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Status of New Physics Simulations

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2016.07.05

OUTLINE

- Motivation
- Summary of status
- New physics applications
  - Colored particle production
    - Supersymmetric QCD
  - diHiggs in Vector-like Quark Model
  - Spin-2 particle production
  - Dark matter production @ LHC
- Conclusions

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Motivation

NEW PHYSICS @ LHC

- **How to get hints of new physics at the LHC ?**
  - Compare data with the "known/old" physics (=Standard Model)
  - Observe the deviations at a good confidence.

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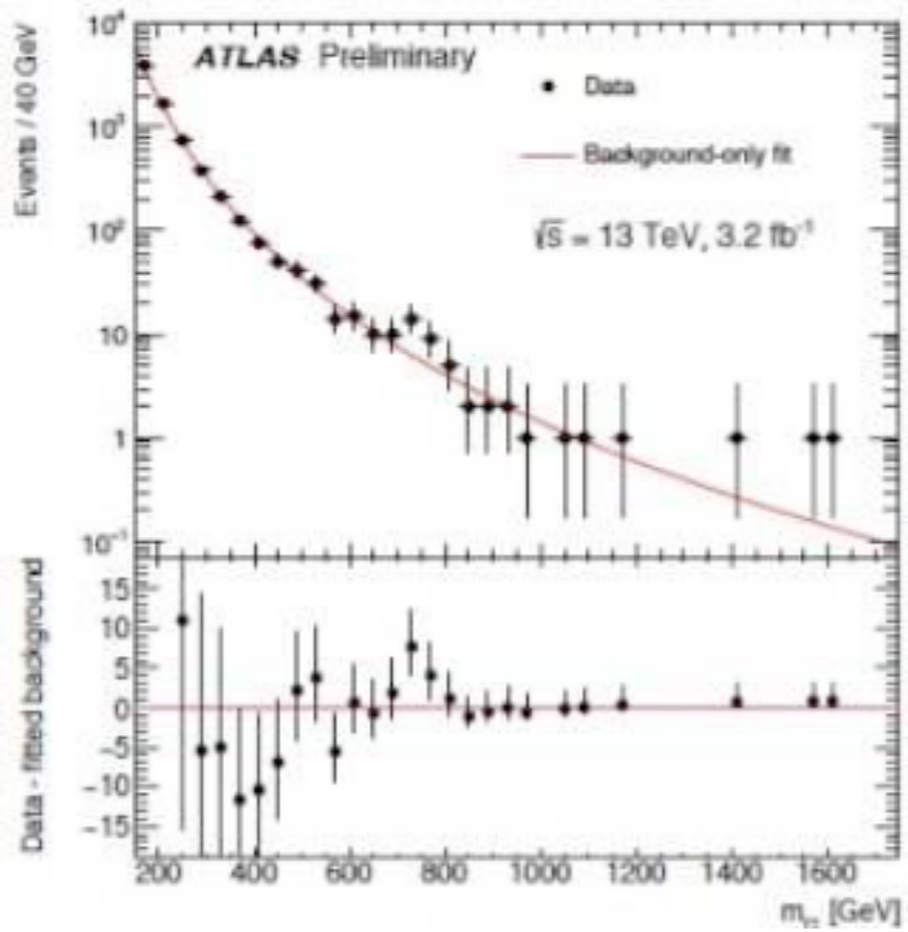
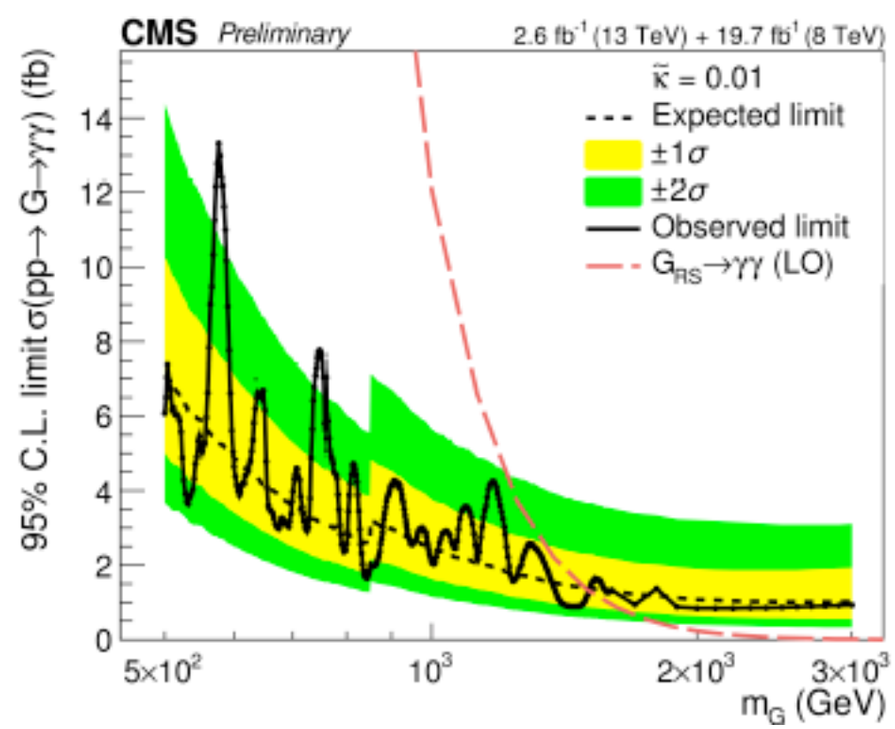
Ex: diphoton excess !!!





NEW PHYSICS @ LHC

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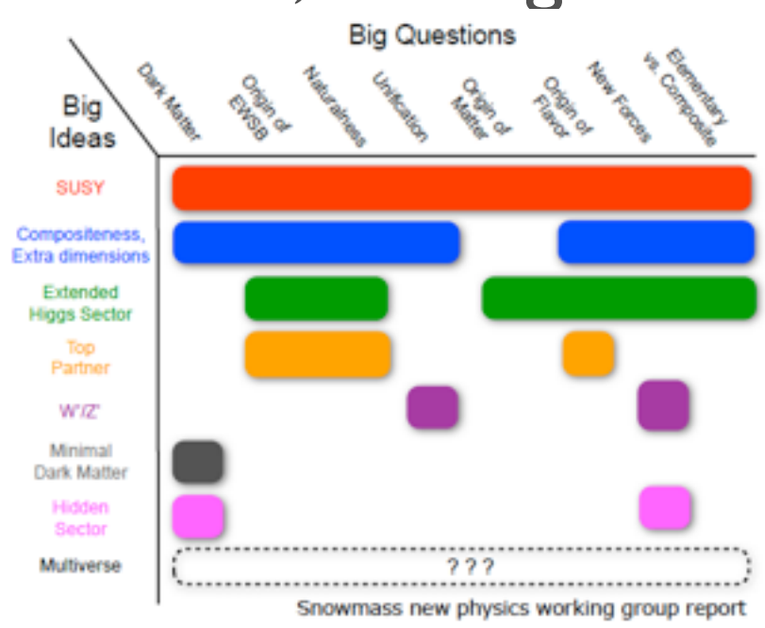
  - Fitting deviation by new physics signals and reinterpretation
  - Most of the time, leading order Monte Carlo simulation is enough



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  - Fitting deviation by new physics signals and reinterpretation
  - Most of the time, leading order Monte Carlo simulation is enough
- **Precision measurements of the model parameters**
  - Reliable theoretical interpretation and hints of undiscovered new physics
  - The most precise simulations are mandatory

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Summary of Status

BSM TECH. OVERVIEW IN MG5AMC

	Yes	No
FeyRules +MadLoop	*General CTs (UV&R2); Fermion-flow violation; Majorana particles; Non-renormalized opt; Spin-2 particles; Finite renormalization;*	*Complex-Mass Scheme; Corrections other than QCD; Four-fermion operators; General color repres; Spin-3/2 particle; others ?*
MadFKS +MC@NLO	*General Soft CTs; Restricted Coll. CTs; Restricted MC CTs; Color can be 1,3,8; Reweighting for aS;*	*On-shell subtraction; General Coll./MC CTs; General color; General Reweighting; Corrections other than QCD; others ?*

BSM (NLO) PROCESS OVERVIEW IN MG5AMC

- Colored particle production
  - Colored scalar pair production — Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)
  - Supersymmetric QCD — Degrande, Fuks, Hirschi, Proudom, HSS (PLB'16)
  - Vector-like quark pair production — Les Houches 2015 (1605.02684) ; Fuks, HSS (to appear)
  - MSSM — Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)
- BSM Higgs production
  - Higgs characterisation model — Artoisenet et al. (JHEP'13); Maltoni, Mawatari, Zaro (EPJC'14); Demartin, Maltoni, Mawatari, Page, Zaro (EPJC'14); Demartin, Maltoni, Mawatari, Zaro (EPJC'15)
  - Two-Higgs-Doublet Model — Degrande (CPC'15); Degrande, Ubiali, Wiesemann, Zaro (JHEP'15)
  - Georgi-Machacek model — Degrande, Hartling, Logan, Peterson, Zaro (PRD'16)
- Spin-2 particle production — Das, Degrande, Hirschi, Maltoni, HSS (1605.09359)
- Dark matter collider production (see also Antony Martini's talk)
  - s-channel mediator
    - spin 0 or 1 mediator — Mattelaer Vryonidou (EPJC'15); Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen (EPJC'15); Neubert, Wang, Zhang (JHEP'16); Arina et al. (1605.09242)
    - spin 2 mediator — Das, Degrande, Hirschi, Maltoni, Mawatari, HSS (in preparation)
  - t-channel mediator — Fuks, Hirschi, Mattelaer et al. (in preparation)

BSM (NLO) PROCESS OVERVIEW IN MG5AMC

- SM effective field theory (see also Eleni Vryonidou and Celine Degrande's talks)
  - Top FCNC processes — Degrande, Maltoni, Wang, Zhang (PRD'15); Durieux, Maltoni, Zhang (PRD'15)
  - ttbarZ/gamma production — Bylund, Maltoni, Tsinikos, Vryonidou, Zhang (JHEP'16)
  - Single-top production — Zhang (PRL'16)
  - Top pair production via chromomagnetic dipole momenta — Franzosi, Zhang (15)
- Other colorless particle production
  - Heavy neutrino production — Degrande, Mattelaer, Ruiz, Tumer (1602.06957)

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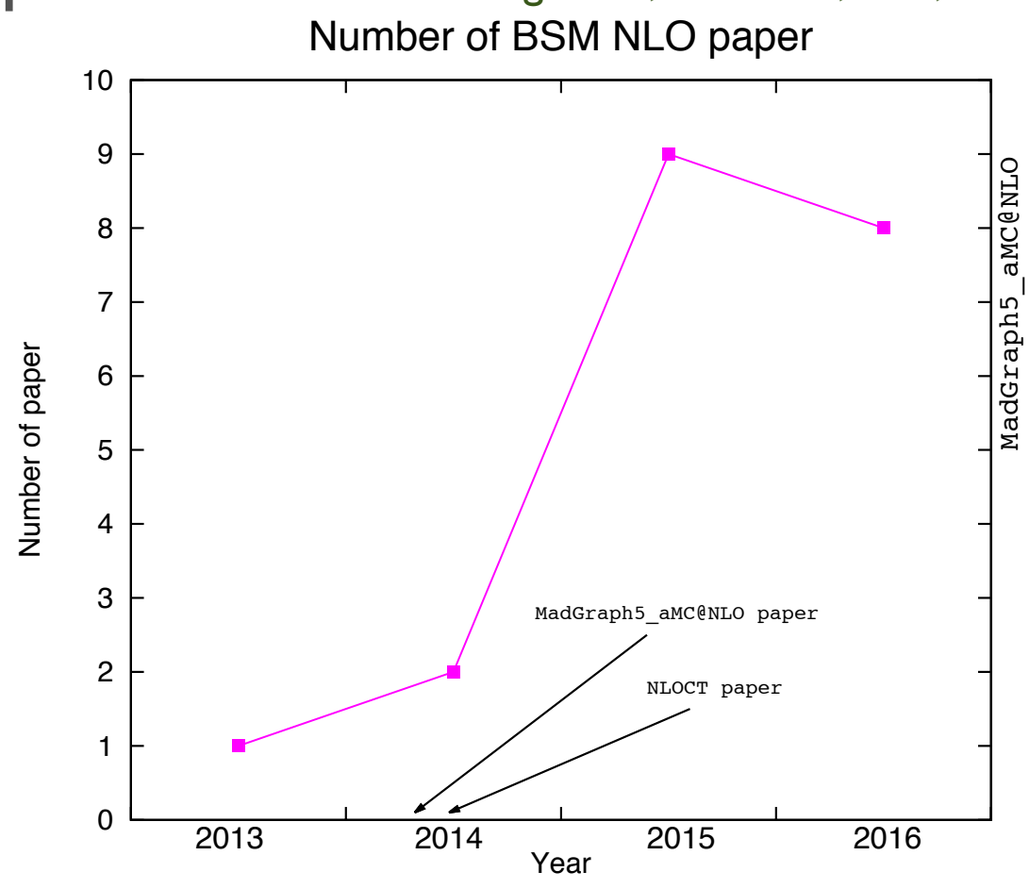

New Physics Applications:

Selected Results

SUPERSYMMETRIC QCD

Degrande, Fuks, Hirschi, Proudom, HSS (PLB'16)

✦ SUSY QCD: Production of gluino-pair

$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g} - m^2_{\tilde{q}_L} \tilde{q}_L^\dagger \tilde{q}_L - m^2_{\tilde{q}_R} \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}} \tilde{g}$$

$$+ \sqrt{2} g_s \Big[- \tilde{q}_L^\dagger T (\bar{\tilde{g}} P_L q) + (\bar{q} P_L \tilde{g}) T \tilde{q}_R + \text{h.c.} \Big] - \frac{g_s^2}{2} \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big]$$

- ✤ Besides new UV and R2 (I will not listed here), we also need some special counter terms
- ✤ Mixing angle renormalization (mass and wavefunction)

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \delta Z_{\tilde{t}_L} & \delta Z_{\tilde{t},\rm LR} \\ \delta Z_{\tilde{t},\rm RL} & \delta Z_{\tilde{t}_R} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\delta \mathcal{L}_{\rm off} = -\delta m^2_{\tilde{t},\rm LR} (\tilde{t}_L^\dagger \tilde{t}_R + \tilde{t}_R^\dagger \tilde{t}_L)$$

- ✤ SUSY restoring counter terms

$$\mathcal{L}_{\rm SCT} = \sqrt{2} g_s \frac{\alpha_s}{3\pi} \Big[- \tilde{q}_L^\dagger T_a (\bar{\tilde{g}}^a P_L q) + (\bar{q} P_L \tilde{g}^a) T_a \tilde{q}_R + \text{h.c.} \Big]$$

$$+ \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger \{T_a, T_b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T_a, T_b\} \tilde{q}_L \Big] \times \Big[\tilde{q}_R^\dagger \{T^a, T^b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T^a, T^b\} \tilde{q}_L \Big]$$

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✦ Decay of gluino

$$\mathcal{L}_{\rm decay} = \frac{i}{2} \bar{\chi} \not{\partial} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi + \sqrt{2} g' \Big[- \tilde{q}_L^\dagger Y_q (\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + \text{h.c.} \Big]$$

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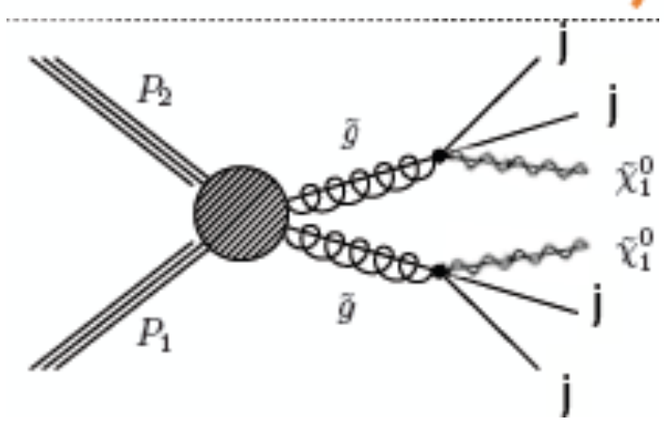
Physics case: gluino searches in the multijet pair+MET channel



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Splitting SUSY

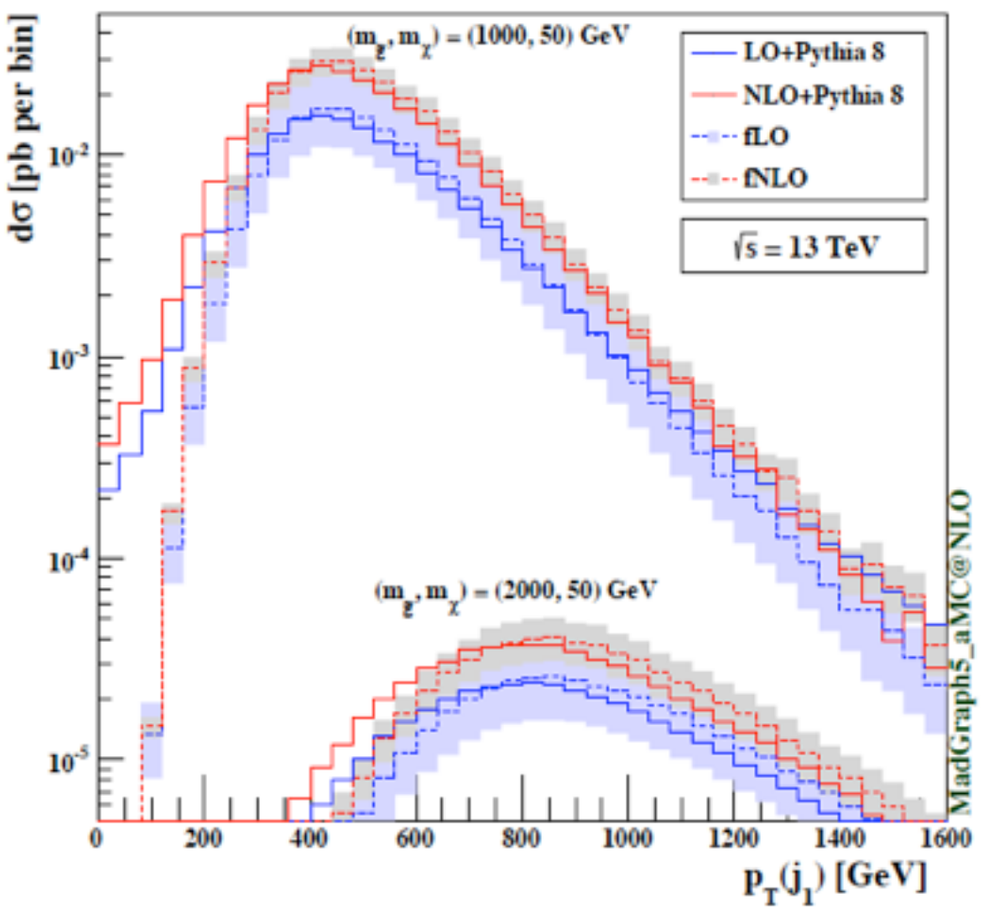
✦ Total rates at 8 TeV and 13 TeV

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%\,+14.0\%}_{-21.9\%\,-14.0\%}$	$3183^{+10.8\%\,+1.8\%}_{-11.6\%\,-1.8\%}$
500	$15.46^{+34.7\%\,+19.5\%}_{-24.1\%\,-19.5\%}$	$24.90^{+12.5\%\,+3.7\%}_{-13.4\%\,-3.7\%}$
750	$1.206^{+35.9\%\,+23.5\%}_{-24.6\%\,-23.5\%}$	$2.009^{+13.5\%\,+5.5\%}_{-14.1\%\,-5.5\%}$
1000	$1.608\cdot 10^{-1}{}^{+36.3\%\,+26.4\%}_{-24.8\%\,-26.4\%}$	$2.743\cdot 10^{-1}{}^{+14.4\%\,+7.3\%}_{-14.8\%\,-7.3\%}$
1500	$6.264\cdot 10^{-3}{}^{+36.2\%\,+29.4\%}_{-24.7\%\,-29.4\%}$	$1.056\cdot 10^{-2}{}^{+16.1\%\,+11.3\%}_{-15.8\%\,-11.3\%}$
2000	$4.217\cdot 10^{-4}{}^{+35.6\%\,+29.8\%}_{-24.5\%\,-29.8\%}$	$6.327\cdot 10^{-4}{}^{+17.7\%\,+17.8\%}_{-16.6\%\,-17.8\%}$

✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case

✤ Validation with PROSPINO 2.1

✤ Sizeable reduction of the scale uncertainties



✦ Differential distributions at NLO

✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions

✤ Gluino decays: MadSpin

✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands

✤ Jet reconstruction: anti-k_T & FASTJET

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✤ Analysis & figure: MADANALYSIS 5

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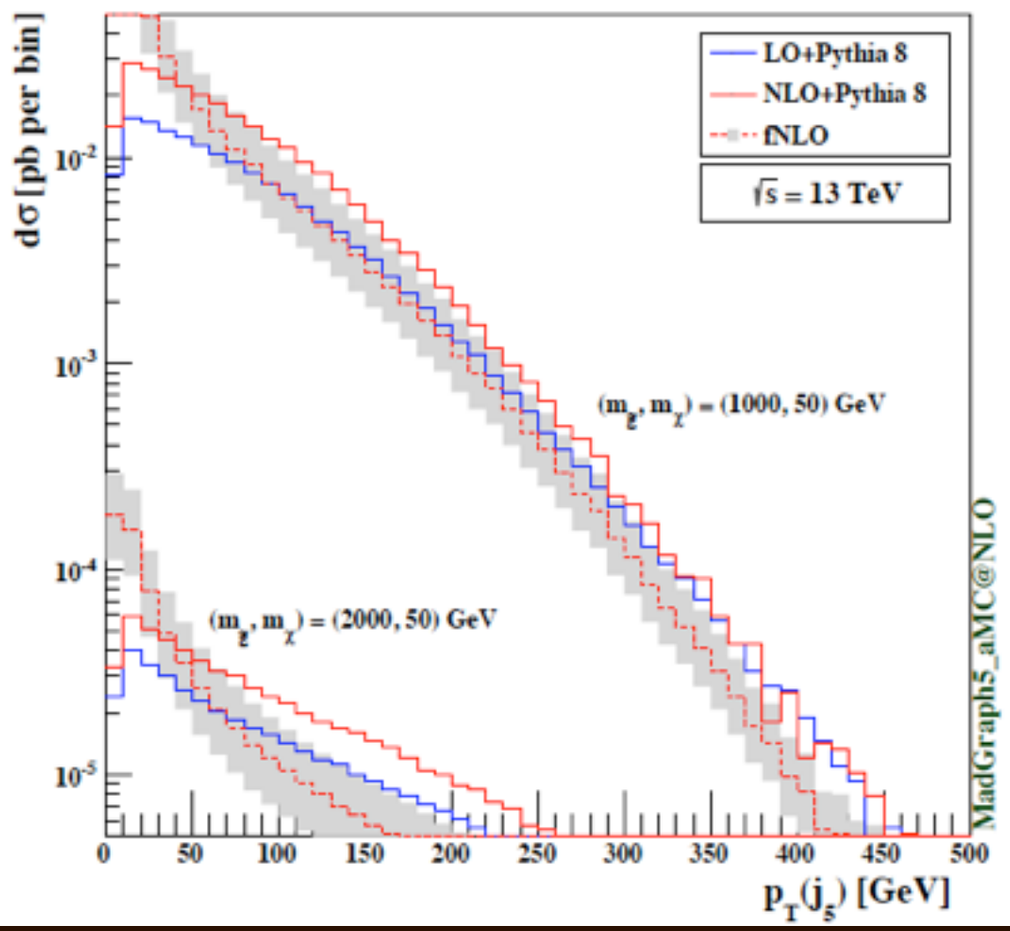

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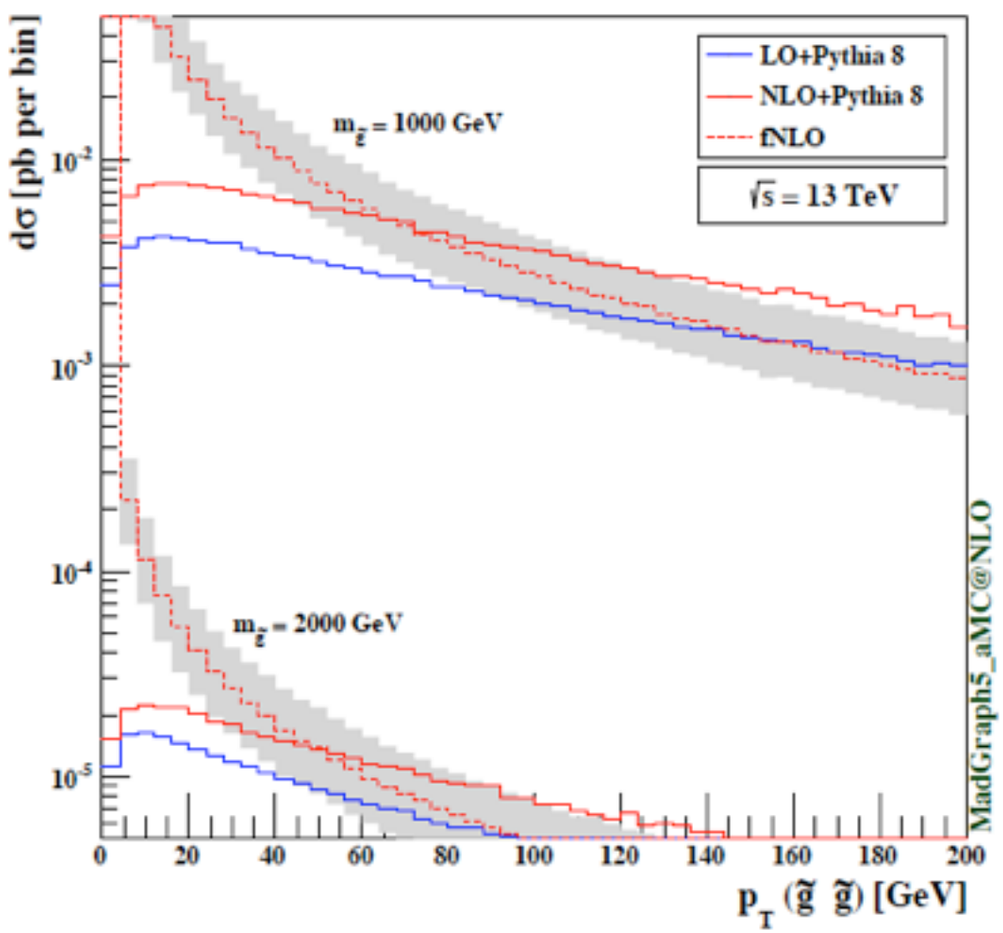

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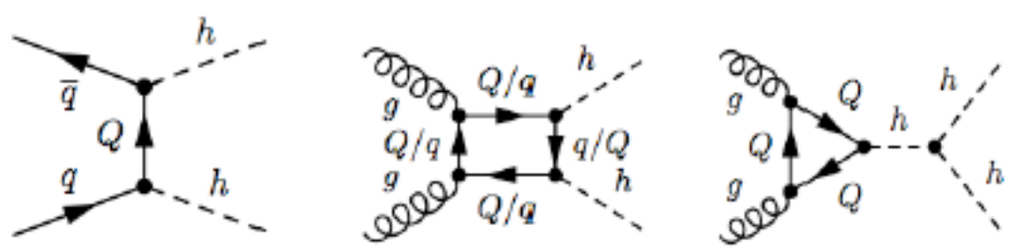
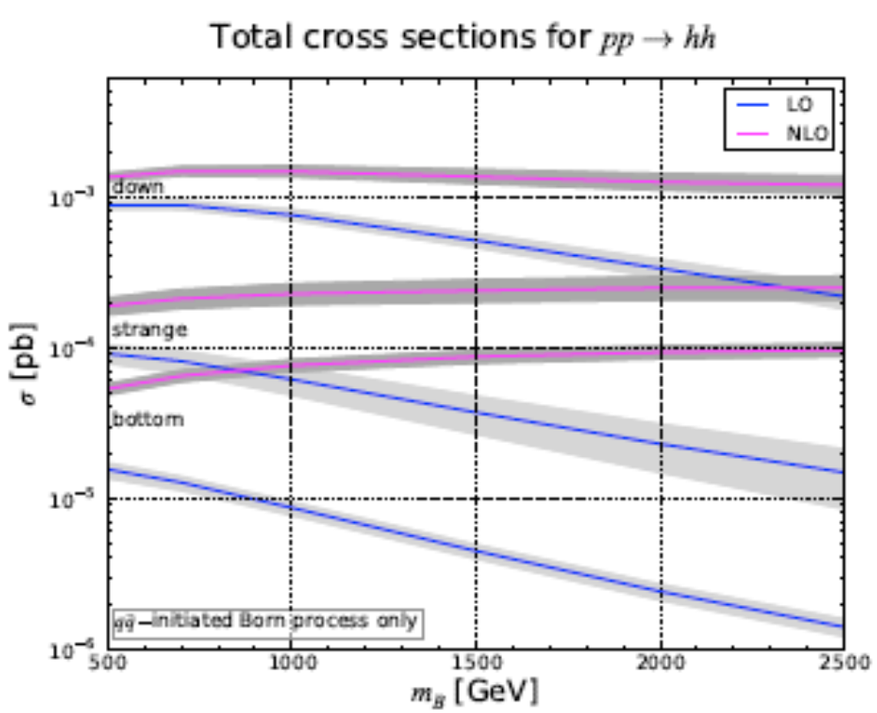
DIHIGGS IN VECTOR-LIKE QUARK

Les Houches 2015: New Physics Working Group Report (1605.02684)

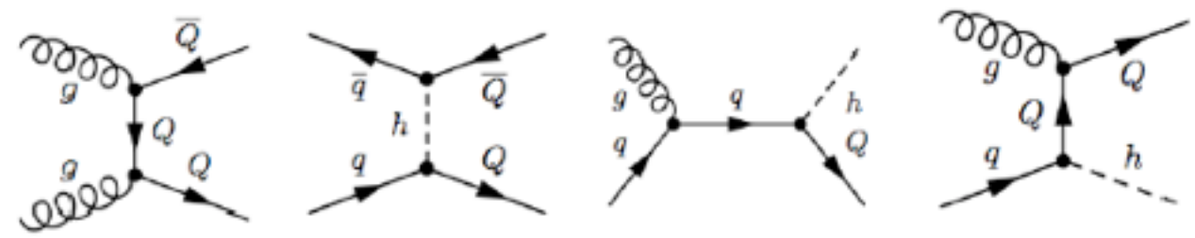
- Small diHiggs production cross section in SM
- Potentially it can be enhanced by new physics
- Vector-like quark model(s) can be an example

Direct production

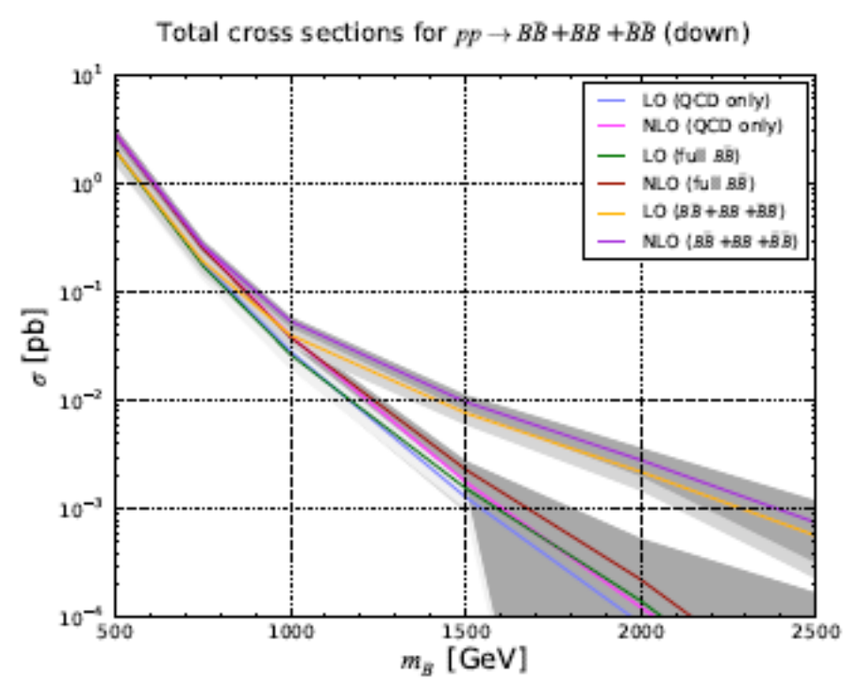




Feeddown production



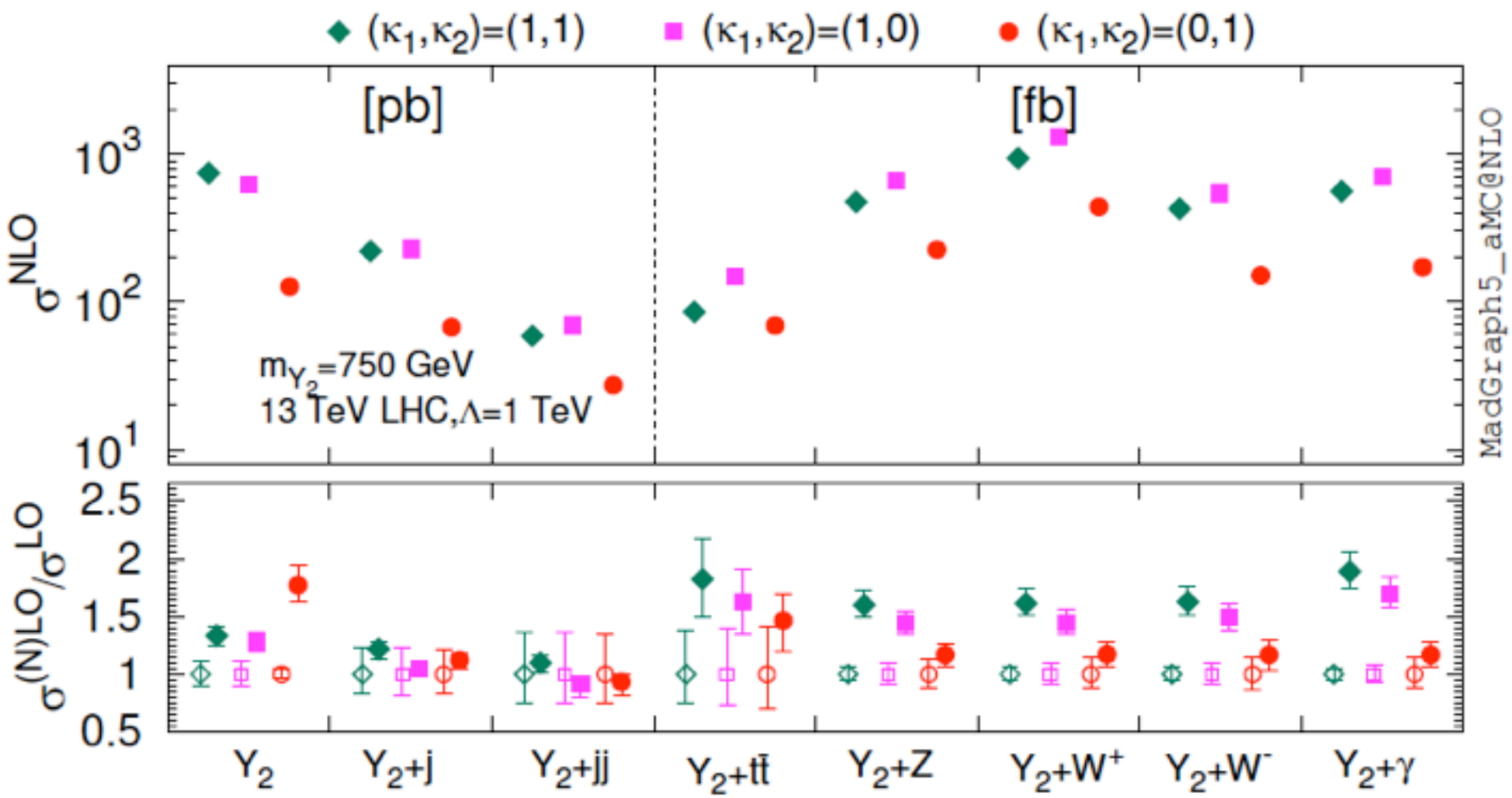
$$\otimes Q(\bar{Q}) \to H + q(\bar{q})$$



SPIN-2 PARTICLE PRODUCTION

Das, Degrande, Hirschi, Maltoni, HSS (1605.09359)

- Many theories predict spin-2 particles
- e.g. graviton in warped extra dimension
- Interpret new excess at the LHC (present and future)
- MG5aMC: the only simulation tool for spin 2 at NLO



SPIN-2 PARTICLE PRODUCTION

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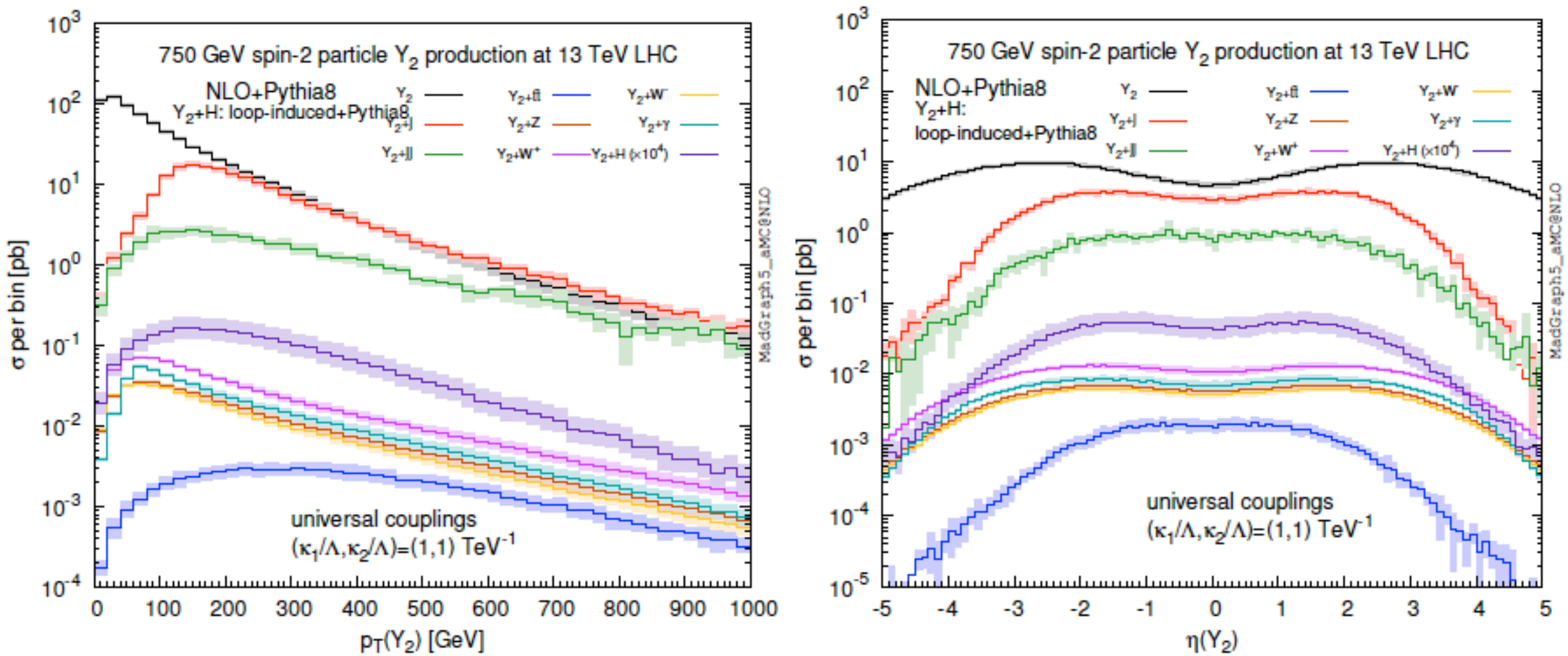

(a) Transverse momentum distribution

(b) Pseudorapidity distribution

SPIN-2 PARTICLE PRODUCTION

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Warning: Do not read it !!!

```
V_8 = CTVertex(name = 'V_8',
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               particles = [ P.g, P.g, P.g, P.g, P.Y2 ],
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'f(-1,1,4)*f(-1,2,3)', 'Identity(1,2)*Identity(3,4)', 'Identity(1,3)*Identity(2,4)', 'Identity(1,4)*Identity(2,3)' ],
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               couplings = {(0,0,0):C.R2GC_285_65,(0,0,1):C.R2GC_285_66,(0,0,2):C.R2GC_285_67,(2,0,0):C.R2GC_285_65,(2,0,1):C.R2GC_285_66,(2,0,2):C.R2GC_285_67,(7,0,0):C.R2GC_427_143,(7,0,1):C.R2GC_427_144,
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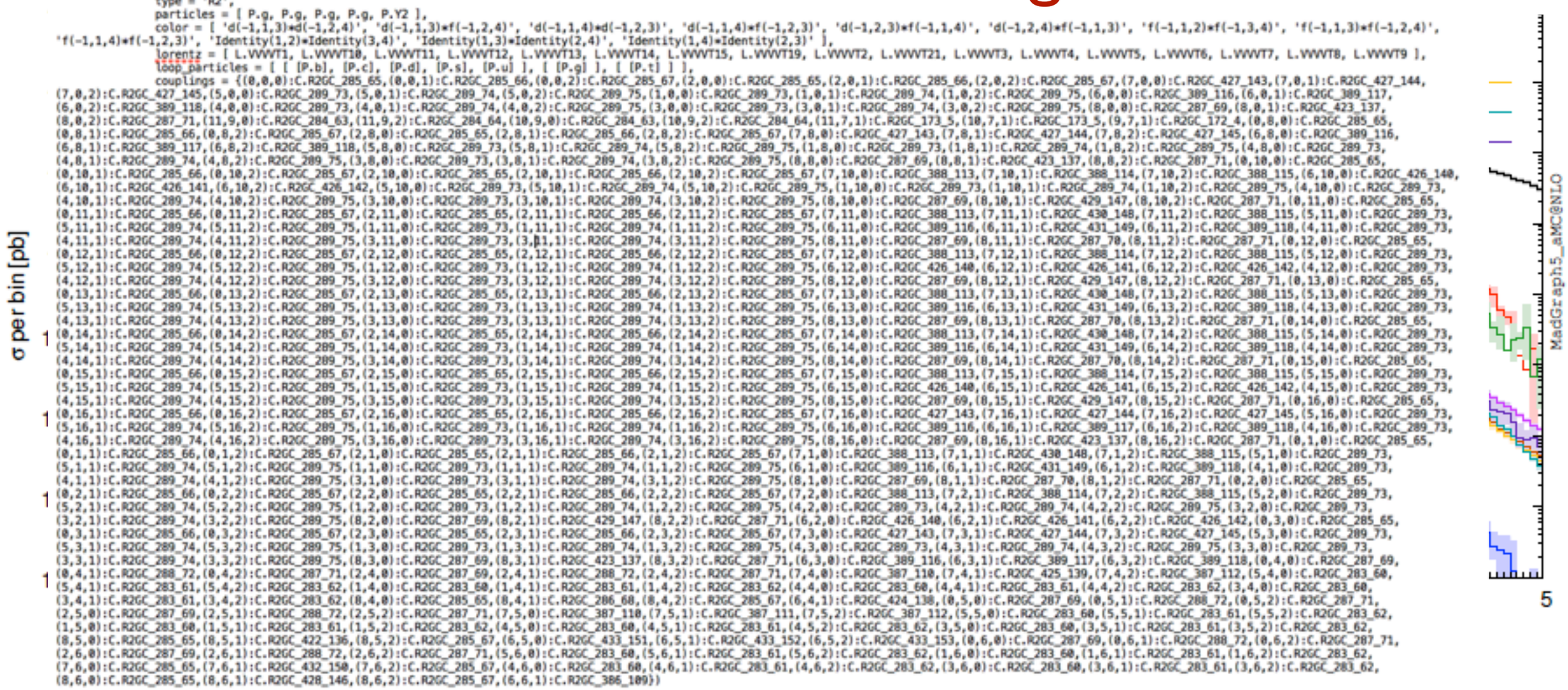

DARK MATTER PRODUCTION AT THE LHC

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  - Mono-X = X + missing energy
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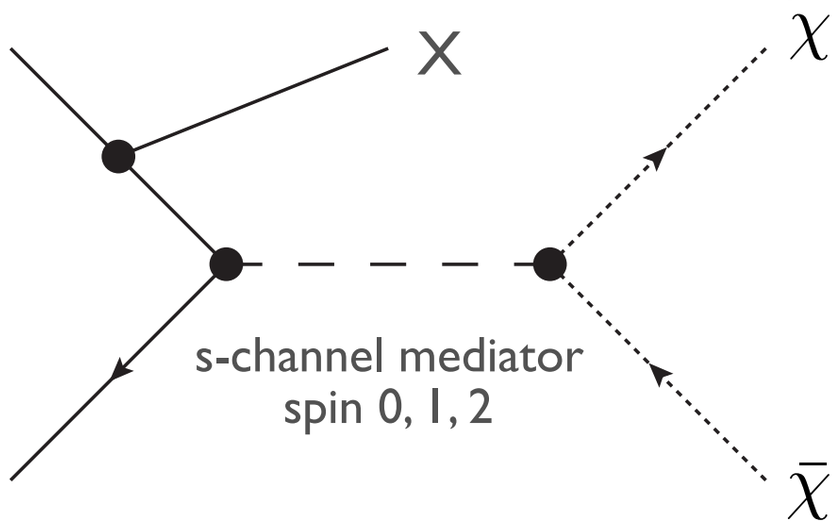

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- **Simplified DM models (cf. DM EFT)**

$$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$

$$\mathcal{L}_{\text{graviton}} = -\frac{\kappa}{\Lambda} Y_2^{\mu\nu} \left(T^G_{\mu\nu} + T^q_{\mu\nu} + T^{\text{FP}}_{\mu\nu} \right)$$

DARK MATTER PRODUCTION AT THE LHC

- **Mono-X DM searches at the LHC**
  - Mono-X = X + missing energy
  - X is one or more reconstructable objects: X=jet, top, ttbar, V, Higgs...
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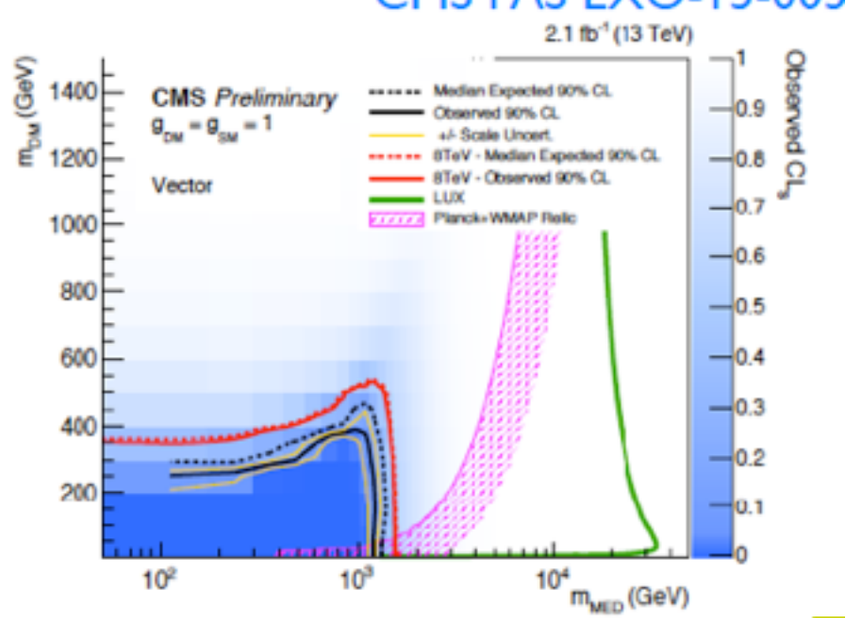
  - The signal is determined by the mediator type, the DM and mediator masses and the couplings

CMS PAS EXO-15-003



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- **Pushing at NLO**
  - Mono-jet, ttbar+MET via spin-0,1 s-channel mediator

    Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen (EPJC'15)
  - Mono-Z via spin-0,1 s-channel mediator

    Neubert, Wang, Zhang (JHEP'16)
  - Mono-jet, ttbar+MET, Mono-V via spin-2 s-channel mediator

    Das, Degrande, Hirschi, Maltoni, Mawatari, HSS (in prep)

DARK MATTER PRODUCTION AT THE LHC

- Let us take mono-jet as an example

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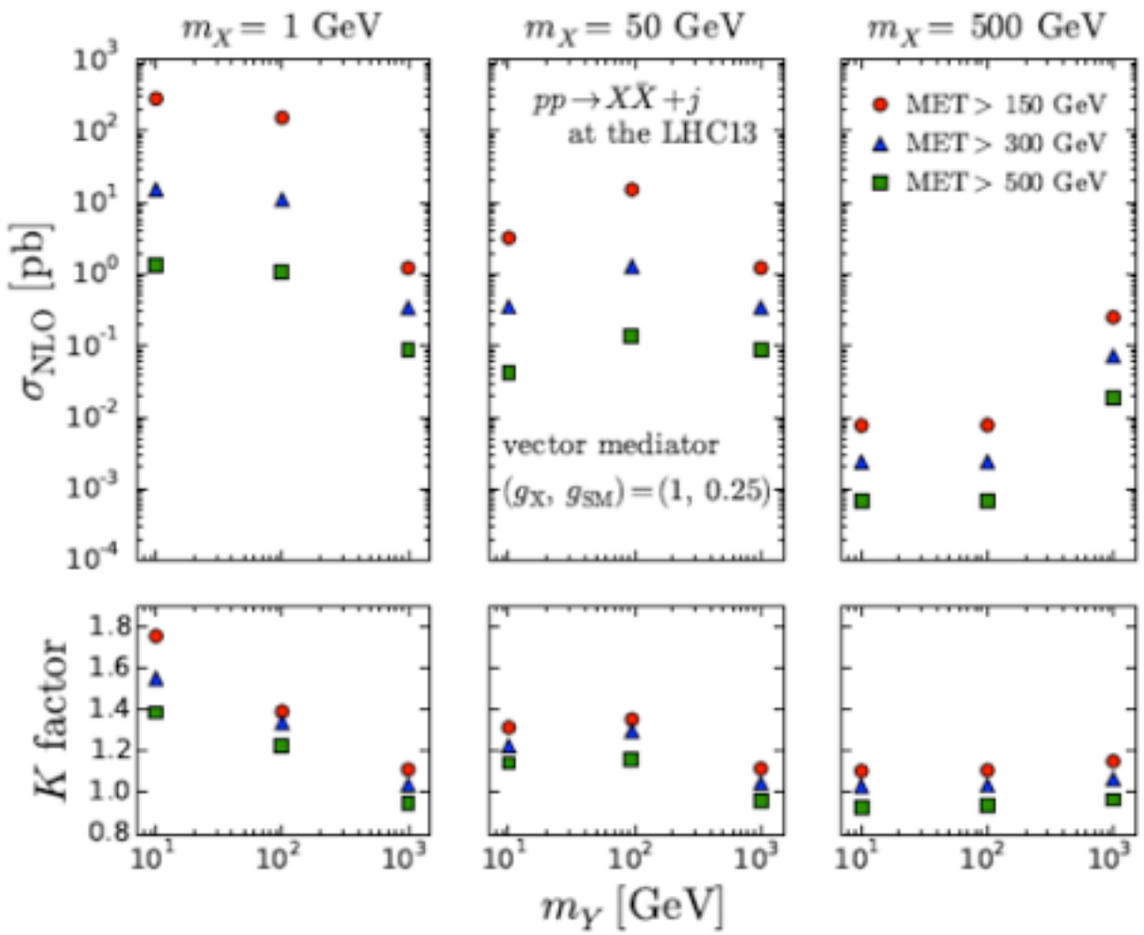
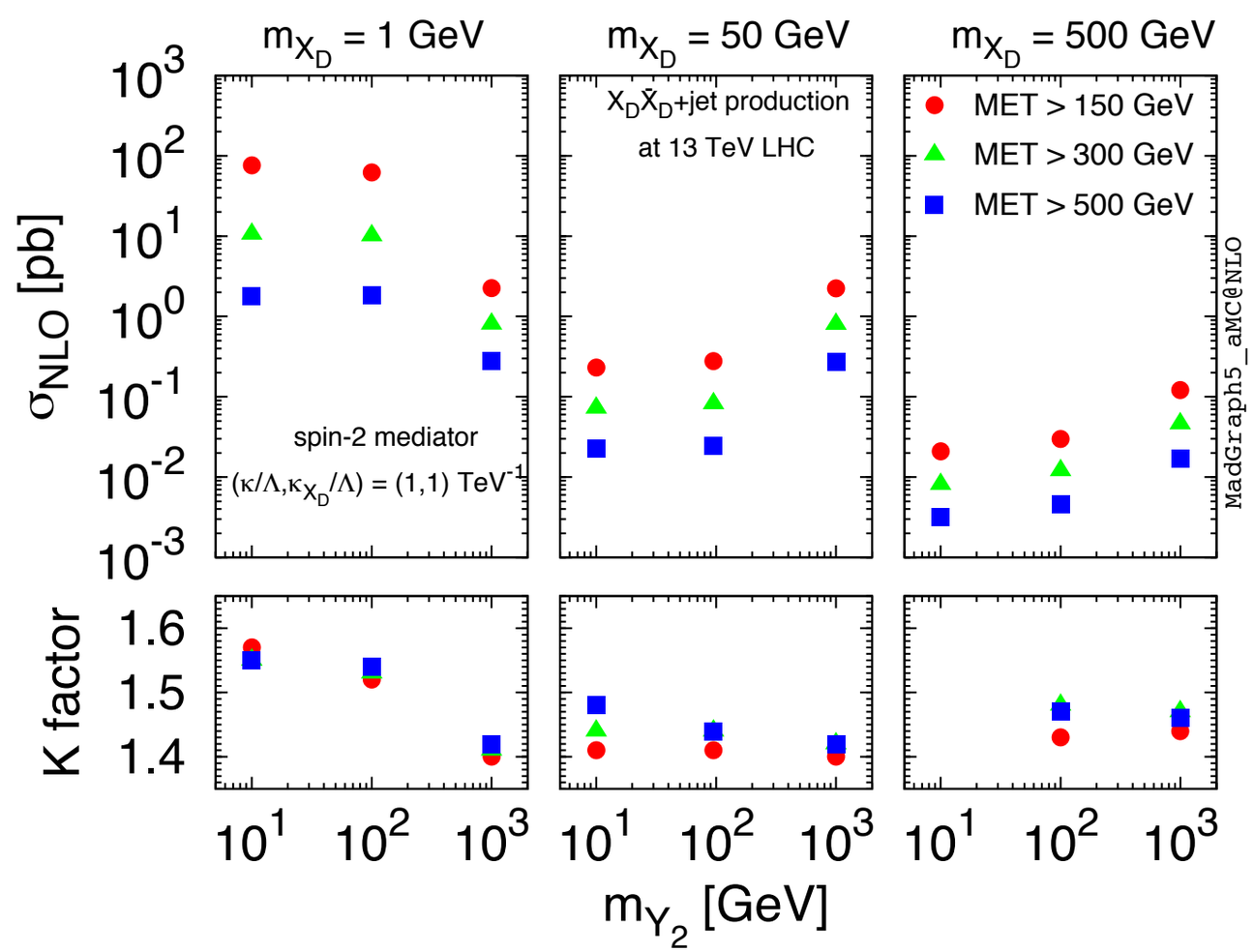


Spin 1



Spin 2

- Strong dependence on the mass spectrum and the kinematical regions
- Sizable reduction of the scale and PDF uncertainties

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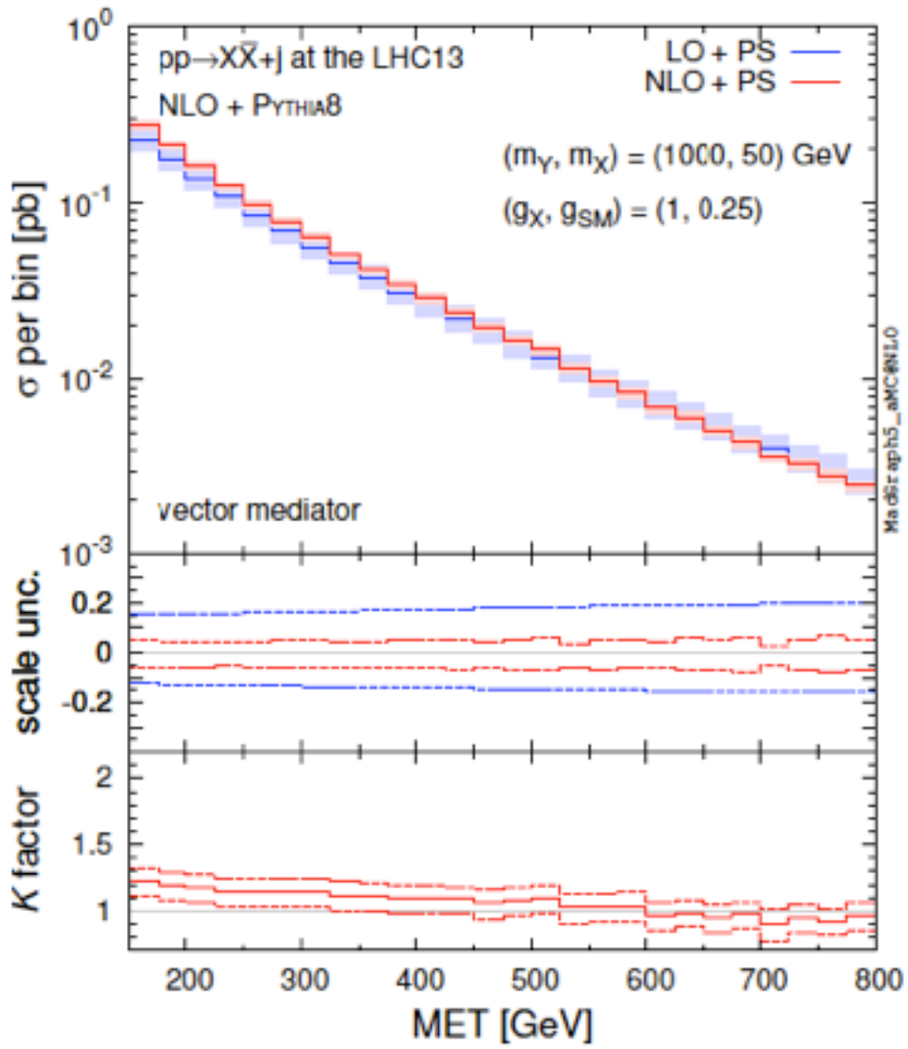

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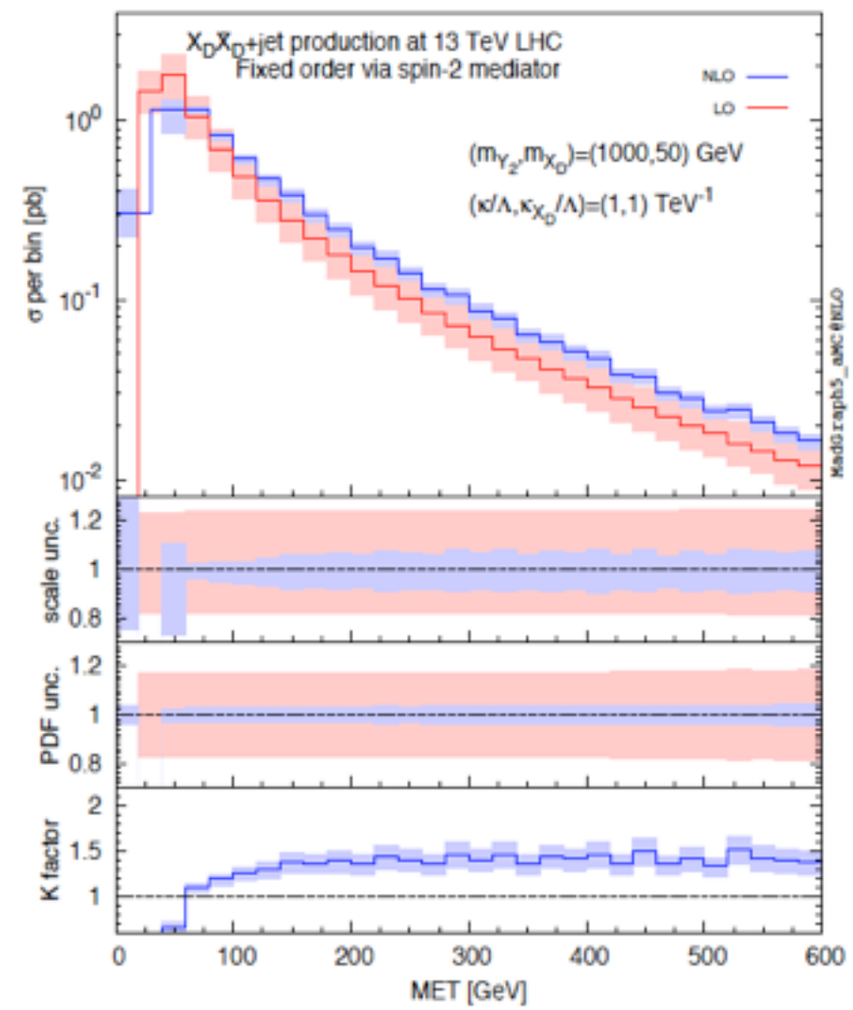

Spin 2

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Conclusion

NLO QCD SIMULATIONS FOR NEW PHYSICS

- The automation of accuracy simulations at NLO QCD for new physics is now feasible
  - *Via a joint use of FeynRules and MadGraph5_aMC@NLO*
  - *A few models are publicly available (more to come soon)*

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-
Top FCNC Model (more details)	C. Zhang	arXiv:1412.5594	TopEFTFCNC.fr	TopFCNC UFO	-
GM (more details)	A. Peterson	arXiv:1512.01243	-	GM_NLO UFO	-
Heavy Neutrino (more details)	R. Ruiz	-	heavyN.fr	HeavyN NLO UFO	-
Spin-2 (more details)	C. Degrande	http://arxiv.org/abs/1605.09359	dm_s_spin2.fr	SMspin2 NLO UFO	-