When new physics meets the top quark

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LPTHE - CNRS - UPMC

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New physics at the LHC

- ✦ The top quark is widely believed to be a sensitive probe for new physics
  - ✤ The top mass is close to the electroweak scale
  - ✤ Top partners are necessary for stabilizing the Higgs mass
- ✦ The study of the top properties has played an important role
  - ✤ In the experimental program at the LHC
  - ✤ In theoretical prospectives studies for physics beyond the Standard Model
- ✦ Prospects for the LHC Run II (larger center-of-mass energy and luminosity)
  - ✤ Great expectation for direct new physics discovery
  - ✤ Could be indirectly found: precision measurements of the top properties

Outline

1. Top properties I - the dipole moments of the top quark

   [Aguilar-Saavedra, BF & Mangano (PRD'15)]

2. Top properties II - flavor changing neutral interactions of the top quark

   [Abu Zeid, Alloul, Andrea, Basso, Collard, Conte, D'Hondt, Deroover, BF, Hammad, Kim, Van Onsem & Van Parijs (*in prep*)]

3. NLO predictions for top partners (in composite & supersymmetric models)

   [Degrande, BF, Hirschi, Proudom & Shao (PRD'15, PLB'15); Ambrogi, Conte, BF, Kulkarni & Molter (*in prep*)]

   [BF & Shao (*in prep*); Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (*1605.02684; in prep*)]

Top properties in the effective field theory context

✦ The effective field theory (EFT) approach

- ✤ New phenomena are assumed to appear at a large scale Λ
- ✤ No assumption on the form of new physics
  - ★ Addition of higher-dimensional operators

✦ Leading new physics effects: dimension-six operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_x \frac{C_x}{\Lambda^2} O_x$$

- ✤ Effective terms:
  - ★ Modification of the Standard Model interactions
  - ★ New interactions not present at tree-level (e.g. top dipole moments and FCNCs)

Top dipole moments: definitions

✦ Top dipole moments d_V and d_A [Buchmuller & Wyler (NPB'86); Aguilar-Saavedra (NPB'09)]

✤ Parameterized by adding to the Standard Model $\mathcal{L}_{tg} = \frac{g_s}{m_t} \bar{t} \sigma^{\mu\nu} (d_V + i d_A \gamma_5) \frac{\lambda_a}{2} t\, G^a_{\mu\nu}$

✤ Generated by the dimension-six effective operator $O^{33}_{uG\phi} = (\bar{q}_{L3} \lambda_a \sigma^{\mu\nu} t_R) \tilde{\phi}\, G^a_{\mu\nu}$

★ Induced chromomagnetic moment $d_V = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \mathrm{Re}\, C^{33}_{uG\phi}$

★ Induced chromoelectric moment $d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \mathrm{Im}\, C^{33}_{uG\phi}$

✦ In the case of TeV-scale new physics and O(1) Wilson coefficients

✤ d_V and d_A are of about 0.05

✤ Largely exceeds the Standard Model predictions

★ $d_V^{(SM)} = -0.007$ [Martinez, Perez & Poveda (EPJC'08)]

★ $d_A^{(SM)} \approx 0$ [Soni & Xu (PRL'92)]

Top dipole moment measurements as probes of new physics

✦ Current best constraints (EDMs and rare B-decays):

✤ $| d_A | \leq 1.2\ 10^{-3}$ @ 95% CL [Kamenik, Papucci & Weiler (PRD'12)]

✤ $-3.8\ 10^{-3} \leq d_V \leq 1.2\ 10^{-3}$ @ 95% CL [Martinez & Rodriguez (PRD'02)]

From total rates measurements at the Tevatron and the LHC

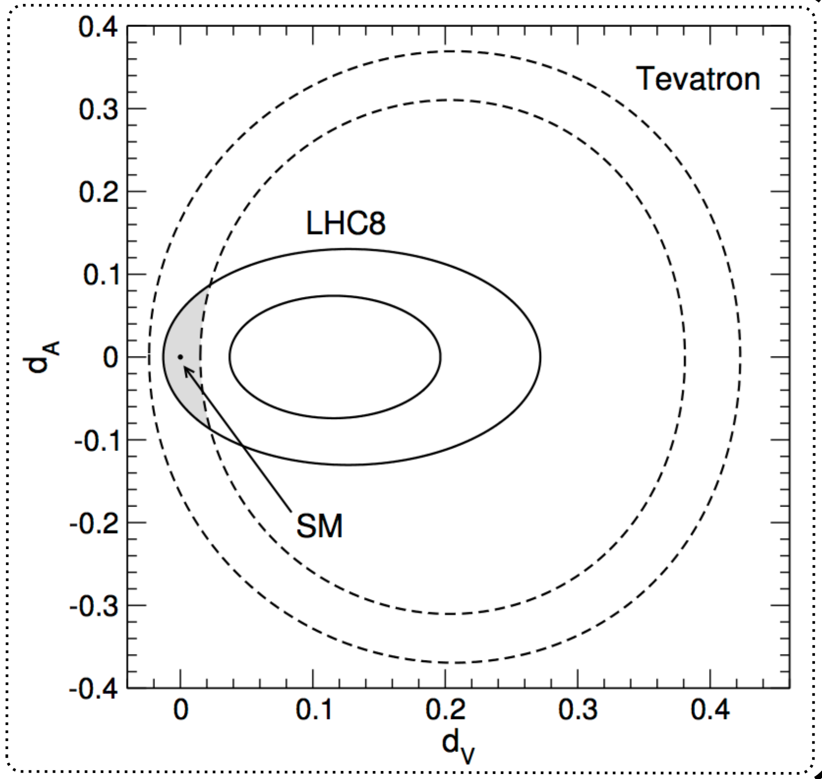
✦ Top-antitop total rate: complementarity of both the Tevatron and the LHC

- Proton-proton *versus* proton-antiproton collisions
- Different center-of-mass energies (1.96 TeV *versus* 8 TeV)
- Different functional form of the cross section on the top dipole moments

$$
\begin{aligned}
\sigma_{t\bar t}^{(2)}(\mathrm{pb}) &= \sigma_{\mathrm{SM}}^{(2)}(\mathrm{pb}) - 45.5\, d_V + 131\, d_V^2 - 64.7\, d_V^3 \\
&\quad + 55.5\, d_V^4 + 40.7\, d_A^2 + 56.5\, d_A^4 \\
&\quad - 66.2\, d_V d_A^2 + 116\, d_V^2 d_A^2 \\
\sigma_{t\bar t}^{(8)}(\mathrm{nb}) &= \sigma_{\mathrm{SM}}^{(8)}(\mathrm{nb}) - 1.53\, d_V + 10.1\, d_V^2 - 23.0\, d_V^3 \\
&\quad + 28.6\, d_V^4 + 7.0\, d_A^2 + 28.6\, d_A^4 \\
&\quad - 23.1\, d_V d_A^2 + 57.3\, d_V^2 d_A^2
\end{aligned}
$$

✦ Joint use of Tevatron and LHC-8 results

- Favored parameter space regions: different shapes
- Combination:
  - ➢ Stronger constraints than for a single collider



Improvements at the LHC Run II - the boosted top case

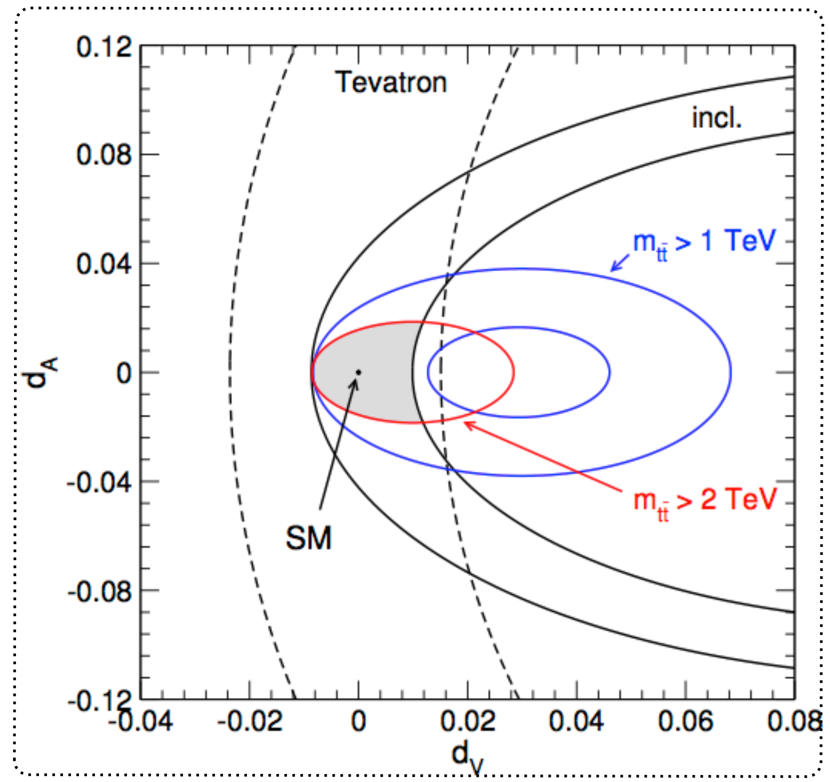
- Important amount of top-antitop pairs to be collected
  - Going beyond the use of total rate measurements
  - Benefitting from differential cross sections
- Three representative cases
  - (1) Total rate
  - (2) Production rate of top-antitop systems with m_{tt} > 1 TeV
  - (3) Production rate of top-antitop systems with m_{tt} > 2 TeV

- Heavier top-antitop systems
  - Enhanced sensitivity to top dipole moments (large momentum transfer)
  - (Maybe) more statistically challenged
- Rely on boosted top tagging techniques to reject multijet background
  - Boosted top similar to boosted jet
  - Restriction to the central part of the detector ($|\eta| < 2$)
    - ★ Better detector granularity ➢ better background rejection
  - Choice inspired by the CMS WP3 [CMS-PAS-JME-13-007]
    - ★ ≈ 12% of tagging efficiency
    - ★ ≈ 0.03% of mistagging rate of a QCD jet as a top quark

Prospects for the LHC Run II on the top dipole moments

✦ Predictions for 100 fb^{-1}

- ✤ Dashed black: Tevatron
- ✤ Solid black: LHC inclusive (5% uncertainties)
- ✤ Solid blue: LHC with m_{tt} > 1 TeV
  (5% systematics + computed statistics)
- ✤ Solid red: LHC with m_{tt} > 2 TeV
  (5% systematics + computed statistics)



✦ Huge gain in being differential:

$|d_A| \leq 1.9\ 10^{-2}$
$-8.6\ 10^{-3} \leq d_V \leq 1.2\ 10^{-2}$ ⇔ $\Lambda > 5$ TeV

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Top flavor changing neutral currents

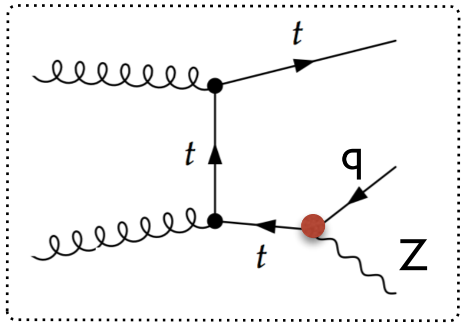
✦ Dimension-six operators yielding top flavor changing neutral interactions:

✤ New rare top decay processes (to be probed via top-antitop production)

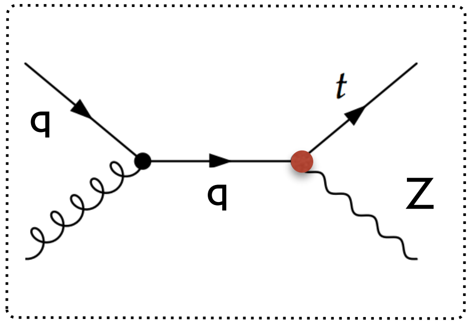
✤ New single top production mechanisms

✦ Example: a top-Z-quark dipole-like interaction

$$\mathcal{L}_{\rm eff}^t = \frac{\sqrt{2}}{2} \sum_{q=u,c} \frac{g\kappa_{zqt}}{2c_W\Lambda} Z_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f^L_{Zq}P_L + f^R_{Zq}P_R)q$$



Top pair-production followed by a rare decay



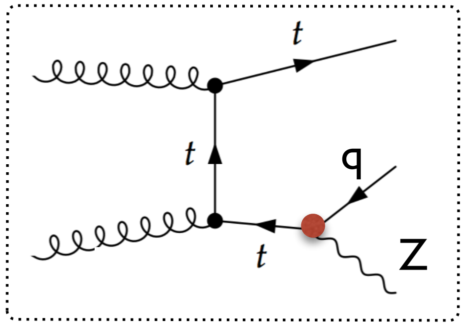
Top-Z associated production

✤ Potential gain in combining both channels

Analysis strategy

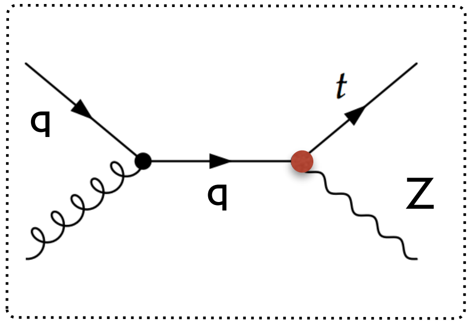
✦ Selection strategy: exploiting the final state topology in the three-lepton mode

✤ Low backgrounds



★ Final state: 3 leptons, ≥2 jets (≥1 b-jet)
★ 2 leptons l_1 and l_2 compatible with a Z-boson
★ W-transverse mass $M_T(l_3, \not{E}_T) \geq 50$ GeV
★ $M(l_1,l_2,j)$ invariant mass compatible with m_t
★ MVA improvement: $M(l_3,b)$, $M(l_1,l_2,j)$, n_b

Reduction of the multijet background: $M_T(l_3, \not{E}_T)$

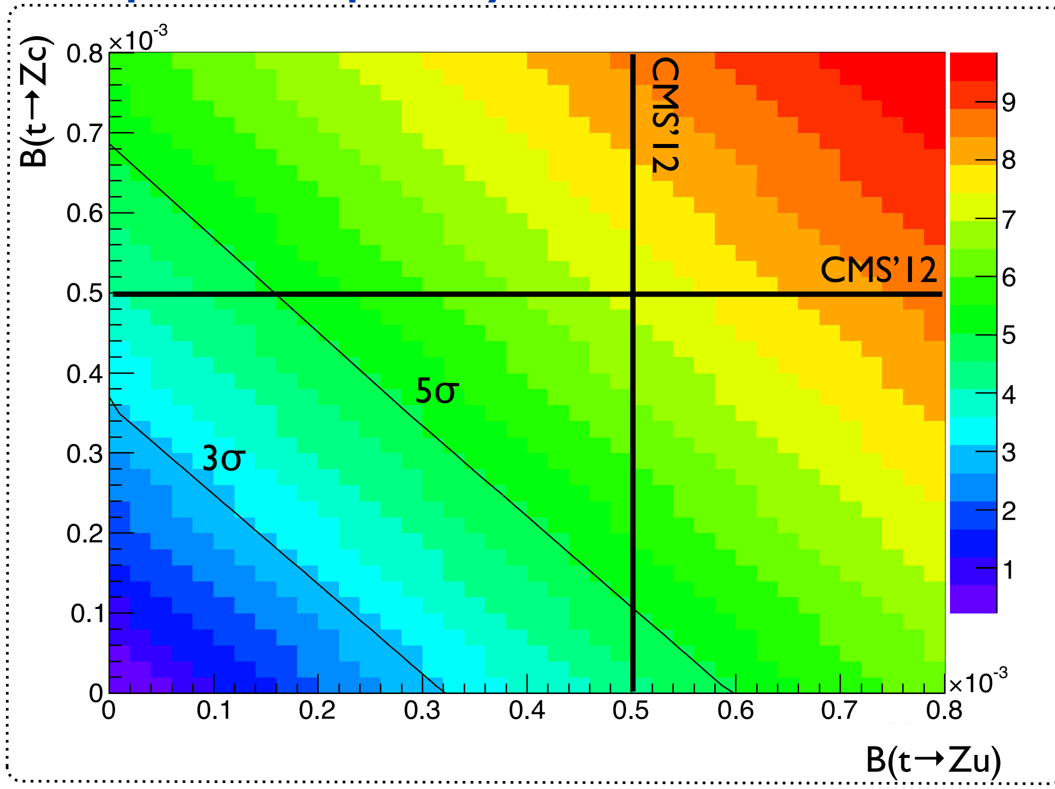


★ Final state: 3 leptons, 1 jets (1 b-jet)
★ 2 leptons l_1 and l_2 compatible with a Z-boson
★ W-transverse mass $M_T(l_3, \not{E}_T)$ in [50,120] GeV
★ Top-reconstructed mass $(l_3,b, \not{E}_T) \leq 220$ GeV
★ $M(l_3,b) \leq 150$ GeV
★ MVA: $p_T(j)$, invariant masses, angular distances

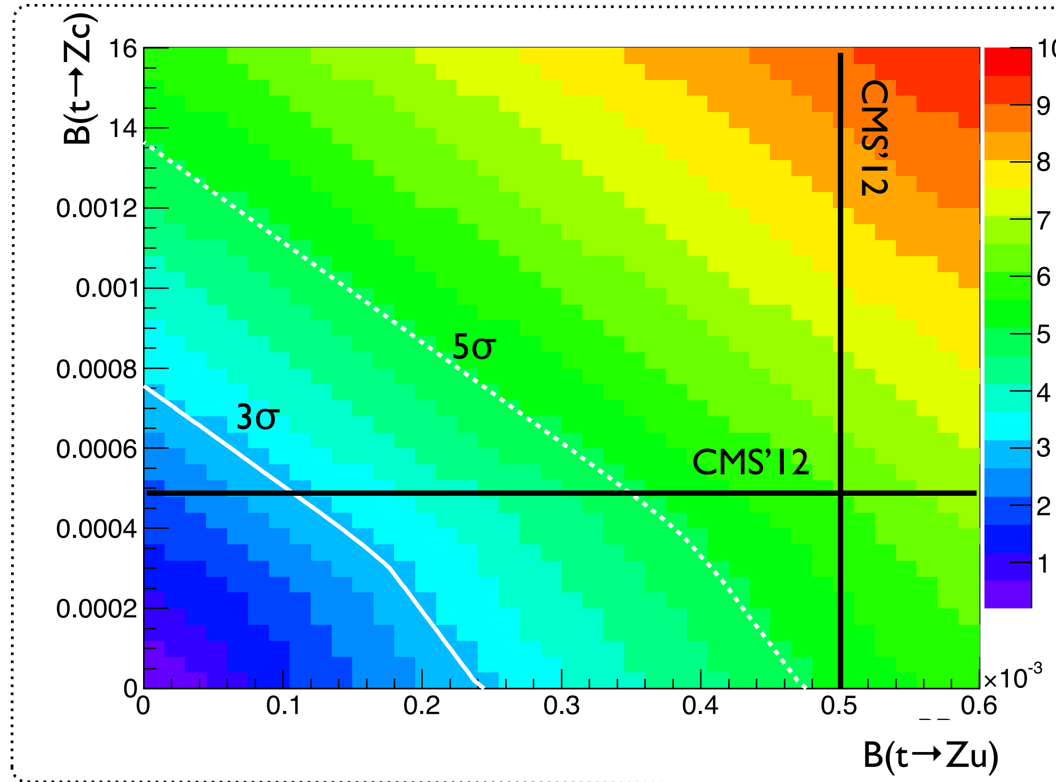
Combination
★The 1-jet requirement becomes: ≥1 jet
★The MVA is trained on both signals

Results for 100 fb^{-1}

✦ Top-antitop only:



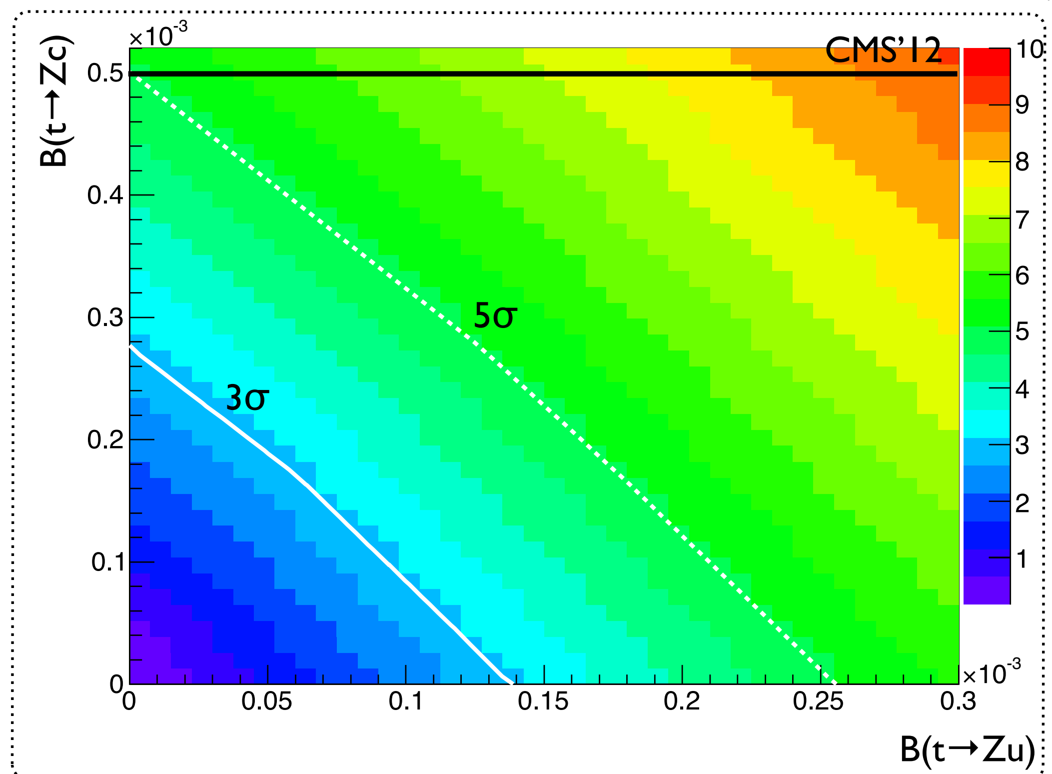
✦ Single top only:



✦ Combination

- ✤Analysis sensitivities:
  - ✤ Single top: t-Z-u interactions (PDFs)
  - ✤ top-antitop: both types of interactions (the b-tagging makes the small difference)
- ✤ Non negligible gain on the reach
  - ★ 3σ for B(Z→ct) from 0.038% to 0.028%
  - ★ 3σ for B(Z→ut) from 0.024% to 0.014%

Efforts should be made to combine both signals



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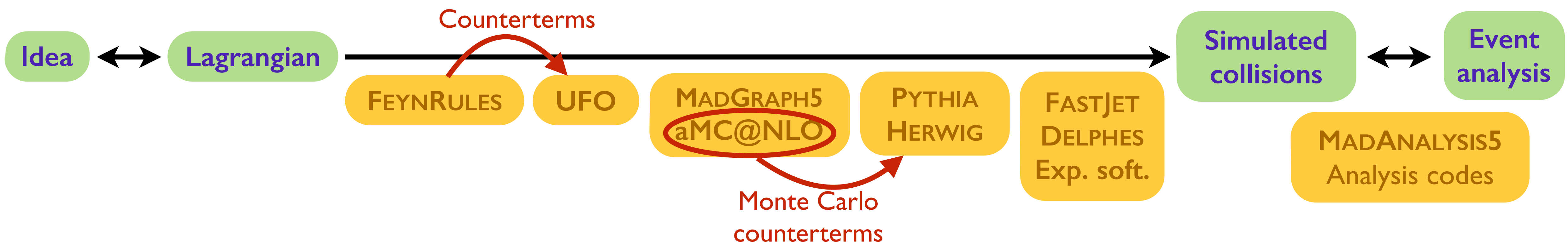
NLO predictions for top partners productions

✦ A comprehensive approach to Monte Carlo simulations



✦ Streamline the chain from the model Lagrangian to analyzed simulated collisions

✤ FeynRules is linked to the NLOCT module [Alloul, Christensen, Degrande, Duhr & BF (CPC'14); Degrande (CPC'15)]

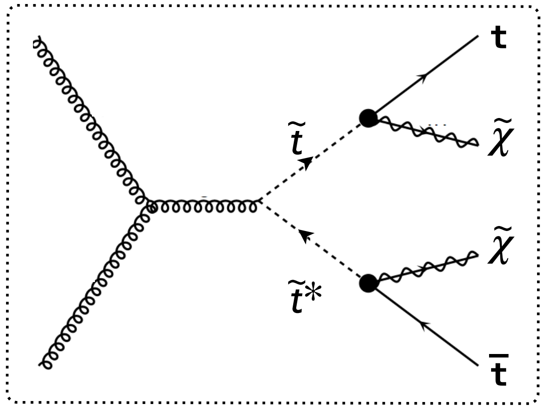
- ★ Calculation of UV and R_2 counterterms [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
- ★ Export of the information to the UFO [Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

✤ Matching to parton showers with MadGraph5_aMC@NLO [Alwall, Frederix, Frixione, Hirschi, Mattelaer, Shao, Stelzer, Torrielli & Zaro (JHEP'14)]

- ★ Monte Carlo counterterms associated with the new colored states are included (for standard colored states)

Stop pair production at the LHC

- ✦ Stop searches in the top-antitop plus missing energy mode
- ✦ Total rates at 13 TeV (NNPDF 2.3)
  - ✤ NNPDF 2.3 (uncertainties: 100 replica)
  - ✤ Scales set to the stop mass (uncertainties: factor of 2 / 0.5)



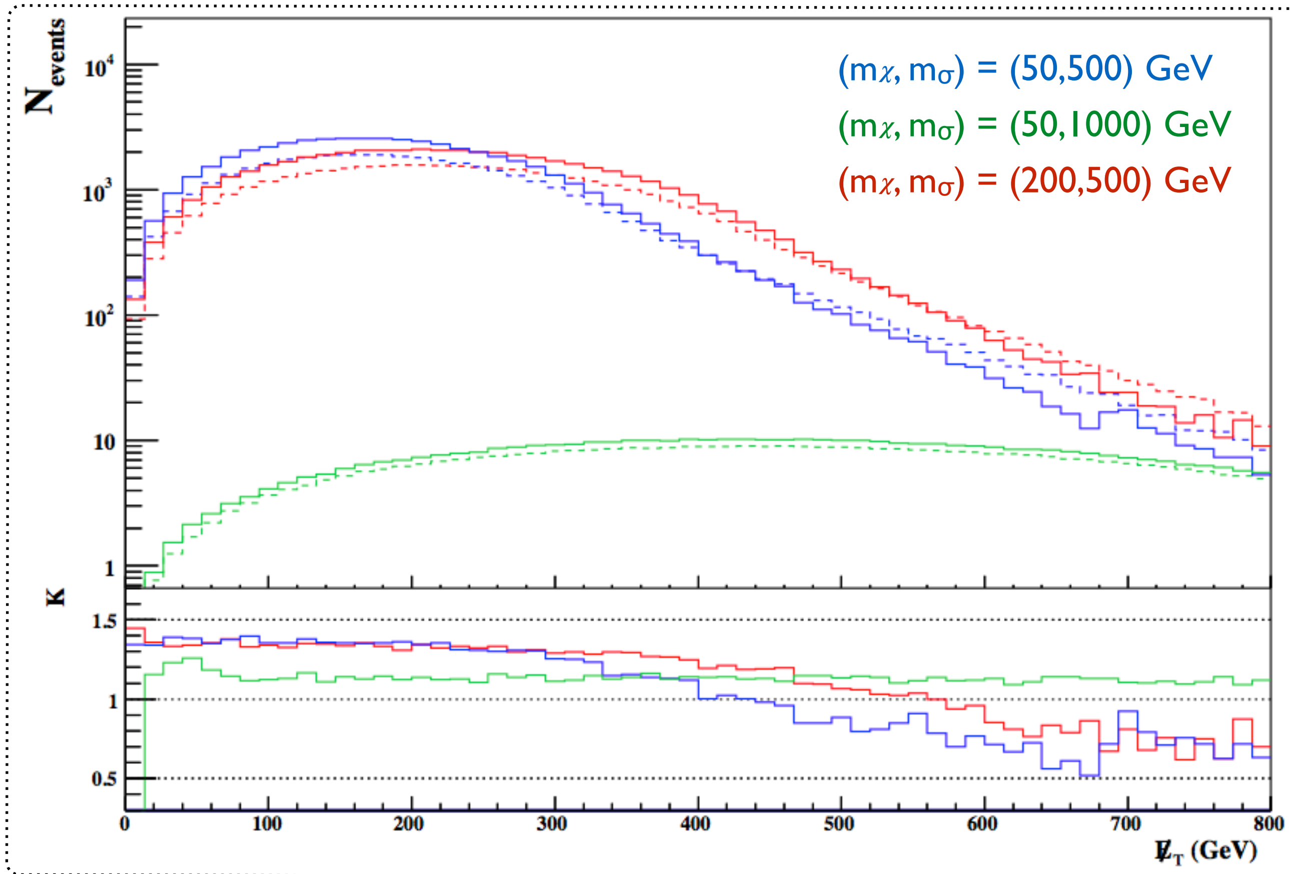
m_3 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$1.066 \pm 0.0025 \cdot 10^{3}\ ^{+29.1\%}_{-21.4\%}$	$1.497 \pm 0.0054 \cdot 10^{3}\ ^{+14.1\%}_{-12.1\%}\ ^{+1.2\%}_{-1.2\%}$
250	$1.553 \pm 0.0037 \cdot 10^{1}\ ^{+35.2\%}_{-24.8\%}$	$2.156 \pm 0.0067 \cdot 10^{1}\ ^{+12.1\%}_{-12.3\%}\ ^{+2.4\%}_{-2.4\%}$
500	$3.890 \pm 0.0093 \cdot 10^{-1}\ ^{+39.6\%}_{-26.4\%}$	$5.062 \pm 0.015 \cdot 10^{-1}\ ^{+11.2\%}_{-12.8\%}\ ^{+4.4\%}_{-4.4\%}$
750	$3.306 \pm 0.0081 \cdot 10^{-2}\ ^{+41.8\%}_{-27.5\%}$	$4.001 \pm 0.012 \cdot 10^{-2}\ ^{+10.8\%}_{-12.9\%}\ ^{+6.1\%}_{-6.1\%}$
1000	$4.614 \pm 0.011 \cdot 10^{-3}\ ^{+43.6\%}_{-28.3\%}$	$5.219 \pm 0.016 \cdot 10^{-3}\ ^{+10.9\%}_{-13.2\%}\ ^{+7.9\%}_{-7.9\%}$

- ✤ Agreement with PROSPINO
  [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]
- ✤ NLO effects: 25/50% for heavy/light stops
- ✤ Sizeable reduction of the uncertainties

- ✦ Differential distributions at NLO (illustrative example)
  - ✤ Comparing LO+PS and NLO+PS
    - ★ Constant *K*-factors not accurate
    - ★ *K*-factors scenario-dependent

How do the experimental results depend on the NLO effects?
➢ MADANALYSIS 5

[Conte, BF, Serret (CPC '13)]
[Conte, Dumont, BF, Wymant (EPJC '14)]



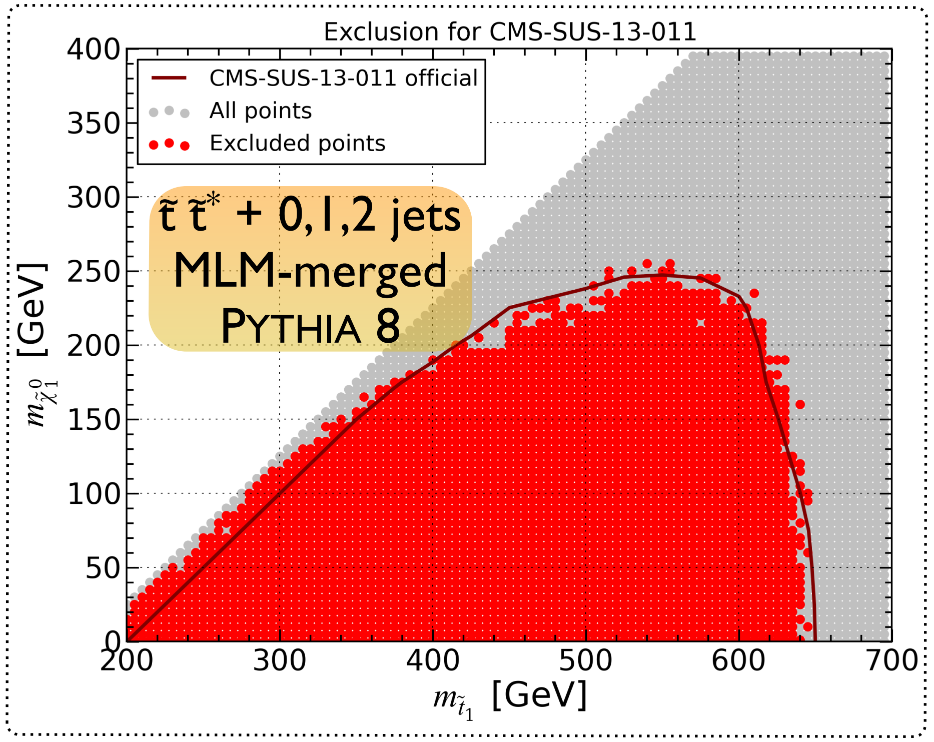
NLO effects on the CMS single lepton stop search

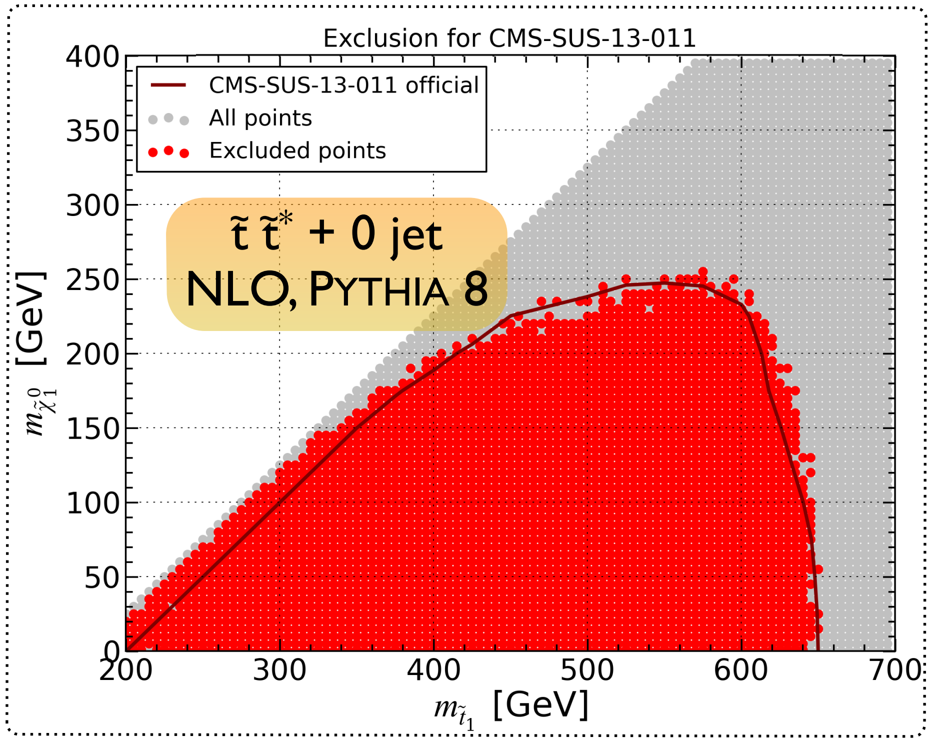
✦ LO and NLO

1. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0,1,2 jets @LO ; PYTHIA 8 with the MONASH tune
2. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0 jet @NLO ; PYTHIA 8 with the MONASH tune

✦ How are the limits changing?

✤ Stable constraints (due to the many jets already there at the leading order)



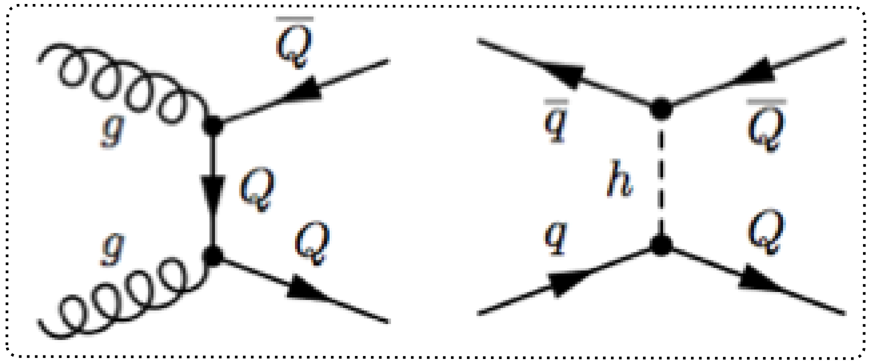


This is an analysis dependent statement
NLO effects could be crucial for some analyses!!!
Better control of the uncertainties in all cases!

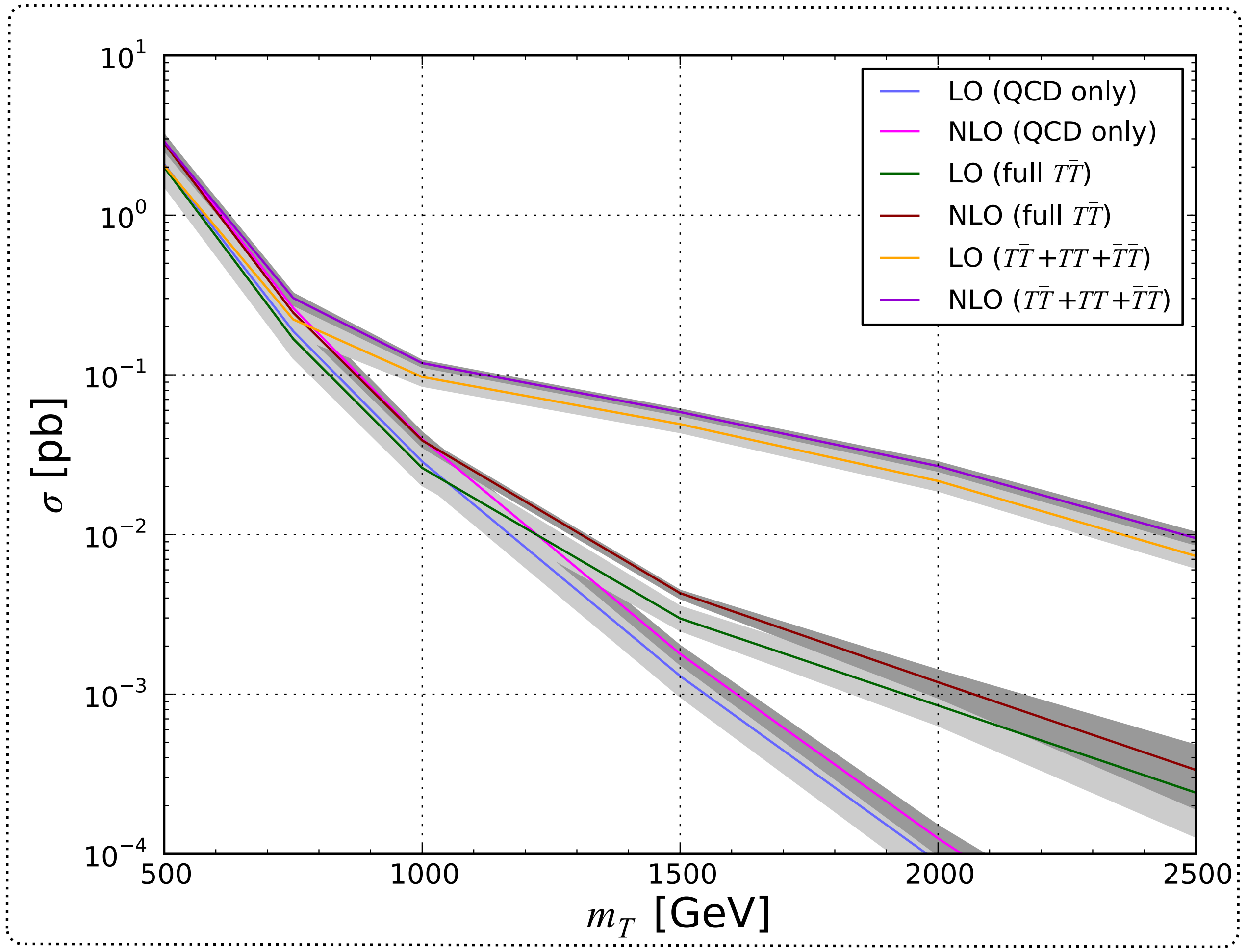
Vector-like quark partners

✦ Heavy quark can mix with all light quarks

- ✤ QCD production of the top partners
- ✤ New mechanisms yielding the production of top partners



✦ Total rates (up-T mixing case)



- ✤ Light T: QCD production dominates
- ✤ Heavier T: EW production dominates

QCD corrections and electroweak diagrams are important

- ✤ NLO: sizeable reduction of the uncertainties

Summary

- **The top quark is widely believed to be a sensitive probe for new physics**
  - The top properties are key players
  - Top partners are necessary for stabilizing the Higgs mass and heavily searched for
- **Top properties**
  - The boosted regime offers a novel way to directly access the top dipole moments
  - Great expectation for discovering a top flavor changing neutral interaction at Run II
- **Top partners**
  - NLO corrections are available (for free)
  - Neglected channels are not negligible in specific scenarios