Higgs Spin/CP properties

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Higgs Quo Vadis

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Disclaimer & Credits

What I present here is a perspective on Spin/CP Higgs issues mainly developed through discussions within the LM group of the Higgs XS WG

I am indebted with Sara Bolognesi, Andre David, Abdelhak Djouadi, Michael Duehrssen, Christophe Grojean, Fabio Maltoni, Margarete Muehlleitner, Giampiero Passarino, Georg Weiglein for useful discussions and correspondence.......

......but please blame me if you don't find your favorite paper quoted !

Outline

- Introduction: the golden channel
- Effective lagrangian or anomalous couplings ?
- MELA & JHU
- Madgraph & aMC@NLO
- Production (in)dependence
- The latest results
- Summary & Outlook

Introduction

What do we know about the newly discovered resonance X ?

It manifests itself most clearly in the ZZ and $\gamma\gamma$ high resolution channels (but now also in WW, bb and $\tau\tau$)

Its width is consistent with being smaller than the experimental resolution

$H \to \gamma\gamma$ ➡ $J \neq 1$ (Landau-Yang) and C=+

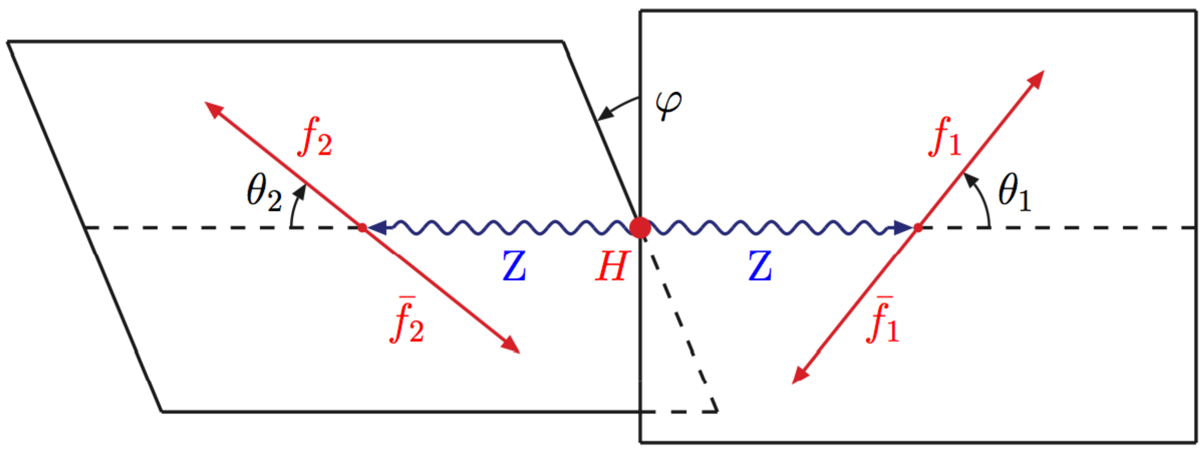
It has significant decay fraction in WW and ZZ

➡ Likely to play a role in EWSB

➡ very likely to have a significant CP even component, since the couplings of a pseudoscalar to VV are loop induced, and thus expected to be small.........

but difficult to rule out the existence of a (small) CP odd component ! (fermionic couplings are more democratic)

The golden channel

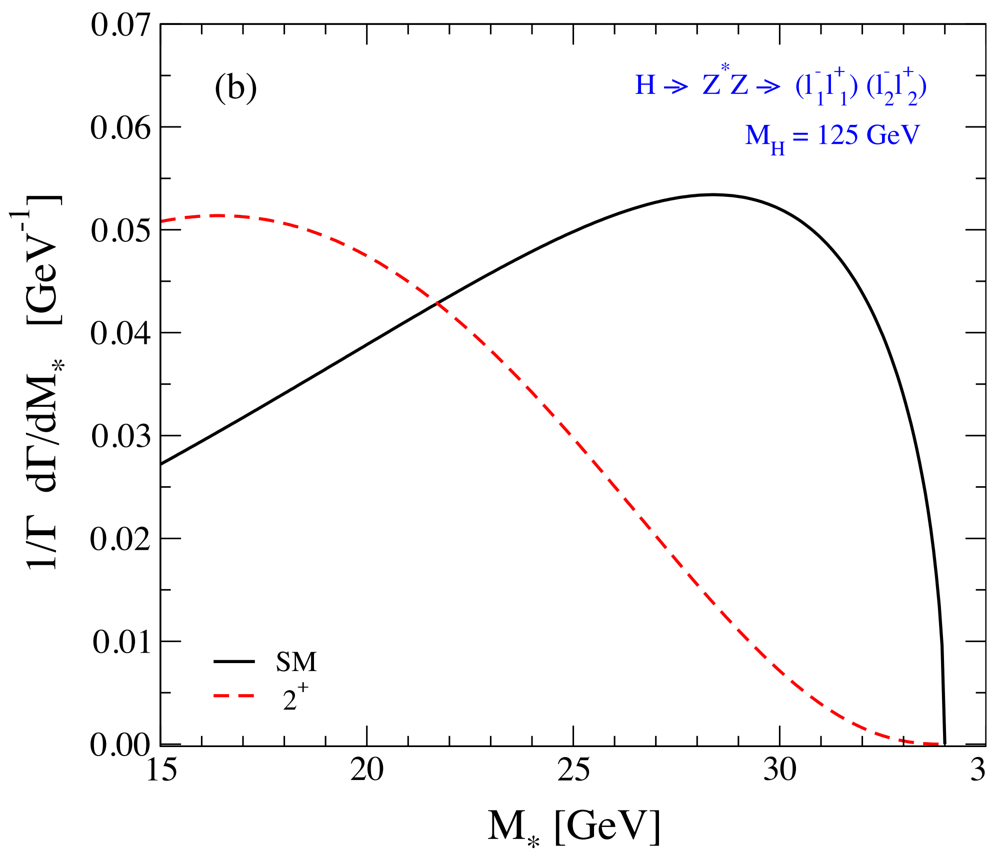


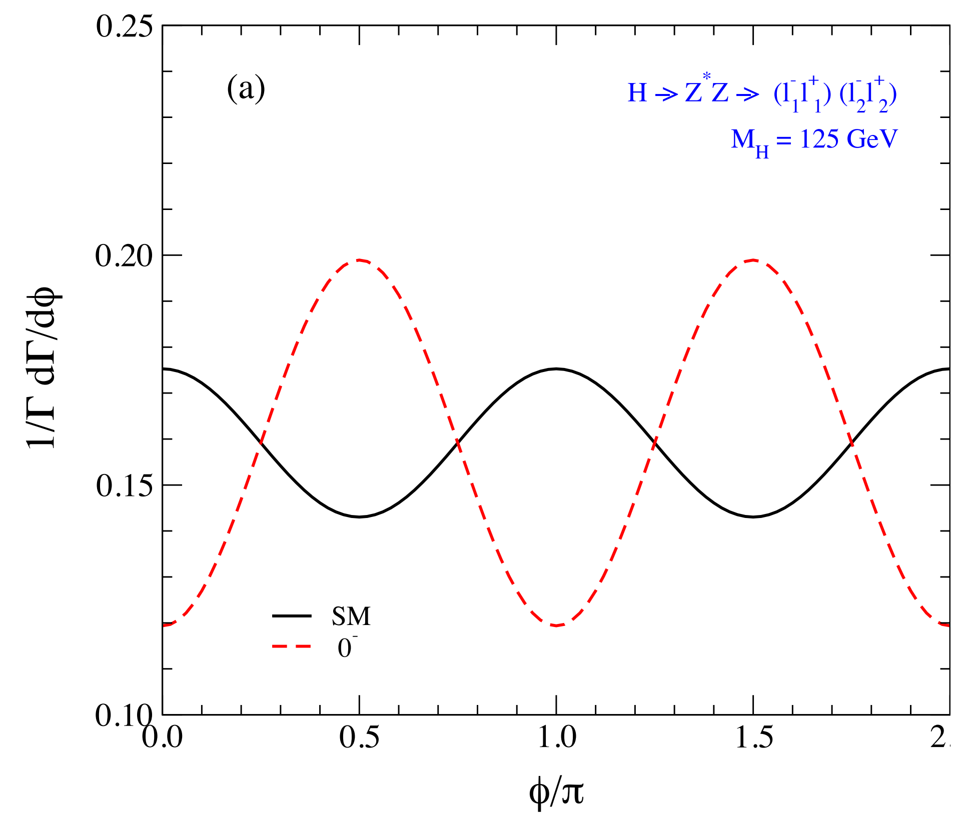
For $m_H \sim 125$ GeV and $H \to ZZ \to 4l$ one of the two Z is virtual

J. Dell'Aquila, C.Nelson (1986)
A.Djouadi et al. (1994)
S.Choi, D.J.Miller, P.Zerwas, M.Muehlleitner (2002)

Classical discriminating variables are M* and ϕ

Threshold behavior $d\Gamma/dM_*^2 \sim \beta^{2J+1}$ $\beta \sim \sqrt{(m_H - m_Z)^2 - M_*^2}$





plots from Margarete Muehlleitner

Matrix element method

Instead of relying on specific kinematical variables, one can try to exploit the full information of the event

The MEM starts from a tree level amplitude to construct a likelihood

$$\mathcal{P}(\mathbf{x}|\Omega) = \frac{1}{\sigma_\Omega^{LO}} \int dx_a dx_b \, d\mathbf{y} \sum_{ij} \frac{f_i(x_a) f_j(x_b)}{x_a x_b s} \mathcal{B}_\Omega^{ij}(p_a, p_b, \mathbf{y}) \, W(\mathbf{x}, \mathbf{y})$$

integration over phase space

PDFs

squared amplitude

transfer function from parton to detector level

The amplitude should describe the interaction of the X resonance with the gauge bosons

Recently there have been attempts to extend MEM to NLO

J.Campbell, W.Giele, C.Williams (2012)

Effective lagrangian or anomalous couplings ?

How do we parametrize the amplitude ?

There are essentially two strategies:

- Effective lagrangian

Write the most general effective lagrangian compatible with Lorentz and gauge invariance

- Anomalous couplings

Write the most general amplitude compatible with Lorentz and gauge invariance: couplings become momentum dependent form factors

Effective lagrangian (EFT)

- + Clear ordering between relevant and subdominant operators
- + Consistent beyond LO

Anomalous couplings (AC)

- + Somewhat more “general” but....
- - “Agnostic” approach (more parameters)
- - Inconsistent beyond LO

Effective lagrangian (EFT)

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- + Somewhat more "general" but....
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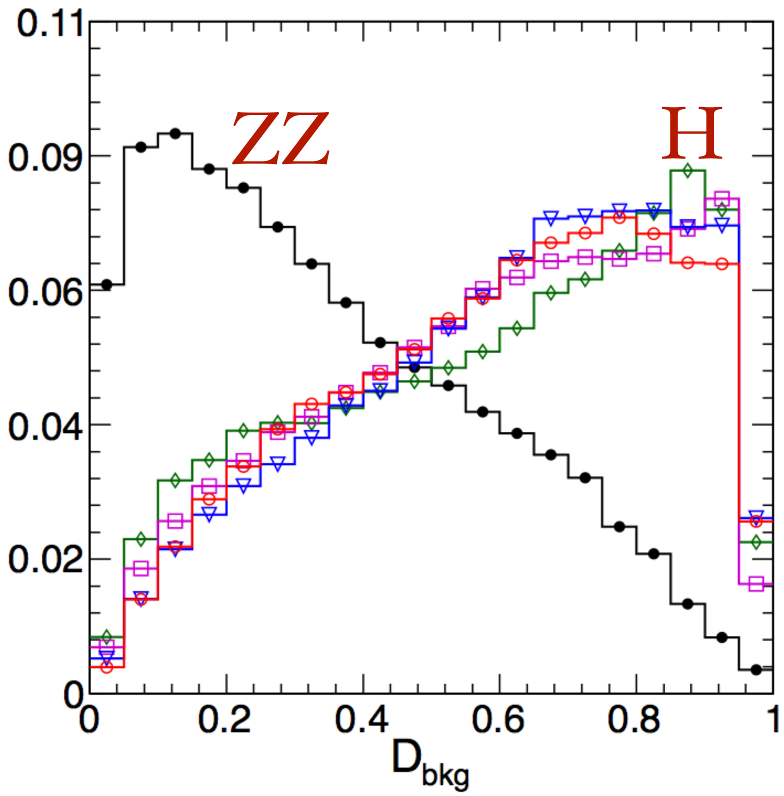
My opinion: the only reasons why you could prefer AC to EFT are:

- if you believe that there can still be relatively light and weakly coupled degrees of freedom that can circulate in the loops (but then why have they not been observed ?)
- if you don't have a clue on how a consistent model looks like (spin 2 case ?)

MELA

MELA (Matrix Element Likelihood Analysis)

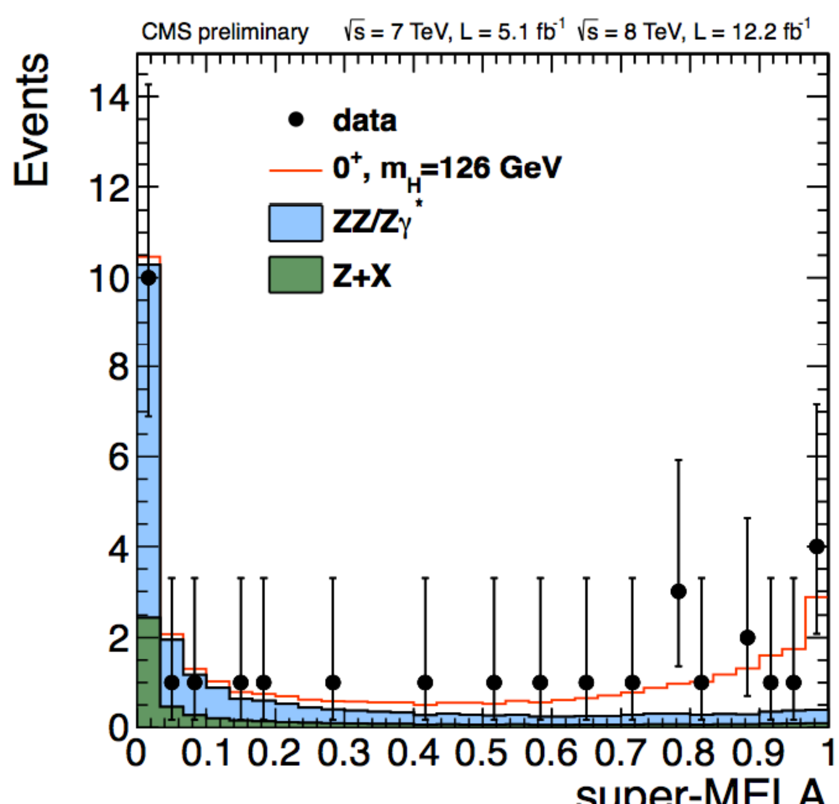


simplest MEM (no PS integration, no transfer function)

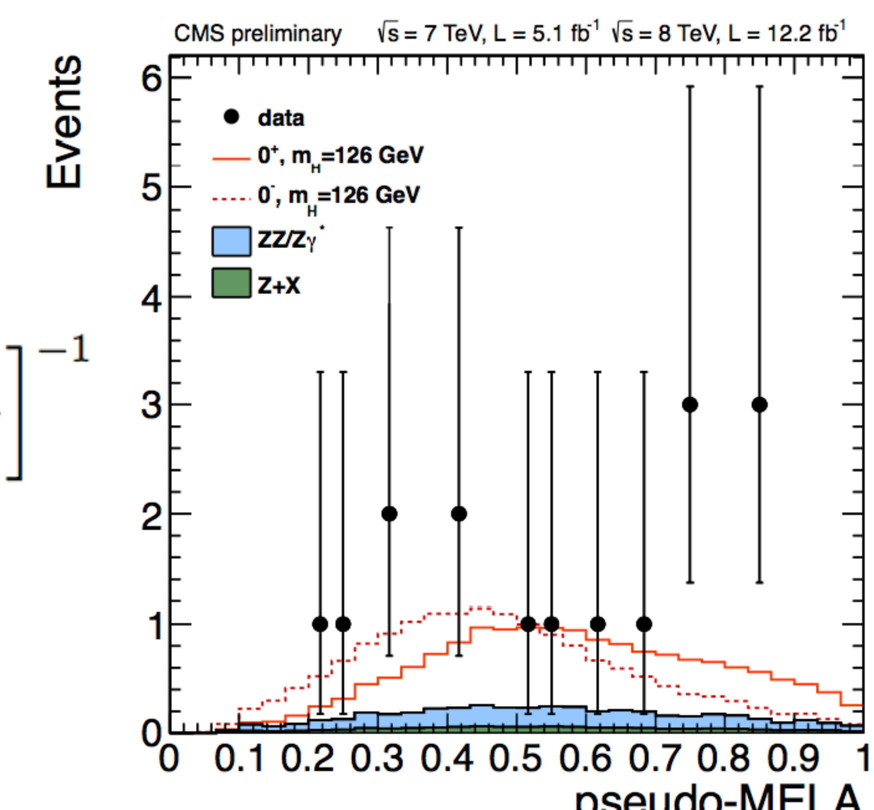
$$D_{\rm bkg} = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}{\mathcal{P}_{\rm sig}(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}\right]^{-1}$$

kinematic discriminant constructed from the ratio of probabilities for signal and backgrounds (superMELA)

the discriminant can be extended to discriminate two different JCP hypothesis



$$D_{J^P_x} = \left[1 + \frac{\mathcal{P}_2(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}{\mathcal{P}_1(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}\right]^{-1}$$



JHU

K.Melnikov et al. (2009, 2012)

Model independent production of a resonance X followed by its decay in two vector bosons and in four fermions

See also:
De Rujula, Lykken, Pierini, Rogan, Spiropulu (2010)
MEKD, Avery et al. (2012)

→ The approach is the one of anomalous couplings

spin 0

$$A(X \to V_1 V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

spin 2

$$\begin{aligned} A(X \to V_1 V_2) = \Lambda^{-1}\Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)}\right) \\ & + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}\right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*\right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)\right)\right)\Big], \end{aligned} \quad (18)$$

Used by ATLAS and CMS through MELA

MADGRAPH 5

P. de Aquino , LM Higgs meeting (2013)

We have implemented a model that contains the following possibilities in spin/parity of a new resonance X:

[http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterization]

(1) Spin–0 sector:

$$\mathcal{L}_0^f = \left[c_\alpha y_{Hff}\,\bar\psi_f\psi_f\right]X_0,\;\; \mathcal{L}_0^V = \Big[\kappa_{\rm SM} c_\alpha g_{HVV}\,V_\mu V^\mu$$

$$-\frac{1}{4}\kappa_\gamma\left[c_\alpha g_{H\gamma\gamma}\,A_{\mu\nu}A^{\mu\nu} + s_\alpha g_{A\gamma\gamma}\,A_{\mu\nu}\widetilde{A}^{\mu\nu}\right]$$

$$-\frac{1}{4}\kappa_\gamma\left[c_\alpha g_{HZ\gamma}\,Z_{\mu\nu}A^{\mu\nu} + s_\alpha g_{AZ\gamma}\,Z_{\mu\nu}\widetilde{A}^{\mu\nu}\right]$$

$$-\frac{1}{4}\kappa_g\left[c_\alpha g_{Hgg}\,G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha g_{Agg}\,G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\right]$$

$$-\frac{1}{4}\frac{\kappa_V}{\Lambda}\left[c_\alpha\,V_{\mu\nu}V^{\mu\nu} + s_\alpha\,V_{\mu\nu}\widetilde{V}^{\mu\nu}\right]\Big]X_0,$$

VV = ZZ, WW
AA = γγ, γZ

$0^+ \Rightarrow c\alpha = 1$

$0^- \Rightarrow c\alpha = 0$

Mixed state $\Rightarrow 0 < c\alpha < 1$

MADGRAPH 5

P. de Aquino , LM Higgs meeting (2013)

(2) Spin-1 sector:

[K. Hagiwara, R.D. Peccei, D. Zeppenfeld, Nuclear Physics B282 (1987)]

$$\mathcal{L}_1^f = \sum_{f=q,b,t,\ell,\tau} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu, \quad \mathcal{L}_1^Z = -\kappa_{V_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma).$$

$$\begin{aligned}\mathcal{L}_1^W = &+ i\kappa_{V_1} g_{WWZ} (W_{\mu\nu}^+ W^{-\mu} - W_{\mu\nu}^- W^{+\mu}) X_1^\nu \\ &+ i\kappa_{V_2} g_{WWZ} W_\mu^+ W_\nu^- X_1^{\mu\nu} \\ &- \kappa_{V_3} W_\mu^+ W_\nu^- (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ &+ i\kappa_{V_4} W_\mu^+ W_\nu^- \widetilde{X}_1^{\mu\nu} \\ &- \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} [W^{+\mu} (\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu}) W^{-\nu}] X_1^\sigma,\end{aligned}$$

MADGRAPH 5

P. de Aquino , LM Higgs meeting (2013)

(3) Spin-2 sector:

$$\mathcal{L}_2 = \frac{1}{\Lambda} \sum_{i=V,\gamma,g,\psi} k_i \, T^i_{\mu\nu} \, X^{\mu\nu}$$

$$T^V_{\mu\nu} = \frac{1}{4}\eta_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} - F_\mu^{\ \rho} F_{\nu\rho}$$

$$T^\psi_{\mu\nu} = -\eta_{\mu\nu} \left(\bar\psi\, i\gamma^\rho D_\rho \psi - m\bar\psi\,\psi\right) + \frac{1}{2}\bar\psi\, i\,\gamma_\mu D_\nu \psi + \\ + \frac{1}{2}\bar\psi\, i\,\gamma_\nu D_\mu \psi + \frac{1}{2}\eta_{\mu\nu}\partial^\rho(\bar\psi\, i\,\gamma_\rho\psi) - \frac{1}{4}\partial_\mu(\bar\psi\, i\,\gamma_\nu\psi)\frac{1}{4}\partial_\nu(\bar\psi\, i\,\gamma_\mu\psi)$$

ED models with only the spin-2 in the bulk: "universal coupling κ"

At the minimal dimension a spin-2 particle is graviton-like, and higher dimensional operators can be included.

TH Intermezzo: Spin 2

The Spin 2 possibility seems so unlikely that everybody would like to discard it

- Minimal coupling of Pauli-Fierz lagrangian to U(1) leads to the Velo-Zwanziger problem

  → acausality/superluminality

  M.Porrati, R.Rahman (2008)

  The model turns out to have a cut off $\Lambda \sim m/e^{1/3}$

A consistent effective description (with a cut off $\Lambda \sim O(m)$) could be obtained by interpreting the spin 2 particle as a KK graviton (but then how about the corresponding W and Z modes that should also be around 100 GeV ?)

However:

A graviton-like massive spin 2 with a warped extra dimension of AdS type will have too small couplings to WW and ZZ with respect to $\gamma\gamma$

J.Ellis et al. (2012)

$c_{W,Z}/c_\gamma < O(35)$ effective volume of the extra dimension: $\log(M_{Plank}/TeV)$

Couplings to gg and $\gamma\gamma$ equal in many models with a compactified extra dimension

→ $\Gamma(H\to gg) = 8\,\Gamma(H\to\gamma\gamma)$

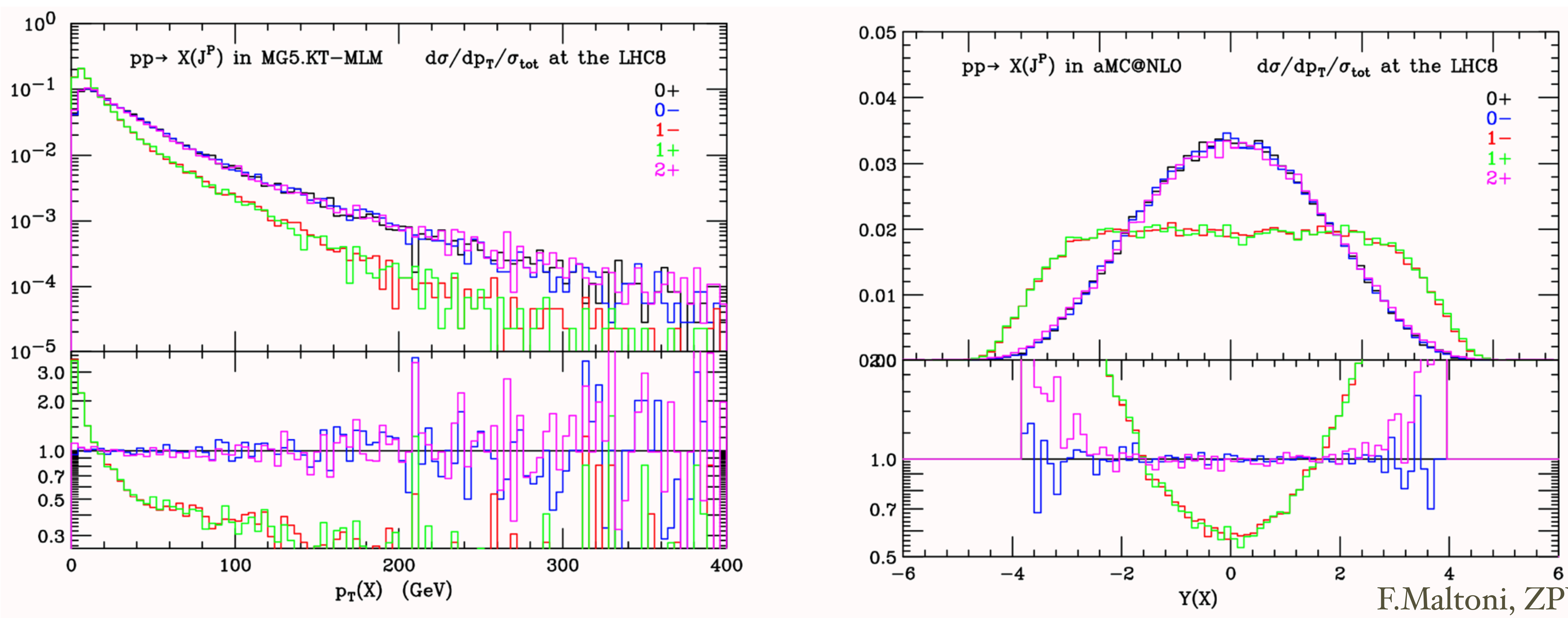
But this seems very different from what the data tell us: $\Gamma(H\to gg) >> 8\,\Gamma(H\to\gamma\gamma)$

Production (in)dependence

One of the most frequent questions asked by experimentalists nowadays is:

- How would the shape of the Higgs p_T spectrum change in case the Higgs has spin 2 ?

But the shape of the p_T spectrum is strongly driven by the production channel (so it has actually little to do with the spin)



F.Maltoni, ZPW (2013)

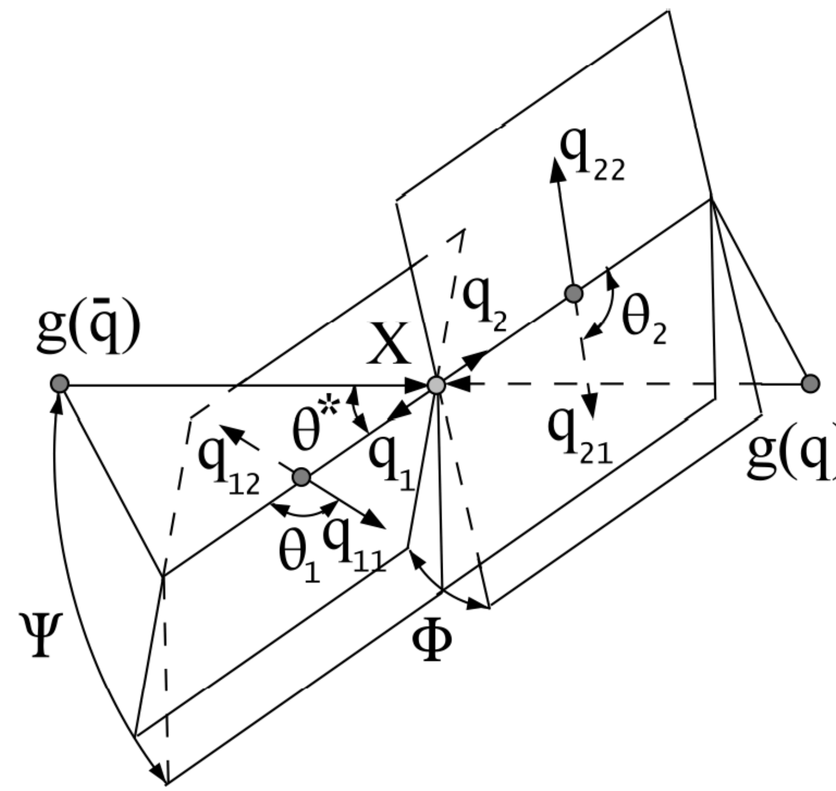
Gluons radiate more than quarks → The gg initial state tends to produce harder spectra than the qqb initial state

Production (in)dependence

S.Bolognesi , LM Higgs meeting (2013)

H→ZZ→4l described by 7 variables

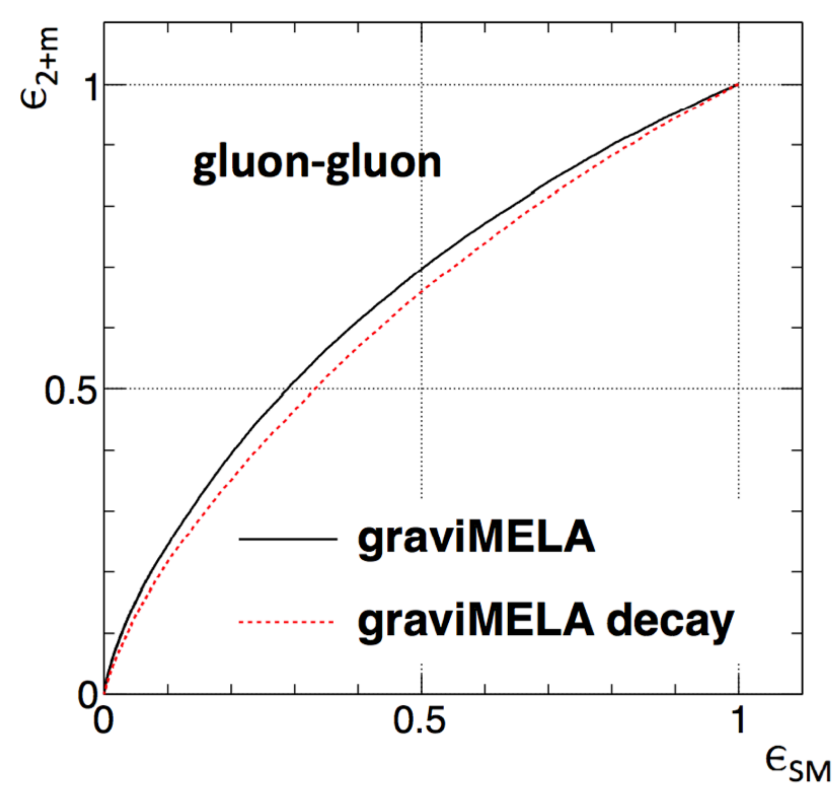
- 2 production angles θ^* Φ_1
- 3 decay angles
- the two Z invariant masses

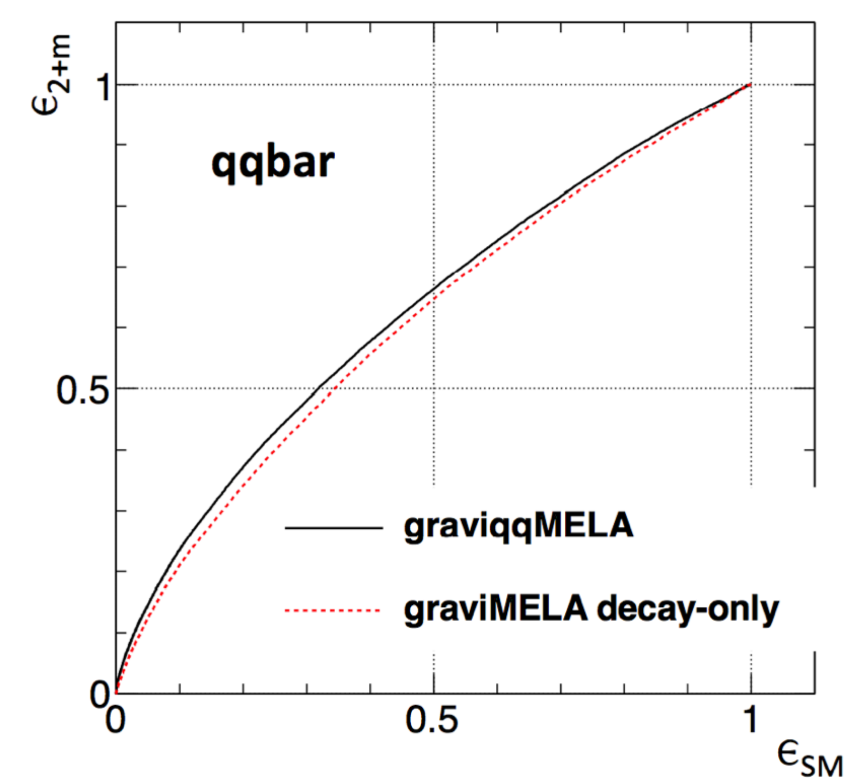


One can define a new discriminant by integrating out the production angles

$$P^{decay}_{J^P} = \int d\Phi_1 \, d\theta^* P(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, m_1, m_2)$$
$$= P(\theta_1, \theta_2, \Phi, m_1, m_2)$$

→ production independent (but looses some discrimination power)

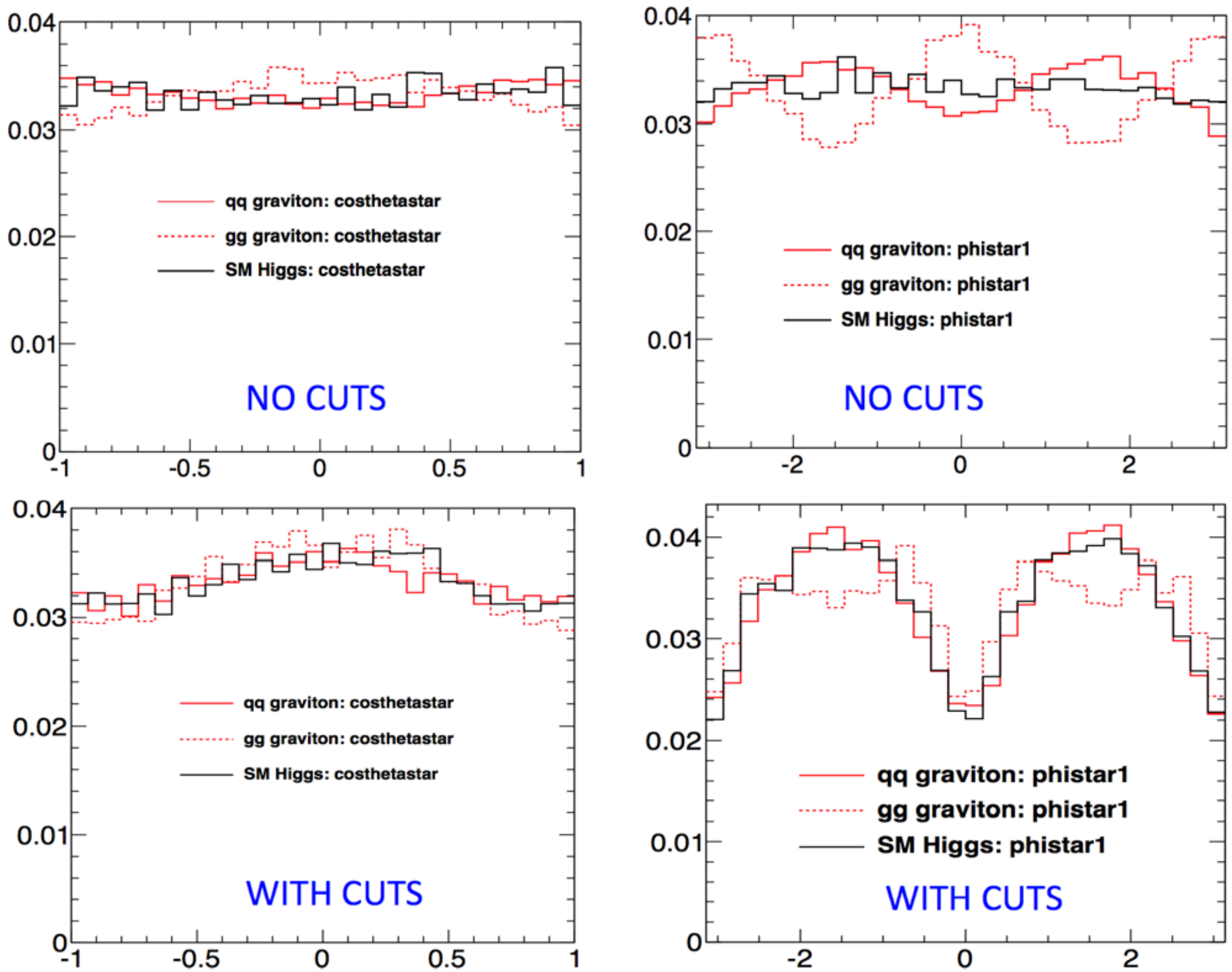




Production (in)dependence

S.Bolognesi , LM Higgs meeting (2013)

However: production dependence of standard MELA significantly reduced by selection cuts

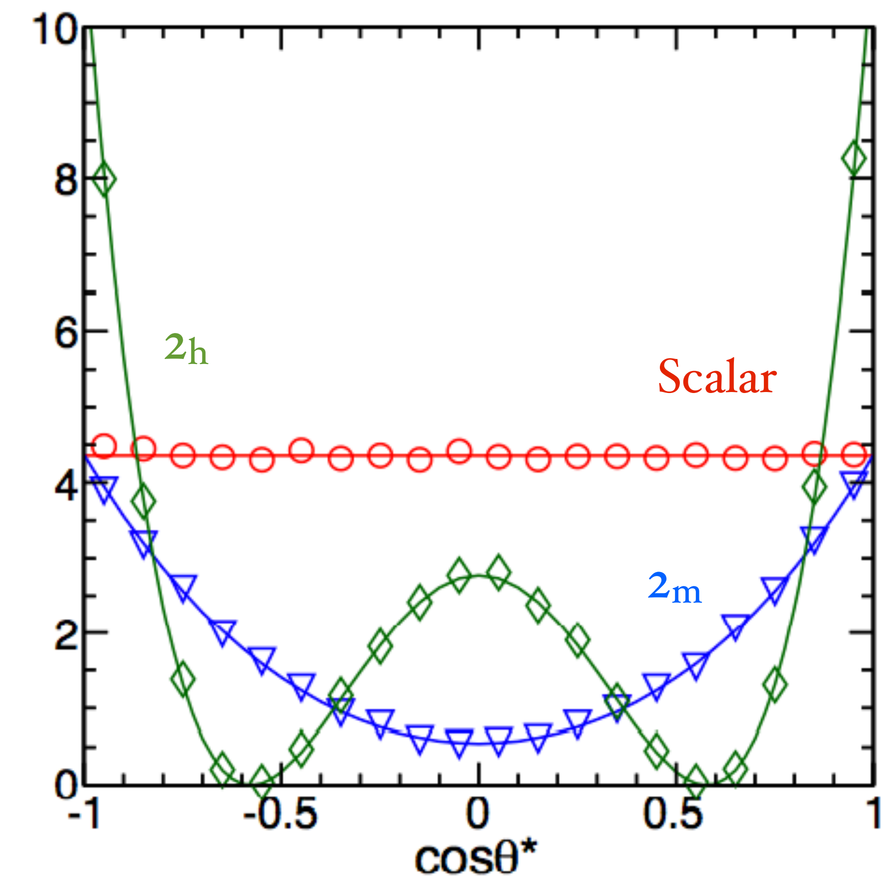


The cuts “sculpt” the angular distributions right in the region where the differences are larger

For a related discussions see also: De Rujula, Lykken, Pierini, Rogan, Spiropulu (2010)

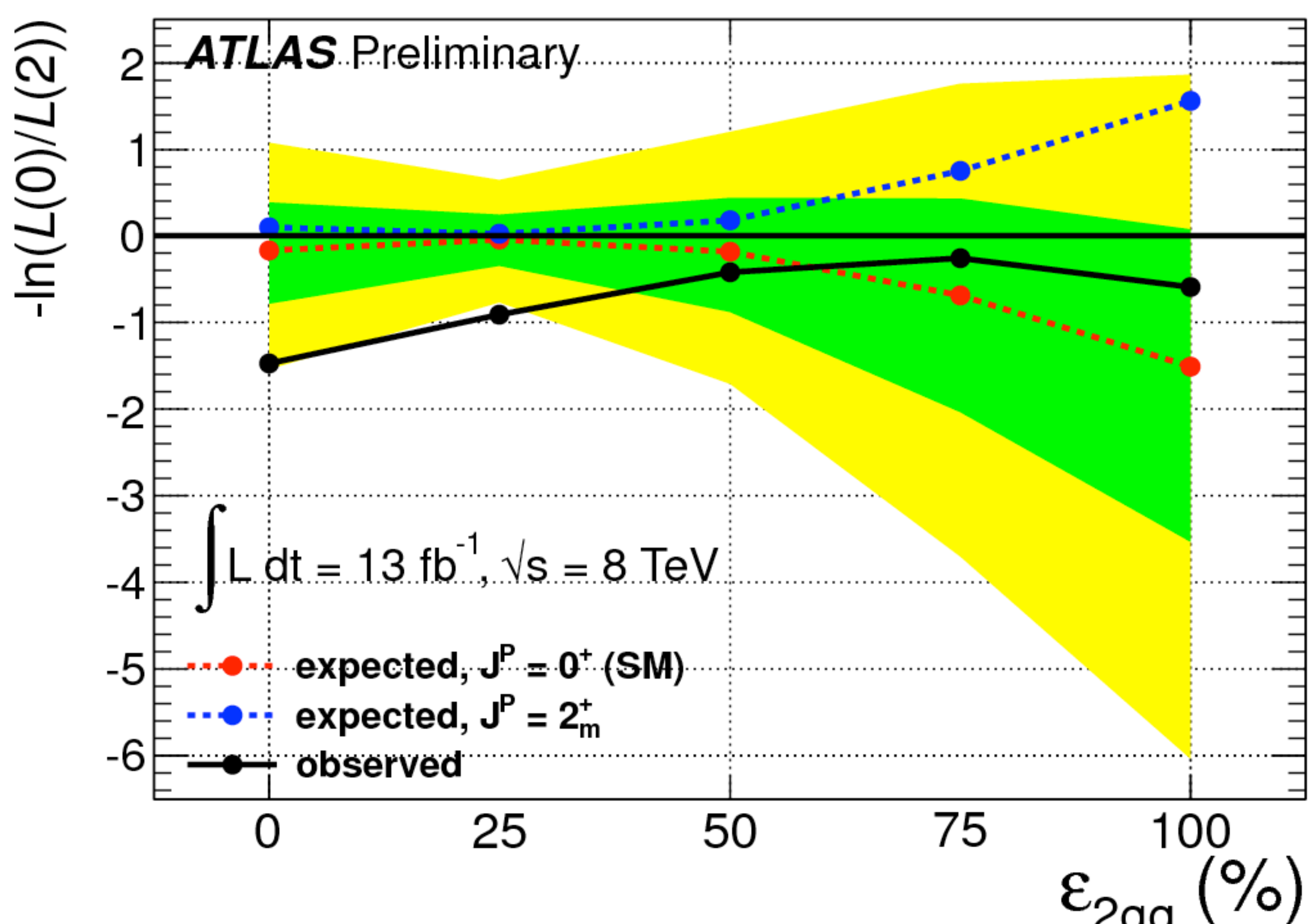
$X \to \gamma\gamma$

In $X \to \gamma\gamma$ the final state is fully reconstructed but there is only one distribution: $\cos\theta^*$ which is flat in the scalar case



K.Melnikov et al. (2009, 2012)

Dependence on the production model comes from spin correlations



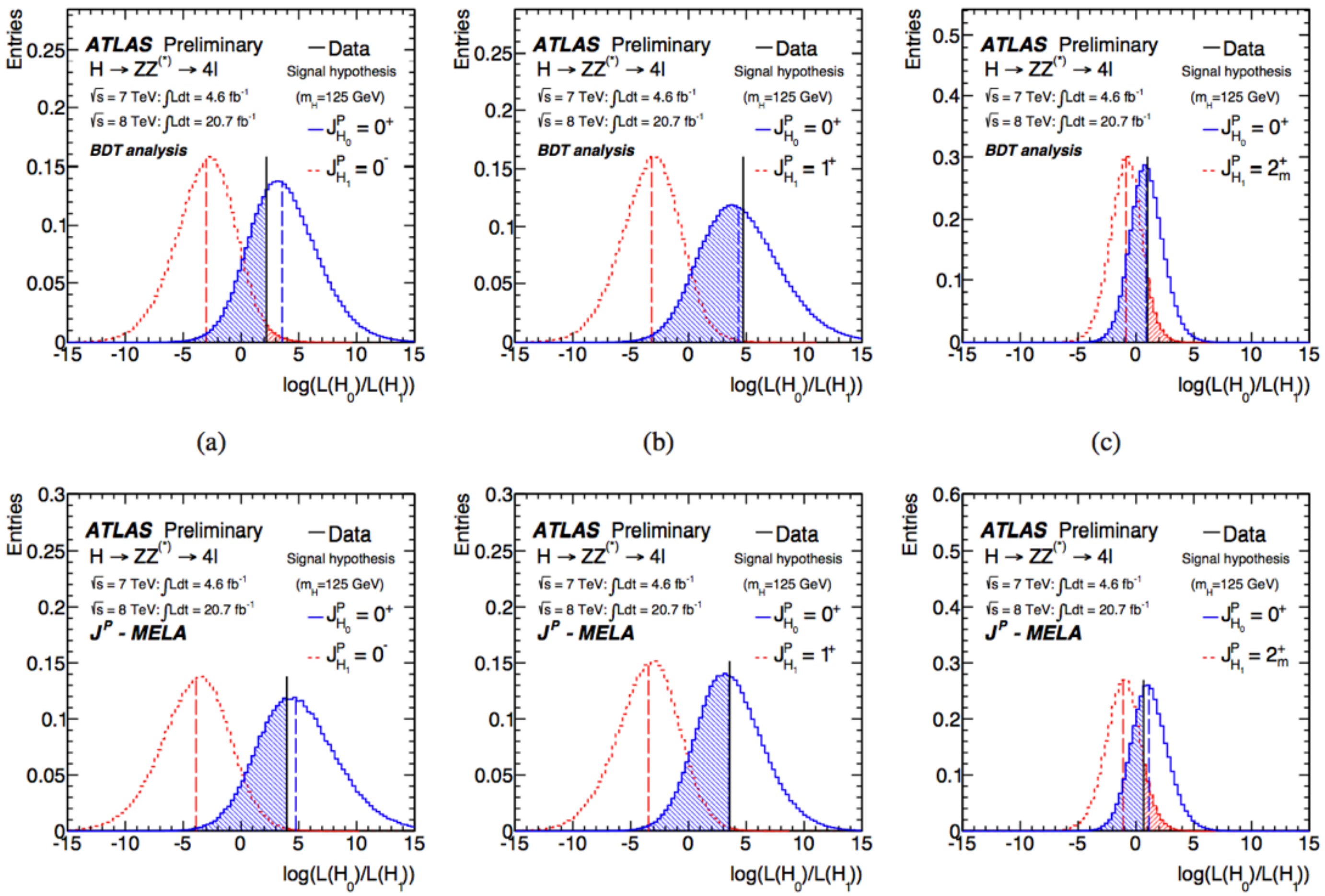
Discrimination only if the spin 2 is produced in the gg channel

The latest results

How a theorist feels following ATLAS and CMS presentations....

...and still new stuff is being shown at Moriond !

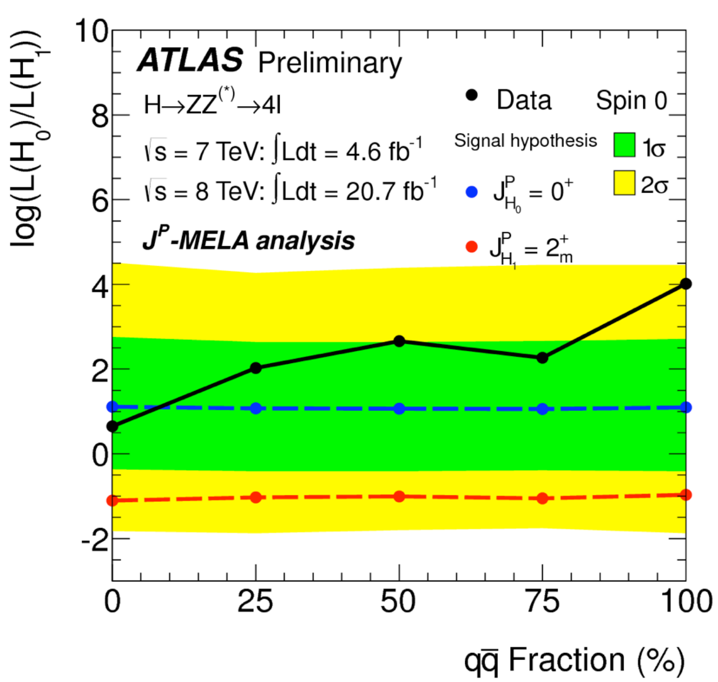
ATLAS H→ZZ→4l

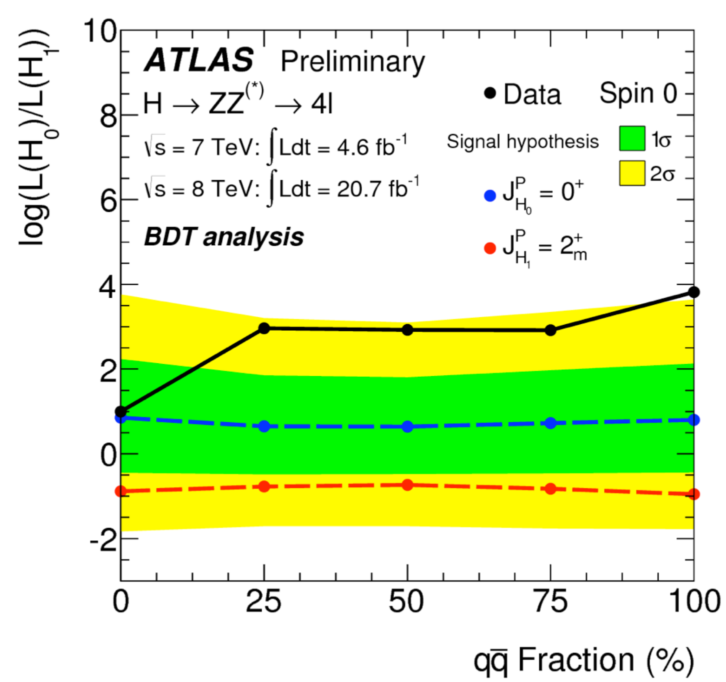


ATLAS uses MELA and BDT

→ results look consistent

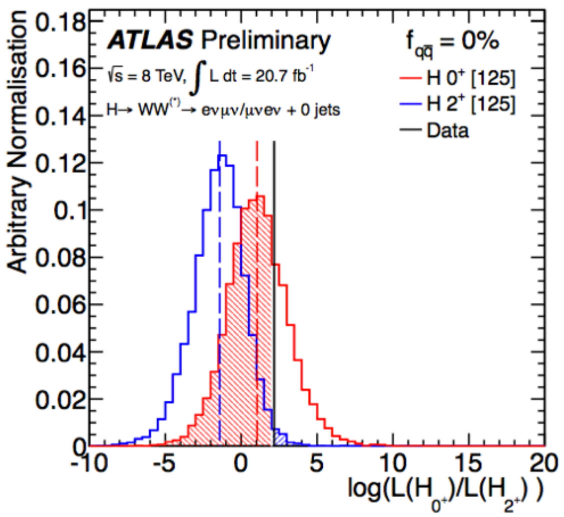
Effect of p_T reweighting very small (1% level)

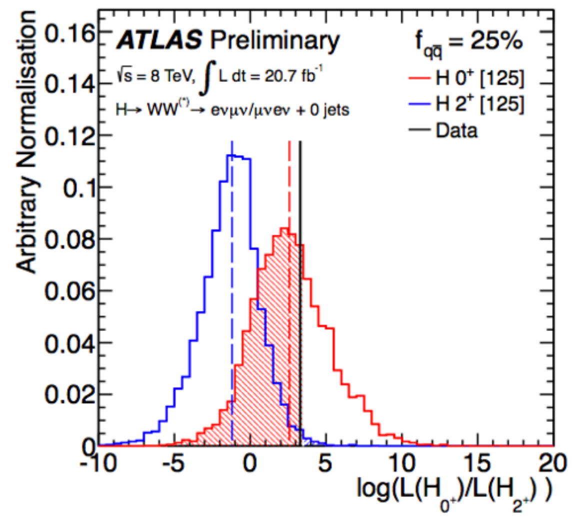


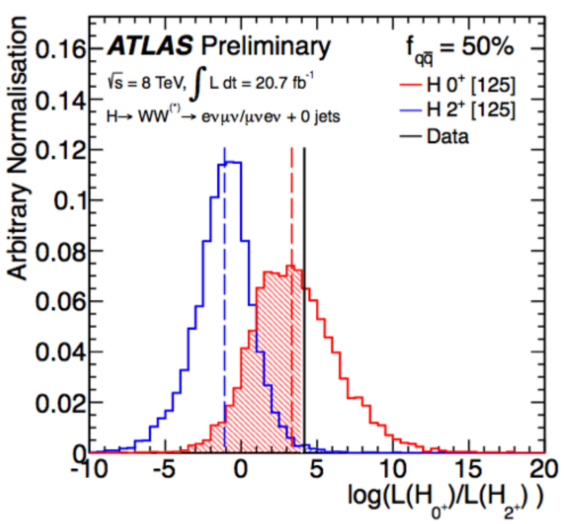


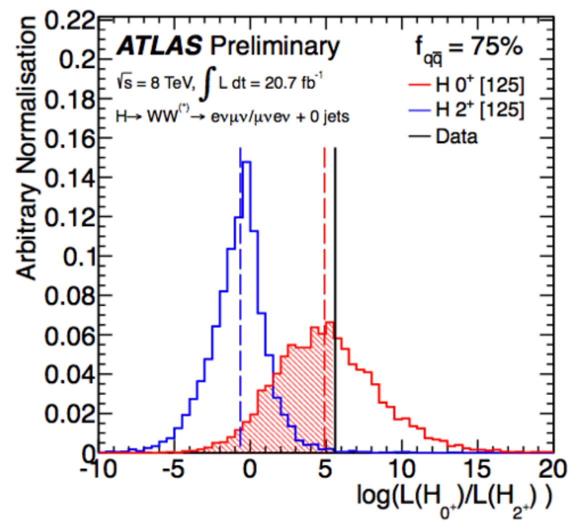
Production independent !

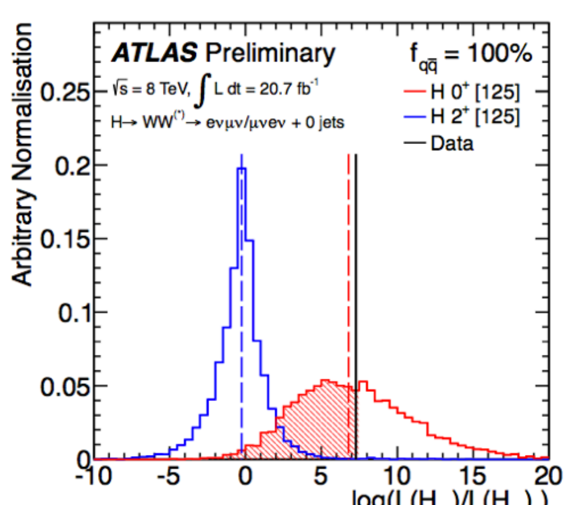
ATLAS H→WW

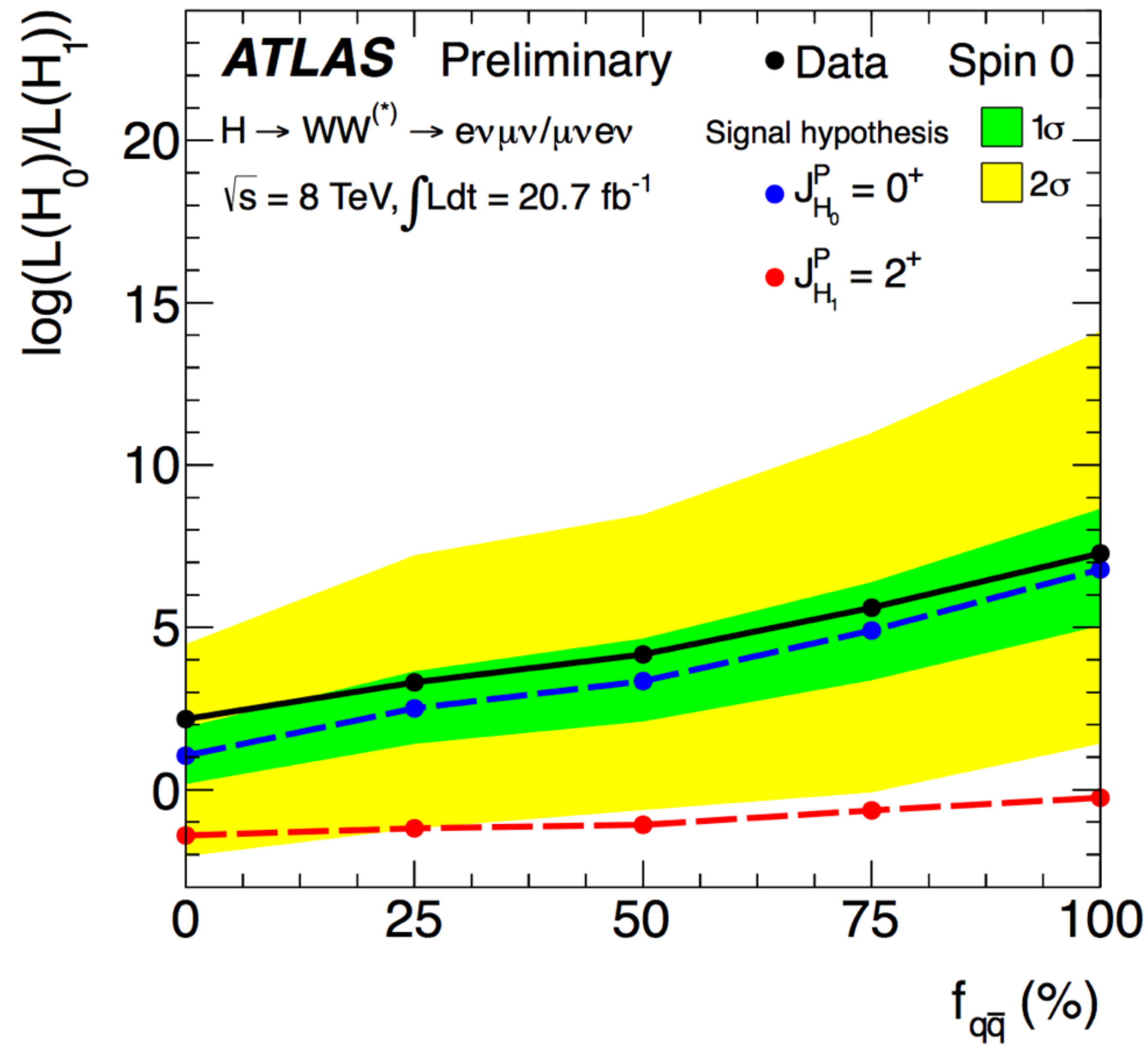








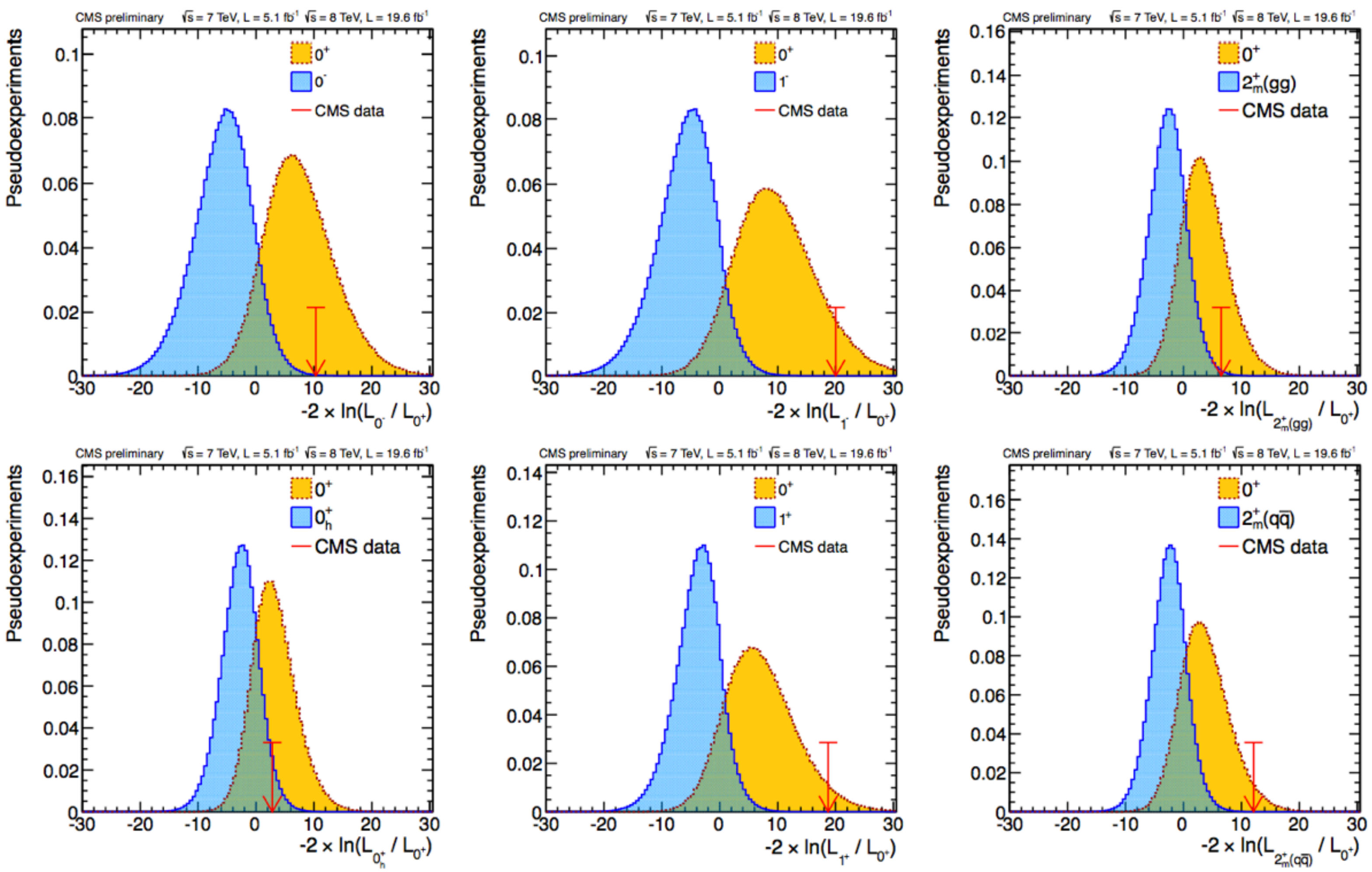




2^+ with f_{qq}=100 % is more WW background like

→ better discrimination with respect to 0^+ but worse with respect to background

CMS H→ZZ→4l



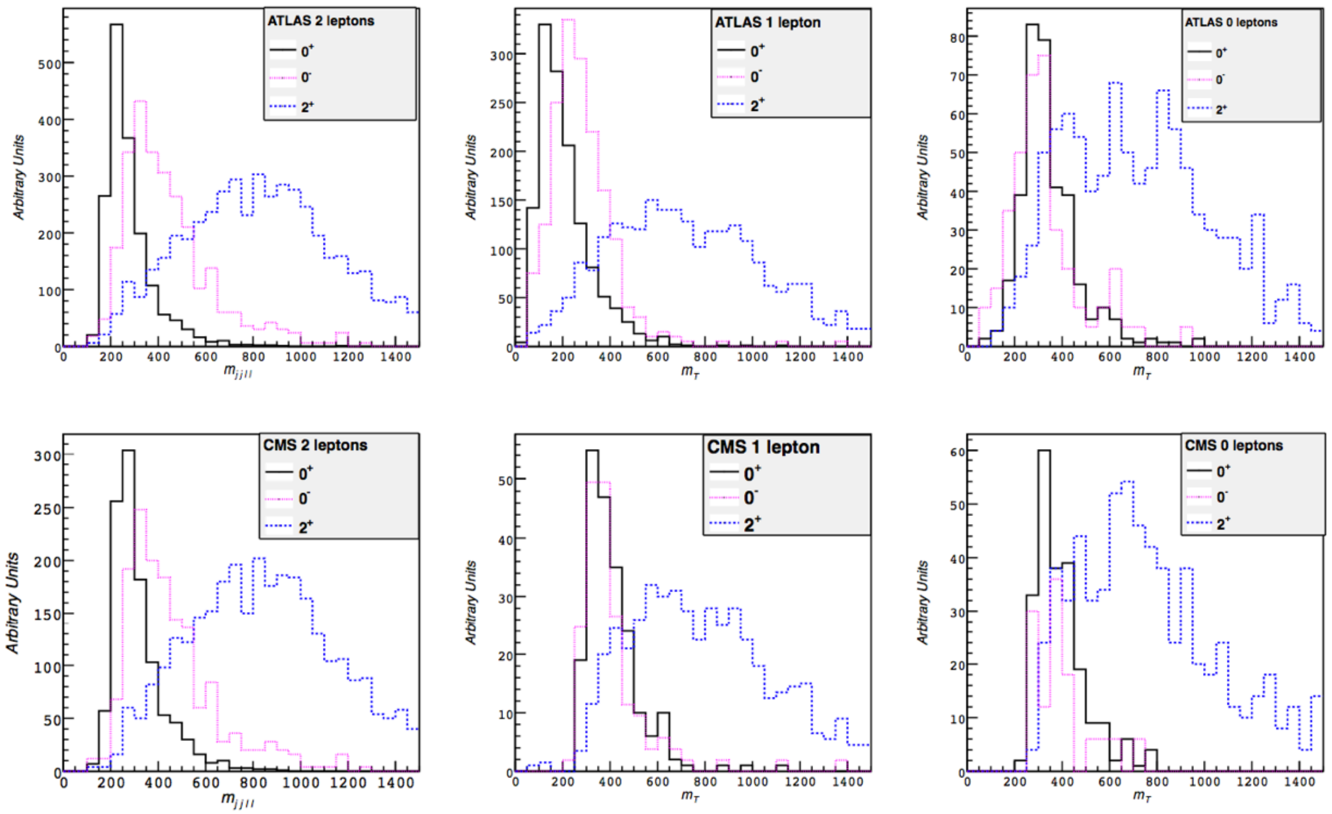
Equivalent results from CMS (MELA only)

They also study for the first time the fraction of a CP odd contribution in the amplitude

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

Neglect A_2 and define $f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$ → get $f_{a3} < 0.58$ at 95% CL

What else ?



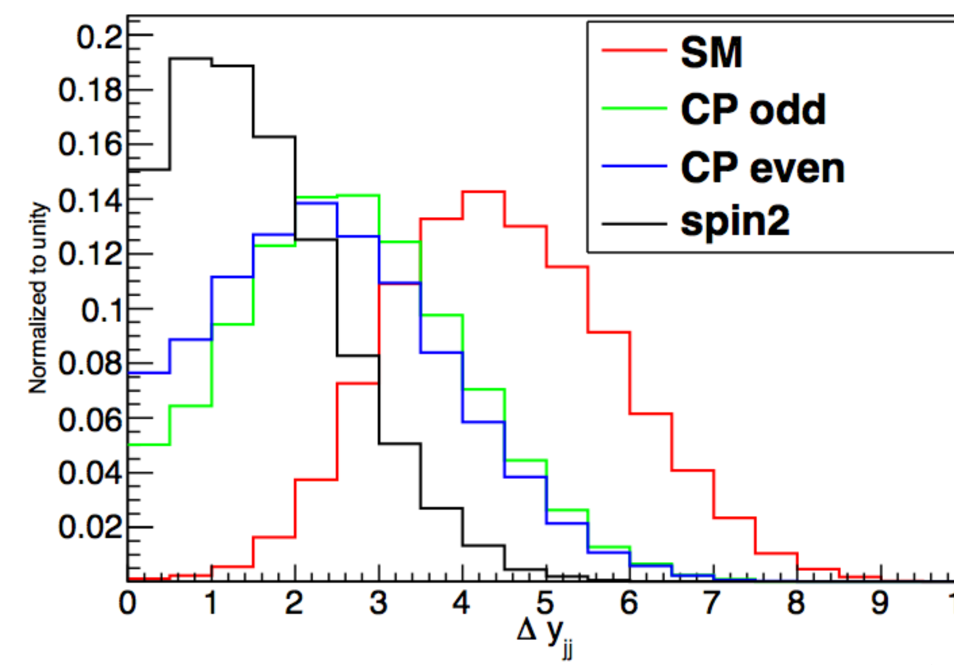
VH:

Invariant mass distribution of VH system very different for 0^+ 0^- and 2

J.Ellis, V.Sanz, T.You (2012,2013)

VBF:

Rapidity difference of tagging jets shifted to smaller values with respect to the SM Higgs



A.Djouadi et al. (2013)
(see also T.Plehn et al. (2012))

These effects are due to the derivatives in higher dimensional operators for the VVH interaction

Summary & Outlook

- The methods to determine the properties of a resonance through its decays to gauge bosons and then into four leptons date back to more than 50 years ago

- In the $X \to ZZ \to 4l$ decay mode the final state can be completely reconstructed and the various angular variables available allow to study JCP almost independently on the production mechanism (effects from Higgs p_T found to be small as expected)

  → golden channel is indeed golden !

- In the $X \to \gamma\gamma$ the final state is also fully reconstructed but we have only one handle through the $\cos\theta^*$ distribution

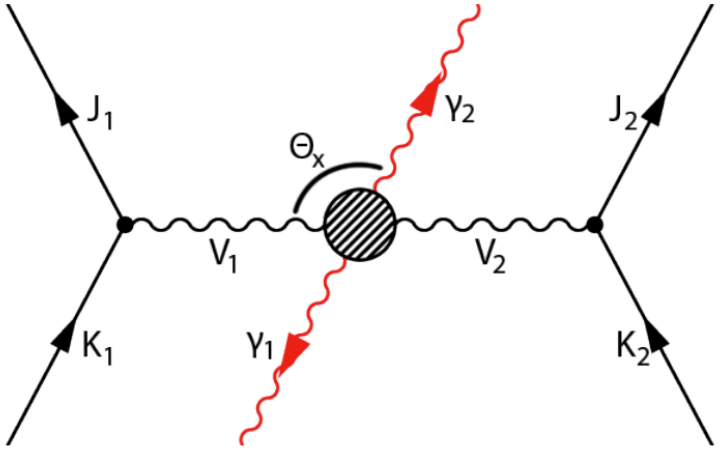
- The $H \to WW$ channel can be complementary to $X \to ZZ \to 4l$ and $X \to \gamma\gamma$ and first results on spin discrimination have been presented by ATLAS at this conference

Summary & Outlook

- Despite these very nice results it would be important to use other tools like MADGRAPH5 (and aMC@NLO) that have been devised to do these studies (and could provide an independent viewpoint)

- Use other channels as more data become available

For example $X \to \gamma\gamma$ in VBF: it has 6 legs as inclusive $X \to ZZ \to 4l$



- BSM effects will in general affect both couplings and tensor structures

→ Common strategy for couplings and JCP determination (work in progress within LM Higgs WG)

BACKUP SLIDES

VBF@NLO

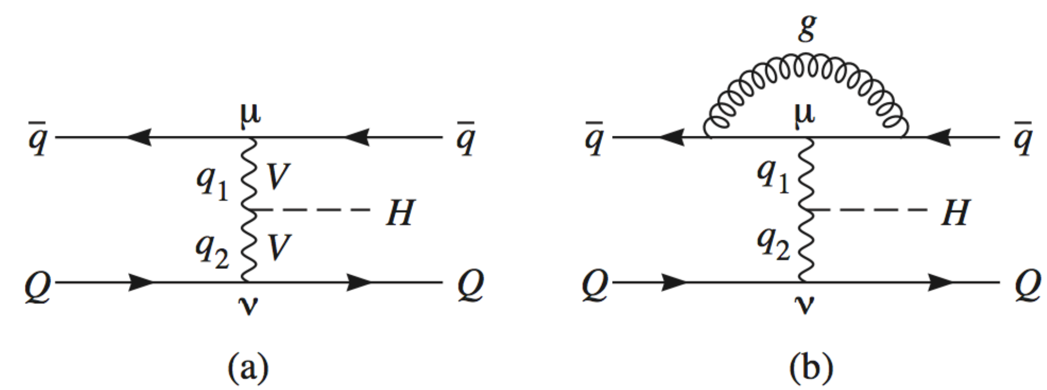
D.Zeppenfeld et al.

Spin 0: general HVV coupling given by

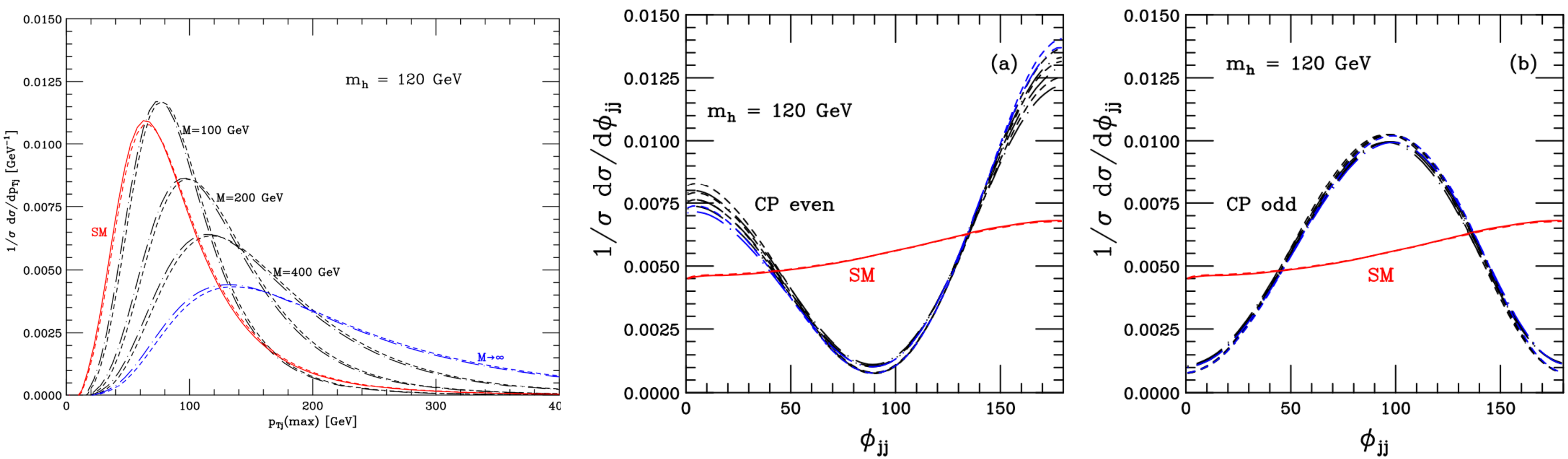
$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)g^{\mu\nu} + a_2(q_1,q_2)(q_1 q_2 g^{\mu\nu} - q_2^\mu q_1^\nu) + a_3(q_1,q_2)\epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho}$$

Where a_1, a_2, a_3 are scalar functions

Form factors are introduced in order to cure bad high-energy behavior



Strongly affect jet p_T but mildly the ϕ_{jj} distribution that discriminates parity



Spin-2 Resonances in VBFNLO

from Jessica Frank

(J. Frank, M. Rauch, D. Zeppenfeld, arXiv:1211.3658 [hep-ph])

- Spin-2 resonances implemented in VBFNLO as new processes $pp \to T\,jj \to \gamma\gamma jj$, $pp \to T\,jj \to W^+W^- jj \to l_1^+ \nu_{l_1} l_2^- \bar{\nu}_{l_2} jj$ and $pp \to T\,jj \to ZZjj \to l_1^+ l_1^- l_2^+ l_2^- jj$ at NLO QCD (analogous to VBF Higgs production processes)
- Analysis of distributions to distinguish between spin-0 and spin-2
- Effective model for the interaction of a spin-2 particle T with electroweak bosons:

$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1 \, B^{\alpha\nu} B^{\mu}{}_{\alpha} + f_2 \, W_i^{\alpha\nu} W^{i\mu}{}_{\alpha} + 2 f_5 \, (D^{\mu}\Phi)^{\dagger} (D^{\nu}\Phi) \right)$$

f_1, f_2, f_5, Λ: free parameters

$\Longrightarrow$ Relevant vertices: TW^+W^-, TZZ, $T\gamma\gamma$ and $T\gamma Z$

  - Additionally, a formfactor can be multiplied with the amplitudes to preserve unitarity and to adjust transverse-momentum distributions.

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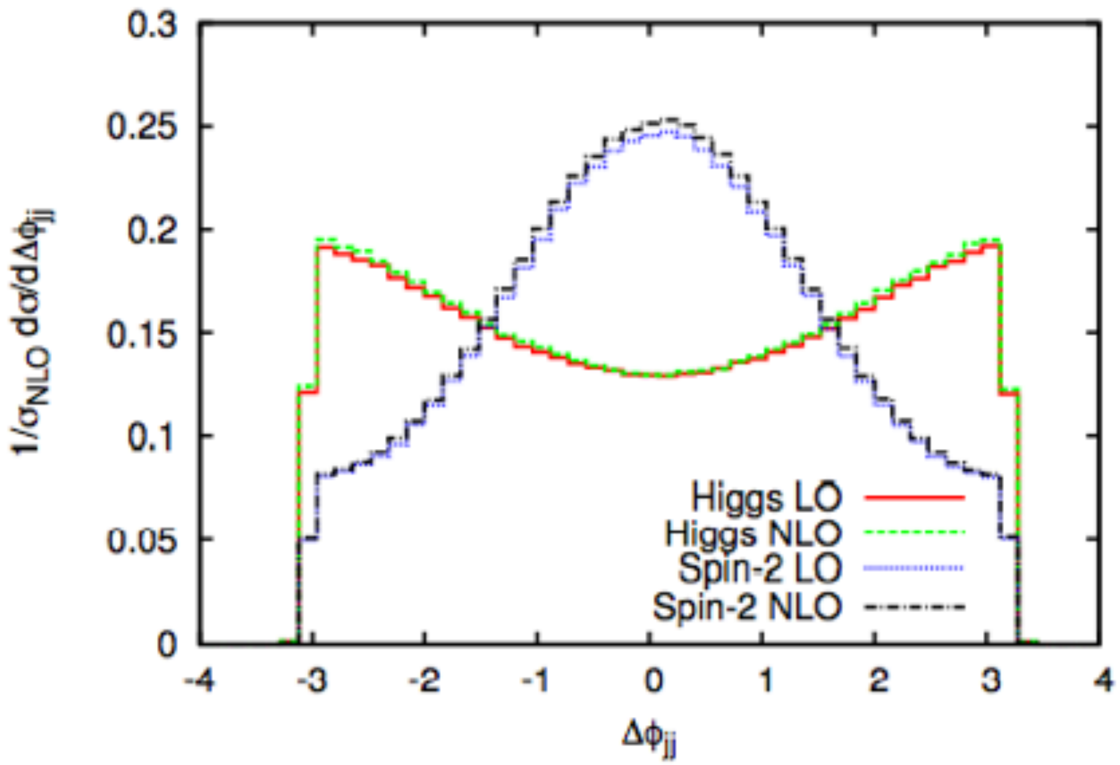
- Implementation in VBFNLO
  - VBFNLO: parton-level Monte Carlo program which simulates VBF processes at hadron colliders with NLO QCD accuracy
  - $pp \to T jj \to \gamma\gamma jj$ public [Arnold et al., arXiv:1107.4038 [hep-ph]]
  - $pp \to T jj \to W^+W^- jj \to l_1^+ \nu_{l_1} l_2^- \bar{\nu}_{l_2} jj$ and $pp \to T jj \to ZZjj \to l_1^+ l_1^- l_2^+ l_2^- jj$ so far only as private version (please contact us if you want to use it)
  - $pp \to T jj \to \tau\tau jj$ planned for the near future

- Results
  - For $\gamma\gamma jj$, see arXiv:1211.3658 [hep-ph], $W^+W^- jj$ and $ZZjj$ preliminary
  - With a suitable choice of model parameters, spin-2 resonances can mimic SM Higgs cross sections and transverse-momentum distributions.
  - Even then, several (angular) distributions can distinguish between spin-0 and spin-2.

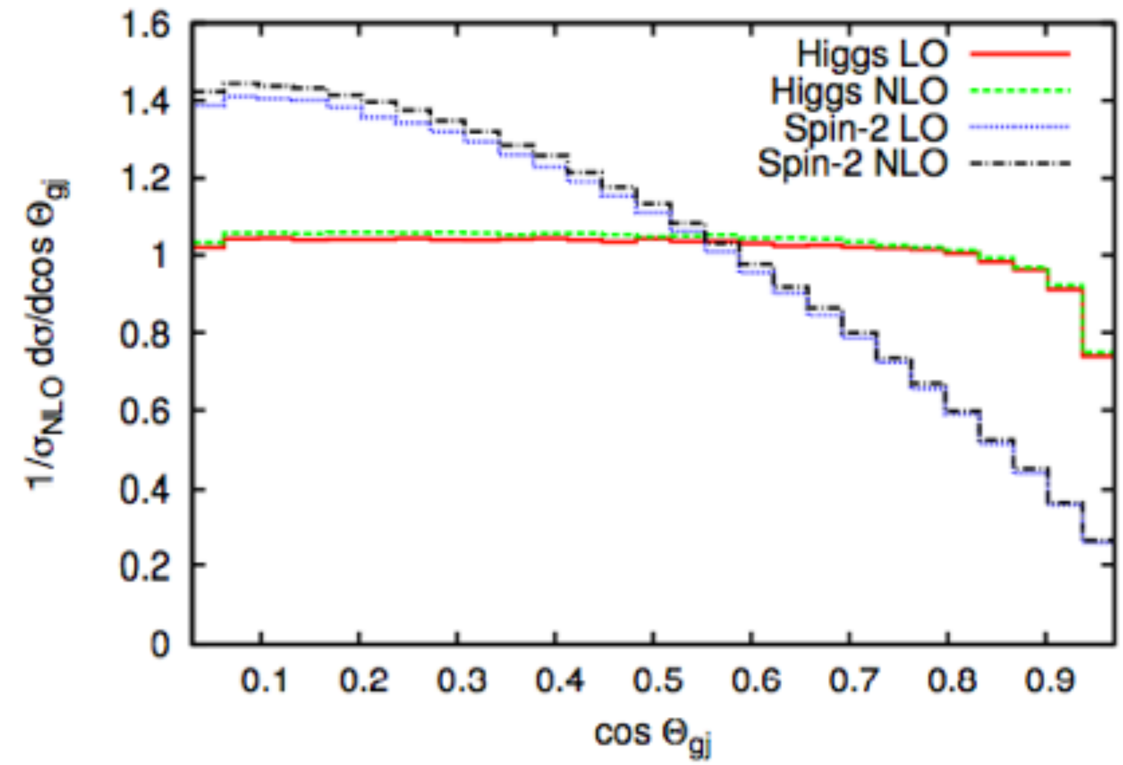
Angular distributions in $\gamma\gamma jj$

from Jessica Frank

SM Higgs vs. spin-2, $m = 126$ GeV, LHC 8, VBF cuts



Azimuthal angle difference between the two tagging jets at LO and NLO QCD accuracy.



Cosine of the Gottfried-Jackson angle at LO and NLO QCD accuracy.

- Distinct shape for SM Higgs and spin-2 ($\Delta\Phi_{jj}$: also for W^+W^-jj and $ZZjj$)
- Nearly independent of NLO corrections and spin-2 model parameters

$W^+W^-jj \to e^+\nu_e\mu^-\overline{\nu}_\mu jj$ (preliminary)

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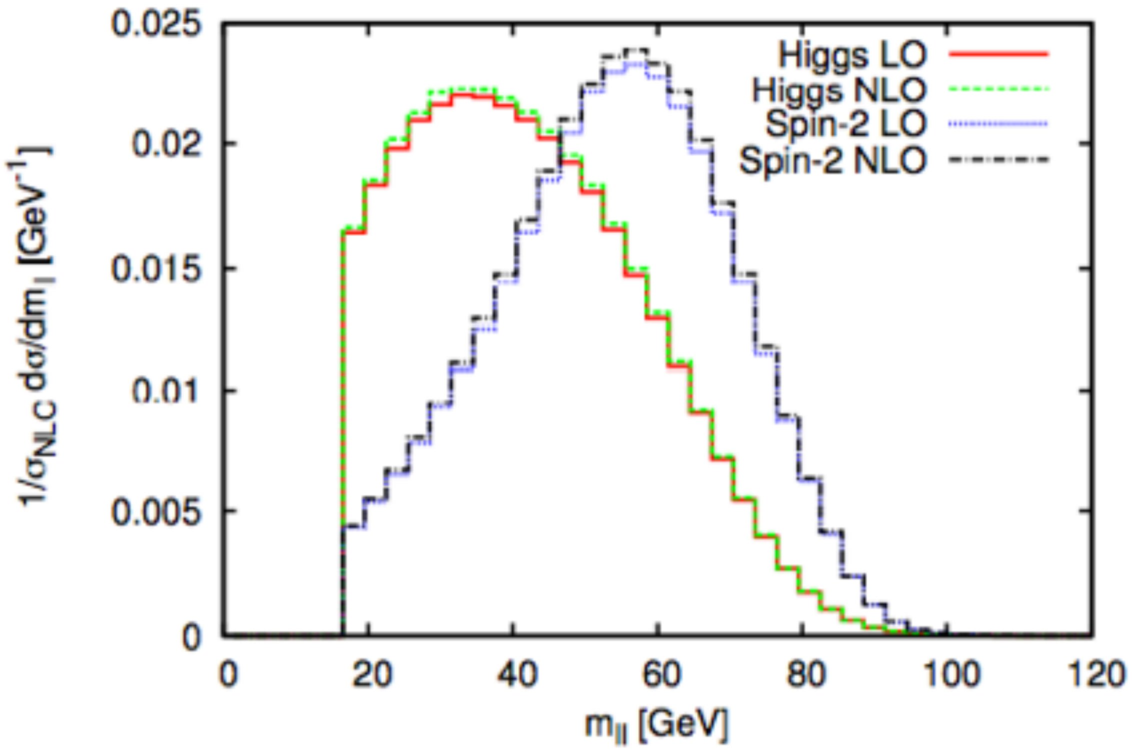
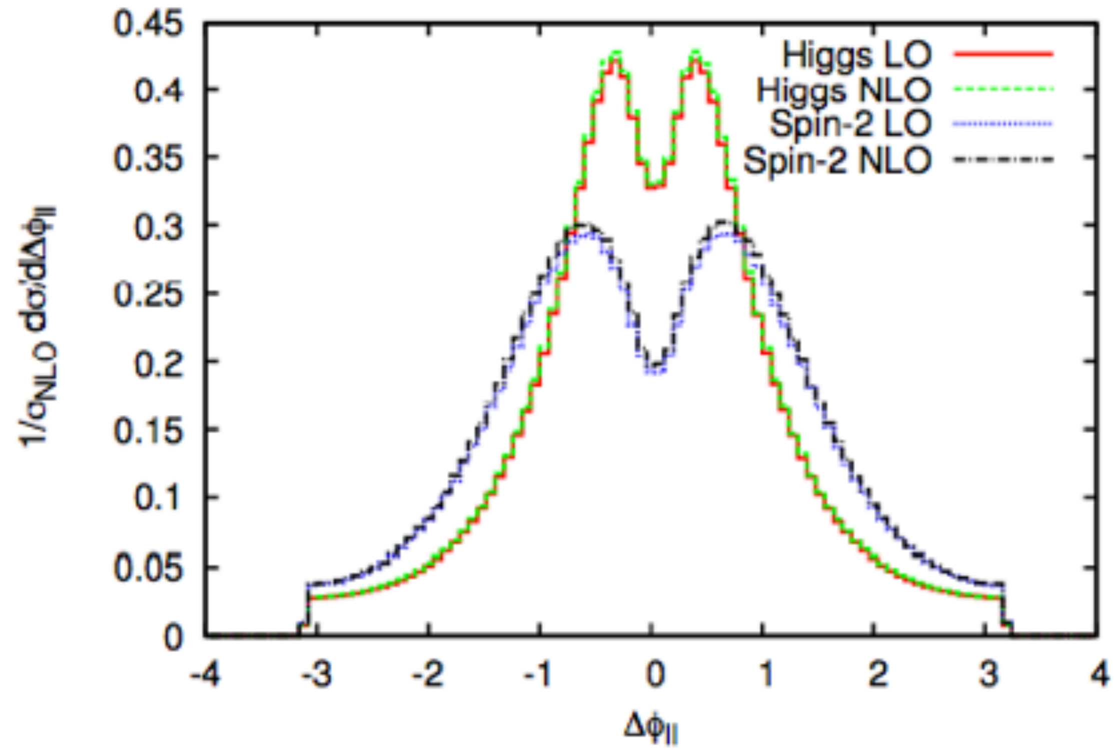
SM Higgs vs. spin-2, $m = 126$ GeV, LHC 8, VBF cuts



Invariant dilepton mass at LO and NLO QCD accuracy.



Azimuthal angle difference of the two charged leptons at LO and NLO QCD accuracy.

More on spin 2

The Spin 2 possibility seems so unlikely that everybody would like to discard it

Start from Pauli-Fierz lagrangian

$$L = -\frac{1}{2}(\partial_\mu h_{\nu\rho})^2 + (\partial_\mu h^{\mu\nu})^2 + \frac{1}{2}(\partial_\mu h)^2 - \partial_\mu h^{\mu\nu}\partial_\nu h - \frac{m^2}{2}[h_{\mu\nu}^2 - h^2]$$

Use Stueckelberg trick

$$h_{\mu\nu} \to \tilde{h}_{\mu\nu} = h_{\mu\nu} + \frac{1}{m}\partial_\mu\left(B_\nu - \frac{1}{2m}\partial_\nu\phi\right) + \frac{1}{m}\partial_\nu\left(B_\mu - \frac{1}{2m}\partial_\mu\phi\right)$$

$$\begin{aligned} \delta h_{\mu\nu} &= \partial_\mu\lambda_\nu + \partial_\nu\lambda_\mu, \\ \delta B_\mu &= \partial_\mu\lambda - m\lambda_\mu, \\ \delta\phi &= 2m\lambda. \end{aligned}$$

Then try to couple the model with U(1) through minimal substitution

→ Velo-Zwanziger problem: acausality/superluminality

The model turns out to have a cut off $\Lambda \sim m/e^{1/3}$

M.Porrati, R.Rahman (2008)

JHU

TABLE I: The list of scenarios chosen for the analysis of the production and decay of an exotic X particle with quantum numbers J^P. For the two 2^+ cases, the superscripts m (minimal) and L (longitudinal) distinguish two scenarios, as discussed in the last column. When relevant, the relative fraction of gg and $q\bar{q}$ production is taken to be 1:0 at $m_X = 250$ GeV and 3:1 at $m_X = 1$ TeV. The spin-zero X production mechanism does not affect the angular distributions and therefore is not specified.

scenario (J^P)	$X \to ZZ$ decay parameters	X production parameters	comments
0^+	$a_1 \neq 0$ in Eq. (2)	$gg \to X$	SM Higgs-like scalar
0^-	$a_3 \neq 0$ in Eq. (2)	$gg \to X$	pseudo-scalar
1^+	$g_{12} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: ρ_{11}, $\rho_{12} \neq 0$ in Eq. (9)	exotic pseudo-vector
1^-	$g_{11} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: ρ_{11}, $\rho_{12} \neq 0$ in Eq. (9)	exotic vector
2_m^+	$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_{21} \neq 0$ in Eq. (10)	Graviton-like tensor with minimal couplings
2_L^+	$c_2 \neq 0$ in Eq. (6)	$gg \to X$: $g_2^{(2)} = g_3^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: ρ_{21}, $\rho_{22} \neq 0$ in Eq. (10)	Graviton-like tensor longitudinally polarized and with $J_z = 0$ contribution
2^-	$g_8^{(2)} = g_9^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: ρ_{21}, $\rho_{22} \neq 0$ in Eq. (10)	"pseudo-tensor"