Vrije Universiteit Brussel

Higgs characterisation at colliders

[arXiv: 1306.6464]

The FeynRules and MadGraph5 framework

FeynRules model
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MadWeight
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spin2 in aMC@NLO
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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.
- The production and decay of such a boson with various spin and parity assignments can be simulated by means of multi-parton, tree-level matrix elements and of NLO QCD calculations, both matched with parton showers.
- Several sample applications are presented which show, in particular, that beyond-leading-order effects in QCD have non-trivial phenomenological implications.

Higgs Characterisation model in FeynRules

- We implemented an effective Lagrangian featuring bosons
  X(JP=0+,0−,1+,1−,2+)
  in FeynRules (http://feynrules.irmp.ucl.ac.be).
  - Effective field theory approach, valid up to a cutoff scale Λ
  - Only one new bosonic state X(JP) 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
Λ [GeV]	10^3	cutoff scale
$c_\alpha (\equiv \cos\alpha)$	1	mixing between 0^+ and 0^-
κ_i	0 , 1	dimensionless coupling parameter

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

Effective Lagrangian -- spin0

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

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

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm),$$
$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu,$$
$$\widetilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$$

```
###################################
## INFORMATION FOR FRBLOCK
###################################
Block FRBlock
    1 1.000000e+03 # Lambda
    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
    9 1.000000e+00 # kAll
   10 1.000000e+00 # kHaa
   11 1.000000e+00 # kAaa
   12 1.000000e+00 # kHza
   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
```

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:

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

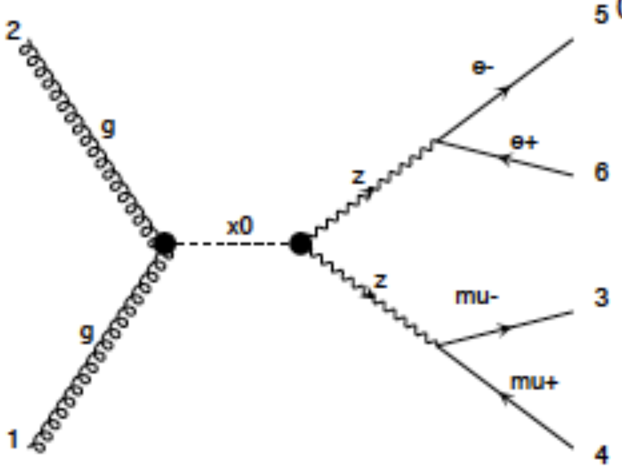
$$\mathcal{L}_2^V = -\frac{1}{\Lambda}\sum_{V=Z,W,\gamma,g} \kappa_V T^V_{\mu\nu} X_2^{\mu\nu}$$

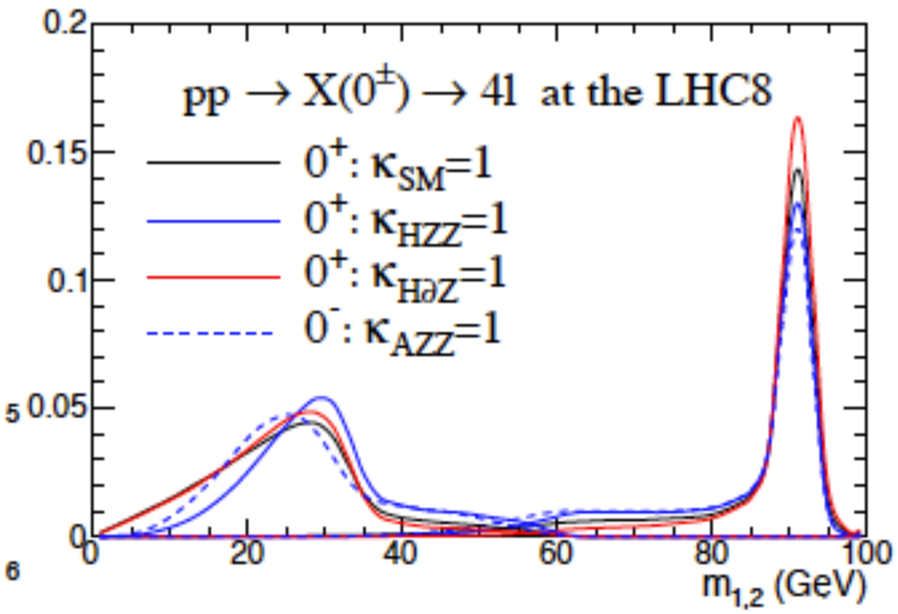
  - The E-M tensor for QED:

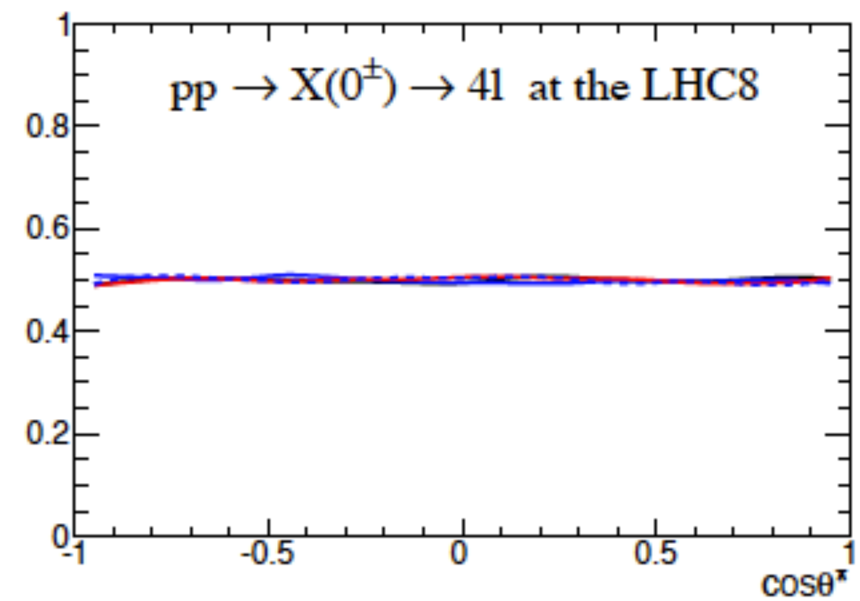
$$T^f_{\mu\nu} = -g_{\mu\nu}\Big[\bar\psi_f(i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar\psi_f i\gamma_\rho\psi_f)\Big] + \Big[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu(\bar\psi_f i\gamma_\nu\psi_f) + (\mu\leftrightarrow\nu)\Big],$$

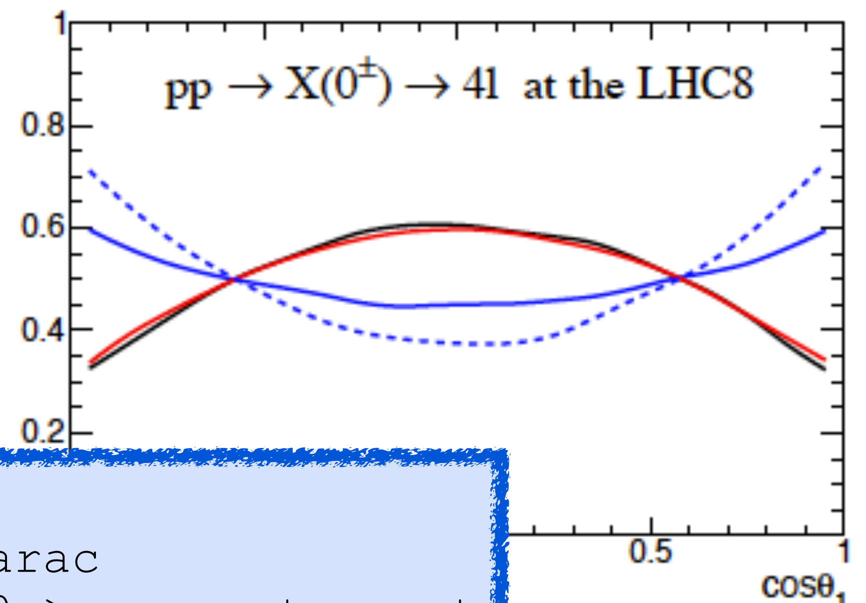
$$T^\gamma_{\mu\nu} = -g_{\mu\nu}\Big[-\frac{1}{4}A^{\rho\sigma}A_{\rho\sigma} + \partial^\rho\partial^\sigma A_\sigma A_\rho + \frac{1}{2}(\partial^\rho A_\rho)^2\Big] - A_\mu^{\ \rho}A_{\nu\rho} + \partial_\mu\partial^\rho A_\rho A_\nu + \partial_\nu\partial^\rho A_\rho A_\mu,$$

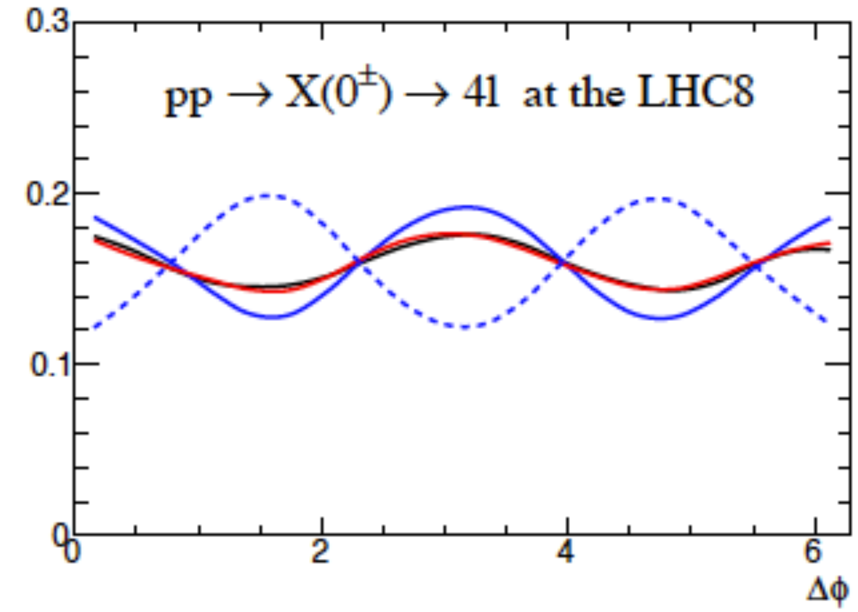
Mass and angular distributions -- spin0





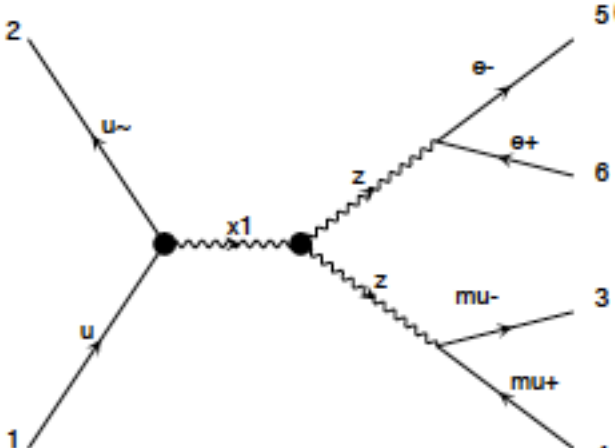


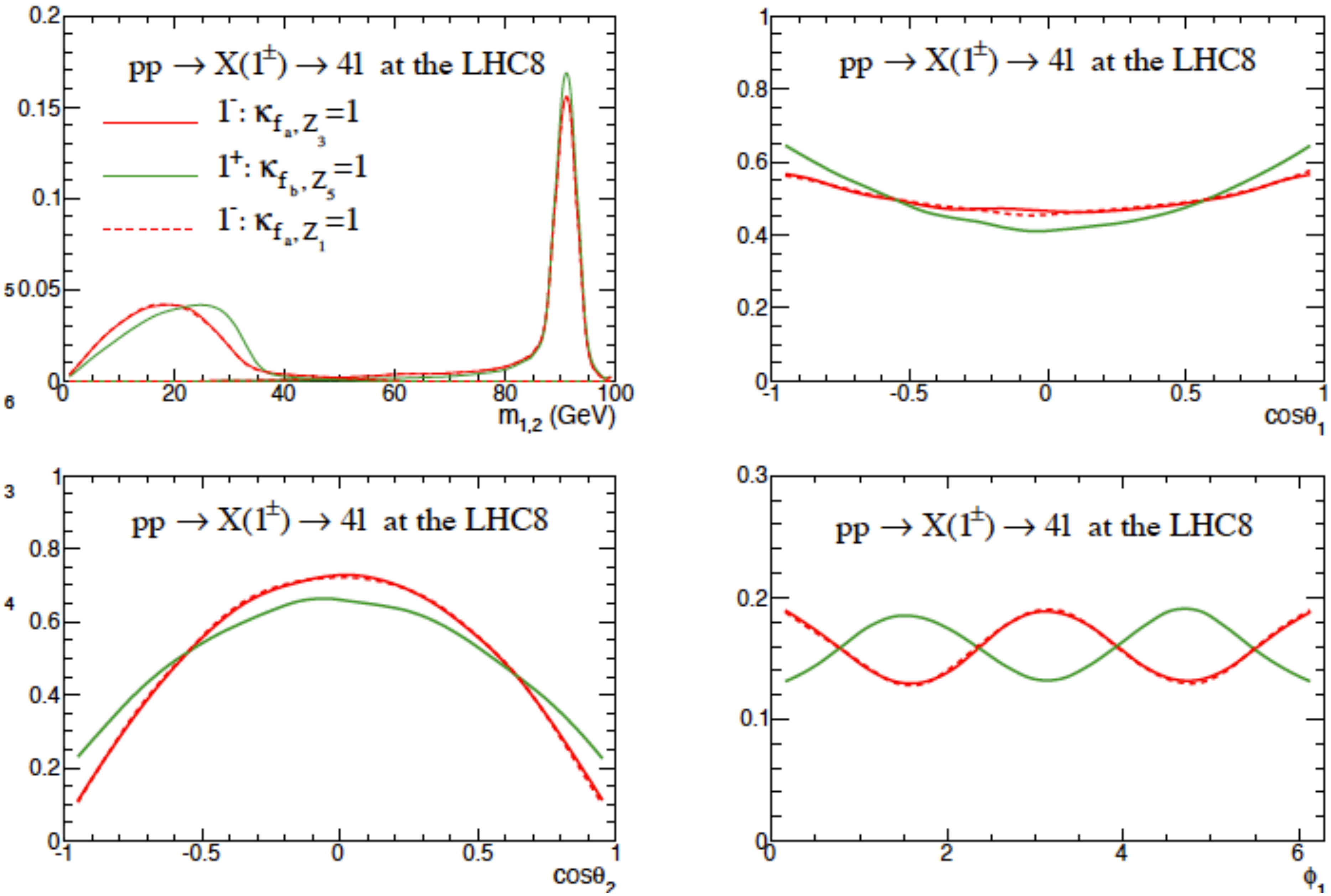




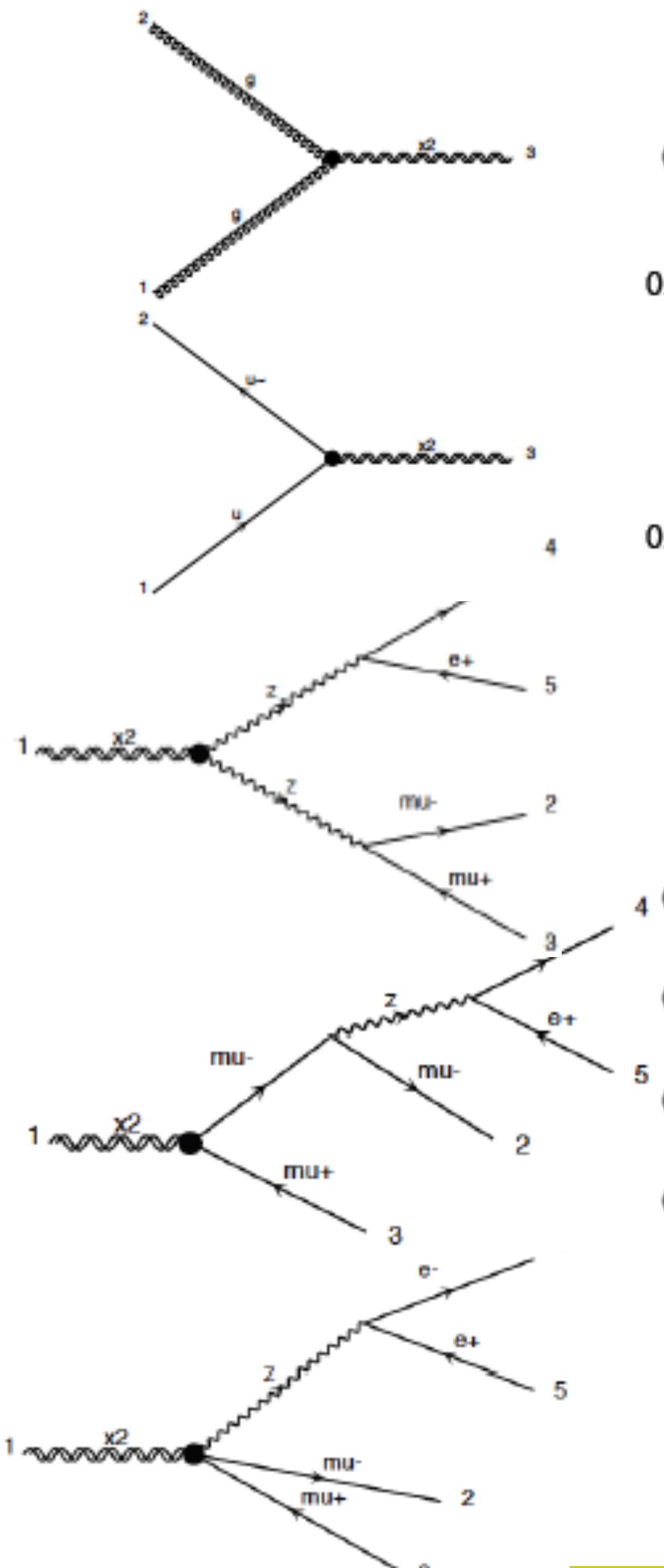

```
./bin/mg5
>import model HiggsCharac
>generate p p > x0, x0 > mu- mu+ e- e+
>output
>launch
```

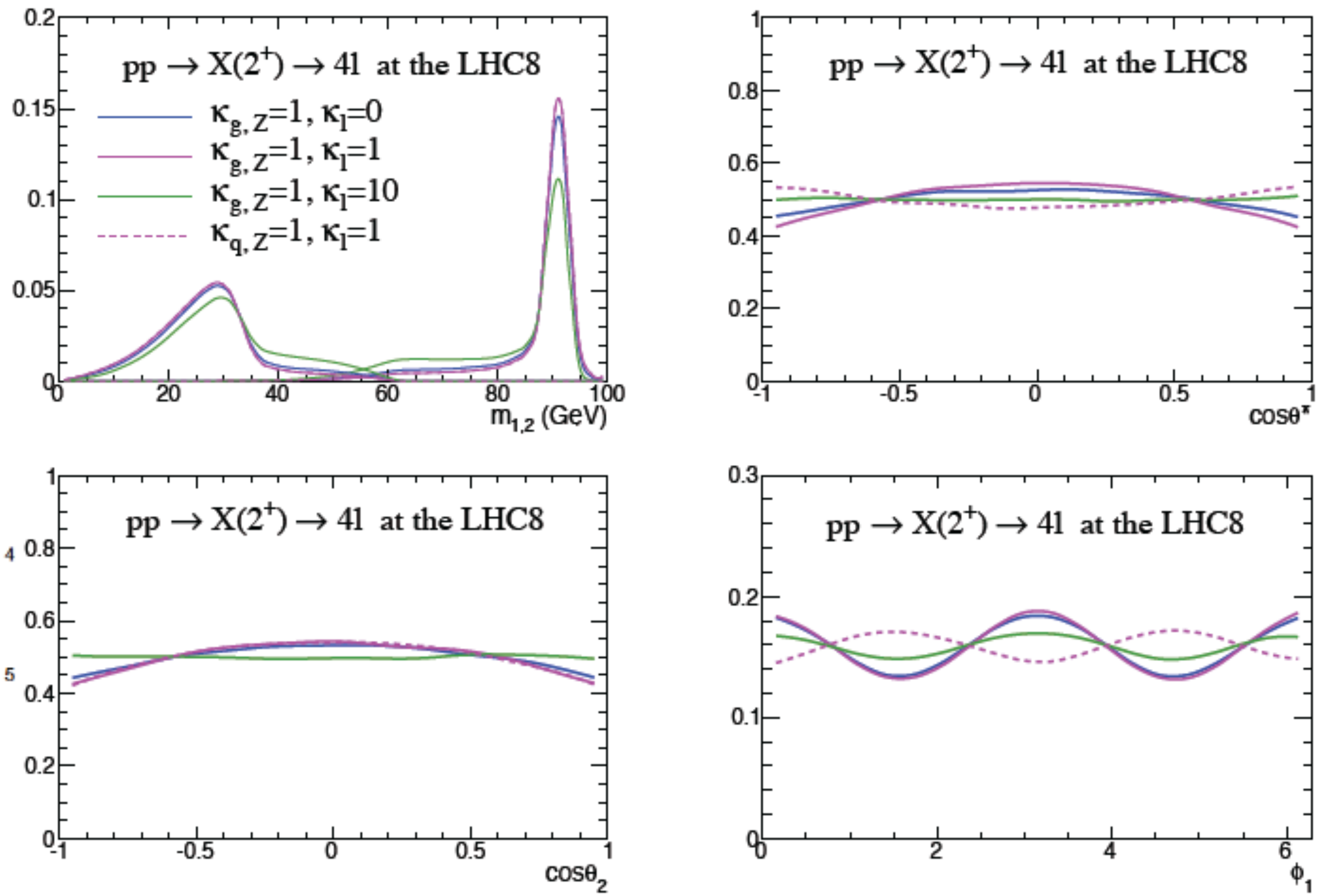
Mass and angular distributions -- spin1





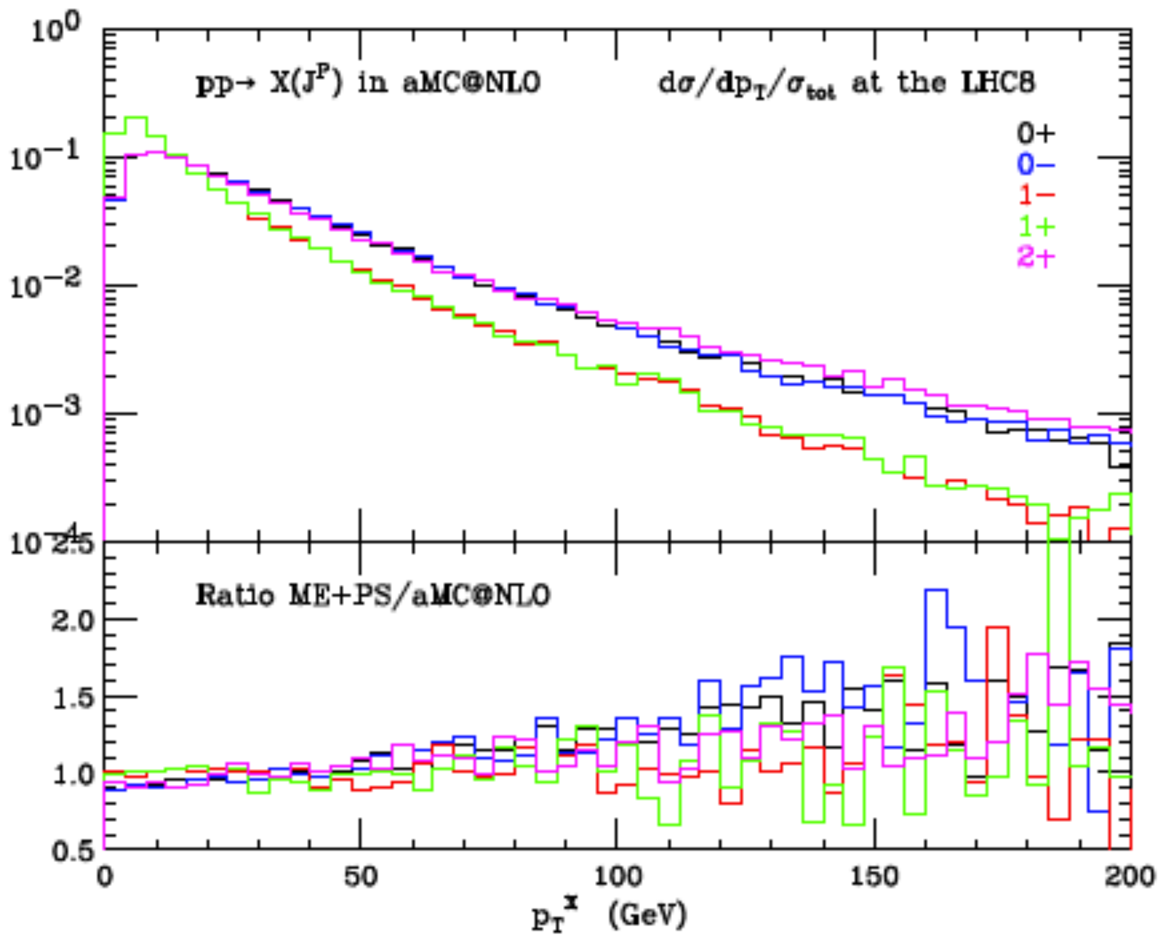
Mass and angular distributions -- spin2

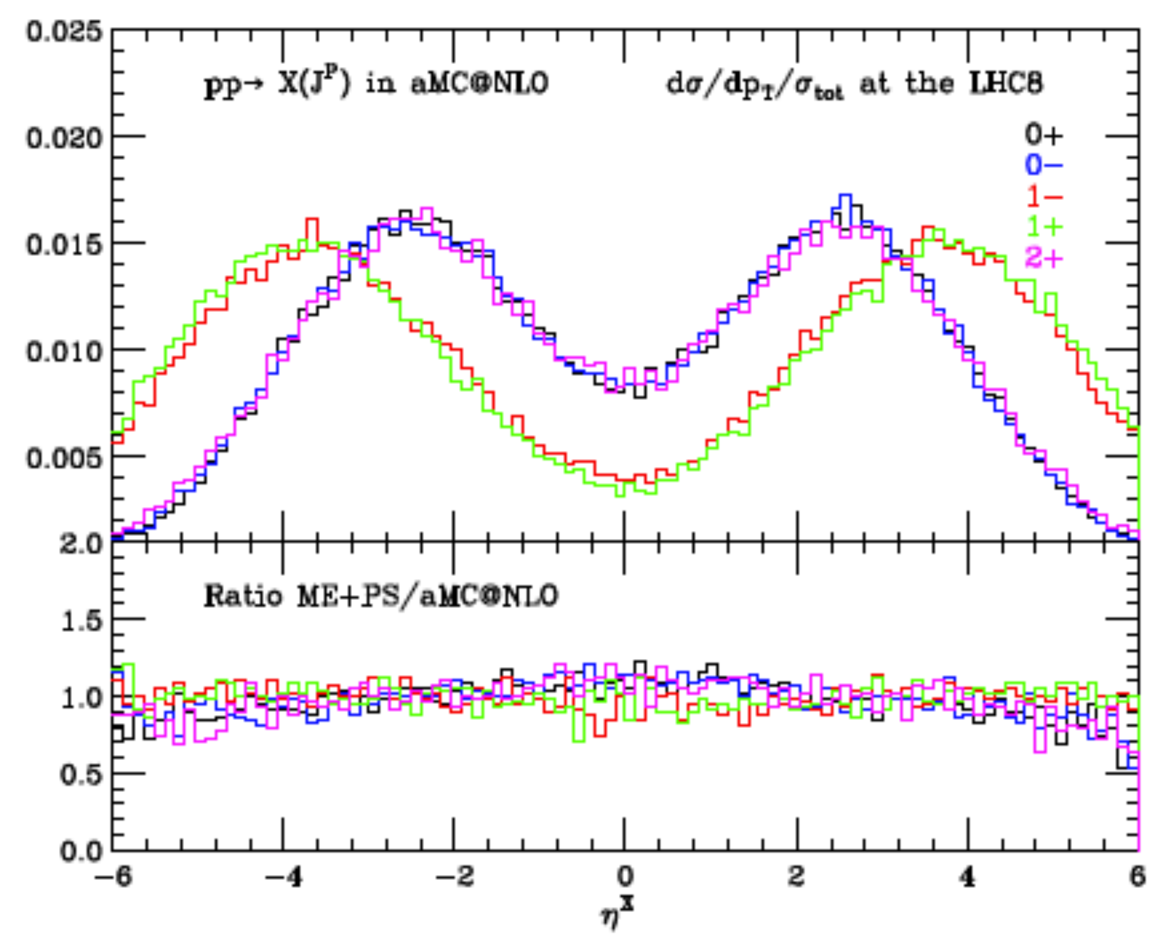




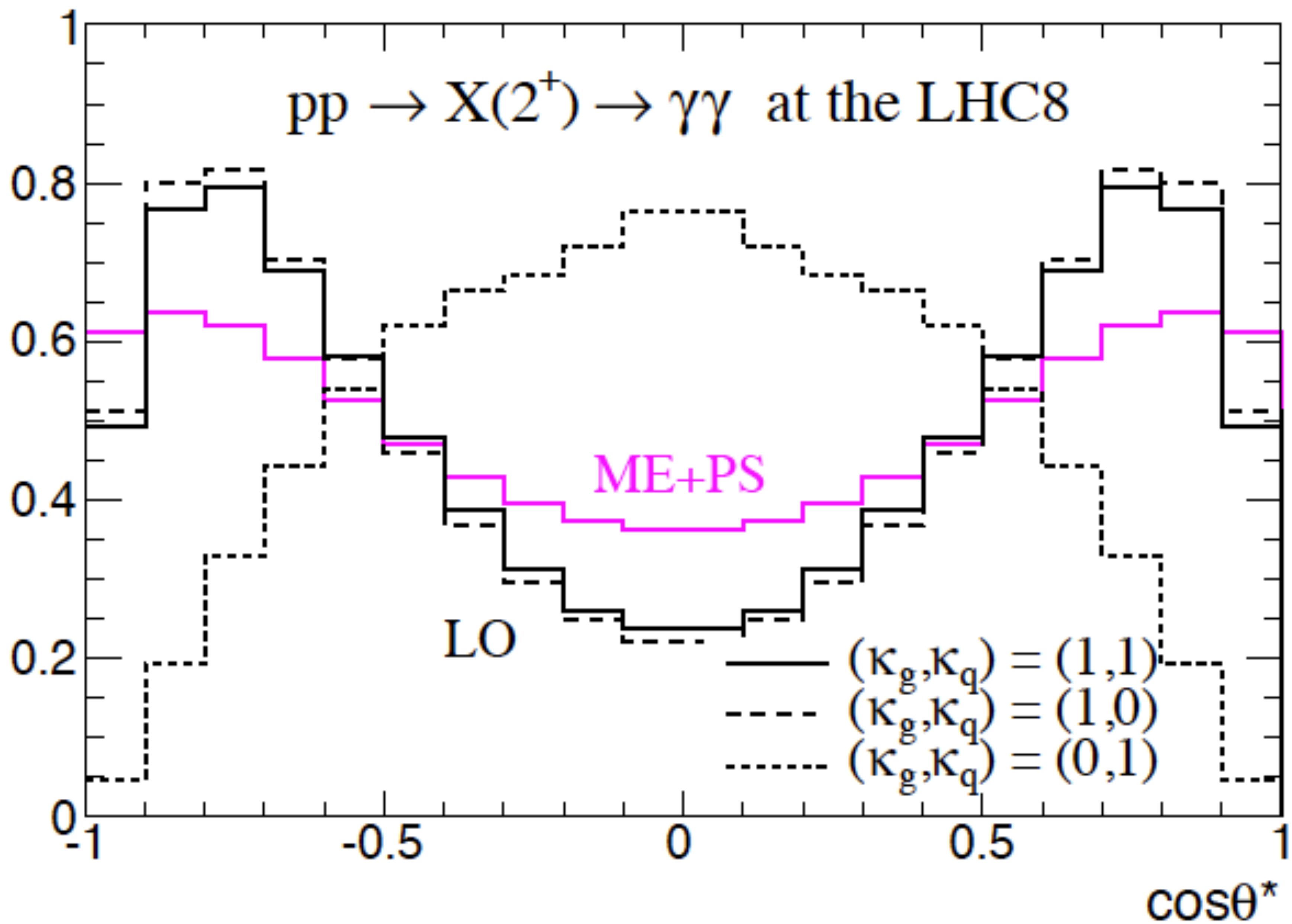
Higher order effects in QCD

- 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]

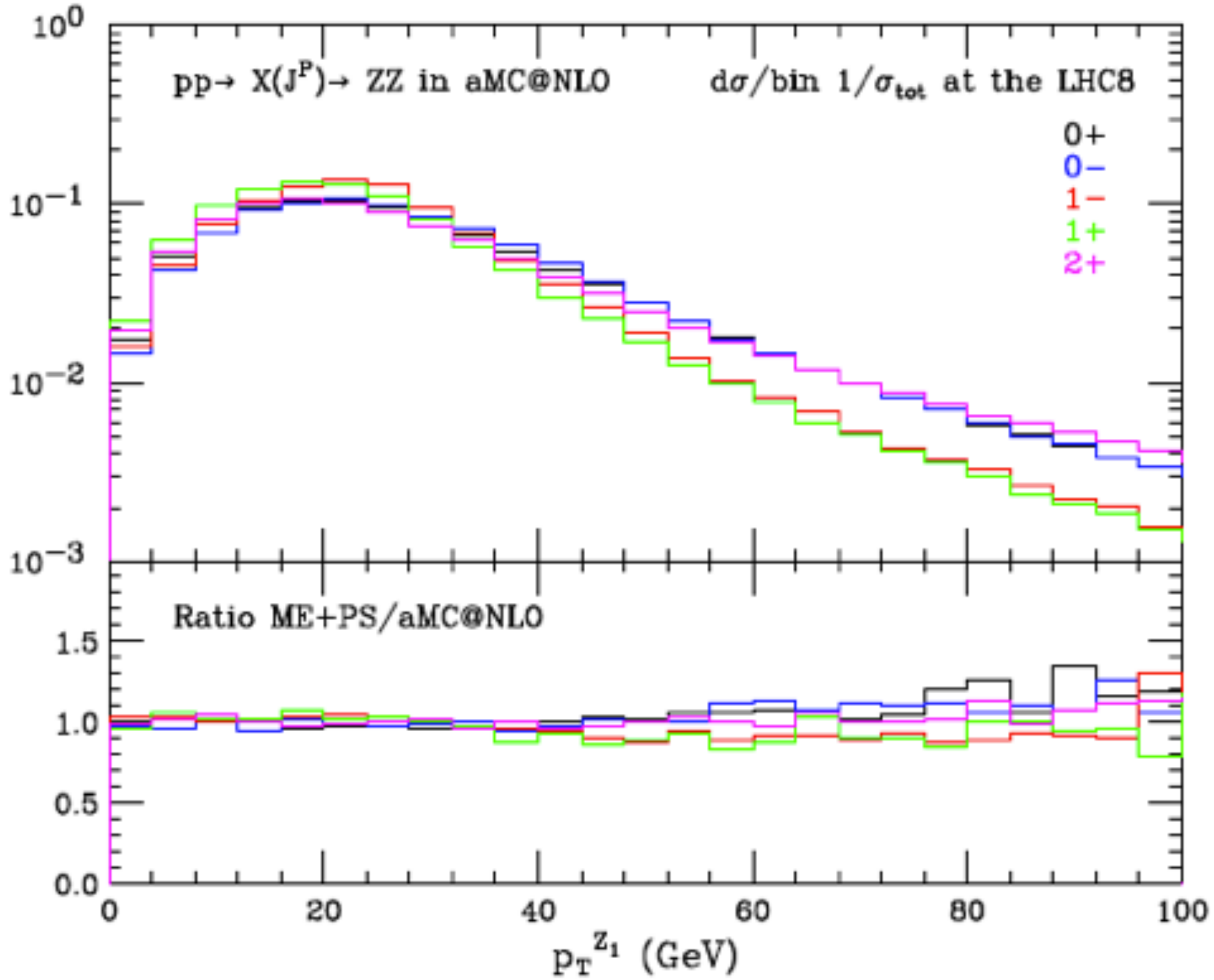


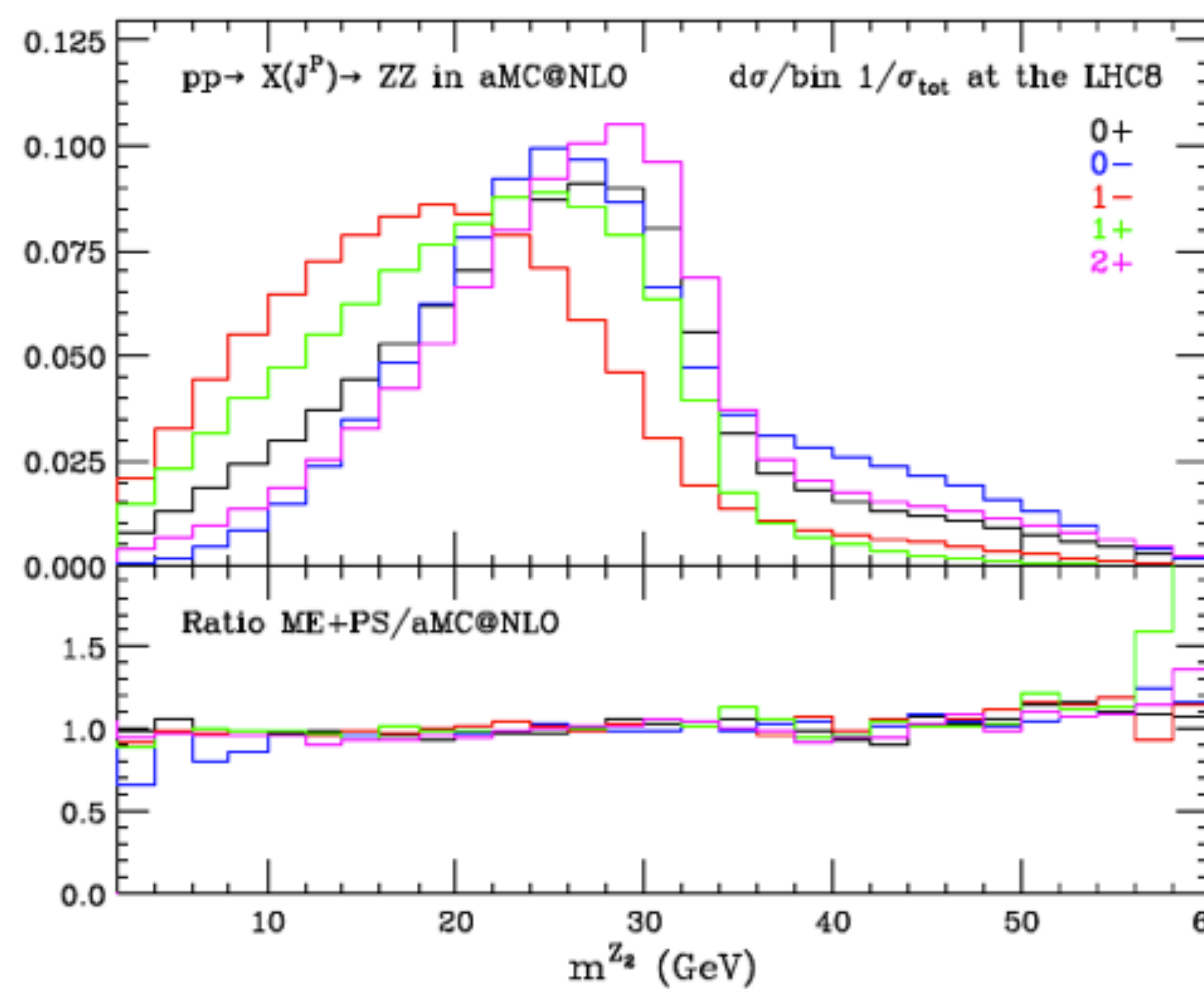


Spin/parity determination
1. X→γγ



Spin/parity determination
2. X→VV*→4l

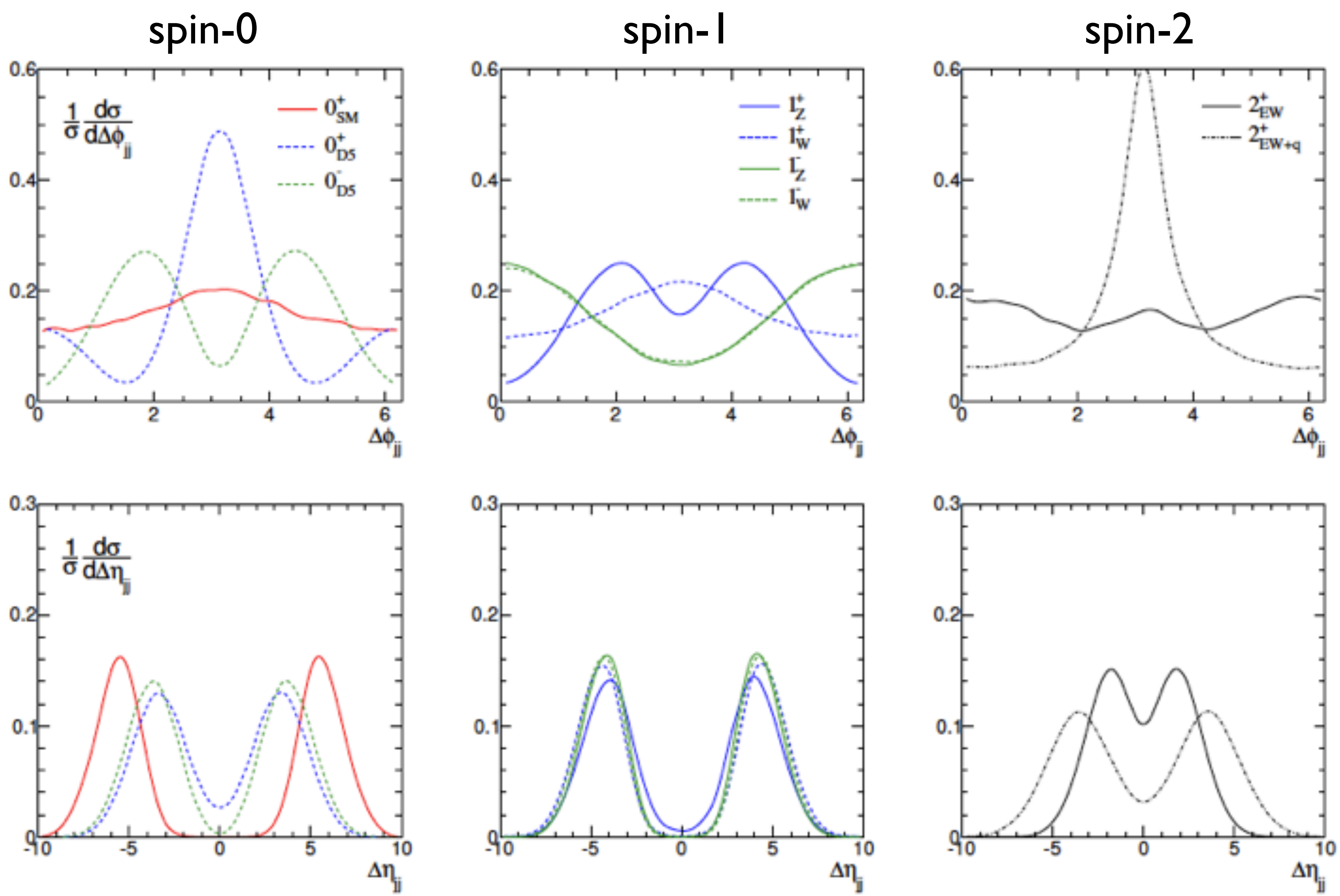




Spin/parity determination
3. pp→jjX

di-jet correlations

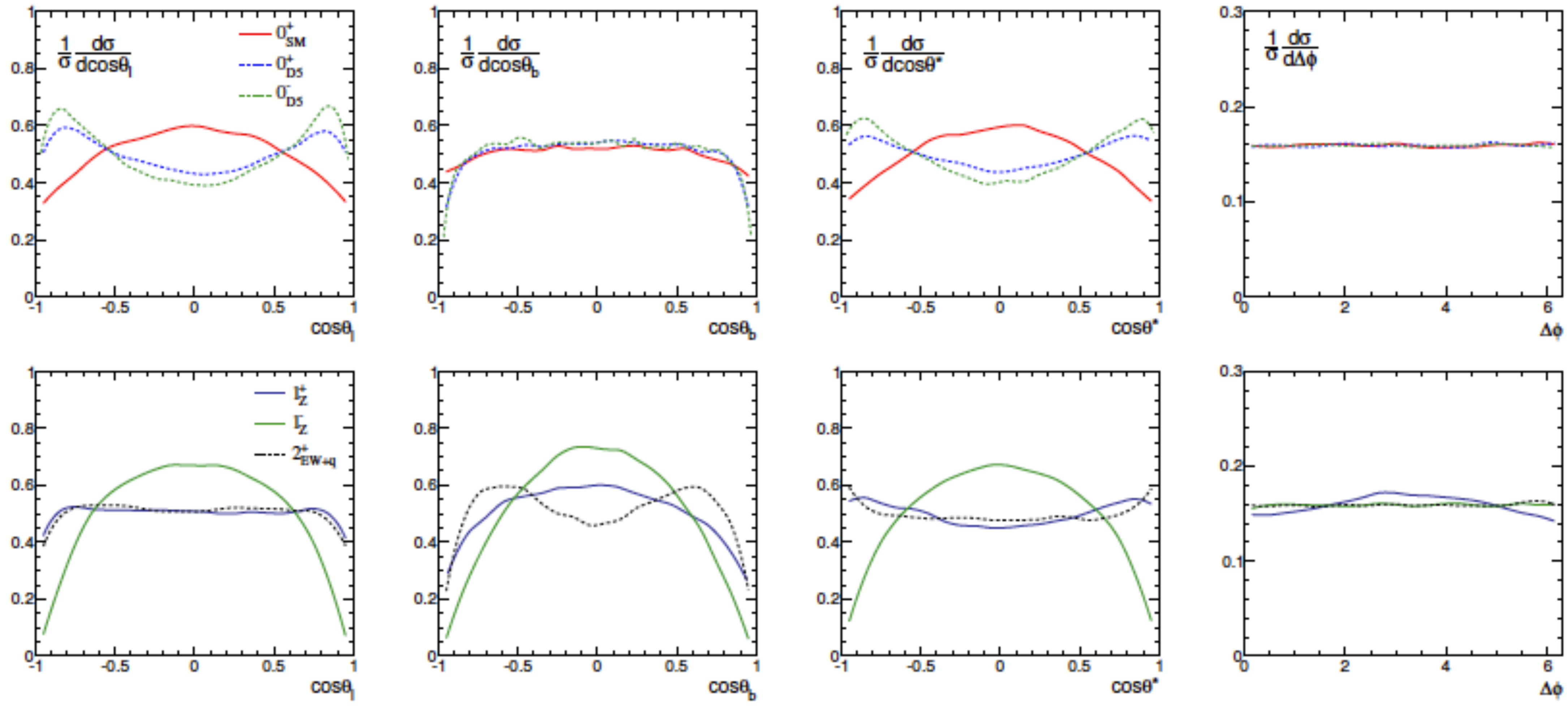
Englert, Goncalves-Netto, KM, Plehn (2013)



Δη as well as ΔΦ are the powerful observables.

Spin/parity determination
4. pp→ZX

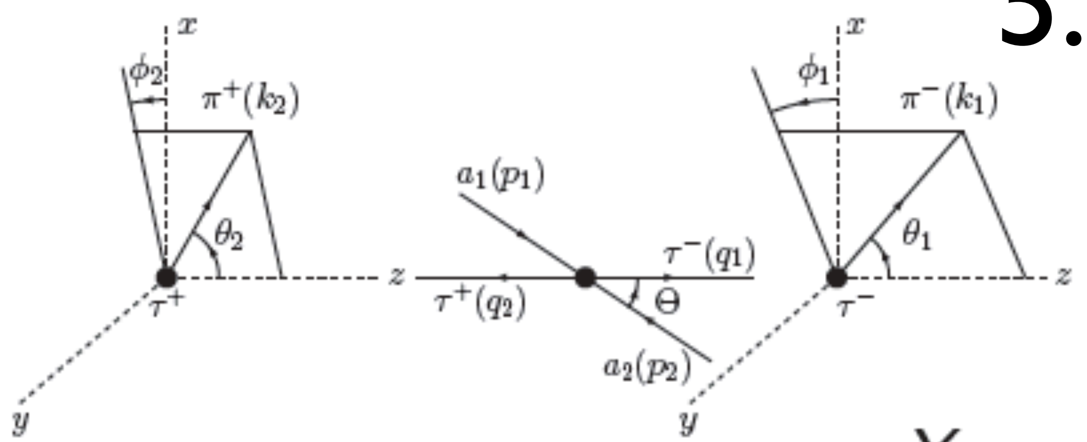
Englert, Goncalves-Netto, KM, Plehn (2013)



Spin/parity determination
5. X→ττ

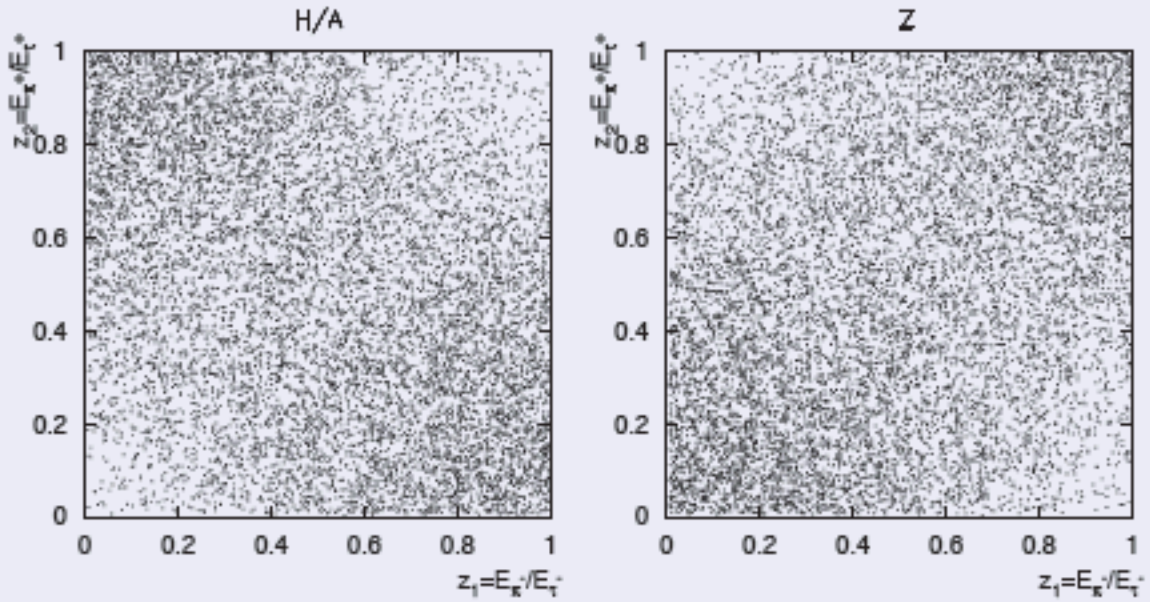
[Bullock, Hagiwara, Martin, NPB(1993)]
[Krämer, Kühn, Stong, Zerwas, ZPC(1994)]
[Pierzchala, Richter-Was, Was, Worek, APPB(2001,2002,...)]

[Hagiwara, Li, KM, Nakamura, 1212.6247]

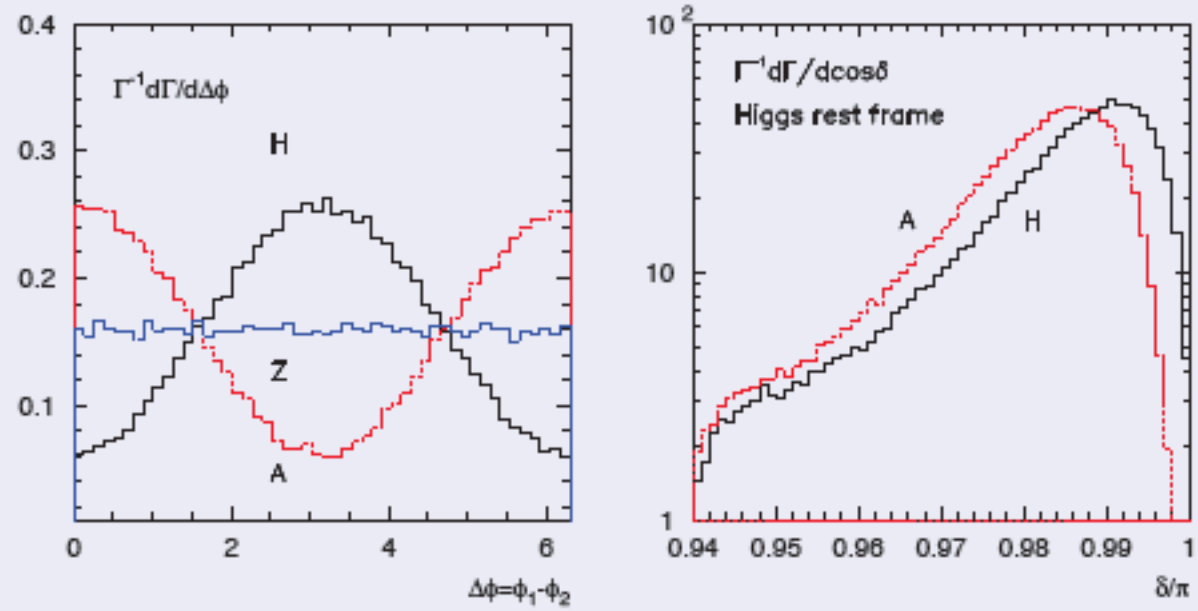


$$pp \to X \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$$

Longitudinal spin (helicity) effect



Transverse spin effect



$d^2\Gamma/dz_1dz_2 \sim 1 \mp z_1z_2$ for spin-0/1, $\quad d\Gamma/d\Delta\phi \sim 1 \mp A\cos\Delta\phi$ for $0^\pm$

τ could be a spin/parity analyzer!

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TauDecay

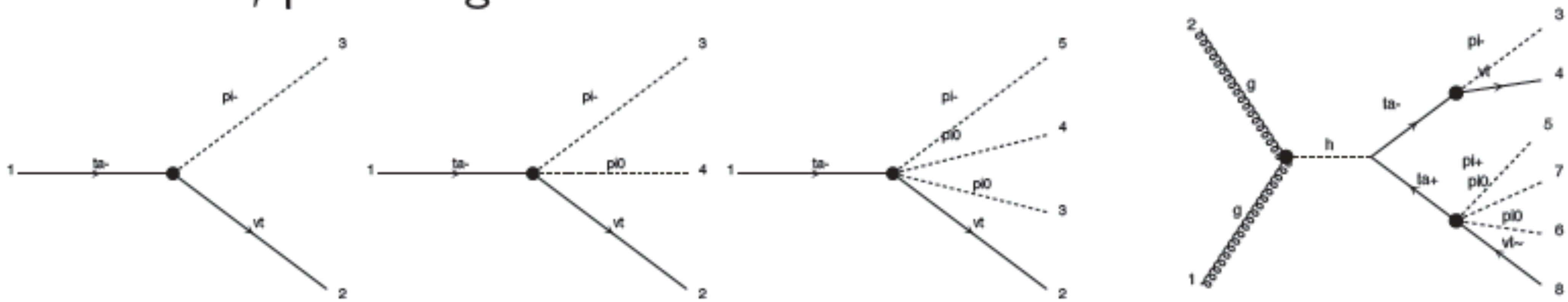
a library to simulate polarized tau decays via FeynRules/MadGraph5

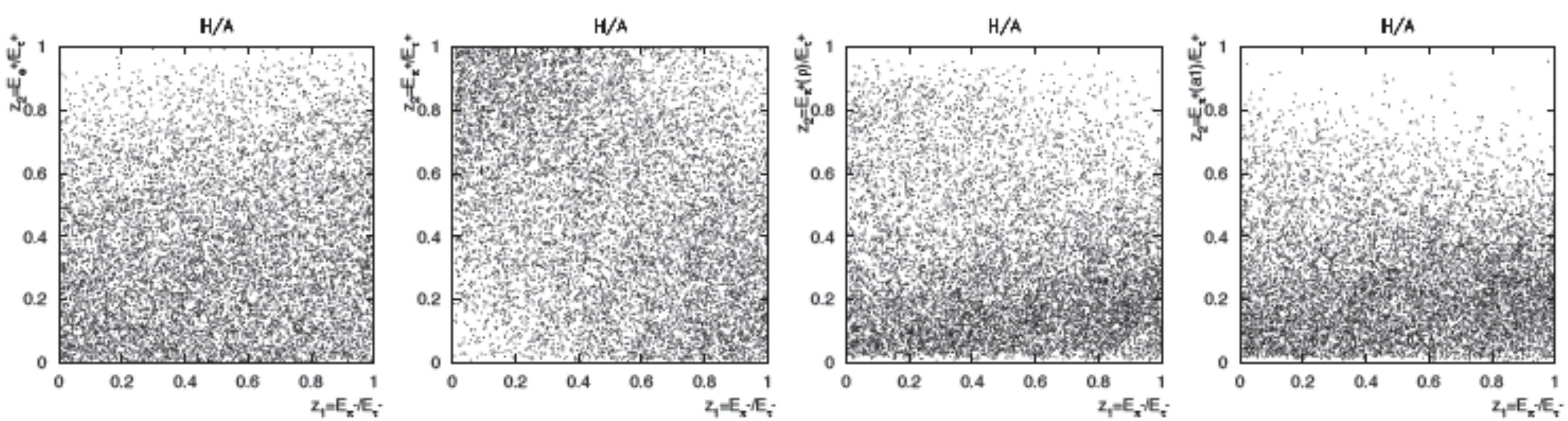
We implemented the effective Lagrangians [Hagiwara, Li, KM, Nakamura, 1212.6247]

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

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

into FeynRules, providing the model file for MadGraph5.





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

Outlook

- 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 Characterization model is ready for the spin/parity determination.

Vrije Universiteit Brussel

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, ...

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