ANOMALOUS & EXOTIC HIGGS

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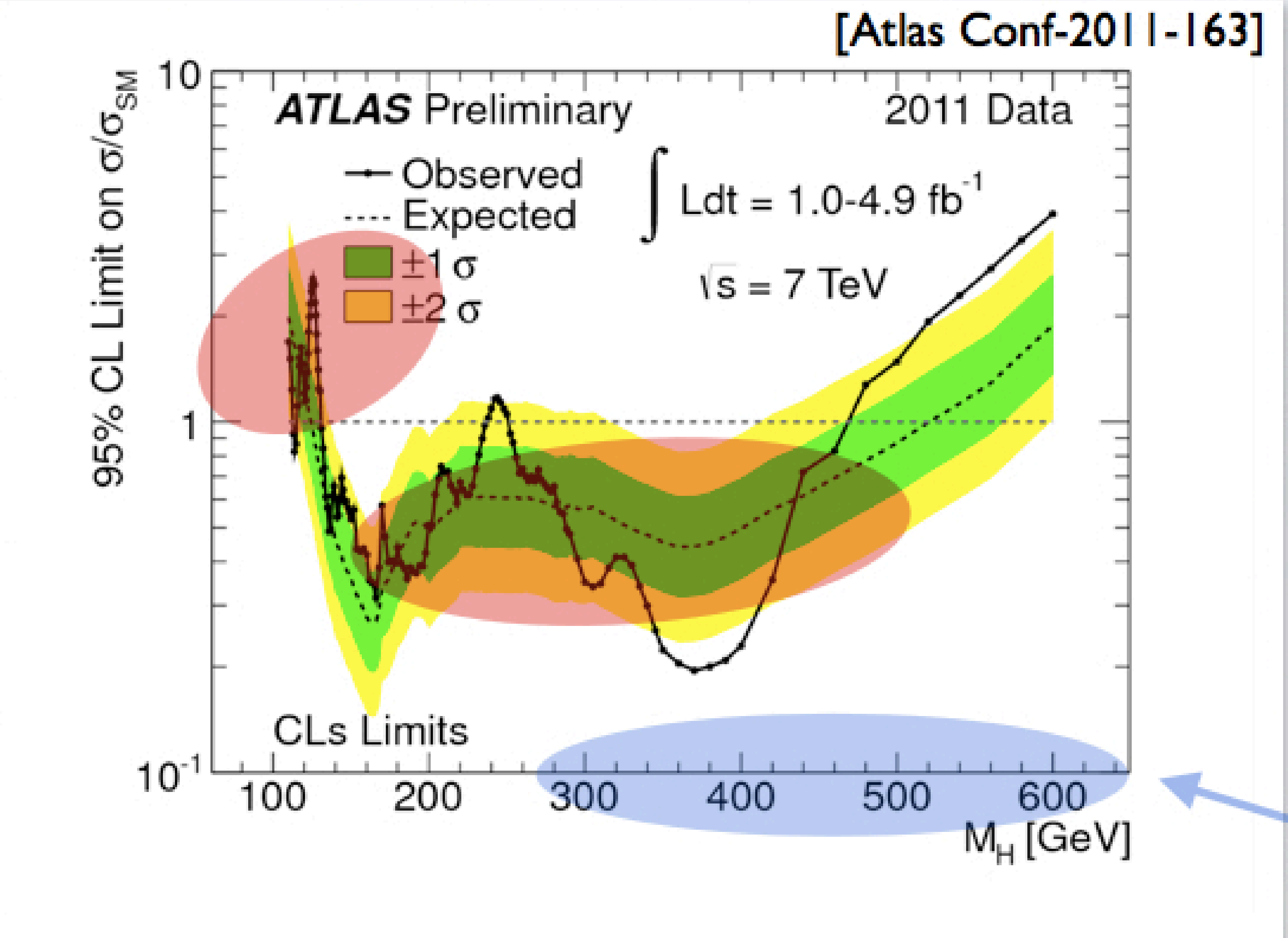
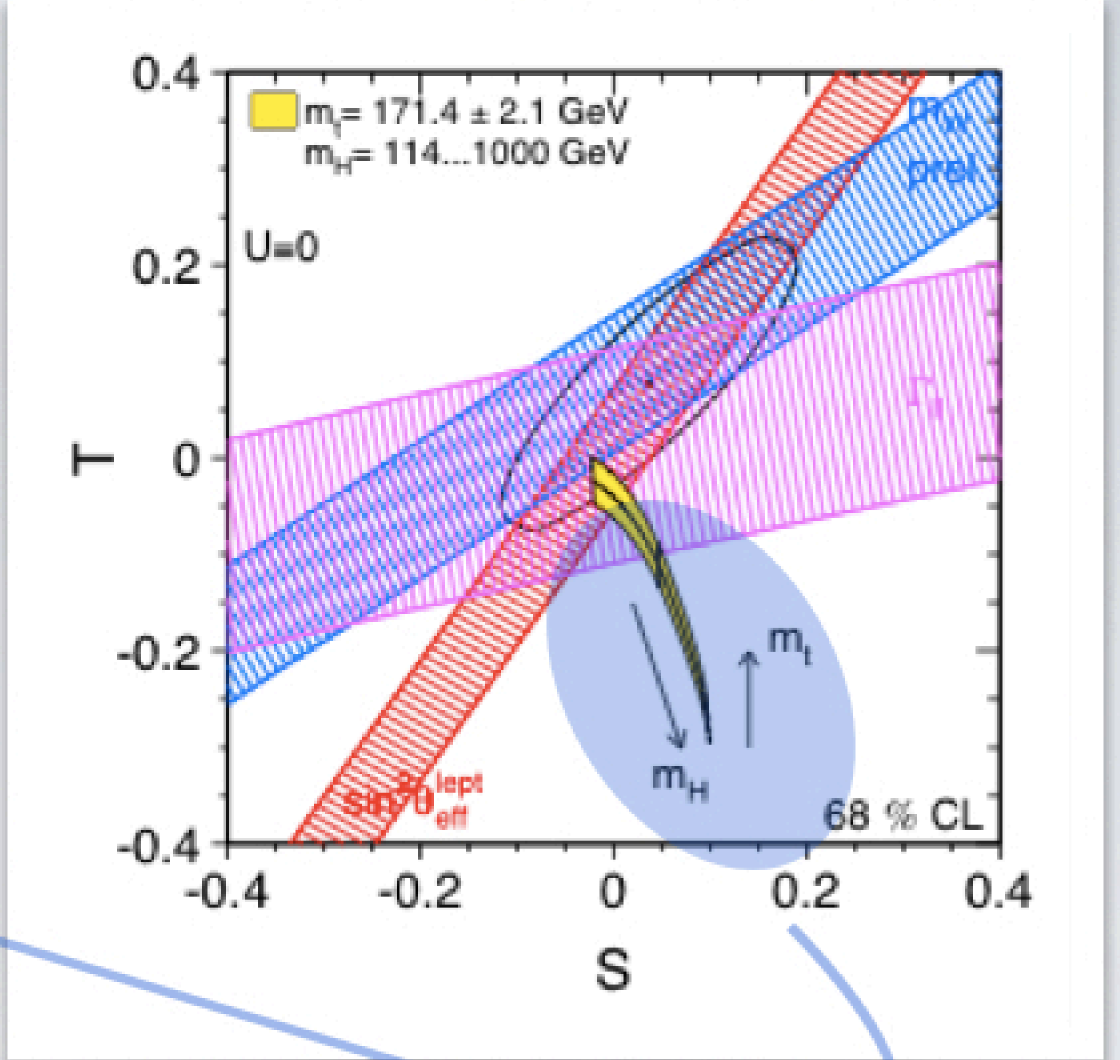
Higgs limits





- bounds and couplings are determined by measurements of

$$\kappa_{p,d} = (\sigma_p \times \mathrm{BR}_d)/(\sigma_p \times \mathrm{BR}_d)^{\mathrm{SM}}$$

fixed as a consequence of EWSB and fermion masses in the SM

- two possibilities for heavy Higgses:

1) $\sigma_p < \sigma_p^{\mathrm{SM}}$ 2) $\mathrm{BR}_d < \mathrm{BR}_d^{\mathrm{SM}}$

non-standard/ anomalous/exotic Higgs !!

Higgs limits

- two ways to "understand" current bounds (no way to reconcile in the SM)

  1) $\sigma_p < \sigma_p^{\rm SM}$ 2) $\mathrm{BR}_d < \mathrm{BR}_d^{\rm SM}$

- there's of course a plethora of theoretical examples:
  - anomalous Higgs interactions (higher d operators) ...[Hankele et al. `06] [Bonnet et al.`12]
  - (holographic) PNGB Higgs [Agashe et al. '04], [Giudice et al. `07], ...
  - fermiophobic, gaugephobic Higgses (2HDMs....)
  - .....

[Tao Han's talk]

- many of these models have common (collider) phenomenological aspects:
  - what are the implications of (universal) Higgs coupling modifications?
  - are there non-SM signatures (invisible Higgs branching ratio)?
  - what is the influence of anomalous Higgs mass dimensions?
  - what is the influence of non-local Higgs properties?

more exotic & model dependent ↓

a theoretical baseline: the Higgs portal

[Schabinger, Wells `05]
[Patt, Wilczek `06]...

- $\phi_s^\dagger \phi_s$ is a singlet under the electroweak group and can act as a portal to a hidden sector: $\mathcal{L} \supset \eta\, \phi_s^\dagger \phi_s \phi_h^\dagger \phi_h$ → model invisible branching ratios

  → EWPD

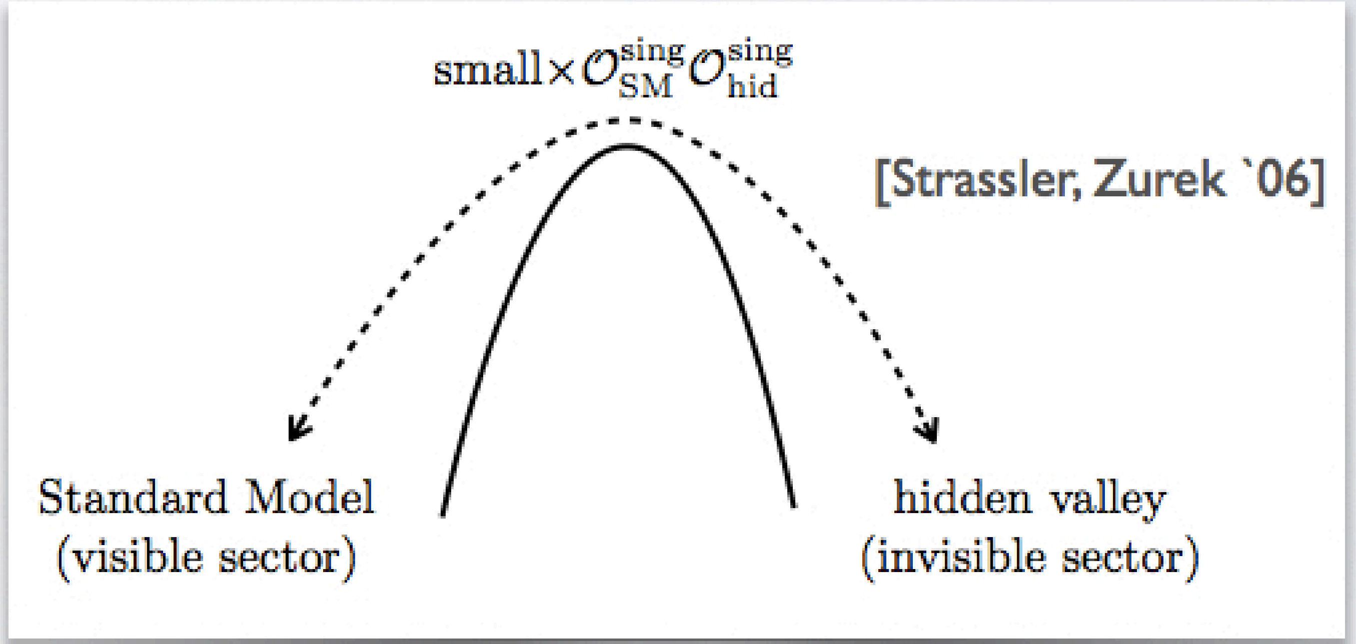
  → "distributed" $V_L V_L$ unitarization

  → cascade decays

- 2 Higgs states and modified production cross sections and decay widths

"SM"

$$\sigma_1 = \cos^2\chi\, \sigma_1^{SM} \qquad \sigma_2 = \sin^2\chi\, \sigma_2^{SM}$$
$$\Gamma_1^{vis} = \cos^2\chi\, \Gamma_1^{SM} \qquad \Gamma_2^{vis} = \sin^2\chi\, \Gamma_2^{SM}$$
$$\Gamma_1^{inv} = \sin^2\chi\, \Gamma_1^{hid} \qquad \Gamma_2^{inv} = \cos^2\chi\, \Gamma_2^{hid}$$

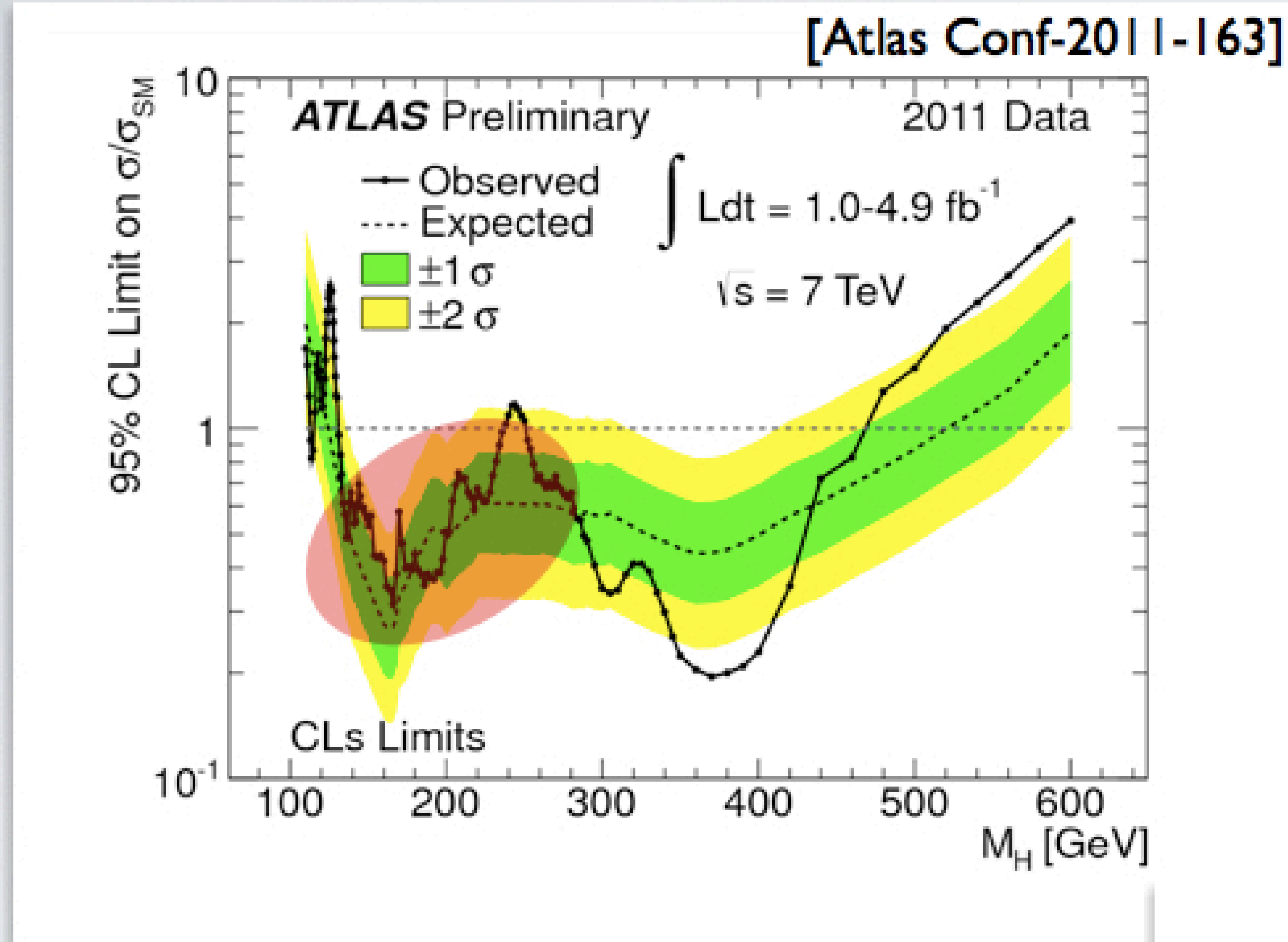


- characteristic mixing angle: there's a phenomenological relation to strongly interacting composite Higgs scenarios [Giudice, Grojean, Pomarol, Rattazzi `07]

[Bock, Lafaye, Plehn, Rauch, Zerwas, Zerwas `10]

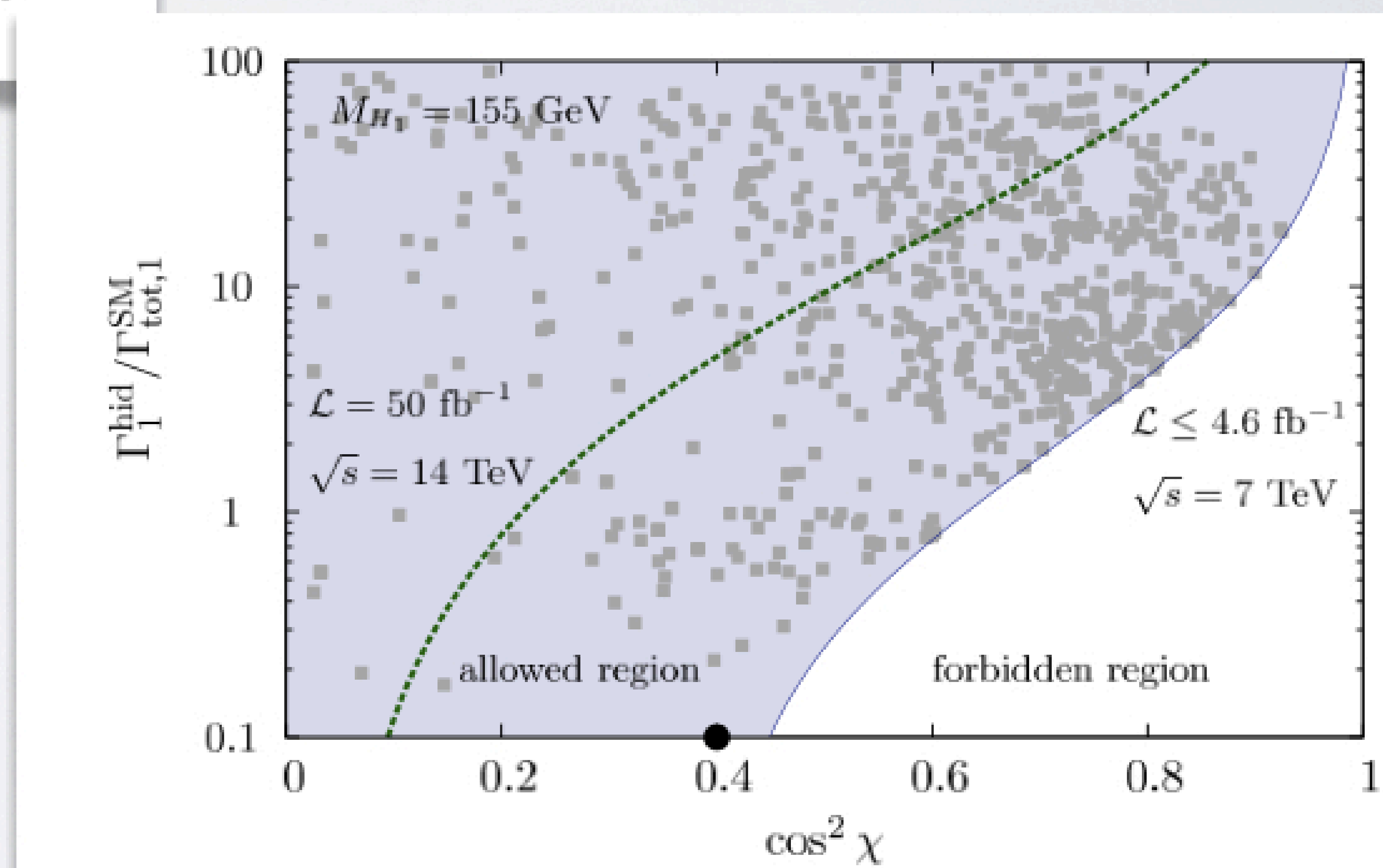
see also Csaba Csaki's talk

Higgs profiling



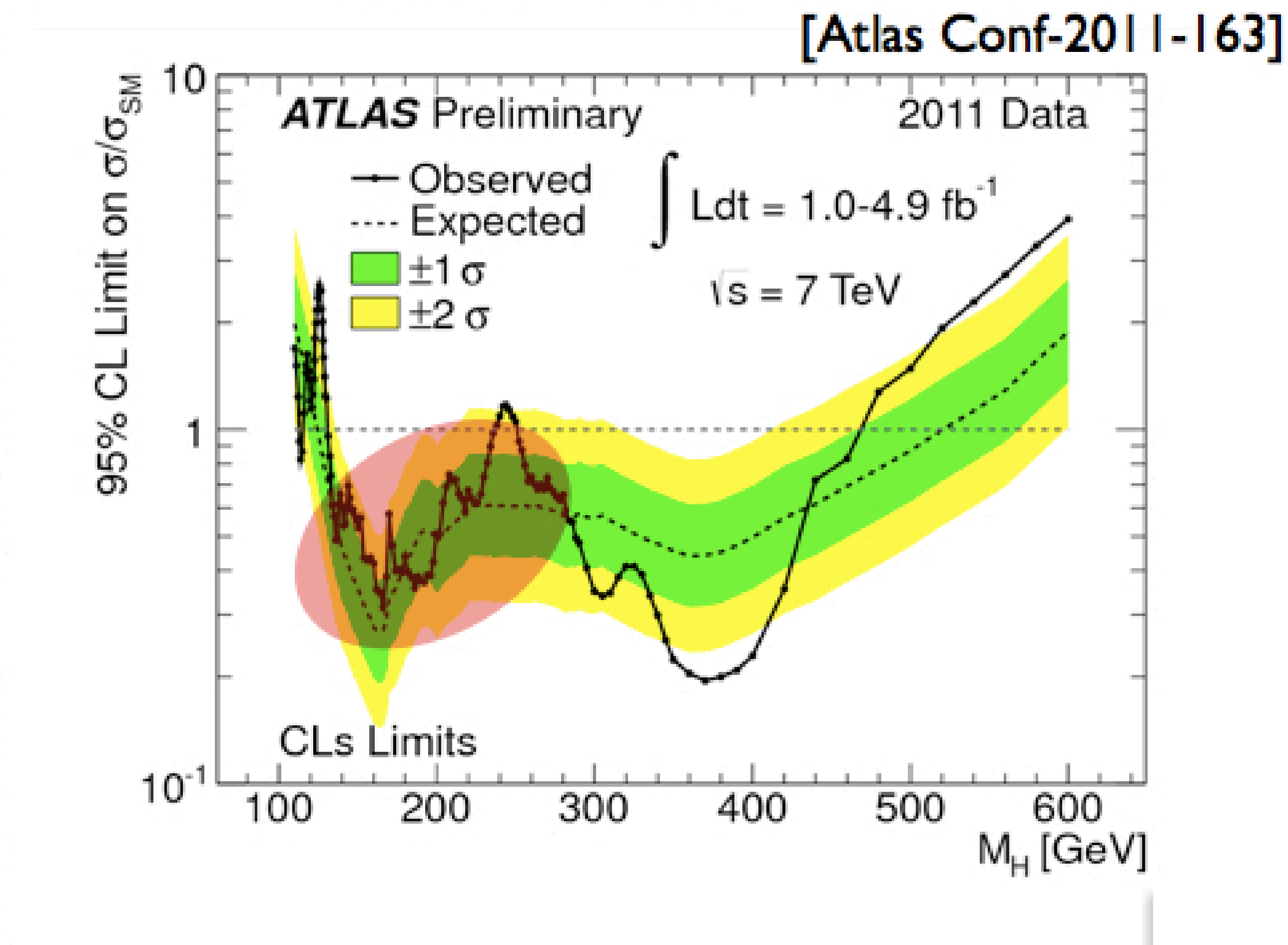
$$\frac{\sigma[pp \to H_1 \to F]}{\sigma[pp \to H_1 \to F]^{\rm SM}} = \frac{\cos^2\chi}{1+\tan^2\chi\,[\Gamma_1^{\rm hid}/\Gamma_{\rm tot,1}^{\rm SM}]} \leq \mathcal{R}$$

$$\frac{\sigma[pp \to H_1 \to inv]}{\sigma[pp \to H_1]^{\rm SM}} = \frac{\sin^2\chi\,[\Gamma_1^{\rm hid}/\Gamma_{\rm tot,1}^{\rm SM}]}{1+\tan^2\chi\,[\Gamma_1^{\rm hid}/\Gamma_{\rm tot,1}^{\rm SM}]} \leq \mathcal{J}$$



[CE, Plehn, Zerwas, Zerwas `11]
[CE, Plehn, Rauch, Zerwas, Zerwas `11]

Higgs profiling



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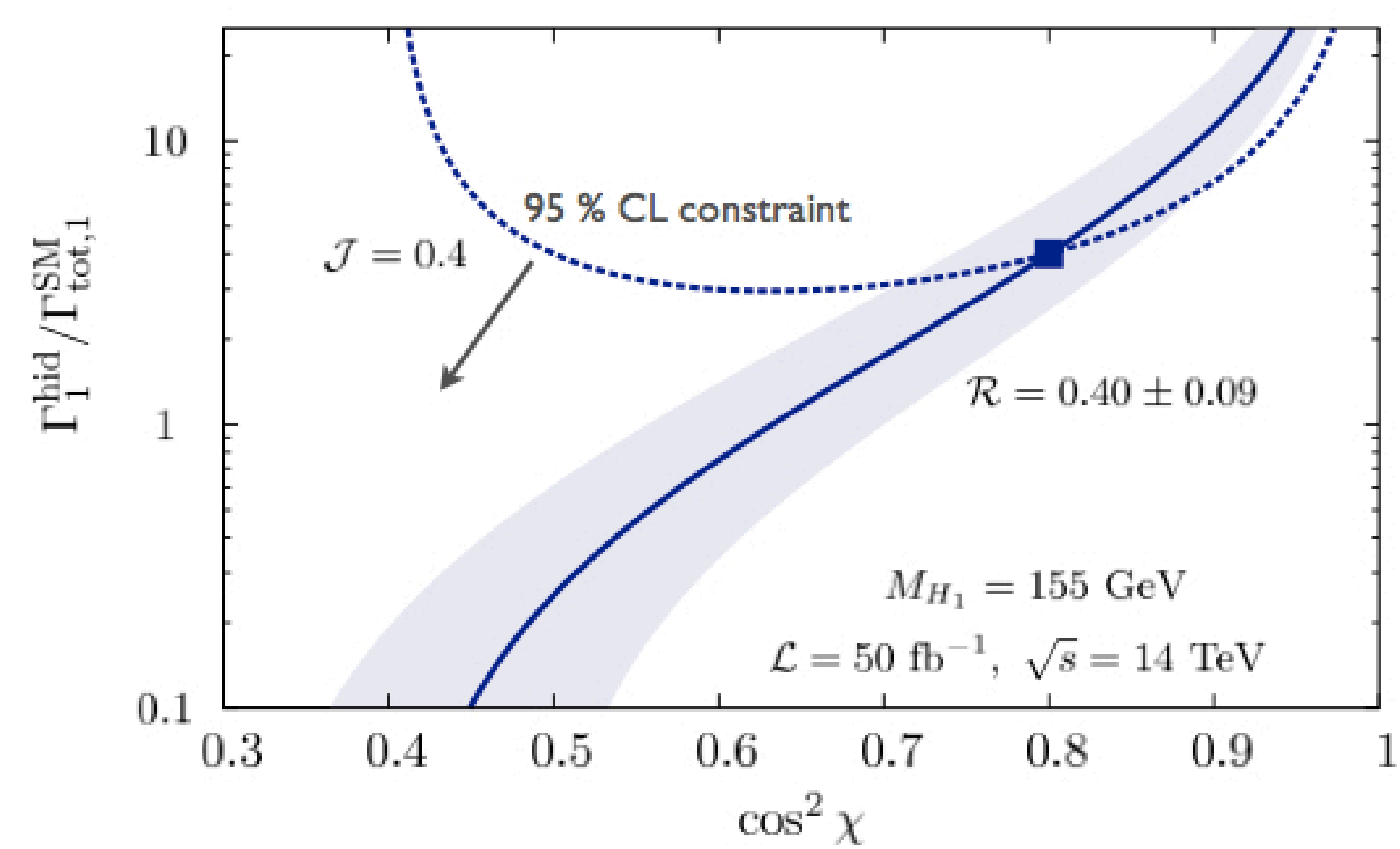
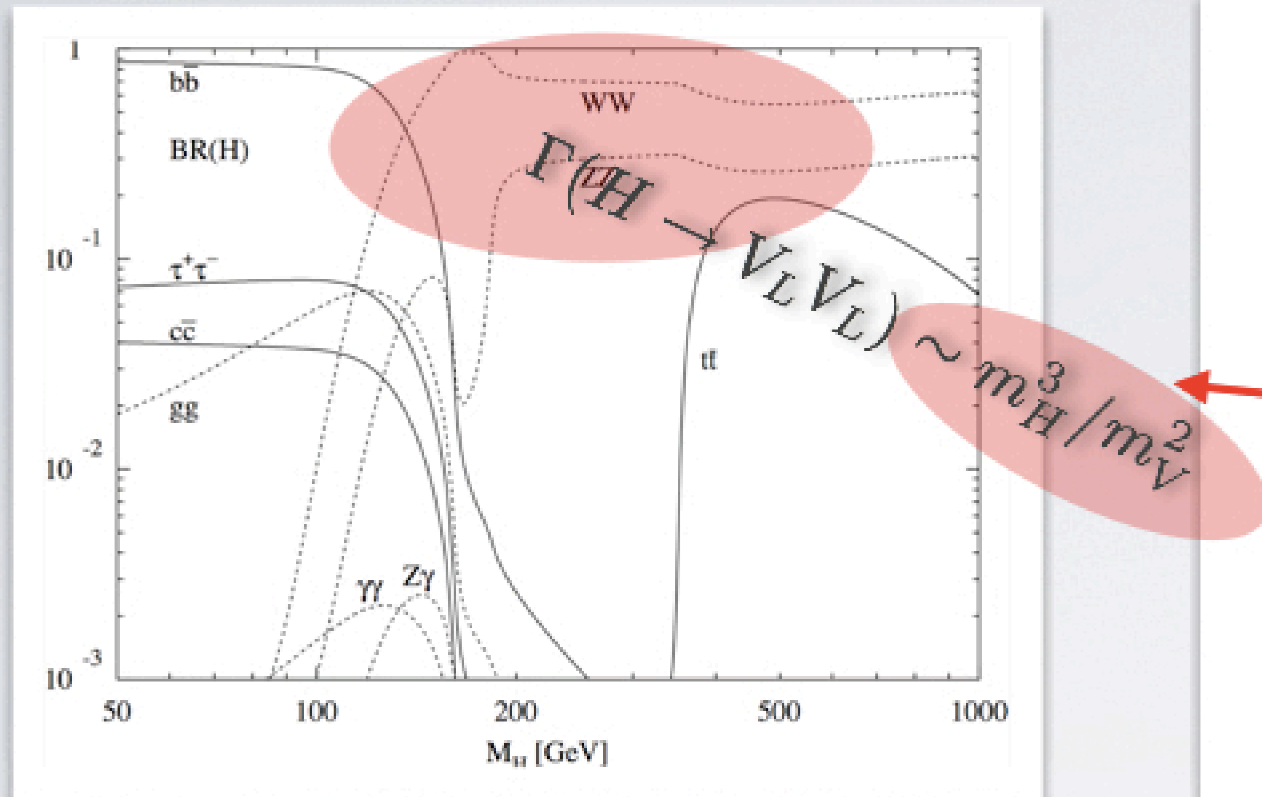
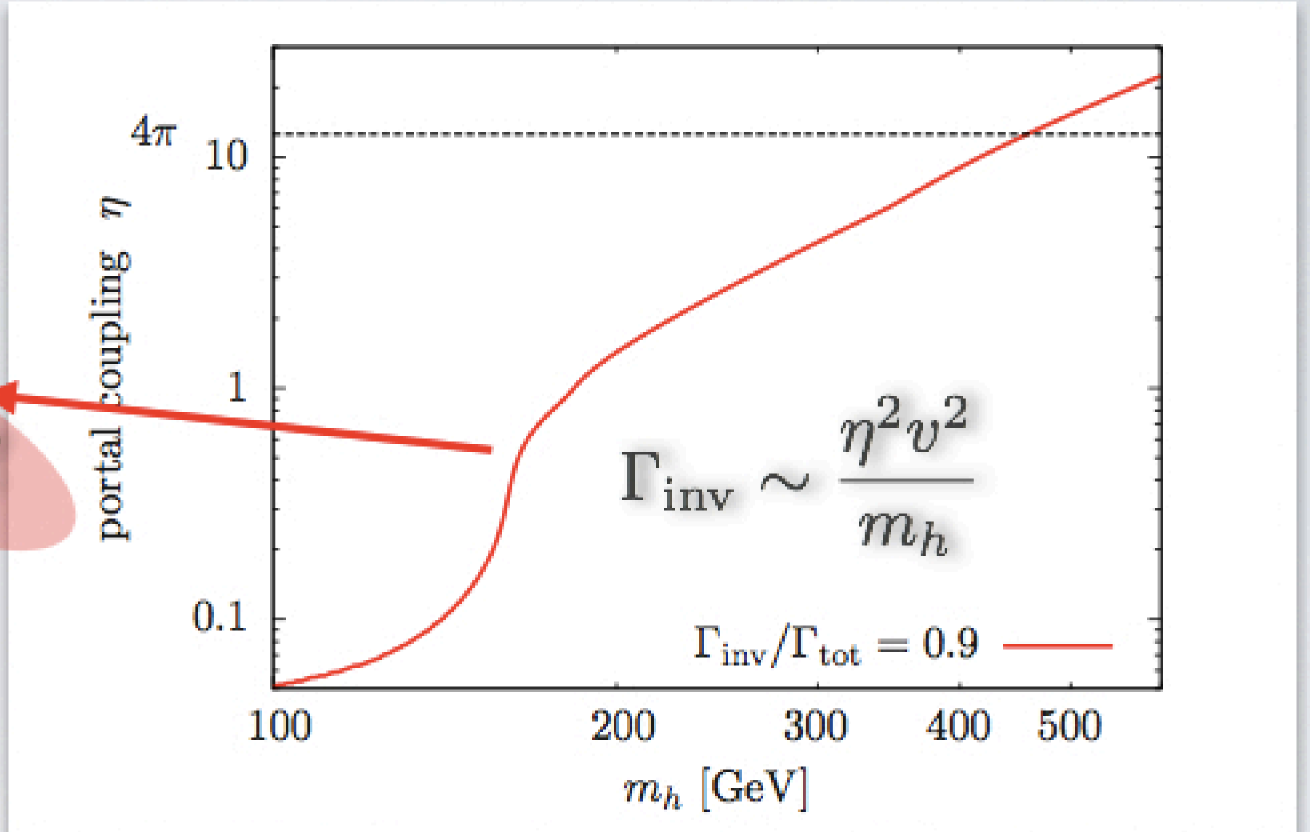


[CE, Plehn, Zerwas, Zerwas `11]
[CE, Plehn, Rauch, Zerwas, Zerwas `11]

heavy hidden Higgs states?

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \eta|\phi_h|^2|\phi_s|^2 + \partial_\mu\phi_h^\star\partial^\mu\phi_h - m^2|\phi_h|^2$$





"easy" to hide a light Higgs

- accommodate heavy hidden Higgs non-perturbatively and non-locally

anomalous couplings
anomalous propagators

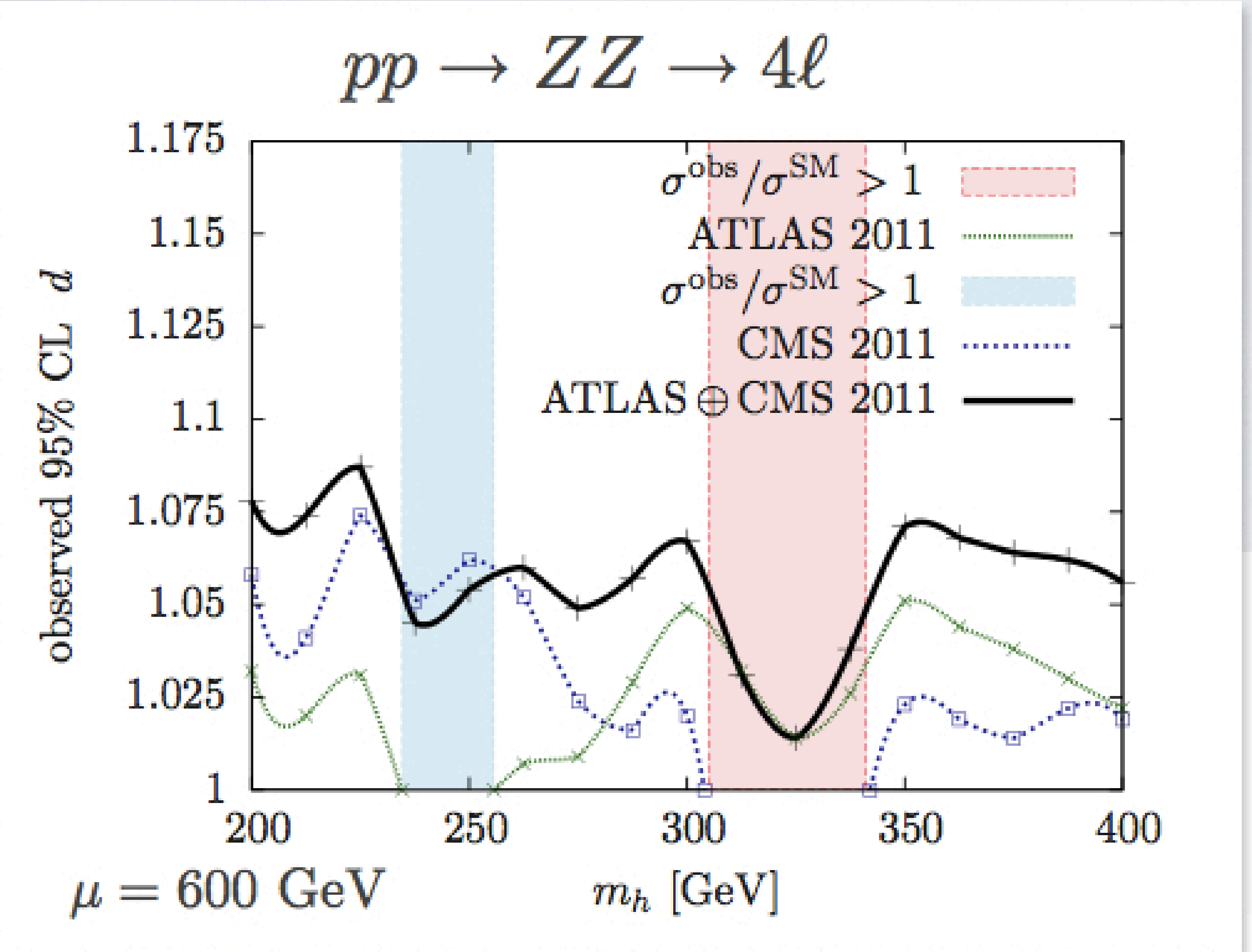
$$\mathcal{L} \supset H^\dagger \left(D^\mu D_\mu + \mu^2\right)^{2-d} H$$
$$[H] = d$$

[Stancato, Terning `08]
[Falkowski, Perez-Victoria `08, `09]

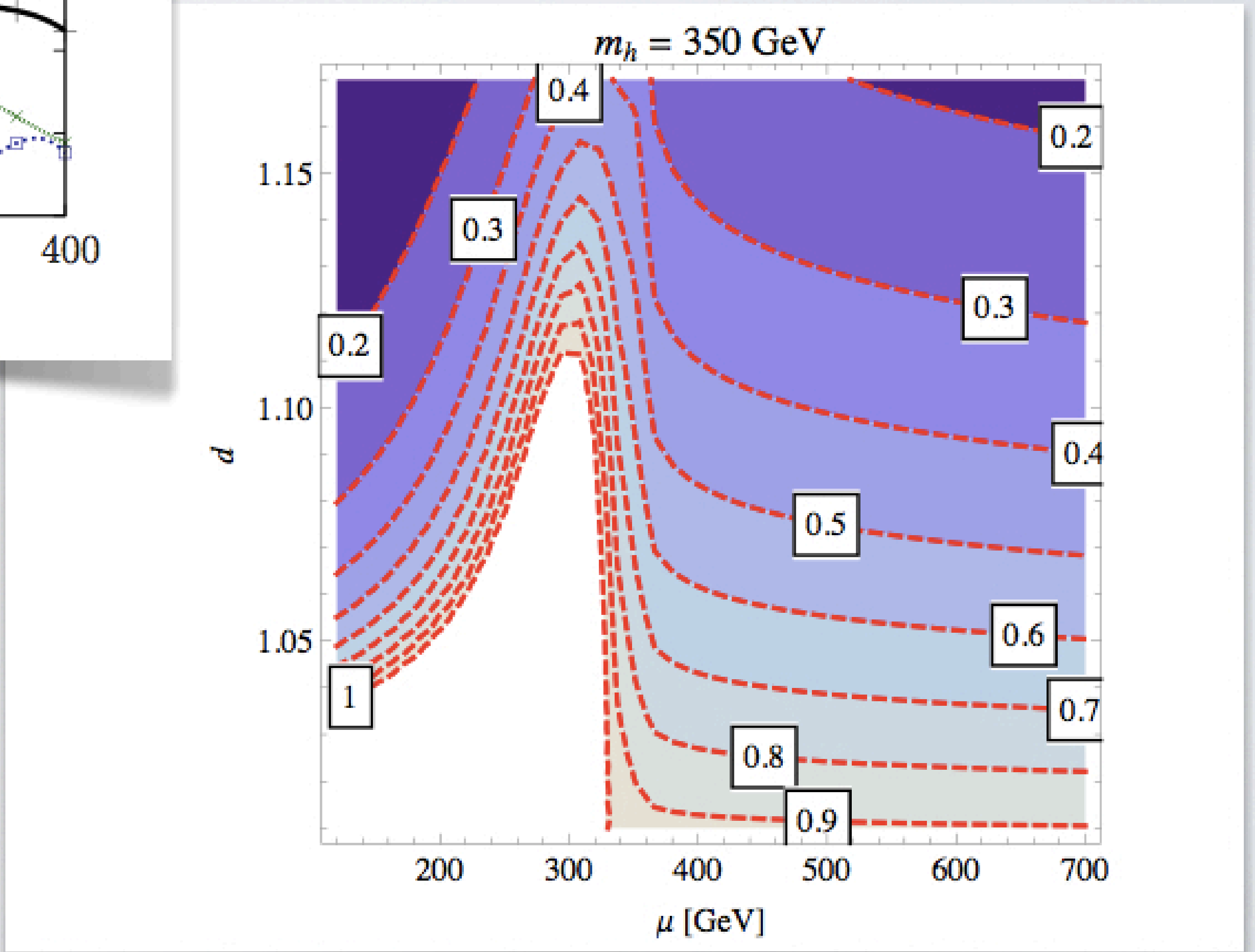
- $1 < d \lesssim 1.5$ scale away gauge boson interactions <u>consistently</u>

[CE, Spannowsky, Stancato, Terning `12]

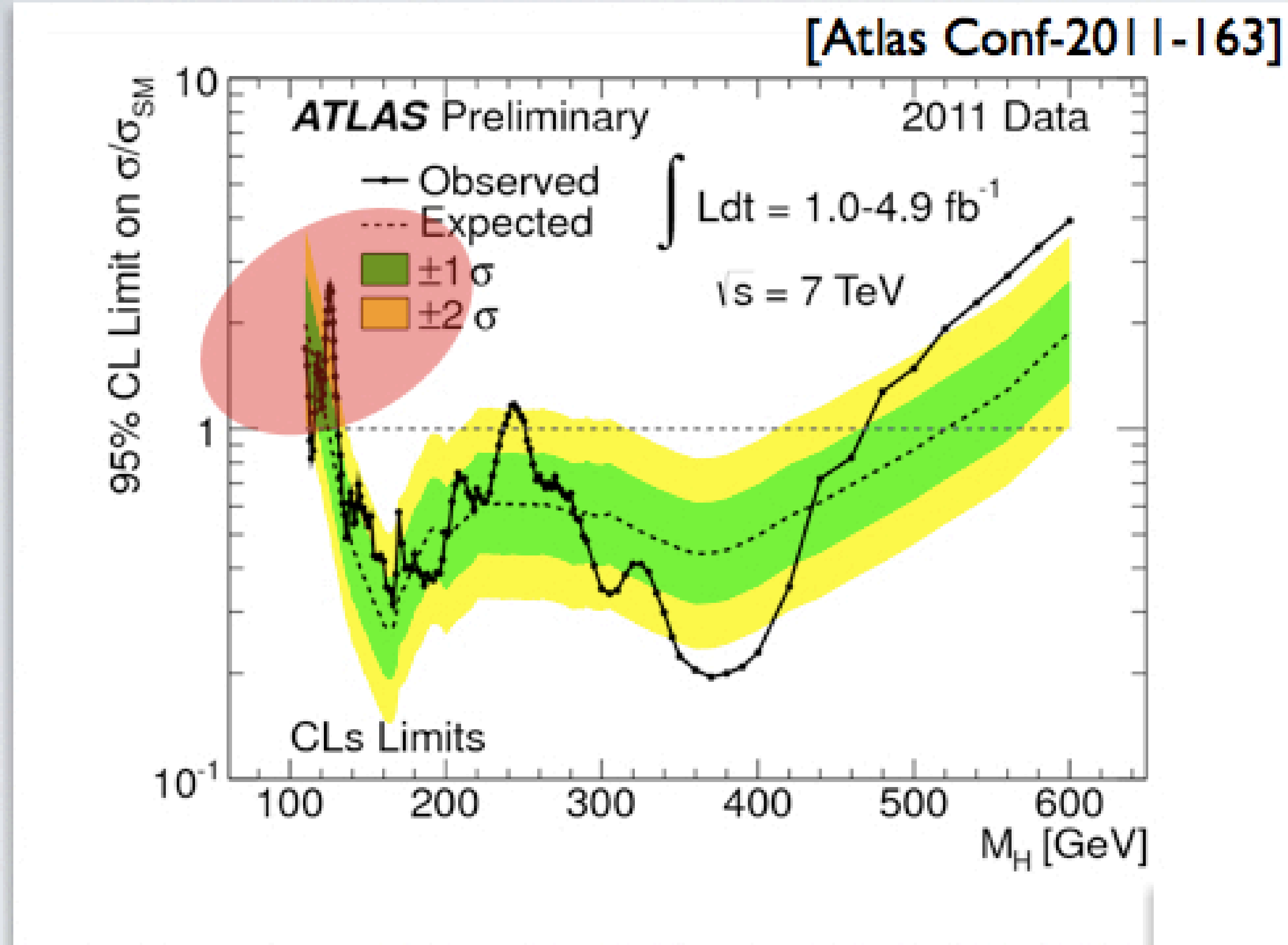
unparticle-like Higgs



[CE, Spannowsky, Stancato, Terning `12]



Higgs profiling

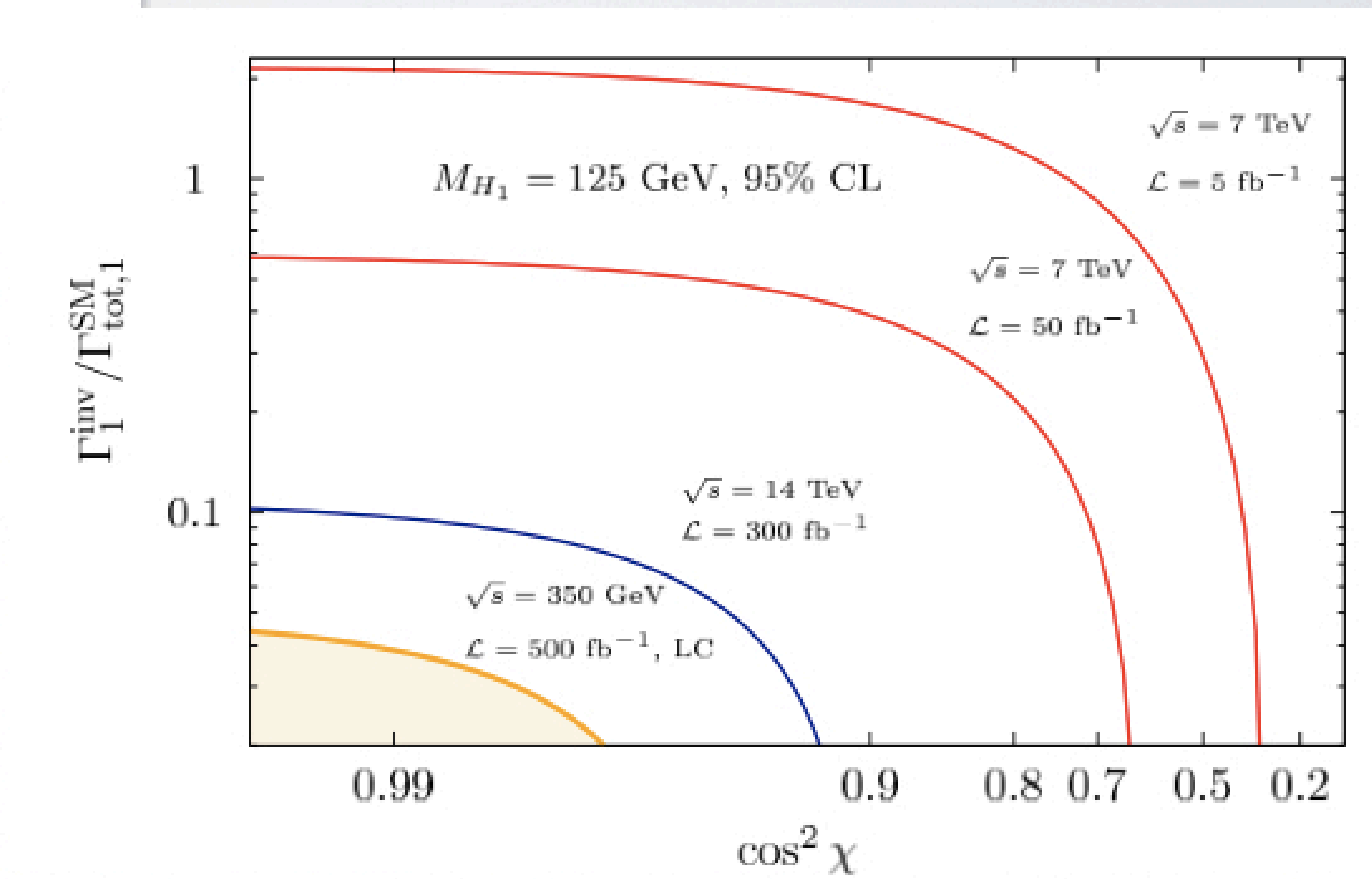


$$\frac{\sigma[pp \to H_1 \to F]}{\sigma[pp \to H_1 \to F]^{SM}} = \frac{\cos^2\chi}{1 + \tan^2\chi\,[\Gamma_1^{hid}/\Gamma_{tot,1}^{SM}]} \leq \mathcal{R}$$

$$\frac{\sigma[pp \to H_1 \to inv]}{\sigma[pp \to H_1]^{SM}} = \frac{\sin^2\chi\,[\Gamma_1^{hid}/\Gamma_{tot,1}^{SM}]}{1 + \tan^2\chi\,[\Gamma_1^{hid}/\Gamma_{tot,1}^{SM}]} \leq \mathcal{J}$$

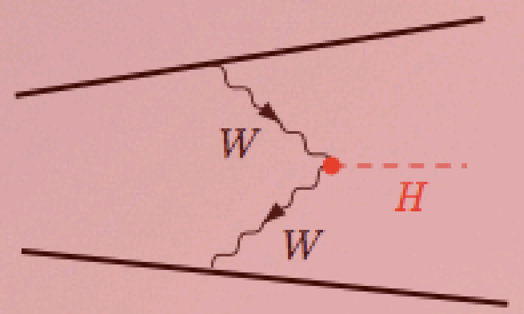
- constraining invisible decays necessary for coupling measurements

[CE, Plehn, Zerwas, Zerwas `11]
[CE, Plehn, Rauch, Zerwas, Zerwas `11]



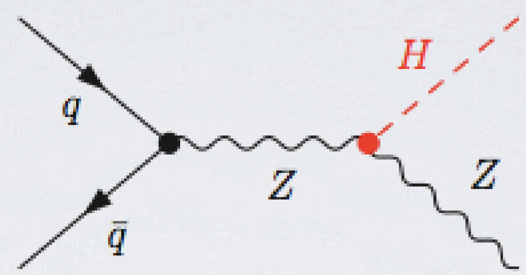
constraining invisible Higgs decays

weak boson fusion



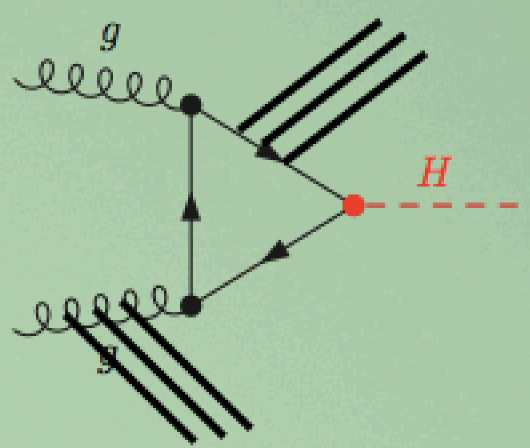
[Eboli, Zeppenfeld `00]

associated production



[Godbole et al. `03] [Davoudiasl et al. '05]

gluon fusion



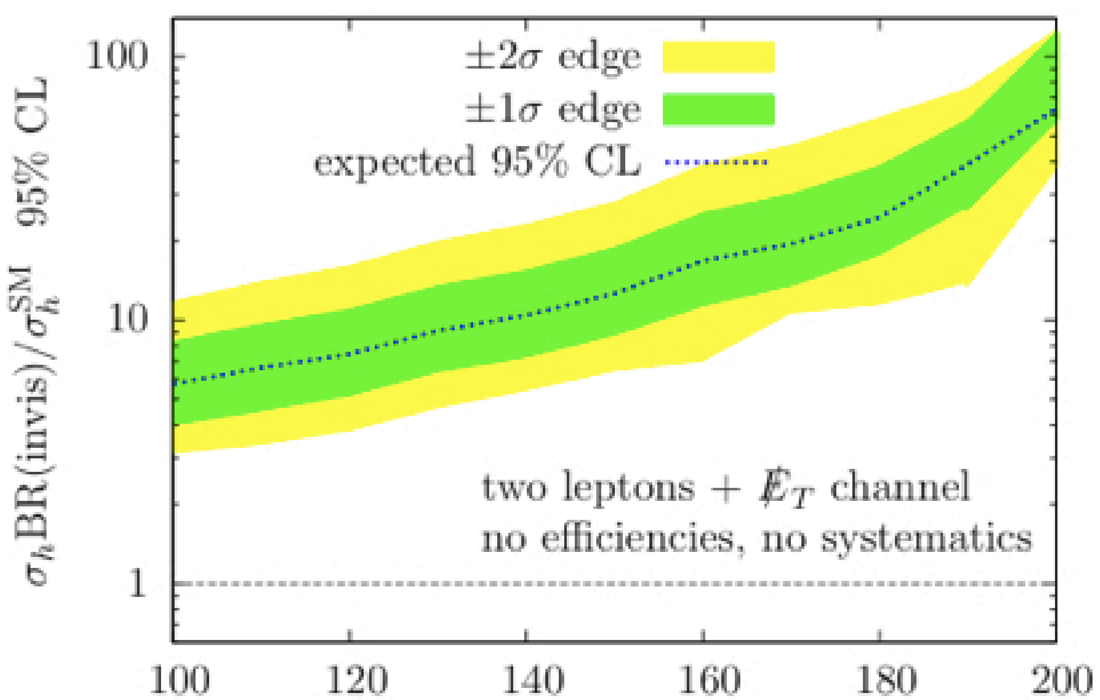
Initial state radiation

challenging:

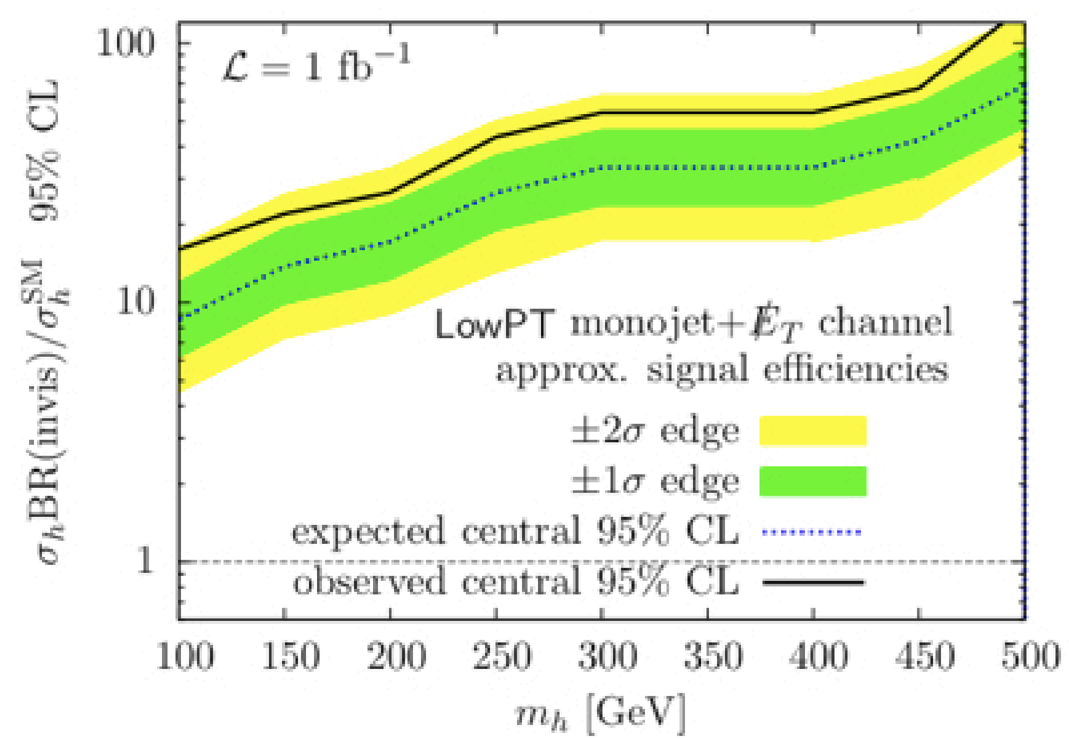
pile up, systematics of CJV

[Atlas Conf 2011-096]

managable backgrounds @ 7TeV



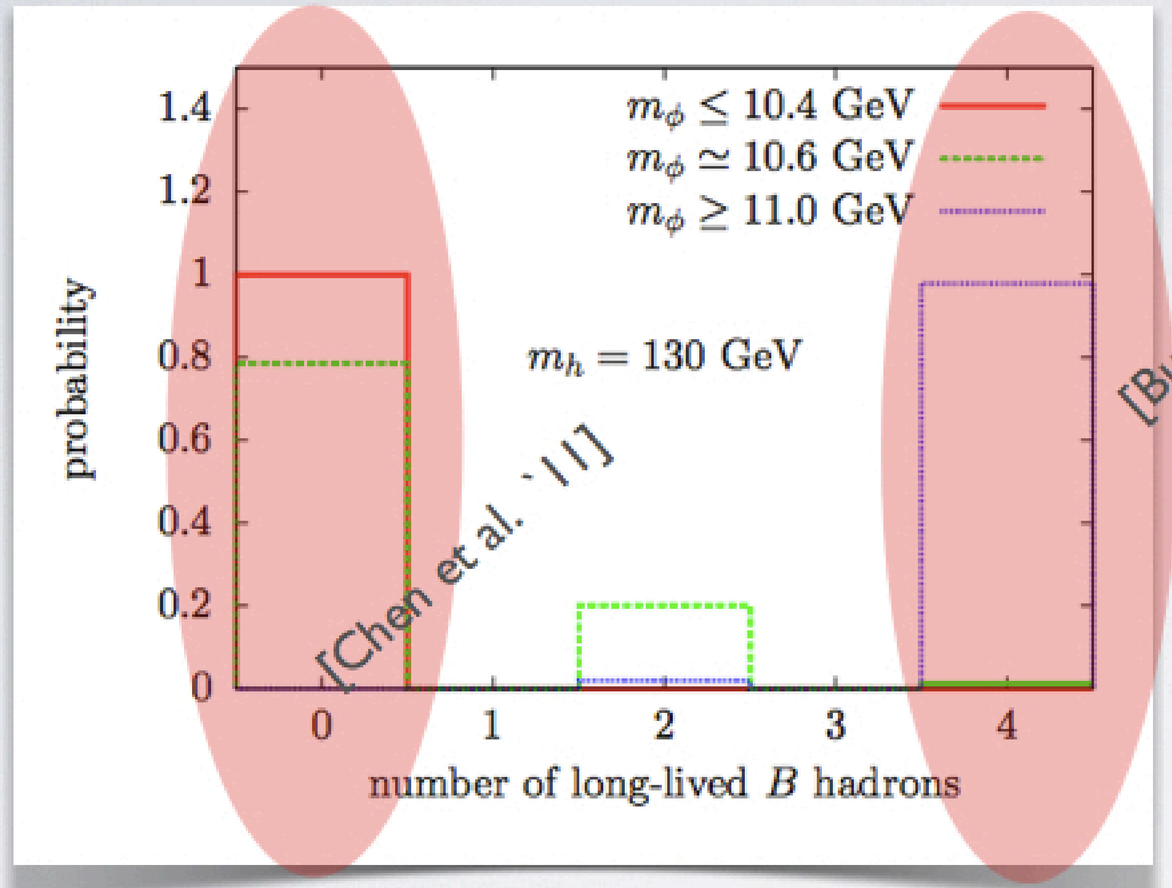
[Monte Carlo]

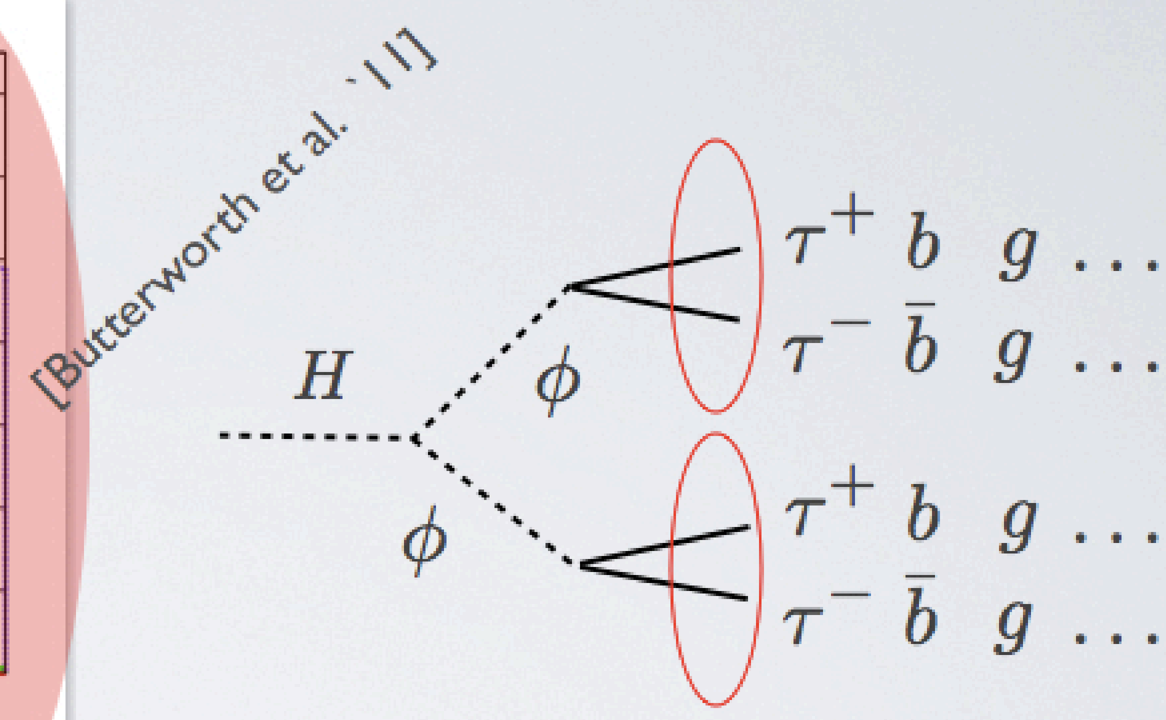


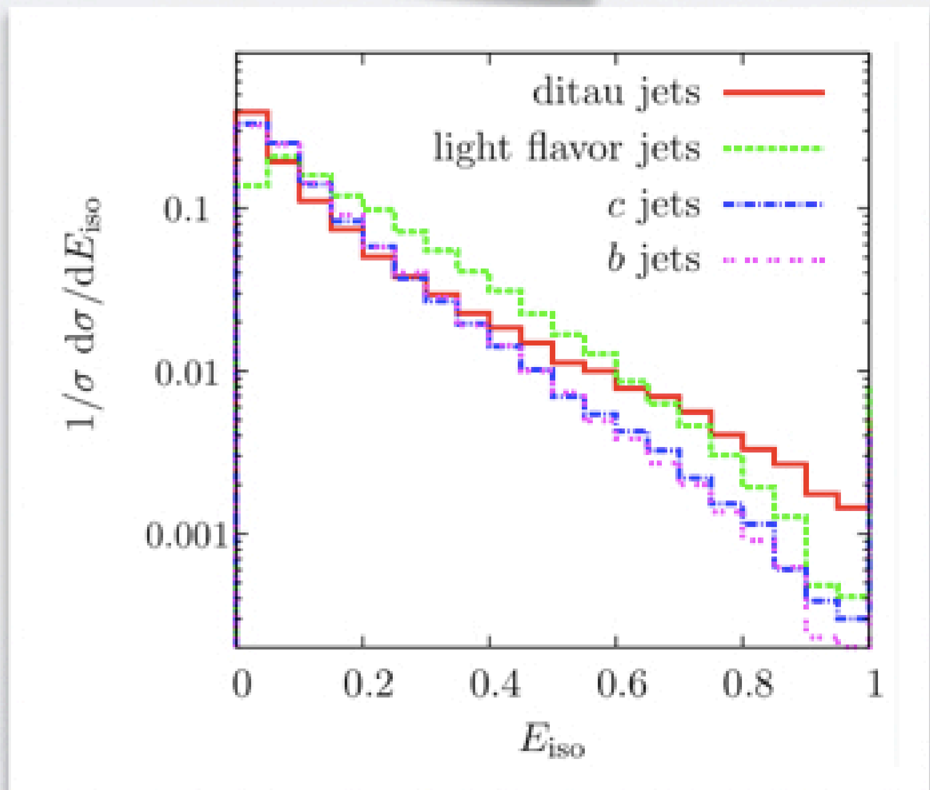
[CE, Jaeckel, Re, Spannowsky `11]

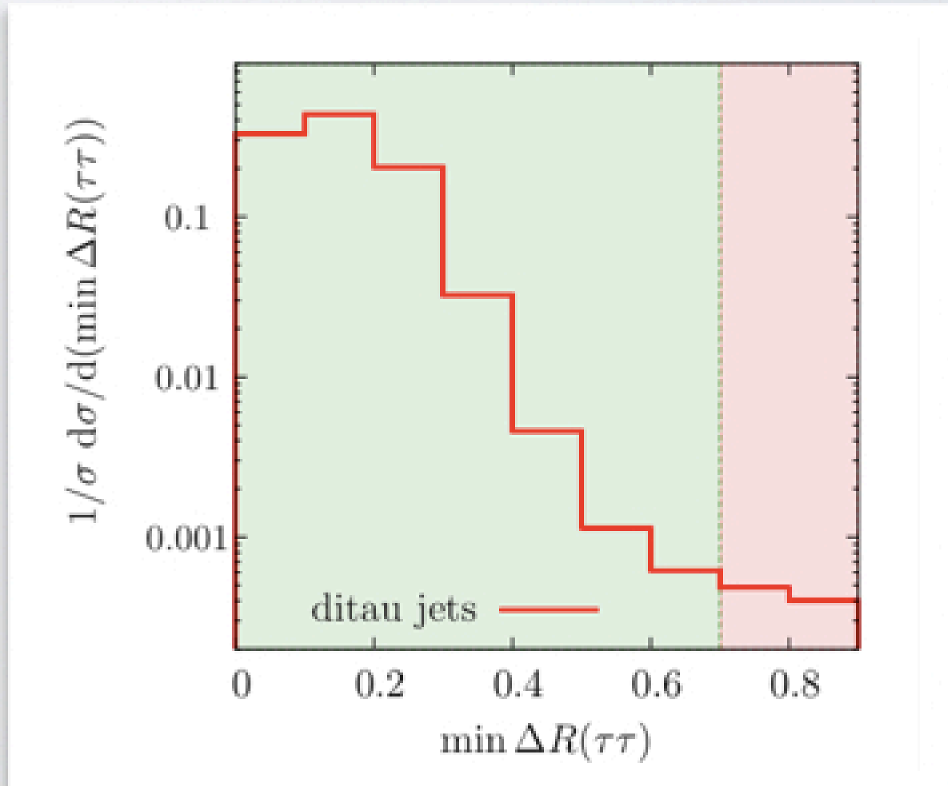
non-standard signatures

- For large mass drops $m_H \gg m_A$ with subjets (i.e. radiation profile)









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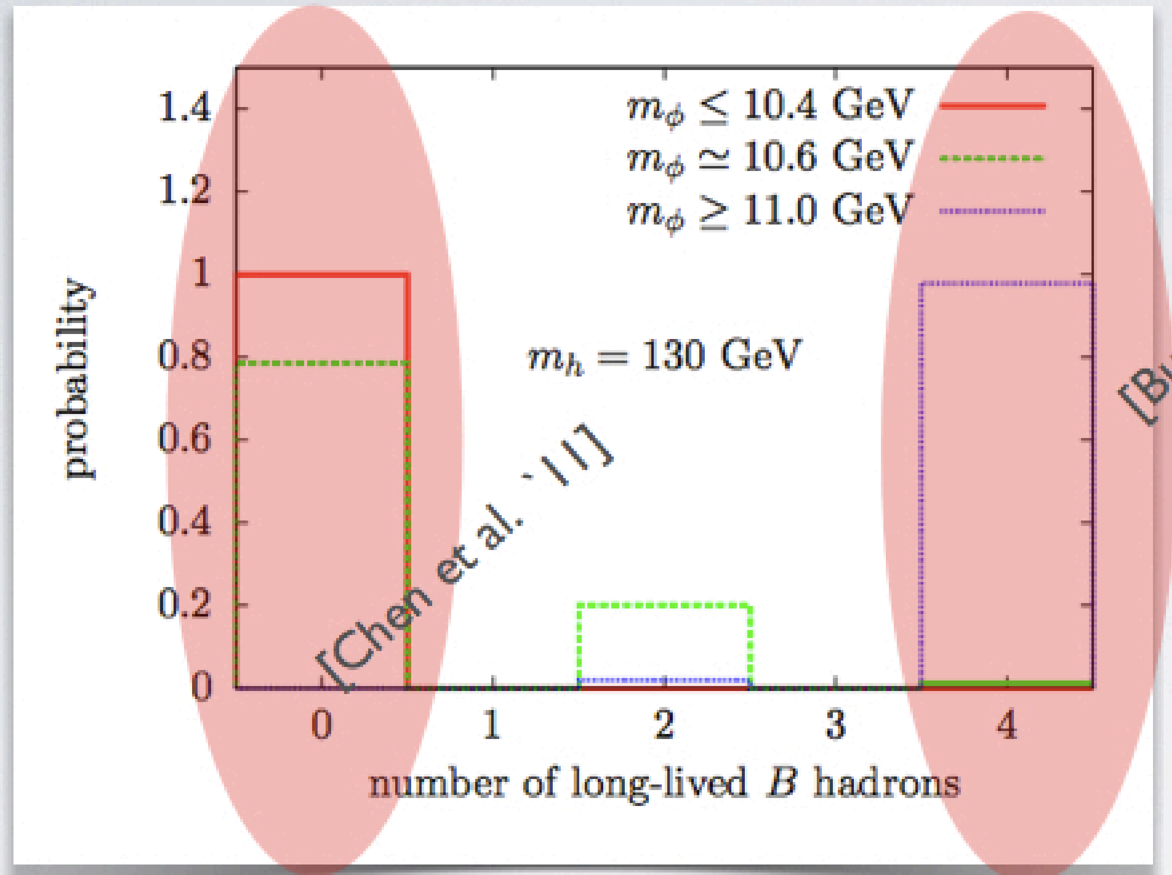
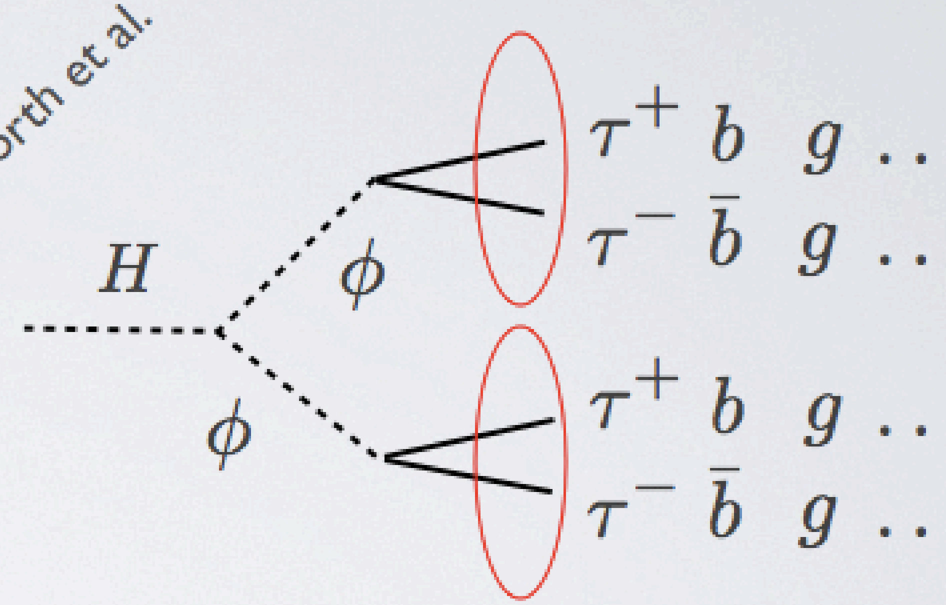


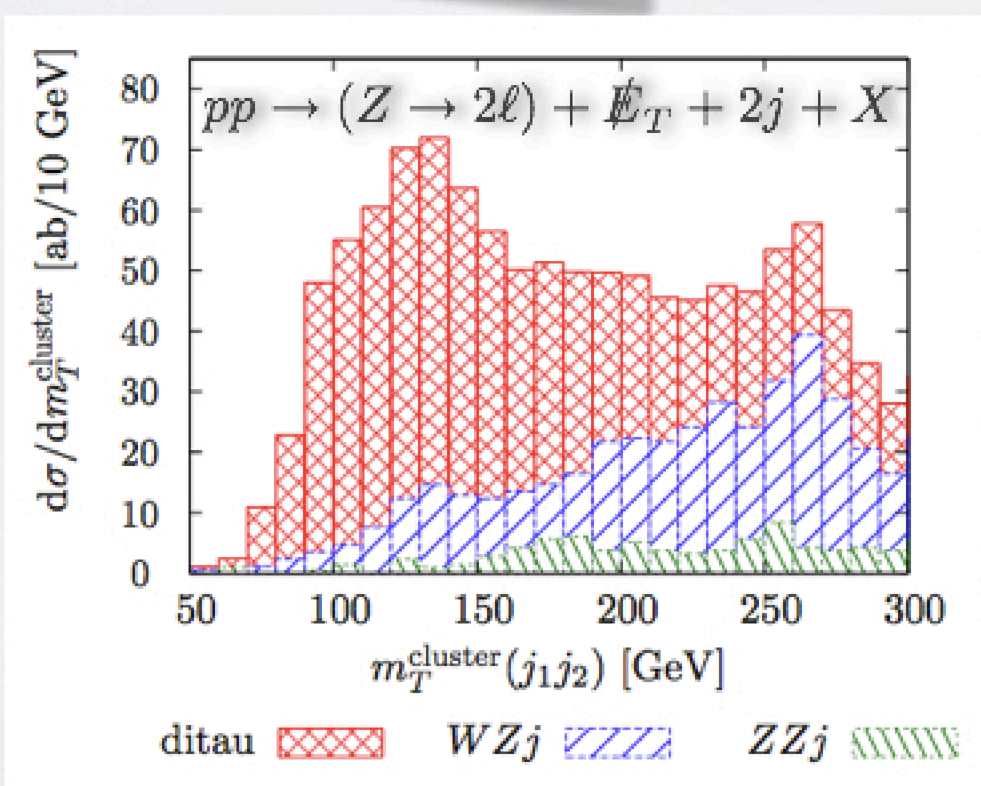
[Butterworth et al. `11]

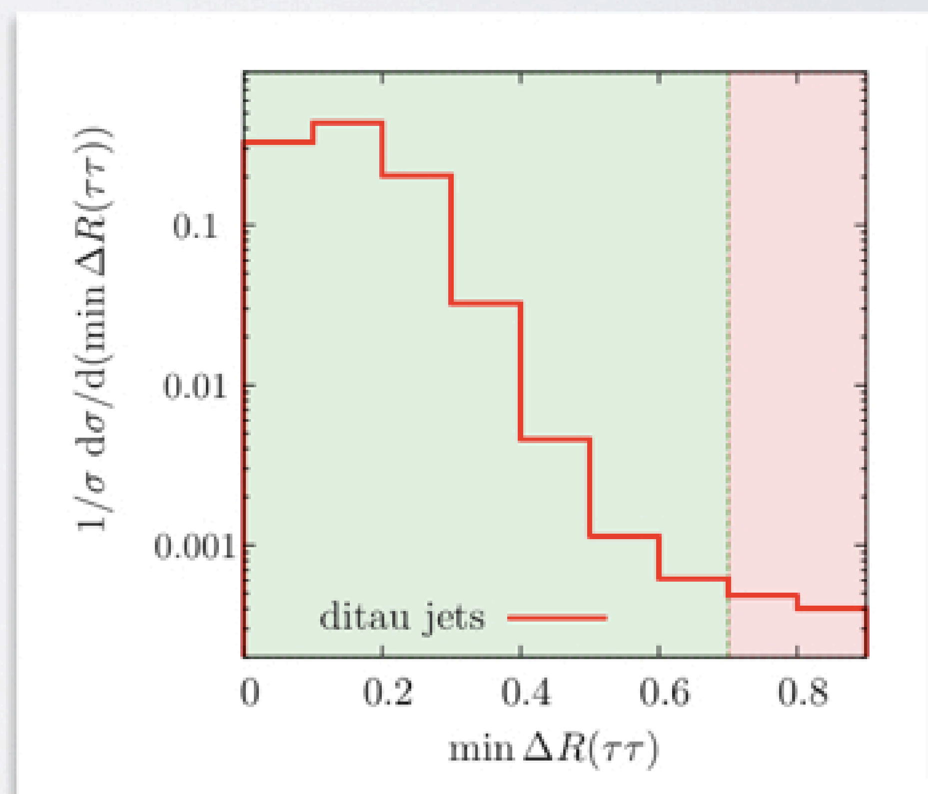


jet mass and momentum and jet enery clustering via N-subjettiness

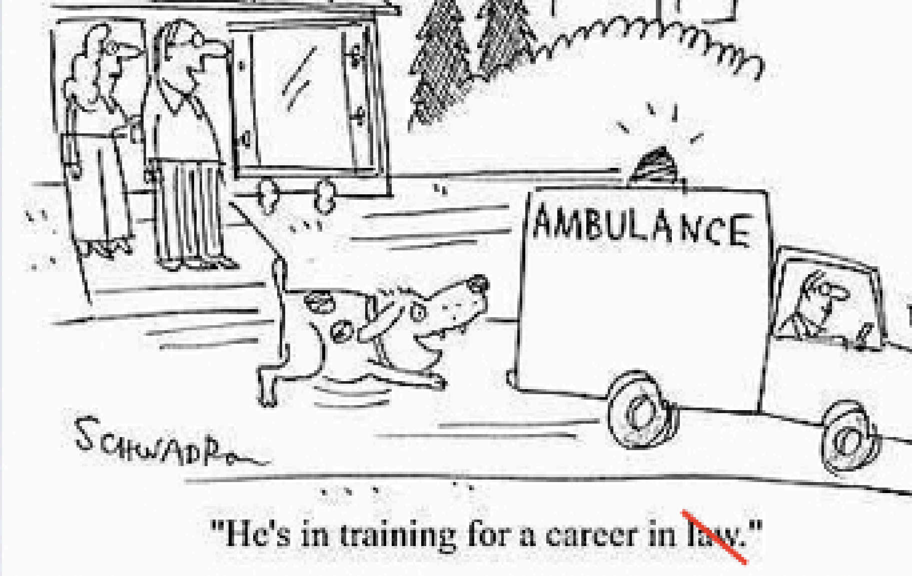
[Thaler, van Tilburg `10]
[CE, Roy, Spannowsky `10]

$\mathcal{L} = 12 \text{ fb}^{-1}$ ($\sqrt{s} = 14$ TeV)





summary

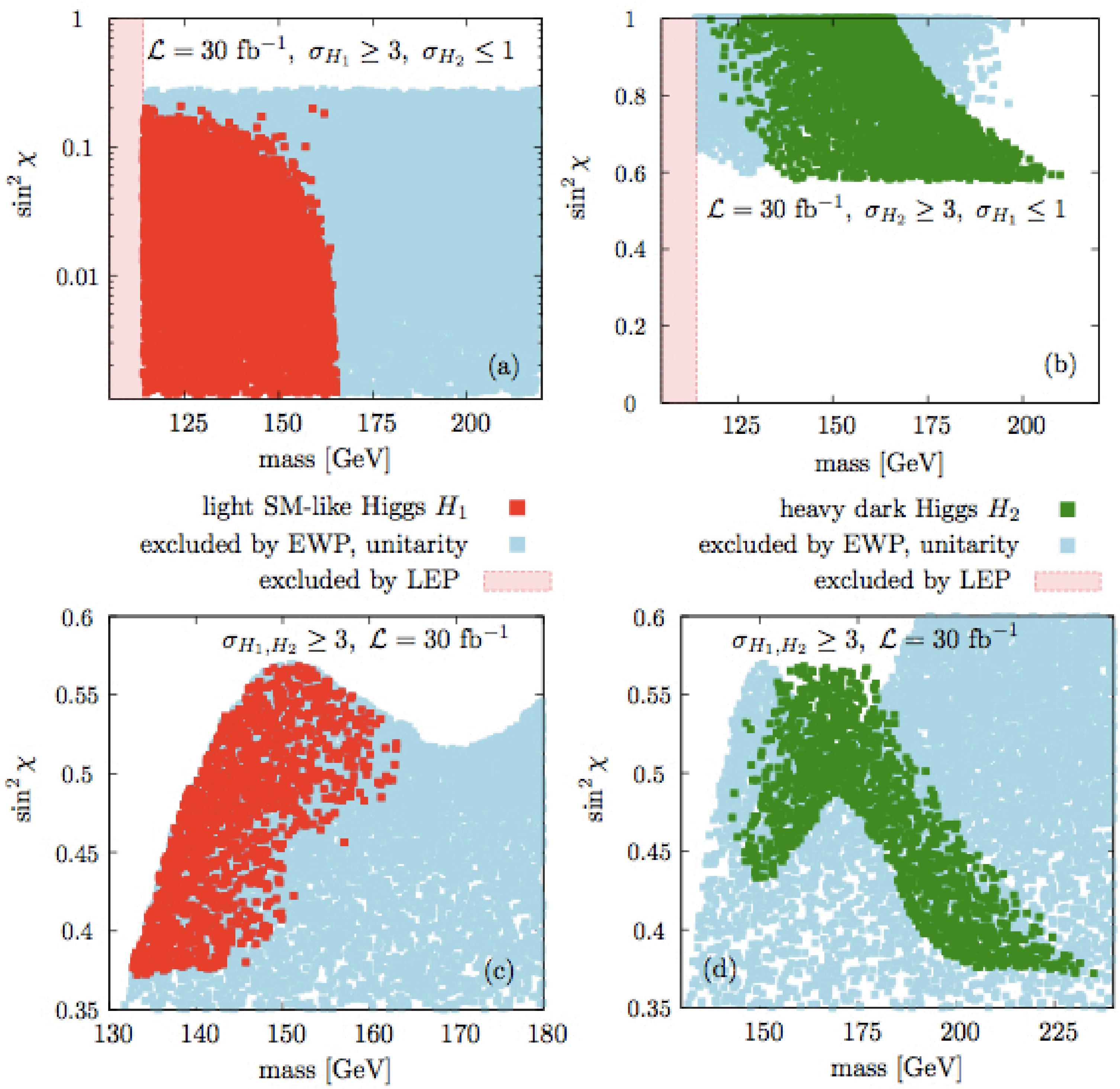


Higgs phenomenology

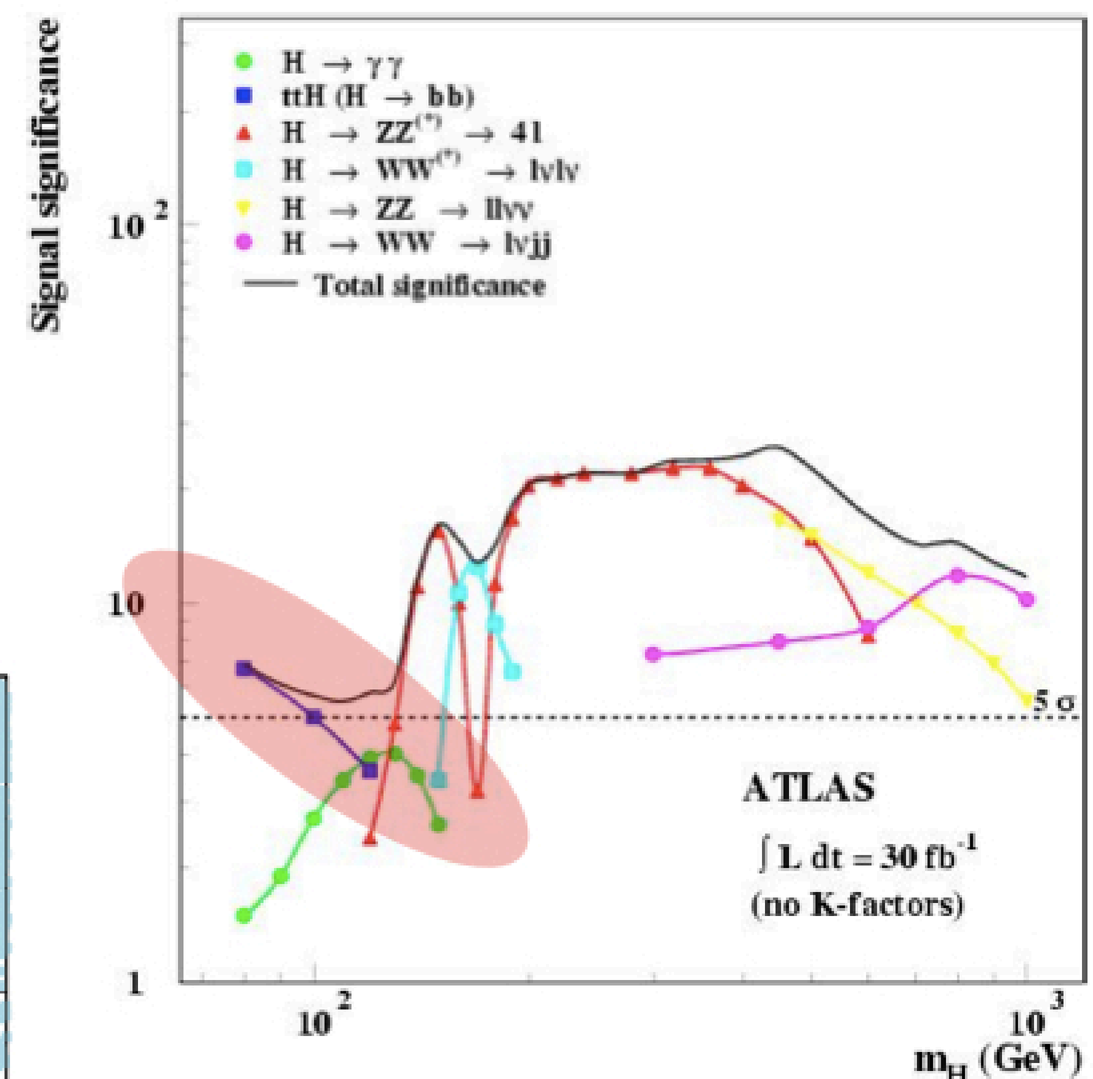
- Higgs hunters are off the leash
- we are theoretically biased towards a light SM-like Higgs but it's important not to miss potentially important channels
- if a light Higgs particle is discovered (and the hangover has faded) we have to face the fact that there's a long way to go
  - precise measurements of the couplings and (exotic) branching ratio [Klute, Lafaye, Plehn, Rauch, Zerwas `12]
  - (direct!) measurement of spin & CP [Plehn, Rainwater, Zeppenfeld `01] [Ellis, Hwang `12] [CE, Spannowsky, Takeuchi `12]
  - constrain Higgs sector extensions

BACKUP

Higgs portal phenomenology @ LHC



$\Gamma^{\text{hid}} \equiv \Gamma^{\text{SM}}$



fatjet/subjet methods

[Butterworth, Davison, Rubin, Salam `08]

[Plehn, Salam, Spannowsky `09]

Higgs portal profiling

- bounds are determined by measurement of twin ratios

$$\kappa_{p,d} = \left(\frac{\Gamma^p\Gamma^d}{\Gamma^{\rm tot}}\right) \Big/ \left(\frac{\Gamma^p\Gamma^d}{\Gamma^{\rm tot}}\right)^{\rm SM} = (\sigma_p \times {\rm BR}_d)/(\sigma_p \times {\rm BR}_d)^{\rm SM}$$

- strategy to acquire <u>*complete*</u> set of model parameters

$$\Gamma_1^{\rm tot} = \cos^2\chi\,\Gamma_1^{\rm SM} + \sin^2\chi\,\Gamma_1^{\rm hid} \qquad \Gamma_2^{\rm tot} = \sin^2\chi\,\Gamma_2^{\rm SM} + \cos^2\chi\,\Gamma_2^{\rm hid} + \Gamma_2^{HH}$$

$$\frac{\Gamma_1^{\rm inv}}{\Gamma_1^{\rm SM}} = \cos^2\chi\left[\frac{\cos^2\chi}{\kappa_1} - 1\right], \qquad \frac{\Gamma_1^{\rm tot}}{\Gamma_1^{\rm SM}} = \frac{\cos^4\chi}{\kappa_1} \quad \Rightarrow {\rm BR}_1^{\rm inv}$$

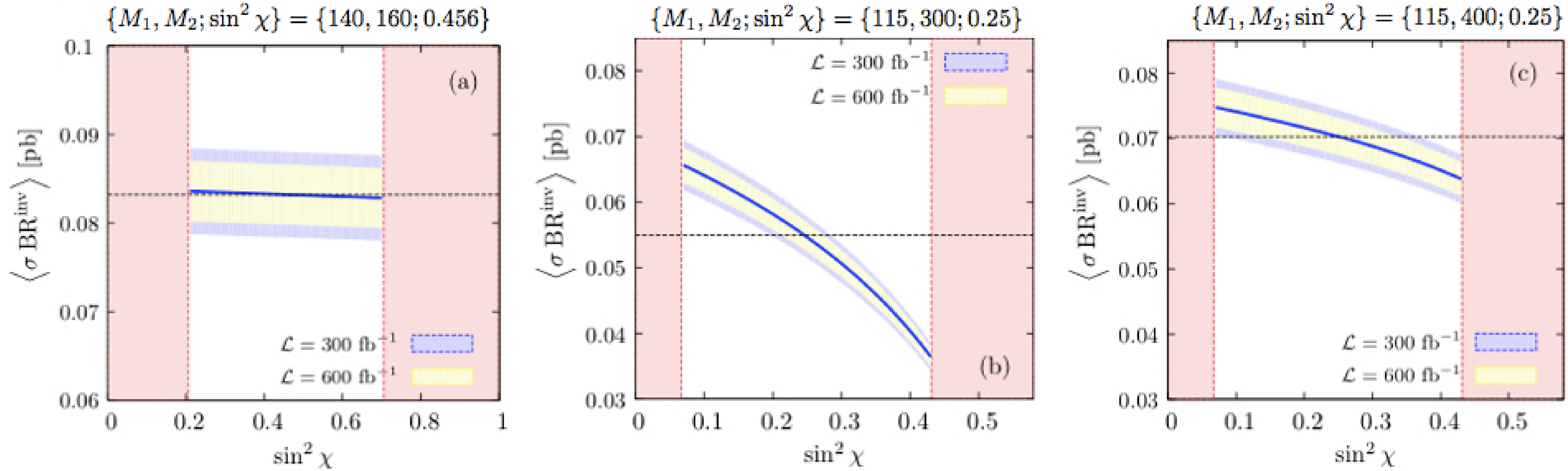
$$\frac{\Gamma_2^{\rm inv}}{\Gamma_2^{\rm SM}} = \sin^2\chi\left[\frac{\sin^2\chi}{\kappa_2} - 1 - \frac{1}{\cos^4\chi}\frac{{\rm BR}_2^{HH,{\rm vis}}}{{\rm BR}_2^{\rm vis}}\right], \qquad \frac{\Gamma_2^{\rm tot}}{\Gamma_2^{\rm SM}} = \frac{\sin^4\chi}{\kappa_2} \quad \Rightarrow {\rm BR}_2^{\rm inv}$$

$\kappa_2 \leq \sin^2\chi \leq 1 - \kappa_1$ due to positivity of Γ_i

- invisible decays cannot be separated, instead we measure

$$\langle \sigma {\rm BR}^{\rm inv}\rangle = \sigma_1 {\rm BR}_1^{\rm inv} + \sigma_2 {\rm BR}_2^{\rm inv} + {\rm Bkg}_{\rm inv}$$
$$\sim f(\Lambda_{211}) - [\cos^2\chi + \{\sigma_2^{\rm SM}/\sigma_1^{\rm SM}\}\sin^2\chi] + {\rm Bkg}_{\rm inv}$$

Higgs portal profiling



	reference point #1		reference point #2		
v_s [GeV]	246.22		246.22		
λ_s	0.18 ± 0.01	[0.19]	0.58 ± 0.03	(0.58 ± 0.02)	[0.58]
v_h [GeV]	85.72 ± 32.88	[85.75]	36.19 ± 5.06	(36.42 ± 3.63)	[36.42]
λ_h	1.53 ± 0.10	[1.52]	12.21 ± 1.25	(12.12 ± 0.89)	[12.11]
$\|\eta_\chi\|$	0.13 ± 0.40	[0.13]	3.67 ± 0.53	(3.66 ± 0.38)	[3.61]

large luminosity searches with established resonances!

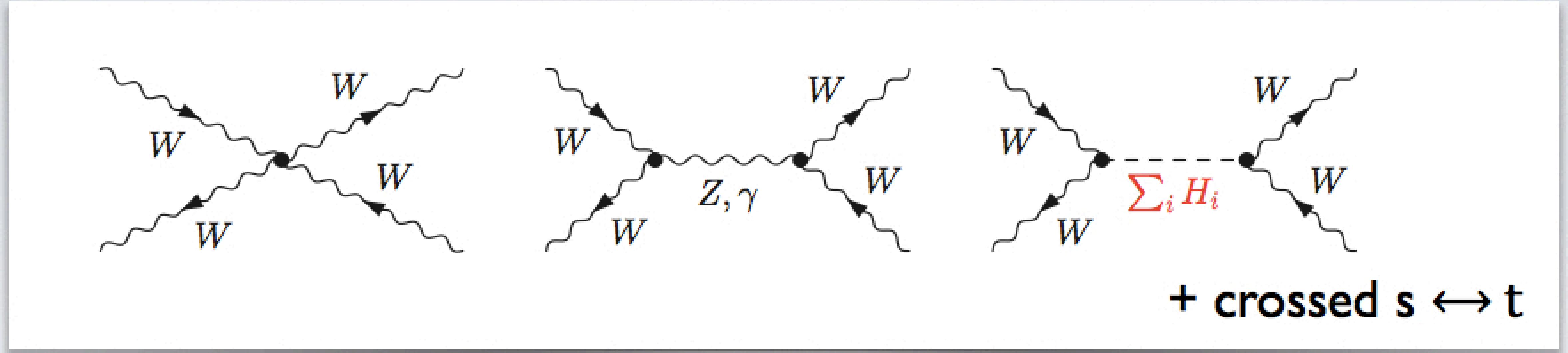
- invisible decays cannot be separated, instead we measure

$$\langle \sigma \mathrm{BR}^{\mathrm{inv}} \rangle = \sigma_1 \mathrm{BR}_1^{\mathrm{inv}} + \sigma_2 \mathrm{BR}_2^{\mathrm{inv}} + \mathrm{Bkg}_{\mathrm{inv}}$$

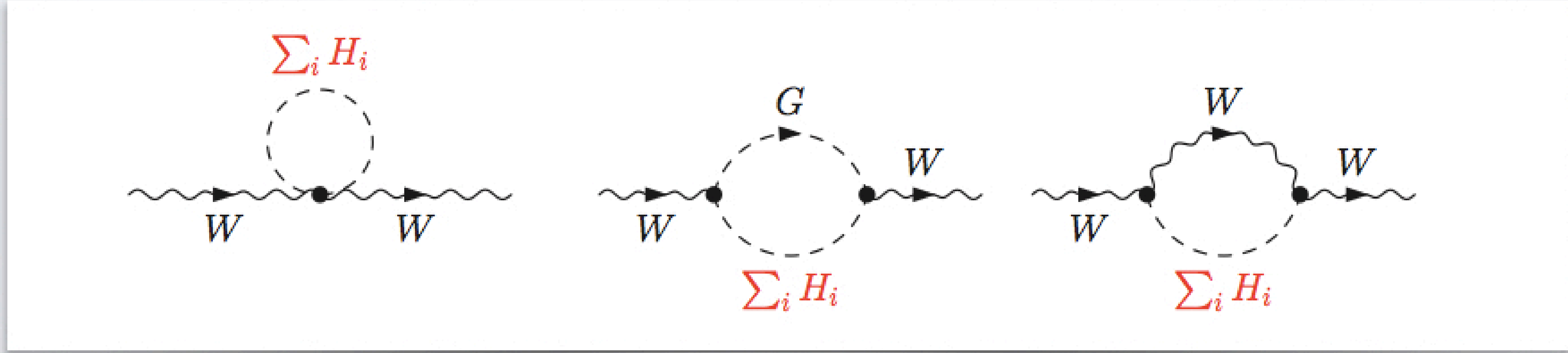
$$\sim f(\Lambda_{211}) - [\cos^2\chi + \{\sigma_2^{\mathrm{SM}}/\sigma_1^{\mathrm{SM}}\} \sin^2\chi] + \mathrm{Bkg}_{\mathrm{inv}}$$

Higgs portal phenomenology

unitarity and electroweak precision data constrain the model parameter space:



$$\rightsquigarrow M^2_{H_{\rm SM}} \to \langle M_i^2 \rangle \equiv \cos^2\chi\, M_1^2 + \sin^2\chi\, M_2^2 \leq 4\pi\sqrt{2}/3G_F \simeq (700\,{\rm GeV})^2$$



$$\rightsquigarrow \rho \text{ param.}: \log M^2_{H_{\rm SM}} \to \langle \log M_i^2 \rangle \equiv \cos^2\chi \log M_1^2 + \sin^2\chi \log M_2^2 \leq \log(175\ \ {\rm GeV})^2$$