BSM phenomenology at the next-to-leading order

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Mini-workshop on precision physics and future colliders

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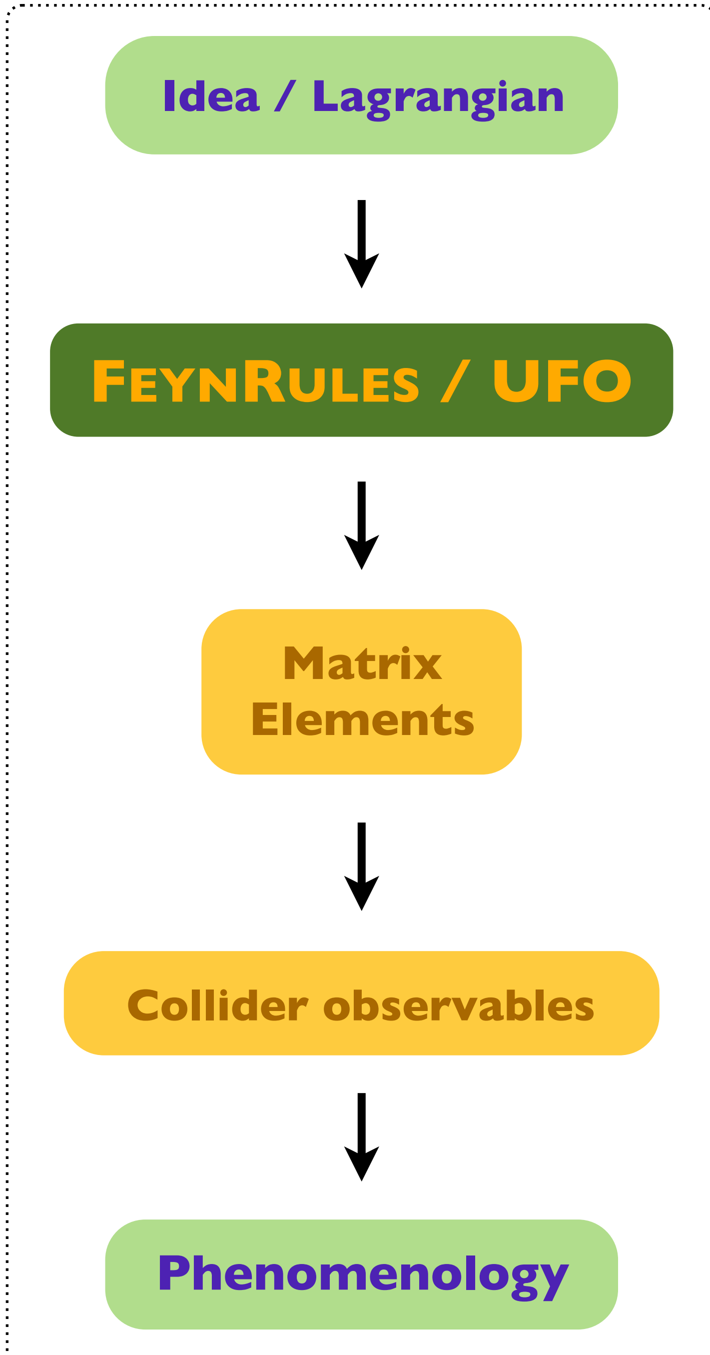
A need for precision predictions for BSM?

- ✦ Final words on any potential new physics at the LHC
  - ✤ Accurate measurements + precision predictions (NLO QCD + PS)
- ✦ New physics is standard in the simulation tools
  - ✤ 20-25 years of developments
  - ✤ Simulations at the NLO accuracy in QCD can be easily achieved
    - ★For any model → the MADGRAPH5_aMC@NLO framework

A comprehensive approach to new physics calculations

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]



✦ Model building: from Lagrangian to tools

- ✤ FeynRules ⊕ MoGRe ⊕ NLOCT → UFO @ NLO
- ✤ General on-shell renormalisation scheme

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

✦ Hard scattering

- ✤ Feynman diagram, matrix elements
- ✤ MG5aMC → predictions at LO/NLO

[Alwall *et al.* (JHEP'14)]

✦ Collider phenomenology with MG5_aMC

- ✤ Matching matrix elements with parton showers
- ✤ Simplified treatment of the resonances (MadStr)

[Alwall *et al.* (JHEP'14)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

Outline

1. Automating NLO calculations in QCD for new physics
2. Examples: supersymmetry, dark matter & vector-like quarks
3. Summary - conclusions

Automating NLO calculations in QCD for new physics

NLO calculations in a nutshell

✦ Dissecting an NLO calculation in QCD

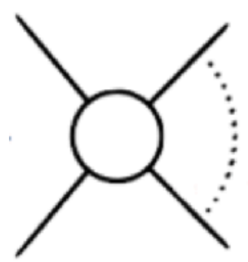
✤ Three ingredients: the Born, virtual loop and real emission contributions

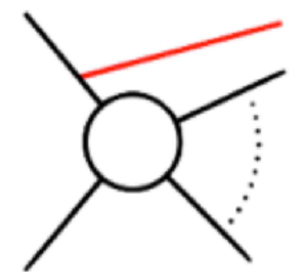
$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \mathcal{B} \quad + \quad \int \mathrm{d}^4\Phi_n \int_{\mathrm{loop}} \mathrm{d}^d\ell\ \mathcal{V} \quad + \quad \int \mathrm{d}^4\Phi_{n+1}\ \mathcal{R}$$

Born

Virtuals: one extra power of α_s and divergent

Reals: one extra power of α_s and divergent





Loop calculations

- **Dimensional regularisation: calculations in $d = 4 - 2\varepsilon$**
  - Divergences explicit ($1/\varepsilon^2$, $1/\varepsilon$)
  - Reduction of tensor loop-integrals to scalar integrals
- **The reduction must be performed in a d-dimensional space**
  - Numerical methods work in 4 dimensions → R_1 and R_2 terms

$$\int \mathrm{d}^d\ell \frac{N(\ell,\tilde{\ell})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}} \quad \text{with } \underbrace{\bar{\ell}}_{\text{D-dim}} = \underbrace{\ell}_{\text{4-dim}} + \underbrace{\tilde{\ell}}_{(-2\varepsilon)\text{-dim}}$$

[Ossala, Papadopoulos, Pittau (NPB'07; JHEP'08)]

- **The R_1 terms originate from the denominators**

MadLoop

$$\frac{1}{\bar{D}} = \frac{1}{D}\left(1 - \frac{\tilde{\ell}^2}{\bar{D}}\right)$$

- 3 generic non-vanishing integrals

[Hirschi *et al.* (JHEP'11)]

- **The R_2 terms originate from the numerator**

NLOCT

  - Process-dependent contributions proportional to $\tilde{\ell}^2$
  - Renormalisable theory: finite number of R_2's → *R_2 Feynman rules*

[Degrande (CPC'15)]

Matching fixed order with parton showers

[Frederix, Frixione, Maltoni & Stelzer (JHEP'09); Frixione & Webber (JHEP'02)]

MADFKS

✦ Subtracting the poles

✤ The structure of the poles is known → subtraction

★ $\mathcal{C}$ subtracted from the reals → finite

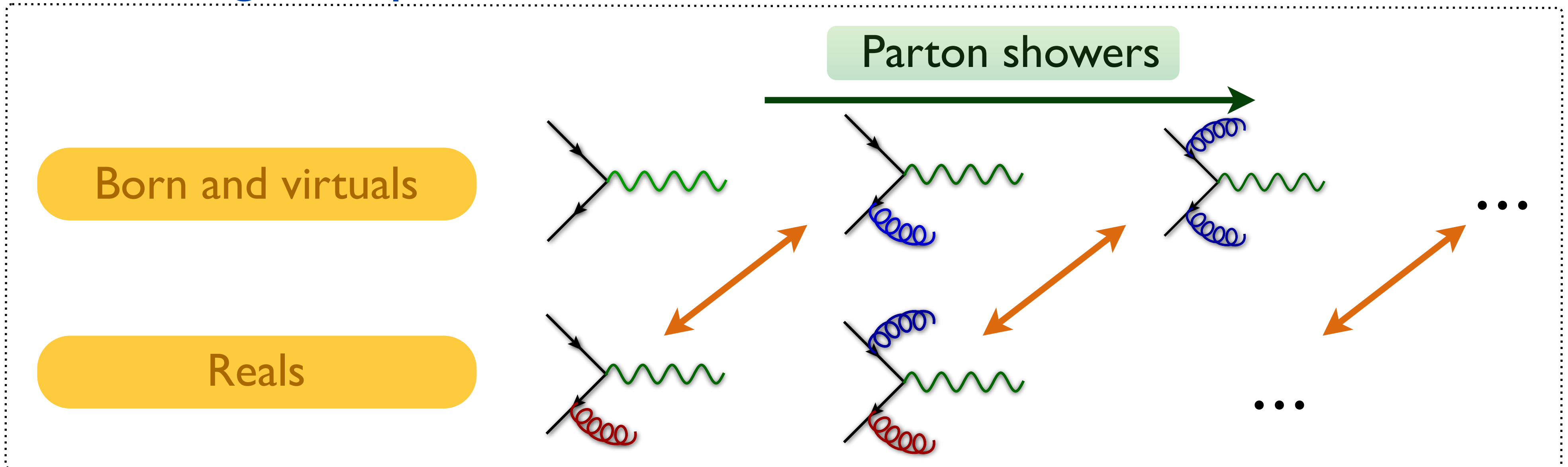
★ $\mathcal{C}$ integrated and added back to the virtuals → finite

★ Integrals can be calculated numerically (and in 4D)

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n\ \mathcal{B} + \int \mathrm{d}^4\Phi_{n+1}\ \Big[\mathcal{R} - \mathcal{C}\Big] + \int \mathrm{d}^4\Phi_n \Big[\int_{\mathrm{loop}} \mathrm{d}^d\ell\ \mathcal{V} + \int \mathrm{d}^d\Phi_1 \mathcal{C}\Big]$$

MC@NLO

✦ Matching with parton showers



✤ Two sources of double counting

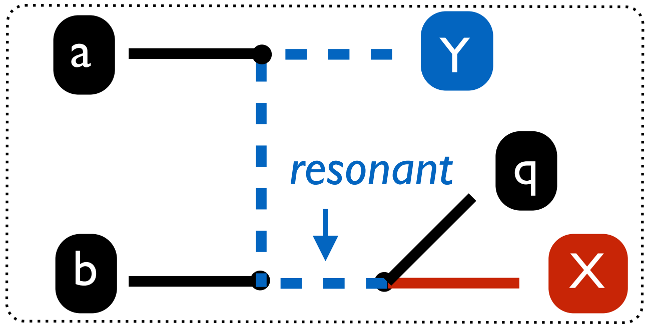
★ Radiation: reals *vs.* shower

★ No radiation: virtuals *vs.* no-emission probability

Intermediate resonances

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

✦ Resonant contribution could appear at NLO (real emission)



- ✤ Overlap
  - ★ YY @ LO ⊗ Y → Xq decay
  - ★ YX @ NLO (real emission)
- ✤ Possible (huge) enhancement w.r.t. LO (if YY dominates over XY)
  - ★ Spoiling the perturbative expansion for the original process
- ✤ All potential subprocesses may need to be considered separately
  - ★ Resonances must be subtracted

✦ Resonance subtraction/removal from the squared matrix element

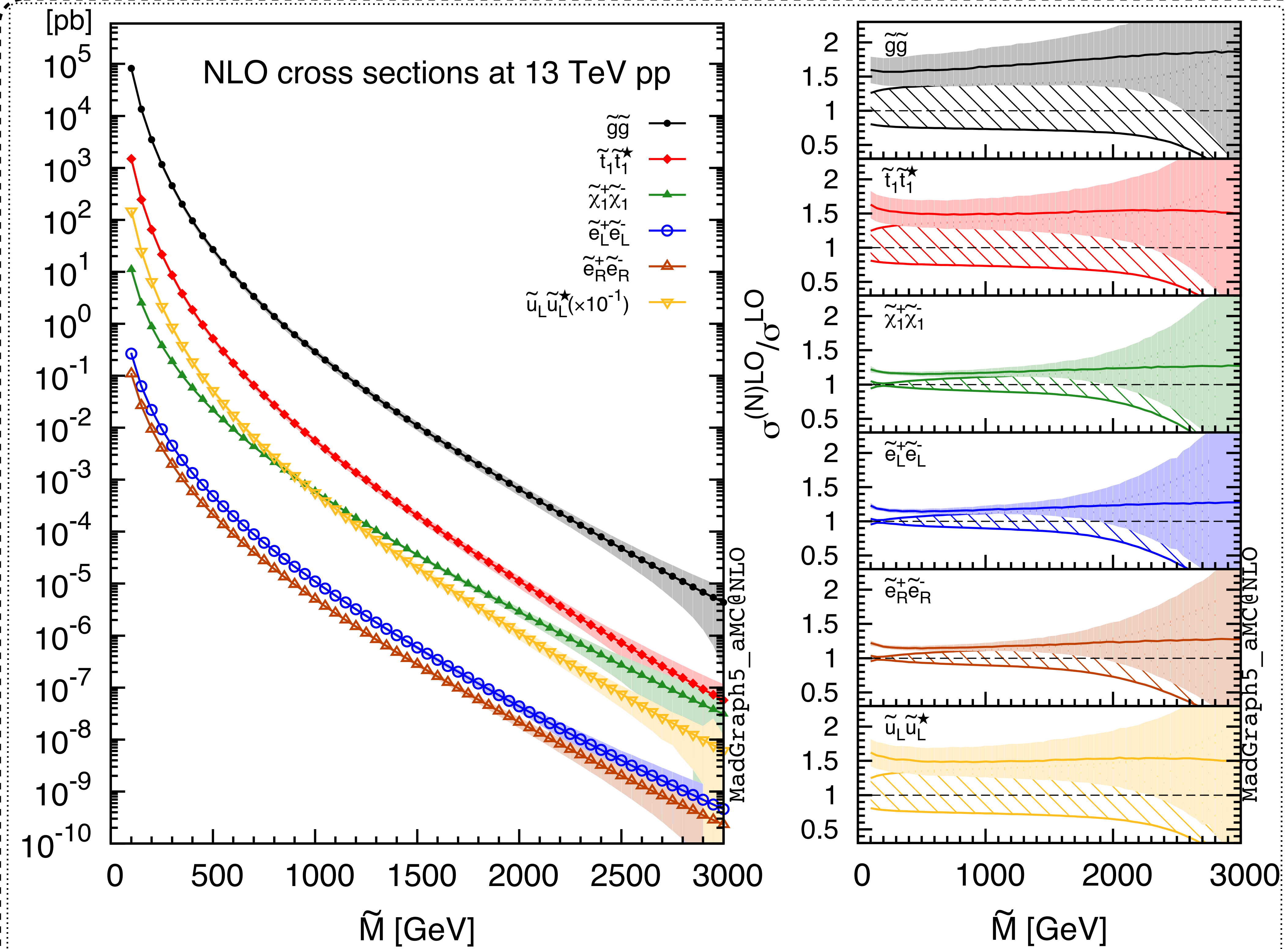
$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\mathrm{non-res.})}\right|^2 + 2\Re\Big(\mathcal{A}^{(\mathrm{non-res.})}\mathcal{A}^{(\mathrm{res.})\dagger}\Big) + \left|\mathcal{A}^{(\mathrm{res.})}\right|^2$$

- ✤ DR: the resonant diagrams are removed
- ✤ DR+I: diagram removal while keeping the interferences
- ✤ DS: the purely resonant part is subtracted from the last term
  - ★ There are different ways to handle this (momenta projections)

Supersymmetry @ NLO

SUSY rates at 13 TeV (simplified models)

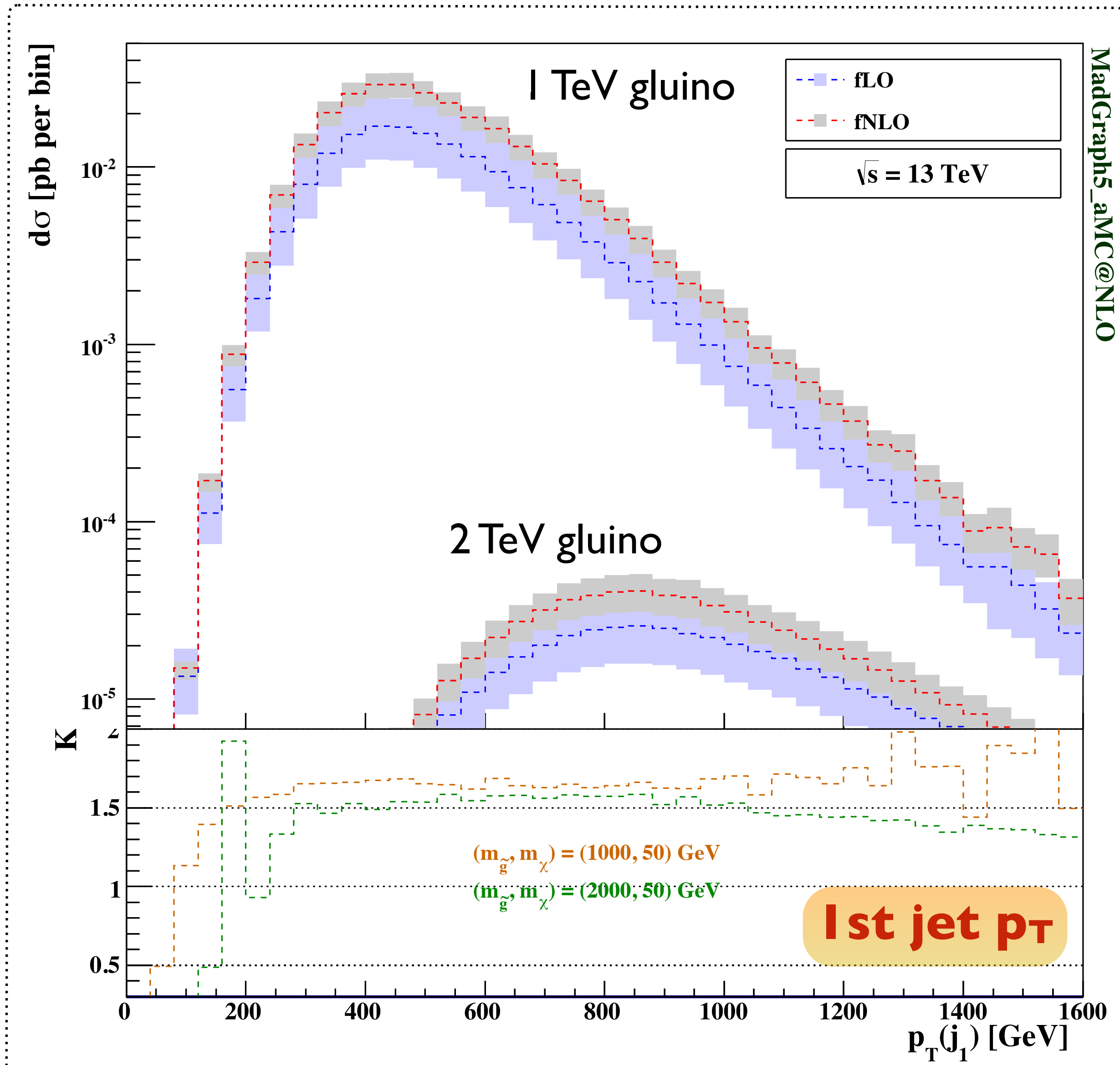
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

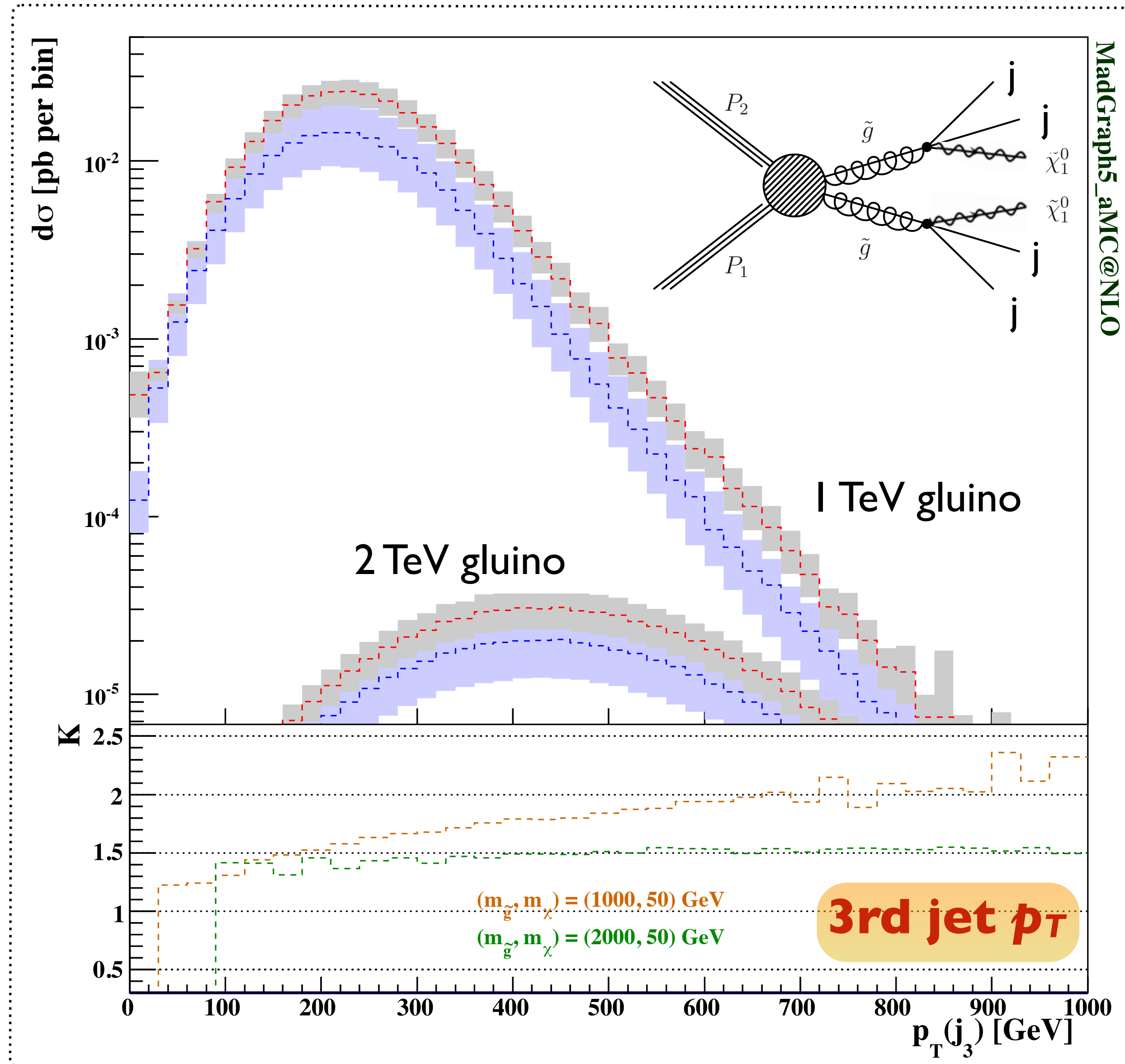


- K~ 1.2-1.5
- $K = f(\tilde{M})$
- Errors are reduced
- PDF error can be large

Fixed-order distributions: jet properties

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15; PLB'16)]

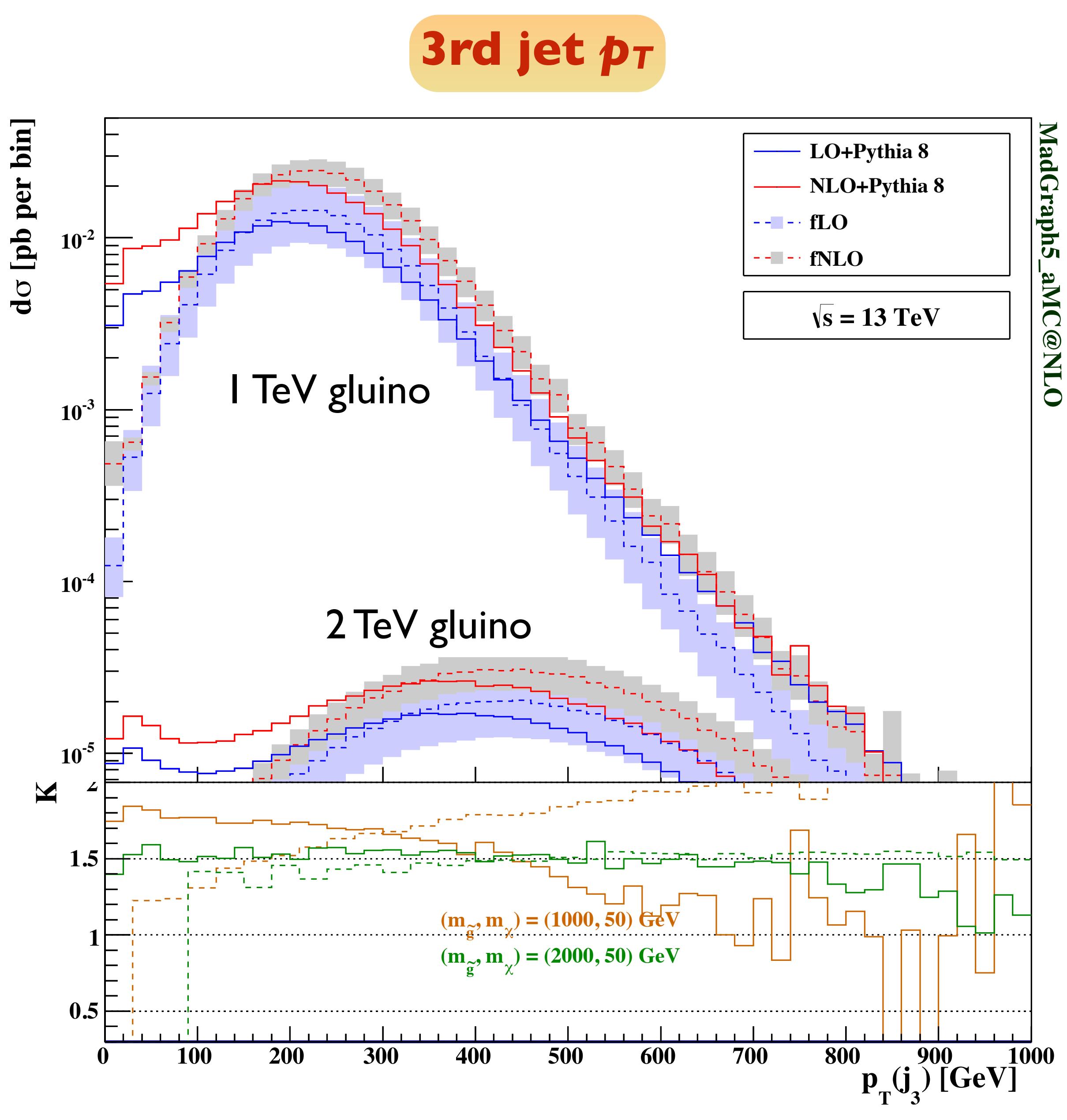




- ✤ Two potential jet origins
  - ★ Decay jet (hard)
  - ★ Radiation jet (soft, not for the 1st/2nd jets)
- ✤ Constant *K*-factors not accurate
  - ★ Normalisation modification
  - ★ Distortion of the shapes
  - ★ Reduction of the theoretical uncertainties

NLO+PS distributions: jet properties

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15; PLB'16)]



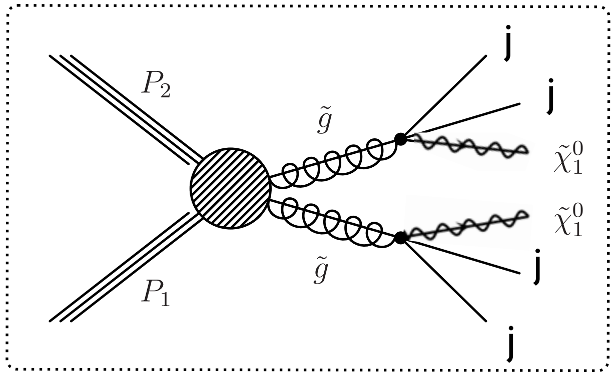
- Parton showers populate the low-p_T region
  - ★ Emitted partons often not reclustered back
  - ★ Extra softer jets
  - ★ Distortion of the spectrum
  - ★ Effects milder for hard p_T (the matrix element drives the shape)
- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes a radiation jet
  - ★ Entanglement of the two effects: two peaks

Impact of the uncertainties → future colliders

[Araz, Frank & BF (to appear)]

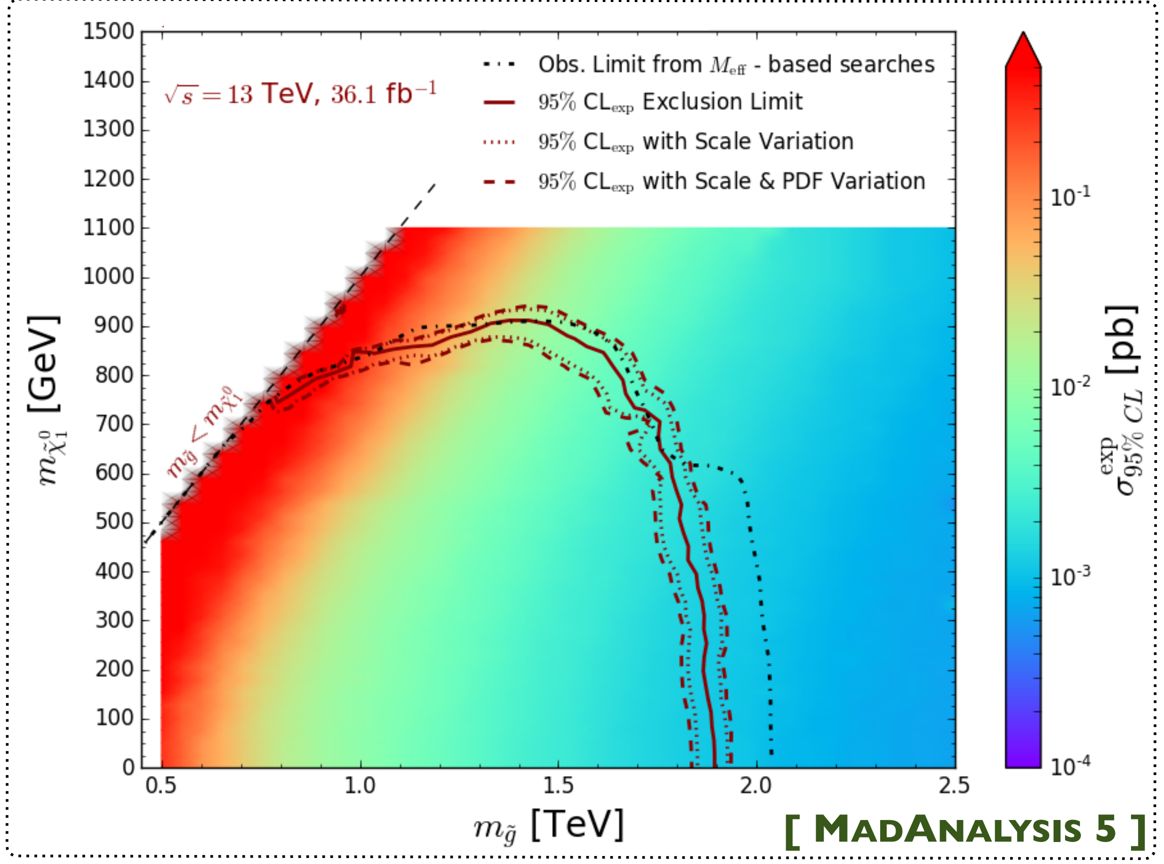
✦ Constraining gluino pair production and decay @ LHC

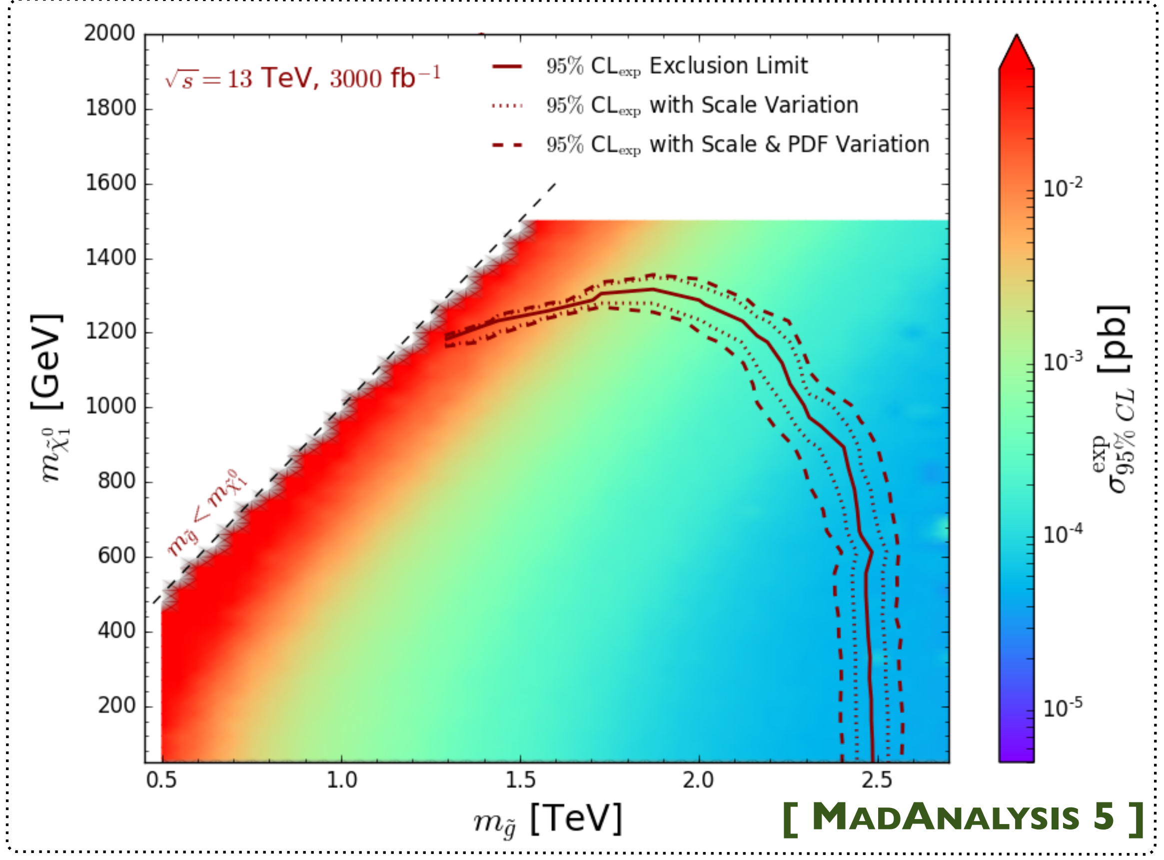
- NLO impact on the shapes of the distributions
- Impact on the limits?
- Impact of the theory uncertainties?



✦ Recasting ATLAS multijet + MET analysis (ATLAS SUSY 2016-07)

- Left: reproduction of the ATLAS results (LO-merged; $\sigma_{NLL/NLO}$) with NLO signals
- Right: extrapolation for HL-LHC → impact of the errors





Treatment of the resonances

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

	[fb]	DR	DR + I	DS				LO
$\tilde{g}\tilde{g}$	$\sigma_{\text{inclusive}}$	0.331	$0.330^{+19\%}_{-18\%} \pm 28\%$	0.327	0.322	0.330	0.330	$0.187^{+44\%}_{-29\%} \pm 27\%$
	σ_{fiducial}	0.228	$0.227^{+19\%}_{-18\%} \pm 28\%$	0.225	0.222	0.228	0.227	$0.128^{+44\%}_{-29\%} \pm 27\%$
$\tilde{g}\tilde{q}$	$\sigma_{\text{inclusive}}$	8.42	$8.39^{+12\%}_{-14\%} \pm 6.9\%$	8.38	8.35	8.41	8.40	$5.49^{+38\%}_{-25\%} \pm 7.0\%$
	σ_{fiducial}	5.93	$5.91^{+12\%}_{-14\%} \pm 6.9\%$	5.90	5.87	5.93	5.92	$3.86^{+38\%}_{-26\%} \pm 7.0\%$
$\tilde{q}\tilde{q}$	$\sigma_{\text{inclusive}}$	20.4	$20.4^{+7.8\%}_{-10\%} \pm 2.2\%$	20.4	20.4	20.4	20.4	$14.9^{+30\%}_{-22\%} \pm 2.2\%$
	σ_{fiducial}	14.8	$14.8^{+7.8\%}_{-9.9\%} \pm 2.2\%$	14.8	14.7	14.8	14.8	$10.8^{+30\%}_{-21\%} \pm 2.2\%$

- Benchmark (allowed by data)
  - ★ Multi-TeV squarks and gluinos
  - ★ 50 GeV lightest neutralino (decays into jets and missing energy)
  - ★ Typical H_T/MET selection (+ N_{jets} requirement)
- NLO impact
  - ★ Large K-factors (especially for $\tilde{g}\tilde{g}$), reduction of the theory errors
  - ★ 50 GeV lightest neutralino (decays into jets and missing energy)
  - ★ Results compatible regardless of how resonances are treated

No double counting

Dark matter @ NLO

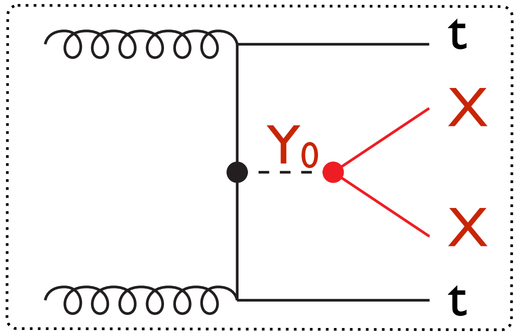
Top-philic dark matter

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

✦ A simplified model for top-philic dark matter

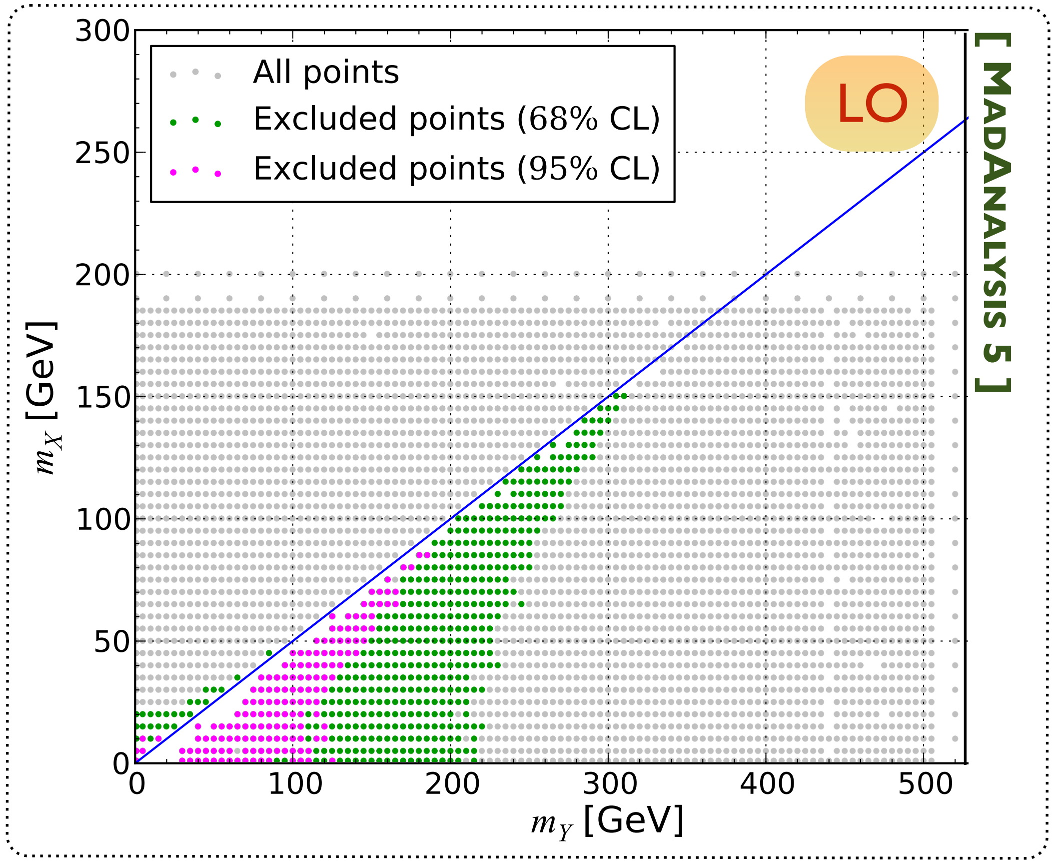
- ✤ A dark sector with a fermionic dark matter candidate X
- ✤ A (scalar) mediator Y_0 linking the dark sector and the top

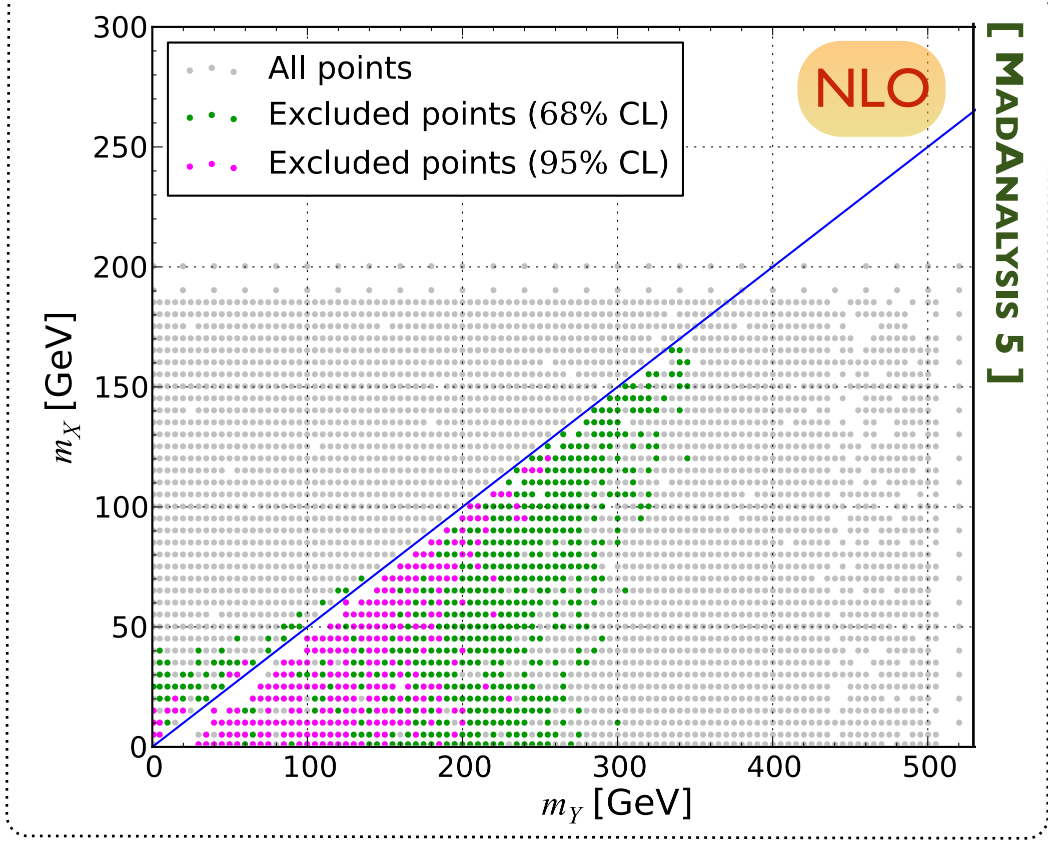
$$\mathcal{L}_{t,X}^{Y_0} = -\left(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\right) Y_0$$



- ✤ Could be probed with $t\bar{t}$+MET events (CMS-B2G-14-004)

✦ For central scales: mild (but visible) NLO effects on the exclusions





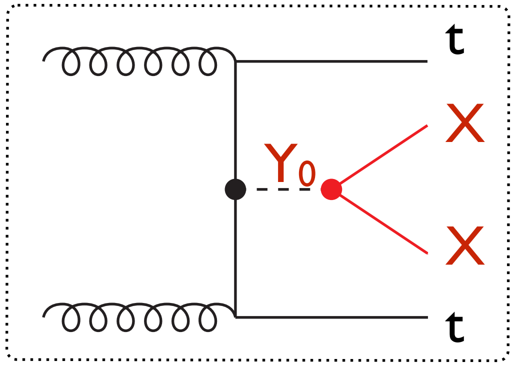
- ✤ How is the picture changing when including scale variations?

NLO effects on a CLs

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

✦ There are theoretical uncertainties on a CLs number

	(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]	$\rm CL_{LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\rm CL_{NLO}$ [%]
I	(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$98.7^{+0.8\%}_{-13.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$	$95.0^{+2.7\%}_{-0.4\%}$
II	(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$74.7^{+19.7\%}_{-17.7\%}$	$0.926^{+5.7\%}_{-10.4\%}$	$84.2^{+0.4\%}_{-14.4\%}$
III	(240, 100) GeV	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$

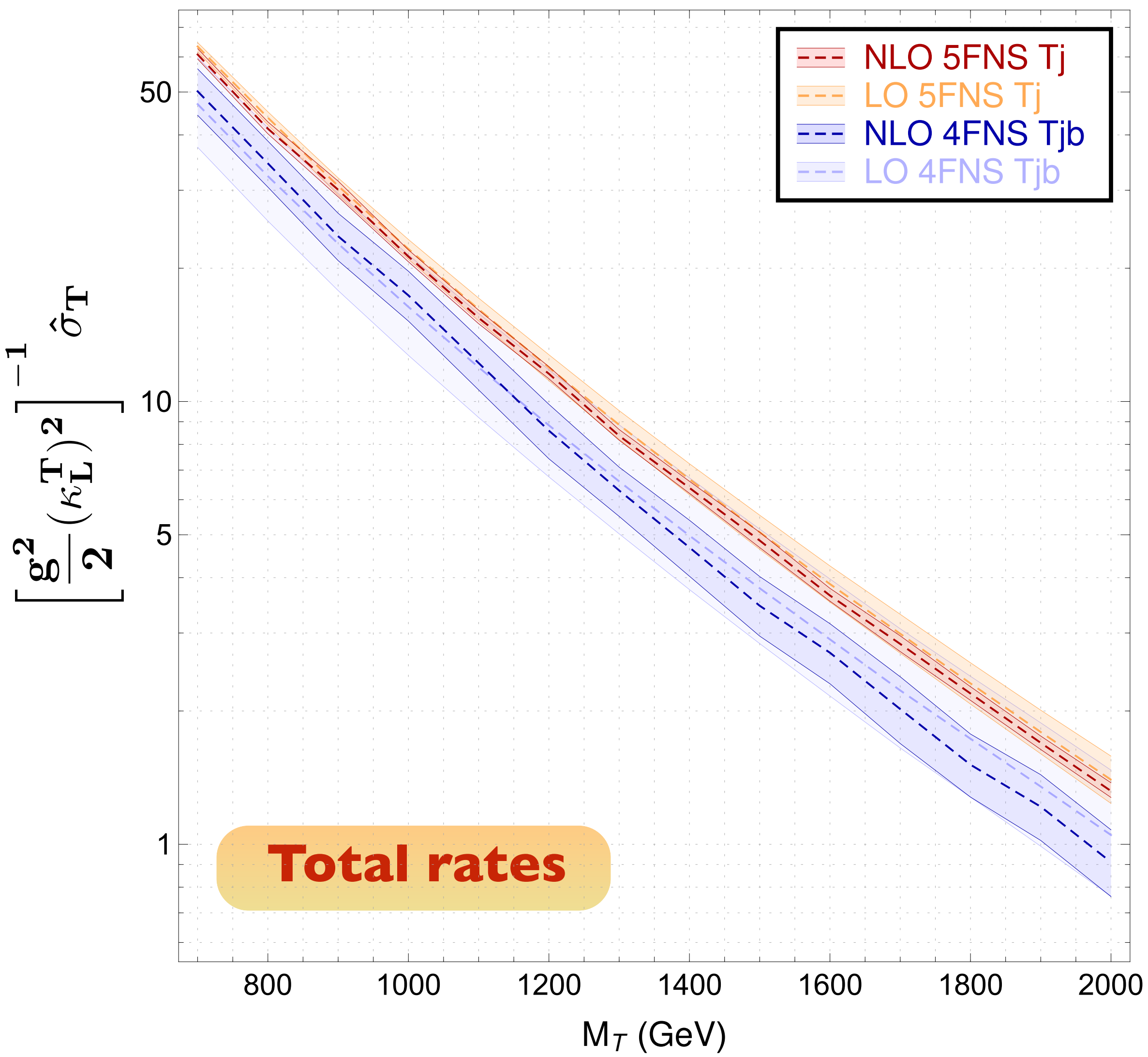


- ✤ An excluded point may not be excluded when accounting for uncertainties
- ✤ The CLs number can increase / decrease at NLO
- ✤ The error band is reduced

3rd generation VLQ @ NLO

[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB`19)]

✦ Single VLQ production (top partner)

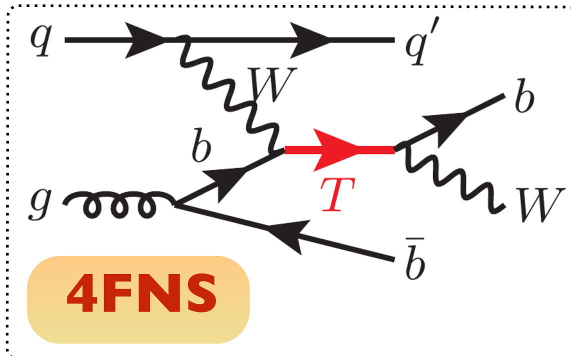


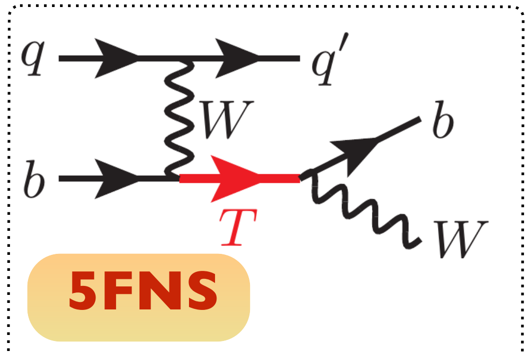
✦ Lagrangian and diagrams

✤ Production through W-couplings

$$\mathcal{L}_{\rm VLQ} = i\bar{T}\not{D}T - m_T\bar{T}T + \frac{\sqrt{2}g}{2}\,\kappa_L^T\left[\bar{T}\not{W}P_L q_d + \text{h.c.}\right]$$

✤ Diagrams



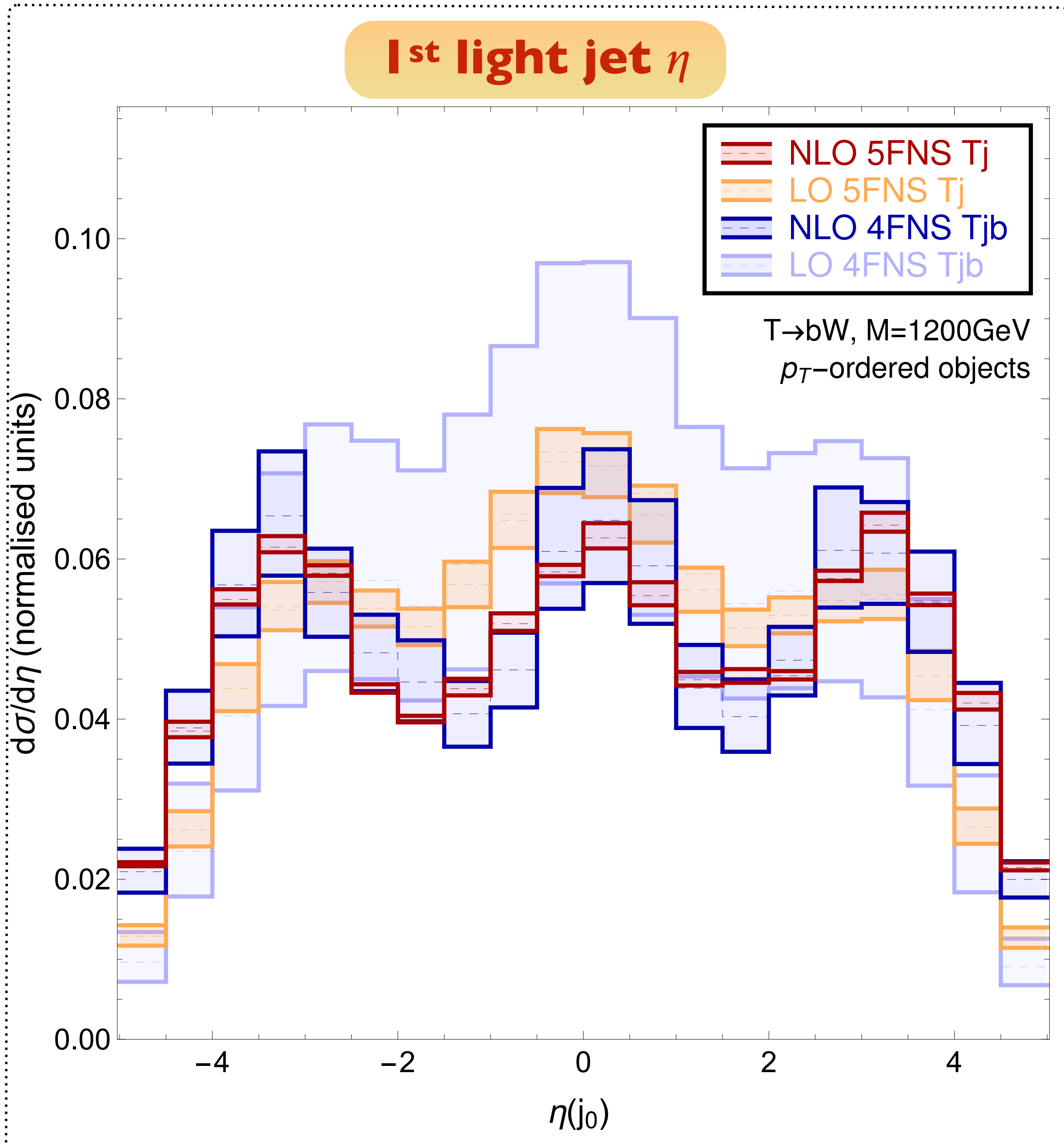


✦ Total rates at NLO (4 and 5 FNS)

- ✤ 5FNS: $K < 1$ (virtuals)
- ✤ 4FNS: $K = f(M_T)$
- ✤ Reduction of the uncertainties
- ✤ Log Q/m_b resummation (5FNS) (differences at NLO for large masses)

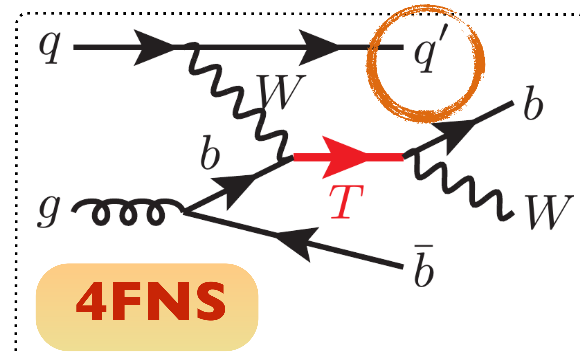
Leading jet pseudorapidity

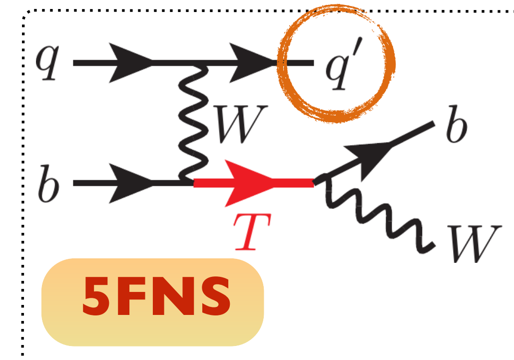
[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB`19)]



✤ Top-partner VLQ coupled to the W-boson

✤ The leading jet: key handle on the signal





✤ 4FNS/5FNS shape agreement @NLO

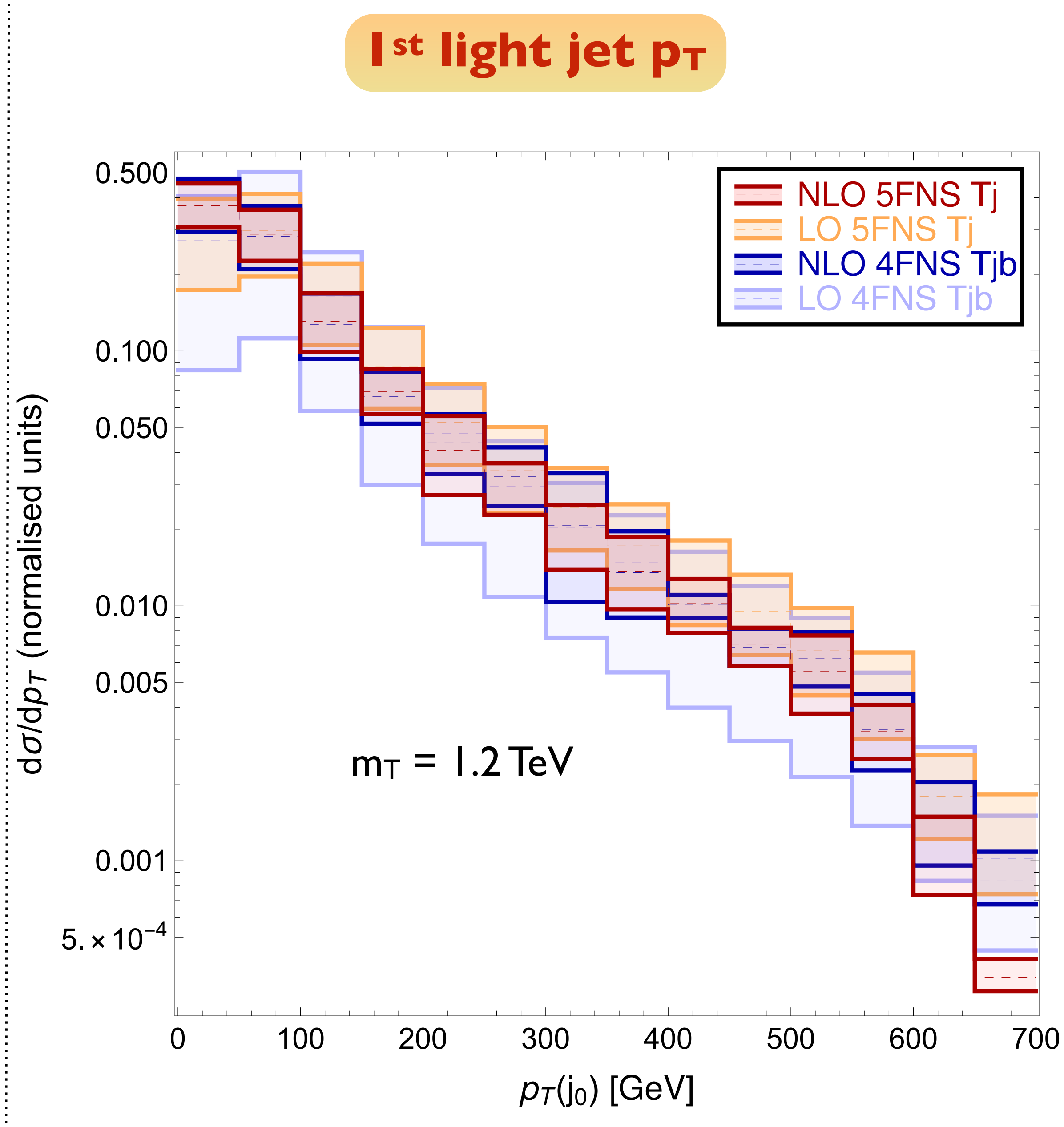
- ★ Forward jets crucial for signal selection

✤ NLO effects

- ★ Important distortion of the shapes
  - ➢ K factors are NOT constant
- ★ Reduction of the uncertainties at NLO

Leading jet transverse momentum

[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB`19)]



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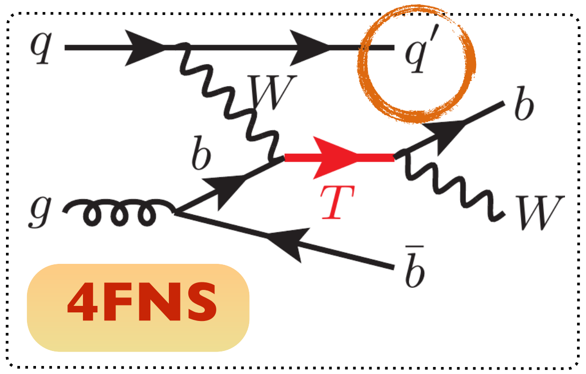

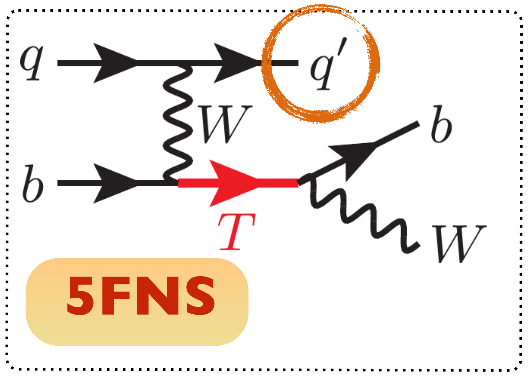

✤ NLO effects
- ★ Reduction of the uncertainties at NLO
- ★ Important distortion of the shapes

✤ 4FNS/5FNS: large differences at high p_T
- ★ A gg channel kicks in at NLO
  - → impact the tails

Impact on a search investigated…

Summary

Summary

✦ NLO-QCD simulations for new physics are easy to handle

- In particular via a joint use of FeynRules and MadGraph5_aMC@NLO
- Many models are publicly available
  - ★ Supersymmetric (simplified or not) models
  - ★ BSM Higgs models
  - ★ Dark matter simplified models
  - ★ Higgs and top effective field theories
  - ★ Vector-like quark models
  - ★ Extra gauge bosons

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

✦ Impact

- NLO effects are important and should be accounted for
- Shape distortion, large K-factors
- Uncertainties under better control
- More robust predictions