New Signatures of Flavor Violating Higgs Coupling

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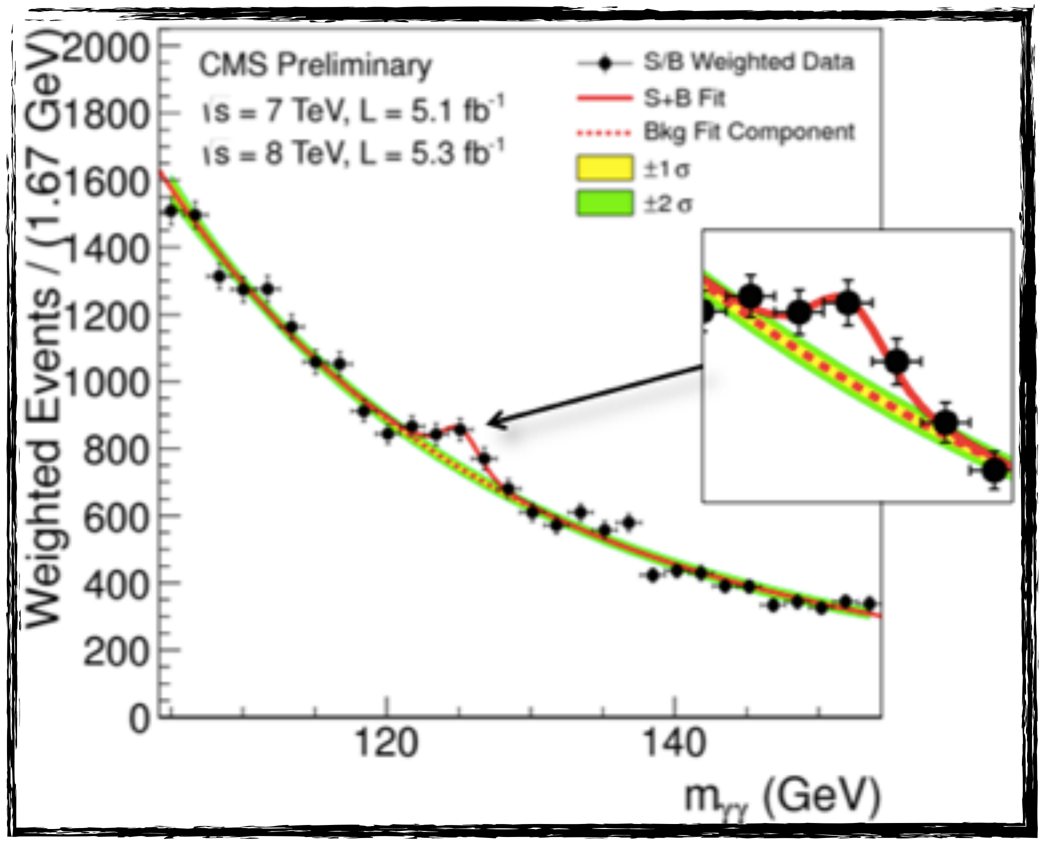
05, Aug, 2016

Based on JHEP06(2016)149 [arXiv:1601.02616]

Collaborated with Malte Buschmann, Joachim Kopp,and Jia Liu

Higgs Discovery



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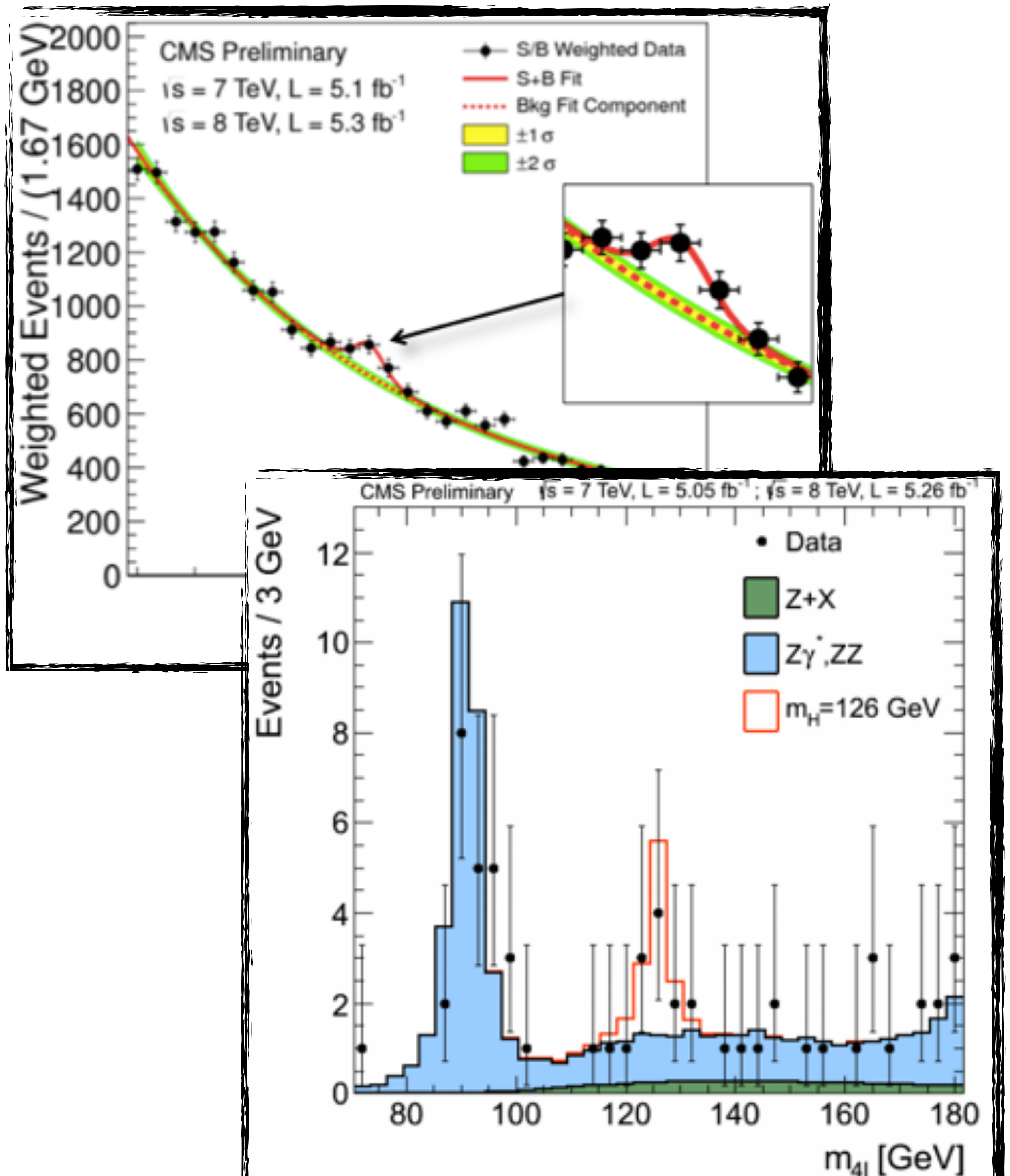

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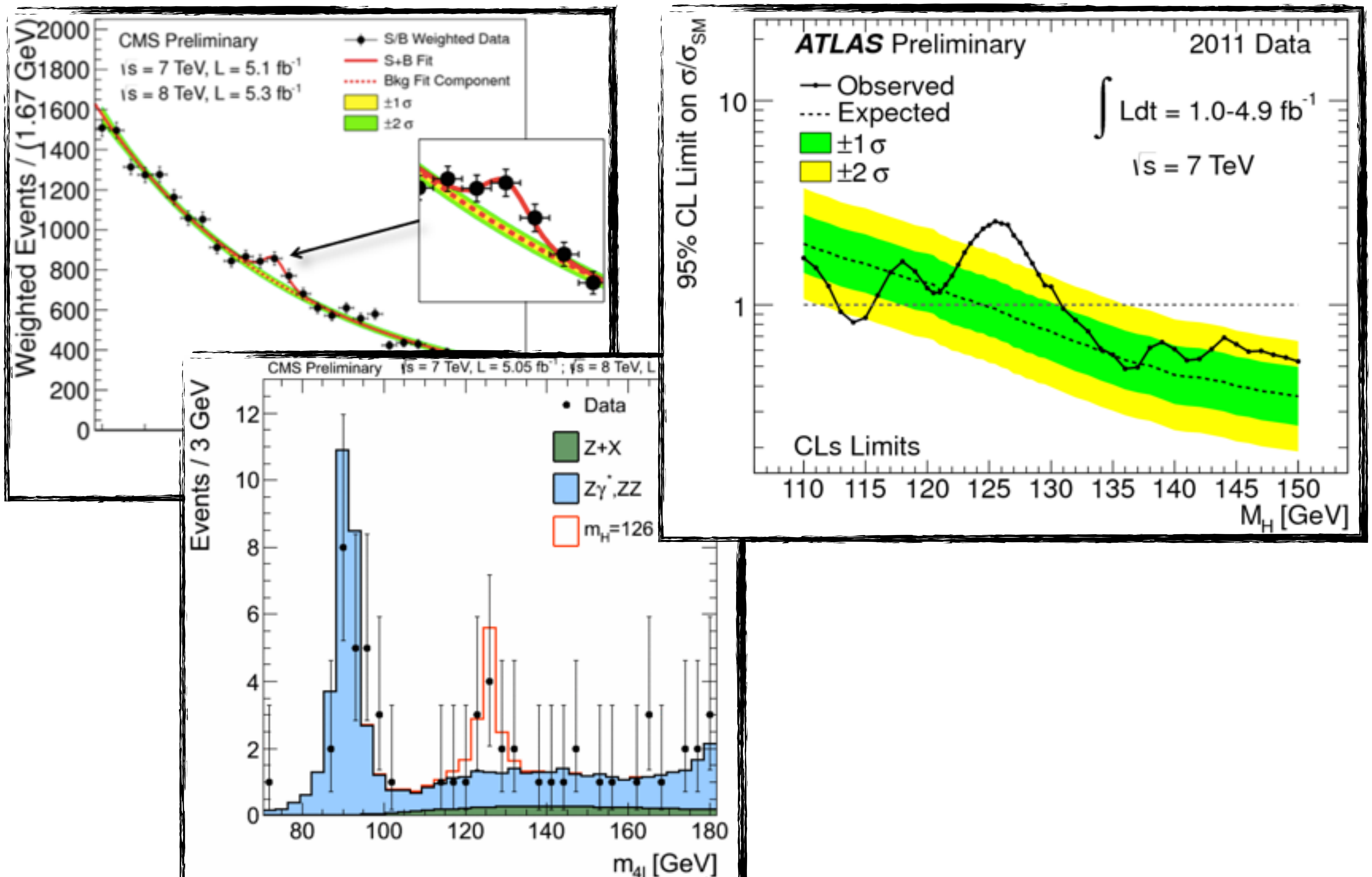

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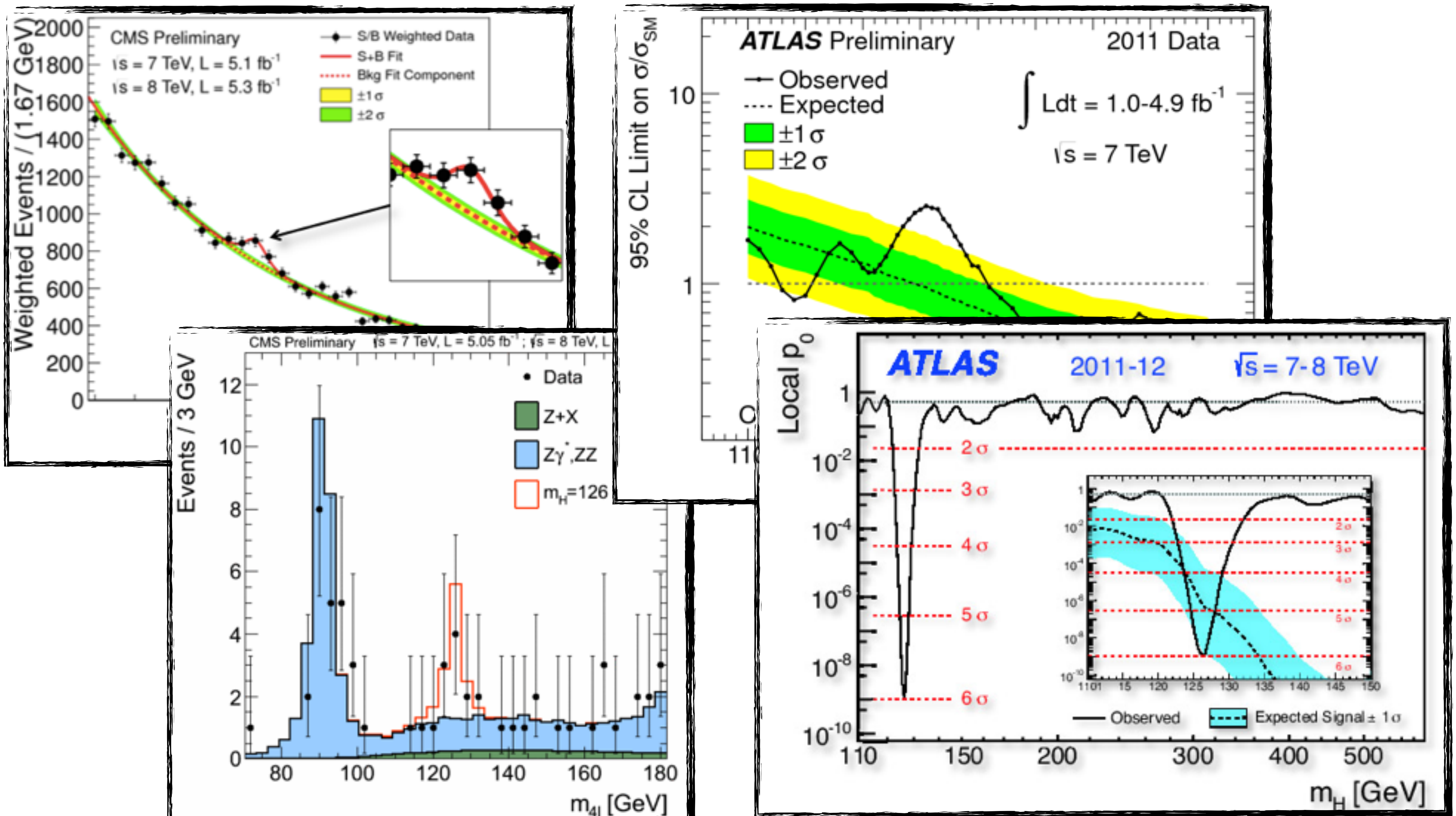
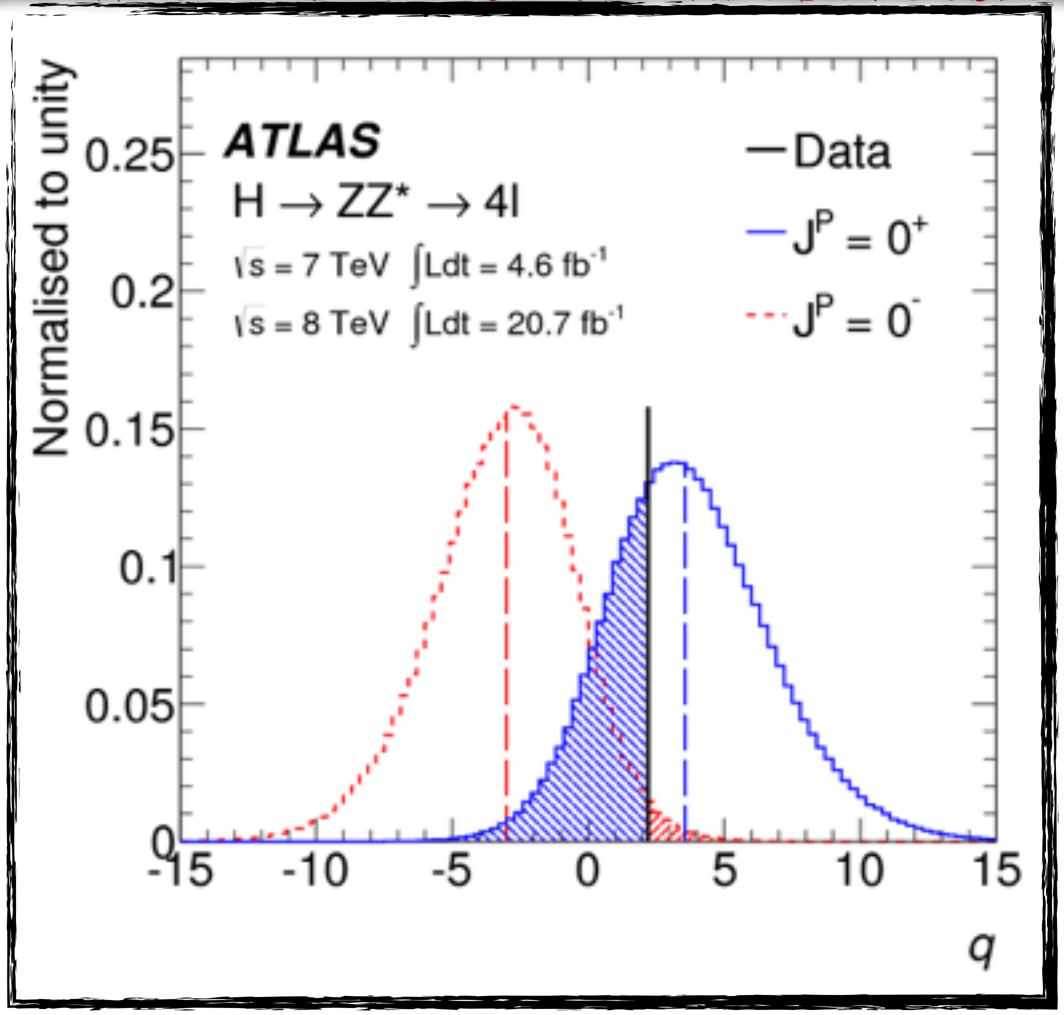
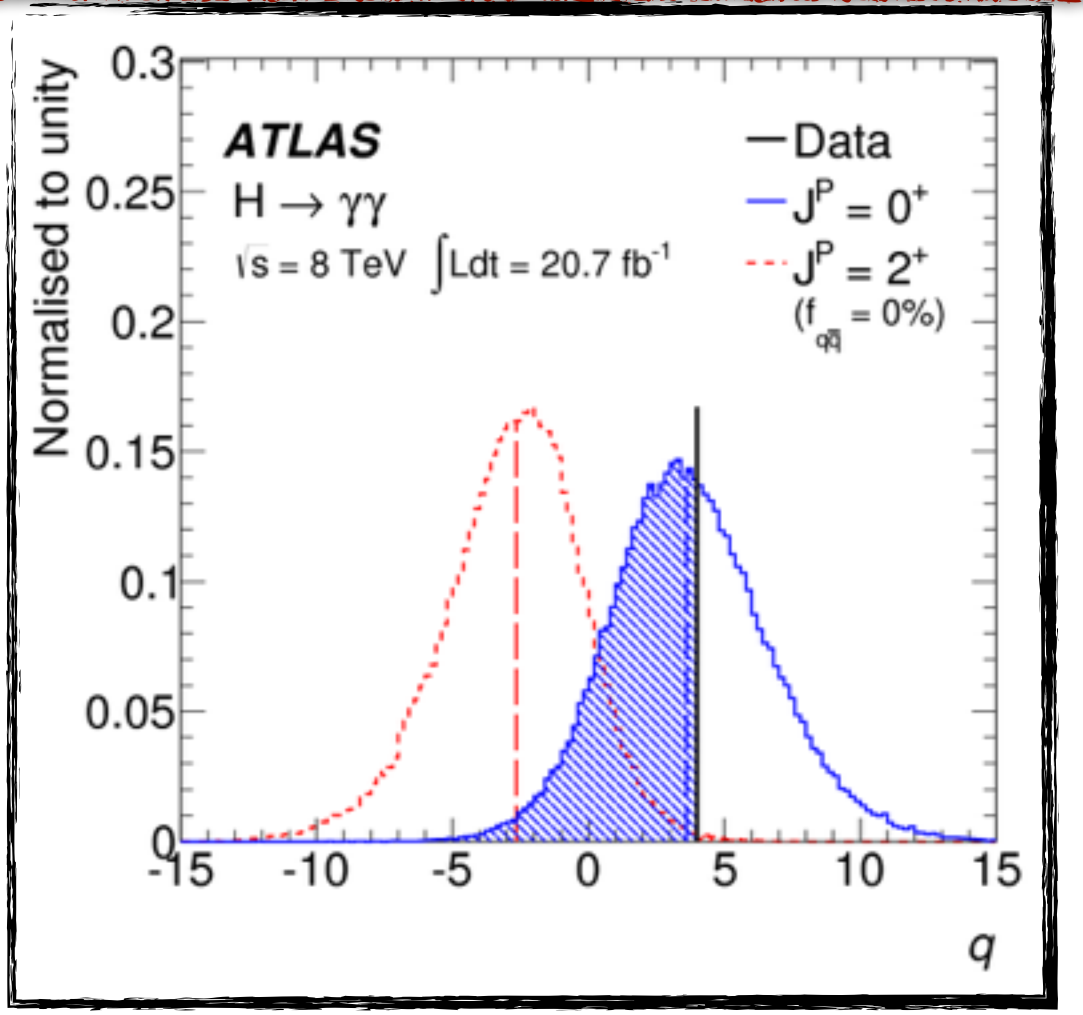


Higgs Properties





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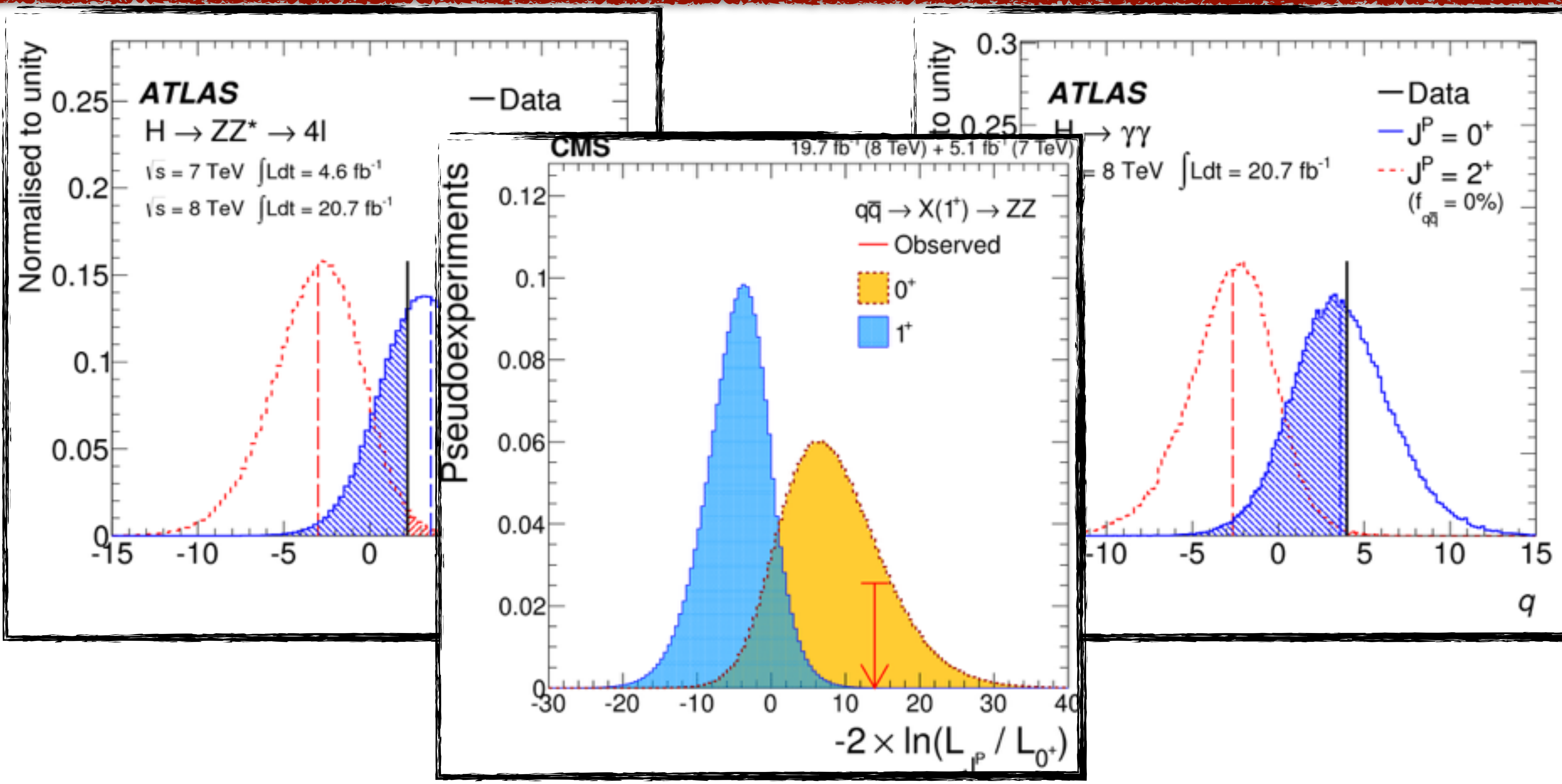

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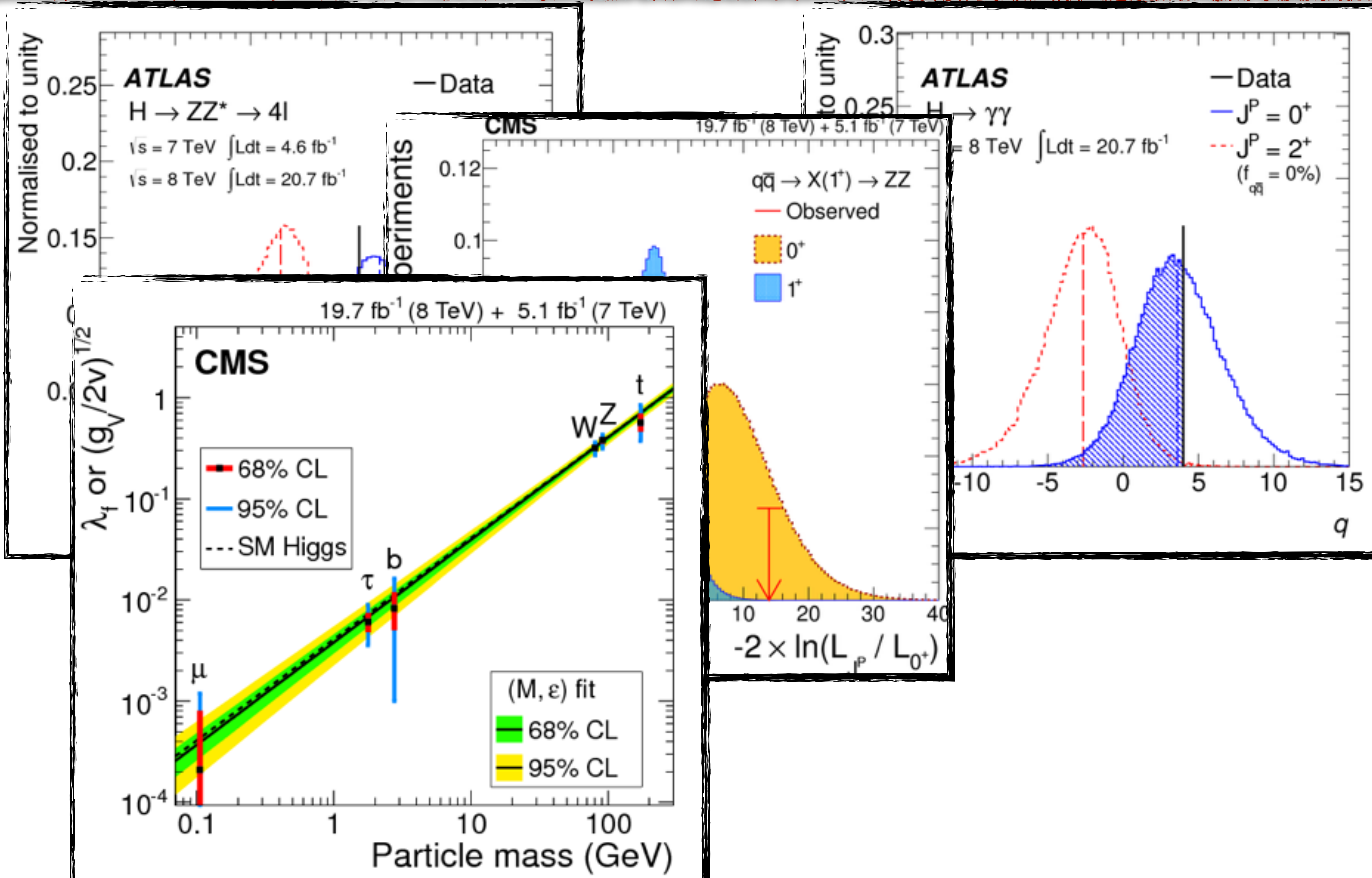

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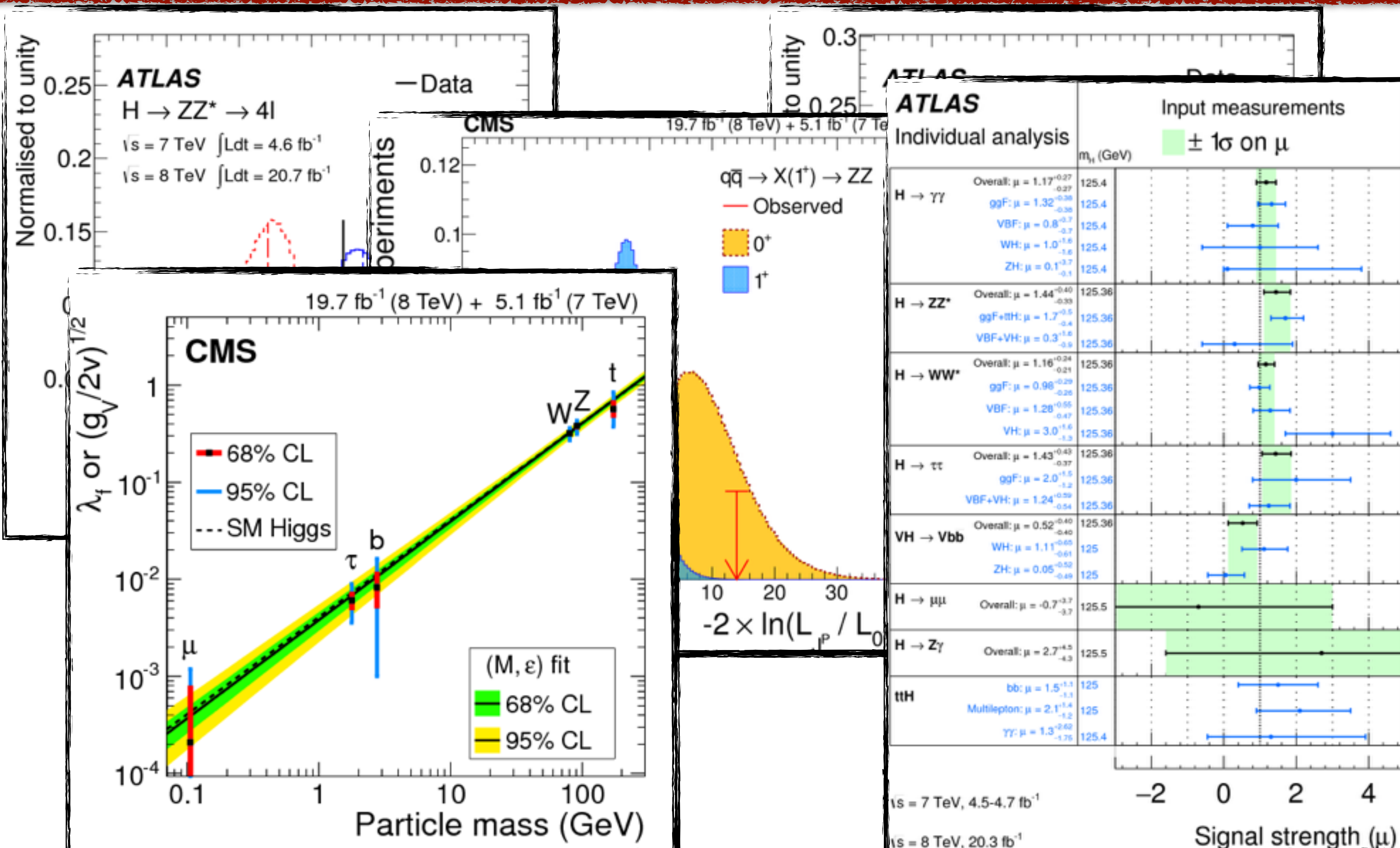


Unknown Higgs properties

- Other source of EW symmetry breaking? more Higgs, **2HDM**
- Higgs self-interaction coupling? stability of EW vacuum
- light quark coupling? e.g. h->J/Psi + photon
- Exotic Higgs decay?
- Flavor alignment? **Flavor violation**? FV couplings?

Outline

- thh search in higher dimension operator
- thh search in type III 2HDM, via H -> h h
- $H^0 \to \tau\mu$ decay in type III 2HDM

Higher dimension operator

- The dimension 4 and 6 couplings in the up-type sector

$$\mathcal{L} \supset -\lambda_u^{ij}\overline{Q_L^i}\tilde{H}u_R^i - \frac{\lambda_u^{\prime ij}}{\Lambda^2}\overline{Q_L^i}\tilde{H}u_R^i\left(H^\dagger H\right) + h.c.$$

$$\to -m_u^{ij}\overline{u_L^i}u_R^j - y_u^{ij}\overline{u_L^i}u_R^j h - \frac{f_u^{ij}}{v}\overline{u_L^i}u_R^j h^2 + \mathcal{O}\left(h^3\right) + h.c.$$

$$f_u^{ij} = \frac{3}{2}y_u^{ij}\ (i \neq j)$$

- Constraints on couplings

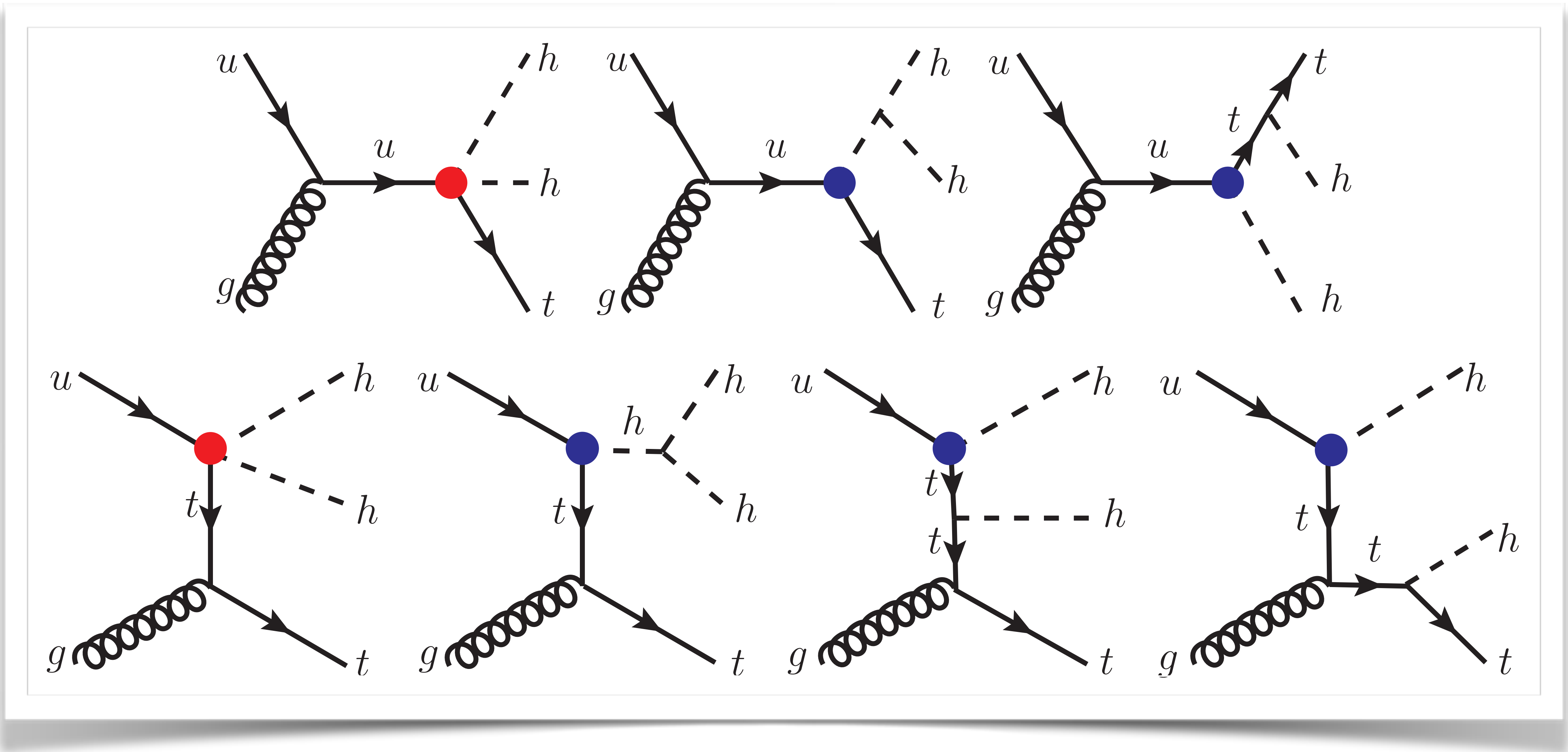
$$\mathrm{BR}\left(t \to ch\right) < 0.0046$$
$$\mathrm{BR}\left(t \to uh\right) < 0.0045$$

- Our Benchmark point

$$y^{ct} = y^{tc} = 0.08$$
$$y^{ut} = y^{tu} = 0.08$$

thh from dimension 6 operator

- thh production processes @ LHC



thh from dimension 6 operator

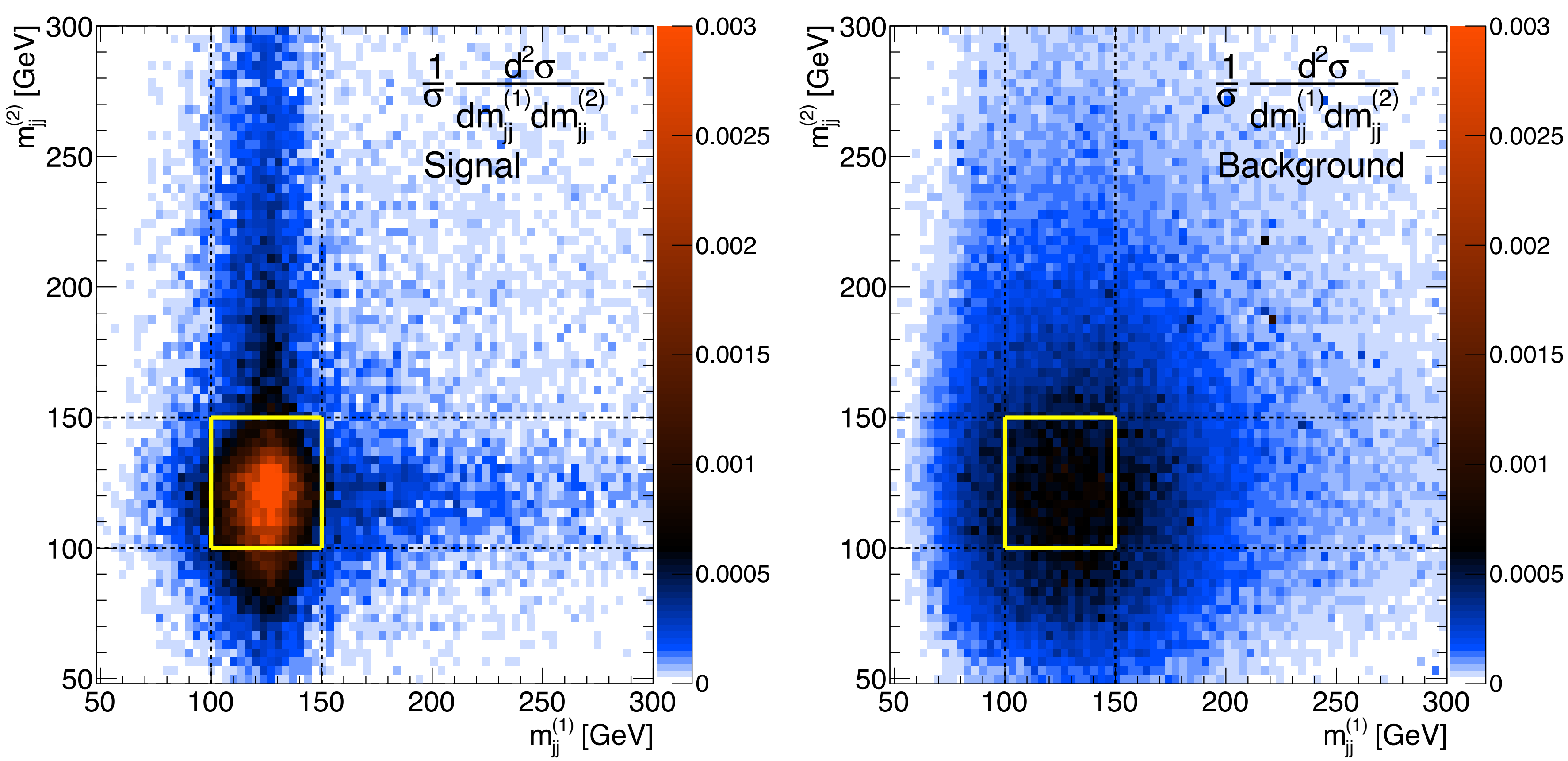
$thh \quad vs \quad t\bar{t} + jets$

- Topology:

$$(h \to b\bar{b})(h \to b\bar{b})(t \to b\ell^+\nu_\ell)$$

- reconstruction of two h and top mass

$$\chi^2 \equiv \frac{(m_{jj}^{(1)} - m_h)^2}{(\Delta m_h)^2} + \frac{(m_{jj}^{(2)} - m_h)^2}{(\Delta m_h)^2} + \frac{(m_{j\ell\nu} - m_t)^2}{(\Delta m_t)^2}$$



thh search @ LHC

- Cut Flow Table

cut	signal (thh)	background ($t\bar{t}$)
σ_{prod} [fb]	6.1	5.9×10^5
preselection	24.0%	2.20%
b-tagging	19.6%	0.55%
$p_T^{j_1} > 140$ GeV	76.5%	31.1%
$p_T^{j_2} > 100$ GeV	90.9%	66.3%
$p_T^{j_3} > 60$ GeV	95.7%	84.6%
Higgs, top mass window	24.4%	8.55%
$p_T^{h_2} > 150$ GeV	73.3%	35.3%
$p_T^{h_1} > 300$ GeV	65.5%	32.3%
$\Delta R_{b\bar{b}}^{\max} < 1.5$	96.1%	77.2%
σ_{final} [fb]	0.022	0.093

- Need Integrate Luminosity to Exclude EFT

$$870 fb^{-1} (95\% C.L.)$$

QFV Type III 2HDM

- General Scalar Potential for 2HDM

$$V=\mu_1^2\Phi_1^\dagger\Phi_1+\mu_2^2\Phi_2^\dagger\Phi_2+(\mu_3^2\Phi_1^\dagger\Phi_2+h.c.)$$
$$+\lambda_1(\Phi_1^\dagger\Phi_1)^2+\lambda_2(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left[(\lambda_5\Phi_1^\dagger\Phi_2+\lambda_6\Phi_1^\dagger\Phi_1+\lambda_7\Phi_2^\dagger\Phi_2)(\phi_1^\dagger\Phi_2)+h.c.\right]$$

$$\Phi_1=\begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v+h_1+iG^0)\end{pmatrix}$$
$$\Phi_2=\begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2+ih_3)\end{pmatrix}$$

- Reducing the parameters into four

$$\{\sin\alpha \quad \lambda_3 \quad \lambda_7 \quad m_{H^0}=m_{H^\pm}=m_{A^0}\}$$

$$m_h \quad \lambda_2$$

- Yukawa coupling for up-type quarks

$$\mathcal{L}=-\eta_{u,1}^{ij}\overline{Q_L^i}\tilde{\Phi}_1u_R^i-\eta_{u,2}^{ij}\overline{Q_L^i}\tilde{\Phi}_2u_R^i+h.c.$$
$$=-m_i\overline{u_L^i}u_R^i-y_{u,h}^{ij}\overline{u_L^i}u_R^ih-y_{u,H}^{ij}\overline{u_L^i}u_R^iH^0+h.c.$$

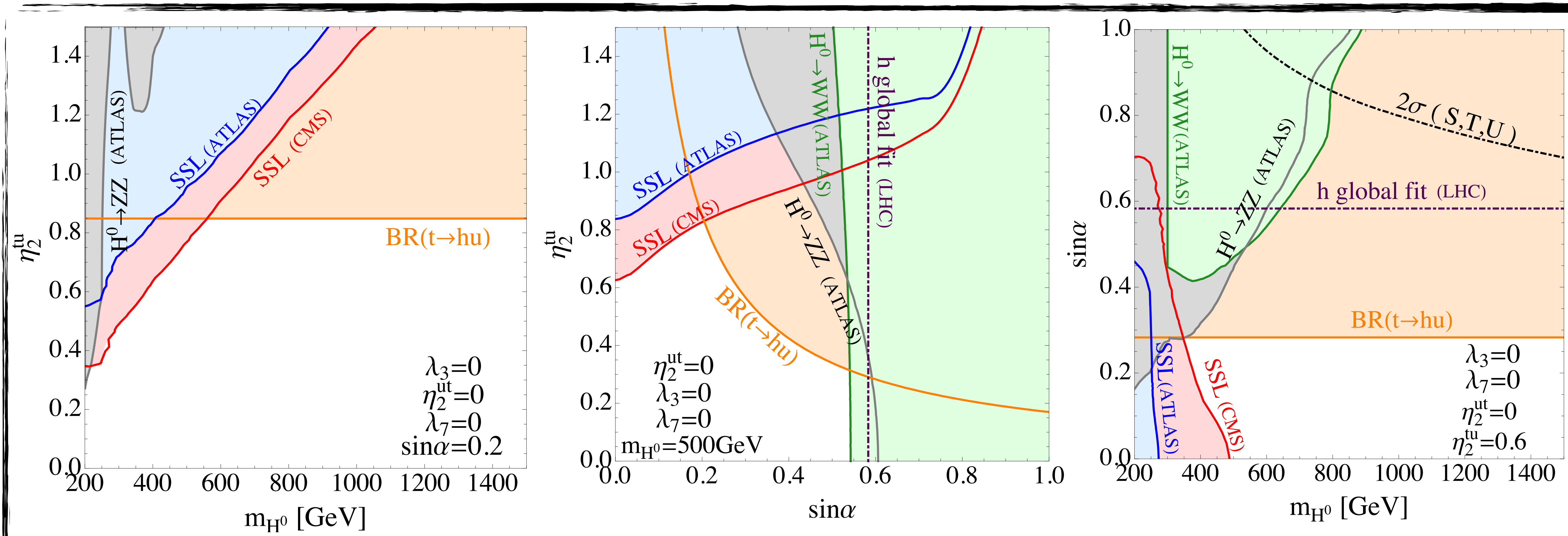
Where

$$y_{u,h}^{ij}=\frac{m_i}{v}\delta^{ij}\cos\alpha+\frac{1}{\sqrt{2}}\eta_{u,2}^{ij}\sin\alpha$$
$$y_{u,H}^{ij}=-\frac{m_i}{v}\delta^{ij}\sin\alpha+\frac{1}{\sqrt{2}}\eta_{u,2}^{ij}\cos\alpha$$

Five free parameters totally

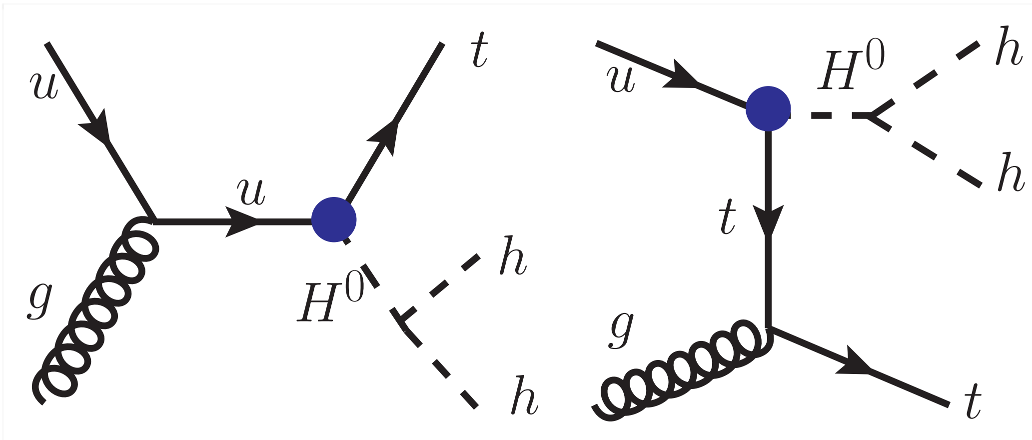
Constraints on QFV 2HDM

- ✤Direct Search for t-> qh decay
- ✤Same-sign di-leptons and b-jet (CMS/ATLAS)
- ✤Heavy Higgs decay to WW
- ✤Heavy Higgs decay to ZZ
- ✤Global fits on Higgs couplings



thh in 2HDM @ LHC

- thh production processes in 2HDM



- Benchmark Points for QFV 2HDM

	Benchmark 1	Benchmark 2	Comments
$\sin\alpha$	0.2	0.2	
η_2^{ut}	0	0	$b \to d\gamma$
η_2^{tu}	0.6	0.6	see fig. 5
λ_7	0	0	enters g_{H^0hh} only at $\mathcal{O}(\sin^2\alpha)$
λ_3	0	-3	influences g_{H^0hh}
m_{A^0}	$m_{H^\pm}$	$m_{H^\pm}$	preferred by custodial symmetry
$m_{H^\pm}$	m_{H^0}	m_{H^0}	preferred by perturbativity (see fig. 4 (b))

thh in 2HDM @ LHC

- Cut Flow Table for 2HDM

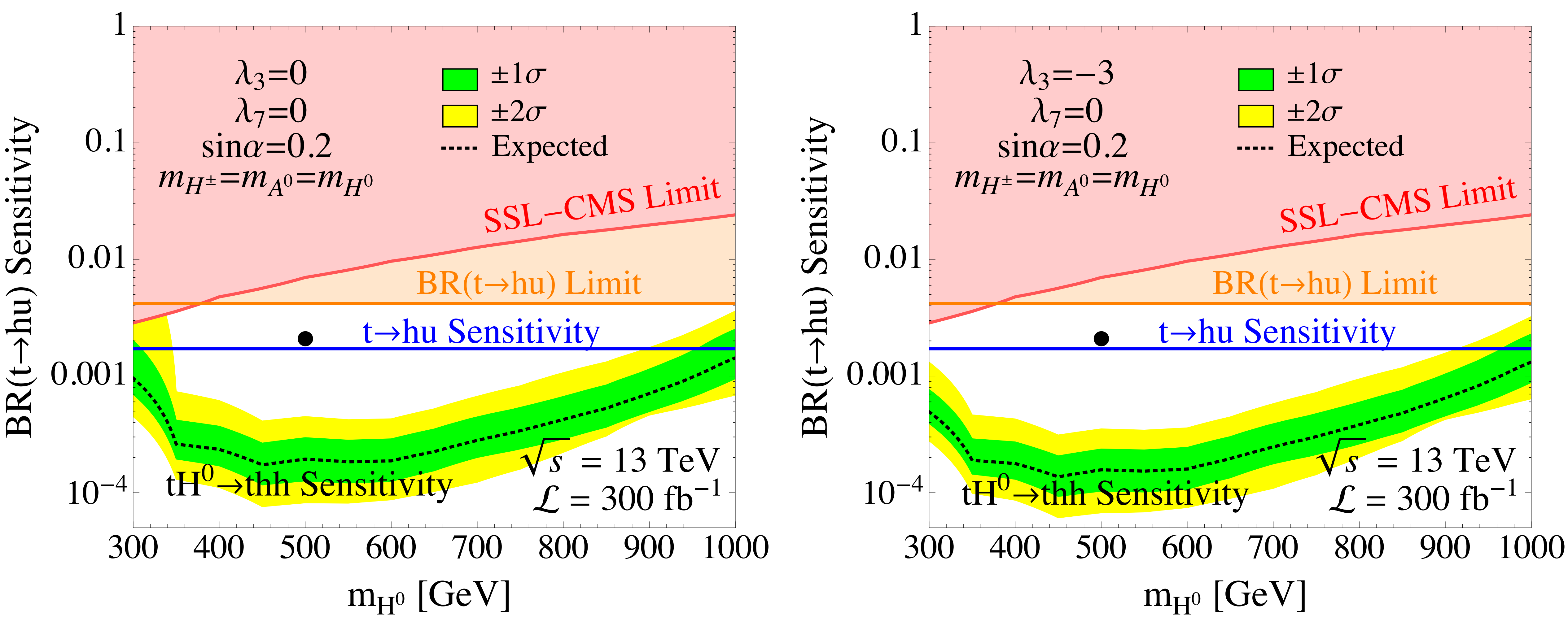
cut	signal (thh)	background ($t\bar{t}$)
σ_{prod} [fb]	273.6	5.9×10^5
preselection	28.5%	2.20%
b-tagging	18.4%	0.55%
$p_T^{j_1} > 140$ GeV	90.6%	31.1%
$p_T^{j_2} > 100$ GeV	93.9%	66.3%
$p_T^{j_3} > 60$ GeV	97.3%	84.6%
Higgs, top mass window	14.3%	8.6%
$p_T^{h_2} > 150$ GeV	71.9%	35.3%
$p_T^{h_1} > 200$ GeV	94.4%	90.3%
$0.9 \leq \Delta R_{b\bar{b}}^{\max} < 2.1$	89.8%	67.8%
m_{H^0} mass window	69.9%	31.1%
σ_{final} [fb]	0.72	0.071

- Results for different benchmark points in2HDM

$$\lambda_3 = -3 \quad \sigma_{\text{final}} = 0.72 fb$$

$$\lambda_3 = 0 \quad \sigma_{\text{final}} = 0.508 fb$$

thh in 2HDM @ LHC



LFV Type III 2HDM

- Lepton Yukawa Couplings

$$\mathcal{L}_l \supset -\eta^{ij}_{l,1}\overline{L^i_L}\Phi_1 e^j_R - \eta^{ij}_{l,2}\overline{L^i_L}\Phi_2 e^j_R + h.c.$$
$$= -\bar{e}^i_L e^j_R[y^{ij}_{l,h}h + y^{ij}_{l,H}H^0] + h.c.$$

Where

$$y^{ij}_{l,h} = \frac{m_i}{v}\delta^{ij}\cos\alpha + \frac{1}{\sqrt{2}}\eta^{ij}_{l,2}\sin\alpha$$
$$y^{ij}_{l,H} = -\frac{m_i}{v}\delta^{ij}\sin\alpha + \frac{1}{\sqrt{2}}\eta^{ij}_{l,2}\cos\alpha$$

- H^0 production cross section

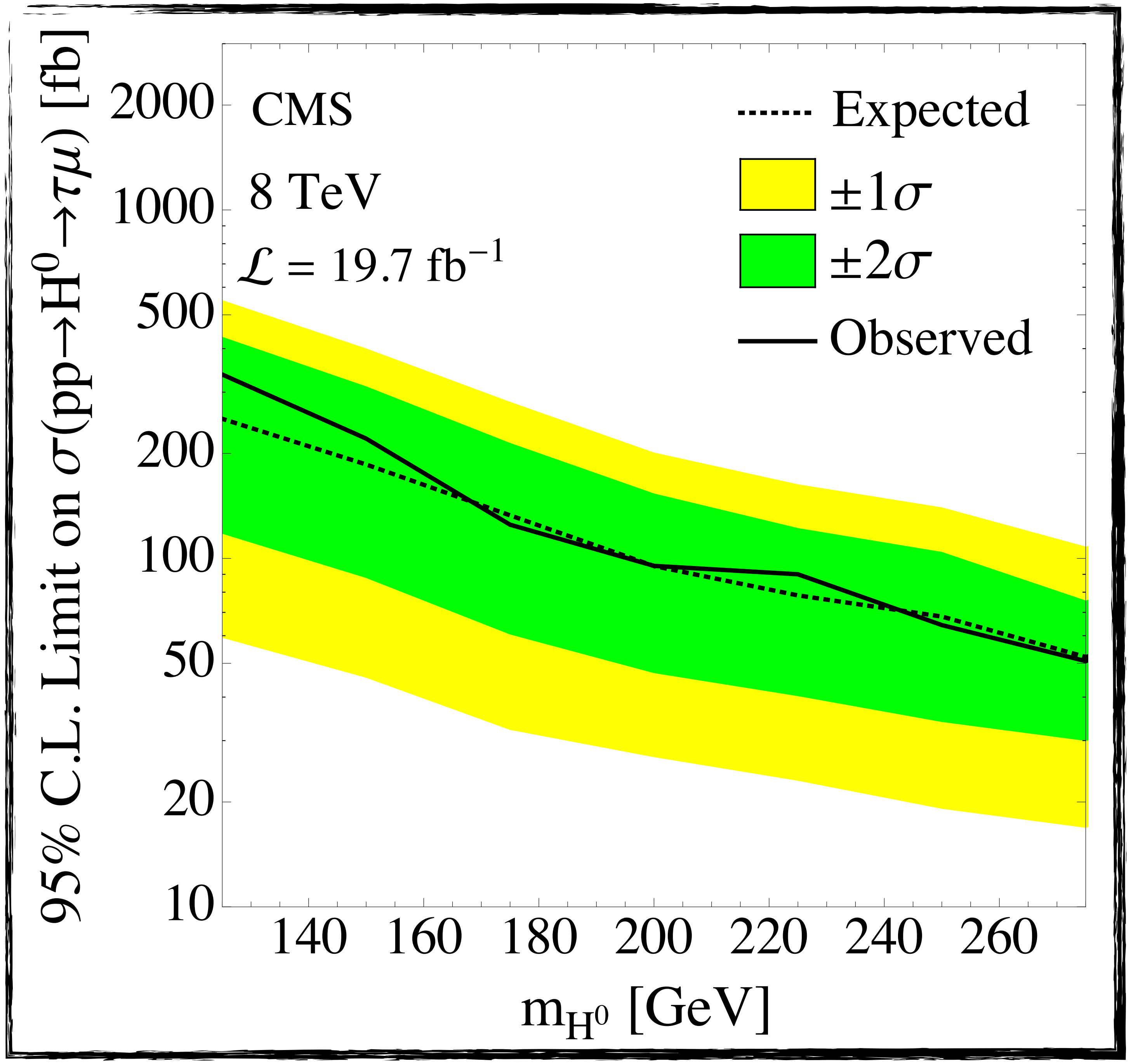
$$\sigma(pp\to H^0) \simeq \left(\sin\alpha - \eta^{tt}_2\cos\alpha\frac{v}{\sqrt{2}m_t}\right)^2 \times \sigma(gg\to h)|^{\rm SM}_{m_h=m_{H^0}}$$

- The decay rates for $\mathrm{h}, \mathrm{H}^0 \to \tau\mu$

$$\Gamma(H^0\to\tau\mu) = \frac{1}{16\pi}m_{H^0}\cos^2\alpha(|\eta^{\mu\tau}_2|^2 + |\eta^{\tau\mu}_2|^2)$$
$$\Gamma(h\to\tau\mu) = \frac{1}{16\pi}m_h\sin^2\alpha(|\eta^{\mu\tau}_2|^2 + |\eta^{\tau\mu}_2|^2)$$

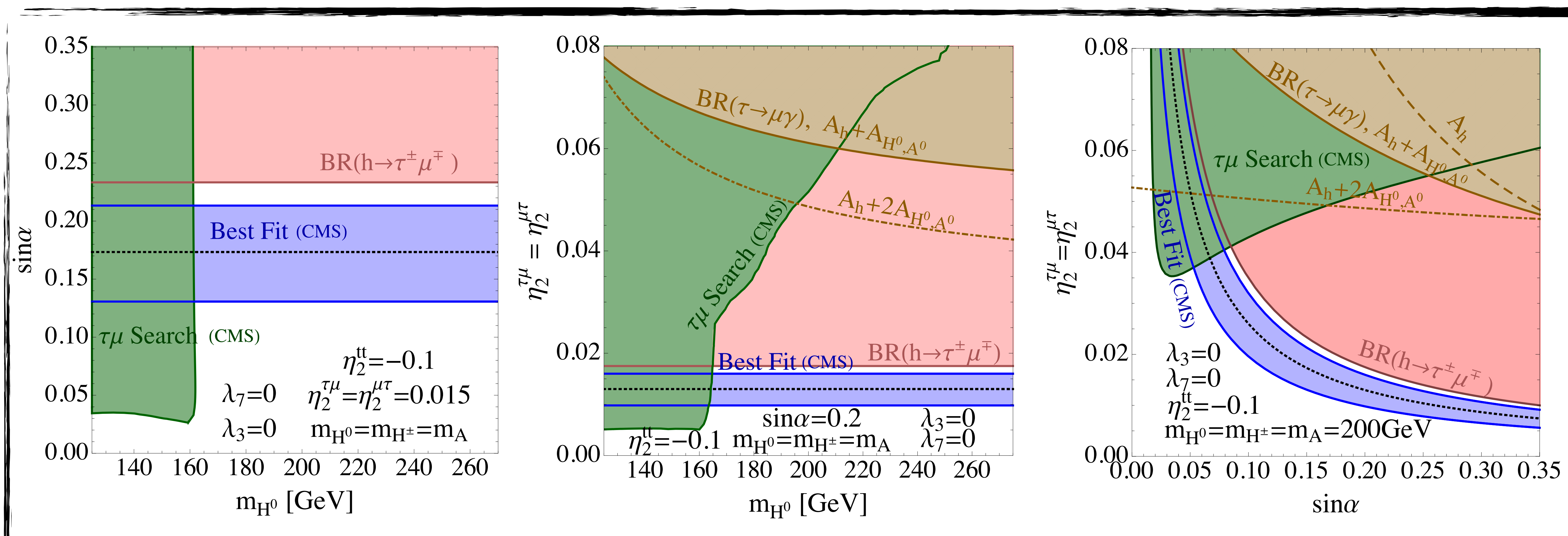
$H^0 \to \tau\mu$ search @ LHC

- Recasting LFV search of SM Higgs for Heavy Higgs



Constraints on LFV 2HDM

- CMS Search recasting for $H^0 \to \tau\mu$
- CMS Best fit for $h \to \tau\mu$, BR~0.84%
- BR Constraint from $h \to \tau\mu$
- Loop constraint for $\tau \to \mu\gamma$



Summary

- In the EFT, thh search is only sensitive by high-luminosity LHC.
- In 2HDM, discovery prospects for thh are excellent already in LHC Run II, which could be more sensitive than t decay to hq.
- CMS excess of $h \to \tau\mu$ can be explained by LFV 2HDM.
- CMS search also can set limit on LVF 2HDM from $pp \to H^0 \to \tau\mu$

Thanks for your attention