BSM phenomenology at the next-to-leading order

The vector-like-quark case

Benjamin Fuks

LPTHE / Sorbonne Université

IBS CTPU Focus Meeting on Composite Dynamics & Phenomenology

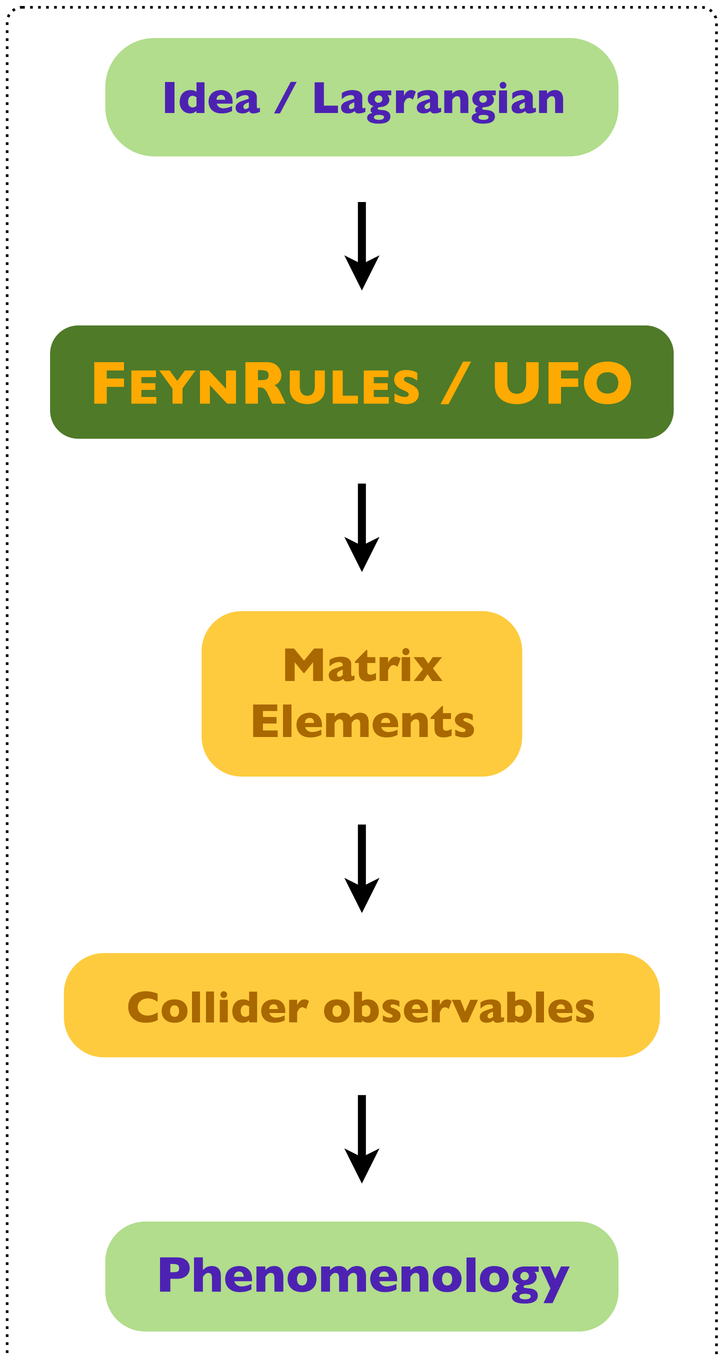
Daejeon, Korea, 12-15 November 2019

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

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, vector-like quarks and charged scalars
3. Summary - conclusions

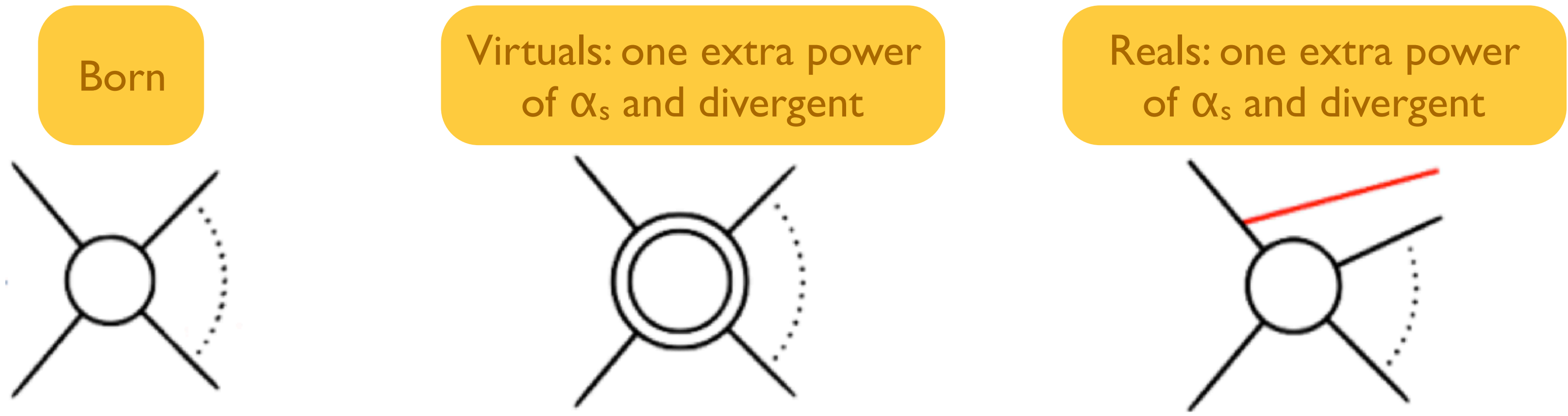
Automating NLO calculations in QCD for new physics

NLO calculations in a nutshell

✦ Dissecting an NLO calculation in QCD

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

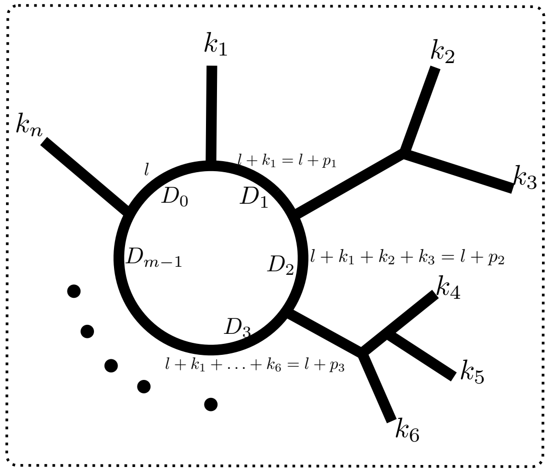
$$\sigma_{NLO} = \int d^4\Phi_n \mathcal{B} \quad + \quad \int d^4\Phi_n \int_{\text{loop}} d^d\ell \; \mathcal{V} \quad + \quad \int d^4\Phi_{n+1} \; \mathcal{R}$$



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)]

✦ Subtracting the poles

MadFKS

✤ The structure of the poles is known → subtraction

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

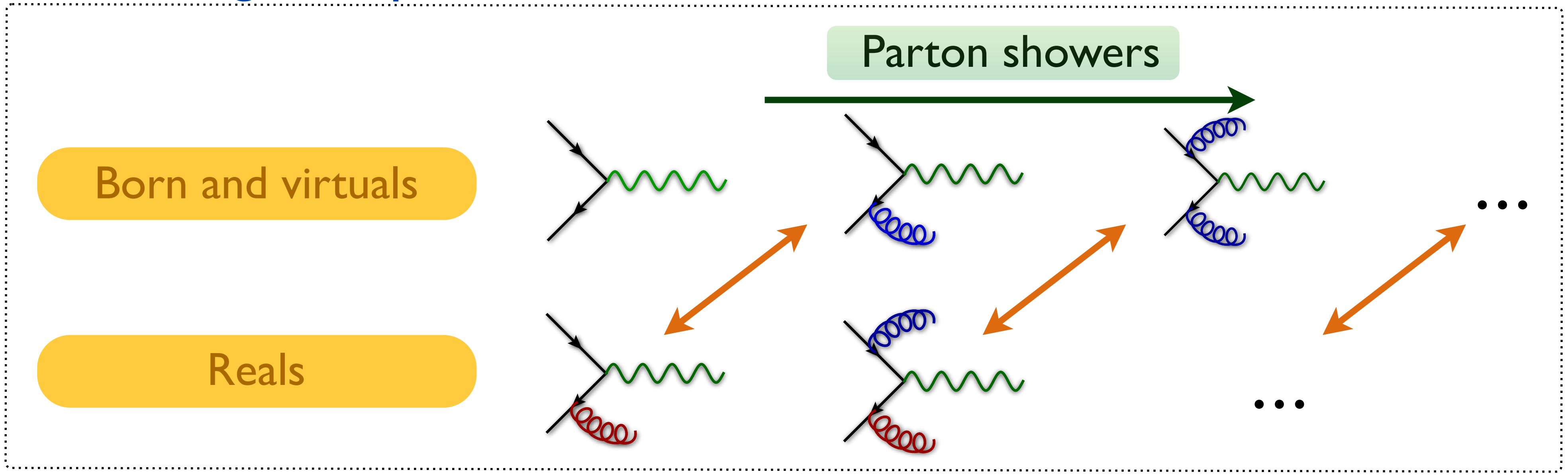
★ $\mathcal{C}$ integrated and added back to the virtuals → finite

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

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

✦ Matching with parton showers

MC@NLO



✤ Two sources of double counting

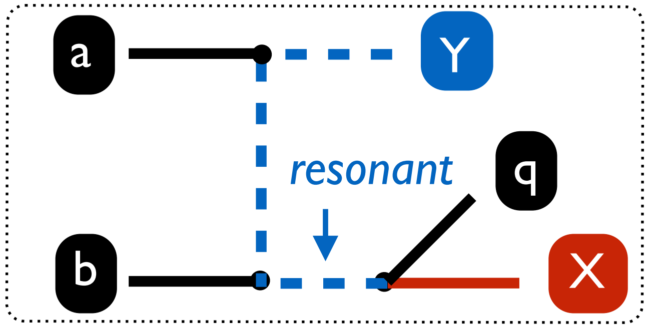
★ Radiation: reals *vs.* shower

★ 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

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

✤ 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)

A general vector-like quark model

[BF & Shao (EPJC'17)]

✦ An effective Lagrangian with four VLQ (T, B, X and Y)

$$
\begin{aligned}
\mathcal{L}_{\rm VLQ} = & \, i\bar{Y}\not{D}Y - m_{_Y}\bar{Y}Y + i\bar{B}\not{D}B - m_{_B}\bar{B}B + i\bar{T}\not{D}T - m_{_T}\bar{T}T + i\bar{X}\not{D}X - m_{_X}\bar{X}X \\
& - h\, \Big[\bar{B}\Big(\hat{\kappa}^B_{_L}P_L + \hat{\kappa}^B_{_R}P_R\Big)q_d + \bar{T}\Big(\hat{\kappa}^T_{_L}P_L + \hat{\kappa}^T_{_R}P_R\Big)q_u + \text{h.c.}\Big] \\
& + \frac{g}{2c_W}\, \Big[\bar{B}\not{Z}\Big(\tilde{\kappa}^B_{_L}P_L + \tilde{\kappa}^B_{_R}P_R\Big)q_d + \bar{T}\not{Z}\Big(\tilde{\kappa}^T_{_L}P_L + \tilde{\kappa}^T_{_R}P_R\Big)q_u + \text{h.c.}\Big] \\
& + \frac{\sqrt{2}g}{2}\, \Big[\bar{Y}\not{W}\Big(\kappa^Y_{_L}P_L + \kappa^Y_{_R}P_R\Big)q_d + \bar{B}\not{W}\Big(\kappa^B_{_L}P_L + \kappa^B_{_R}P_R\Big)q_u + \text{h.c.}\Big] \\
& + \frac{\sqrt{2}g}{2}\, \Big[\bar{T}\not{W}\Big(\kappa^T_{_L}P_L + \kappa^T_{_R}P_R\Big)q_d + \bar{X}\not{W}\Big(\kappa^X_{_L}P_L + \kappa^X_{_R}P_R\Big)q_u + \text{h.c.}\Big]
\end{aligned}
$$

1st generation VLQ @ NLO

Total cross sections for pair production

[BF & Shao (EPJC'17)]

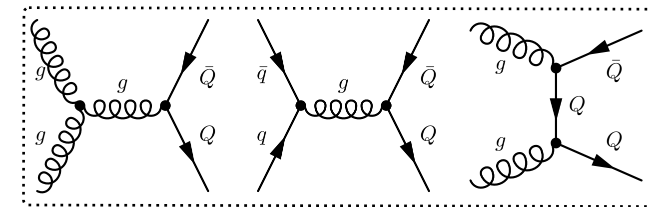
✦ Total rates for pair production at 13 TeV

m_T [GeV]	Scenario	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
400	QCD	$(7.069\ 10^{0})^{+32.0\%+2.7\%}_{-22.6\%-2.7\%}$	$(1.004\ 10^{1})^{+9.4\%\ +2.5\%}_{-11.3\%-2.5\%}$
	TH1	$(7.022\ 10^{0})^{+30.2\%+1.2\%}_{-23.8\%-4.1\%}$	$(9.980\ 10^{0})^{+8.0\%\ +1.2\%}_{-12.5\%-3.8\%}$
800	QCD	$(1.261\ 10^{-1})^{+33.2\%+3.8\%}_{-23.2\%-3.8\%}$	$(1.733\ 10^{-1})^{+8.5\%\ +4.4\%}_{-11.1\%-4.4\%}$
	TH1	$(1.244\ 10^{-1})^{+18.8\%+7.3\%}_{-31.2\%-14.0\%}$	$(1.702\ 10^{-1})^{+2.3\%\ +6.0\%}_{-20.0\%-13.9\%}$
1200	QCD	$(7.685\ 10^{-3})^{+34.0\%+5.8\%}_{-23.7\%-5.8\%}$	$(1.061\ 10^{-2})^{+8.8\%\ +5.8\%}_{-11.4\%-5.8\%}$
	TH1	$(1.053\ 10^{-2})^{+1.7\%\ +18.4\%}_{-36.7\%-25.8\%}$	$(1.372\ 10^{-2})^{+16.6\%+18.2\%}_{-29.0\%-25.8\%}$
1600	QCD	$(7.477\ 10^{-4})^{+34.9\%+8.5\%}_{-24.2\%-8.5\%}$	$(1.030\ 10^{-3})^{+9.0\%\ +8.6\%}_{-11.6\%-8.6\%}$
	TH1	$(3.395\ 10^{-3})^{+3.3\%\ +13.3\%}_{-27.0\%-19.9\%}$	$(4.117\ 10^{-3})^{+14.6\%+14.4\%}_{-21.8\%-20.9\%}$
2000	QCD	$(8.980\ 10^{-5})^{+35.5\%+18.3\%}_{-24.5\%-18.3\%}$	$(1.260\ 10^{-4})^{+8.7\%\ +17.8\%}_{-11.7\%-17.8\%}$
	TH1	$(1.563\ 10^{-3})^{+4.2\%\ +5.4\%}_{-20.0\%-13.0\%}$	$(1.960\ 10^{-3})^{+6.3\%\ +6.0\%}_{-14.0\%-13.6\%}$

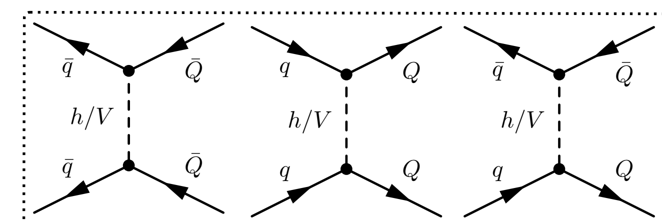
★ NNPDF 3.0 densities

★ Central scale: average M_T

★ QCD: QCD diagrams only



★ TH1: all diagrams (with Higgs exchanges)



✤ NLO effects

★ 50% increase of the rate

★ Reduction of the scale uncertainties

✤ Higgs-exchange diagrams

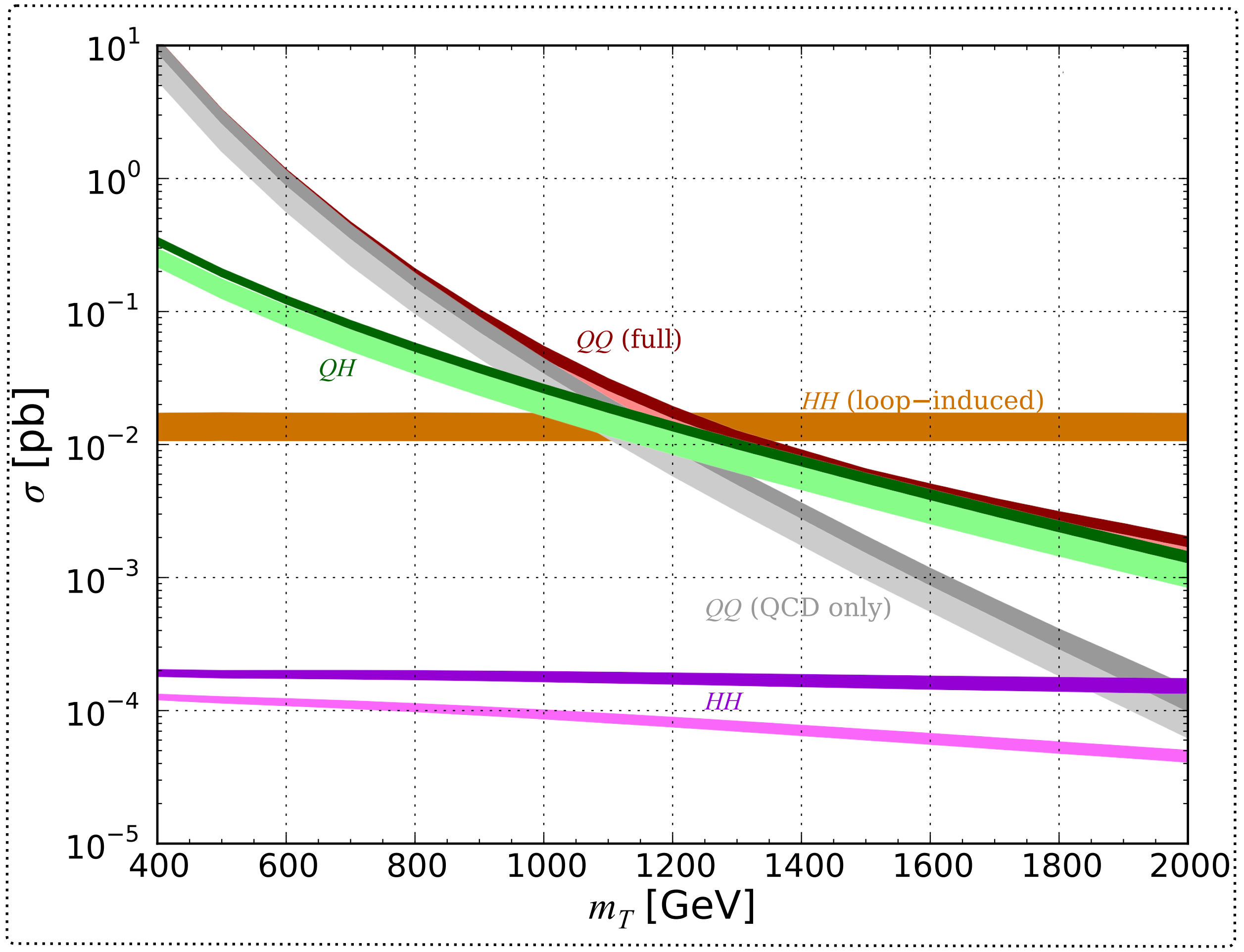
★ Dominate for large masses

★ Impact on the uncertainties

NLO total rates for diHiggs production

[Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (JHEP`17)]

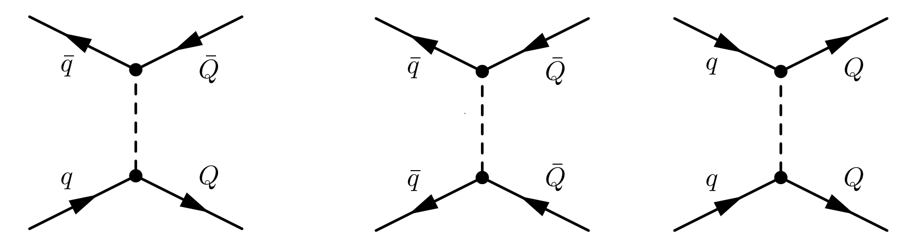
✦Total rates (first NLO-QCD calculations in many cases)



✤ NLO: large K-factors, smaller errors

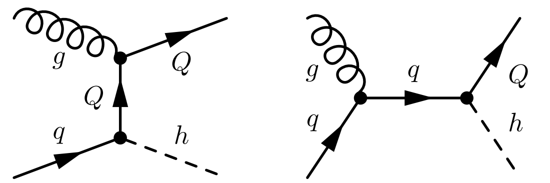
✤ EW diagrams for TT production

★ Dominates QCD prod. at large mass



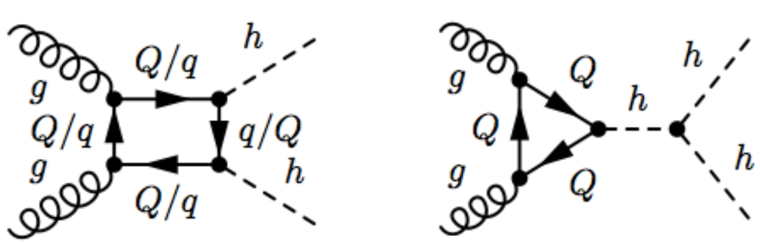
✤ TH production

★ Competes with TT prod. at large mass



✤ H-boson pair production

★ Loop-induced diagrams dominate

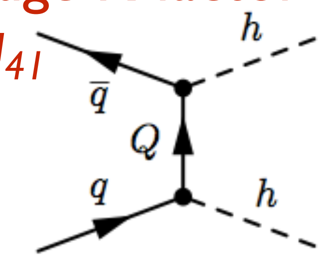


★ t-channel VLQ exchange diagrams: huge K-factor

➢ Coupling proportional to $m_Q/v_{SM}\ U_{4I}$

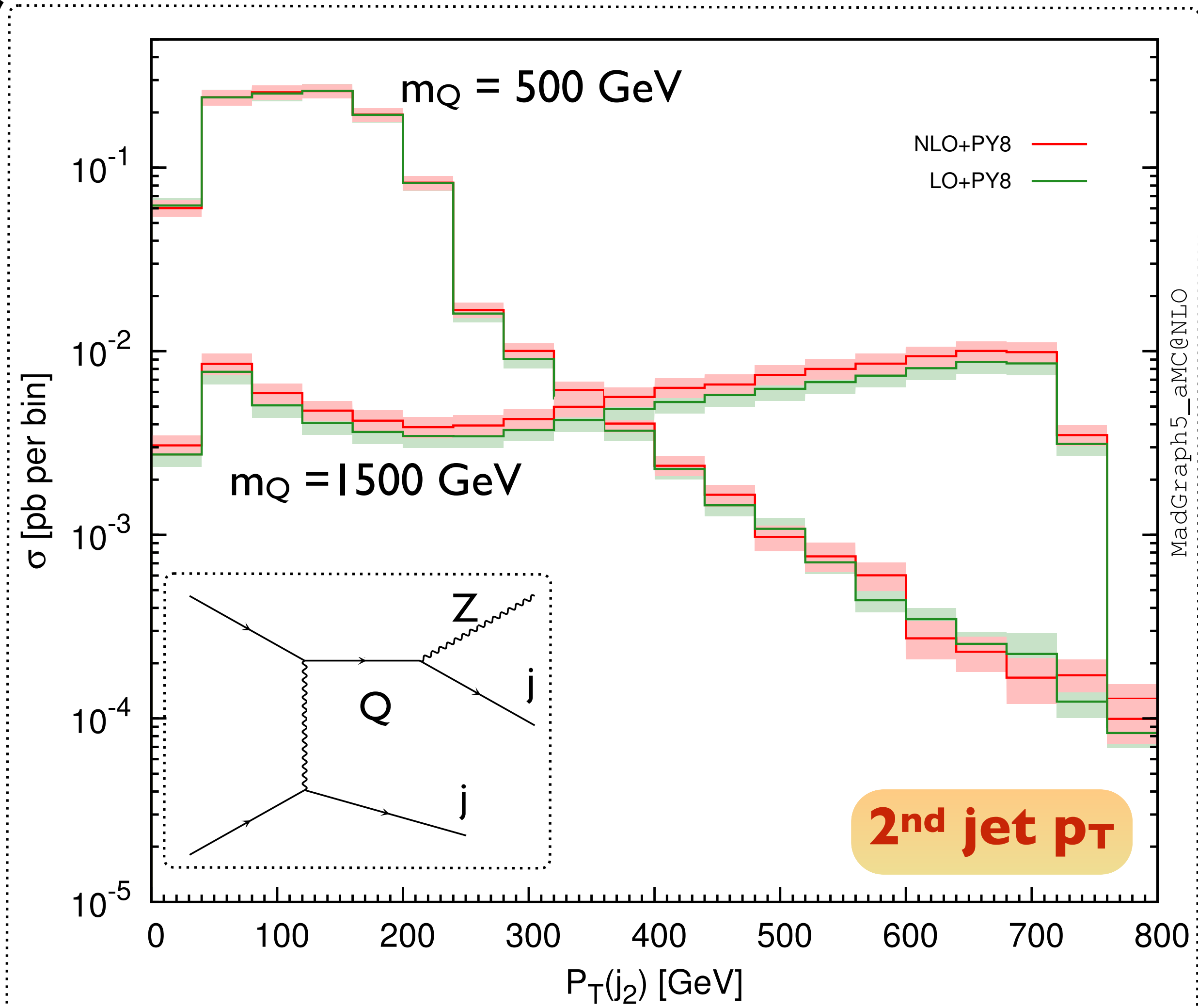
➢ Driven by the u-VLQ mixing U

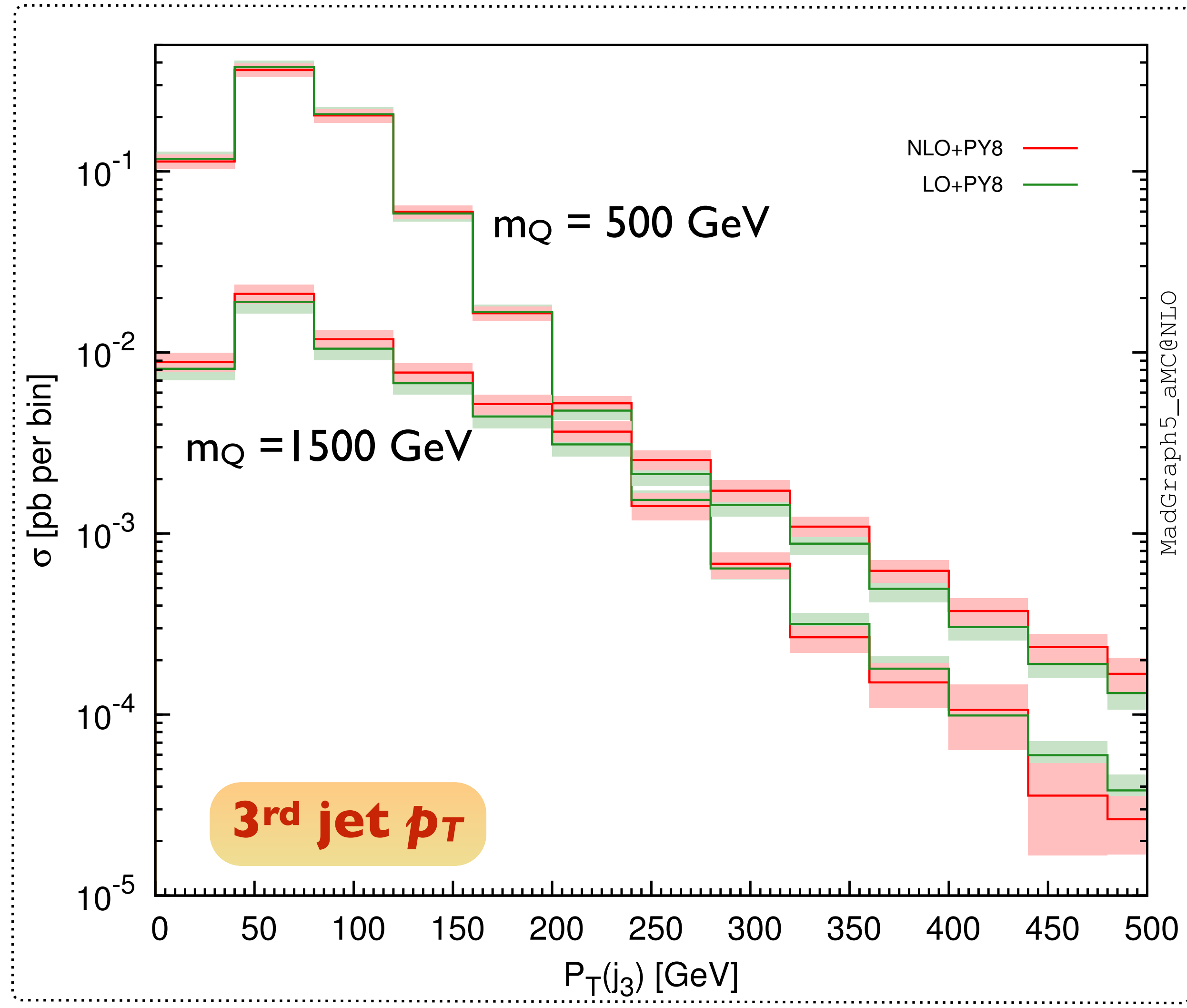
➢ VLQ mass enhancement



Fixed-order distributions: jet properties

[BF & Shao (EPJC'17)]





- Two potential jet origins
  - ★ Decay jet (from Q or Z)
    - → Plateau from $m_Z/2$ $m_Q/2$ ($Q \to Z\, j \to 3j$)
  - ★ Radiation jet (soft, not for the 1st/2nd jets)

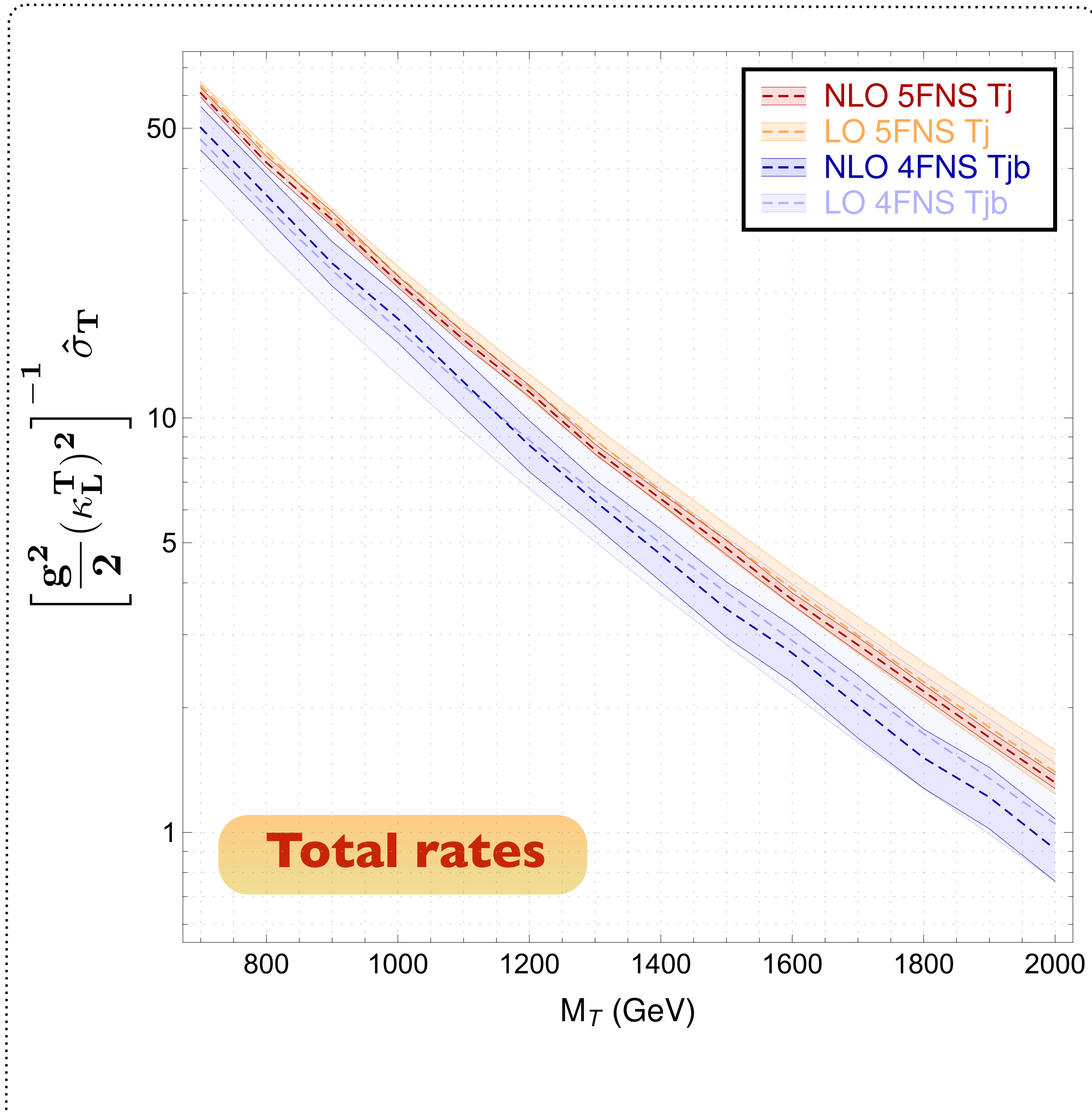
- Constant *K*-factors not accurate
  - ★ Normalisation modification
  - ★ Distortion of the shapes
  - ★ Reduction of the theoretical uncertainties

3^{rd} generation VLQ @ NLO

Single VLQ production: third generation

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

✦ Single VLQ production (top partner)

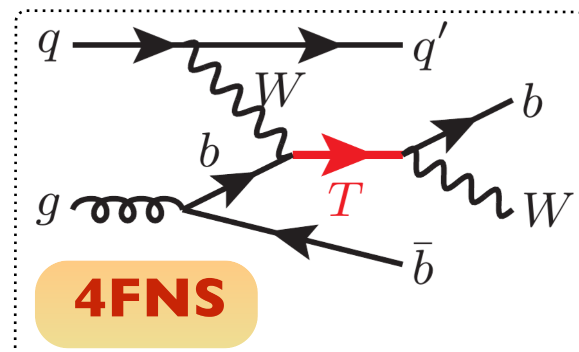


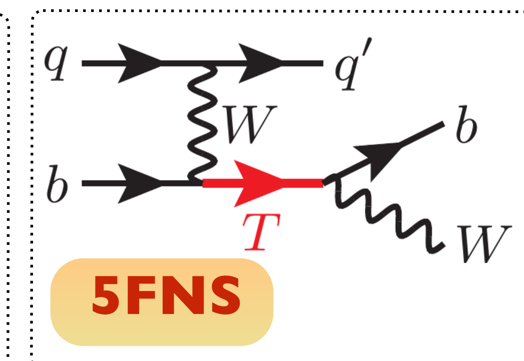
✦ Lagrangian and diagrams

✤ Production through W-couplings

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

✤ Diagrams





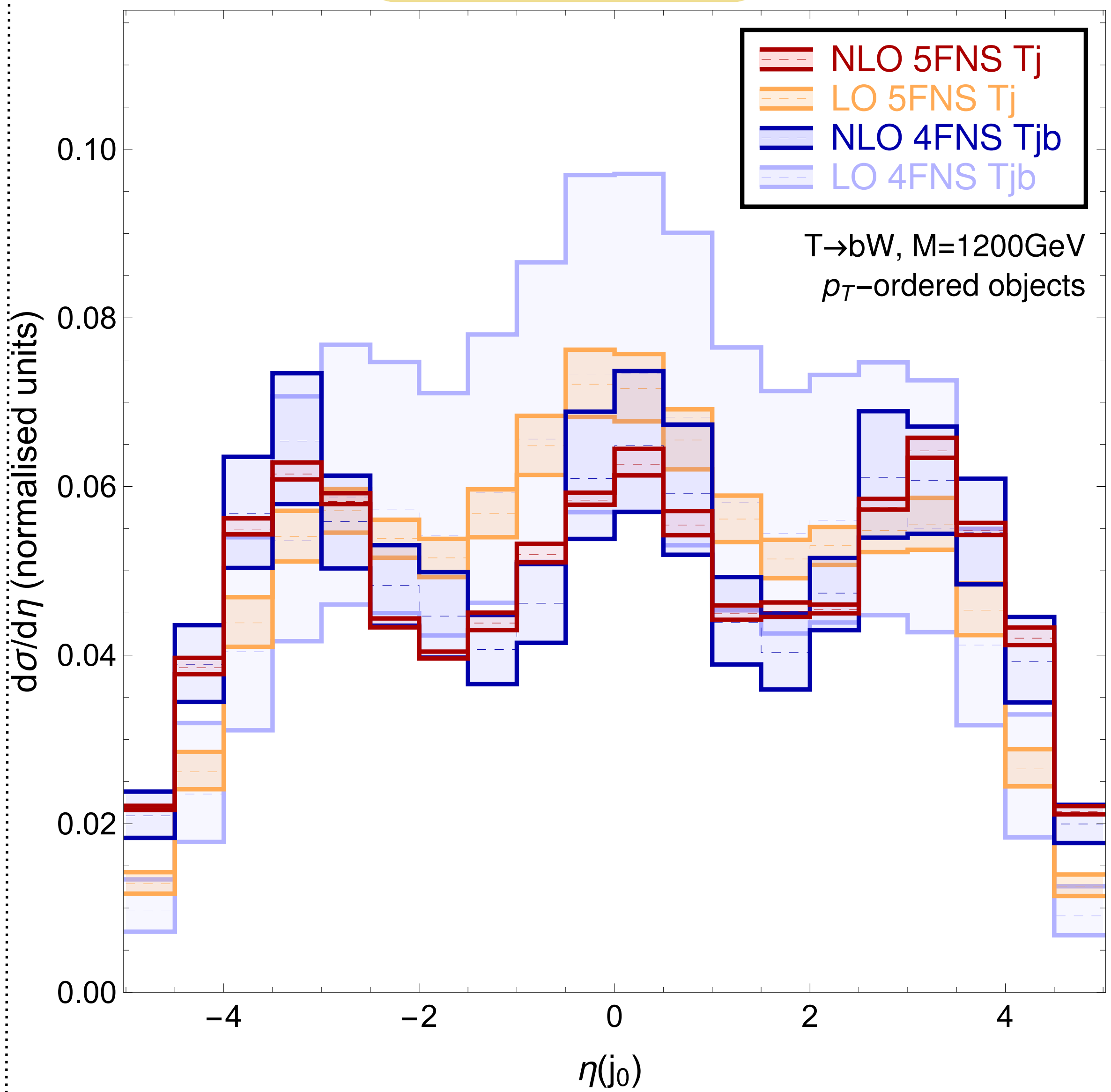
✦ Total rates at NLO (4 and 5 FNS)

- ✤ 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

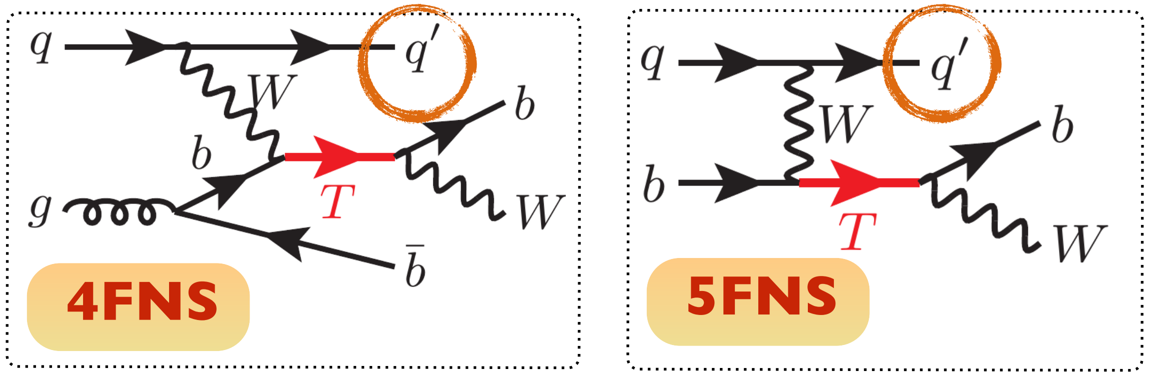
[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB`19)]

1st light jet η



✤ Top-partner VLQ coupled to the W-boson

✤ The leading jet: key handle on the signal



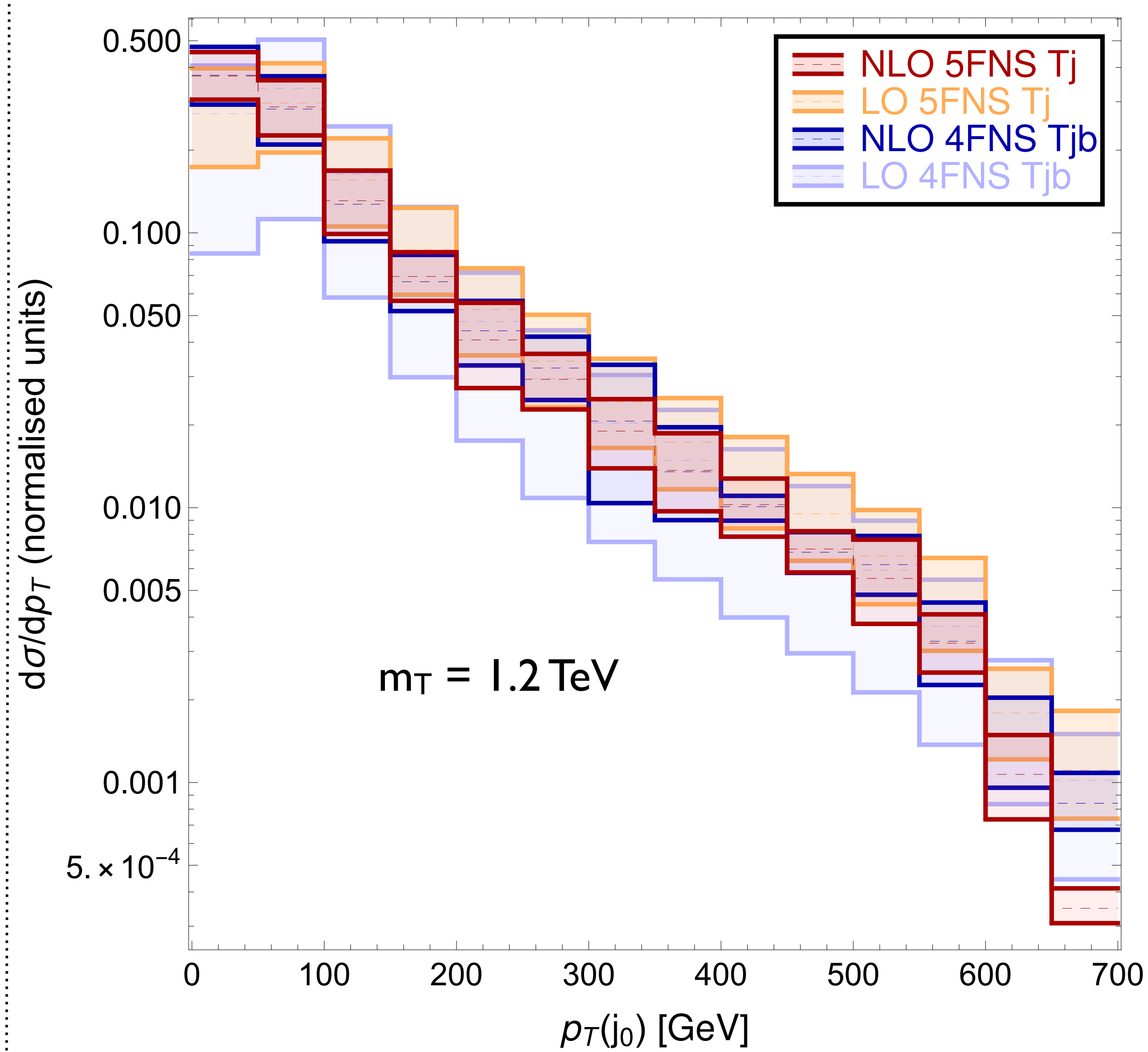
✤ 4FNS/5FNS shape agreement @NLO
- ★ Forward jets crucial for signal selection

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

Leading jet transverse momentum

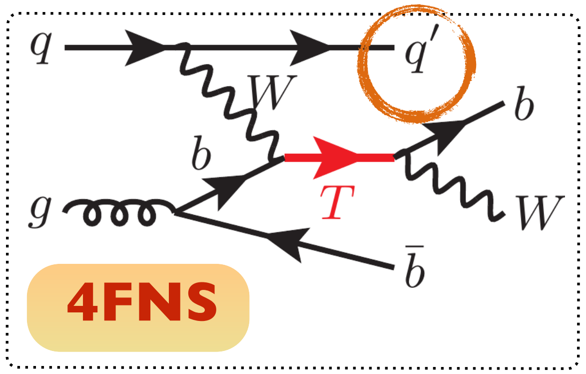
[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB`19)]

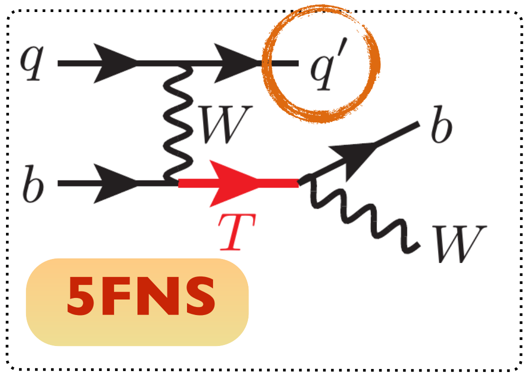
1st light jet p_T



✤ 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

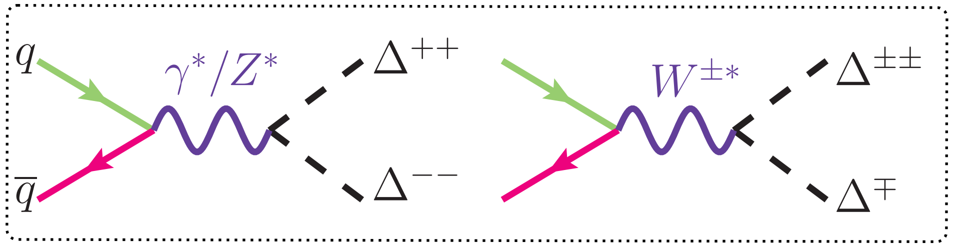
Impact on a search investigated…

Charged scalars @ NLO

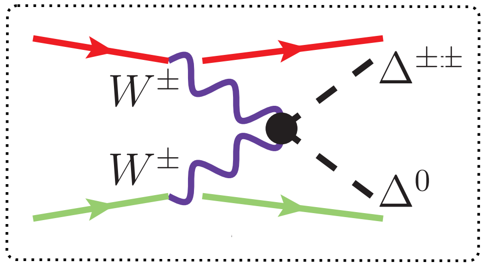
Total rates for di-scalar production

[BF, Nemevšek & Ruiz (to appear)]

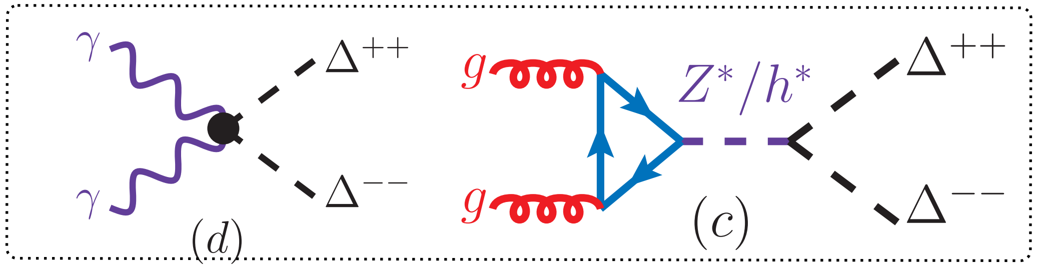
- ✦ Theoretical framework
  - ✤ SM + weak triplet ($\Delta^{\pm\pm}$, $\Delta^{\pm}$, Δ^{0})
- ✦ Drell-Yan production (K~1.2)

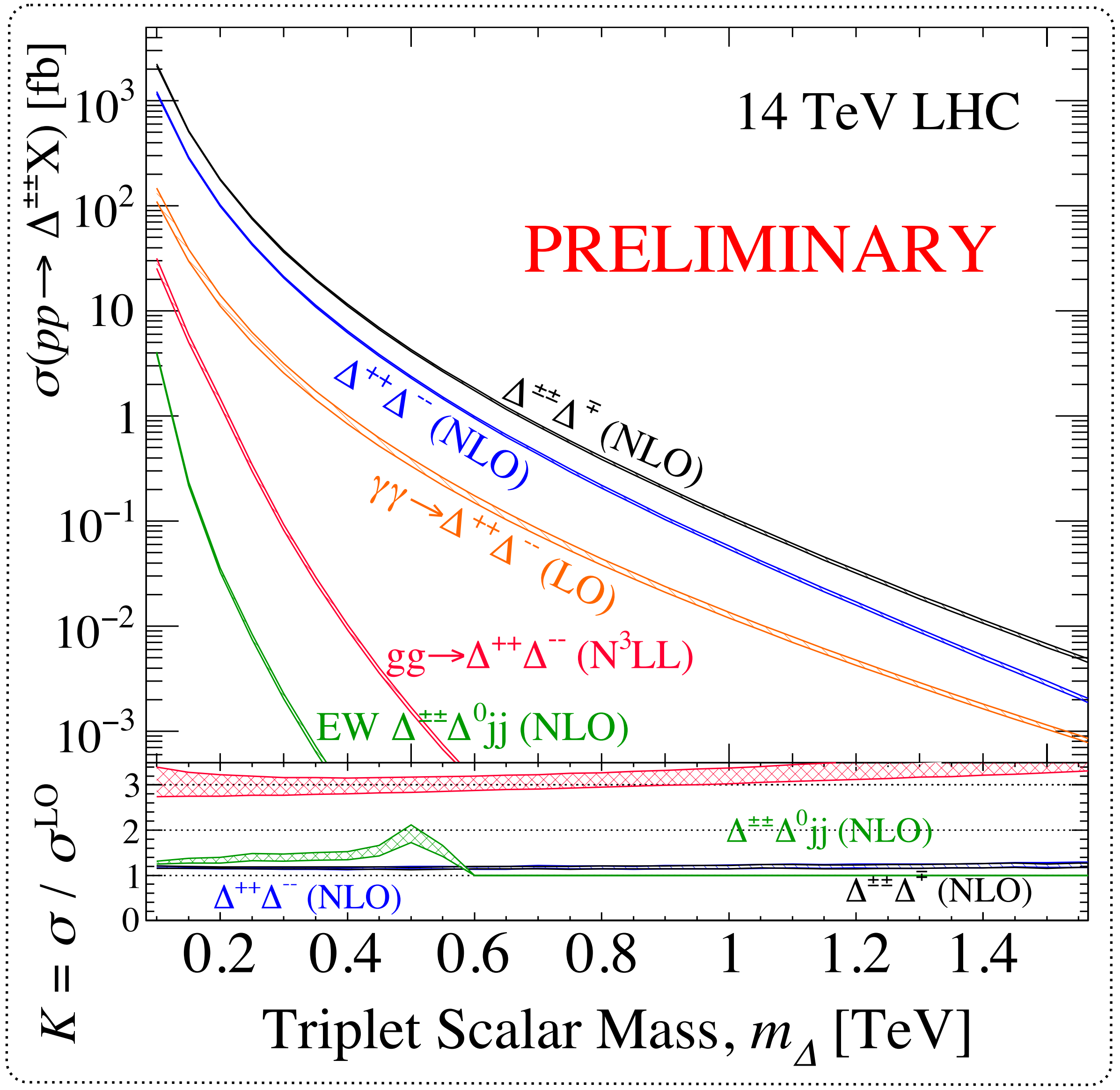


- ✦ VBF production (K~1)



- ✦ Gluon/photon fusion





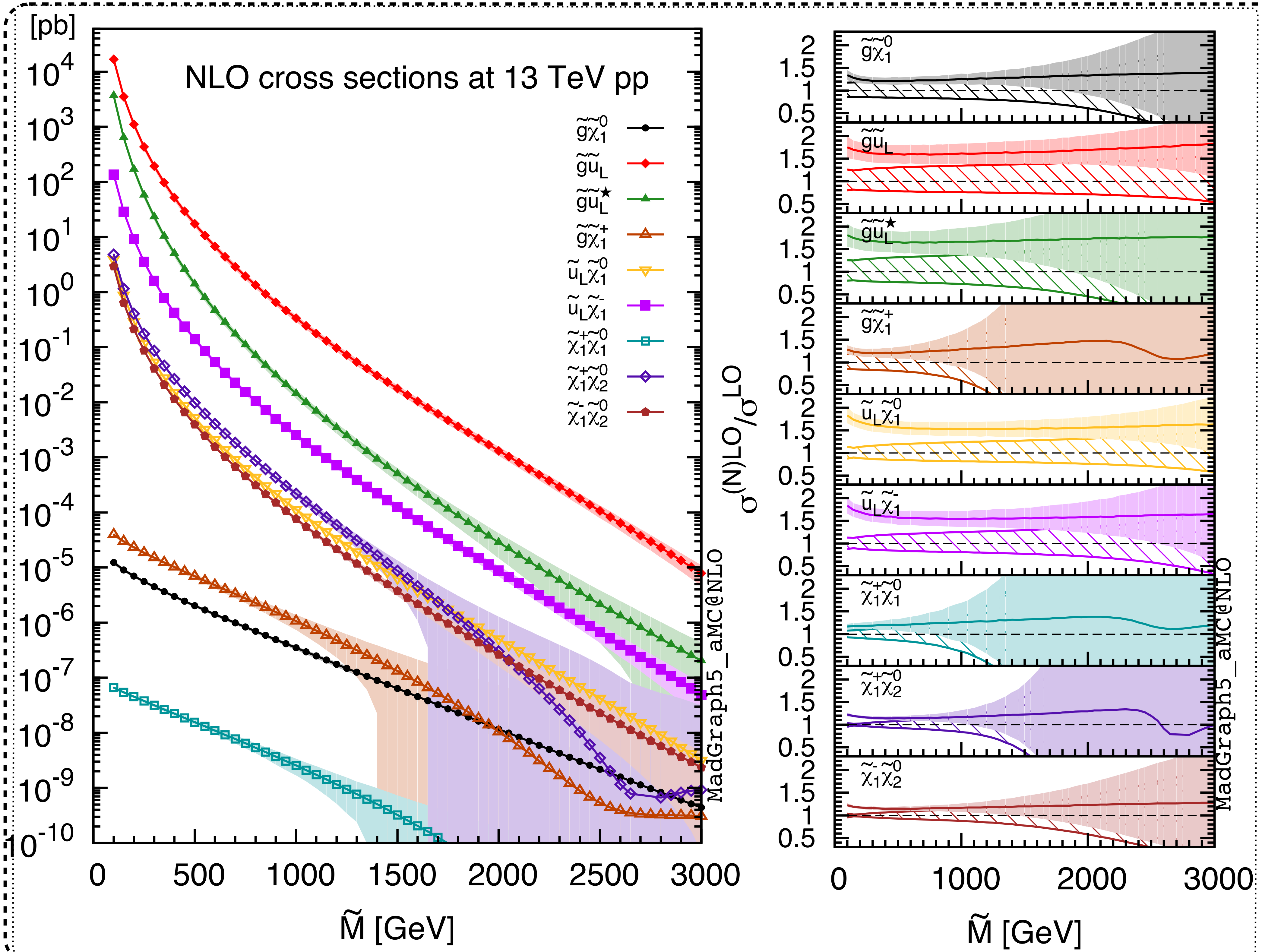
One unique framework for all calculations

Supersymmetry @ NLO

$\rightsquigarrow$ Parton densities

Next-to-simplified SUSY models: PDF issues

[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 $\tilde{M}$

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	$10.8^{+30\%}_{-21\%} \pm 2.2\%$

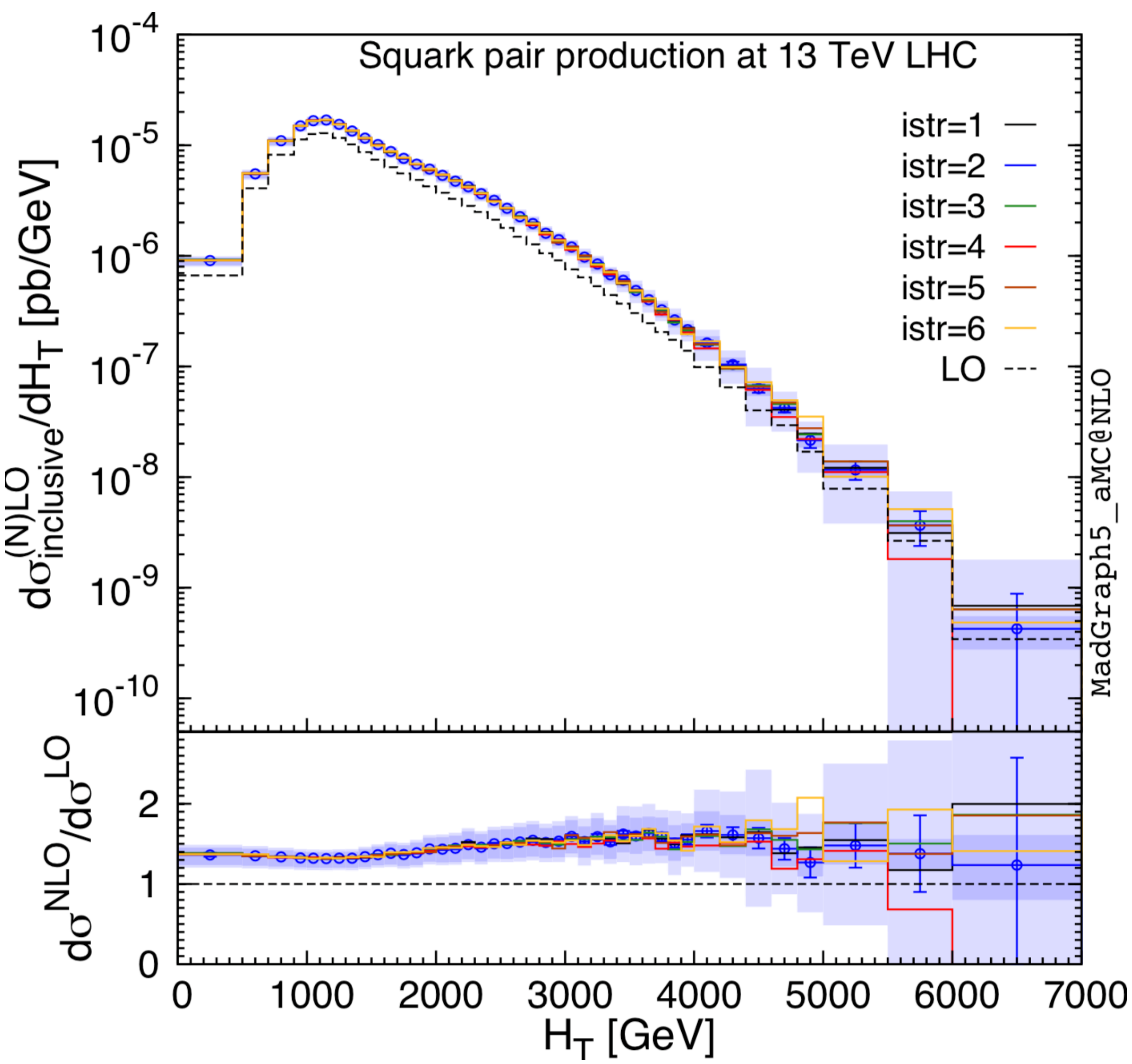
- Benchmark (allowed by data)
  - ★ Multi-TeV squarks and gluinos
  - ★ 50 GeV lightest neutralino (decays into jets and missing energy)
  - ★ Fiducial volume: typical H_T/MET selection (+ N_{jets} requirement)
- NLO impact
  - ★ Large K-factors (especially for $\tilde{g}\tilde{g}$), reduction of the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

No double counting

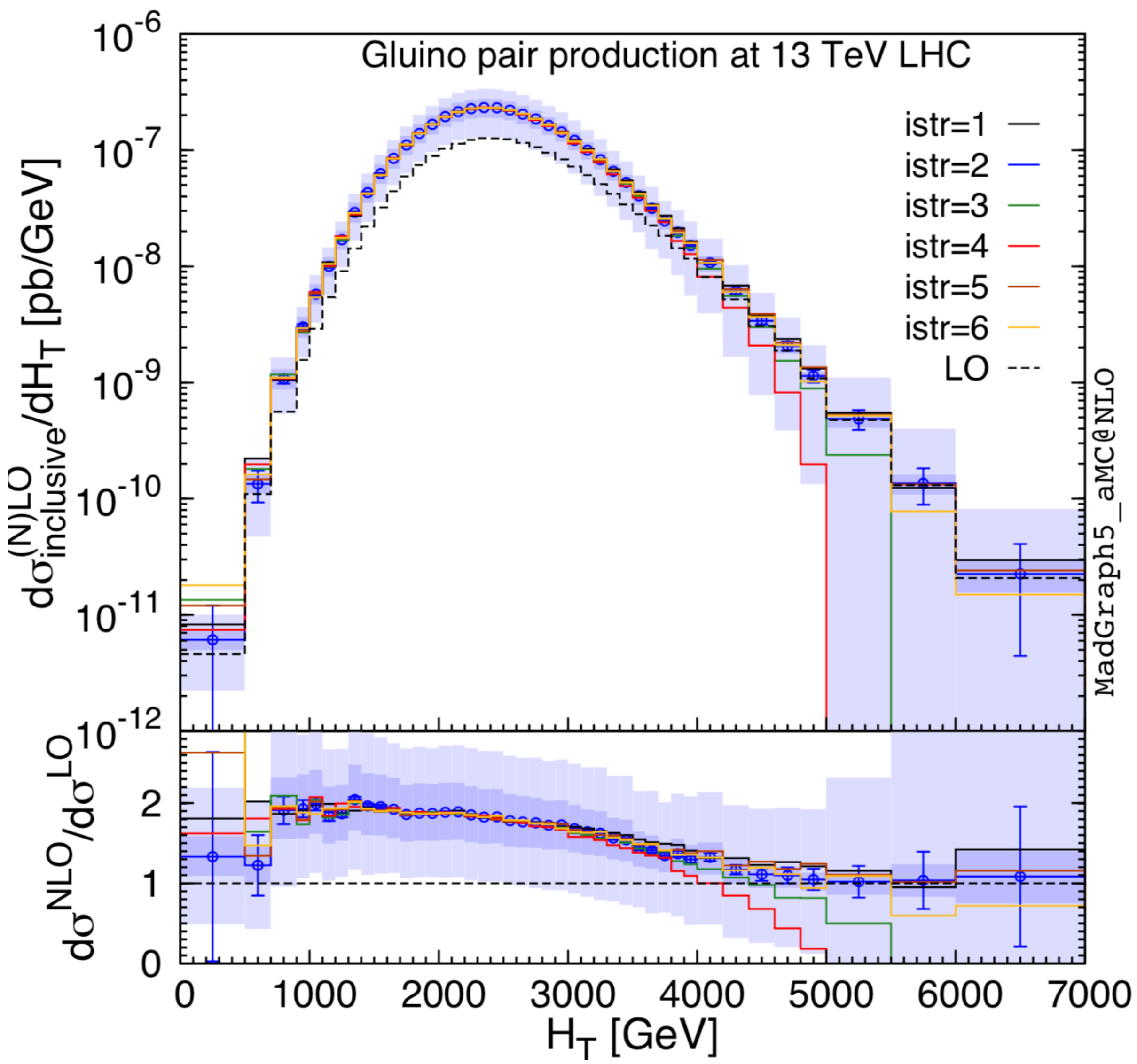
Treatment of the resonances: spectra

[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

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

★ Neutrino mass models

[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