New physics simulations at the next-to-leading order

Benjamin Fuks

LPTHE / Sorbonne Université

High-energy physics seminar

LAPTH, Annecy, 29 October 2019

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

Outline

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

NLO calculations in a nutshell

✦ Dissecting an NLO calculation in QCD

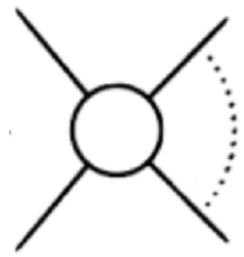
✤ Three ingredients: the Born, virtual loop and real emission contributions

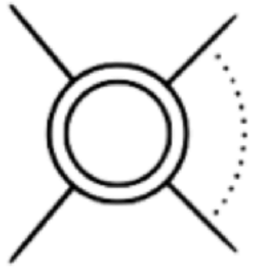
$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \mathcal{B} \quad + \quad \int \mathrm{d}^4\Phi_n \int_{\text{loop}} \mathrm{d}^d\ell \ \mathcal{V} \quad + \quad \int \mathrm{d}^4\Phi_{n+1} \ \mathcal{R}$$

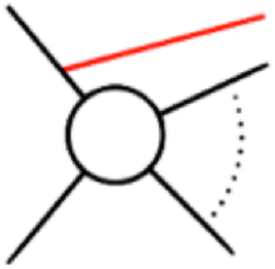
Born

Virtuals: one extra power of α_s and divergent

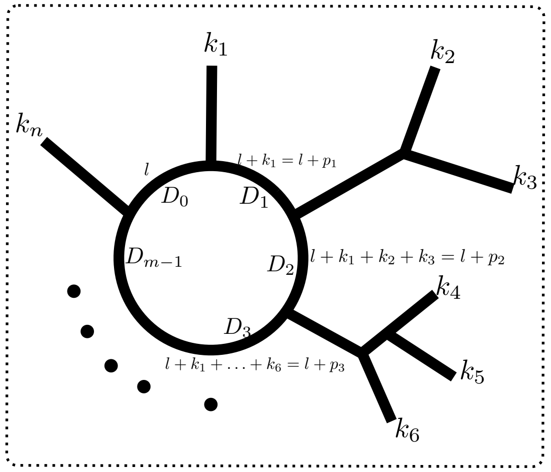
Reals: one extra power of α_s and divergent







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 d dimensions
  - ✤ 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

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

- ✤ 3 generic non-vanishing integrals

MadLoop

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

- ✦ The R_2 terms originate from the numerator
  - ✤ Process-dependent contributions proportional to $\tilde{\ell}^2$
  - ✤ Renormalisable theory: finite number of R_2's → *R_2 Feynman rules*

NLOCT

[Degrande (CPC'15)]

Subtraction of the IR divergences

✦ Subtracting the poles

- The structure of the poles is known ➢ subtraction methods

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

- ★ $\mathcal{C}$ subtracted from the reals → finite
- ★ $\mathcal{C}$ integrated and added back to the virtuals → finite
- ★ Integrals can be calculated numerically (and in 4D)

✦ Choice of the subtraction terms

- Must match the infrared structure of the real
- Should be integrable over the one-body phase space conveniently (*cf.* virtuals)
- Should be integrable numerically conveniently

✦ FKS subtraction

[Frixione, Kunszt, Signer (NPB'96)]

- Decomposition → at most one singularity per term → regulators

$$\mathrm{d}\sigma^{(n+1)} = \sum_{ij} \mathcal{S}_{ij} \mathrm{d}\sigma_{ij}^{(n+1)}$$

- ★ $\mathcal{S}_{ij} \to 1$ if the partons *i* and *j* are collinear
- ★ $\mathcal{S}_{ij} \to 1$ if the parton *i* is soft
- ★ $\mathcal{S}_{ij} \to 0$ for all other infrared limits

Events and counter-events

✦ Regulators: events and counter-events

MadFKS

Controls the soft pieces $\xi_i = E_i\sqrt{\hat{s}}$

Controls the collinear pieces $y_{ij} = \cos\theta_{ij}$

Event

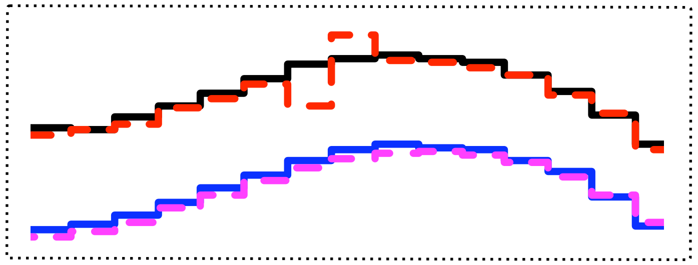
Counter-event

$$
\begin{aligned}
\mathrm{d}\sigma_{ij}^{(n+1)} &= \left[\frac{1}{\xi_i}\right]_c \left[\frac{1}{1-y_{ij}}\right]_\delta \Sigma_{ij}(\xi_i, y_{ij})\mathrm{d}\xi_i\ \mathrm{d}y_{ij} \\
&= \int_0^{\xi_{\max}} \mathrm{d}\xi_i \int_{-1}^{+1} \mathrm{d}y_{ij}\, \frac{1}{\xi_i(1-y_{ij})} \Big[\boxed{\Sigma_{ij}(\xi_i, y_{ij})}\ \boxed{- \Sigma_{ij}(\xi_i, 1)\Theta(y_{ij} - 1 + \delta)} \\
&\qquad \boxed{- \Sigma_{ij}(0, y_{ij})\Theta(\xi_{\rm cut} - \xi_i) + \Sigma_{ij}(0,1)\Theta(y_{ij} - 1 + \delta)\Theta(\xi_{\rm cut} - \xi_i)}\Big]
\end{aligned}
$$

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

✦ Some properties

- ✤ *i* and *j* on-shell (event) ⇔ combined *ij* parton on-shell (counter-event)
  - → Reshuffling of all particle momenta
  - → Events and counter-events kinematically mismatched
  - → Unweighting not possible
- ✤ Events and counter-events can fill ≠ histogram bins
  - ★ Peak-dip structure for the (fixed-order) distributions



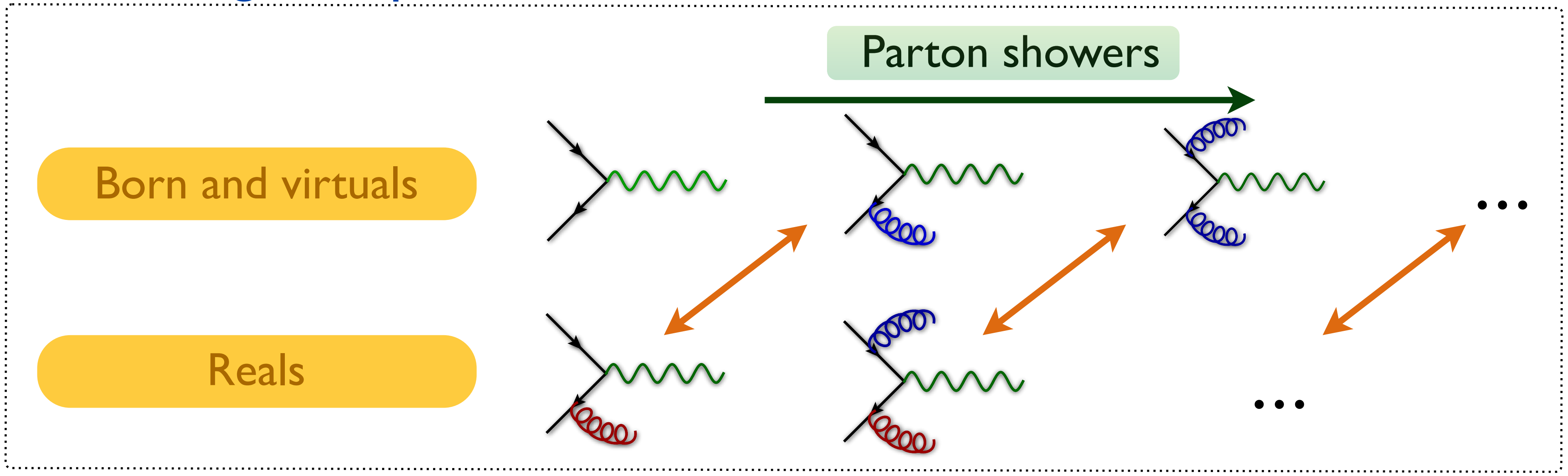
Matching with parton showers

✦ Parton shower / hadronisation effects

- ✤ Evolution of hard partons to more realistic final states made of hadrons
  - ★ Fully exclusive description of the events
- ✤ Resummation of the soft-collinear QCD radiation
  - ★ Cures the fixed-order instabilities

✦ Matching with parton showers

MC@NLO



- ✤ Two sources of double counting
  - ★ Radiation: reals *vs.* shower
  - ★ No radiation: virtuals *vs.* no-emission probability

The MC@NLO prescription

[Frixione, Webber (JHEP'02)]

✦ Properties of the MC counterterms

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

- Exact NLO normalisation (after α_s-expansion)
- Definition: MC counterterms match the reals in the IR
  - ★ Same kinematics: no need for reshuffling → exact cancellation
  - ★ Weights for the *n* and *n*+1 components bounded from above → unweighting possible
- Smooth transition between the hard and soft-collinear regions
  - ★ Soft-collinear: $\mathcal{R} \approx \mathcal{MC}$ → shower-dominated
  - ★ Hard: $\mathcal{MC} \approx 0, \quad \mathcal{I}_{\text{MC}}^{(n)} \approx 0, \quad \mathcal{I}_{\text{MC}}^{(n+1)} \approx 1$ → hard-radiation-dominated
- The MC counterterms are shower-dependent

Monte Carlo and FKS counterterms

aMC@NLO

- The MC counterterms cannot be integrated numerically
  - Issue for the virtuals (pole cancellation)
  - Simultaneous usage of the FKS and MC counterterms

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

S-events H-events

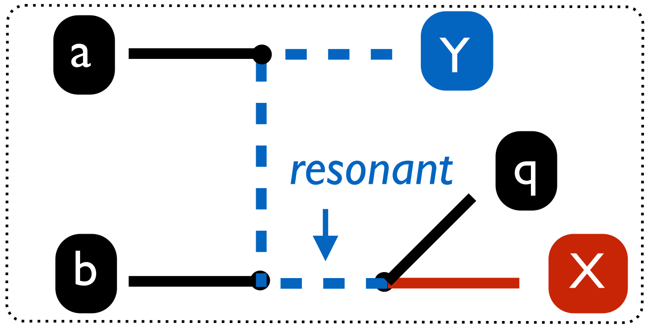
  - Separated generation of the S-events and H-events
    → Negative weights

[Alwall, Frederix, Frixione, Hirschi, Mattelaer, Shao, Stelzer, Torrielli & Zaro (JHEP'14)]

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

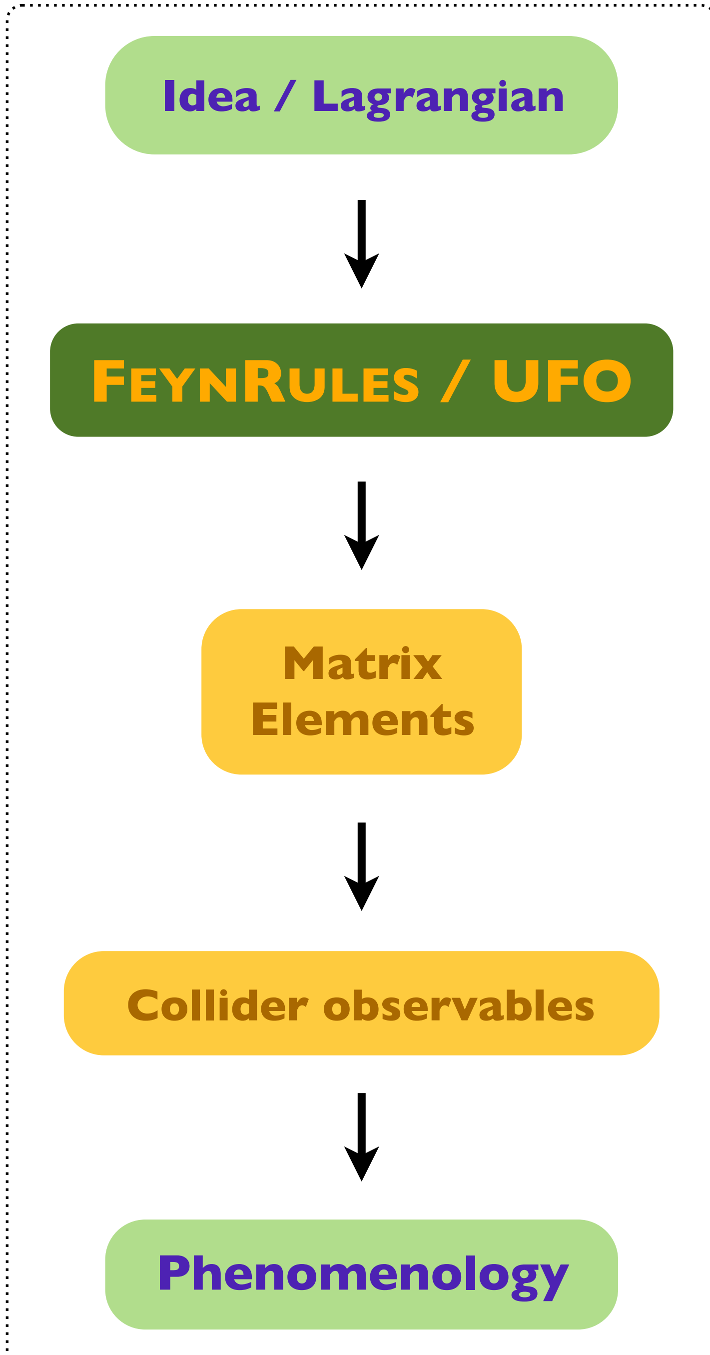
$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\mathrm{non-res.})}\right|^2 + 2\Re\left(\mathcal{A}^{(\mathrm{non-res.})}\mathcal{A}^{(\mathrm{res.})\dagger}\right) + \left|\mathcal{A}^{(\mathrm{res.})}\right|^2$$

- 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)

MadSTR

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)]

✦ BSM phenomenology @ colliders 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)]

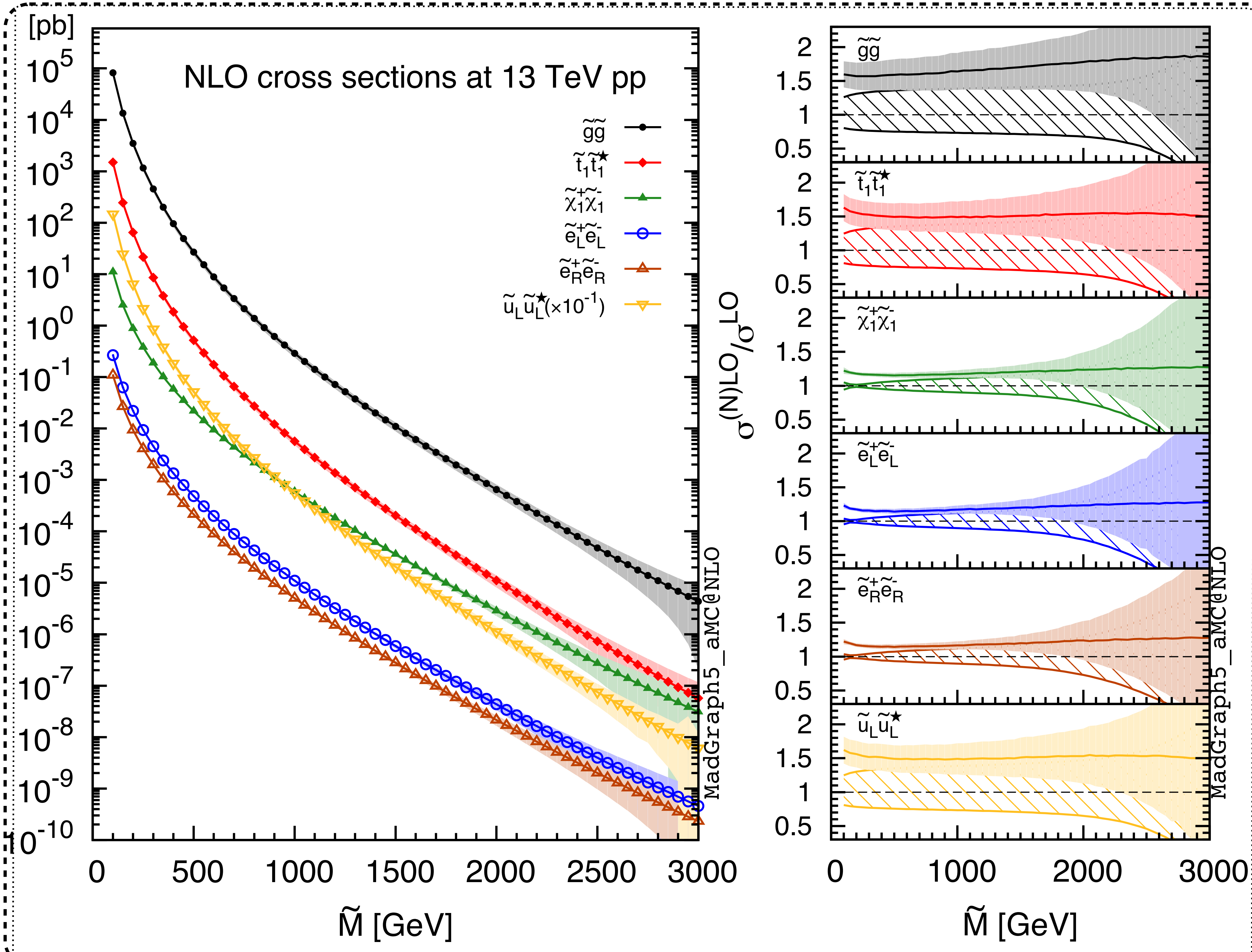
Outline

1. Automating NLO calculations in QCD for new physics
2. **Phenomenology: SUSY, DM & VLQs**
3. Summary - conclusions

Supersymmetry @ NLO

SUSY rates: simplified models

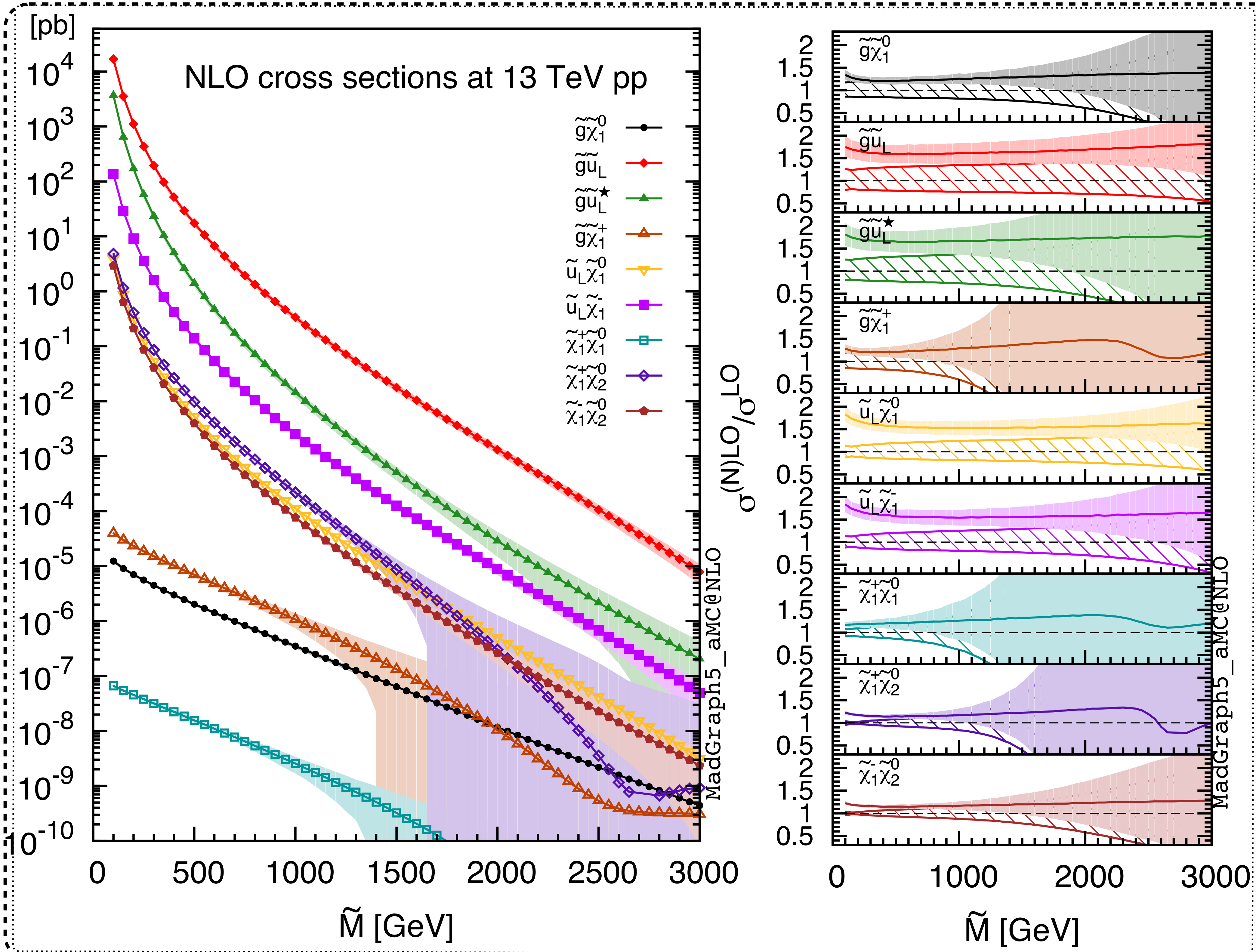
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]



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

SUSY rates: next-to-simplified models

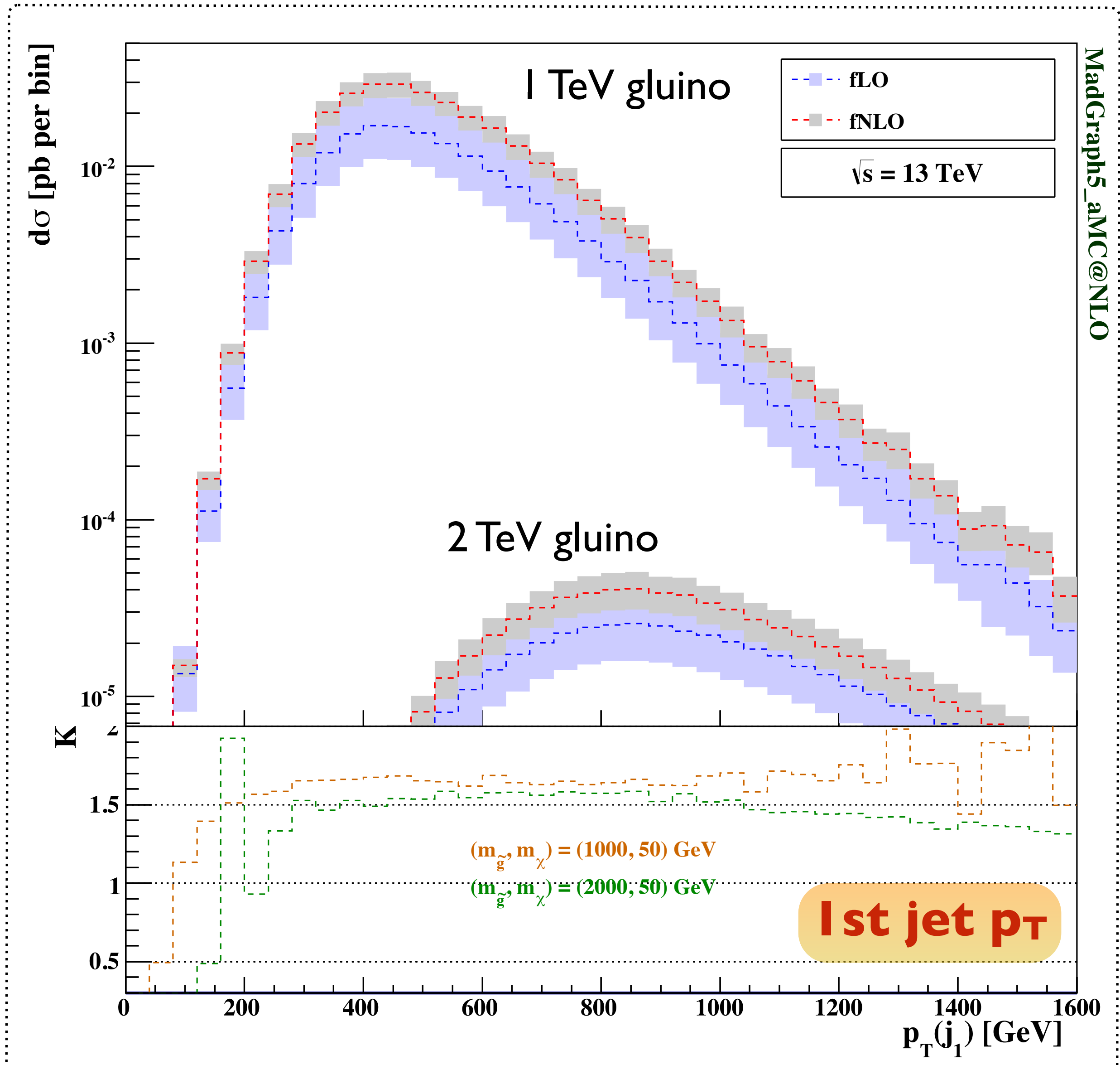
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

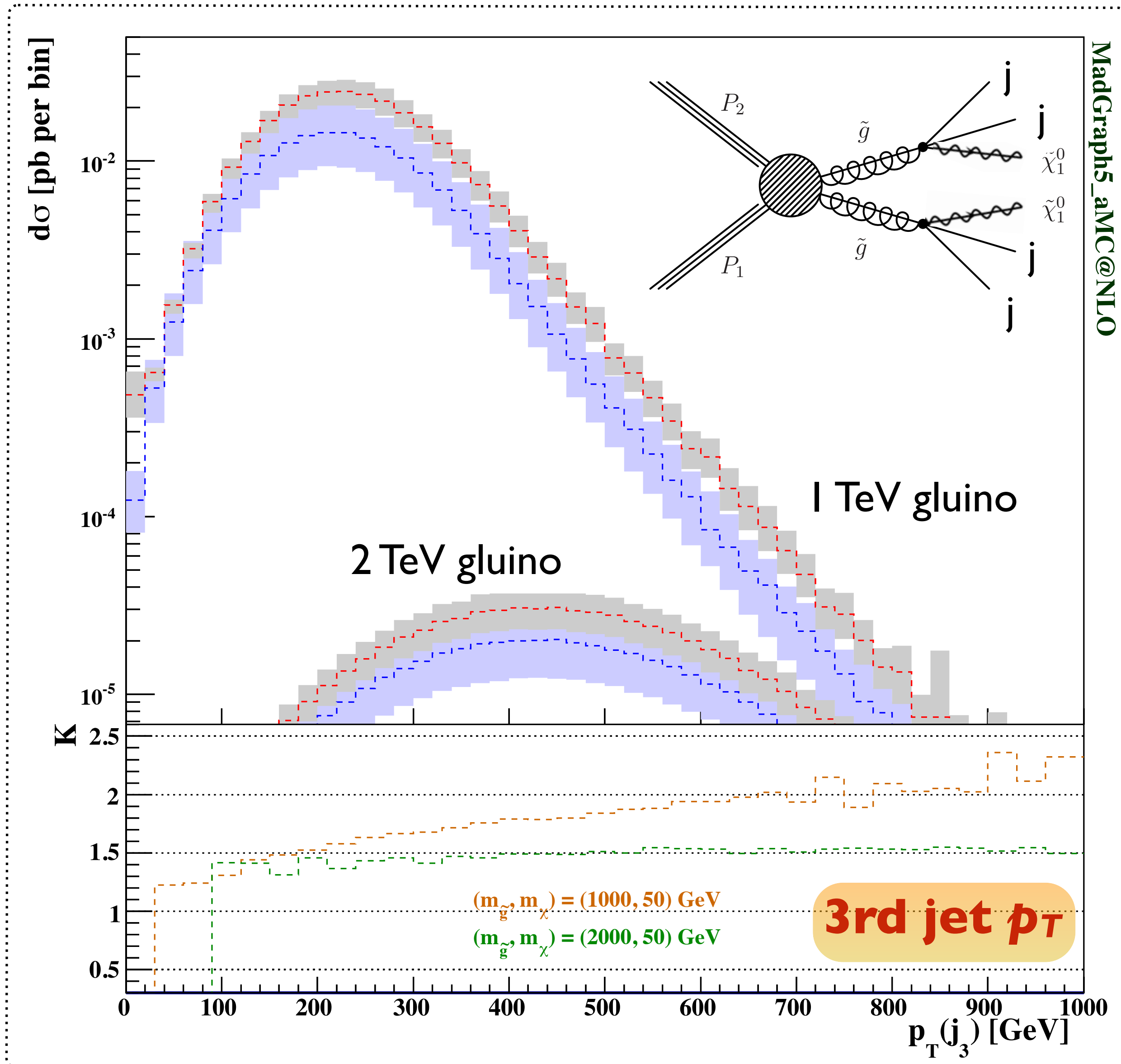


- K~ 1-2 *cf.* gluino
- $K = f(\tilde{M})$
- Errors are reduced
- PDF impact at large $\tilde{M}$

Fixed-order distributions: jet properties

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



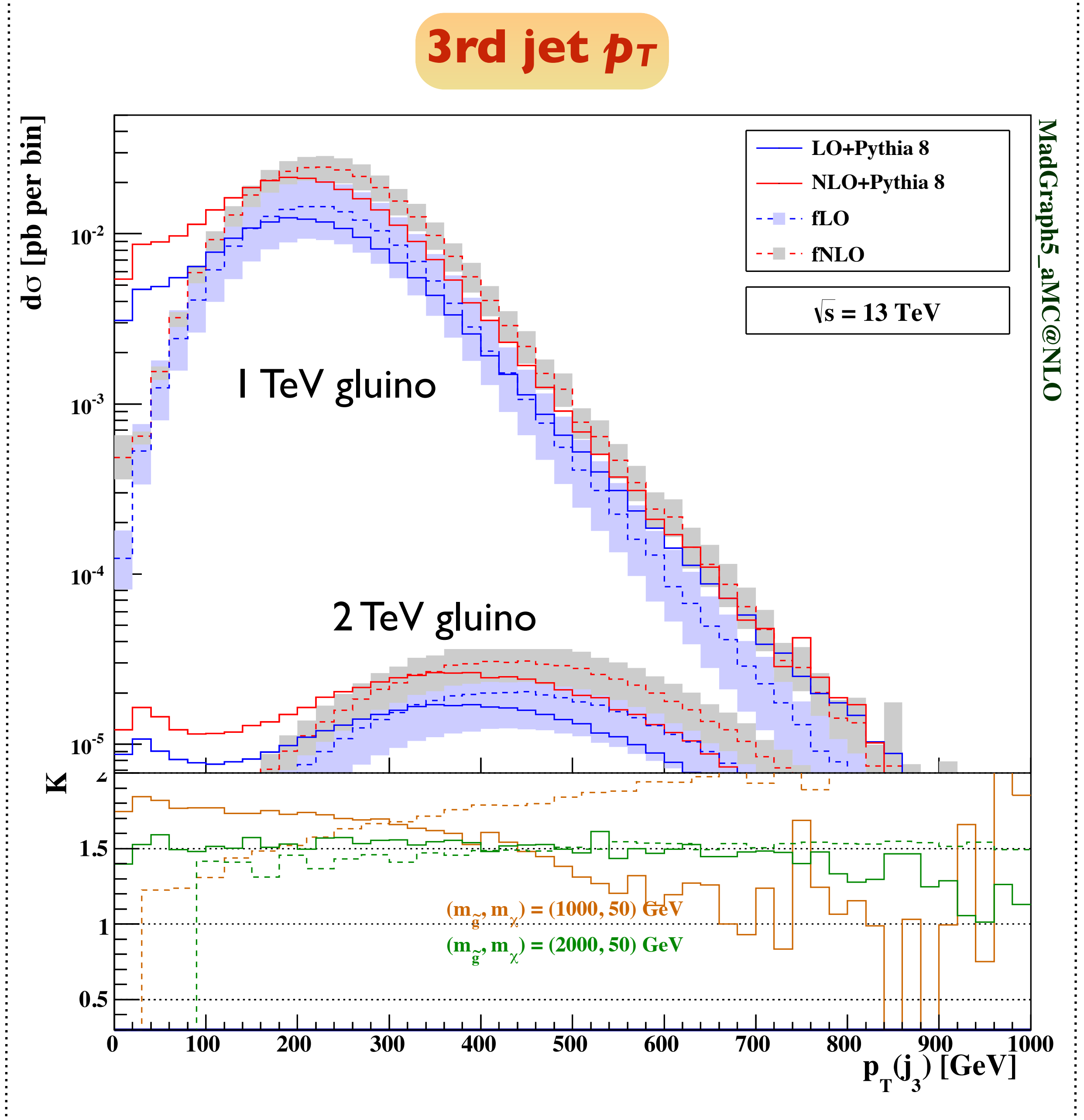


✤ Two potential jet origins
- ★ Decay jet (hard)
- ★ Radiation jet (soft, not for the 1st/2nd jets)

✤ 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)]

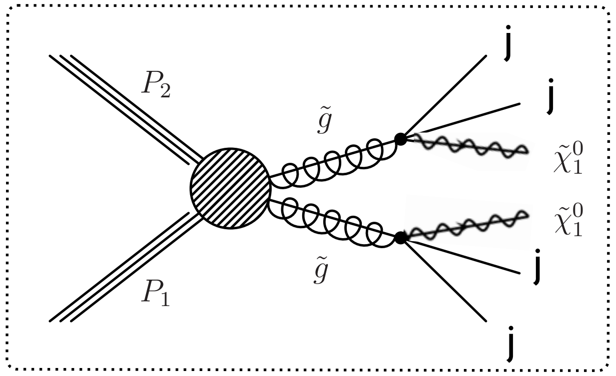


- Parton showers populate the low-p_T region
  - ★ Emitted partons often not reclustered back
  - ★ Extra softer jets
  - ★ Distortion of the spectrum
  - ★ Effects milder for hard p_T (the matrix element drives the shape)
- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes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

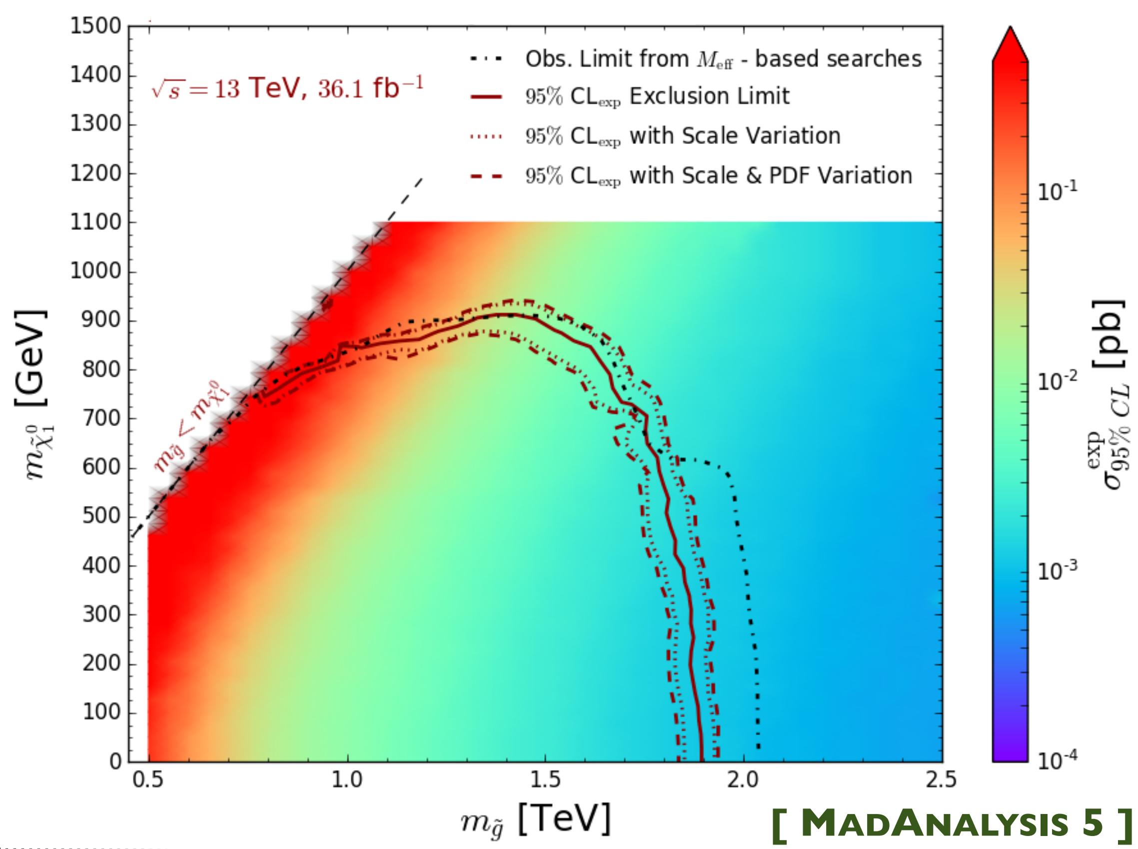
Impact of the uncertainties → future colliders

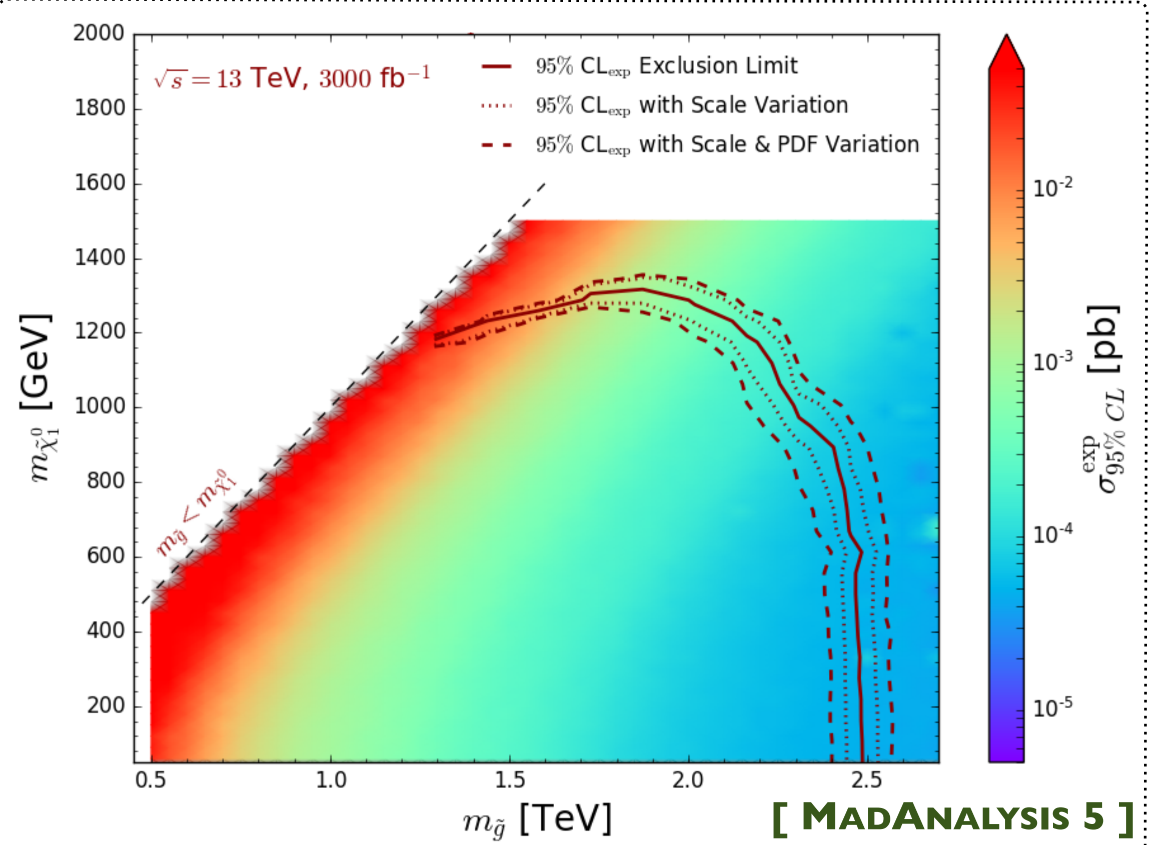
[Araz, Frank & BF (1910.11418)]

✦ 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: rates

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

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

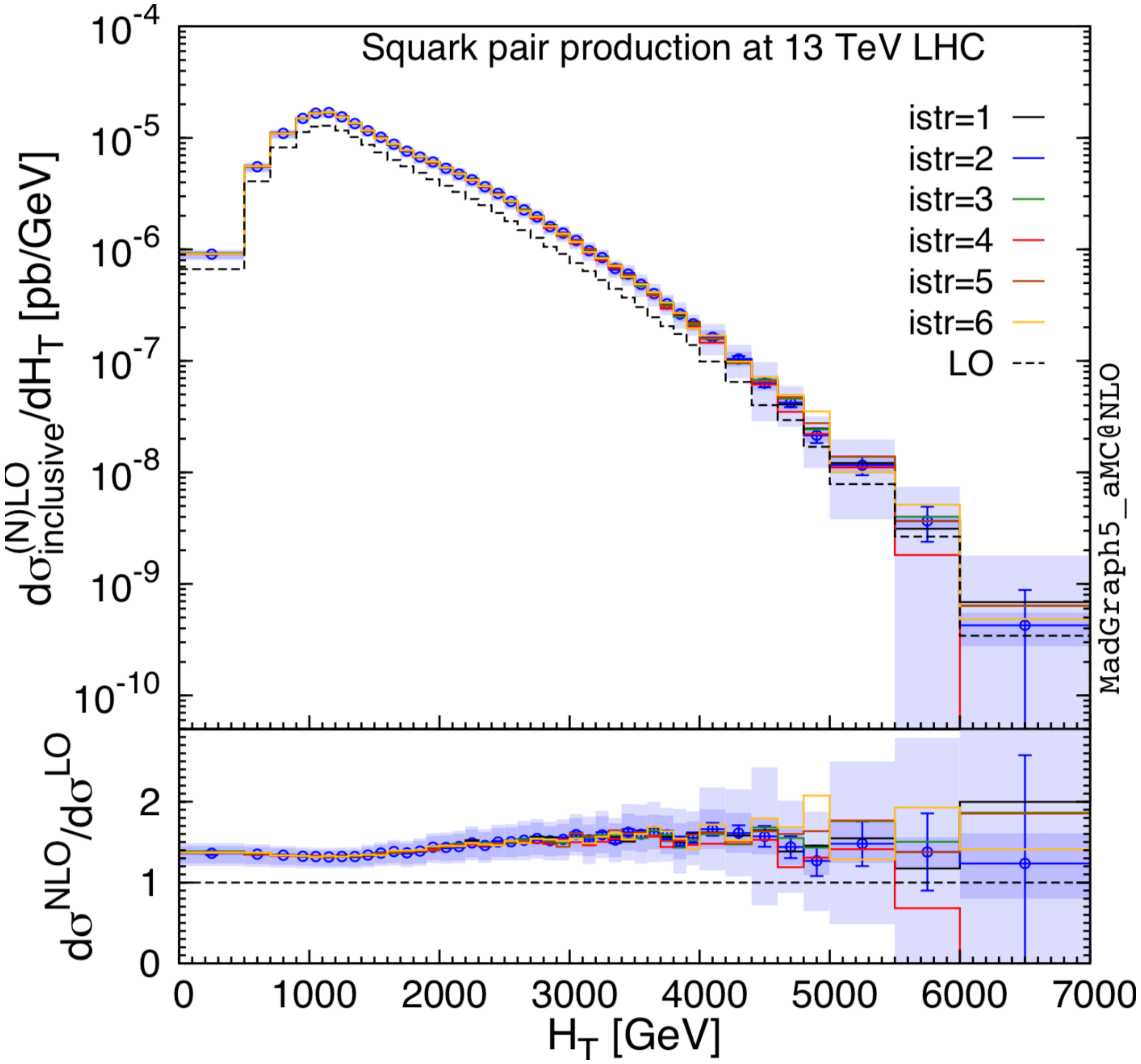
- Benchmark (allowed by data)
  - ★ Multi-TeV squarks and gluinos
  - ★ 50 GeV lightest neutralino (decays into jets and missing energy)
  - ★ Typical H_T/MET selection (+ $N_{\rm jets}$ requirement)
- NLO impact
  - ★ Large K-factors (especially for $\tilde{g}\tilde{g}$), reduction of the theory errors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

No double counting

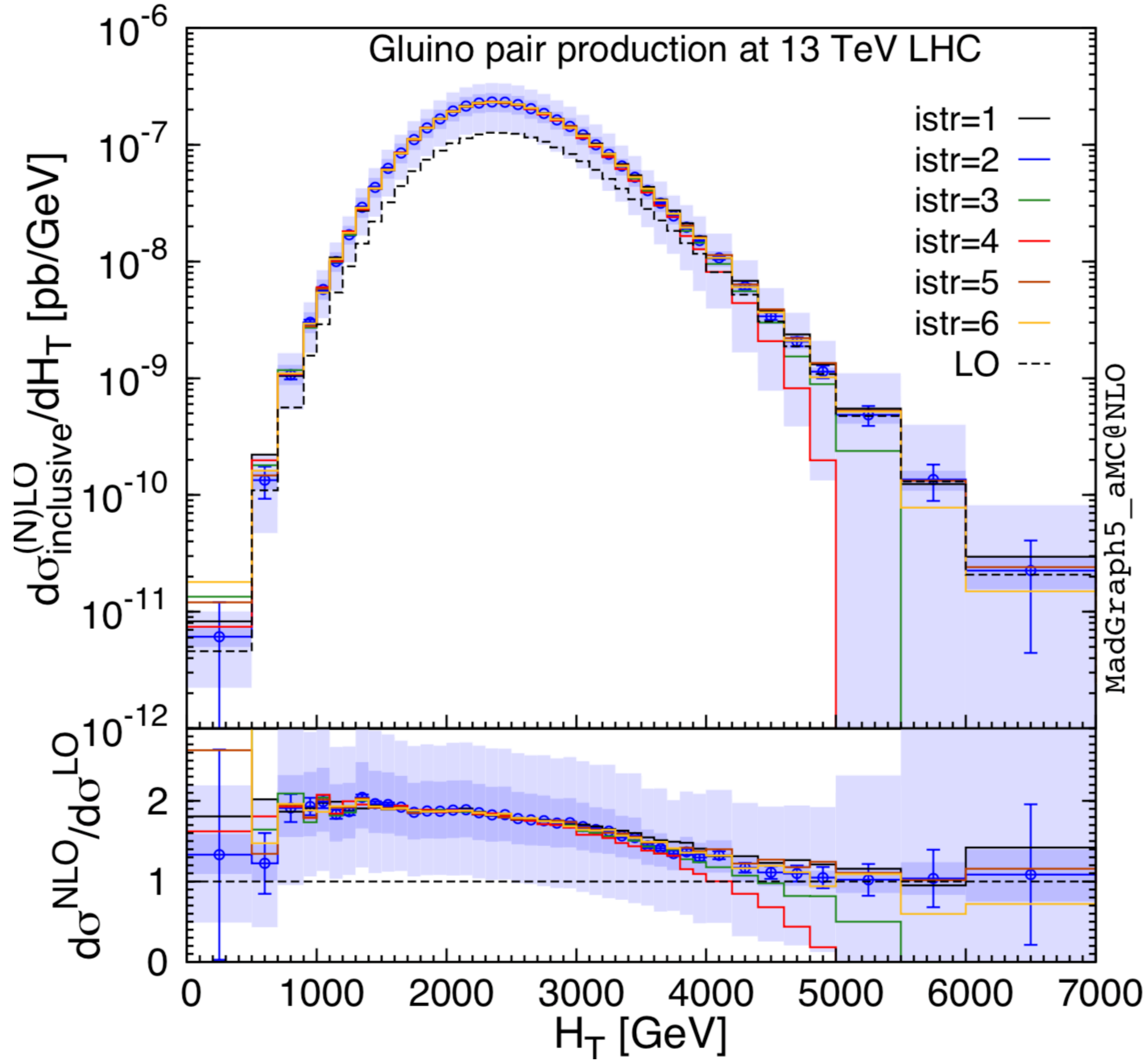
Treatment of the resonances: spectra

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

H_T for squark pair production



H_T for gluino pair production



- Initial momenta reshuffled for some STR options (and some observables)
  - ★Large dependence related to the gluon PDF at large *x* → large TH uncertainties

Dark matter @ NLO

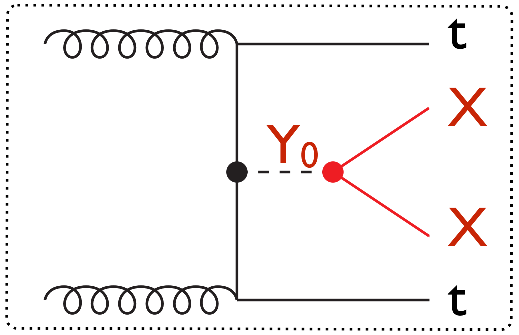
Top-philic dark matter

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

✦ A simplified model for top-philic dark matter

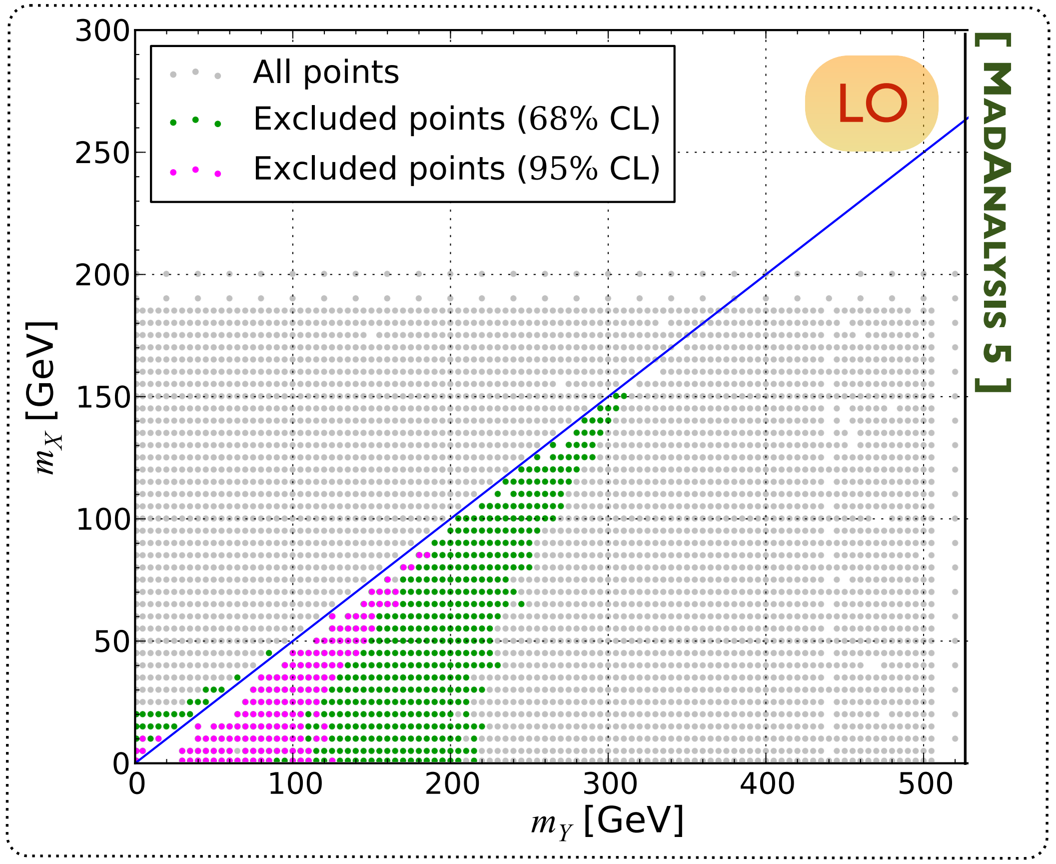
- ✤ A dark sector with a fermionic dark matter candidate X
- ✤ A (scalar) mediator Y_0 linking the dark sector and the top

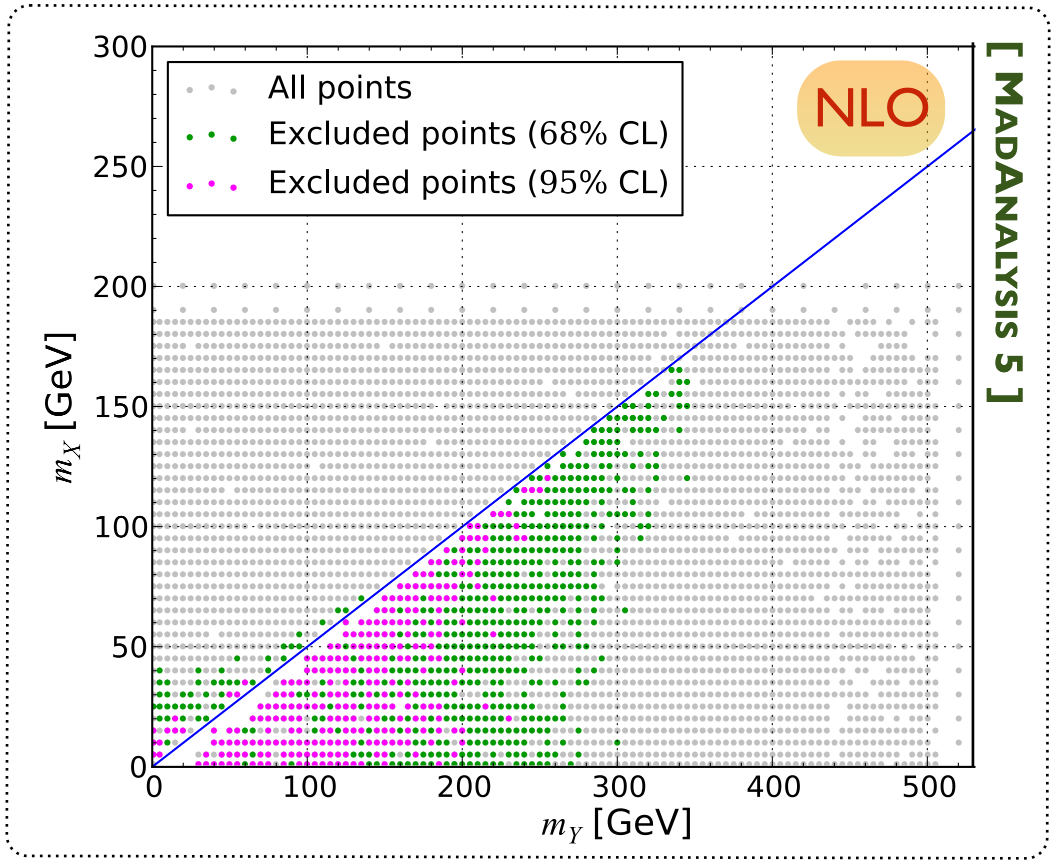
$$\mathcal{L}_{t,X}^{Y_0} = -\Big(g_t \frac{y_t}{\sqrt{2}}\, \bar{t}t + g_X\, \bar{X}X\Big) Y_0$$



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

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





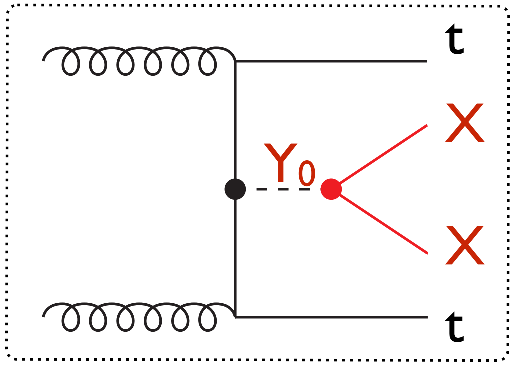
- ✤ How is the picture changing when including scale variations?

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]	$\text{CL}_{\rm LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\text{CL}_{\rm NLO}$ [%]
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	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$



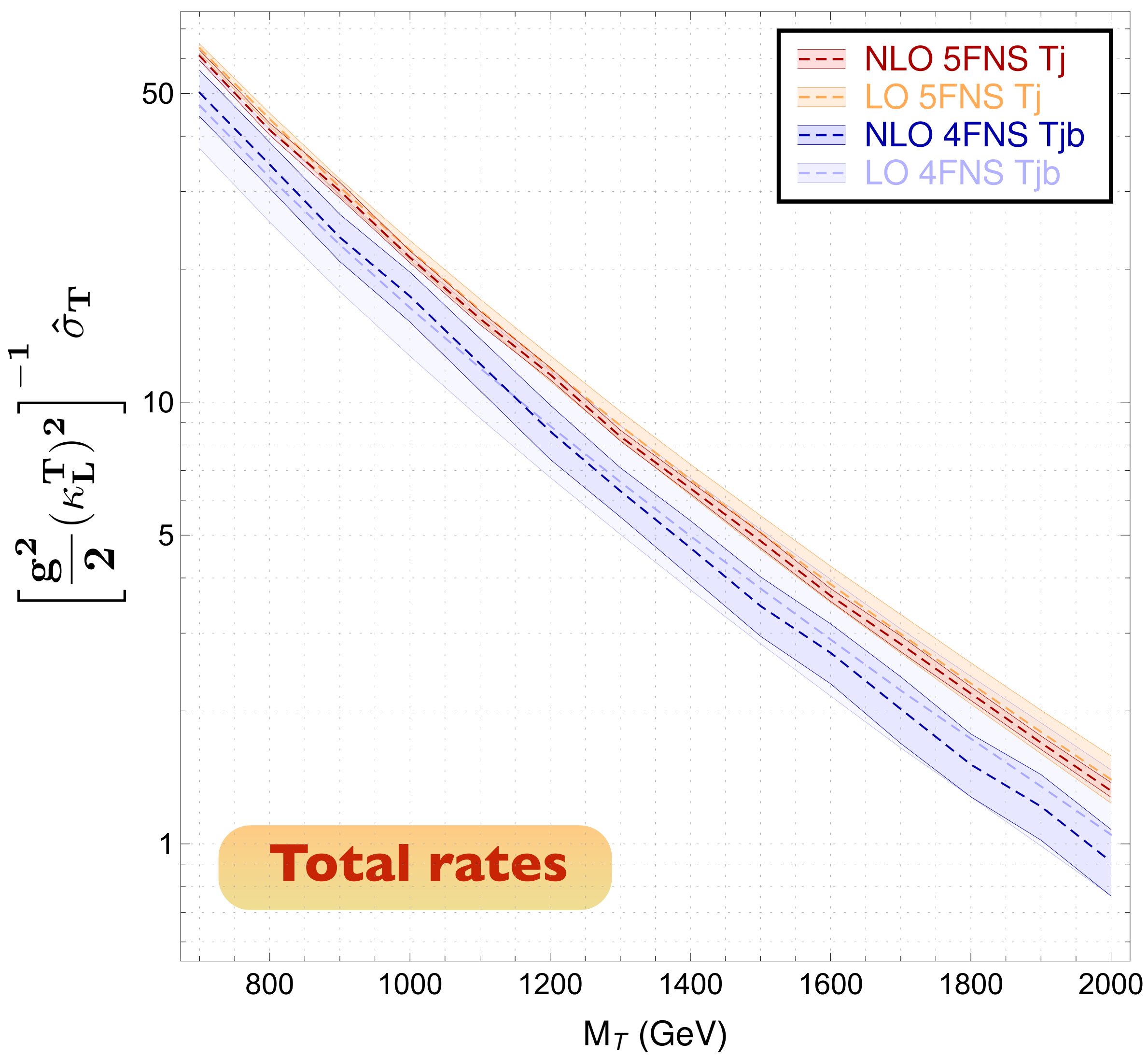
- ✤ An excluded point may not be excluded when accounting for uncertainties
- ✤ The CLs number can increase / decrease at NLO
- ✤ The error band is reduced

3rd generation VLQ @ NLO

Single VLQ production: third generation

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

✦ Single VLQ production (top partner)

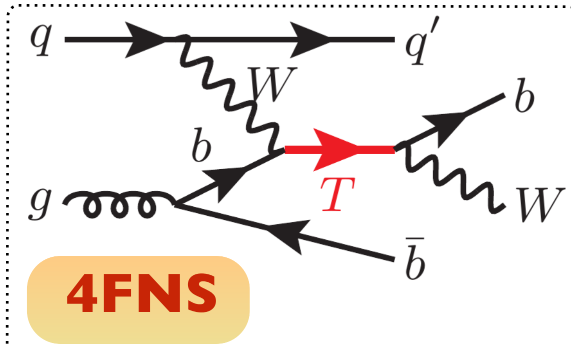


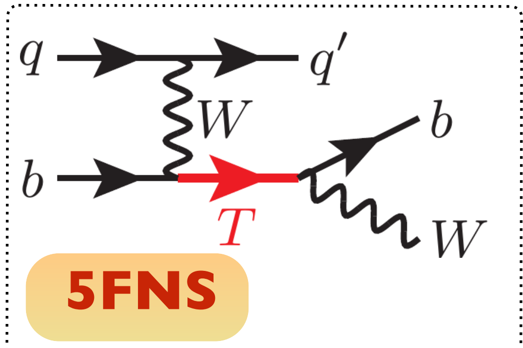
✦ Lagrangian and diagrams

✤ Production through W-couplings

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

✤ Diagrams





✦ Total rates at NLO (4 and 5 FNS)

✤ 5FNS: *K*< *1* (virtuals)

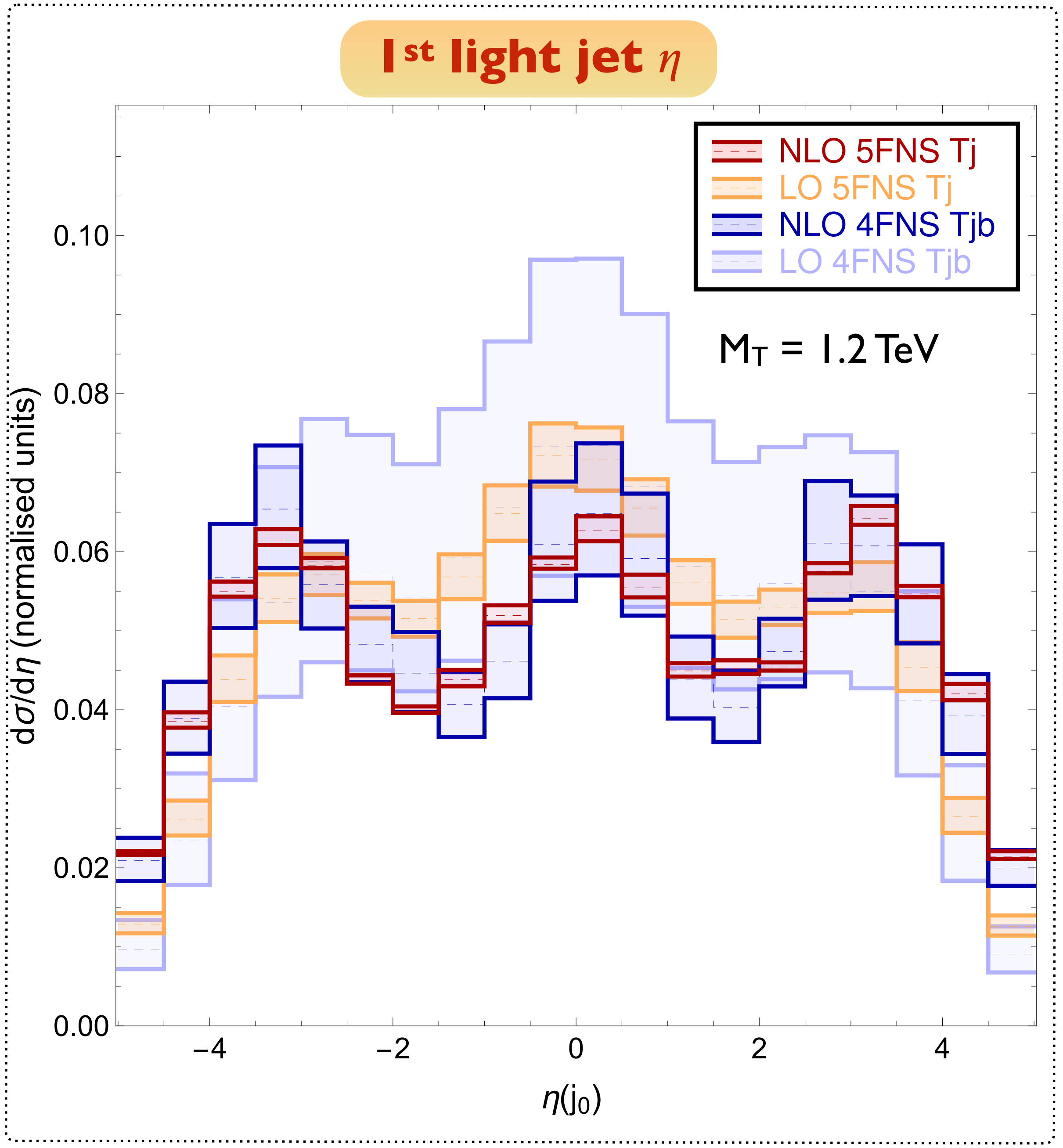
✤ 4FNS: *K* = *f*(M_T)

✤ Reduction of the uncertainties

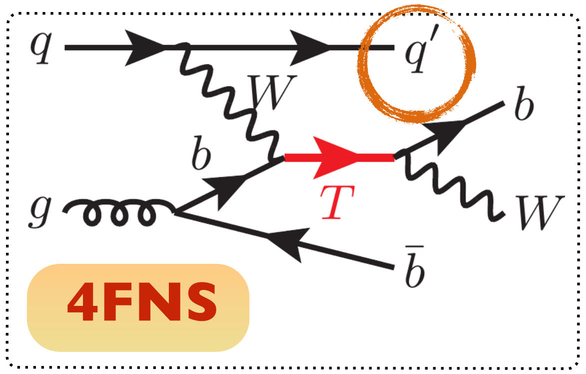
✤ Log Q/m_b resummation (5FNS) (differences at NLO for large masses)

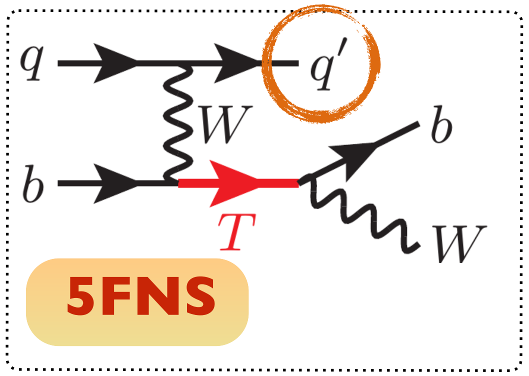
Leading jet pseudorapidity

[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



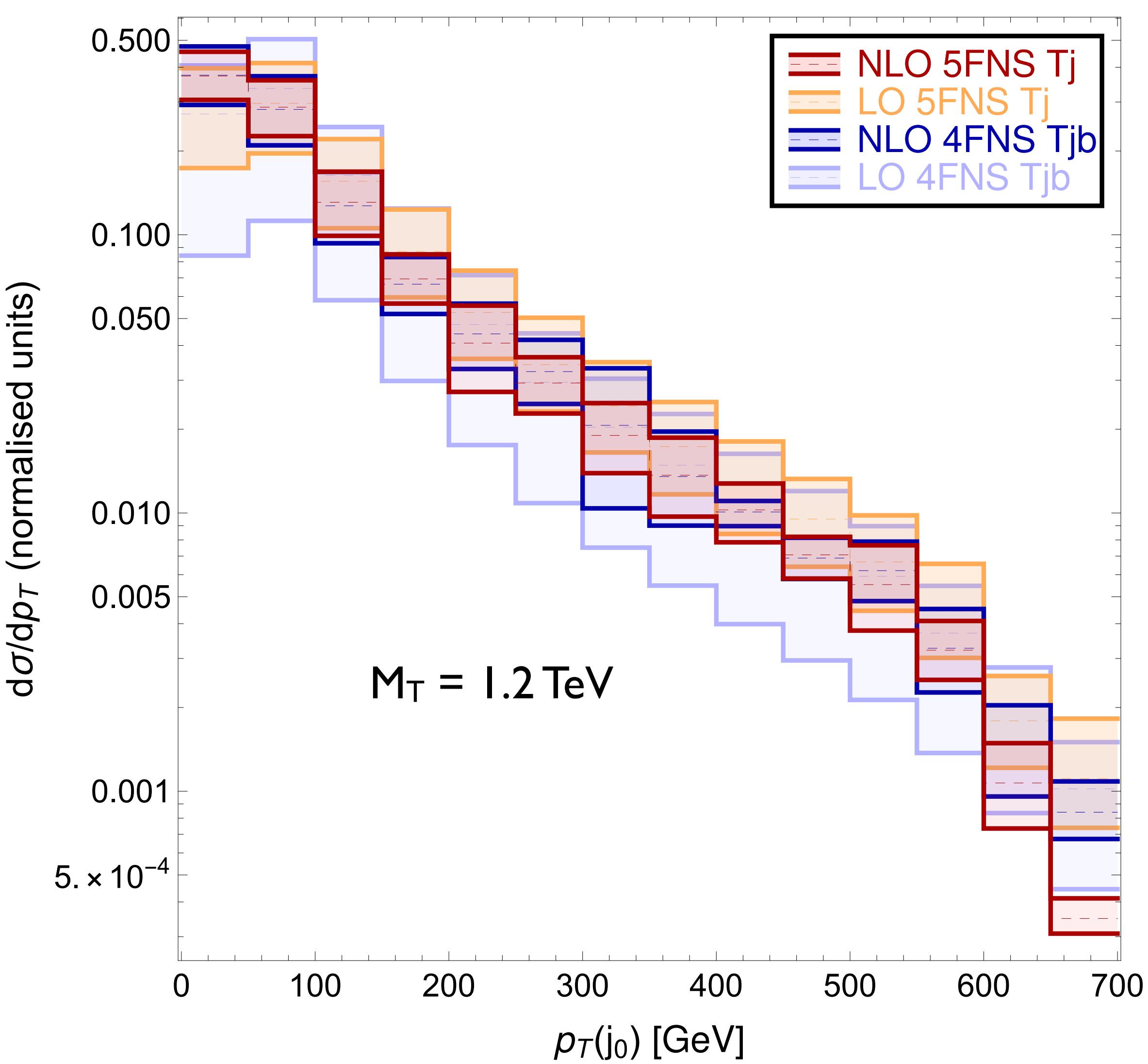


- 4FNS/5FNS shape agreement @NLO
  - ★ Forward jets crucial for signal selection
- NLO effects
  - ★ Important distortion of the shapes
    - ➢ K factors are NOT constant
  - ★ Reduction of the uncertainties at NLO

Leading jet transverse momentum

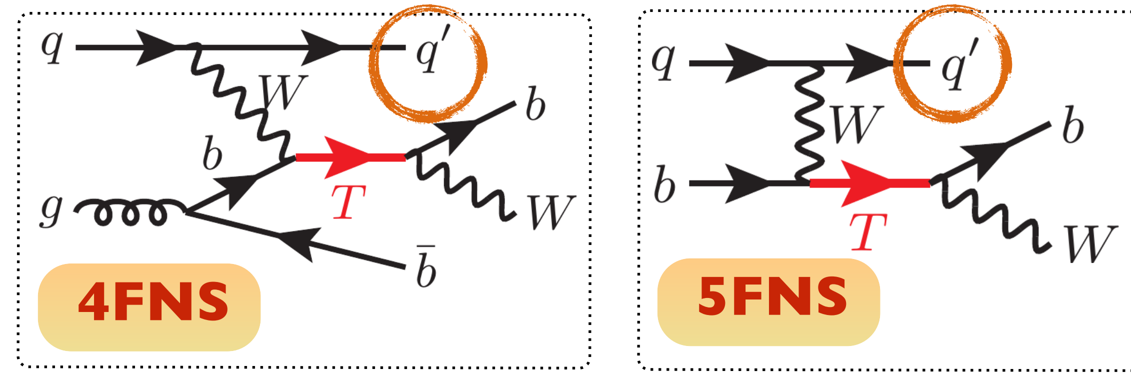
[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB`19)]

1st light jet p_T



✤ Top-partner VLQ coupled to the W-boson

✤ The leading jet: key handle on the signal



✤ NLO effects

★ Reduction of the uncertainties at NLO

★ Important distortion of the shapes

✤ 4FNS/5FNS: large differences at high p_T

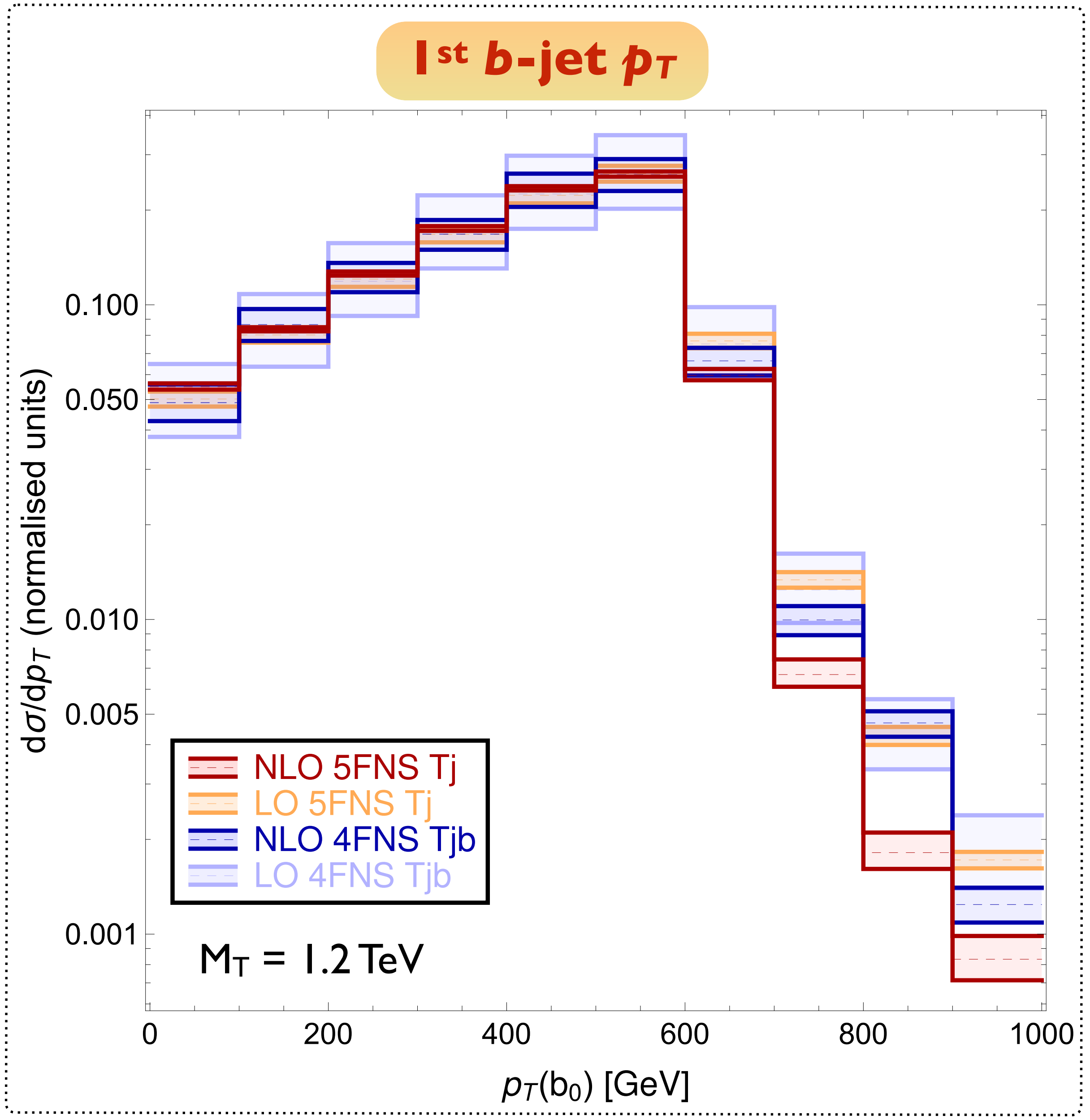
★ A gg channel kicks in at NLO

→ impact the tails

Impact on a search investigated…

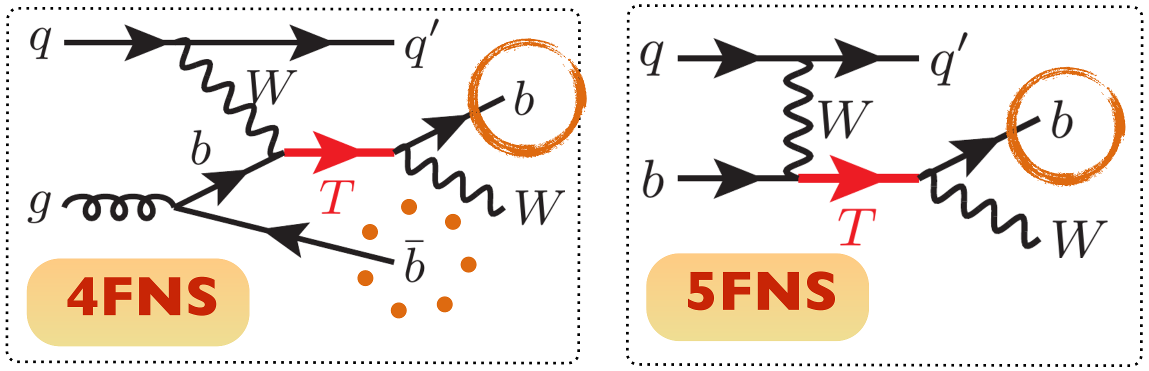
Leading b-jet transverse momentum

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



✤ Top-partner VLQ coupled to the W-boson

✤ The leading b-jet: T-quark reconstruction



✤ The leading b-jet originates from the T-decay
- ★ No scheme/accuracy dependence (LO decays)
- ★ Impact at high p_T: gg channel contributions
  - → Crucial at the analysis level?
- ★ Reduction of the uncertainties at NLO

✤ Peak at $M_T/2$
- ★ The VLQ is mainly produced at rest
- ★ Its energy is shared between the b and the W

Impact on a search investigated…

Outline

1. Automating NLO calculations in QCD for new physics

2. Phenomenology: SUSY, DM & VLQs

3. **Summary - conclusions**

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