CHARACTERIZING THE 126 GEV BOSON: STRATEGIES AND TOOLS

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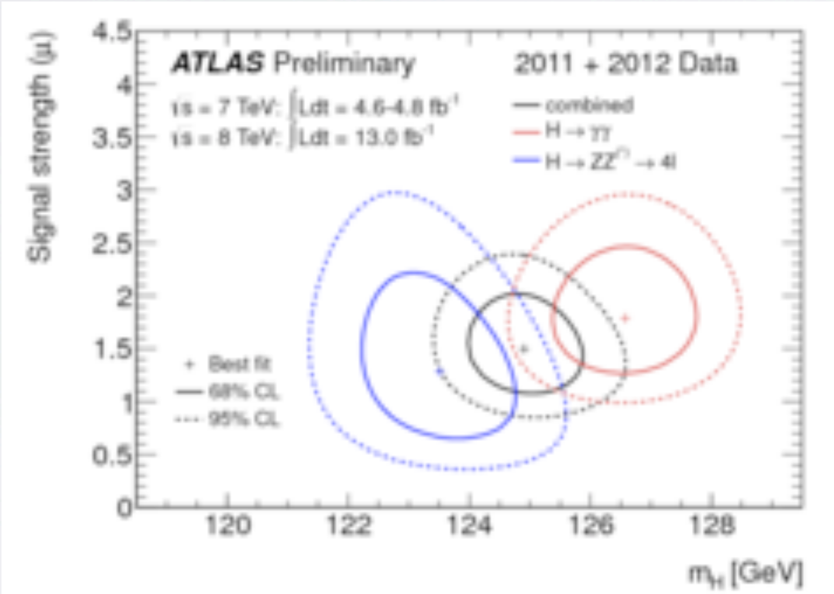
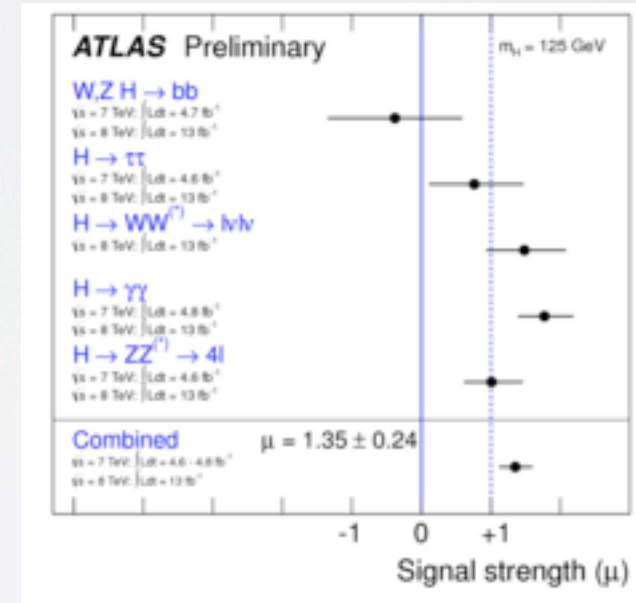
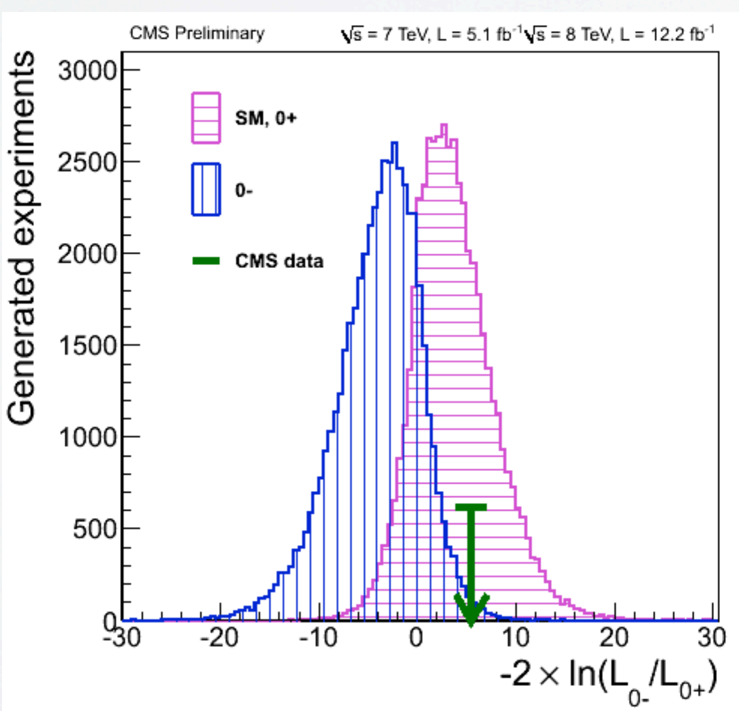
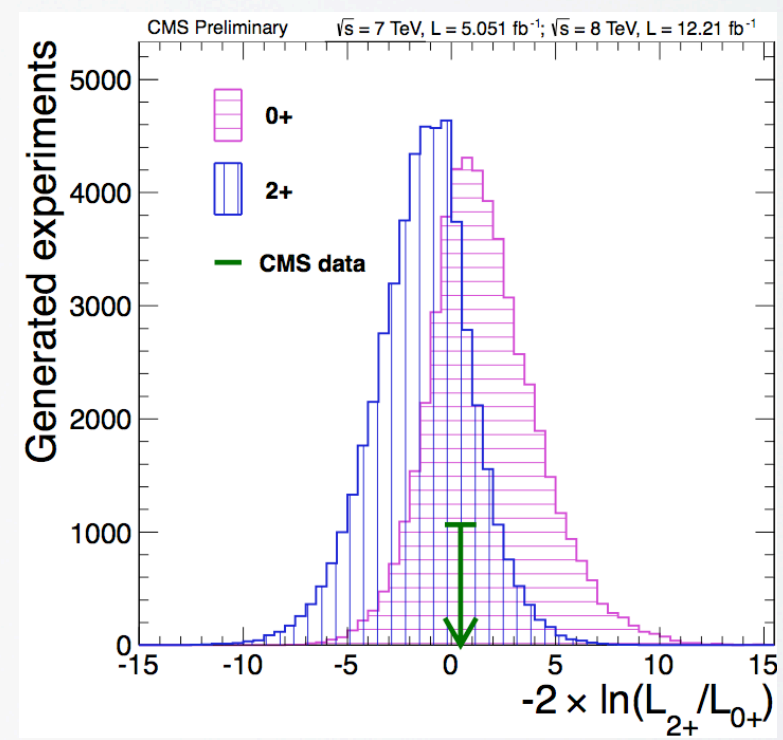




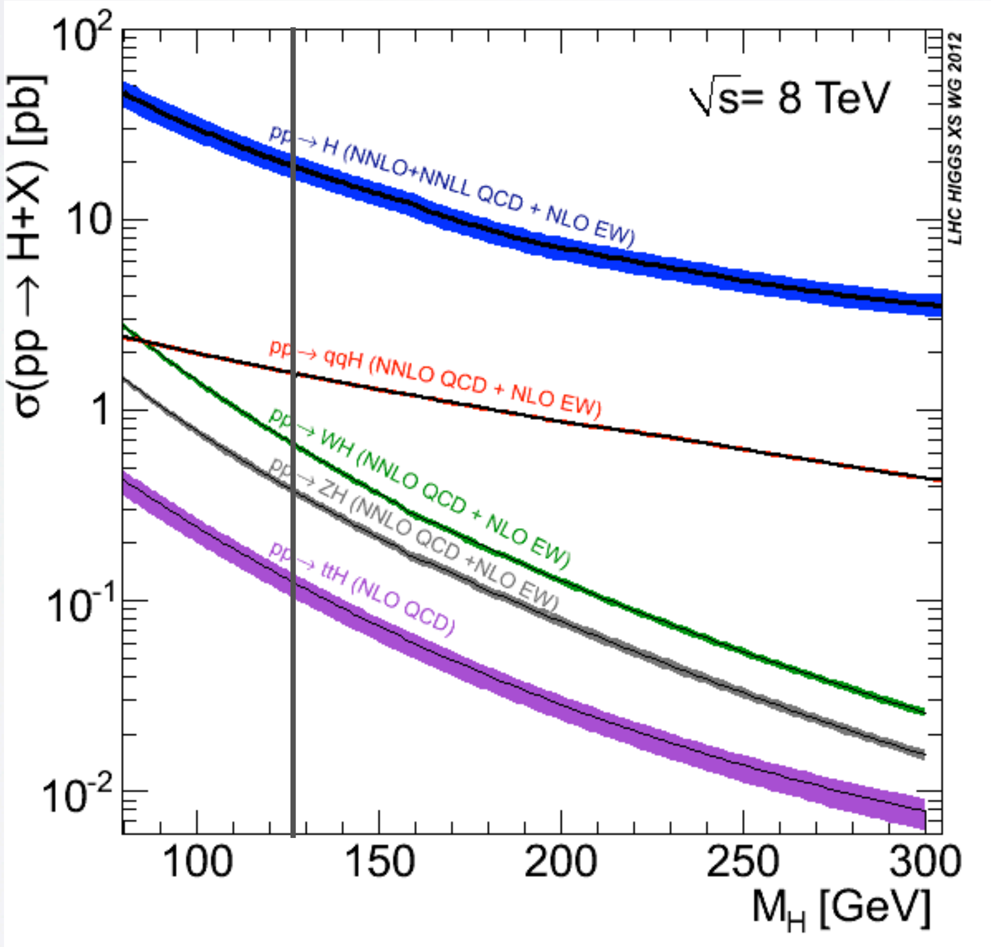
IS IT THE SM SCALAR (AKA THE HIGGS)?

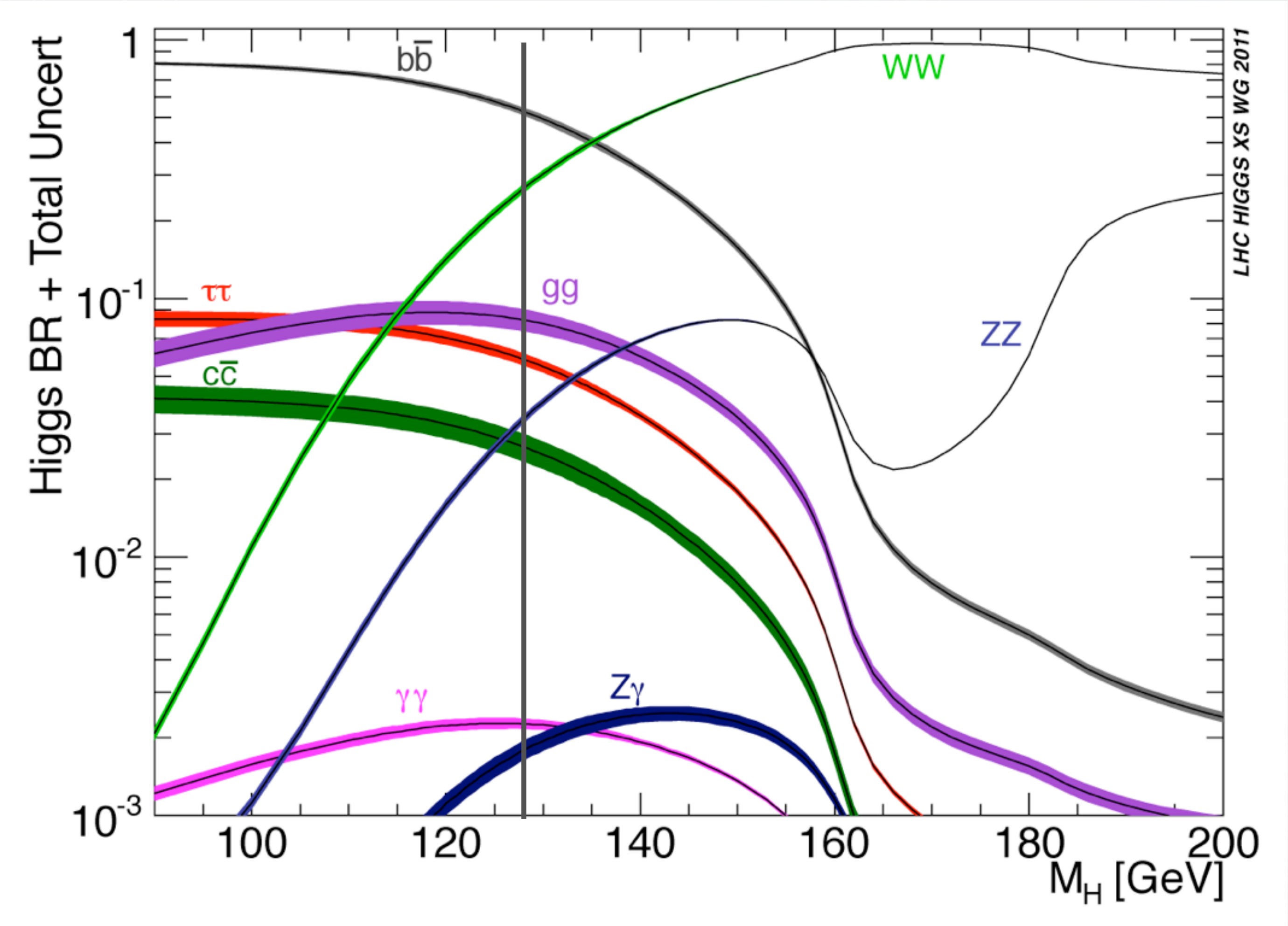


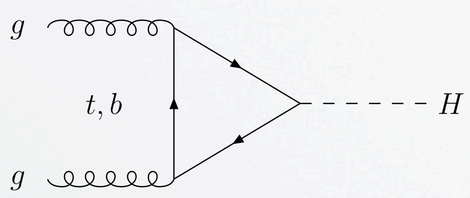


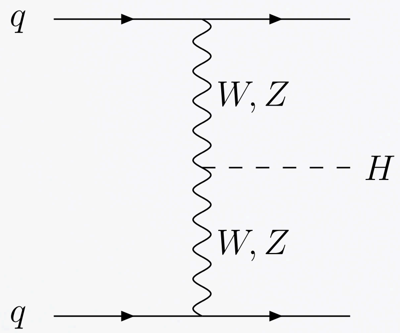
Strategy v0

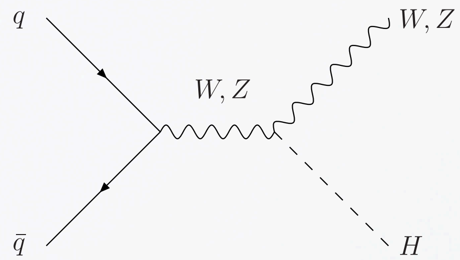
Compare the most precise predictions we have for the Higgs with data and look for differences.

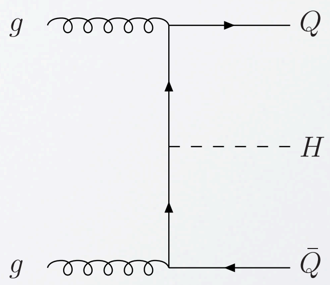










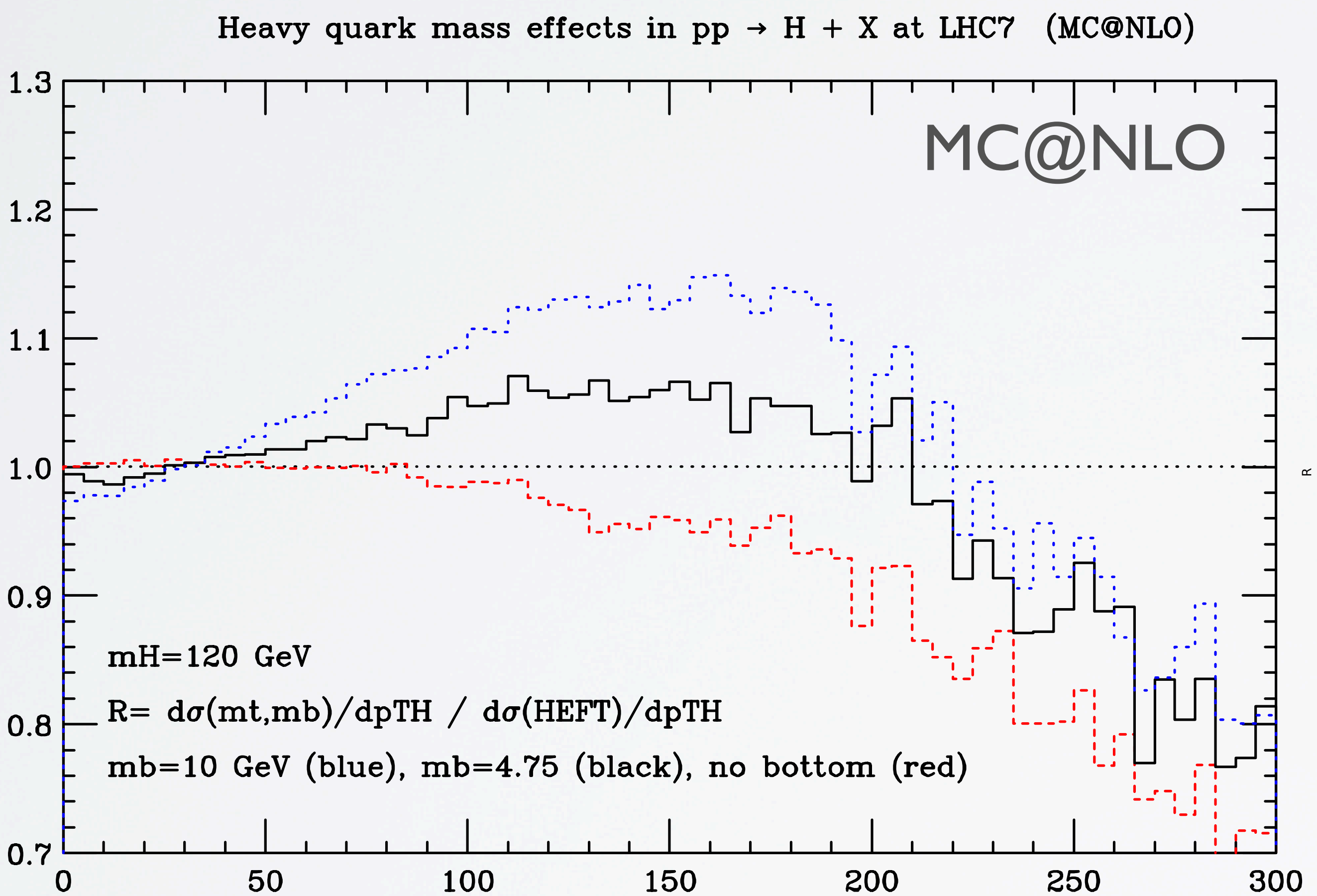


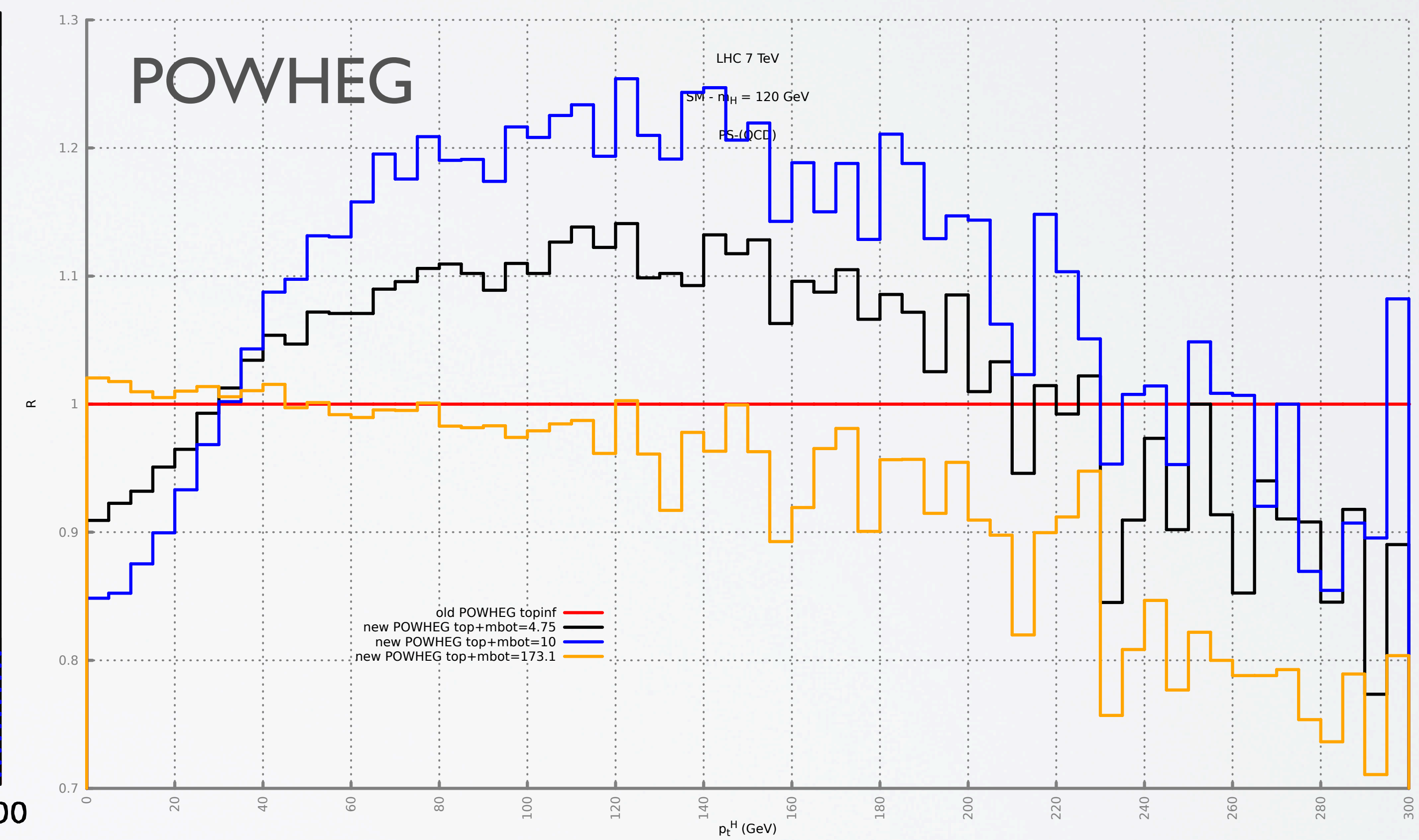
Strategy v0

Compare the most precise predictions we have for the Higgs with data and look for differences.

- Total cross sections at NNLO in QCD and NLO EW (ttH at NLO)
- Some differential observables at NNLO, most at NLO.
- Resummed/Improved results for selected observables.
- NLO in QCD with PS for all processes of interest, including $gg \to H$ in the full theory.
- Jet merging at NLO with PS for main procs starts to be available.

Higgs pT : HEFT vs full theory





Unexpected effects always popping up... and for the first time NLO+PS came before analytic computations!

Beware : significant differences at small pT for the Higgs!
This is due to the different treatment of the probability of the first emission within the two methods. Note that POWHEG has been now tuned to HqT at high pT.

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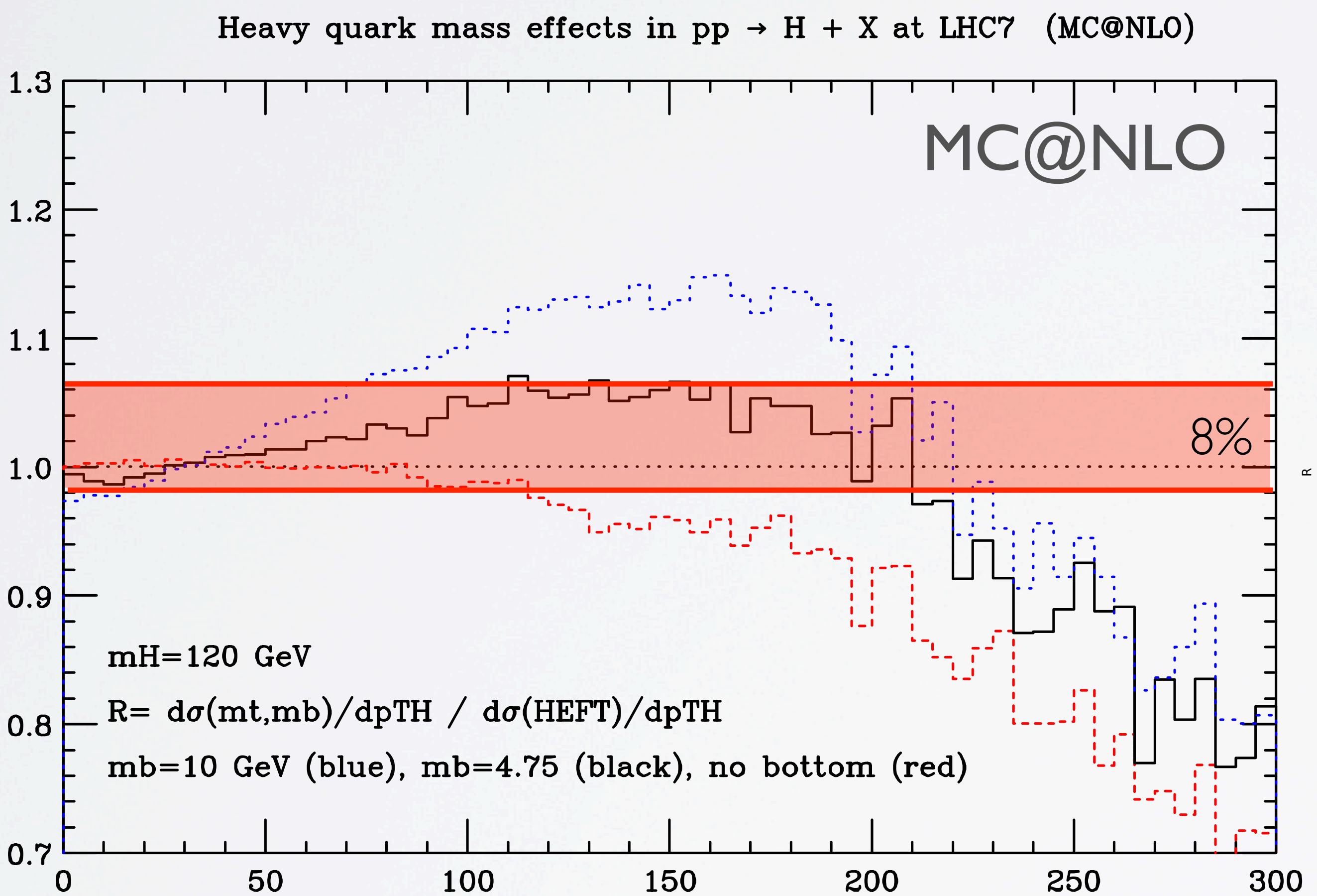

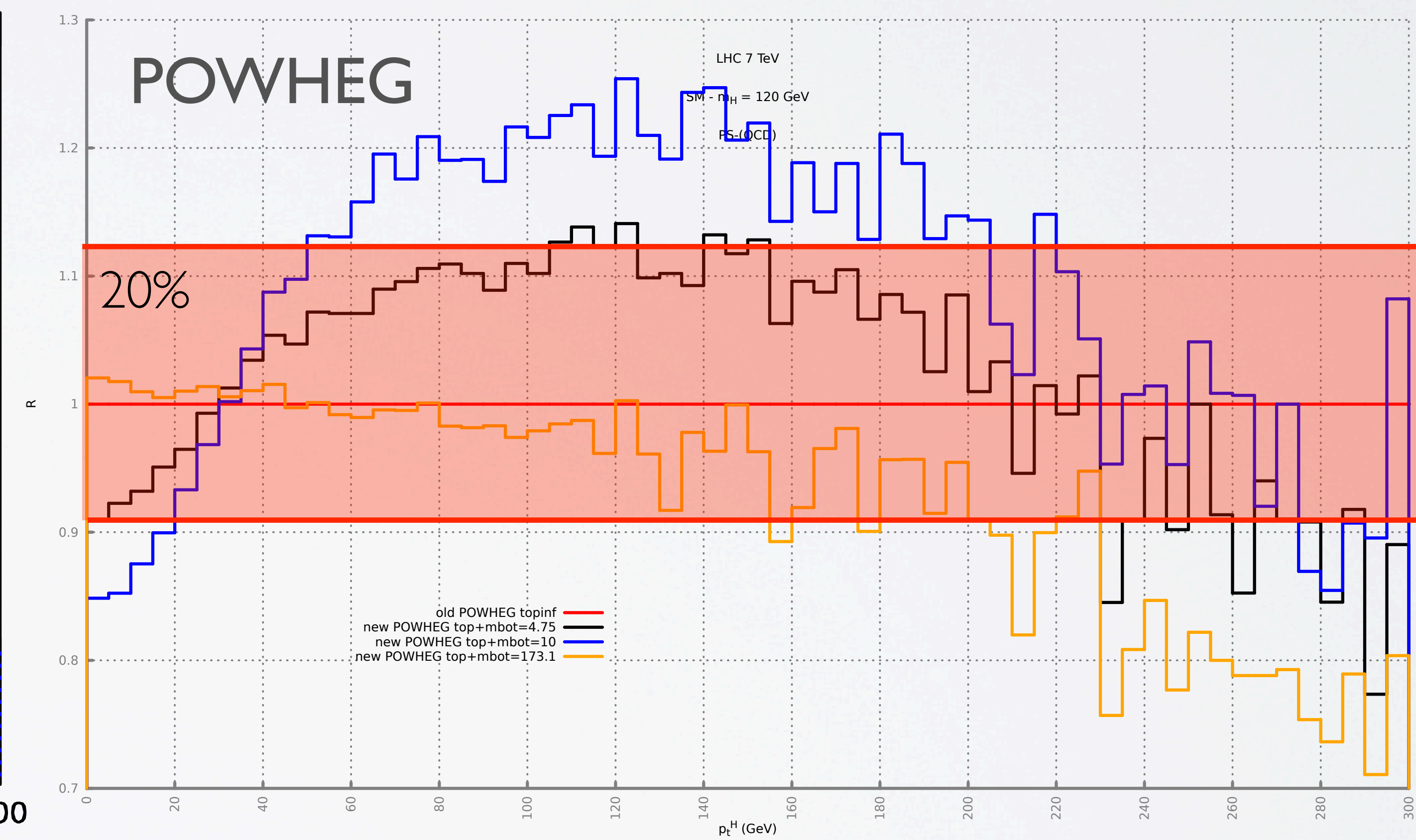

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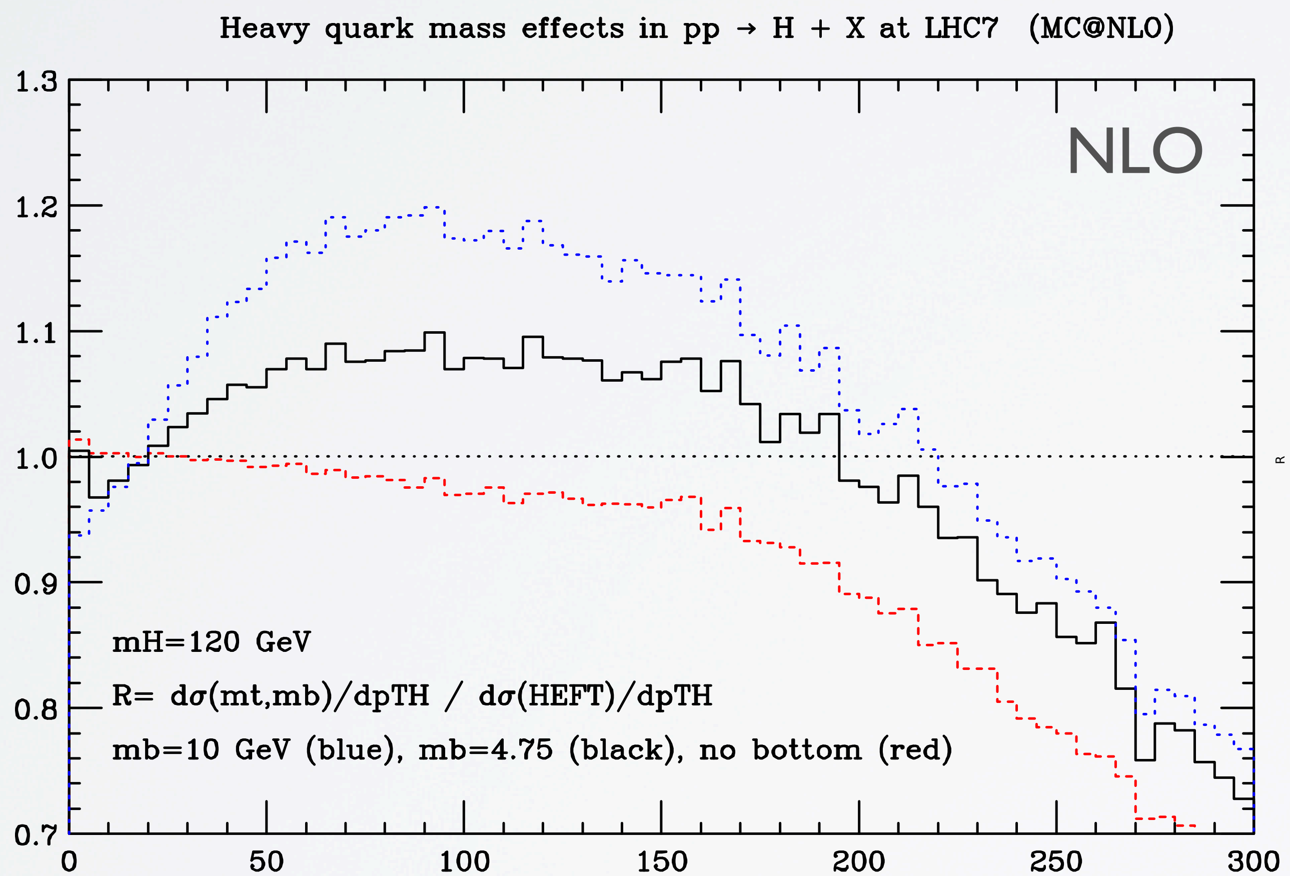
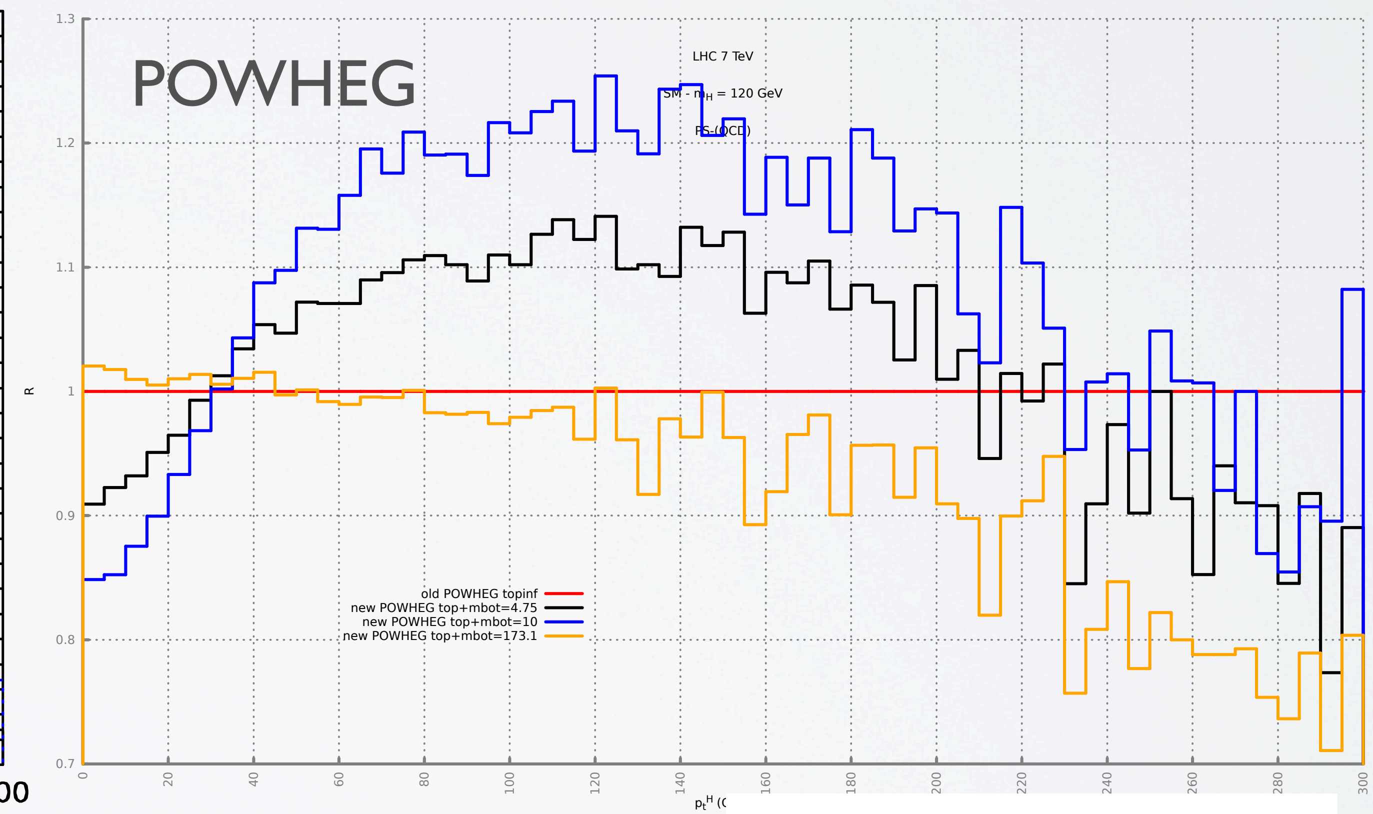
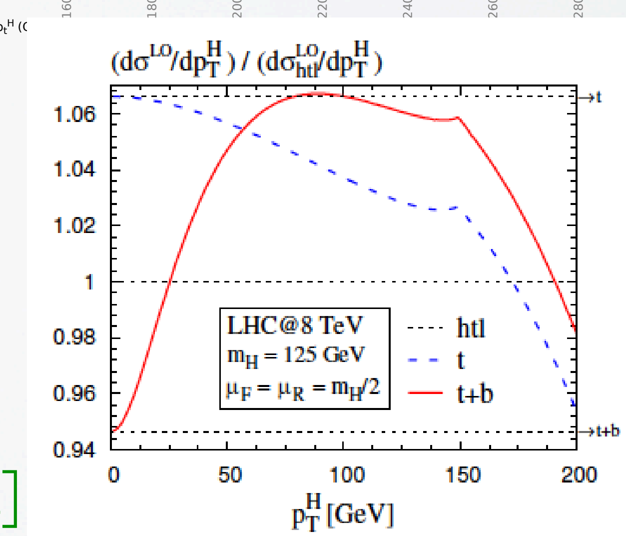


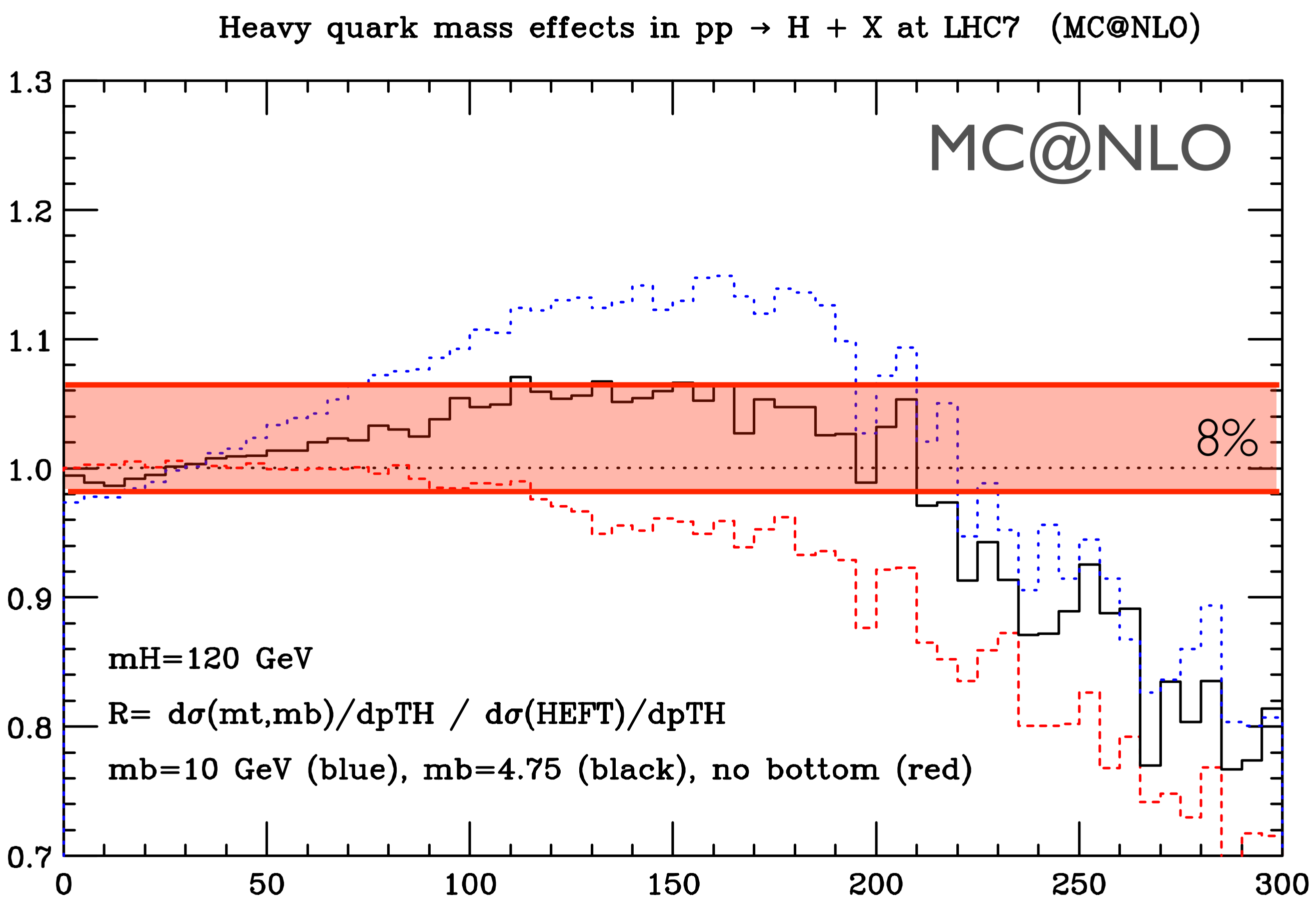


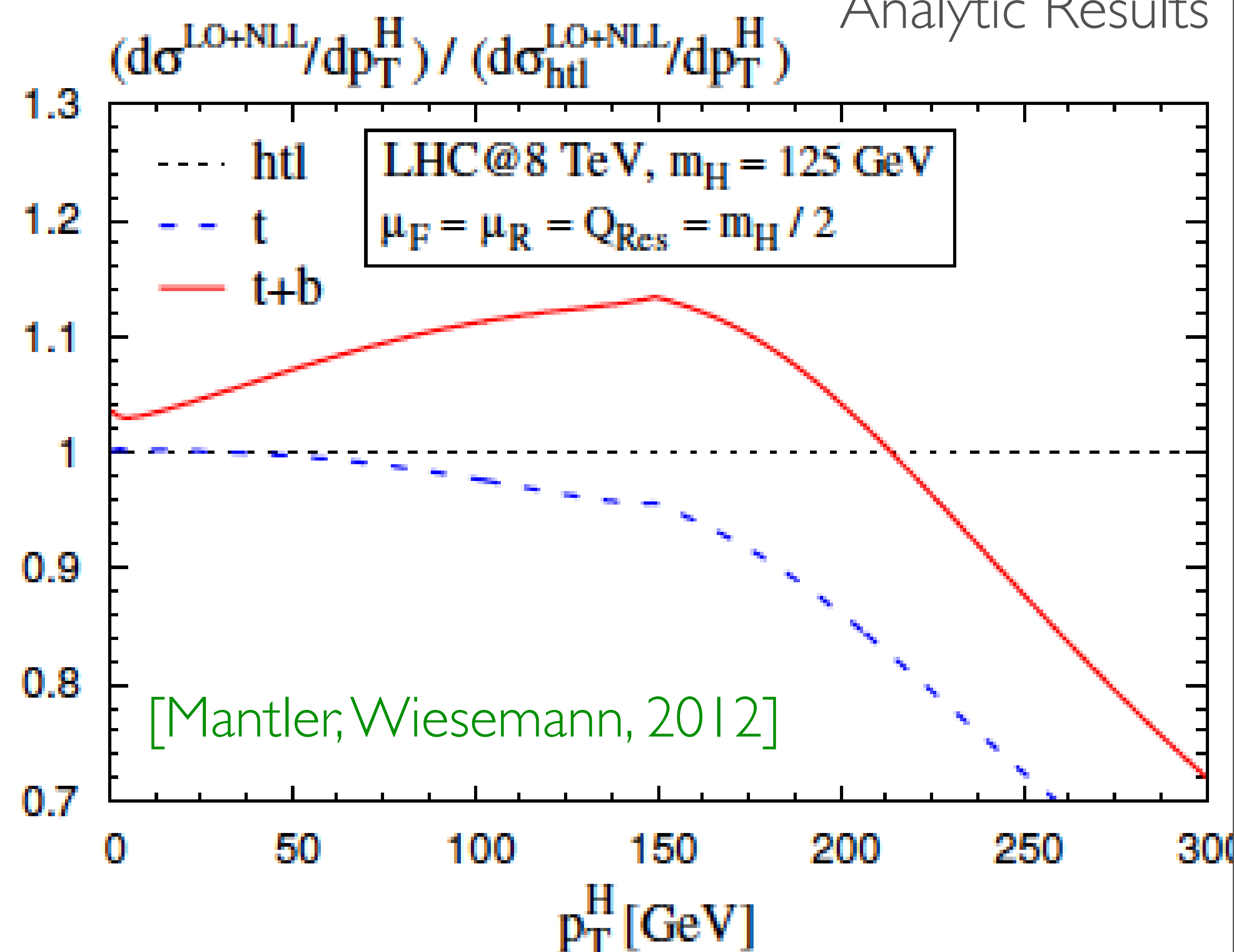


Excellent agreement at NLO among all calculations.
POWHEG "amplifies" NLO corrections to the shapes.

[Mantler, Wiesemann, 2012]

Higgs pT : HEFT vs full theory



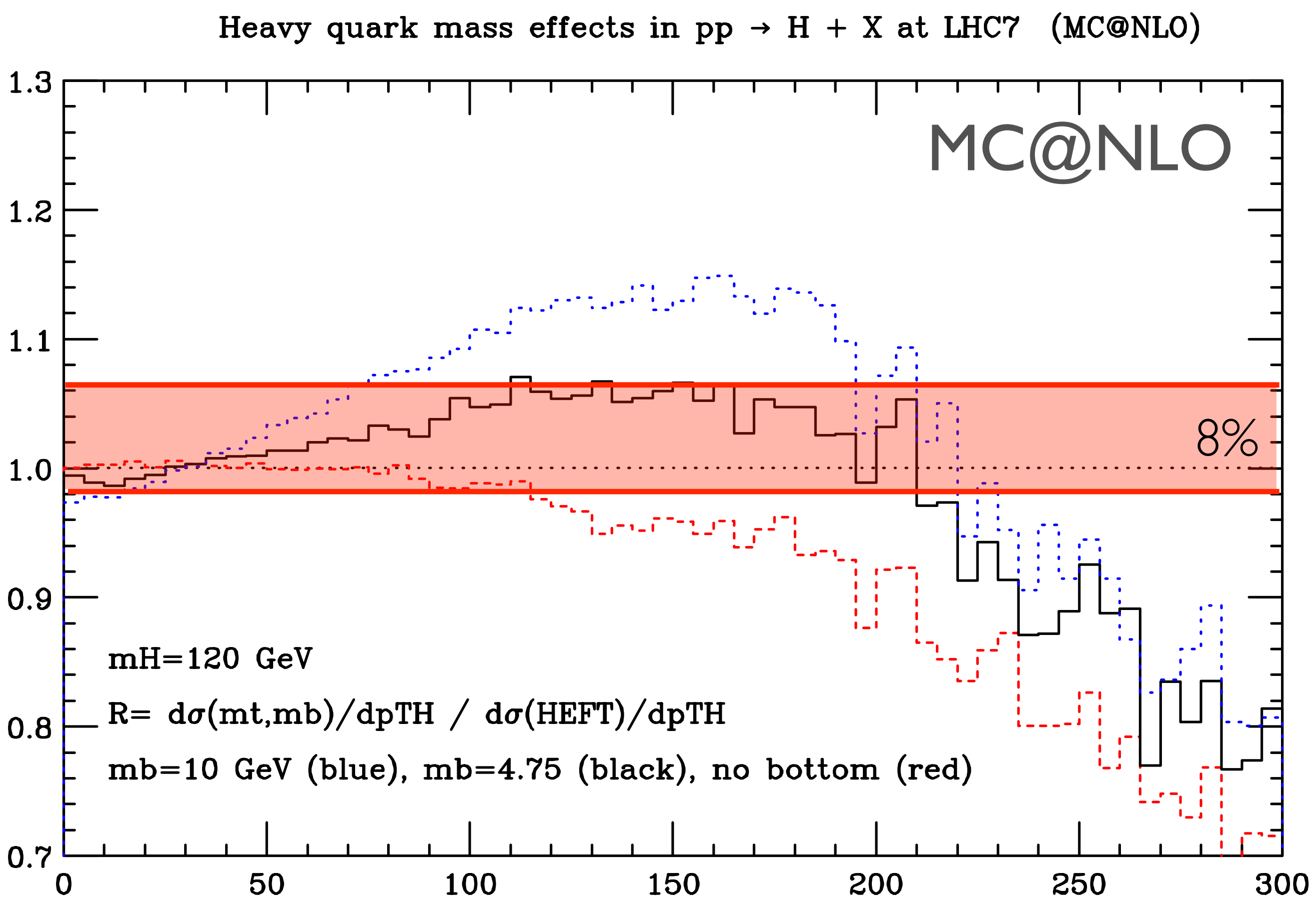


aMC@NLO **shape** closer to the resummed analytic computation.

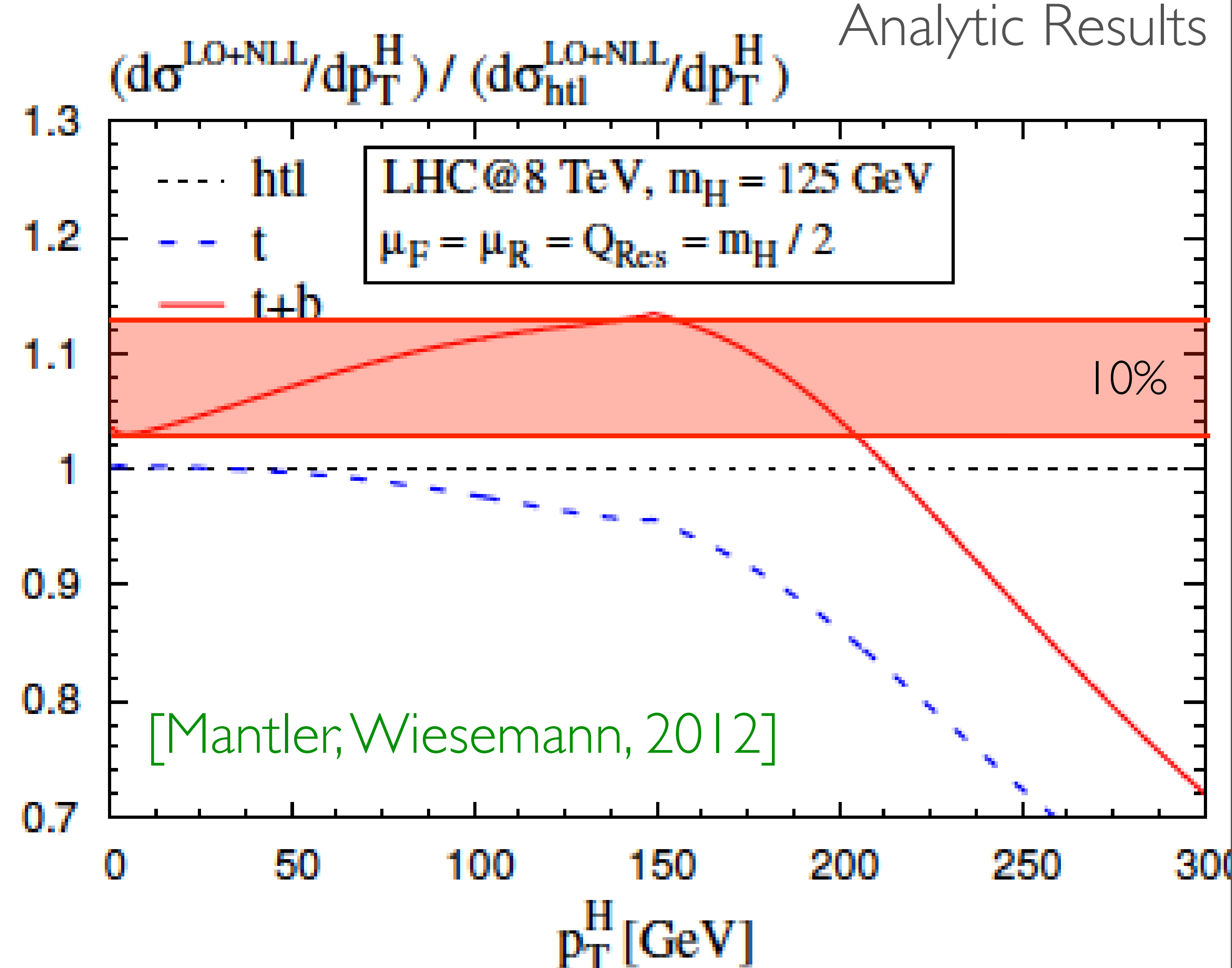
Reasonable agreement between **aMC@NLO** and the HqT-approach.

Needs further investigation.

Higgs pT : HEFT vs full theory



Analytic Results



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Strategy v1

Strategy v1

LO

Only resonance?

↓ yes

Spin 0?

↓ yes

+ Parity?

↓ yes

SM couplings strength?

↓ yes

SM couplings form?

↓ yes

SMS

Strategy v1

L0 Only resonance?

↓ yes

L1 Spin 0?

↓ yes

+ Parity?

↓ yes

L2 SM couplings strength?

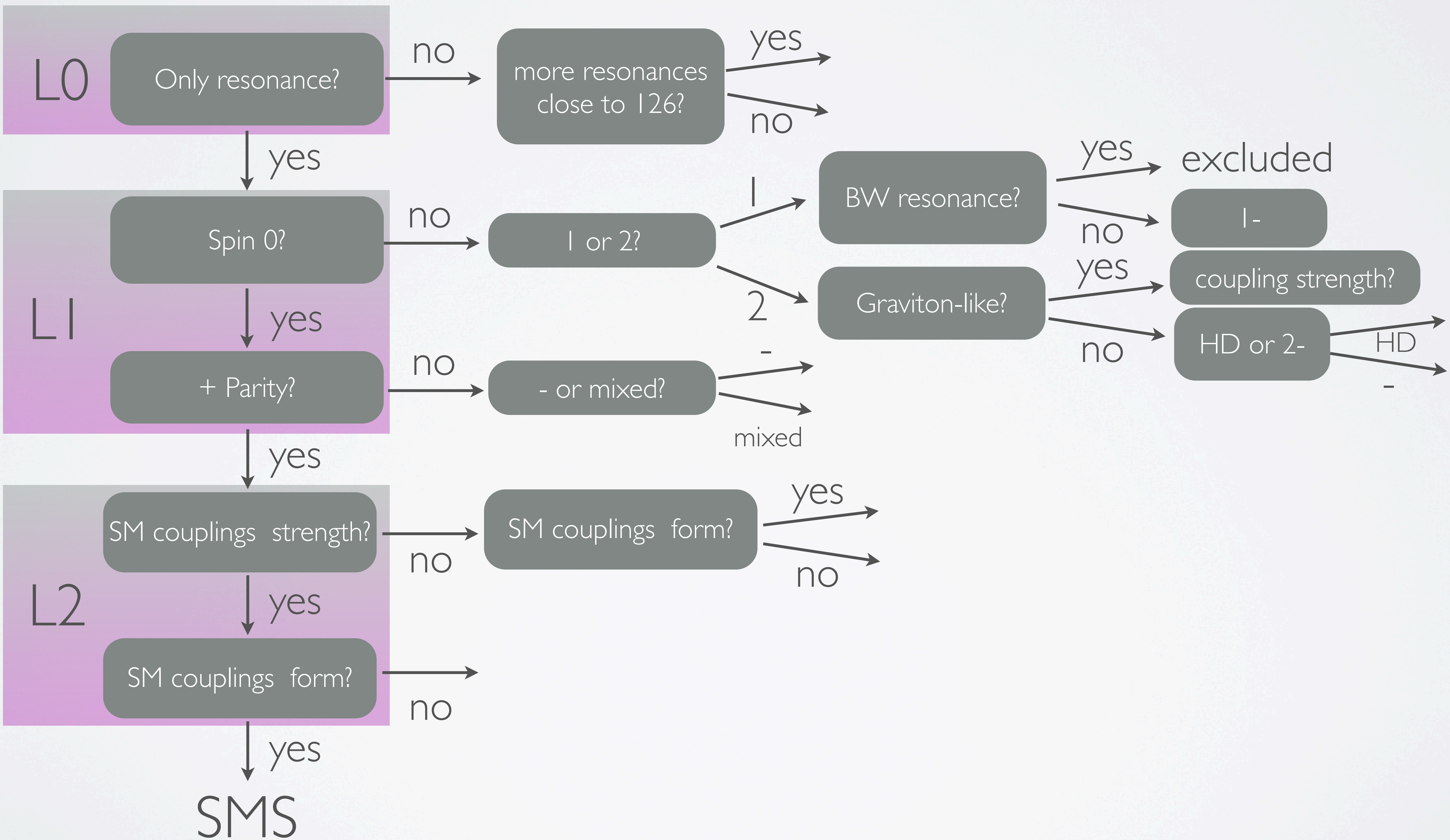
↓ yes

SM couplings form?

↓ yes

SMS

Strategy v1


L0
Only resonance?
no
more resonances close to 126?
yes
no
yes
L1
Spin 0?
no
1 or 2?
1
BW resonance?
yes
excluded
no
1-
2
Graviton-like?
yes
coupling strength?
no
HD or 2-
HD
-
yes
+ Parity?
no
- or mixed?
-
mixed
yes
L2
SM couplings strength?
no
SM couplings form?
yes
no
yes
SM couplings form?
no
yes
SMS

Strategy v1: comments

- The represented vertical flow does not respect the order/accuracy of the information we gather from the LHC.
- The hierarchy in the horizontal questions seems quite general. However, it is tempting to give some answers directly.
- It should be kept in mind that also for the L1 questions several production channels could be employed.
- Whatever, strategy one follows, a consistent working framework is needed.

Frameworks

1. Anomalous couplings (AC):

☺ Only requirement is Lorentz symmetry
☺ Agnostic on new physics (can be light)
☹ Born contribution only
☹ Large number of extra couplings
☹ Possibly violates unitarity, yet (model dependent) form factors can be included.

2. Effective field theory (ETF):

☺ Based on all the symmetries of the SM.
☺/ ☹ New physics is heavier than the resonance itself : $\Lambda > M_X$
☺ Renormalizable (order by order in $1/\Lambda$)
☺ Number of extra couplings reduced by symmetries and dimensional analysis
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Ex: JHU
[Melnikov et al., 1001.3396 1208.4018]

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Frameworks

my "even more personal" comments

- For The EFT is somewhat superior to AC as it provides a consistent "renormalizable" framework where higher-order effects can be systematically and consistently included.

- So for L2 questions and if there is no evidence for any other light new state around there is little doubt that this is the most convenient framework.

- For L1 questions the border between AC and EFT becomes more blurry as typically one builds an EFT below the weak scale, where $SU(2)_L \times U(1)_Y$ is broken. However, one can still use $1/\Lambda$ expansion as a guiding principle.

Spin 0 state

$$\mathcal{L}_0 = X_0 \Big[k_{SM} c_\alpha g_{HVV} V^\mu V_\mu - \frac{1}{4} k_V (c_\alpha V_{\mu\nu} V^{\mu\nu} + s_\alpha V_{\mu\nu} \tilde{V}^{\mu\nu})$$
$$- \frac{1}{4} k_A (c_\alpha g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu})$$
$$- \frac{1}{4} k_g (c_\alpha g_{Hgg} G^a_{\mu\nu} G^{\mu\nu,a} + s_\alpha g_{Agg} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}) \Big]$$
$$+ X_0 \left[c_\alpha y_H \, \bar{\psi}\psi + s_\alpha y_A \, \bar{\psi} i \gamma_5 \psi \right]$$

Very simple setting.

The above formulation allows X to be a mixed P state for generic α [see fo instance A. Freitas, Schwaller, 1211.1980]

VV=ZZ,WW and A A=$\gamma\gamma$, γZ.

Spin 1 state

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

$$\mathcal{L}_1 = \bar{\psi}(a + b\gamma_5)\gamma^\mu \psi X^\mu + \qquad V = Z, W, \gamma$$

$$+ig_1(V^\dagger_{\mu\nu} V^\mu X^\nu - V^\dagger_\mu X_\nu V^{\mu\nu}) + ik_V V^\dagger_\mu V_\nu X^{\mu\nu}$$
$$-g_4 V^\dagger_\mu V_\nu (\partial^\mu X^\nu + \partial^\mu X^\nu) + g_5 \epsilon^{\mu\nu\rho\sigma}(V^\dagger_\mu \overleftrightarrow{\partial}_\rho V_\nu) X_\sigma$$

$$+i\tilde{k}_V V^\dagger_\mu V_\nu \tilde{X}^{\mu\nu}$$

$$+\frac{i\lambda_V}{\Lambda^2} V^\dagger_{\lambda\mu} V^\mu_\nu X^{\nu\lambda} + \frac{i\tilde{\lambda}_V}{\Lambda^2} V^\dagger_{\lambda\mu} V^\mu_\nu \tilde{X}^{\nu\lambda}$$

Effective lagrangian involving a new vector state X coupling to V=W,Z, γ below the weak scale. For V=Z,γ at the lowest dimension only g_4, g_5 are non zero (These are the only terms included in JHU also for V=W !). g_5 can come from the U(1) anomaly, while λ_V can come from the triangle diagrams after anomaly cancellation.

LANDAU-YANG THEOREM

The Landau-Yang theorem states that a massive vector cannot decay to two massless identical vectors due to angular momentum conservation and Bose symmetry.

Using $\mathcal{L}_{VVX}$ one can explicitly check that the $X^\mu \to \gamma\gamma$ amplitudes vanish, If X is on-shell. However, amplitudes are non-zero off-shell.

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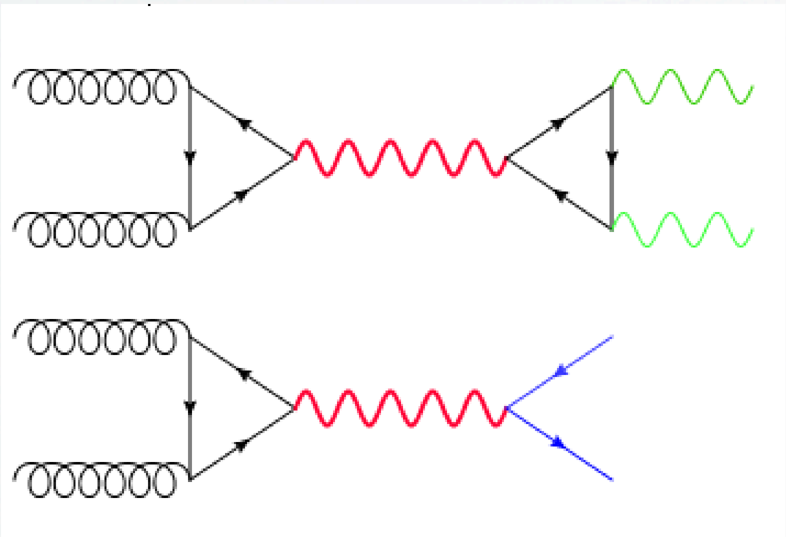

$$|Amp(gg \to X \to \gamma\gamma)|^2 \sim \frac{(Q^2 - M_X^2)^2}{(Q^2 - M_X^2)^2 + M_X^2 \Gamma_X^2}$$

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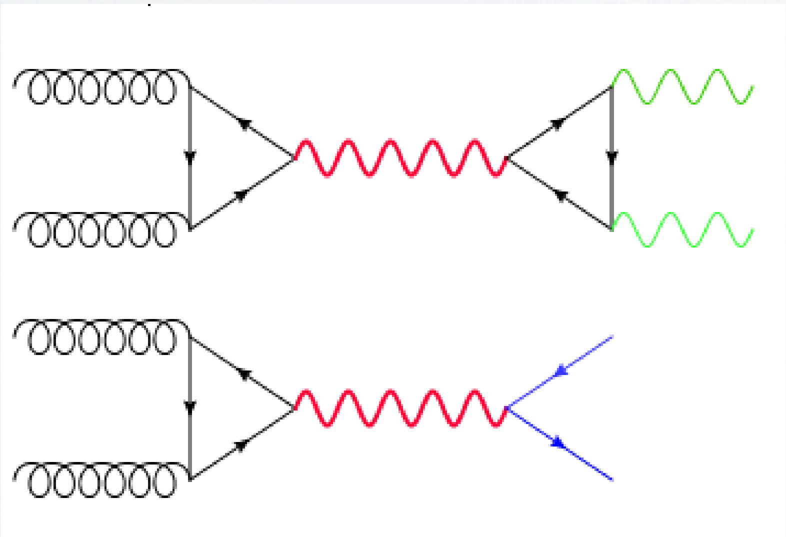

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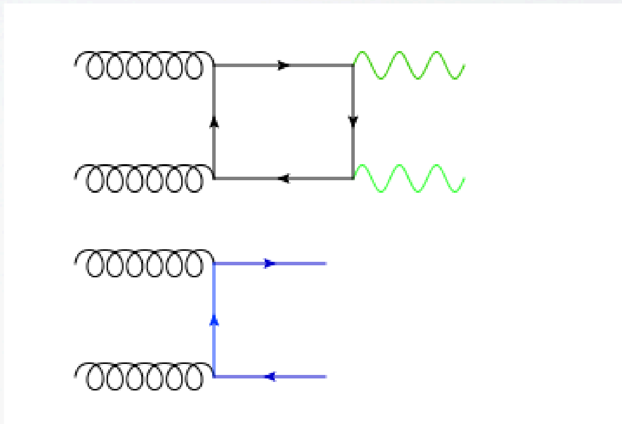

Wednesday 9 January 2013

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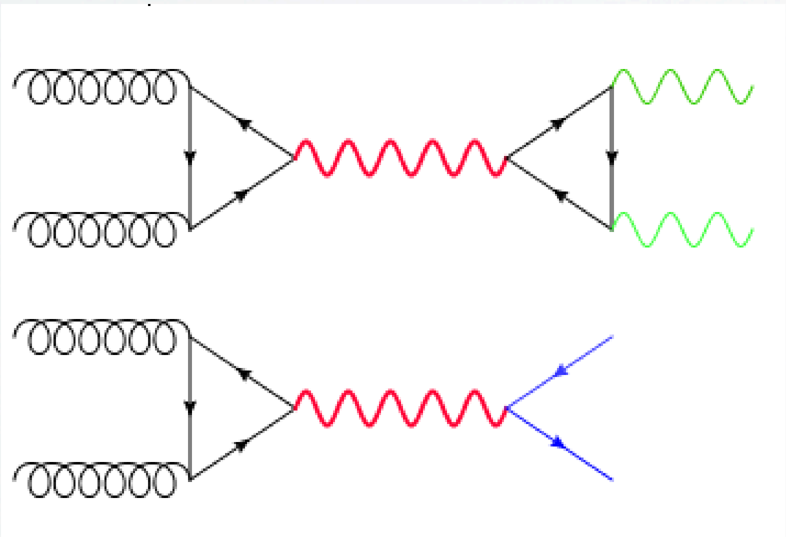

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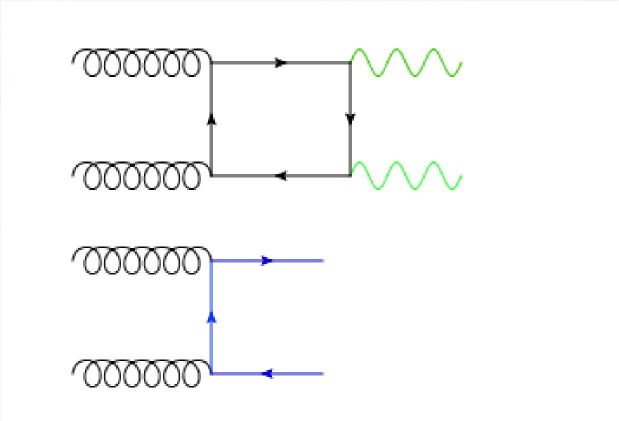


Very small contribution leading to a dip not to a peak. However, by interfering it with the continuous background one might get an enhancement and a peak-dip structure. It can be rather easily checked...

[See Ralston 1211.2288]

Spin 2 state

[see for example, Ellis, Sanz, You, 1211.3068, 1210.5229, 1208.6002]

Extra dimensional theory (like RS):

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

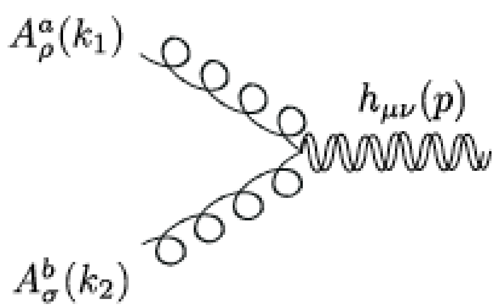
$$\mathcal{T}^V_{\mu\nu} = \frac{1}{4}\eta_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} - F_\mu^{\ \rho} F_{\nu\rho}$$

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

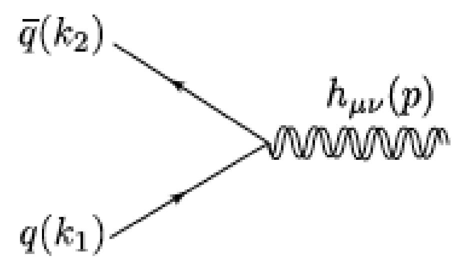
At the minimal dimension a spin-2 particle is graviton-like. Higher dimensional operators can be included. We have implemented (a few of) such terms in our model to account for a 2^- state and to check unitarity violations in the graviton production amplitudes a high-Q^2.

Couplings k_i already need to be different to accommodate current information $c_V/c_A < 35$

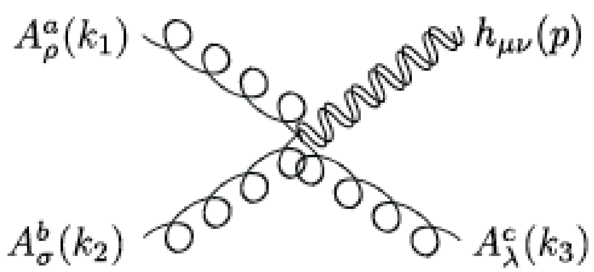
Spin 2 state



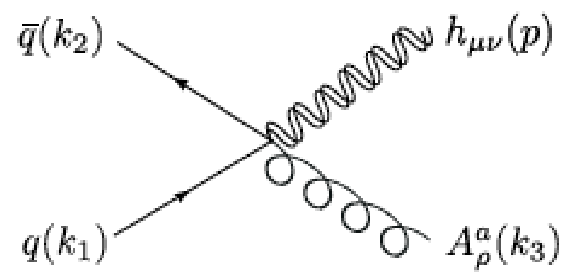
$$= i\,\frac{\kappa}{2}\delta^{ab}\left[(k_1\cdot k_2)\,C_{\mu\nu\rho\sigma} + D_{\mu\nu\rho\sigma} + \xi^{-1}E_{\mu\nu\rho\sigma}\right]$$



$$= -\,i\,\frac{\kappa}{8}\left[\gamma^\mu\,(k_1-k_2)_\nu - \gamma^\nu\,(k_1-k_2)_\mu \;-2\,\eta_{\mu\nu}\,(\not{k}_1-\not{k}_2)\right]$$



$$= g\,\frac{\kappa}{2}f^{abc}\left[C_{\mu\nu\rho\sigma}\,(k_1-k_2)_\lambda + C_{\mu\nu\rho\lambda}\,(k_3-k_1)_\sigma + C_{\mu\nu\sigma\lambda}\,(k_2-k_3)_\rho + F_{\mu\nu\rho\sigma\lambda}\right]$$



$$= i\,g\,\frac{\kappa}{4}T^a\left[C_{\mu\nu\rho\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma}\right]\gamma^\sigma$$

The L_2 lagrangian is gauge invariant by construction, even for different k_i.

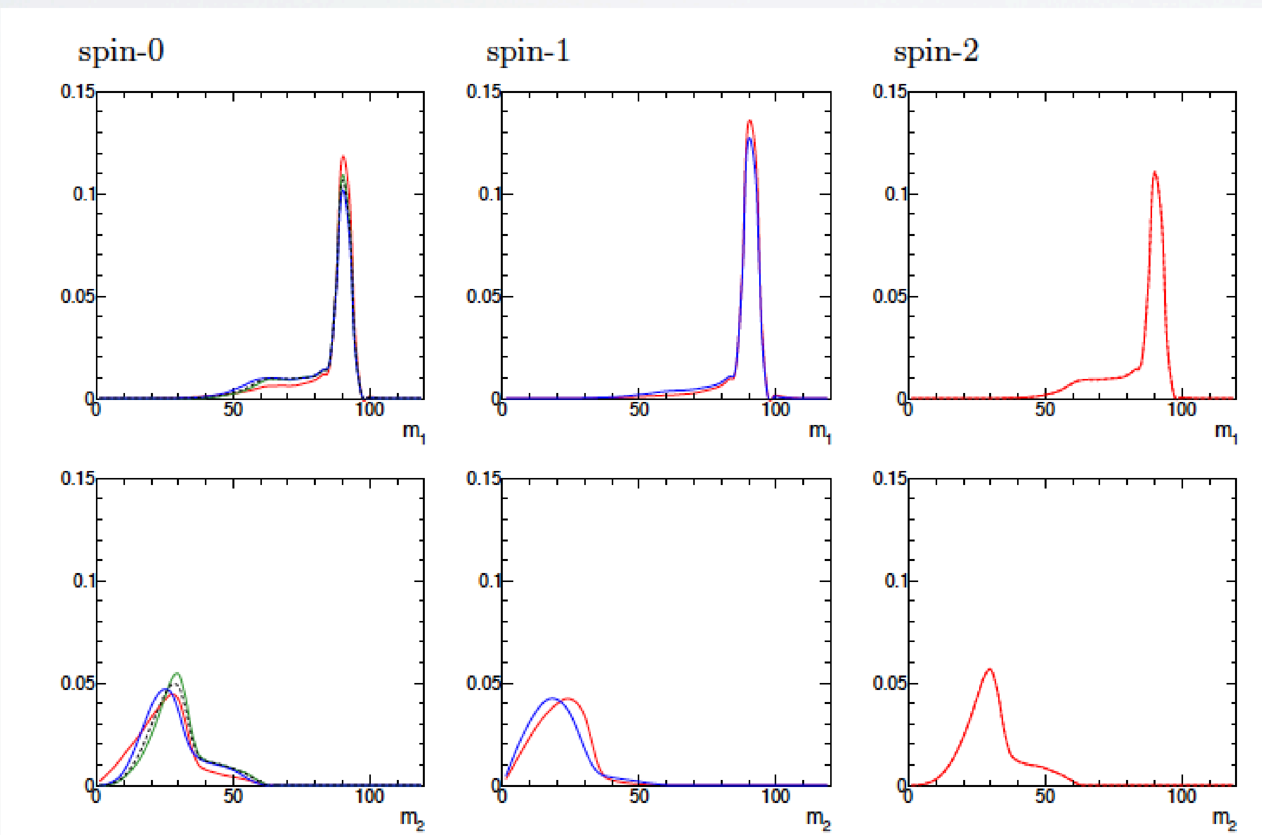
At NLO in QCD, pp→X_2 does not even need renormalization for $k_g=k_q$.

Claim: higher order (multi-parton amplitudes) and NLO in QCD results for any production mode via L_2 for any k_i are consistently gauge invariant.

Verified explicitly in MG5 and by 1-loop analytic computations.

Validation of the FR model in MG5

p p→X→ Z Z* →mu+mu-e+e-



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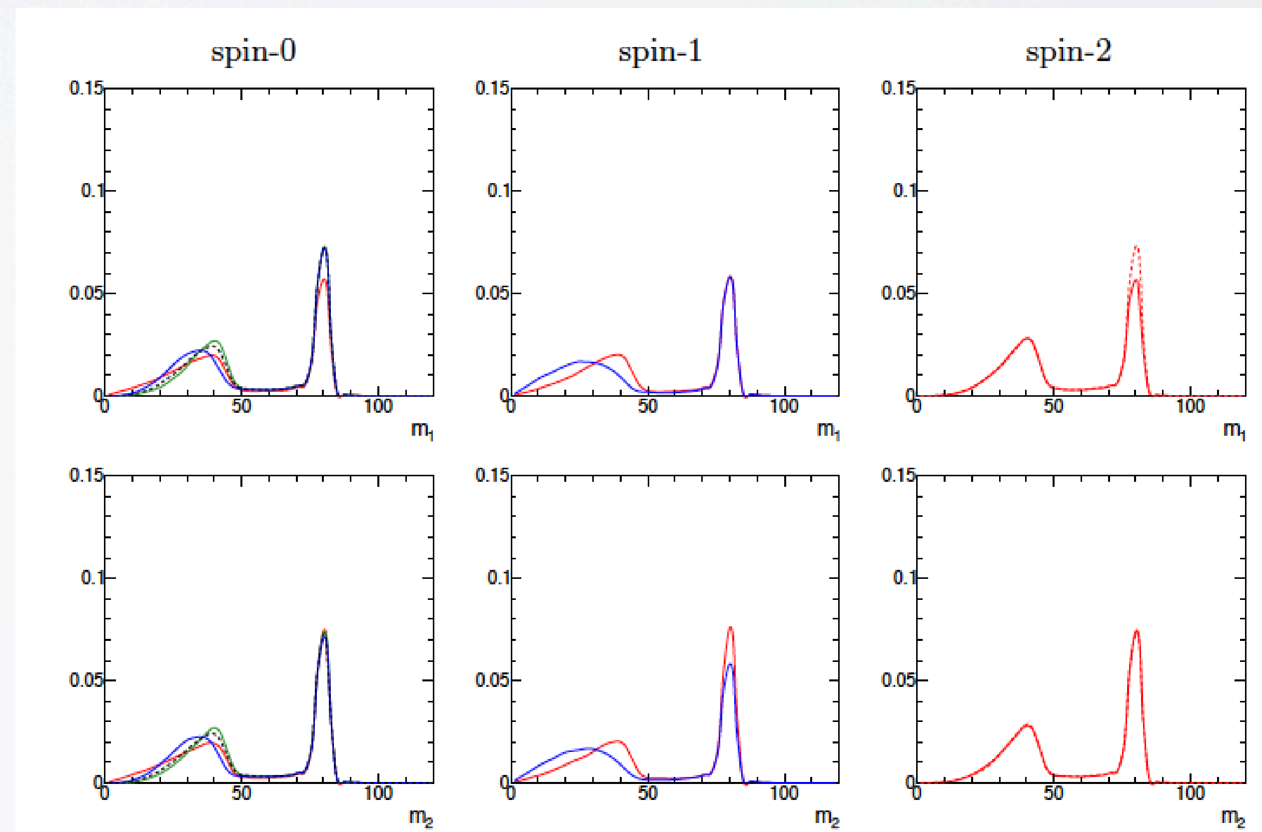
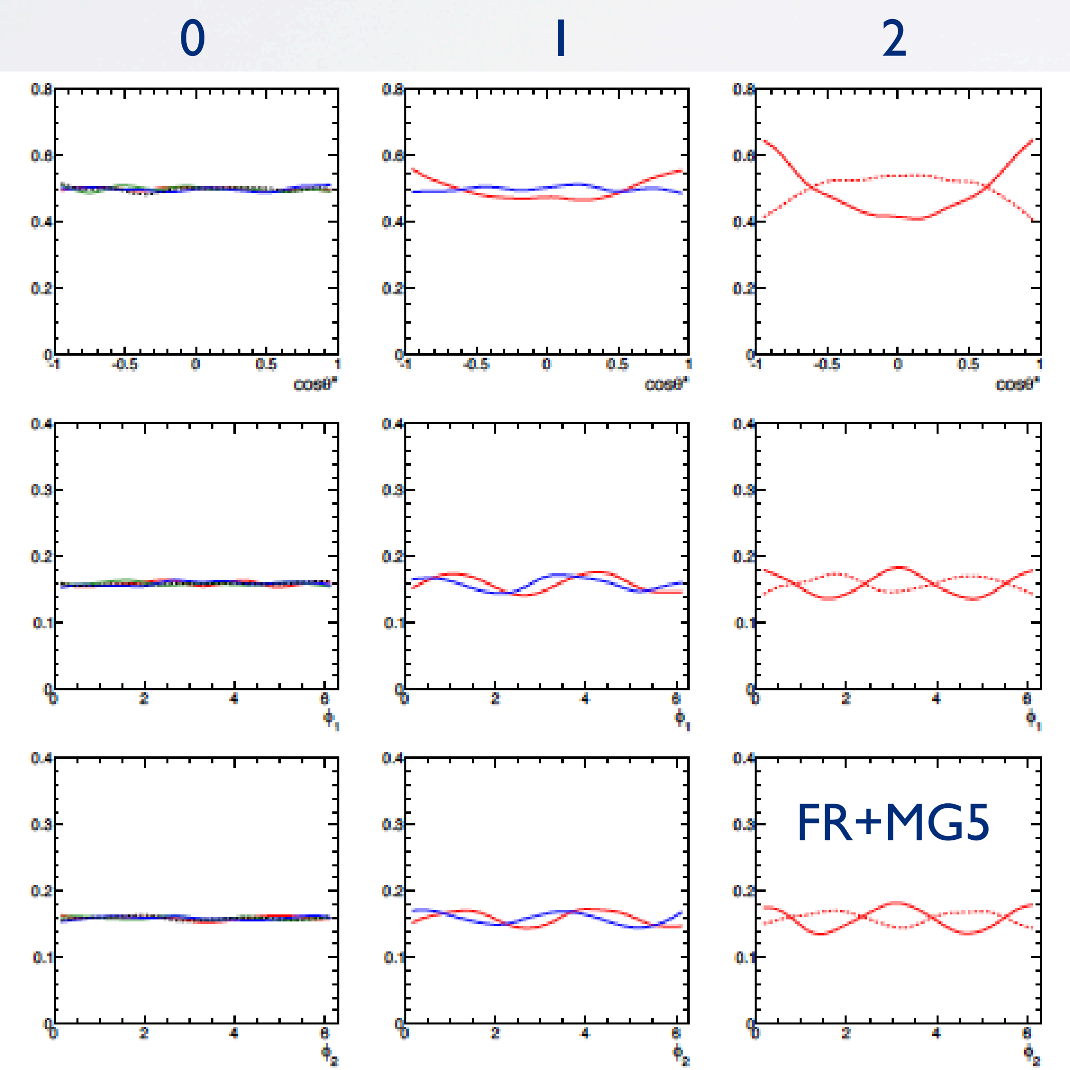


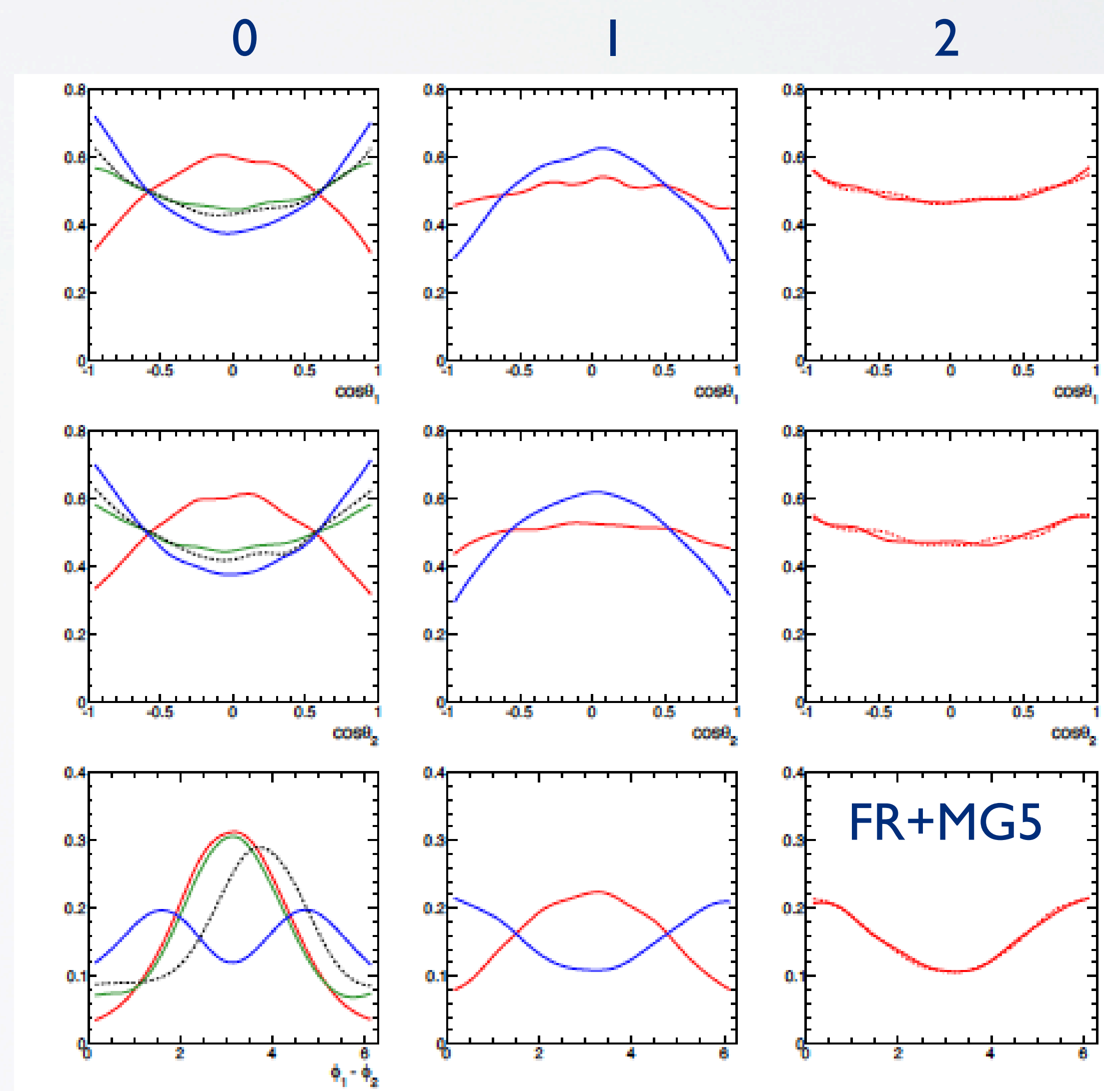
$m_1 > m_2$

m_{muvm} , m_{eve}

Validation of the FR model in MG5

p p→X→ W W* →mu+ vm e− ve

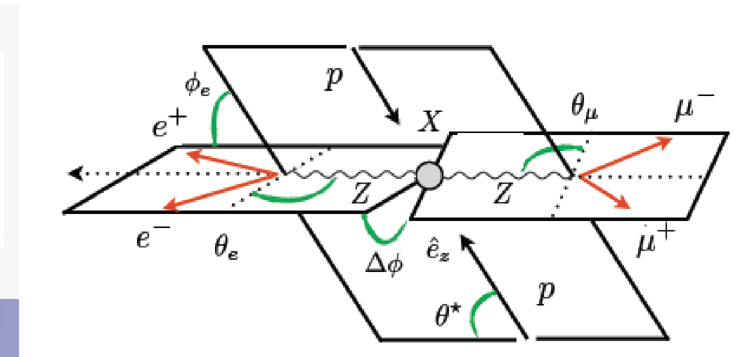




The translation of the notation to the JHU paper:

$$\phi_1 \to \Phi_1, \quad \phi_1 - \phi_2 \to \Phi, \quad \phi_1 + \phi_2 \to 2\Psi = 2(\Phi_1 + \Phi/2), \quad \theta_2 \to \pi - \theta_2.$$

Note also that the azimuthal angles are defined from 0 to 2π here, while $-\pi$ to π in the JHU paper.



Strategy v2 : model-by-model

- Several angles (observables), some of which are in fact accessible only in ZZ $\rightarrow$ 4l, could bring information on the spin/parity/gg-qq initial state composition.

- From there the idea to use MEM technics to maximally extract information.

- This strategy is also maximally dependent on the model itself and aims at excluding all specific models one by one (JHU/MELA strategy).

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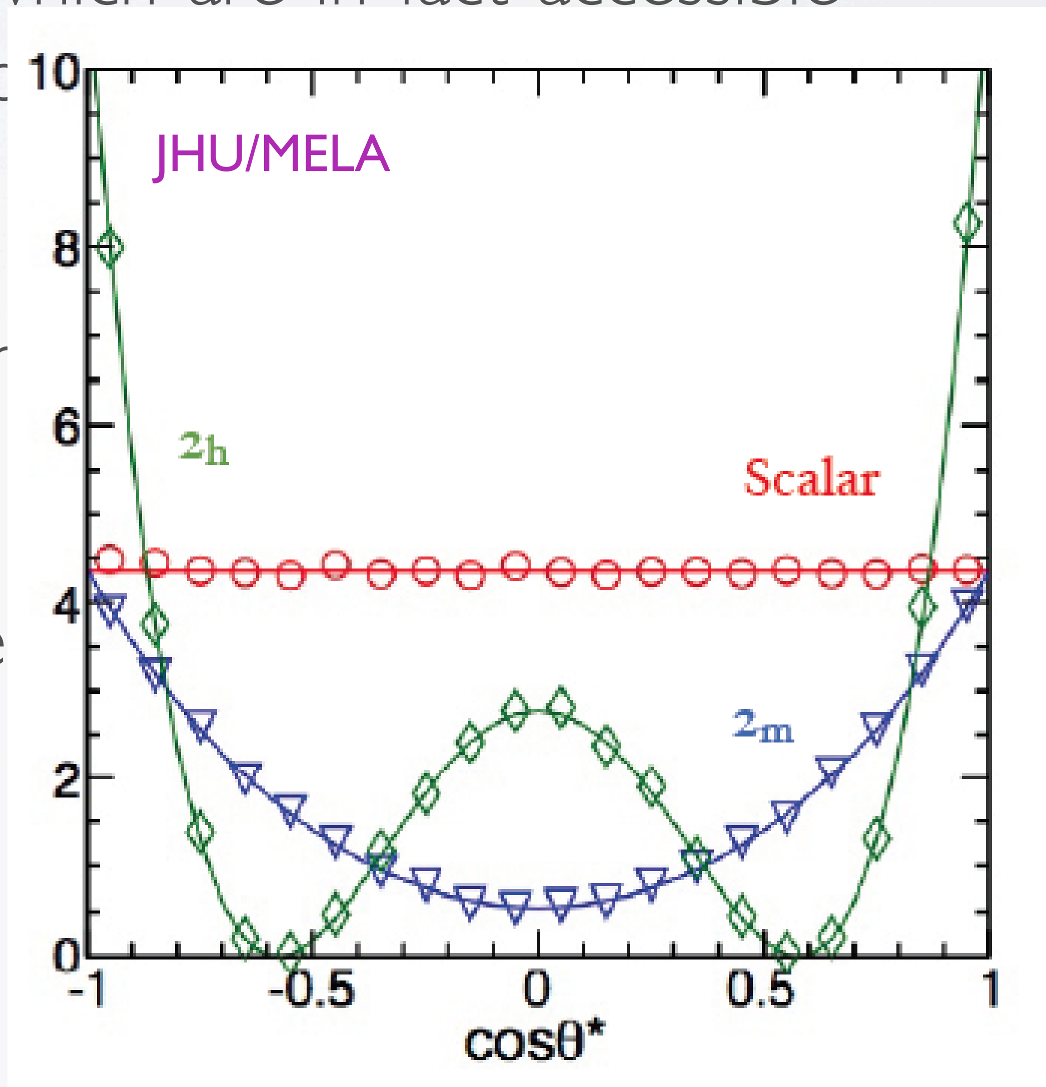

Strategy v2 : model-by-model

- Several angles (observables), some of which are in fact accessible only in ZZ → 4l, could bring information on the spin/parity/gg-qq initial state composition.
- From there the idea to use MEM technics to maximally extract information.
- This strategy is also maximally dependent on the model itself and aims at excluding all specific models one by one (JHU/MELA strategy).

MODEL SELECTION VIA MEM

The matrix element method builds upon the information that can be gathered from the amplitude squared to define a likelihood.

$$P(\boldsymbol{x}_i,\alpha) = \frac{1}{\sigma^{obs}}\frac{1}{N}\sum_{\text{jet perm.}}\int d\phi_{\boldsymbol{y}}|M|^2(\boldsymbol{y})W(\boldsymbol{x}_i,\boldsymbol{y})Acc(x)$$

integration on the parton-level phase-space (non trivial!)

tree-level matrix element

transfer function extracted from MC simulation

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transfer function extracted from MC simulation

MELA uses a super-simple case of the formula above (no integration, no TF) for the 4 lepton case [Melnikov et al., 1001.3396 1208.4018]. MEKD is an alternative implementation of the same method [Avery et al. , 1210.0896].

Since a few years, MadGraph has the possibility to test hypotheses using an automatized implementation of the Matrix Element Method using **MadWeight** [Artoisenet, Lemaitre, FM, Mattelaer, 1007.3300].

Note also ecent work that presents a proposal to promote the MEM at NLO [Campbell, Giele, Williams,arXiv:1204.4424]

MODEL SELECTION VIA THE MEM

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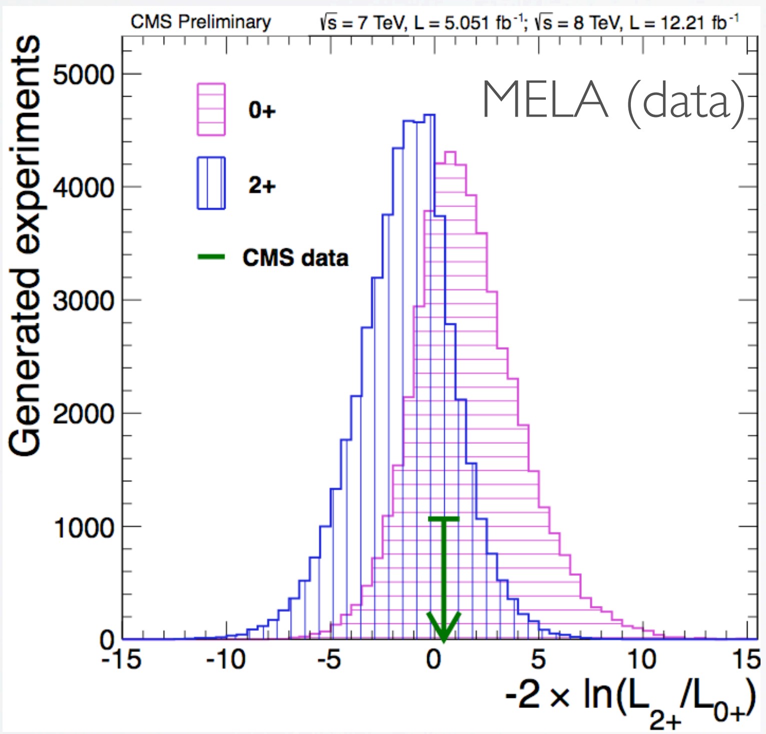
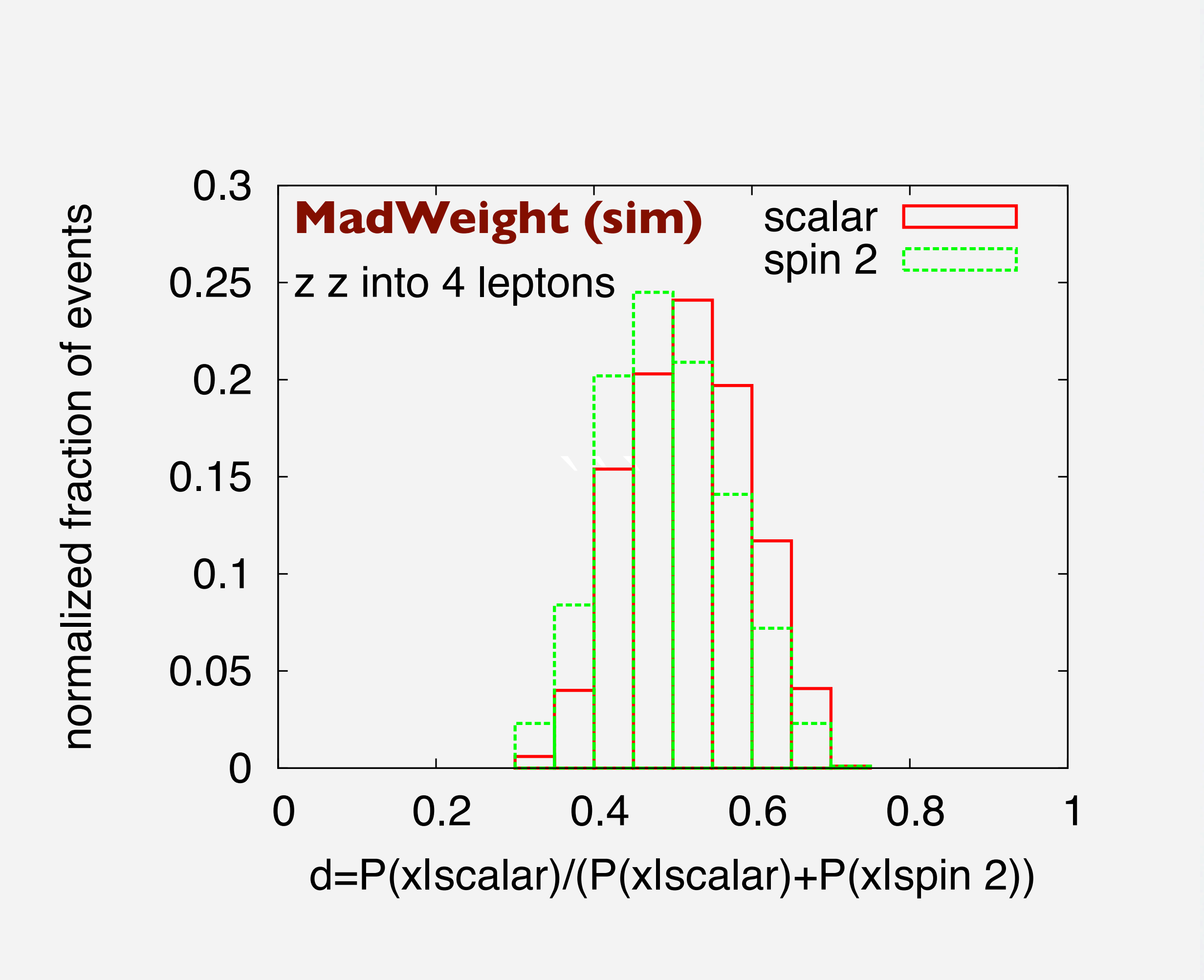
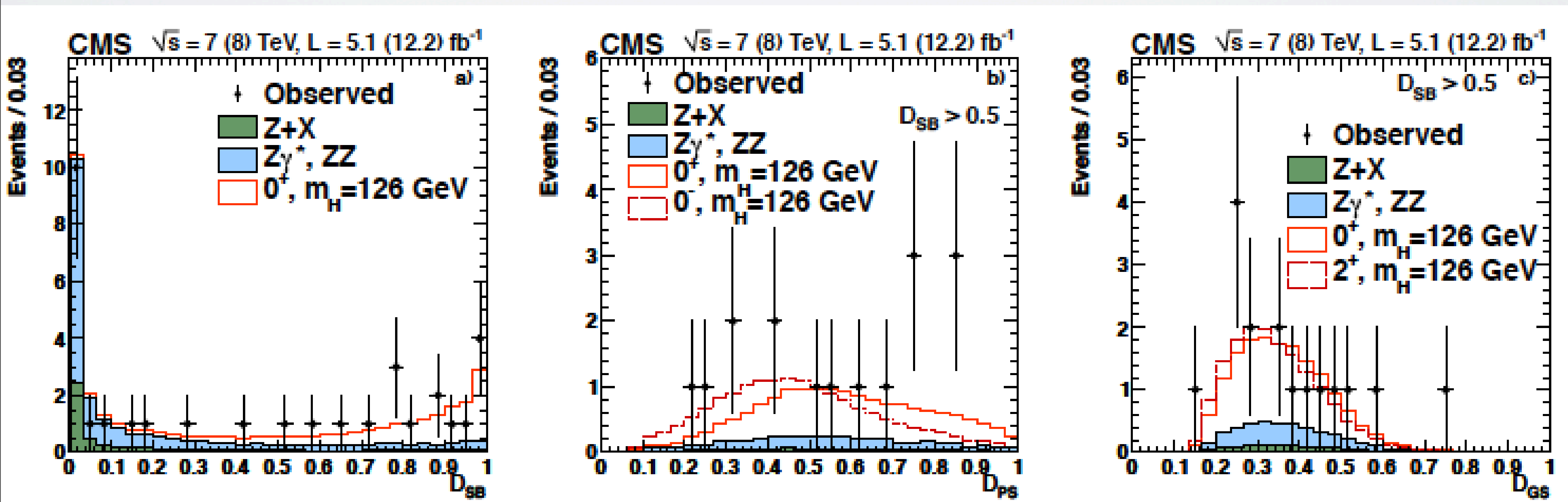




X=J^P determination in CMS via MELA



S vs B | 0+ vs 0- | 0+ vs 2+

- The 0- is disfavored.
- The 2+ is the graviton hypothesis. It cannot be excluded yet.

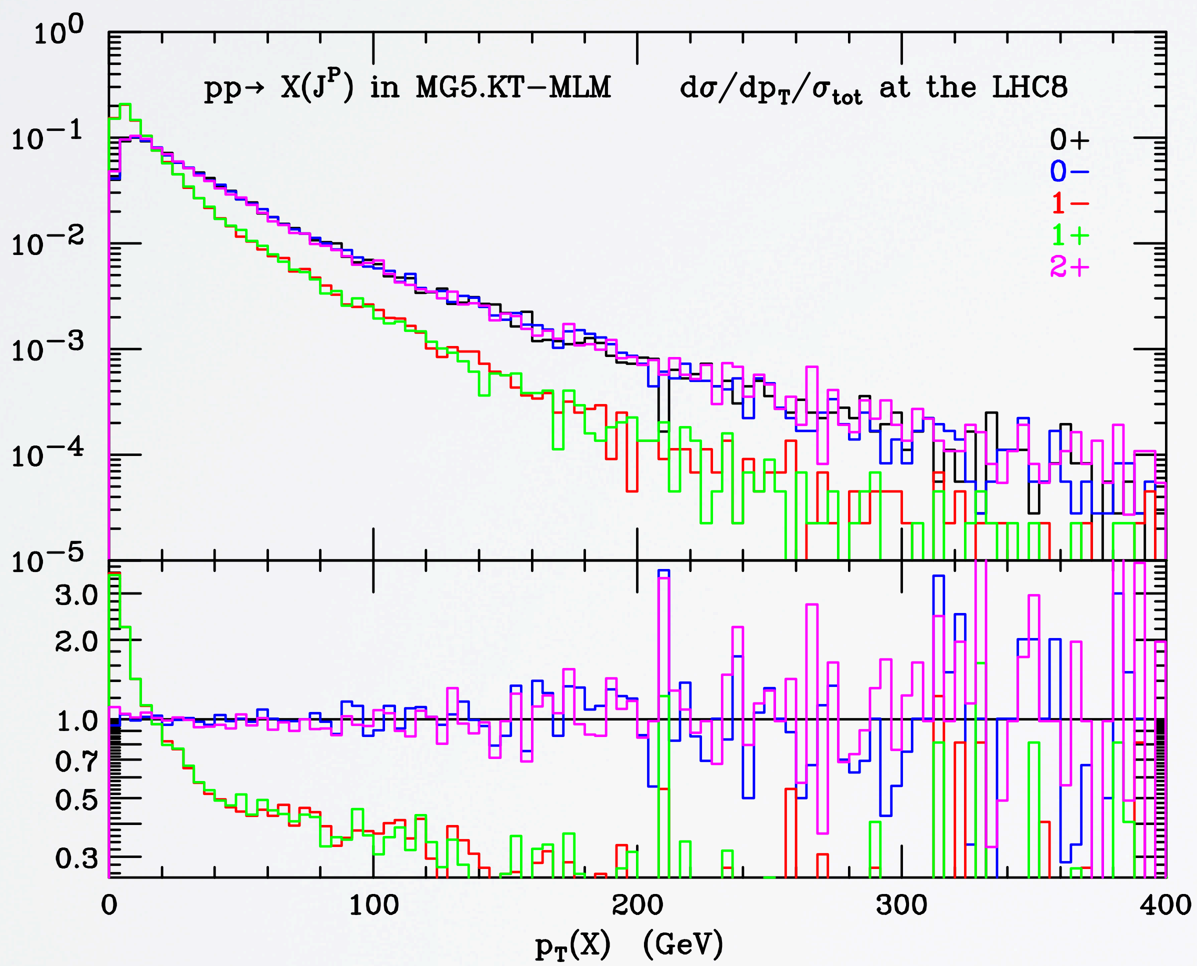
MELA results have been checked also via MEKD.

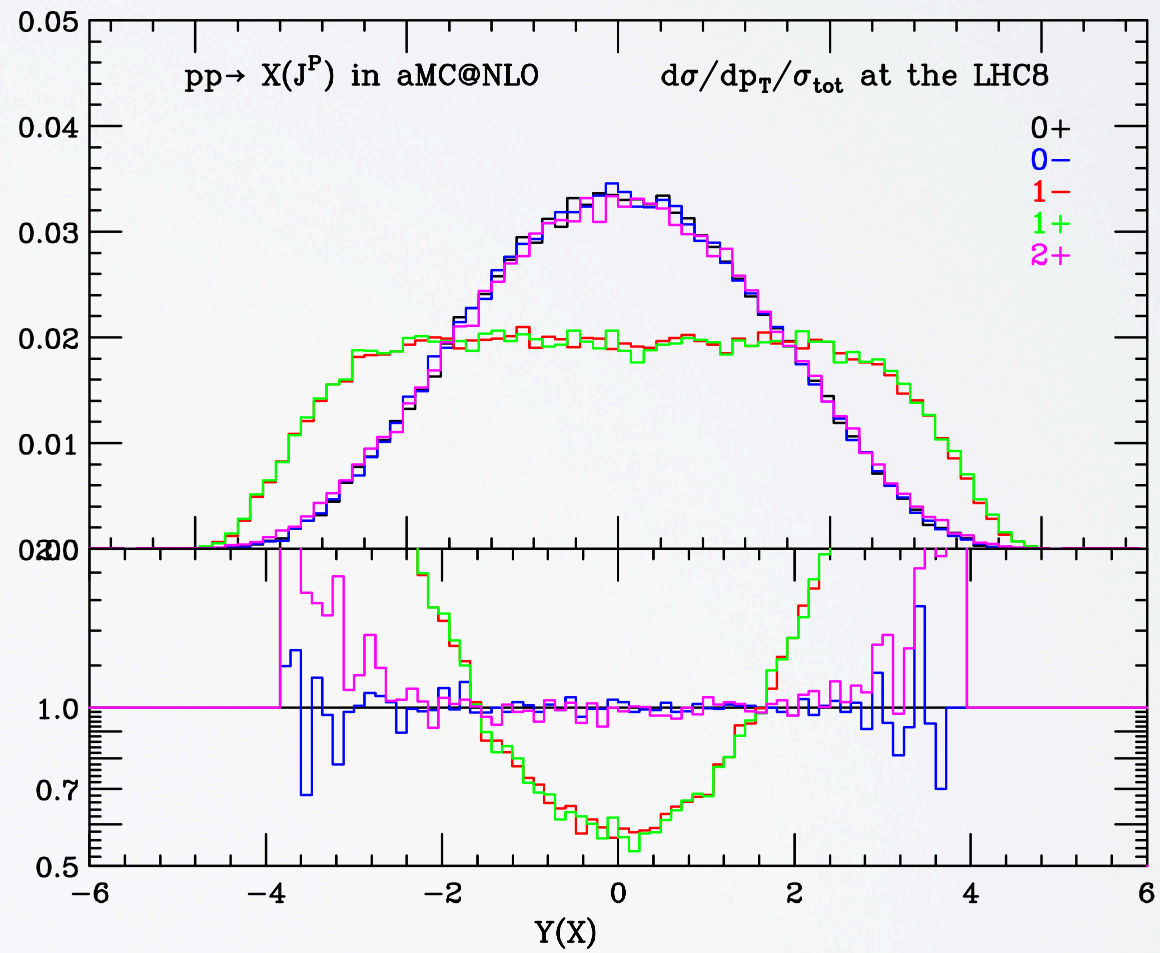
Strategy v2 : further comments

- The v2 strategy is maximally model dependent and therefore not suitable to exclude generic hypothesis (like the "spin 2" hypothesis) in one go.
- The only way to employ it is to compare all the possible models (couplings) with data.
- On top of being difficult to be exhaustive, it also poses the question that specific models can be excluded much faster from other available data.
- Alternative "one-observable based" strategies (v1) might be more convenient to exclude the generic spin/parity hypothesis.

Samples with kt-MLM merging in MG5

Production observables:

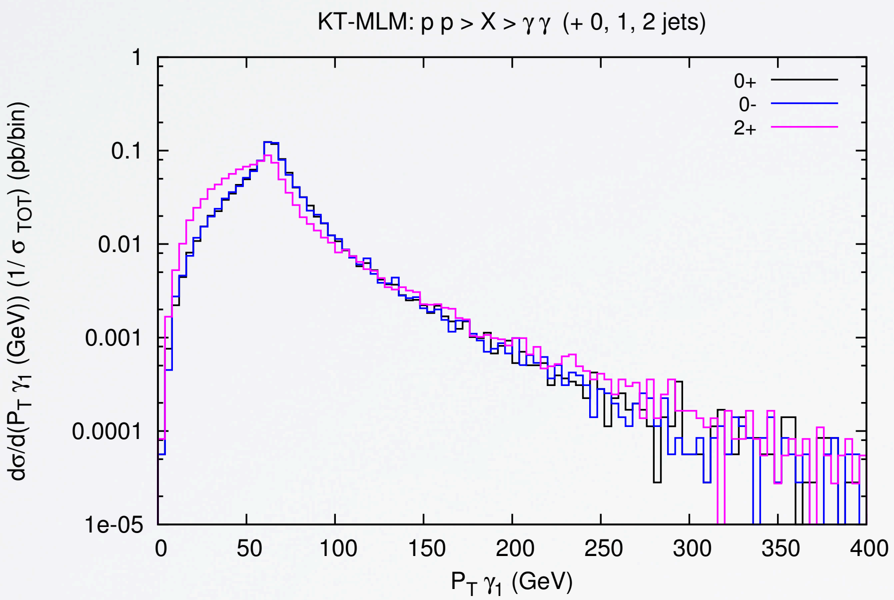


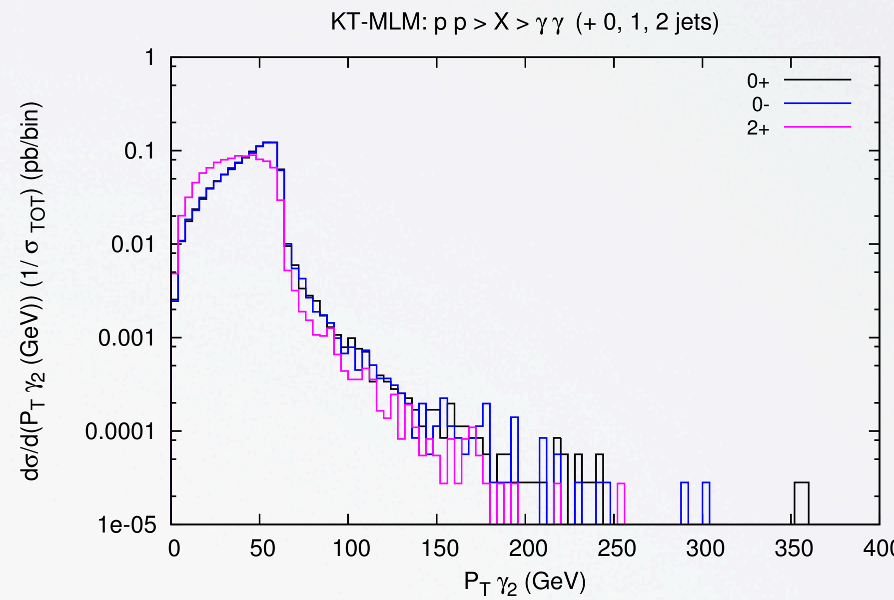


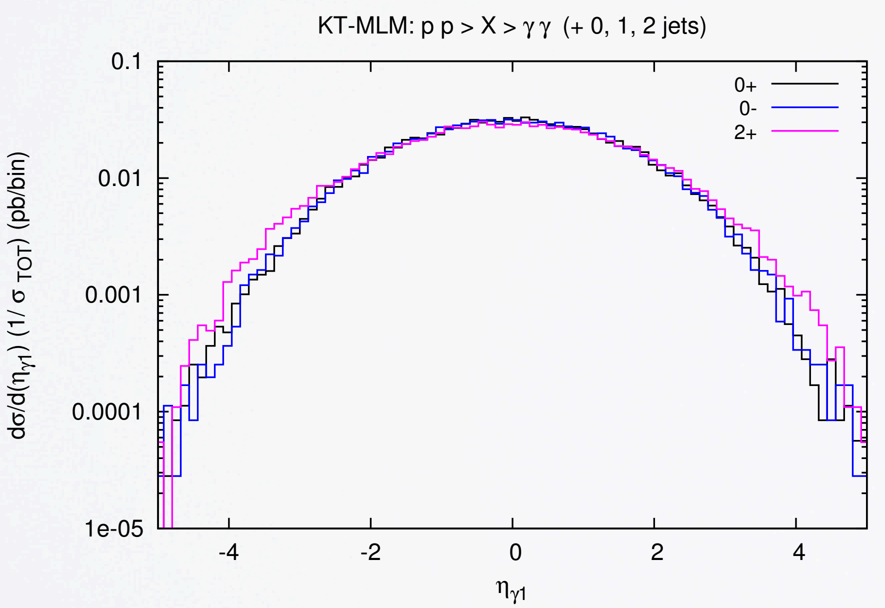
gg or qqbar initial state is of great importance.

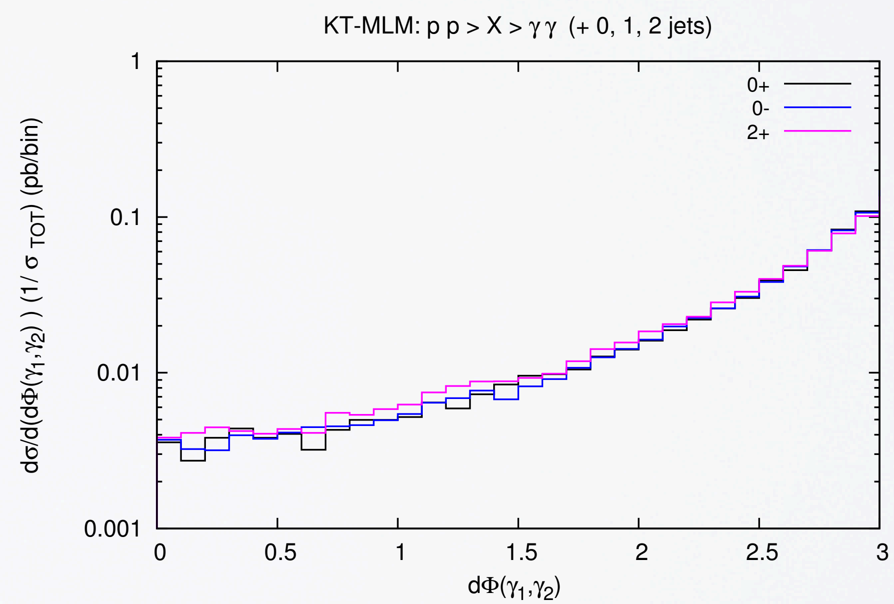
Samples with KT-MLM merging in MG5

p p → X → γ γ (+ 0, 1, 2 partons)



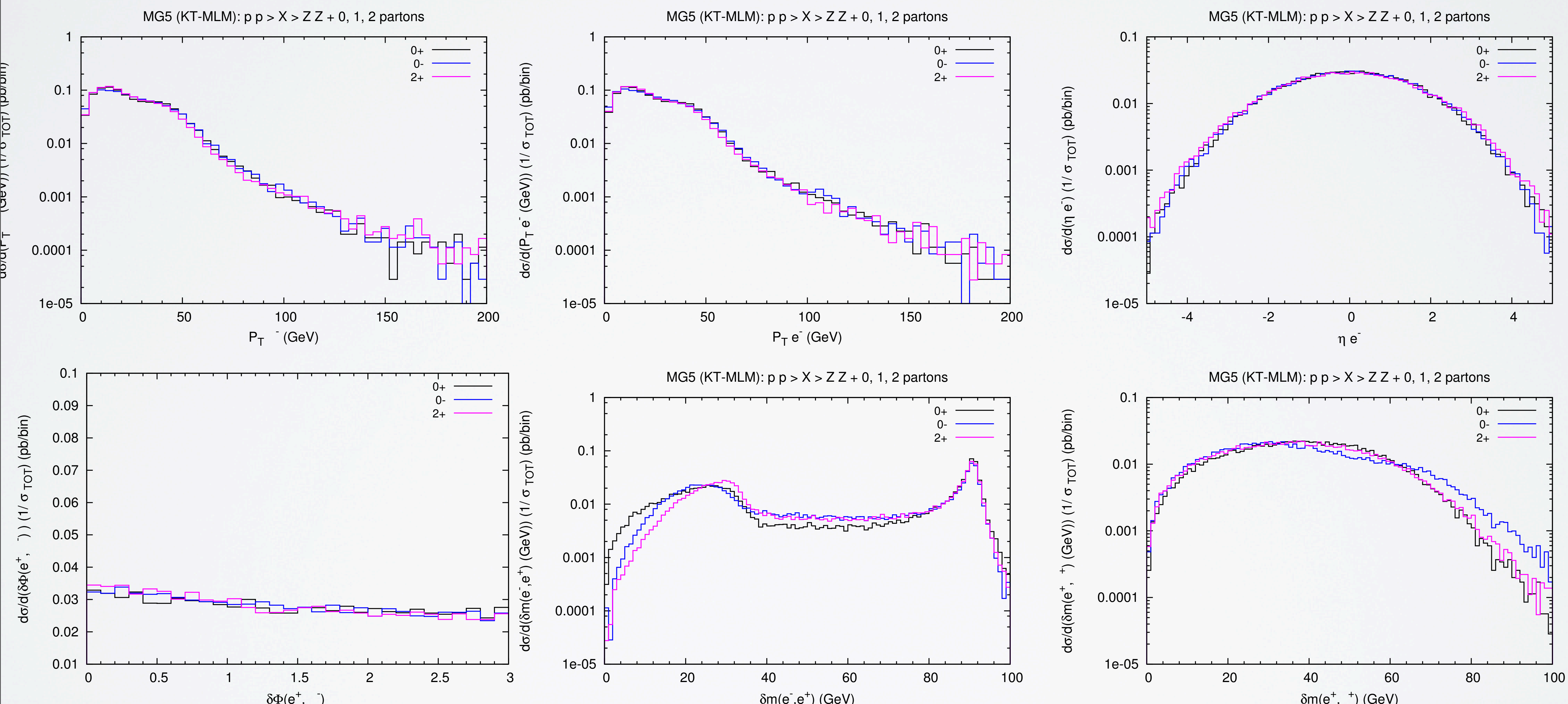






Samples with KT-MLM merging in MG5

p p →X→ Z Z* →4 lep (+ 0, 1, 2 partons)



All spin correlations are kept. Even interference effects with SM contributions can be included.

WHAT ABOUT THE OTHER CHANNELS?

- VBF
  [K. Hagiwara, Q. Li and K. Mawatari, JHEP 0907, 101(2009)] : spin 2
  [J. Frank, M. Rauch, D. Zeppenfeld 1211.3658] : VBFNLO : spin 0, 2
  [C. Englert, D. Gocalves-Netto, K. Mawatari, T. Plehn, 1212.0843] : spin 0,1,2
- VH
  [J.Ellis, D. S. Hwang, V. Sanz, and T. You, 1208.6002] : spin 0, 2
  [C. Englert, D. Gocalves-Netto, K. Mawatari, T. Plehn, 1212.0843] : spin 0, 1, 2
- ttH
  No dedicated study. Some information available for 0- vs 0+ in [Frederix et al. 1104.5613, Artoisenet et al. 1212.3460]

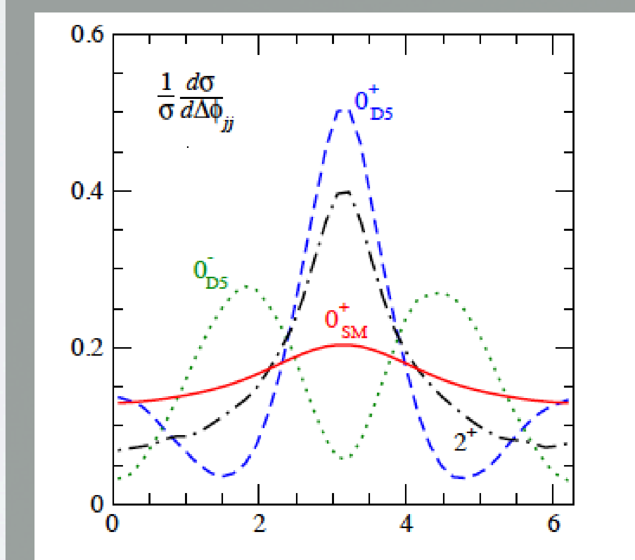
The main point here to keep in mind is a trivial one: the very same organization of Higgs production into channels is unique to the Higgs! VBF or Hjj can become indistinguishable or interfere. Another simple example is the gg vs qqbar dominance...

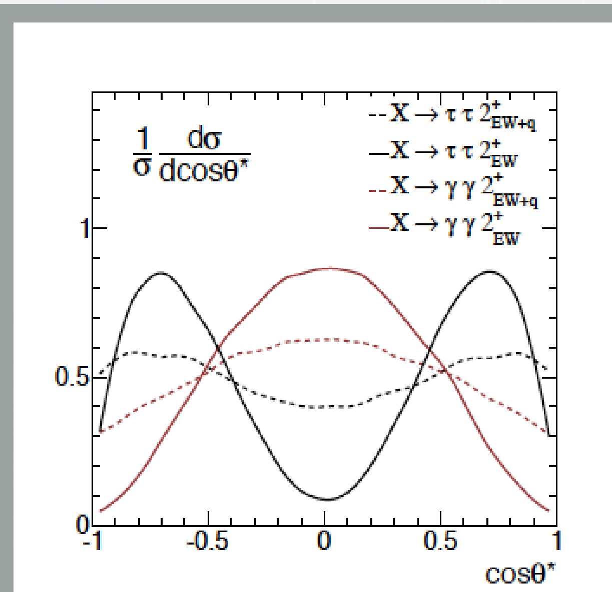
Disclaimer: here citing some recent studies only

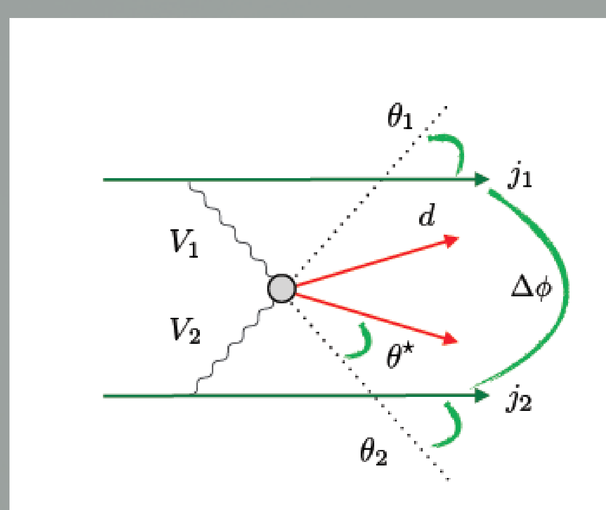
OTHER PROCESSES : VBF AND VH

[C. Englert, D. Gocalves-Netto, K. Mawatari, T. Plehn, 1212.0843]

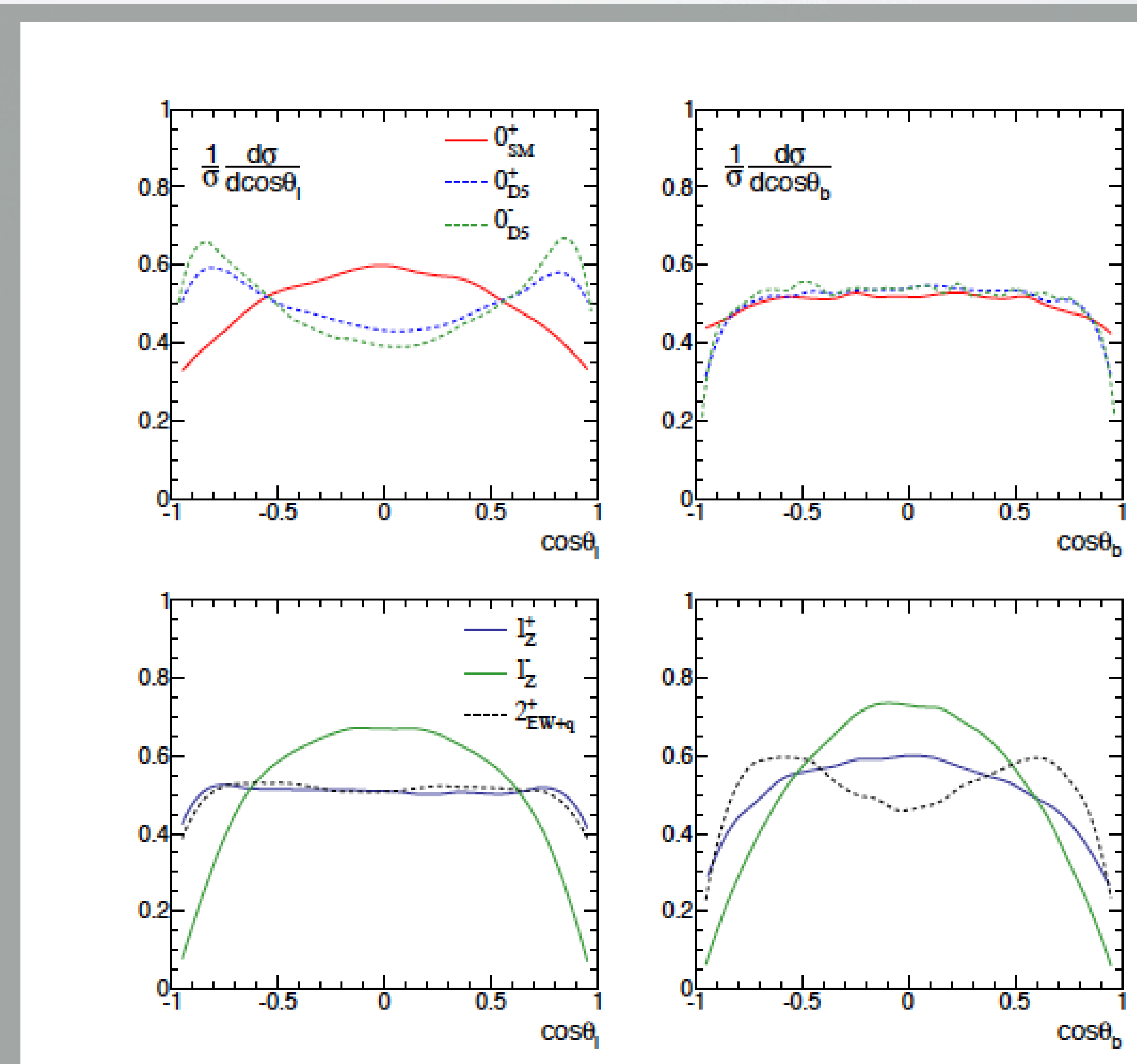
Most complete study in FR+MG5 available for VBF and VH.







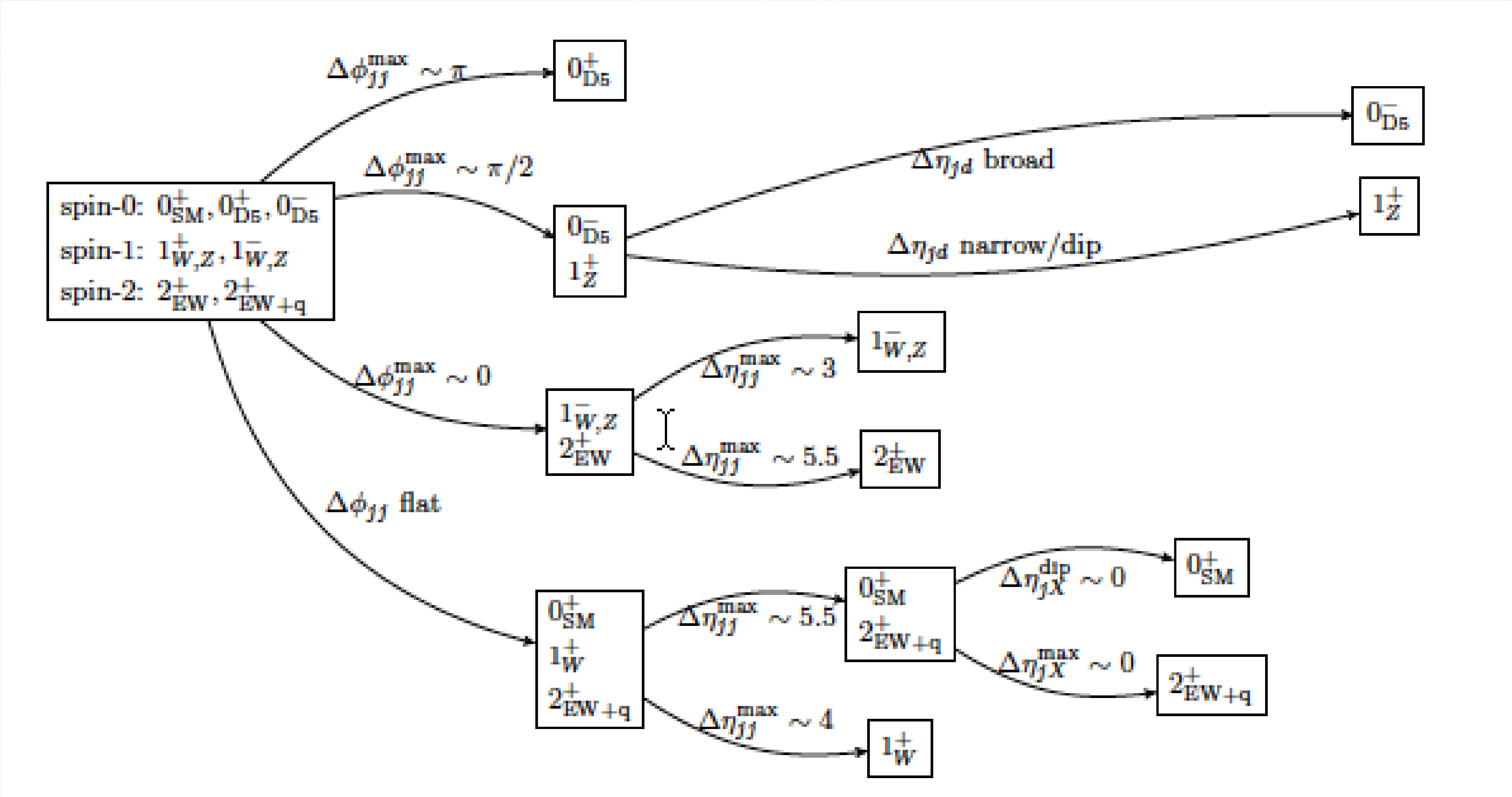
VBF



VH

OBS-BY-OBS BASED STRATEGY IN VBF

[C. Englert, D. Gocalves-Netto, K. Mawatari, T. Plehn, 1212.0843]



Obs-by-Obs but "equivalent" to the model-by-model strategy.
(=one can use a MEM)

FR+MG5 SUMMARY

- An effective Lagrangian has been built by including all minimal dimension operators for a given state $X(J^P)$. Its implementation is publicly available in FeynRules and can be used in MG5.
- It allows to generate any tree-level process of interest, including all spin correlations, possible interference with backgrounds and to build inclusive samples via KT-MLM merging.
- Finally, with MadWeight, one can automatically build likelihoods via the MEM.

Can we test/validate/improve simulations at the NLO accuracy?

aMC@NLO

[Alwall, Hirschi, Frederix, Frixione, FM, Mattelaer, Pittau, Torrielli, Zaro]

aMC@NLO

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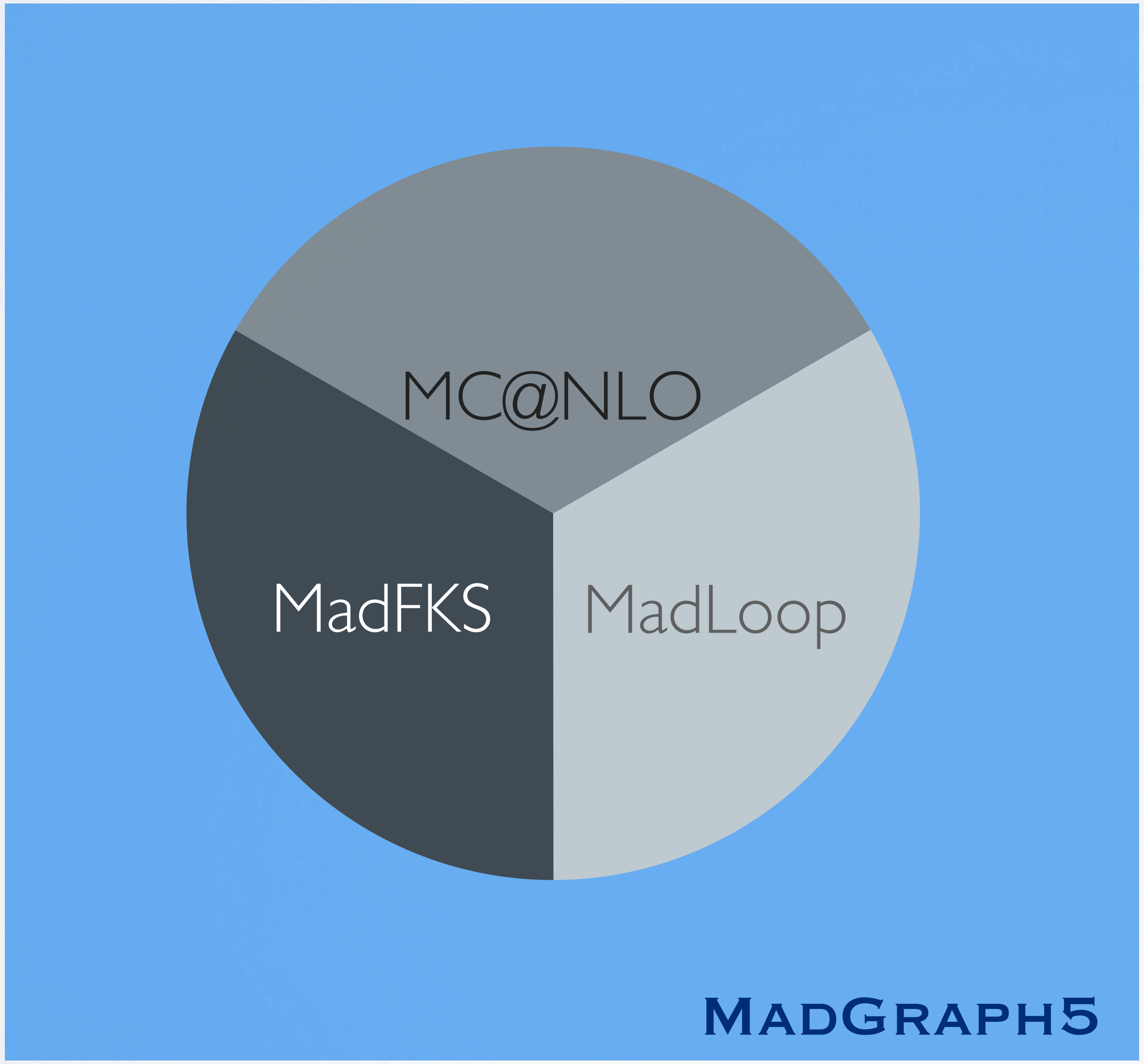
Modular structure in the MadGraph5 framework:

aMC@NLO

[Alwall, Hirschi, Frederix, Frixione, FM, Mattelaer, Pittau, Torrielli, Zaro]



Modular structure in the **MADGRAPH5** framework:

- MadLoop (w/ Cuttools)
- MadFKS for subtractions
- MC@NLO counterterms for Pythia6Q^2, Herwig, HW++. (Pythia8 validation on-going).

aMC@NLO

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THE a OF aMC@NLO

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Suppose now you are interested in studying HH production in VBF:

```
./bin/mg5
> generate p p > H H j j [QCD]
> output HHvbf
> launch
```

or in studying spin-2 production in association with a vector boson:

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```
> import model RS_NLO
> generate p p > Gr Z, Gr > b b~ [QCD]
> output vbf_gr
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```

THE a OF aMC@NLO

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```

The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power so it improves with time.

aMC@NLO APPLICATIONS TO X(J^P) PHYSICS

http://amcatnlo.cern.ch

Process	Codes	Plots	Extra info
Higgs characterization. **Comparison plots:** pt of the "Higgs" rapidity of the "Higgs" jet rates			
$pp \to 0^+ + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Scalar resonance. Process generated in the HEFT model
$pp \to 0^- + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Pseudo scalar resonance. Process generated in the HEFT model
$pp \to 1^- + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Fully automatic in aMC@NLO. Vector resonance (Obtained from the Z using only vector coupling to quarks).
$pp \to 1^+ + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Fully automatic in aMC@NLO. Pseudo vector resonance (Obtained from the Z using only axial coupling to quarks).
$pp \to (2^+ \to \gamma\gamma) + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Virtuals Provided by Frederix et al. arXiv:1209.6527 Code generated using the RS model. Spin 2 (graviton like)
More to come soon...			

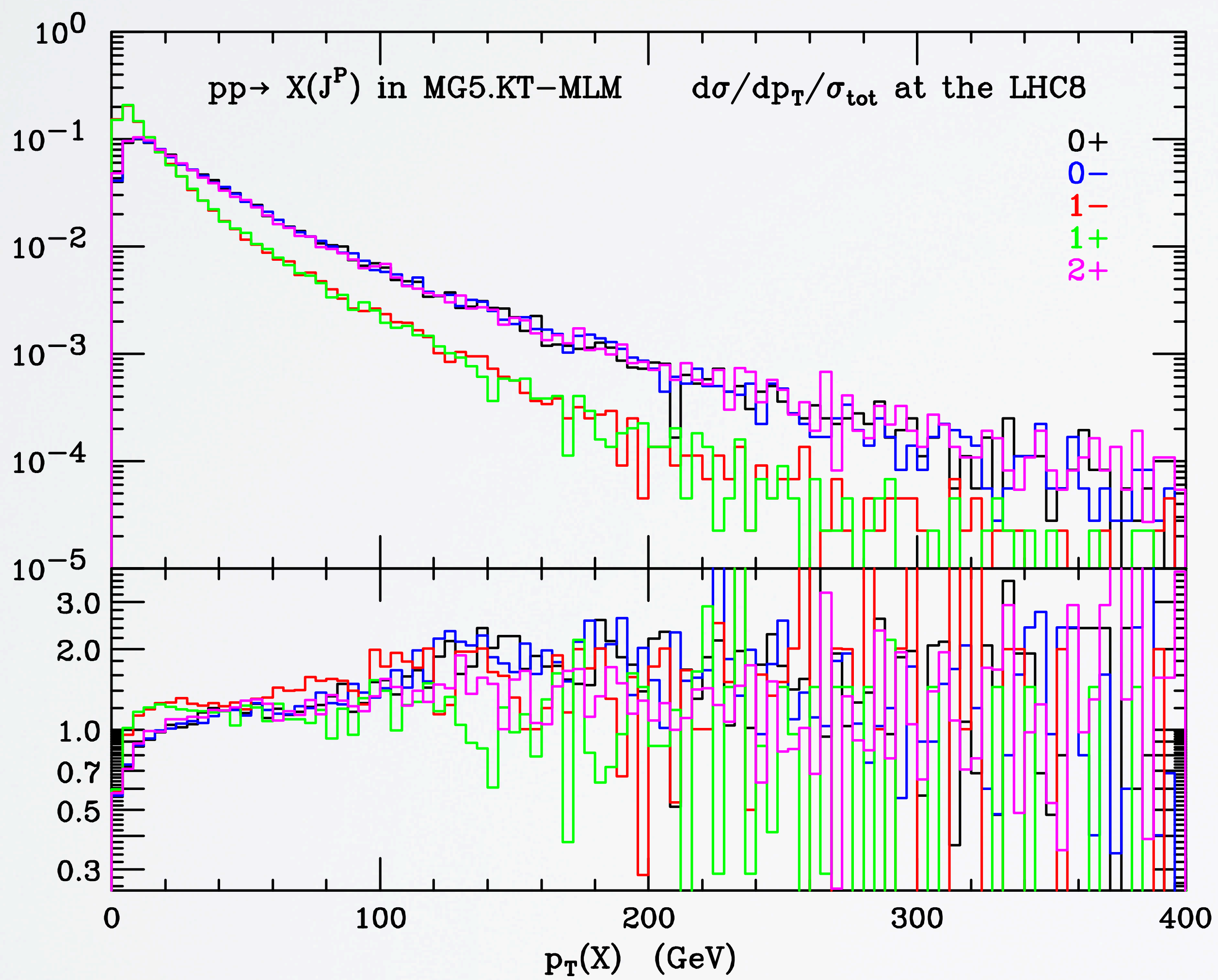
Updates for 2+: a. pp →X→ZZ→4l and pp →X→WW→2l+2ν ready.

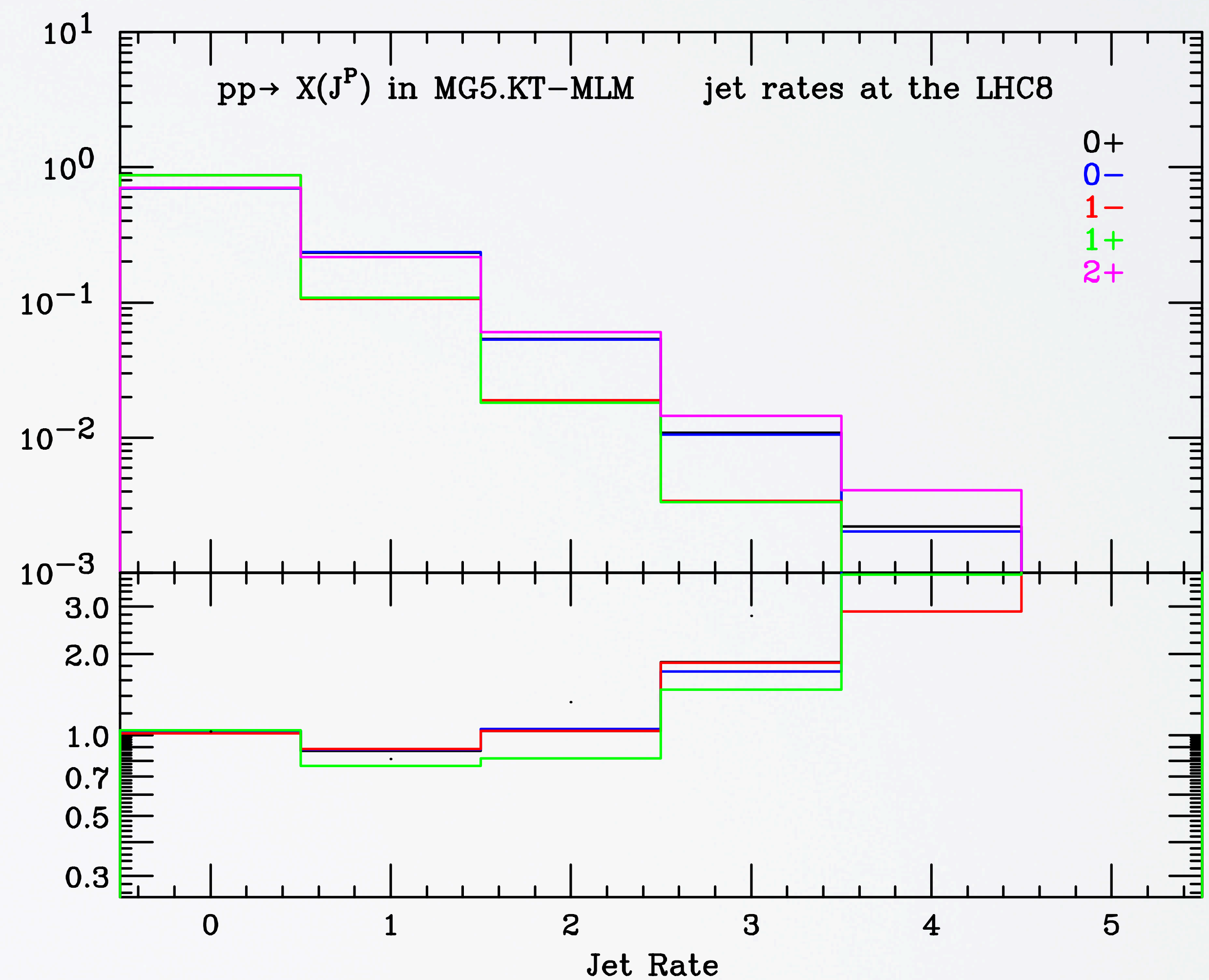
b. General case $k_g \neq k_q$ ready.

Wednesday 9 January 2013

aMC@NLO applications to X(J^P) physics

Comparison between MLM-KT merged and aMC@NLO

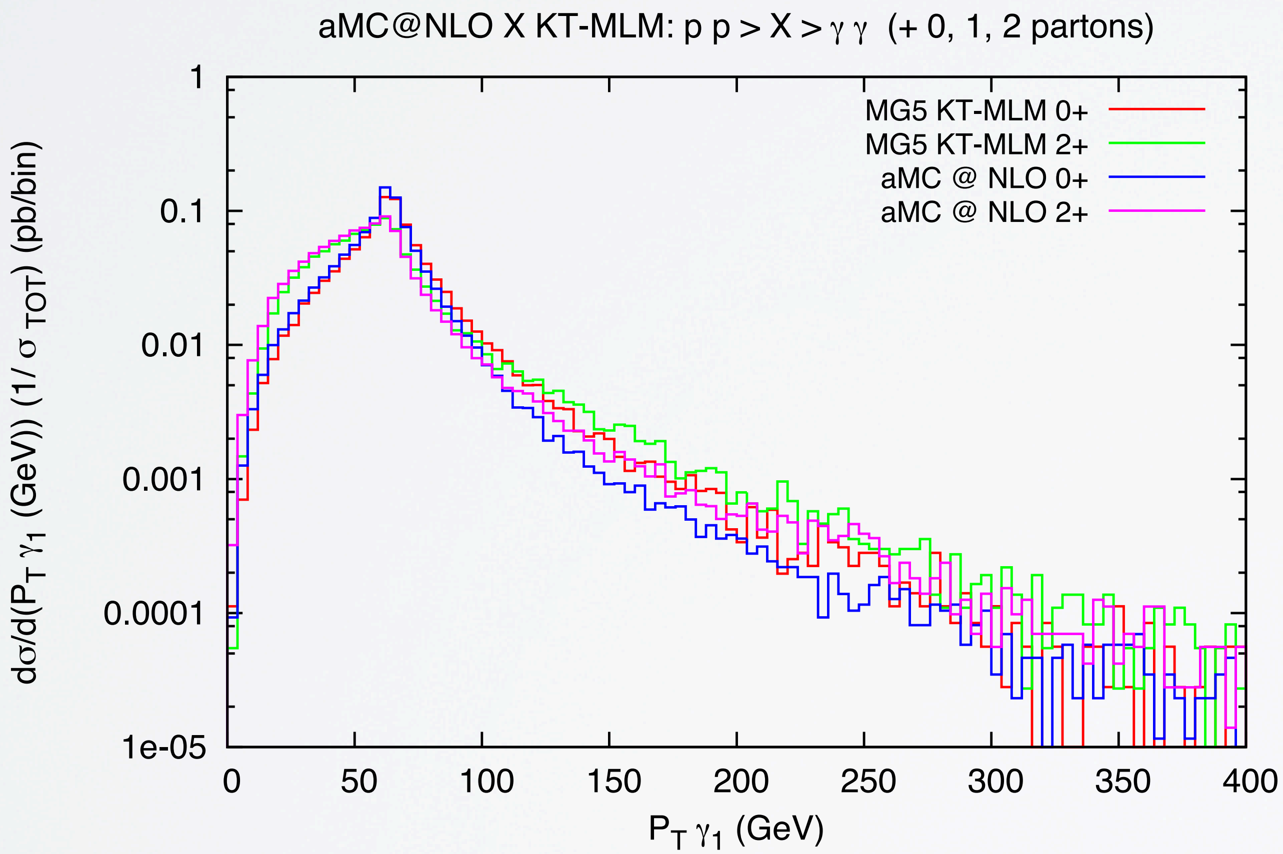


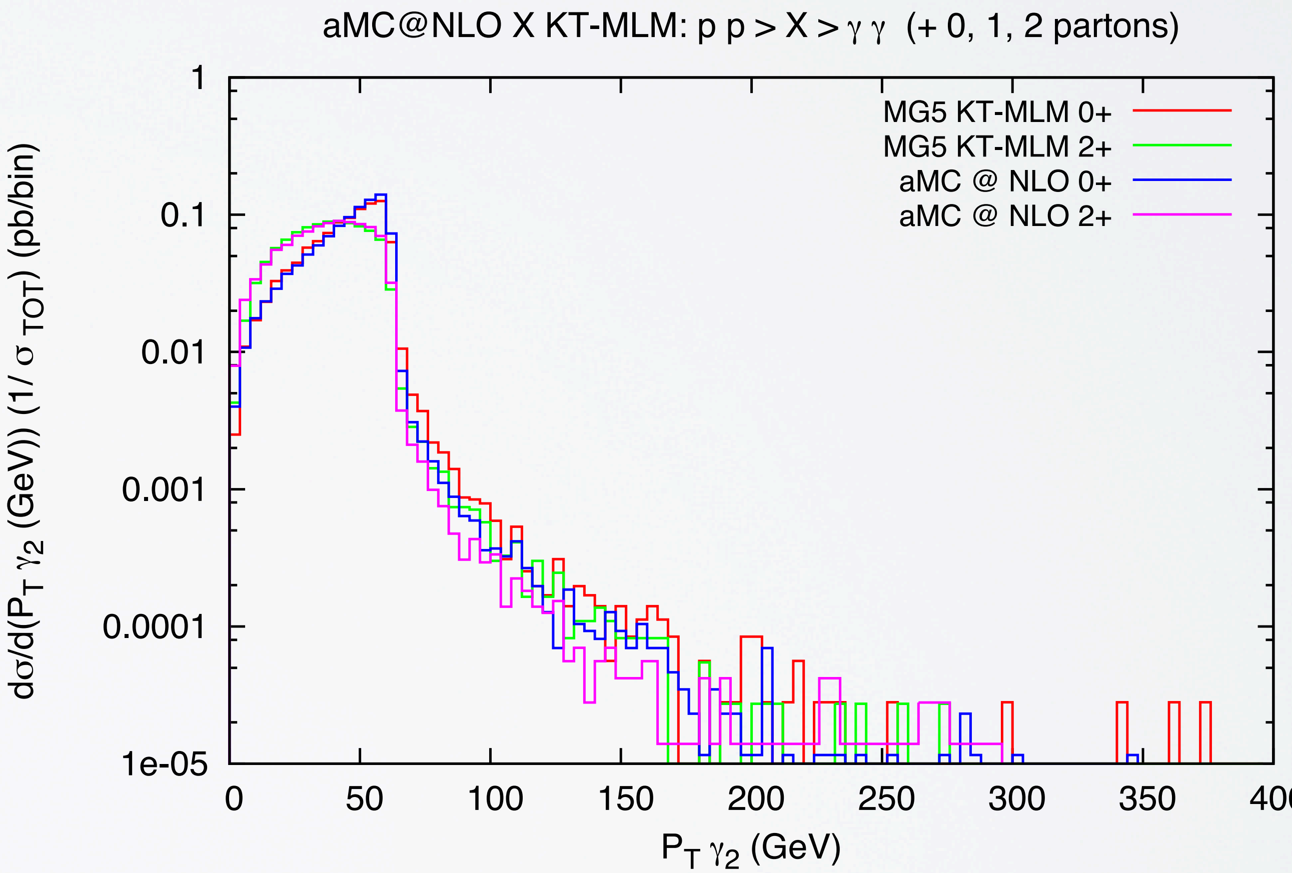


The p_T shapes and jet rates are a bit harder in the merged samples.

aMC@NLO applications to X(J^P) physics

Comparison between MLM-KT merged and **aMC@NLO**





Quite different spectra between spin 0 and spin 2 hypothesis.

Very consistent p_T shapes between k_T-MLM and **aMC@NLO**.

In practice, will be very difficult to measure due to the large non-resonant background.

CONCLUSIONS

- The discovery of the SM Higgs will happen through tests of compatibility with the SM predictions together with the systematic exclusions of other hypothesis.
- Two main framework used for testing alternatives in a "model independent" way, AC and EFT.
- Several implementations at the tree level are now available from 2→1 processes (JHU) to any process with generic EFT (FR+MG5).
- Event generation at NLO is possible for (several) spin 0,1,2 hypothesis and can be used to validate merged samples.
- Model-by-Model exclusion strategy being employed by exps so far with MEM or other MVA. Alternative or more generic strategies would be useful.

CREDITS

- Thanks to all the collaborators in this "choral" project: P. Artoisenet, P. de Aquino, R. Frederix, K. Mawatari, M. K. Mandal, P. Mathews, V. Ravindran, S. Seth, P. Torrielli, M. Zaro.

- Thanks to the HXSWG for the always stimulating discussions and in particular to Massimiliano Grazzini, Christophe Grojean, Giampiero Passarino and Rei Tanaka.

- A big thanks to all contributors to MG5 and aMC@NLO teams for their help and support.

aMC@NLO applications to X(J^P) physics

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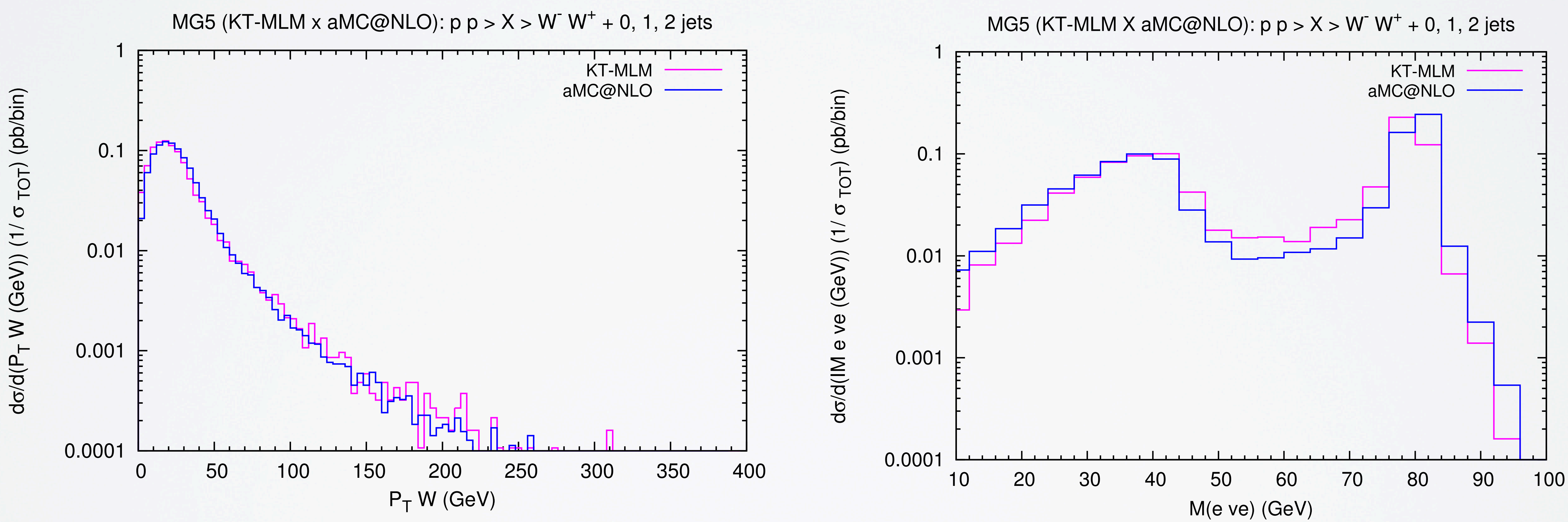

$p\ p \rightarrow X(2^+) \rightarrow W\ W^* \rightarrow l+l-\ \nu\ \nu + \text{jets}$