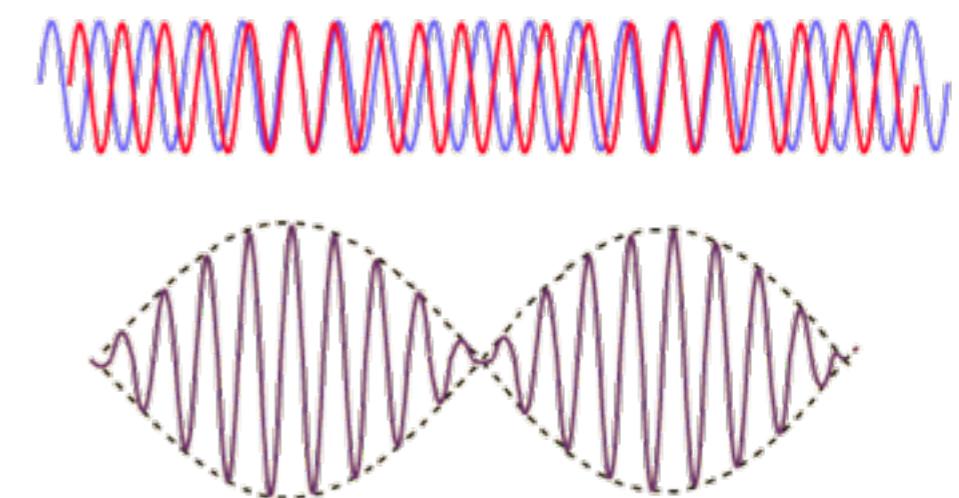
Is nature more complicated?

$$\phi = \cos \alpha H + \sin \alpha A$$

CP-Even

CP-Odd

$$\phi' = -\sin \alpha H + \cos \alpha A$$



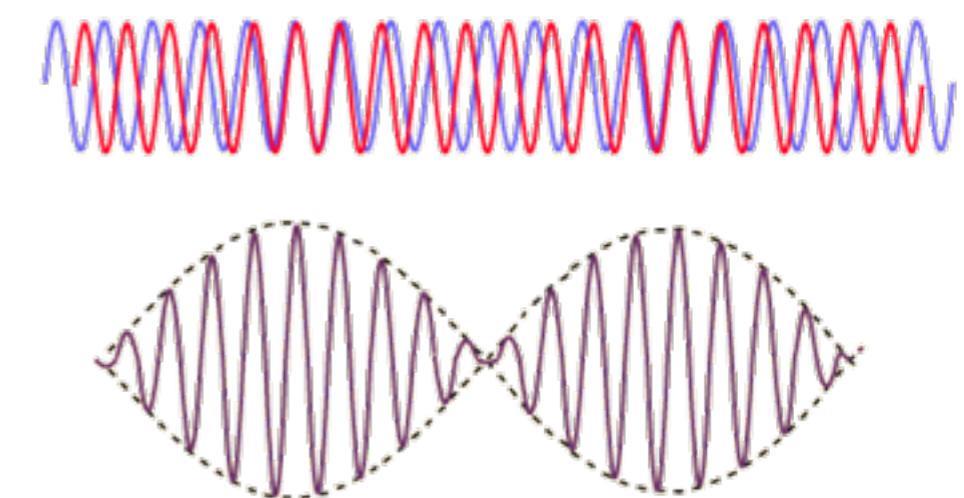
Superposition?

Eg, Two Higgs Doublet Model

What about this one??

Is nature more complicated?

$$\phi = \cos \alpha H + \sin \alpha A$$



Superposition?

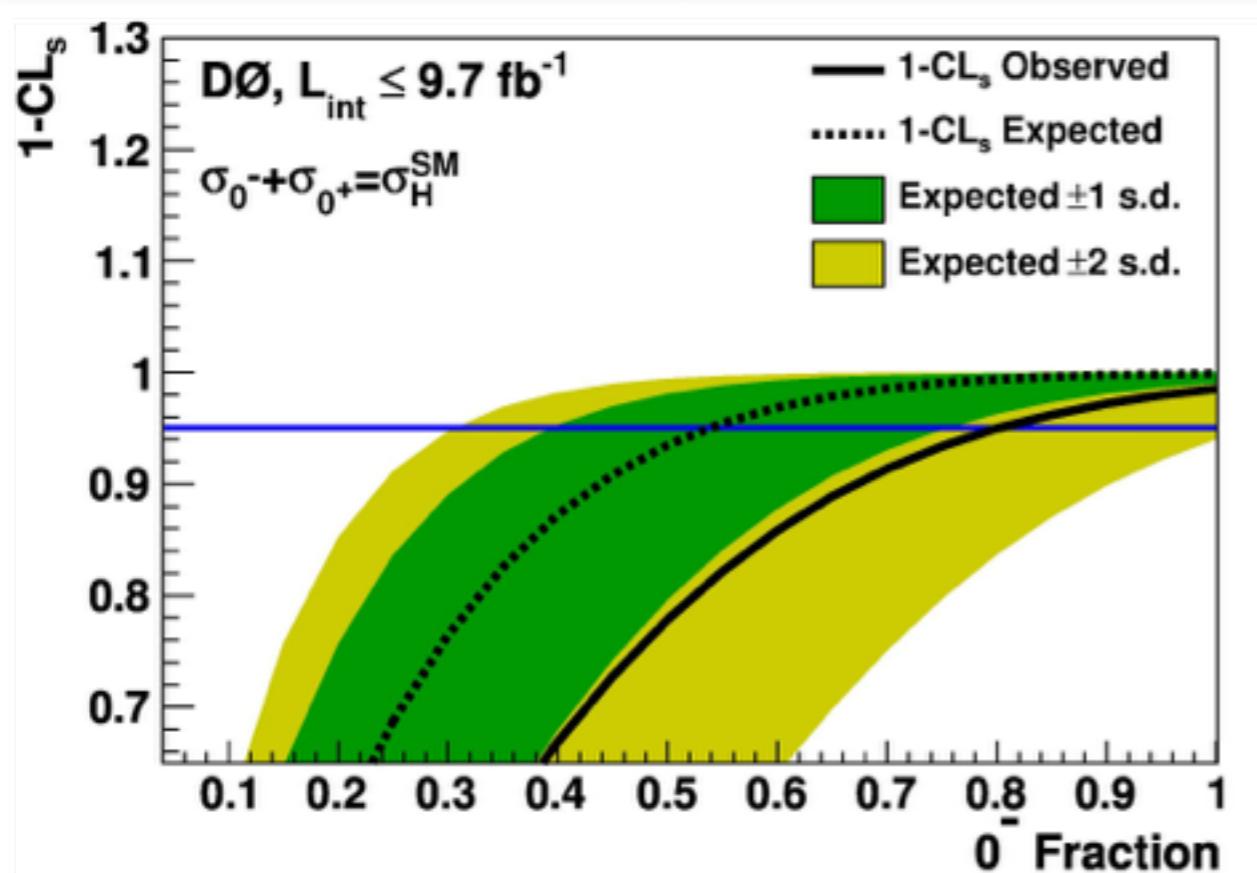
$$\frac{\Gamma[\phi \rightarrow b\bar{b}]}{\Gamma_{SM}[H \rightarrow b\bar{b}]} = \underline{(y_d^H \cos \alpha)^2} + \underline{(y_d^A \sin \alpha)^2}$$

Yukawa Couplings

$$(1) \quad \sigma_{\text{Tot}} = \sigma_A + \sigma_H$$

Scan the $J^P=0^-$
Fraction

$$(2) \quad f_A = \frac{\sigma_A}{\sigma_{\text{Tot}}} = \left(\frac{y_d^A}{y_d^{\text{SM}}} \sin \alpha \right)^2$$

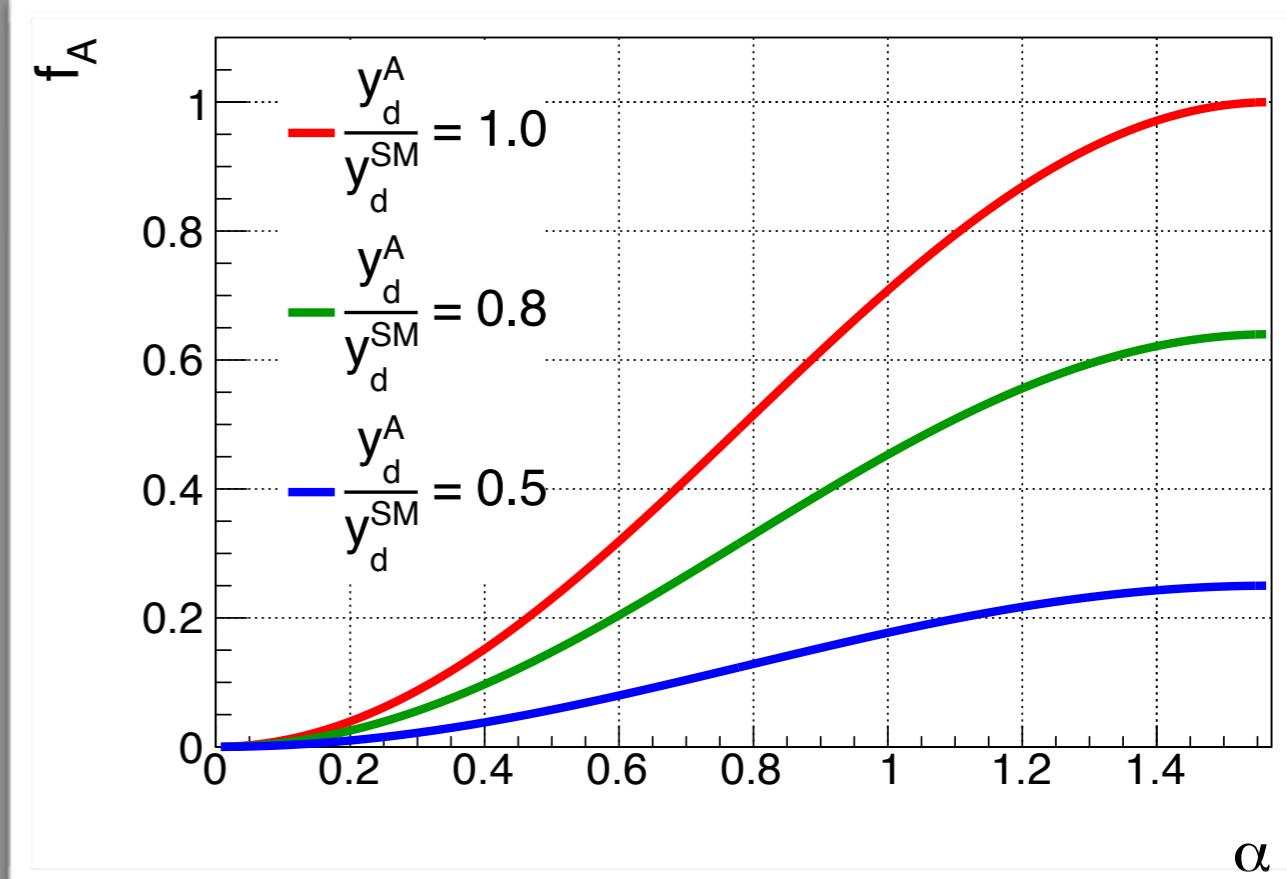
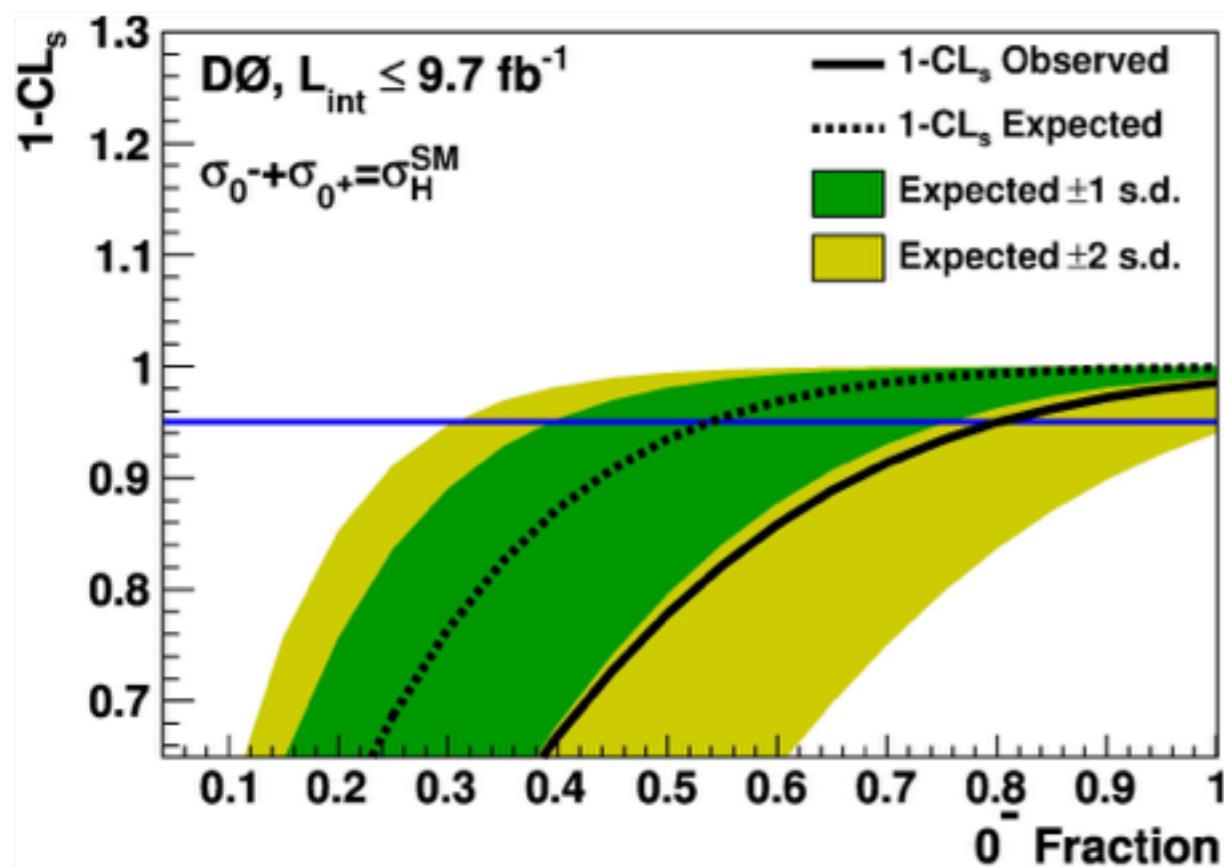


*For illustration only

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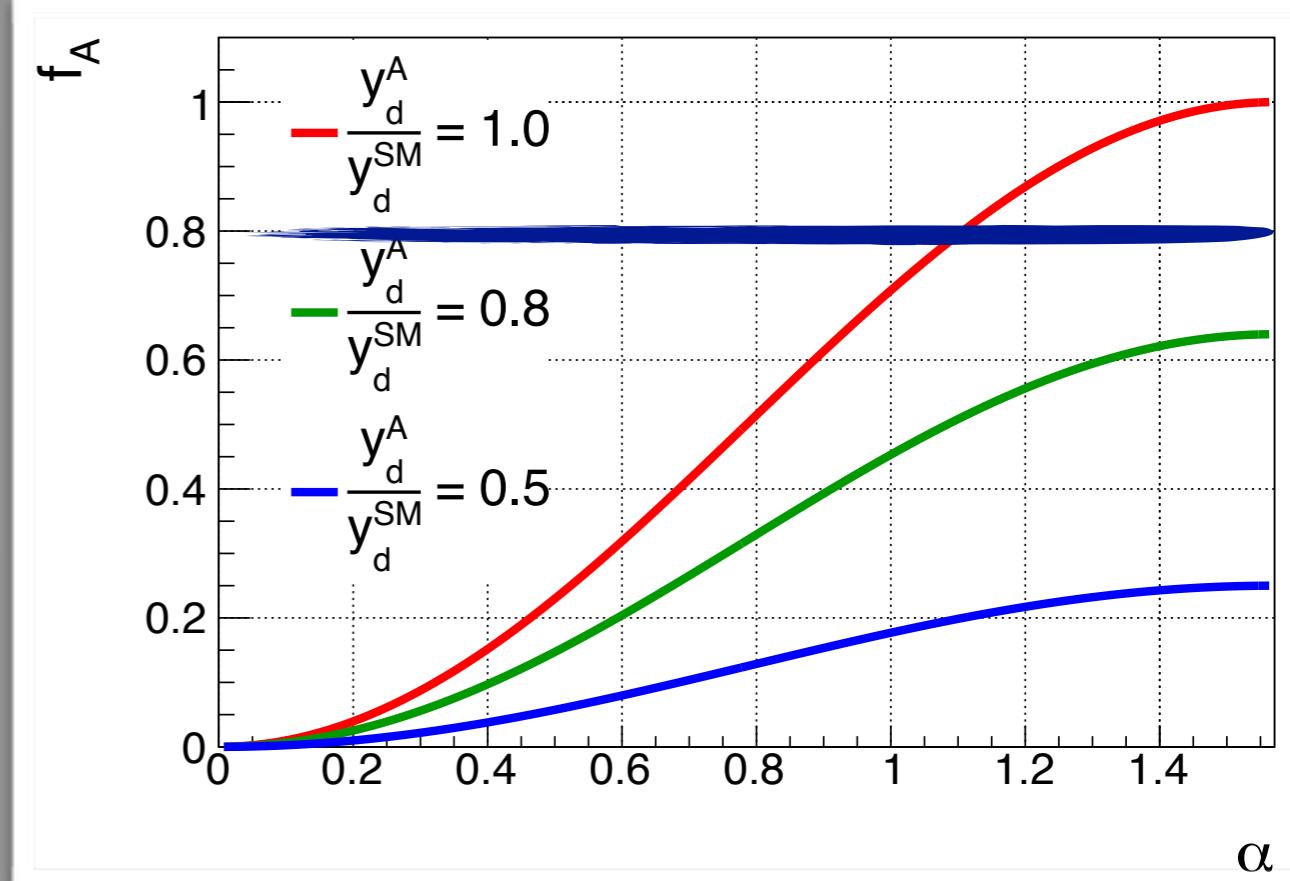
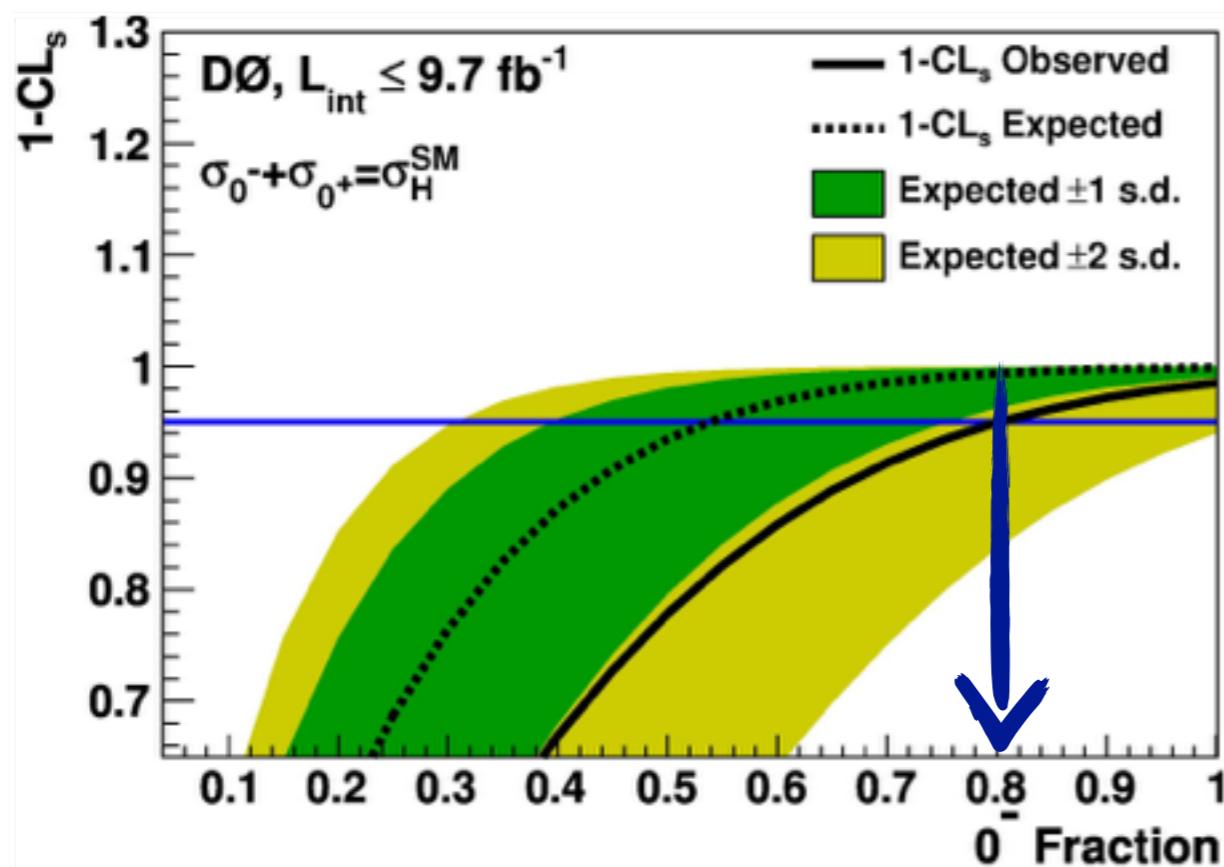


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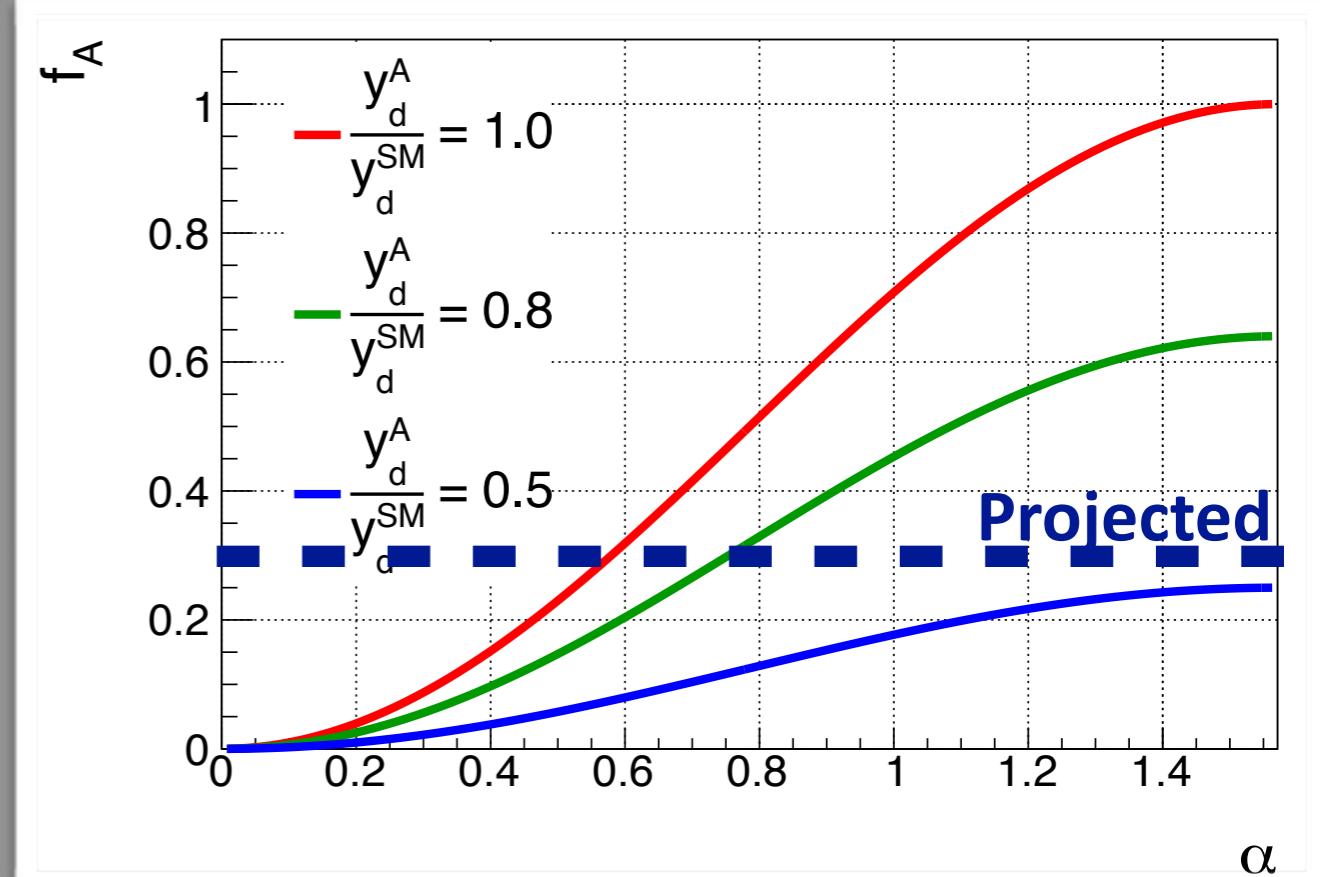
Scan the $J^P=0^-$
Fraction

$$(2) \quad f_A = \frac{\sigma_A}{\sigma_{\text{Tot}}} = \left(\frac{y_d^A}{y_d^{\text{SM}}} \sin \alpha \right)^2$$

Anticipated CDF+D0
combination should
improve constraints
significantly:



Limits similar to $J^P=0^-$
rate exclusion



*For illustration only

Final Tevatron Higgs results

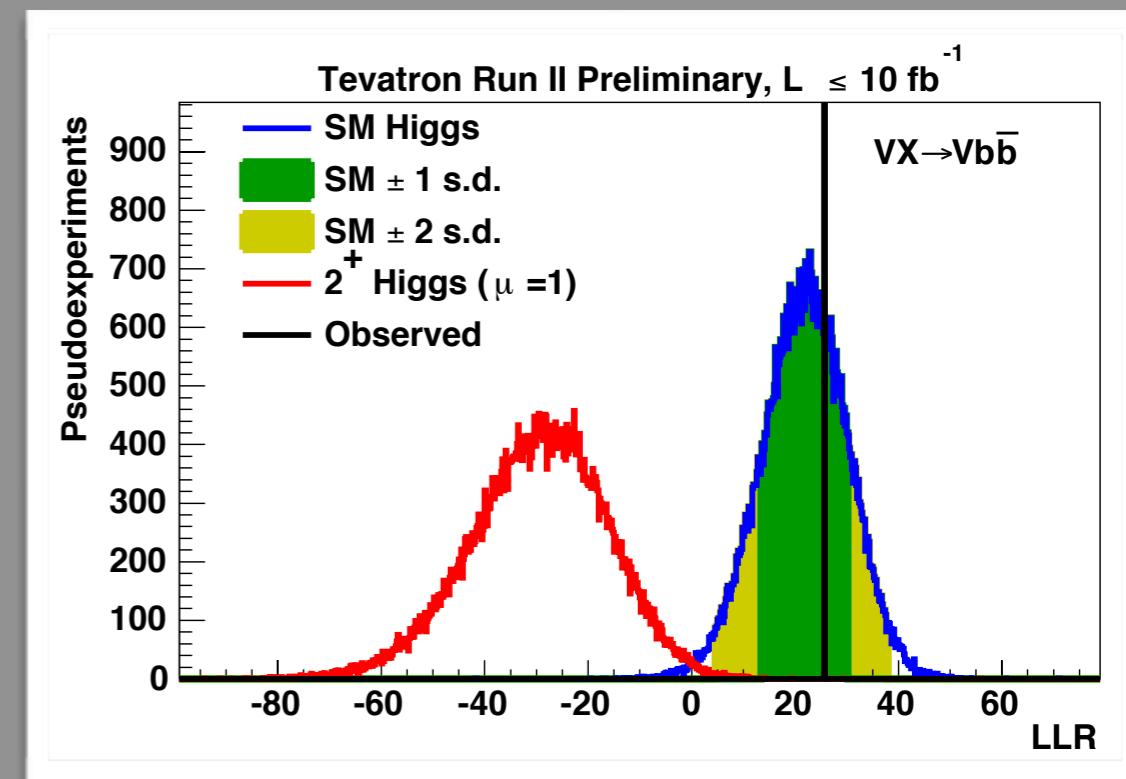
- Search channels using full RunII dataset & published.

Achieved SM sensitivity over most of accessible mass range

- Excess near 125 GeV corresponds to 3.0σ
- + Consistent with LHC results

Sensitive to Higgs properties in Hbb mode

- J^P & couplings measurements are a valuable contribution
- + **DØ J^P paper published, CDF & CDF+DØ papers on the way**



+ tevnphwg.fnal.gov

+ PRL 113, 161802 (2014)
arXiv:1407.6369

+ http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/cdfcomb_JP/

THE

Probes of BSM vs SM rates

