The Tevatron Higgs Search

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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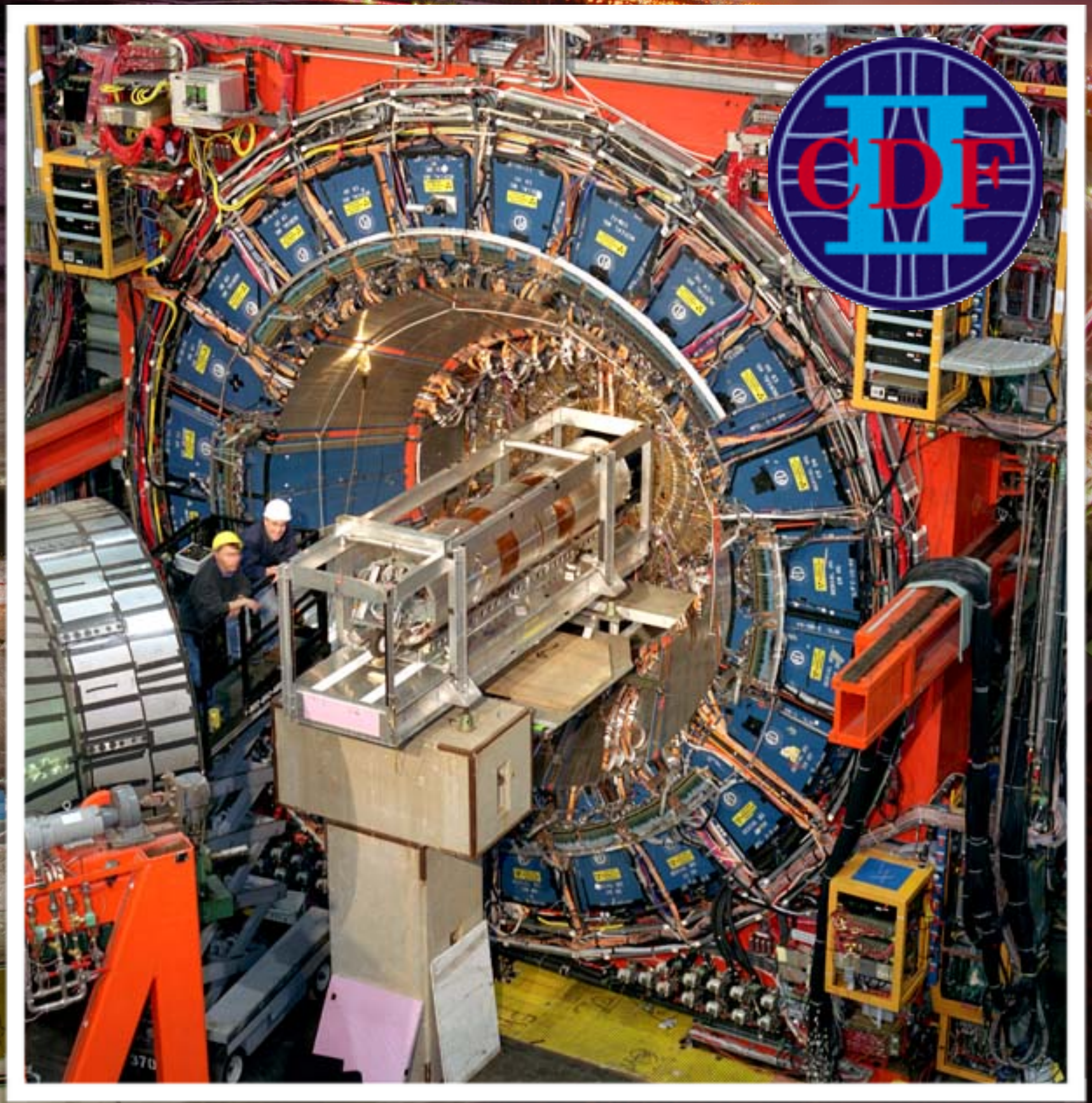

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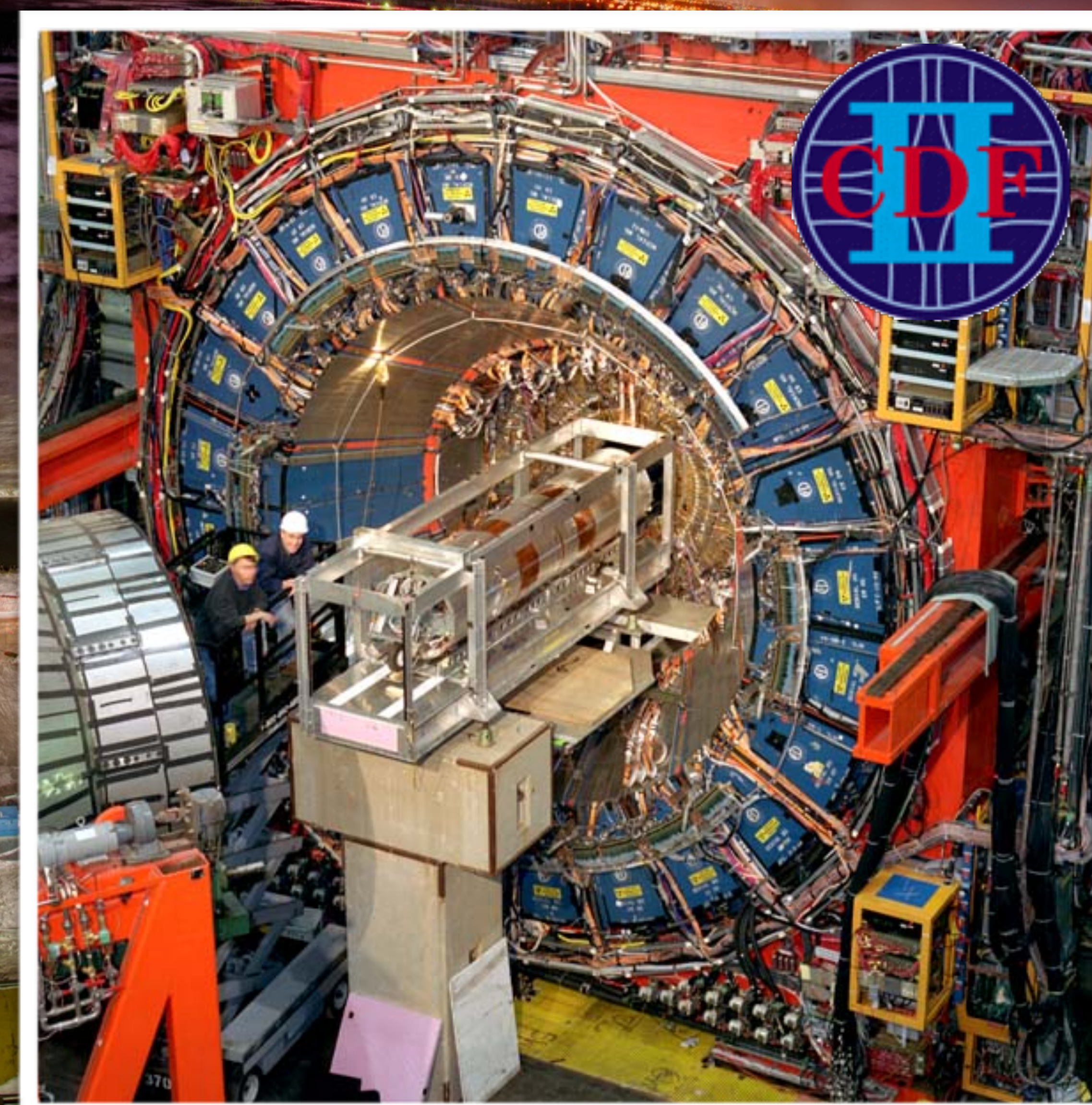


The Tevatron's Higgs Legacy

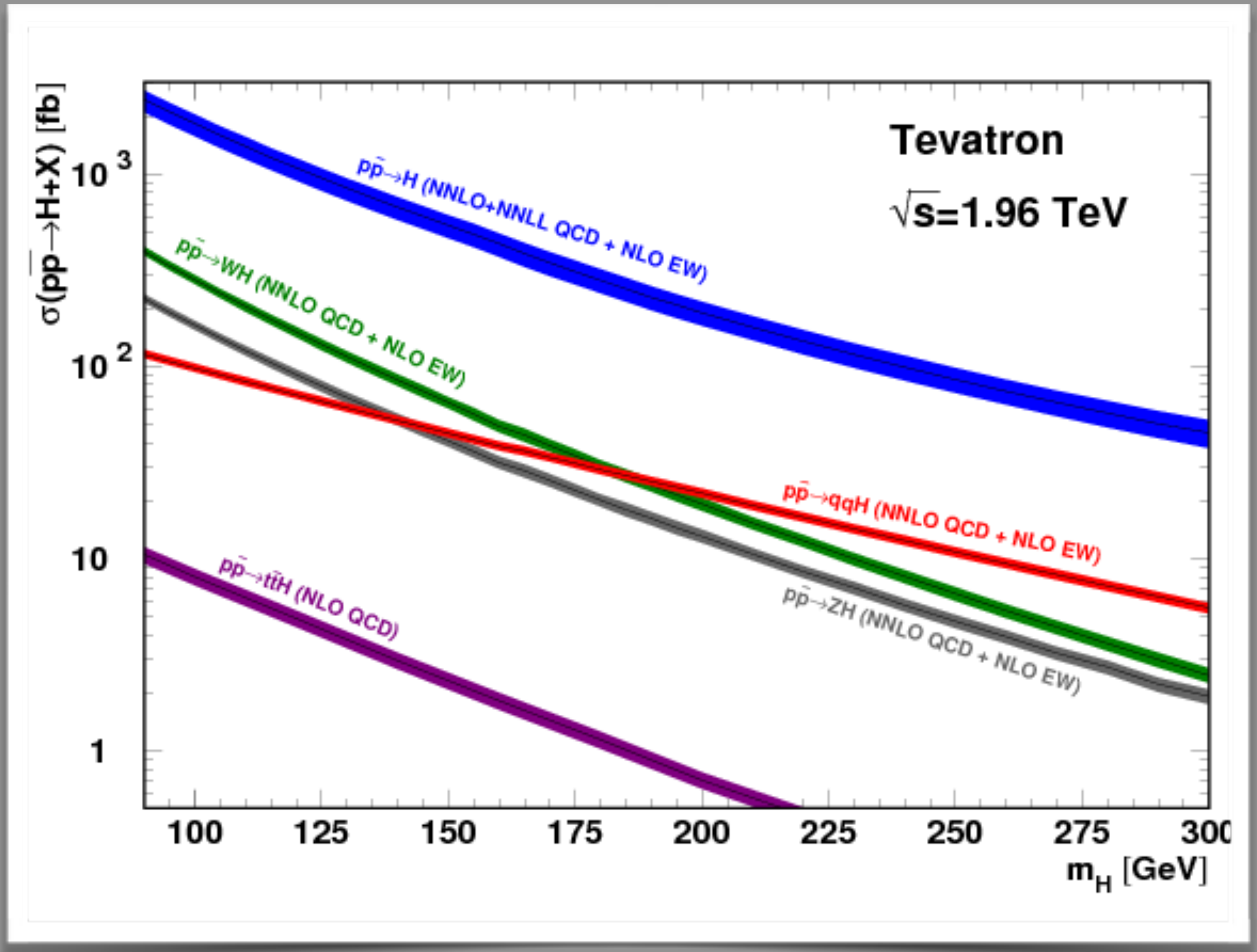
Higgs searches at the Tevatron

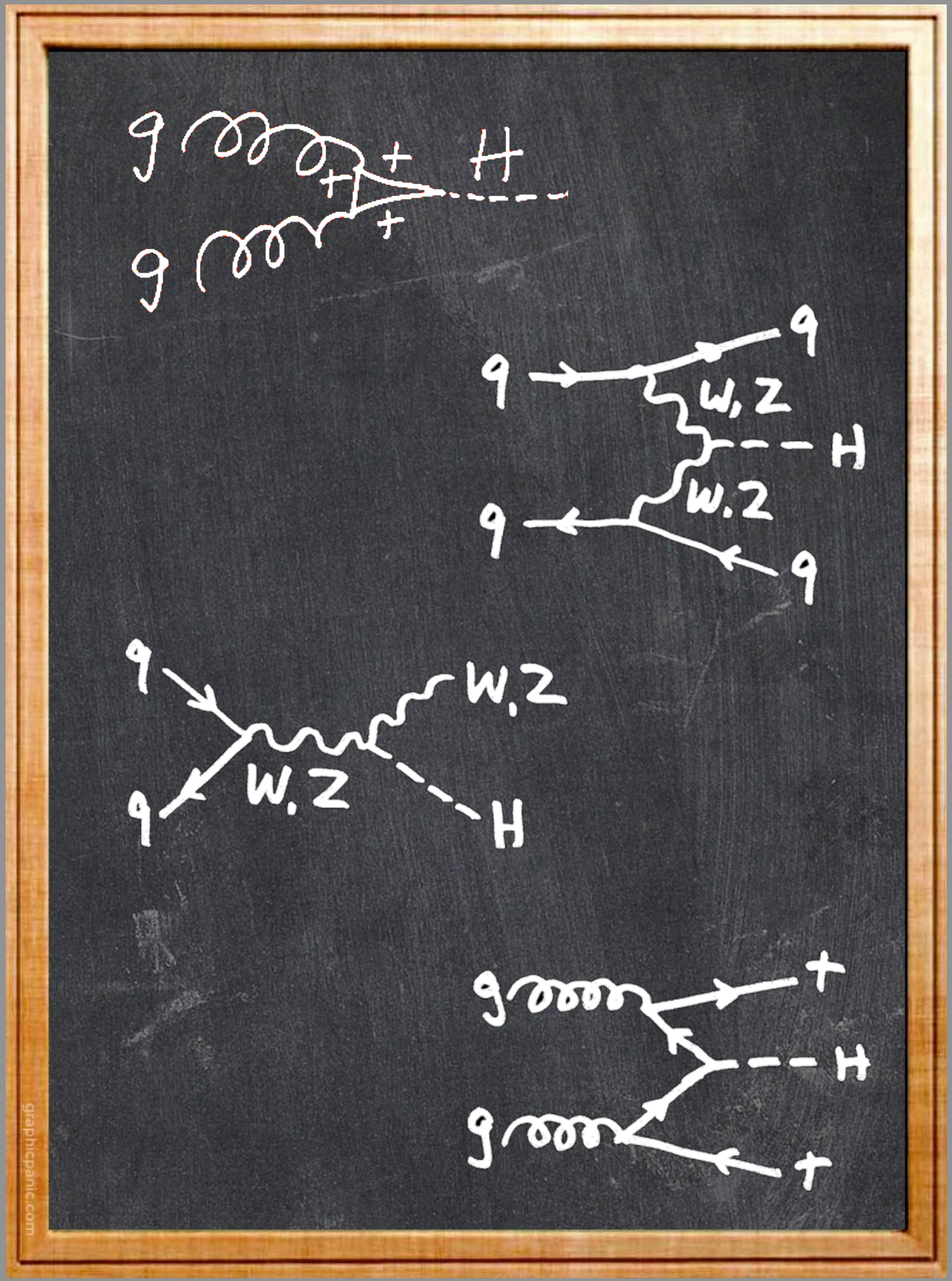
- Production and decay modes
- Search strategies

Studies of Higgs production at M_H=125 GeV

- Signal significance
- Measurements of Higgs properties

Producting Higgs at the Tevatron





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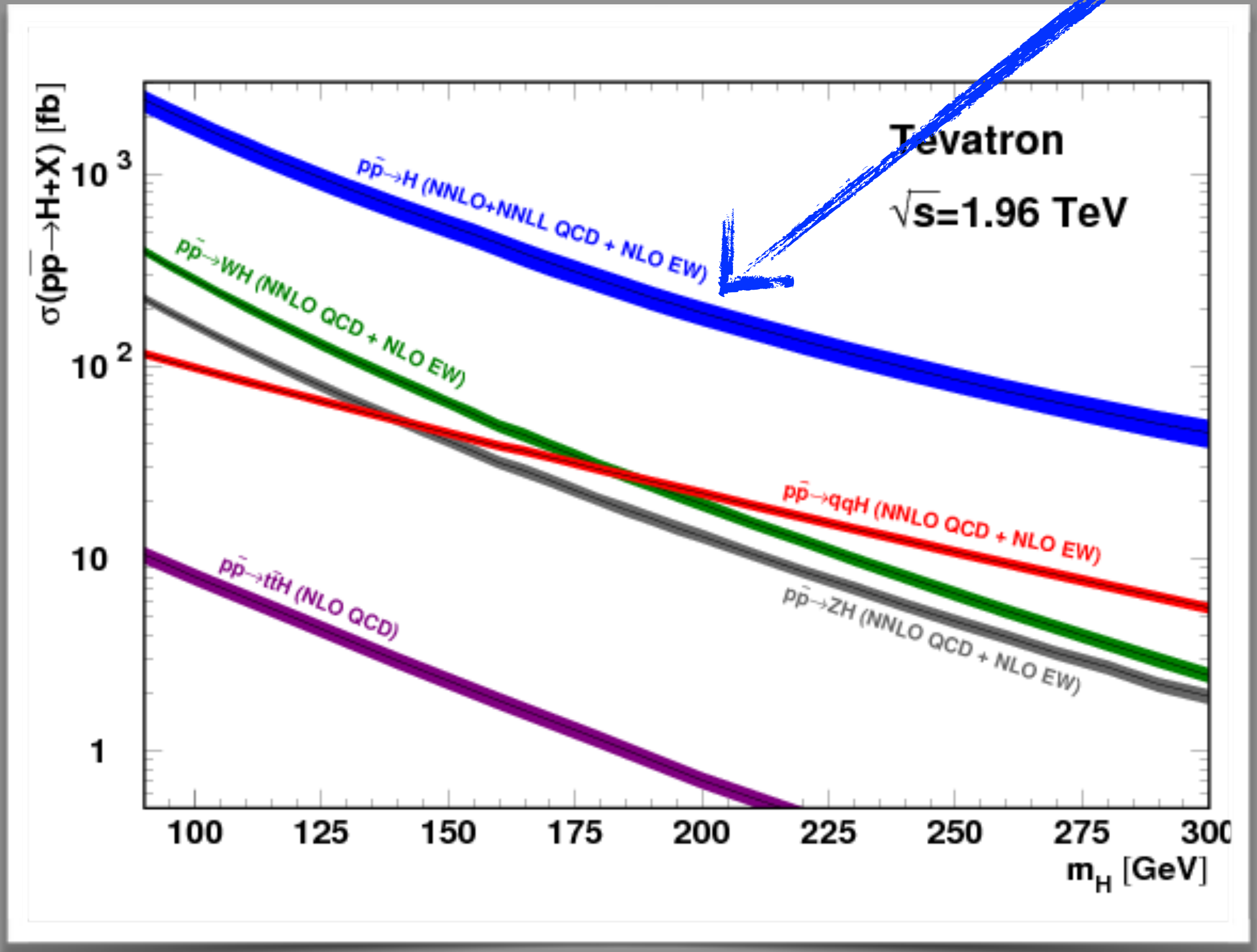

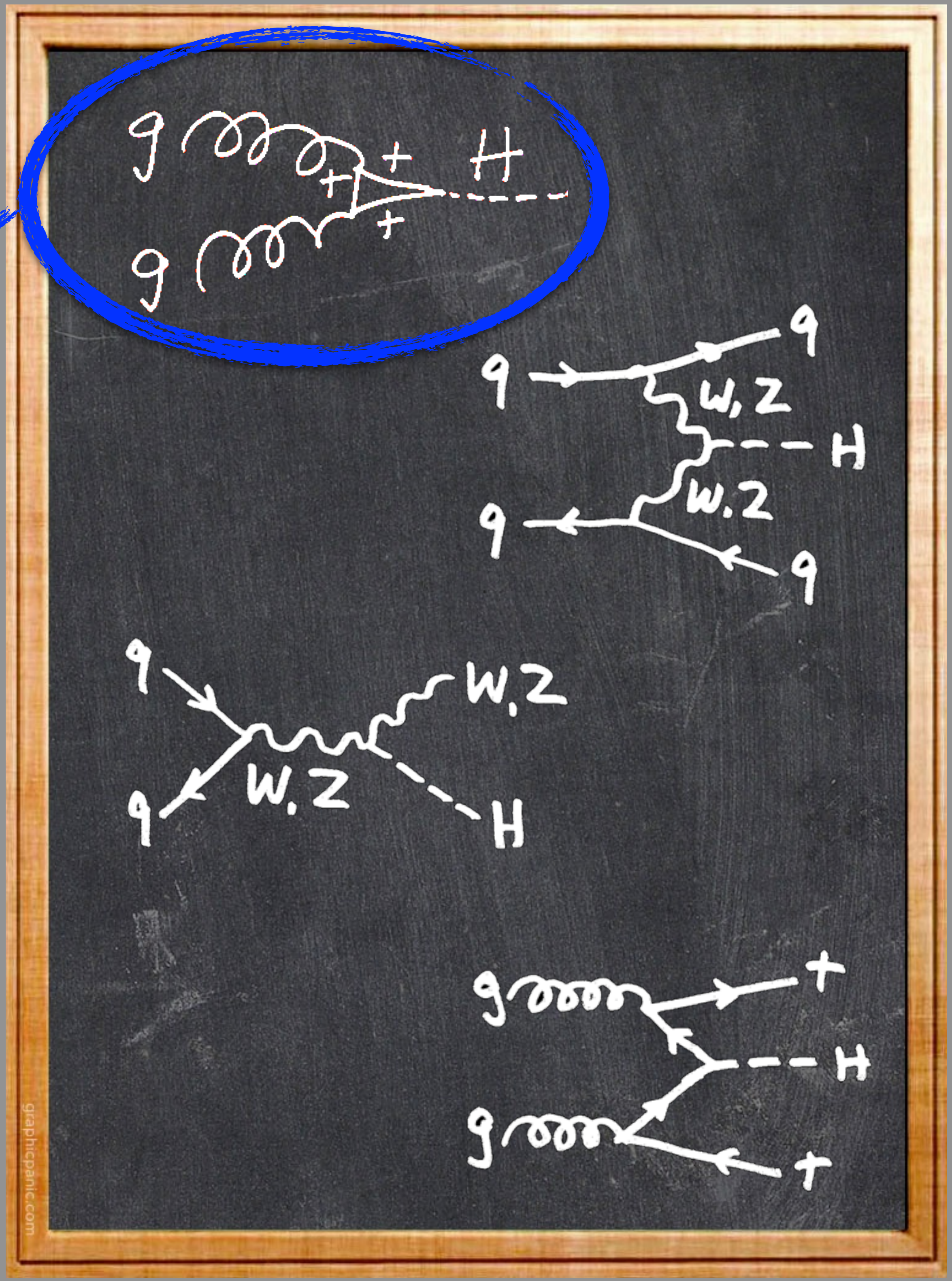

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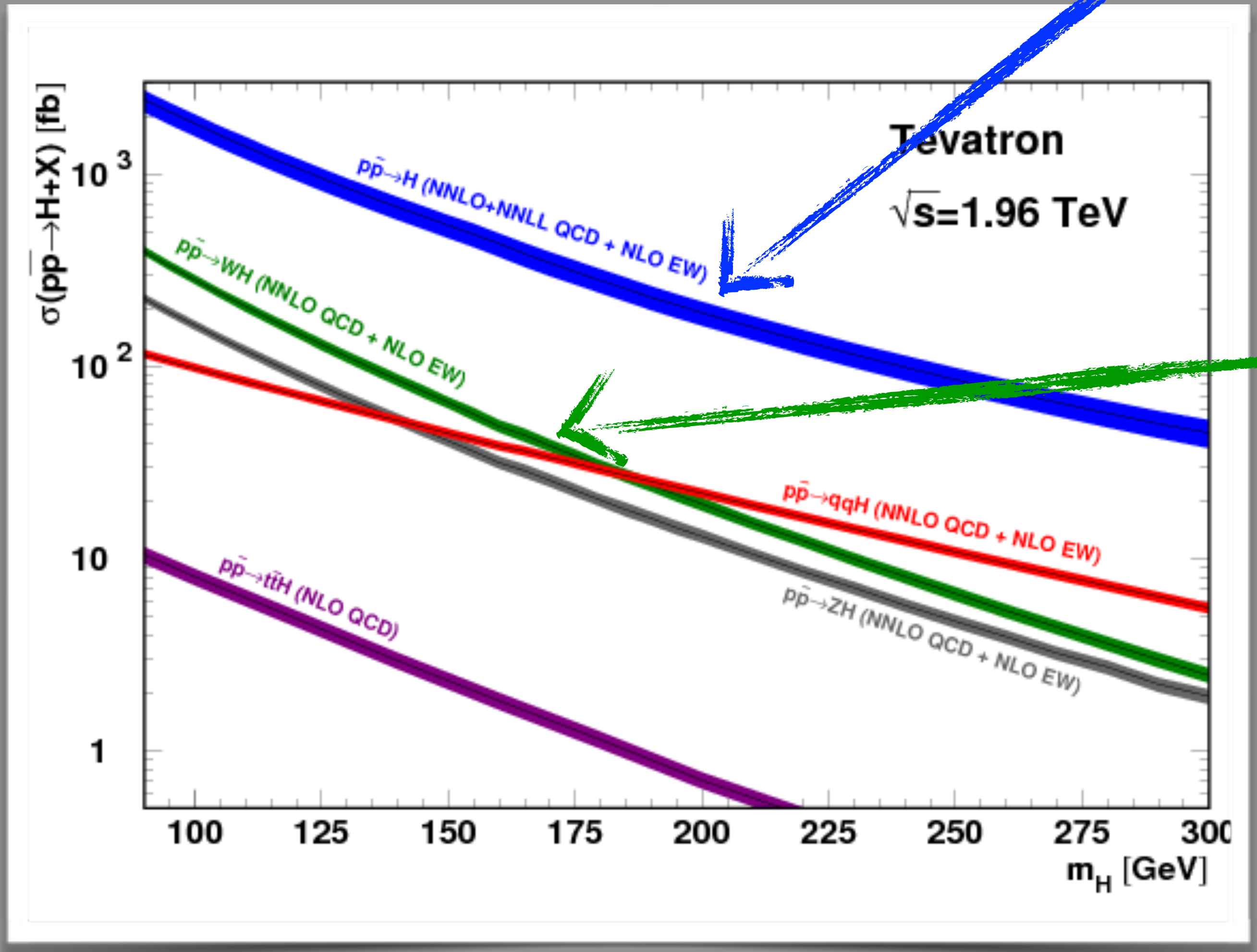

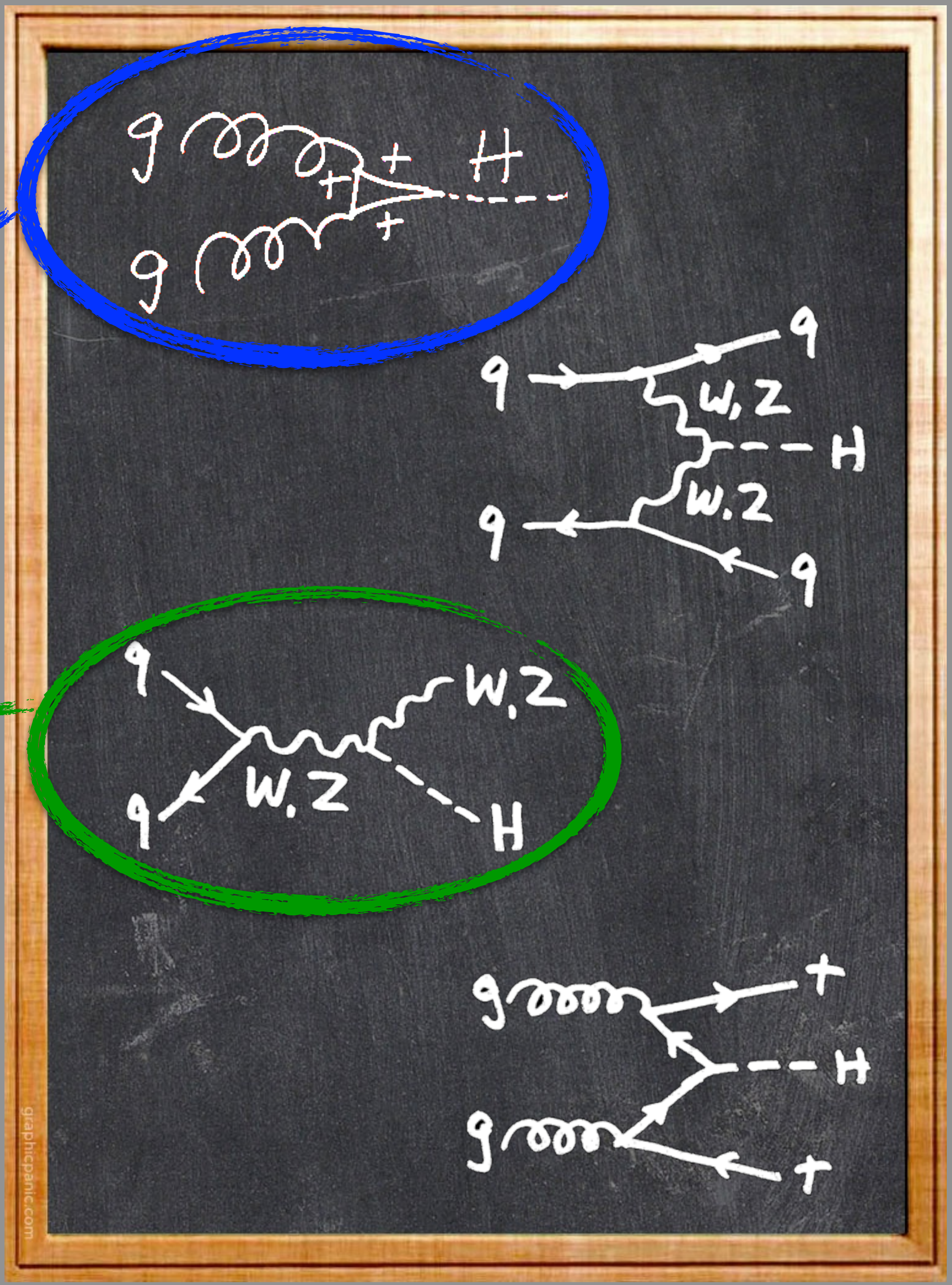

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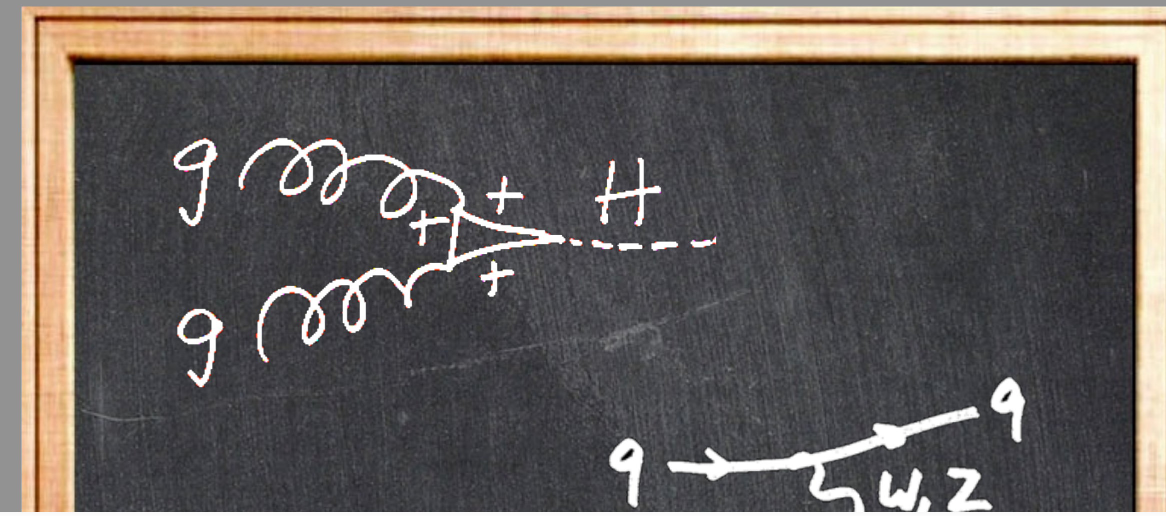
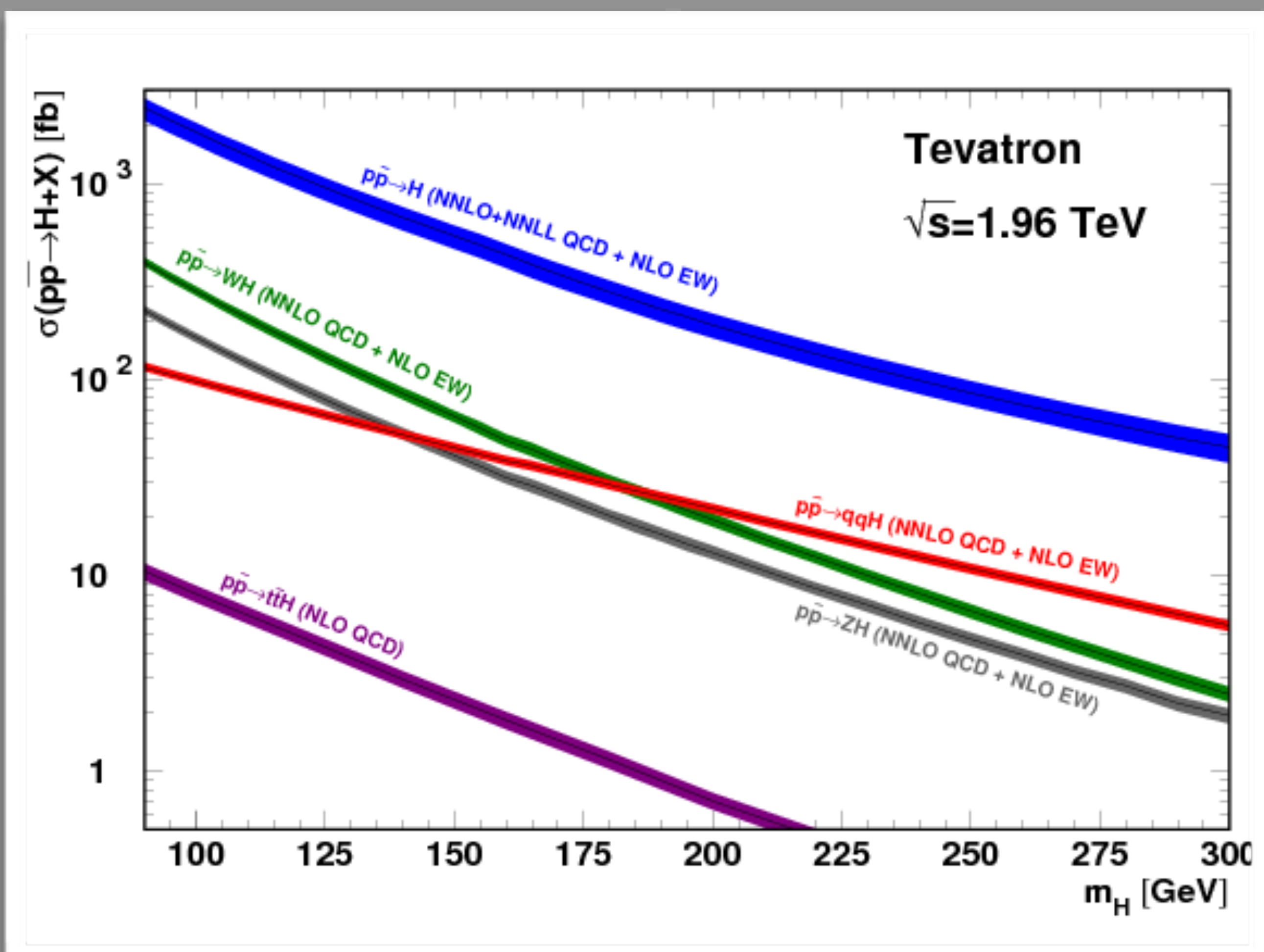
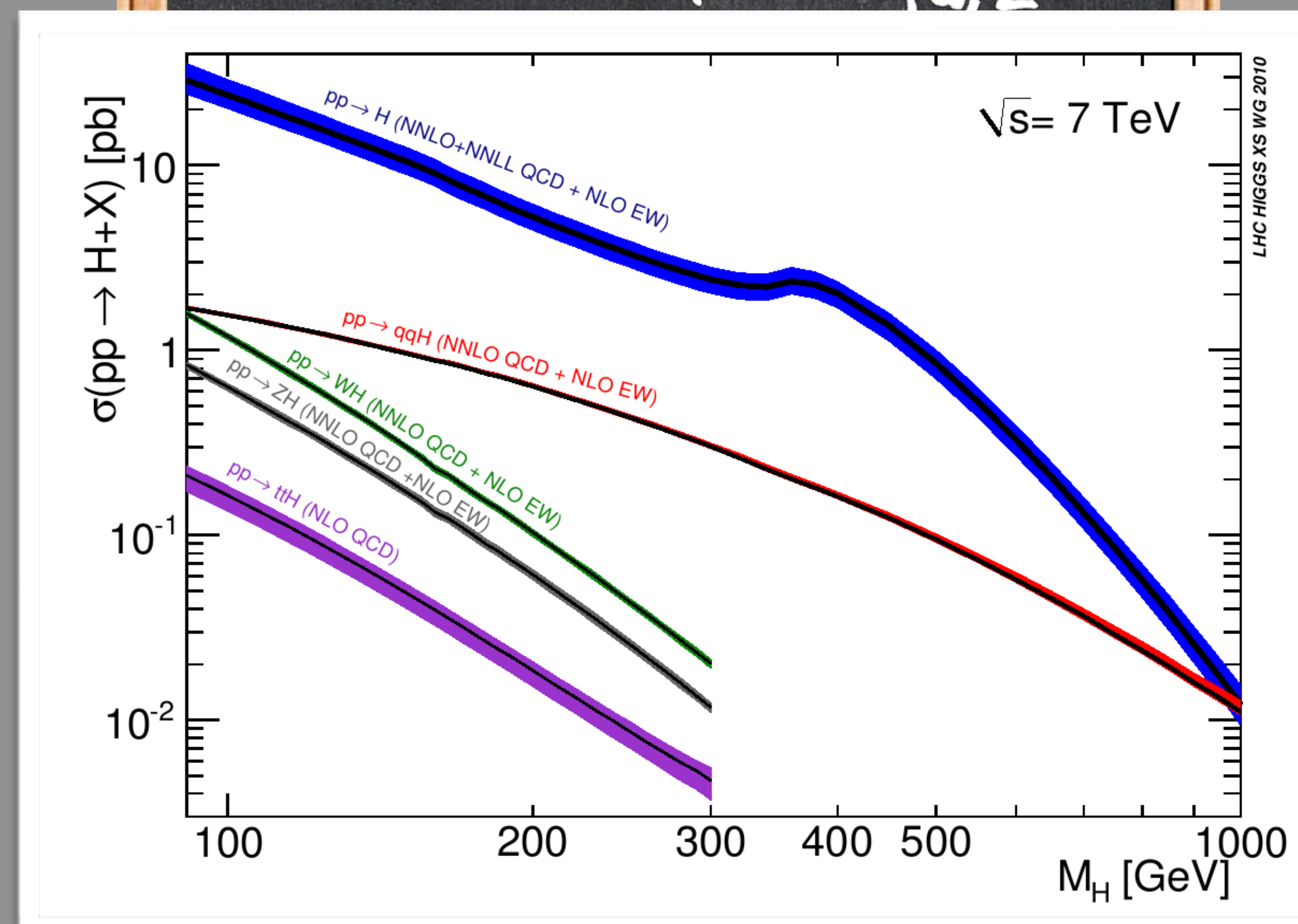
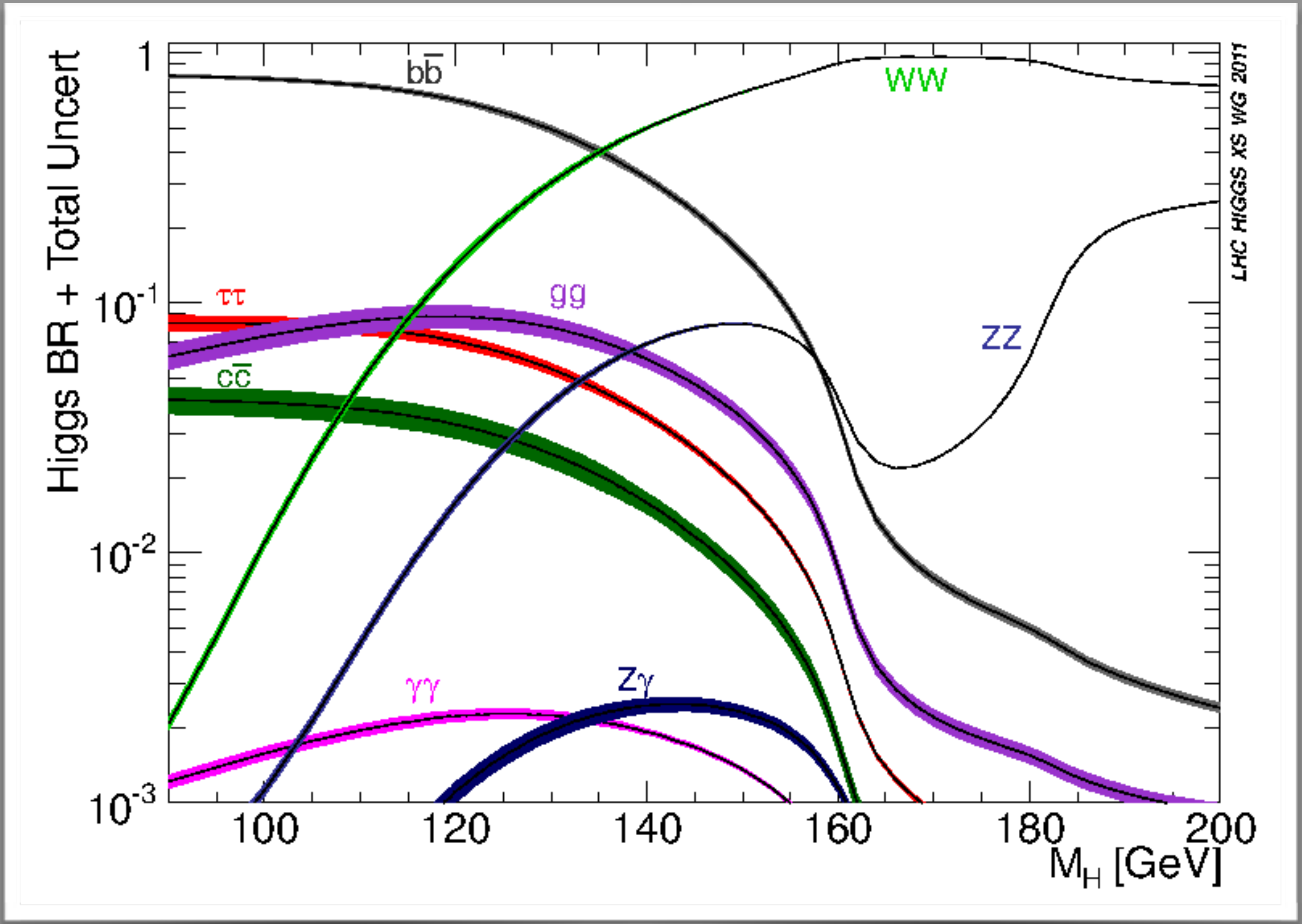






Focusing the Search



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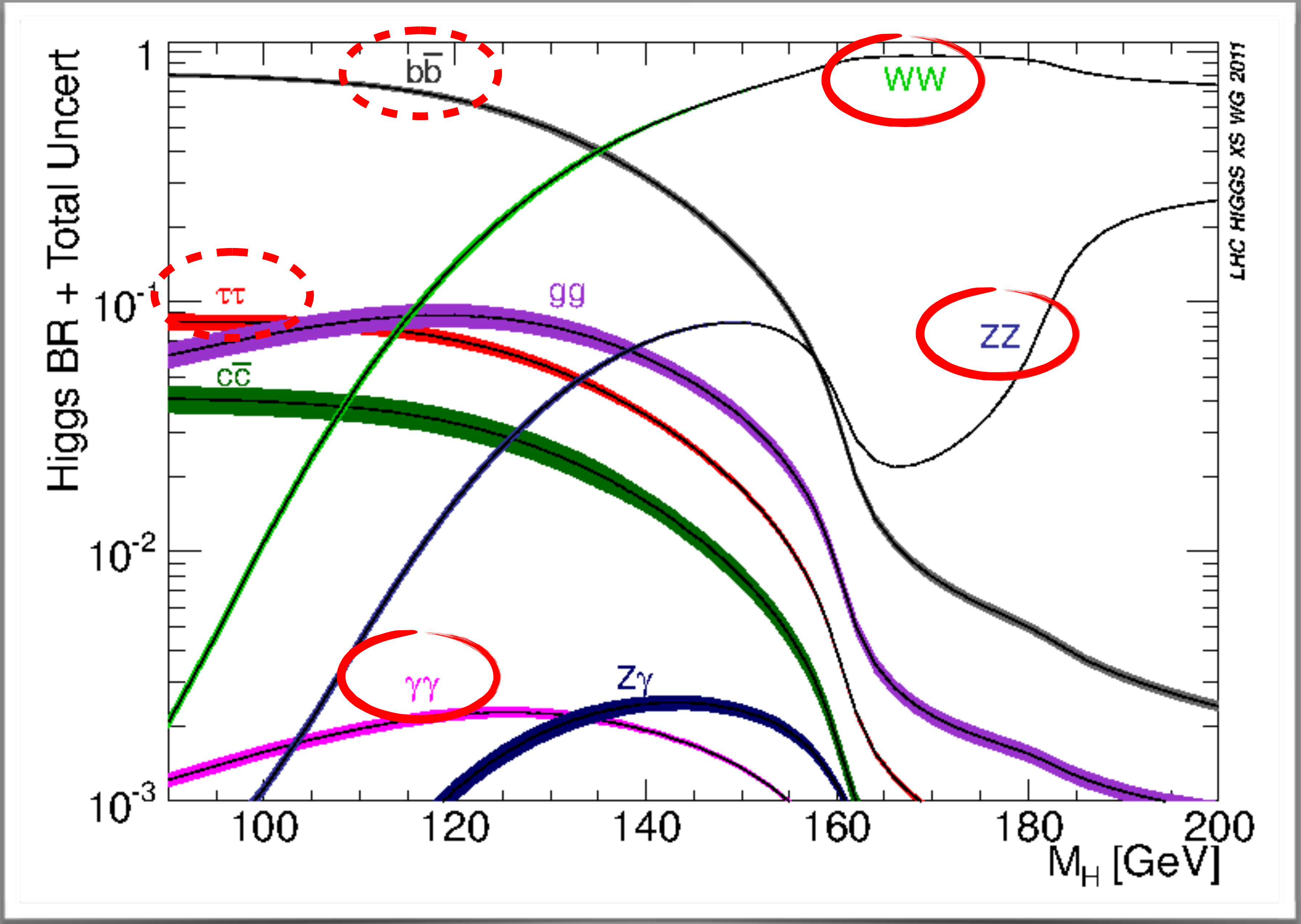
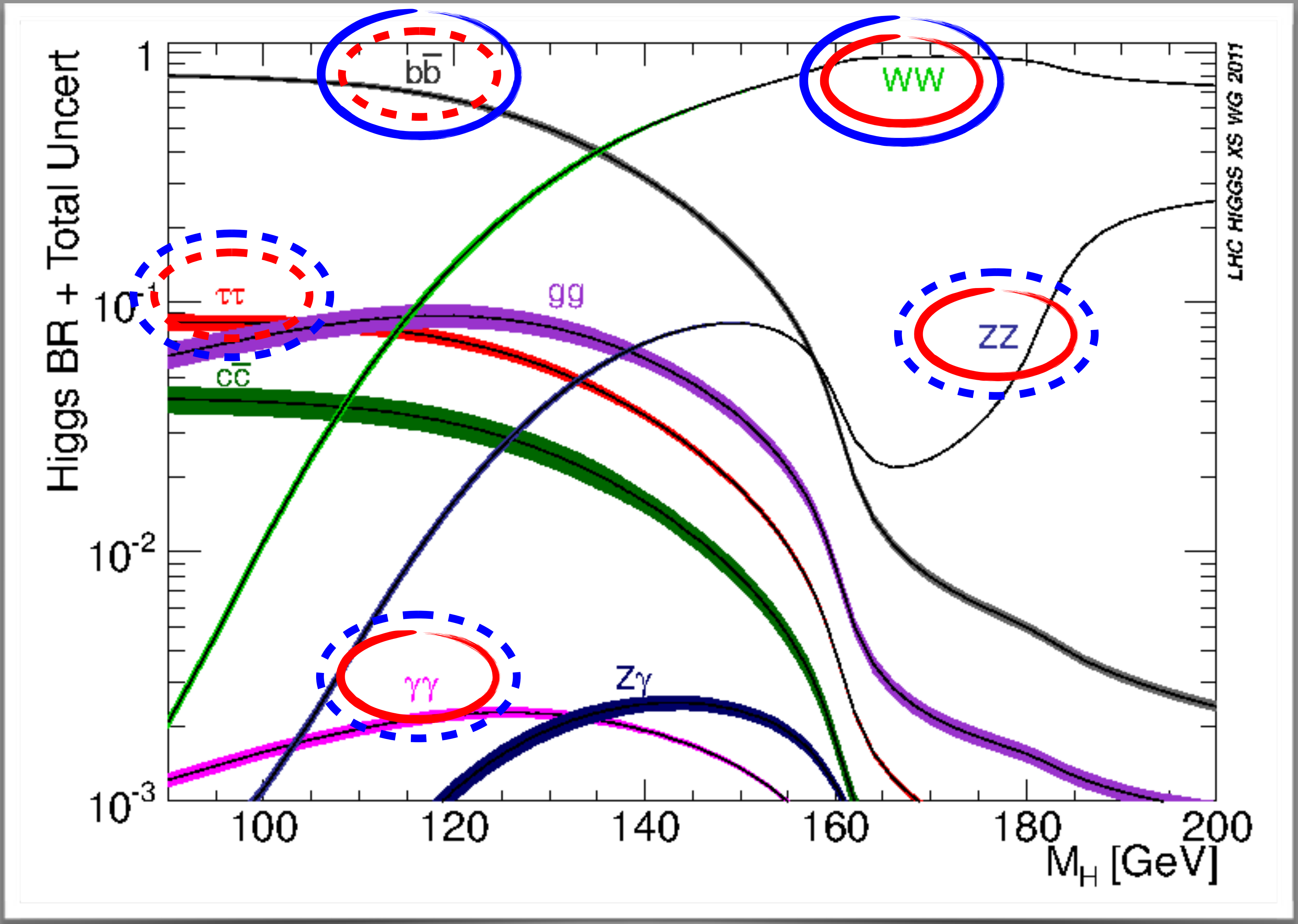


Main mode

Supporting mode

LHC

Focusing the Search

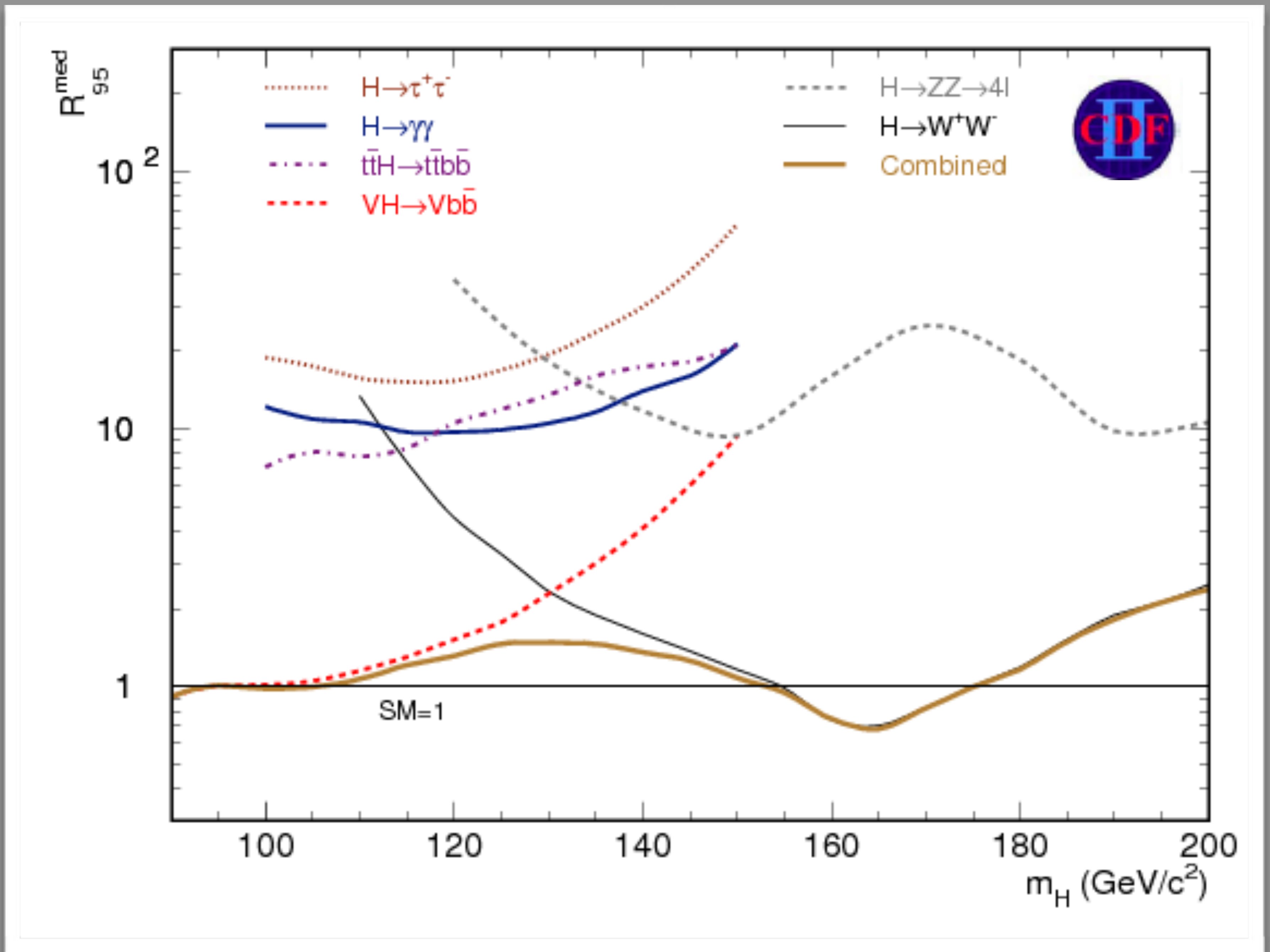


Main mode

Supporting mode

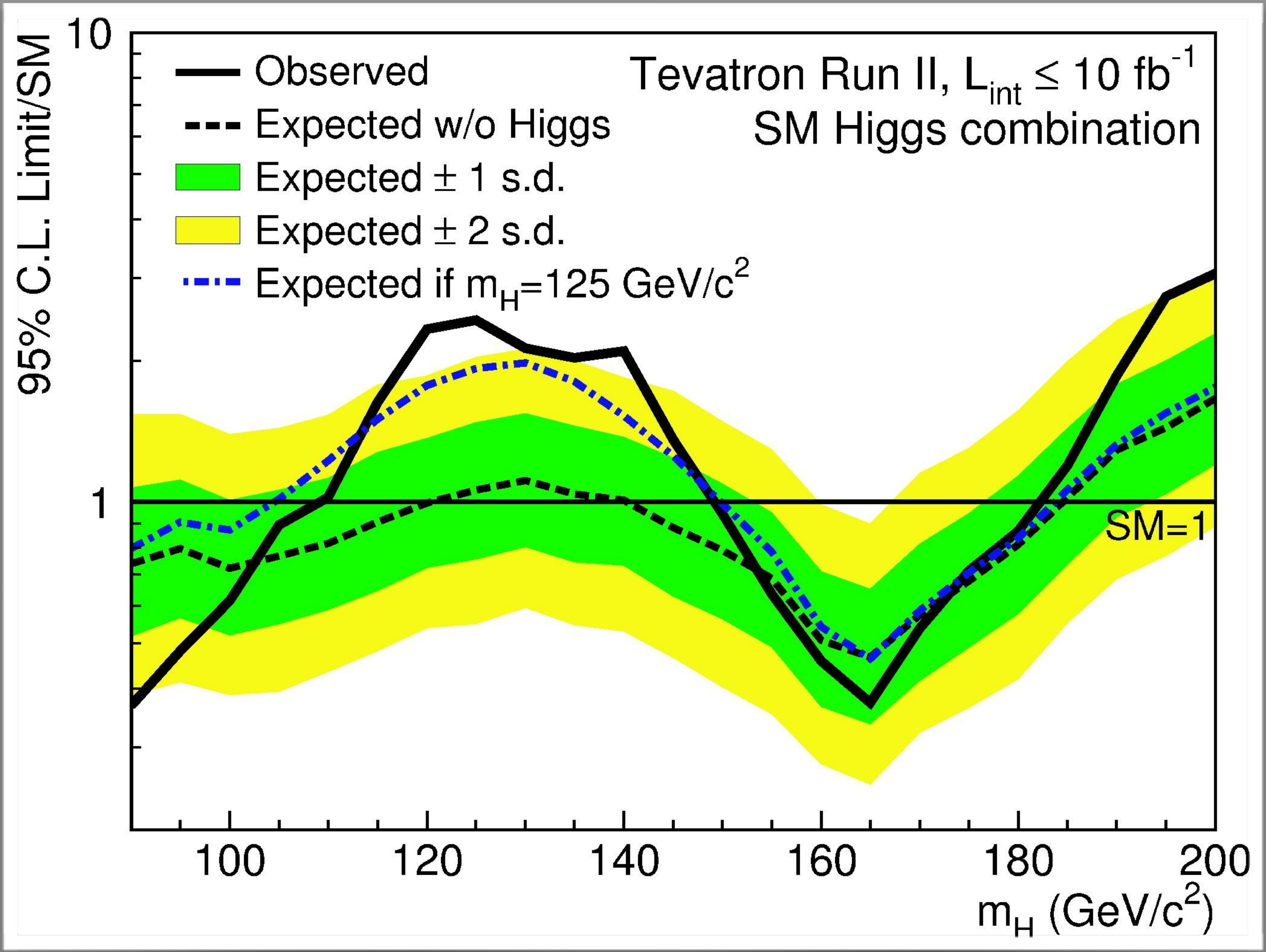
LHC Tevatron

A Combination of Many Searches



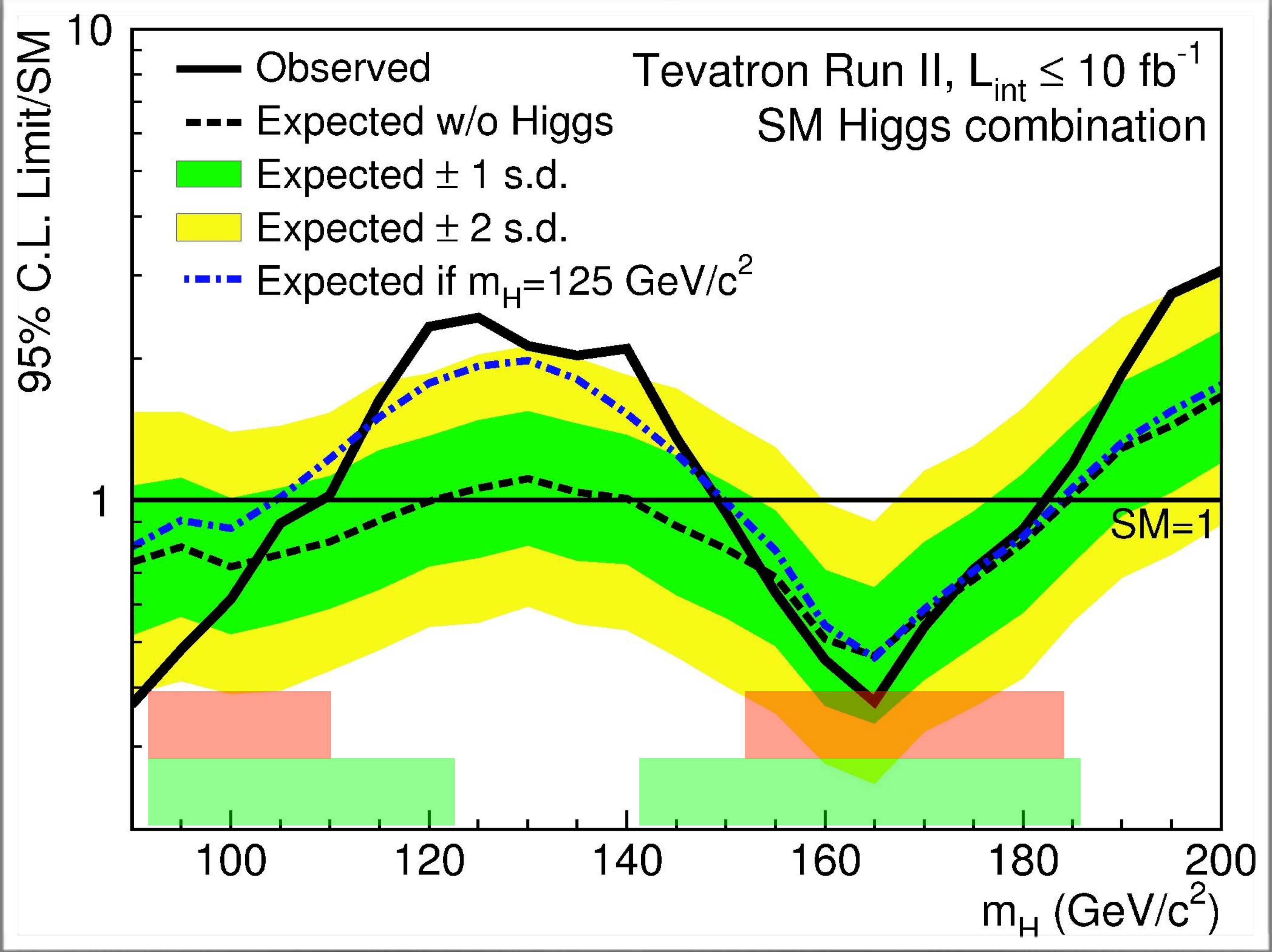
Spring 2013

Tevatron
1983-2011



Observed
Expected w/o Higgs
Expected ± 1 s.d.
Expected ± 2 s.d.
Expected if m_H=125 GeV/c^2
Tevatron Run II, $L_{int} \leq 10\ fb^{-1}$
SM Higgs combination
SM=1
95% C.L. Limit/SM
10
1
100
120
140
160
180
200
m_H (GeV/c^2)

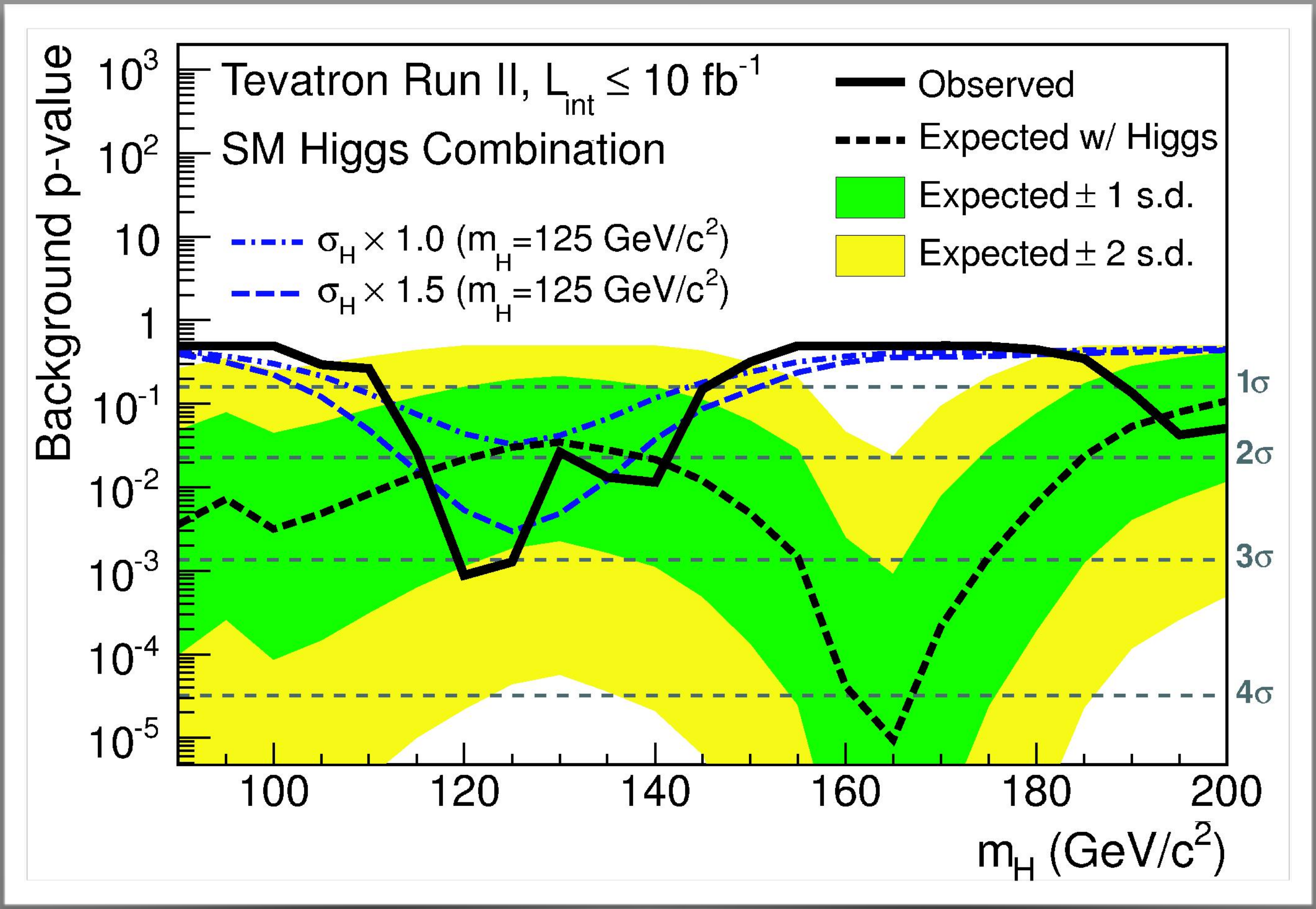
Spring 2013



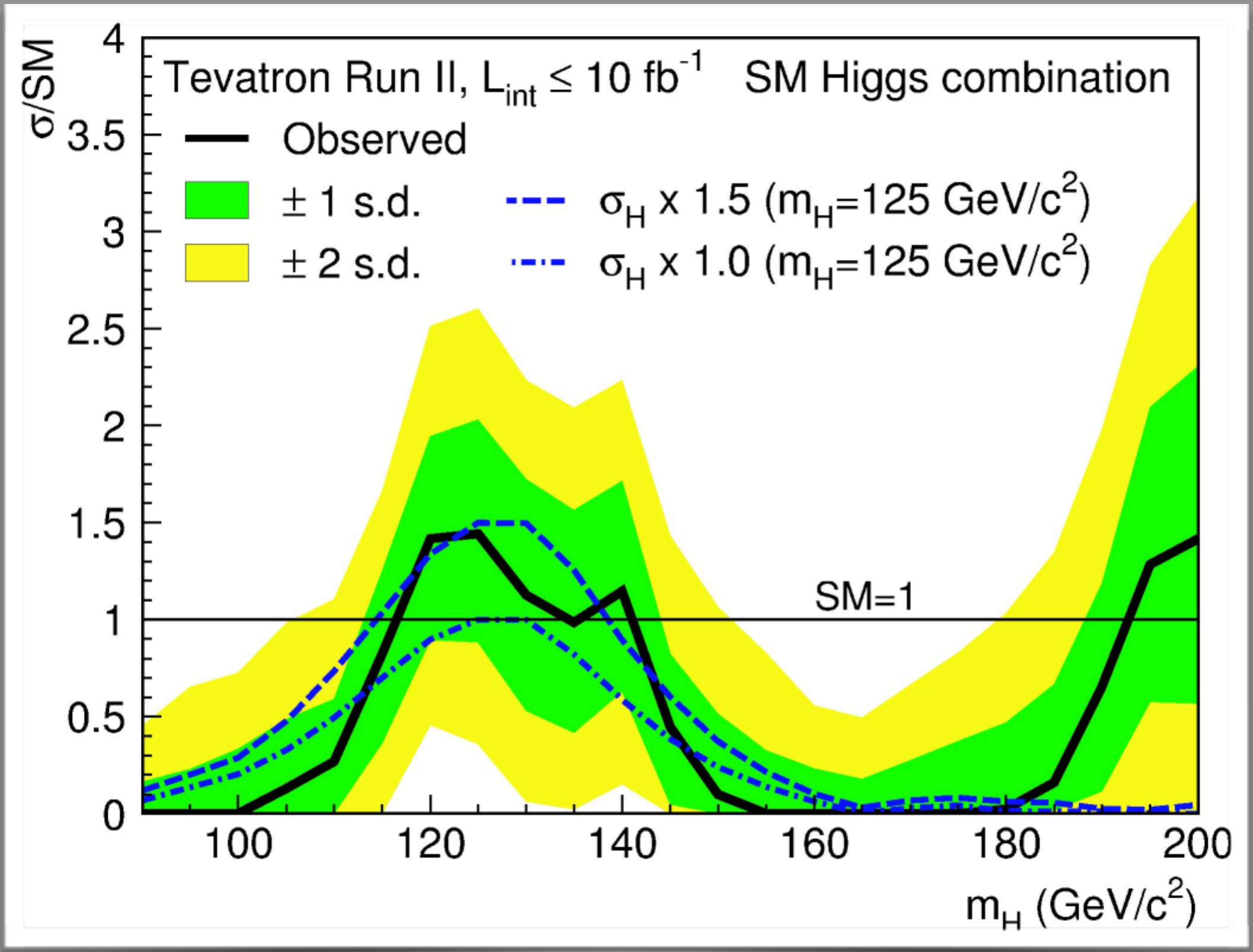
Expected Exclusion | Observed Exclusion

p-val·ue noun :

probability of an outcome as extreme as that observed, assuming the null hypothesis is true.



Production Rates



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

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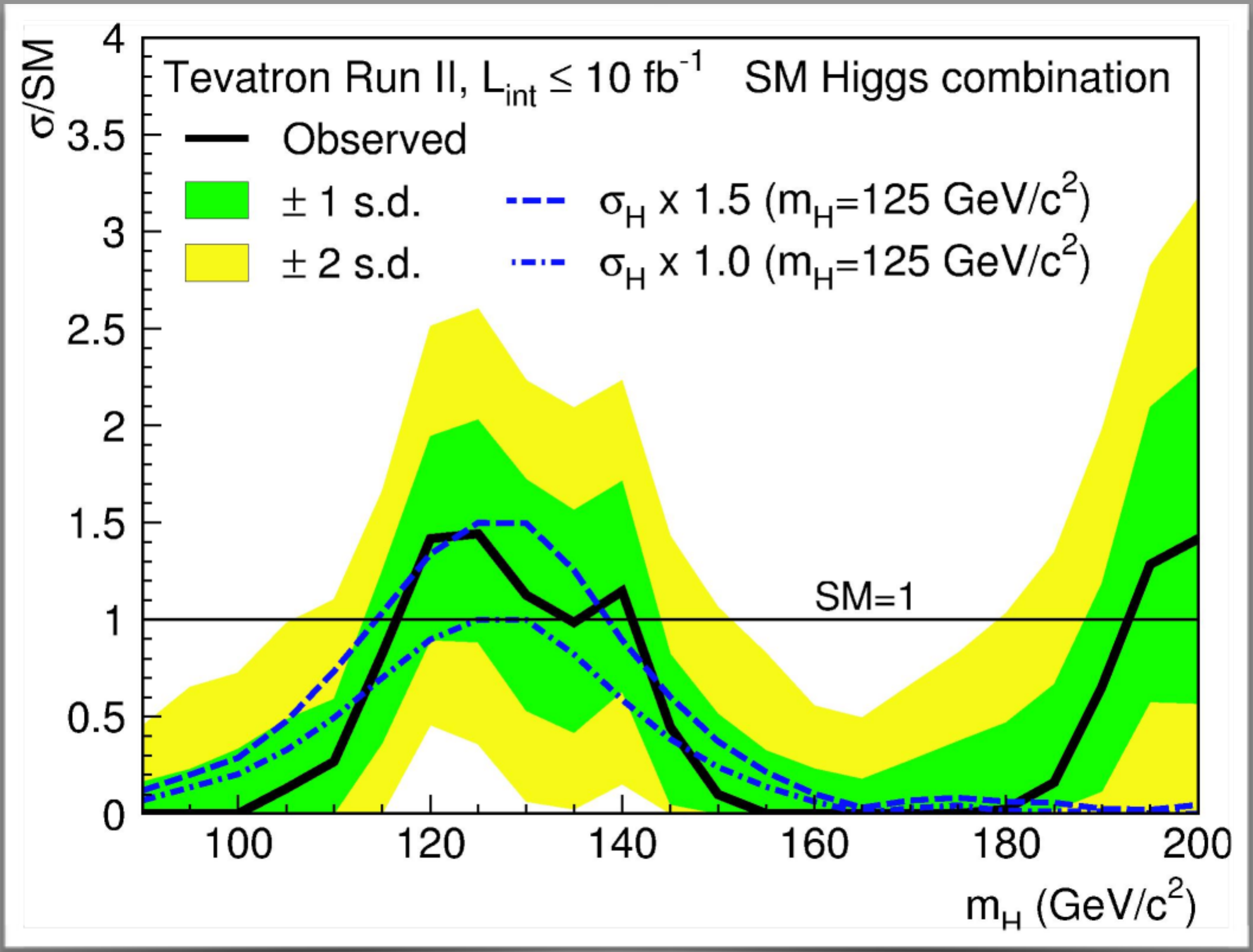

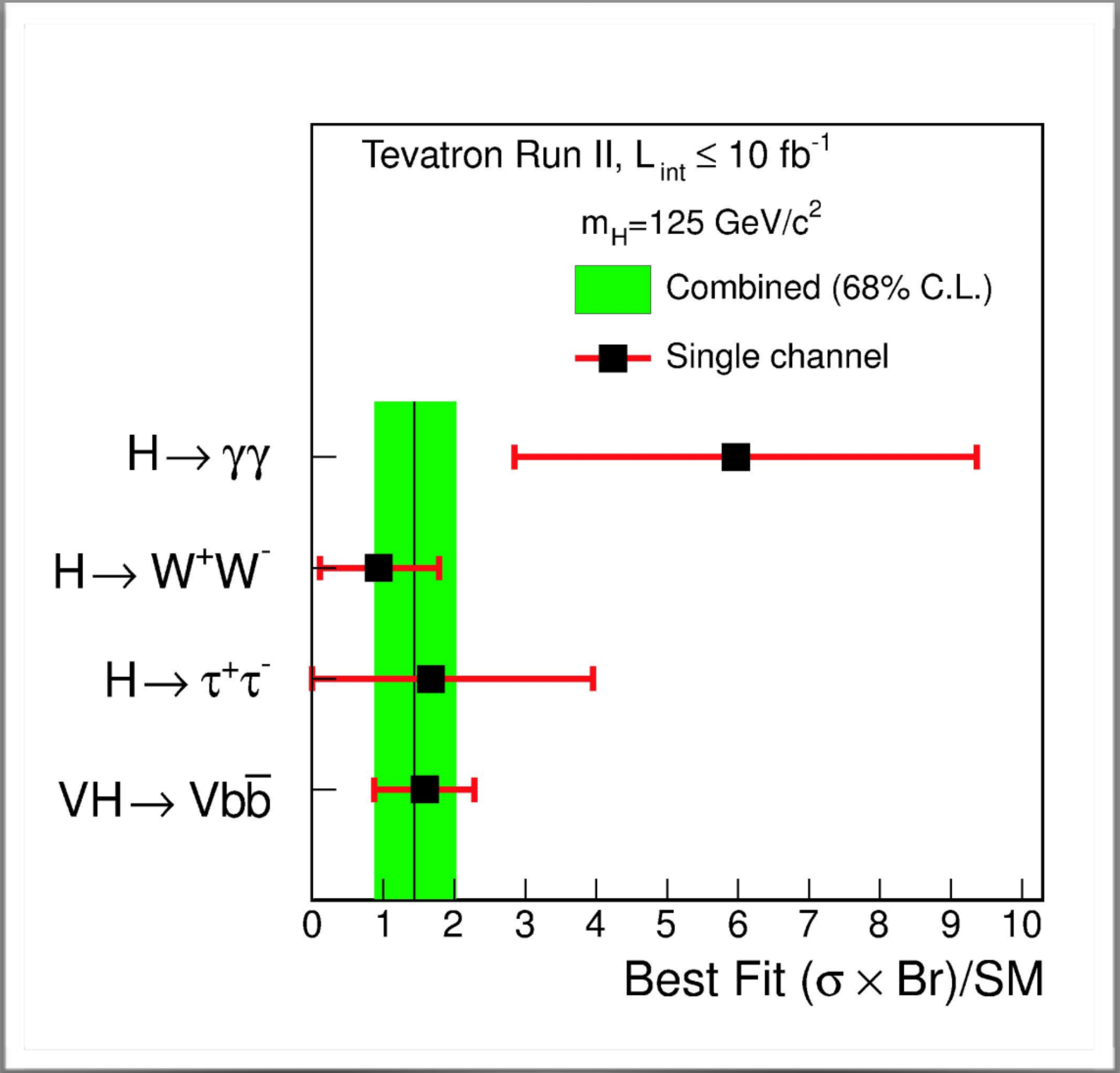

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$$\mu_{H\rightarrow b\bar{b}} = 1.59^{+0.69}_{-0.72}$$

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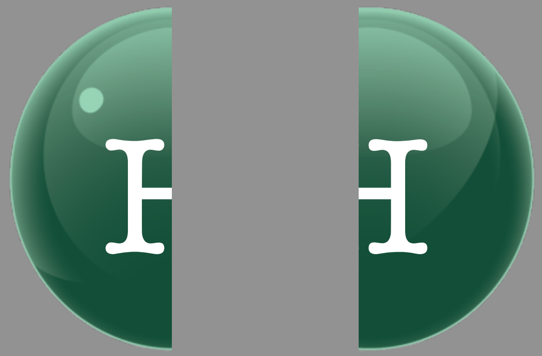

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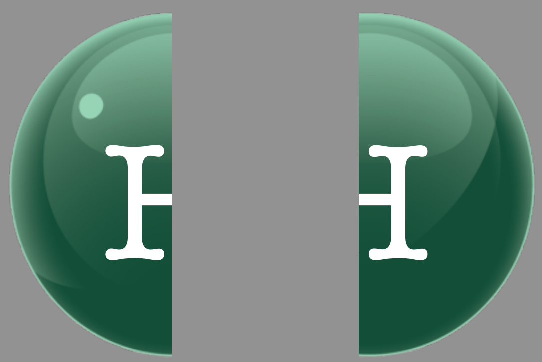



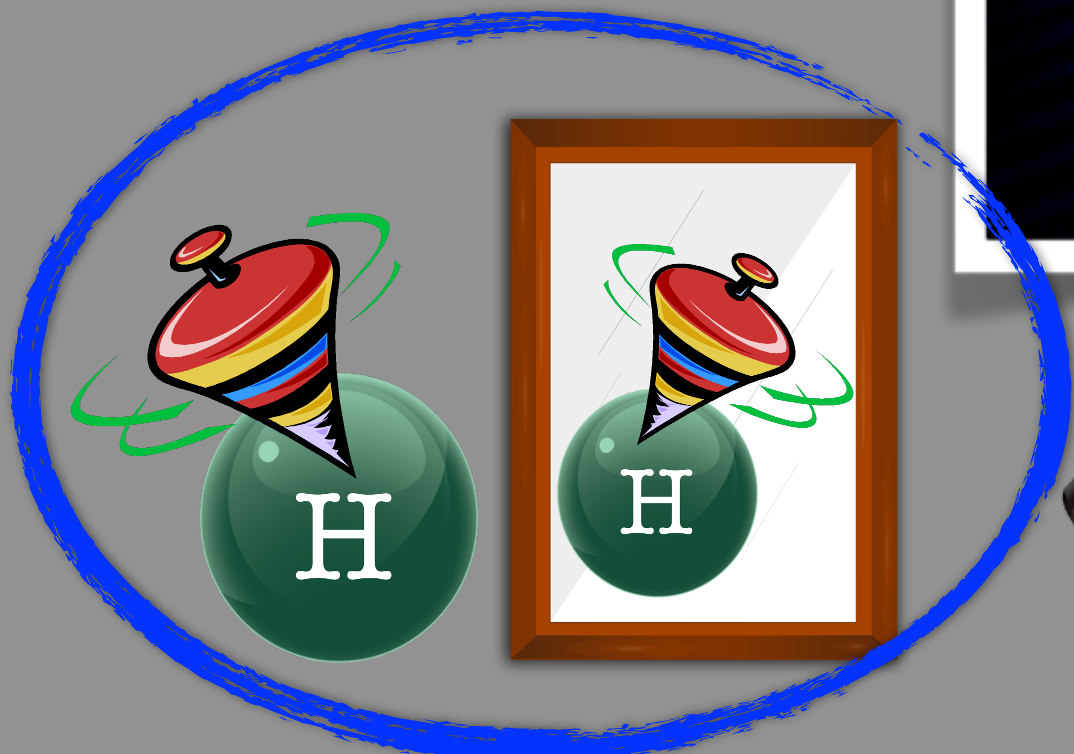

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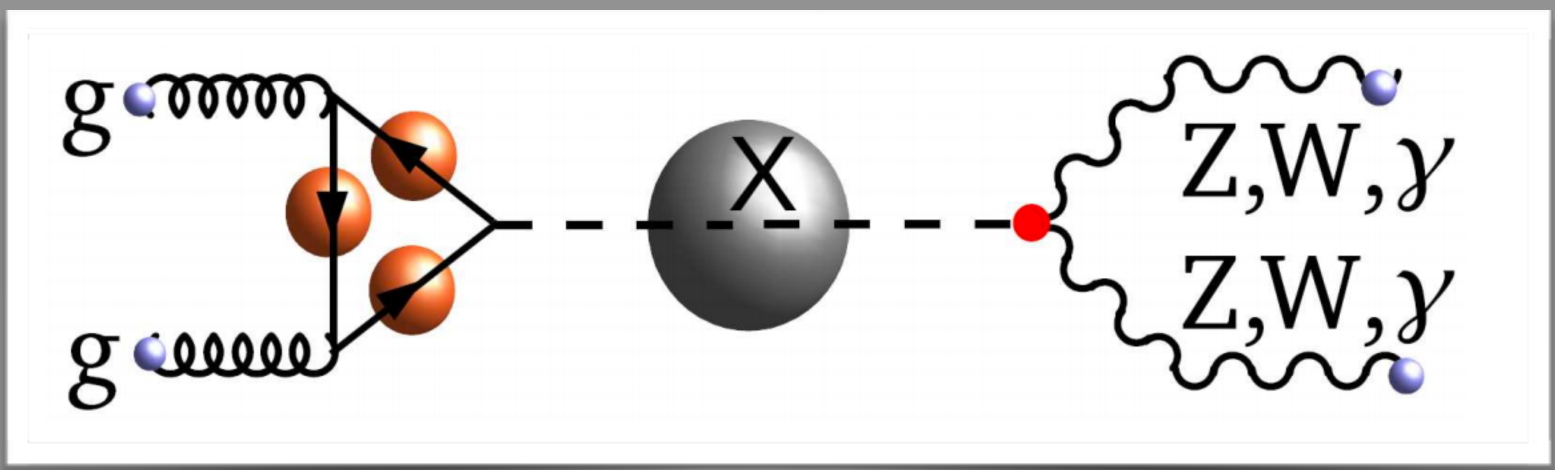
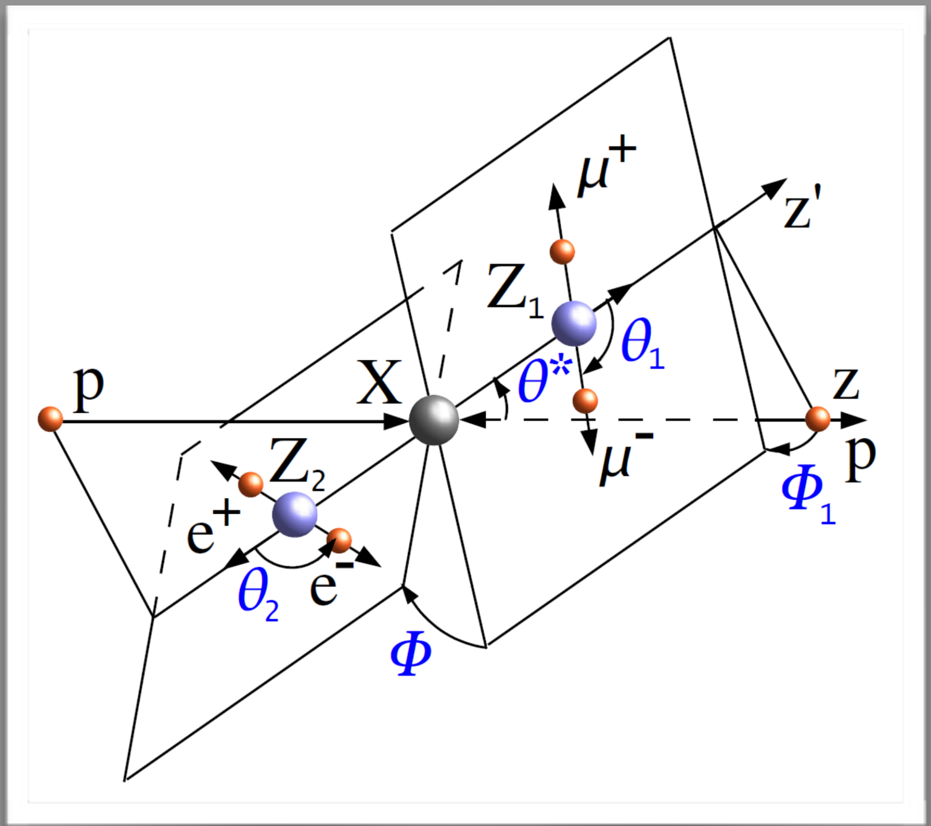
2^+ 2^-	Graviton-like tensor, or pseudo-tensor	Many assumptions to be made, depending on the model constructed

At the LHC, it's all about the angles.





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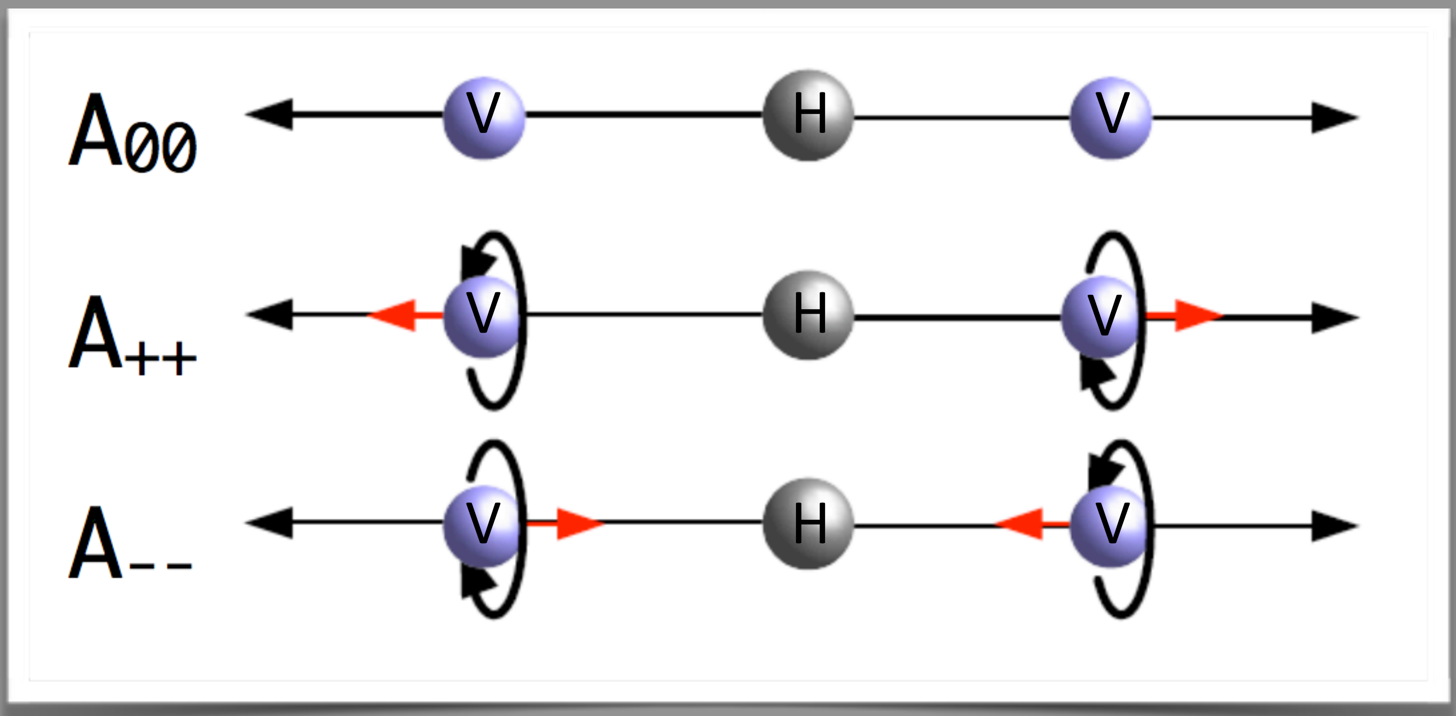

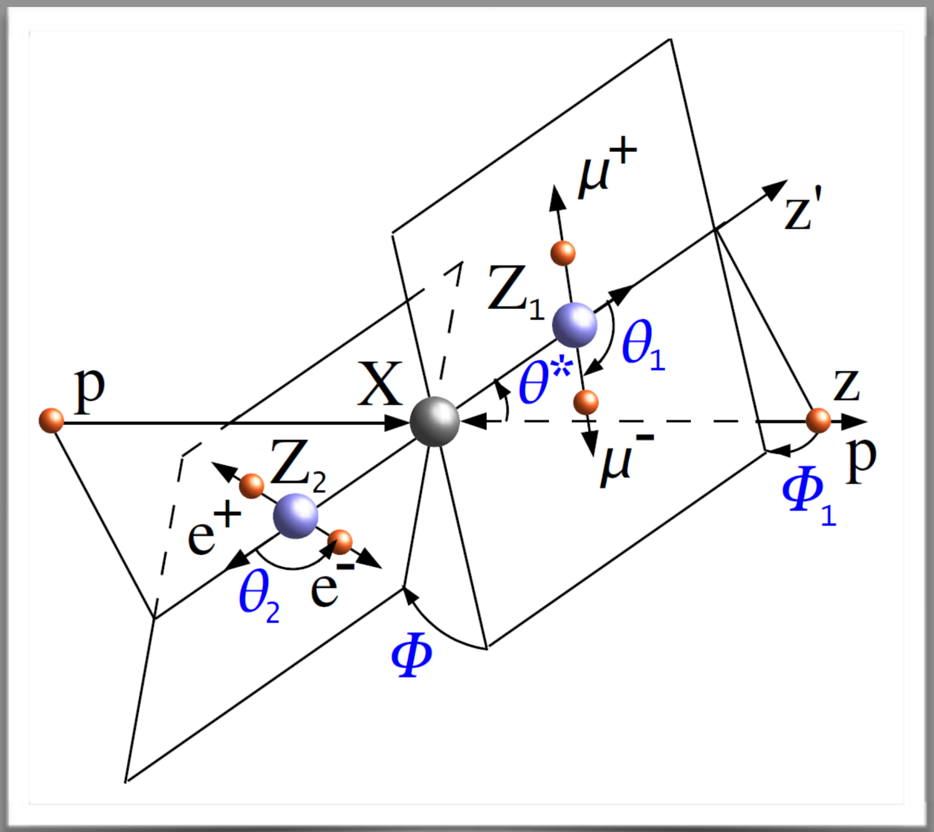

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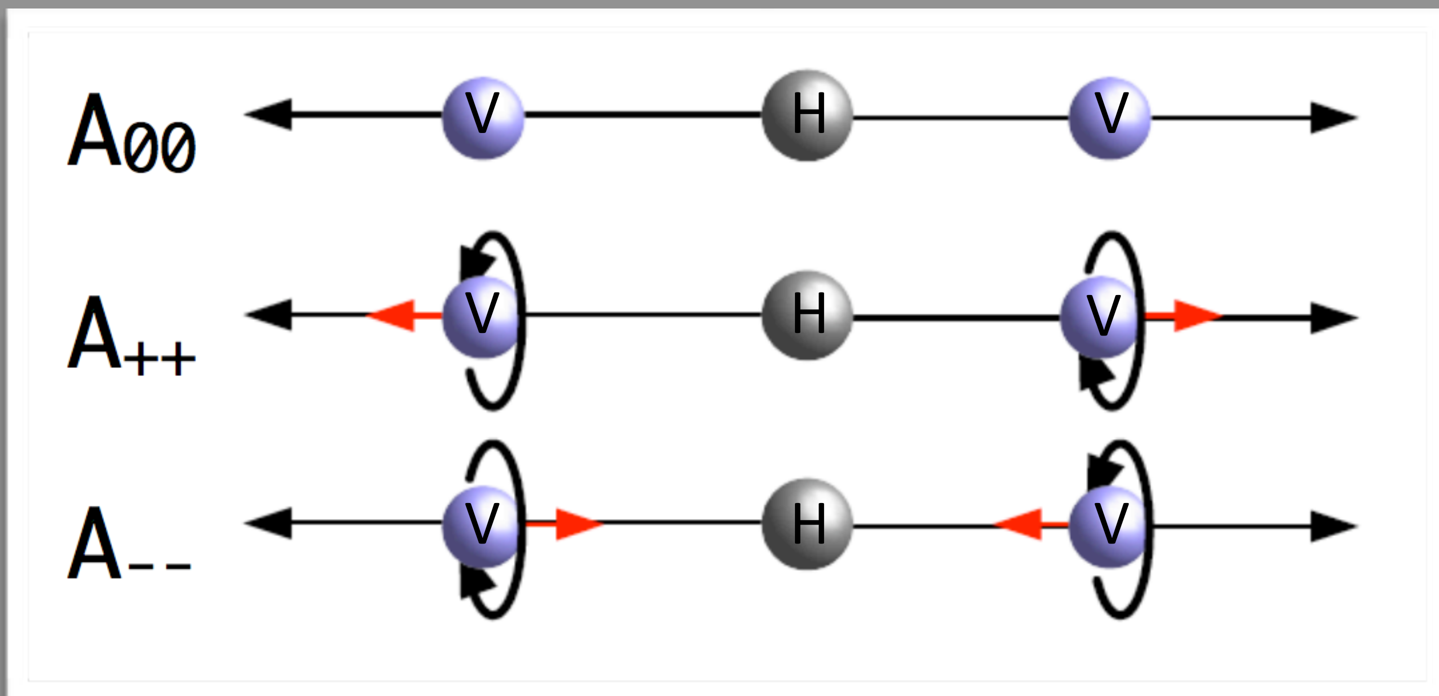

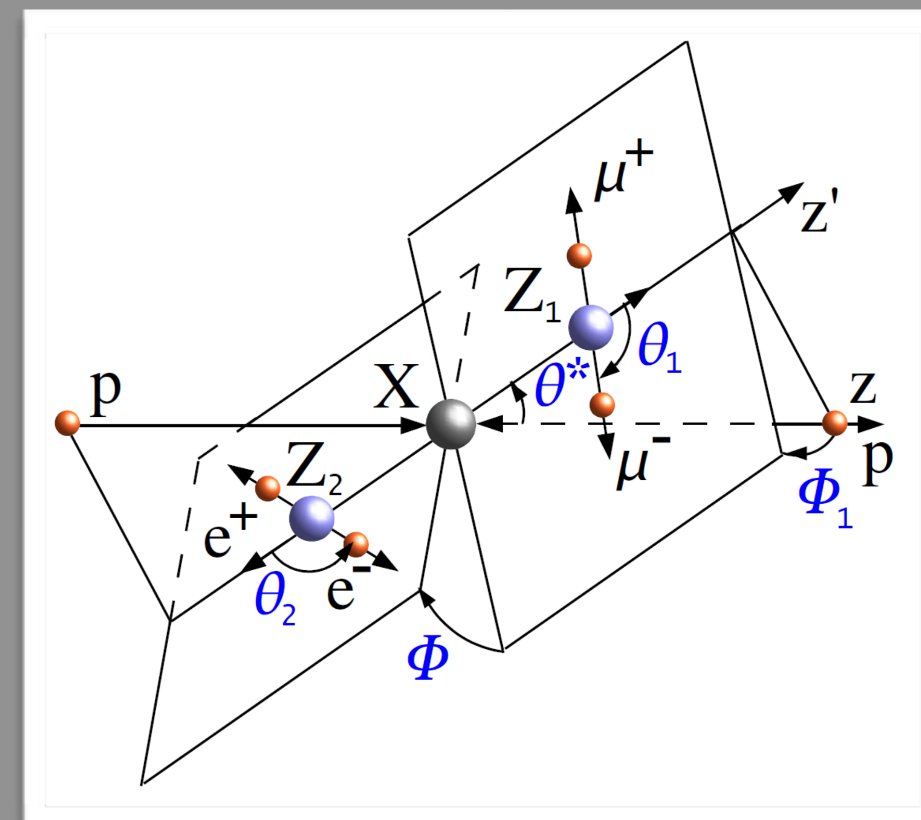

$$A_{00} = -\frac{M_x^2}{v}\left(a_1\chi + a_2\eta(\chi^2 - 1)\right)$$

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

Vector boson helicity amplitudes

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

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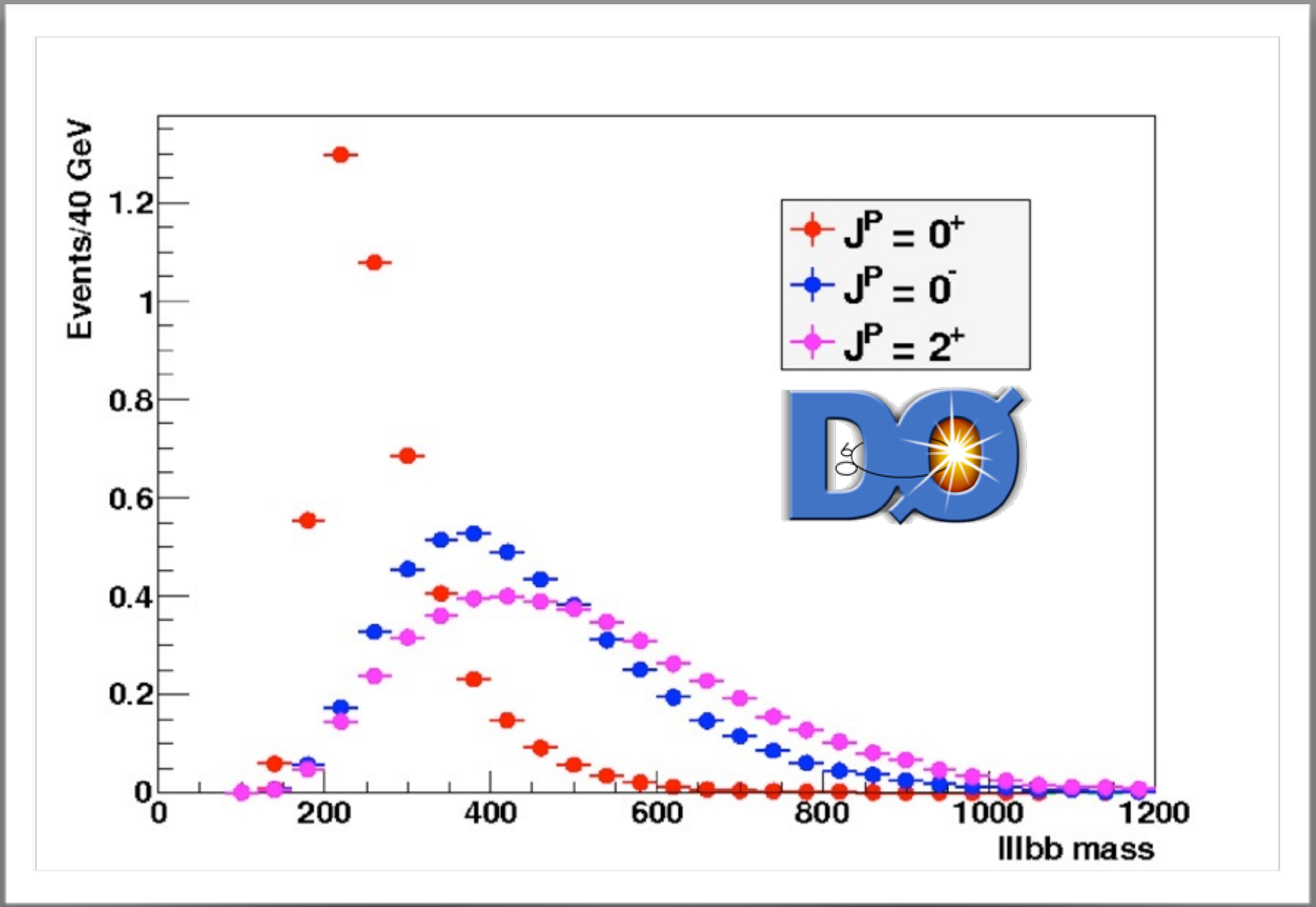
$$\sigma(V^\star \to VH) \propto \beta \sum_{ij} |A_{ij}|^2$$

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)



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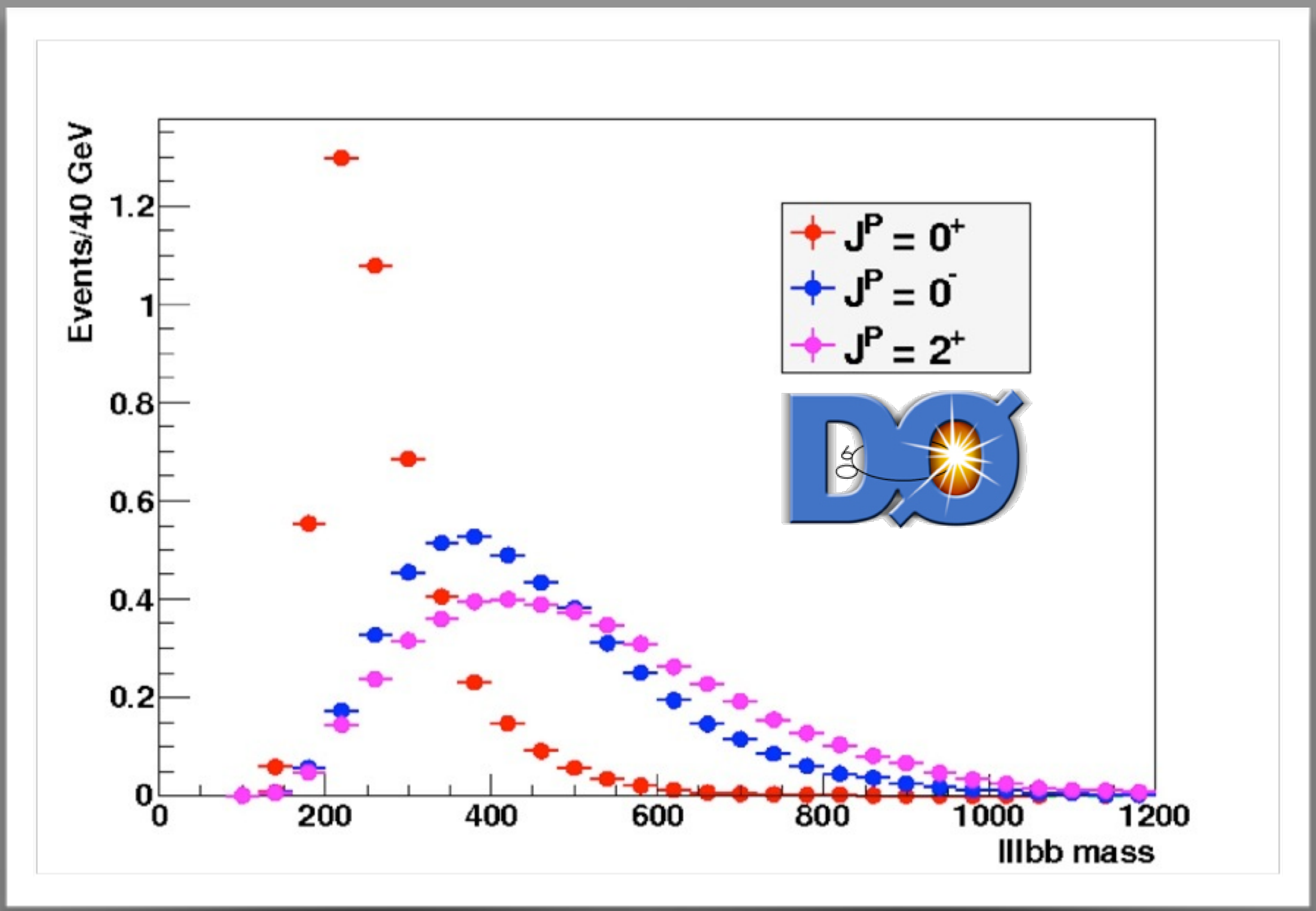
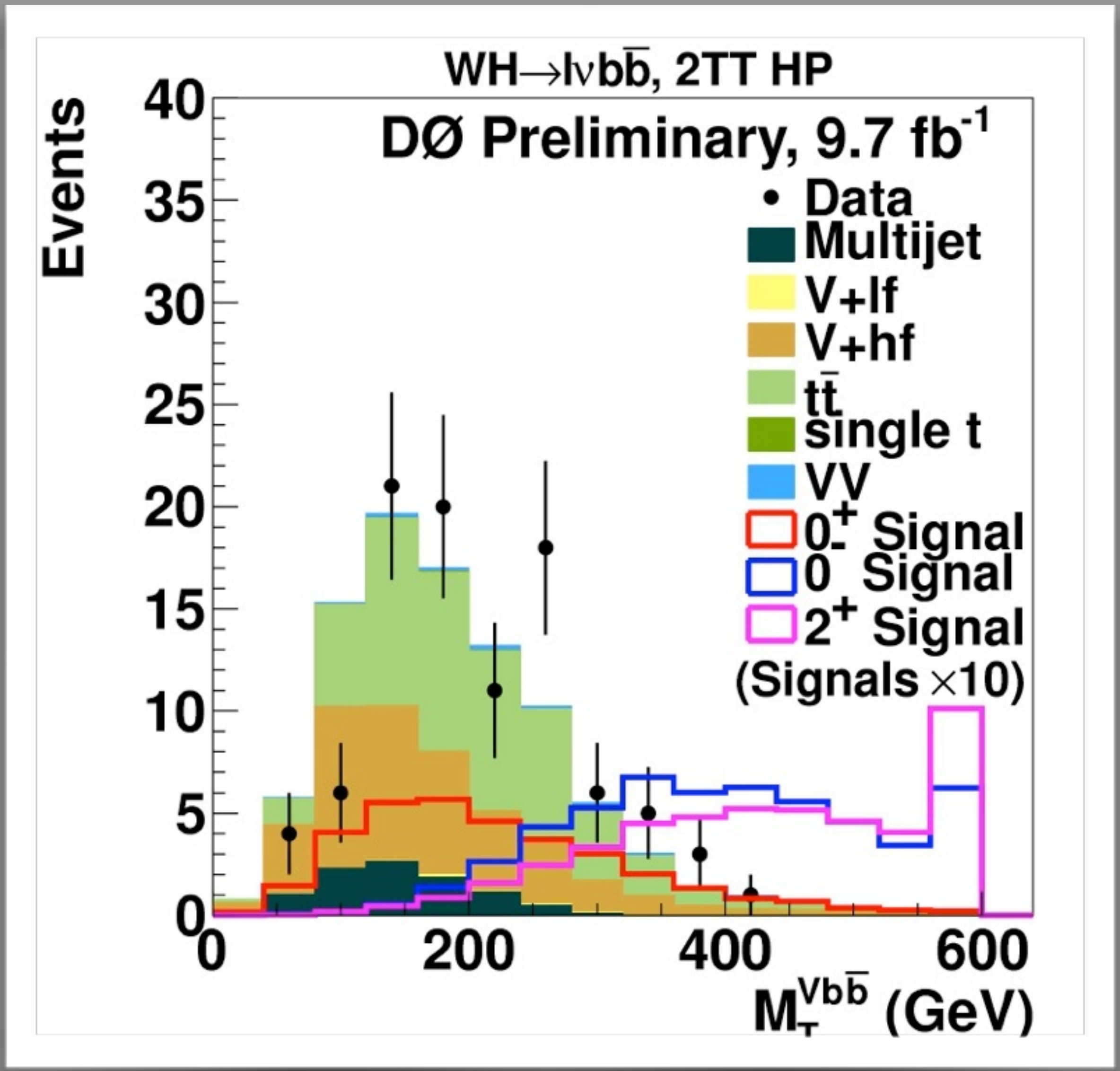
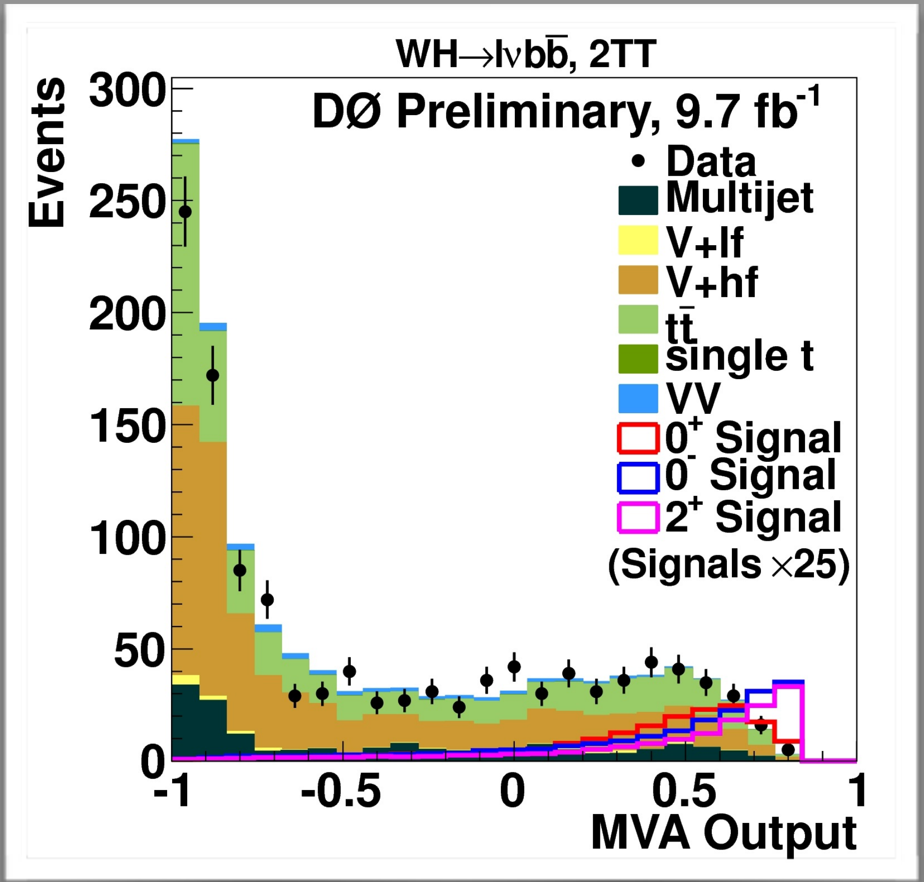
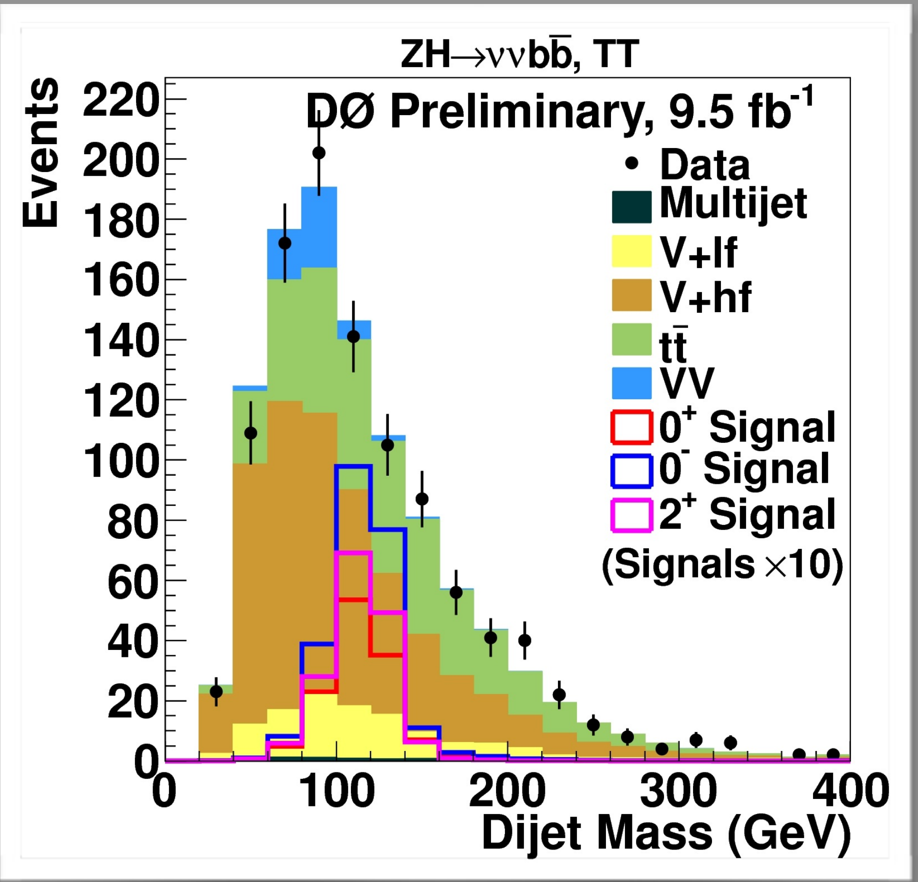
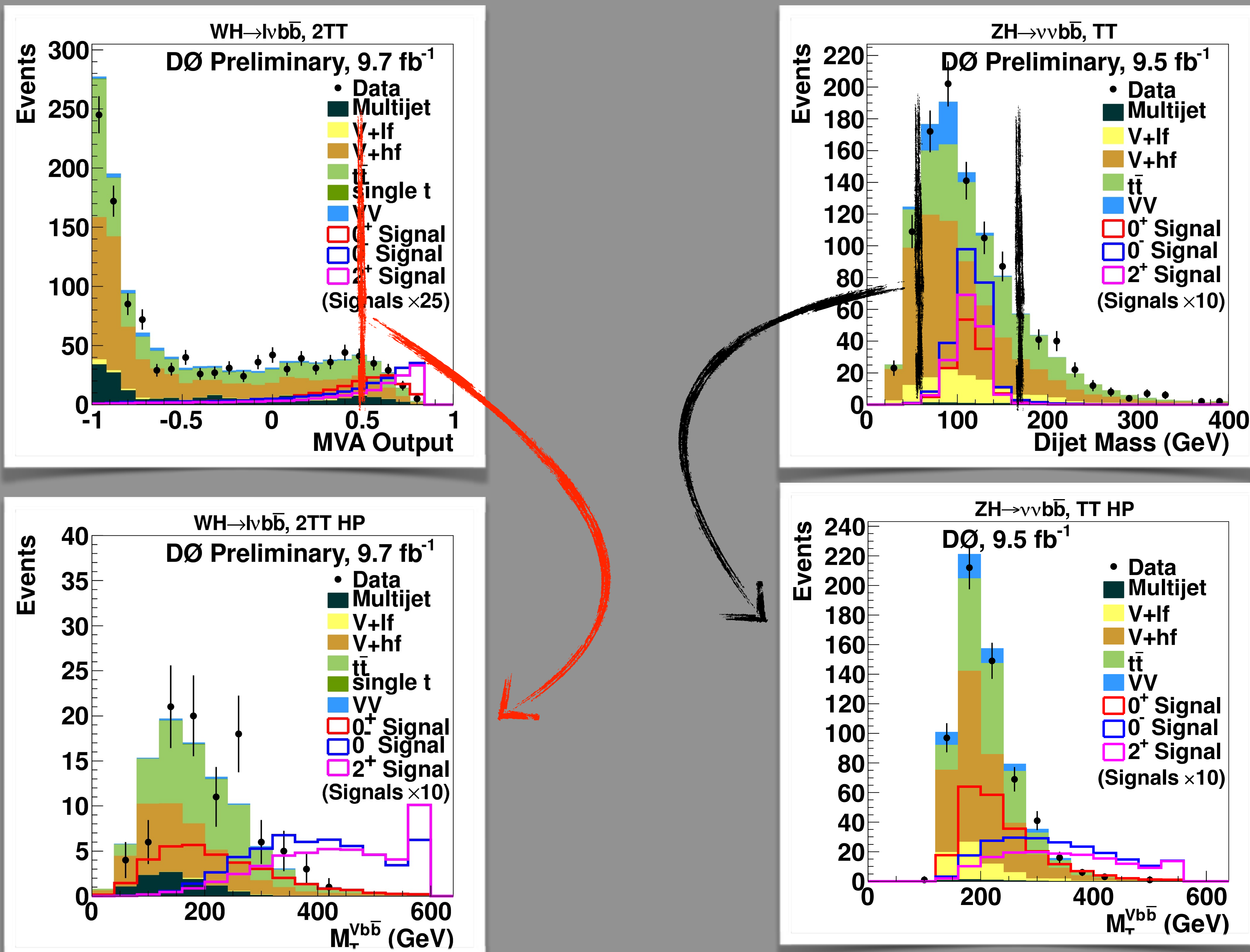





WH→lνbb̄, 2TT
DØ Preliminary, 9.7 fb⁻¹
Events
MVA Output
Data
Multijet
V+lf
V+hf
tt̄
single t
VV
0+ Signal
0- Signal
2+ Signal
(Signals ×25)


ZH→ννbb̄, TT
DØ Preliminary, 9.5 fb⁻¹
Events
Dijet Mass (GeV)
Data
Multijet
V+lf
V+hf
tt̄
VV
0+ Signal
0- Signal
2+ Signal
(Signals ×10)



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Dijet Mass (GeV)
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(Signals ×10)
M_T^Vbb̄ (GeV)
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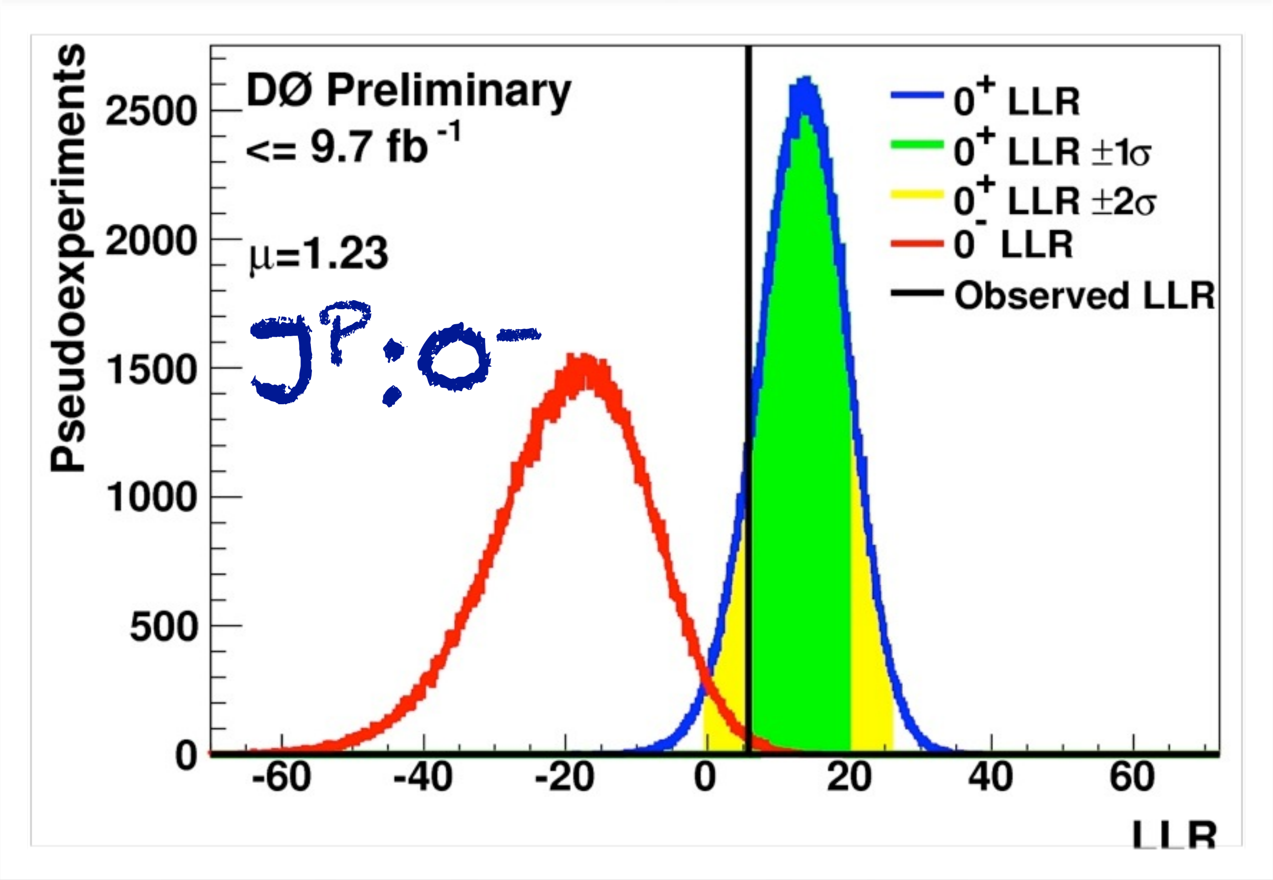
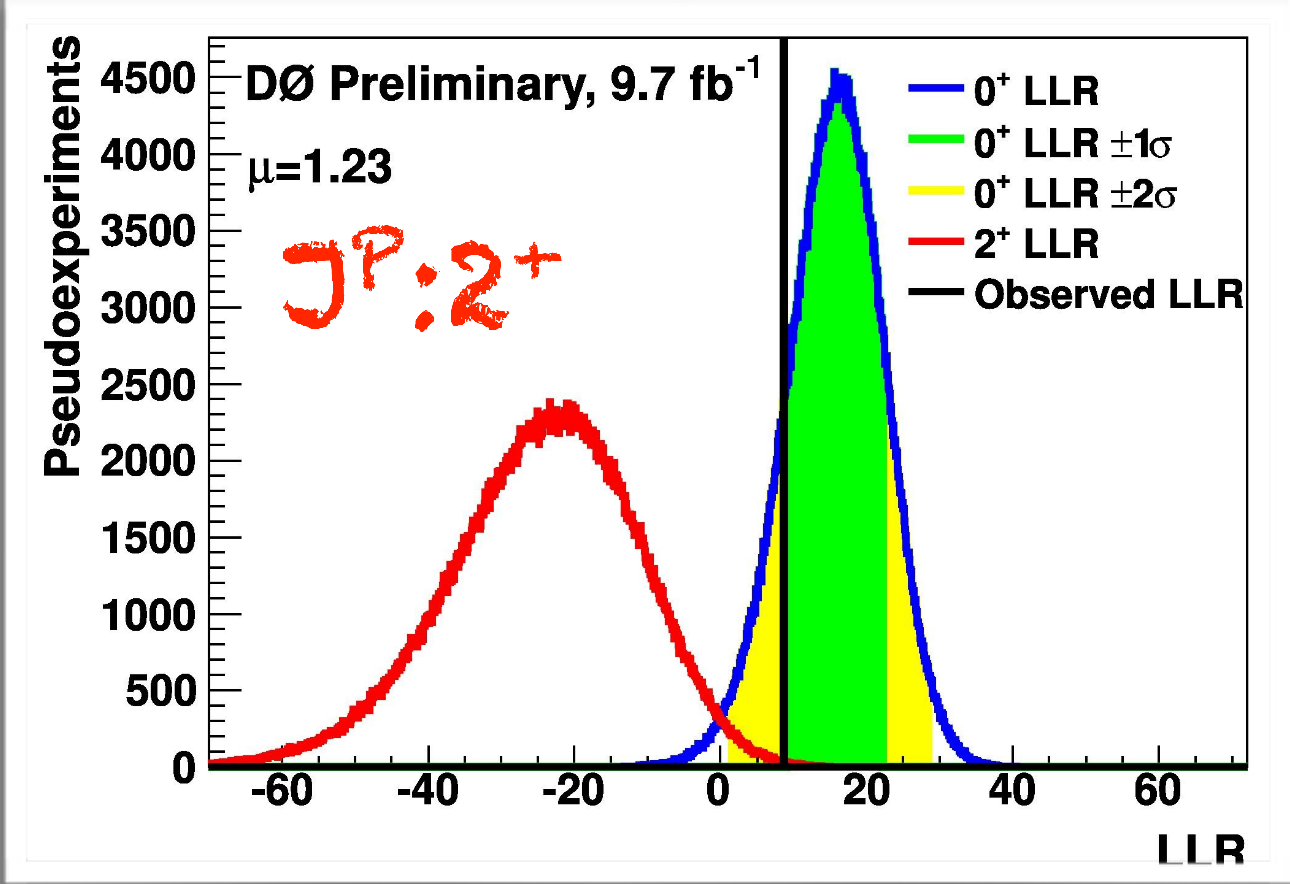
M_T^Vbb̄ (GeV)

DØ excludes J^P models using H→bb decays

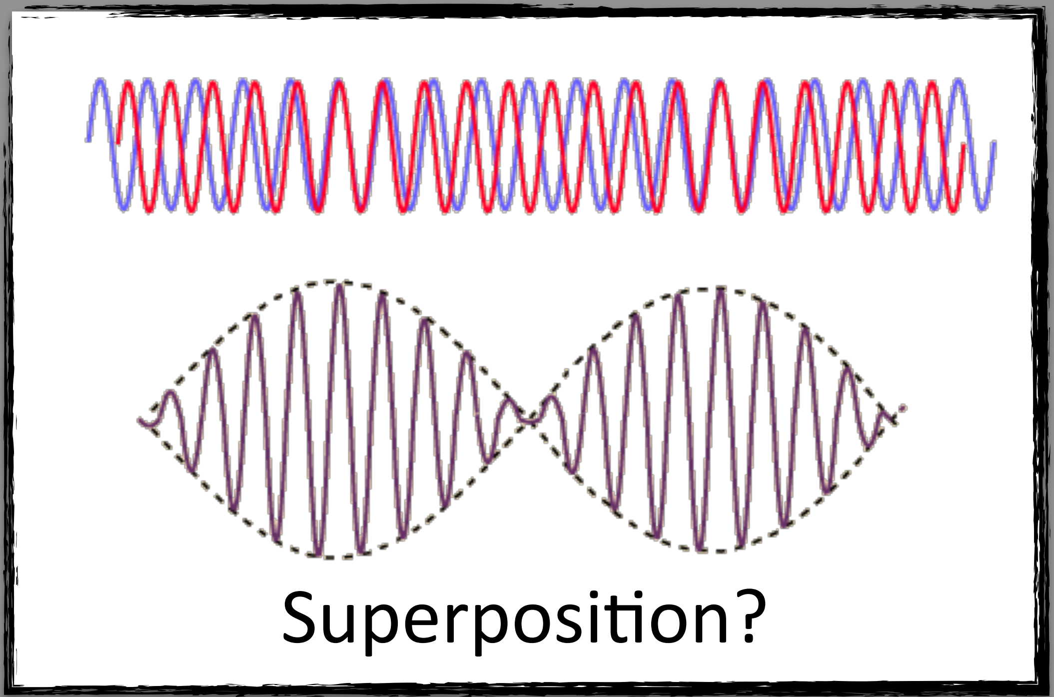
- $J^P=0^-$ excluded at the **99.6%** C.L.
- $J^P=2^+$ excluded at the **99.9%** C.L.





$$\mu^{\text{fit}}_{H\to b\bar{b}} = 1.23$$

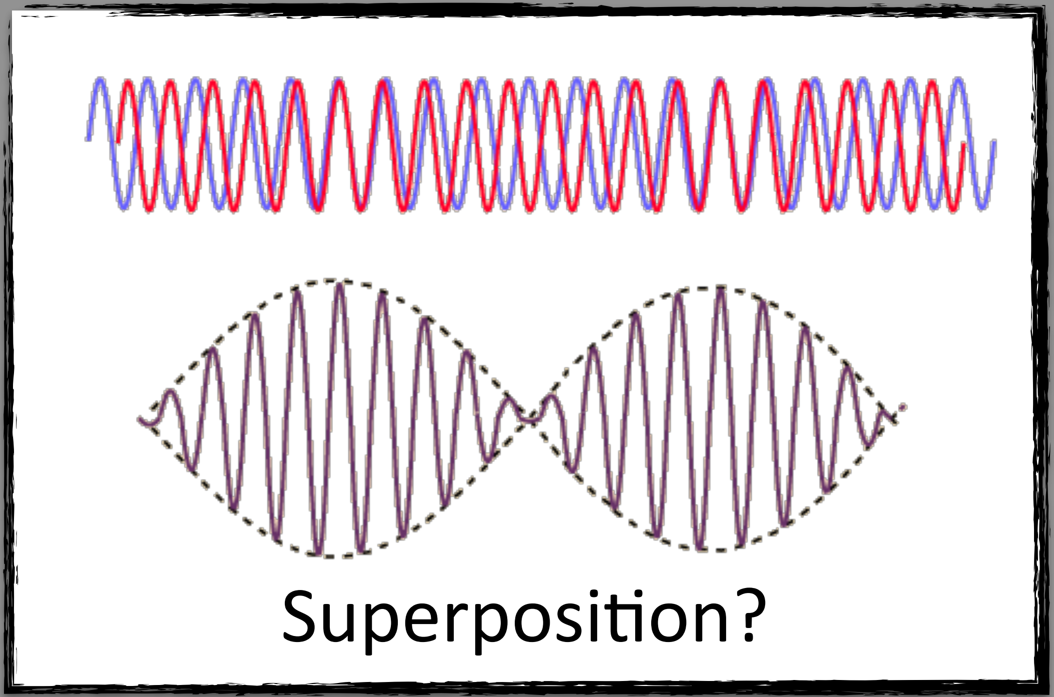
Is nature more complicated?



Is nature more complicated?

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

Eg, Two Higgs Doublet Model



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CP-Even

CP-Odd

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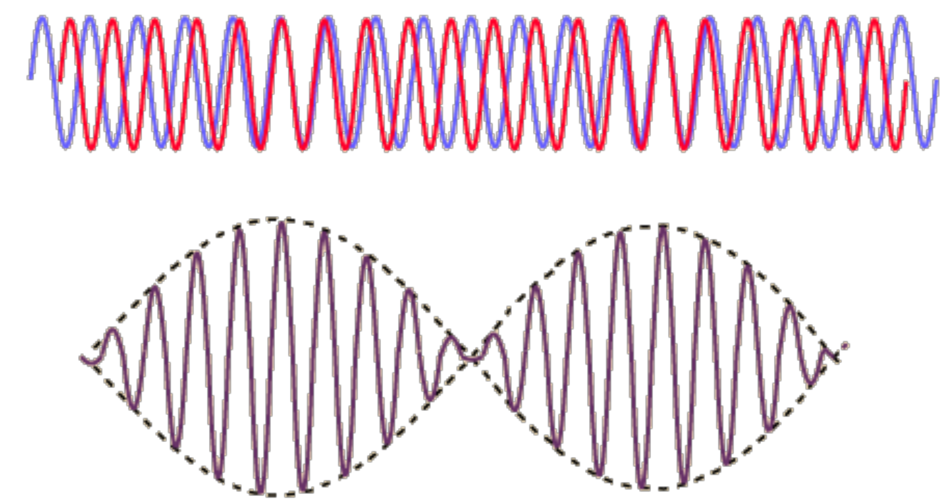
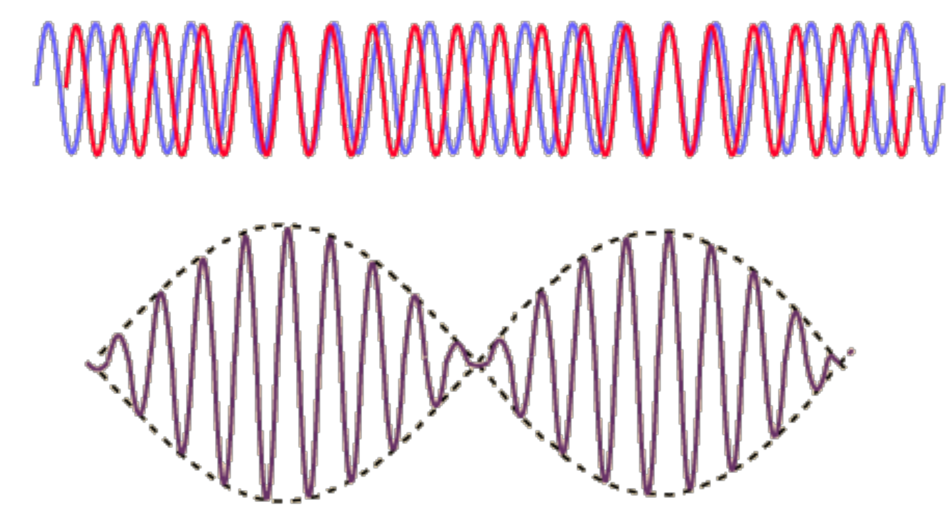


Superposition?

Is nature more complicated?



Superposition?

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

CP-Even (H)

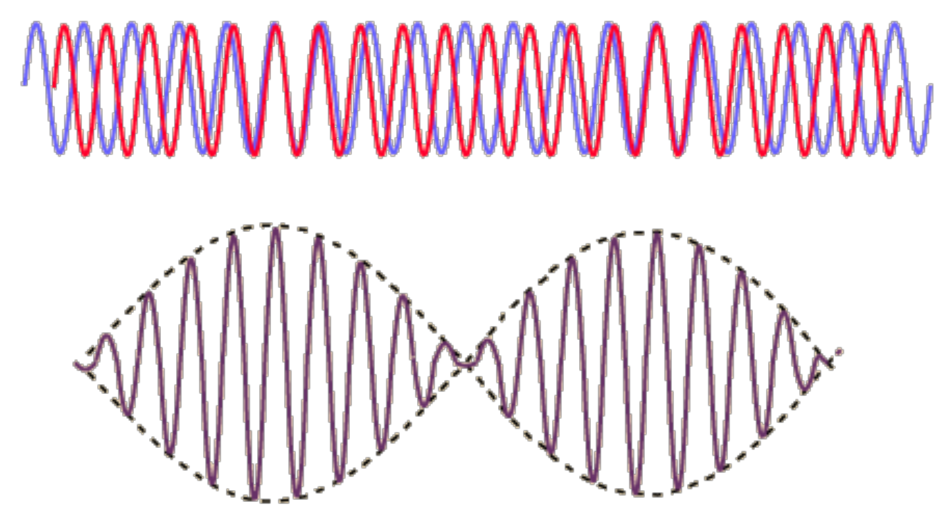
CP-Odd (A)

Eg, Two Higgs Doublet Model

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

What about this one??

Is nature more complicated?


Superposition?

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

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

Yukawa Couplings

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

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

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

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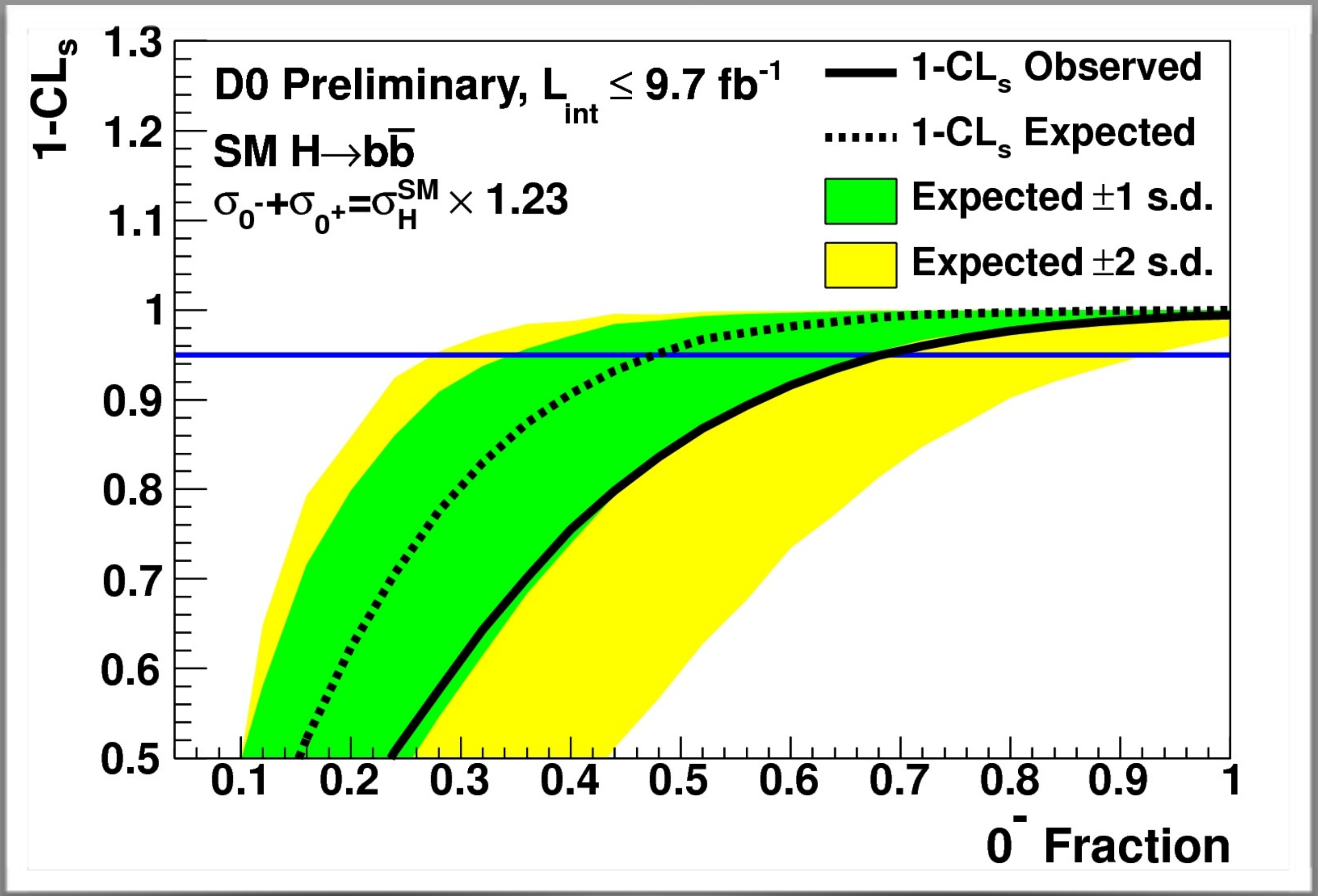

**Neglects Interference in Angular Variables*

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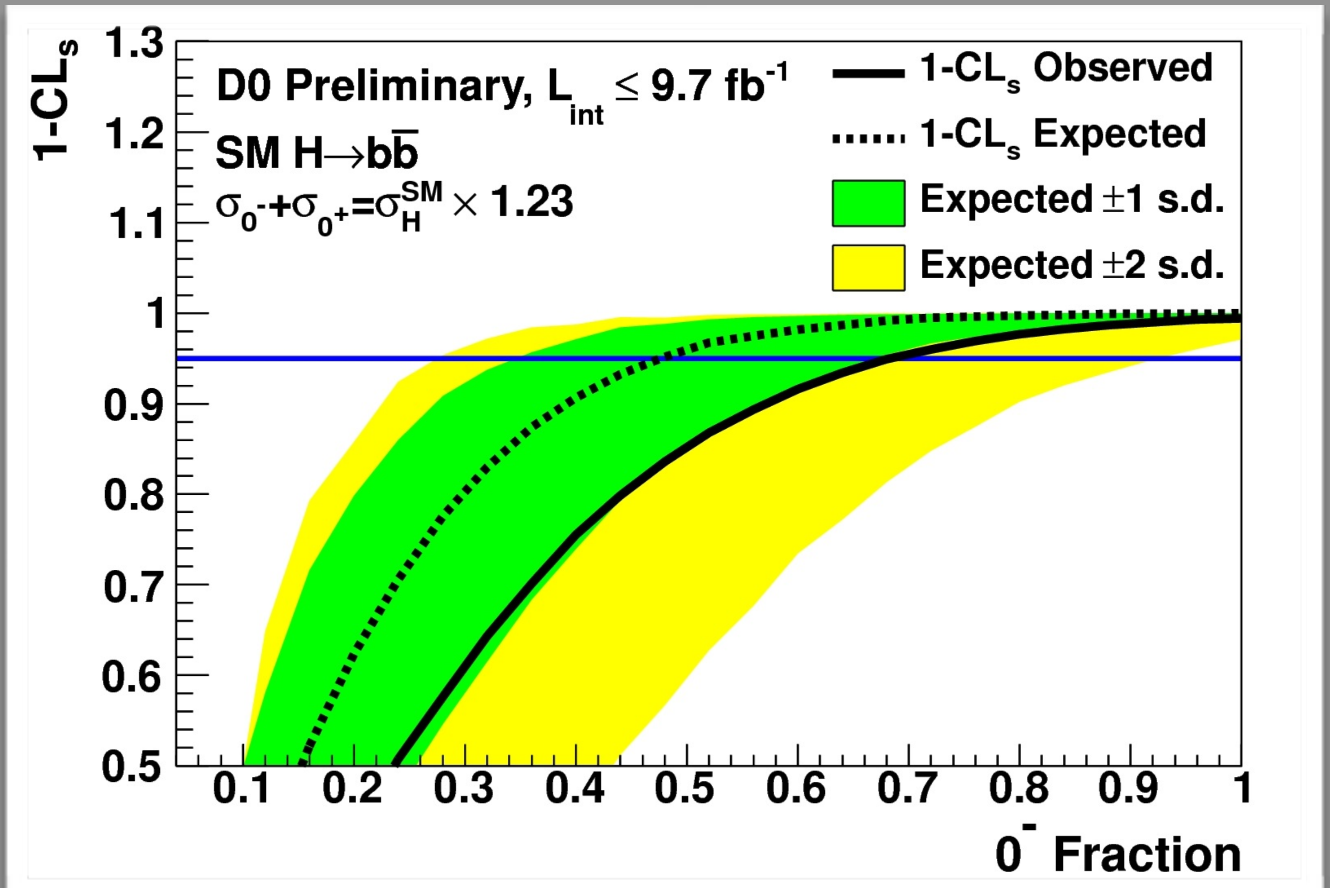

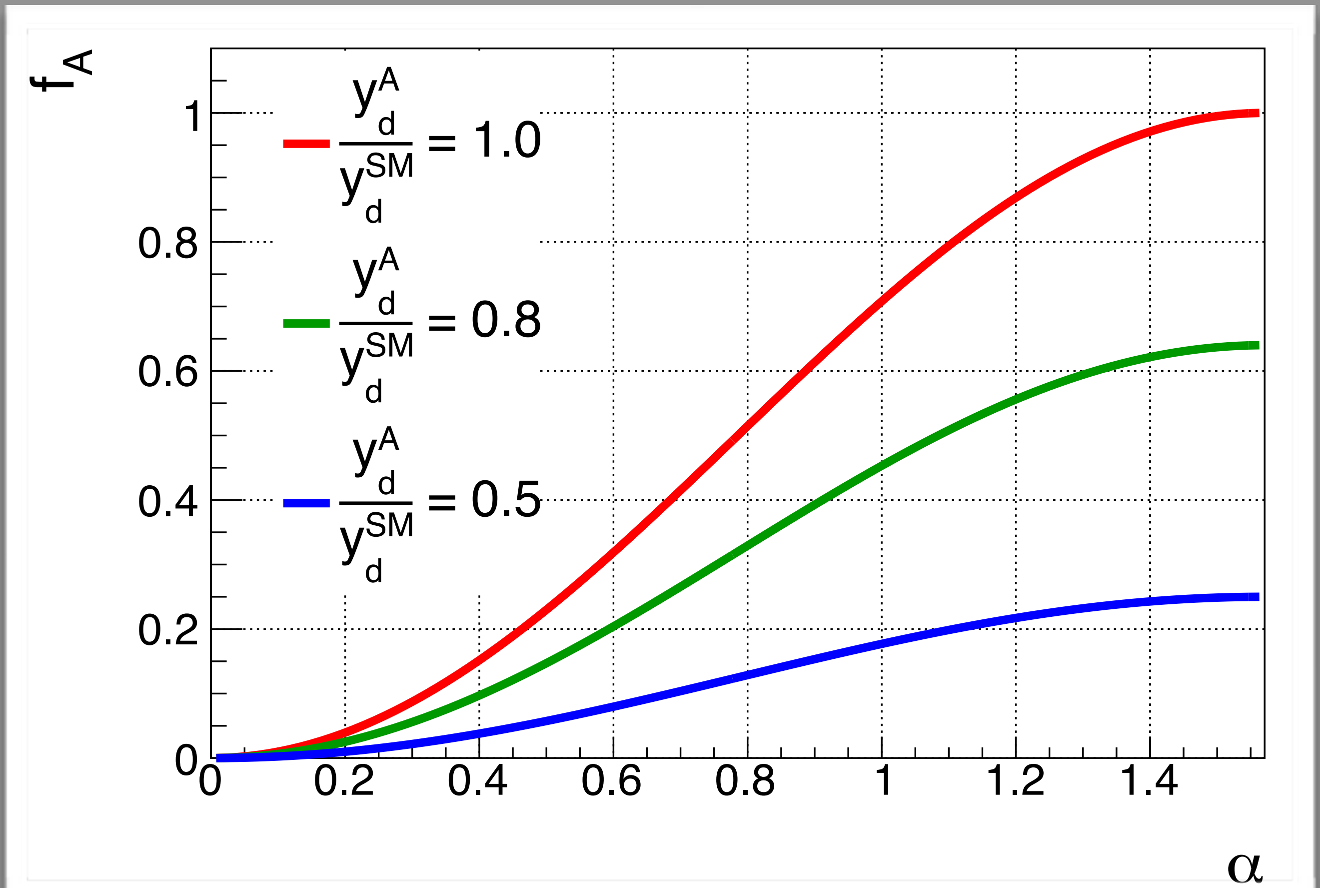

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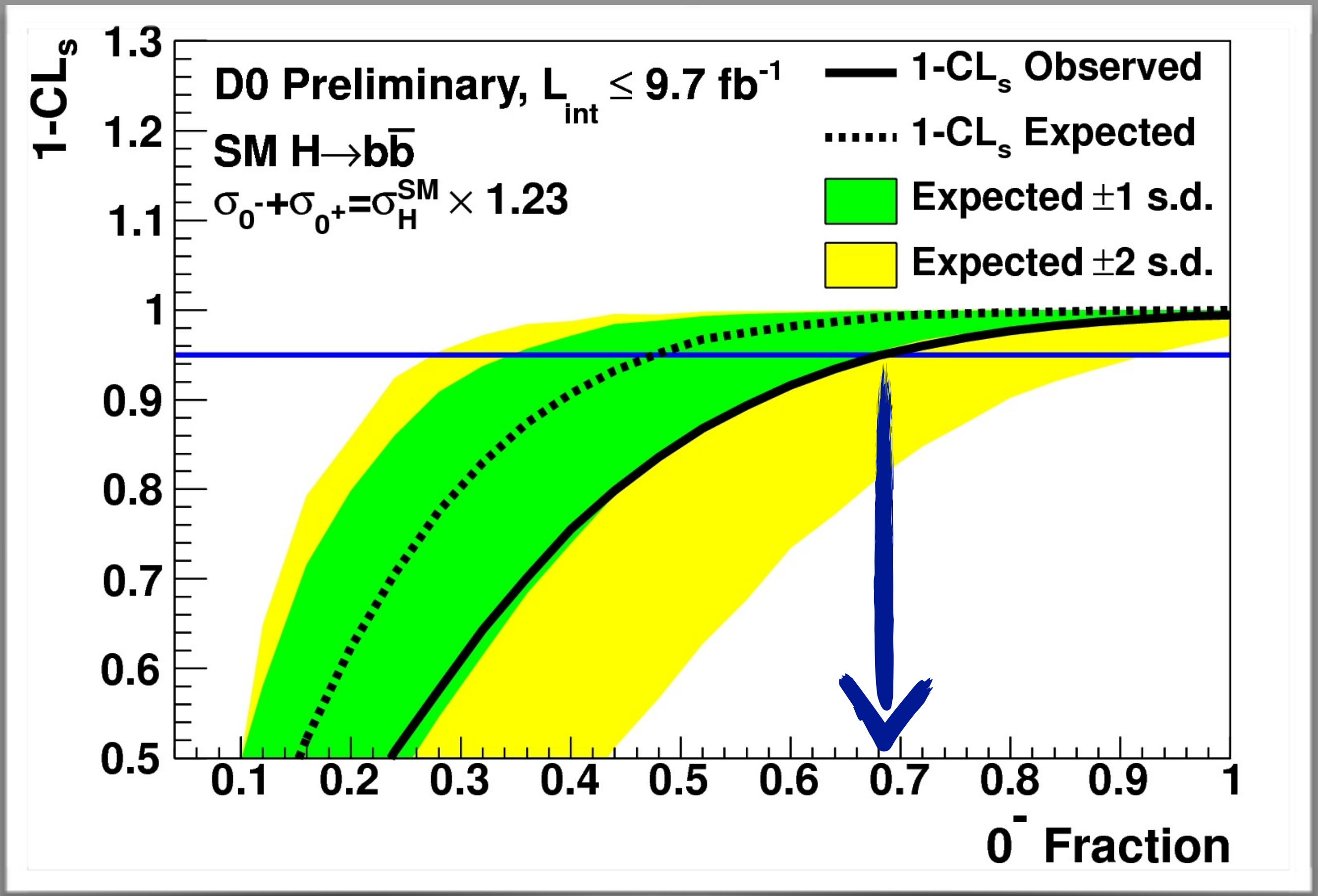
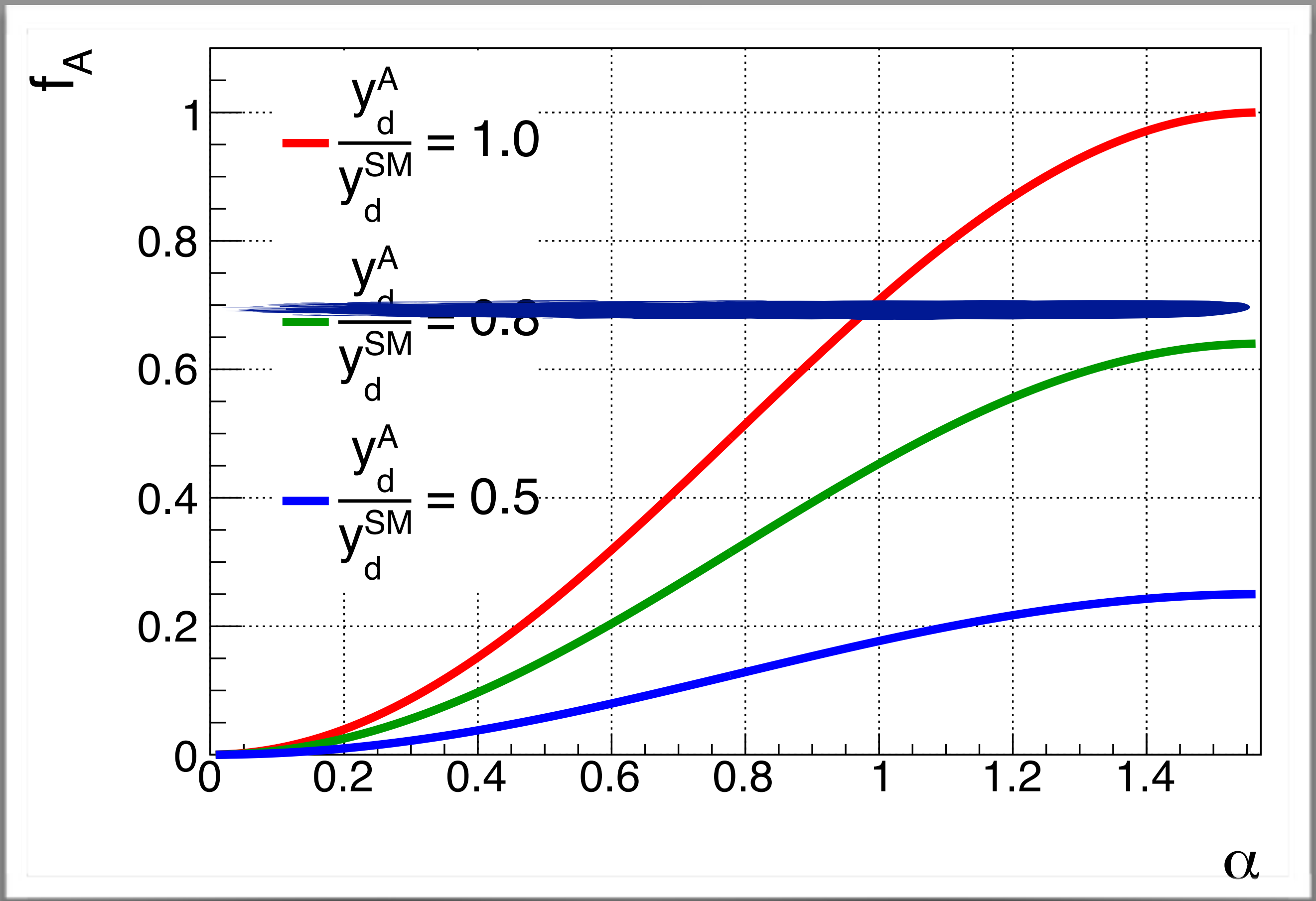
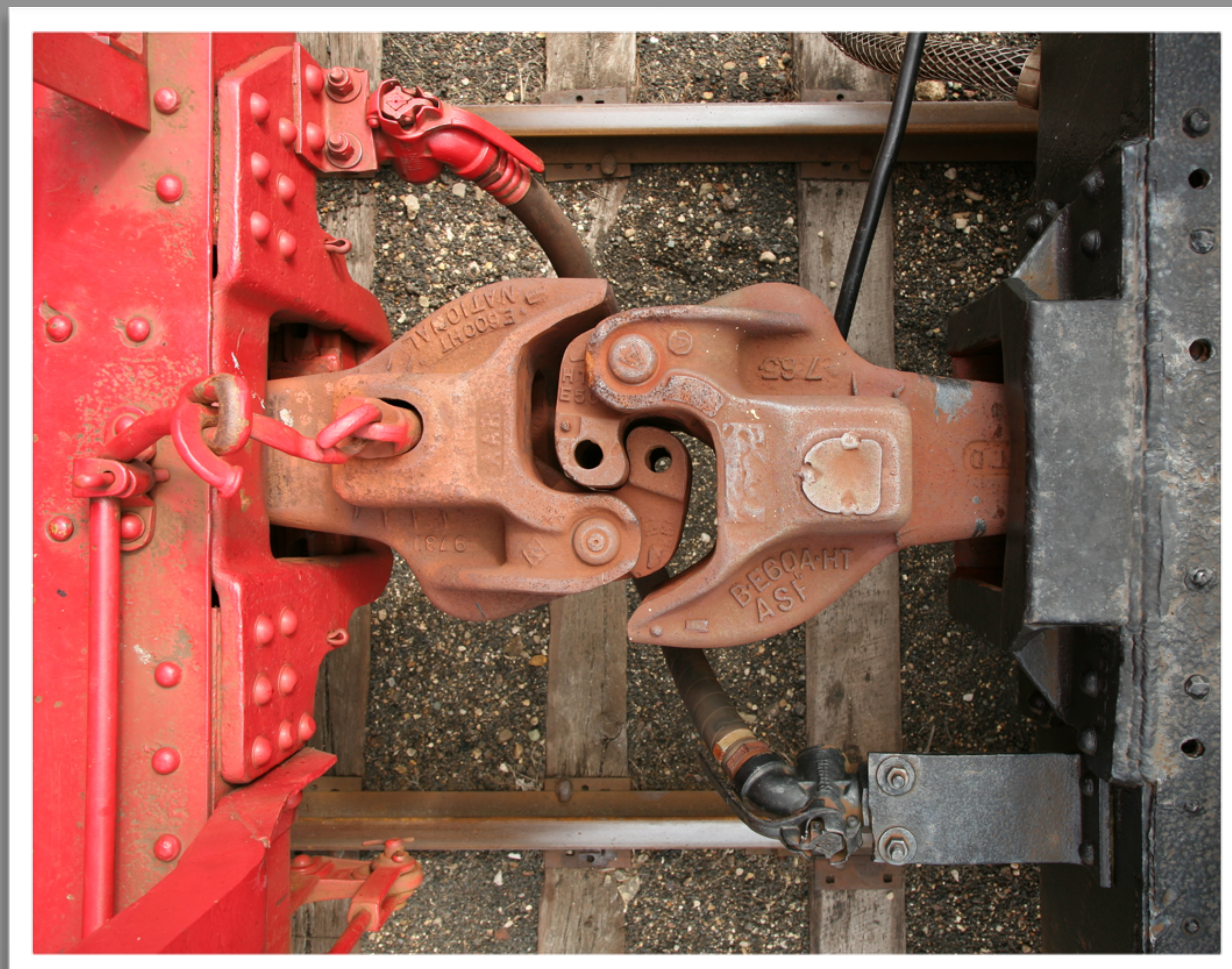
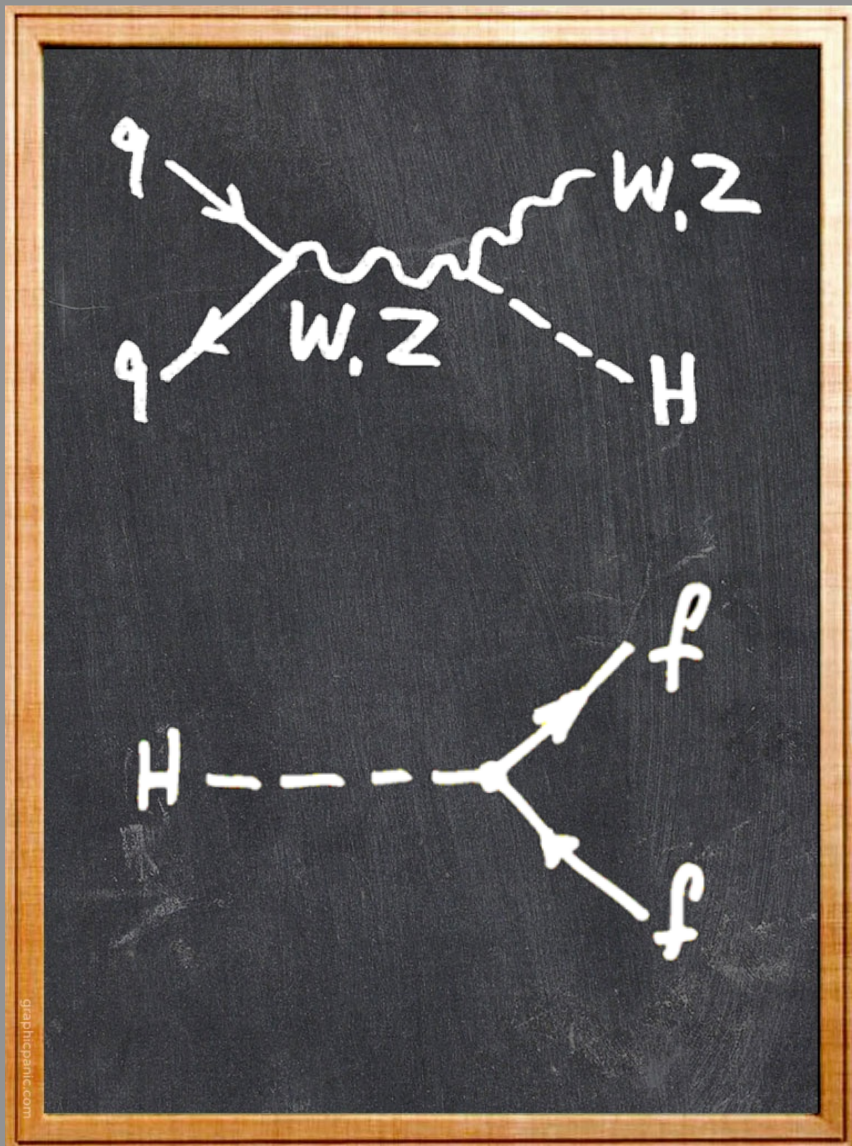


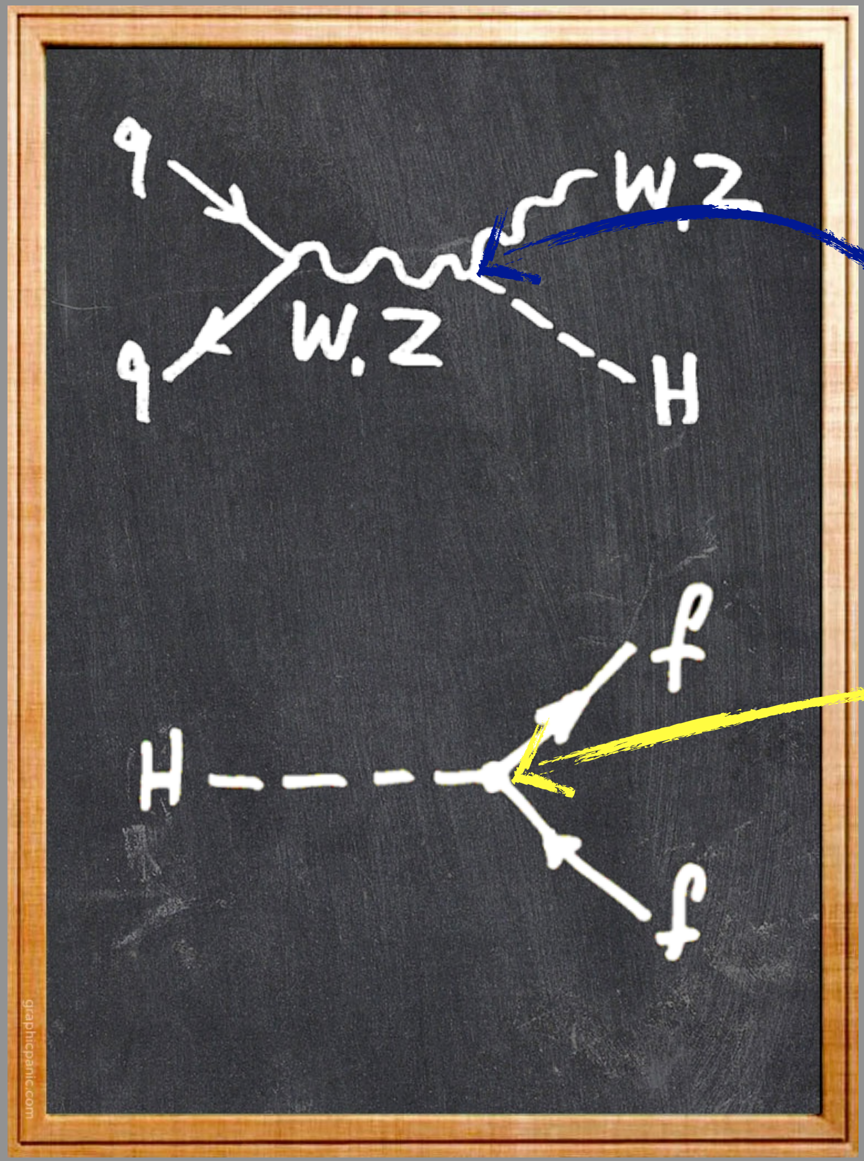


**Neglects Interference in Angular Variables*

Higgs couplings

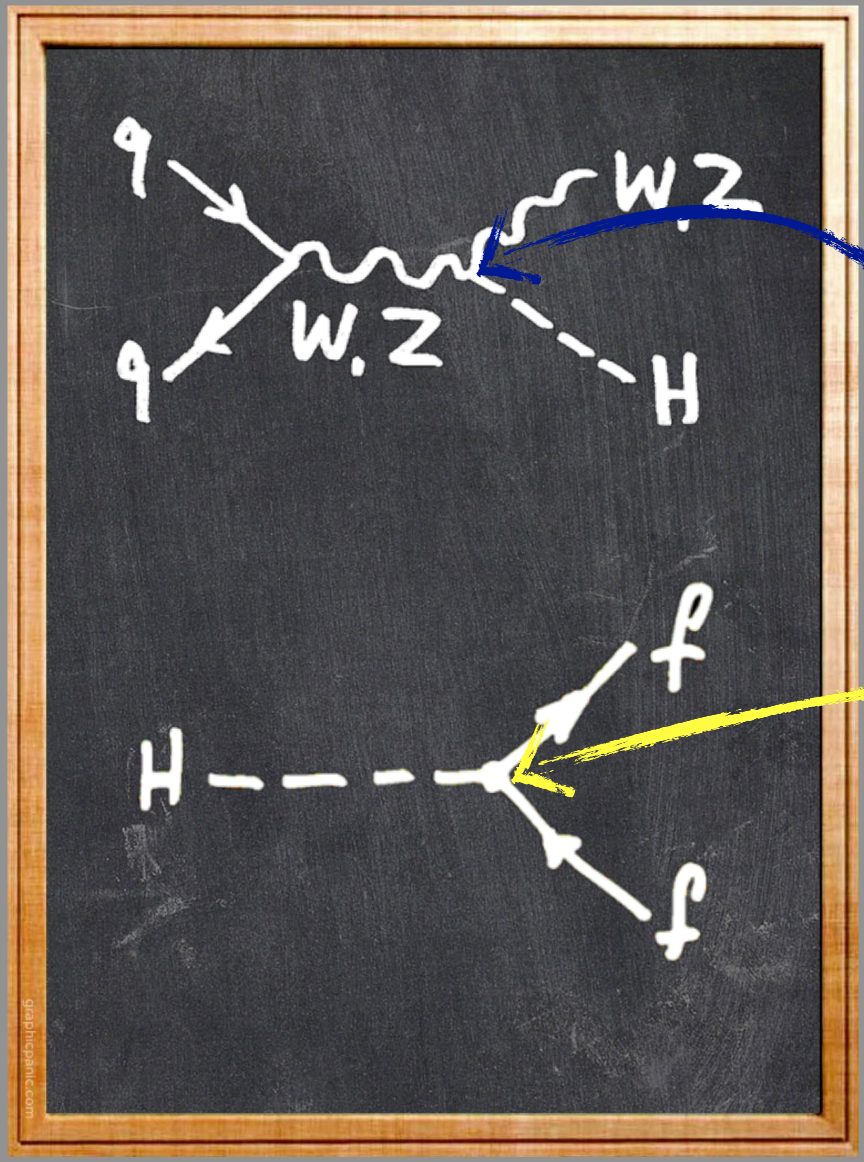



q
W, Z
q
W, Z
H
f
H
f



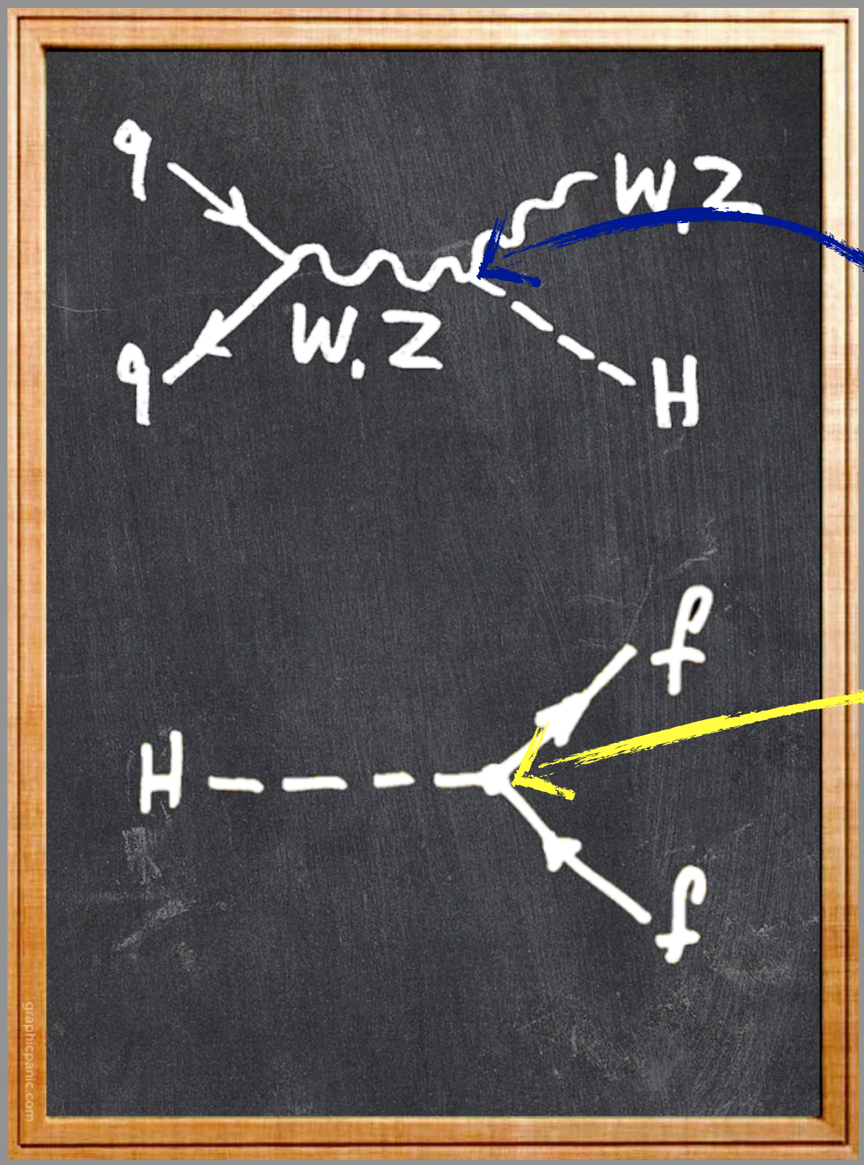
$$2i\frac{m_W^2}{v}g_{\mu\nu}$$

$$i\frac{m_f}{v}\delta_{ij}$$



$$2i\frac{m_W^2}{v}g_{\mu\nu}\times\kappa_W$$

$$i\frac{m_f}{v}\delta_{ij}\times\kappa_f$$



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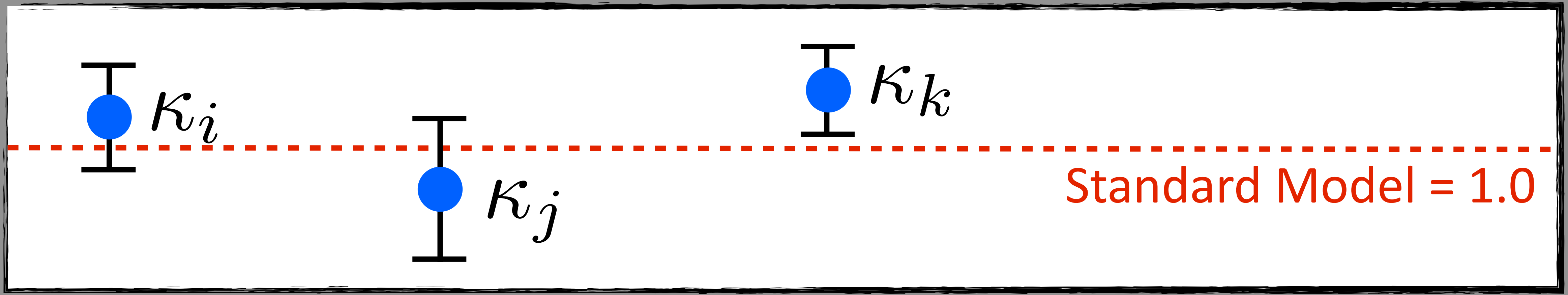
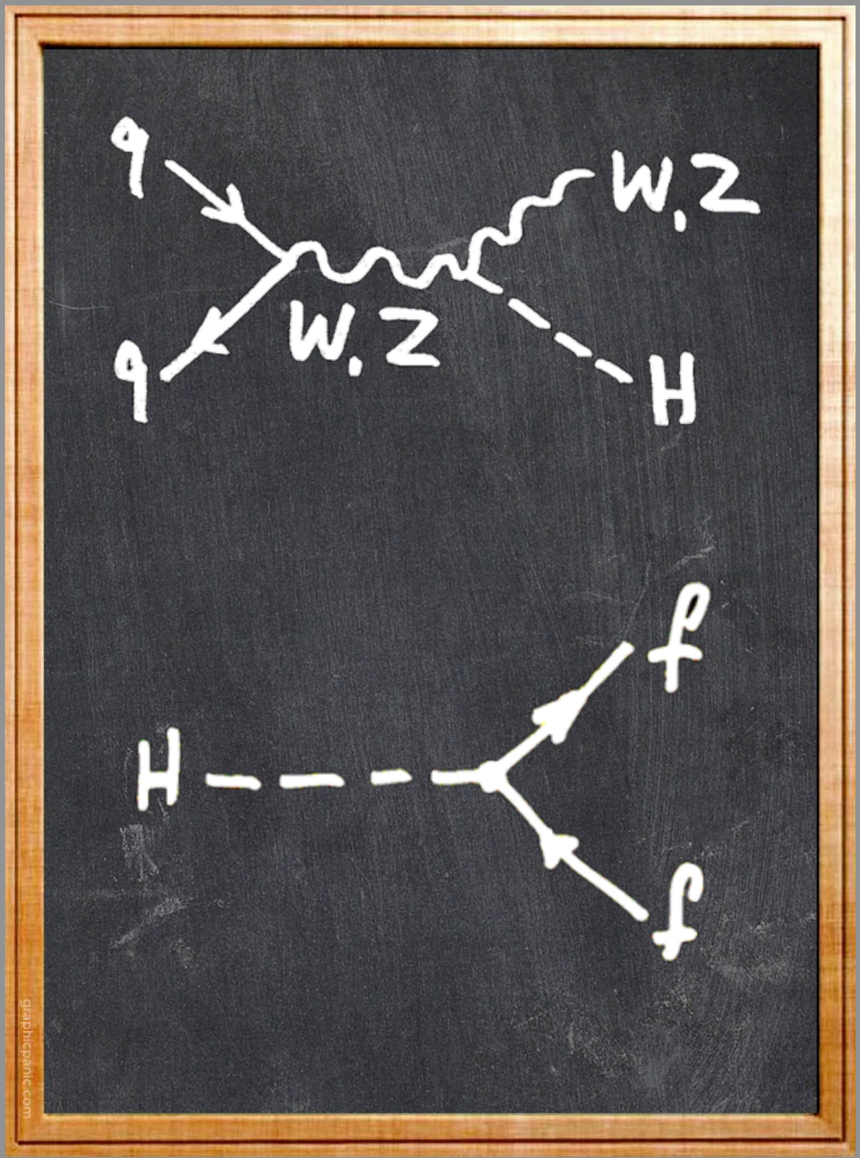
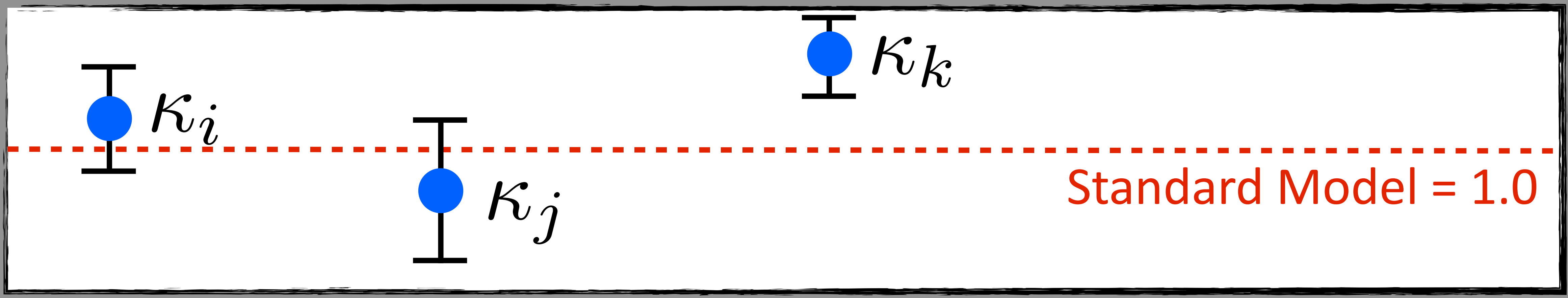




For new particles with M~1TeV, this is a discovery measurement

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



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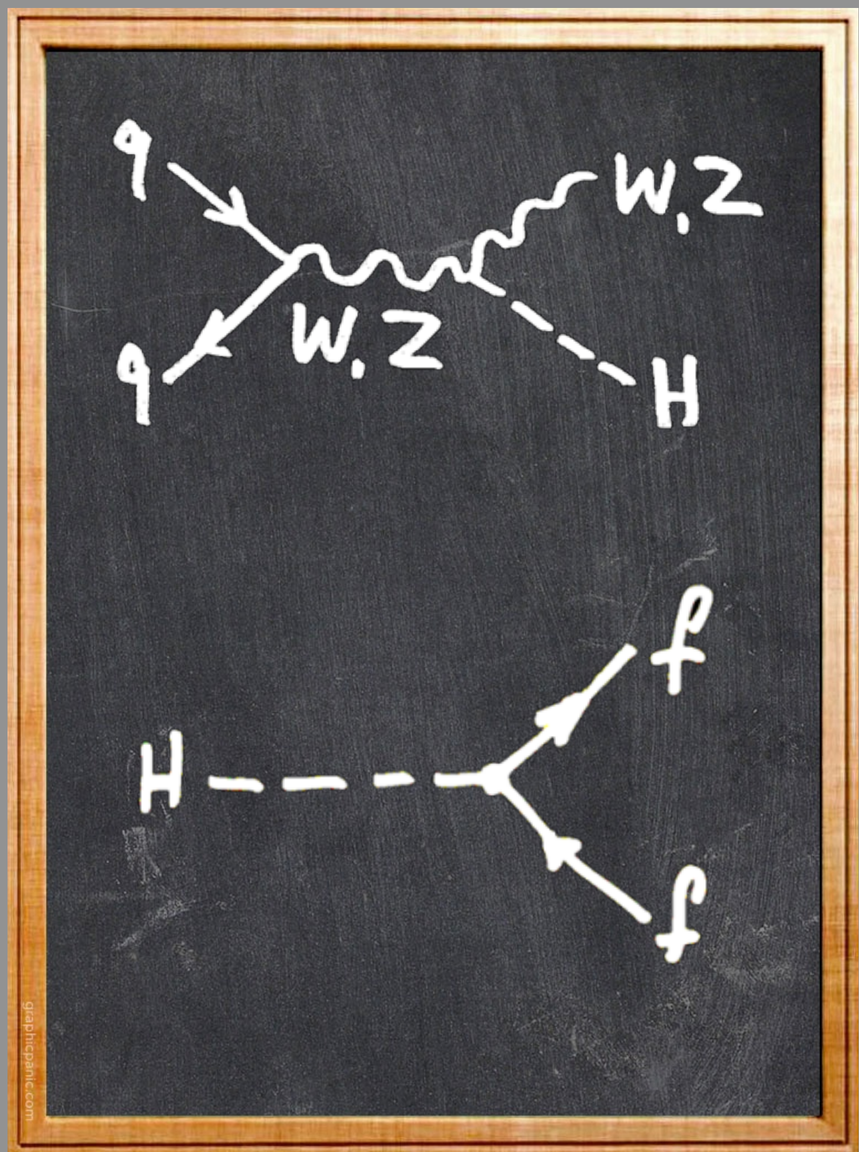

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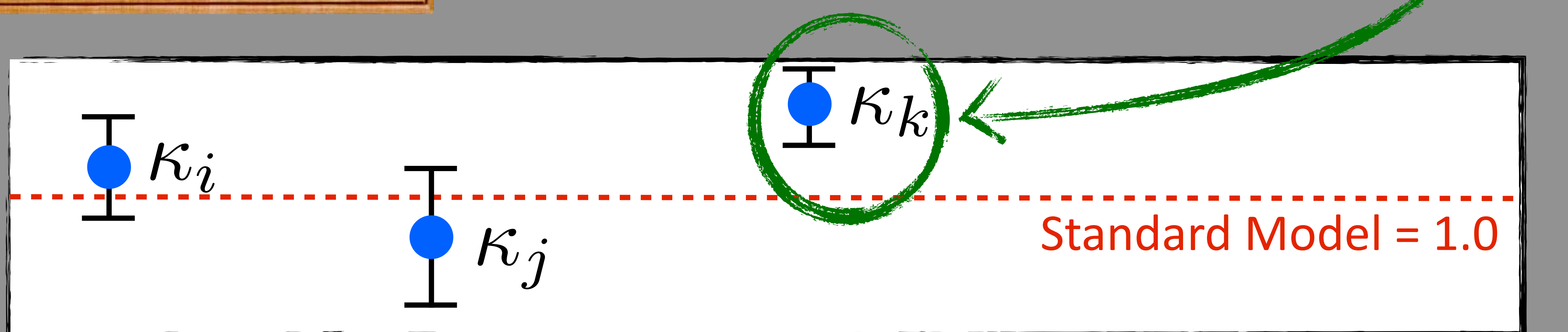

Start with rates…

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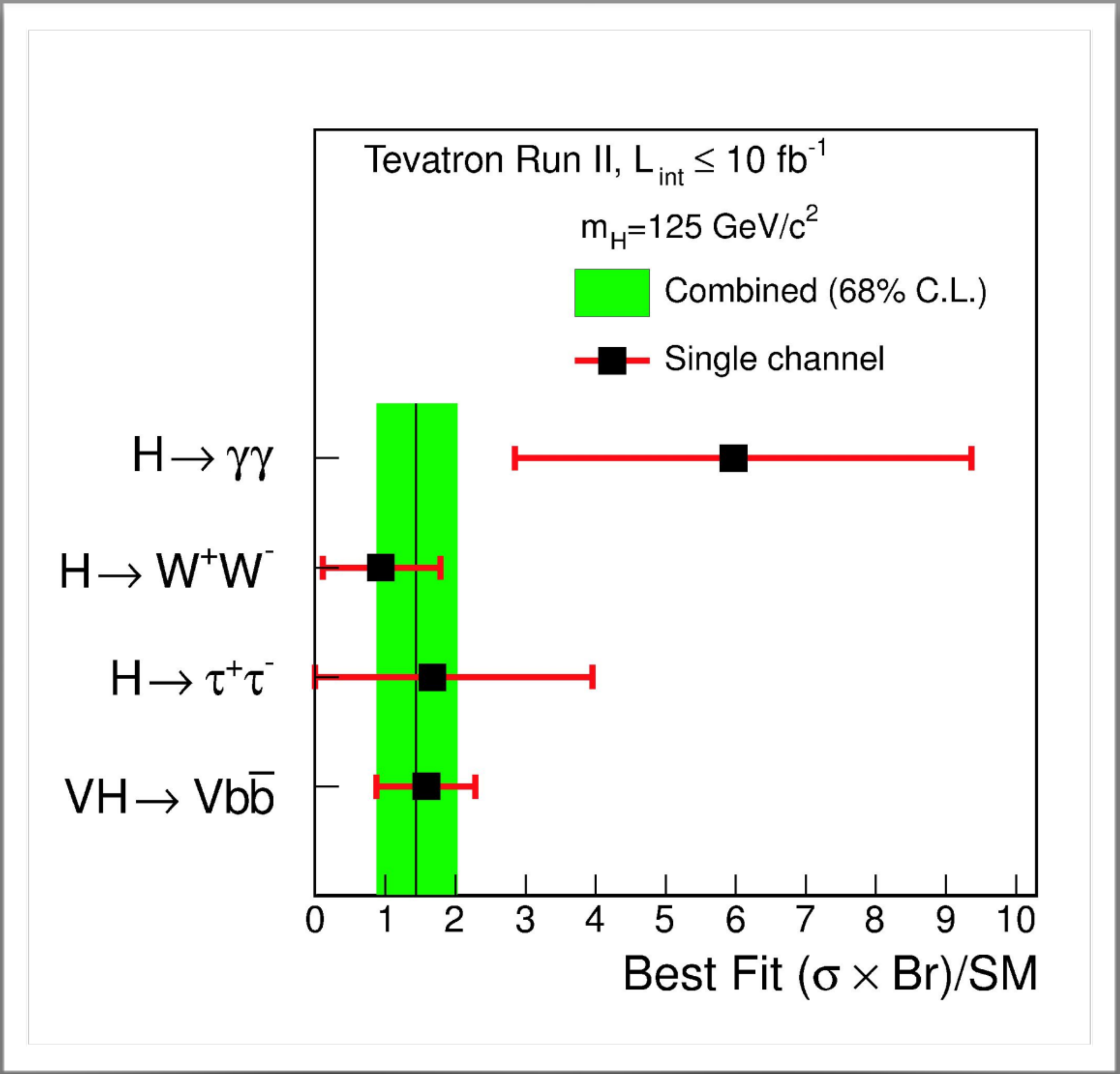

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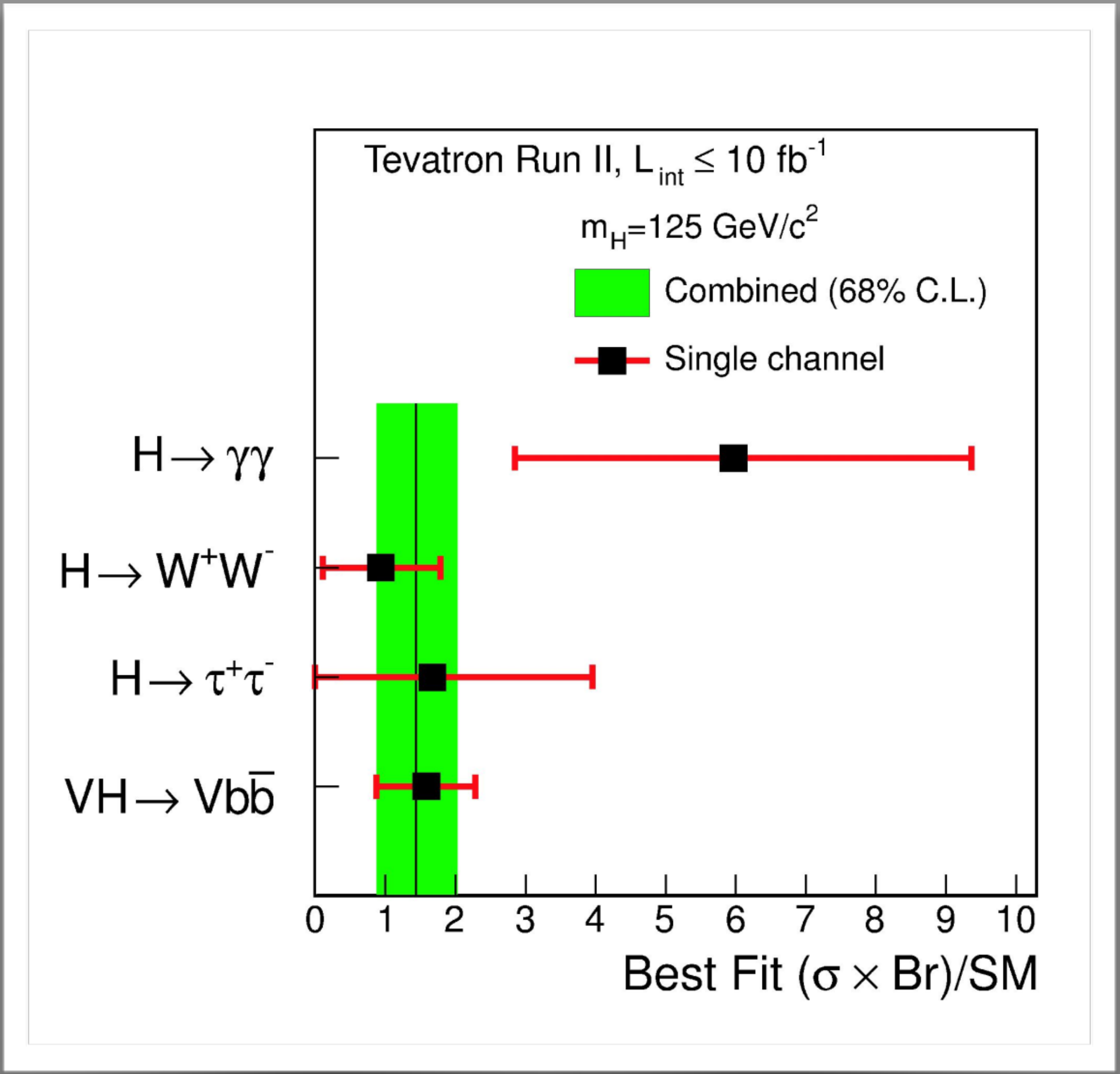
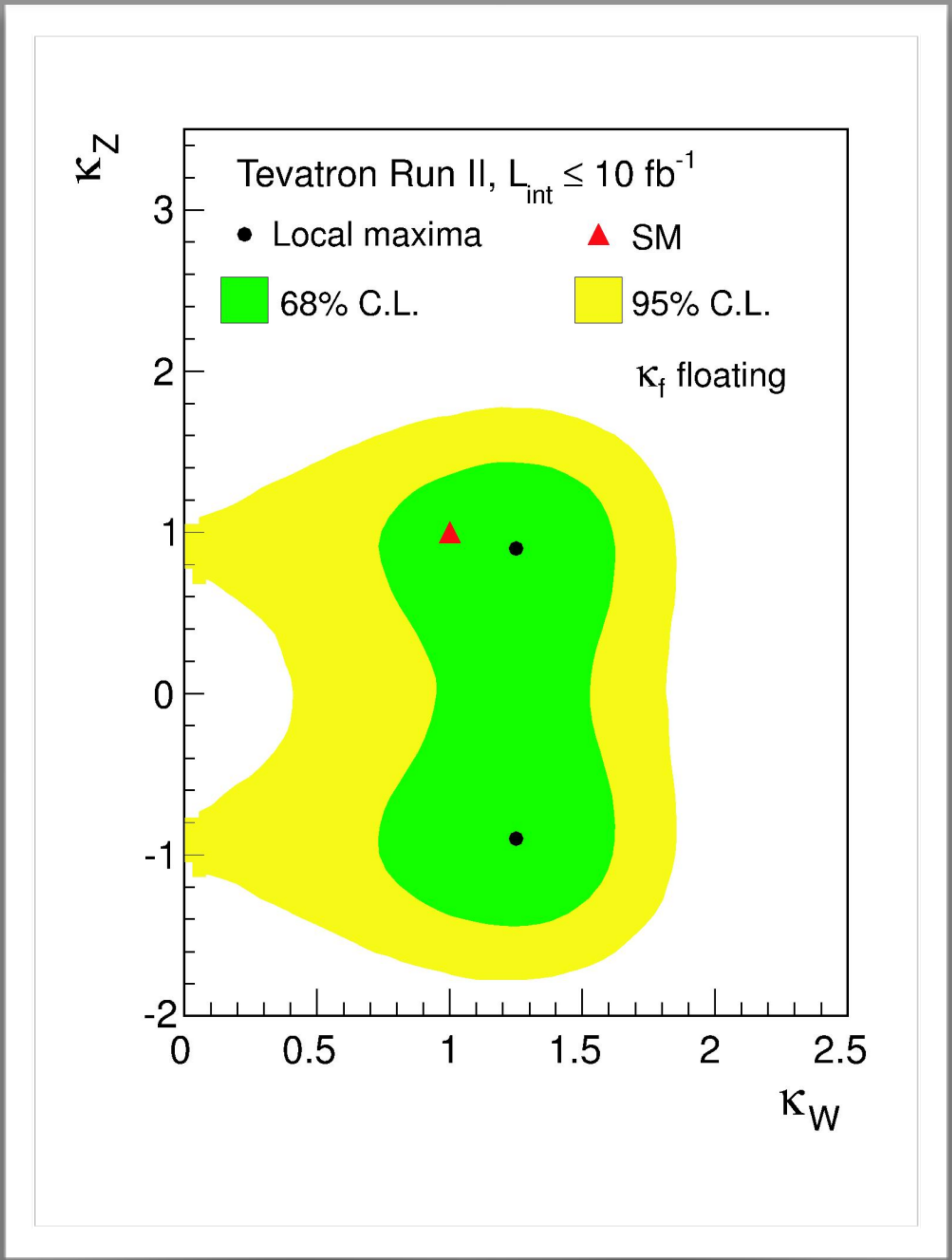


$$\sigma \propto \left|(g_i \times \kappa_i) \cdot (g_j \times \kappa_j)\right|^2 \propto k_i^2 \cdot k_j^2$$



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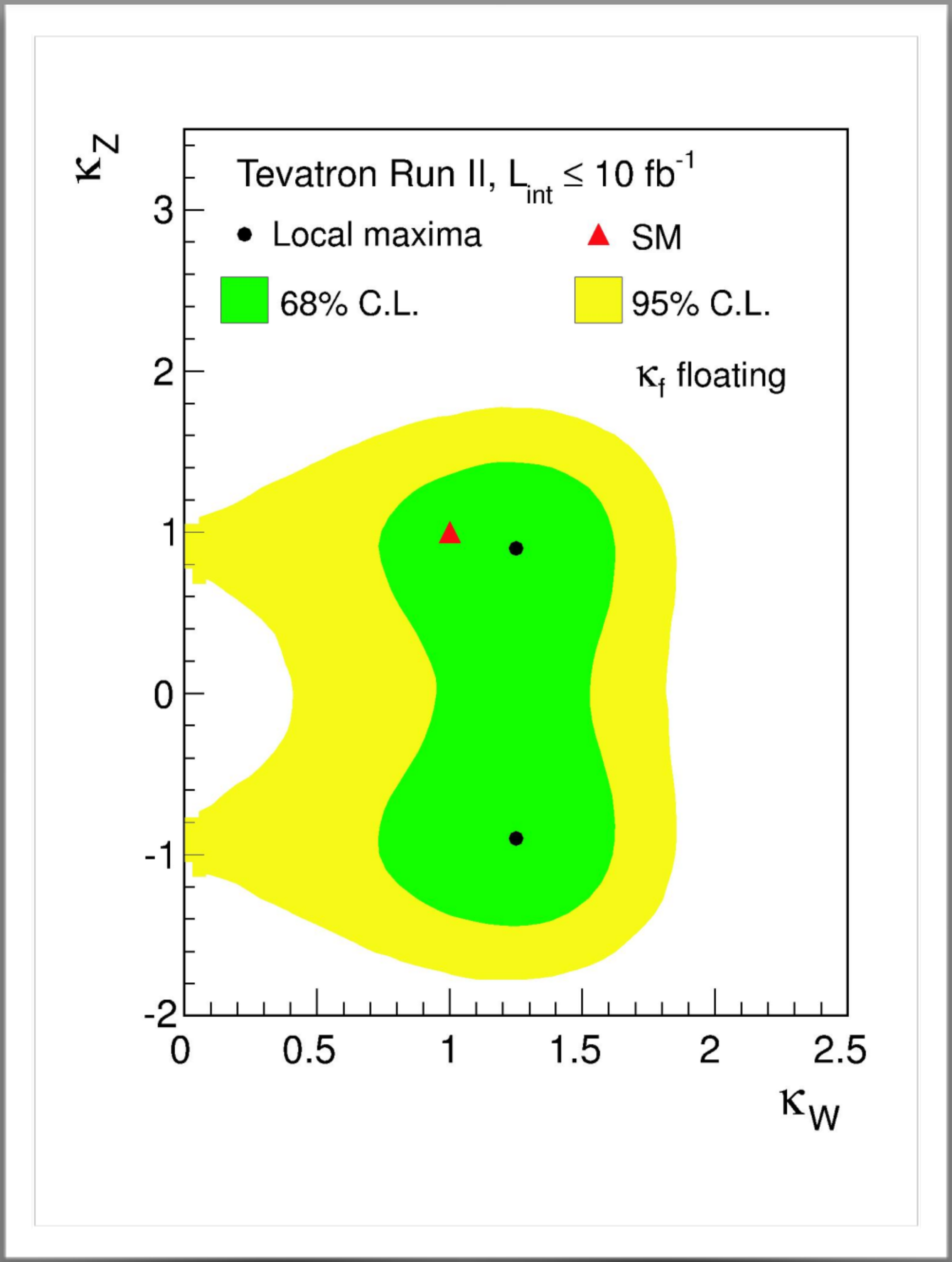

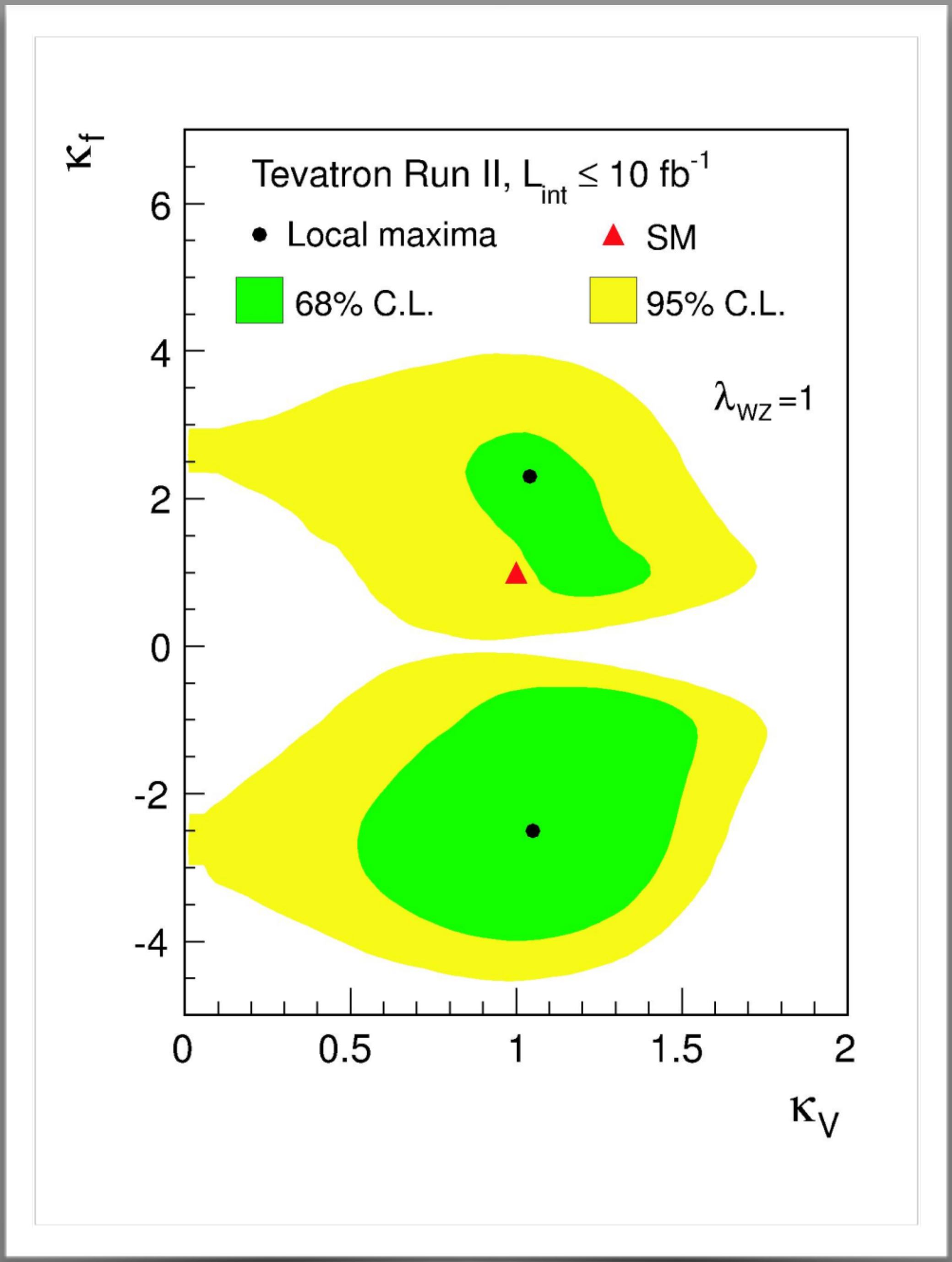

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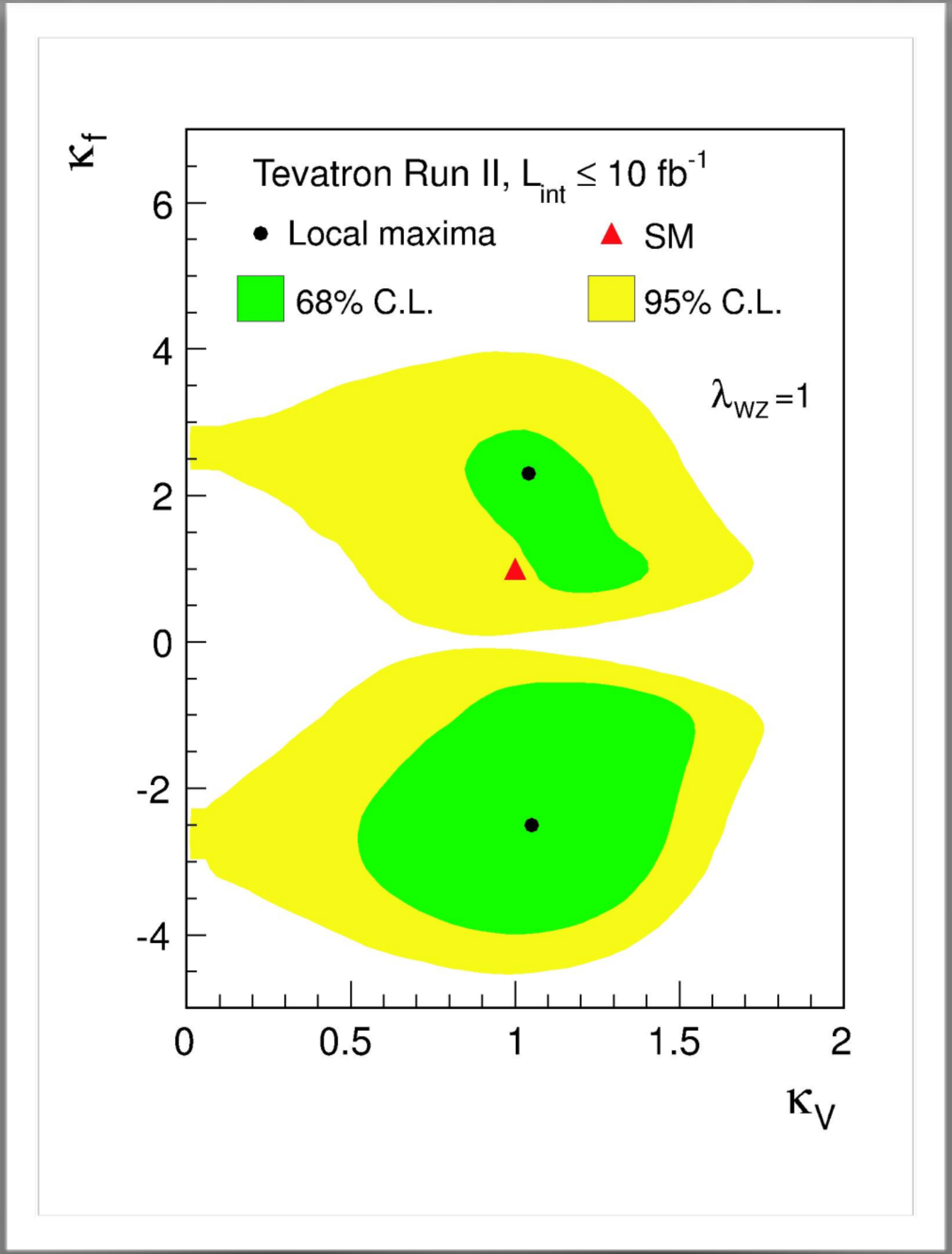

No surprises, but the LHC will continue to improve here

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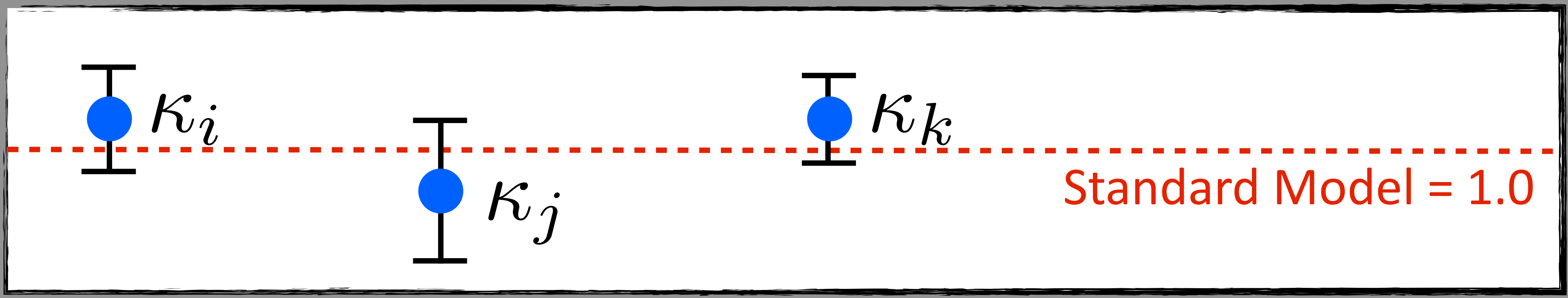
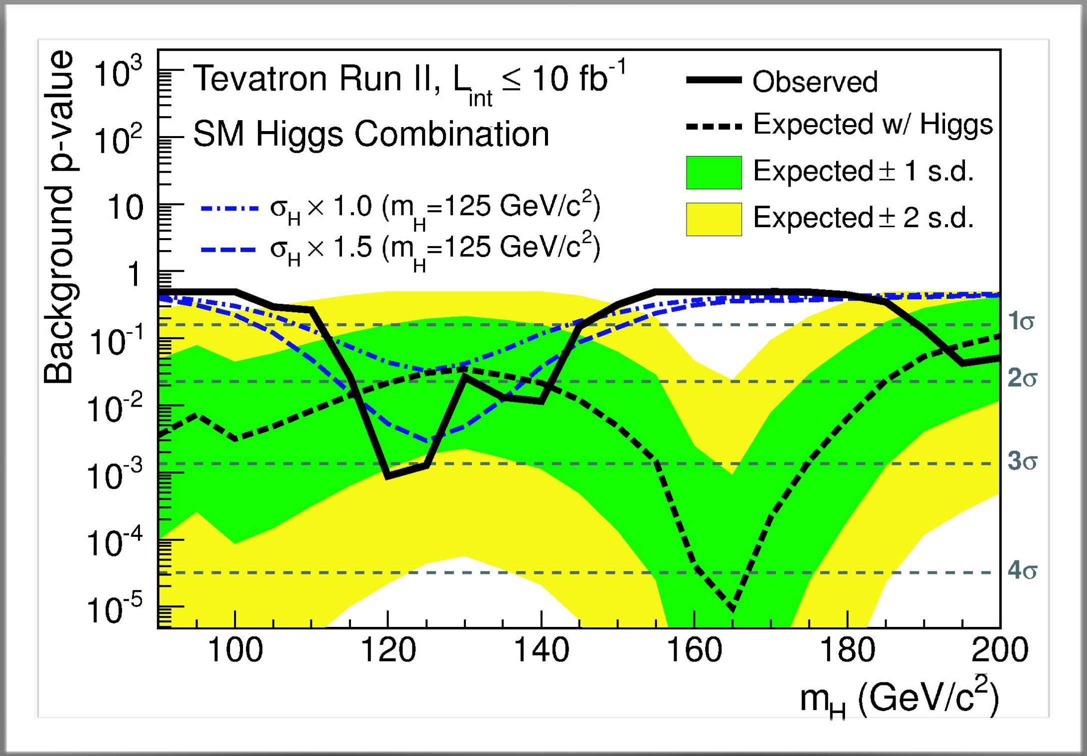
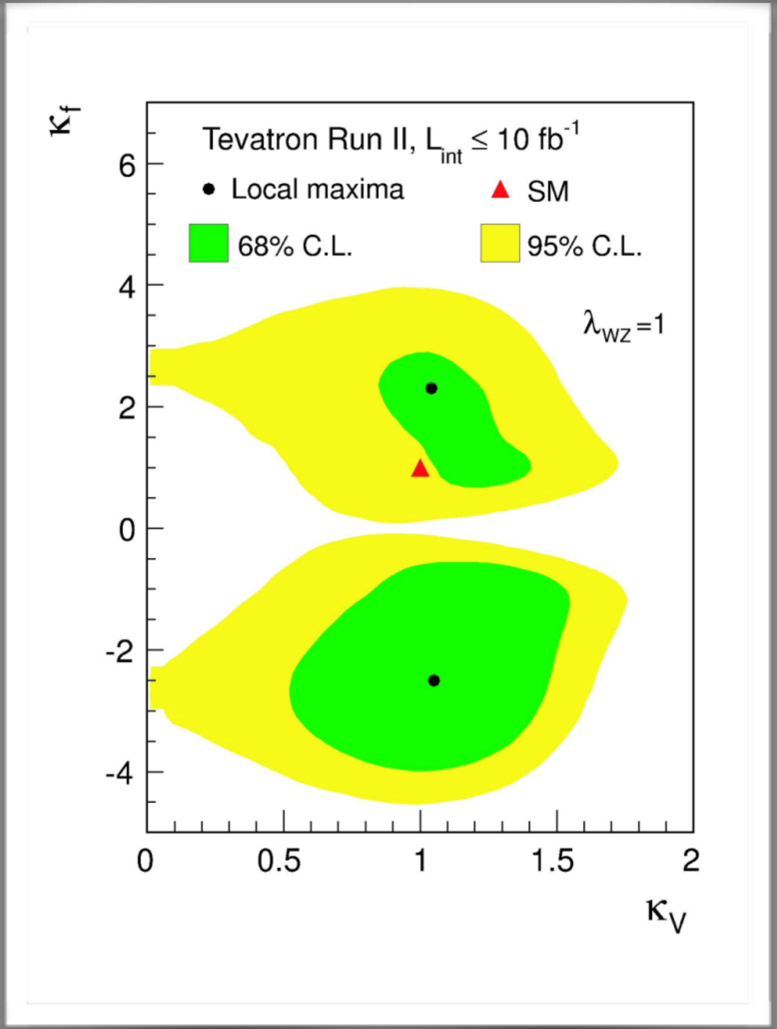


Final Tevatron Higgs results

- Search channels using full RunII dataset & published.
  + tevnphwg.fnal.gov





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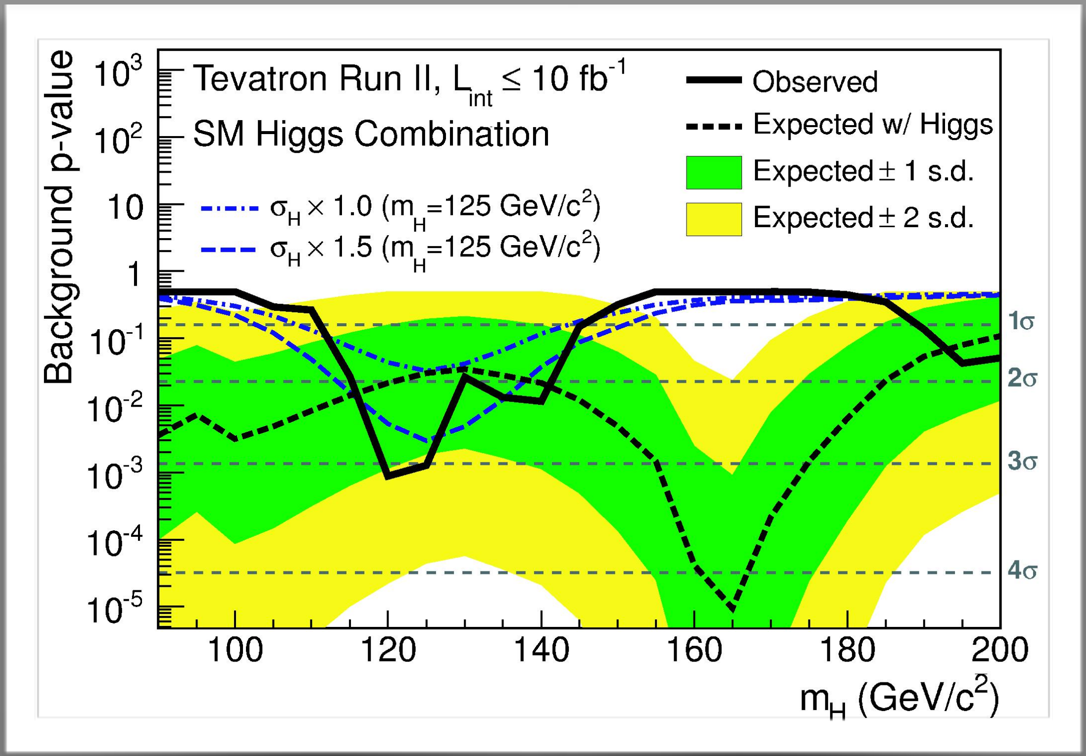
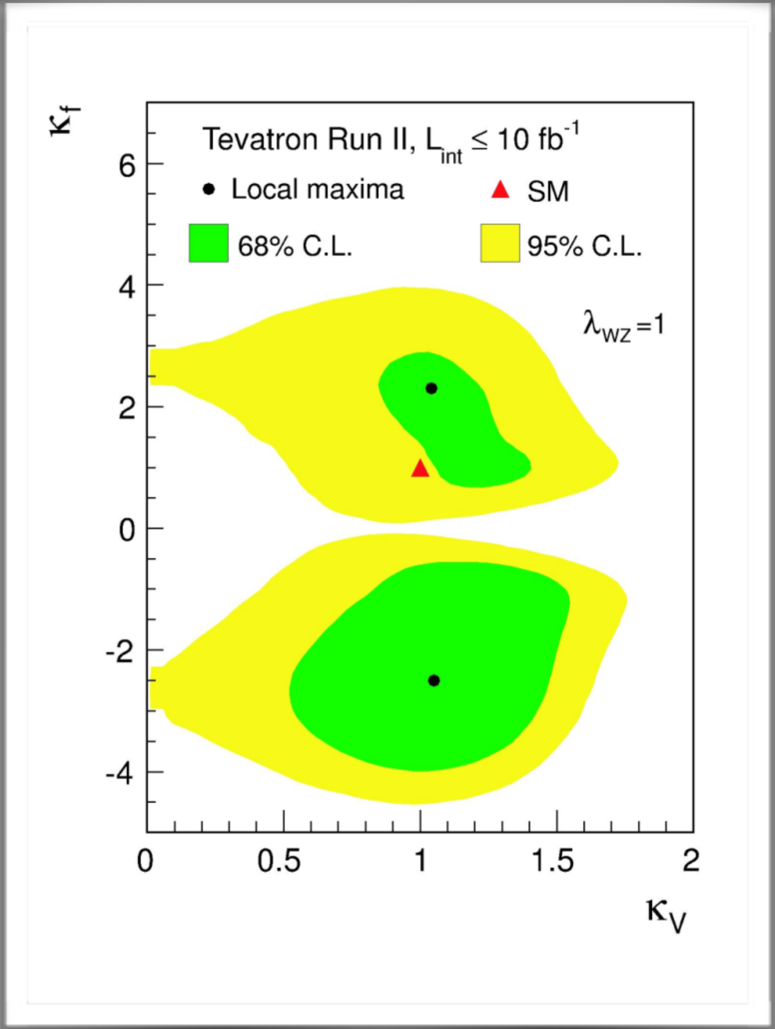
Achieved SM sensitivity over most of accessible mass range

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





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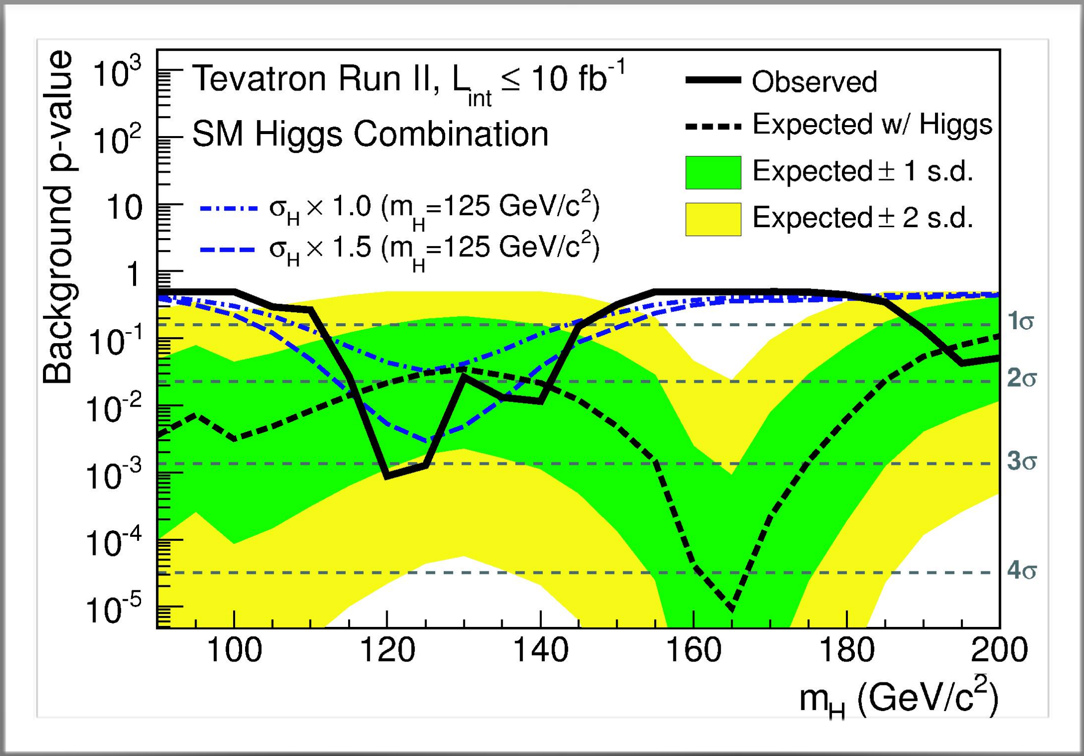
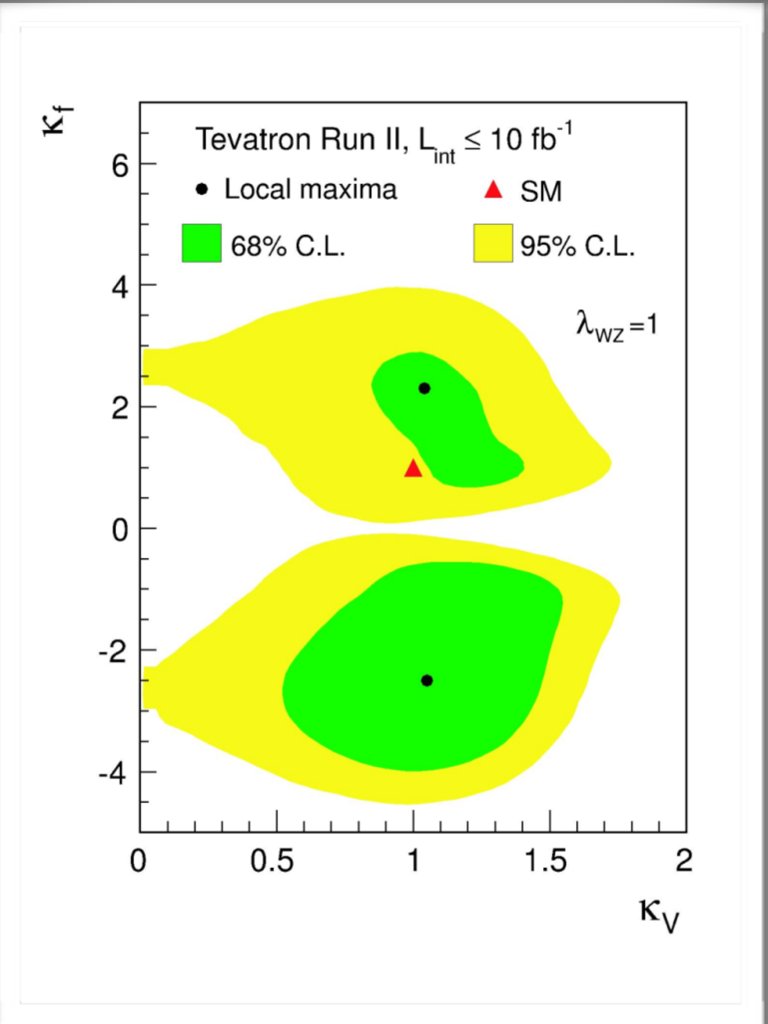
Sensitive to Higgs properties in Hbb mode

- J^P & couplings measurements are a valuable contribution

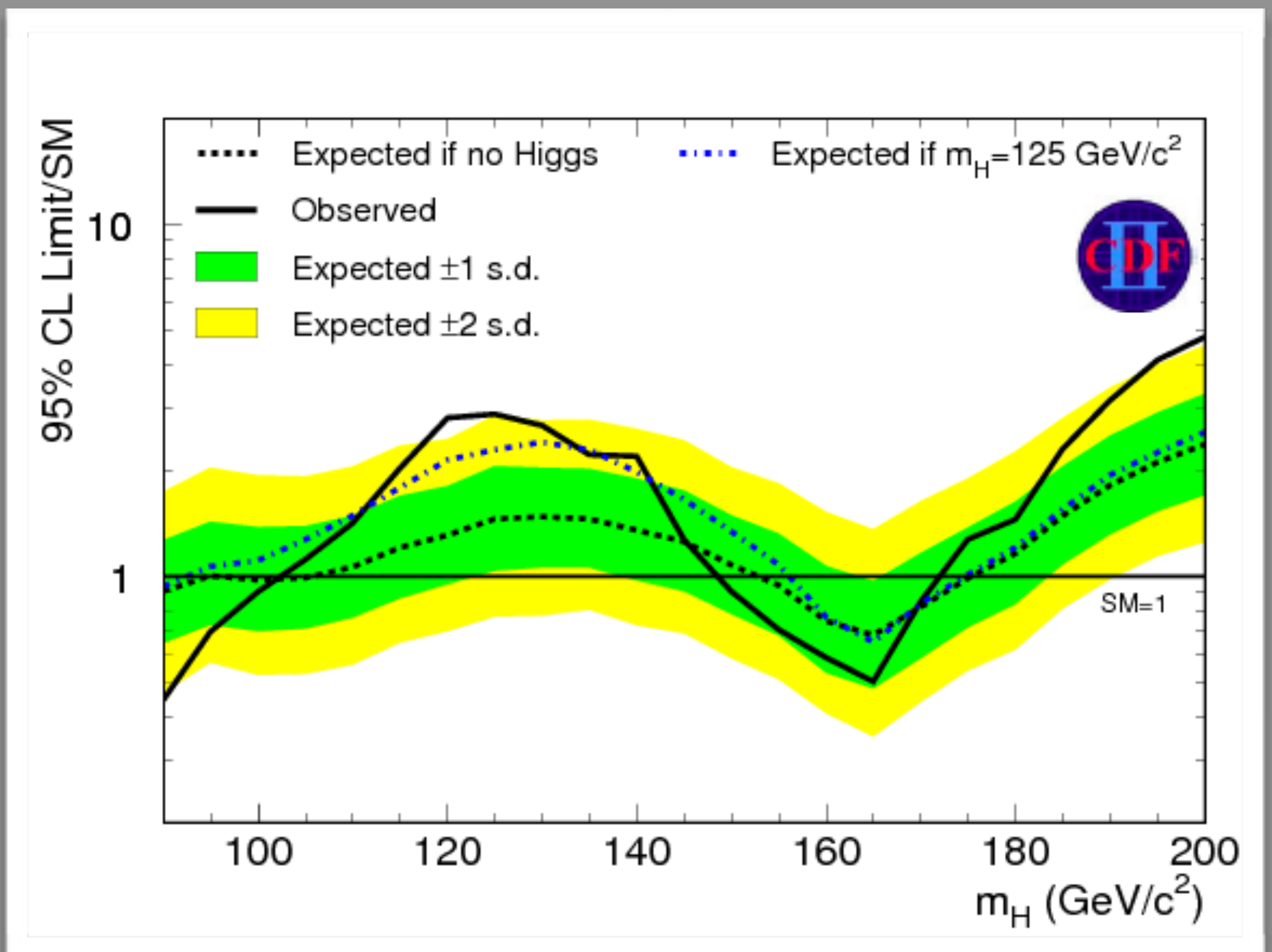
+ Updated J^P results coming from DØ, CDF & CDF+DØ

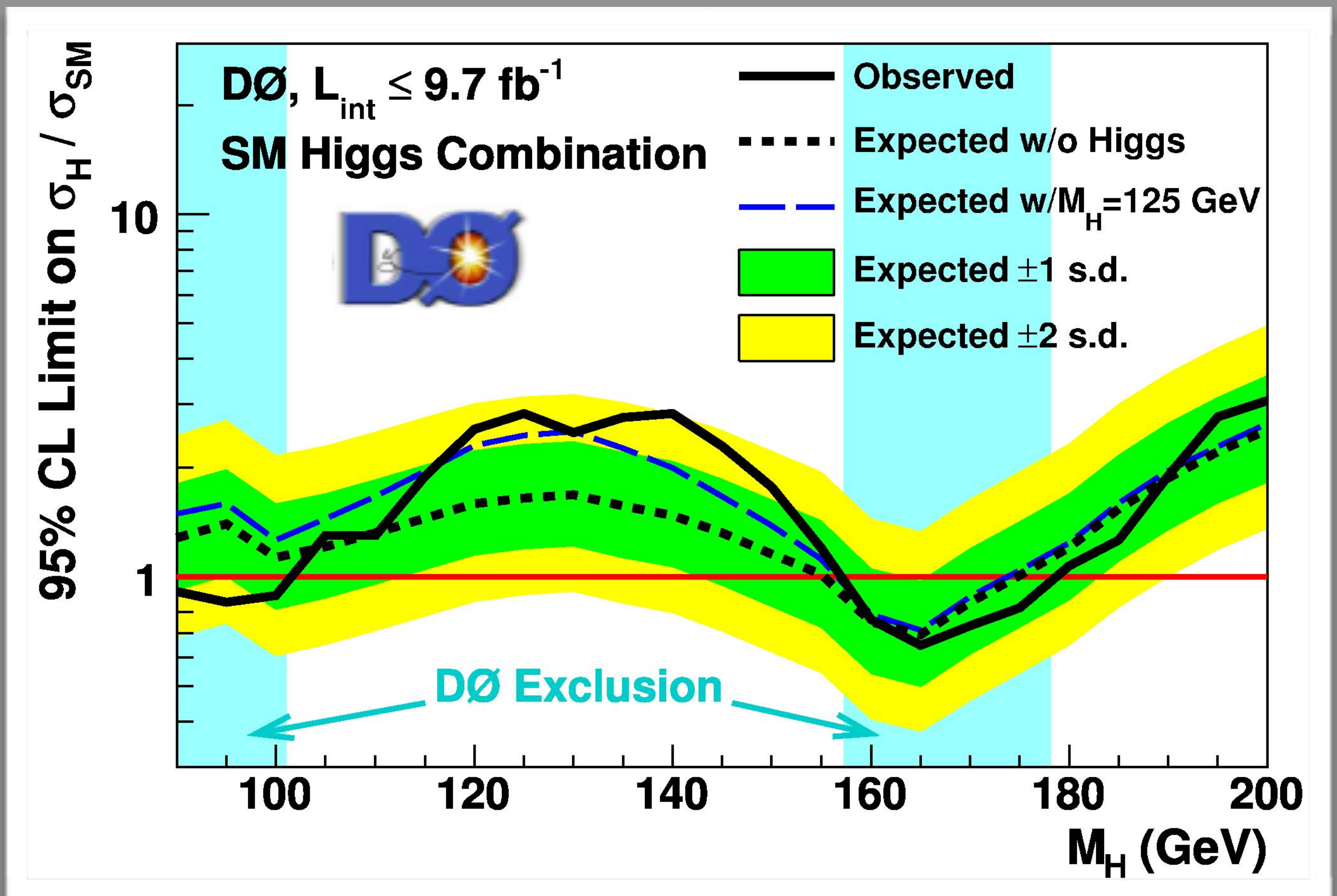




FIN

Individual Results





At M_H = 125 GeV:

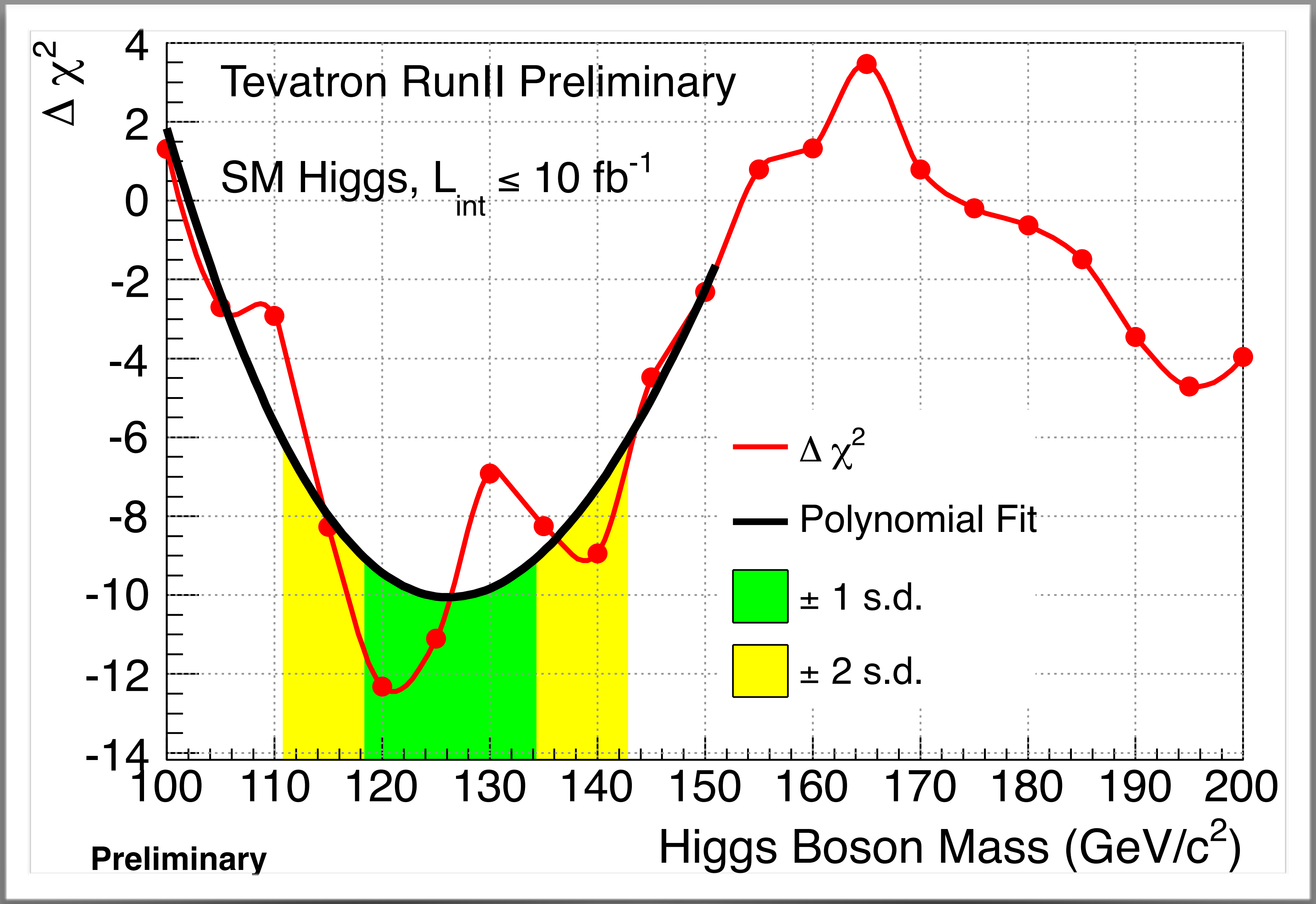
Exp. limit: 1.5 x σ(SM)
Obs. limit: 2.9 x σ(SM)

At M_H = 125 GeV:

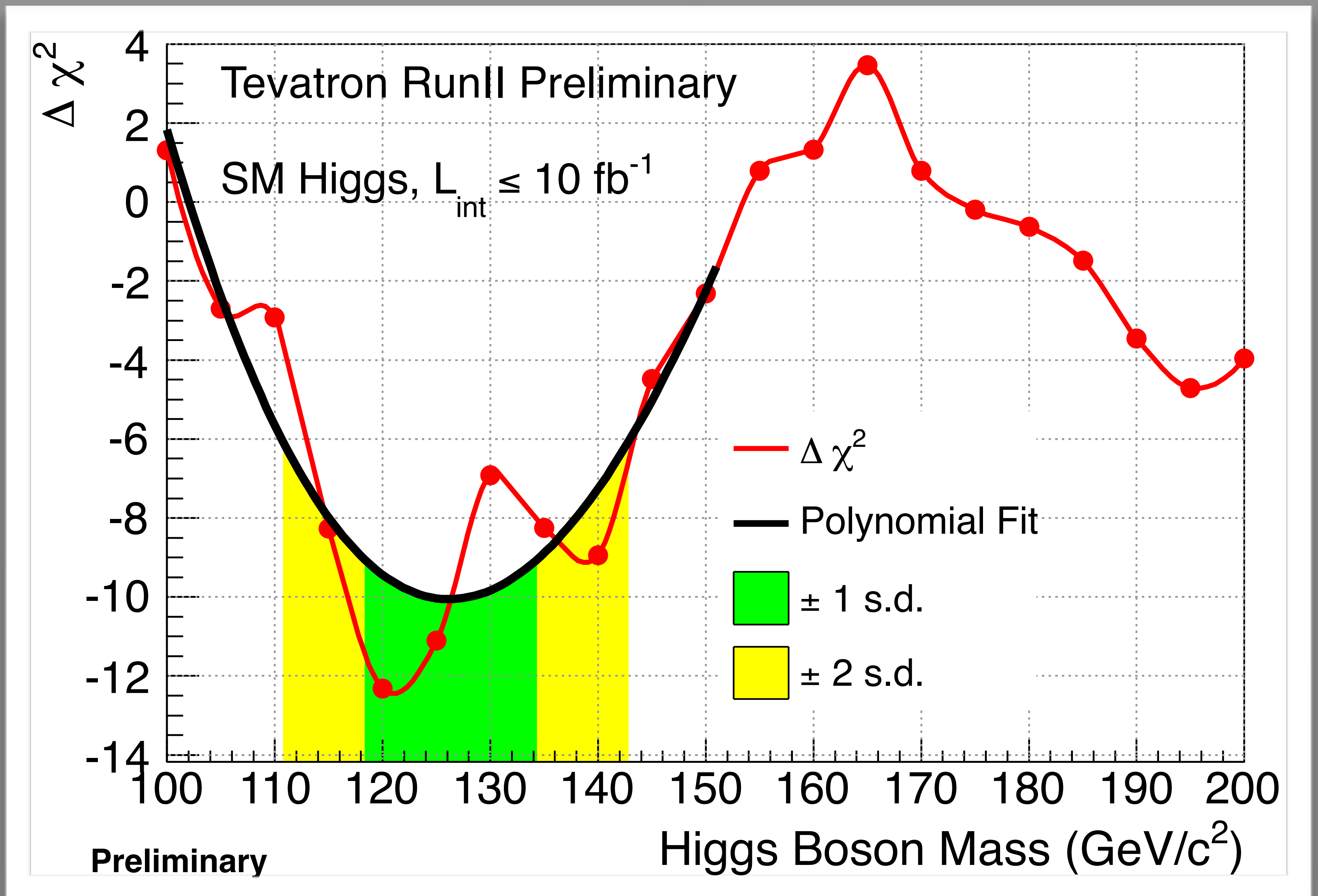
Exp. limit: 1.7 x σ(SM)
Obs. limit: 2.9 x σ(SM)

Higgs Mass

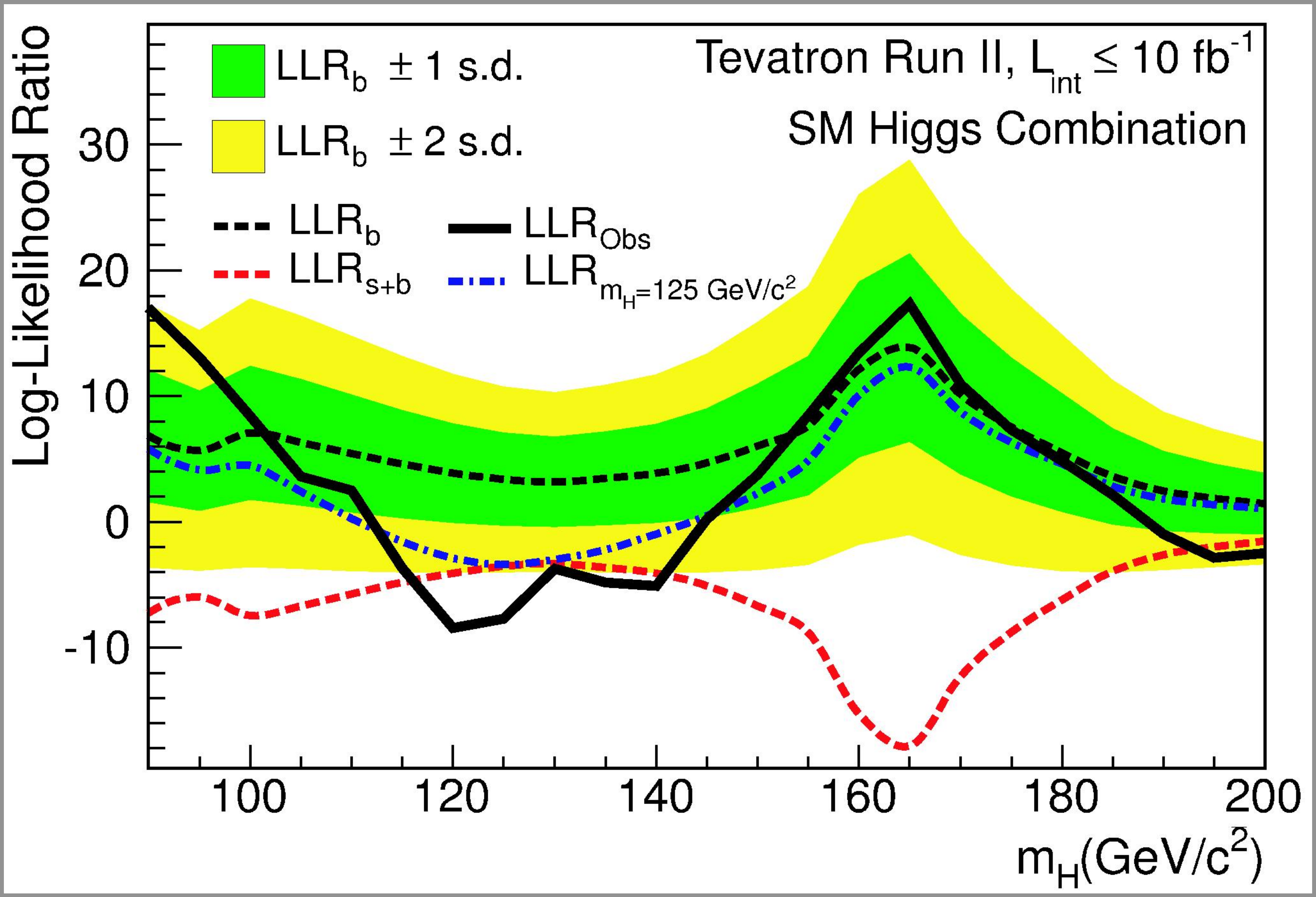
Higgs Mass


Tevatron RunII Preliminary
SM Higgs, $L_{int} \leq 10\ fb^{-1}$
$\Delta\chi^2$
Polynomial Fit
± 1 s.d.
± 2 s.d.
4
2
0
-2
-4
-6
-8
-10
-12
-14
100
110
120
130
140
150
160
170
180
190
200
Higgs Boson Mass (GeV/c^2)
Preliminary

Higgs Mass



$$M_H^{\rm fit} = 126.2^{+8.1}_{-7.8}\ \text{GeV}$$


Log-Likelihood Ratio
LLR$_b$ ± 1 s.d.
LLR$_b$ ± 2 s.d.
LLR$_b$
LLR$_{s+b}$
LLR$_{Obs}$
LLR$_{m_H=125\ GeV/c^2}$
Tevatron Run II, $L_{int} \leq 10\ fb^{-1}$
SM Higgs Combination
30
20
10
0
-10
100
120
140
160
180
200
$m_H(GeV/c^2)$

At the Tevatron, it's all about the threshold.

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

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

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

$$A_{10} = -i a_1 \, \beta \, s$$

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

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$J^P = 0^+$

Isotropic near threshold

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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)

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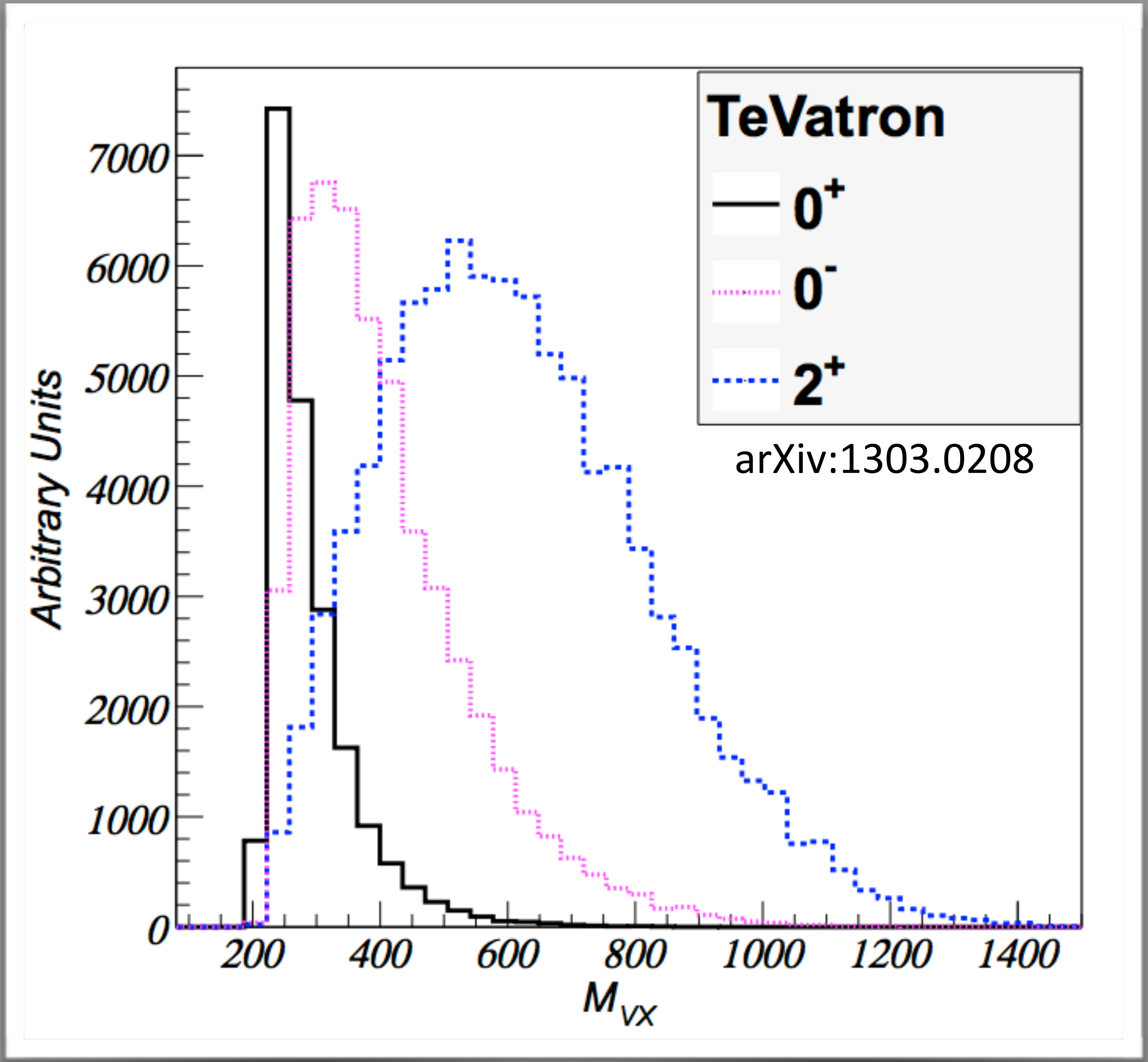
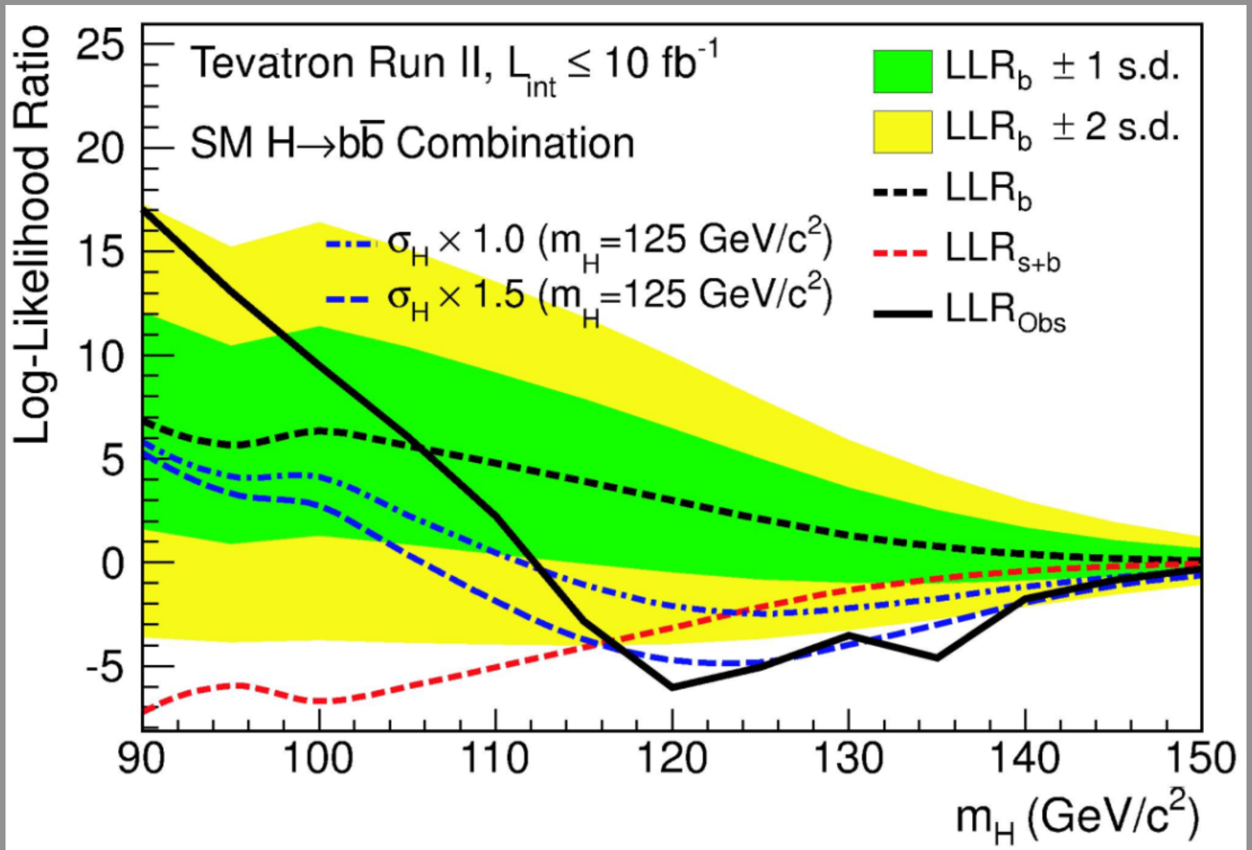
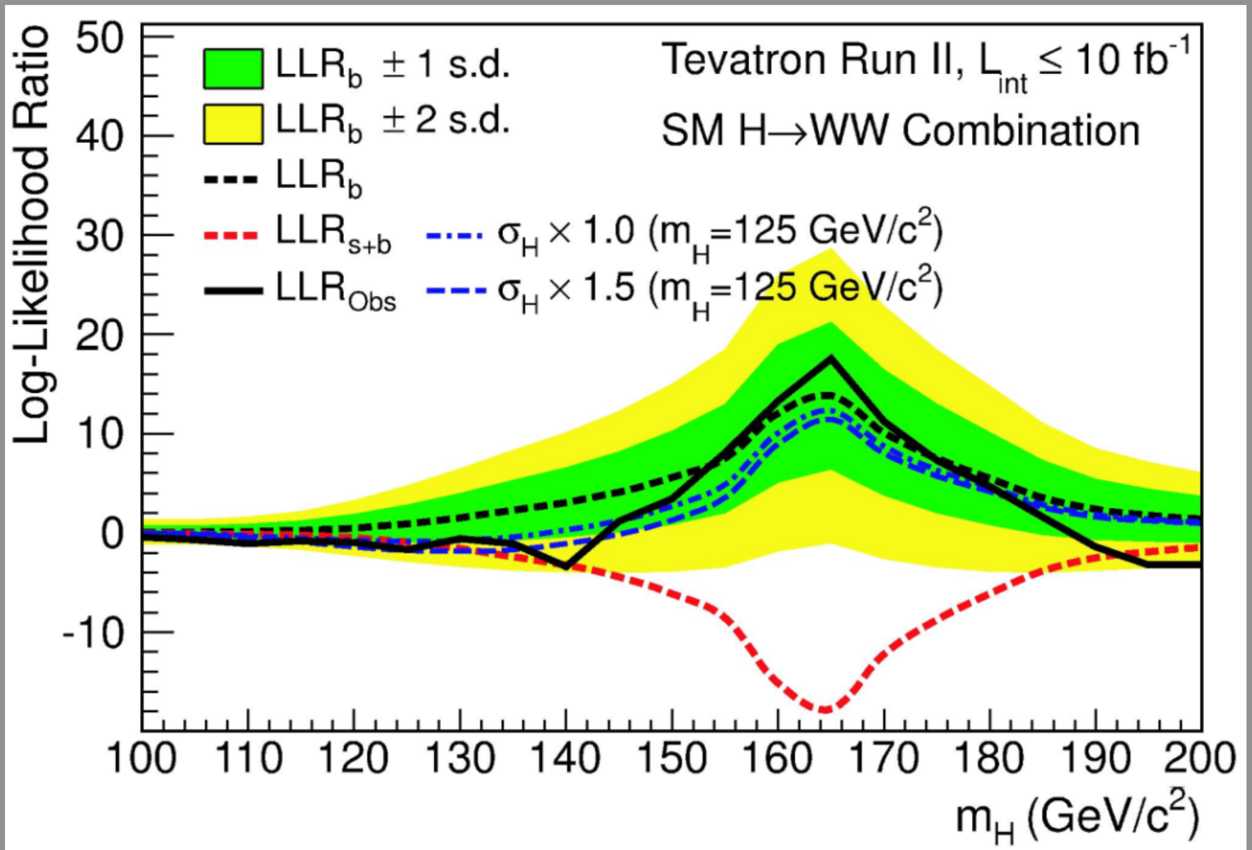
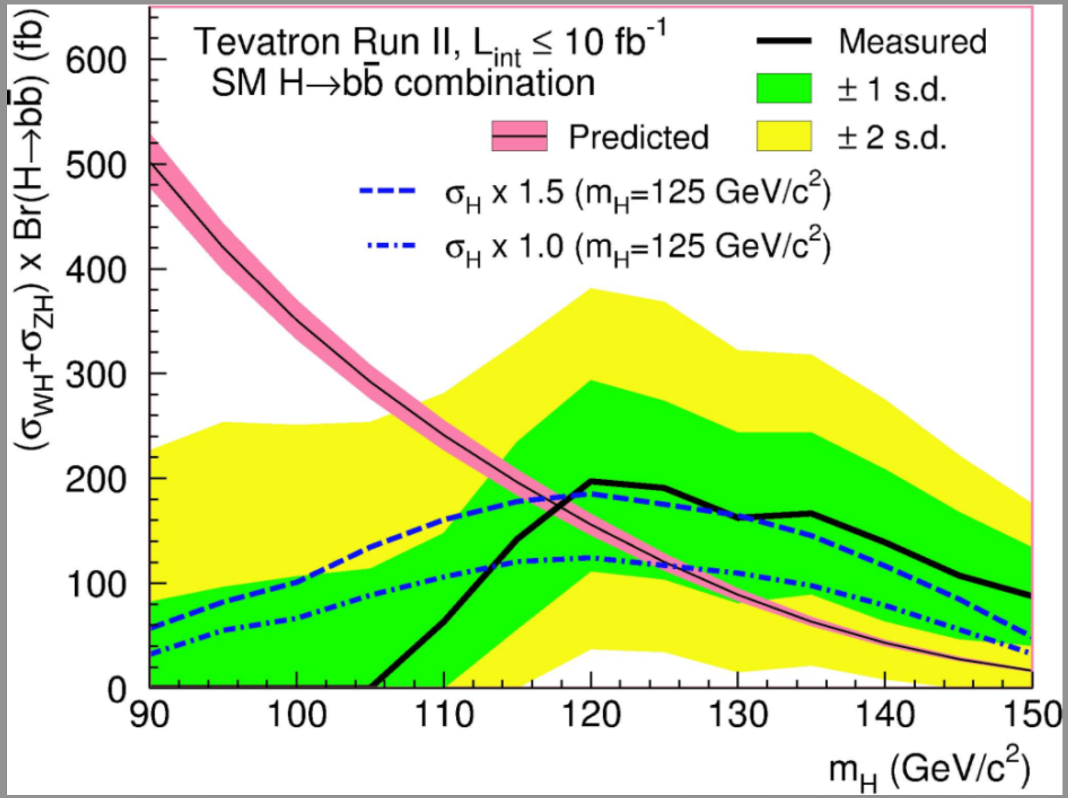


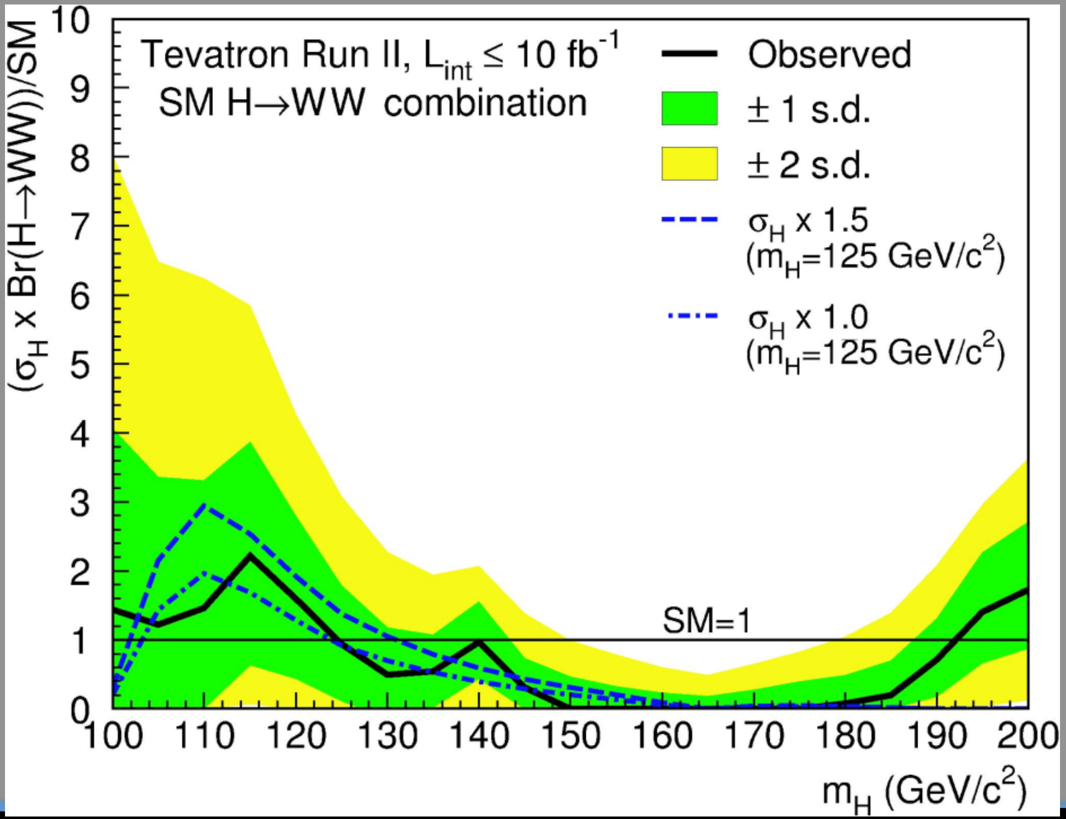
- J. Ellis, D. S. Hwang, V. Sanz, and T. You, J. High Energy Phys. 2012, 134 (2012).
- J. Ellis, V. Sanz, and T. You, arXiv:1303.0208, (2013).
- D. Miller, S. Choi, B. Eberle, M. Muhlleitner, and P. Zerwas, Phys. Lett. B 505, 149 (2001).

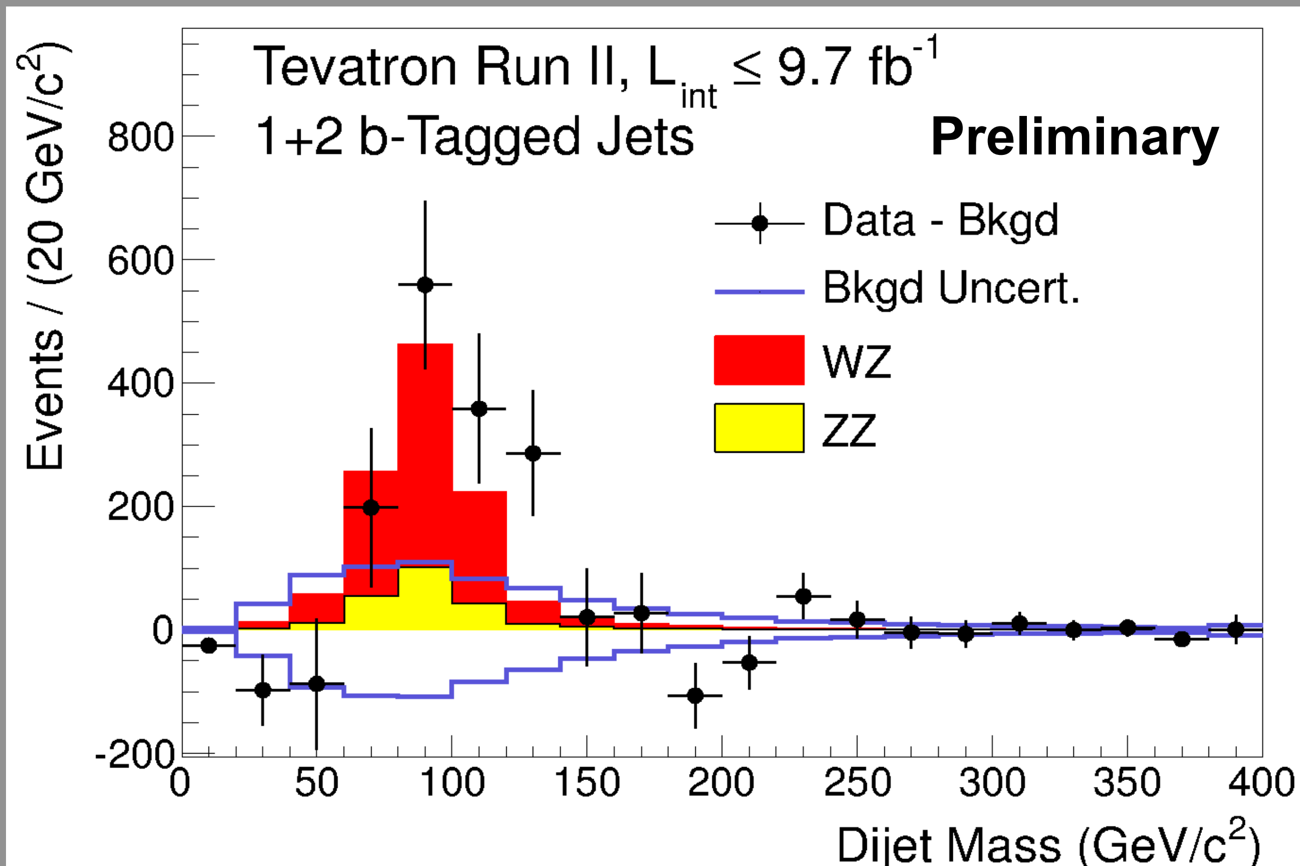
Quantifying the Excess: Sub Channels

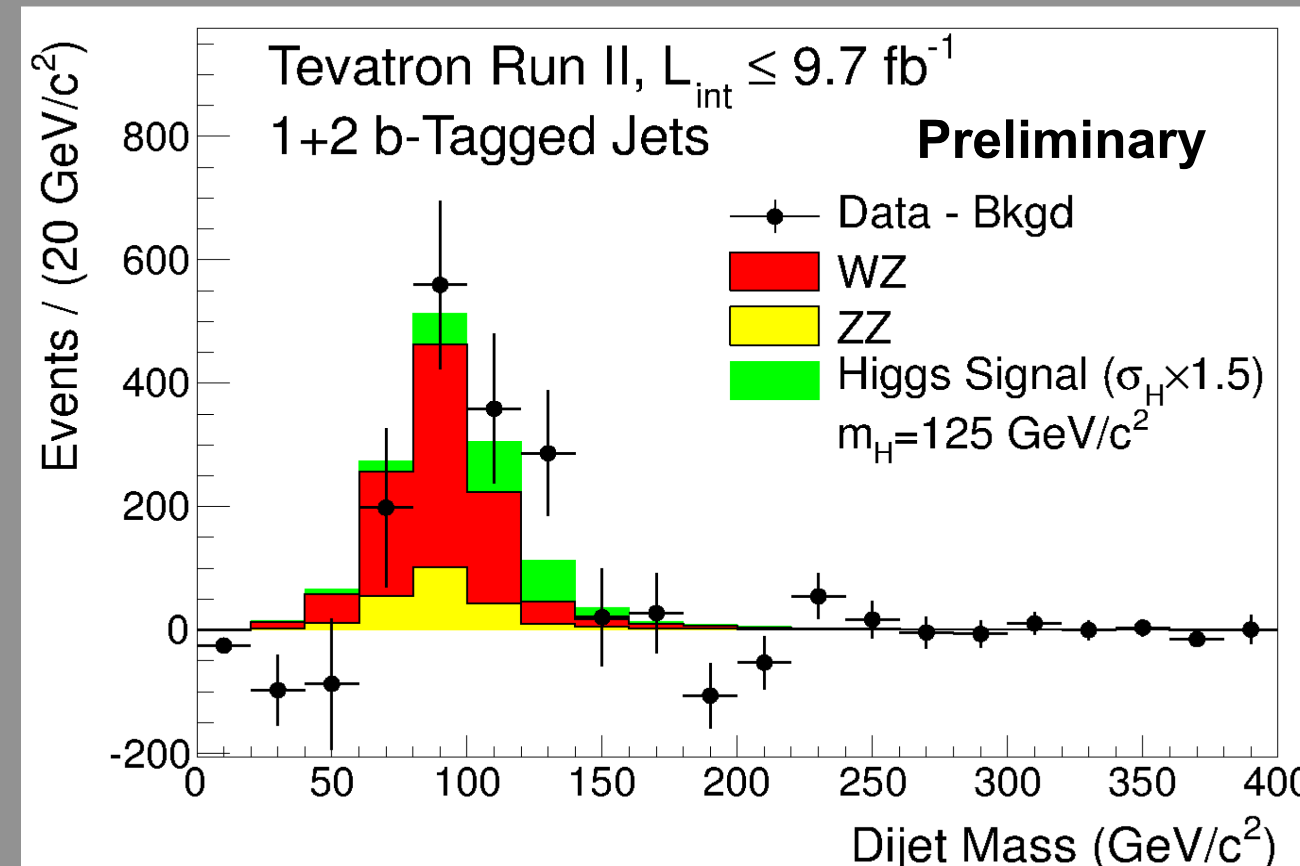


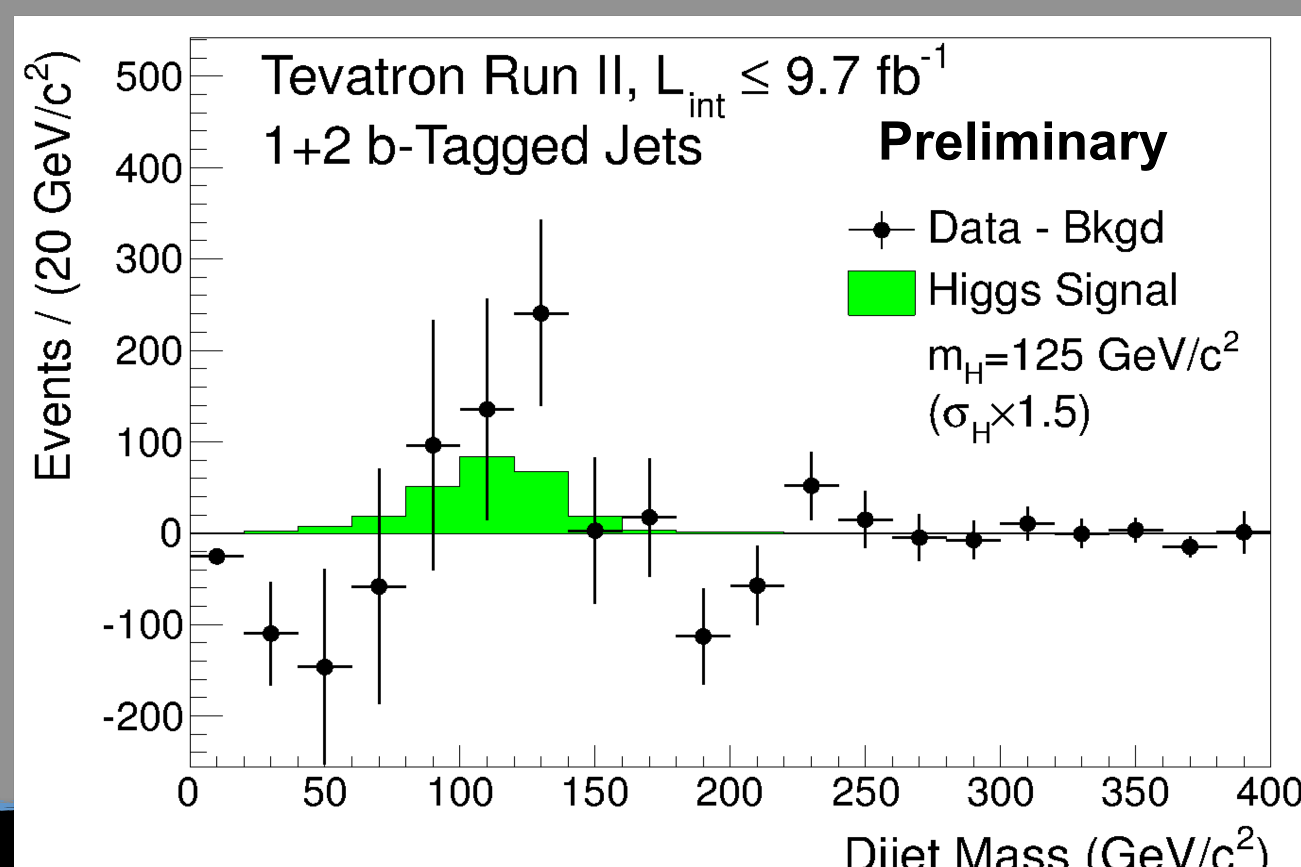


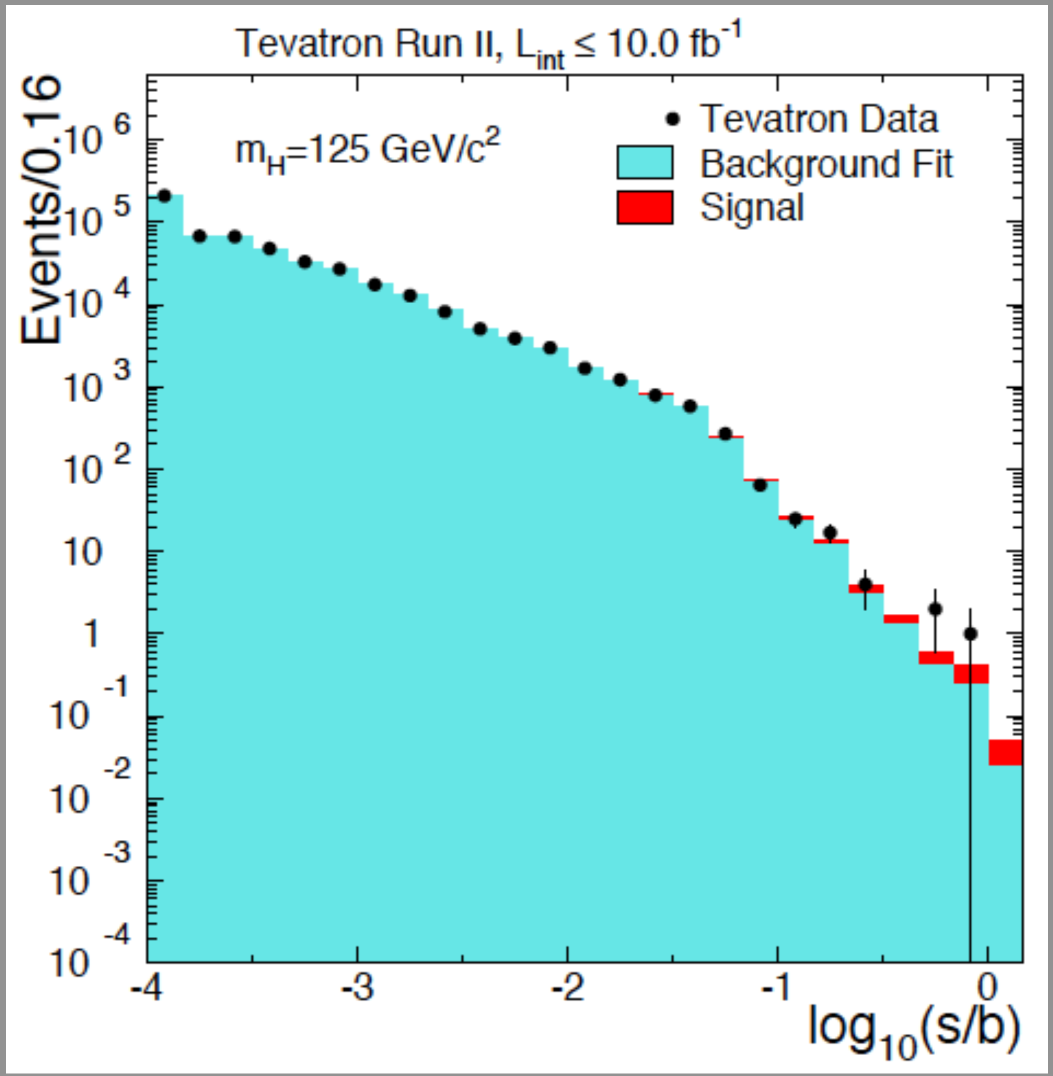


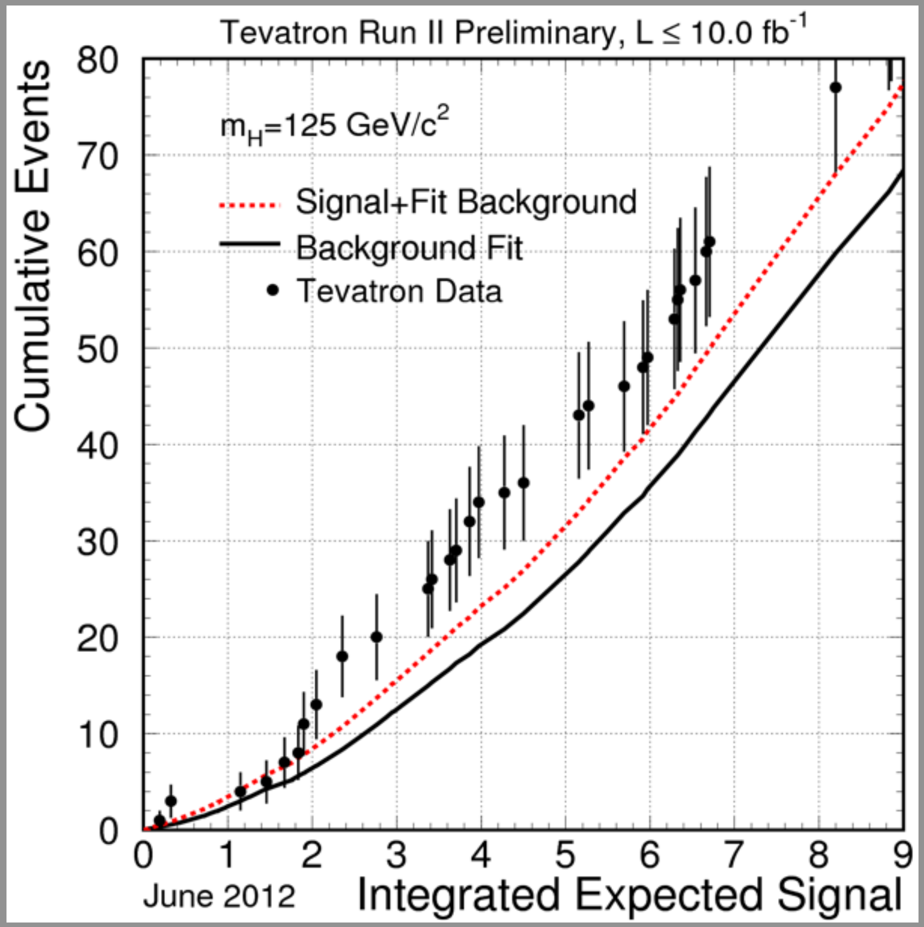



Tevatron Run II, L_int ≤ 9.7 fb^-1
1+2 b-Tagged Jets
Preliminary
Data - Bkgd
Bkgd Uncert.
WZ
ZZ
Events / (20 GeV/c^2)
Dijet Mass (GeV/c^2)


Tevatron Run II, L_int ≤ 9.7 fb^-1
1+2 b-Tagged Jets
Preliminary
Data - Bkgd
WZ
ZZ
Higgs Signal (σ_H×1.5)
m_H=125 GeV/c^2
Events / (20 GeV/c^2)
Dijet Mass (GeV/c^2)

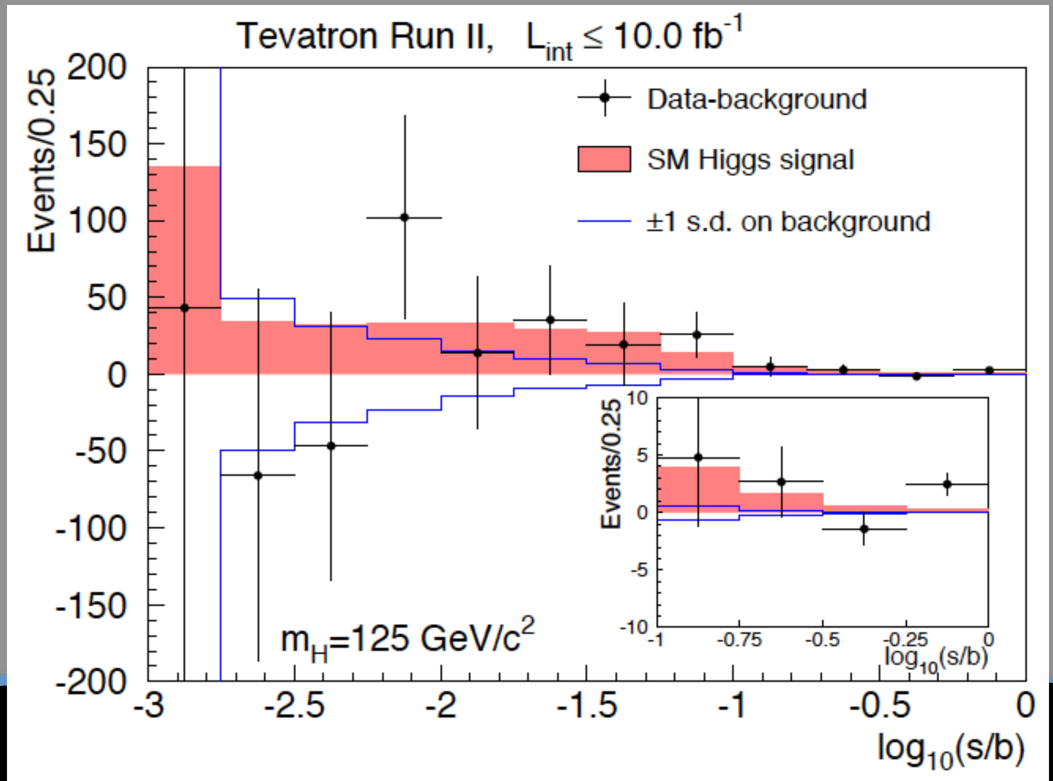

Tevatron Run II, L_int ≤ 9.7 fb^-1
1+2 b-Tagged Jets
Preliminary
Data - Bkgd
Higgs Signal
m_H=125 GeV/c^2
(σ_H×1.5)
Events / (20 GeV/c^2)
Dijet Mass (GeV/c^2)

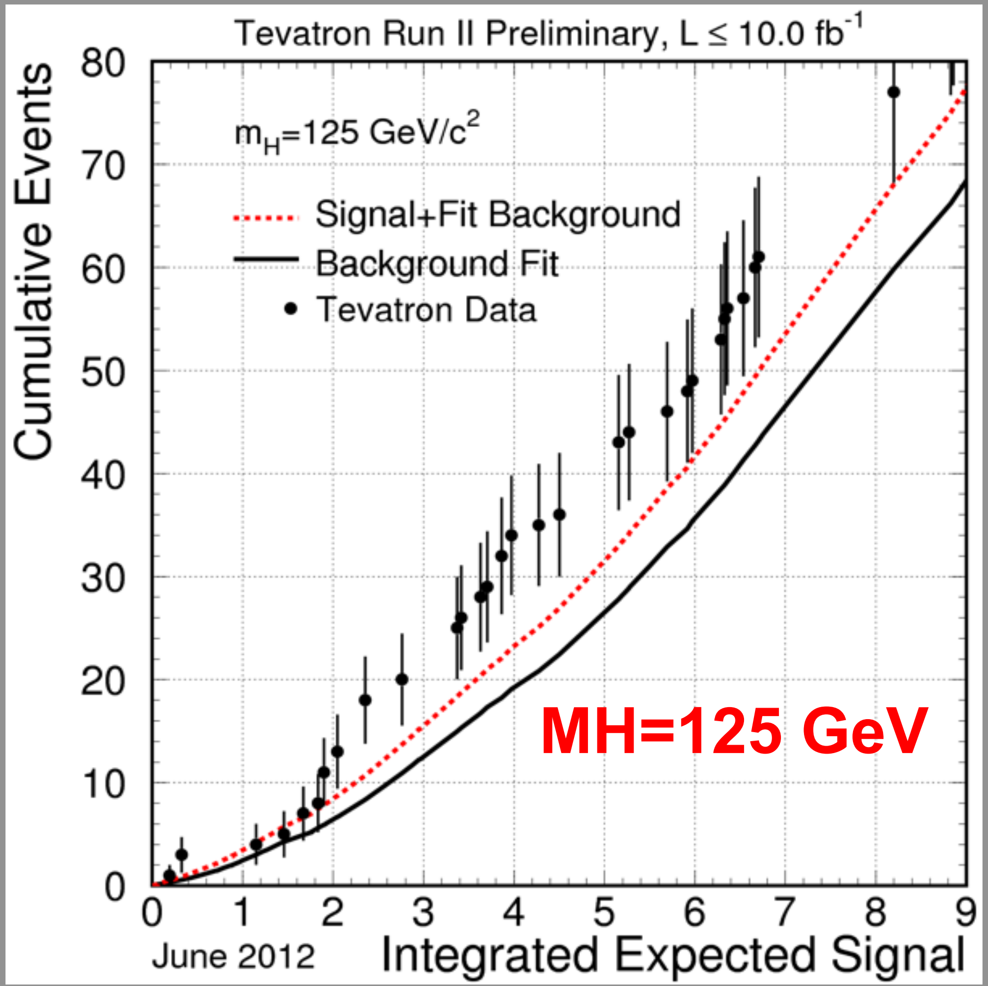




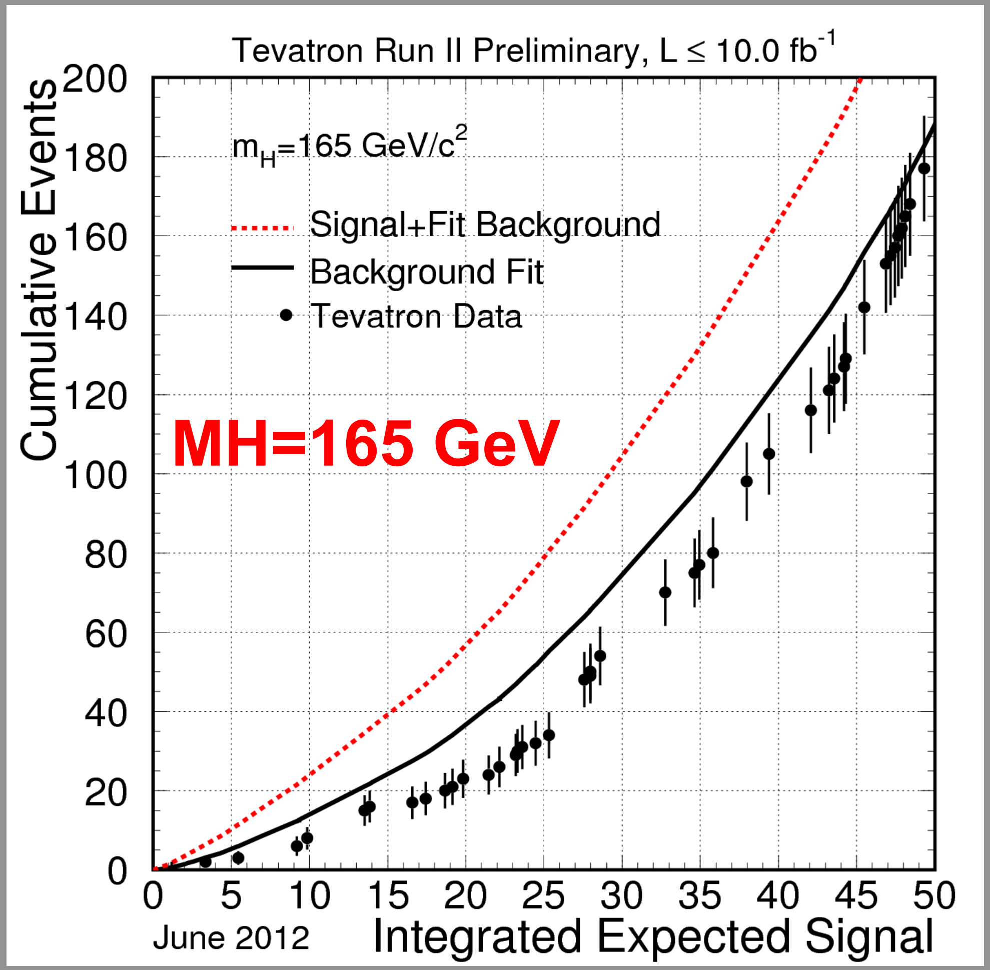
Display all input histogram bins ordered according to S/B in one plot.

– The background model has been constrained by the data.

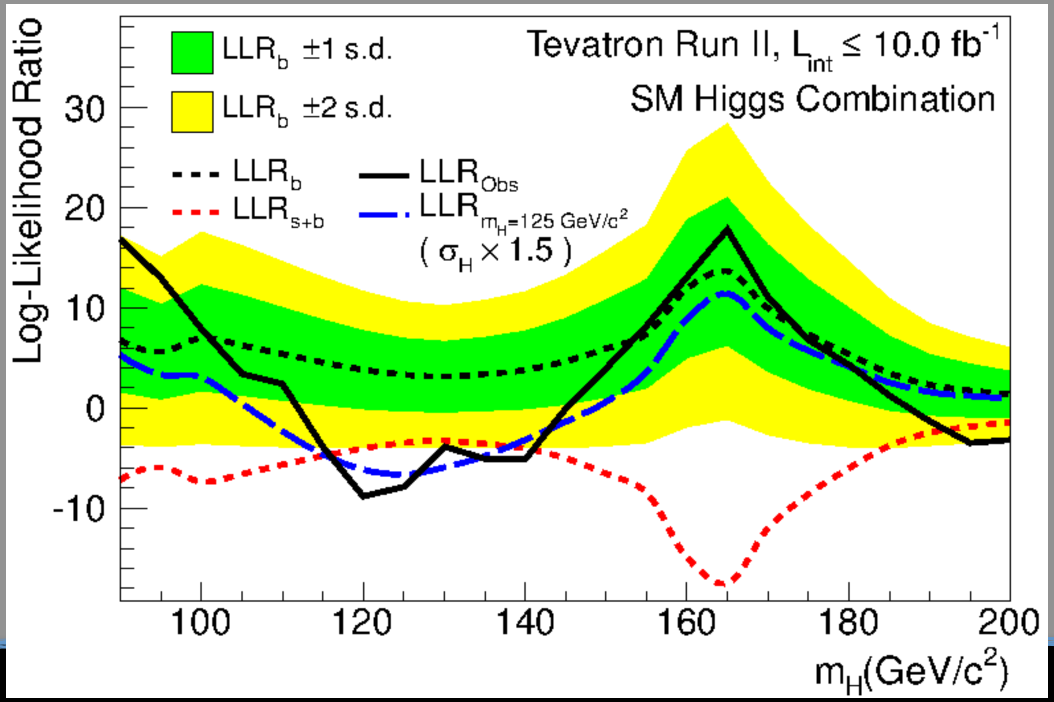




Tevatron Run II Preliminary, L ≤ 10.0 fb^-1
m_H=125 GeV/c^2
Signal+Fit Background
Background Fit
Tevatron Data
MH=125 GeV
Cumulative Events
June 2012
Integrated Expected Signal

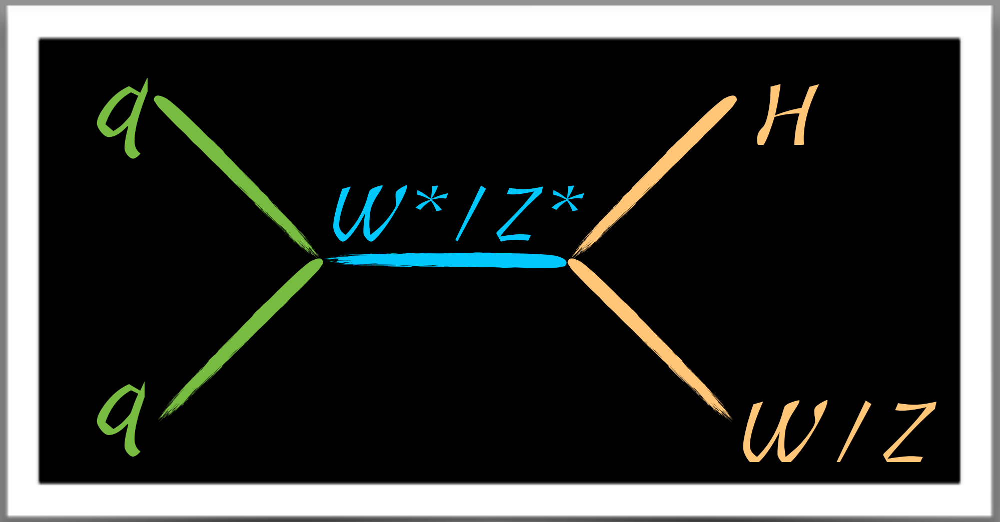


Tevatron Run II Preliminary, L ≤ 10.0 fb^-1
m_H=165 GeV/c^2
Signal+Fit Background
Background Fit
Tevatron Data
MH=165 GeV
Cumulative Events
June 2012
Integrated Expected Signal

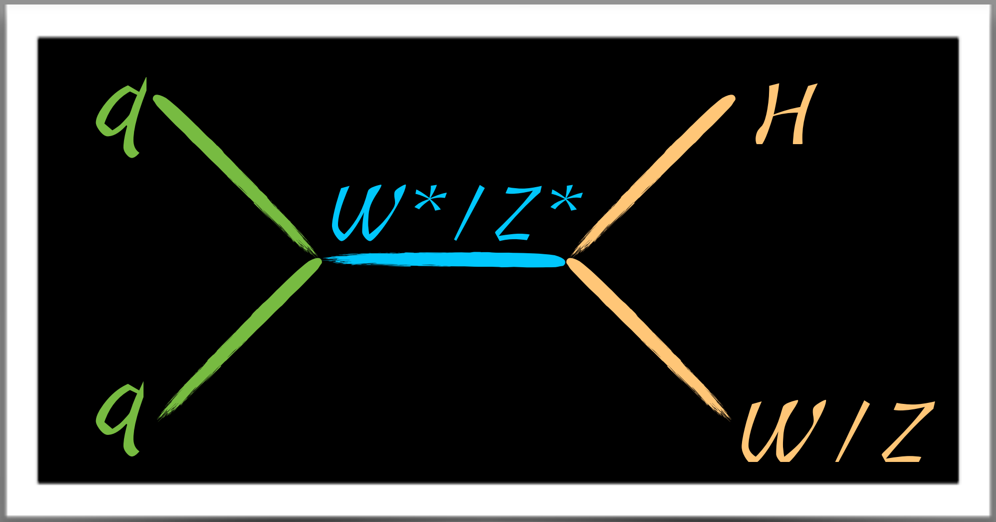


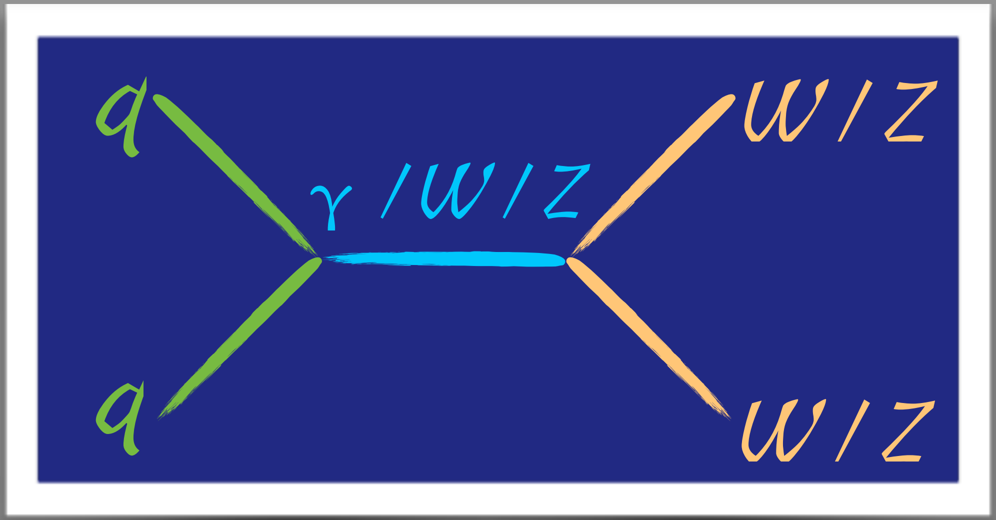
LLR_b ±1 s.d.
LLR_b ±2 s.d.
Tevatron Run II, L_int ≤ 10.0 fb^-1
SM Higgs Combination
LLR_b
LLR_s+b
LLR_Obs
LLR_mH=125 GeV/c^2
(σ_H × 1.5)
Log-Likelihood Ratio
m_H(GeV/c^2)

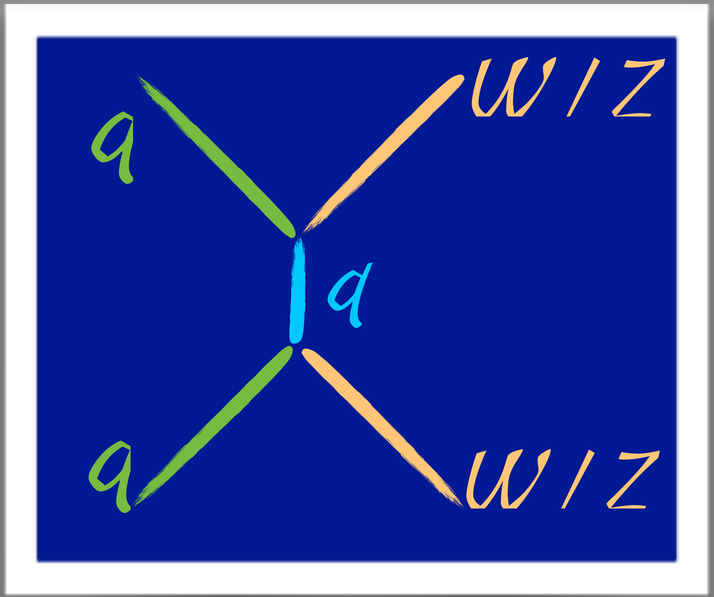
Search Validation?

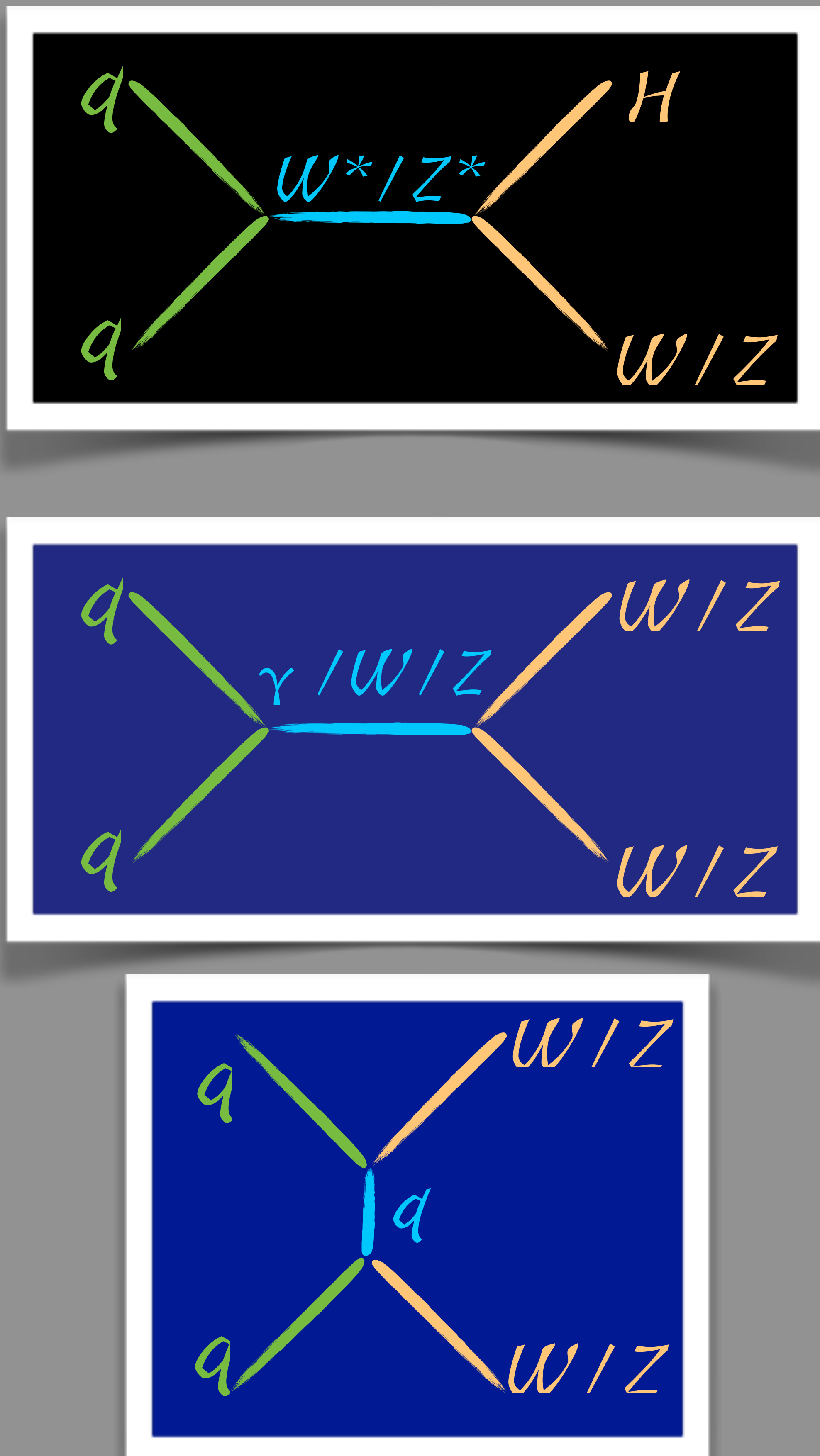


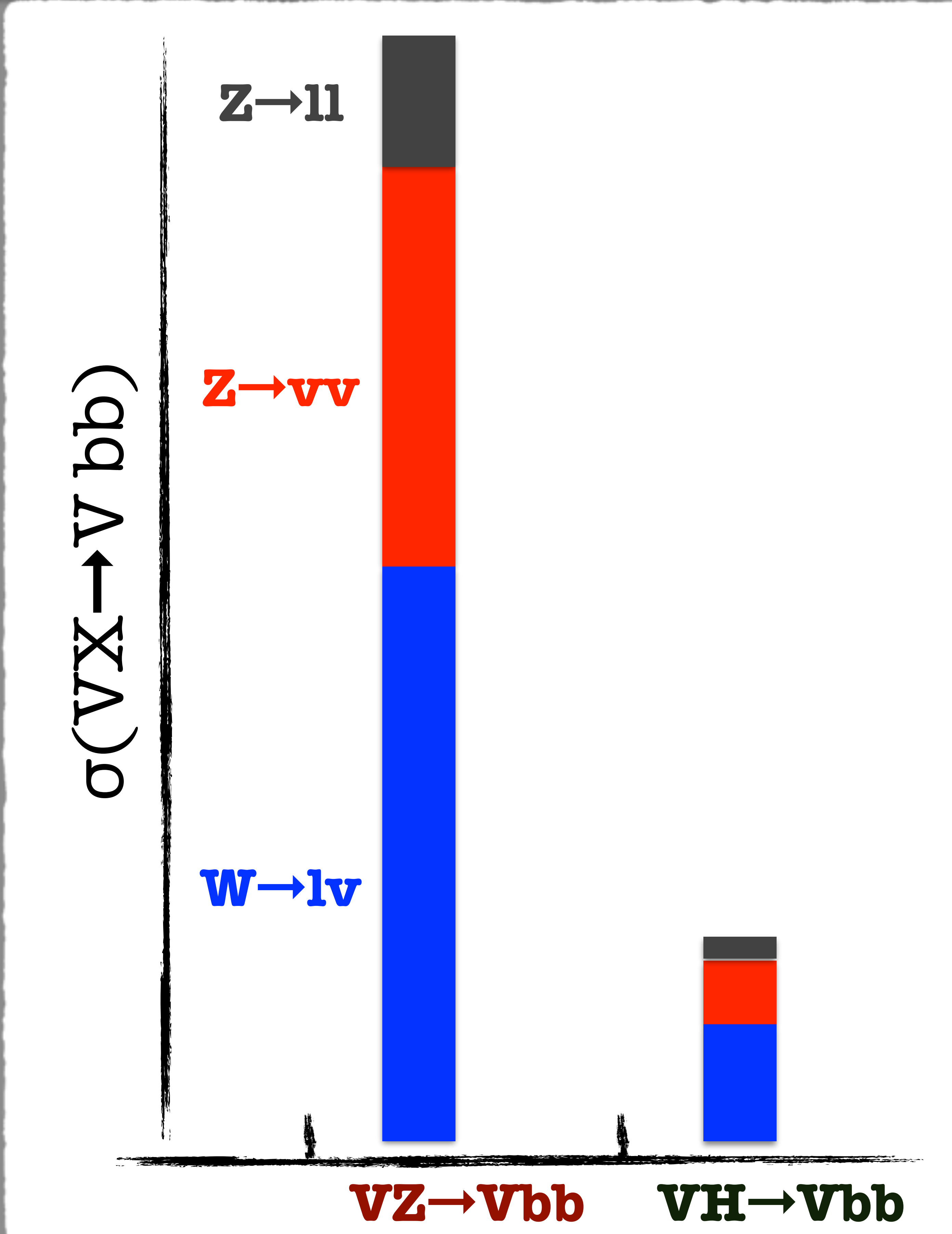
Search Validation?

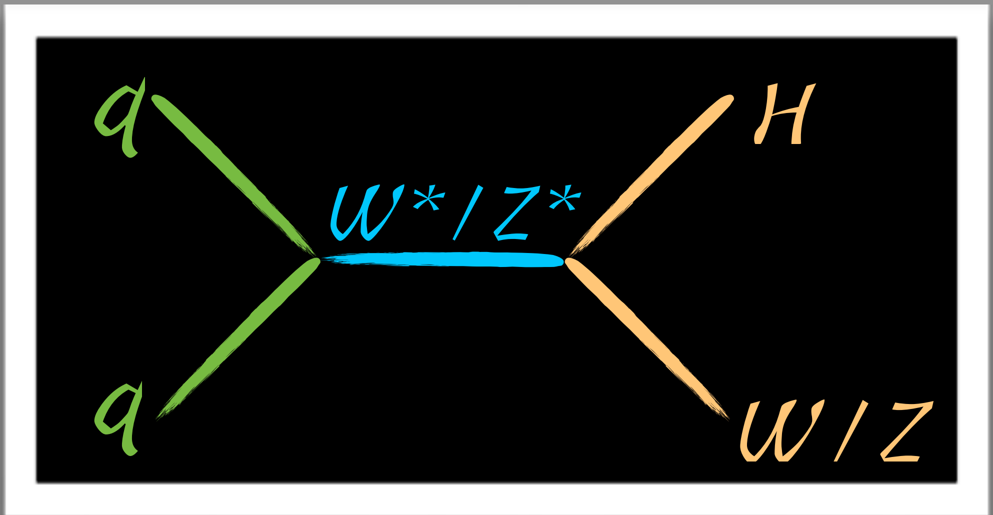


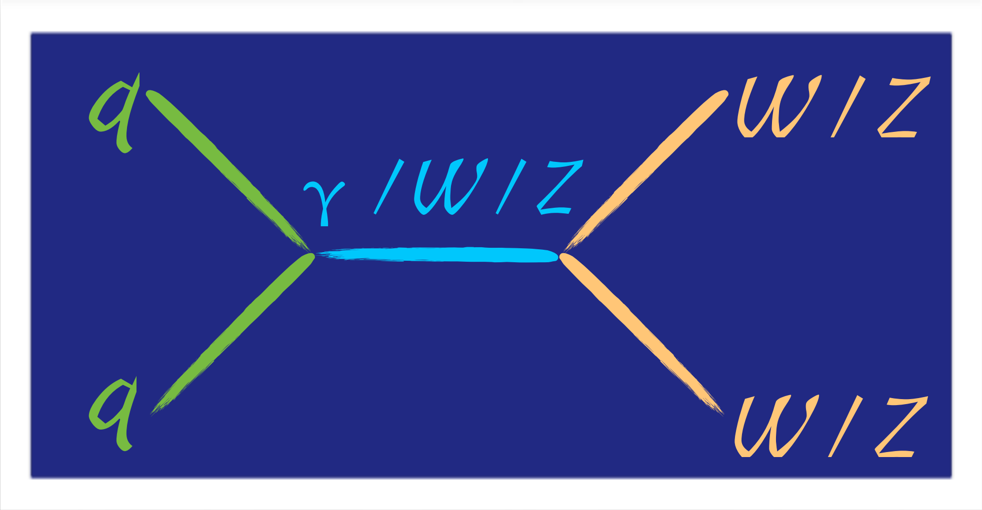


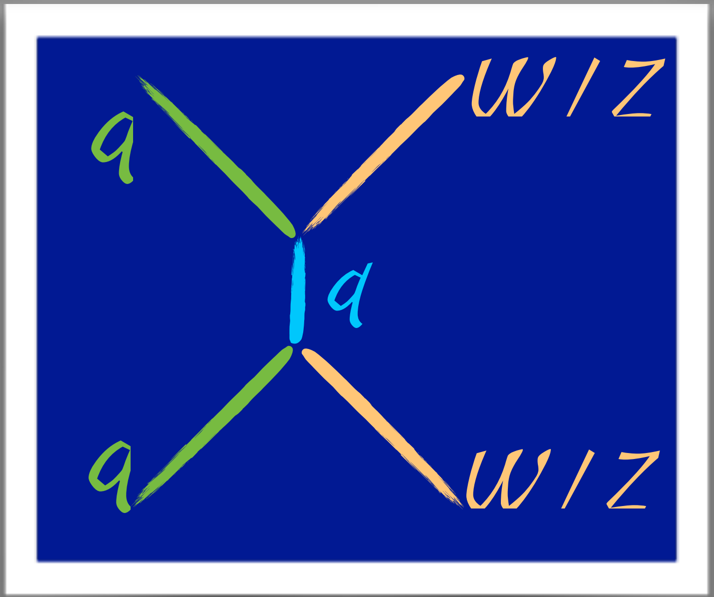


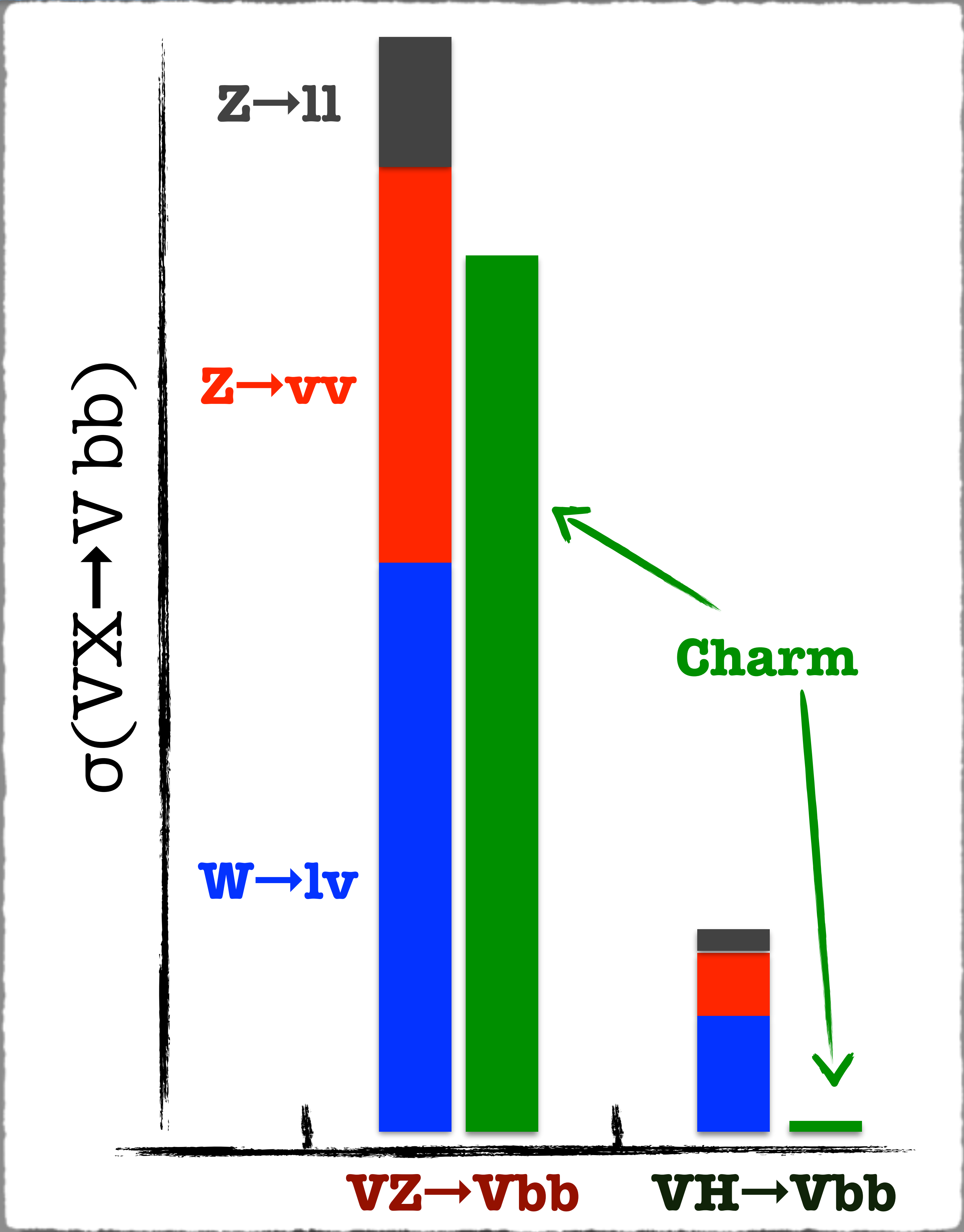

q
q
W*/Z*
H
W/Z
q
q
γ/W/Z
W/Z
W/Z
q
q
q
W/Z
W/Z


σ(VX→V bb)
Z→ll
Z→νν
W→lν
VZ→Vbb
VH→Vbb

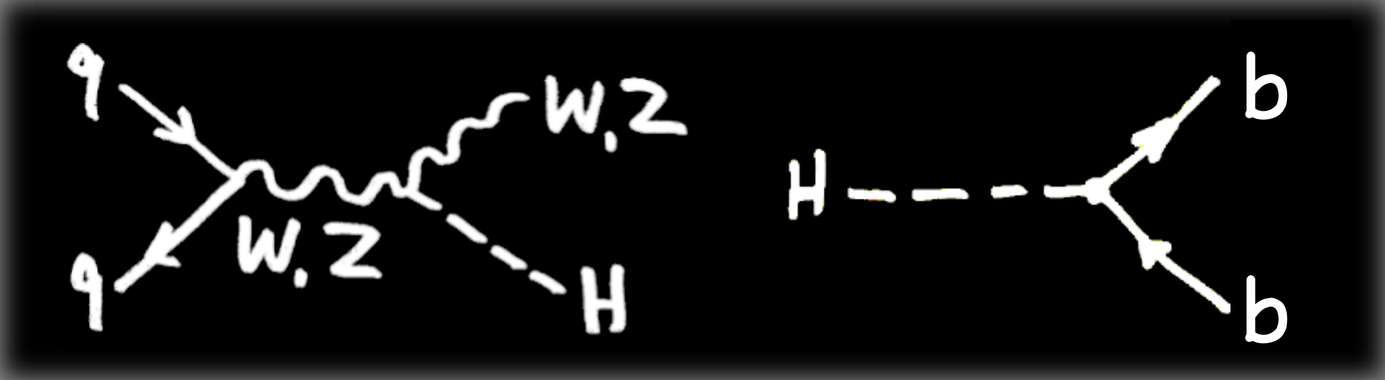

q
q
W*/Z*
H
W/Z


q
q
γ /W/Z
W/Z
W/Z

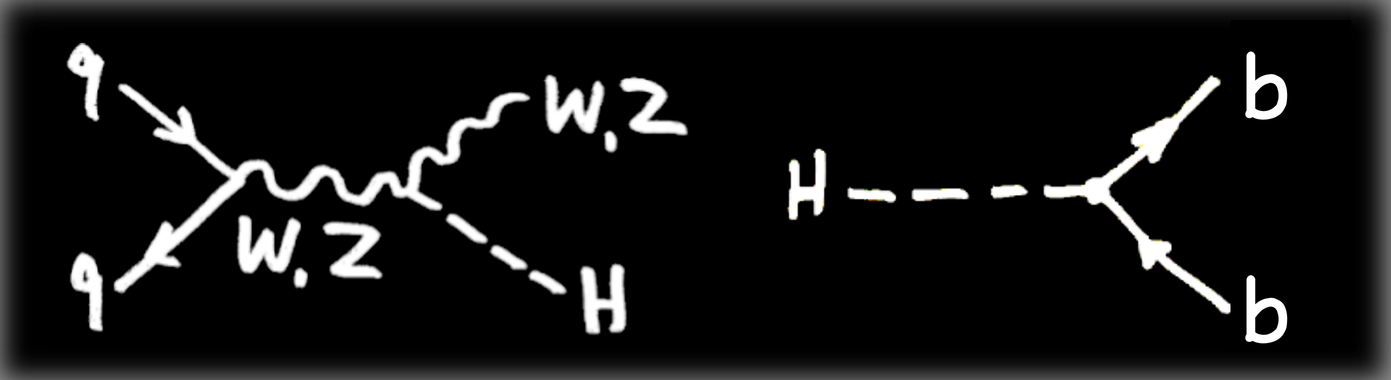

q
q
q
W/Z
W/Z

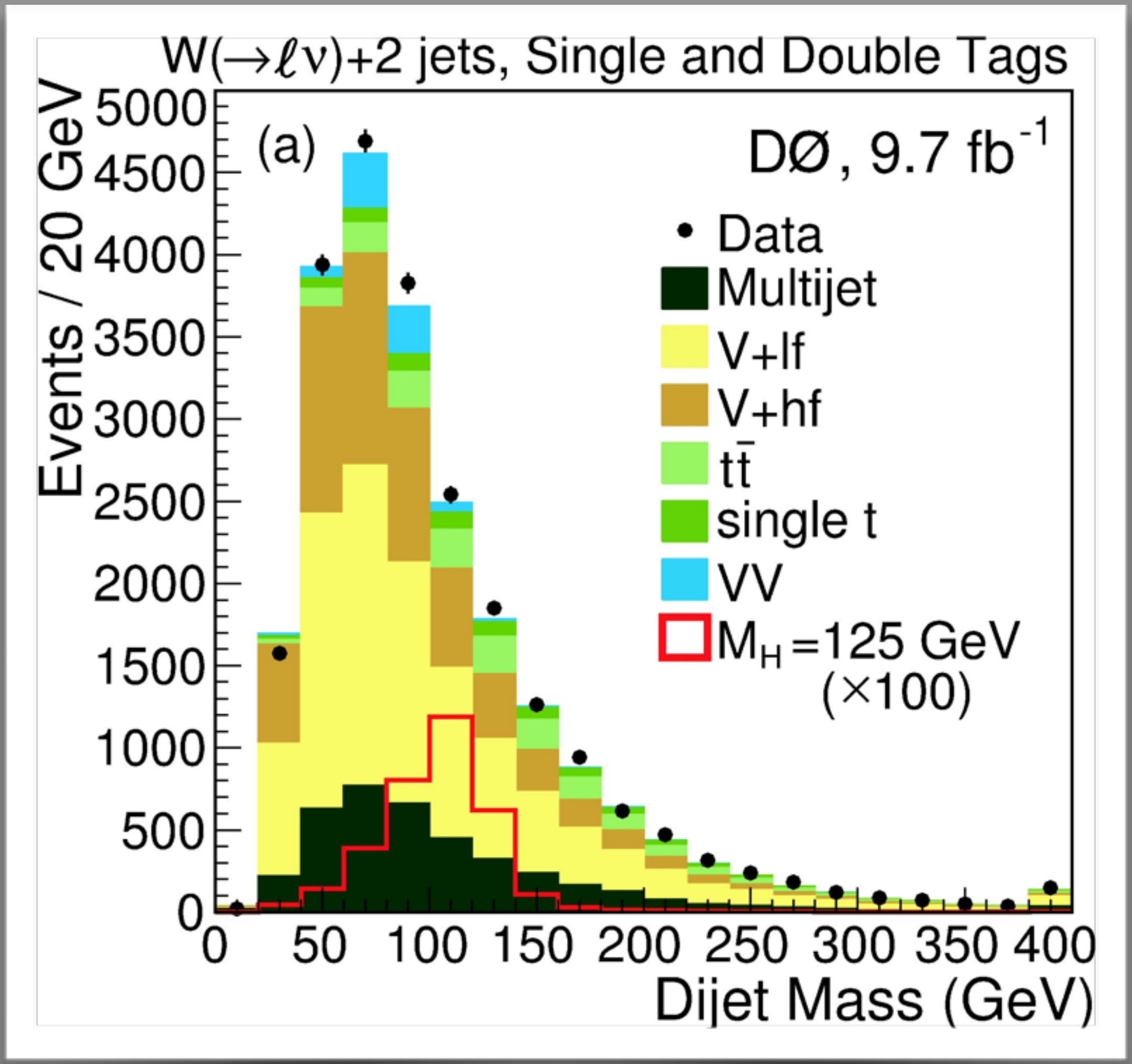

σ(VX→V bb)
Z→ll
Z→νν
W→lν
Charm
VZ→Vbb
VH→Vbb

Low Mass Search

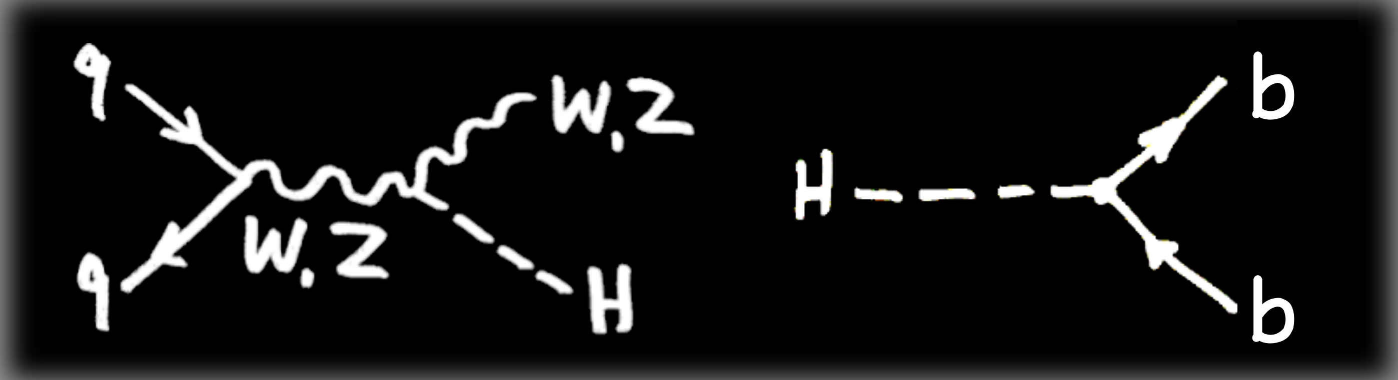


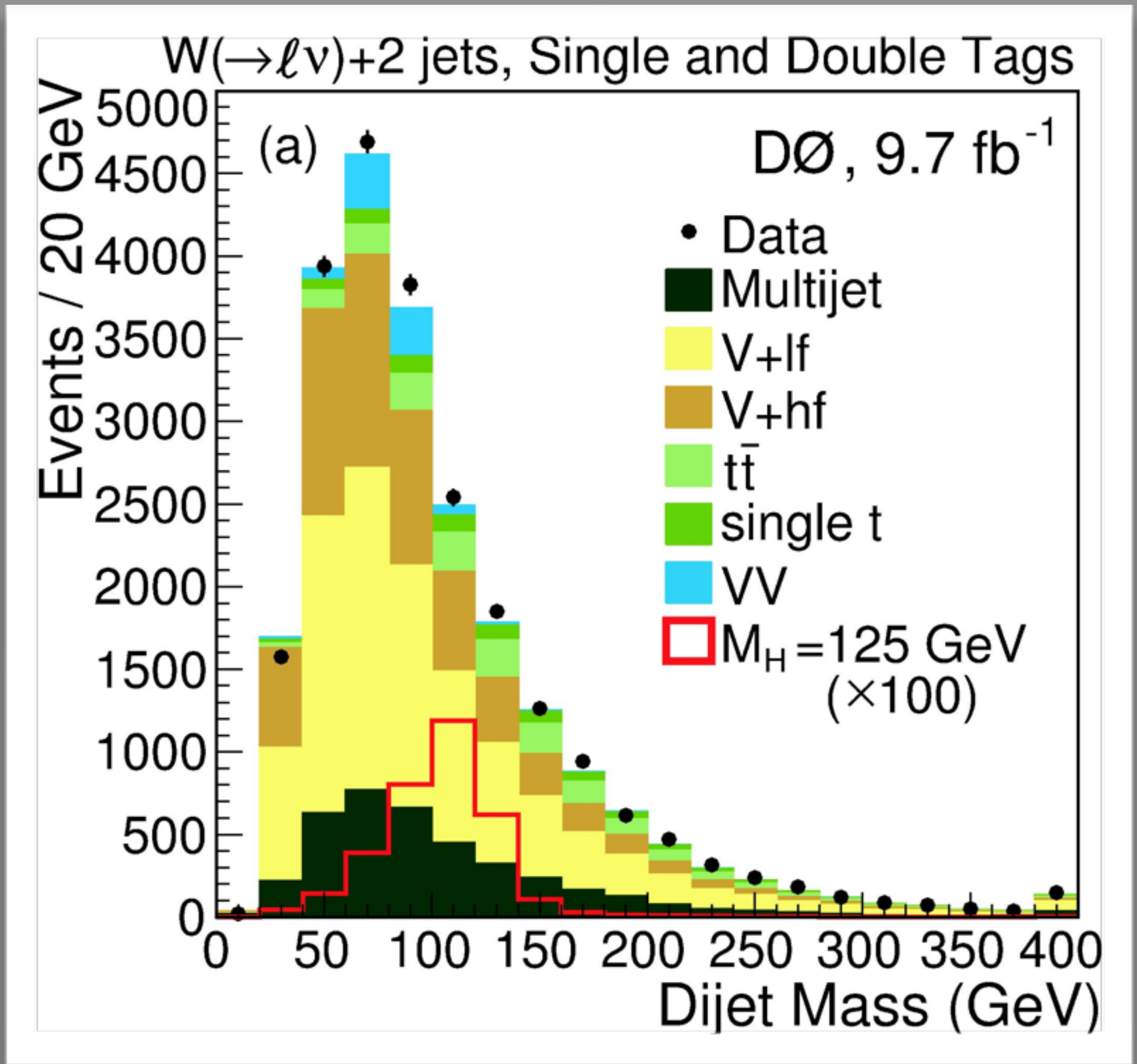
Low Mass Search

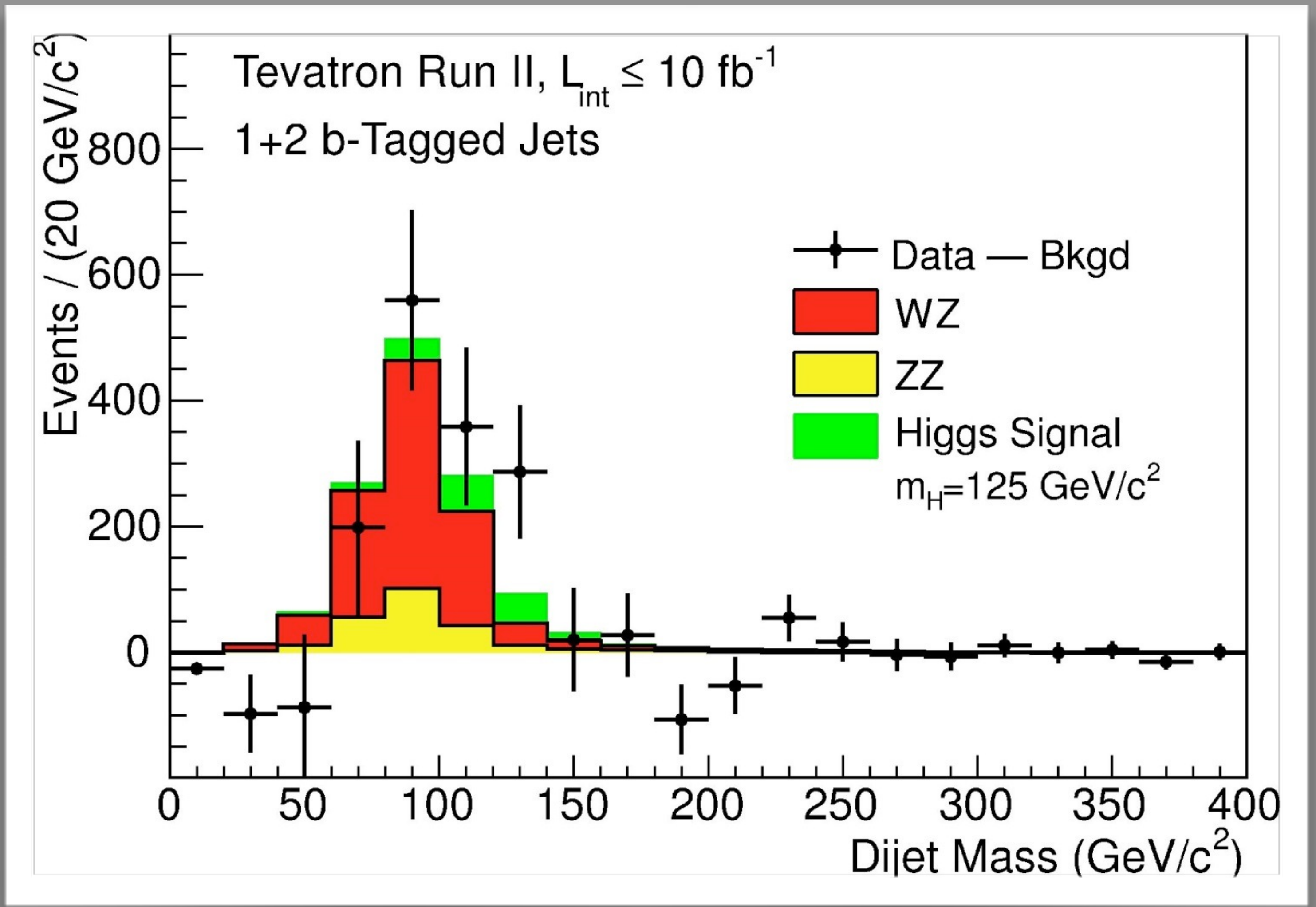




Low Mass Search

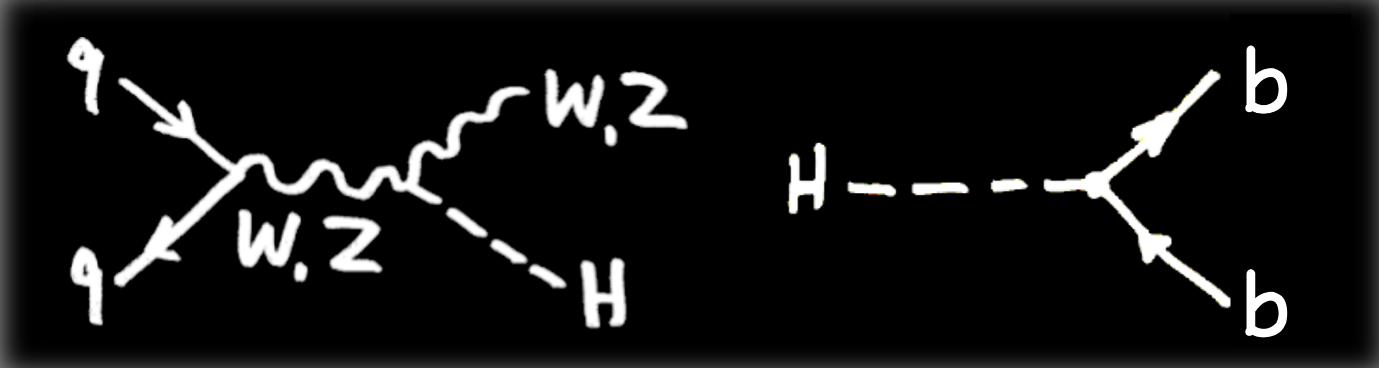


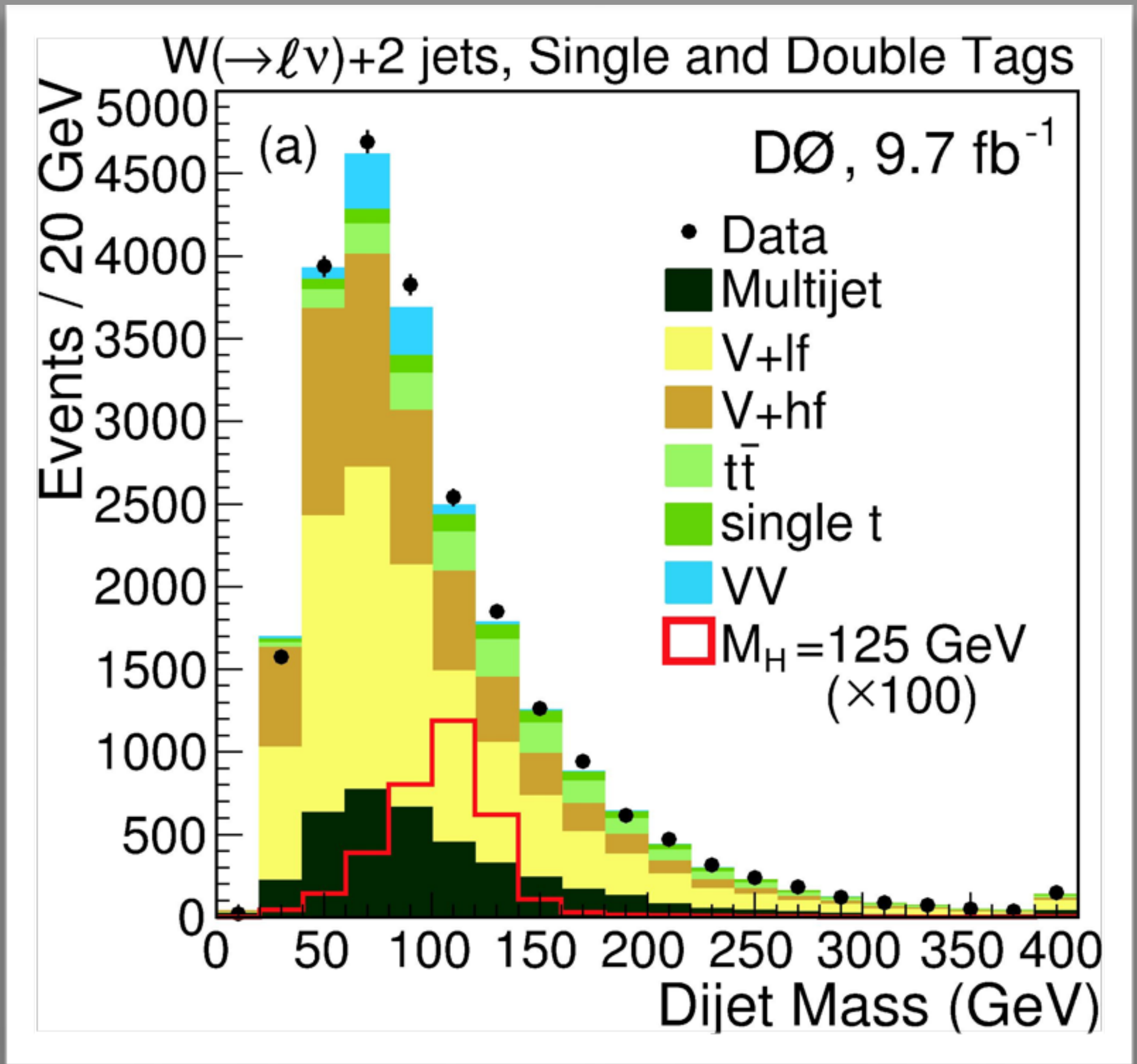


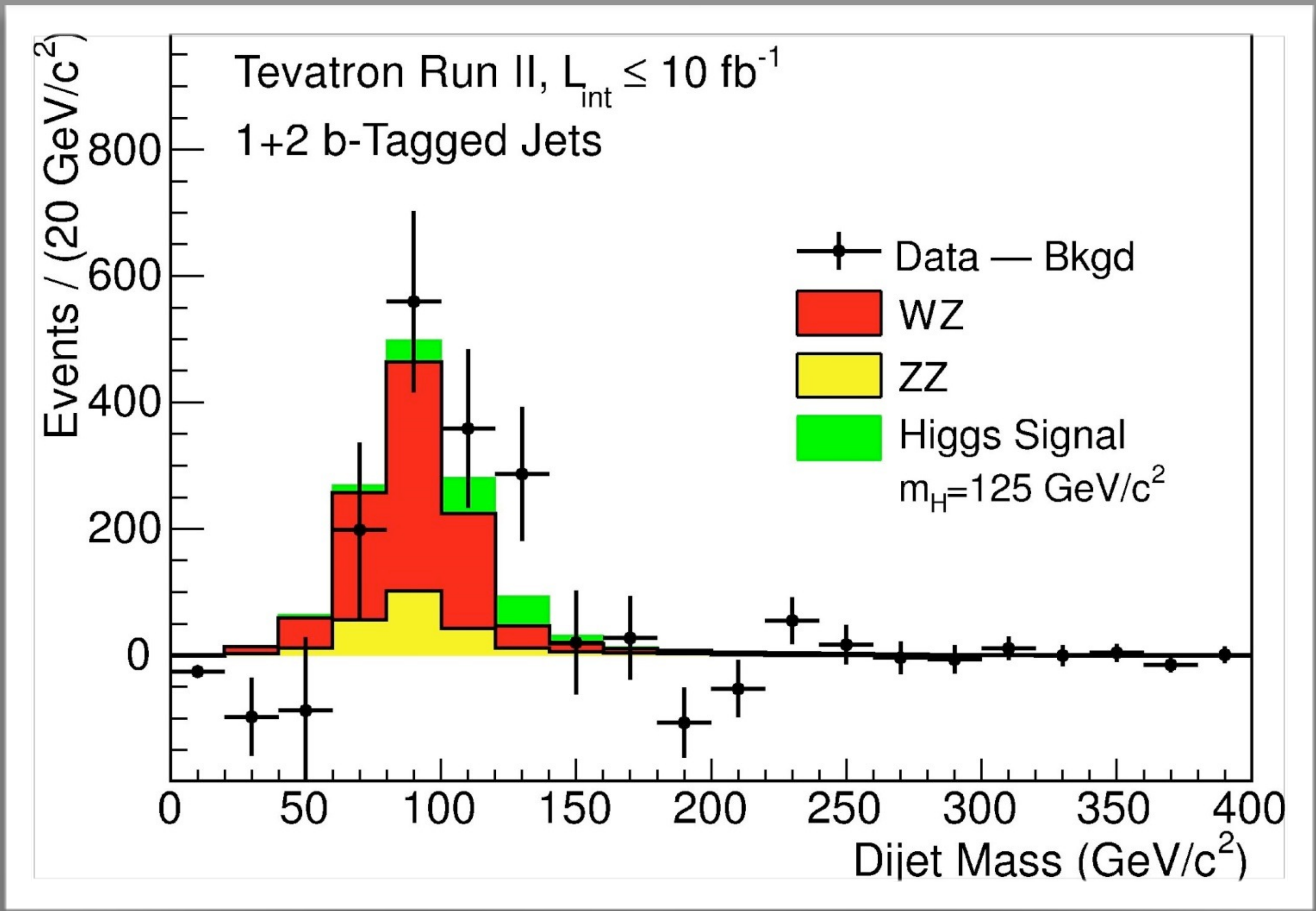


Low Mass Search

VALIDATED

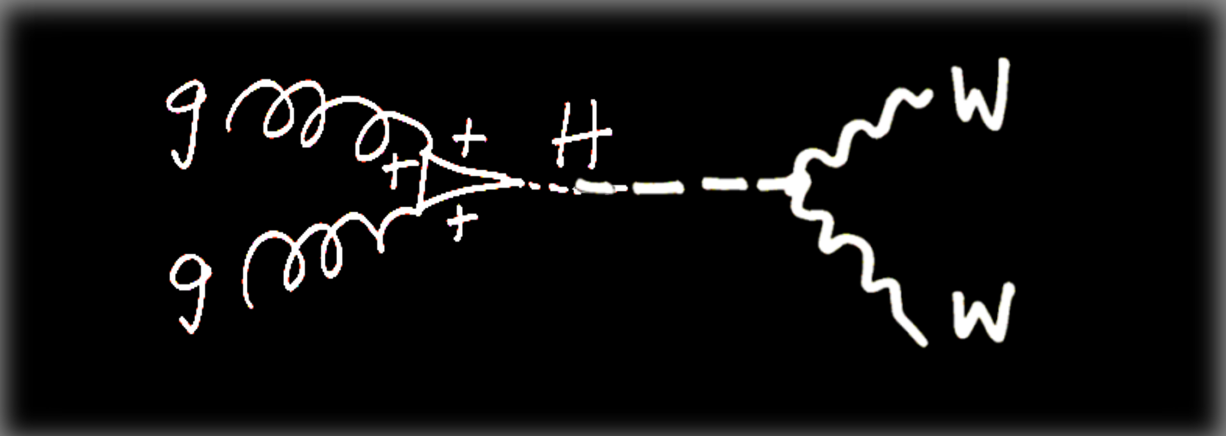


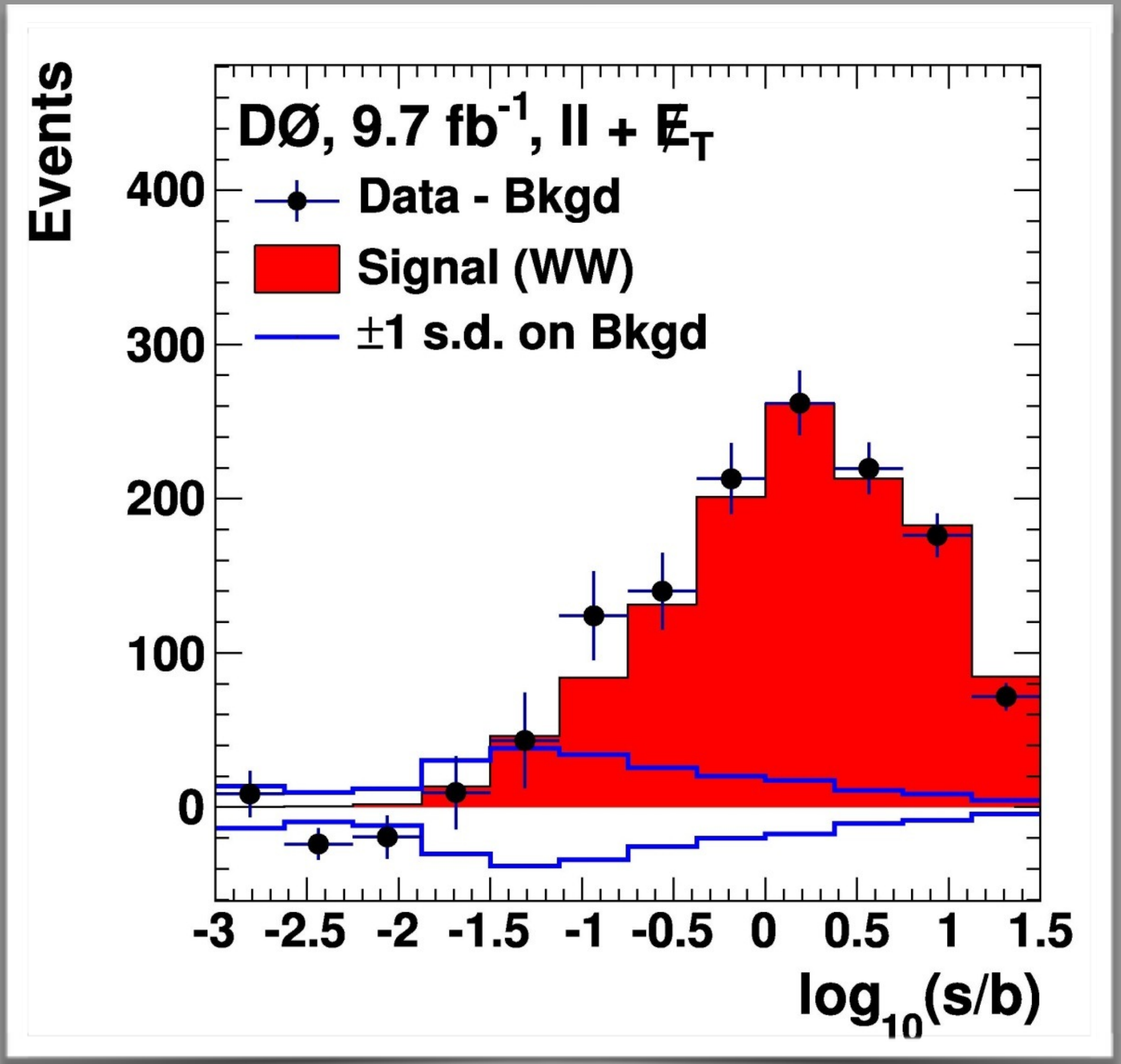




$$\sigma(\mathrm{WZ} + \mathrm{ZZ})/\sigma^{SM} = 0.7 \pm 0.2$$

High Mass Search





High Mass Search