Efficient, automatic and accurate QCD predictions for Higgs (and alike) particles at the LHC

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In collaboration with
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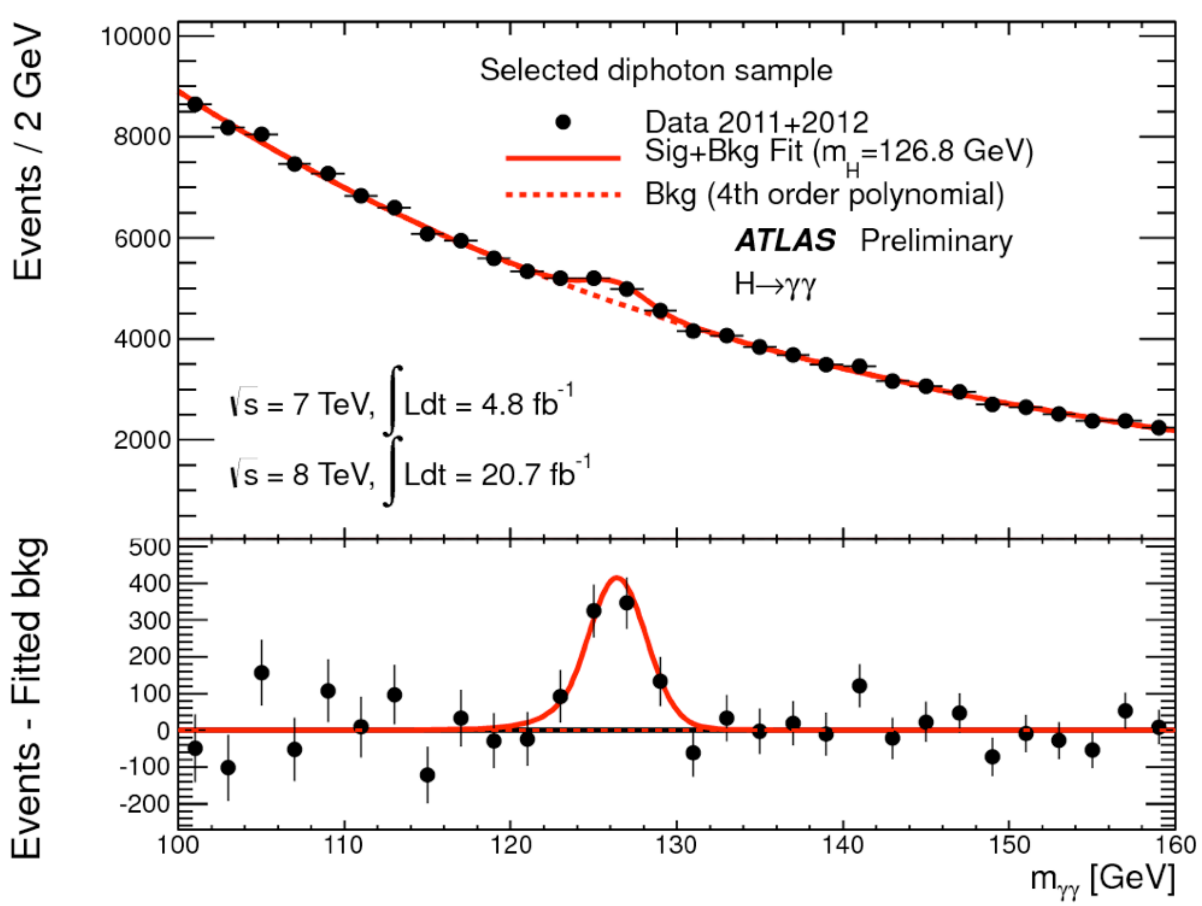
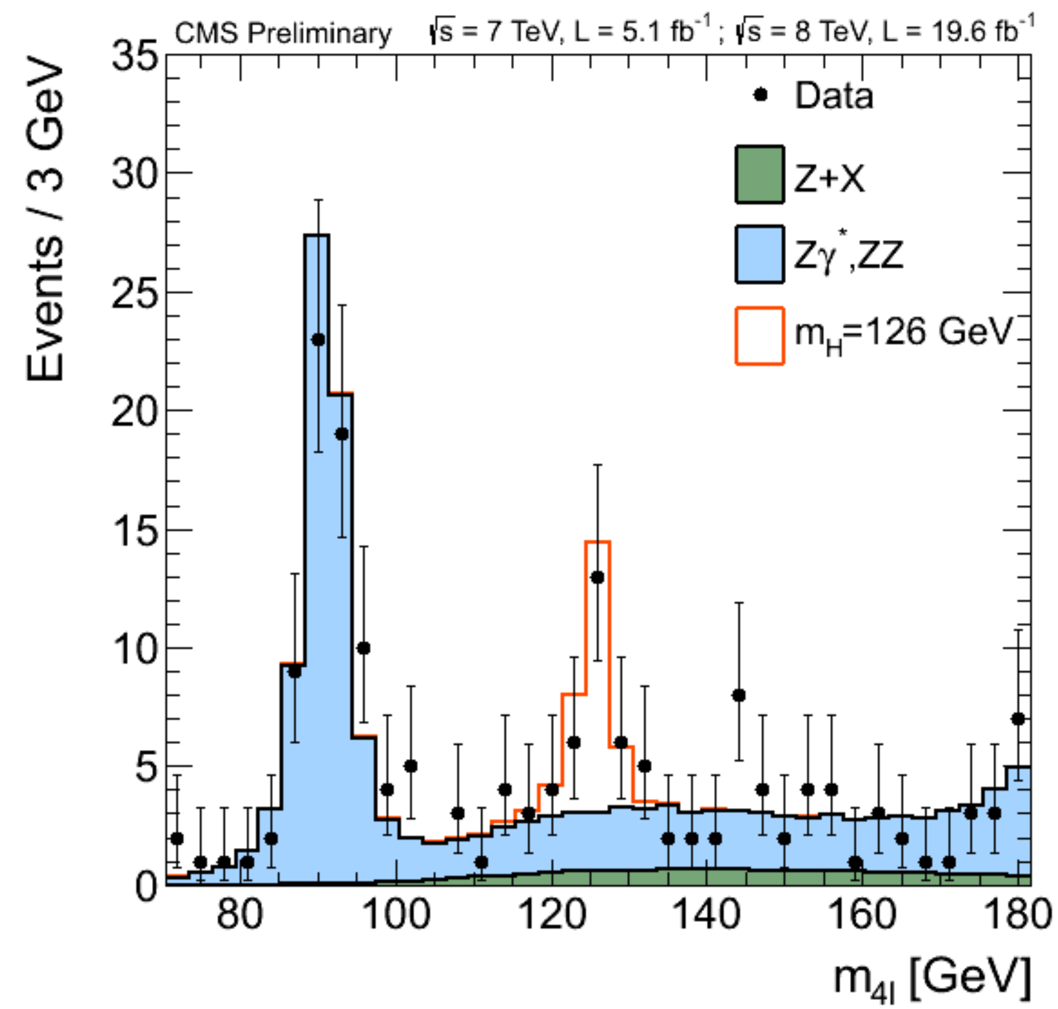
Rencontres de Moriond, La Thuile

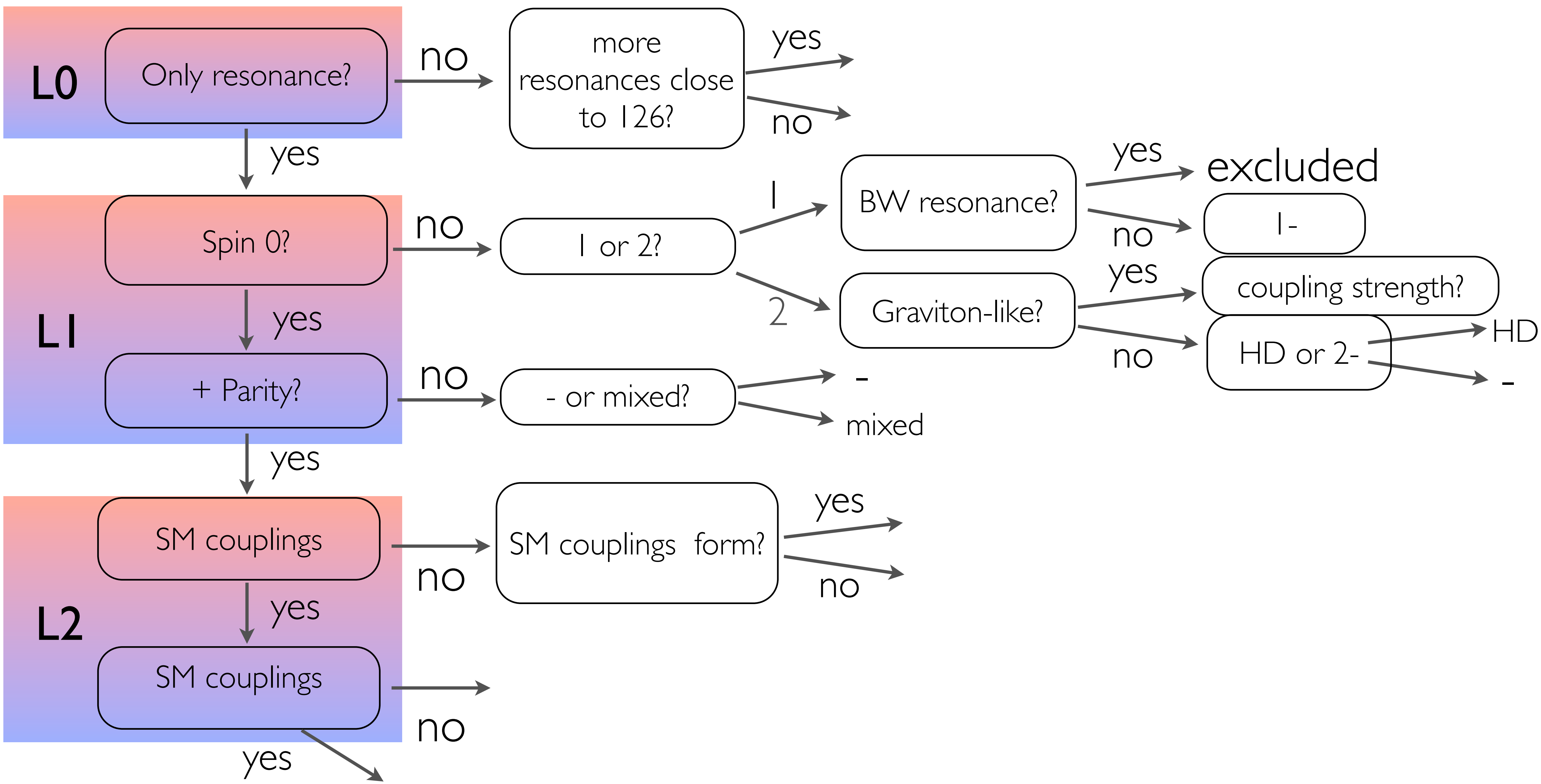
March 14, 2013

The recently discovered particle (from now "the Higgs boson")...





... must answer a lot of questions



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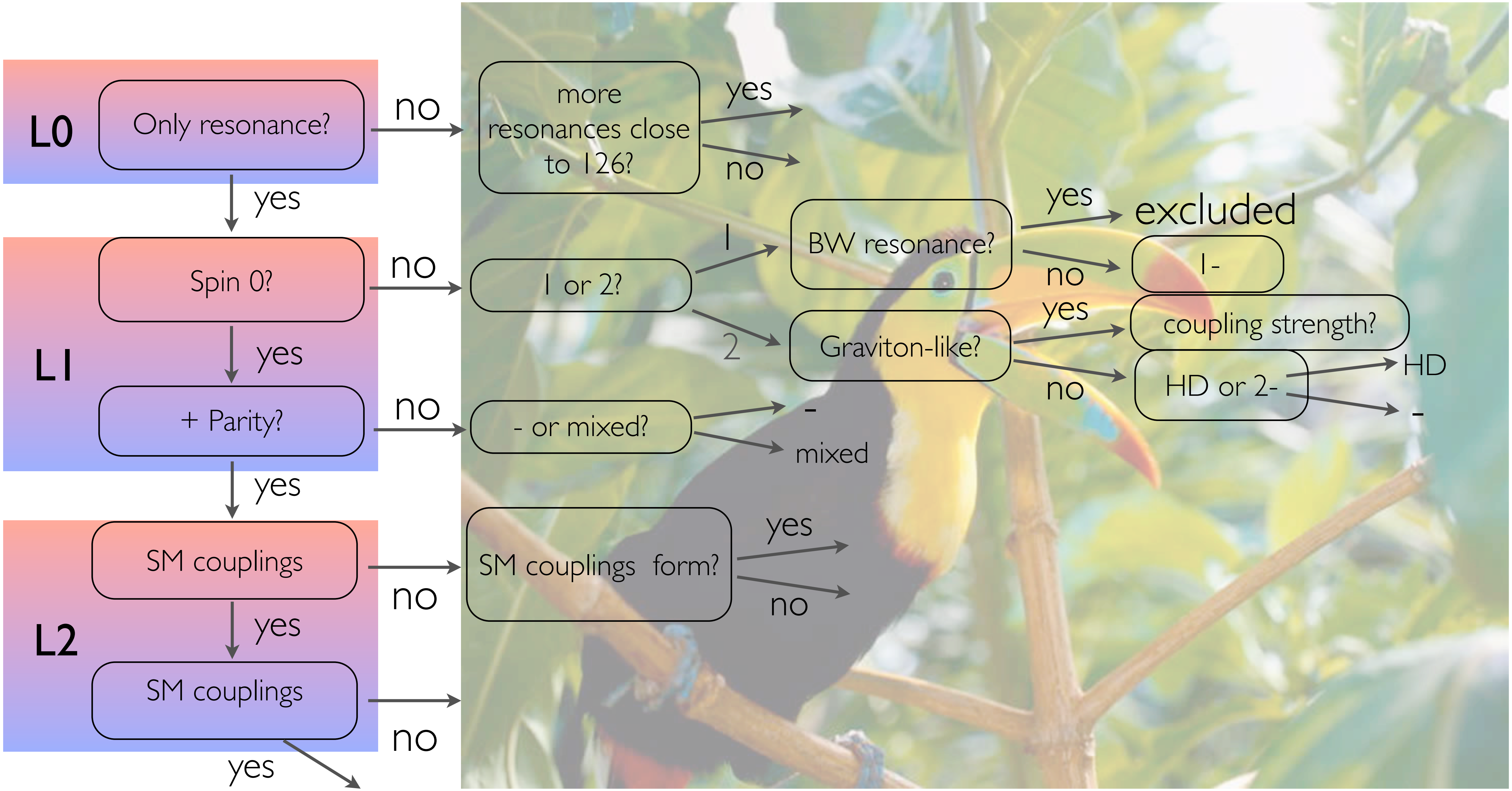

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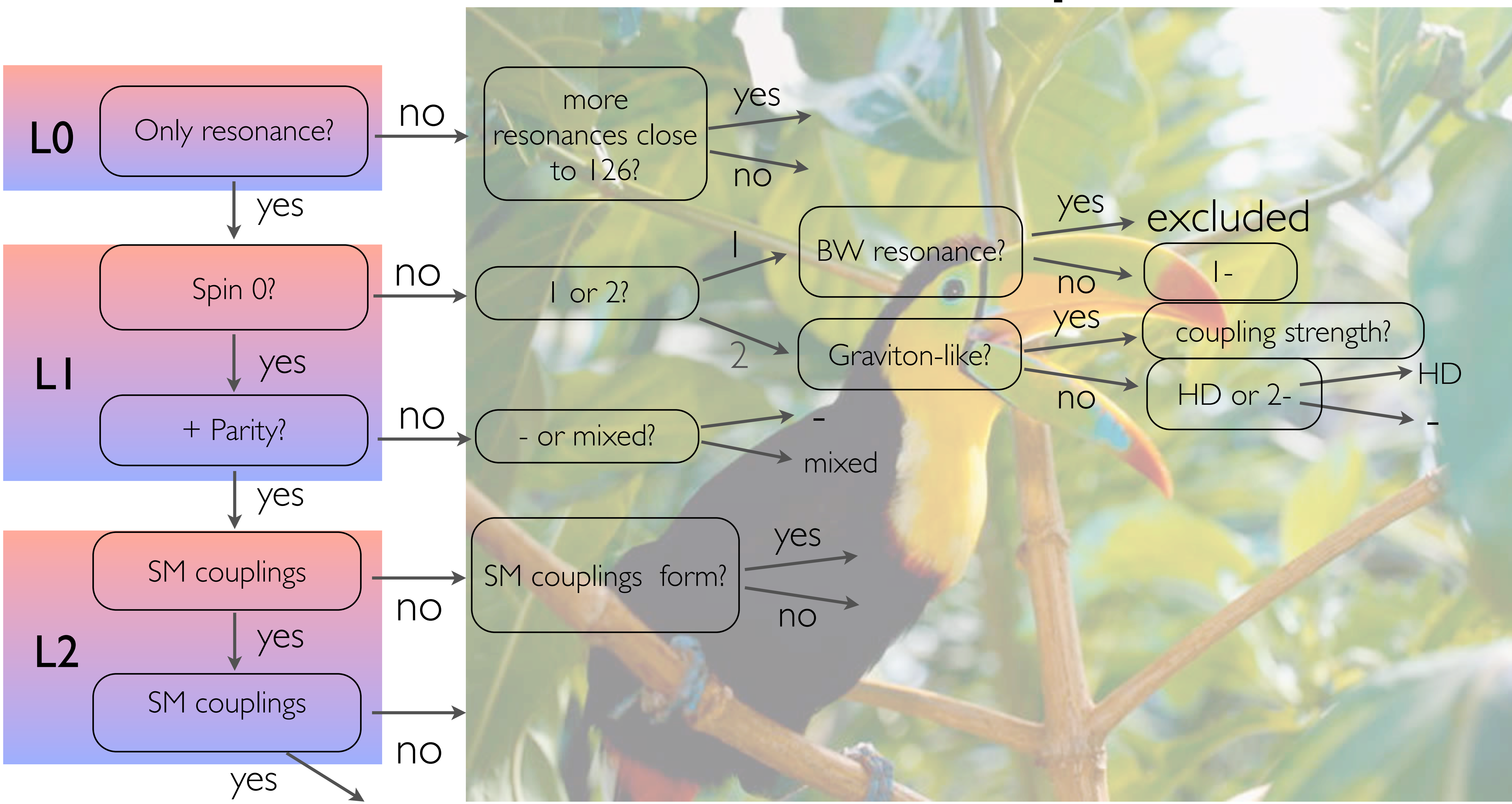

If you got here, then you are...

THE SM HIGGS BOSON

Determining Higgs properties: Philosophy

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- Effective theory approach:
  - Model independent framework (up to some NP scale Λ)
    - Any other states must be heavier than Λ
  - Reduce the lagrangian to the minimal number of interactions
  - Theory is renormalizable order by order in $1/\Lambda$
  - Generate MLM-matched samples with MadGraph 5 (up to 2j)
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  - QCD corrections to p p > X can be included with aMC@NLO
- Remarks:
  - Anybody can implement in FR/MG5 a model with the same couplings of JHU for a check
  - We want to test spin and parity of the new resonance. We do not want to constrain higher dimension operators
    - Just keep the lowest dimension operators

The Lagrangian

[http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterization]

- Spin 0 sector:

$$\mathcal{L}_0^f = \left[c_\alpha y_{Hff}\,\bar\psi_f\psi_f\right]X_0,\ \ \mathcal{L}_0^V = \Big[\kappa_{\rm SM} c_\alpha g_{HVV}\,V_\mu V^\mu$$

$$-\frac{1}{4}\kappa_\gamma\left[c_\alpha g_{H\gamma\gamma}\,A_{\mu\nu}A^{\mu\nu} + s_\alpha g_{A\gamma\gamma}\,A_{\mu\nu}\widetilde{A}^{\mu\nu}\right]$$

$$-\frac{1}{4}\kappa_\gamma\left[c_\alpha g_{HZ\gamma}\,Z_{\mu\nu}A^{\mu\nu} + s_\alpha g_{AZ\gamma}\,Z_{\mu\nu}\widetilde{A}^{\mu\nu}\right]$$

$$-\frac{1}{4}\kappa_g\left[c_\alpha g_{Hgg}\,G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha g_{Agg}\,G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\right]$$

$$-\frac{1}{4}\frac{\kappa_V}{\Lambda}\left[c_\alpha\,V_{\mu\nu}V^{\mu\nu} + s_\alpha\,V_{\mu\nu}\widetilde{V}^{\mu\nu}\right]\Big]X_0,$$

$0^+ \Rightarrow c\alpha = 1$

$0^- \Rightarrow c\alpha = 0$

Mixed state $\Rightarrow 0 < c\alpha < 1$

The Lagrangian

[http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterization]

- Spin 1 sector:

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

$$\mathcal{L}_1^f = \sum_{f=q,b,t,\ell,\tau} \bar\psi_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu, \qquad \mathcal{L}_1^Z = -\kappa_{V_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma),$$

$$\begin{aligned}\mathcal{L}_1^W = &+ i\kappa_{V_1} g_{WWZ} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) X_1^\nu \\ &+ i\kappa_{V_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\ &- \kappa_{V_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ &+ i\kappa_{V_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} \\ &- \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} [W^{+\mu} (\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu}) W^{-\nu}] X_1^\sigma,\end{aligned}$$

- $X_1 = 1^+$ in parity-conserving scenarios
- $X_1 = 1^-$ in parity-conserving scenarios

The Lagrangian

[http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterization]

- Spin 2 sector:

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

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

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

The minimal spin-2 particle is graviton like (2+)
Higher dimension operators and 2- available

The Lagrangian

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$$+\frac{1}{2}\bar\psi\, i\,\gamma_\nu D_\mu \psi + \frac{1}{2}\eta_{\mu\nu}\partial^\rho(\bar\psi\, i\,\gamma_\rho\psi) - \frac{1}{4}\partial_\mu(\bar\psi\, i\,\gamma_\nu\psi)\frac{1}{4}\partial_\nu(\bar\psi\, i\,\gamma_\mu\psi)$$

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It is possible to couple X with different strength
to particles without breaking QCD gauge
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$$\mathcal{L}_2 = \frac{1}{\Lambda}\sum_{i=V,\gamma,g,\psi} k_i\, T^i_{\mu\nu}\, X^{\mu\nu}$$

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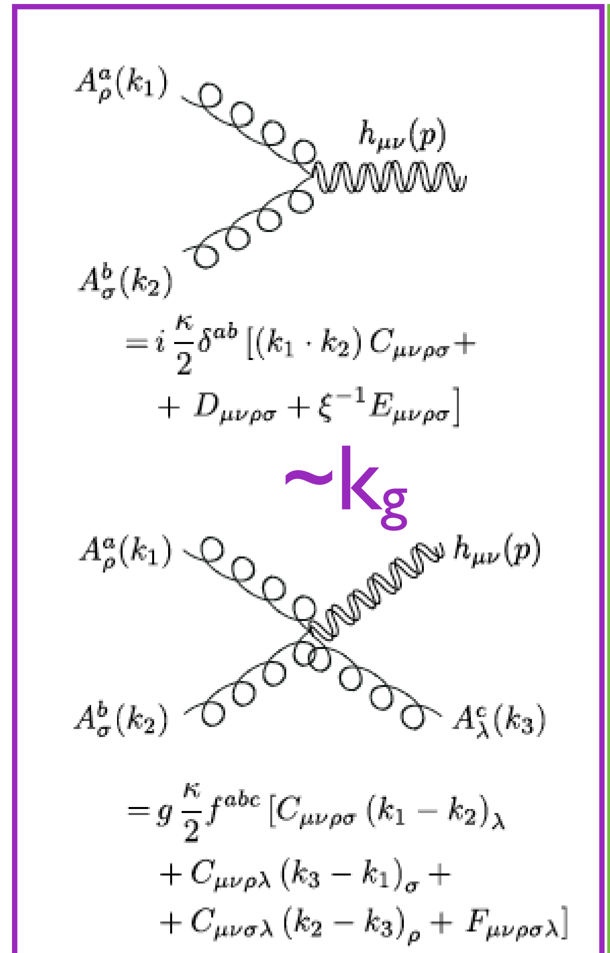

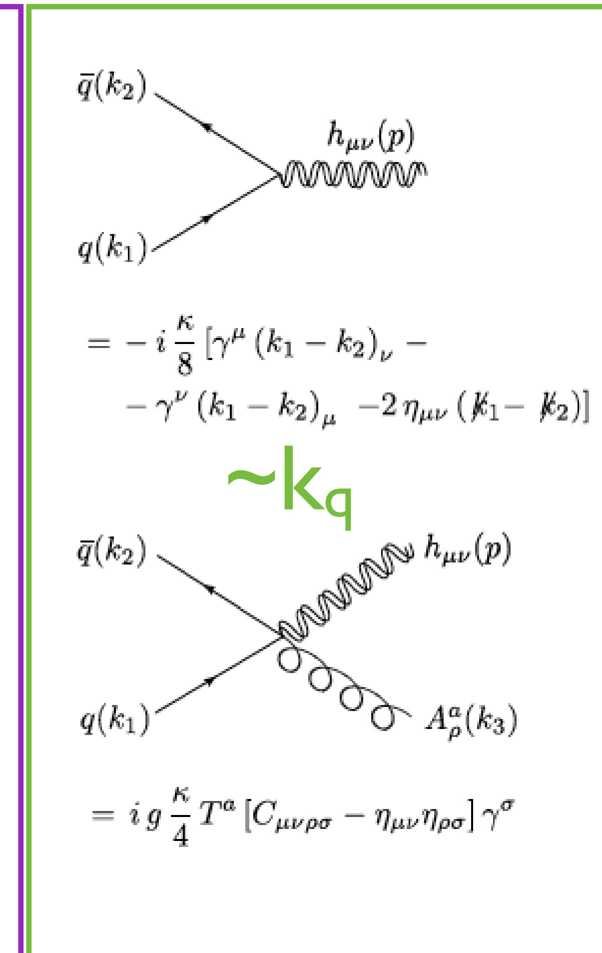

The minimal spin-2 particle is graviton like (2+)

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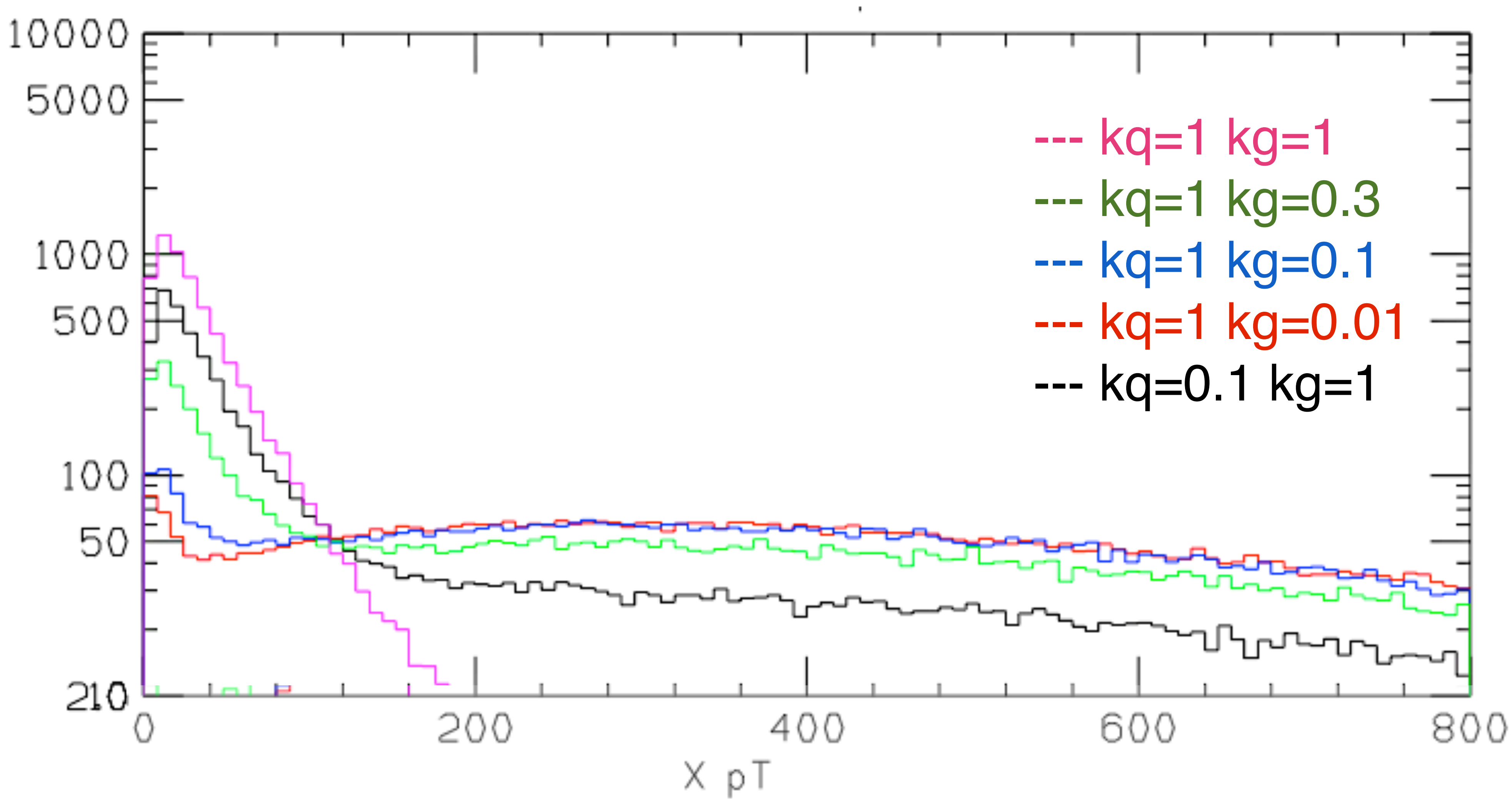
What if $k_q \neq k_g$?

aMC@NLO: p p → 2^+

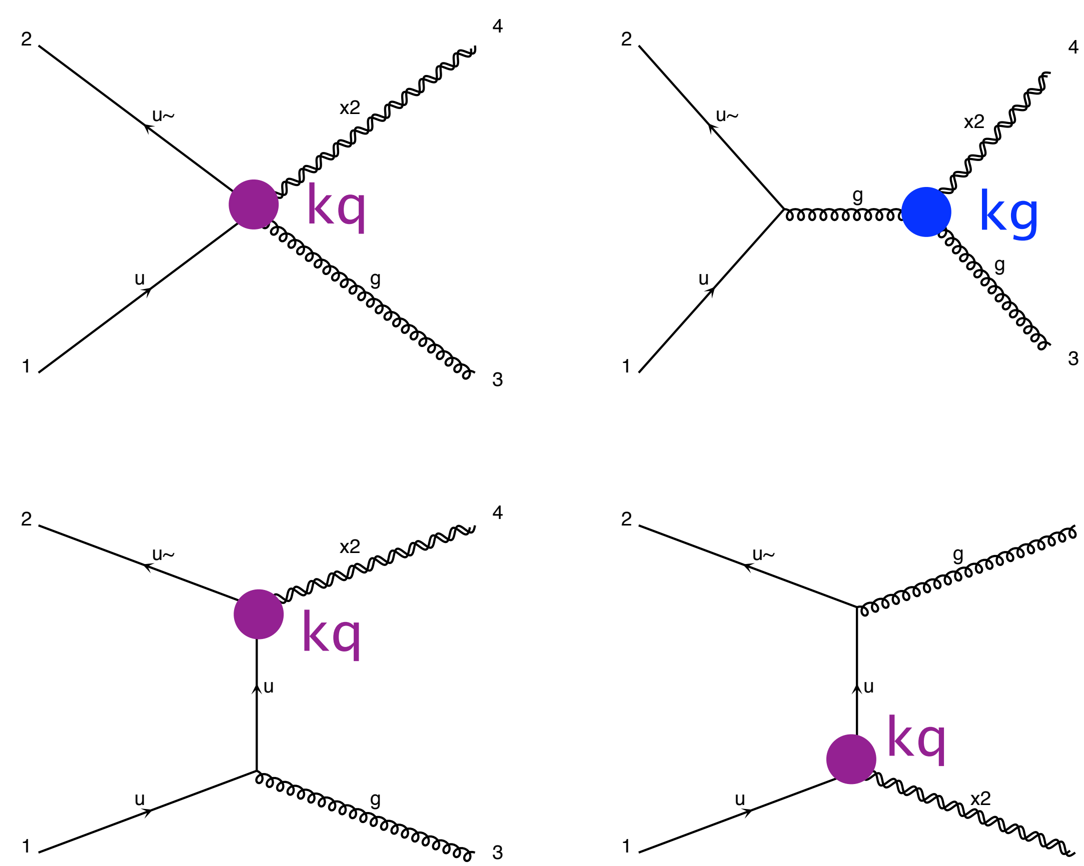


What if $k_q \neq k_g$?

- Unitarity-violating terms appear in the X+j matrix element
  - The ‘gravitational current’ is not conserved any longer
  - Need to renormalize gravitational coupling to matter
- Huge K-factors
  - NLO is *de facto* LO

k_q	k_g	K
0.1	1	2.7
1	1	1.6
1	0.6	2.2
1	0.3	7
1	0.1	23
1	0.01	33

- Pt spectrum completely distorted



What if $k_q \neq k_g$?

$$\mathcal{M}^2 = \frac{g_s^2}{27\Lambda^2 m^4 st\left(s+t-m^2\right)} A^2 \qquad x = k_q/k_g$$

$$\begin{aligned}\frac{A^2}{k_g^2} =& m^{10}(-3sx^2 - 12t) + m^8(18stx^2 - 36stx + 36st + 36t^2) + \\ & m^6(-3s^3x^2 - 32s^2tx^2 + 52s^2tx - 38s^2t - 42st^2x^2 + 84st^2x - 96st^2 - 48t^3) + \\ & m^4(18s^3tx^2 - 24s^3tx + 18s^3t + 66s^2t^2x^2 - 120s^2t^2x + 90s^2t^2 + 48st^3x^2 - 96st^3x + 96st^3 + 24t^4) + \\ & m^2(-6s^4tx^2 + 12s^4tx - 6s^4t - 36s^3t^2x^2 + 72s^3t^2x - 36s^3t^2 - 56s^2t^3x^2 + 112s^2t^3x - 56s^2t^3 \\ & \quad -24st^4x^2 + 48st^4x - 24st^4) + 2s^5tx^2 - 4s^5tx + 2s^5t + 6s^4t^2x^2 - 12s^4t^2x + \\ & +6s^4t^2 + 8s^3t^3x^2 - 16s^3t^3x + 8s^3t^3 + 4s^2t^4x^2 - 8s^2t^4x + 4s^2t^4\end{aligned}$$

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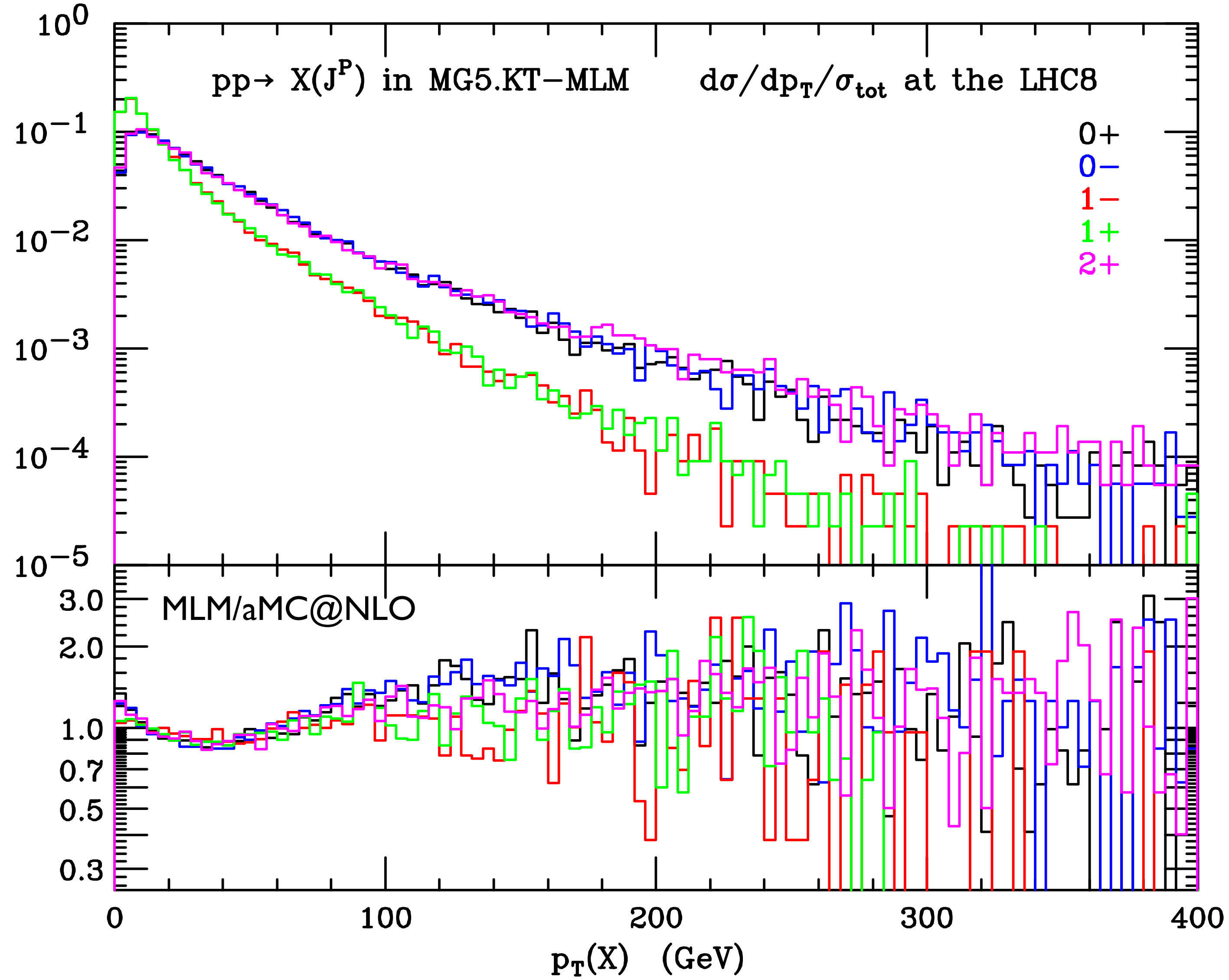
& m^4(18s^3tx^2 - 24s^3tx + 18s^3t + 66s^2t^2x^2 - 120s^2t^2x + 90s^2t^2 + 48st^3x^2 - 96st^3x + 96st^3 + 24t^4) + \\
& m^2(-6s^4tx^2 + 12s^4tx - 6s^4t - 36s^3t^2x^2 + 72s^3t^2x - 36s^3t^2 - 56s^2t^3x^2 + 112s^2t^3x - 56s^2t^3 \\
& \quad -24st^4x^2 + 48st^4x - 24st^4) + 2s^5tx^2 - 4s^5tx + 2s^5t + 6s^4t^2x^2 - 12s^4t^2x + \\
& +6s^4t^2 + 8s^3t^3x^2 - 16s^3t^3x + 8s^3t^3 + 4s^2t^4x^2 - 8s^2t^4x + 4s^2t^4
\end{aligned}$$

vanish for x=1

Results: X pt

- MLM-matching vs aMC@NLO (lower inset).



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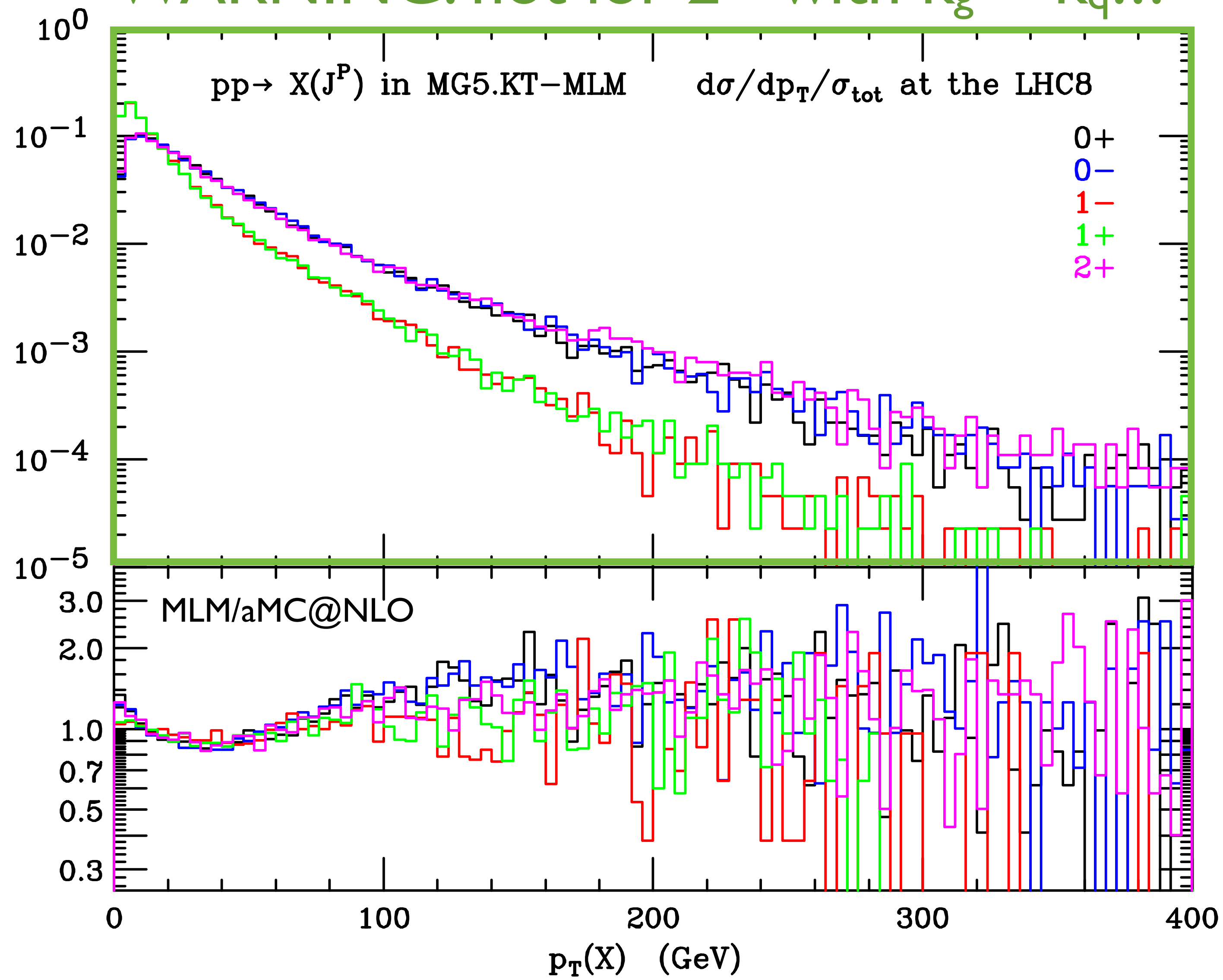
qq-initiated processes softer than gg
WARNING: not for 2+ with $k_g << k_q$!!!



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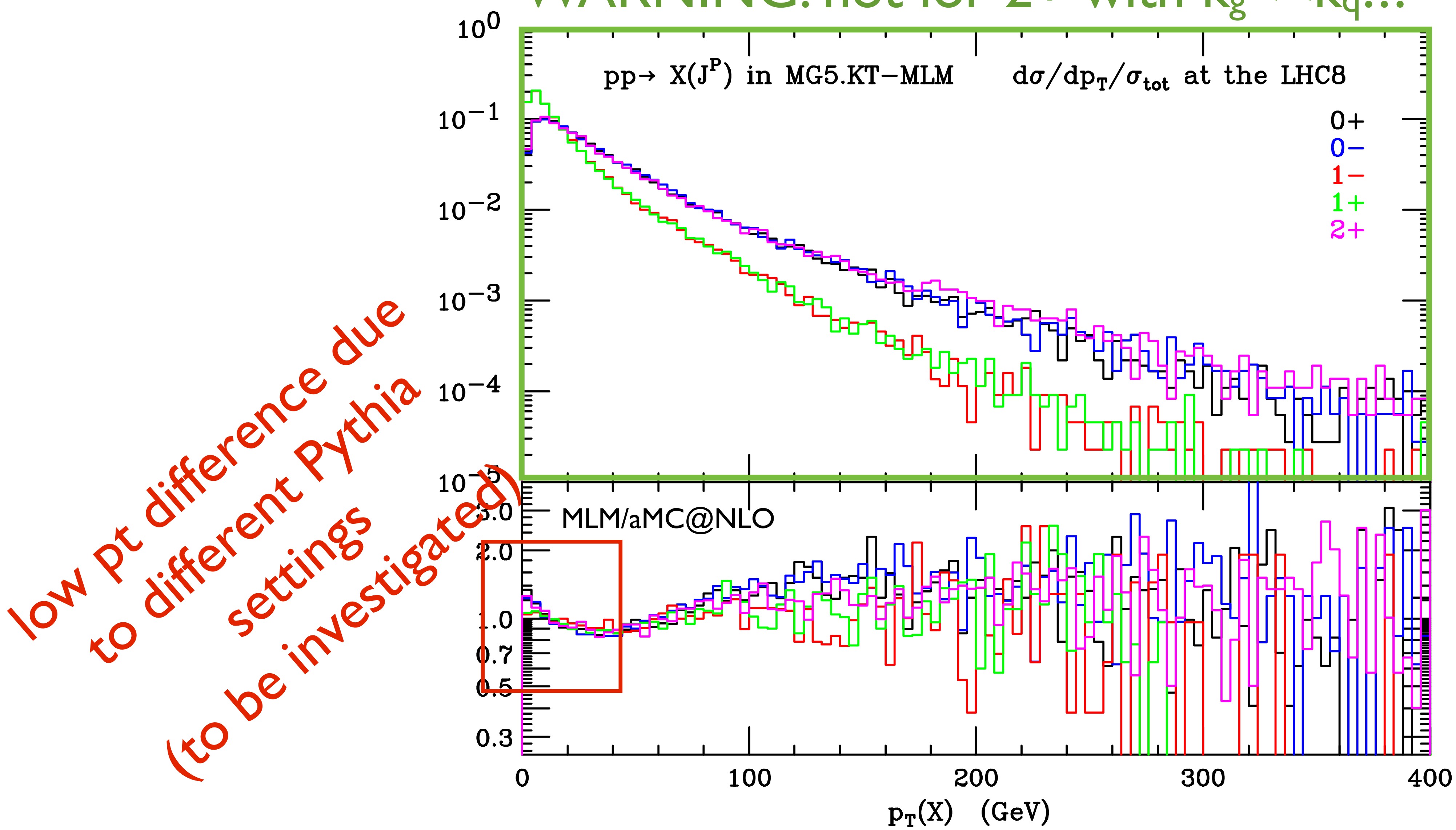

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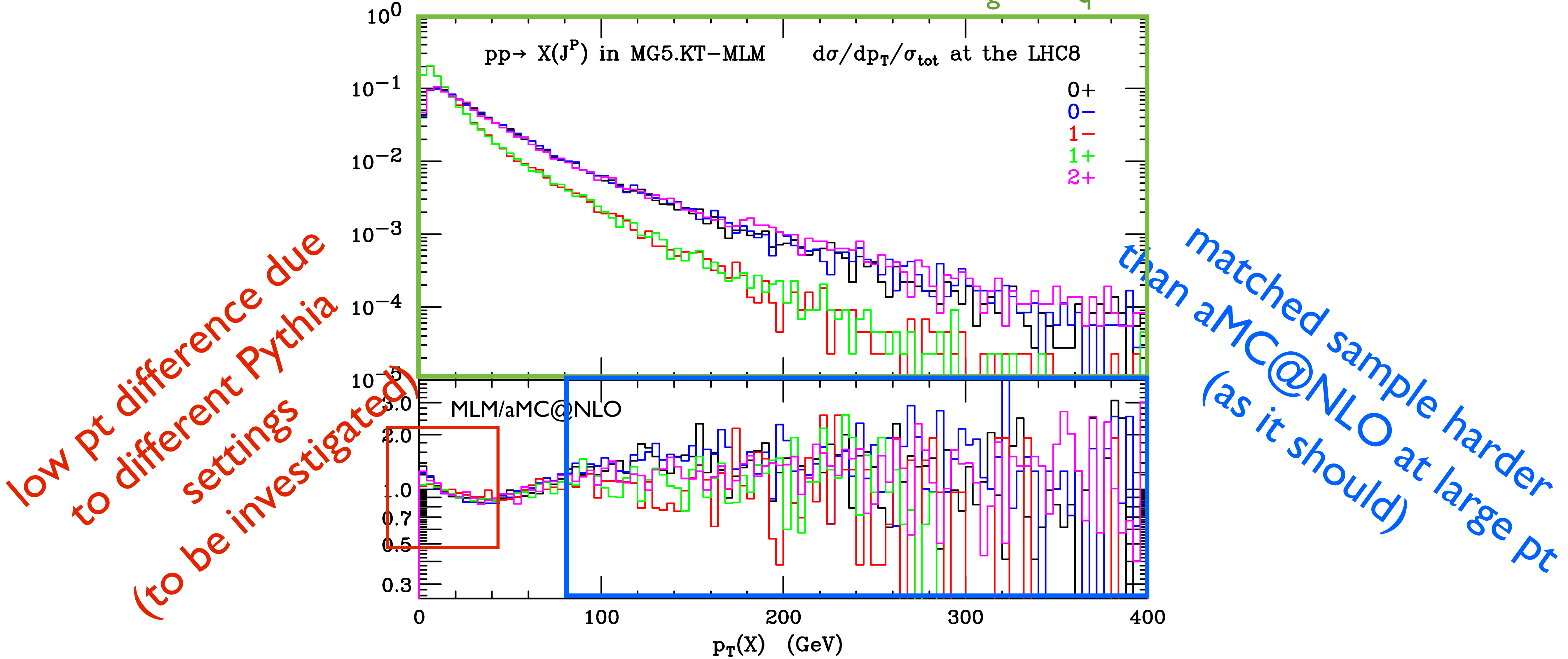

Results: X η

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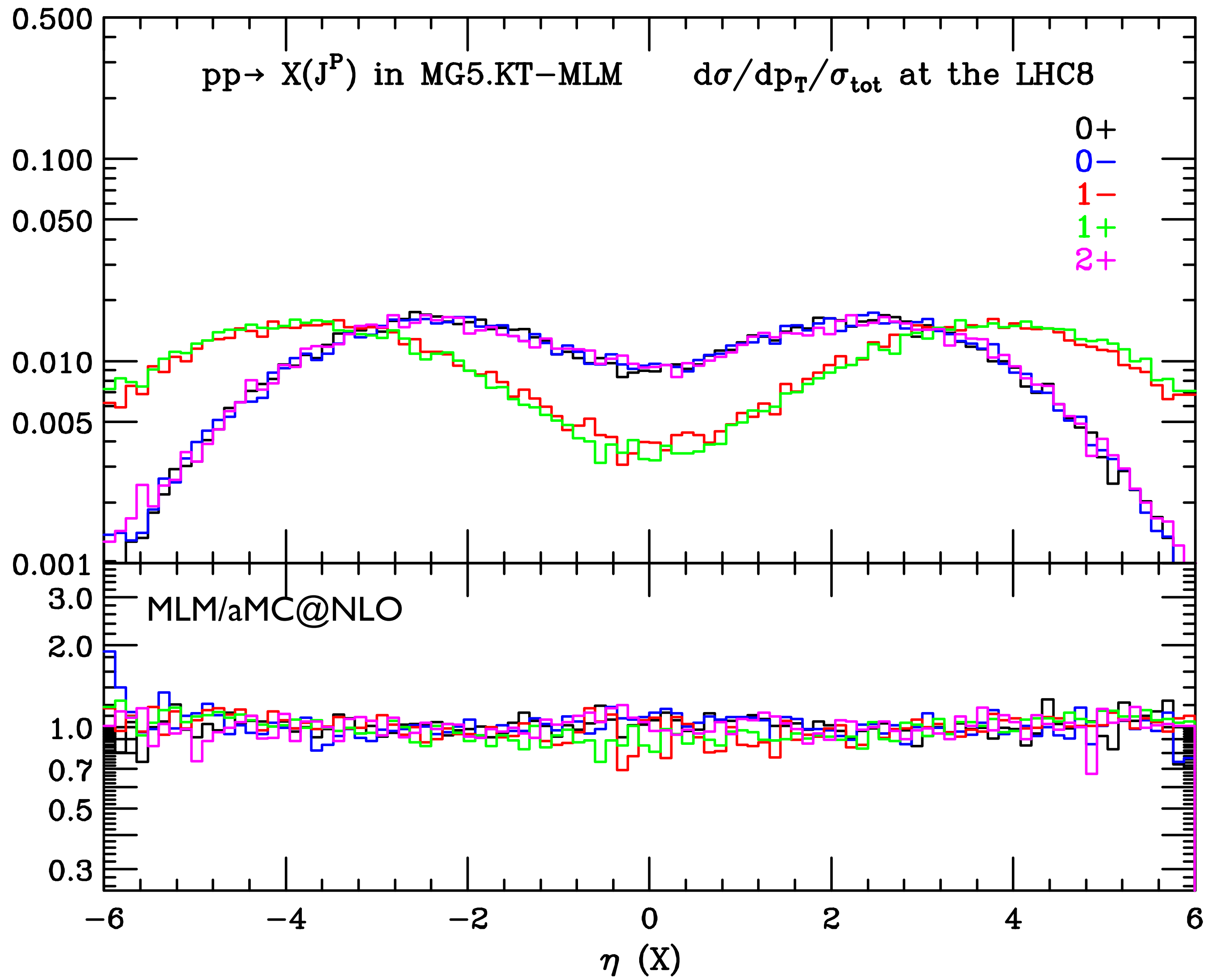

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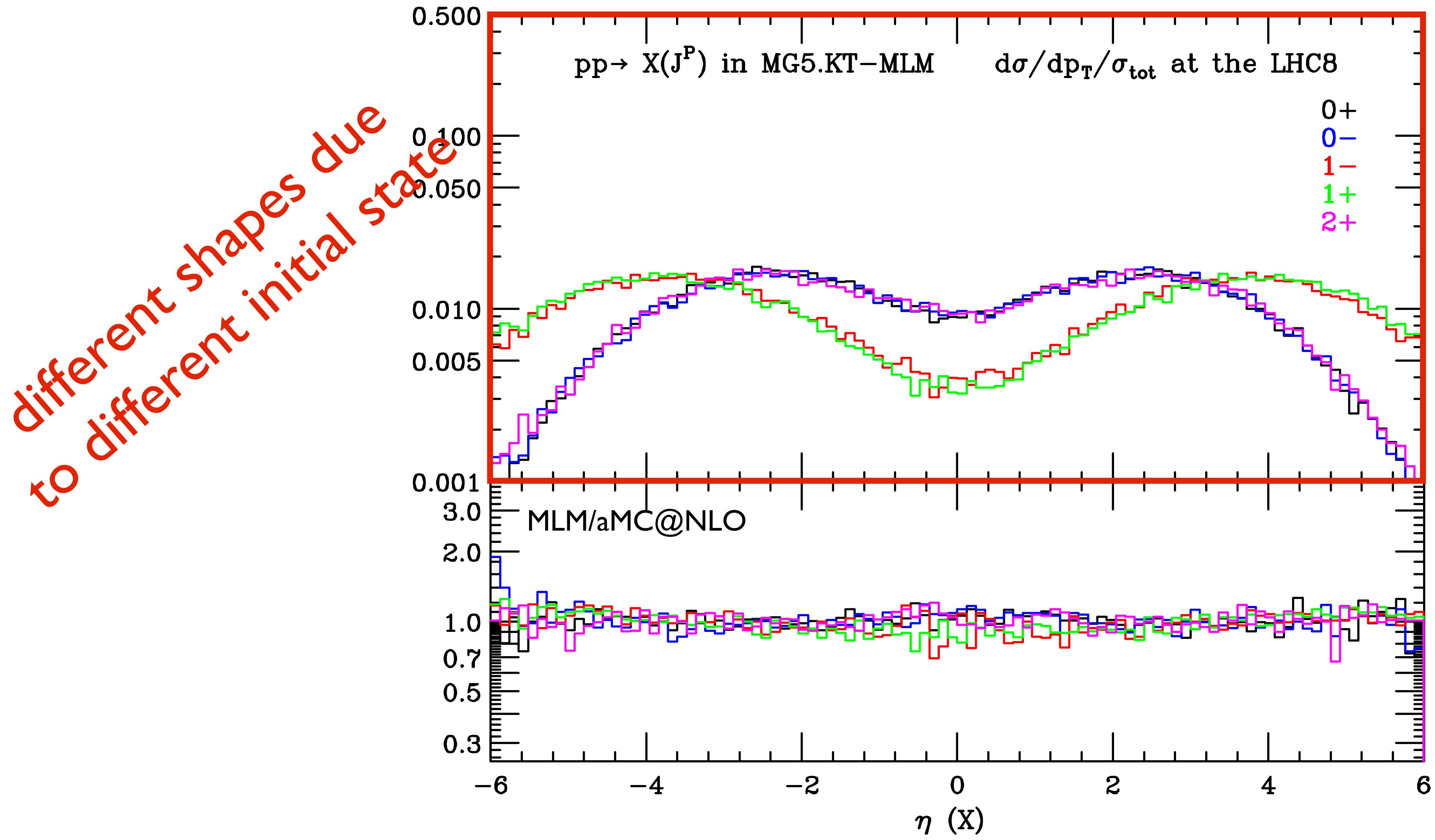

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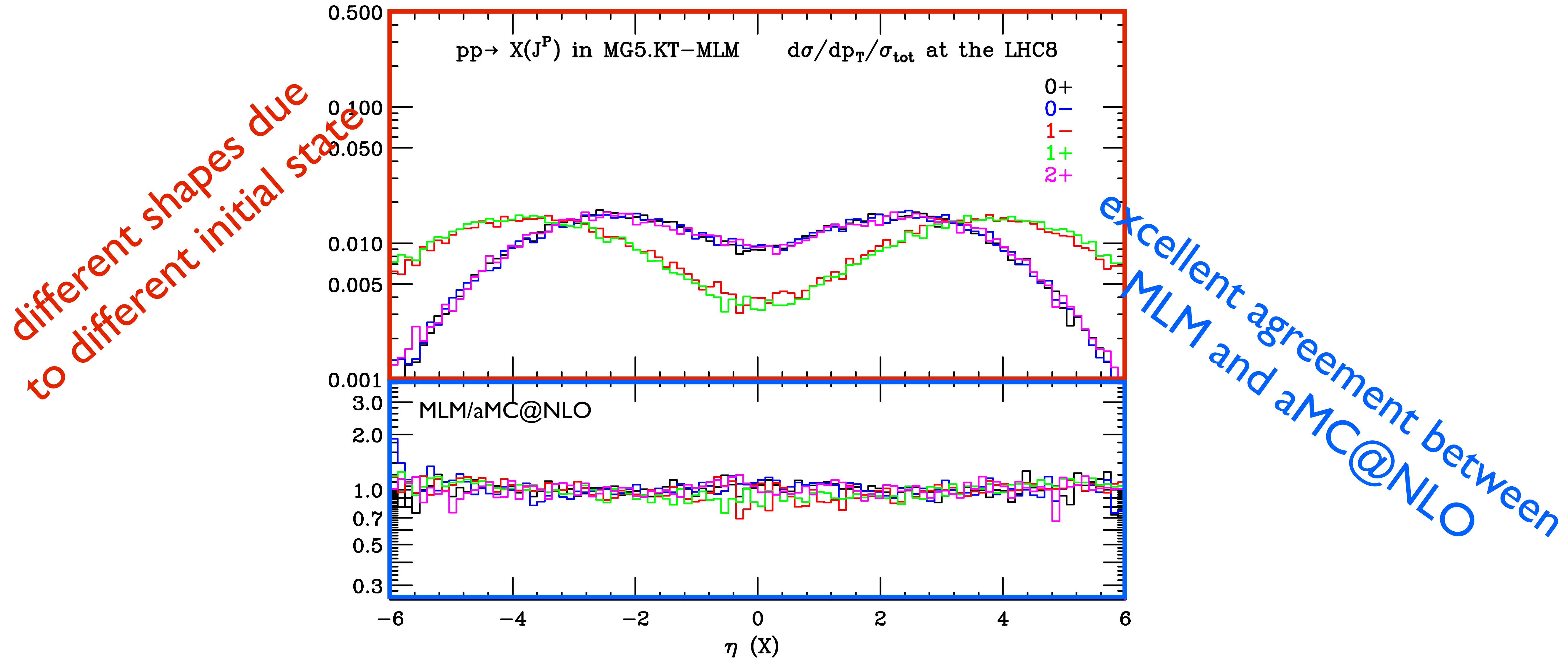
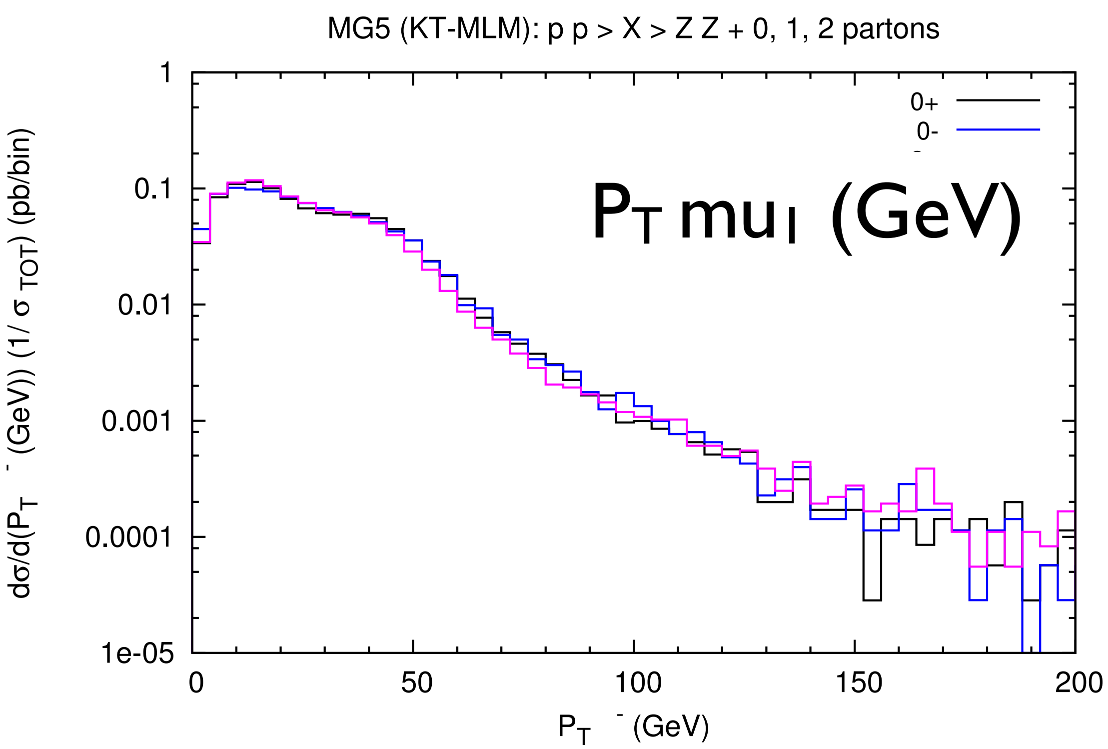
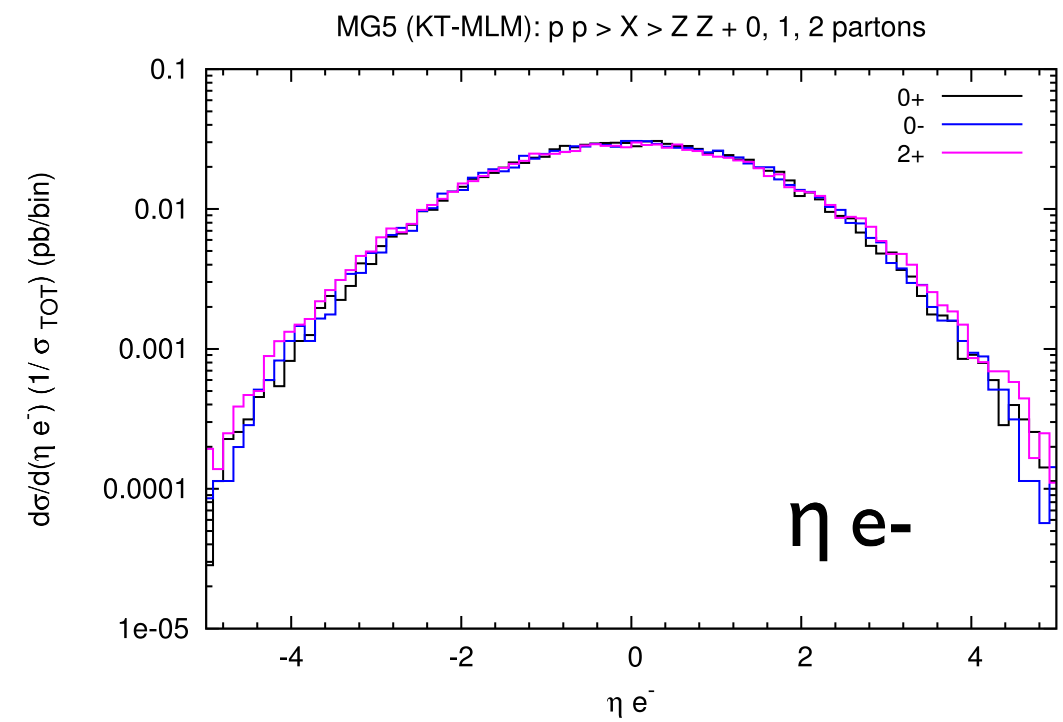
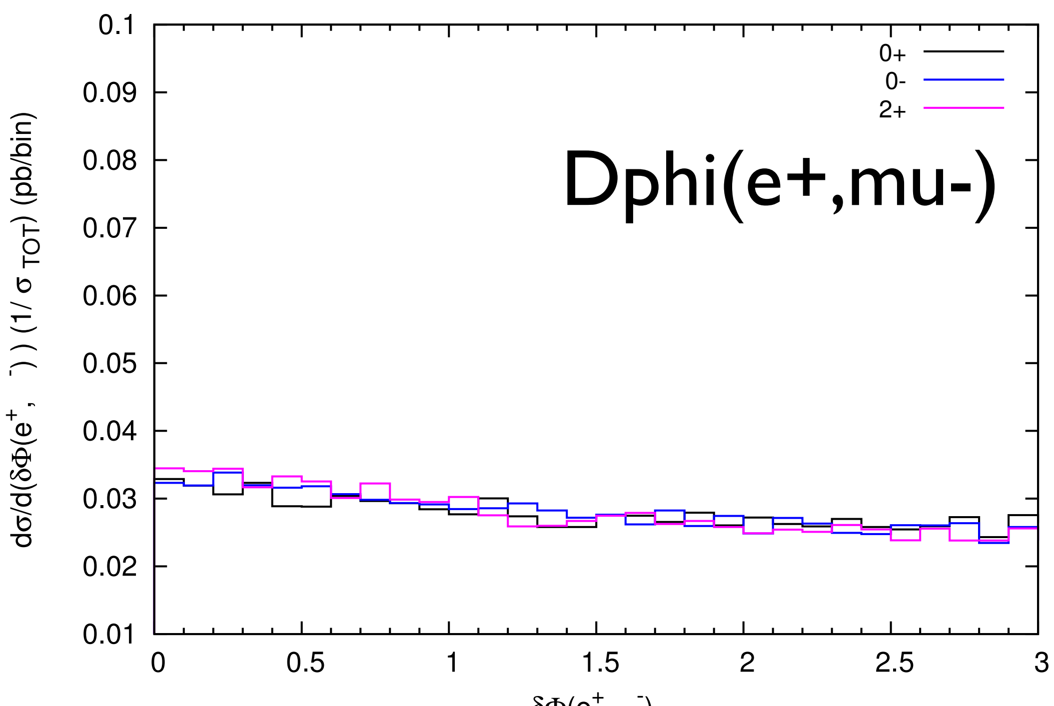
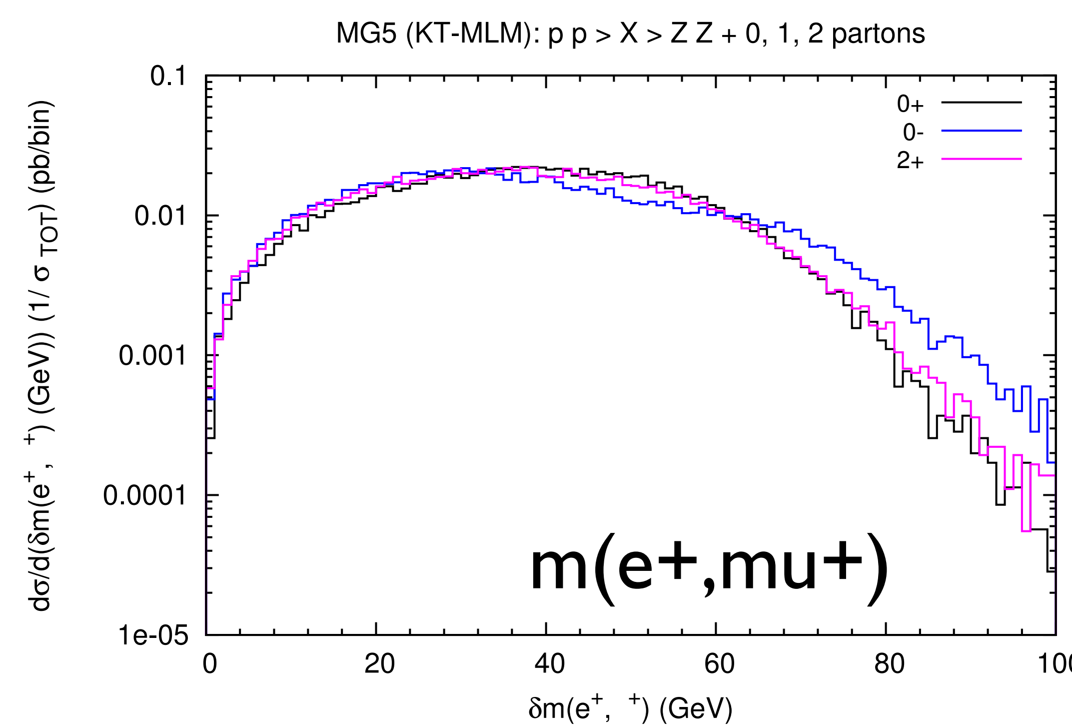


MLM Samples: X to ZZ (to 4l)

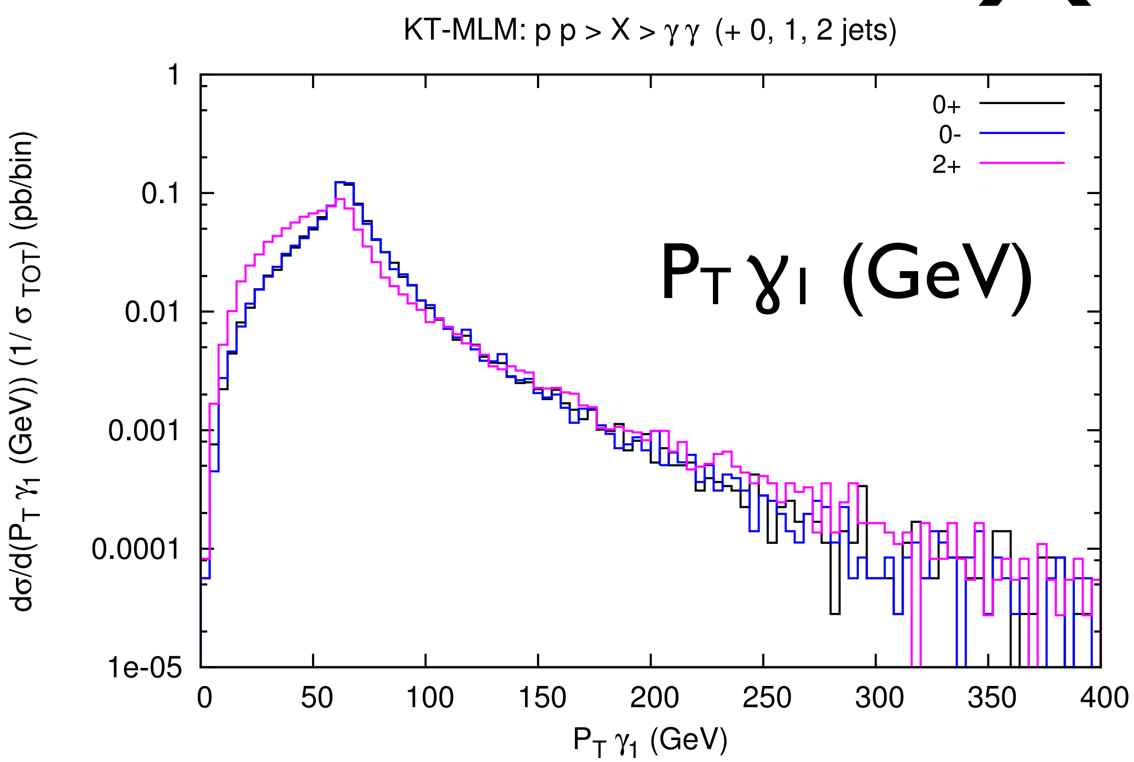


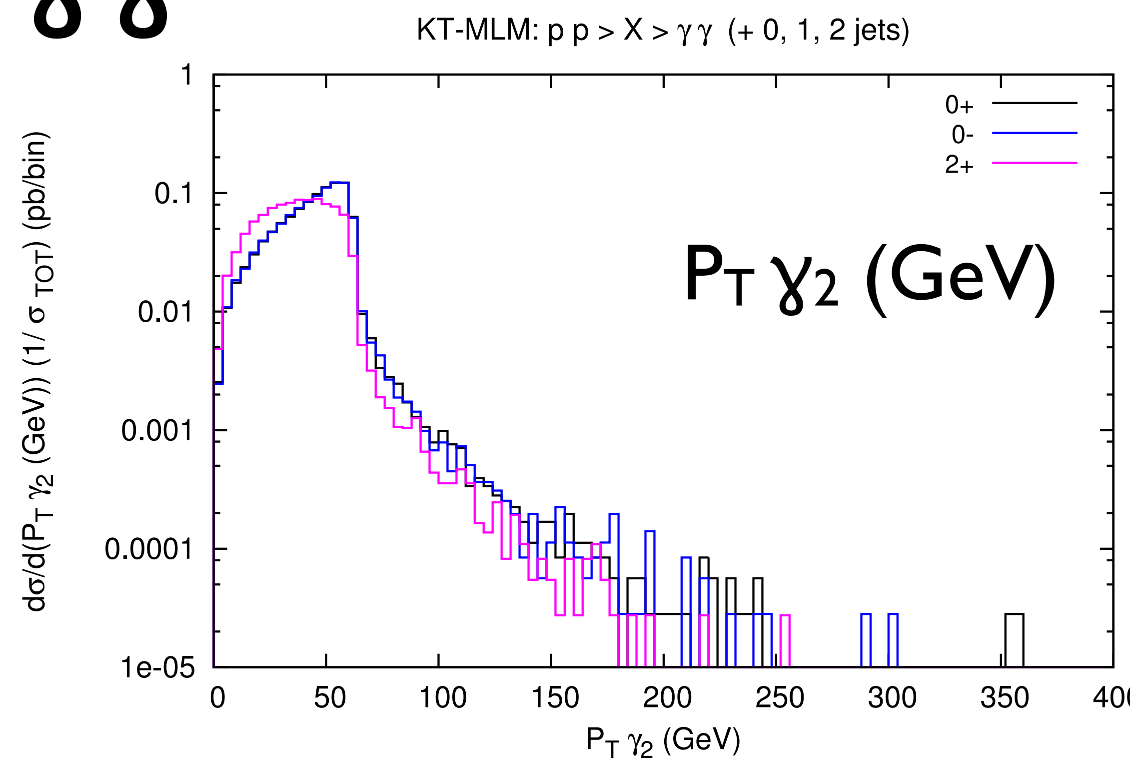


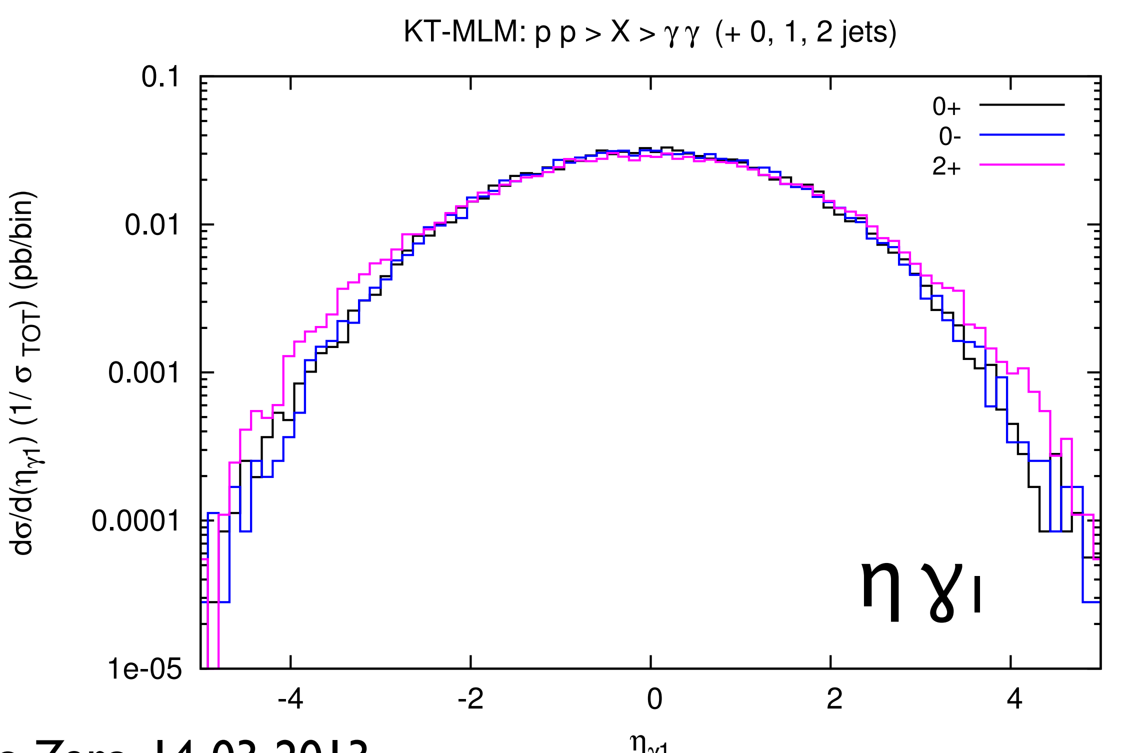


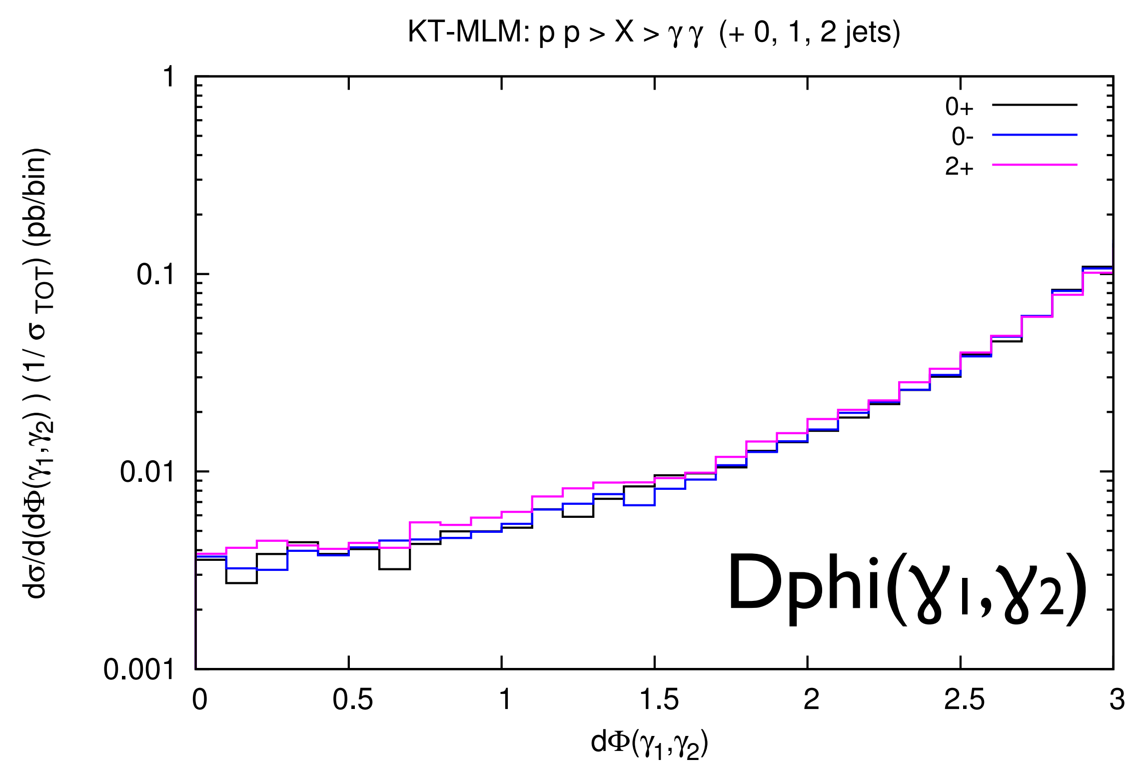


MLM Samples: X to γγ



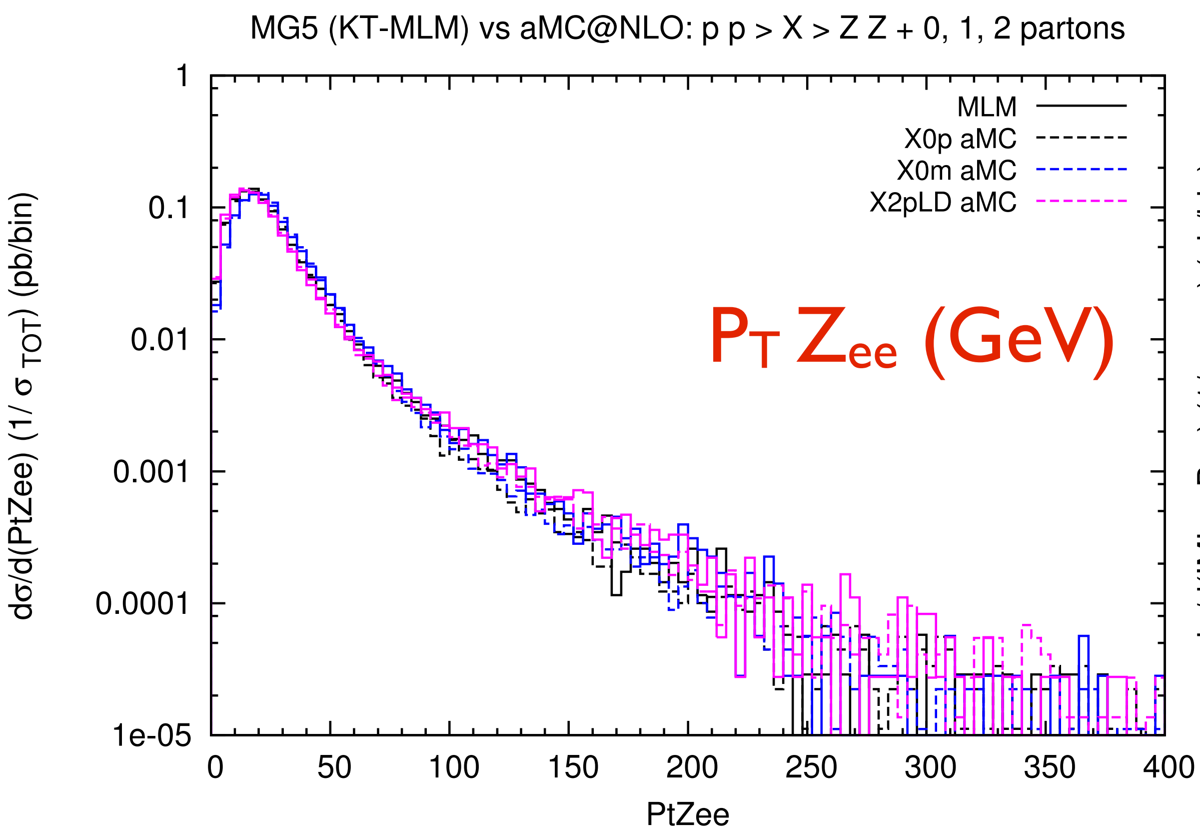


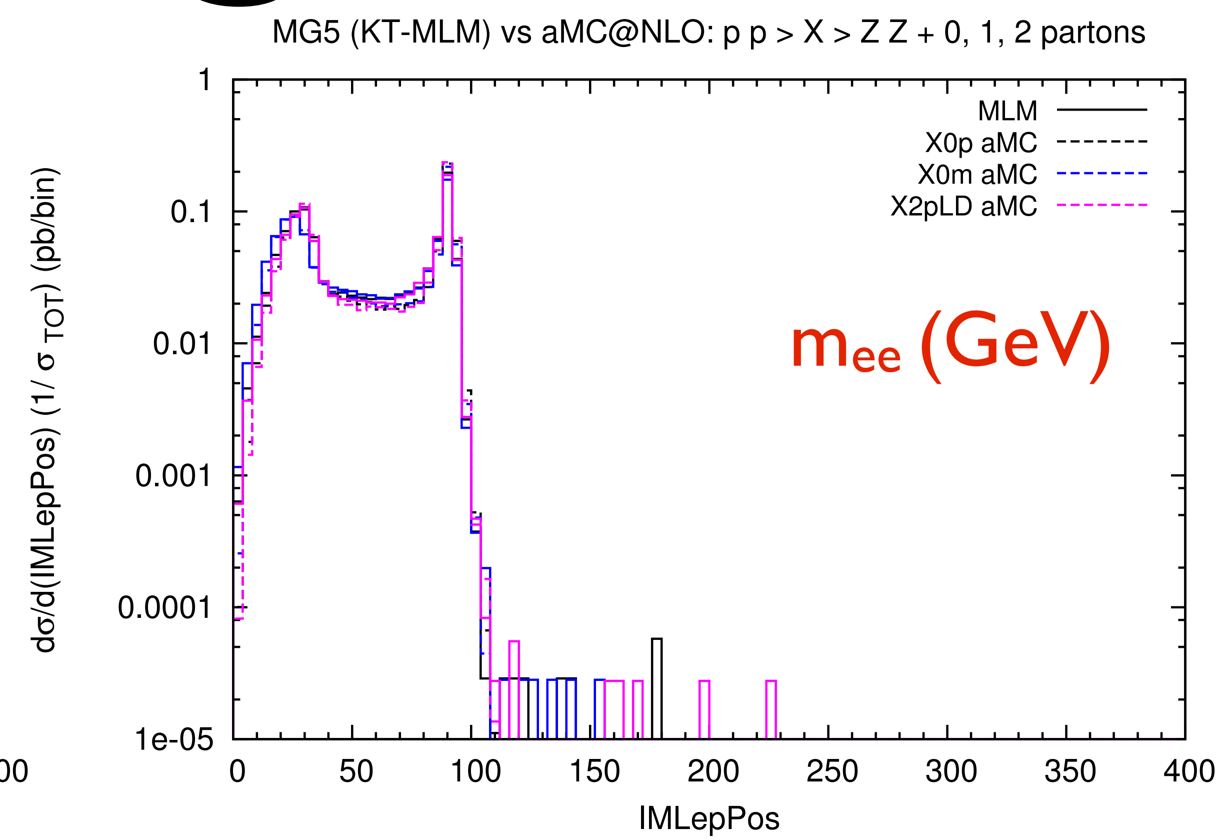




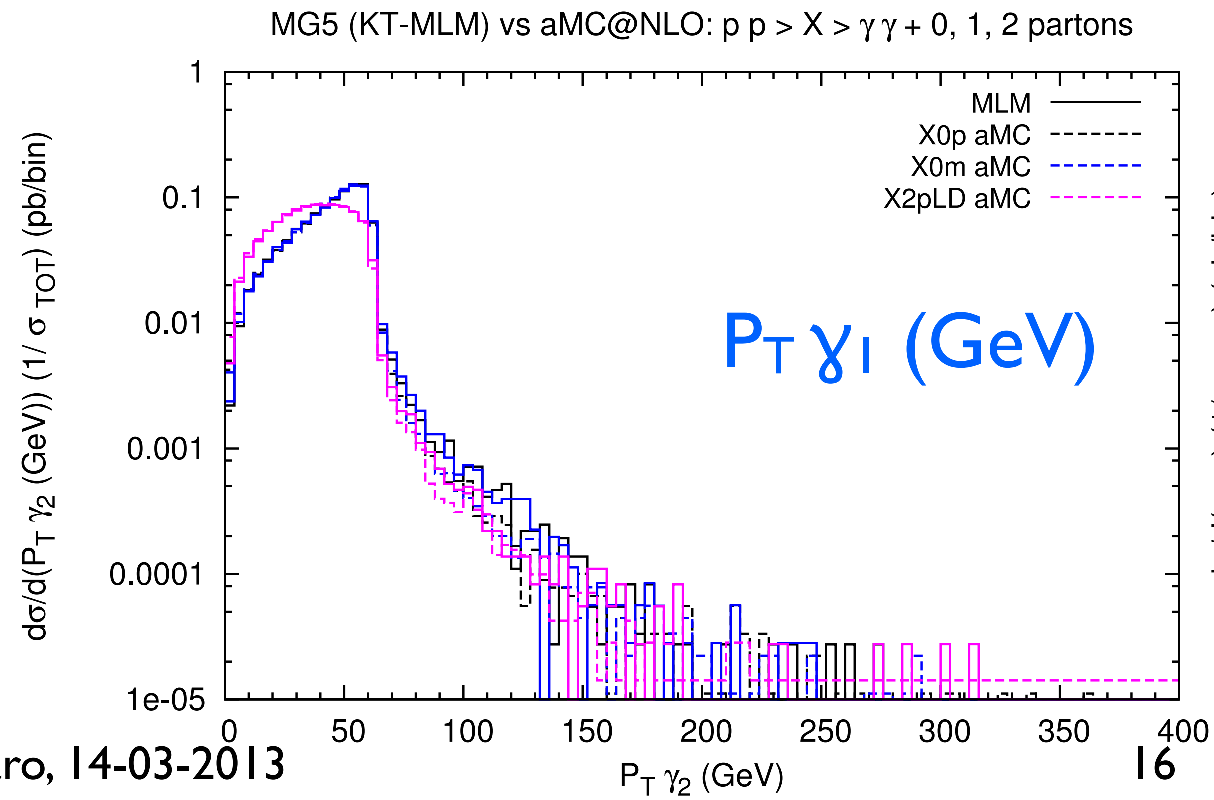
MLM vs aMC@NLO

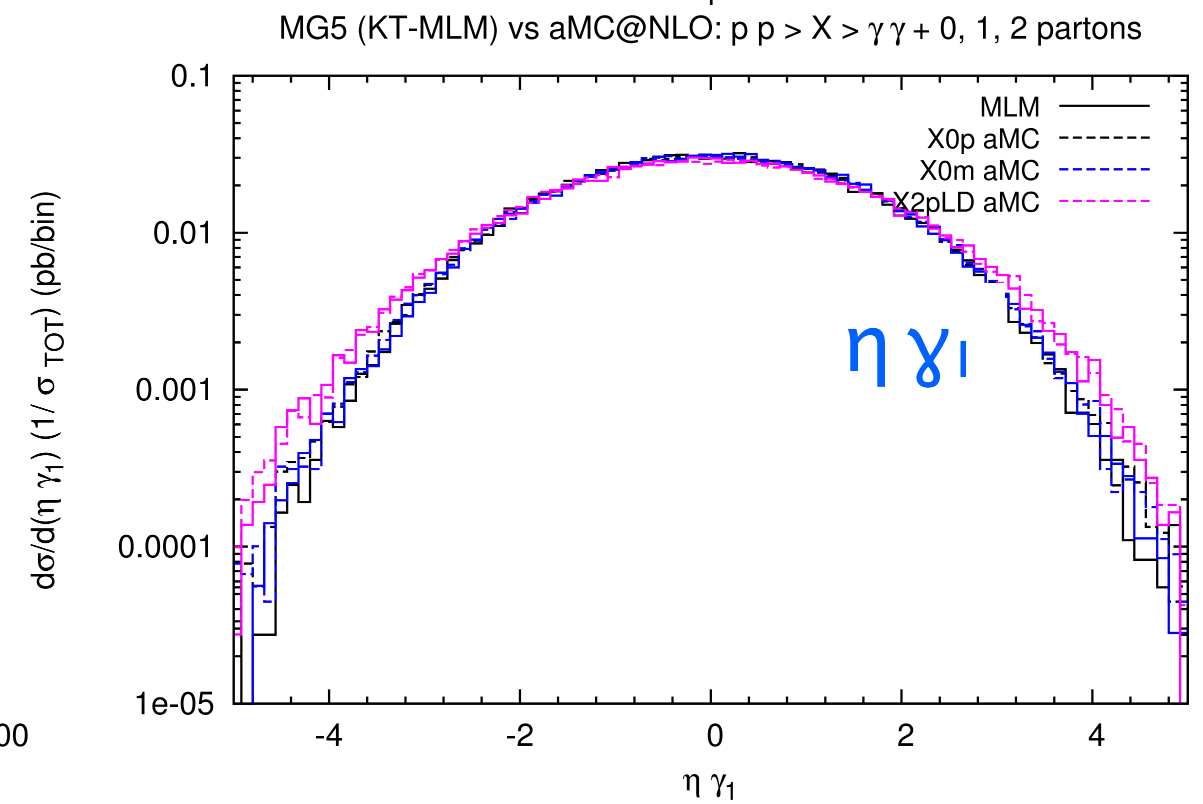
4 leptons





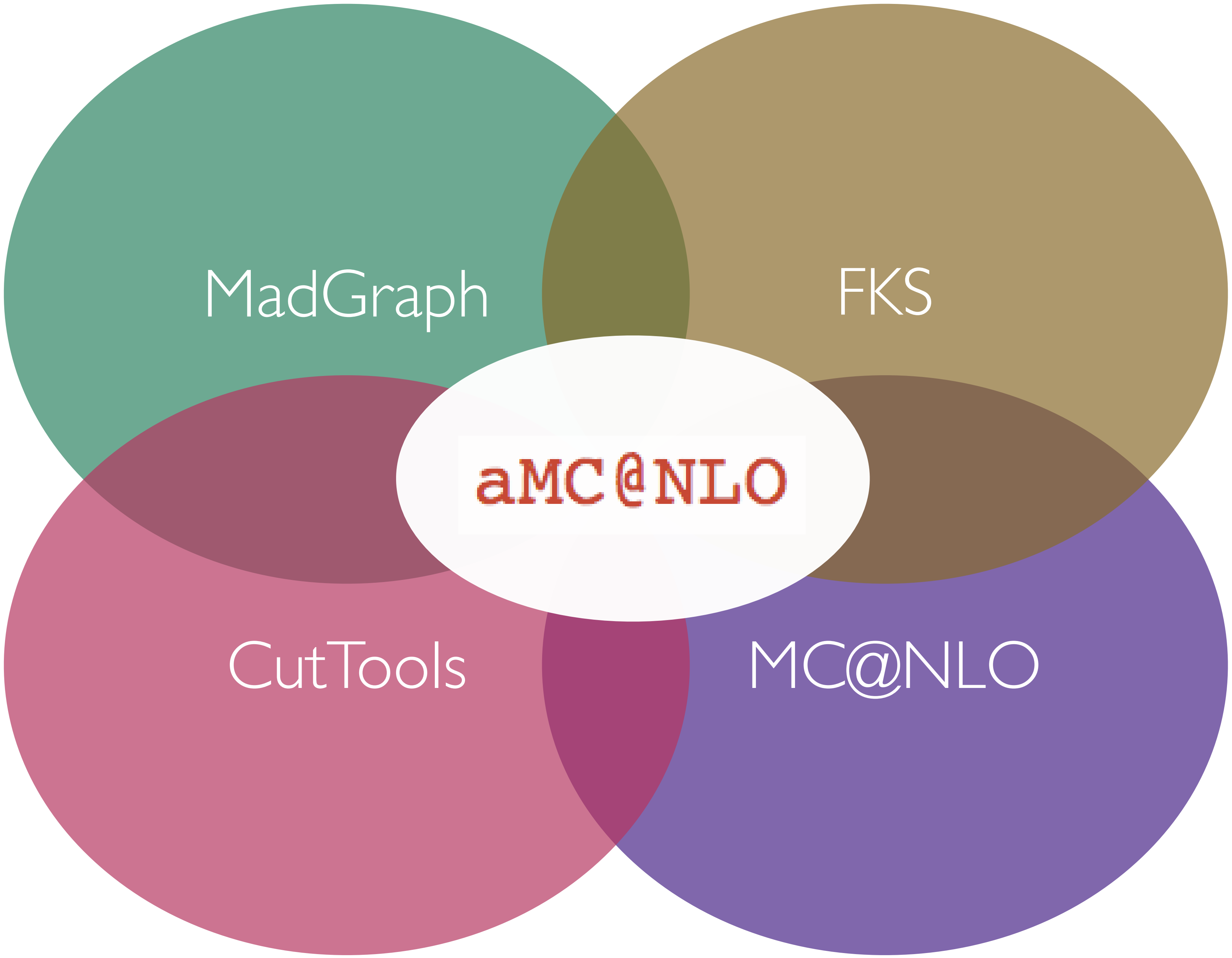
2 photons





aMC@NLO

aMC@NLO



aMC@NLO


MadGraph
FKS
aMC@NLO
CutTools
MC@NLO
beta3 soon available
http://amcatnlo.web.cern.ch

Public codes

- Codes for 0±, 1± and 2+ are available on the aMC@NLO page (to be updated with latest versions)

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...			

Conclusions and outlook

- The identification of the new boson as the Higgs particle will be made through compatibility tests of the SM, and exclusion of all other hypotheses.
- HiggsCharacterization model available on the FeynRules website
- In the EFT approach, QCD radiation can be consistently included at higher orders Full spin correlations for production/decay can be used.
- The strange behavior with $k_q \neq k_g$ for the spin 2 case has been understood.
  - Warning! Pt spectrum distorted
- We have tested aMC@NLO with merged samples and found very good agreement where we would have expected.
  - For updates stay tuned on http://amcatnlo.web.cern.ch
- The MG5 implementation is flexible, consistent and is valid for any production/ decay mechanism with any number of extra jets.
- Extend the study to other channels?

Acknowledgments: Thanks to...

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- ... the MG5 and aMC@NLO team
- ... all you for the attention!

Backup

What if $k_q \neq k_g$?