

Christoph Englert

Vector Boson Fusion — *a theoretical overview* —

- Higgs Physics and VBF
- Theoretical Status
- Higgs Spin/CP
- Higgs couplings and new Physics
- Conclusions



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06.06.2014

“Yang-Mills+Higgs had to be true”

't Hooft, “Under the Spell of the Gauge Principle”

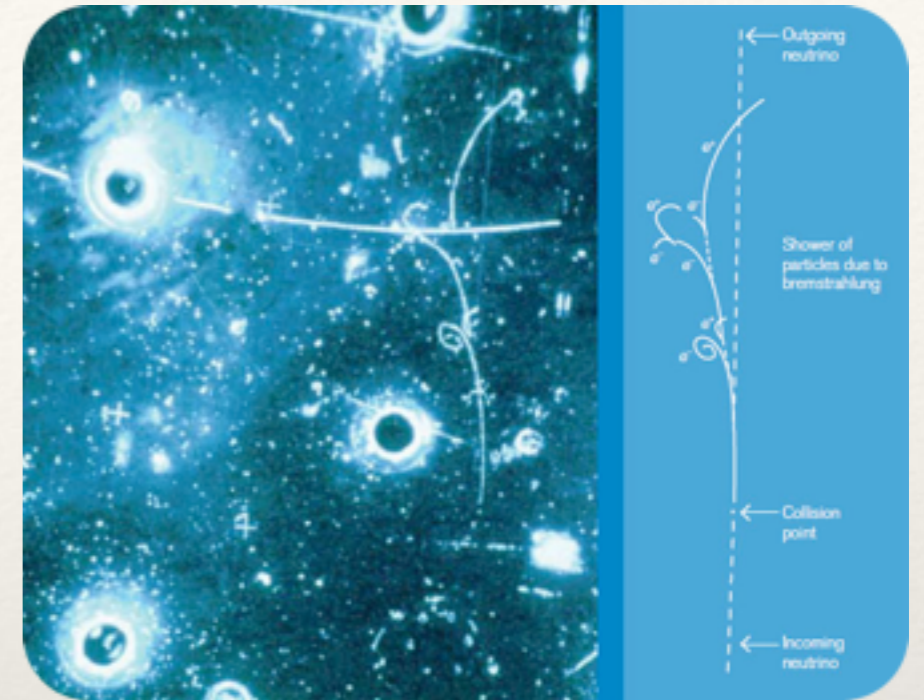
Ws and Zs in 1983 at UA1/UA2

$$m_W \simeq 80.42 \text{ GeV}$$

$$m_Z \simeq 91.19 \text{ GeV}$$

How do you accommodate this in QFT?

[Weinberg '67]



➡ answer to this in 1964

[Higgs '64] [Brout, Englert '64] [Guralnik, Hagen, Kibble '64]

- non-linear realisation of gauge symmetry in a Yang Mills+scalar sector is compatible with $\langle H \rangle \neq 0$
 - ➡ “spontaneous” symmetry breaking
- massive gauge bosons, but no ghost problems at small distances
 - ➡ renormalizability, tightly linked to unitarity

Two Higgs pheno ingredients

1. massive vectors have three degrees of

$$\varepsilon_{\mu}^{(T,1)} = (0, 1, 0, 0)^T$$

$$\varepsilon_{\mu}^{(T,2)} = (0, 0, 1, 0)^T$$

$$\varepsilon_{\mu}^{(L)} = (k/m, 0, 0, E/m)^T$$

$$\sim k_{\mu}/m \quad (|k| \gg m)$$

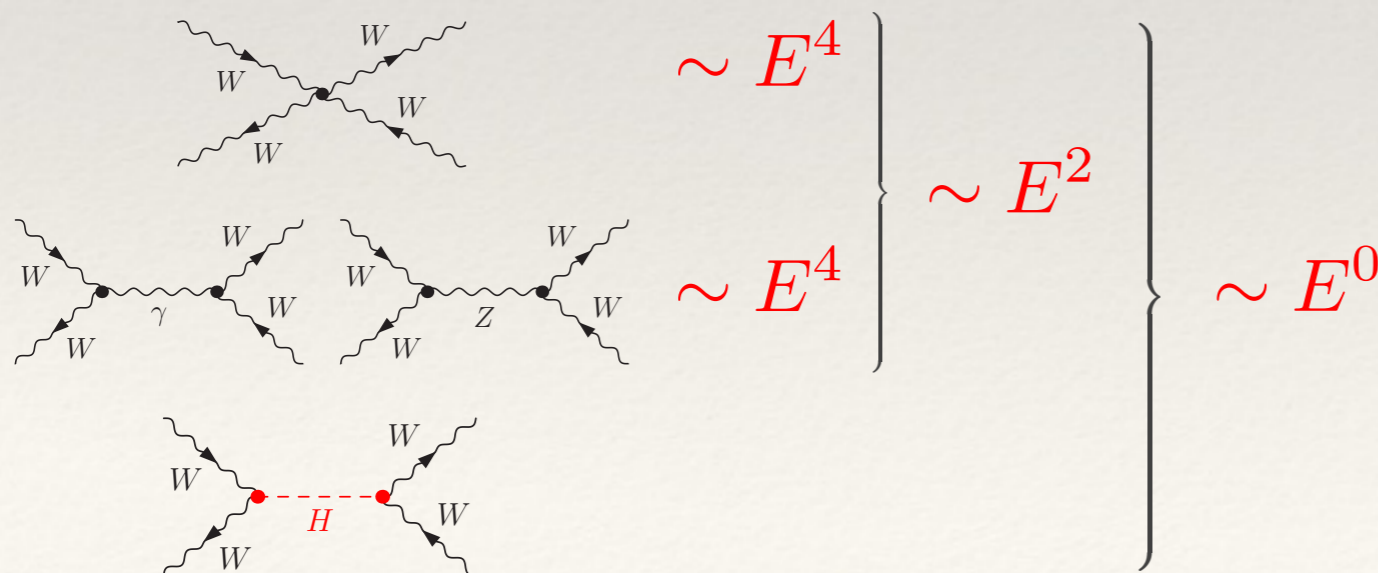
2. probability conservation in scattering processes needs to be conserved

$$a_{\ell} = \frac{1}{32\pi} \int_{-1}^1 d \cos \theta \mathcal{M}(\cos \theta) P_{\ell}(\cos \theta)$$

$$S^{\dagger} S = \mathbb{1} \implies 2\Re\{a_{\ell}\} \leq 0.5$$

➡ UV relations for $E \gg m$ as a consequence of spontaneous symmetry breaking determine the (B)SM Higgs phenomenology!

[Cornwall, Levin, Tiktopoulos '75]

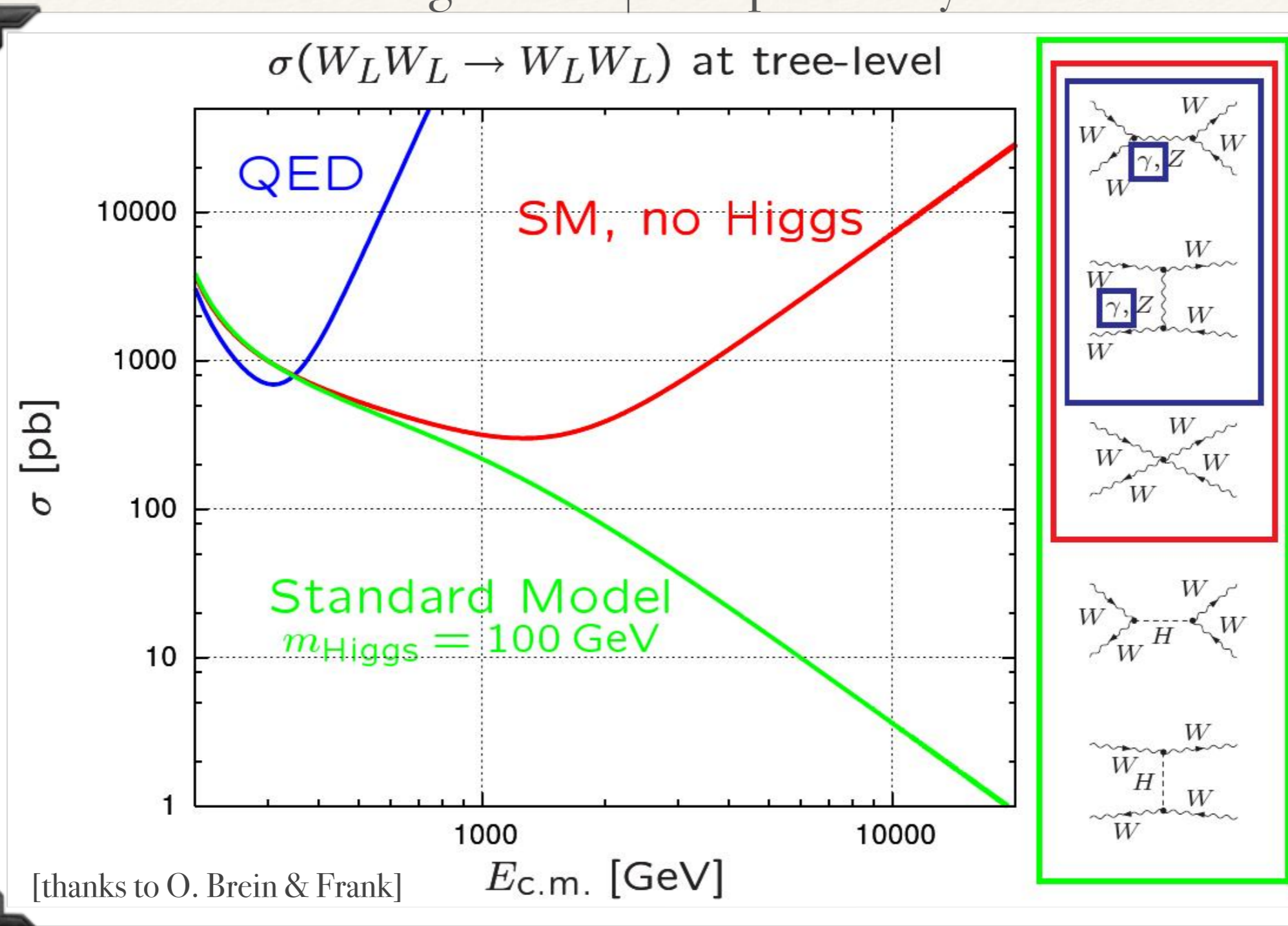


only if* $g_{HVV} = g_{HVV}^{\text{SM}} = g_V m_V$

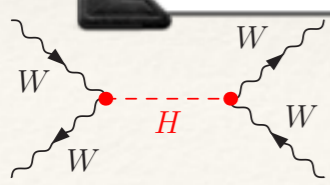
* or replaced by equivalent BSM sum rule

Two Higgs pheno ingredients

1. massive vectors have three degrees of freedom
2. probability conservation in scattering



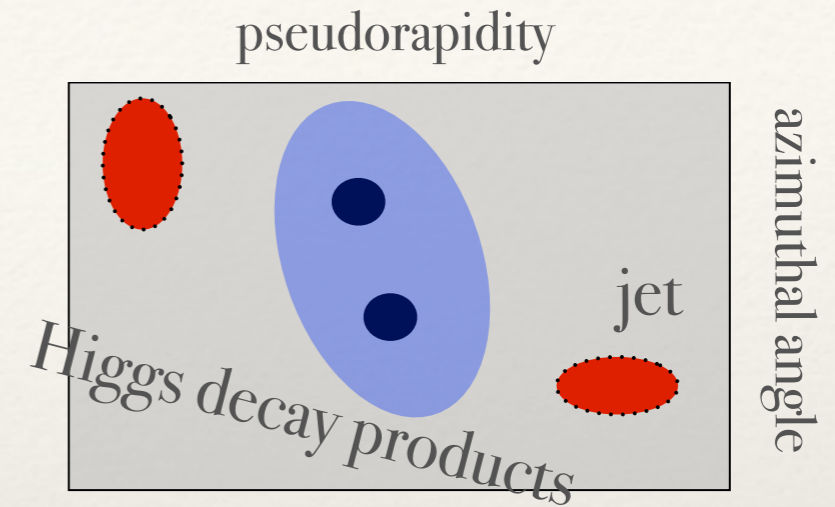
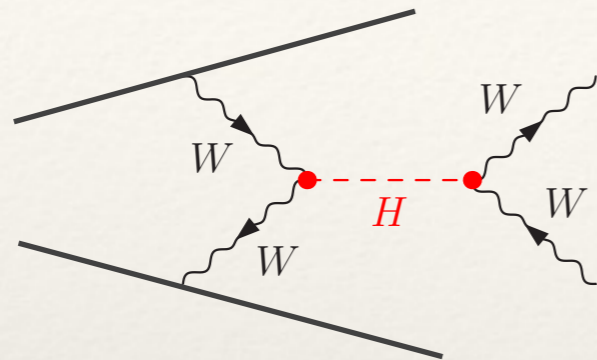
UV re
determin



* or replaced by equivalent BSM sum rule

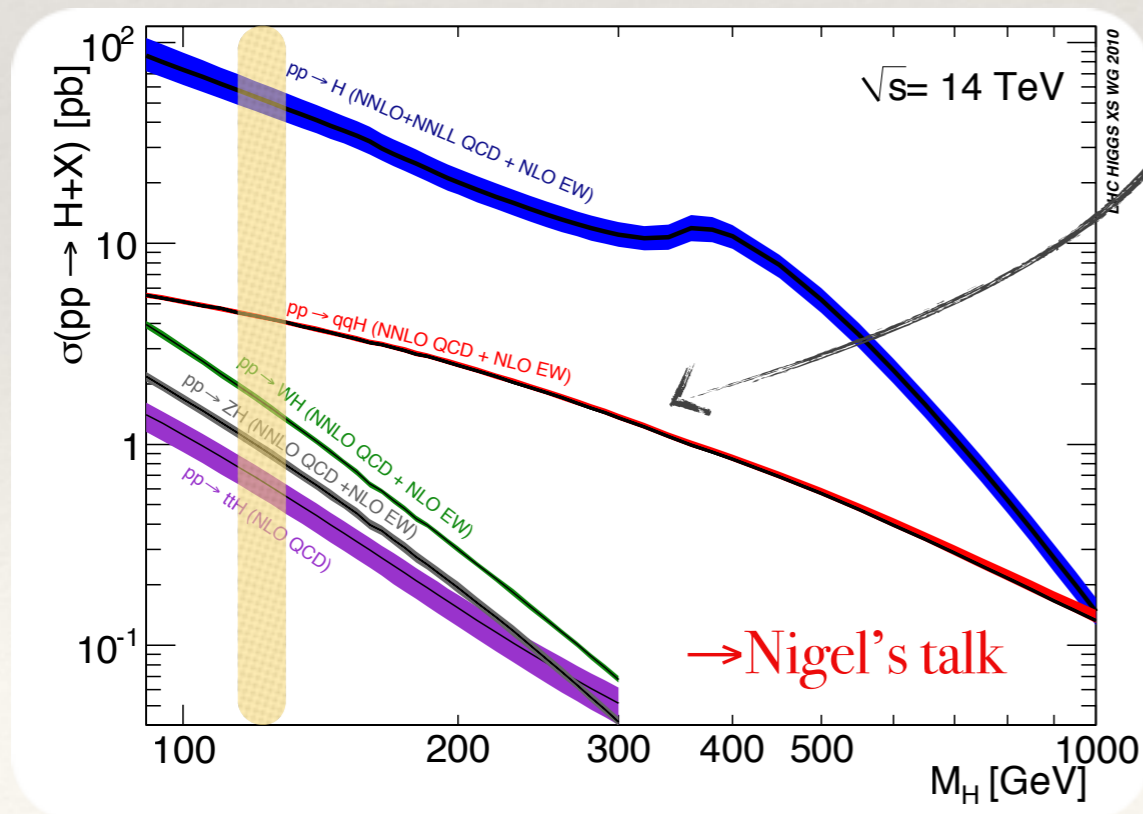
VBF – the swiss army knife of EWSB

➔ VBF is **the** window to study implications of the mechanism of EWSB



→ Michel's talk

• large cross section, small uncertainty

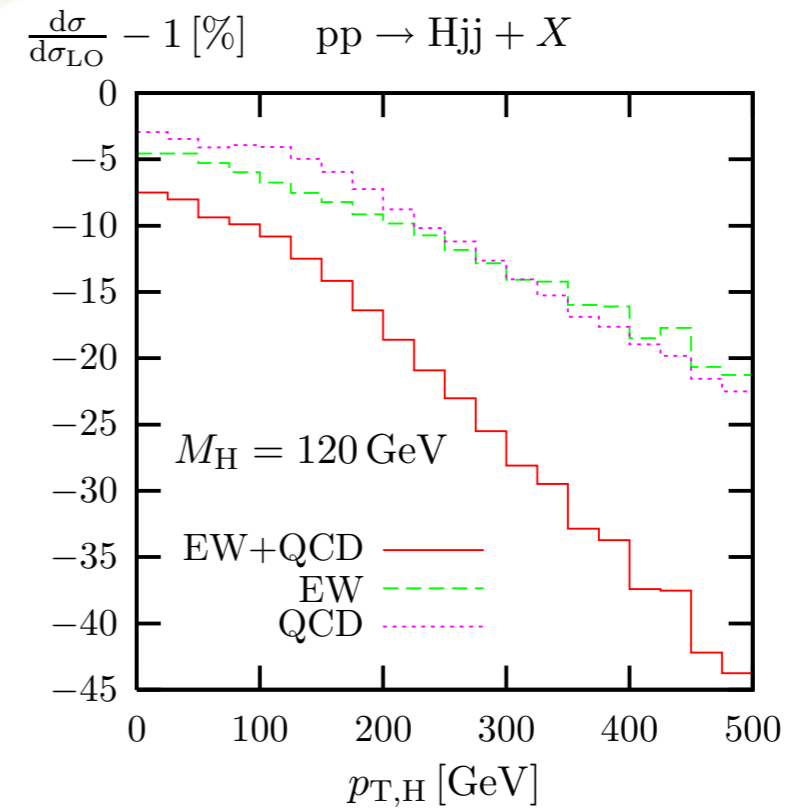
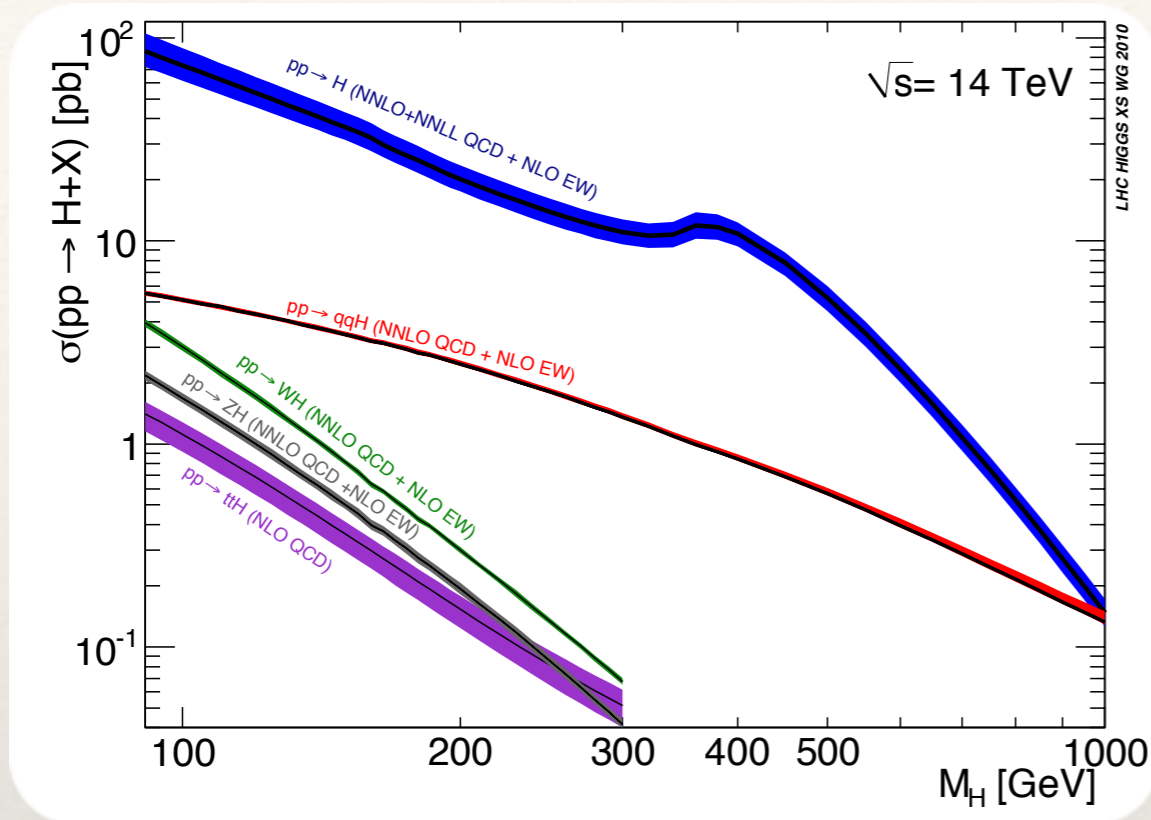


• clean signature:

- heavy particle production: incoming quarks at large x : energetic forward jets, large invariant mass, $p_{T,j} \sim m_W$
- colour singlet t-channel: little QCD in the central part of the detector, CJVs

[Rainwater, Zeppenfeld '99]
 [Plehn, Rainwater, Zeppenfeld '99]
 [Kauer, Rainwater, Zeppenfeld '00]

The SM VBF cross sections



[Ciccolini, Denner, Dittmaier `07]

- approximate NNLO QCD in the structure function approach, available in VBF@NNLO

[Bolzoni, Maltoni, Moch, Zaro `10] [Bolzoni, Maltoni, Moch, Zaro `11]

- full QCD+EW corrections available in Hawk/Vbfnlo, EW corrections **equally important!**

[Ciccolini, Denner, Dittmaier `07] [Denner, Dittmaier, Mück `10]

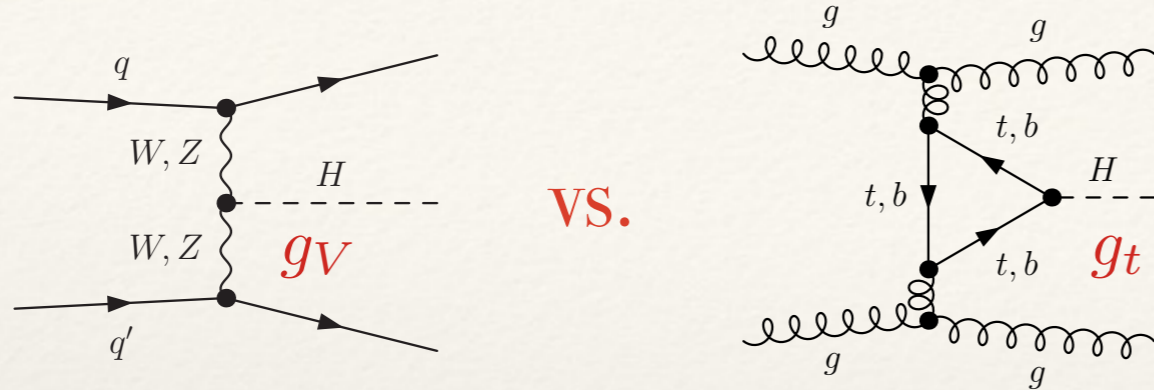
[Jäger, Oleari, Zeppenfeld `06] [Palmer, Figy, Weiglein `12] [Arnold *et al.* `13]

- NLO-matched hadron-level implementations available via MC@NLO and Powheg

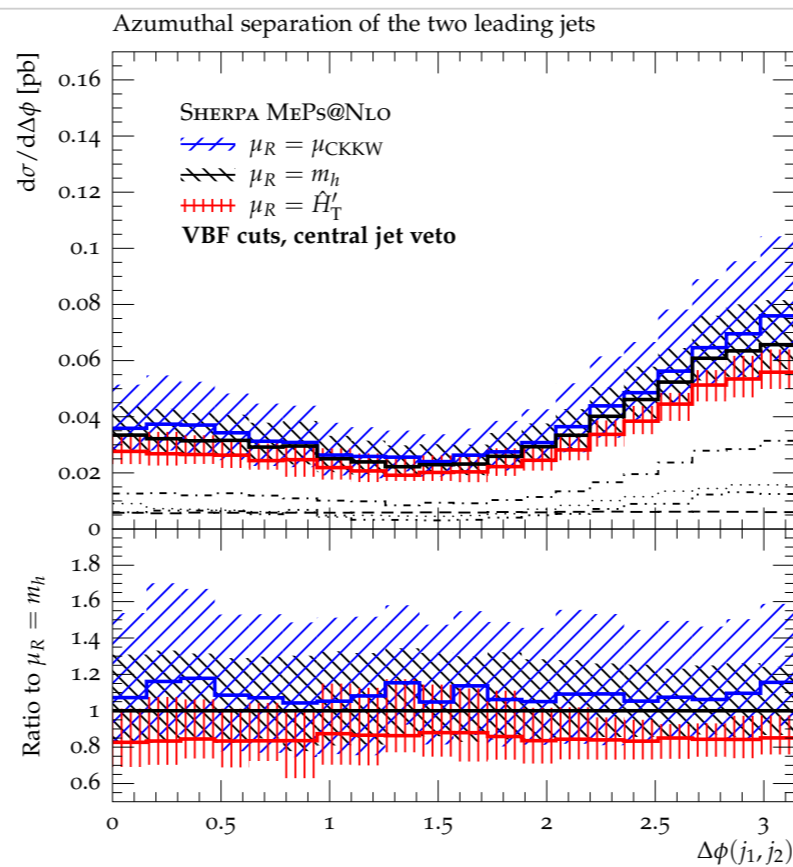
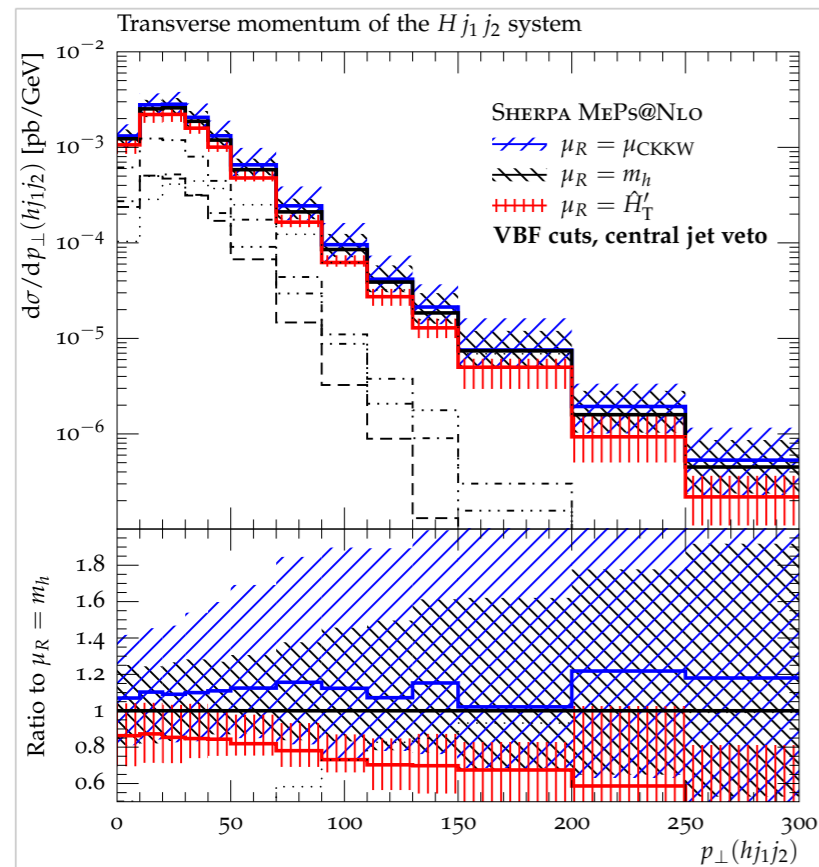
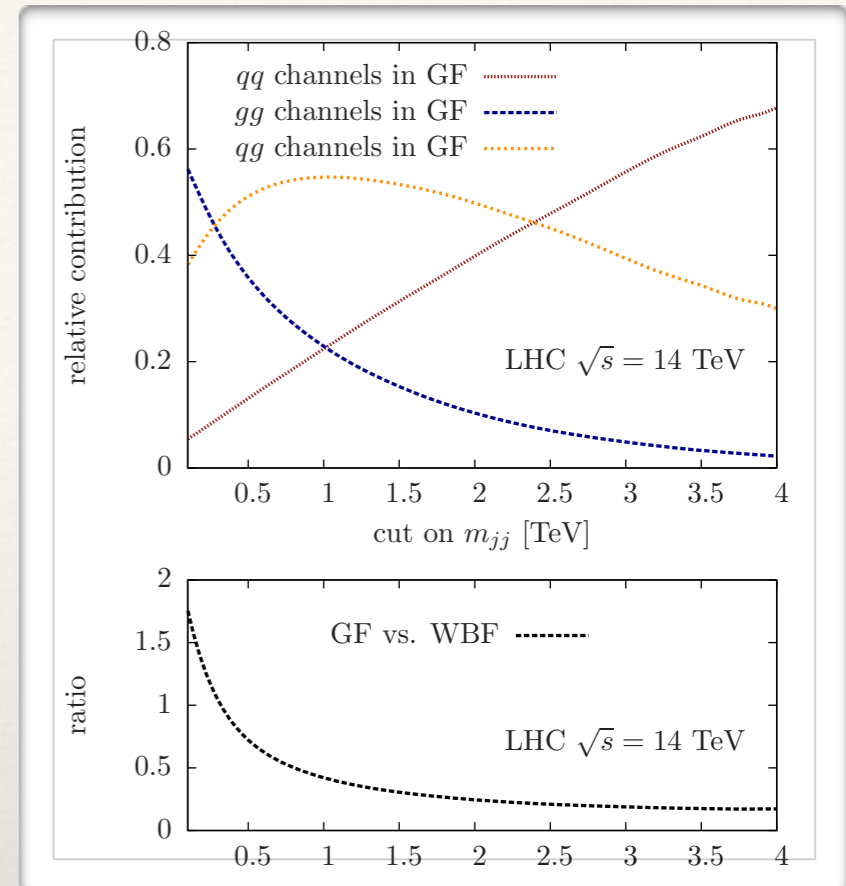
[Nason, Oleari `06] [D'Errico, Richardson `11] [Jäger, Zanderighi `13] [Frixione, Torrielli, Zaro `13]

...but beware of irreducible backgrounds

GF+2 jets is a challenge but can be suppressed



[Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '01]
 [Del Duca *et al.* '06]
 [Campbell, Ellis, Zanderighi '06]



→ Frank's talk

- resummation in MRK-FKL limit studied in detail

[Andersen, White '09]

[Andersen, Del Duca, White '09]

- differential veto systematics available at MePS@NLO level

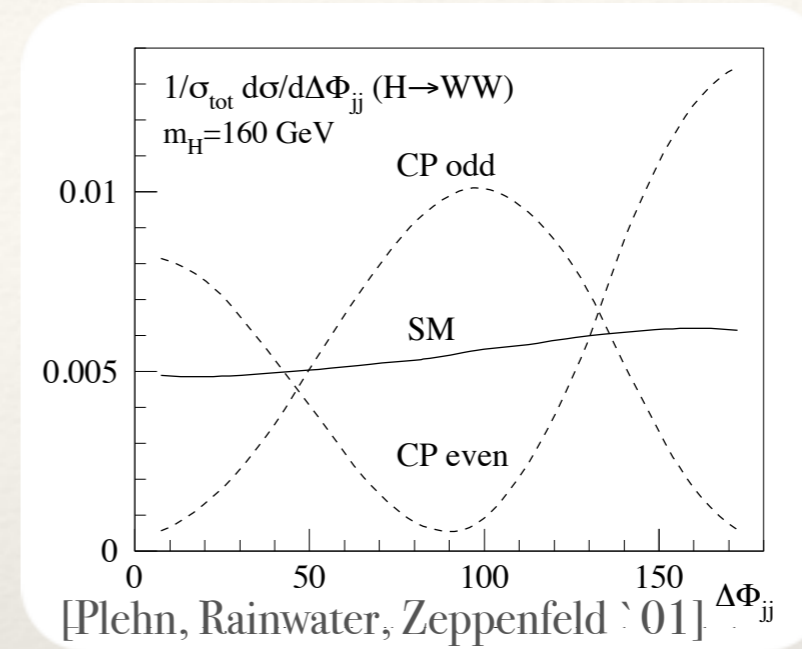
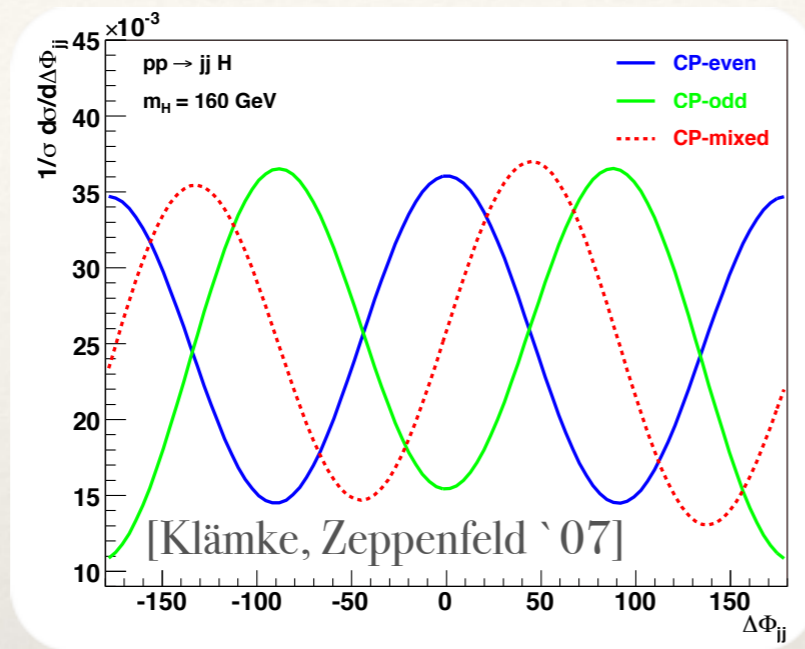
[Höche, Krauss, Schönherr '14]

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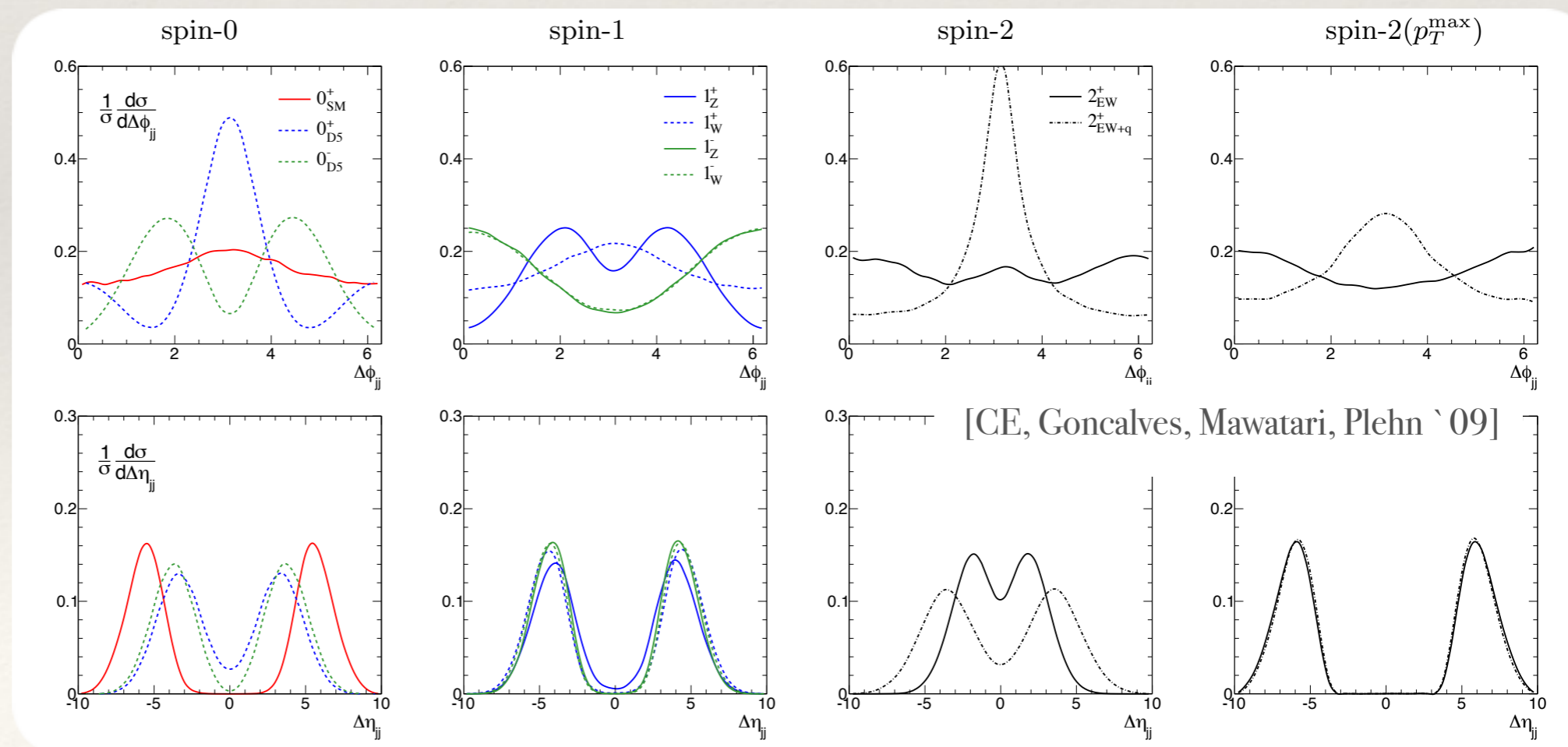
VBF – A tool for Higgs characterisation

- jet kinematics are a sensitive probe for Higgs CP

[Hagiwara, Li, Mawatari '09]



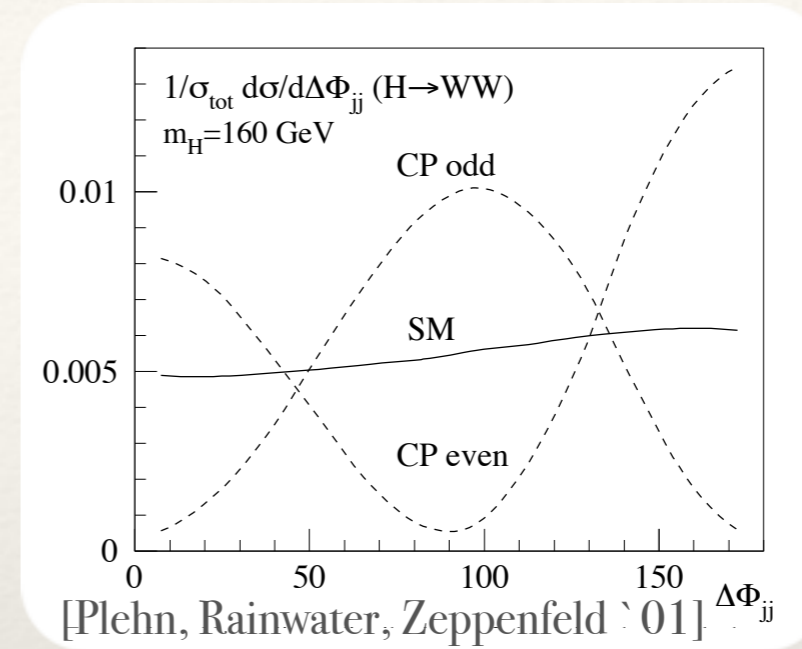
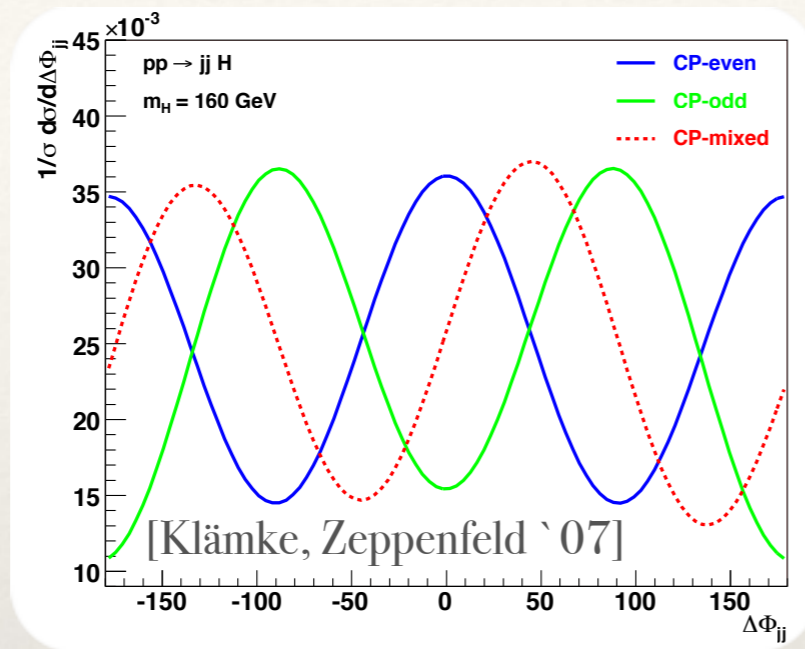
- but also spin!



VBF – A tool for Higgs characterisation

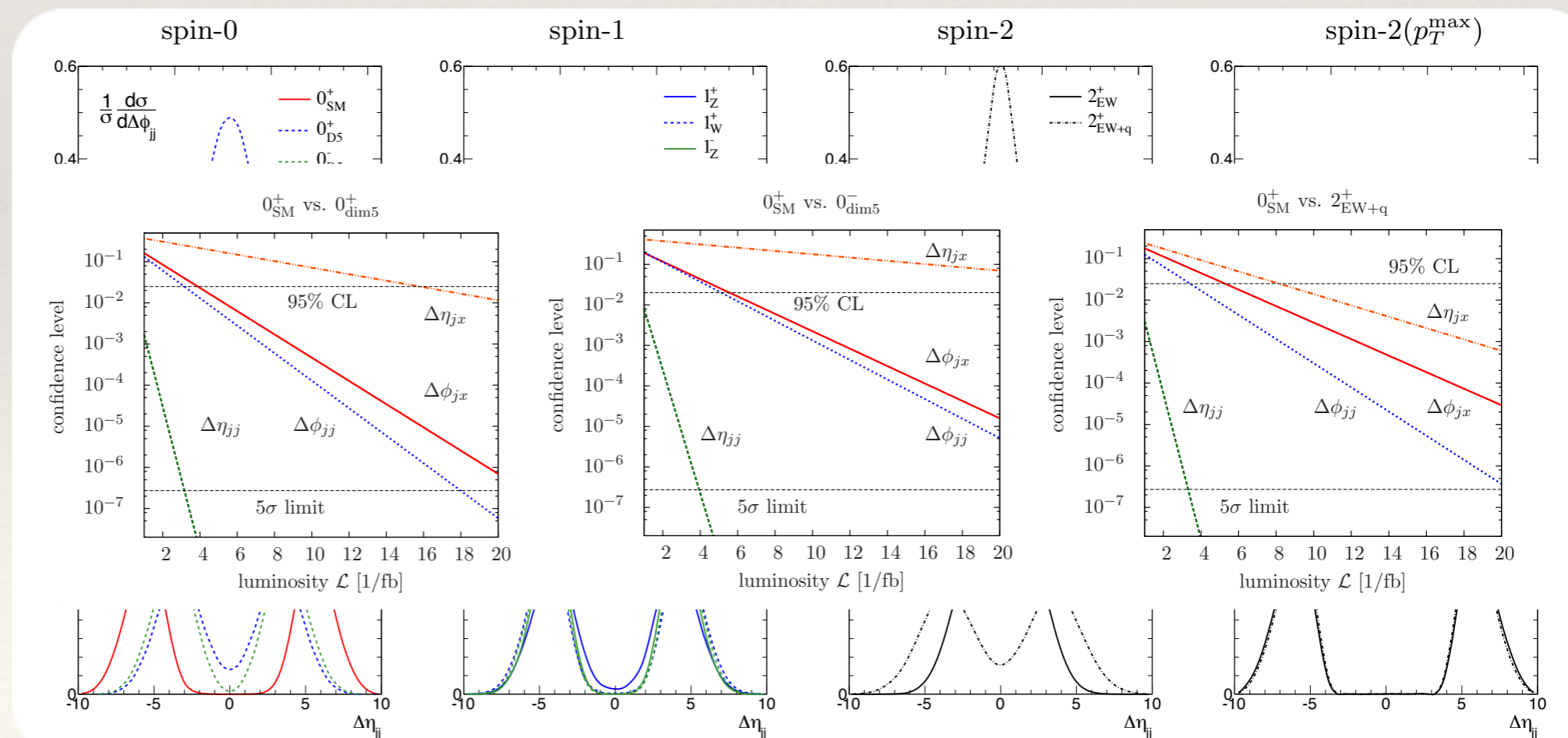
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- but also spin

→ Kentarou's & Markus' talks



VBF – A tool for Higgs characterisation

- how to treat additional emission ? combinatorics becomes an issue

[Arnold, Andersen, Zeppenfeld ` 10]

veto

traditional parton-level

normalisation of composite hypothesis?

include

- jet kinematics reflects the amplitude's CP/spin properties, colour flow and momentum dependence of involved couplings
- additional jet emission could be enhanced depending on the scenario*
- QCD emission \rightarrow colour & momentum flow \rightarrow Event Shapes (non-global)

[CE, Takeuchi, Spannowsky ` 12]

[CE, Goncalves, Nail, Spannowsky ` 13]

* very few alternative hypotheses are theoretically well-behaved and consistent.

VBF – A tool for Higgs characterisation

- how to treat additional emission ? combinatorics...

[Arnold, Andersen, Zeppenfeld `10]

veto

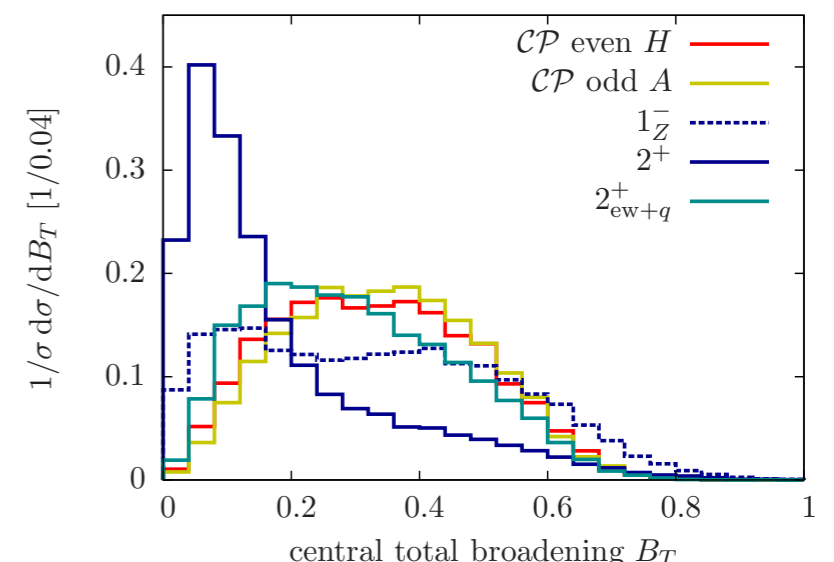
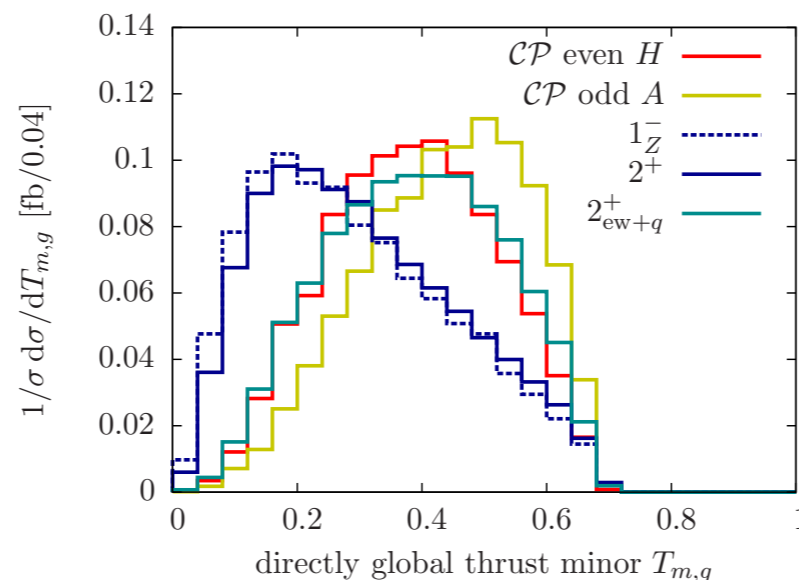
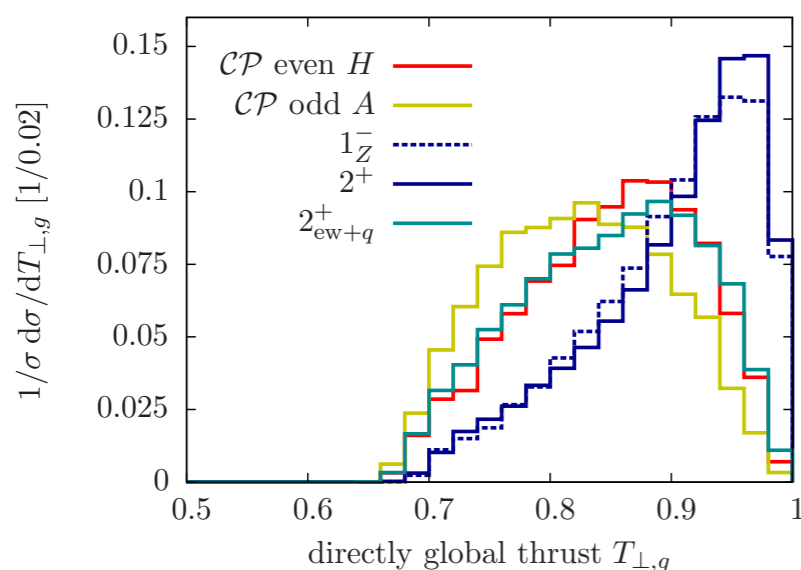
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[CE, Takeuchi, Spannowsky `12]



VBF – A tool for Higgs characterisation

➔ VBF allows a (rather) model-independent constraint on Γ_H

1. on-shell measurement

dominated by Higgs signal

$$\sigma_{WBF} \times \text{BR}(H \rightarrow ZZ \rightarrow 4\ell) \sim \frac{\sum_V g_{HVV}^2 g_{HZZ}^2}{\Gamma_H}$$

custodial SU(2)

2. off-shell measurement

threshold effects and unitarity driven interference, but de-coupling of width parameter $\sim i/(s - m_h^2 + i\Gamma_h m_h)$

$$d\bar{\sigma}_h \sim \frac{\sum_V g_{HVV}^2(\sqrt{s}) g_{HZZ}^2(\sqrt{s})}{s} d\text{LIPS} \times \text{pdfs.}$$

correlate measurements

if off-shell and on-shell Higgs couplings are correlated:

$$\Gamma_h > \Gamma_h^{\text{SM}}, \quad \iff \quad \sum_V g_{HVV} g_{HZZ} > \sum_V [g_{HVV} g_{HZZ}]^{\text{SM}} \quad \iff \quad \bar{\sigma} > \bar{\sigma}^{\text{SM}}$$

$$\sigma \times \text{BR} \simeq [\sigma \times \text{BR}]^{\text{SM}}$$

VBF – A tool for Higgs characterisation

➔ VBF allo

1. on-she

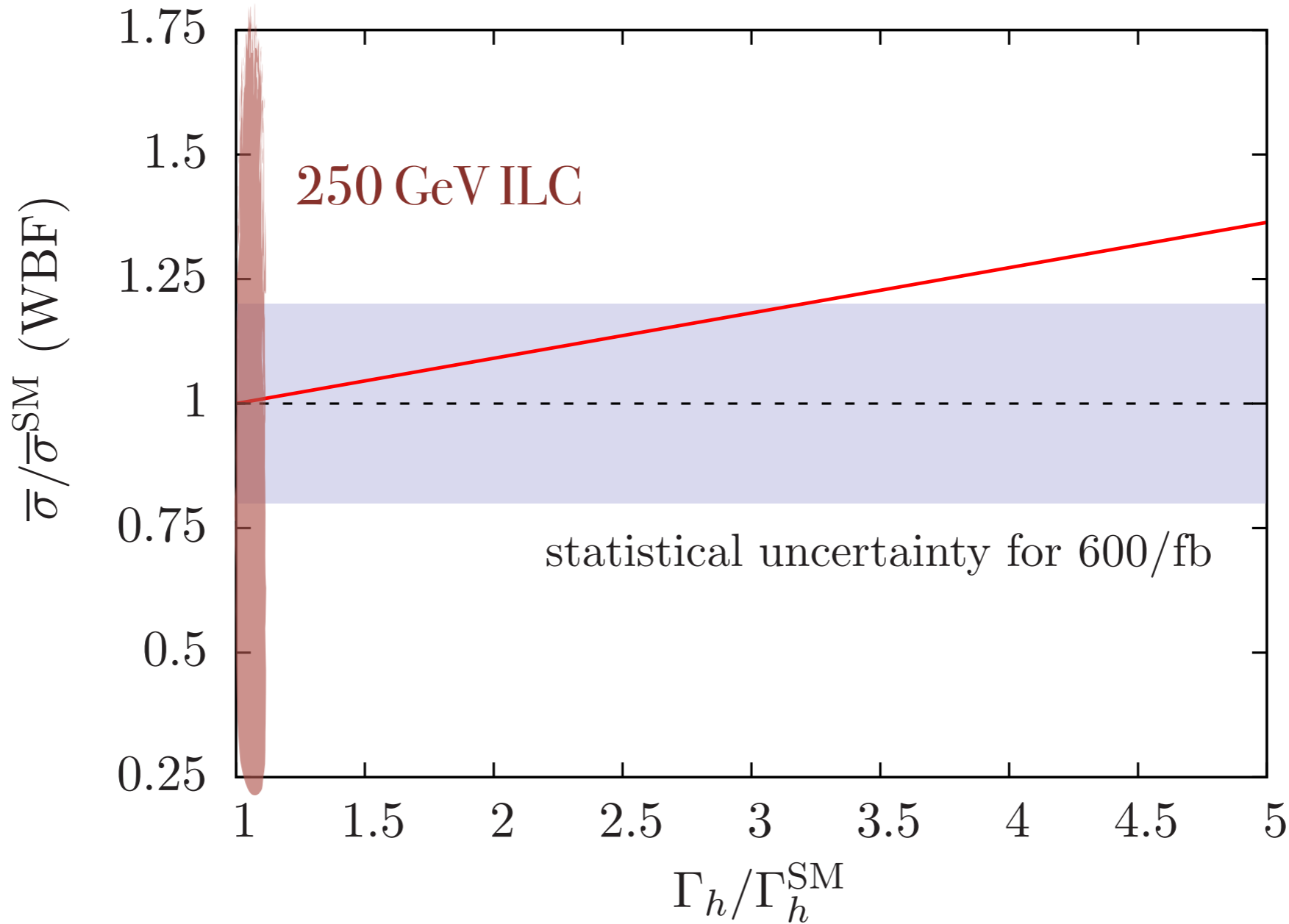
dominated b

$\sigma_{WBF} \times BR(H \rightarrow b\bar{b})$

fo

$\Gamma_h >$

$\sigma \times BR$



t
driven
of width
 m_h)

IPS \times pdfs.

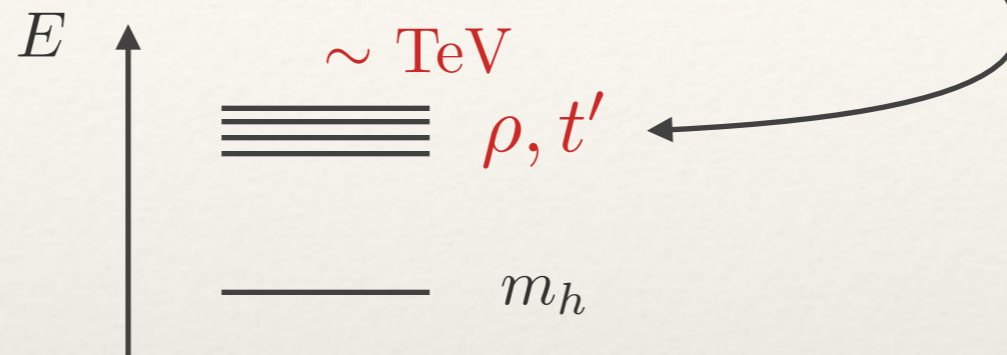
$\bar{\sigma}^{\text{SM}}$

[Kauer, Passarino `12][Caola, Melnikov `13] [Campbell, Ellis, Williams `13]

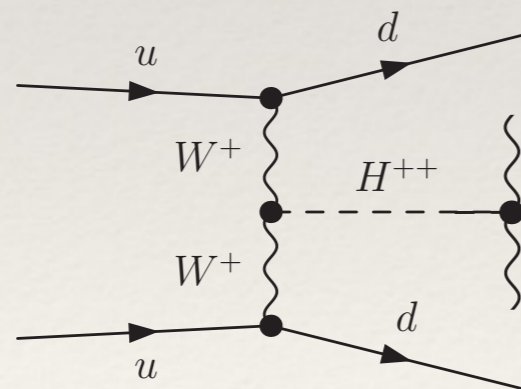
[CE, Spannowsky `14] [Ghezzi, Passarino, Uccirati `14]

resonant

- connection of VBF to EWSB: phenomenology of vector-like mesons in composite Higgs theory, available at NLO QCD [CE, Jäger, Zeppenfeld '08]



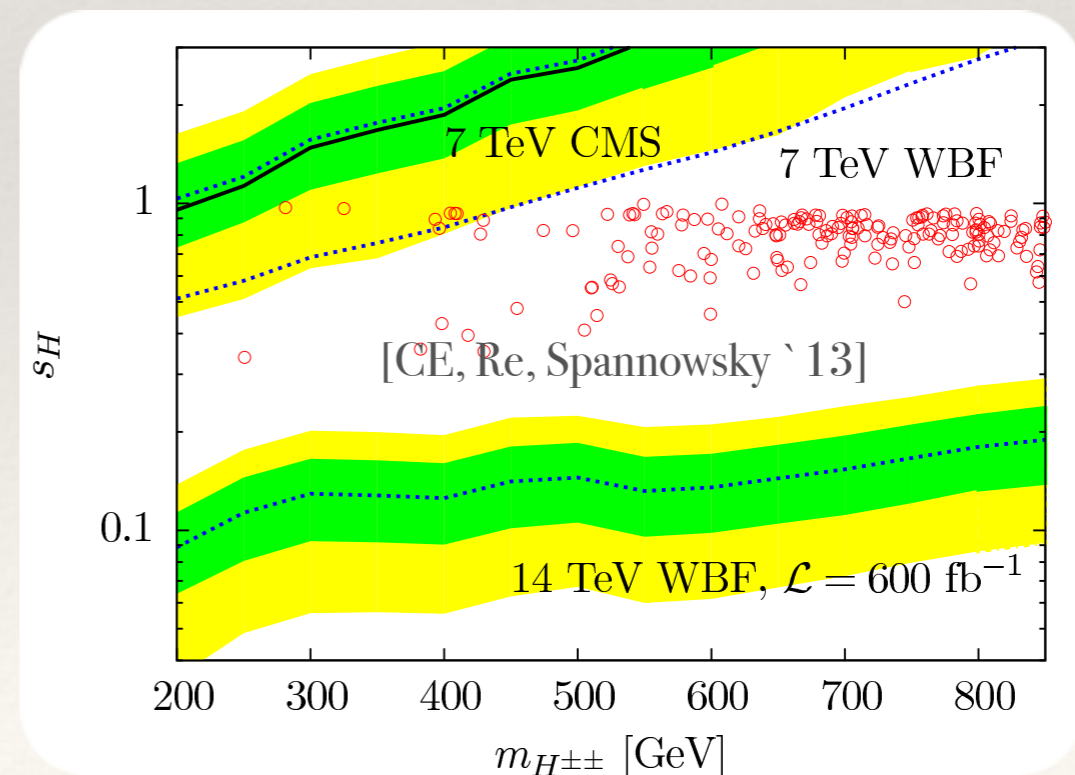
- Higgs sector exotics related to non-standard Higgs gauge representations and complementary searches for *destructive* contributions to longitudinal gauge boson scattering



[Logan, Roy '10]

[Godfrey, Moats '10]

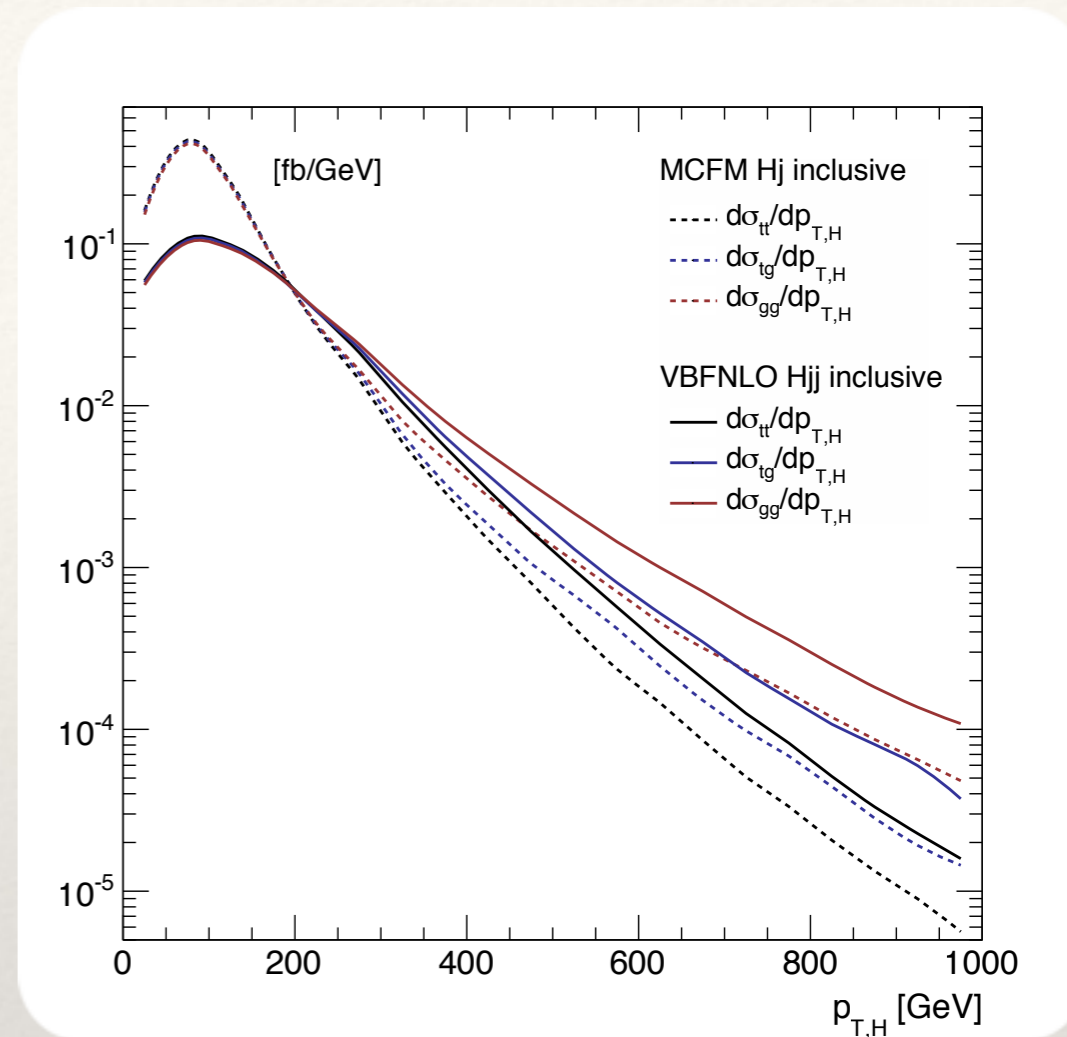
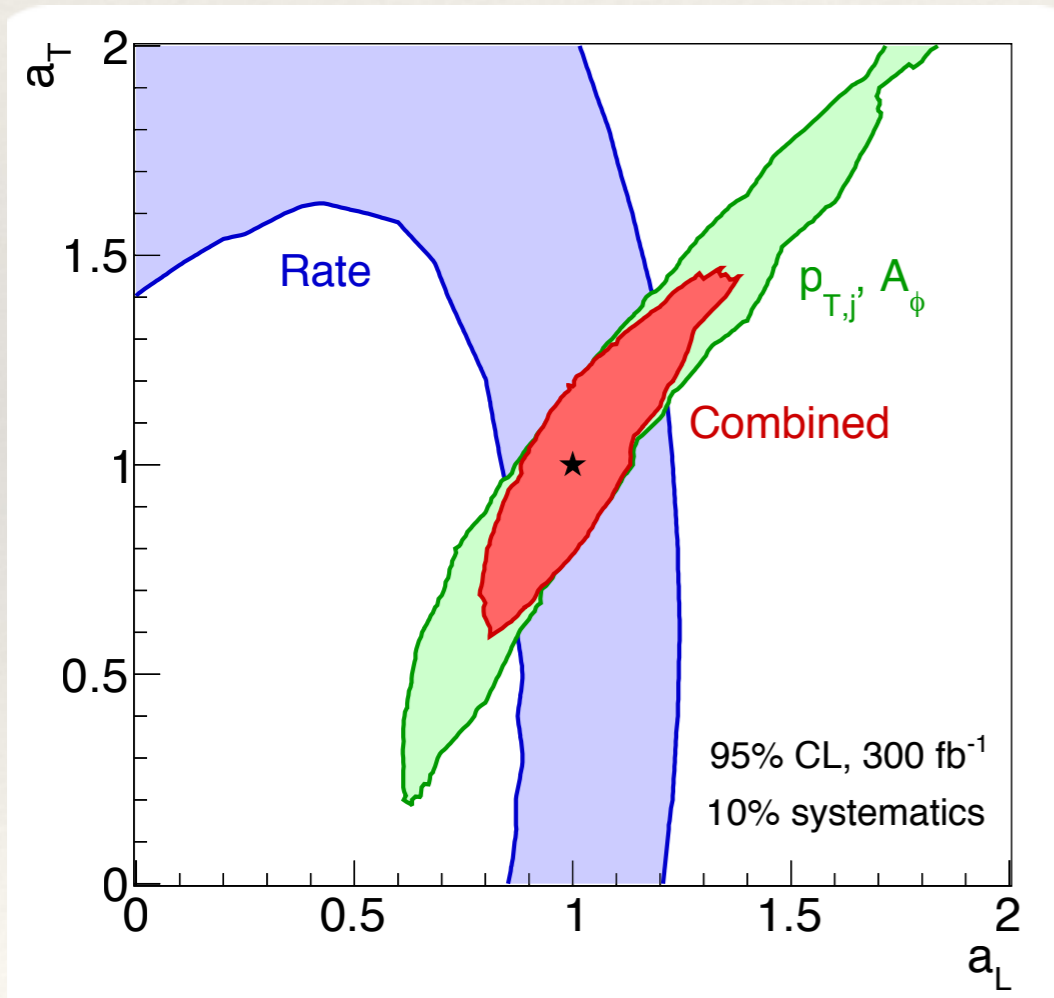
[CE, Re, Spannowsky '13, '13]



non-resonant

- searches for higher-dimensional operators can show improved sensitivity to discriminate ggH and modified top-Yukawa interactions via GF

[Buschmann, CE, Goncalves, Plehn, Spannowsky `14]



- duality-driven exotic searches by disentangling polarizations in WBF

[Brehmer, Jaeckel, Plehn `14]

VBF - an appraisal with a twist

➡ VBF is a major phenomenological opportunity

- completely non-QCD like, phenomenologically clean
- direct probe of (non-)resonant electroweak physics
- new resonant physics **will necessarily** show up if kinematically covered by the LHC and couplings are sufficiently large

➡ pheno opportunities link directly to major precision challenges

- issues with ipso facto WBF tail analyses:
“is new physics small?” *or is* “nature just unitary?”
- VBF tests the foundations of EWSB → EW corrections are sizable and **necessarily model-dependent**: How much can we eventually trust EFT bounds?