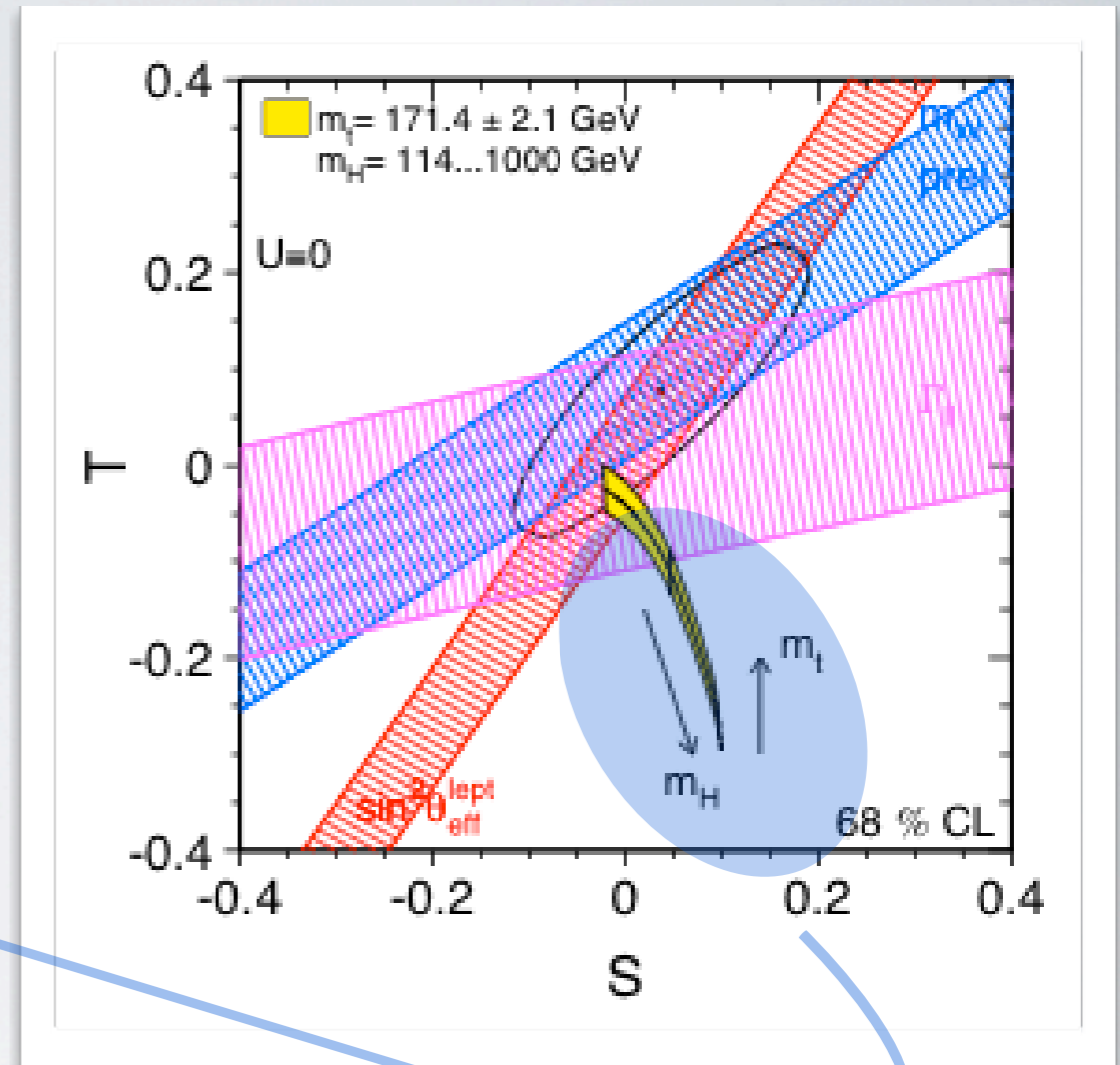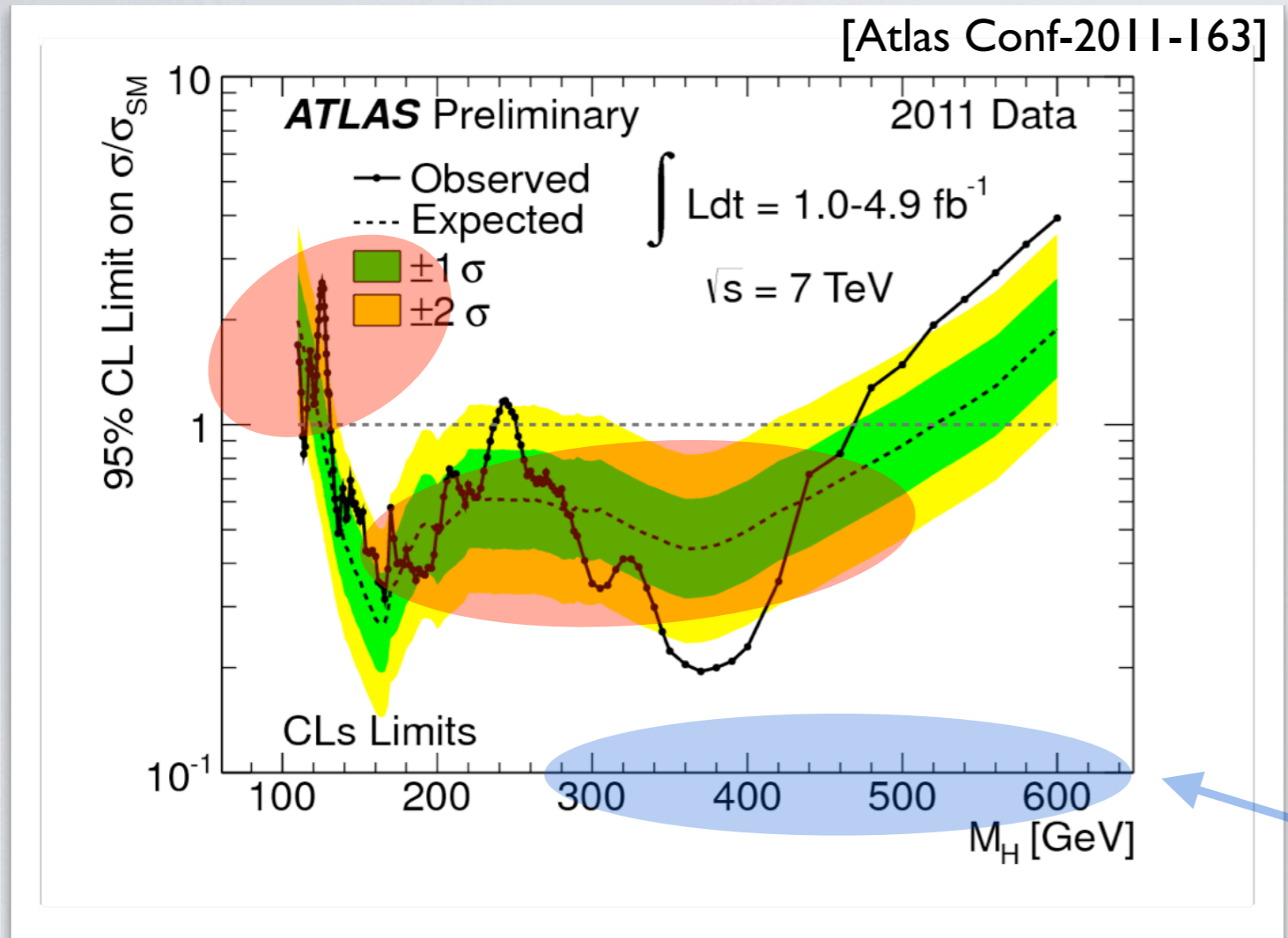# ASPECTS OF HIGGS PHYSICS IN THE LIGHT OF LHC DATA

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Higgs limits

[Atlas Conf-2011-163]

- bounds and couplings are determined by measurements of

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

<u>fixed as a consequence of EWSB and fermion masses in the SM</u>
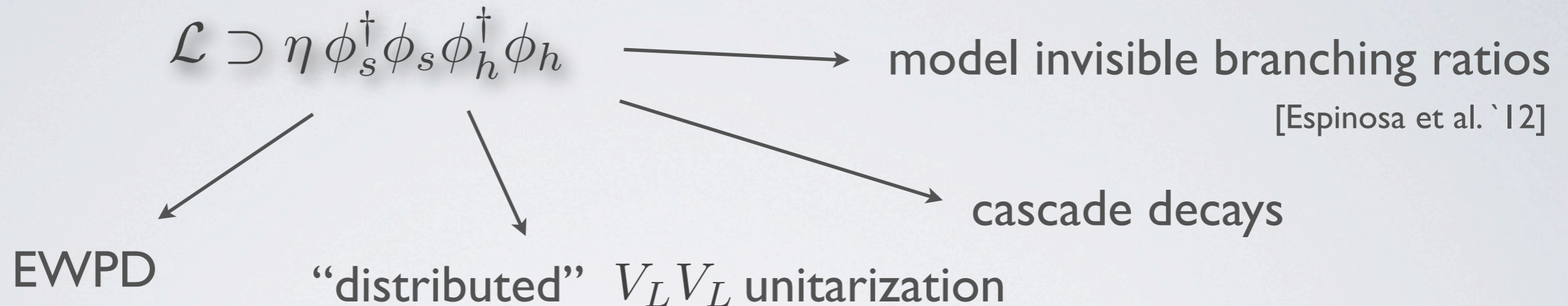
- two possibilities for heavy Higgses:

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

non-standard/ anomalous/exotic Higgs !!

a theoretical baseline: the Higgs portal

- $\phi_s^\dagger \phi_s$ is a singlet under the electroweak group and can act as a portal to a hidden sector:

$$\mathcal{L} \supset \eta \, \phi_s^\dagger \phi_s \phi_h^\dagger \phi_h \longrightarrow \text{model invisible branching ratios}$$

[Espinosa et al. `12]

cascade decays

EWPD

"distributed" $V_L V_L$ unitarization

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

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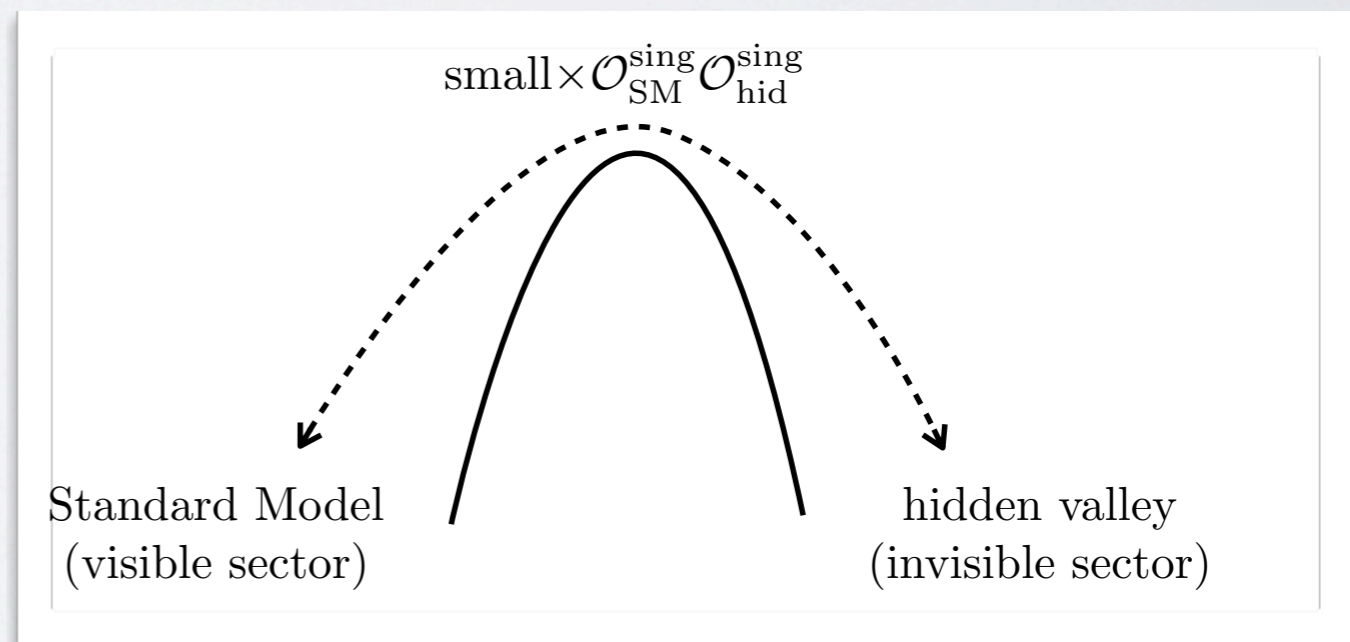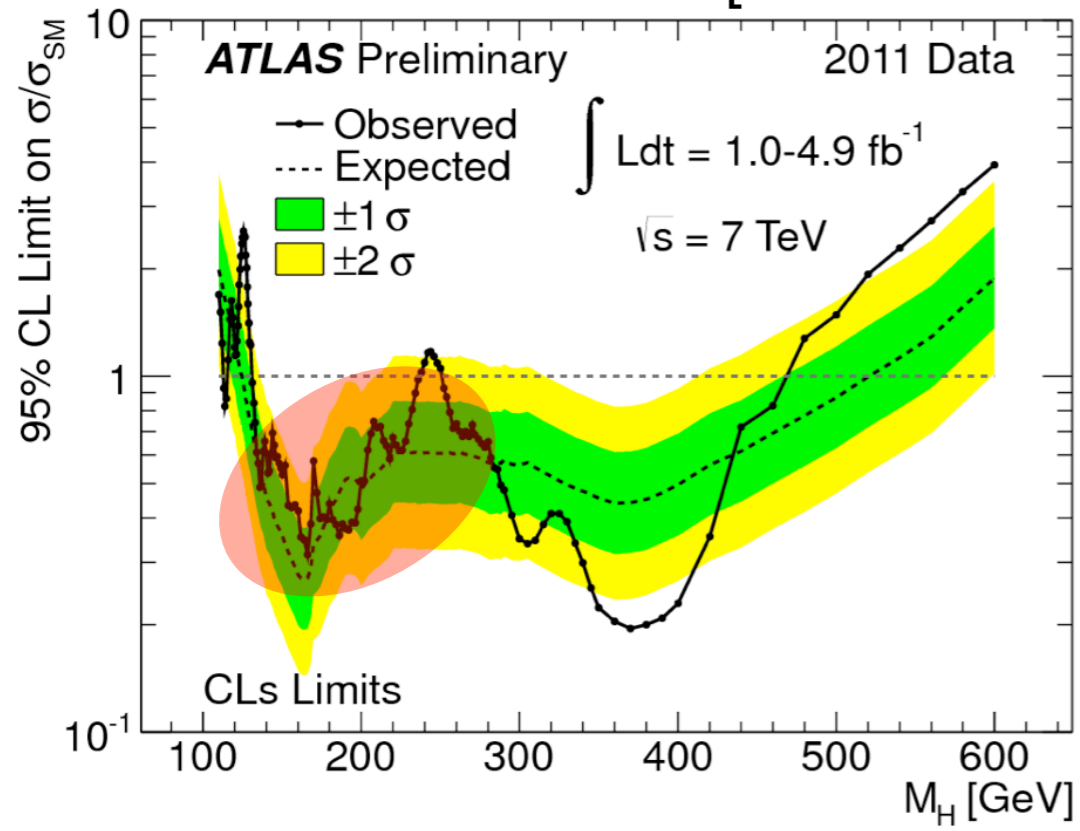
"SM"

$\text{small} \times \mathcal{O}_{\rm SM}^{\rm sing} \mathcal{O}_{\rm hid}^{\rm sing}$

Standard Model (visible sector)

hidden valley (invisible sector)

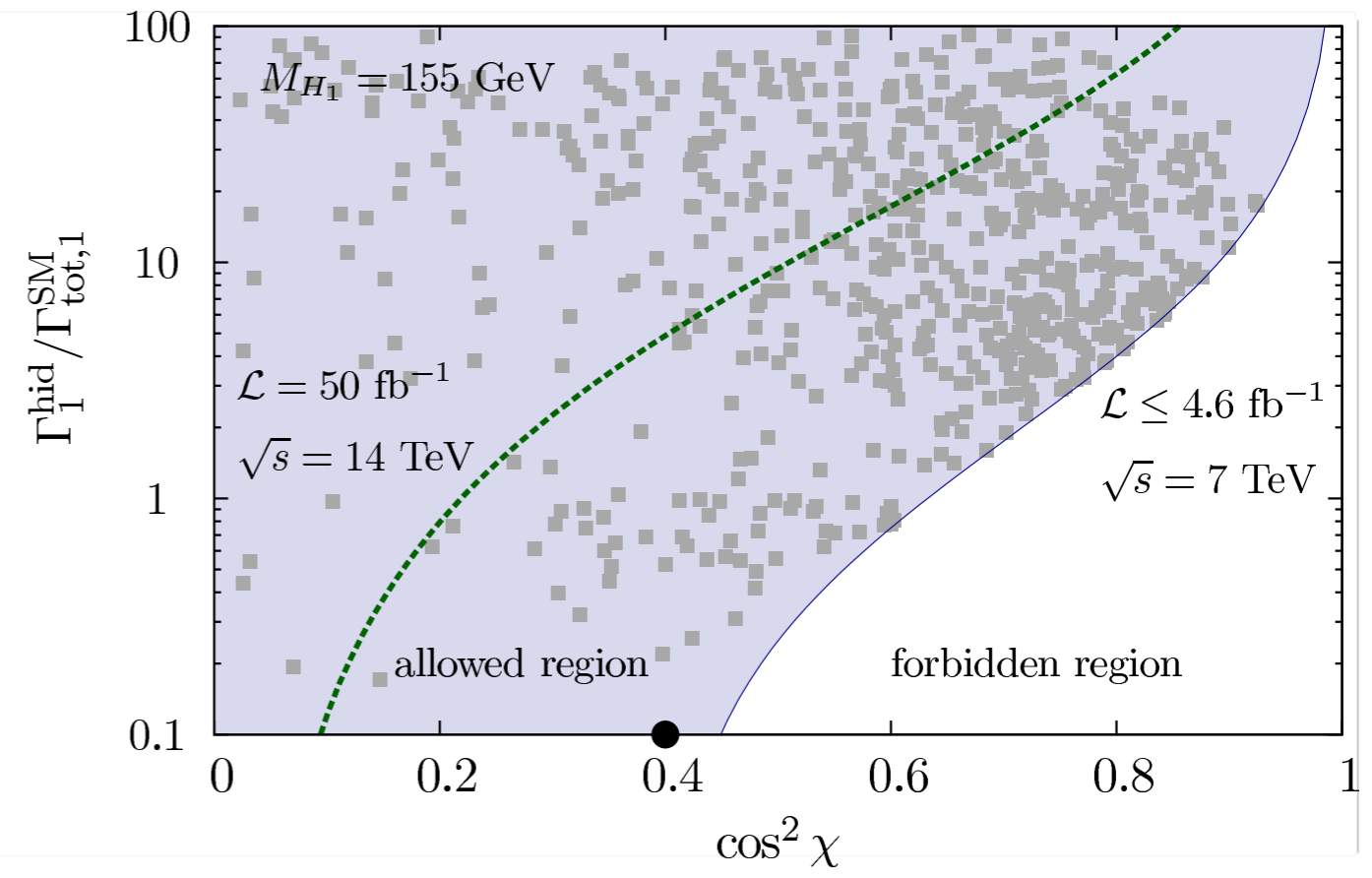# Higgs profiling

[Atlas Conf-2011-163]

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

$$\frac{\sigma[pp \to H_1 \to inv]}{\sigma[pp \to H_1]^{\mathrm{SM}}} = \frac{\sin^2 \chi \left[\Gamma_1^{\mathrm{hid}}/\Gamma_{\mathrm{tot},1}^{\mathrm{SM}}\right]}{1 + \tan^2 \chi \left[\Gamma_1^{\mathrm{hid}}/\Gamma_{\mathrm{tot},1}^{\mathrm{SM}}\right]} \le \mathcal{J}$$
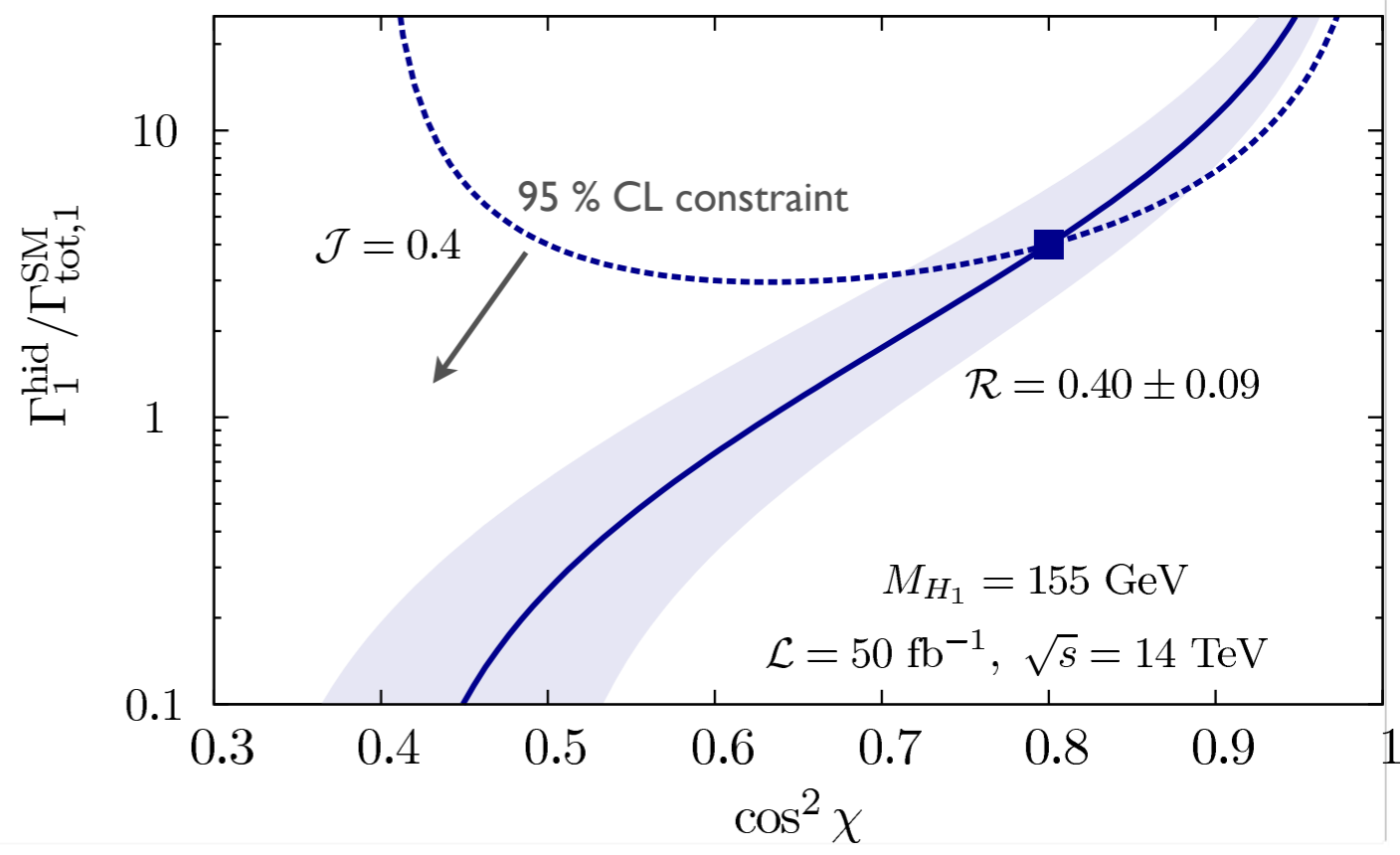
[CE, Plehn, Zerwas, Zerwas `11]
[CE, Plehn, Rauch, Zerwas, Zerwas `11]

Higgs profiling

[Atlas Conf-2011-163]
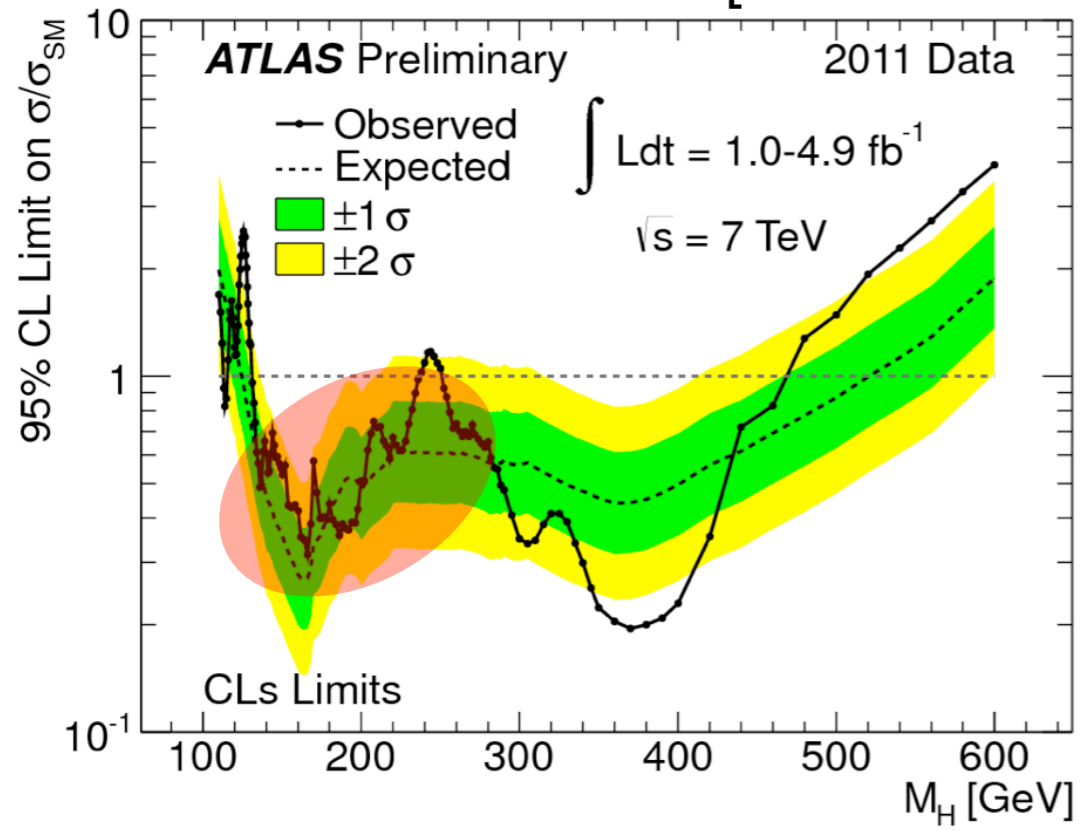
$$\frac{\sigma[pp \to H_1 \to F]}{\sigma[pp \to H_1 \to F]^{\mathrm{SM}}} = \frac{\cos^2 \chi}{1 + \tan^2 \chi \, [\Gamma_1^{\mathrm{hid}}/\Gamma_{\mathrm{tot},1}^{\mathrm{SM}}]} \leq \mathcal{R}$$

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

heavy hidden Higgs states?

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

$$\Gamma(H \to V_L V_L) \sim m_H^3 / m_V^2$$

$$\Gamma_{\mathrm{inv}} \sim \frac{\eta^2 v^2}{m_h}$$

$$\Gamma_{\mathrm{inv}}/\Gamma_{\mathrm{tot}} = 0.9$$
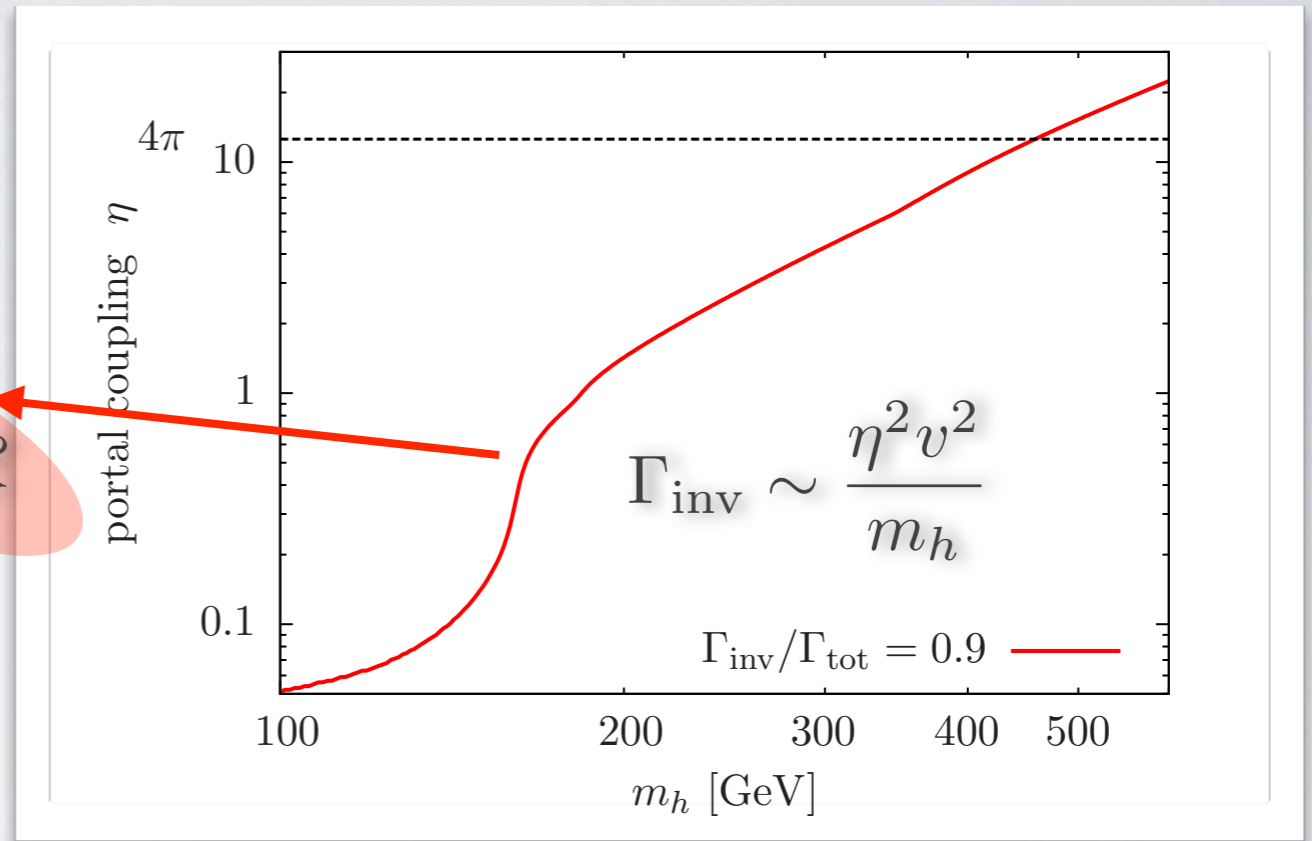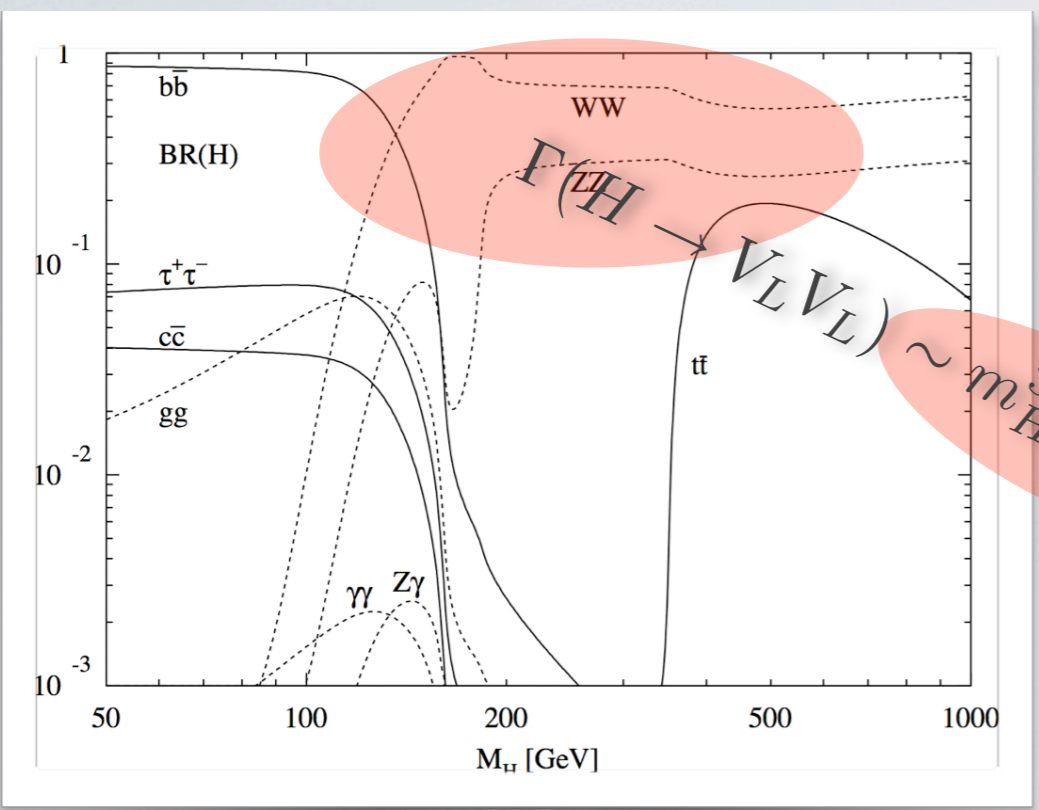
"easy" to hide a light Higgs

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

anomalous couplings

anomalous propagators

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} \quad \mathcal{L} \supset H^\dagger \left(D^\mu D_\mu + \mu^2 \right)^{2-d} H$$

$$[H] = d$$

[Stancato, Terning `08]

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

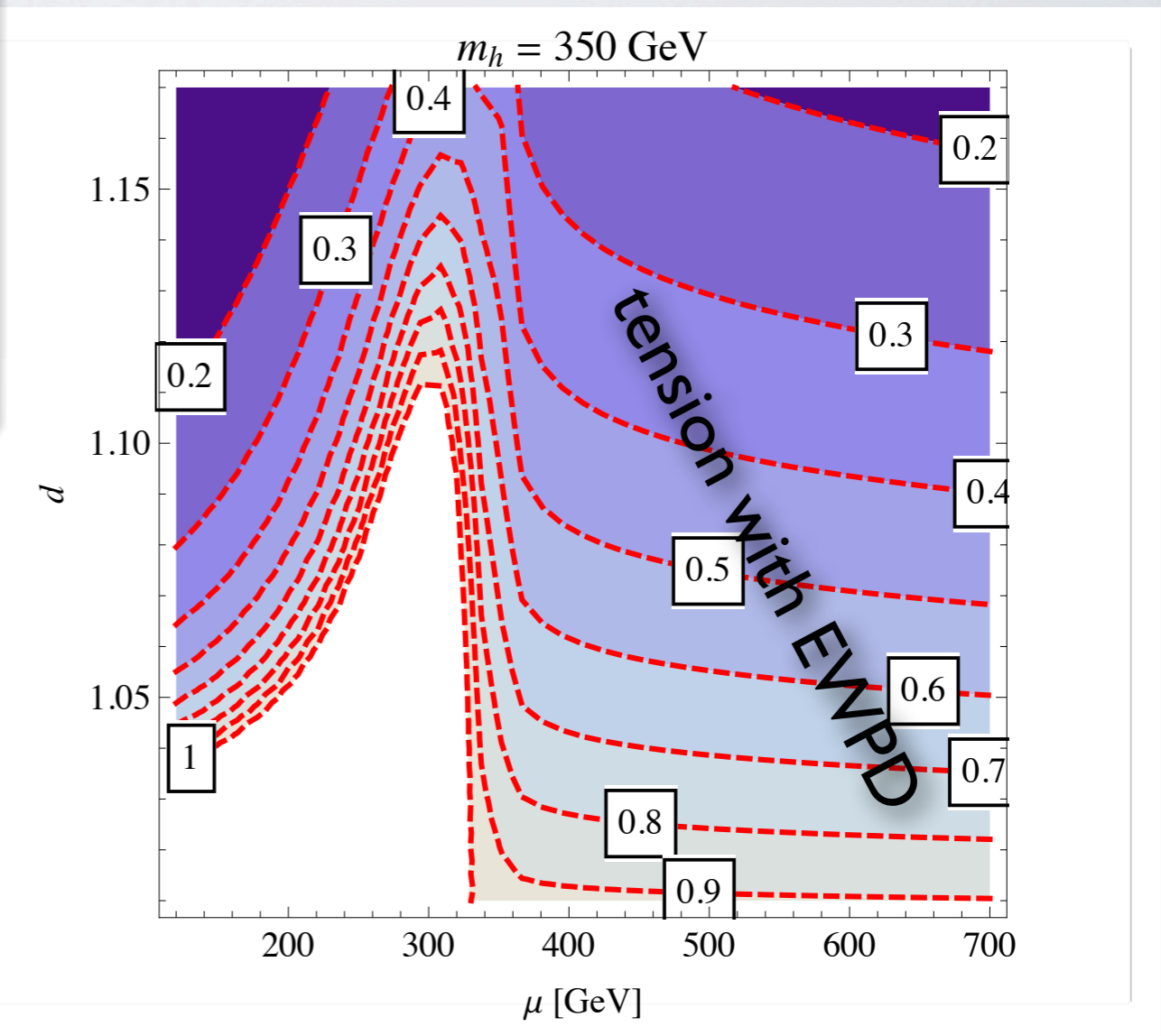- $1 < d \lesssim 1.5$ scale away gauge boson interactions <u>consistently</u>

[CE, Spannowsky, Stancato, Terning `12]

unparticle-like Higgs
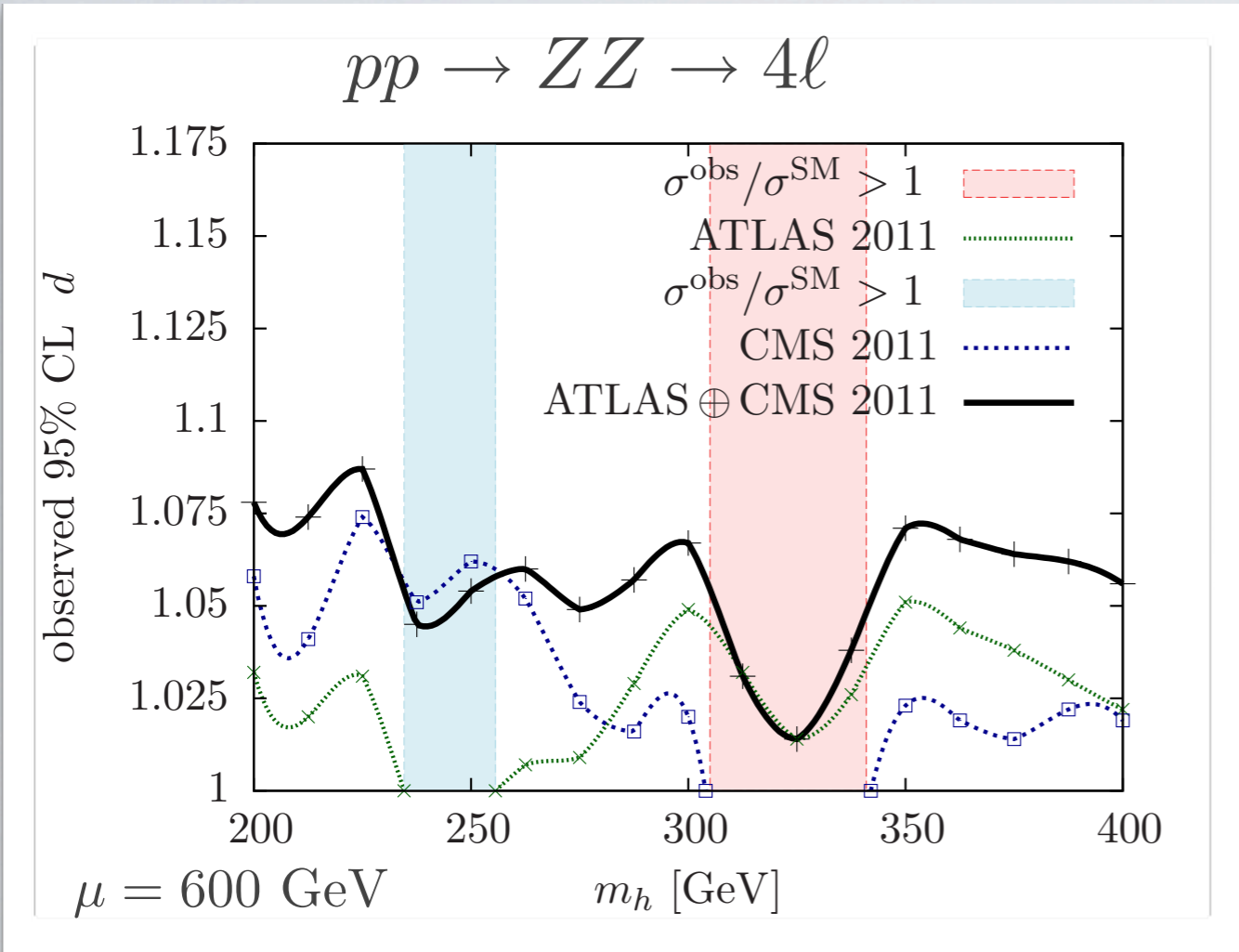
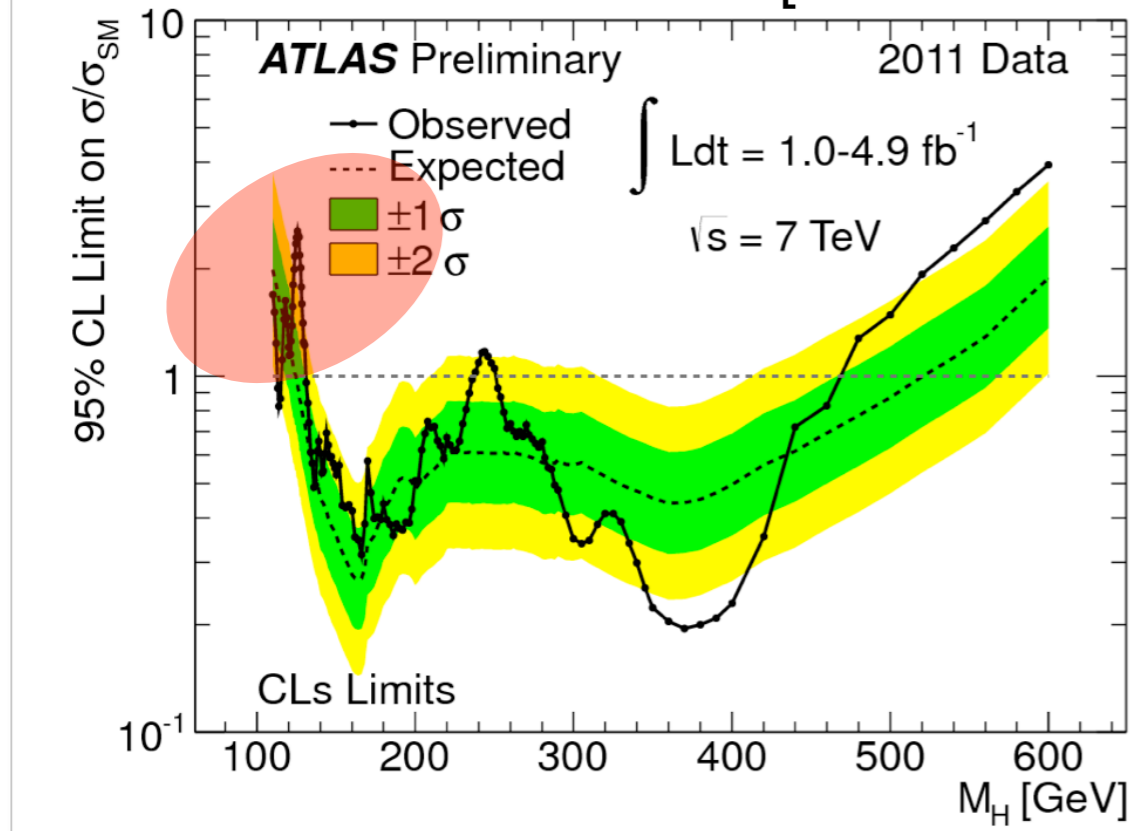$$pp \rightarrow ZZ \rightarrow 4\ell$$

Legend:
- $\sigma^{\text{obs}}/\sigma^{\text{SM}} > 1$ — ATLAS 2011
- $\sigma^{\text{obs}}/\sigma^{\text{SM}} > 1$ — CMS 2011
- ATLAS $\oplus$ CMS 2011

$\mu = 600$ GeV

observed 95% CL d vs m_h [GeV]

[CE, Spannowsky, Stancato, Terning `12]

$m_h = 350$ GeV

tension with EWPD

d vs μ [GeV]

Higgs profiling

[Atlas Conf-2011-163]

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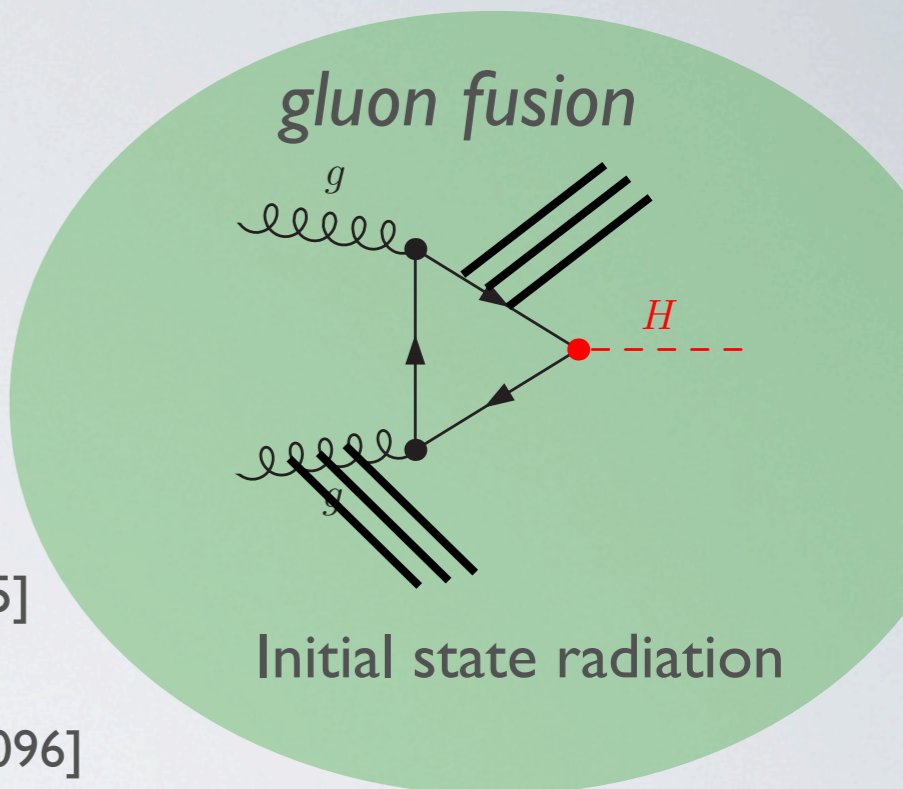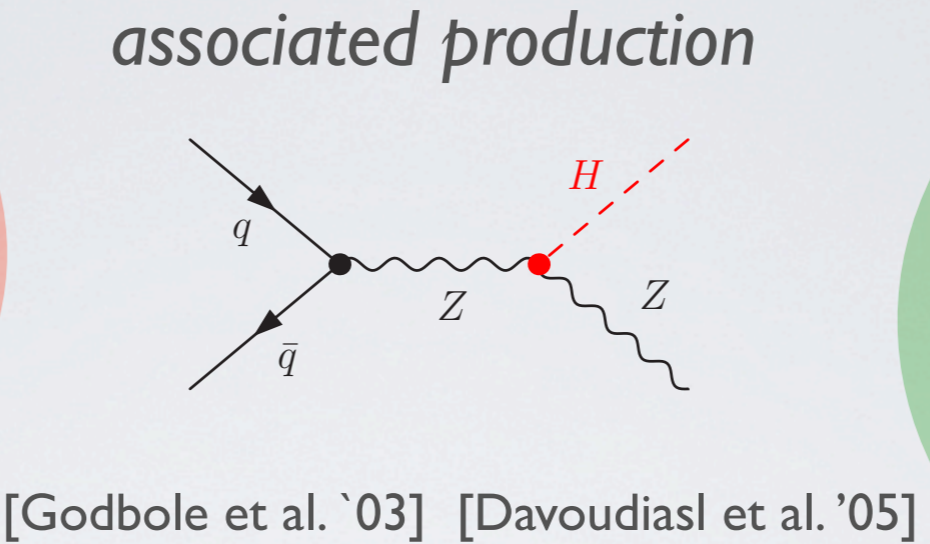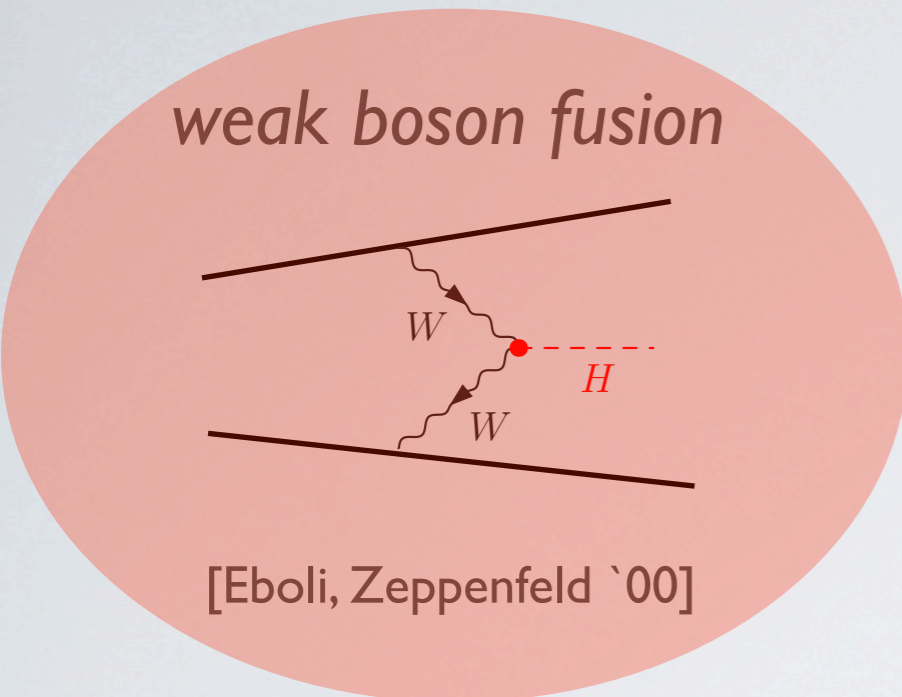
$$\frac{\sigma[pp \to H_1 \to inv]}{\sigma[pp \to H_1]^{\text{SM}}} = \frac{\sin^2 \chi \left[\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}}\right]}{1 + \tan^2 \chi \left[\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}}\right]} \leq \mathcal{J}$$

- constraining invisible decays necessary for coupling measurements

- exploit all available sensitivity

[CE, Plehn, Zerwas, Zerwas `11]
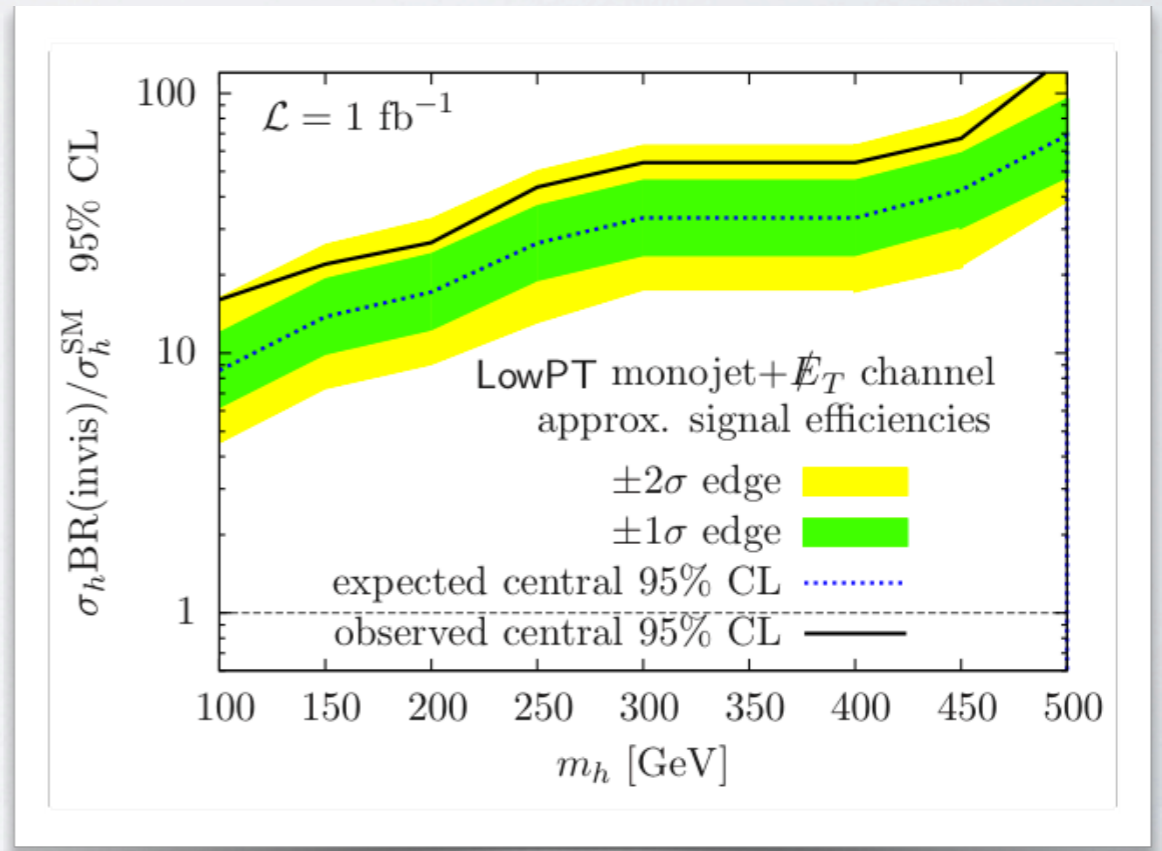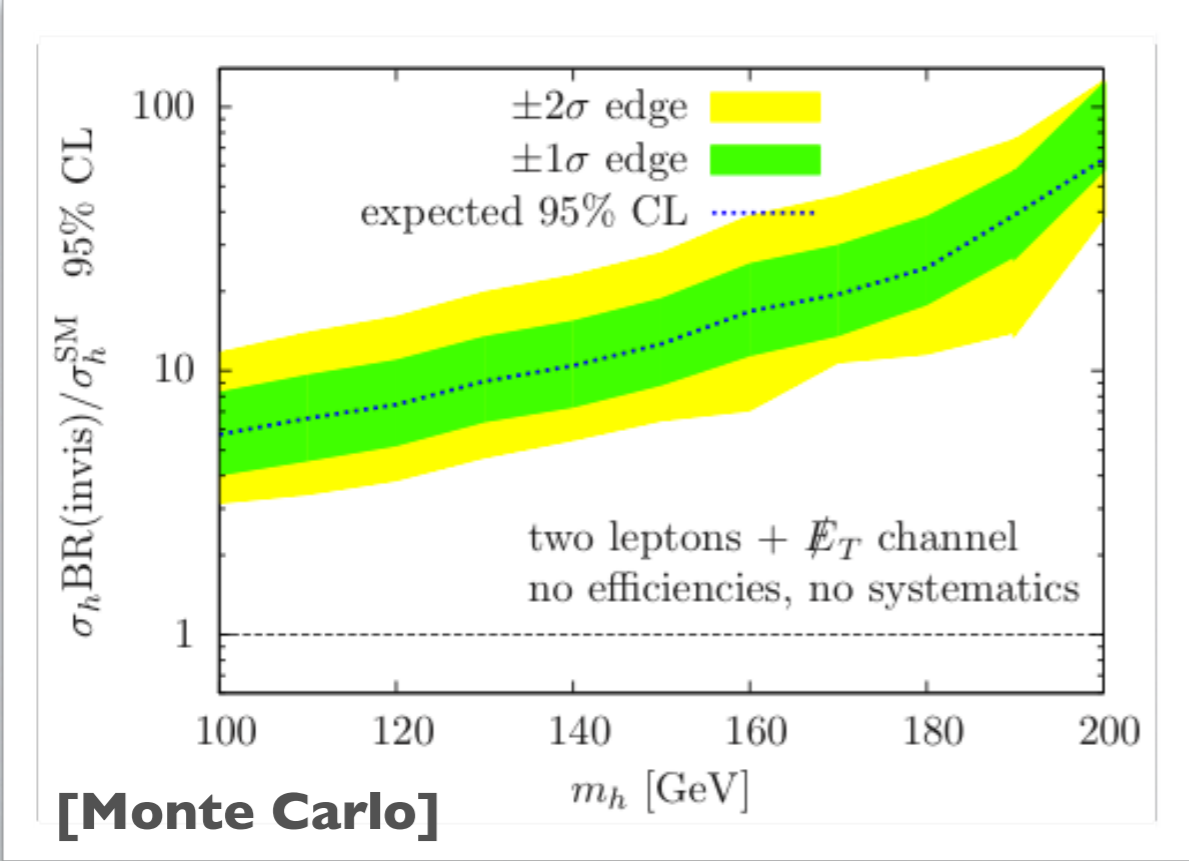[CE, Plehn, Rauch, Zerwas, Zerwas `11]
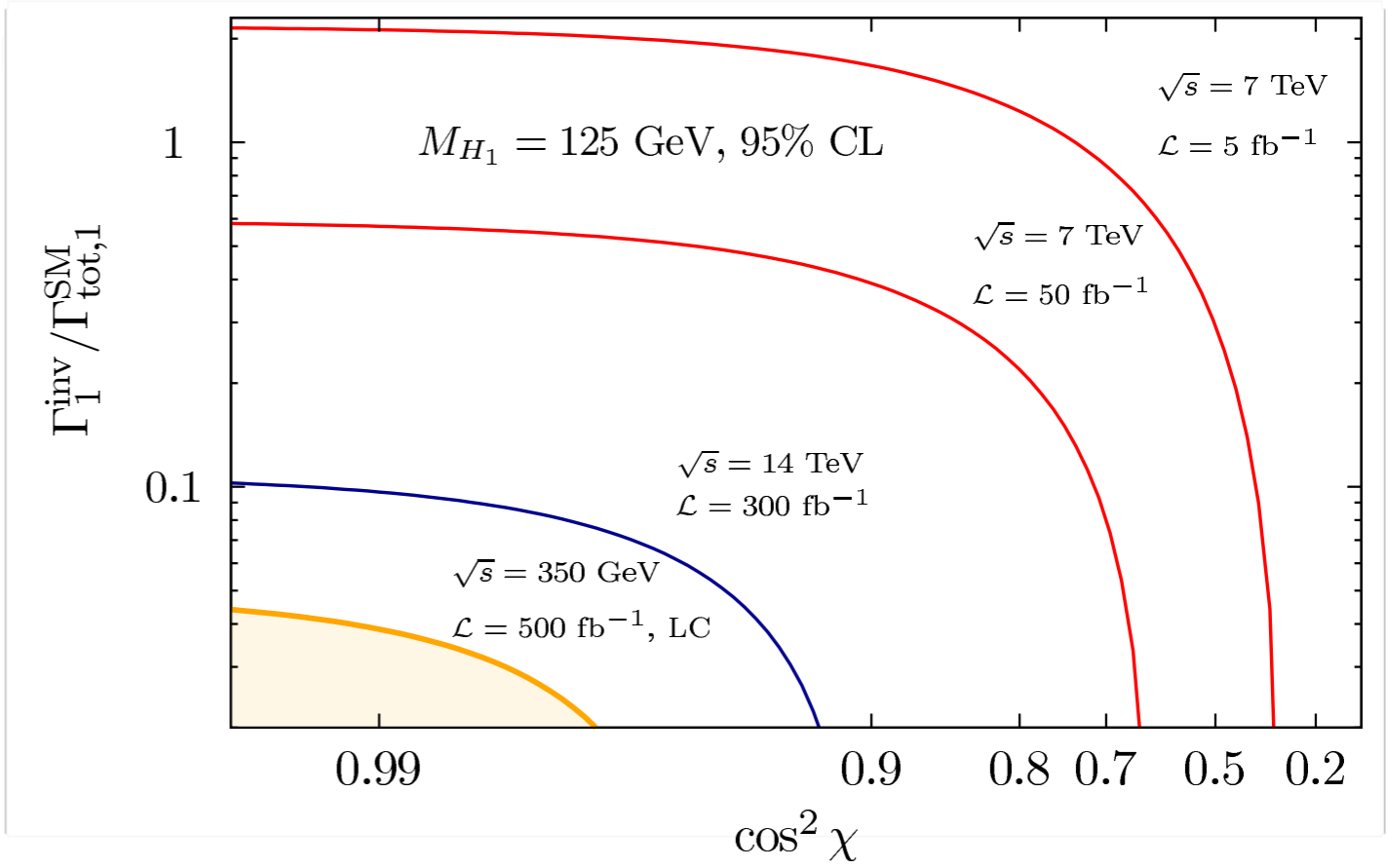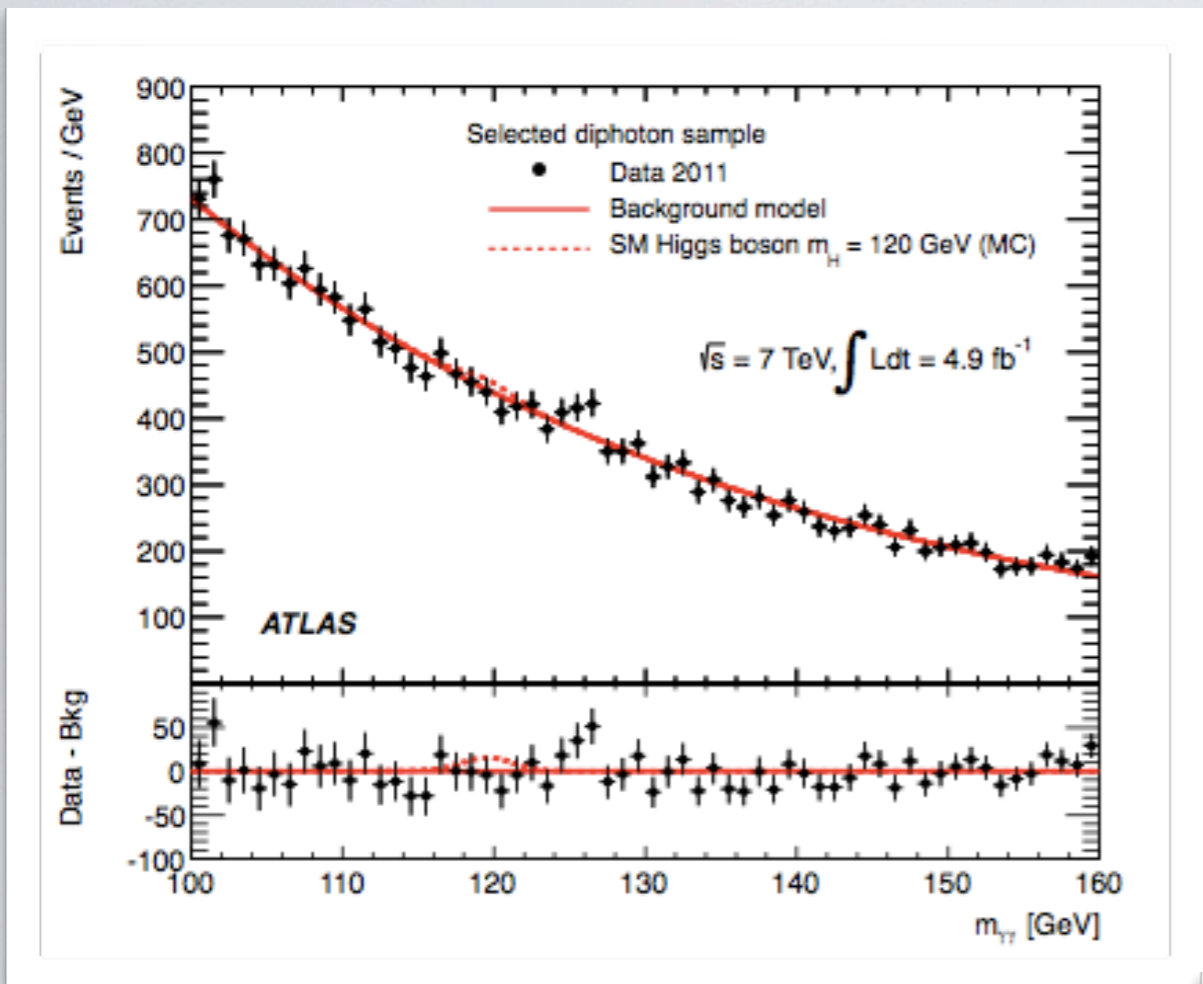
constraining invisible Higgs decays

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

$\pm 2\sigma$ edge
$\pm 1\sigma$ edge
expected 95% CL

two leptons $+ \not{E}_T$ channel
no efficiencies, no systematics

[Monte Carlo]

$\mathcal{L} = 1 \text{ fb}^{-1}$

LowPT monojet$+\not{E}_T$ channel
approx. signal efficiencies

$\pm 2\sigma$ edge
$\pm 1\sigma$ edge
expected central 95% CL
observed central 95% CL

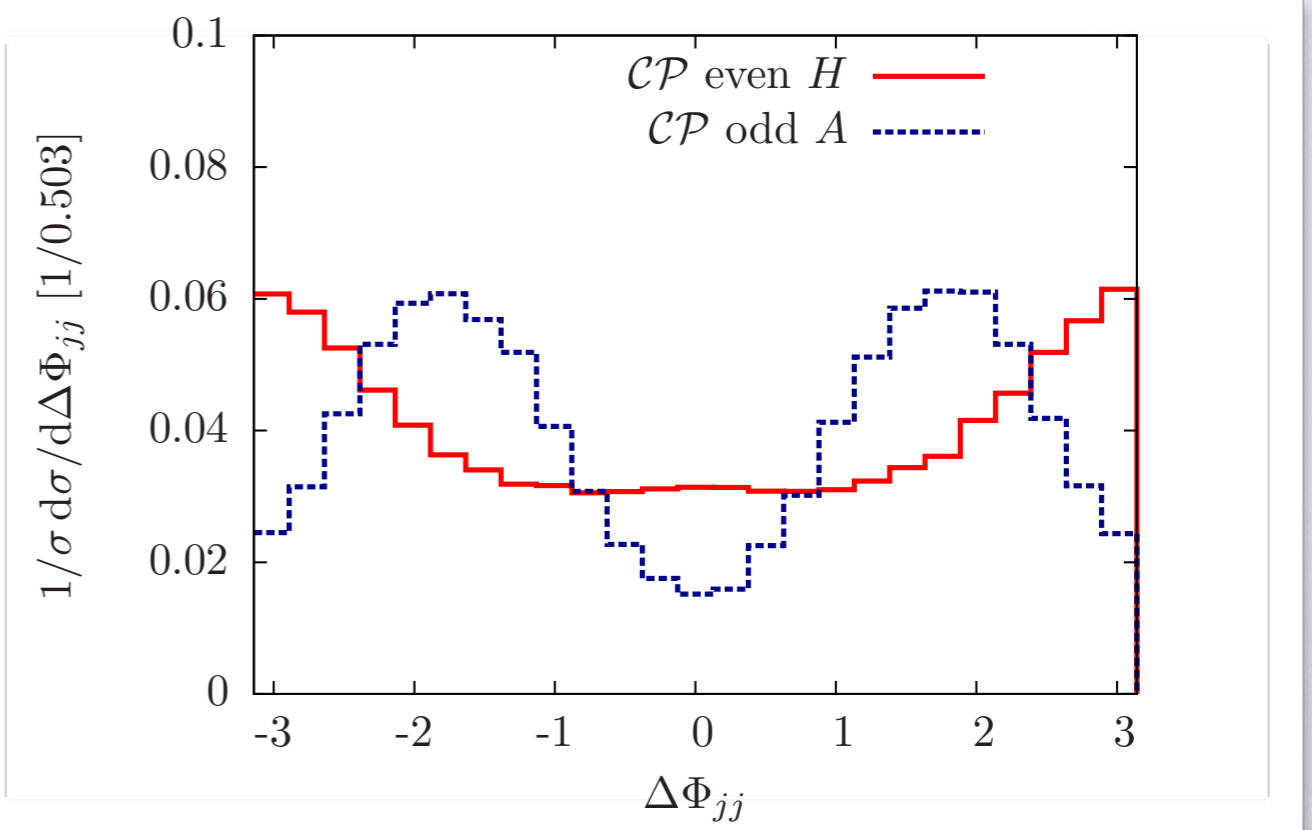[CE, Jaeckel, Re, Spannowsky `11]

Let's say 125 GeV is real! What's next.....

- Landau-Yang: cannot be spin 1

- spin 2 is a theoretical stretch

- What's the resonance's CP ?

$\Delta\Phi_{jj}$ in H+2j events

[Plehn, Rainwater, Zeppenfeld '01]

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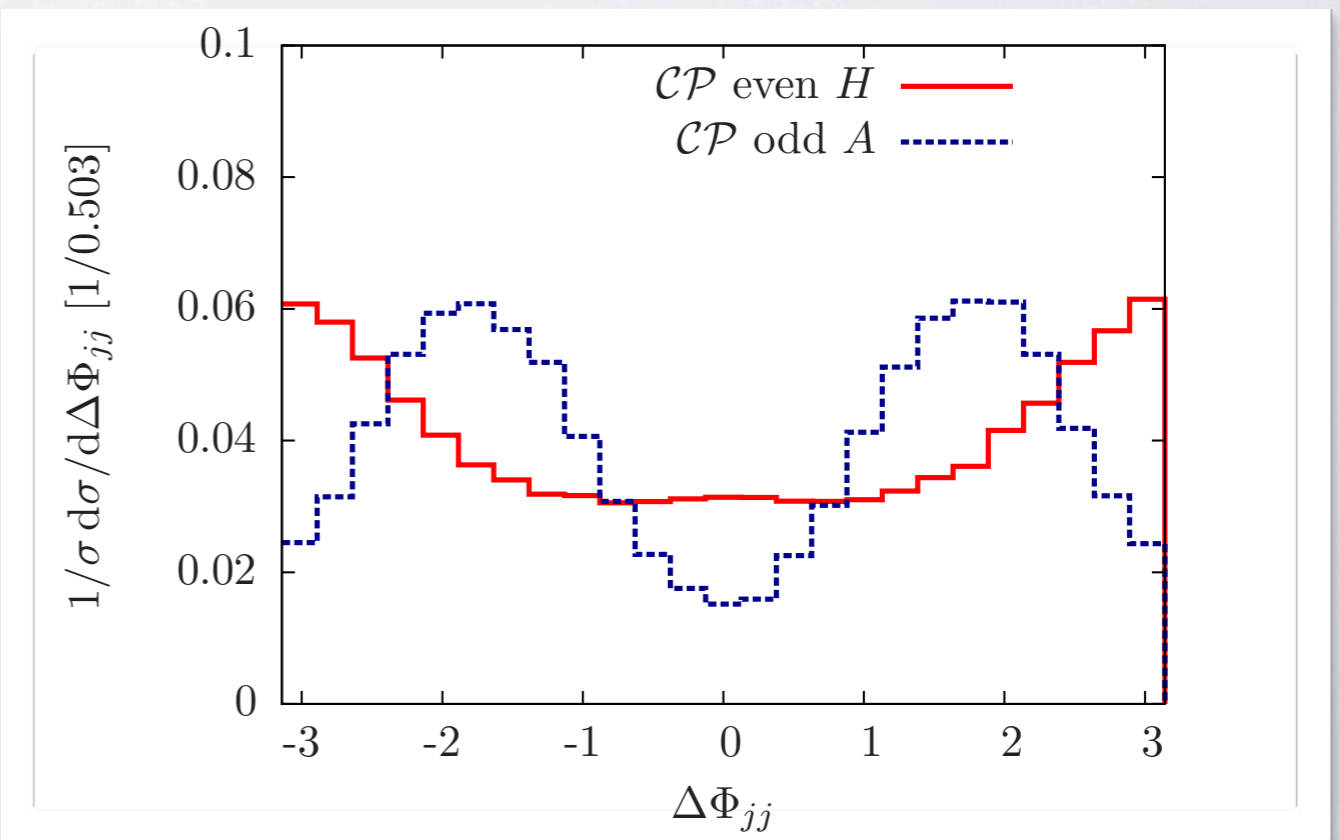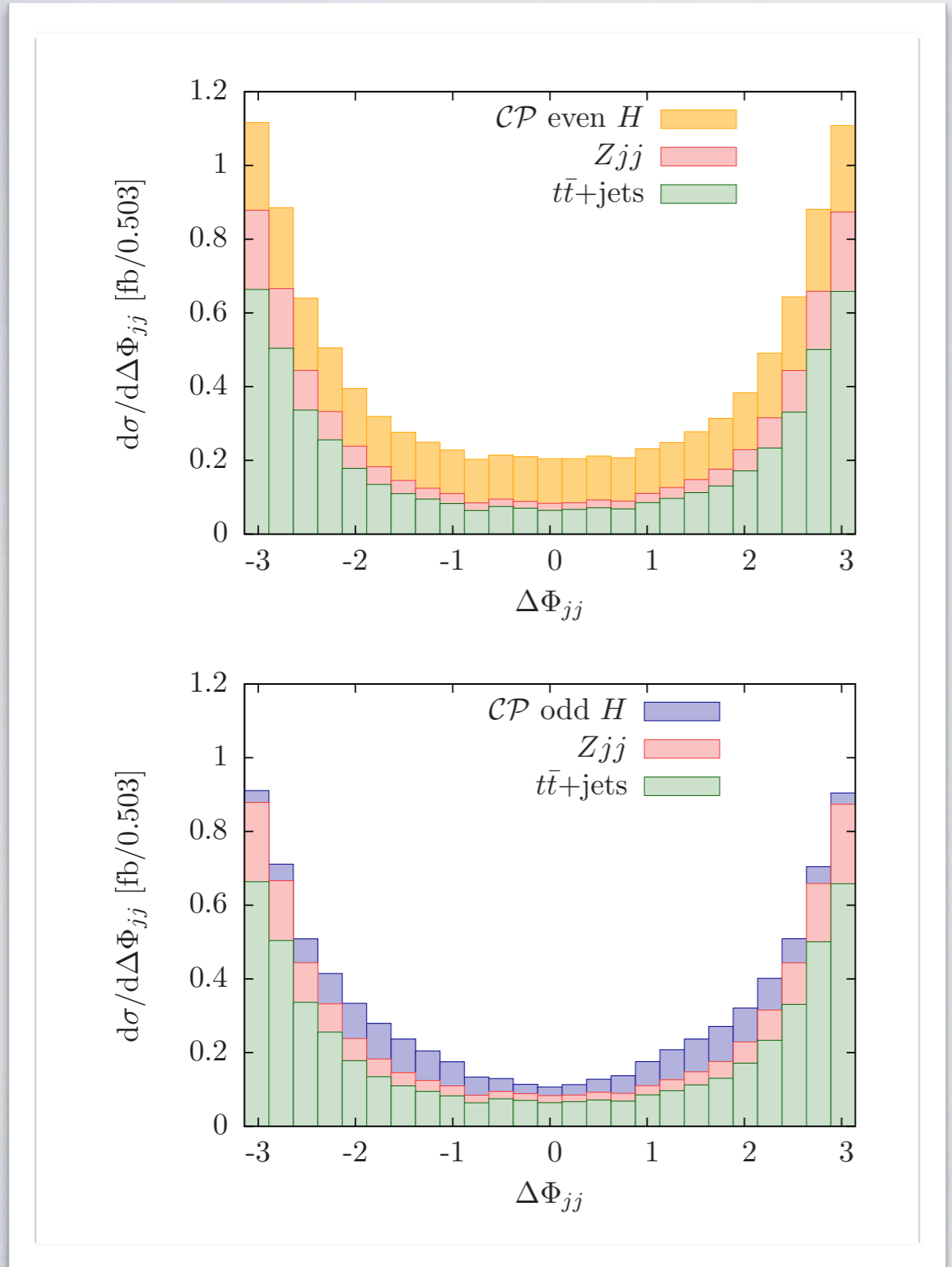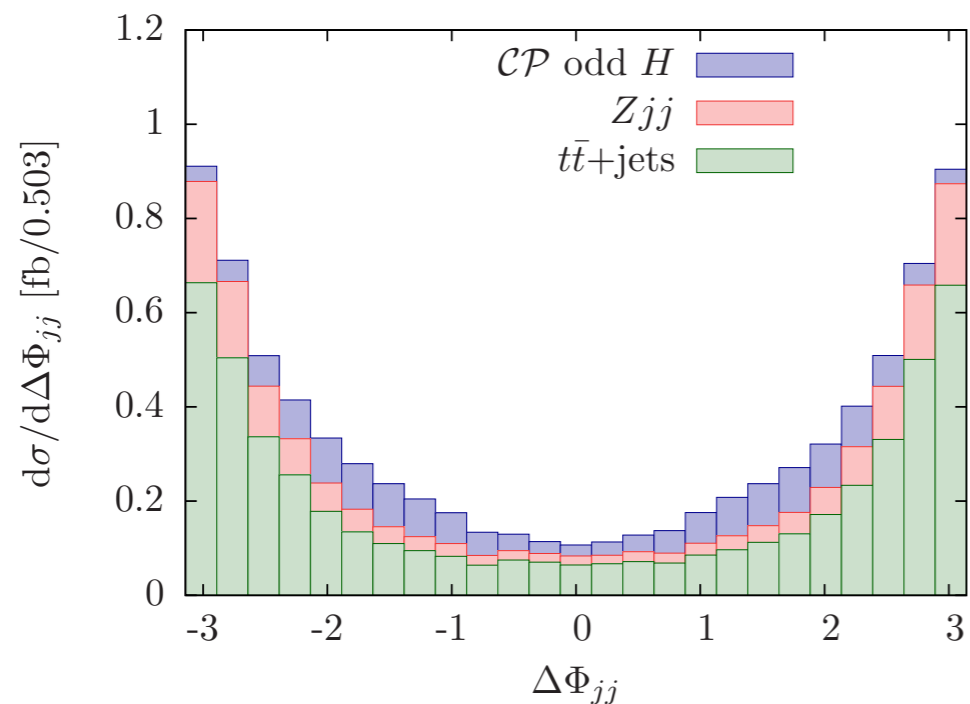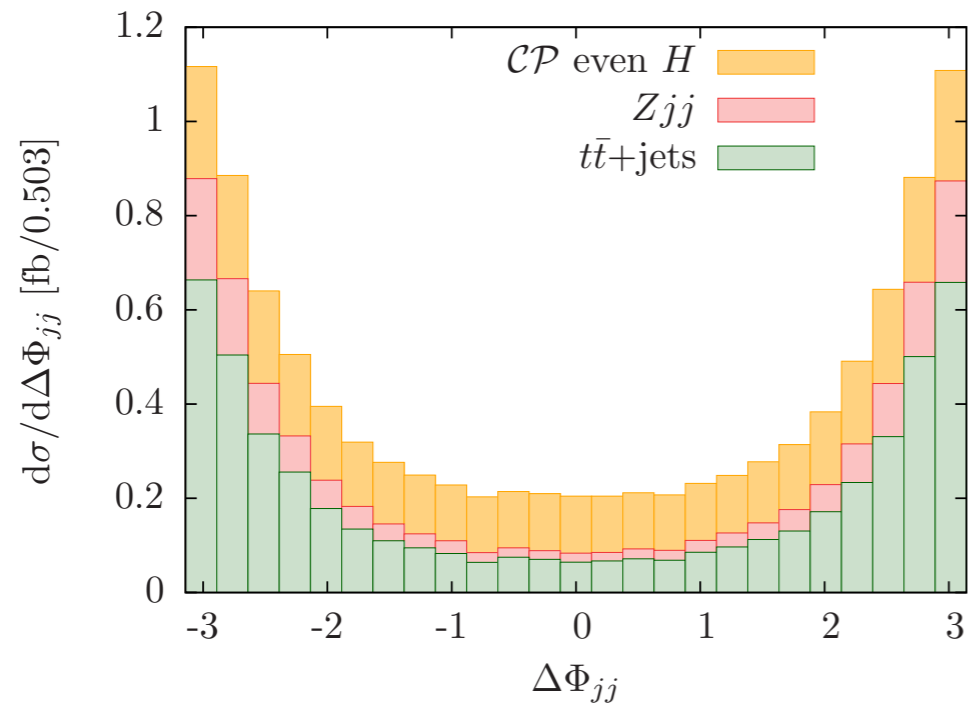- spin 2 is a theoretical stretch

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[Plehn, Rainwater, Zeppenfeld '01]

Higgs spectroscopy

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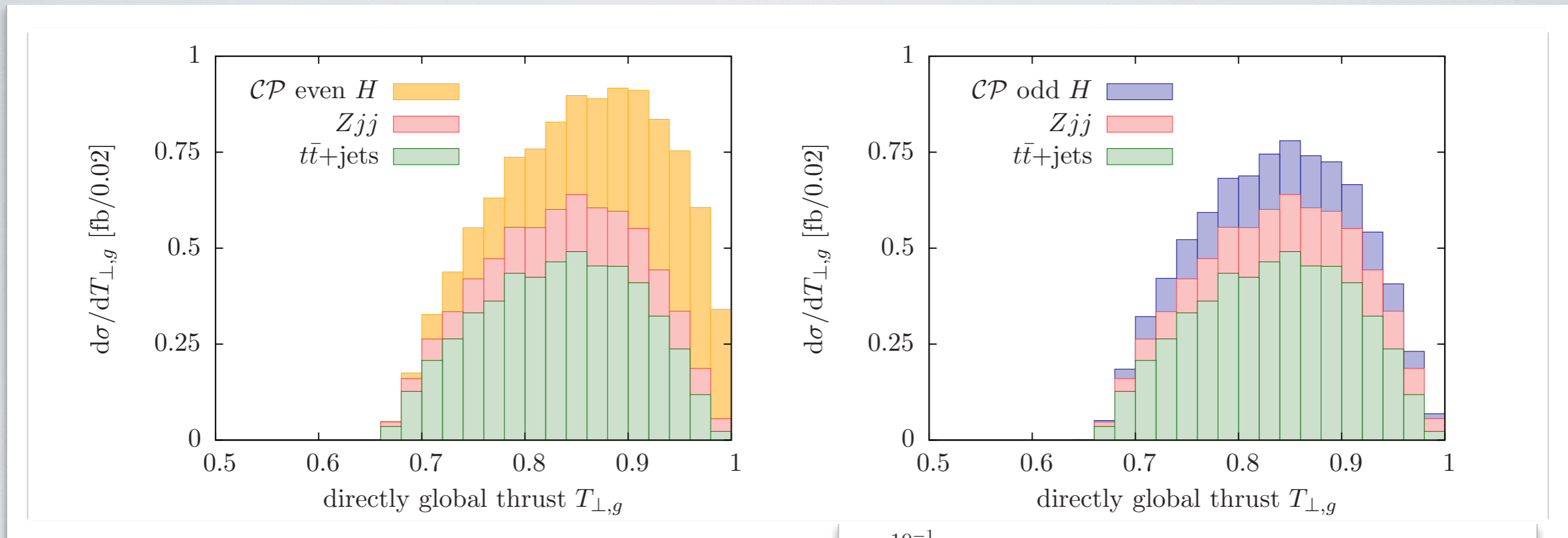
  $\Delta\Phi_{jj}$ in H+2j events

  [Plehn, Rainwater, Zeppenfeld '01]

My take on this:

- (dominant) QCD radiation pattern knows about CP

- color coherence

- QCD → energy momentum

- global energy flow w/o Higgs is a probe of CP

Higgs spectroscopy

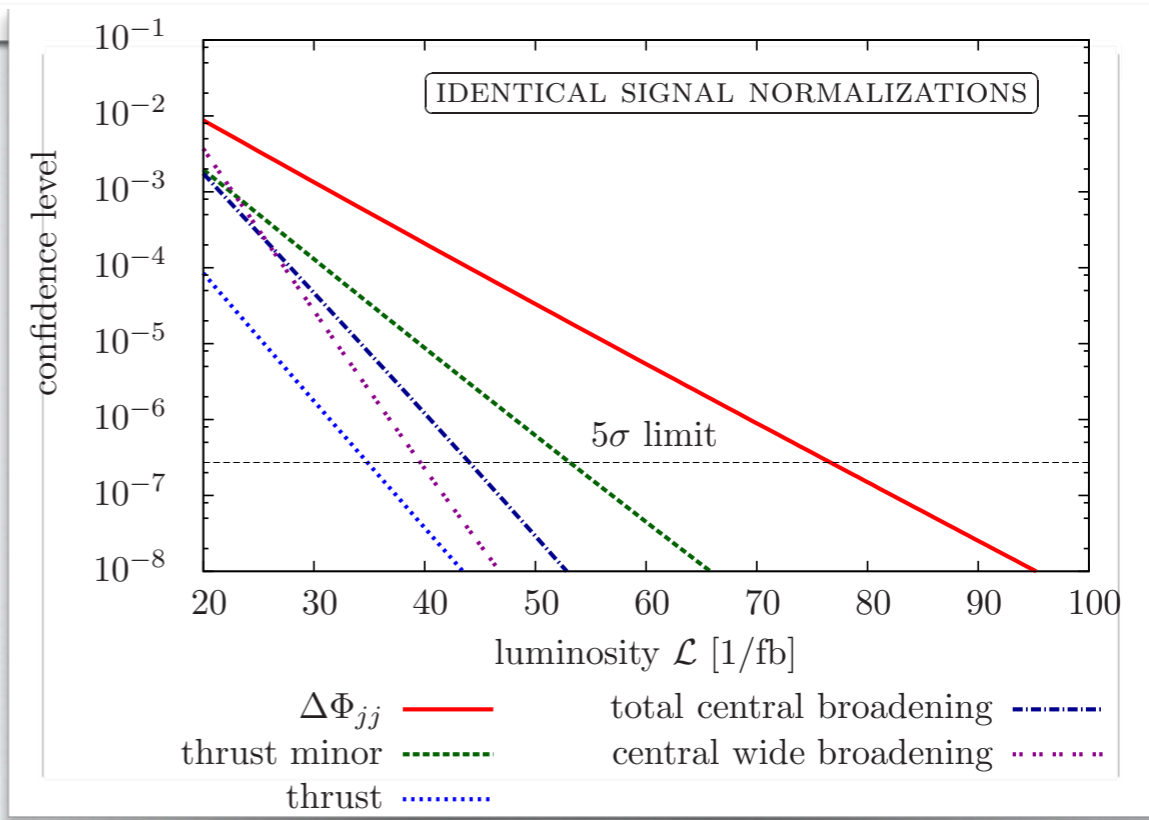- Event shape observables do much better than $\Delta\Phi_{jj}$ on an inclusive level

[CE, Spannowsky, Takeuchi '12]

$$T_{\perp,g} = \max_{\mathbf{n}_T} \frac{\sum_i |\mathbf{p}_{\perp,i} \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|} \,.$$

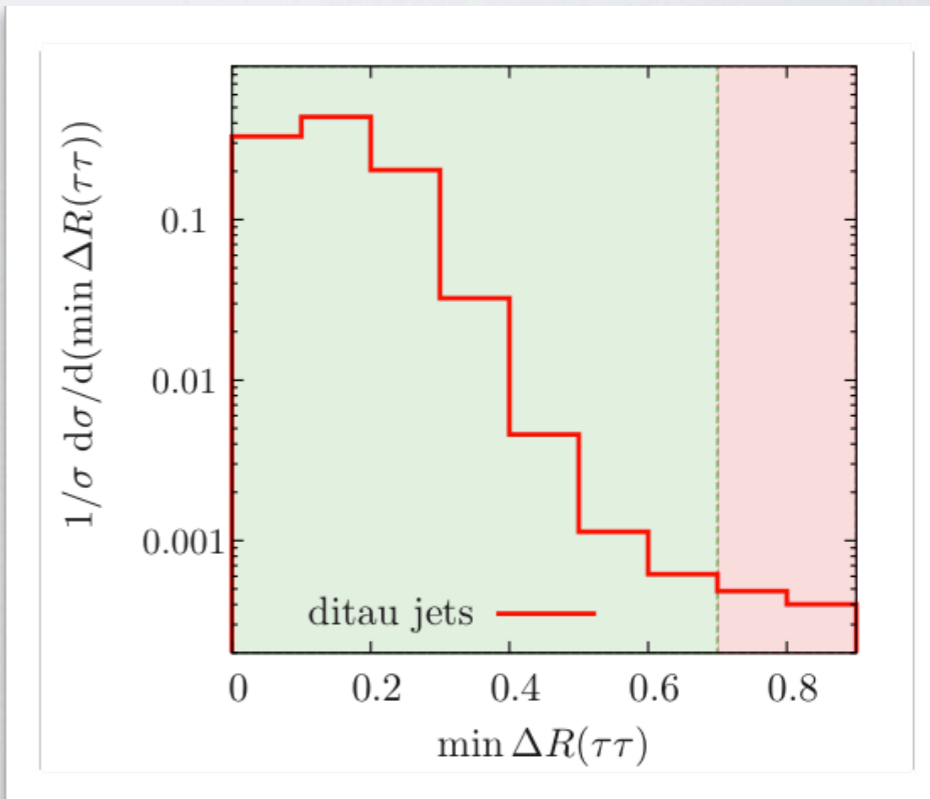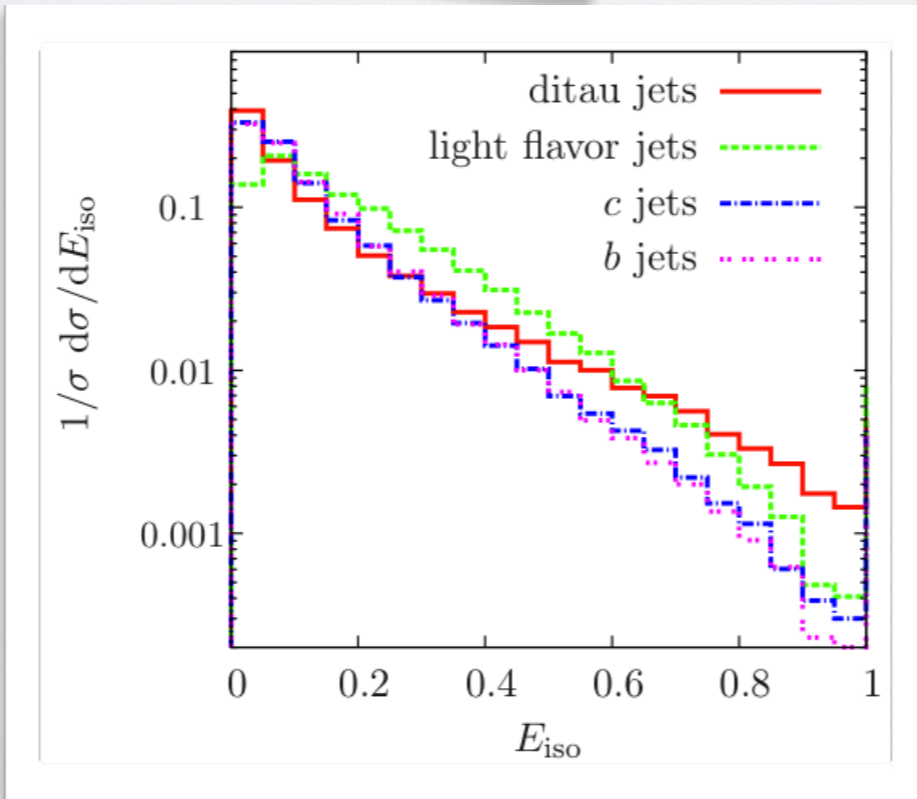- event shape observables can also help serve to separate WBF from GF

  measure Higgs couplings

summary

- 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

  - invisible decays

  - non-standard decays

- 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]

non-standard signatures

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

$m_\phi \leq 10.4$ GeV
$m_\phi \simeq 10.6$ GeV
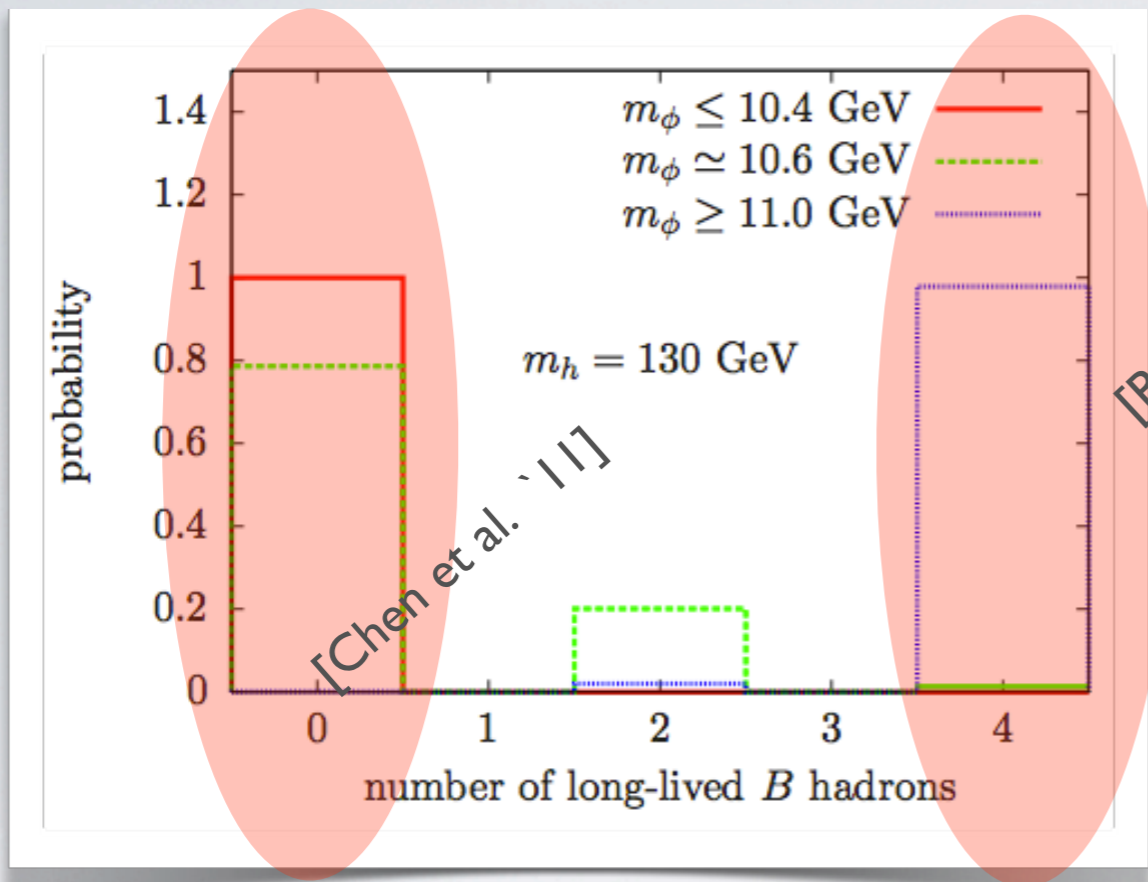$m_\phi \geq 11.0$ GeV

$m_h = 130$ GeV

[Chen et al. `11]

probability

number of long-lived B hadrons

[Butterworth et al. `11]

$$H \longrightarrow \phi \longrightarrow \begin{matrix} \tau^+ & b & g & \dots \\ \tau^- & \bar{b} & g & \dots \end{matrix}$$
$$\phi \longrightarrow \begin{matrix} \tau^+ & b & g & \dots \\ \tau^- & \bar{b} & g & \dots \end{matrix}$$

ditau jets
light flavor jets
c jets
b jets

$1/\sigma \, d\sigma/dE_{\text{iso}}$

E_{iso}

$1/\sigma \, d\sigma/d(\min \Delta R(\tau\tau))$

ditau jets

$\min \Delta R(\tau\tau)$

non-standard signatures

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

[Chen et al. `11]

[Butterworth et al. `11]

$H \cdots \phi \cdots \tau^+ \; b \; g \; \ldots$
$\tau^- \; \bar{b} \; g \; \ldots$

$\phi \cdots \tau^+ \; b \; g \; \ldots$
$\tau^- \; \bar{b} \; g \; \ldots$
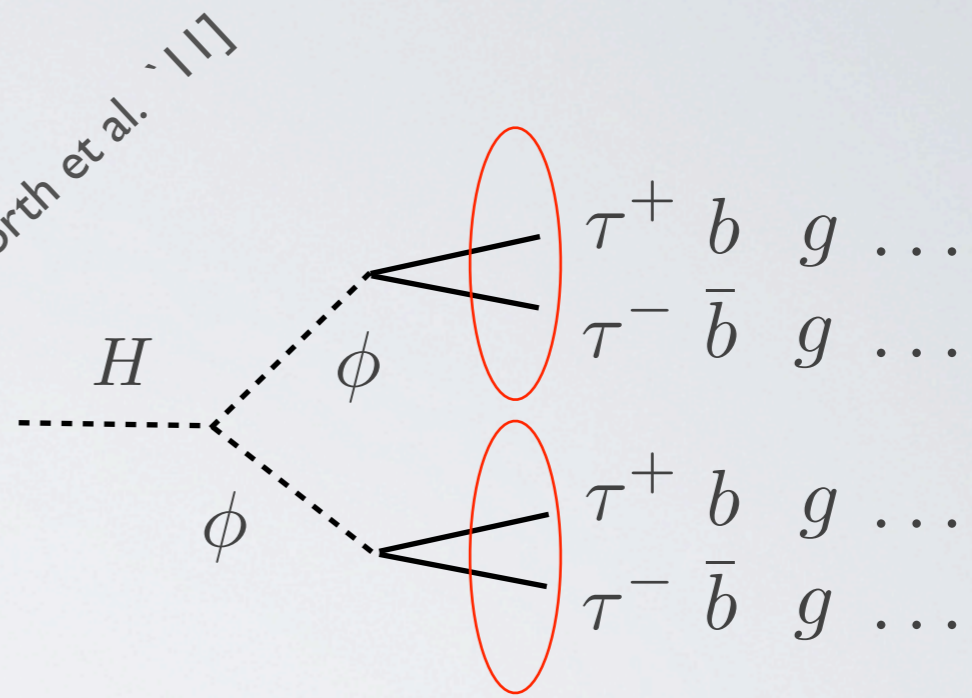
jet mass and momentum
and jet enery clustering
via N-subjettiness

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

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