Vrije Universiteit Brussel

Brout-Englert-Higgs

BEH characterisation framework

Kentarou Mawatari (馬渡 健太郎)

(Vrije Universiteit Brussel and International Solvay Institutes)

July 4th, 2012, at CERN

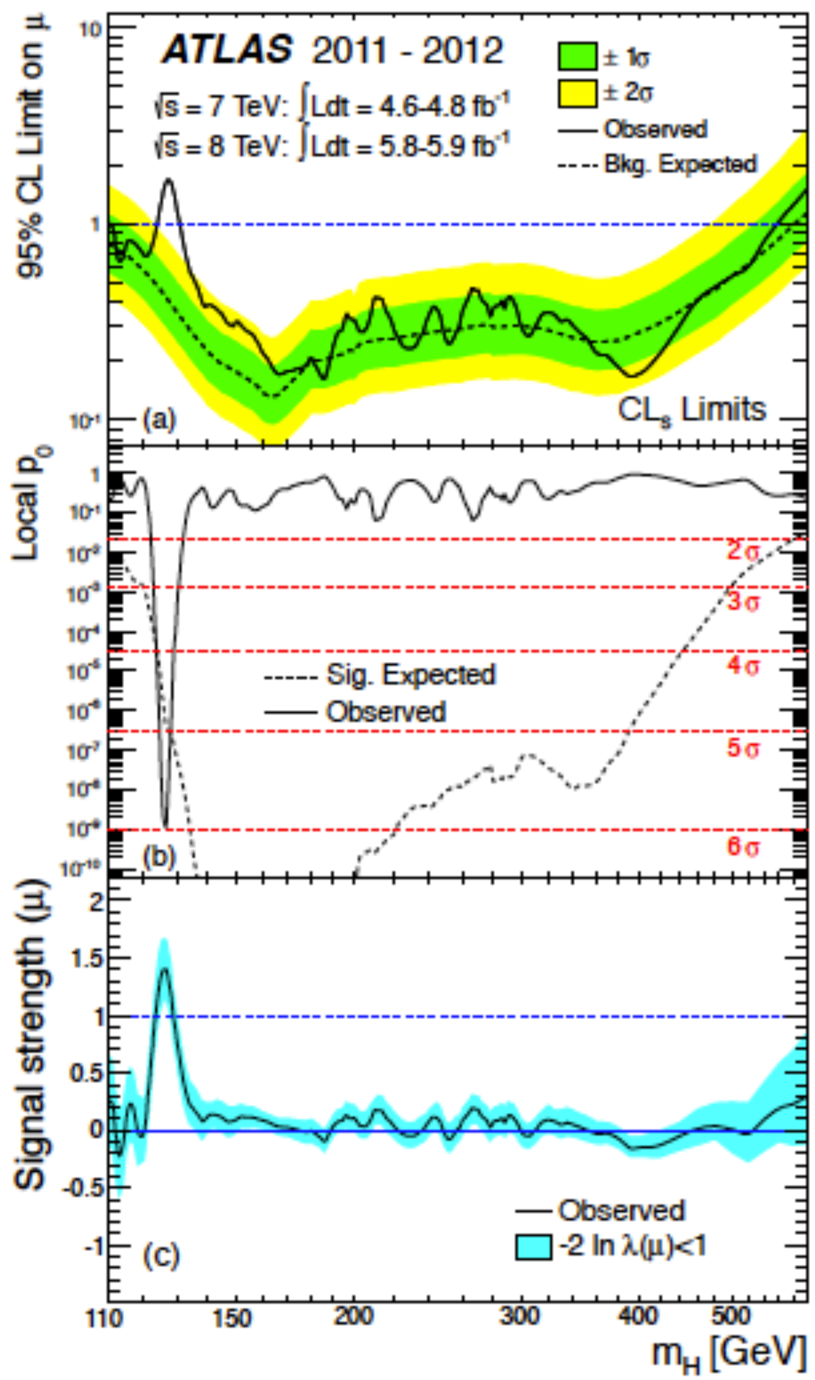
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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



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

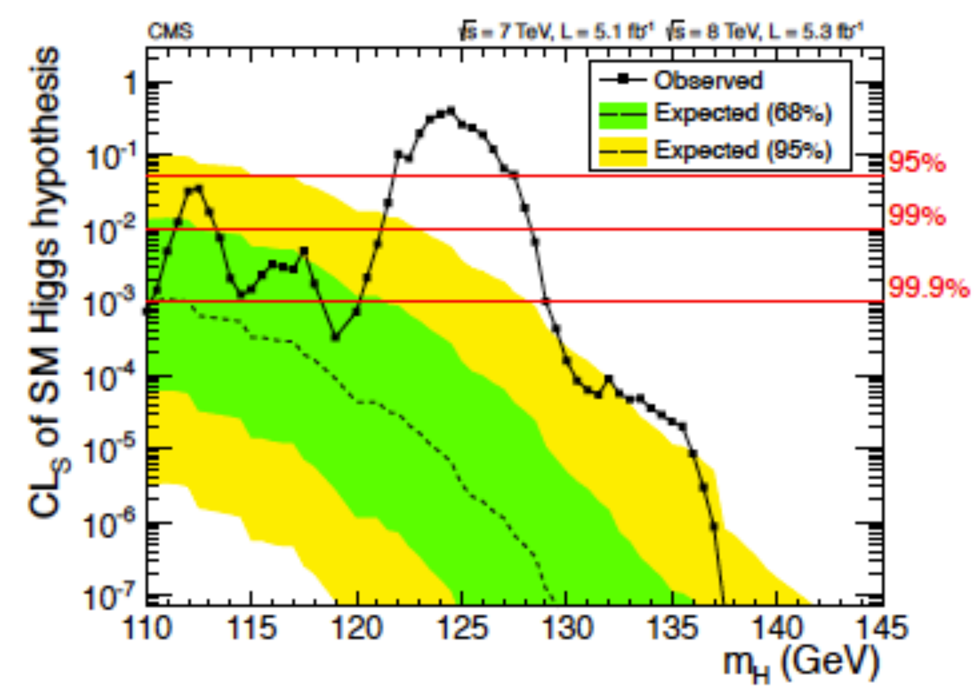
[arXiv: 1207.7214]

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



After one year...

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.

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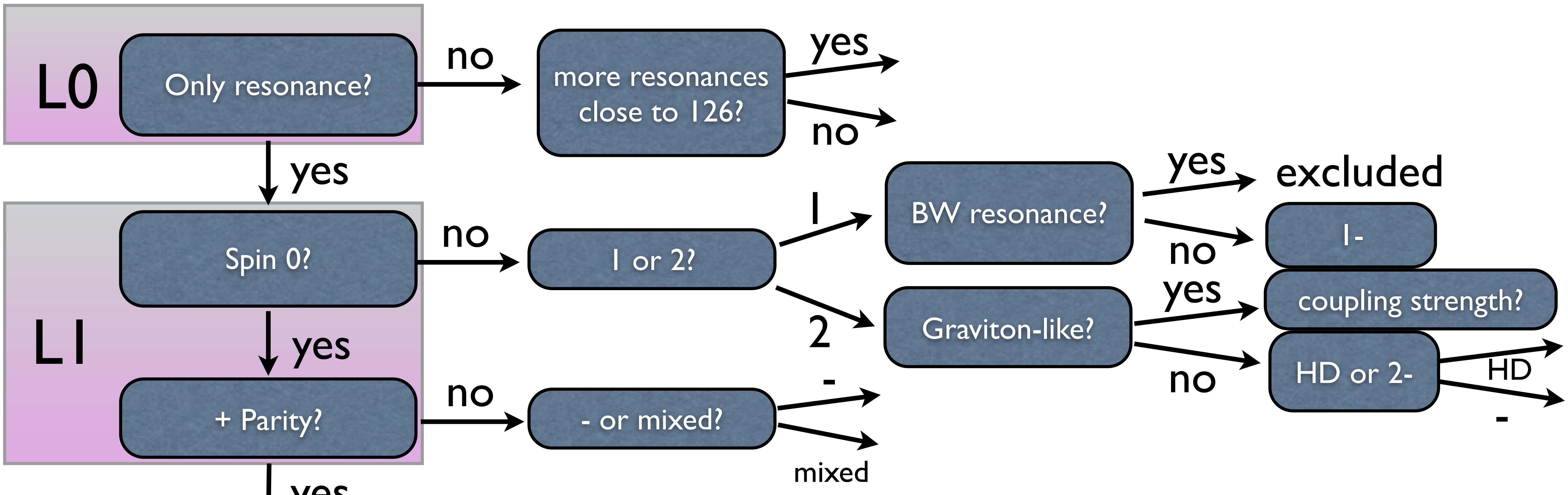
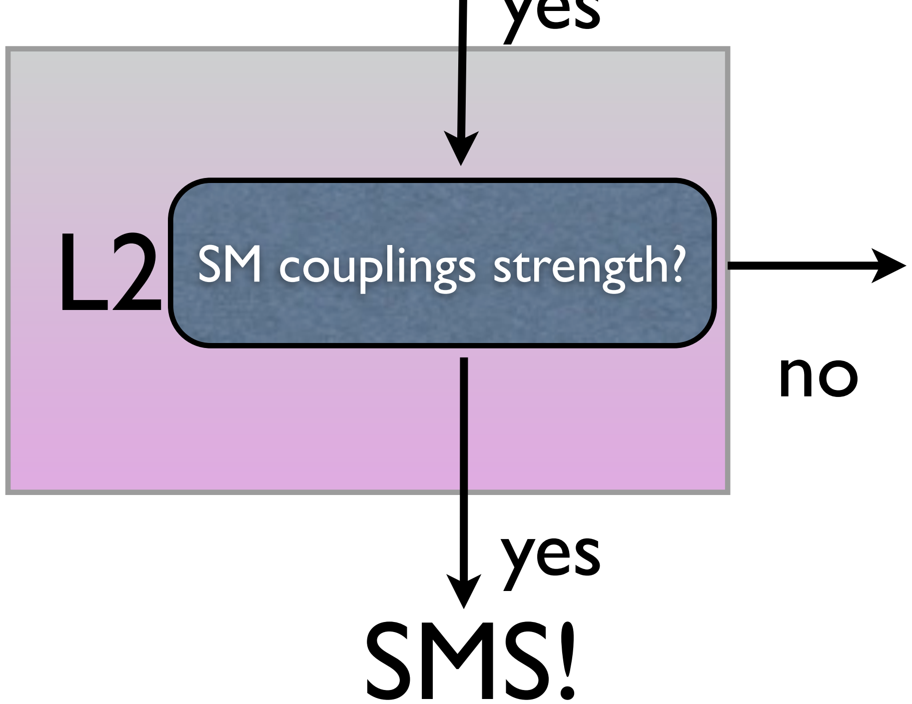
Is this the Standard Model scalar boson?

How can we determine the spin/parity nature at the LHC?

Strategy of the Higgs characterisation





We provide a complete framework, based on an effective field theory description, that allows to perform characterisation studies of the newly discovered boson in all relevant channels in a consistent, systematic and accurate way.

Contents

- Introduction
- Theory - Pheno - Experiment
  - e.g. spin-3/2 particles at the LHC
- Higgs characterization framework

TH

Idea

Volume 62B, number 3 PHYSICS LETTERS 7 June 1976

CONSISTENT SUPERGRAVITY

S. DESER* and B. ZUMINO
CERN, Geneva, Switzerland

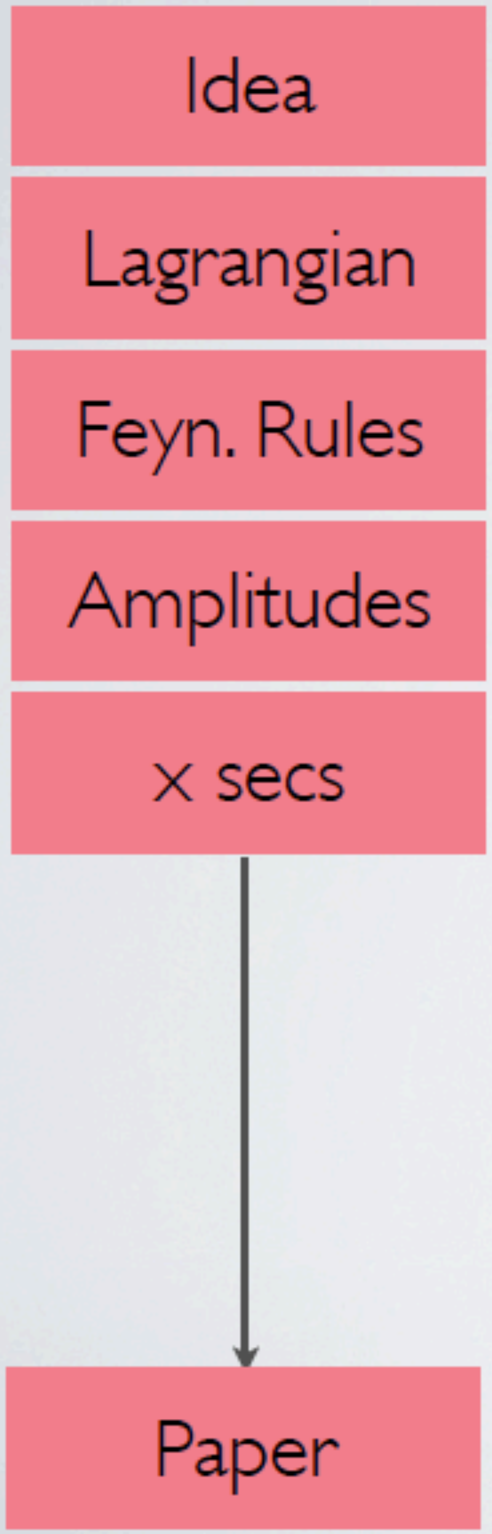
Received 28 April 1976

A combined spin 2 – spin 3/2 extension of general relativity is given which is both free of the usual higher spin inconsistencies and invariant under local supersymmetry transformations.

The unification of the gravitational field with a spin 3/2 system is a natural goal within the framework of supersymmetry [1]. In constructing such a theory

$$L = -\tfrac{1}{2}eR - \frac{1}{2}\epsilon^{\lambda\mu\nu\rho}\,\bar{\psi}_\lambda \gamma_5 \gamma_\mu D_\nu \psi_\rho \qquad (1)$$

TH



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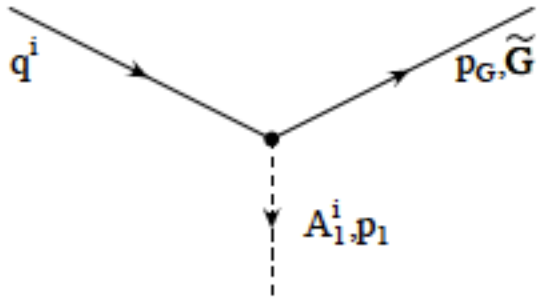
Light-Gravitino Production at Hadron Colliders

Jaewan Kim[1], Jorge L. Lopez[2], D.V. Nanopoulos[1,3], Raghavan Rangarajan[1], and A. Zichichi[4]

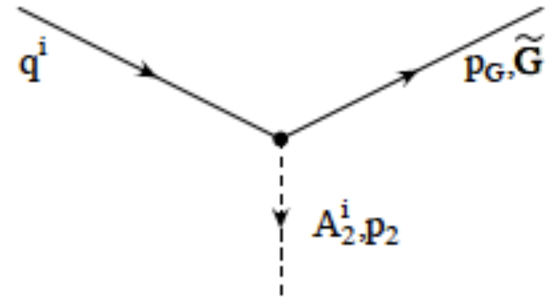
[1]Astroparticle Physics Group, Houston Advanced Research Center (HARC)
The Mitchell Campus, The Woodlands, TX 77381, USA
[2] Bonner Nuclear Lab, Department of Physics, Rice University
6100 Main Street, Houston, TX 77005, USA
[3]Center for Theoretical Physics, Department of Physics, Texas A&M University
College Station, TX 77843–4242, USA, and
Academy of Athens, Chair of Theoretical Physics, Division of Natural Sciences
28 Panepistimiou Avenue, 10679 Athens, Greece
[4]University and INFN-Bologna, Italy and CERN, 1211 Geneva 23, Switzerland

Abstract

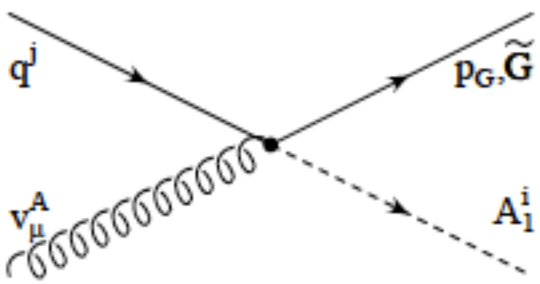
We consider the production of gravitinos ($\widetilde{G}$) in association with gluinos ($\tilde{g}$) or squarks ($\tilde{q}$) at hadron colliders, including the three main sub-processes: $q\bar{q} \to \tilde{g}\widetilde{G}$, $qg \to \tilde{q}\widetilde{G}$, and $gg \to \tilde{g}\widetilde{G}$. These channels become enhanced to the point of being observable for sufficiently light gravitino masses ($m_{\widetilde{G}} < 10^{-4}$ eV),



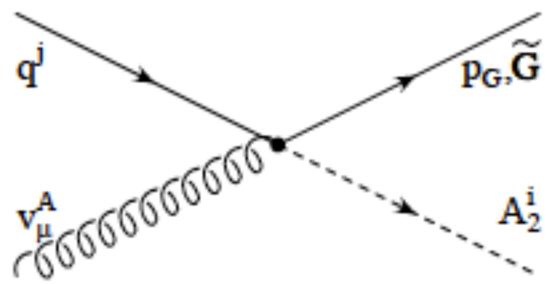
$2/(3^{1/2} M m_{3/2})\, p_1 \cdot p_G\, (\cos\theta\, P_L+\sin\theta\, P_R)$



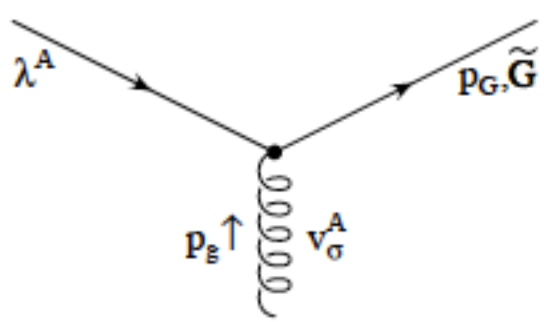
$2/(3^{1/2} M m_{3/2})\, p_2 \cdot p_G\, (\cos\theta\, P_R-\sin\theta\, P_L)$



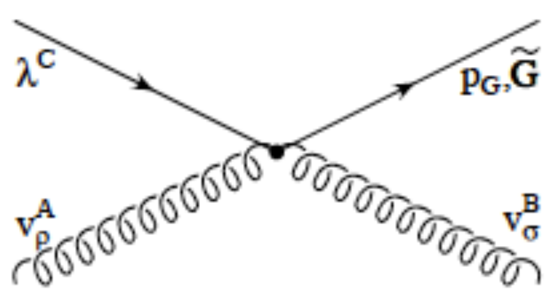
$-2\, g_s/(3^{1/2} M m_{3/2}) T^A_{ij} p^\mu_G\, (\cos\theta\, P_L+\sin\theta\, P_R)$



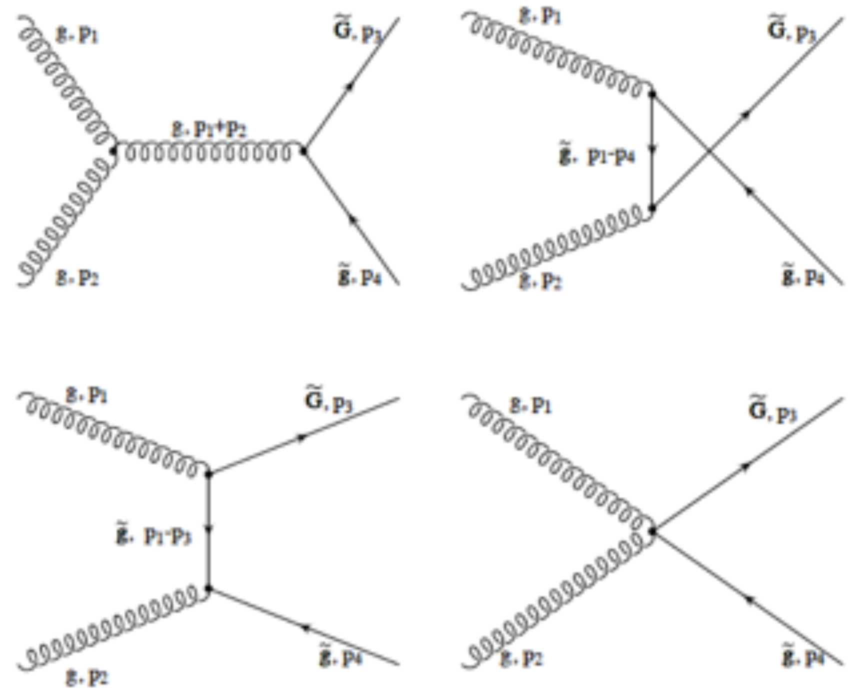
$-2\, g_s/(3^{1/2} M m_{3/2}) T^A_{ij} p^\mu_G\, (\cos\theta\, P_R-\sin\theta\, P_L)$

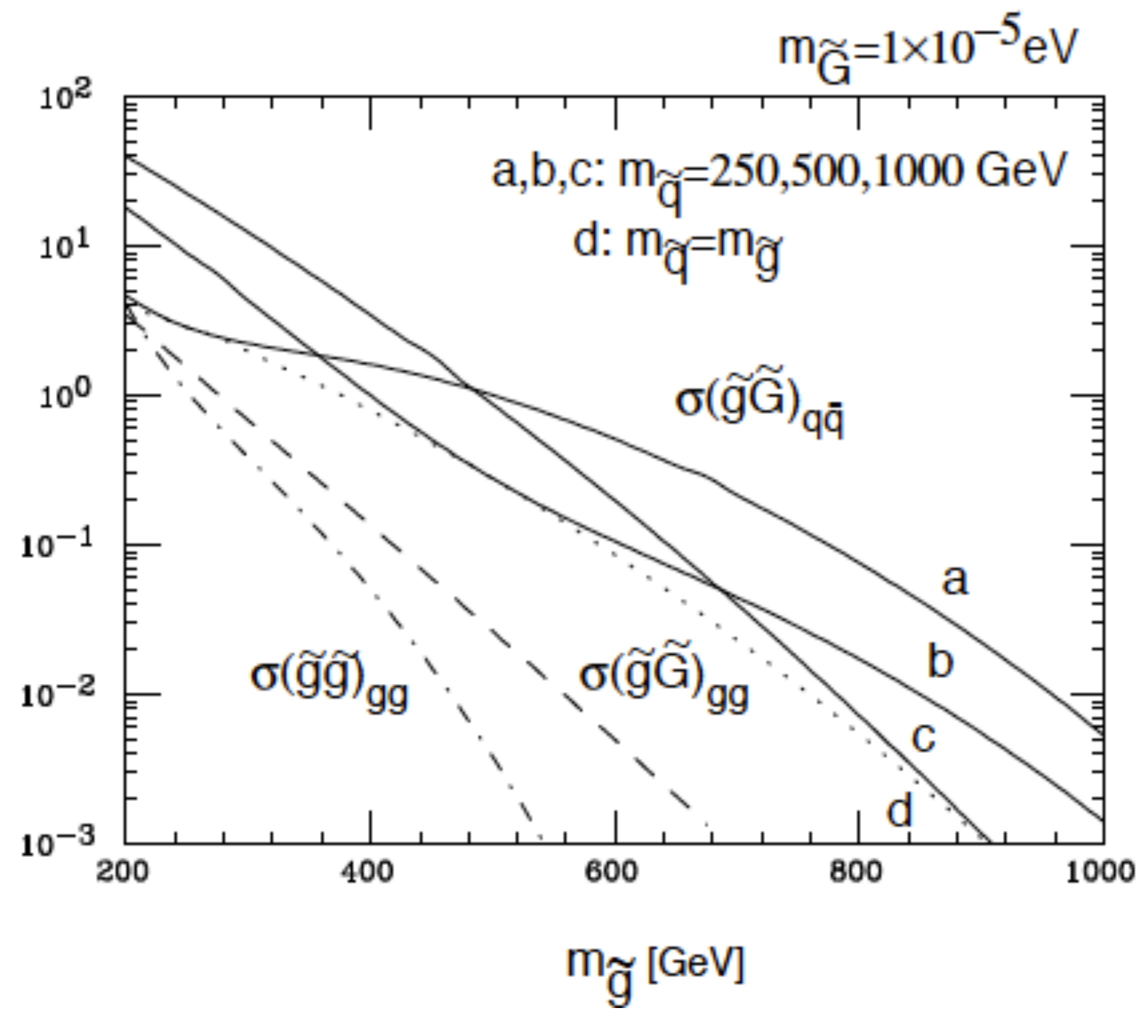


$1/(2\, 6^{1/2} M m_{3/2})\, p^\alpha_{\tilde g}\, p^\beta_G [\gamma_\alpha,\gamma_\sigma]\gamma_\beta\, \gamma^5$



$i/(2\, 6^{1/2} M m_{3/2})\, g_s f^{ABC} p^\beta_G\, [\gamma_\rho,\gamma_\sigma]\, \gamma_\beta\, \gamma^5$





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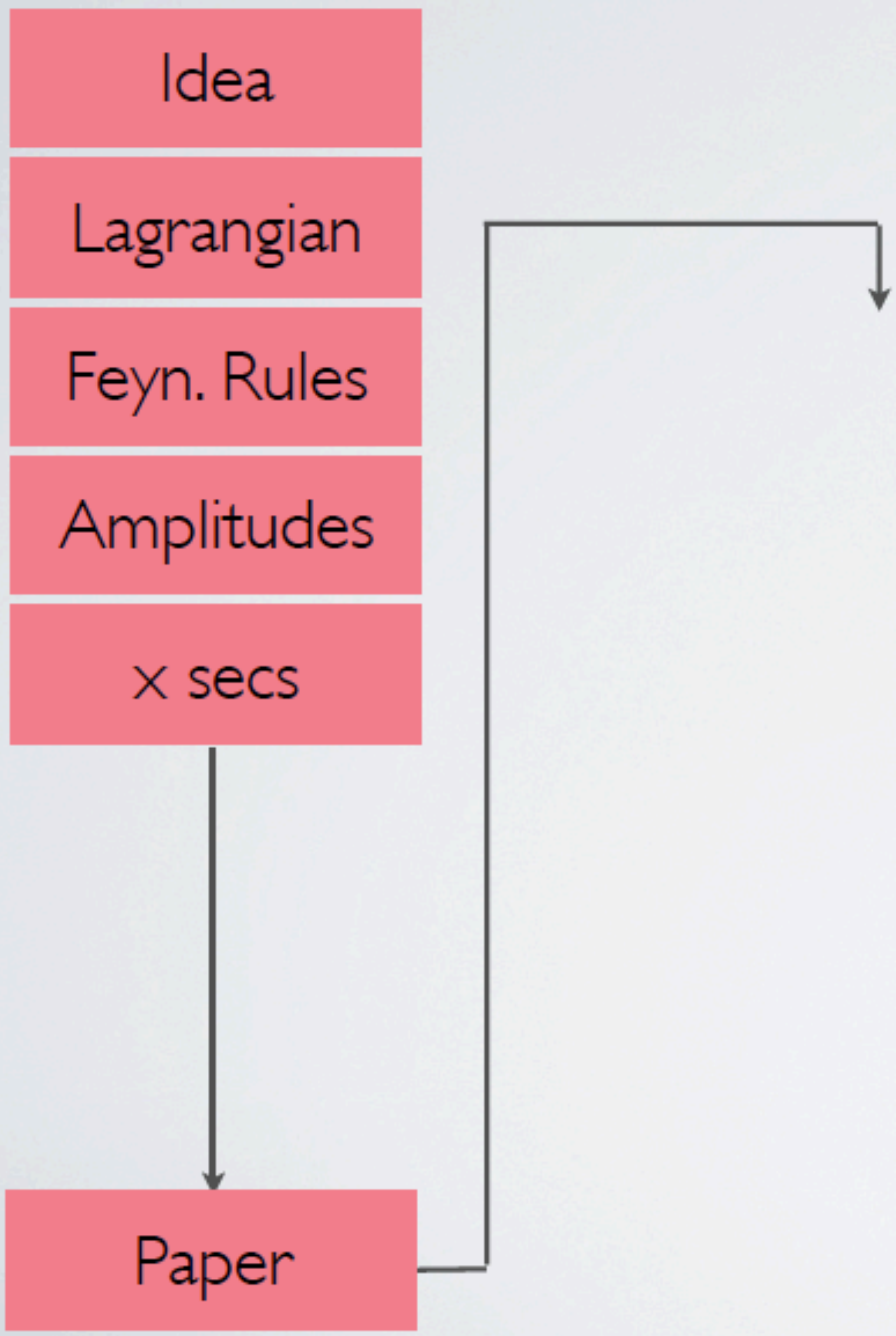

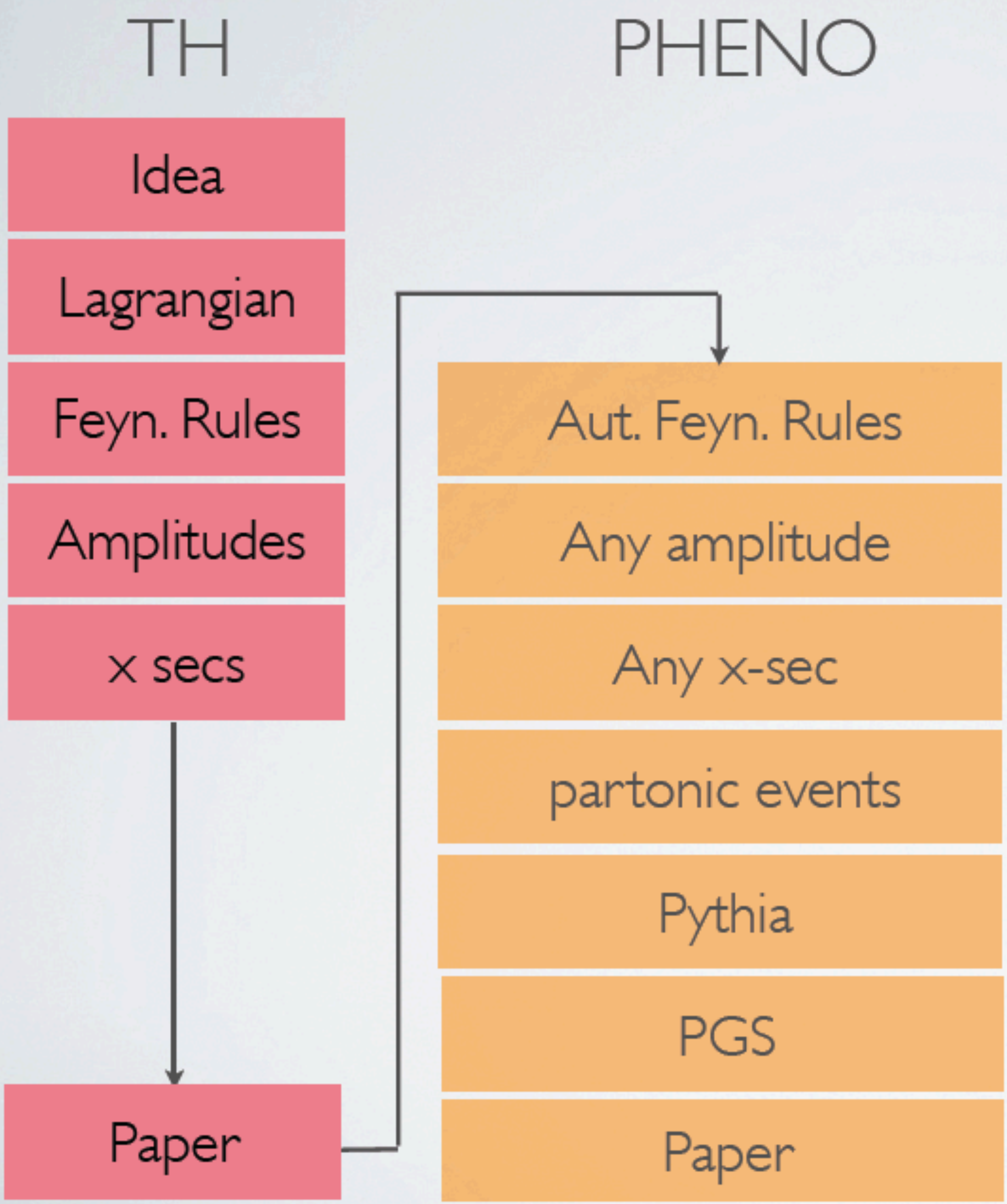
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Eur. Phys. J. C (2011) 71: 1529
DOI 10.1140/epjc/s10052-010-1529-6

Special Article - Tools for Experiment and Theory

HELAS and MadGraph with spin-3/2 particle

K. Hagiwara[1], K. Mawatari[2,3,a], Y. Takaesu[1,b]

[1]KEK Theory Center, and Sokendai, Tsukuba 305-0801, Japan
[2]Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International So
[3]Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelb

Vertex	Inputs	Output	Subroutine
FRS	FRS	Amplitude	IORSXX, IROSXX
	RS	F	FSORXX, FSIRXX
	FR	S	HIORXX, HIROXX
FRV	FRV	Amplitude	IORVXX, IROVXX
	RV	F	FVORXX, FVIRXX
	FR	V	JIORXX, JIROXX
FRVS	FRVS	Amplitude	IORVSX, IROVSX
	RVS	F	FVSORX, FVSIRX
	FRS	V	JSIORX, JSIROX
	FRV	S	HVIORX, HVIROX
FRVV	FRVV	Amplitude	IORVVX, IROVVX
	RVV	F	FVVORX, FVVIRX
	FRV	V	JVIORX, JVIROX

```
      subroutine iorvxx(fi,ro,vc,gc , vertex)
c
c This subroutine computes an amplitude of the fermion-(Rarita-Schwinger
c fermion)-vector coupling.
c
c input:
c       complex fi(6)             : flow-in  fermion                |fi>
c       complex ro(18)            : flow-out RS fermion             v<ro|
c       complex vc(6)             : input    vector                 v'(q)
c       complex gc(2)             : coupling constants              GFRV
c
c output:
c       complex vertex            : amplitude             <ro|[q,v']v|fi>
c
c- by K.Mawatari - 2008/02/27
c
```

```
      vertex = vertex
     &      -gc(2)
     &        *( rc(1,1) *( sssl(1,1)*fi(3)+sssl(1,2)*fi(4) )
     &          +rc(1,2) *( sssl(2,1)*fi(3)+sssl(2,2)*fi(4) )
     &          -rc(2,1) *( sssl(1,2)*fi(3)+sssl(1,1)*fi(4) )
     &          -rc(2,2) *( sssl(2,2)*fi(3)+sssl(2,1)*fi(4) )
     &          -rc(3,1) *( sssl(1,2)*fi(3)-sssl(1,1)*fi(4) )*cImag
     &          -rc(3,2) *( sssl(2,2)*fi(3)-sssl(2,1)*fi(4) )*cImag
     &          -rc(4,1) *( sssl(1,1)*fi(3)-sssl(1,2)*fi(4) )
     &          -rc(4,2) *( sssl(2,1)*fi(3)-sssl(2,2)*fi(4) )
     &         )

      endif

      if ( gc(1).ne.cZero ) then

         spvr(1,1) = pv(1)+pv(4)
         spvr(1,2) = pv(2)-cImag*pv(3)
         spvr(2,1) = pv(2)+cImag*pv(3)
         spvr(2,2) = pv(1)-pv(4)

         svcr(1,1) = vc(1)-vc(4)
         svcr(1,2) = -(vc(2)-cImag*vc(3))
         svcr(2,1) = -(vc(2)+cImag*vc(3))
         svcr(2,2) = vc(1)+vc(4)

         sssr(1,1) = spvr(1,1)*svcr(1,1)+spvr(1,2)*svcr(2,1)
         sssr(1,2) = spvr(1,1)*svcr(1,2)+spvr(1,2)*svcr(2,2)
         sssr(2,1) = spvr(2,1)*svcr(1,1)+spvr(2,2)*svcr(2,1)
         sssr(2,2) = spvr(2,1)*svcr(1,2)+spvr(2,2)*svcr(2,2)

      vertex = vertex
     &      +gc(1)
     &        *( rc(1,3) *( sssr(1,1)*fi(1)+sssr(1,2)*fi(2) )
     &          +rc(1,4) *( sssr(2,1)*fi(1)+sssr(2,2)*fi(2) )
```

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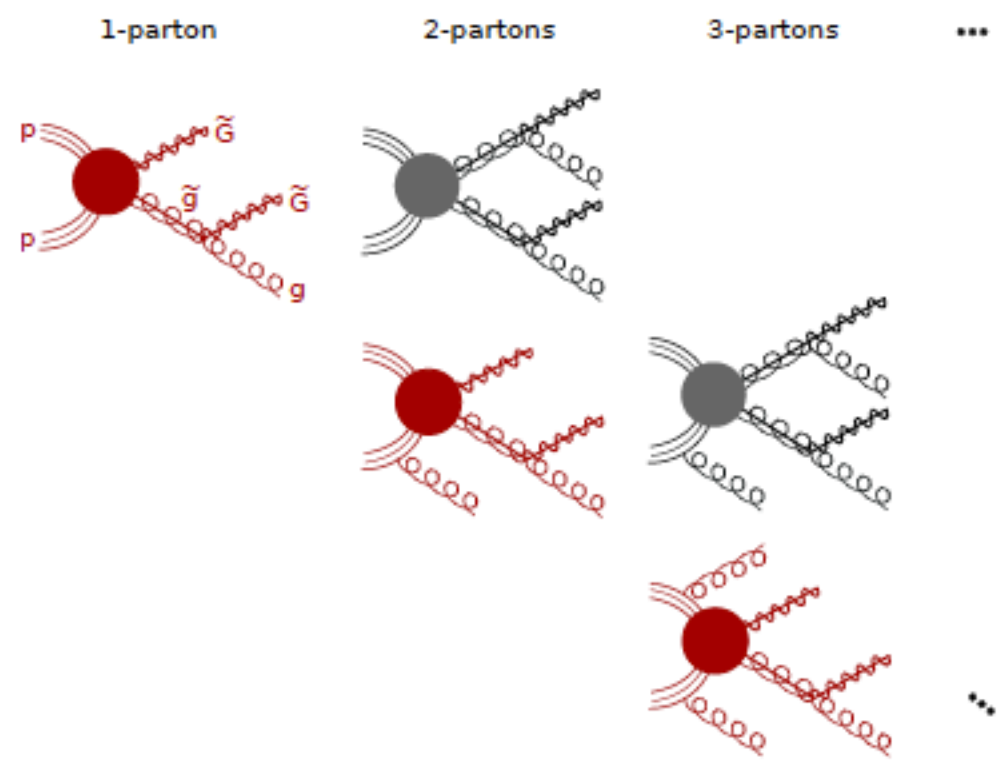
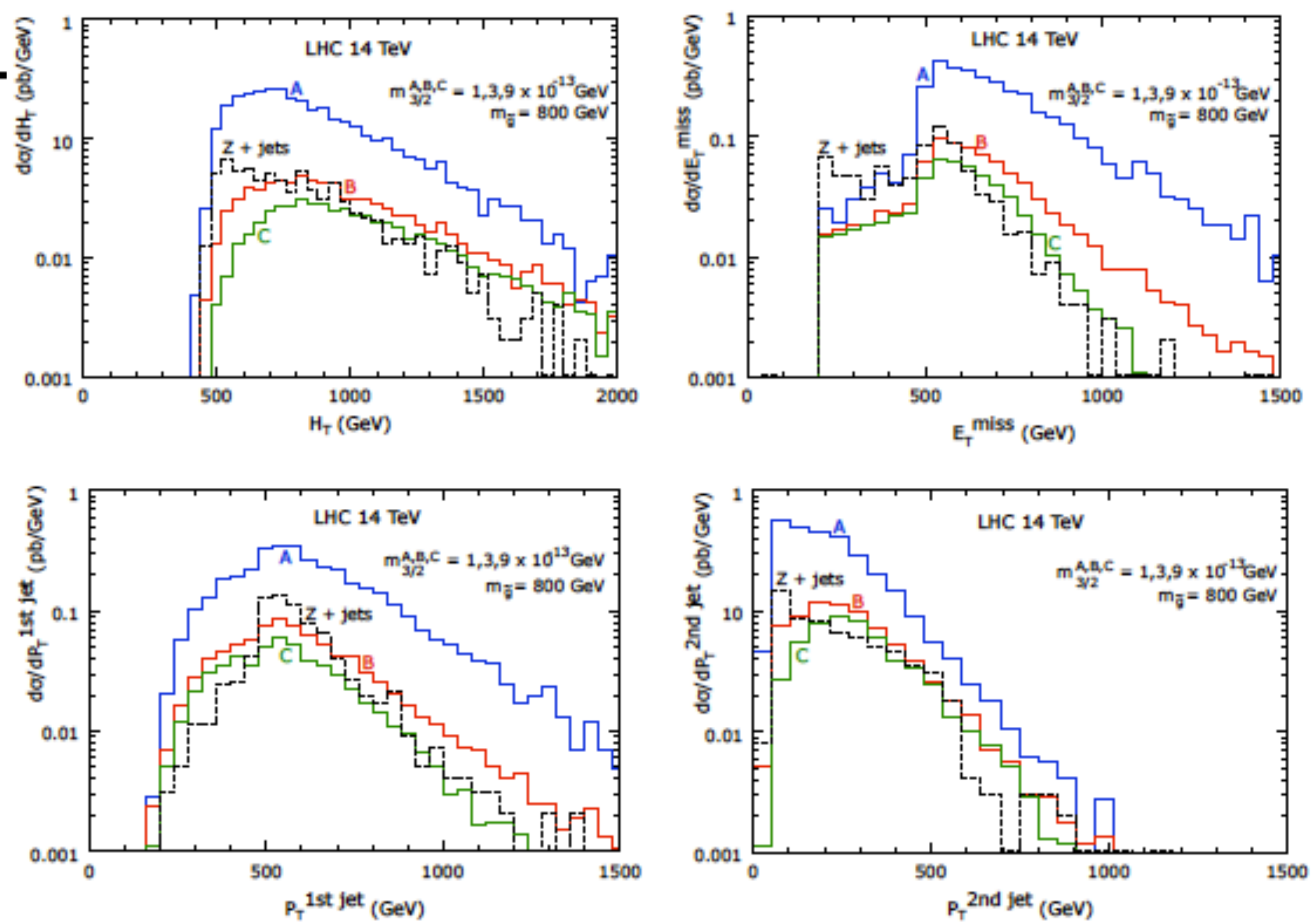
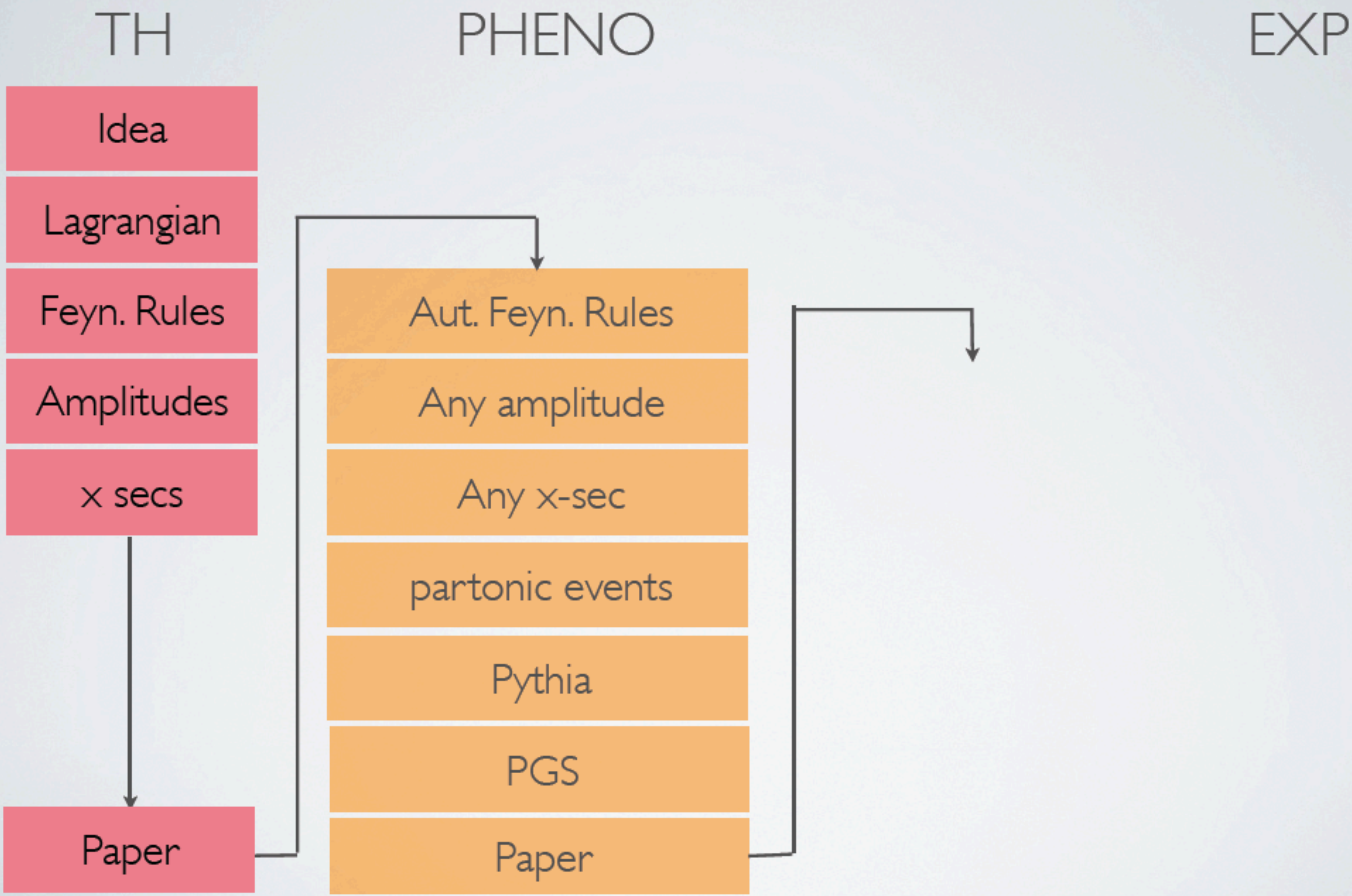
Light gravitino production in association with gluinos at the LHC

P. de Aquino,[a,b] F. Maltoni,[b] K. Mawatari[c] and B. Oexl[c]



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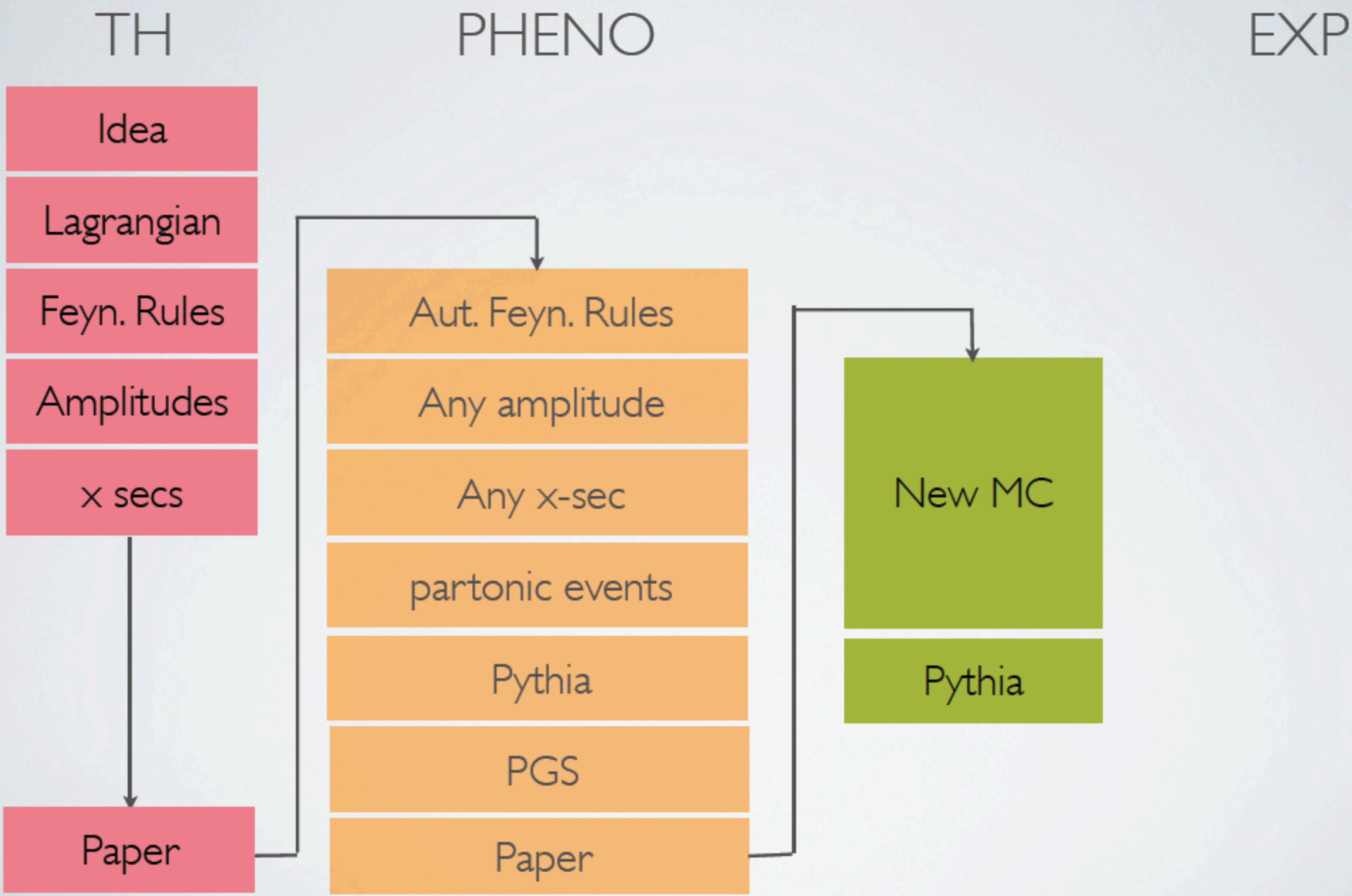
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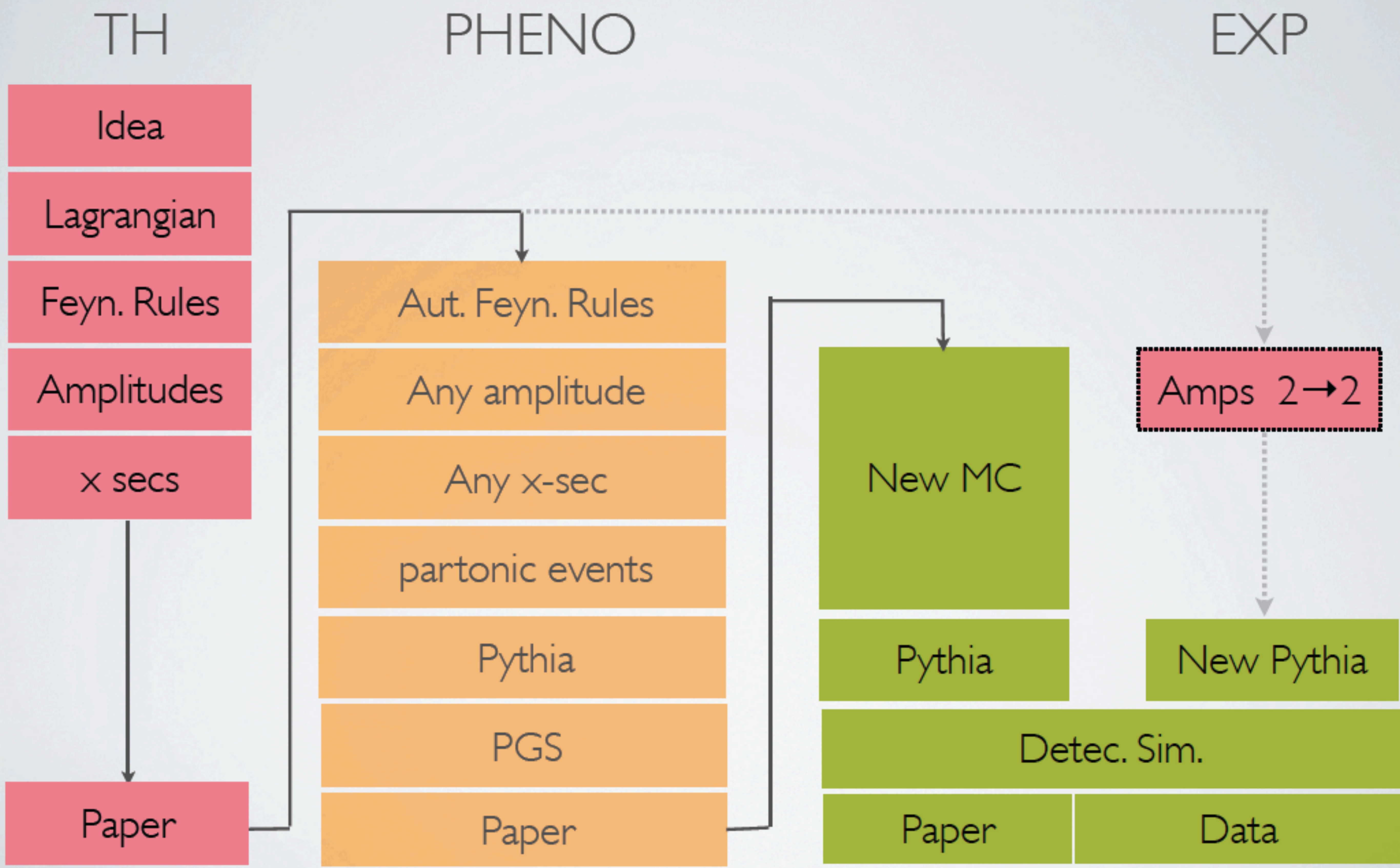
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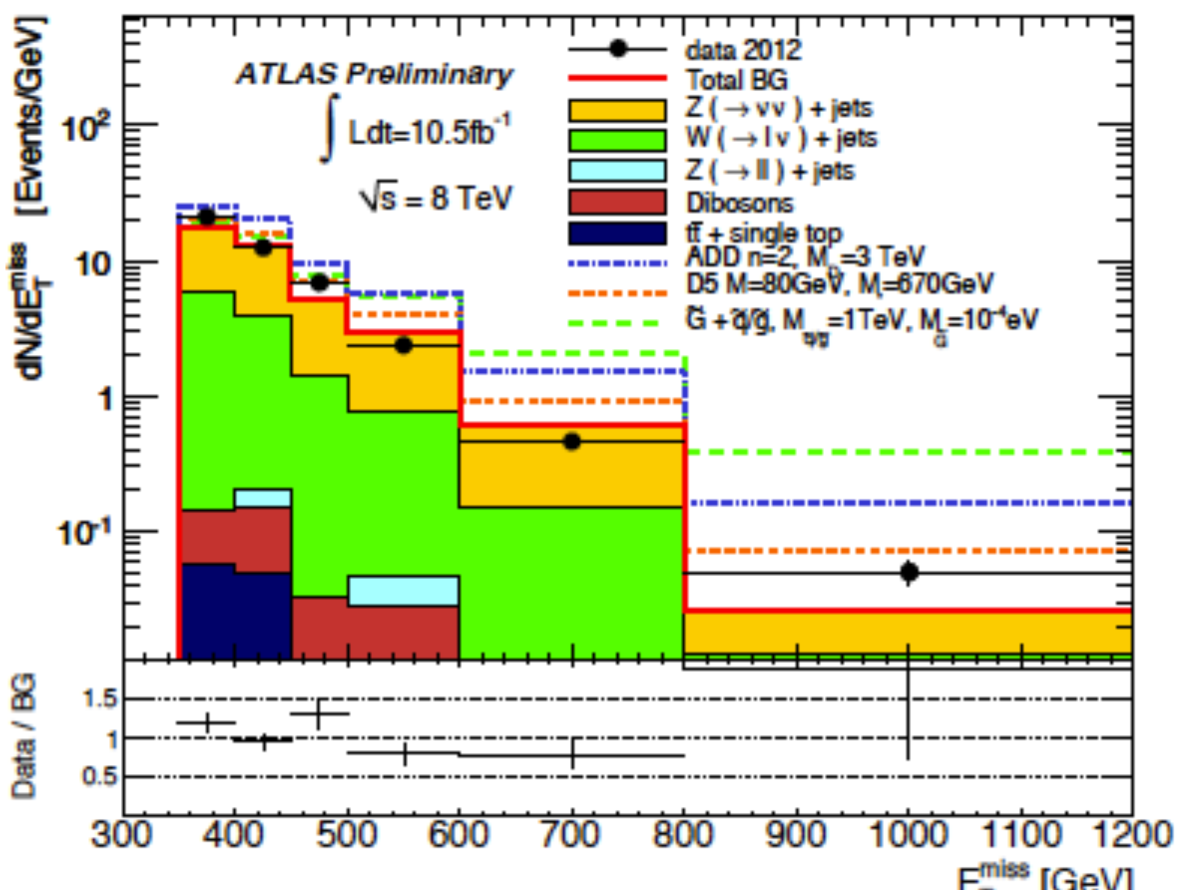
ATLAS-CONF-2012-147

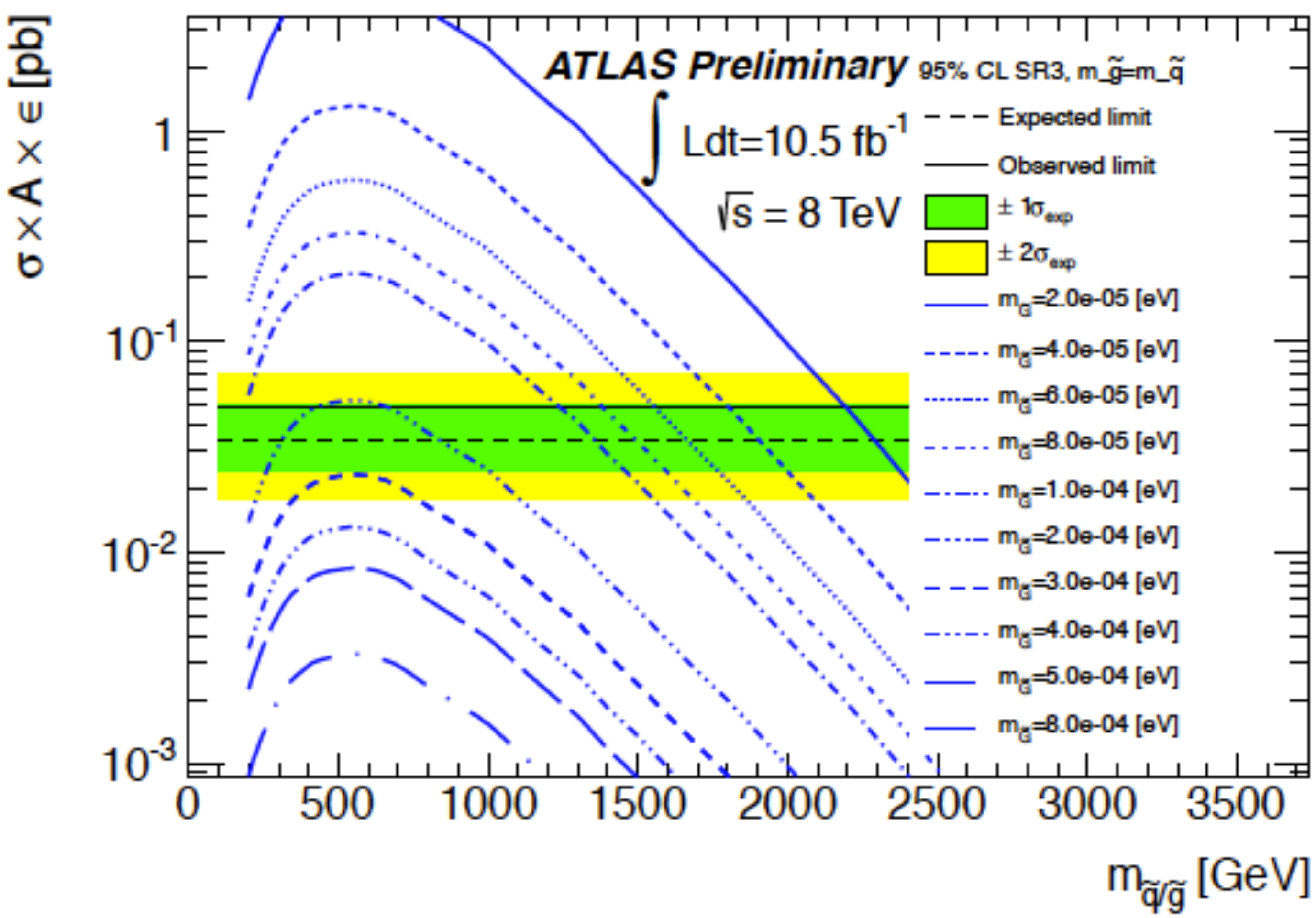
Search for New Phenomena in Monojet plus Missing Transverse Momentum Final States using 10 fb^{-1} of pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC

Finally, MC simulated samples for gravitino production in association witn a gluino or a squark in the final state, $p\bar{p} \to \tilde{G}\tilde{g} + X$ and $p\bar{p} \to \tilde{G}\tilde{q} + X$, are generated using LO matrix elements in MADGRAPH [50] interfaced with PYTHIA and using CTEQ6L1 PDFs. The narrow width approximation (NWA) for the

[50] K. Mawatari and Y. Takaesu, *HELAS and MadGraph with goldstinos*, Eur.Phys.J. **C71** (2011) 1640, arXiv:1101.1289 [hep-ph].

$$\sigma(pp \to \tilde{g}\tilde{G}) \propto 1/(M_{\rm Pl}\, m_{3/2})^2$$





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Search for New Phenomena in Monojet plus Missing Transverse Momentum Final States using 10 fb^{-1} of pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC

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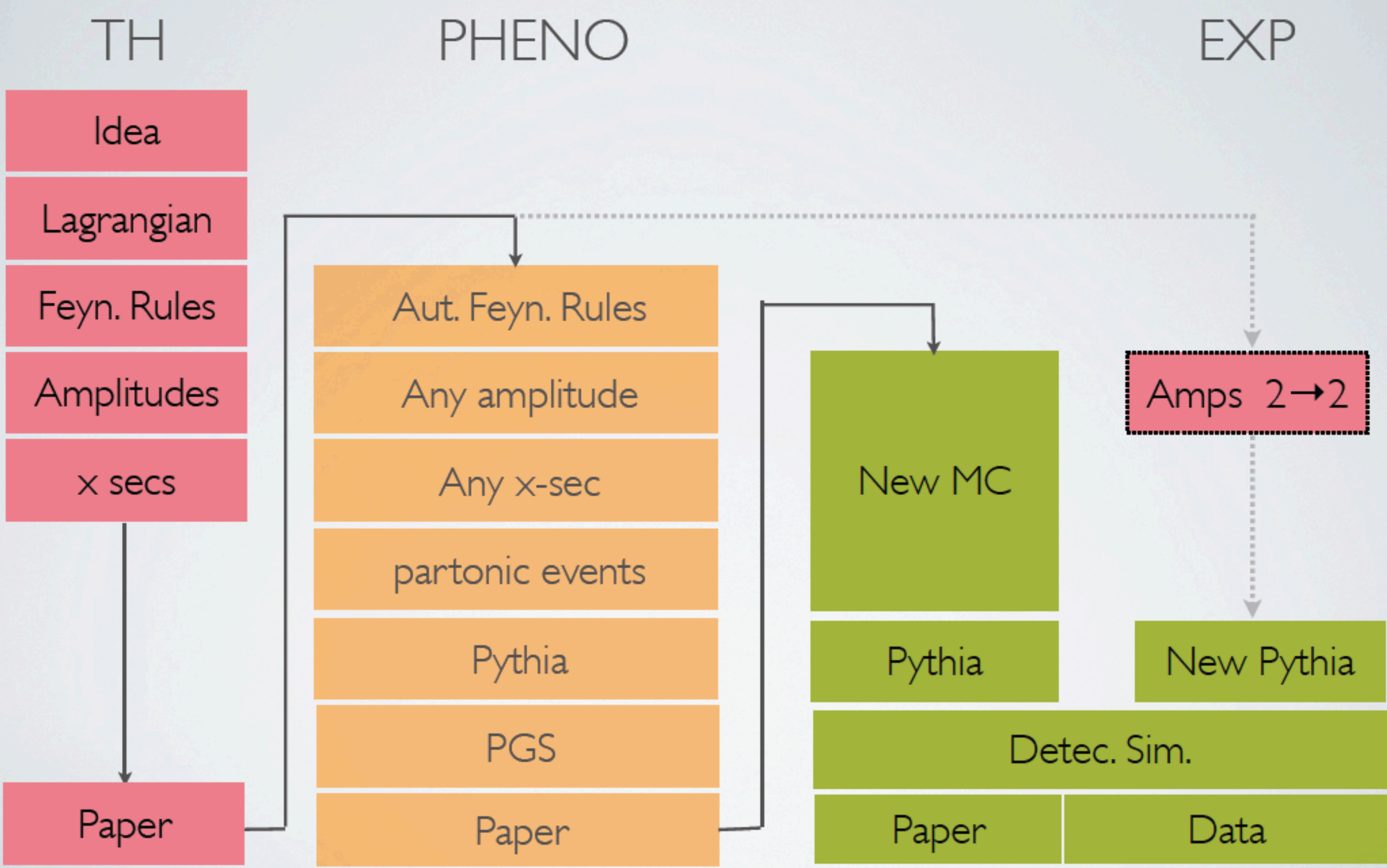
models. Gravitino masses below $1{\cdot}10^{-4}$ eV ($4{\cdot}10^{-5}$ eV) are excluded at 95% CL for squark/gluino masses of 500 GeV (1.7 TeV). These results significantly improve previous results at LEP and the Tevatron and constitute the best bounds on the gravitino mass to date. For very high squark/gluino masses the NWA

LIGHT $\tilde{G}$ (Gravitino) MASS LIMITS FROM COLLIDER EXPERIMENTS

The following are bounds on light ($\ll$ 1 eV) gravitino indirectly inferred from its coupling to matter suppressed by the gravitino decay constant.

Unless otherwise stated, all limits assume that other supersymmetric particles besides the gravitino are too heavy to be produced. The gravitino is assumed to be undetected and to give rise to a missing energy ($\not{E}$) signature.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$> 1.09 \times 10^{-5}$	95	[1] ABDALLAH	05B	DLPH	$e^+e^- \to \tilde{G}\tilde{G}\gamma$
$> 1.35 \times 10^{-5}$	95	[2] ACHARD	04E	L3	$e^+e^- \to \tilde{G}\tilde{G}\gamma$
$> 1.3 \times 10^{-5}$		[3] HEISTER	03C	ALEP	$e^+e^- \to \tilde{G}\tilde{G}\gamma$
$> 11.7 \times 10^{-6}$	95	[4] ACOSTA	02H	CDF	$p\bar{p} \to \tilde{G}\tilde{G}\gamma$
$> 8.7 \times 10^{-6}$	95	[5] ABBIENDI,G	00D	OPAL	$e^+e^- \to \tilde{G}\tilde{G}\gamma$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TH

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EXP

Idea

Lagrangian

Aut. Feyn. Rules

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partonic events

Pythia

Detec. Sim.

Data

TH

EXP

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

PS+Had

PGS | Detect. Sim.

Papers | Data

- One path for all
- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

FeynRules in a nutshell

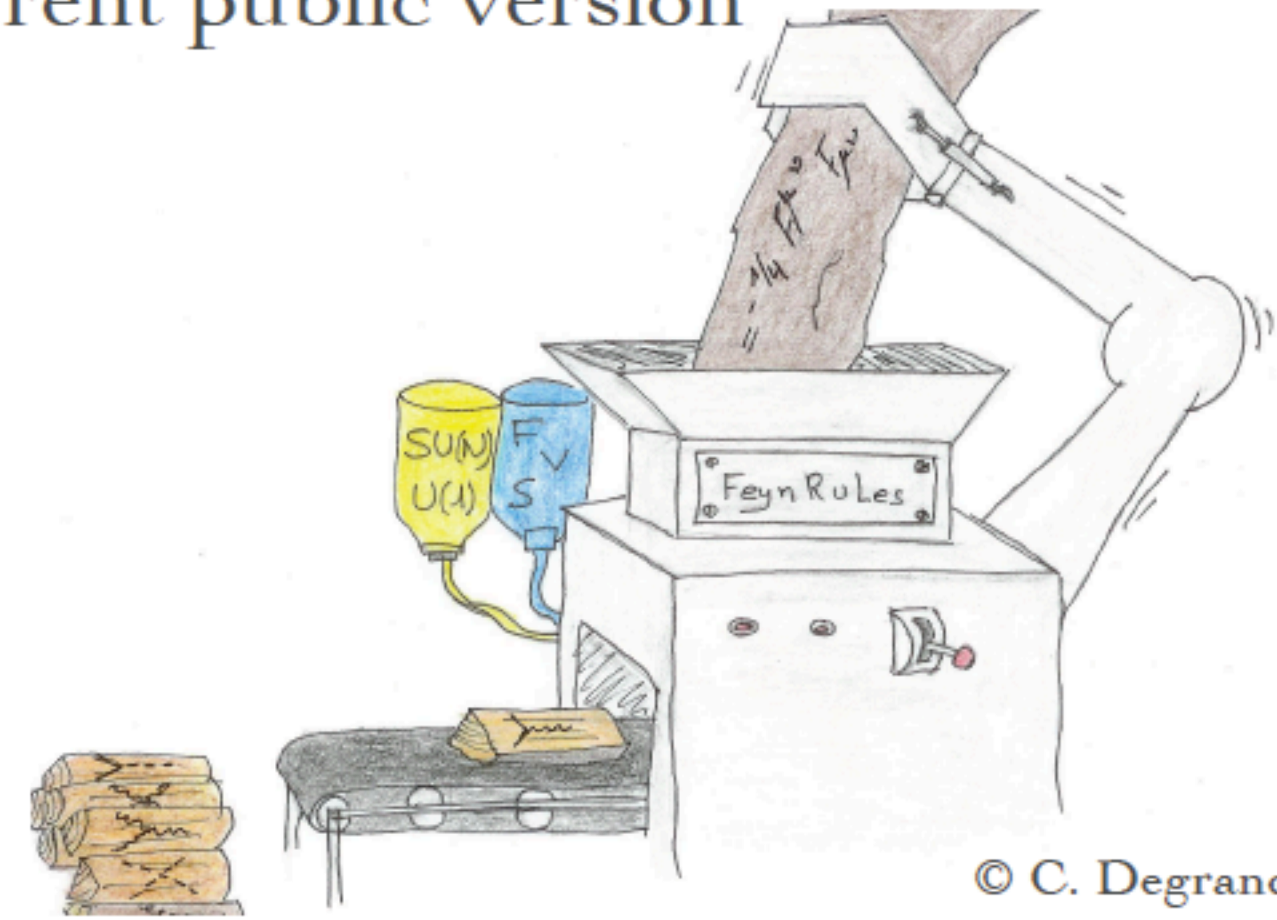
- FeynRules is a Mathematica package that allows to derive Feynman rules from a Lagrangian.
- Current public version: 1.6.x, available from

  http://feynrules.phys.ucl.ac.be
- The only requirements on the Lagrangian are:
  - ➡ All indices need to be contracted (Lorentz and gauge invariance)
  - ➡ Locality
  - ➡ Supported field types: spin 0, 1/2, 1, 2 & ghosts

3/2

FeynRules in a nutshell

- FeynRules comes with a set of interfaces, that allow to export the Feynman rules to various matrix element generators.
- Interfaces coming with current public version
  - ➡ CalcHep / CompHep
  - ➡ FeynArts / FormCalc
  - ➡ MadGraph
  - ➡ Sherpa
  - ➡ Whizard / Omega



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FeynRules in a nutshell

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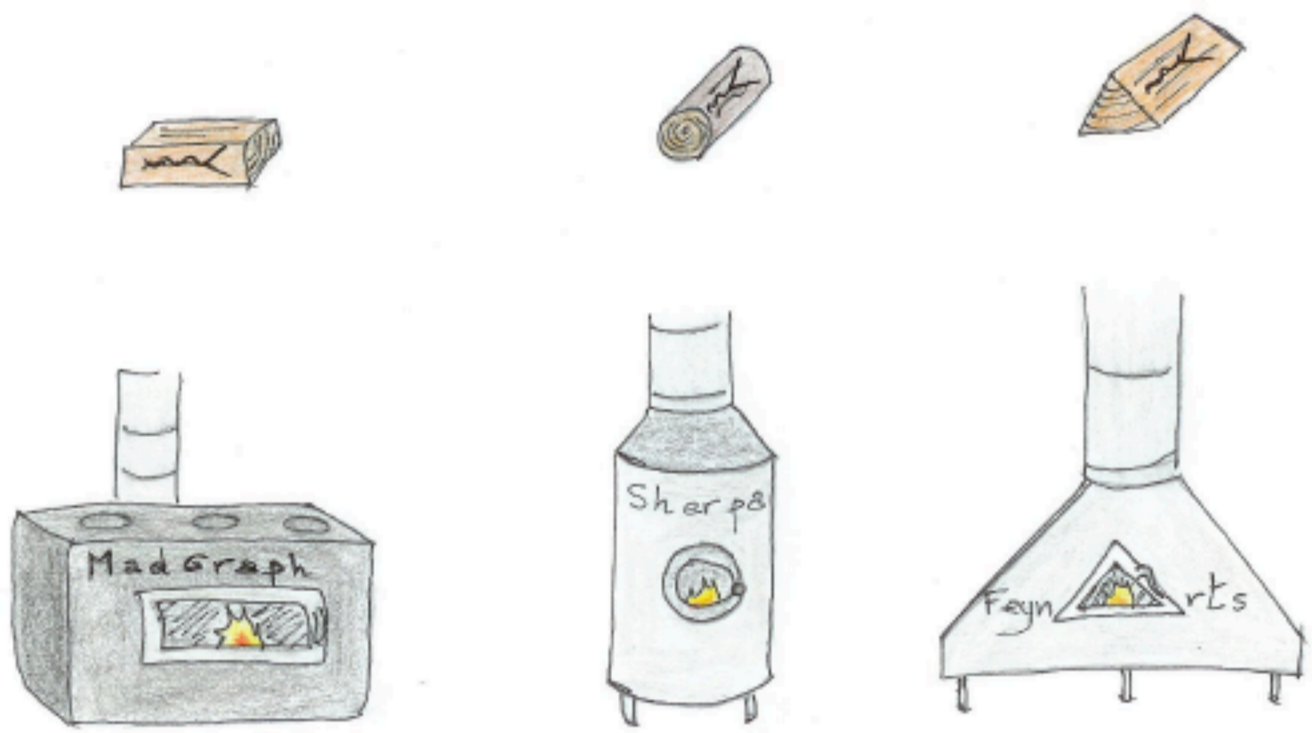

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FeynRules in a nutshell

- The input requested form the user is twofold.

- The Model File:
  Definitions of particles and parameters (e.g., a quark)

```
F[1]  ==
  {ClassName      ->   q,
   SelfConjugate ->  False,
   Indices          -> {Index[Colour]},
   Mass             -> {MQ,  200},
   Width            -> {WQ, 5}   }
```

- The Lagrangian:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu}\, G^{\mu\nu}_a + i\bar{q}\,\gamma^\mu\, D_\mu q - M_q\,\bar{q}\,q$$

```
L =
-1/4 FS[G,mu,nu,a] FS[G,mu,nu,a]
+ I qbar.Ga[mu].del[q,mu]
- MQ qbar.q
```

Simulating spin-3/2 particles at colliders

[arXiv: 1308.1668]

The FeynRules and MadGraph5/CalcHEP collaboration

FeynRules
C. Duhr (Durham)
B. Fuks (CERN)

MadGraph5/UFO/ALOHA
P. de Aquino (Vrije U. Brussel)
O. Mattelaer (UCLouvain)

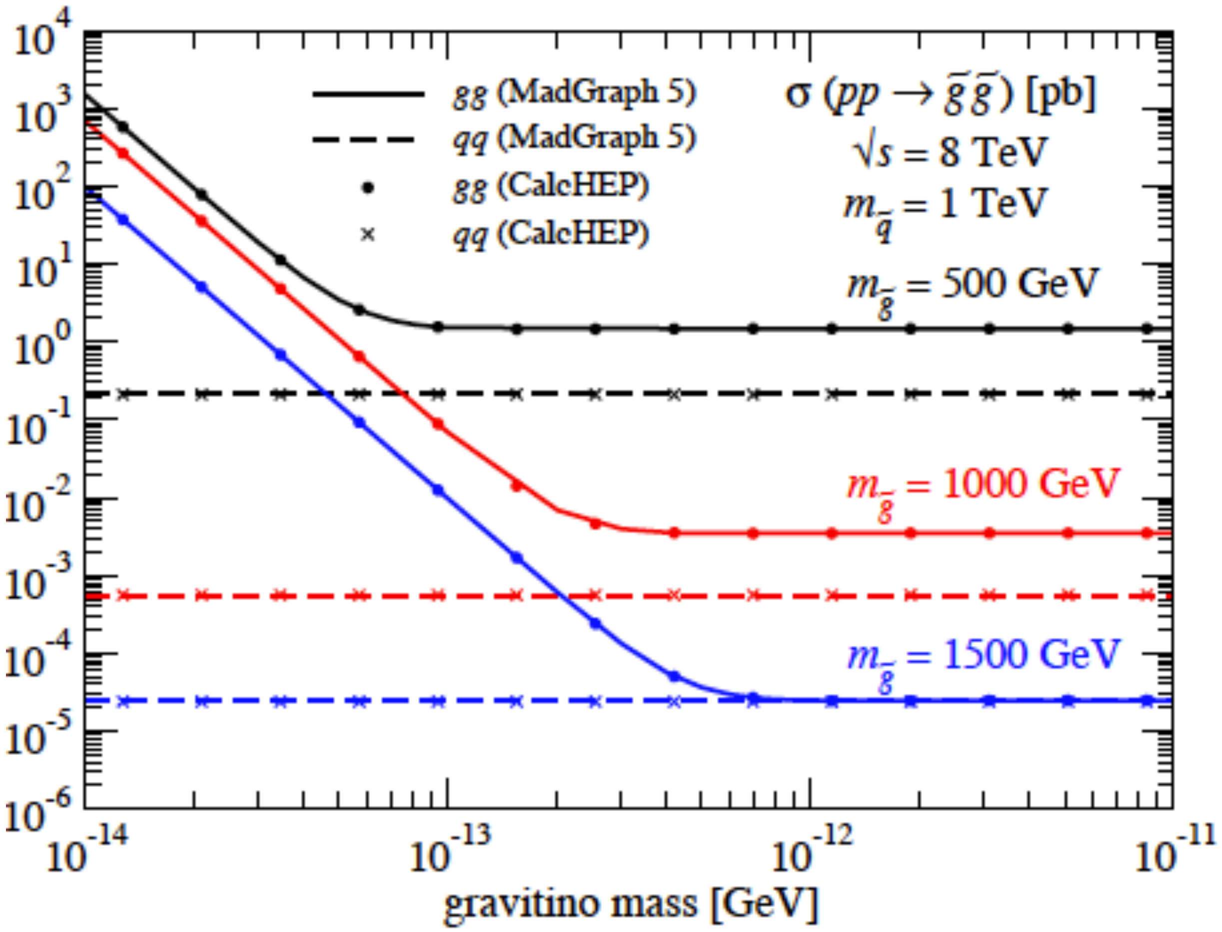
CalcHEP
N.D. Christensen (Pittsburg)
C. Garcia-Cely (TUMunchen)

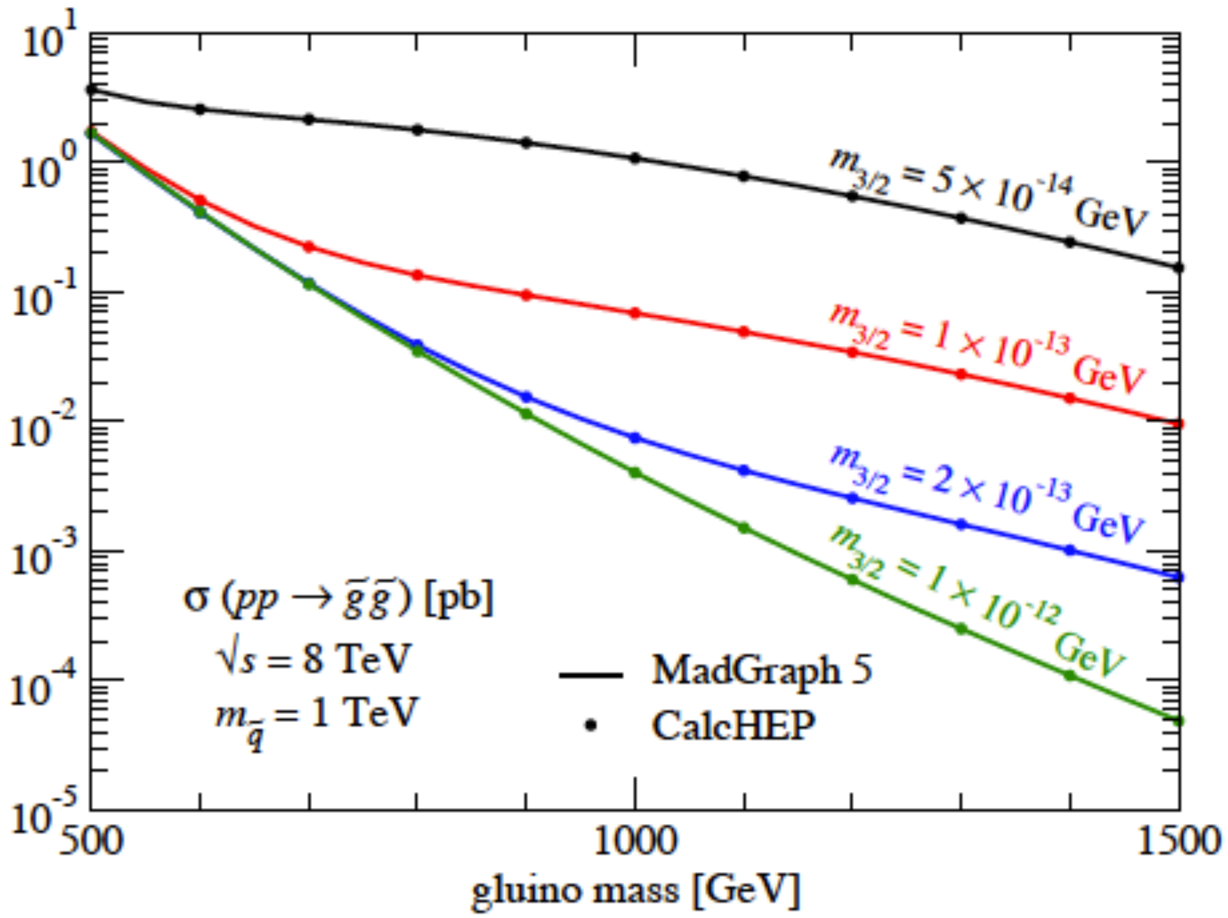
Gravitino model
K. Mawatari, B. Oexl (Vrije U. Brussel)
Y. Takaesu (KIAS)

Top excitation model
N. Deutschumann (Lyon)

Majorana spin-3/2 -- gravitino

$$\mathcal{L} = -\frac{1}{2\overline{M}_{\rm Pl}}\overline{\Psi}_\mu \gamma^{\nu\rho}\gamma^\mu \lambda_a g^a_{\nu\rho}$$

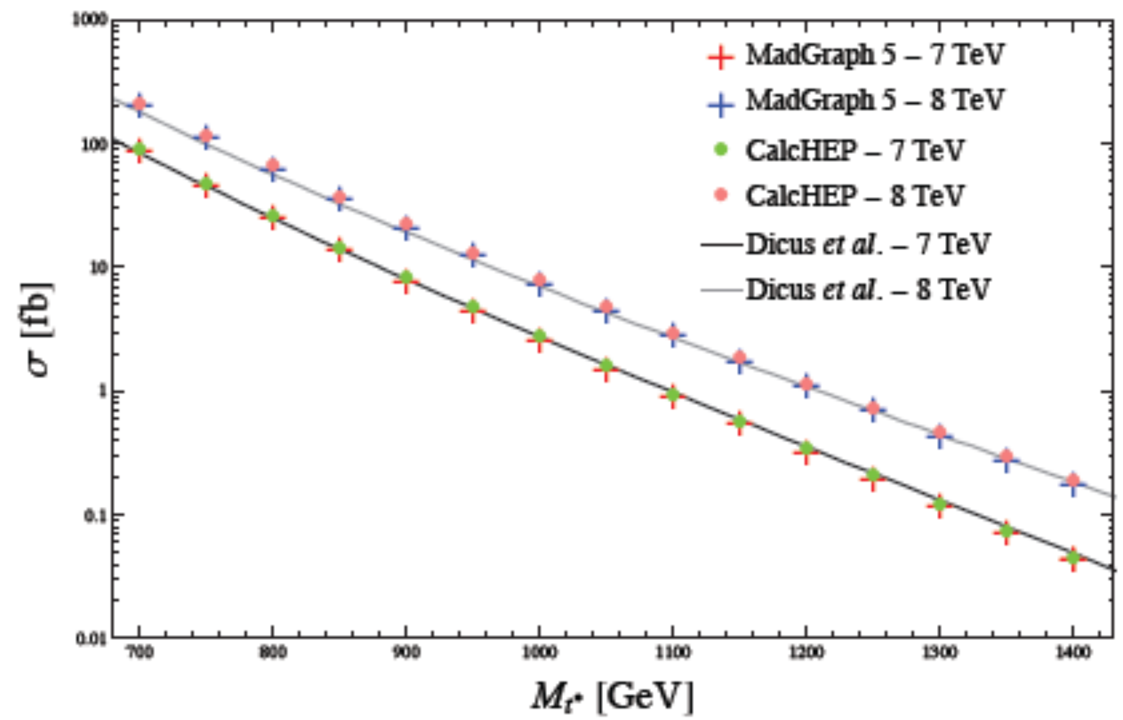


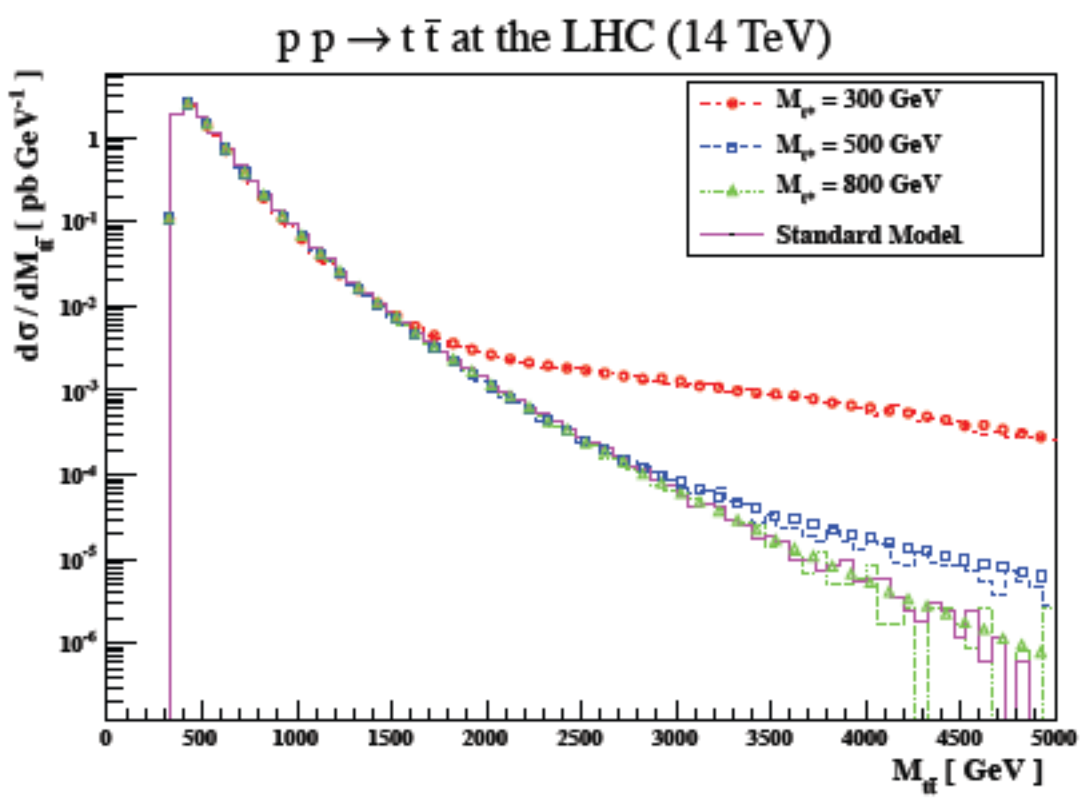


Dirac spin-3/2 -- top quark excitation

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \epsilon^{\mu\nu\rho\sigma}\bar{\Psi}_\mu\gamma_5\gamma_\sigma D_\nu\Psi_\rho + 2iM\bar{\Psi}_\mu\gamma^{\mu\nu}\Psi_\nu$$

$$\mathcal{L}_5 = i\frac{g_s}{\Lambda}\bar{\Psi}_\rho\Big[\eta^{\rho\mu} + z\gamma^\rho\gamma^\mu\Big]\gamma^\nu T_a t\; g^a_{\mu\nu} + {\rm h.c.}$$





A framework for Higgs characterisation

[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)

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)].

Vrije Universiteit Brussel

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	$2m^2_{Z/W}$	$47\alpha_{EM}/18\pi$	$C(94\cos^2\theta_W - 13)/9\pi$	$-\alpha_s/3\pi$
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

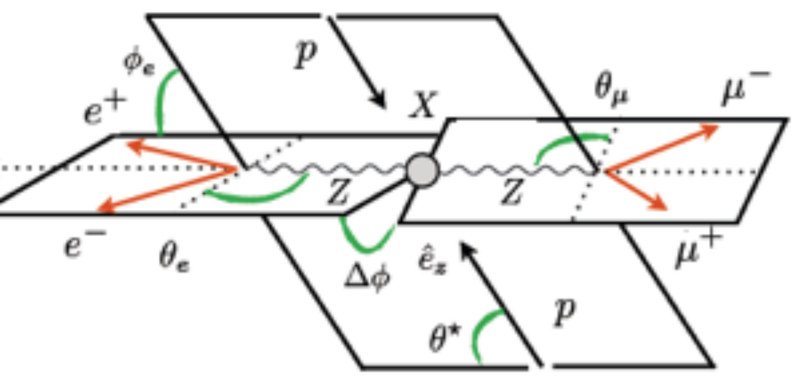
$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar{\psi}_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \, \gamma_5 \big) \psi_f X_0$$

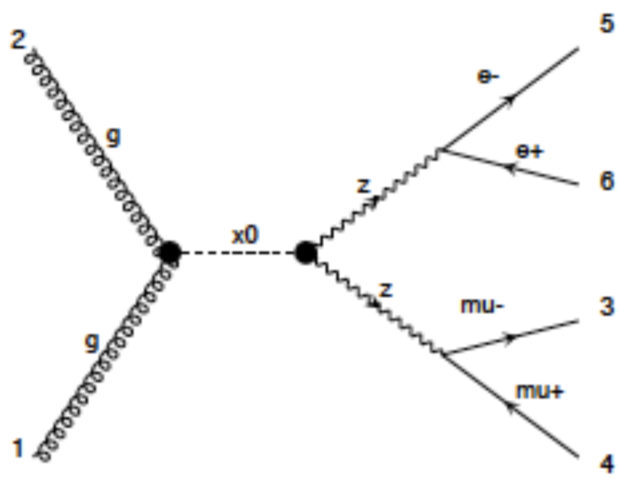
$$\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ} \, Z_\mu Z^\mu + g_{HWW} \, W^+_\mu W^{-\mu} \big] \\
& - \frac{1}{4} \big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} \, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} \,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

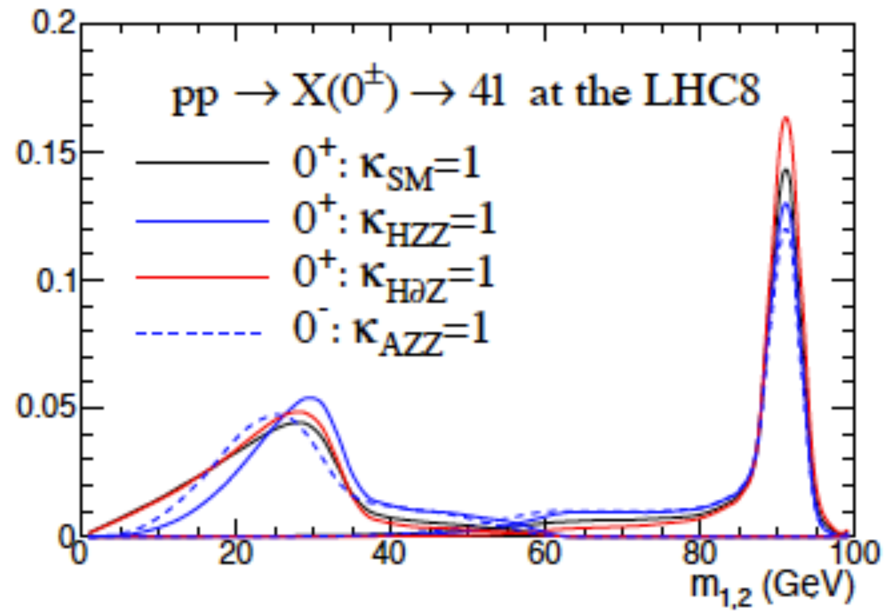
$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm),$$
$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu ,$$
$$\widetilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$$

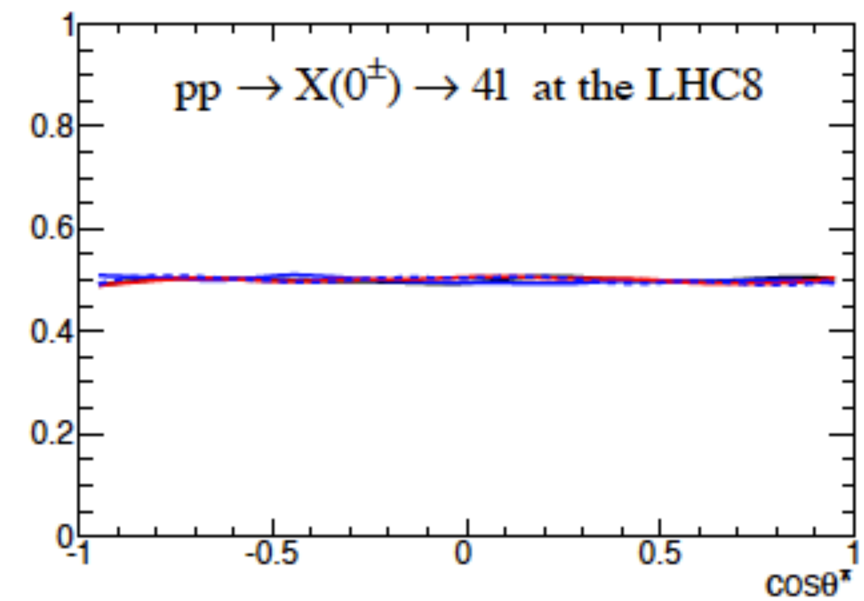
```
#####################################
## INFORMATION FOR FRBLOCK
#####################################
Block FRBlock
    1 1.000000e+03 # Lambda
    2 1.000000e+00 # ca
    3 1.000000e+00 # kSM
    4 1.000000e+00 # kHtt
    5 1.000000e+00 # kAtt
    6 1.000000e+00 # kHbb
    7 1.000000e+00 # kAbb
    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
```

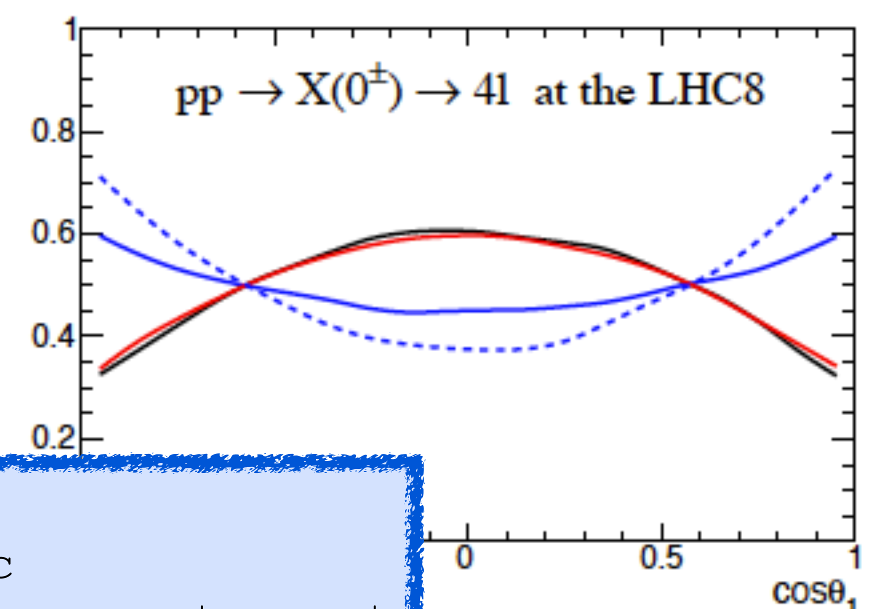
Mass and angular distributions -- spin0

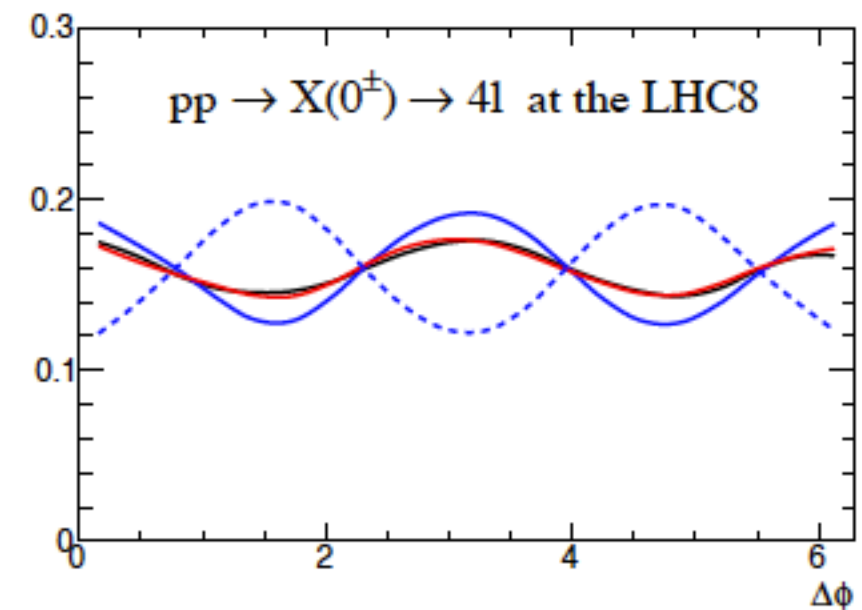













```
./bin/mg5
>import model HiggsCharac
>generate p p > x0, x0 > mu- mu+ e- e+
>output
>launch
```

Effective Lagrangian -- spin1

- The most general interactions at the lowest canonical dimension:

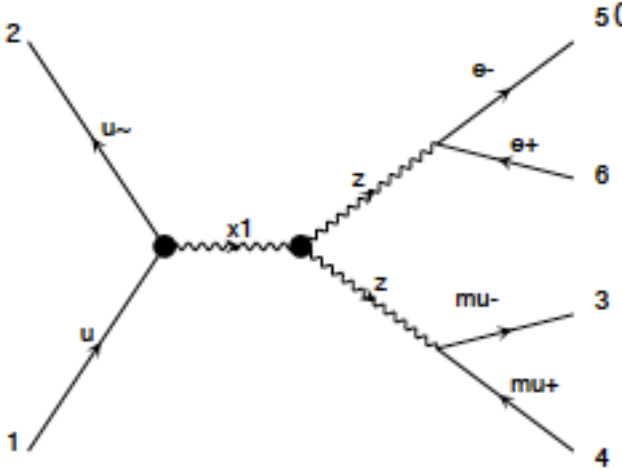
$$\mathcal{L}_1^f = \sum_{f=q,\ell} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu$$

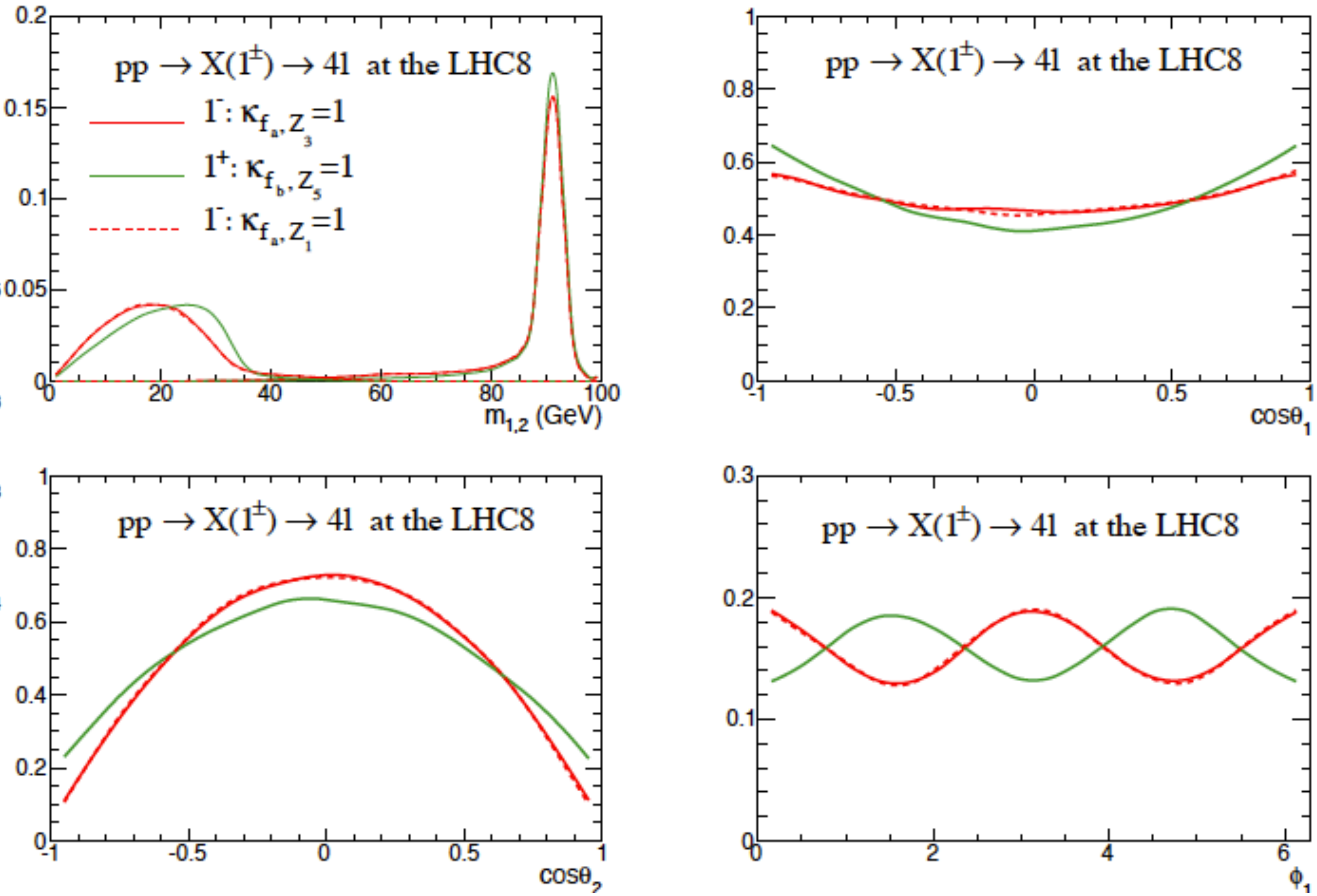
$$\begin{aligned}\mathcal{L}_1^W = & \, i\kappa_{W_1} g_{WWZ} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) X_1^\nu + i\kappa_{W_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\ & - \kappa_{W_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ & + i\kappa_{W_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu}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

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

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

Mass and angular distributions -- spin1





Effective Lagrangian -- spin2

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

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

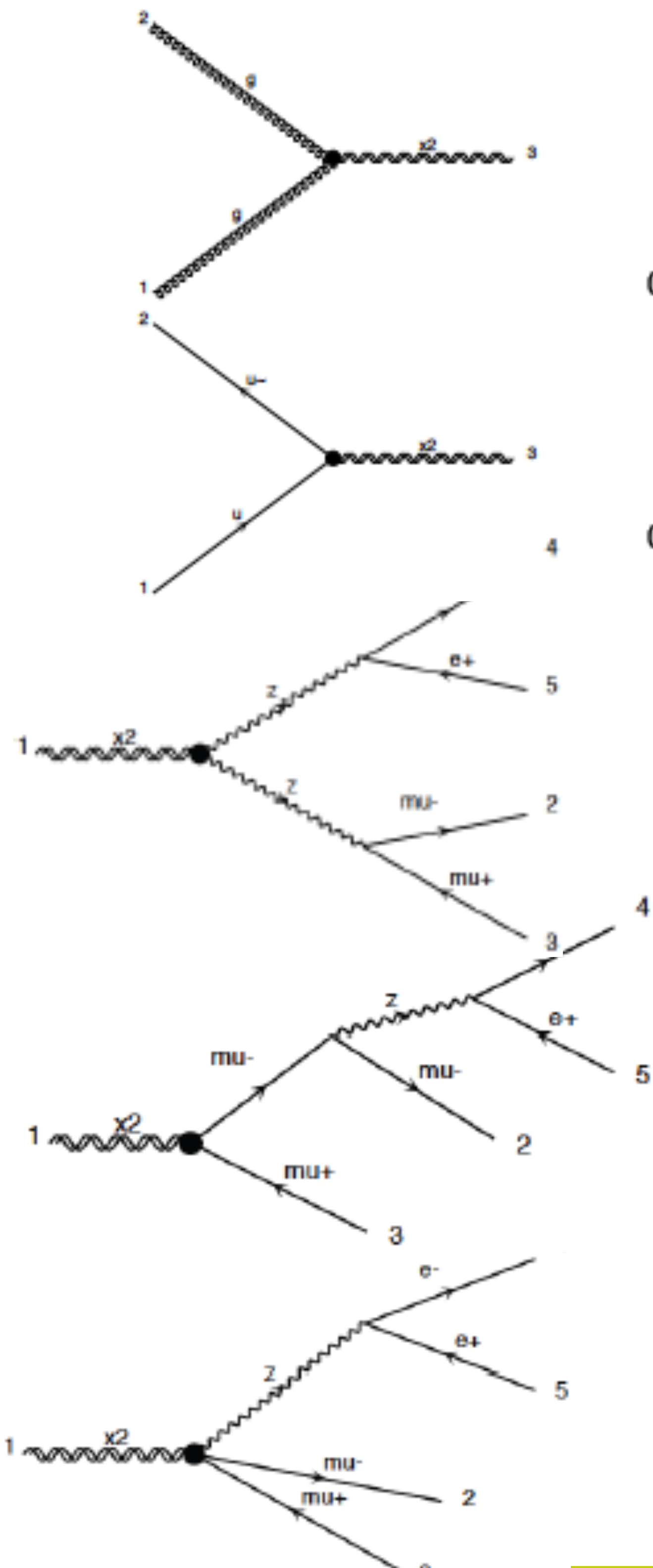
$$\mathcal{L}_2^V = -\frac{1}{\Lambda}\sum_{V=Z,W,\gamma,g} \kappa_V T^V_{\mu\nu} X_2^{\mu\nu}$$

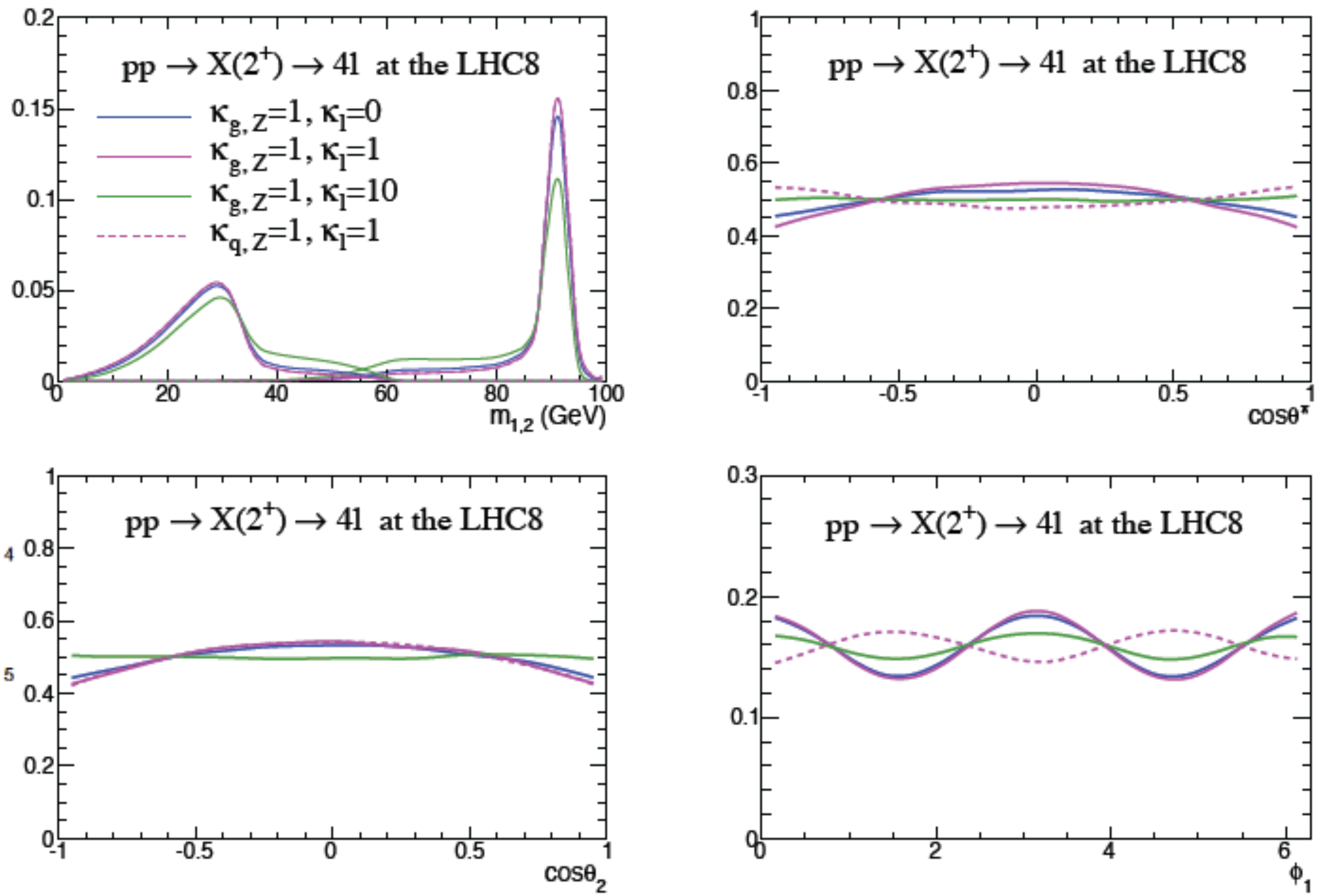
- The E-M tensor for QED:

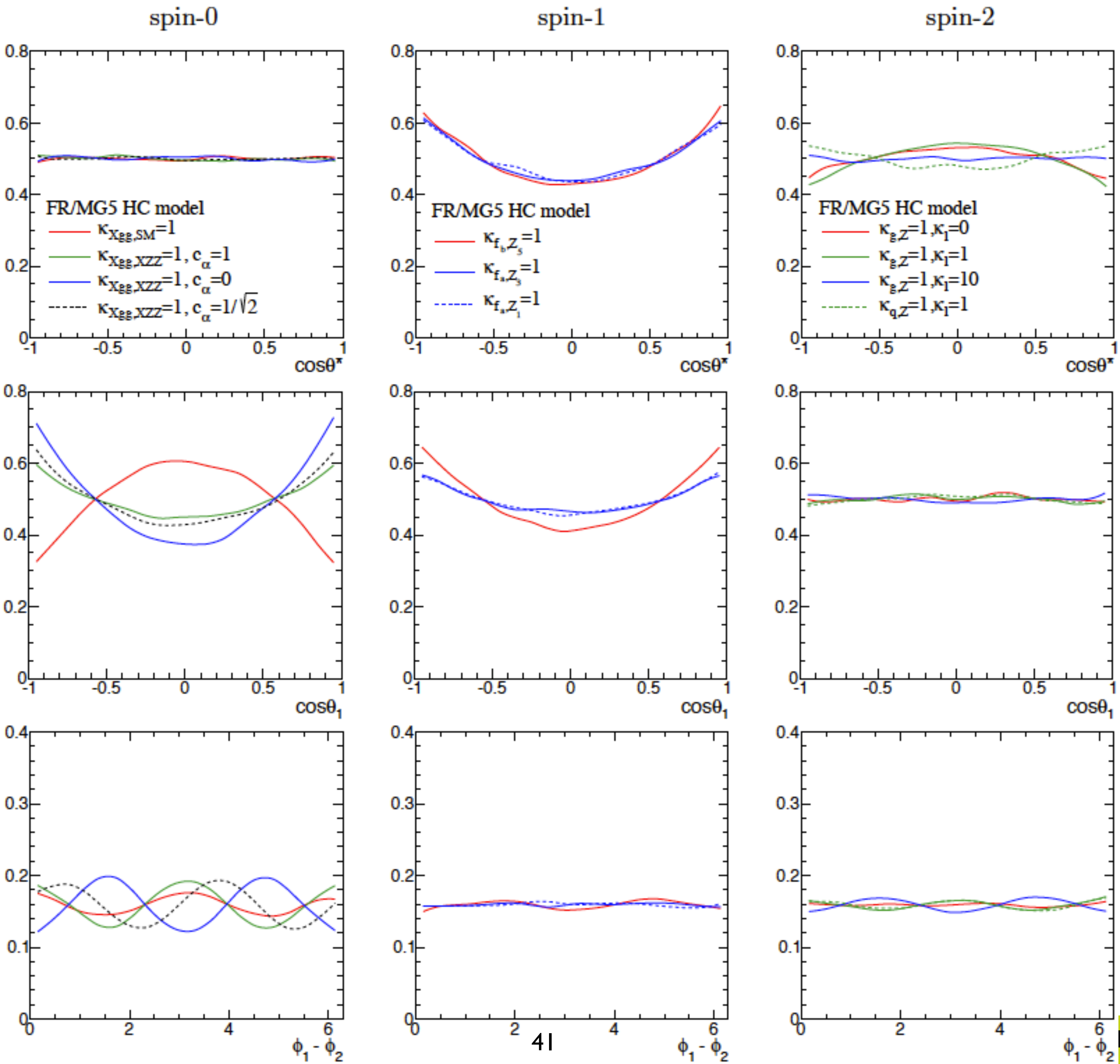
$$T^f_{\mu\nu} = -\, g_{\mu\nu}\Big[\bar\psi_f(i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar\psi_f i\gamma_\rho\psi_f)\Big] + \Big[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu(\bar\psi_f i\gamma_\nu\psi_f) + (\mu\leftrightarrow\nu)\Big]\,,$$

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

Mass and angular distributions -- spin2

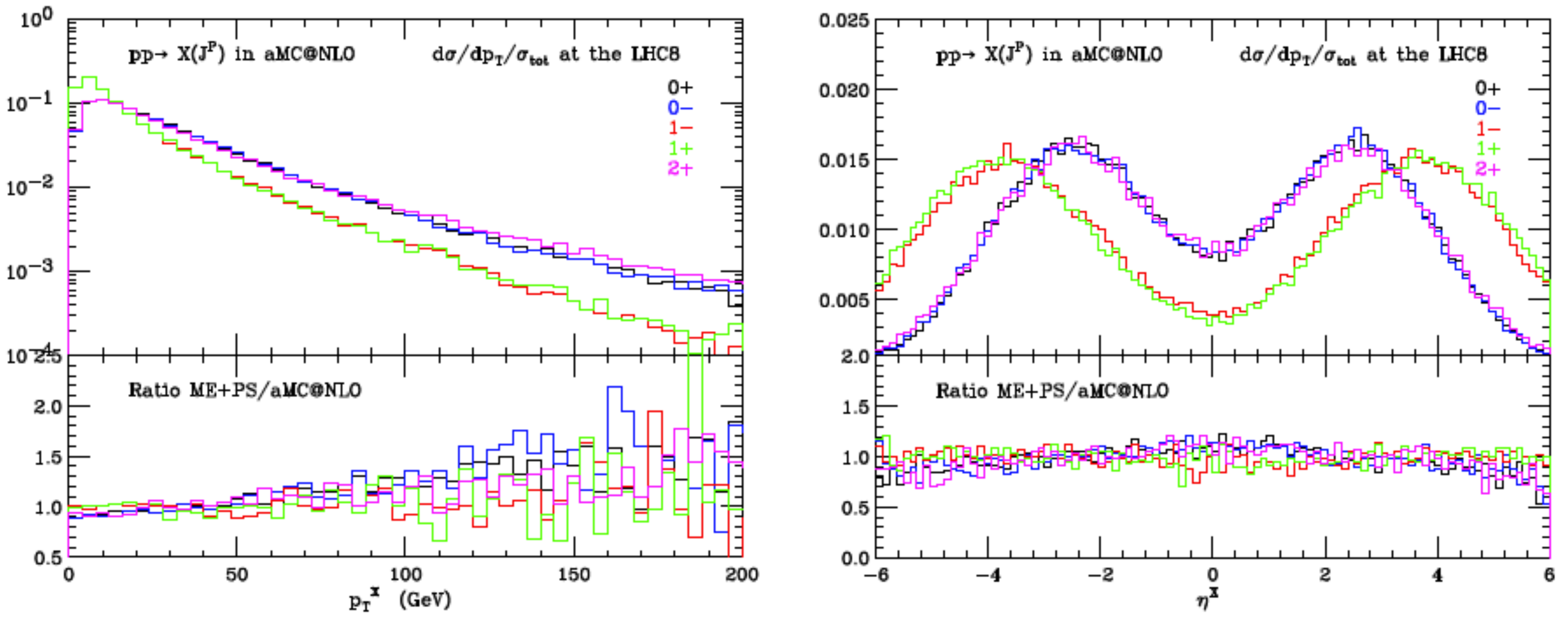





spin-0
spin-1
spin-2
FR/MG5 HC model
$\kappa_{X_{gg,SM}}=1$
$\kappa_{X_{gg},X_{ZZ}}=1, c_\alpha=1$
$\kappa_{X_{gg},X_{ZZ}}=1, c_\alpha=0$
$\kappa_{X_{gg},X_{ZZ}}=1, c_\alpha=1/\sqrt{2}$
FR/MG5 HC model
$\kappa_{f_b,Z_5}=1$
$\kappa_{f_a,Z_5}=1$
$\kappa_{f_a,Z_1}=1$
FR/MG5 HC model
$\kappa_g,Z=1, \kappa_1=0$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

Higher order effects in QCD

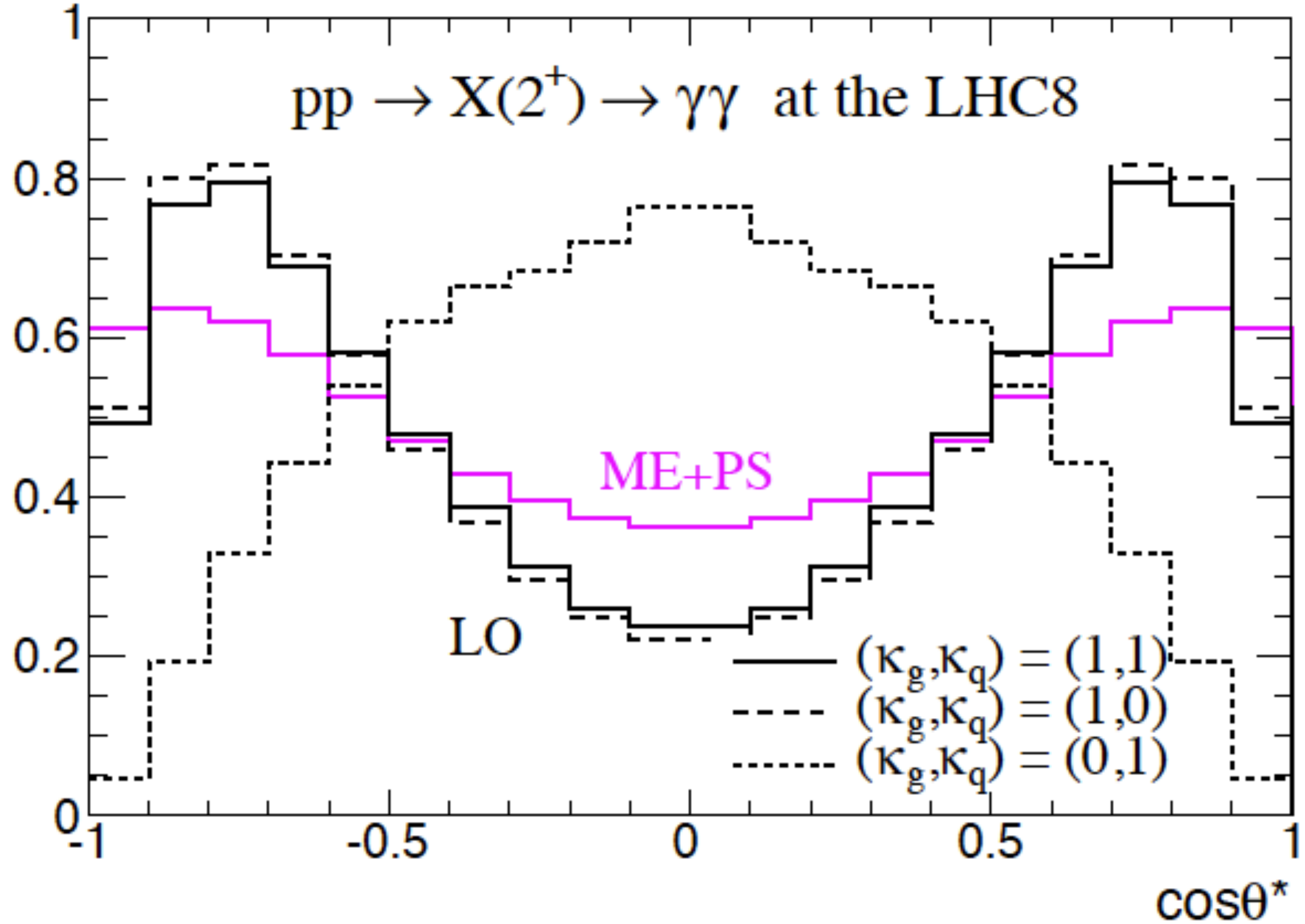
- The LO predictions can be systematically improved by including the effects due to the emission of QCD partons.
  - LO Matrix-Element/Parton-Shower merging [ME+PS]
  - full-NLO matrix element with parton-shower [aMC@NLO]



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



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

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

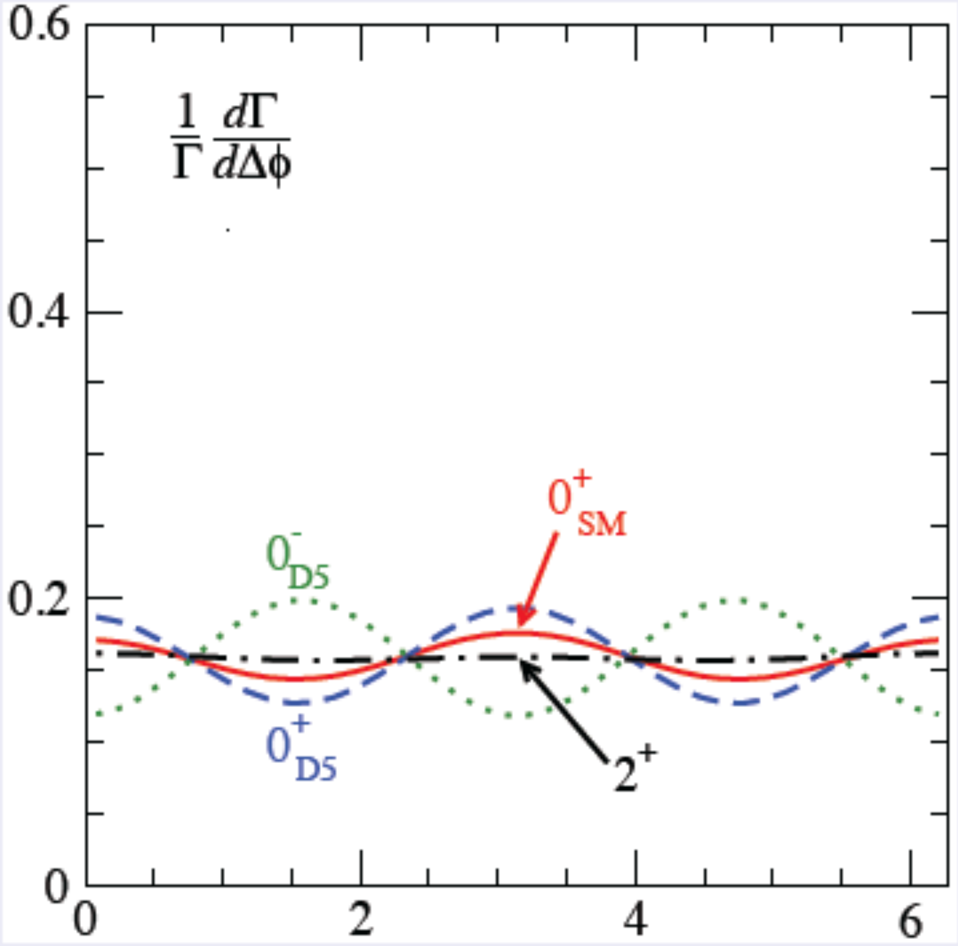
Spin/parity determination
2. X→VV*→4l

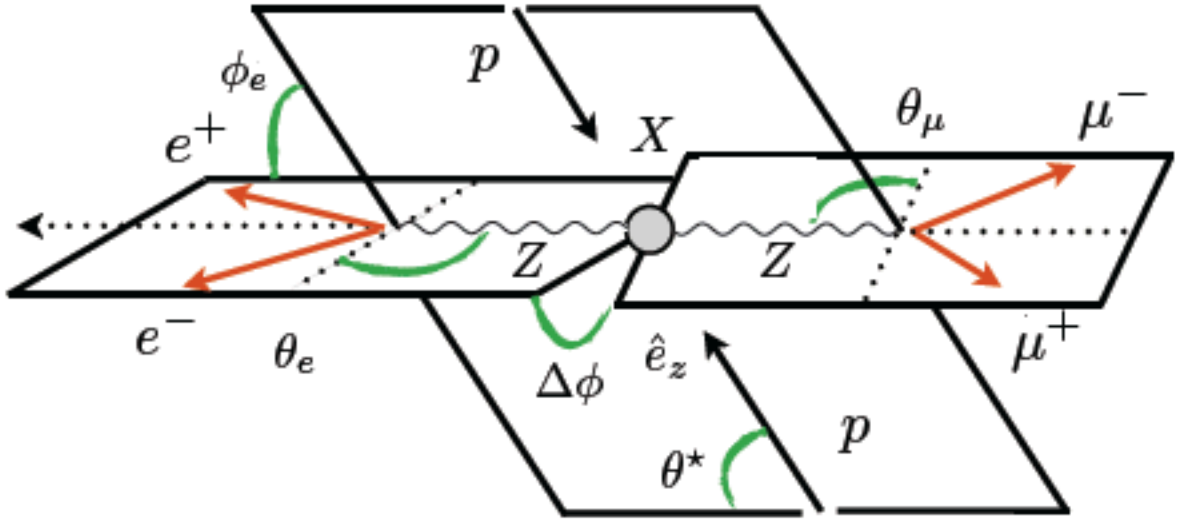
[Dell'Aquilla, Nelson, PRD(1986)]
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[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

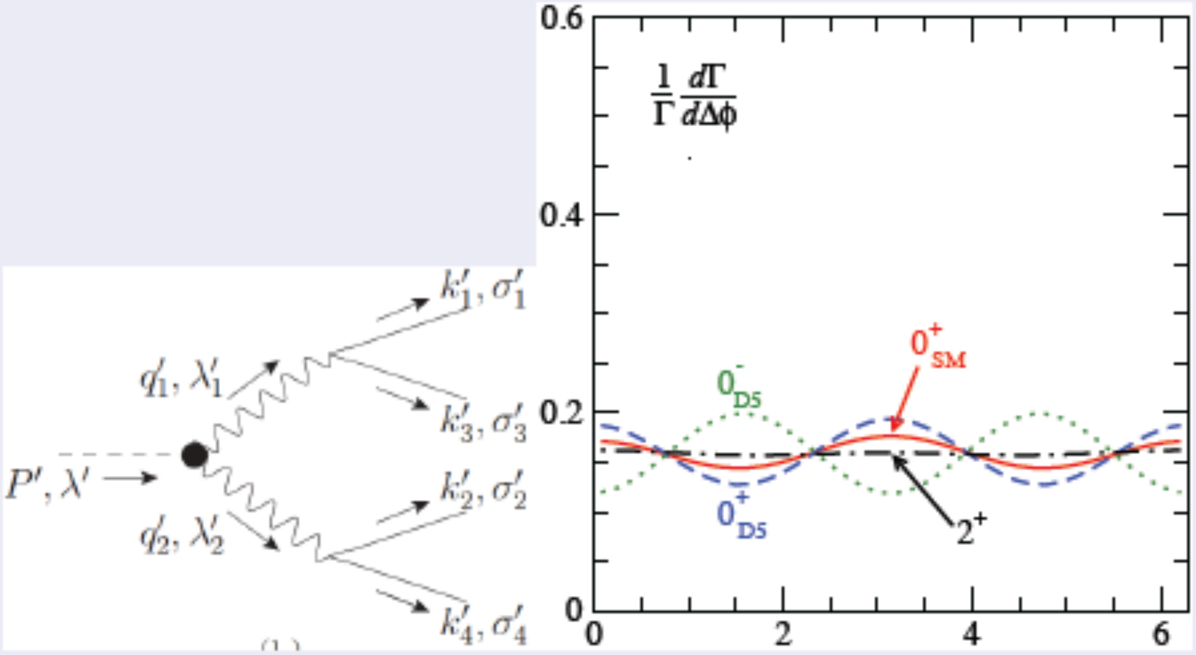
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[Bolognesi et al, PRD(2012)]

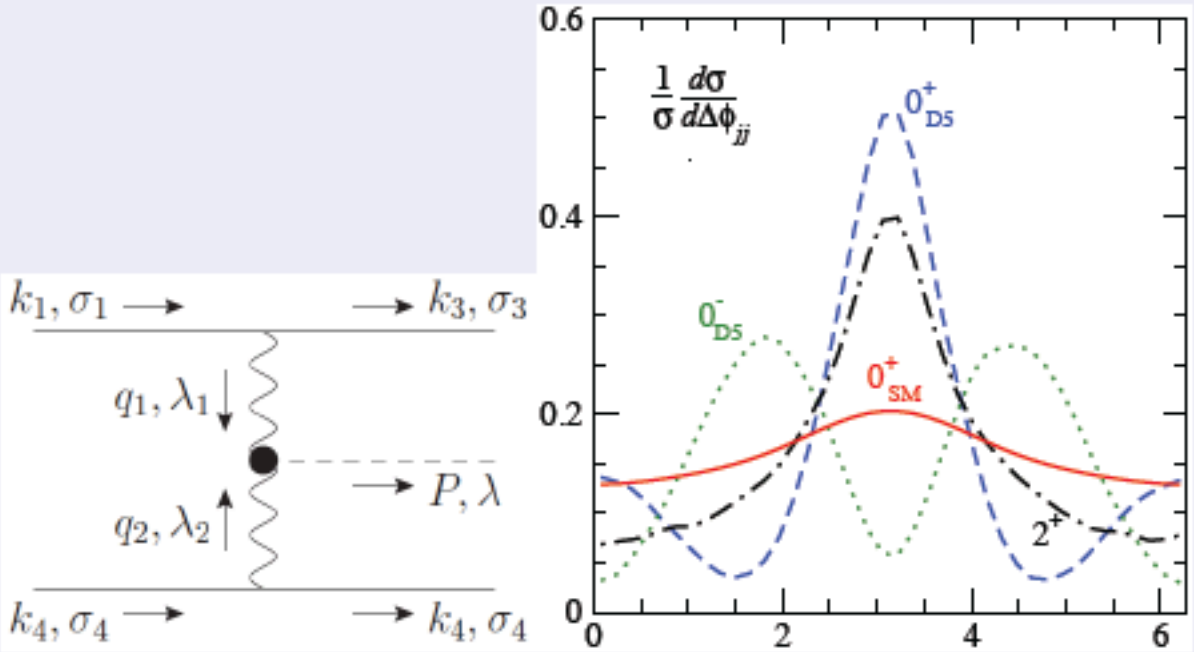
[Plehn, Rainwater, Zeppenfeld, PRL(2002)]
[Hagiwara, Li, KM, JHEP(2009)] ...

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

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



Vector boson fusion (VBF)



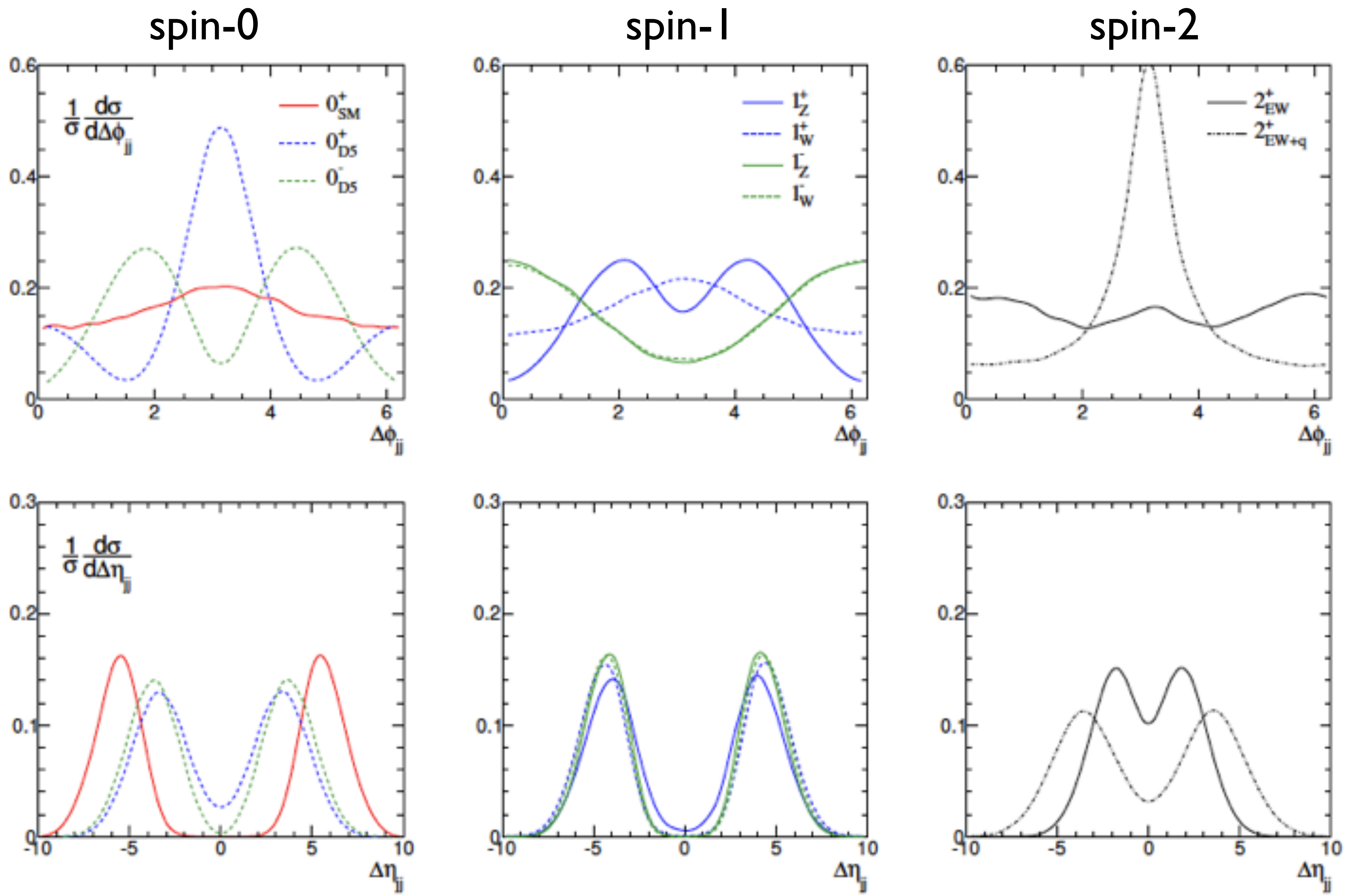
$d\sigma/d\Delta\phi \sim$ const. for $0^+_{\rm SM}$, $\quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$ for $0^\pm_{\rm D5}$.

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

di-jet correlations

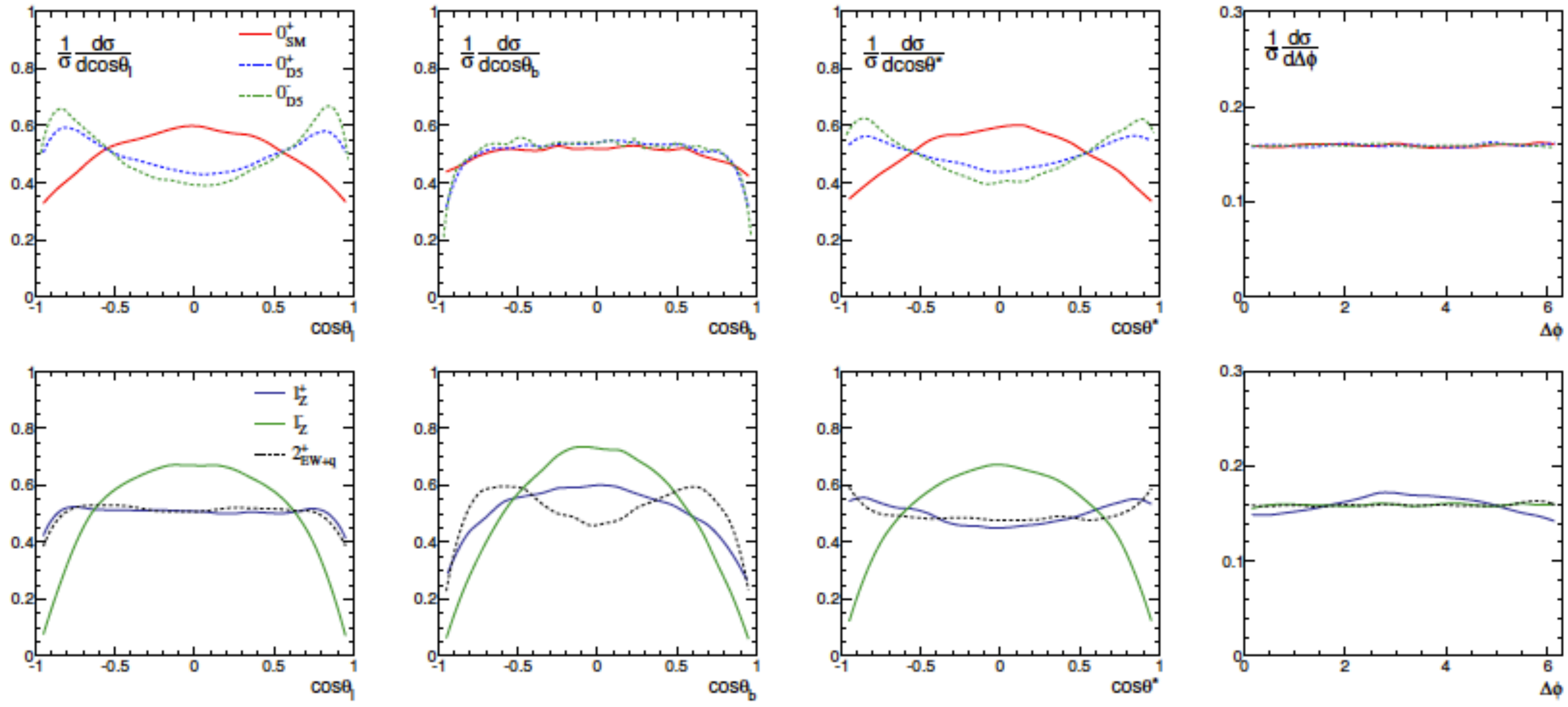
Englert, Goncalves-Netto, KM, Plehn (2013)



Δη as well as ΔΦ are the powerful observables.

Spin/parity determination
4. pp→ZX

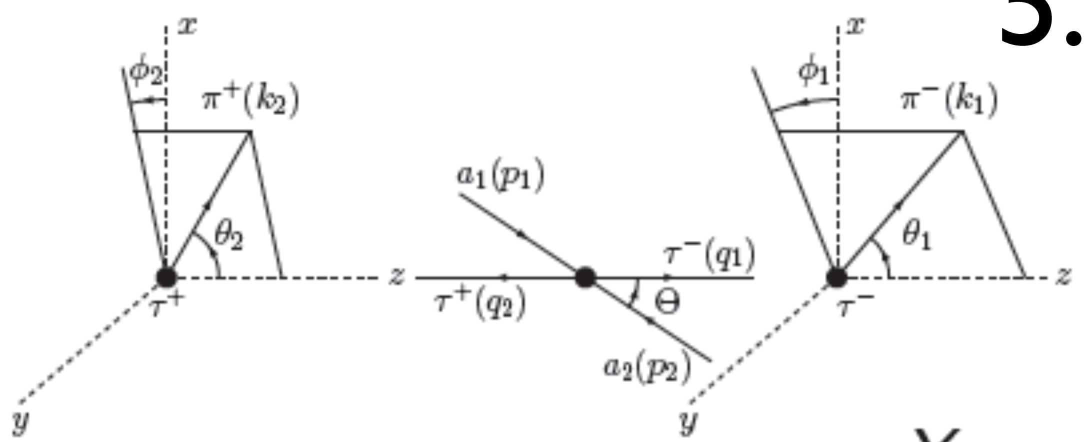
Englert, Goncalves-Netto, KM, Plehn (2013)



Spin/parity determination
5. X→ττ

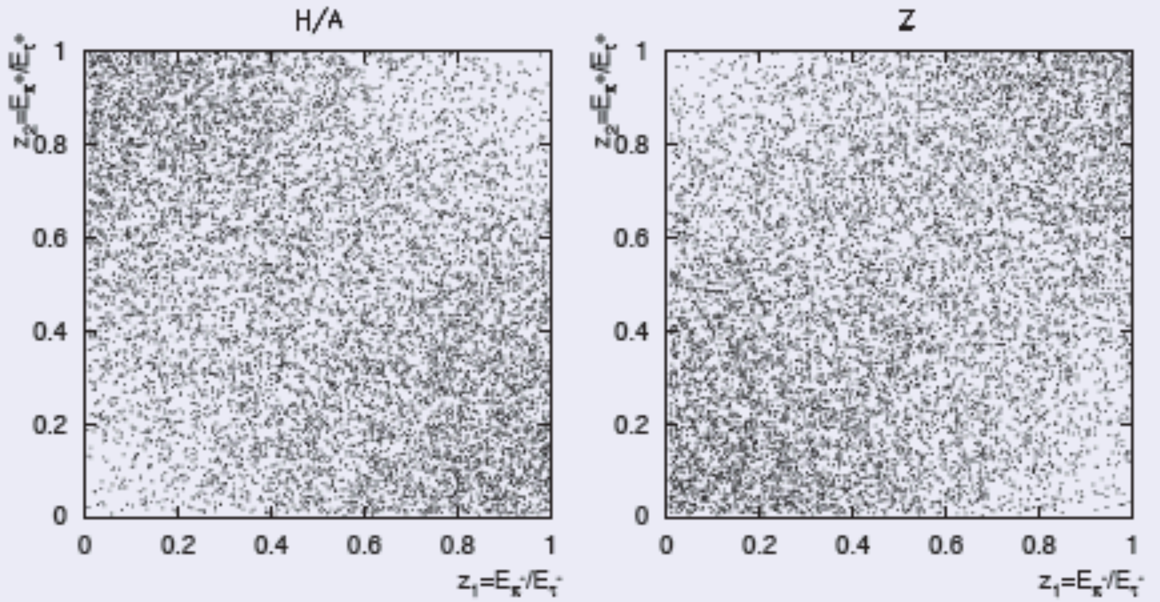
[Bullock, Hagiwara, Martin, NPB(1993)]
[Krämer, Kühn, Stong, Zerwas, ZPC(1994)]
[Pierzchala, Richter-Was, Was, Worek, APPB(2001,2002,...)]

[Hagiwara, Li, KM, Nakamura, 1212.6247]

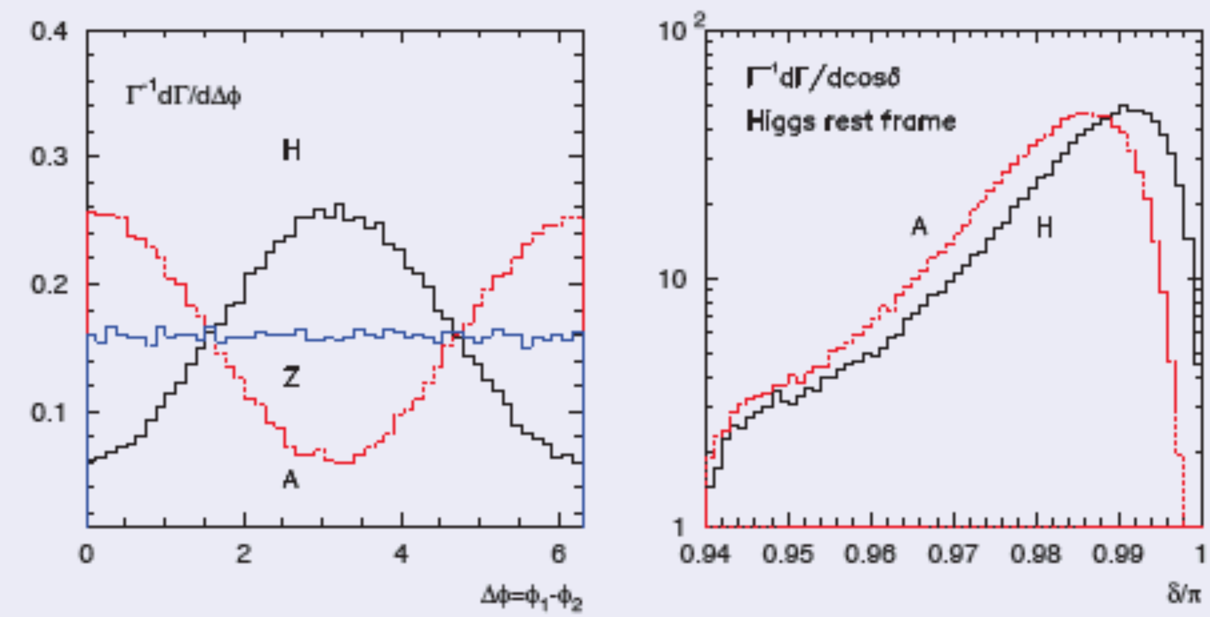


$$pp \to X \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$$

Longitudinal spin (helicity) effect



Transverse spin effect



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

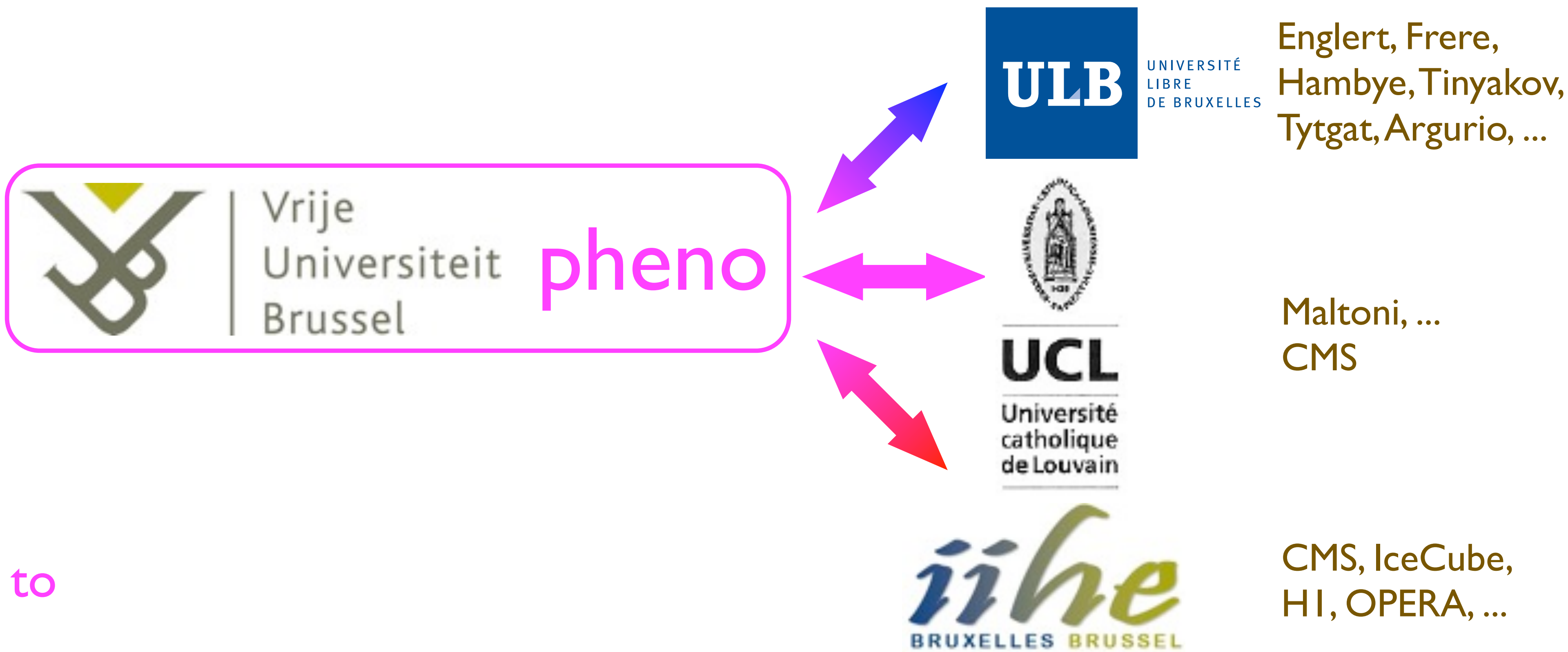
τ could be a spin/parity analyzer!

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 Characterisation model is ready for the spin/parity study of the recently-discovered boson.

Phenomenology group at the Vrije Universiteit Brussel

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



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

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