Vrije Universiteit Brussel

# Higgs characterisation

## - beyond leading order

Kentarou Mawatari

(Vrije Universiteit Brussel and International Solvay Institutes)

[arXiv: 1306.6464]

The FeynRules and MadGraph5 framework

FeynRules model
P. de Aquino, K. Mawatari (Vrije U. Brussel)

MadWeight
P. Artoisenet (Nikhef)

aMC@NLO
F. Demartin, F. Maltoni, M. Zaro (UC Louvain)
R. Frederix, S. Frixione (CERN)
P. Torrielli (Zurich)

spin2 in aMC@NLO
M.K. Mandal (Harish-Chandra)
P. Mathews, S. Seth (Saha Inst.)
V. Ravindran (CIT)

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# about 50 years ago...

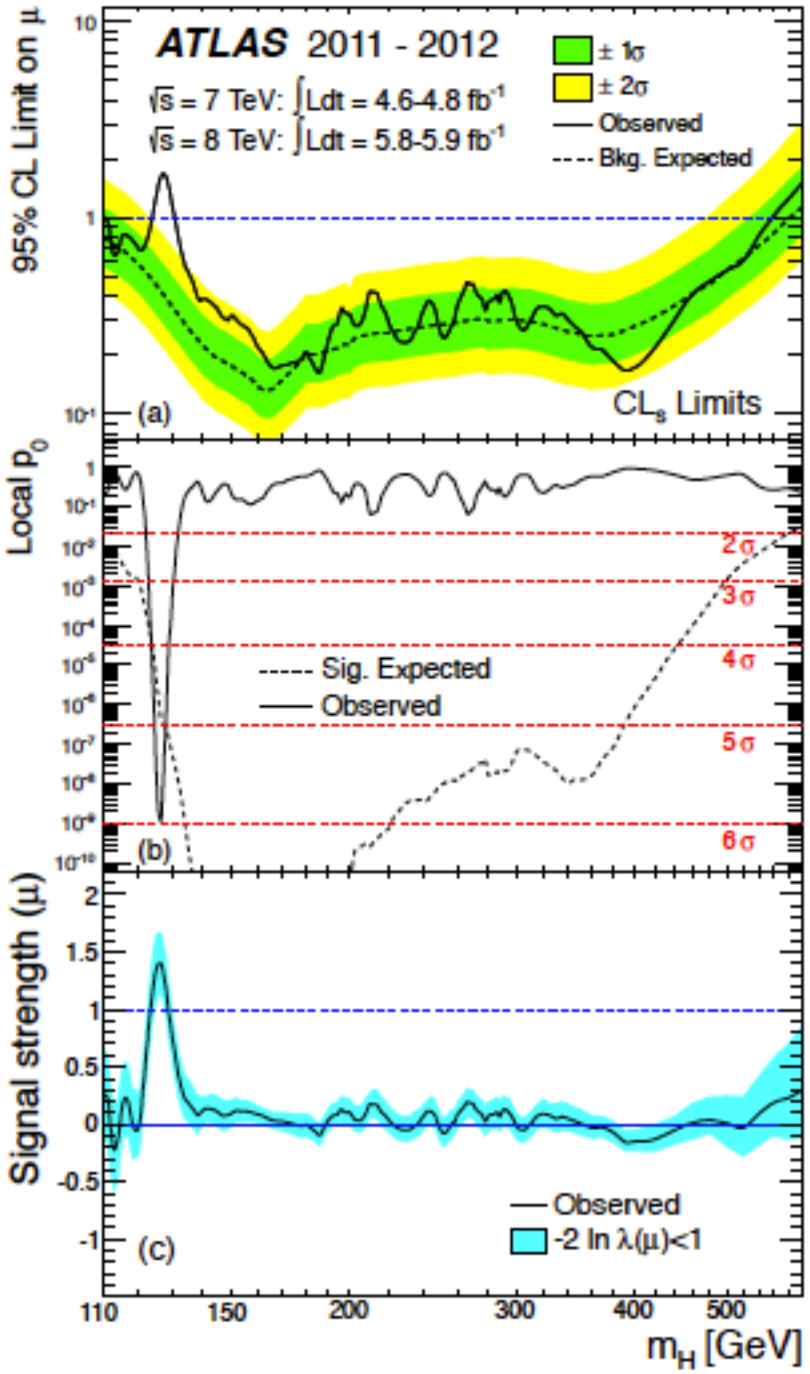
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
*Tait Institute of Mathematical Physics, University of Edinburgh, Scotland*

Received 27 July 1964




# July 4th, 2012

**Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC**

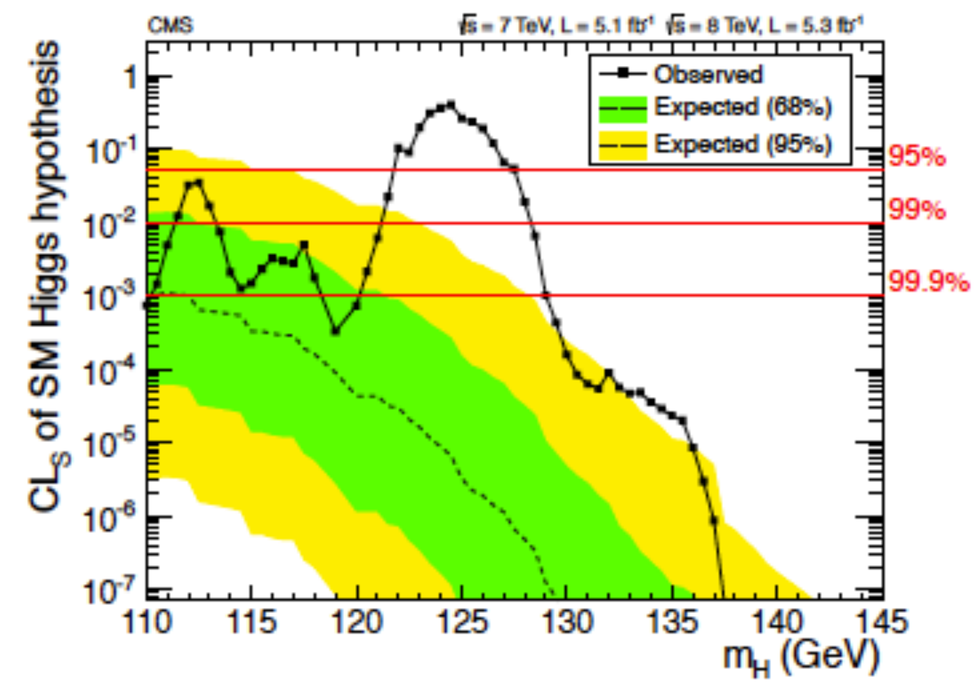
[arXiv: 1207.7214]

The ATLAS Collaboration

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

[arXiv: 1207.7235]

The CMS Collaboration



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# July 4th, 2013

arXiv:1307.1432v1 [hep-ex] 4 Jul 2013

## Evidence for the spin-0 nature of the Higgs boson using ATLAS data

The ATLAS Collaboration

**Abstract**

Studies of the spin and parity quantum numbers of the Higgs boson are presented, based on proton–proton collision data collected by the ATLAS experiment at the LHC. The Standard Model spin–parity $J^P = 0^+$ hypothesis is compared with alternative hypotheses using the Higgs boson decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$, as well as the combination of these channels. The analysed dataset corresponds to an integrated luminosity of 20.7 fb$^{-1}$ collected at a centre–of–mass energy of $\sqrt{s} = 8$ TeV. For the $H \to ZZ^* \to 4\ell$ decay mode the dataset corresponding to an integrated luminosity of 4.6 fb$^{-1}$ collected at $\sqrt{s} = 7$ TeV is added. The data are compatible with the Standard Model $J^P = 0^+$ quantum numbers for the Higgs boson, whereas all alternative hypotheses studied in this letter, namely some specific $J^P = 0^-, 1^+, 1^-, 2^+$ models, are excluded at confidence levels above 97.8%. This exclusion holds independently of the assumptions on the coupling strengths to the Standard Model particles and in the case of the $J^P = 2^+$ model, of the relative fractions of gluon–fusion and quark–antiquark production of the spin-2 particle. The data thus provide evidence for the spin-0 nature of the Higgs boson, with positive parity being strongly preferred.

# Is this the Standard Model scalar boson?

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➡ determination of the Higgs Lagrangian

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## A framework for Higgs characterisation

[arXiv: 1306.6464]

P. Artoisenet,[a] P. de Aquino,[b] F. Demartin,[c] R. Frederix,[d] S. Frixione,[d,e] F. Maltoni,[c] M. K. Mandal,[f] P. Mathews,[g] K. Mawatari,[b] V. Ravindran,[h] S. Seth,[g] P. Torrielli,[i] M. Zaro[c]

ABSTRACT: We introduce a complete framework, based on an effective field theory approach, that allows one to perform characterisation studies of the boson recently discovered at the LHC, for all the relevant channels and in a consistent, systematic and accurate way.

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- Introduction
- Higgs characterisation framework
  - Effective Lagrangians -- $X(J=0,1,2)$
- beyond-leading-order effects in QCD
  - inclusive production $pp \to X(J^P)$
  - unitarity-violating behavior for $X(J=2)$
  - higher order QCD effects on spin observables
- Summary

# FeynRules in a nutshell

Christensen, Duhr, Fuks, http://feynrules.irmp.ucl.ac.be

- a Mathematica package that allows to derive Feynman rules from a Lagrangian.
- allows to export the Feynman rules to various matrix element generators, e.g. MadGraph.

- The only requirements on the Lagrangian are:
  - ✓ All indices need to be contracted.
  - ✓ Locality.
  - ✓ Supported filed types: spin-0, 1/2, 1, 3/2, and 2.

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new!

[arxiv:1308.1668] see B.Oexl talk.

# Higgs Characterisation model

- We implemented an effective Lagrangian featuring bosons

$$X(J^P = 0^+, 0^-, 1^+, 1^-, 2^+)$$

in FeynRules.

  - Effective field theory approach, valid up to a cutoff scale Λ
  - Only one new bosonic state $X(J^P)$ at the EW scale (No other state below the cutoff Λ)
  - Any new physics is described by the lowest dimensional operators.

The parametrization is based on the recent work [Englert, Goncalves-Netto, KM, Plehn (2013)].

# Effective Lagrangian -- spin0

- allows one to recover the SM case easily.
- includes all possible interactions that are generated by gauge-invariant D6 operators above the EW scale
- includes $0^-$ state couplings typical of SUSY or of generic 2HDM
- allows CP-mixing between $0^+$ and $0^-$ states

| parameter | reference value | description |
|---|---|---|
| $\Lambda$ [GeV] | $10^3$ | cutoff scale |
| $c_\alpha (\equiv \cos\alpha)$ | 1 | mixing between $0^+$ and $0^-$ |
| $\kappa_i$ | 0 , 1 | dimensionless coupling parameter |

| $g_{Xyy'} \times v$ | $ff$ | $ZZ/WW$ | $\gamma\gamma$ | $Z\gamma$ | $gg$ |
|---|---|---|---|---|---|
| $H$ | $m_f$ | $2m^2_{Z/W}$ | $47\alpha_{EM}/18\pi$ | $C(94\cos^2\theta_W - 13)/9\pi$ | $-\alpha_s/3\pi$ |
| $A$ | $m_f$ | 0 | $-4\alpha_{EM}/3\pi$ | $-2C(8\cos^2\theta_W - 5)/3\pi$ | $-\alpha_s/2\pi$ |

# Effective Lagrangian -- spin0

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar{\psi}_f \left( c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\, \gamma_5 \right) \psi_f X_0$$

$$\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \left[ \frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu} \right] \\
& - \frac{1}{4} \left[ c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[ c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[ c_\alpha \kappa_{Hgg} g_{Hgg}\, G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[ c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[ c_\alpha \kappa_{HWW}\, W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu} \right] \\
& - \frac{1}{\Lambda} c_\alpha \left[ \kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W}\, \left( W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c. \right) \right] \Big\} X_0
\end{aligned}$$

```
##########################################
## INFORMATION FOR FRBLOCK
##########################################
Block FRBlock
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    2 1.000000e+00 # ca
    3 1.000000e+00 # kSM
    4 1.000000e+00 # kHtt
    5 1.000000e+00 # kAtt
    6 1.000000e+00 # kHbb
    7 1.000000e+00 # kAbb
    8 1.000000e+00 # kHll
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   10 1.000000e+00 # kHaa
   11 1.000000e+00 # kAaa
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   13 1.000000e+00 # kAza
   14 1.000000e+00 # kHgg
   15 1.000000e+00 # kAgg
   16 0.000000e+00 # kHzz
   17 0.000000e+00 # kAzz
   18 0.000000e+00 # kHww
   19 0.000000e+00 # kAww
   20 0.000000e+00 # kHda
   21 0.000000e+00 # kHdz
   22 0.000000e+00 # kHdw
```

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm),$$

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c,$$

$$\widetilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$$

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& - \frac{1}{4} \big[ c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu} \big] \\
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   18 0.000000e+00 # kHww
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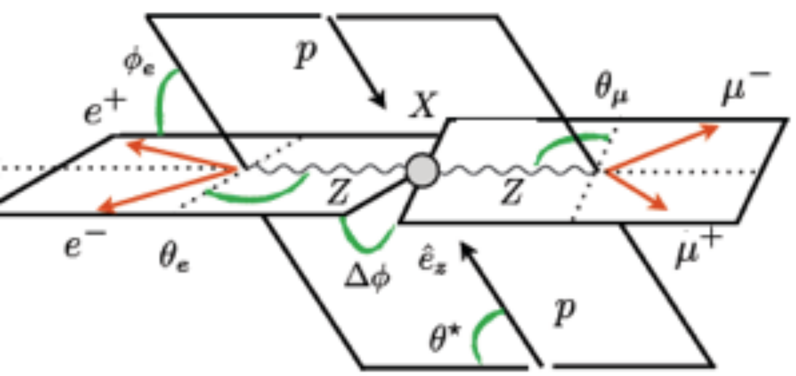
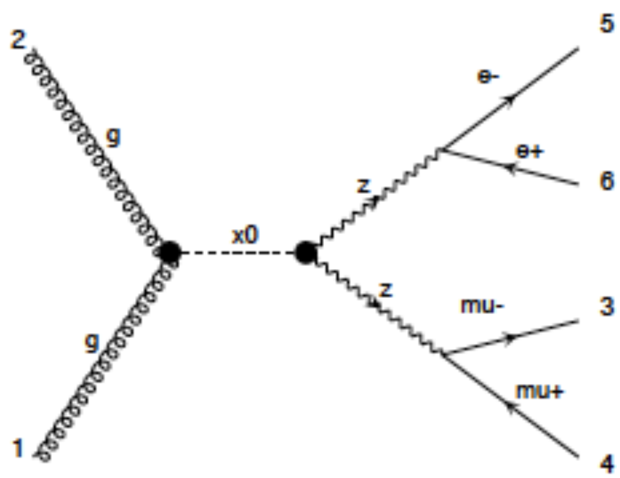
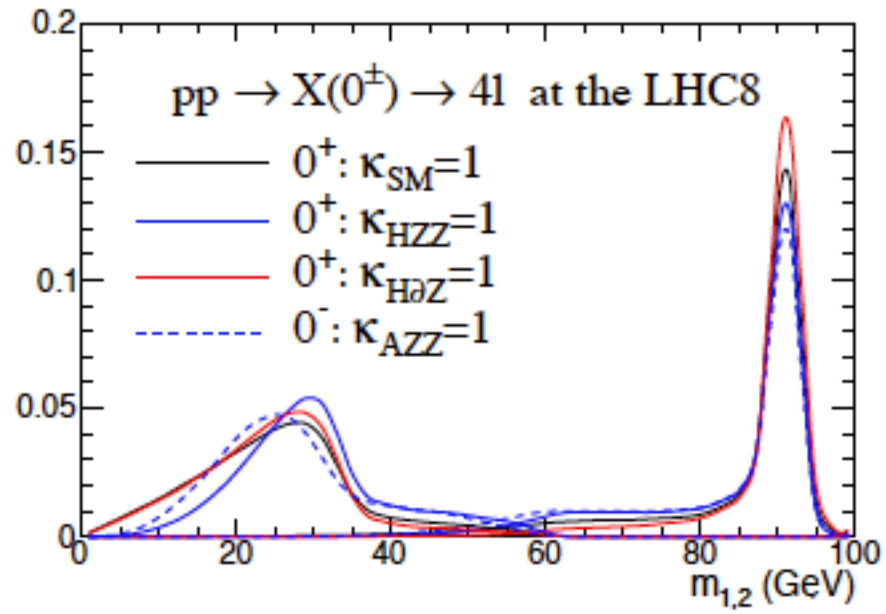
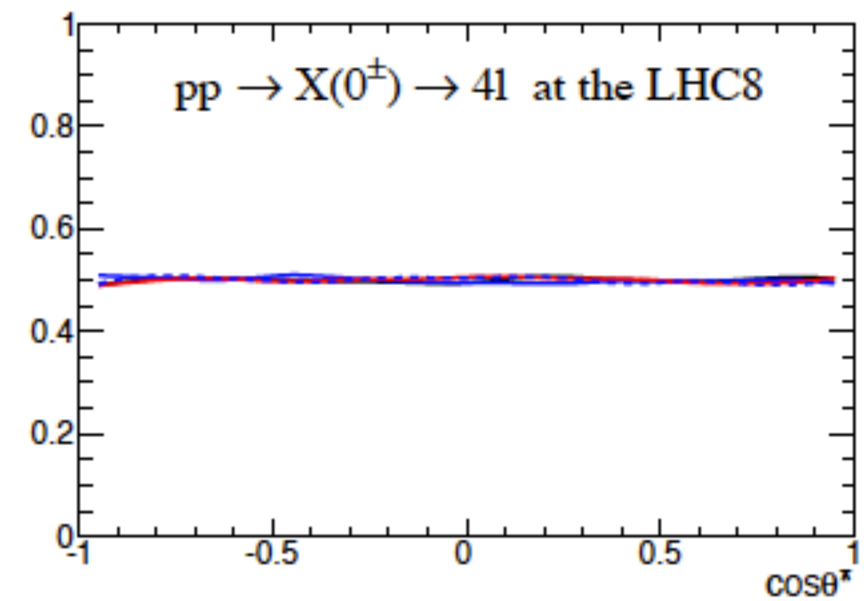
   20 0.000000e+00 # kHda
   21 0.000000e+00 # kHdz
   22 0.000000e+00 # kHdw
```

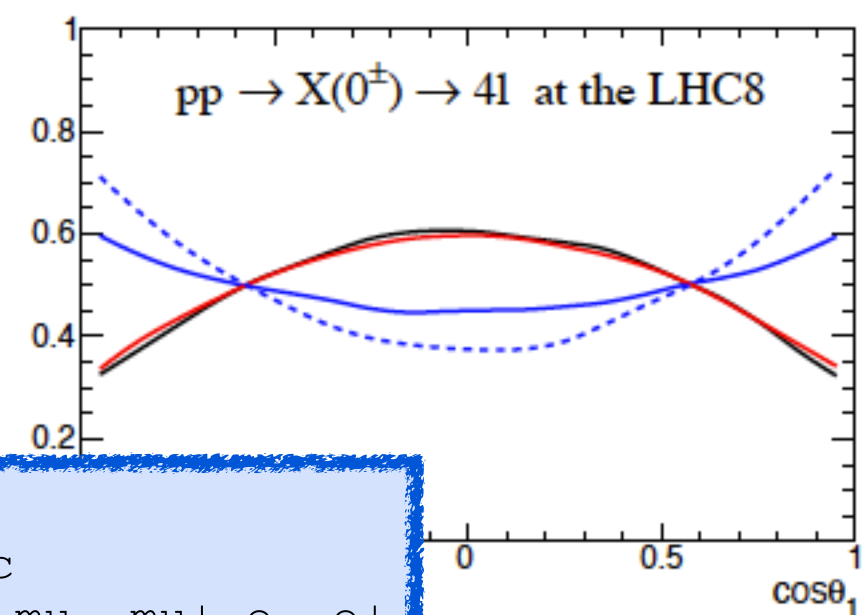
# Mass and angular distributions -- spin0

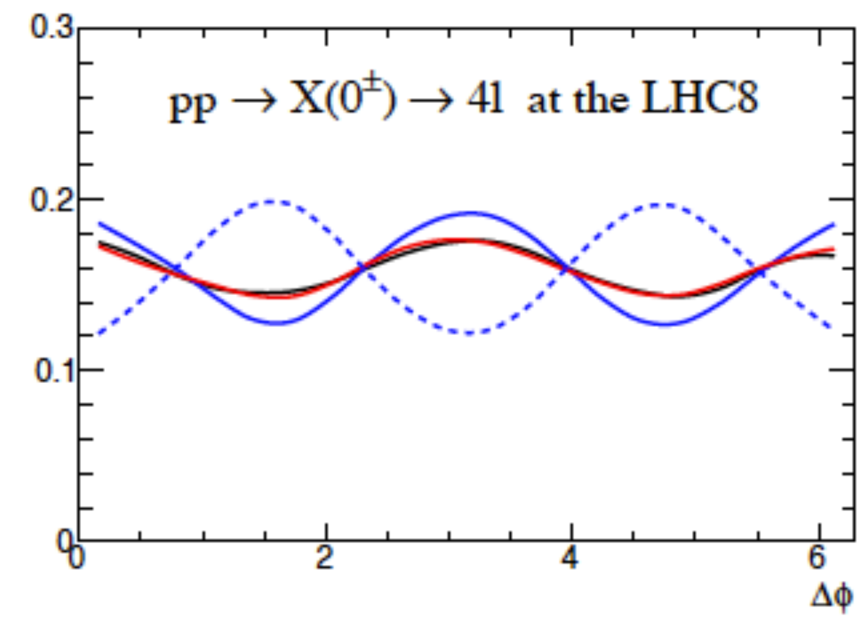



```
./bin/mg5
>import model HiggsCharac
>generate p p > x0, x0 > mu- mu+ e- e+
>output
>launch
```

# Effective Lagrangian -- spin1

- The most general interactions at the lowest canonical dimension:

$$\mathcal{L}_1^f = \sum_{f=q,\ell} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu$$

$$\begin{aligned}\mathcal{L}_1^W = & \, i\kappa_{W_1} g_{WWZ} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) X_1^\nu + i\kappa_{W_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\ & - \kappa_{W_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ & + i\kappa_{W_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} - \kappa_{W_5} \epsilon_{\mu\nu\rho\sigma} [W^{+\mu} (\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu}) W^{-\nu}] X_1^\sigma\end{aligned}$$

$$\mathcal{L}_1^Z = -\kappa_{Z_1} Z_{\mu\nu} Z^\mu X_1^\nu - \kappa_{Z_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{Z_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma)$$

- Parity conservation implies that
  - for $X_1^-$ $\quad \kappa_{f_b} = \kappa_{V_4} = \kappa_{V_5} = 0$
  - for $X_1^+$ $\quad \kappa_{f_a} = \kappa_{V_1} = \kappa_{V_2} = \kappa_{V_3} = 0$

# Effective Lagrangian -- spin2

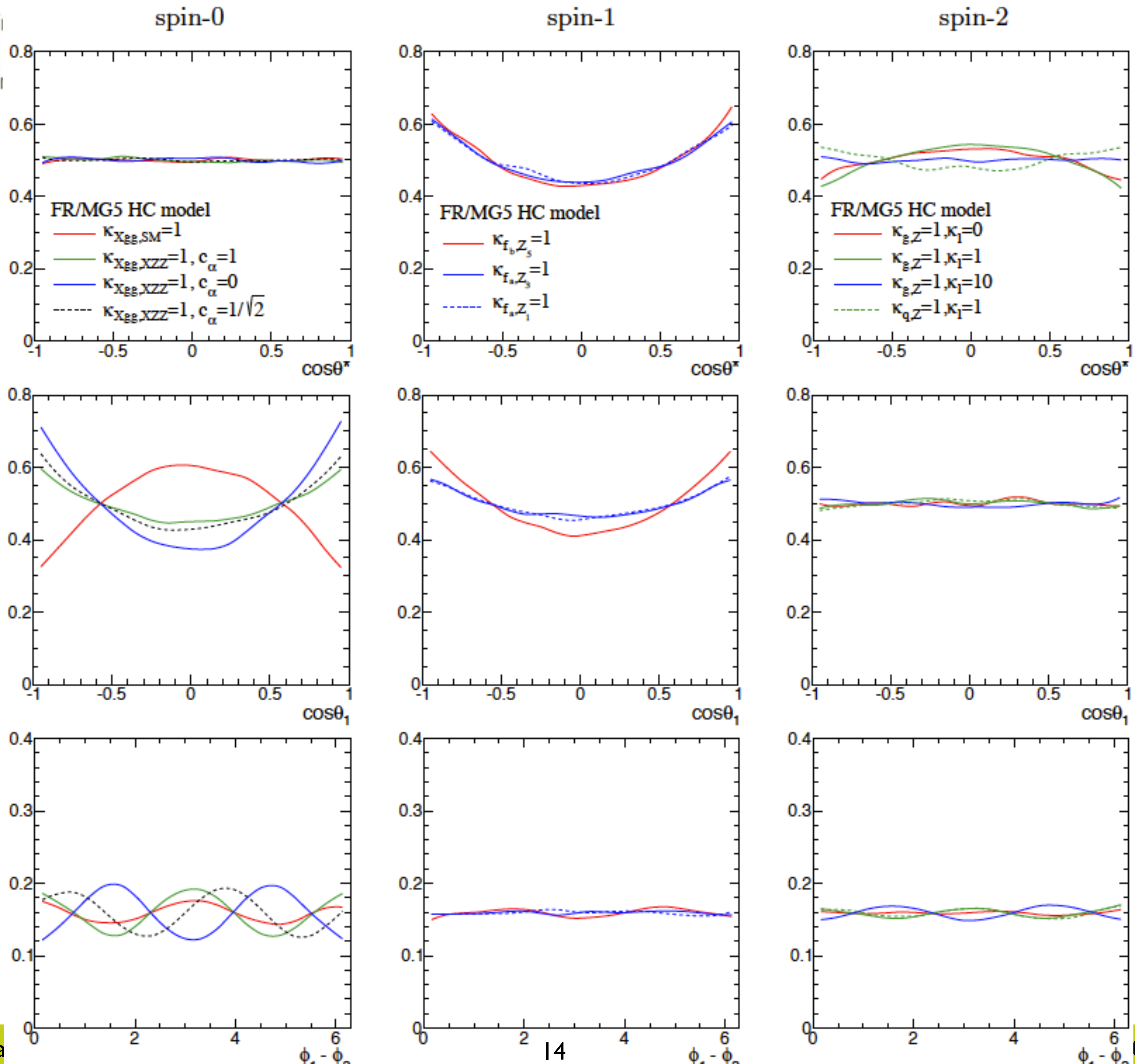
- via the energy-momentum tensor of the SM fields, starting from D5:

$$\mathcal{L}_2^f = -\frac{1}{\Lambda} \sum_{f=q,\ell} \kappa_f T^f_{\mu\nu} X_2^{\mu\nu}$$

$$\mathcal{L}_2^V = -\frac{1}{\Lambda} \sum_{V=Z,W,\gamma,g} \kappa_V T^V_{\mu\nu} X_2^{\mu\nu}$$

- The E-M tensor for QED:

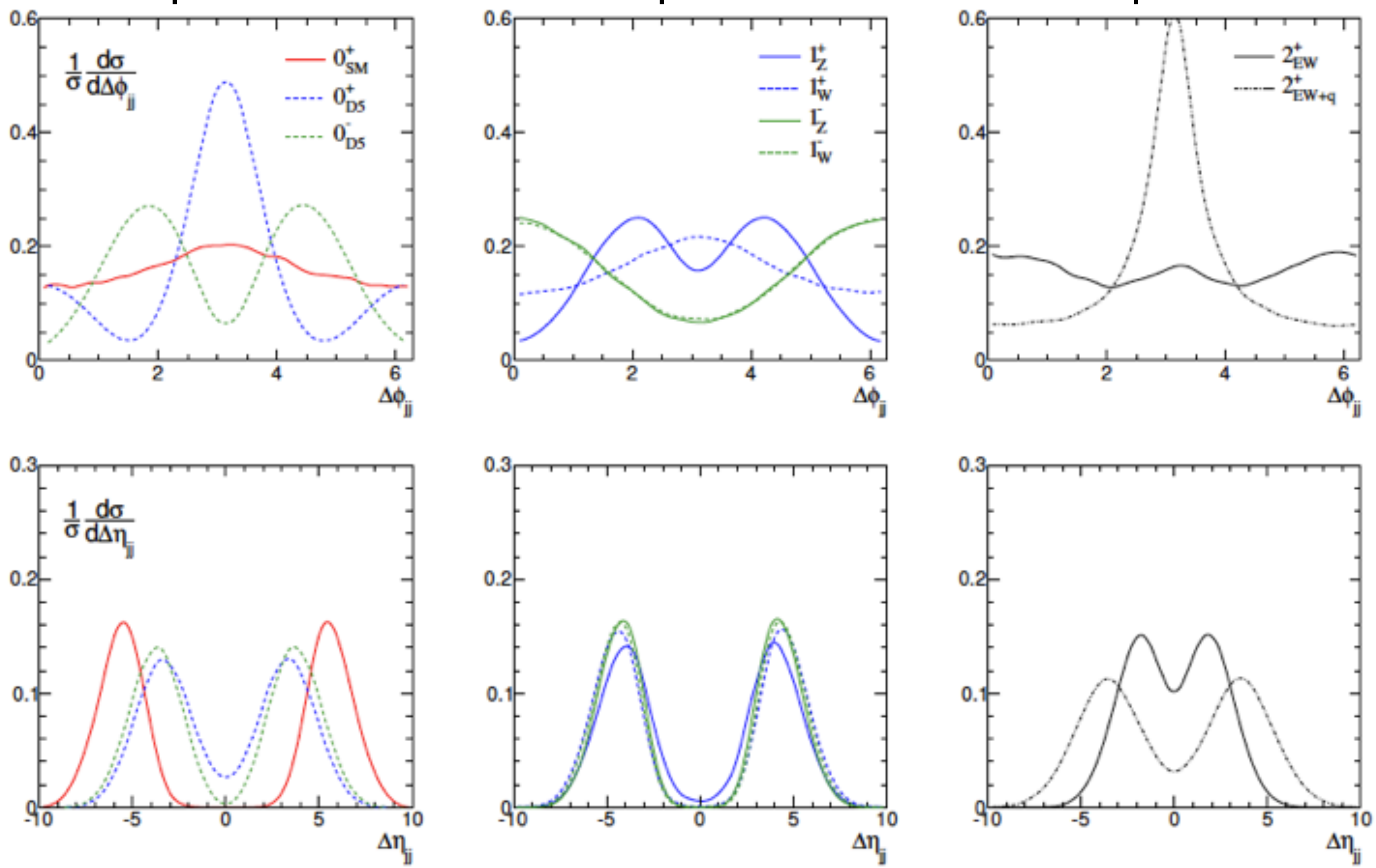
$$\begin{aligned}
T^f_{\mu\nu} =& - g_{\mu\nu}\Big[\bar\psi_f(i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar\psi_f i\gamma_\rho\psi_f)\Big] \\
&+ \Big[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu(\bar\psi_f i\gamma_\nu\psi_f) + (\mu \leftrightarrow \nu)\Big]\,, \\
T^\gamma_{\mu\nu} =& - g_{\mu\nu}\Big[-\frac{1}{4}A^{\rho\sigma}A_{\rho\sigma} + \partial^\rho\partial^\sigma A_\sigma A_\rho + \frac{1}{2}(\partial^\rho A_\rho)^2\Big] \\
&- A_\mu^{\ \rho} A_{\nu\rho} + \partial_\mu\partial^\rho A_\rho A_\nu + \partial_\nu\partial^\rho A_\rho A_\mu\,,
\end{aligned}$$


spin-0
spin-1
spin-2
FR/MG5 HC model
$\kappa_{X_{gg,SM}}=1$
$\kappa_{X_{gg,XZZ}}=1, c_\alpha=1$
$\kappa_{X_{gg,XZZ}}=1, c_\alpha=0$
$\kappa_{X_{gg,XZZ}}=1, c_\alpha=1/\sqrt{2}$
$\kappa_{f_b,Z_5}=1$
$\kappa_{f_a,Z_5}=1$
$\kappa_{f_a,Z_1}=1$
$\kappa_{g,Z}=1, \kappa_1=0$
$\kappa_{g,Z}=1, \kappa_1=1$
$\kappa_{g,Z}=1, \kappa_1=10$
$\kappa_{q,Z}=1, \kappa_1=1$
$\cos\theta^*$
$\cos\theta_1$
$\phi_1 - \phi_2$

# All the relevant channels can be simulated in a consistent, systematic and accurate way. e.g. VBF ($pp \to jjX$)

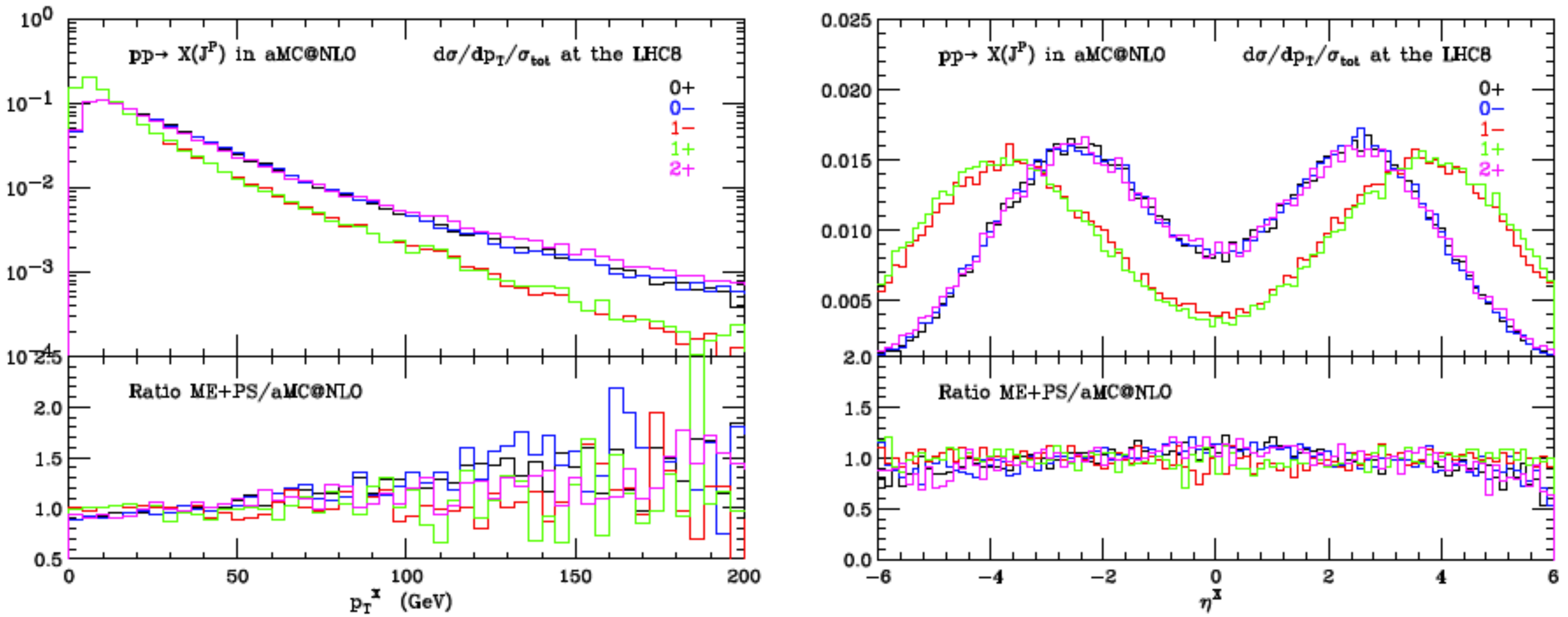
Englert, Goncalves-Netto, KM, Plehn (2013)

di-jet correlations spin-0 spin-1 spin-2



# Higher order effects in QCD

- The LO predictions can be systematically improved by including the effects due to the emission of QCD partons.
  - LO Matrix-Element/Parton-Shower merging [ME+PS]
  - full-NLO matrix element with parton-shower [aMC@NLO]



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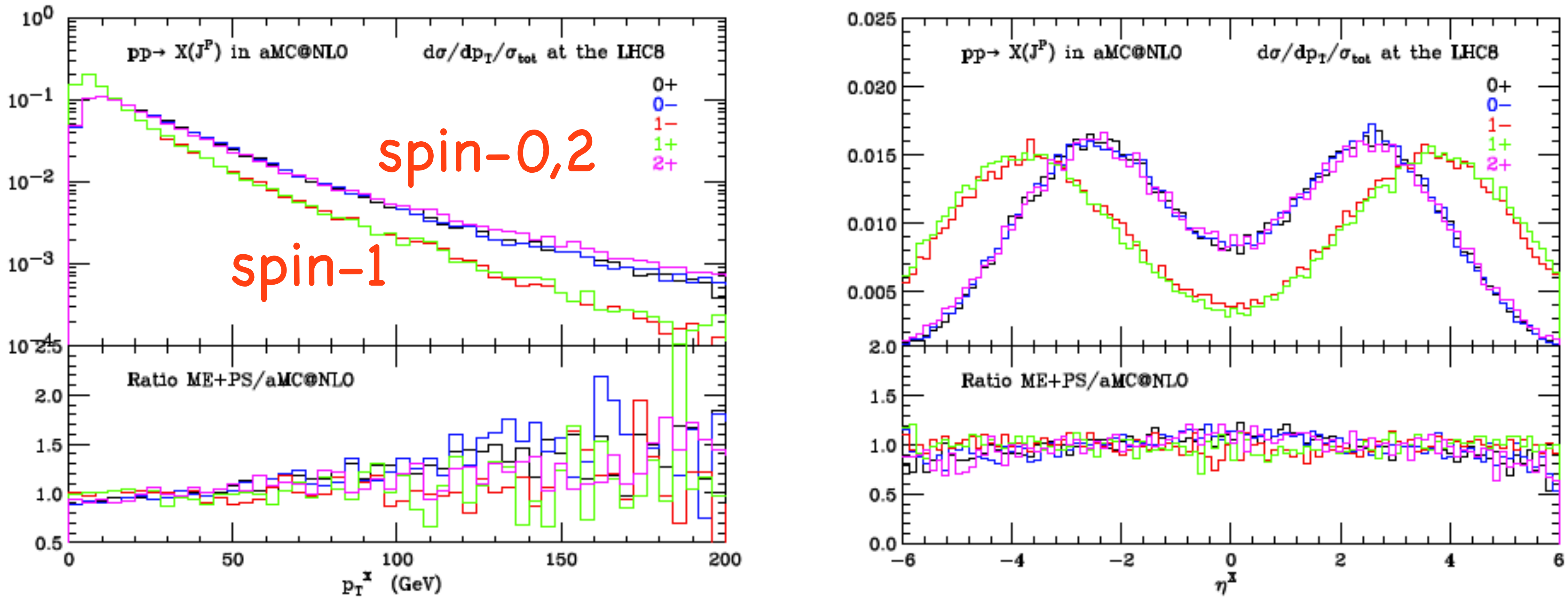
# Higher order effects in QCD (I)

## inclusive production in $pp \to X(J^P)$



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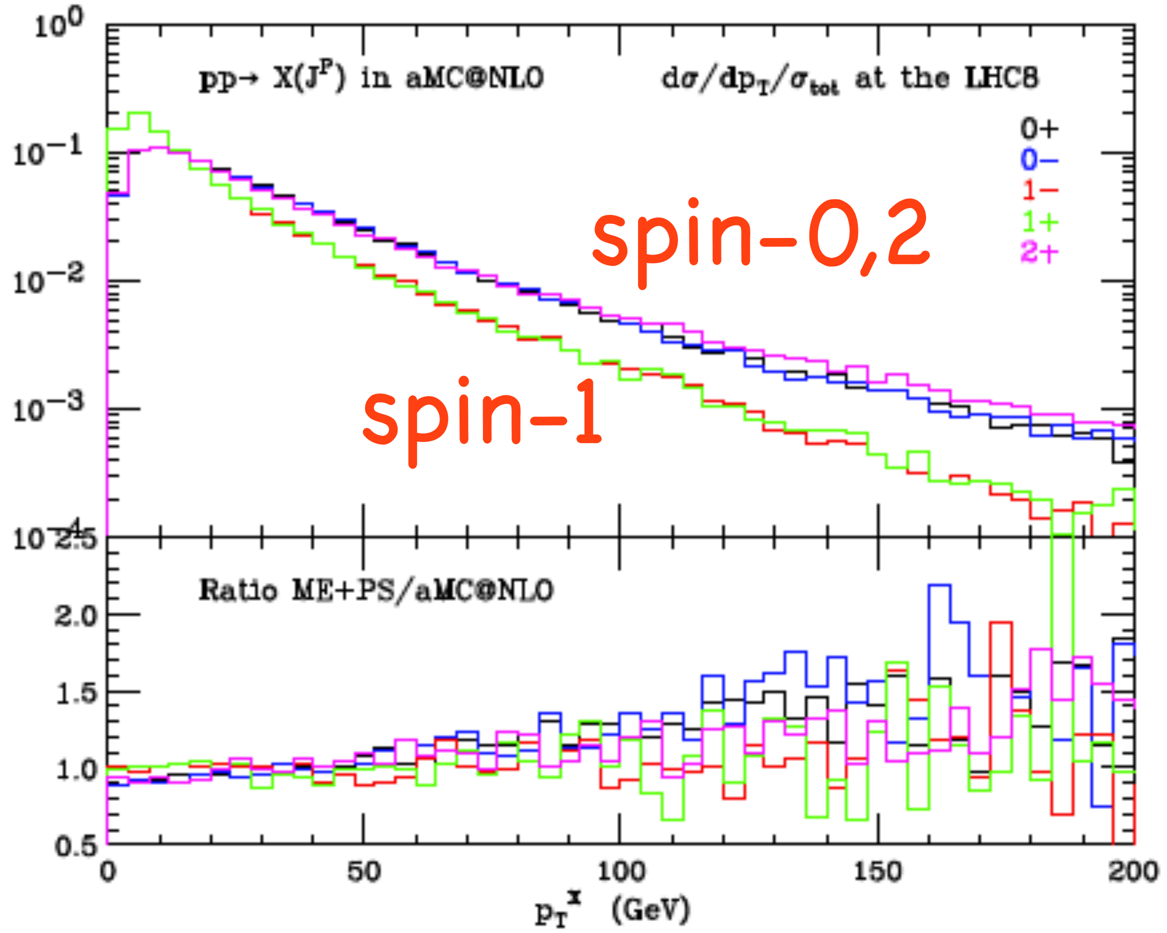
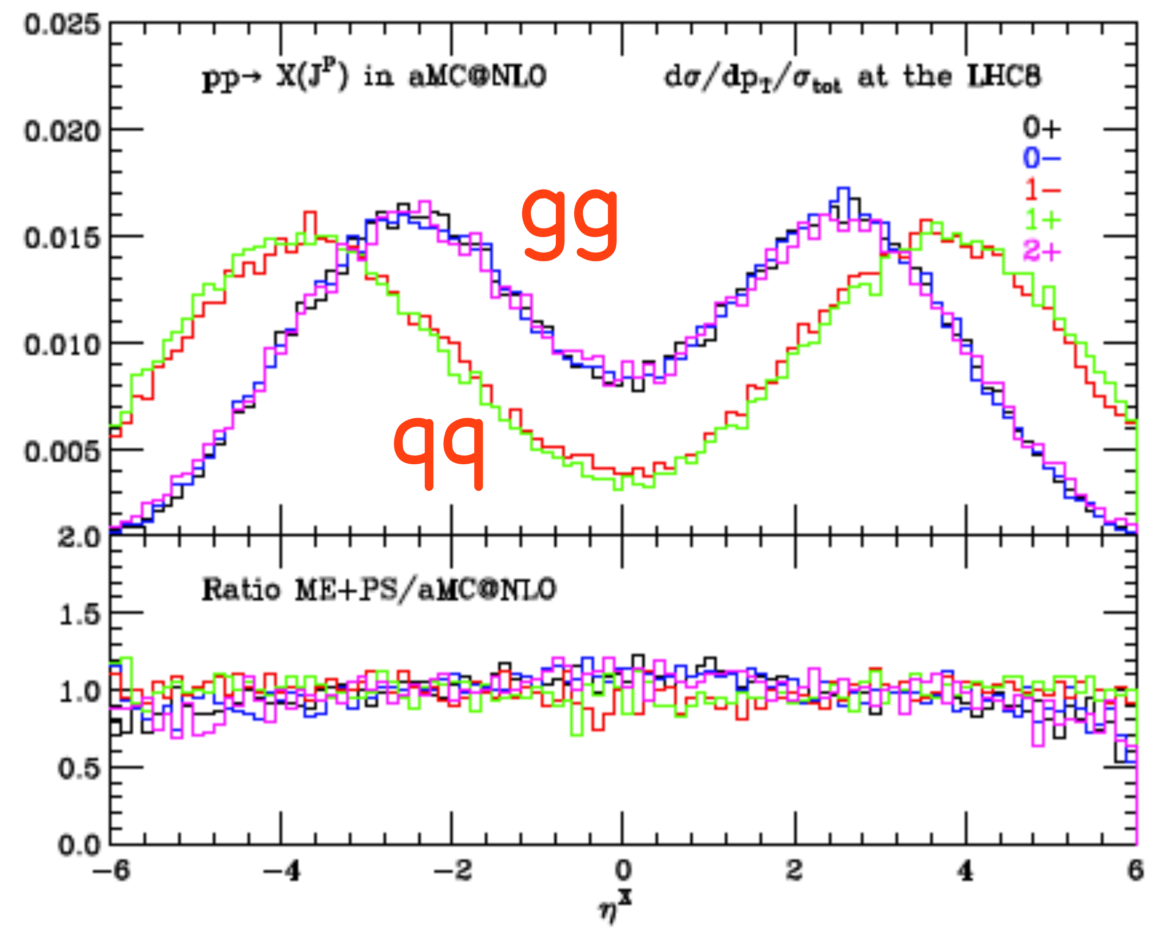



The matched sample is harder than aMC@NLO at large pT due to the extra 2 ME patrons in the matched sample.




The different shapes are due to the different initial state.

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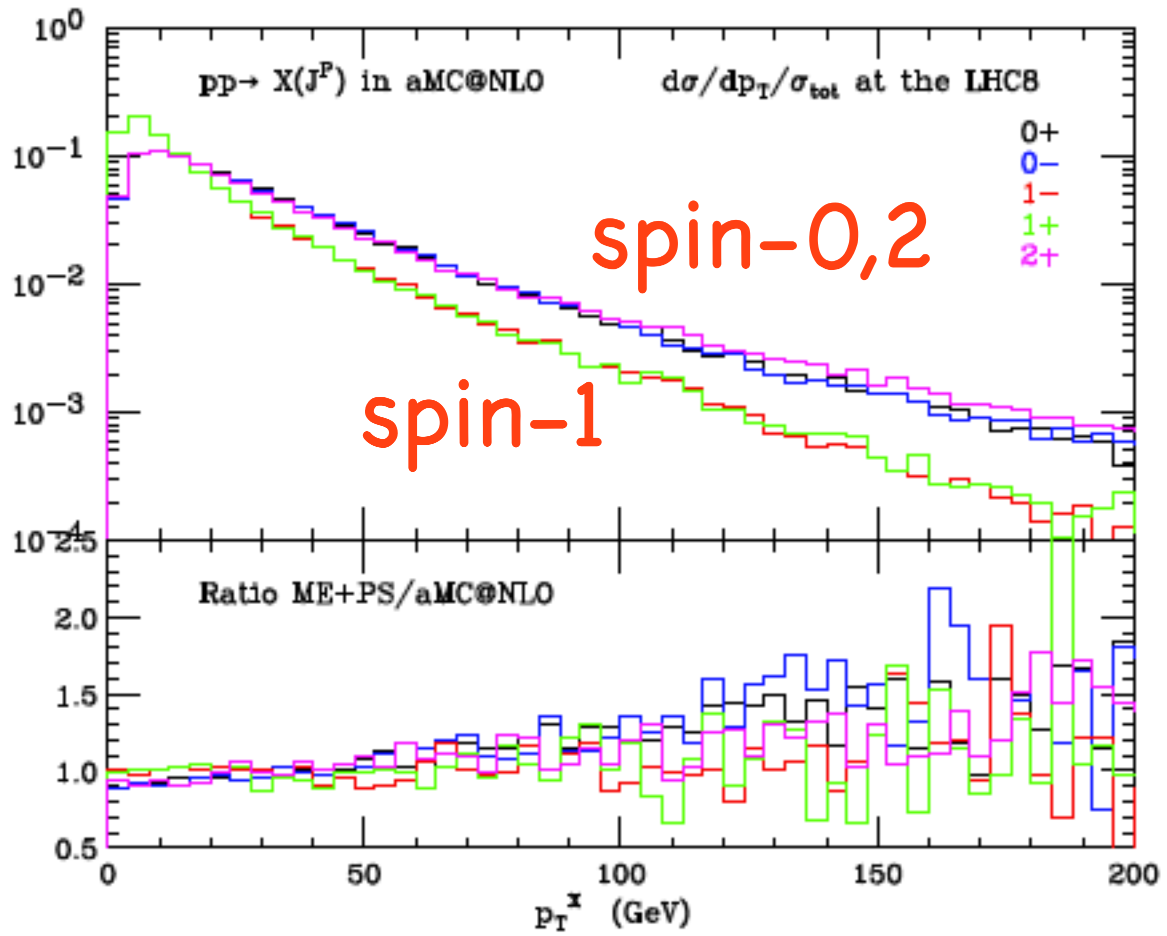
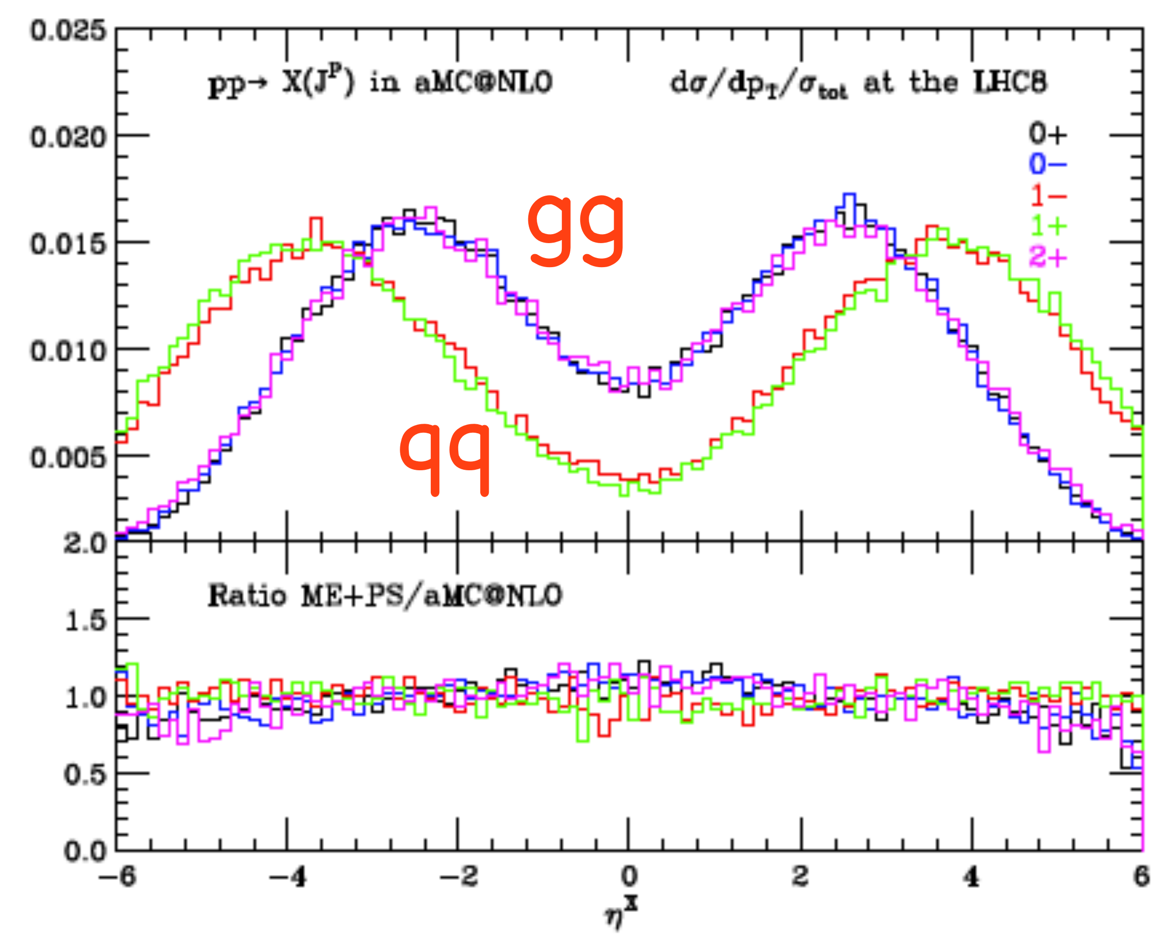
# Higher order effects in QCD (I)

## inclusive production in $pp \to X(J^P)$




The matched sample is harder than aMC@NLO at large pT due to the extra 2 ME patrons in the matched sample.

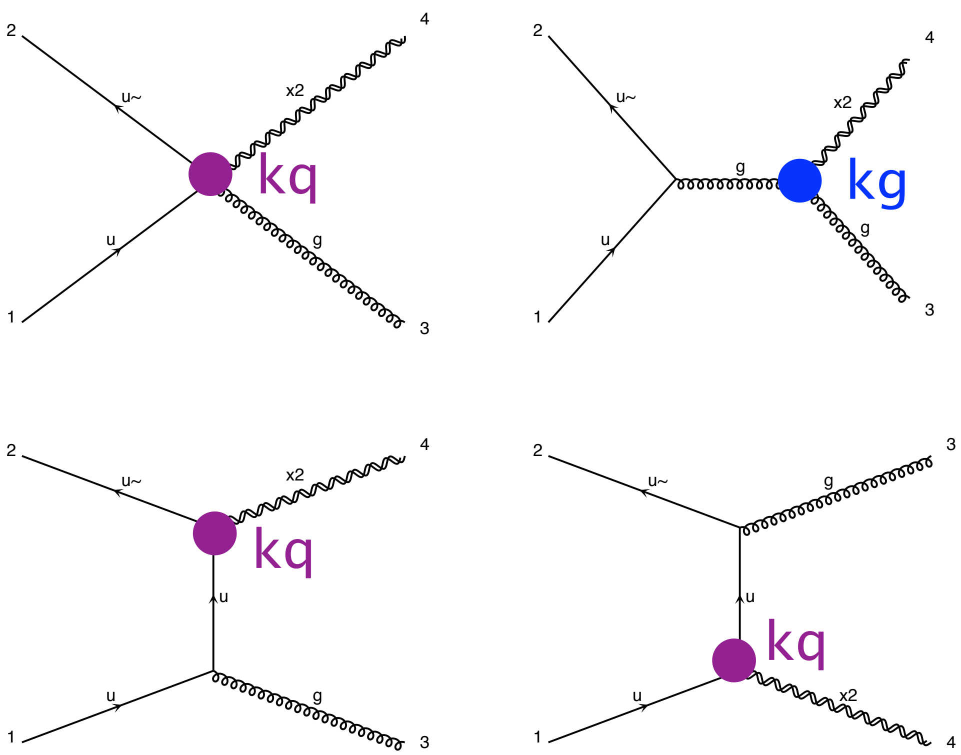
The different shapes are due to the different initial state.

excellent agreement between ME+PS and aMC@NLO

# Higher order effects in QCD (II)

## unitarity-violating behavior of models with a spin-2 state

$$\mathcal{L} = -\frac{1}{\Lambda}\kappa_q T^q_{\mu\nu} X_2^{\mu\nu} - \frac{1}{\Lambda}\kappa_g T^g_{\mu\nu} X_2^{\mu\nu}$$




$$|\mathcal{M}|^2 \propto s/\Lambda^2 \quad \text{for } \kappa_q = \kappa_g$$

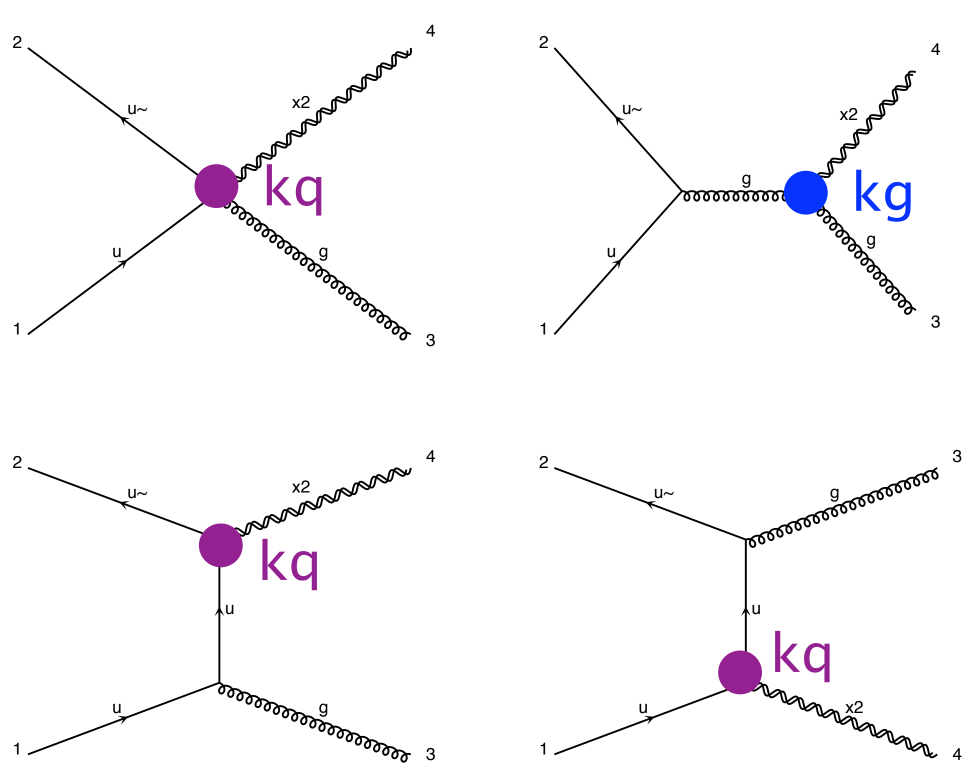
$$|\mathcal{M}|^2 \propto s^3/m^4\Lambda^2 \quad \text{for } \kappa_q \neq \kappa_g$$

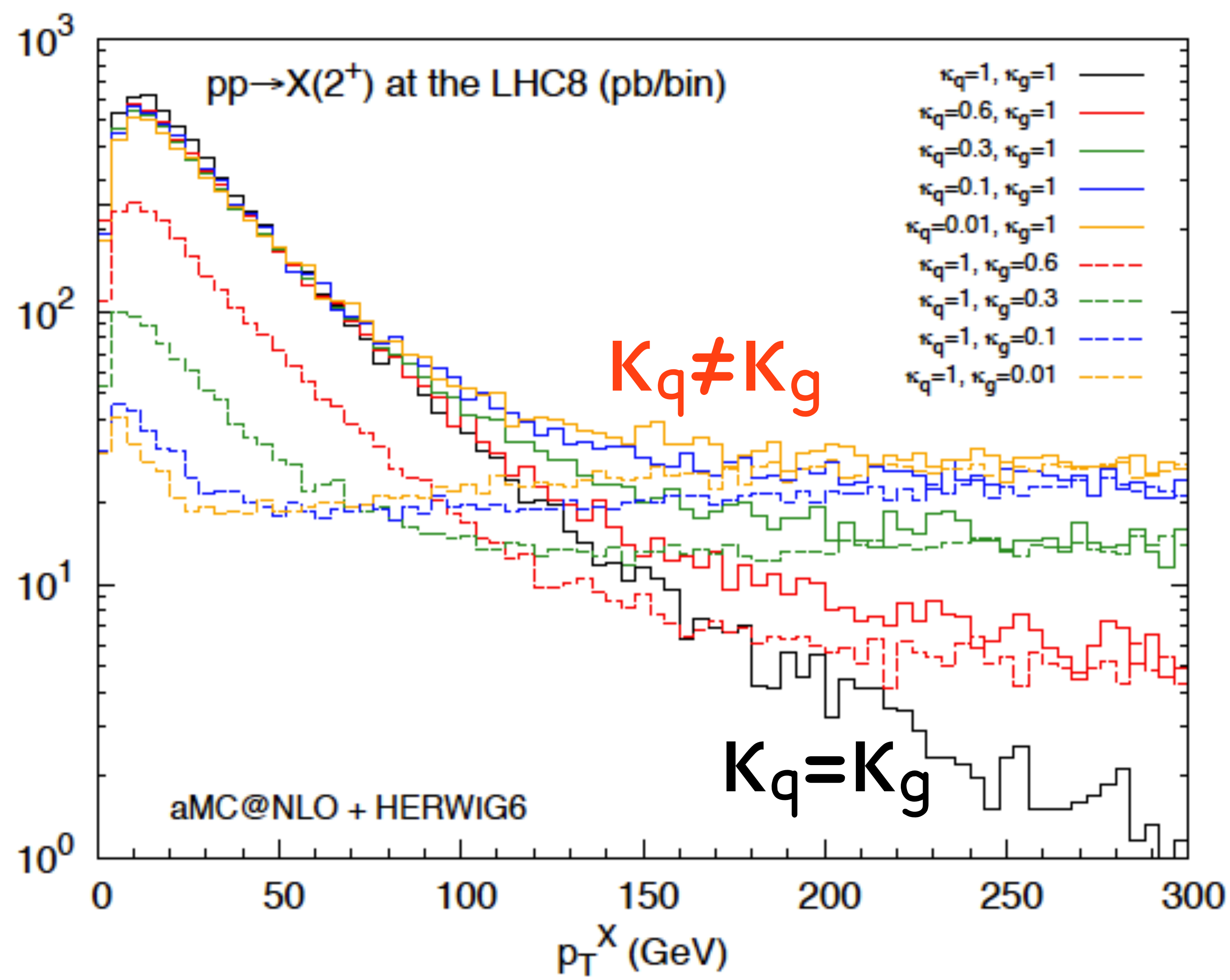
$$\begin{aligned}|\mathcal{M}|^2 = \frac{N}{\Lambda^2 s\,t\,u\,m^4}\Big\{ & 3\kappa_g^2 m^4 \left[2m^4 - 2m^2(t+u) + t^2 + u^2\right]\left[m^4 - m^2(t+u) + 4tu\right] \\ & + (\kappa_q - \kappa_g)\, 6\,\kappa_g m^4 s\left[m^6 + m^2 s(s+2u) - 2su(s+u)\right] \\ & + (\kappa_q - \kappa_g)^2 s\big[6m^{10} - 6m^8(t+u) + 3m^6(t^2+u^2) - 12m^4 tu(t+u) \\ & \quad + 2m^2 tu(t^2 + 12tu + u^2) - 2tu(t^3 + t^2u + tu^2 + u^3)\big]\Big\}, \quad (4.2)\end{aligned}$$

# Higher order effects in QCD (II)

## unitarity-violating behavior of models with a spin-2 state

$$\mathcal{L} = -\frac{1}{\Lambda}\kappa_q T^q_{\mu\nu} X_2^{\mu\nu} - \frac{1}{\Lambda}\kappa_g T^g_{\mu\nu} X_2^{\mu\nu}$$




A model with non-universal couplings dramatically changes the pT(X) spectrum.

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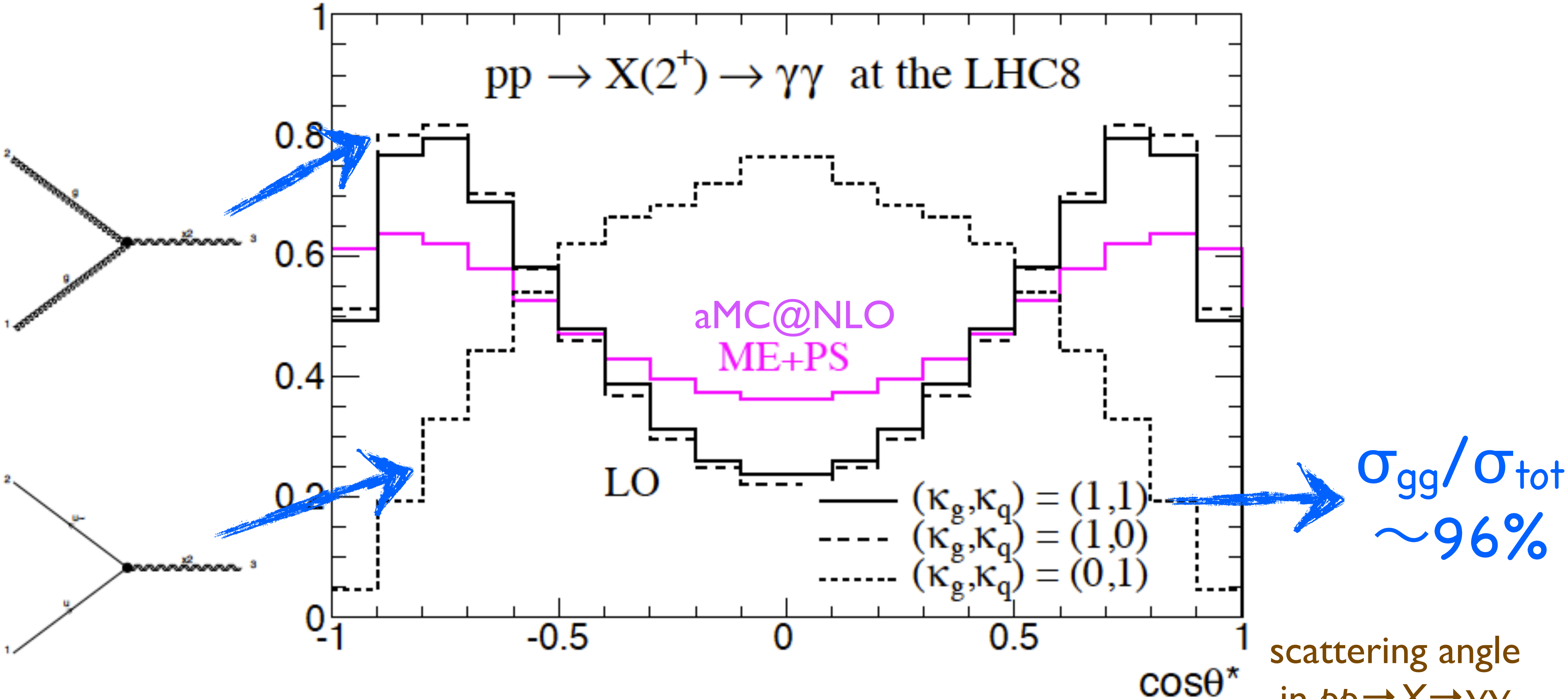
# Higher order effects in QCD (III)

## on spin observables for a spin-2 state




$$\frac{d\sigma(gg)}{d\cos\theta^*} \propto |d^2_{22}(\theta^*)|^2 + |d^2_{2-2}(\theta^*)|^2 = \frac{1}{8}(1 + 6\cos^2\theta^* + \cos^4\theta^*)\,,$$

$$\frac{d\sigma(q\bar{q})}{d\cos\theta^*} \propto |d^2_{12}(\theta^*)|^2 + |d^2_{1-2}(\theta^*)|^2 = \frac{1}{2}(1 - \cos^4\theta^*)\,.$$

# Summary

- After the discovery of a Higgs-like resonance at the LHC, the main focus of the analyses now is the determination of the Higgs Lagrangian.
- This includes
  - the structure of the operators, linked to the spin/parity of the 'Higgs' boson.
  - an independent measurement of the coupling strength.
- Our FR/MG5 Higgs Characterisation model is publicly available, which can provide a framework to perform SMS characterisation studies in a consistent, systematic and accurate way.
  - http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation
  - contact to kentarou.mawatari@vub.ac.be

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# back-up

# Effective Lagrangian → Feynman rules

$$\mathcal{L} = \frac{1}{2} c_\alpha \kappa_{\rm SM} g_{HZZ} Z_\mu Z^\mu X_0 \longrightarrow i c_\alpha \kappa_{\rm SM} g_{HZZ}\, g_{\mu\nu}$$

$$-\frac{1}{4}\frac{1}{\Lambda} c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} \longrightarrow i c_\alpha \frac{\kappa_{HZZ}}{\Lambda} (g_{\mu\nu} q_1 . q_2 - q_{2\mu} q_{1\nu})$$

$$-\frac{1}{4}\frac{1}{\Lambda} s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \longrightarrow i s_\alpha \frac{\kappa_{AZZ}}{\Lambda} \epsilon_{\mu\nu\rho\sigma} q_2^\rho q_1^\sigma$$

$$-\frac{1}{\Lambda} c_\alpha \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} \longrightarrow i c_\alpha \frac{\kappa_{H\partial Z}}{\Lambda} [g_{\mu\nu}(q_1 . q_1 + q_2 . q_2) - q_{1\mu} q_{1\nu} - q_{2\mu} q_{2\nu}]$$

hyp. SM : SM-like coupling to the Z bosons

$$\kappa_{\rm SM} = 1 \qquad \kappa_{HZZ} = 0 = \kappa_{AZZ} \qquad c_\alpha = 1$$

hyp. HD: coupling involving a superposition of HD operators $Z_{\mu\nu} Z^{\mu\nu}$ and $Z_{\mu\nu} \tilde{Z}^{\mu\nu}$

$$\kappa_{\rm SM} = 0 \qquad \kappa_{HZZ} = 1 = \kappa_{AZZ} \qquad c_\alpha \ \text{free}$$

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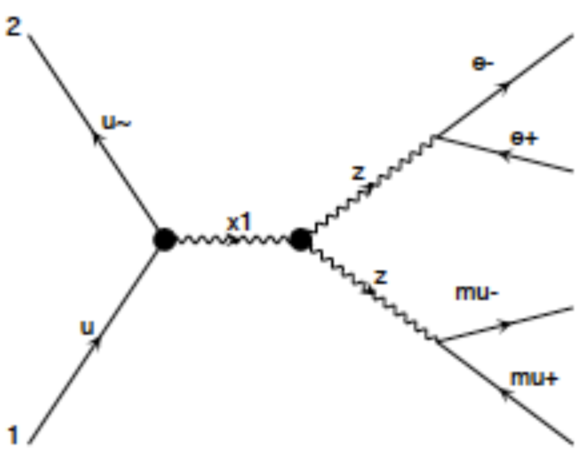
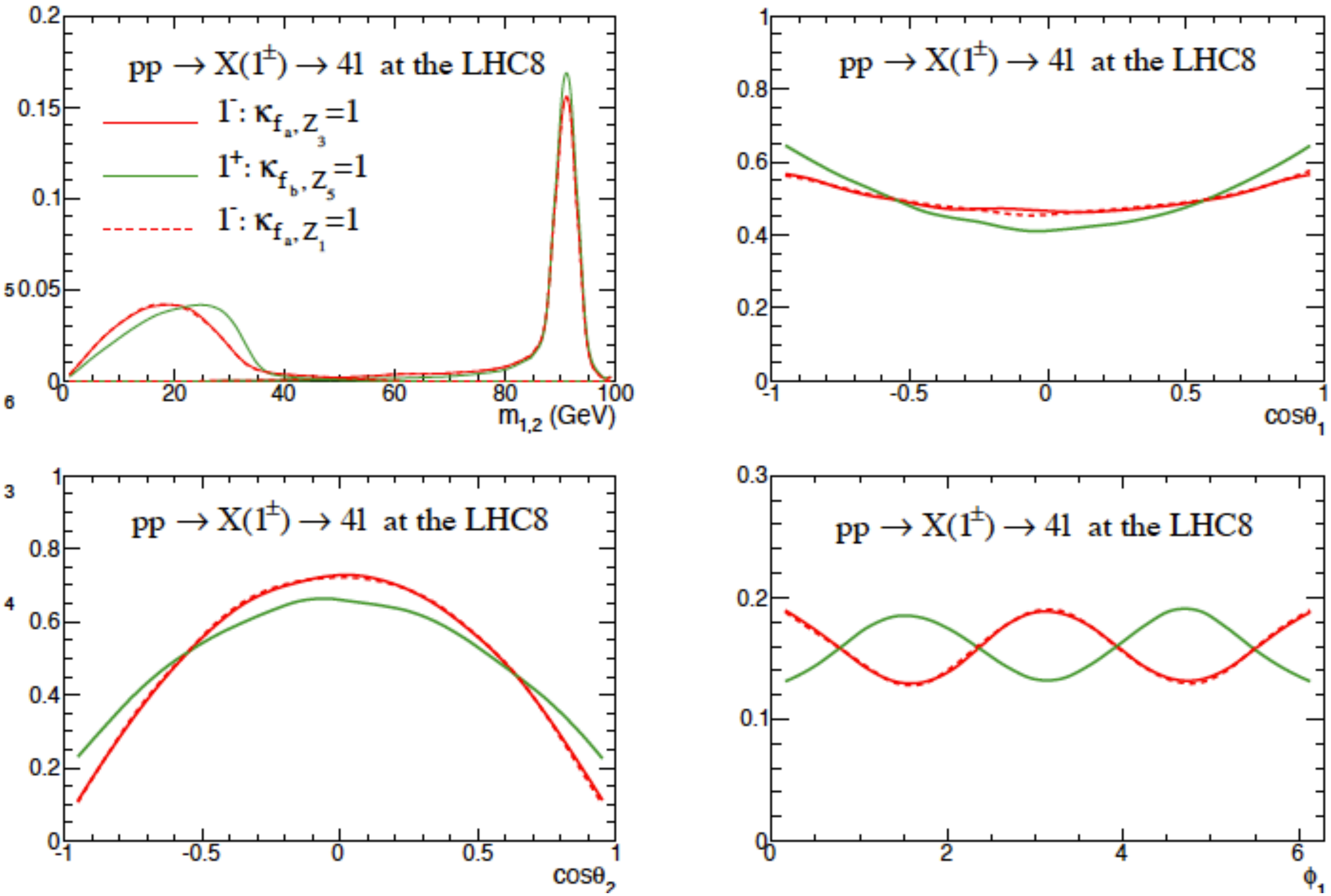
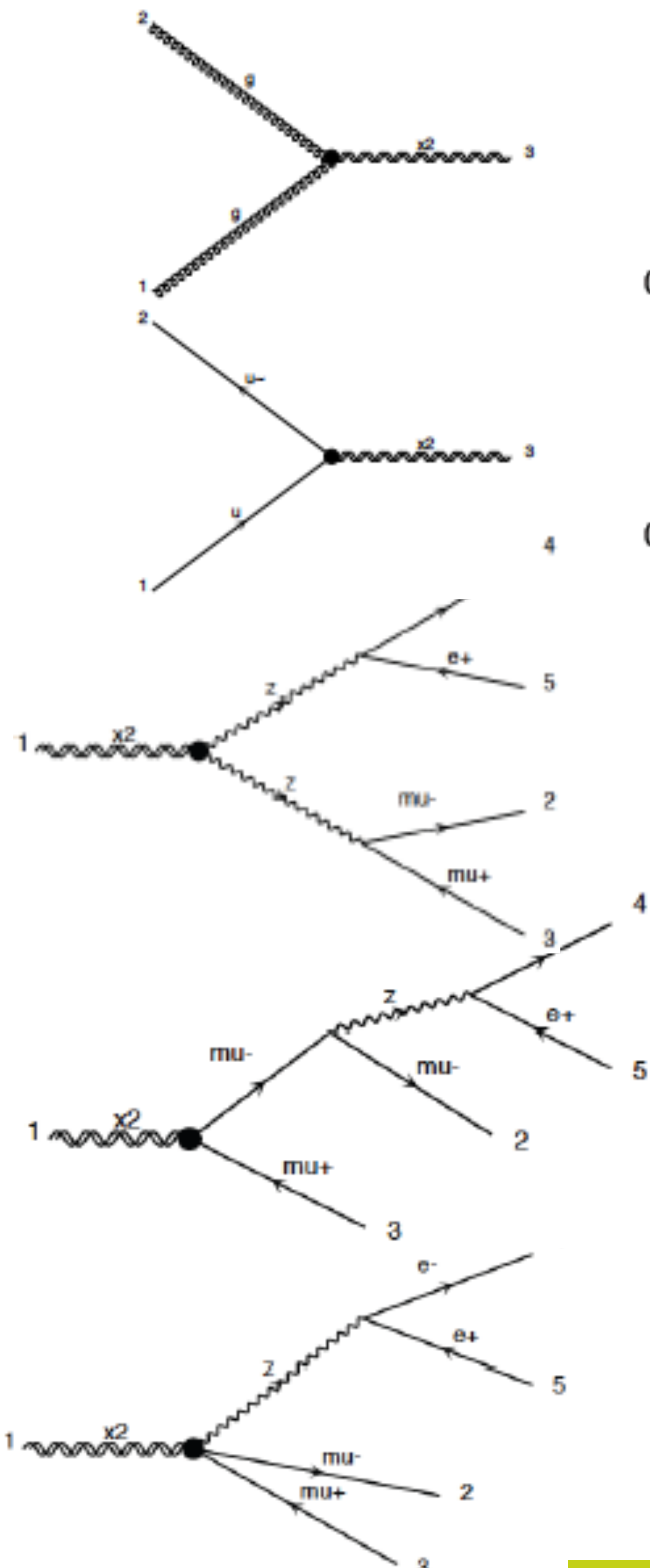
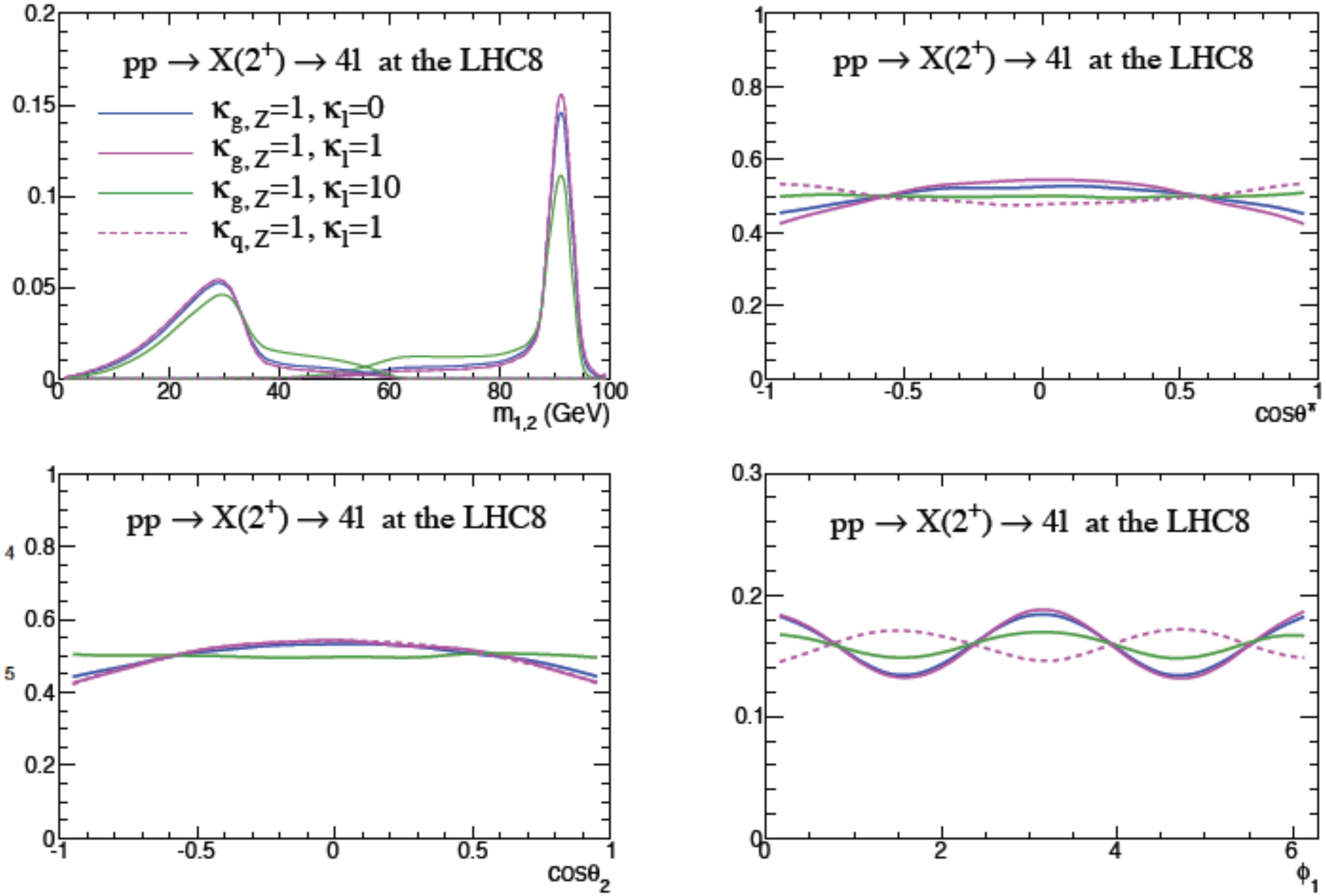
# Mass and angular distributions -- spin1



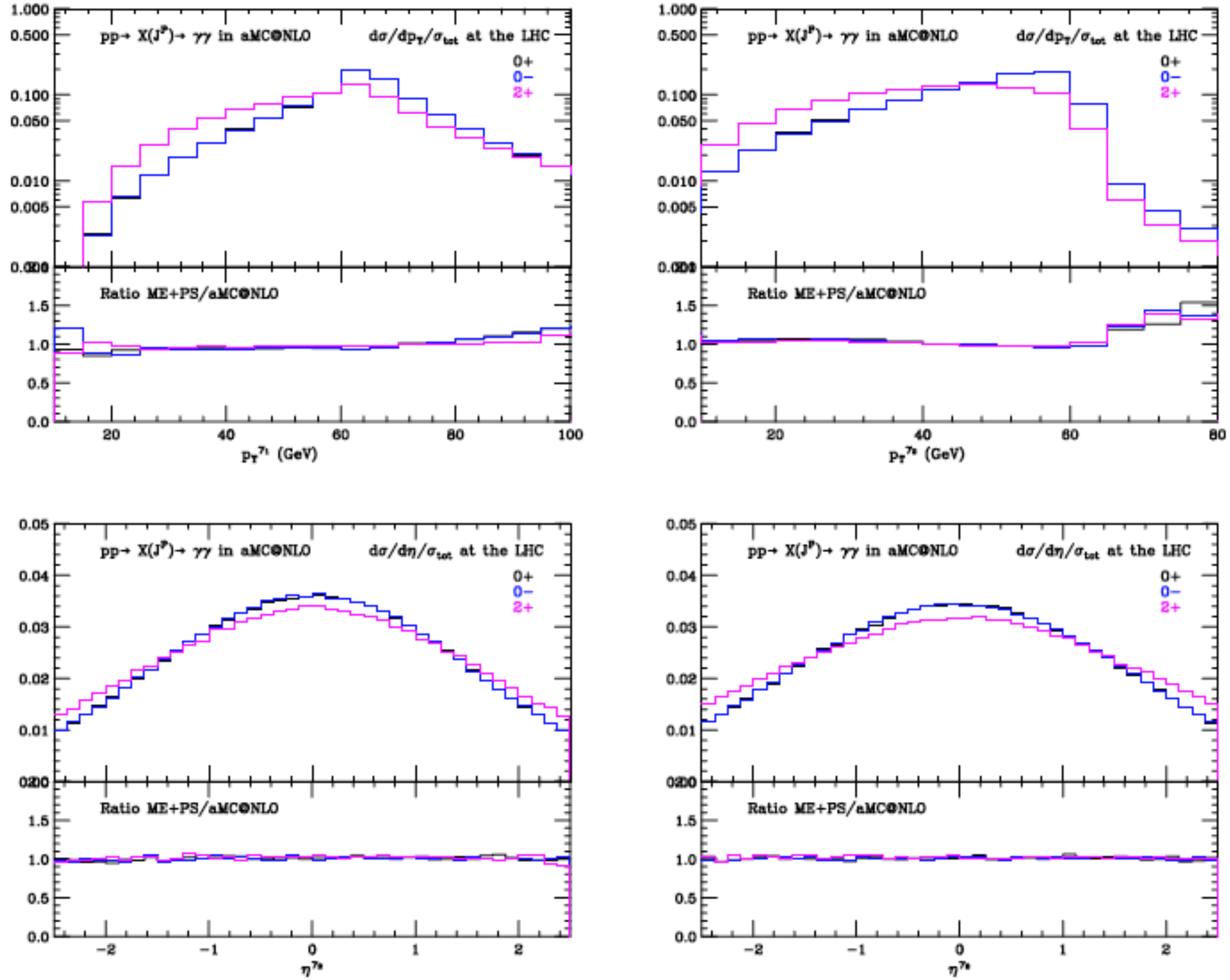



# Mass and angular distributions -- spin2





# Accuracy with aMC@NLO/ME+PS merging



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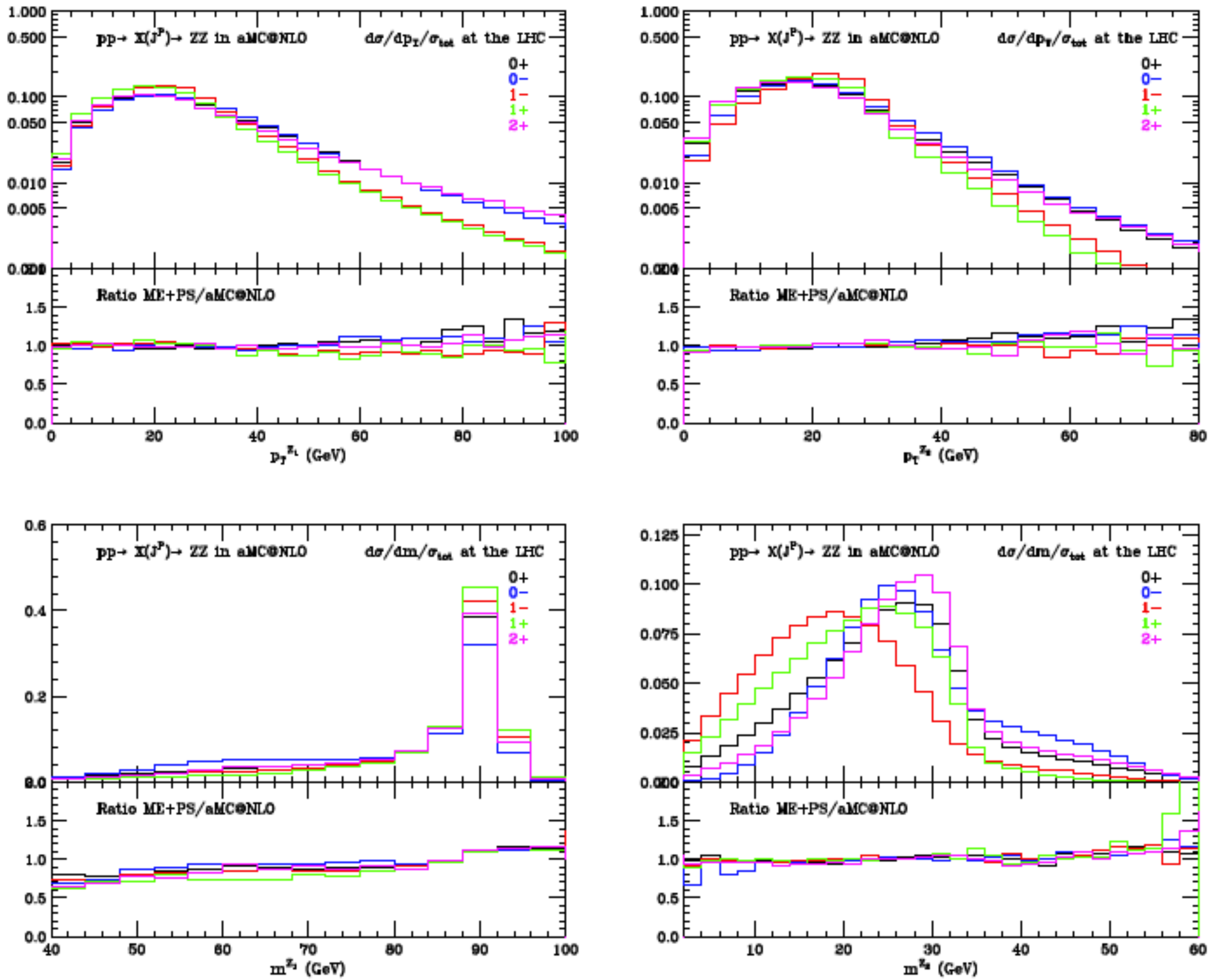
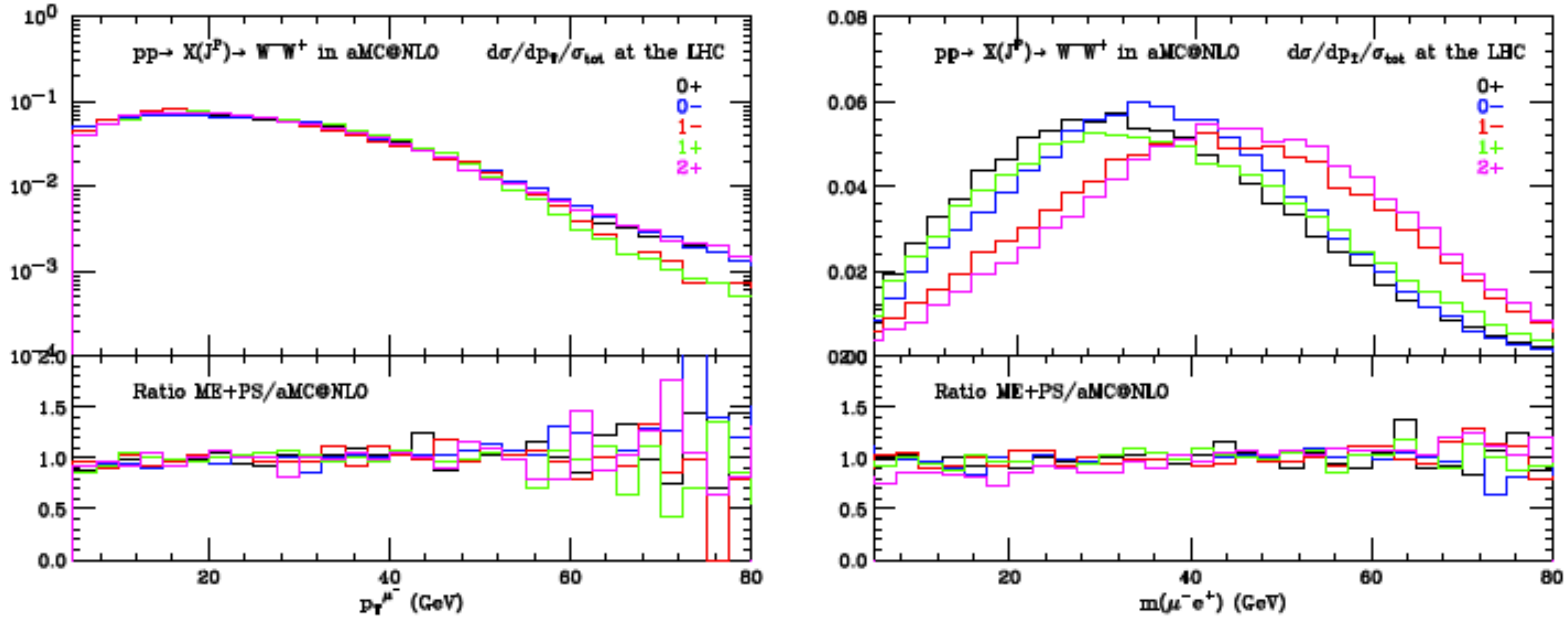


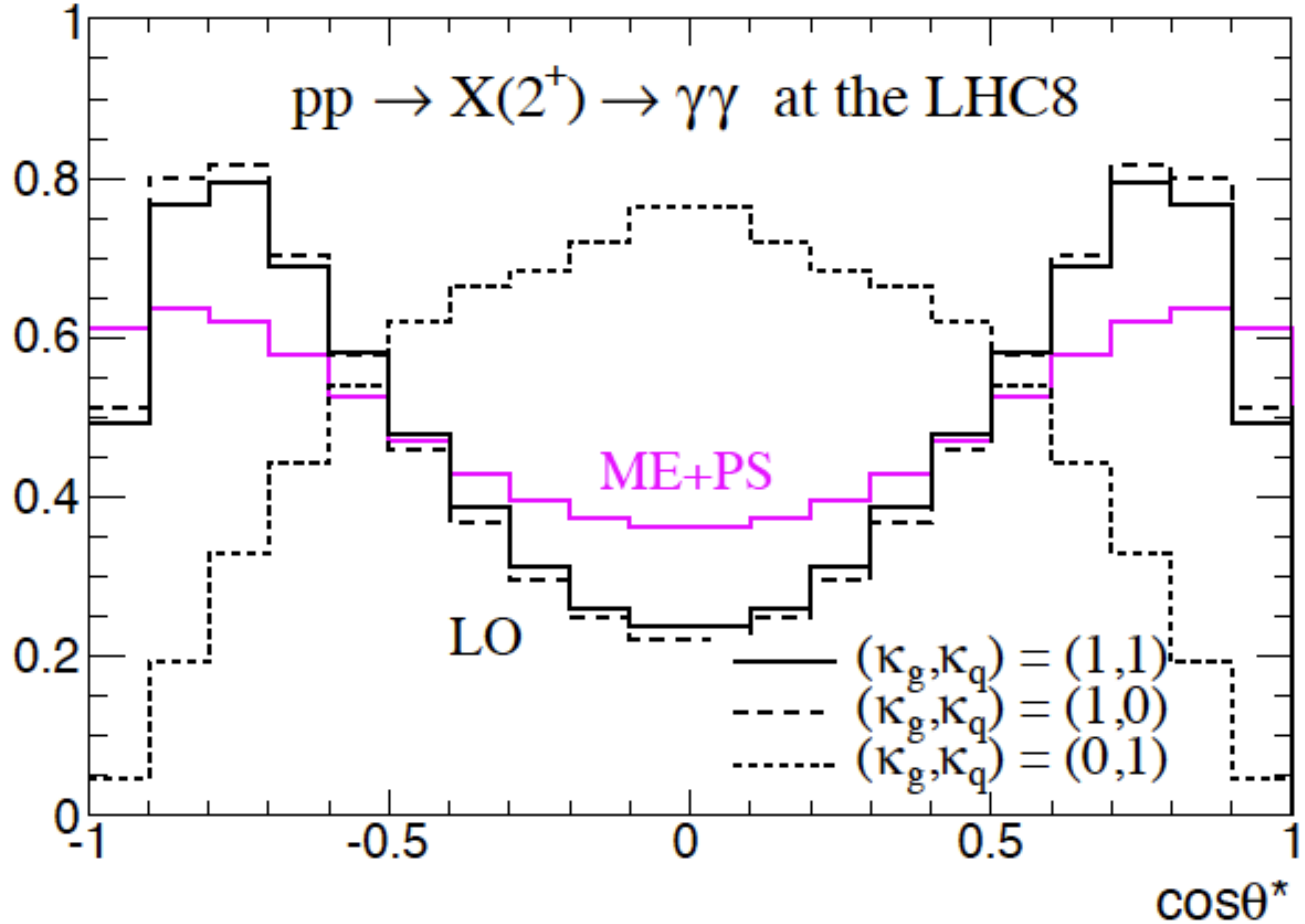
# Accuracy with aMC@NLO/ME+PS merging



# How can we get the spin/parity information?

1. $X \to \gamma\gamma$
2. $X \to VV^* \to 4l$
3. $pp \to jjX$
4. $pp \to VX$
5. $X \to \tau\tau$

# Spin/parity determination
# 1. X→γγ




$$\frac{d\sigma(gg)}{d\cos\theta^*} \propto |d^2_{22}(\theta^*)|^2 + |d^2_{2-2}(\theta^*)|^2 = \frac{1}{8}(1 + 6\cos^2\theta^* + \cos^4\theta^*)\,,$$

$$\frac{d\sigma(q\bar{q})}{d\cos\theta^*} \propto |d^2_{12}(\theta^*)|^2 + |d^2_{1-2}(\theta^*)|^2 = \frac{1}{2}(1 - \cos^4\theta^*)\,.$$

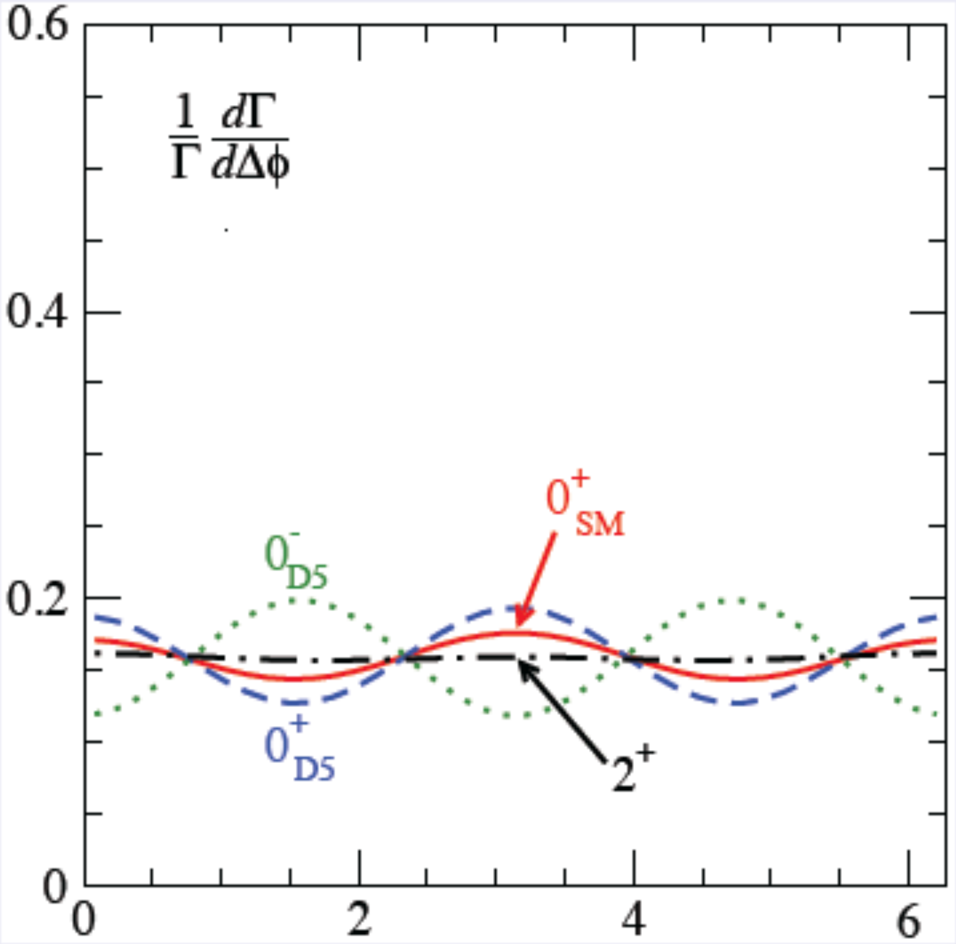
# Spin/parity determination
# 2. X→VV*→4l

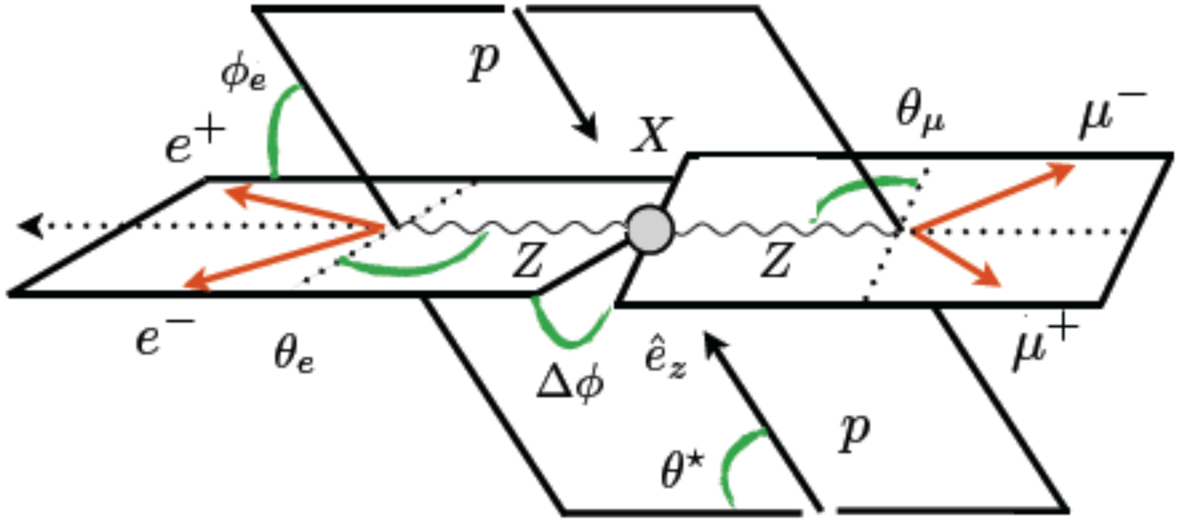
[Dell'Aquilla, Nelson, PRD(1986)]
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[Bolognesi et al, PRD(2012)]

$$\mathcal{L}_{0^+_{\rm SM}} = g_{0^+_{\rm SM}} V_\mu V^\mu X_0$$
$$\mathcal{L}_{0^+_{\rm D5}} = g_{0^+_{\rm D5}} V_{\mu\nu} V^{\mu\nu} X_0$$
$$\mathcal{L}_{0^-_{\rm D5}} = g_{0^-_{\rm D5}} V_{\mu\nu} \widetilde{V}^{\mu\nu} X_0$$

## $X \to ZZ^* \to 4\ell$




$d\sigma/d\Delta\phi \sim$ const. for $0^+_{\rm SM}$, $\quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$ for $0^\pm_{\rm D5}$.

# Spin/parity determination X→4l vs. VBF

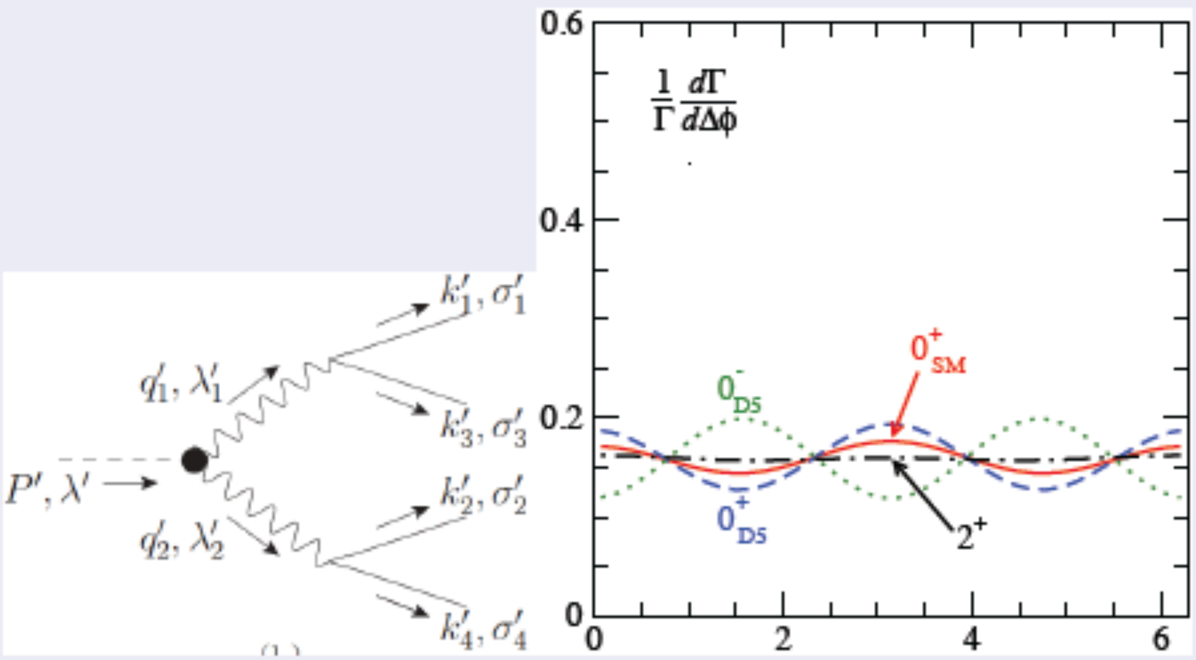
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[Bolognesi et al, PRD(2012)]

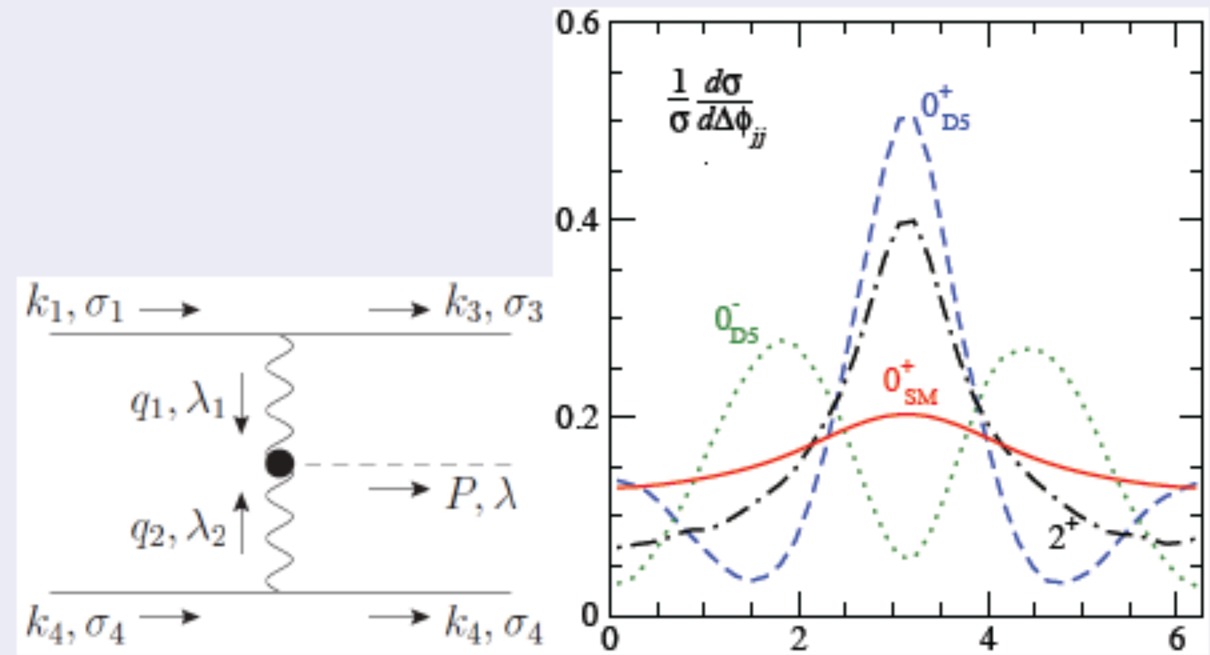
[Plehn, Rainwater, Zeppenfeld, PRL(2002)]
[Hagiwara, Li, KM, JHEP(2009)] ...

[Englert, Goncalves-Netto, KM, Plehn, JHEP(2013)]

## $X \to ZZ^* \to 4\ell$




## Vector boson fusion (VBF)



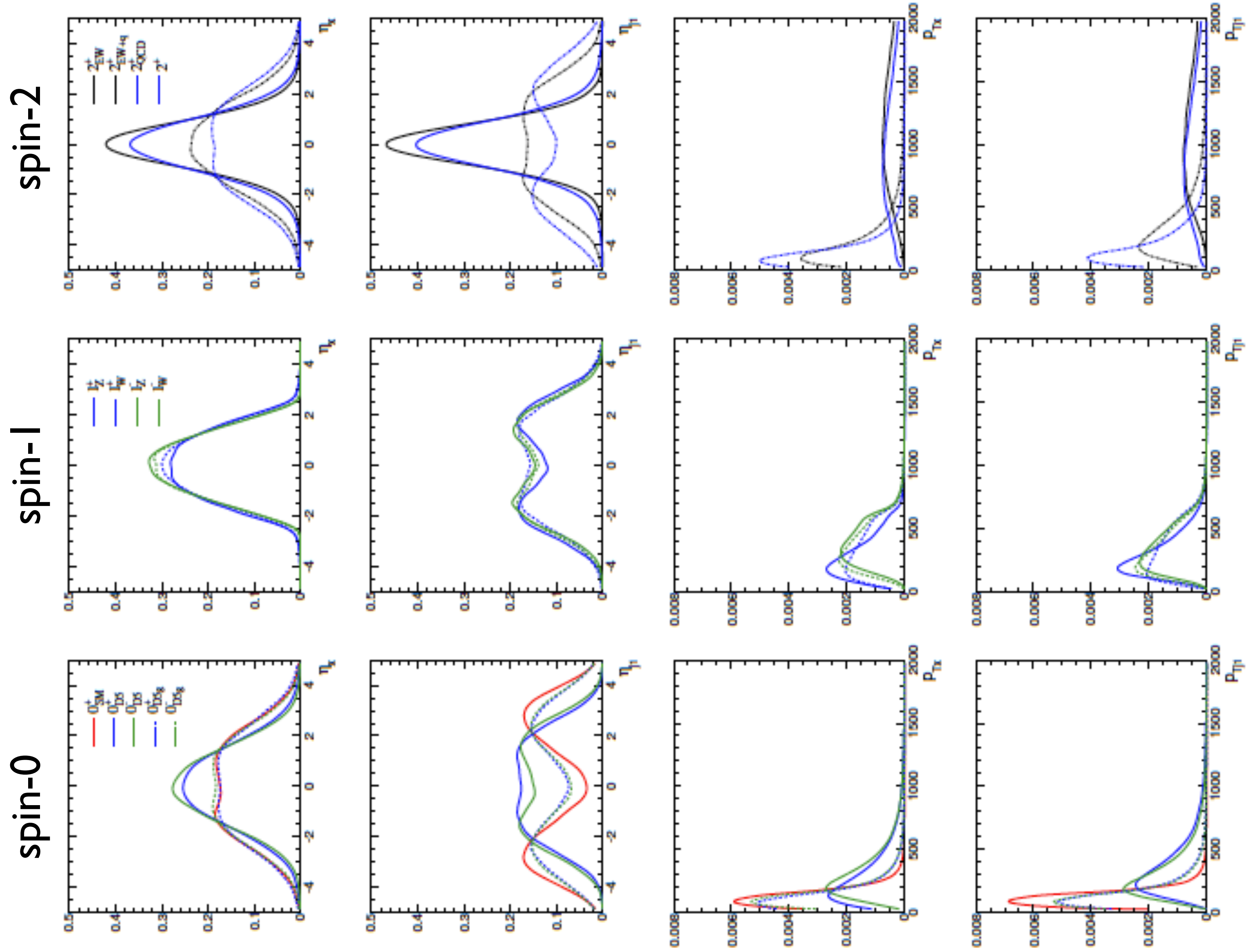

$d\sigma/d\Delta\phi \sim$ const. for $0^+_{\rm SM}$, $\quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$ for $0^\pm_{\rm D5}$.

Nontrivial azimuthal angle correlations of the decay planes ($X \to ZZ$) and the jets (VBF) can be explained as the quantum interference among different helicity states of the intermediate vector-bosons.

# Spin/parity determination
# 3. pp→jjX

X/jet distributions

Englert, Goncalves-Netto, KM, Plehn (2013)




$\sqrt{s} = 14$ TeV

$p_{T_j} > 20$ GeV

$\Delta R_{jj} > 0.6$

$|\eta_j| < 5$

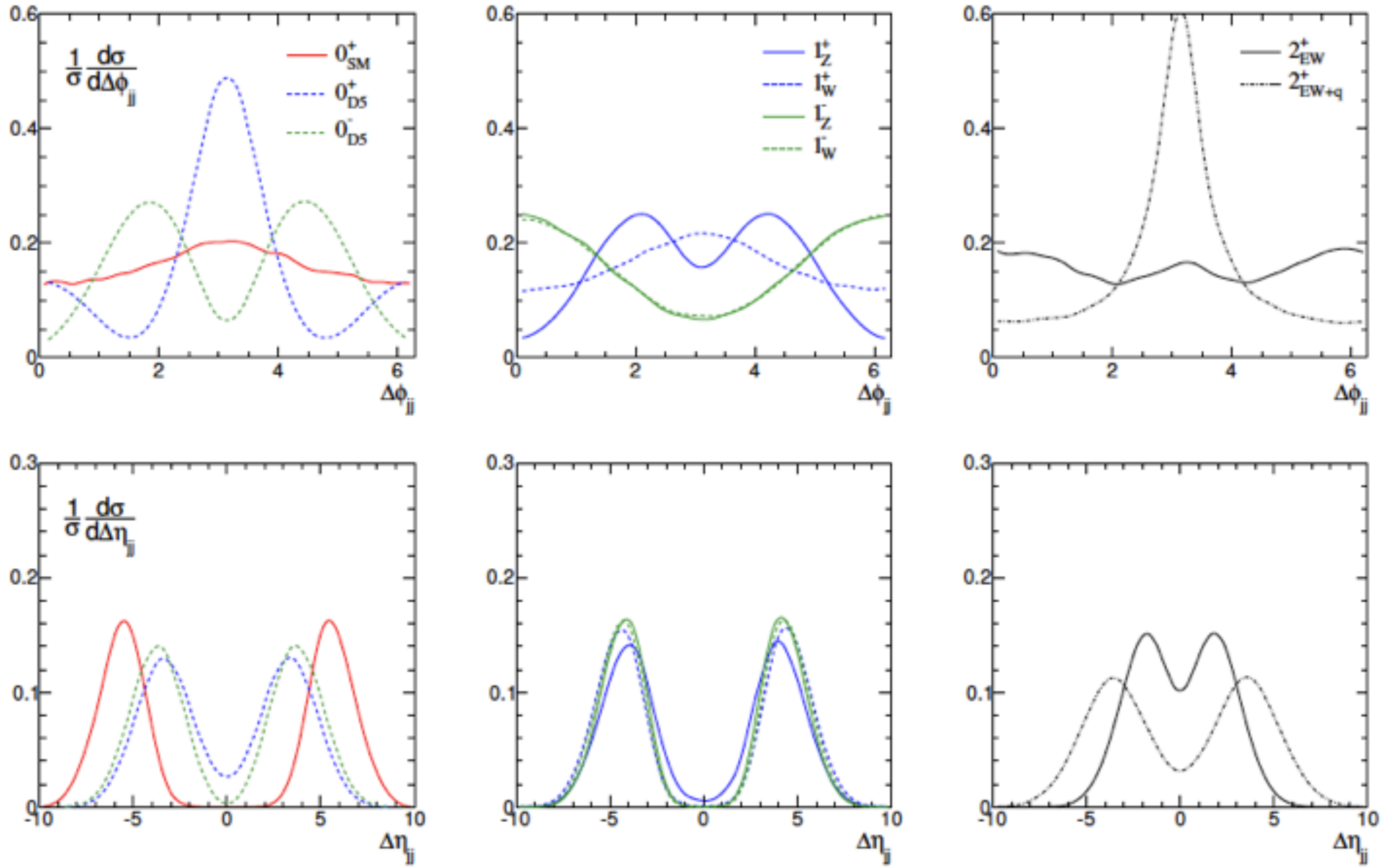
$m_{jj} > 600$ GeV

# Spin/parity determination
# 3. pp→jjX

di-jet correlations

Englert, Goncalves-Netto, KM, Plehn (2013)

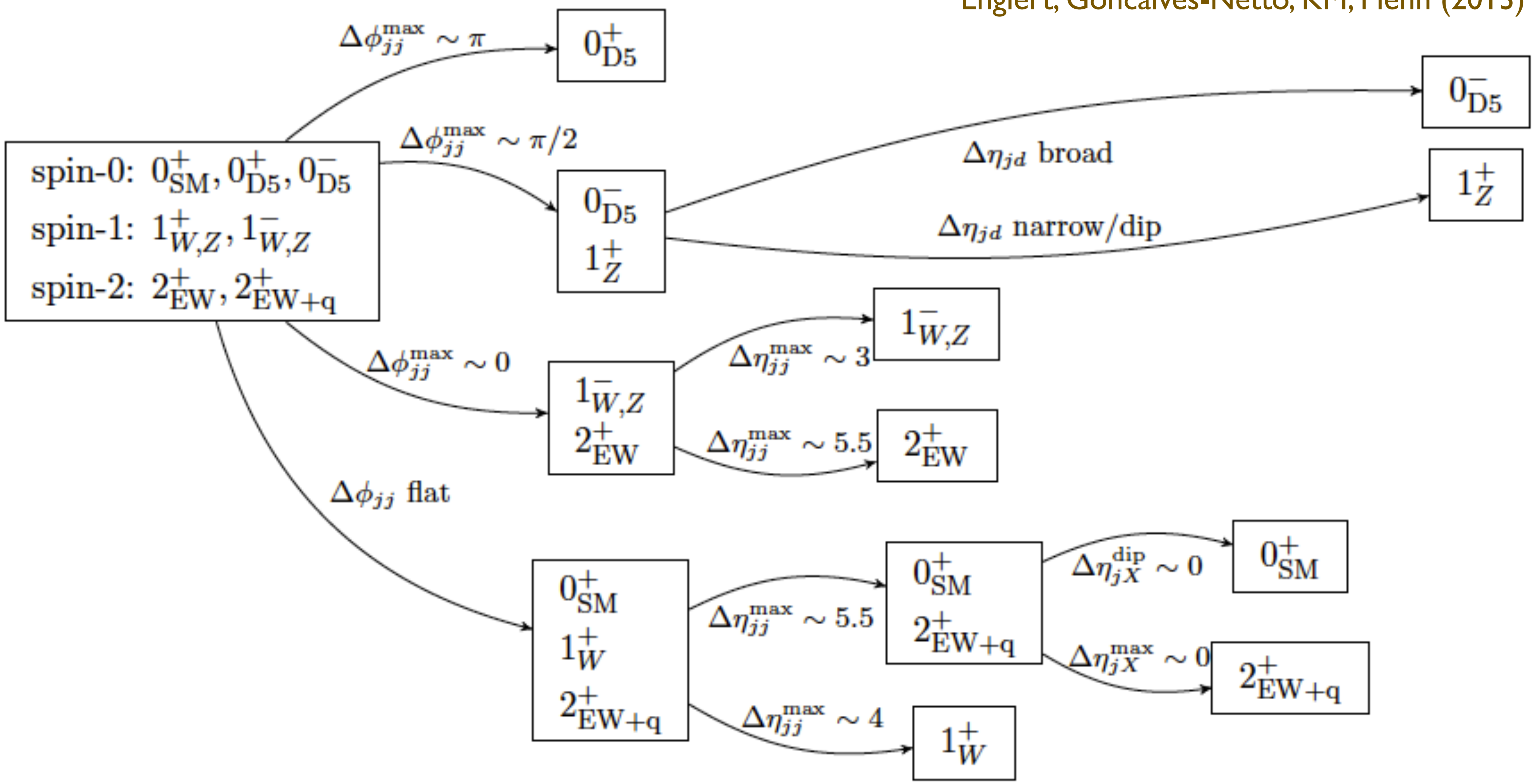
spin-0 spin-1 spin-2




Δη as well as ΔΦ are the powerful observables.

# Obs-by-obs based strategy in VBF

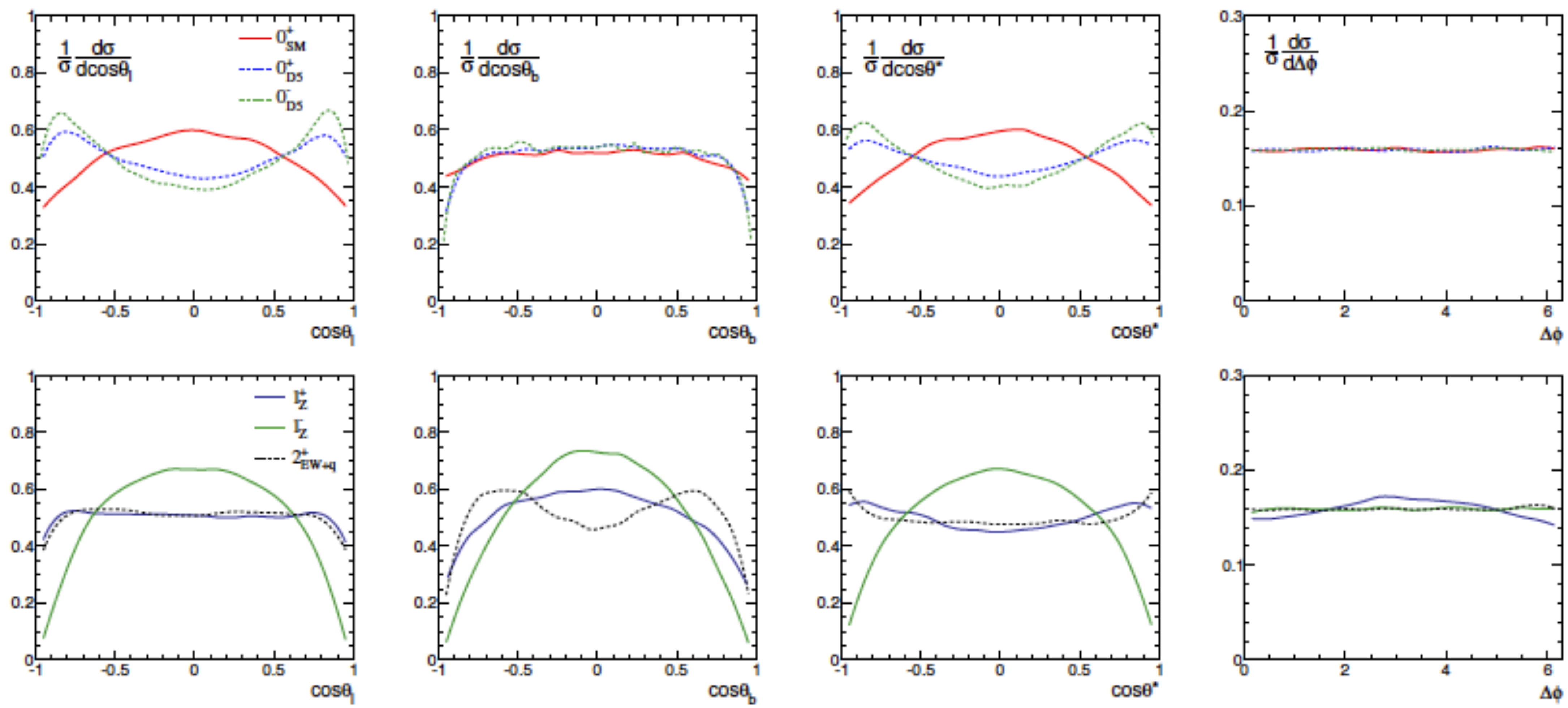
Englert, Goncalves-Netto, KM, Plehn (2013)




The di-jet correlations are the most decisive, in particular to separate the different scalar coupling structures.

# Spin/parity determination
# 4. pp→ZX

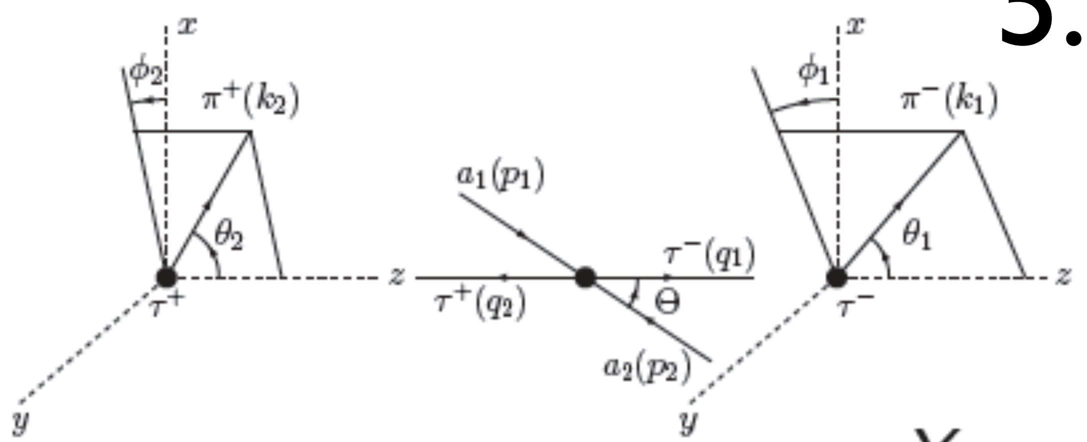
Englert, Goncalves-Netto, KM, Plehn (2013)



# Spin/parity determination
# 5. X→ττ

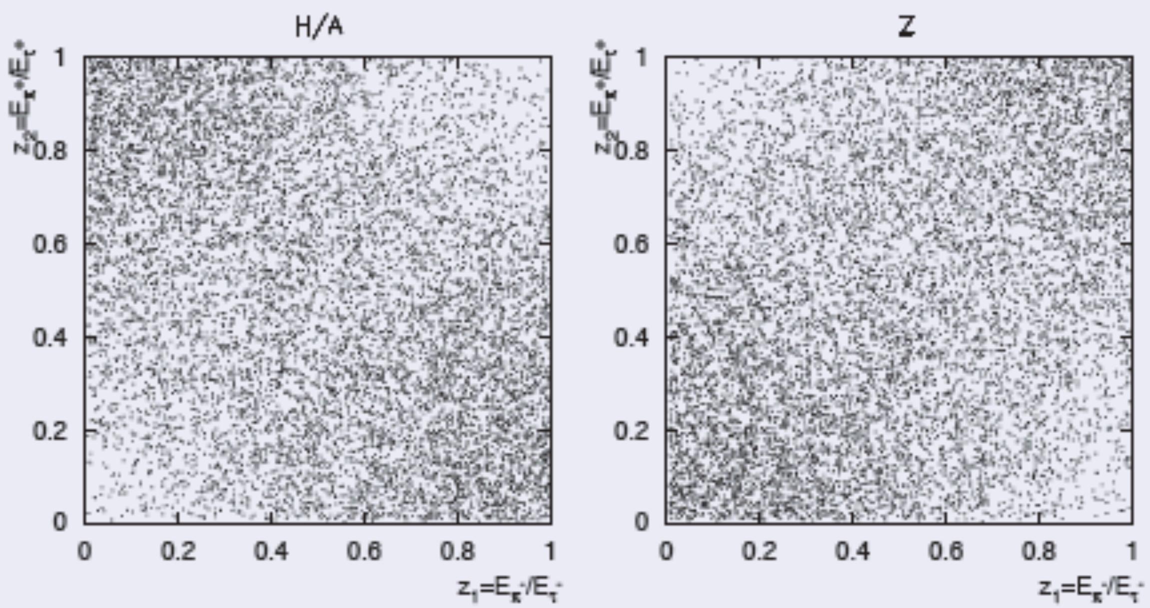
[Bullock, Hagiwara, Martin, NPB(1993)]
[Krämer, Kühn, Stong, Zerwas, ZPC(1994)]
[Pierzchala, Richter-Was, Was, Worek, APPB(2001,2002,...)]

[Hagiwara, Li, KM, Nakamura, 1212.6247]

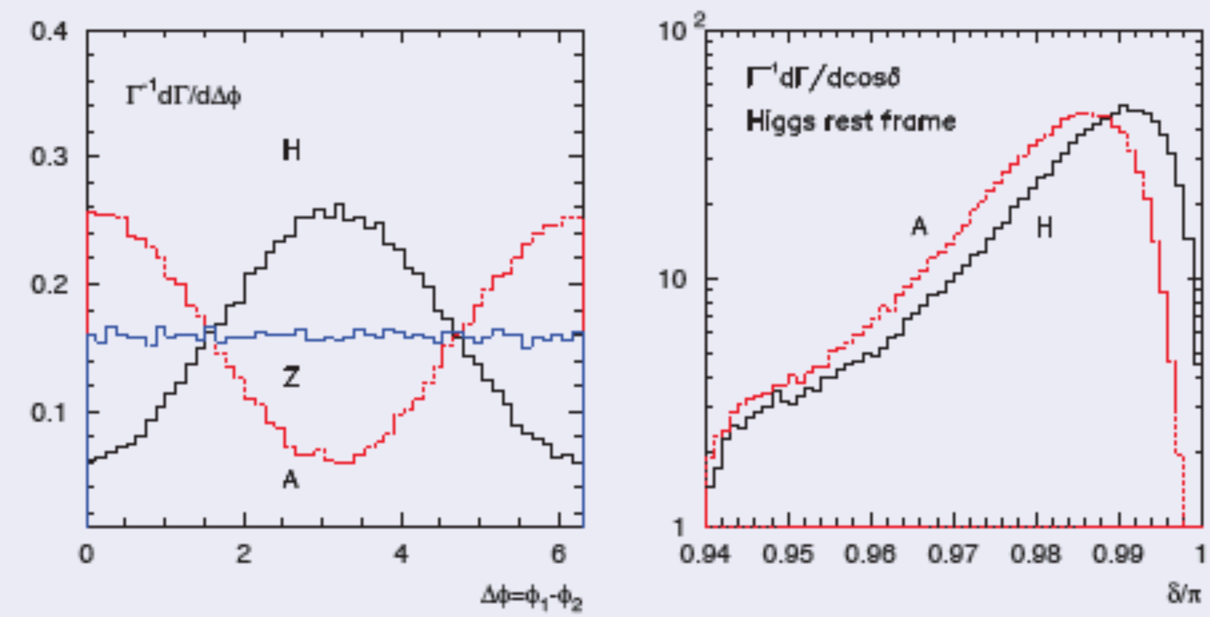


$$pp \to X \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$$

## Longitudinal spin (helicity) effect




## Transverse spin effect




$d^2\Gamma/dz_1 dz_2 \sim 1 \mp z_1 z_2$ for spin-0/1, $\quad d\Gamma/d\Delta\phi \sim 1 \mp A\cos\Delta\phi$ for $0^\pm$

$\tau$ could be a spin/parity analyzer!

# TauDecay

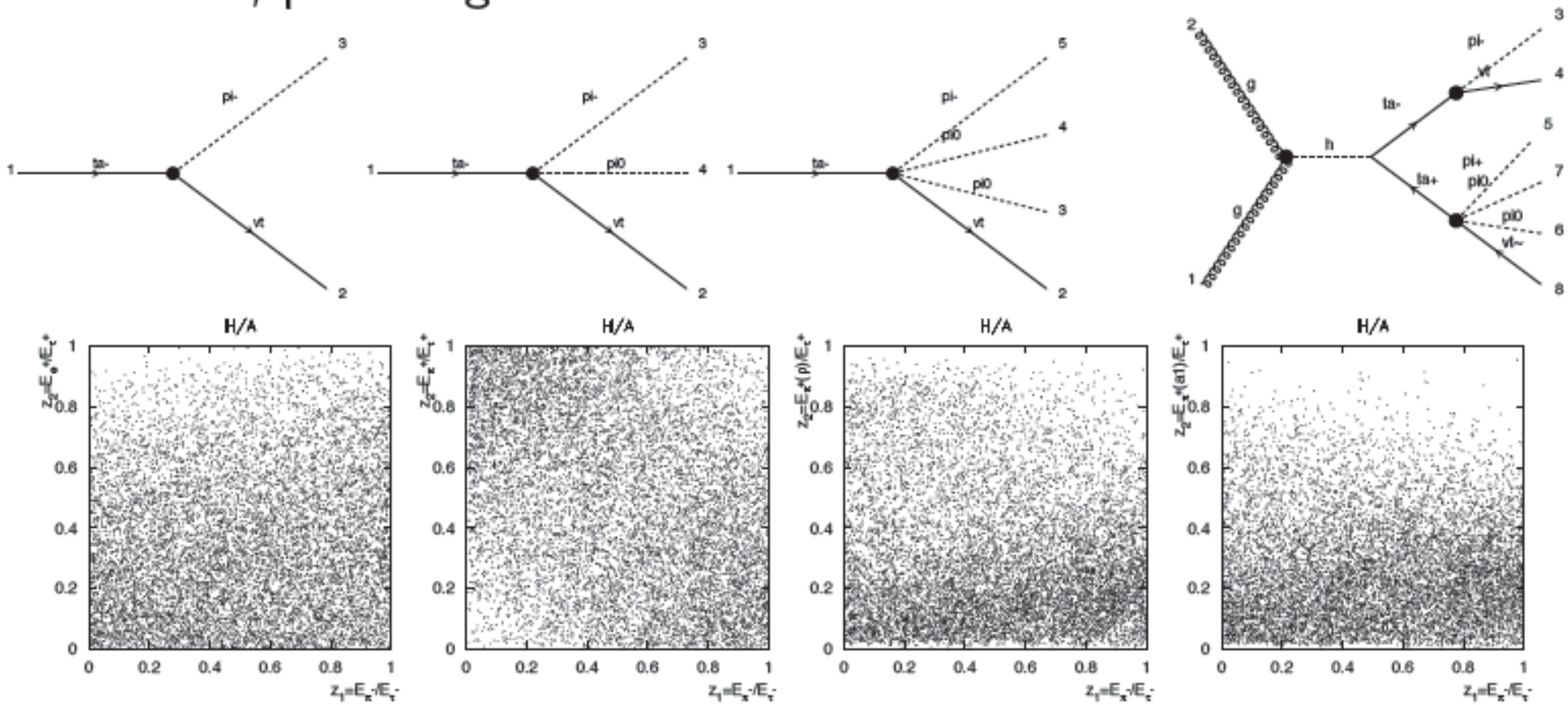
a library to simulate polarized tau decays via FeynRules/MadGraph5

We implemented the effective Lagrangians [Hagiwara, Li, KM, Nakamura, 1212.6247]

$$\mathcal{L}_\pi = \sqrt{2} G_F f_\pi \cos\theta_C \, \bar{\tau}\gamma^\mu P_L \nu_\tau \, \partial_\mu \pi^- + h.c.$$

$$\mathcal{L}_\rho = 2 G_F \cos\theta_C F_\rho(Q^2) \, \bar{\tau}\gamma^\mu P_L \nu_\tau \, (\pi^0 \partial_\mu \pi^- - \pi^- \partial_\mu \pi^0) + h.c.$$

into FeynRules, providing the model file for MadGraph5.




Full spin correlations for any kinds of new physics models can be generated for free.

# Specific channel: $X_0$ into 4 charged leptons

- generation of $X_0 \to \mu^+\mu^-e^+e^-$ events: ME+matching approach (validated with aMC@NLO + parton shower), basic cuts on the leptons ($p_T$ > 7 GeV, |y|<2.4)

- 1M pseudo-experiments with N=10 events under each assumptions (SM of HD)

- Discriminating variable for the statistical test SM versus HD is set to the likelihood ratio, built upon 1-dimension distribution or upon the matrix elements

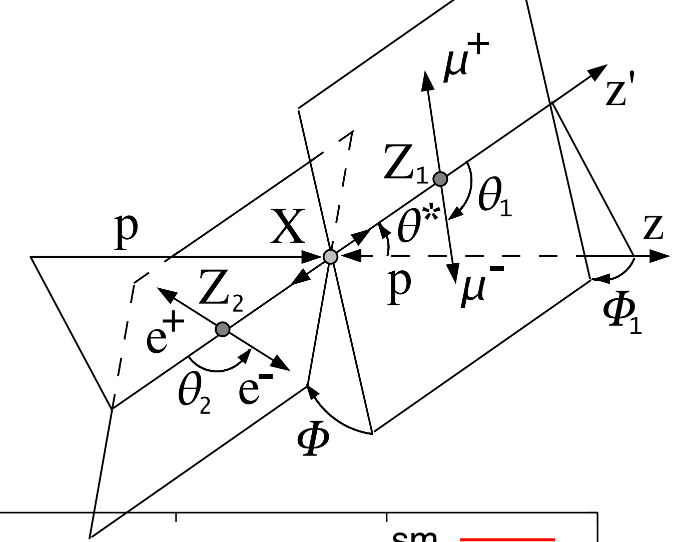
$$L_{\mathcal{O}} = \prod_i^N \frac{\sigma^{-1}_{\mathrm{HD}(c_\alpha)} \frac{d\sigma_{\mathrm{HD}(c_\alpha)}}{d\mathcal{O}}(\mathcal{O}_i)}{\sigma^{-1}_{\mathrm{SM}} \frac{d\sigma_{\mathrm{SM}}}{d\mathcal{O}}(\mathcal{O}_i)} \,.$$

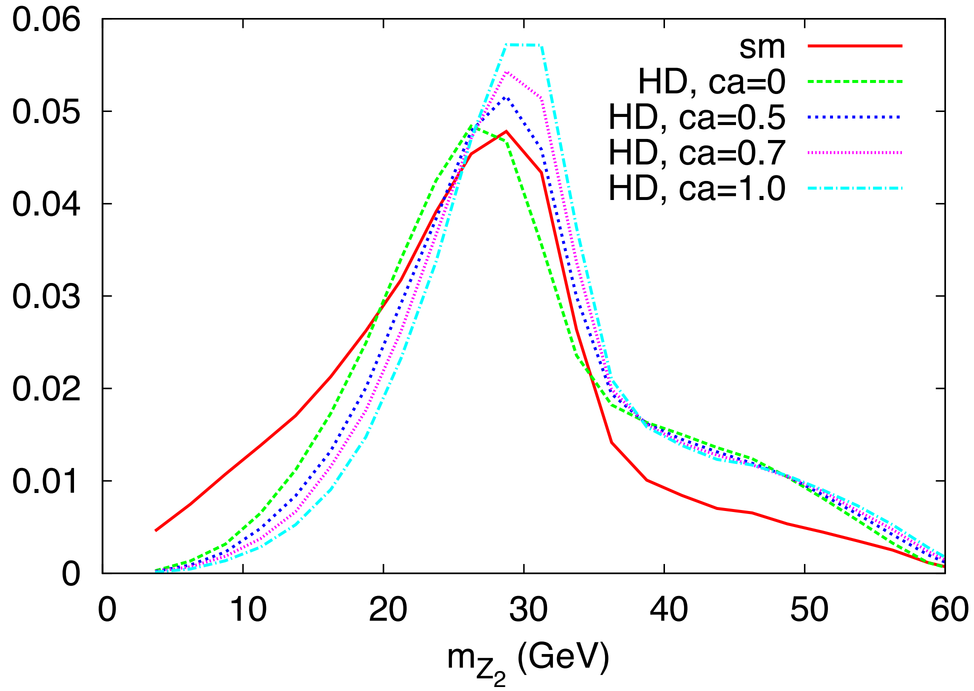
likelihood ratio based on 1-dim. distribution

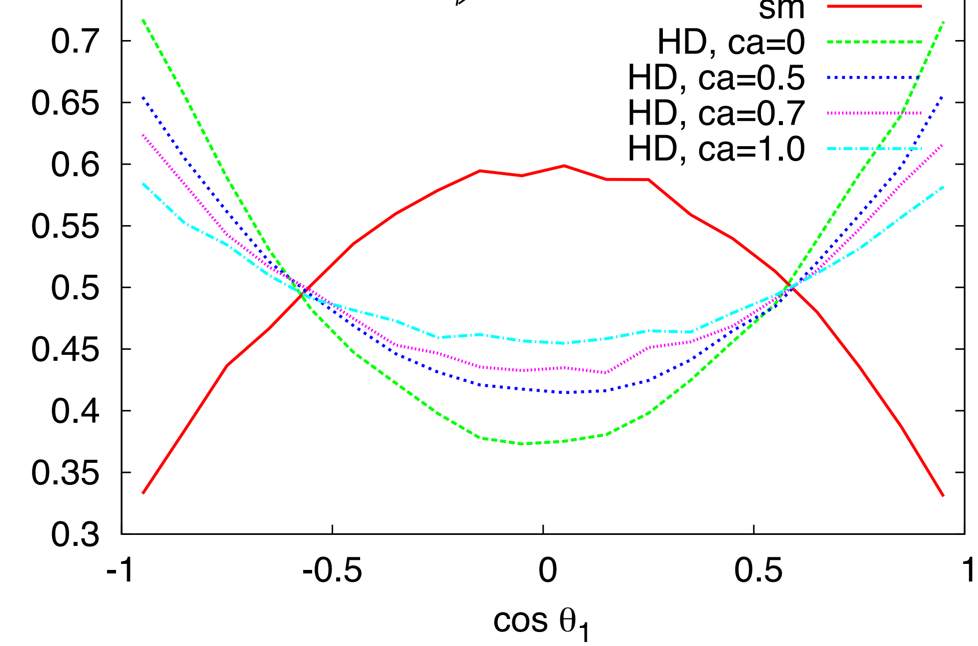
$$L_{\mathrm{MEM}} = \prod_i^N \frac{|M_{HD(c_\alpha)}(i)|^2}{|M_{\mathrm{SM}}(i)|^2}$$

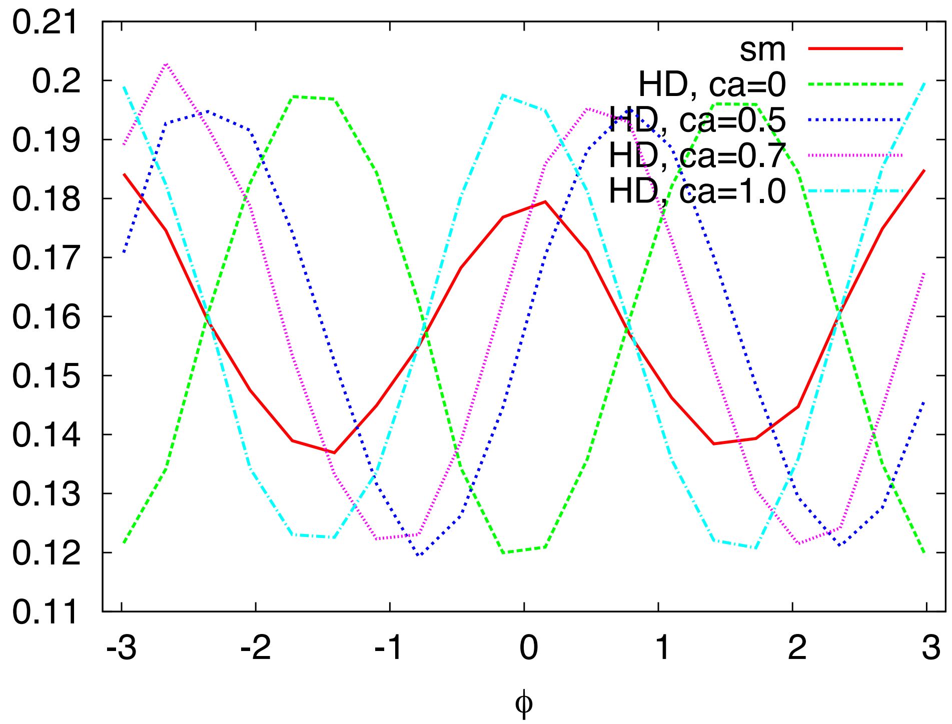
likelihood ratio based on matrix elements

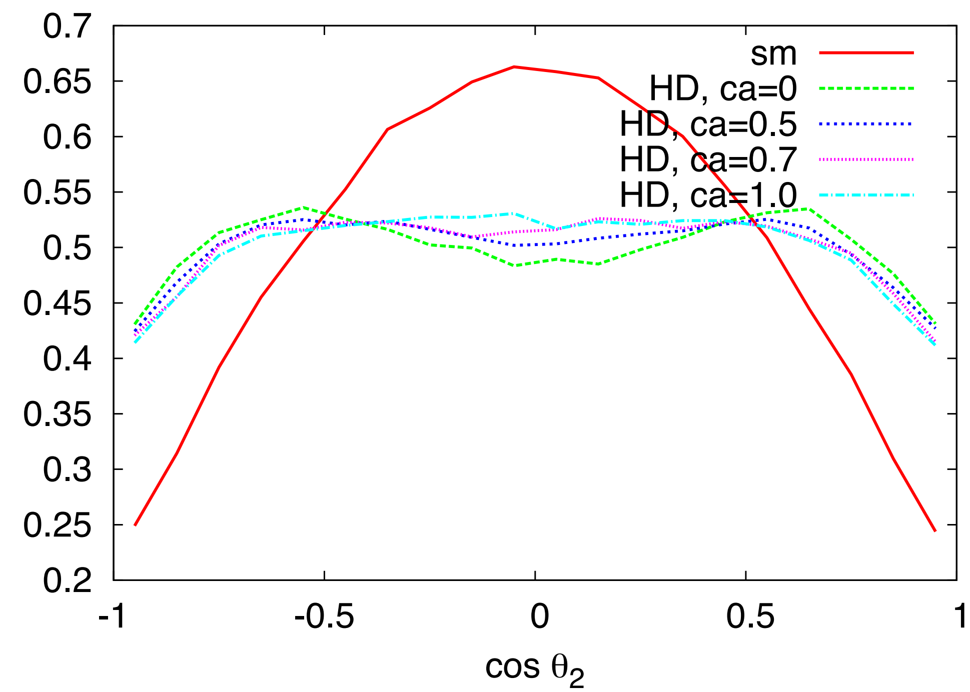
# 1-dimension distributions



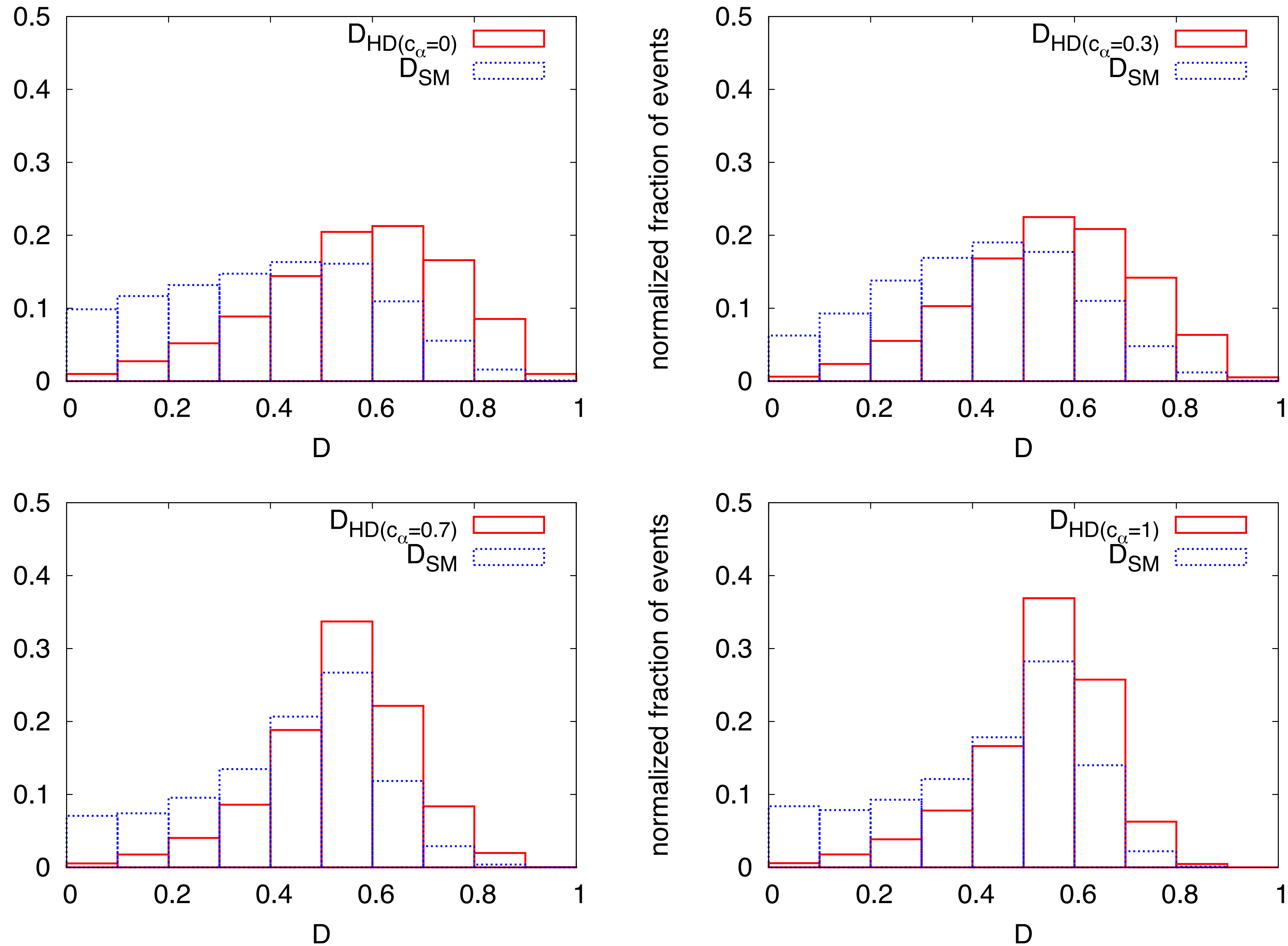



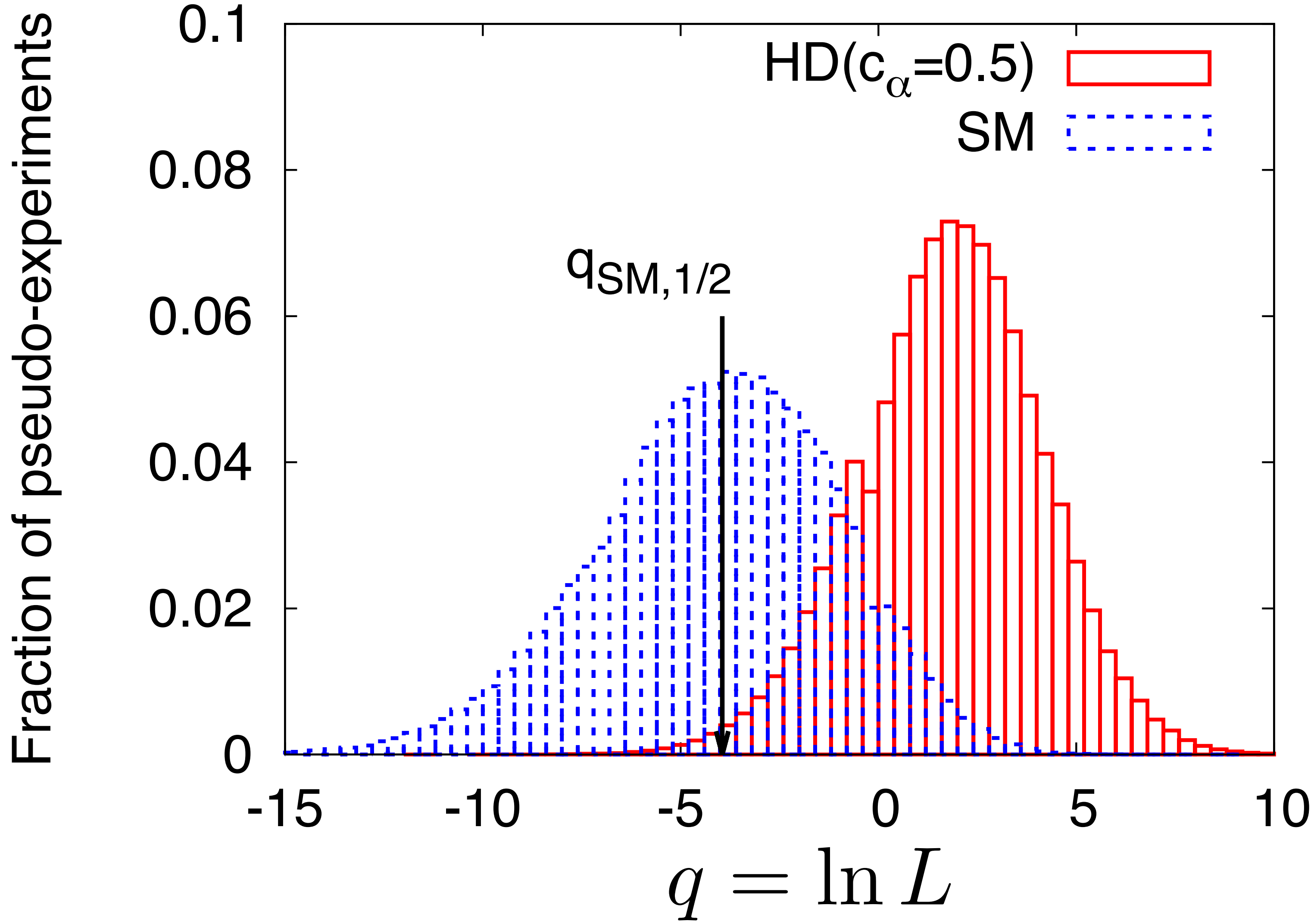
# MEM discriminator

$$D(i) = \frac{|M_{HD(c_\alpha)}(i)|^2}{|M_{HD(c_\alpha)}(i)|^2 + |M_{\rm SM}(i)|^2}$$




Distribution of SM and HD events with respect to the MEM-based discriminator D

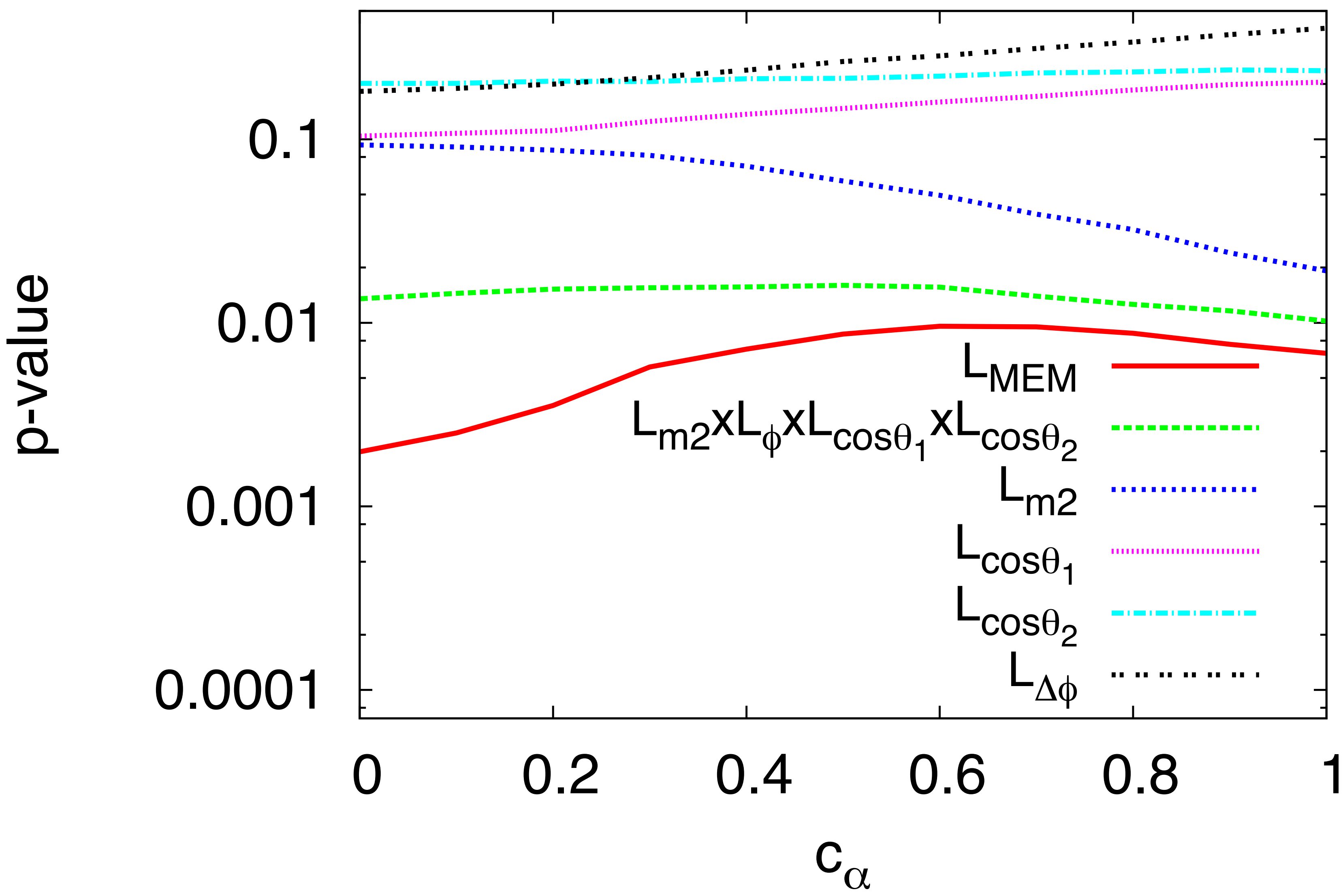
# Significance




Significance estimated by calculating the median $q_{\mathrm{SM},1/2}$ of the SM distribution and by counting the fraction of pseudo-experiments in the HD distribution with $q < q_{\mathrm{SM},1/2}$

This fraction = expected p-value associated with the test of rejecting hypothesis HD if the SM hypothesis is realized.

# Significance




The optimal significance is reached with the MEM-based likelihood approach

# Phenomenology group at the Vrije Universiteit Brussel

- Since October 2010, to make a chain between the theoretical and experimental groups at the VUB.

Vrije Universiteit Brussel pheno

ULB UNIVERSITÉ LIBRE DE BRUXELLES — Englert, Frere, Hambye, Tinyakov, Tytgat, Argurio, ...

UCL Université catholique de Louvain — Maltoni, ... CMS

iihe BRUXELLES BRUSSEL — CMS, IceCube, H1, OPERA, ...

- Contact to
  - http://we.vub.ac.be/HEPVUB/
  - pheno@vub.ac.be, kentarou.mawatari@vub.ac.be

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# HEP@VUB

## High Energy Physics Research Centre @VUB

- The 5-year pheno project was rearranged into a larger framework in January 2013
    - Theory: Ben Craps, Alexander Sevrin (string/cosmology)
    - Collider physics: Jorgen D'Hondt, Freya Blekman, Steven Lowette (CMS)
    - Astor-particle physics: Catherine De Clercq, Nick Van Eindhoven (IceCube)
    - Phenomenology: Kentarou Mawatari
- Pheno members
    - Kentarou Mawatari - Project leader since 2010
    - Laura Lopez Honorez - PD since 2012
    - Priscila de Aquino - PD since 2012
    - Bettina Oexl - PhD since 2010
    - Karen De Causmaecker - PhD since 2011

    - Pantelis Tziveloglou (from Ecole Polytechnique, CPHT) - PD since 2013
    - Jonathan Lindgren (from Chalmers U. of Tech) - PhD since 2013