Theoretical issues in Higgs Spin/Parity determination

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Outline

- Introduction
- Effective lagrangian or anomalous couplings ?
- MELA & JHU
- TH Intermezzo: Spin 2
- VBF@NLO
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- Summary & Outlook

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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

Landau Yang theorem → Since it decays in $\gamma\gamma$ it cannot have spin one (caveat $H \to aa \to 4\gamma$ with two photon pairs too close to be distinguished)

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 !

Introduction

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

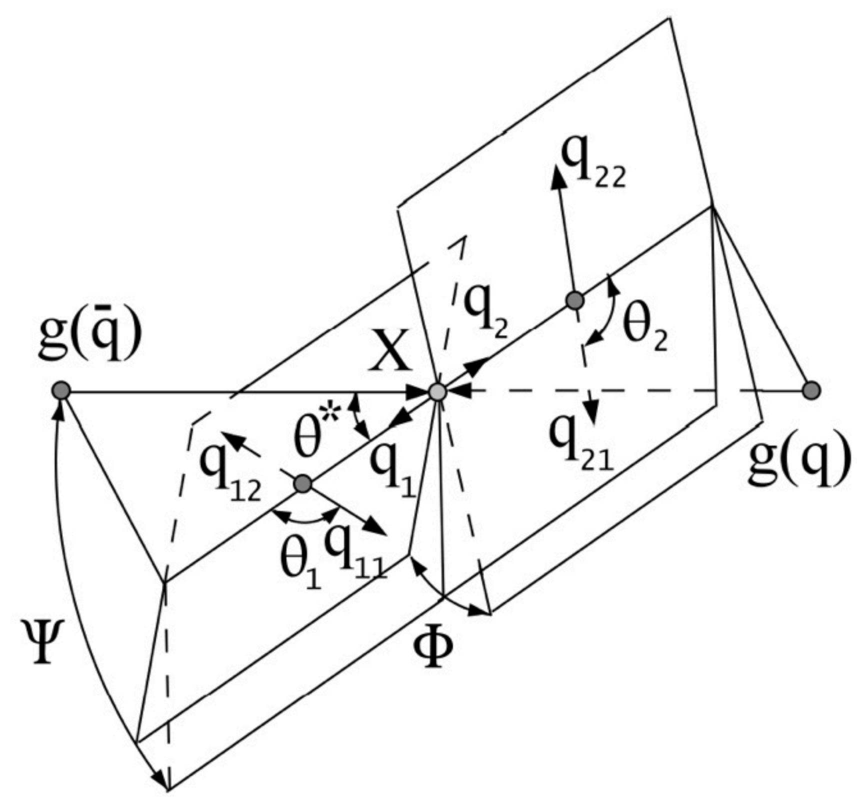
Photon polarization can be used to determine π^0 parity in $\pi^0 \rightarrow \gamma\gamma$

C.N. Yang (1950)

Easier to use orientation in Dalitz pairs in $\pi^0 \rightarrow e^+ e^- e^+ e^-$

R.H. Dalitz (1951)

In the case $X \rightarrow ZZ \rightarrow 4l$ channel where the final state can be fully reconstructed it should be possible to study the JCP properties almost independently on the production process (forget QCD corrections at this stage)



Effective lagrangian or anomalous couplings ?

How do we parametrize the interaction of X with the gauge bosons ?

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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My opinion: the only reasons why you could prefer AC to EFT are:

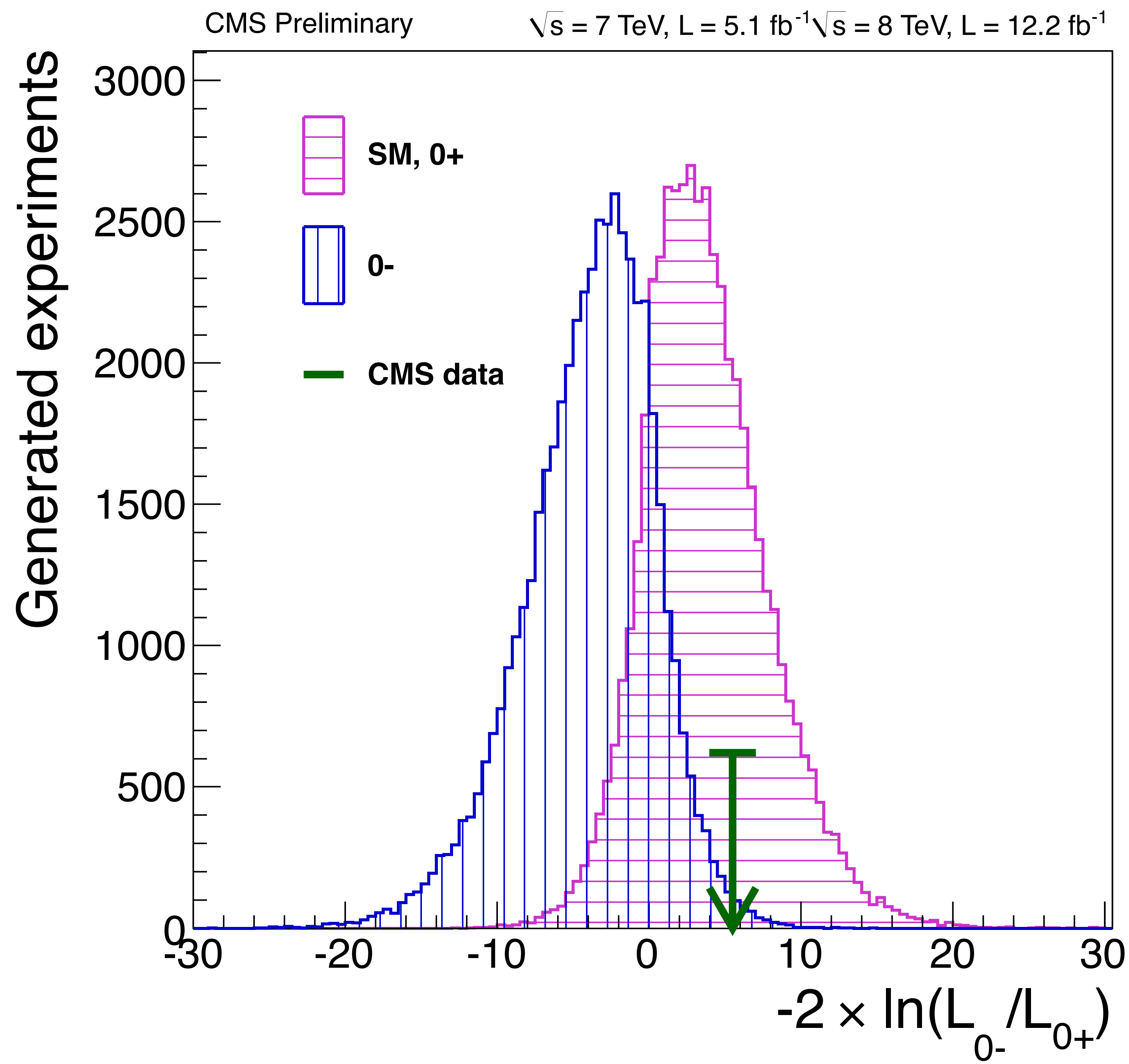
- if you believe that there can still be relatively light and weakly coupled degrees of freedom that can circulate in the loops (but then why have they not been observed ?)
- if you don't have a clue on how a consistent model looks like (spin 2 case ?)

Experimental Results

No public results on Spin/CP out from ATLAS up to now

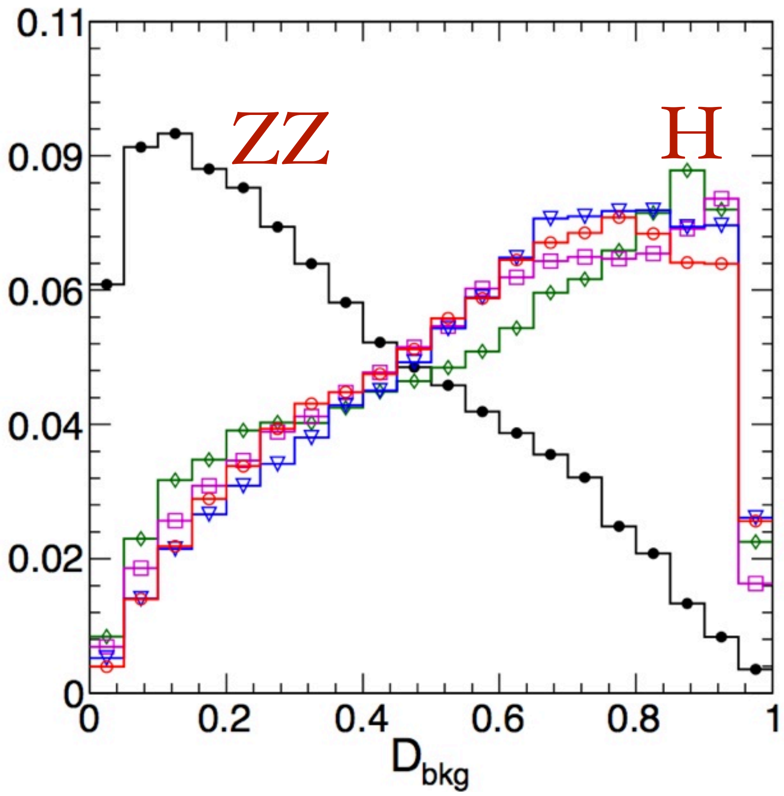
CMS: scalar/ pseudoscalar discrimination using MELA

Data consistent with
0- within 2.4 σ
0+ within 0.5 σ



MELA

MELA (Matrix Element Likelihood Analysis)

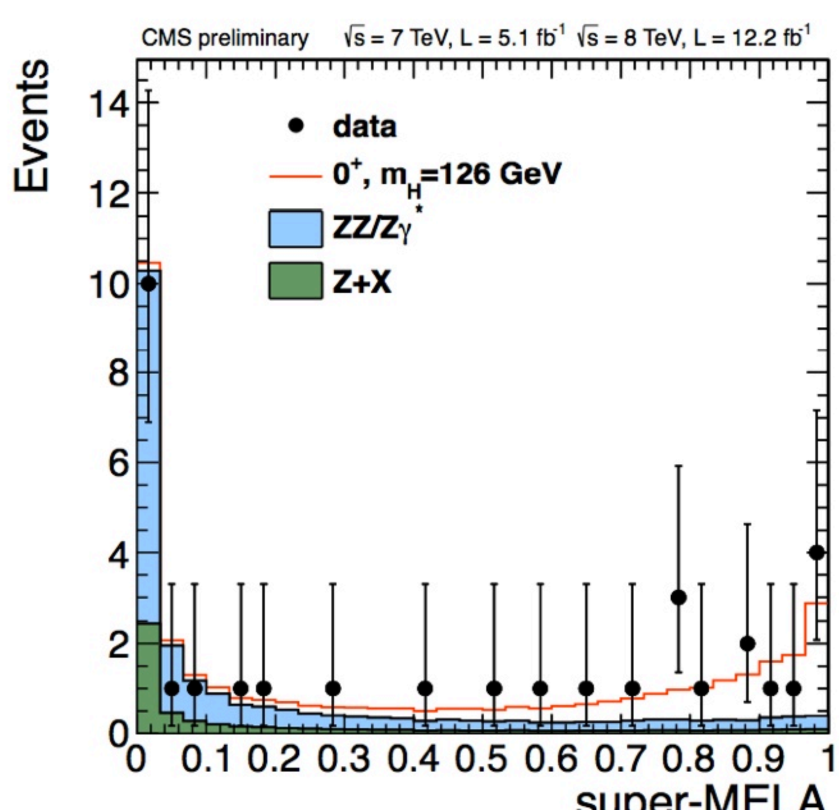


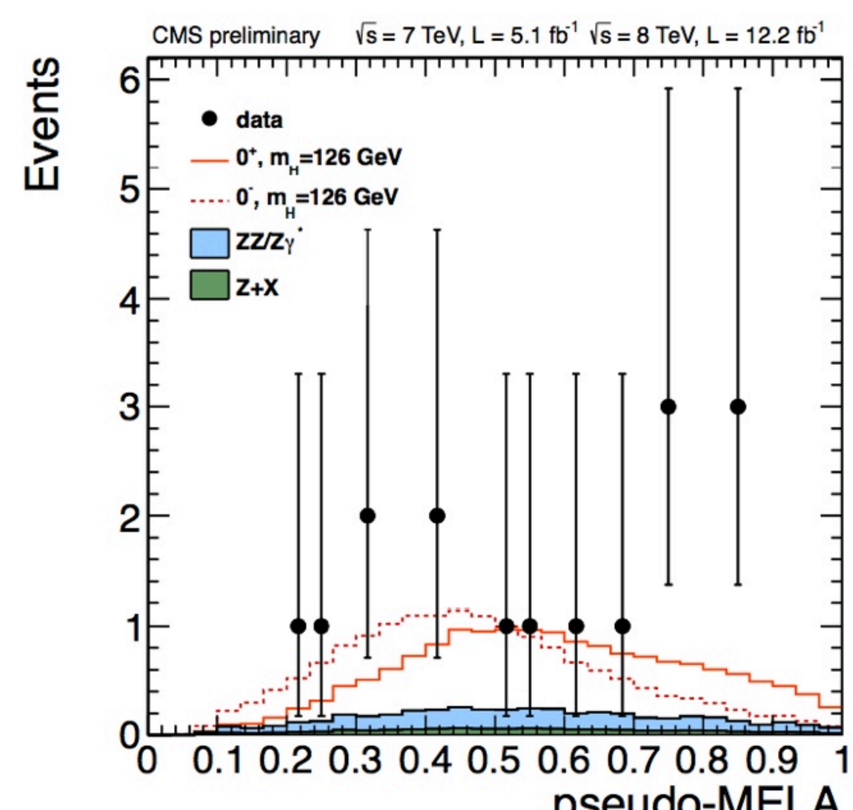
$$D_{\rm bkg} = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}{\mathcal{P}_{\rm sig}(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}\right]^{-1}$$

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

the discriminant can be extended to discriminate two different JCP hypothesis

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





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

→ The approach is the one of anomalous couplings

spin 0

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

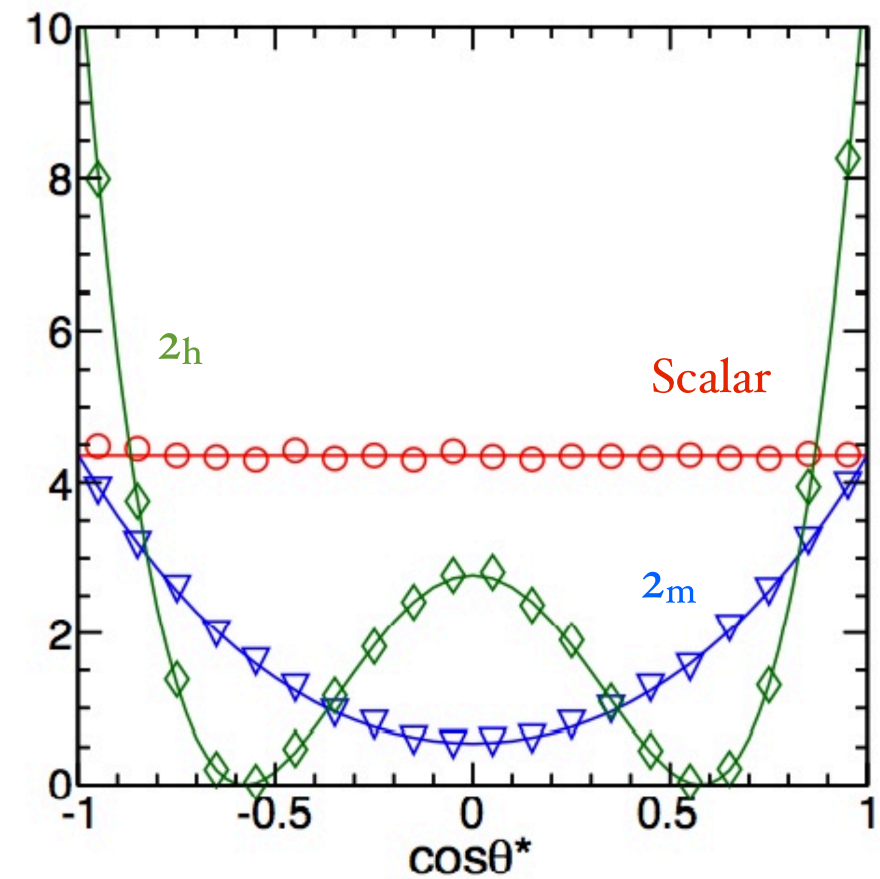
spin 2

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

Used by CMS through MELA

$X \to \gamma\gamma$

K.Melnikov et al. (2009, 2012)



Even 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

Dependence on the production model comes from spin correlations

JHU analysis suggests that $\cos\theta^*$ distribution in $X \to \gamma\gamma$ can discriminate between spin 0 and spin 2 with 2.4σ having 5σ evidence

Too optimistic ?

- very small S/B and background extracted from data
- only one variable available contrary to what happens in $X \to ZZ$
- p_T cuts affect $\cos\theta^*$ significantly

TH Intermezzo: 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)

TH Intermezzo: Spin 2

A consistent effective description (with a cut off at least an order of magnitude larger than the mass) 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

$\Rightarrow$ $\Gamma(H \rightarrow gg) = 8\,\Gamma(H \rightarrow \gamma\gamma)$

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

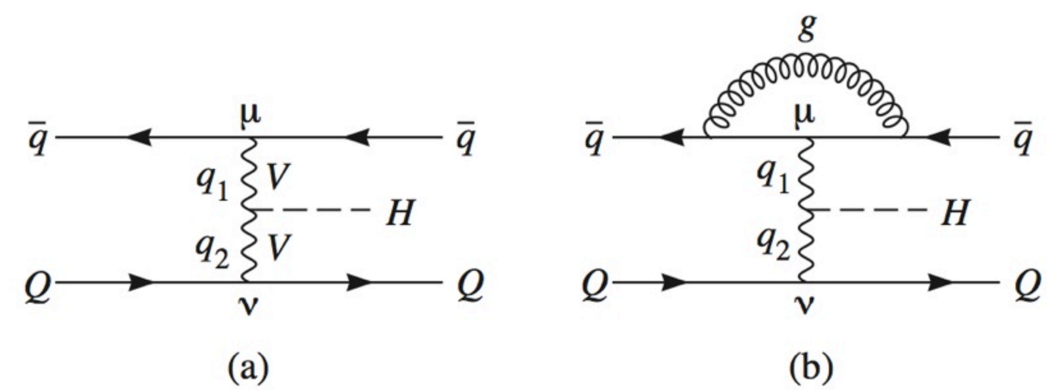
VBF@NLO

D.Zeppenfeld et al.

Spin 0: general HVV coupling given by

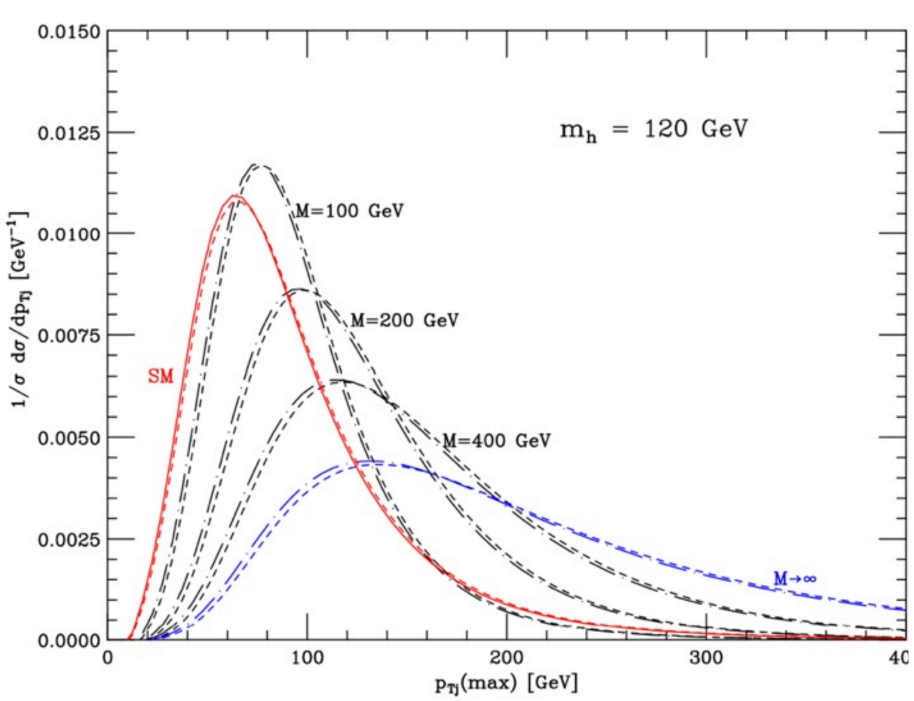
$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2)(q_1 q_2 g^{\mu\nu} - q_2^\mu q_1^\nu) + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho}$$

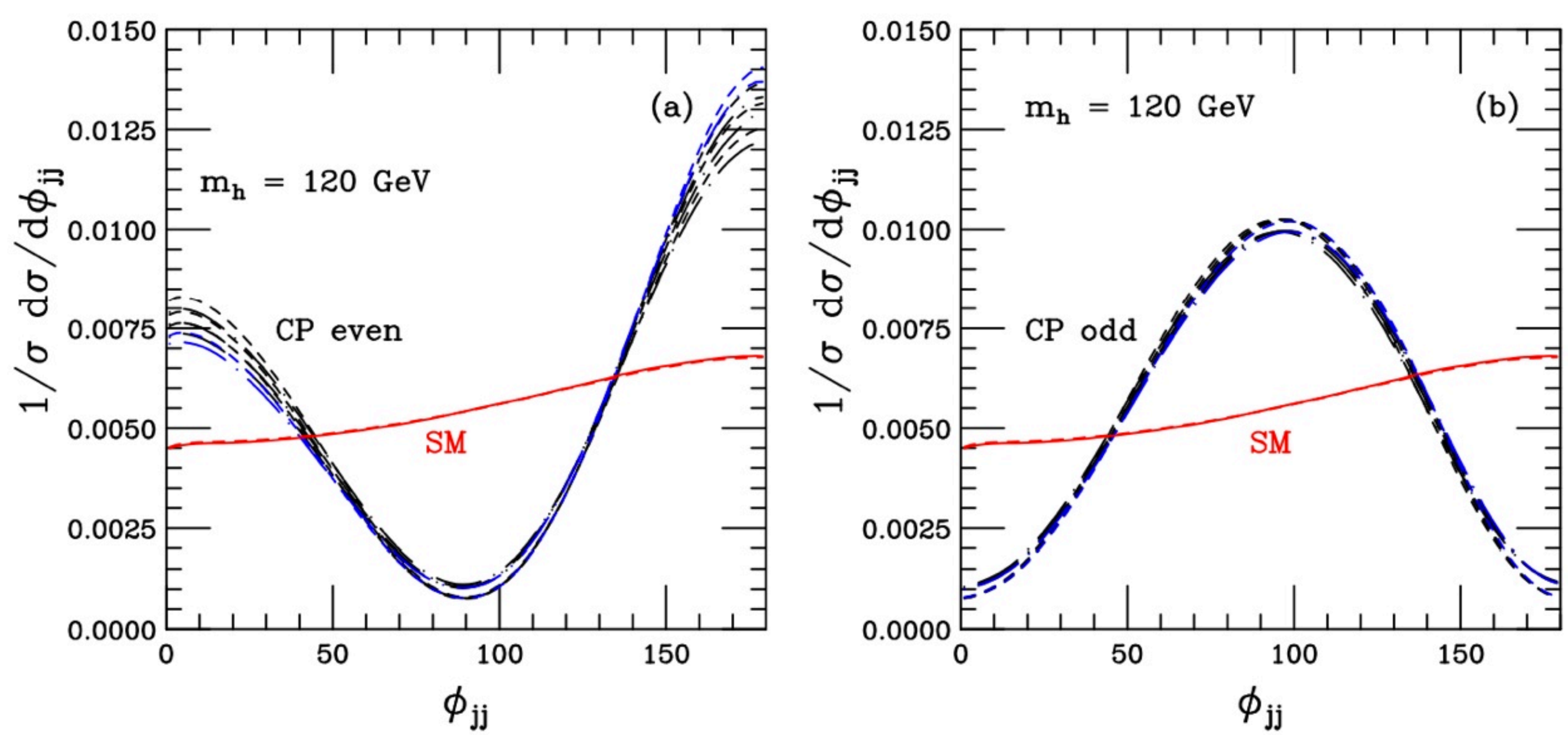
Where a_1, a_2, a_3 are scalar functions



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.

from Jessica Frank

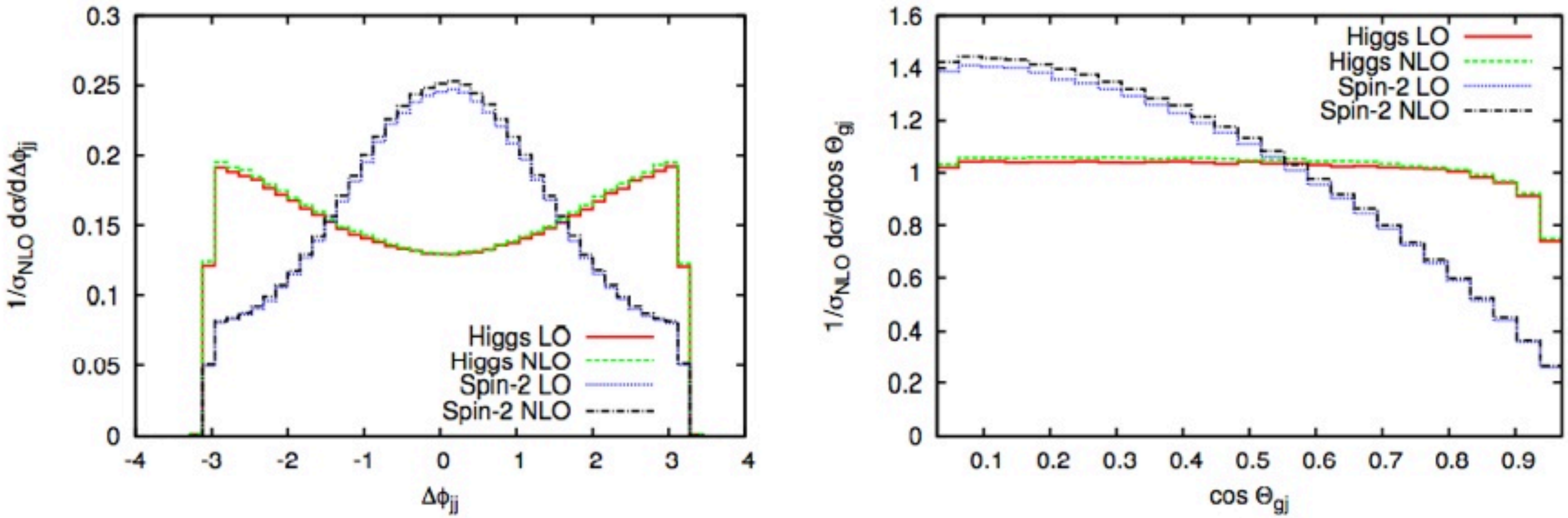
- Implementation in VBFNLO
  - VBFNLO: parton-level Monte Carlo program which simulates VBF processes at hadron colliders with NLO QCD accuracy
  - $pp \to Tjj \to \gamma\gamma jj$ public [Arnold et al., arXiv:1107.4038 [hep-ph]]
  - $pp \to Tjj \to W^+W^-jj \to l_1^+\nu_{l_1} l_2^-\bar{\nu}_{l_2}jj$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

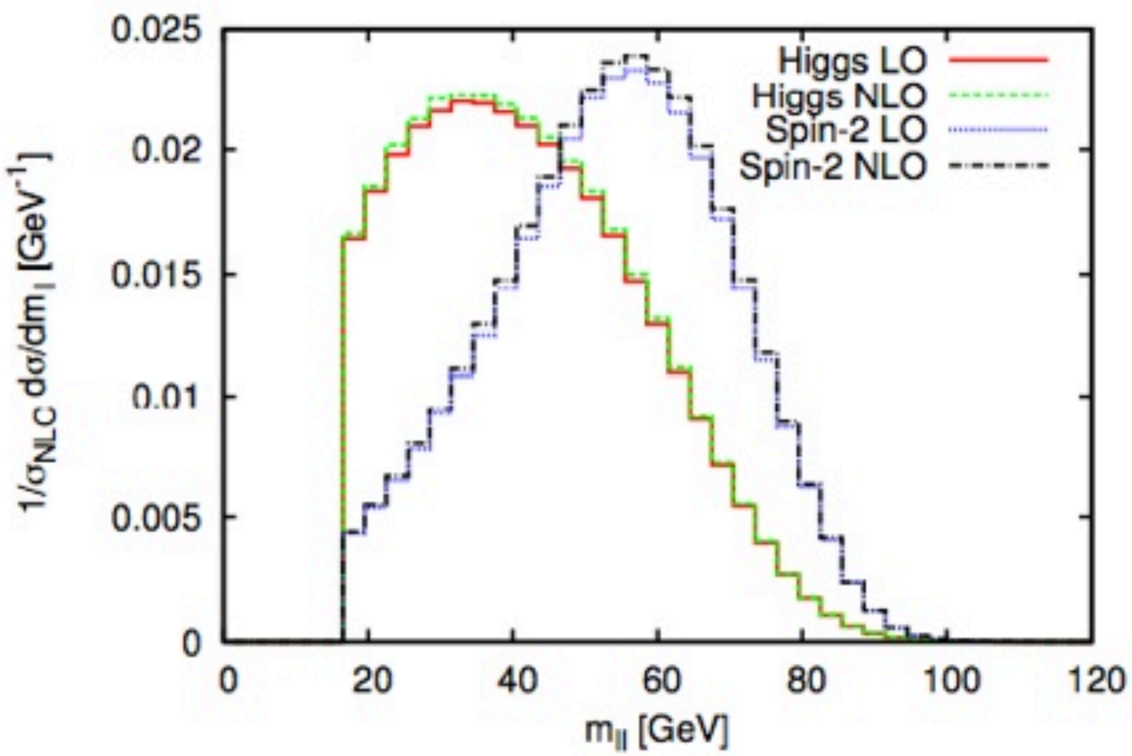
Cosine of the Gottfried-Jackson angle at LO and NLO QCD accuracy.

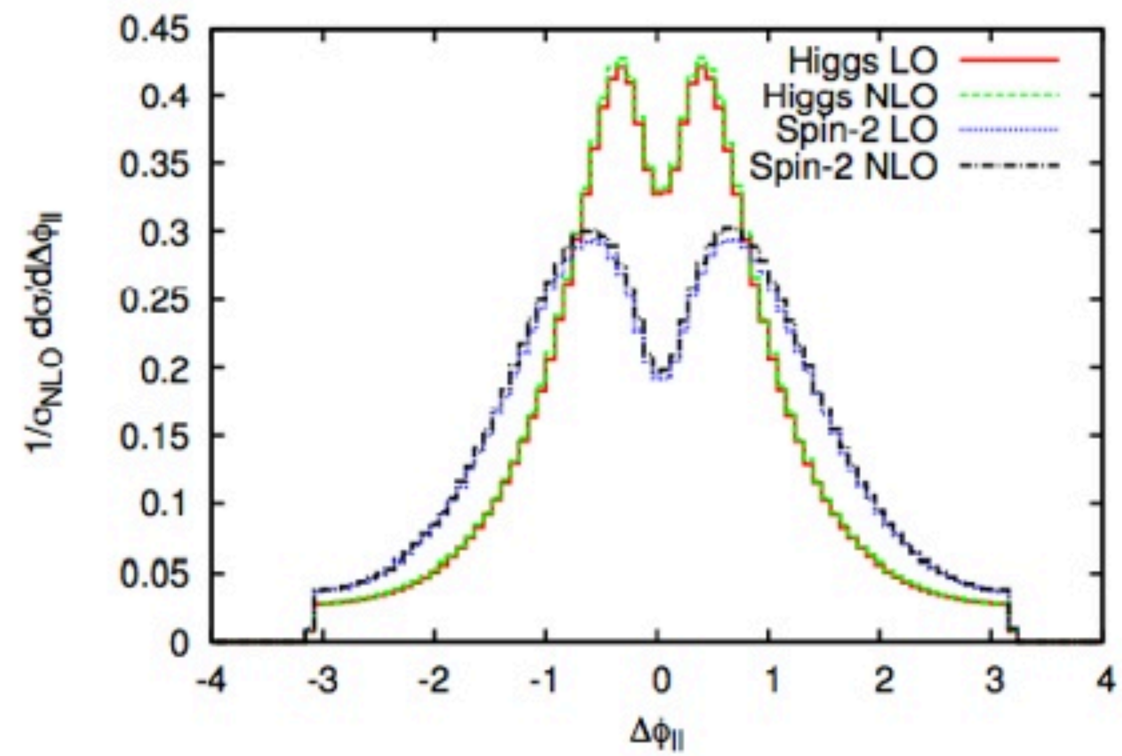
- Distinct shape for SM Higgs and spin-2 ($\Delta\Phi_{jj}$: also for W^+W^-jj and $ZZjj$)
- Nearly independent of NLO corrections and spin-2 model parameters

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

from Jessica Frank

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.

MADGRAPH 5

F.Maltoni, HC2012

0^+ $$\mathcal{L}_h = -\frac{1}{4} g_h G^a_{\mu\nu} G^{\mu\nu,a} \Phi$$

0^- $$\mathcal{L}_A = \frac{1}{2} g_A G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \Phi_A$$

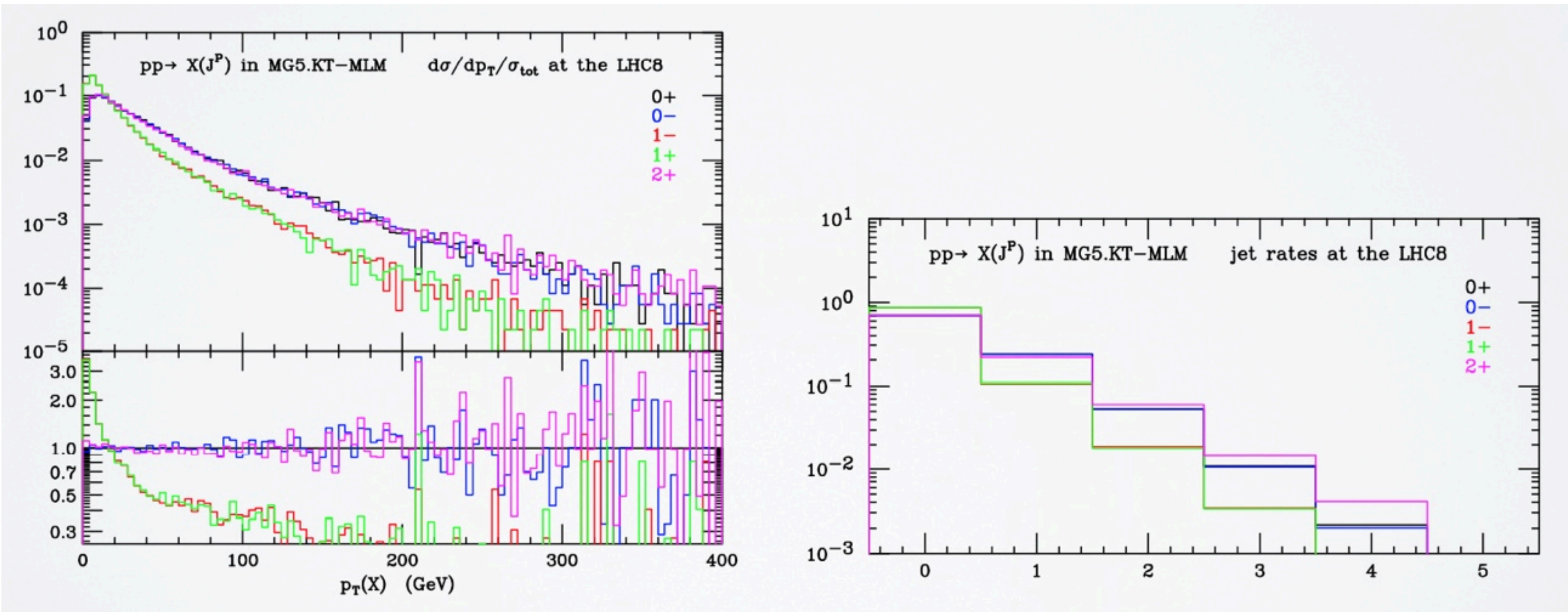
$1^{-/+}$ $$\mathcal{L}_V = \bar{\psi}(a + b\gamma_5)\gamma^\mu \psi V^\mu + \mathrm{Int}(V_\mu, W^+_\nu, W^-_\rho) + \mathrm{Int}(V_\mu, Z_\nu, Z_\rho)$$

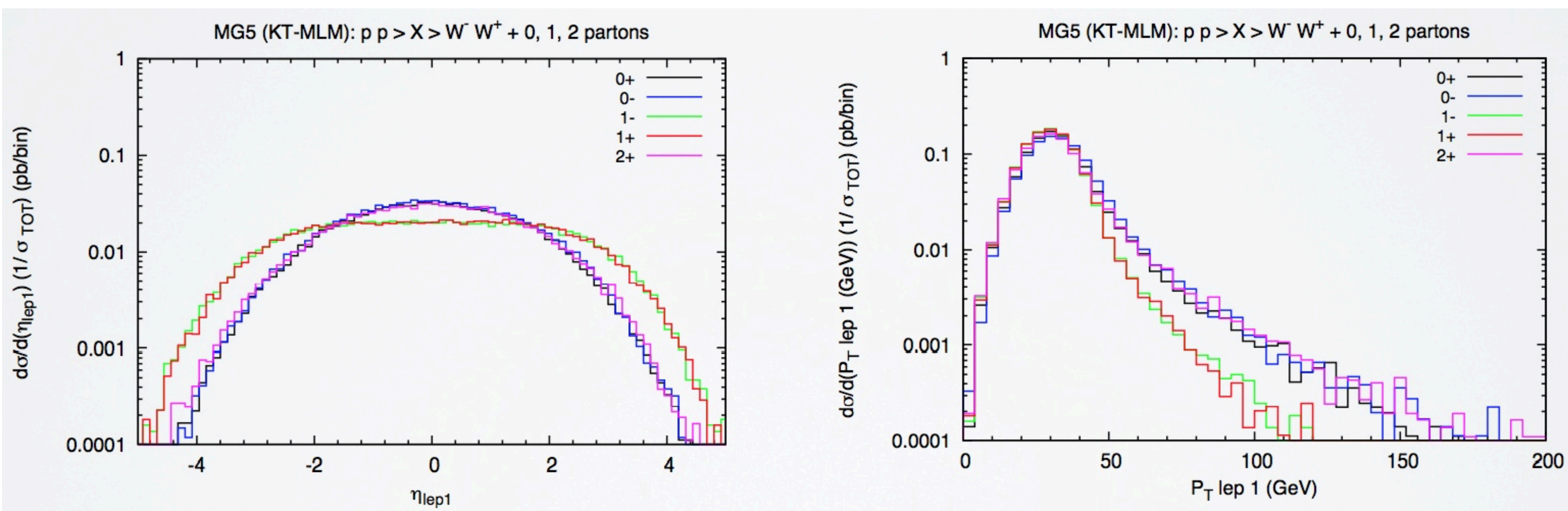
2^+ $$\mathcal{L}_G = -\frac{1}{\Lambda} T_{\mu\nu} \mathcal{T}^{\mu\nu}$$

Any other state/interaction comes from higher-dimensional operators and it is therefore suppressed. For all the above interactions **production and decay,** (possibly including interference with SM processes), can be inherited by **FEYNRULES** and then simulated in **MADGRAPH5** as inclusive merged samples for any production channel (which works out of the box).

MADGRAPH 5

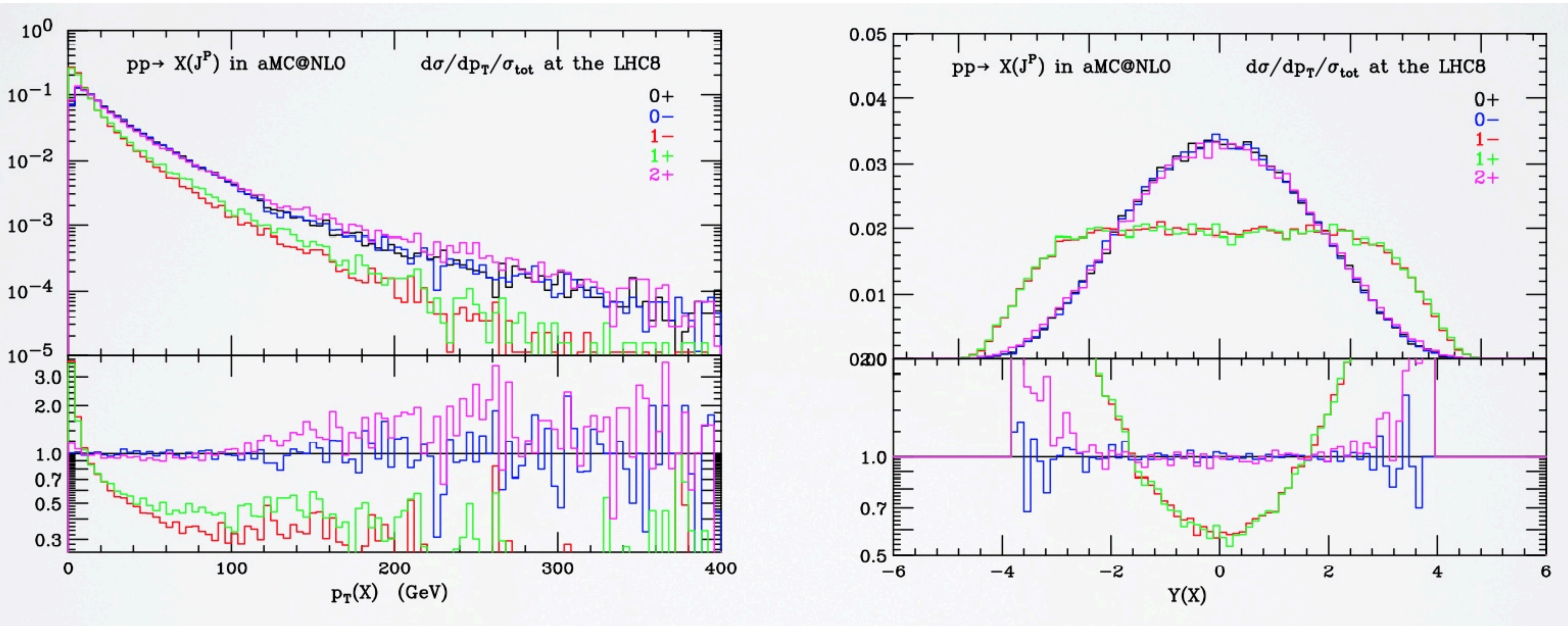
F.Maltoni, HC2012





Main differences between spin 0/2 and spin 1 scenarios

aMC@NLO



F.Maltoni, HC2012

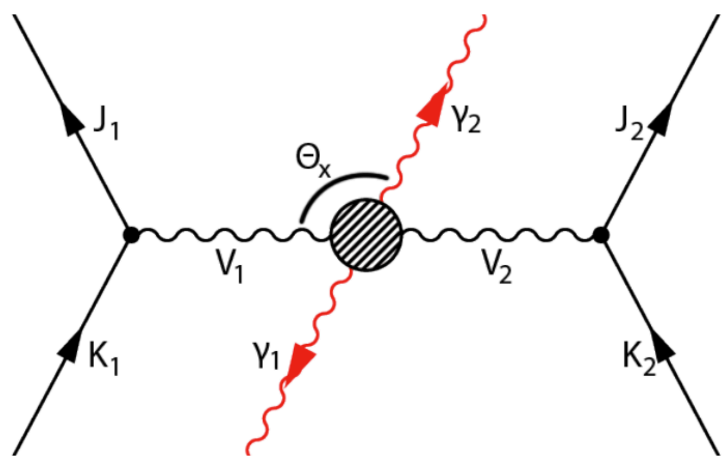
It would be interesting to see the effects of QCD radiation on the relevant angular variables

What else ?

- $X \to WW \to l\nu l\nu$

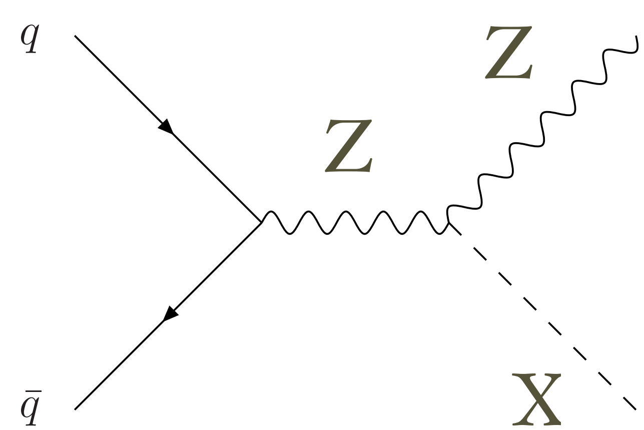
  Final state cannot be fully reconstructed but JHU study shows good discriminating power for spin-2 minimal model

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



- ZX has the same tensor entering in $X \to ZZ \to 4l$

  $O(p^2)$ operators in the spin 2 case will lead to very-high ZX invariant masses



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 should allow to study JCP almost independently on the production mechanism (having enough statistics.....)
- The new tool aMC@NLO can be used to assess the impact of QCD effects (or equivalently of a non zero p_T): presumably small on angular variables (but needs to be checked)
- In the $X \to \gamma\gamma$ the final state is also fully reconstructed but we have only one handle through the $\cos\theta^*$ distribution (and a huge background that is measured from data)

  → things appear to be more difficult

Summary & Outlook

- $X \to WW$ can be complementary to $X \to ZZ$ and $X \to \gamma\gamma$
- Use other channels as ZX ($X \to bb$) and $X \to \gamma\gamma$ in VBF as more data become available
- We should identify new experimental observables (like angular correlations in ZZ, WW, m(ZX), pt(H) in VBF, ...) and the kind of physics to which they are most sensitive
- BSM effects will in general affect both couplings and tensor structures

$\Rightarrow$ Common strategy for couplings and JCP determination ?