Single Top & Dark Matter

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LPTHE - CNRS - UPMC

3rd CMS Single Top Workshop

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Heavy rains in central France region…

1000m^3 of soil falling on the railroad…

Targeting dark matter and top quarks at the LHC

- There is strong (indirect) evidence for dark matter
  - Cosmic microwave background
  - Baryonic acoustic oscillations
  - Gravitational anomalies
  - *etc.*
- Huge endeavor to detect dark matter and measure its properties
  - Underground nuclear recoil experiments (DM-nucleon scattering)
  - Dark matter annihilation in the galaxy, gamma rays
  - Collider searches with missing energy

- 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

Signals of models with a top quark connected to dark matter?

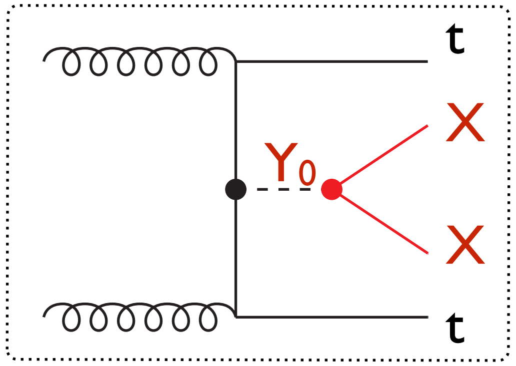
Outline

1. Simplified models for top-philic dark matter
2. Monotop models and their constraints
3. Effects of next-to-leading-order predictions

Top-philic dark matter

✦ 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 to the Standard Model (top quark)



+ 2 new physics couplings

No single top signature

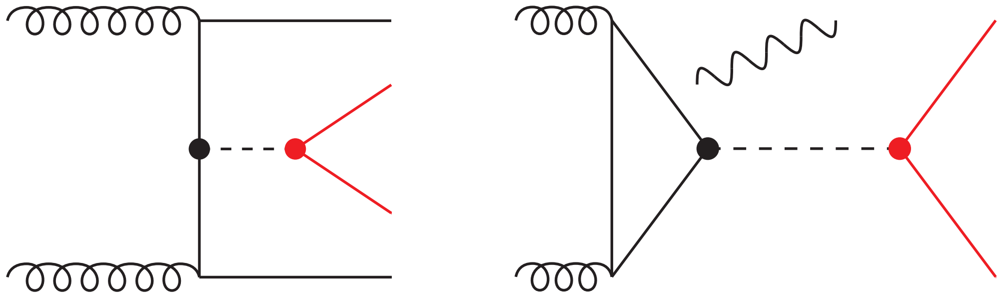
✦ Effective Lagrangian

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

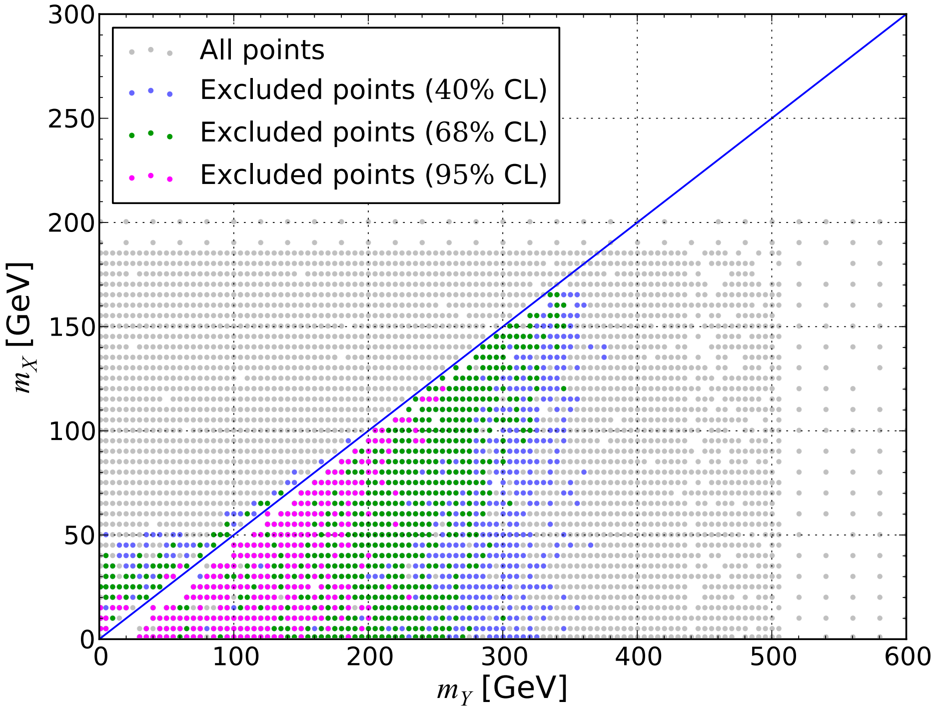
Probing top philic dark matter at the LHC

✦Usual missing energy probes

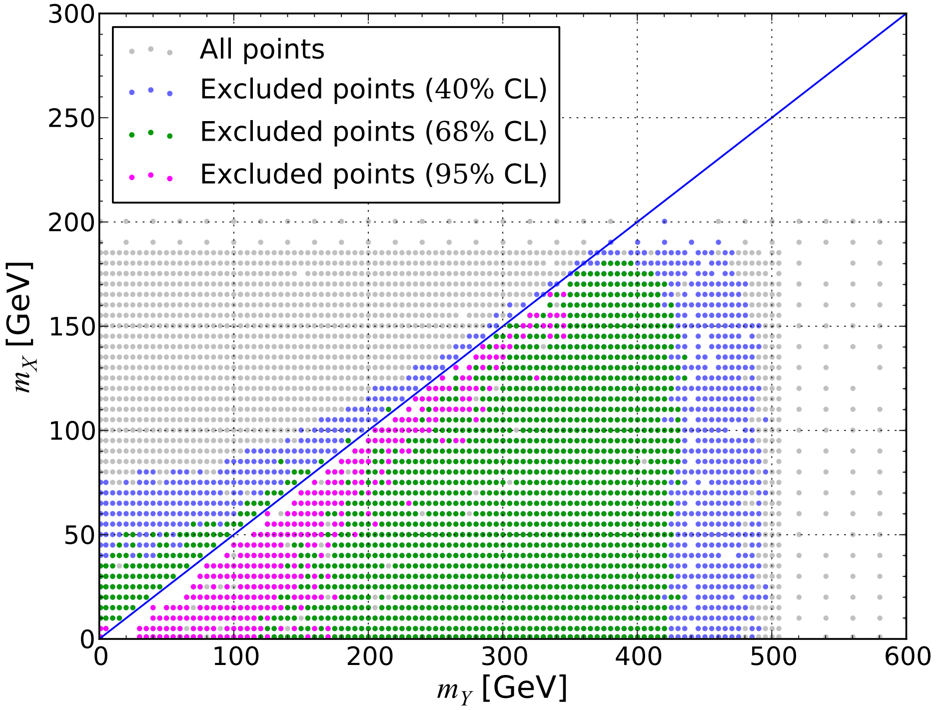
- ✤ Top-antitop plus missing energy
- ✤ Monojet
- ✤ Mono-Z
- ✤ Mono-Higgs



Top-antitop + MET



Monojets



- ✤ Mono-Higgs and mono-Z: good prospects

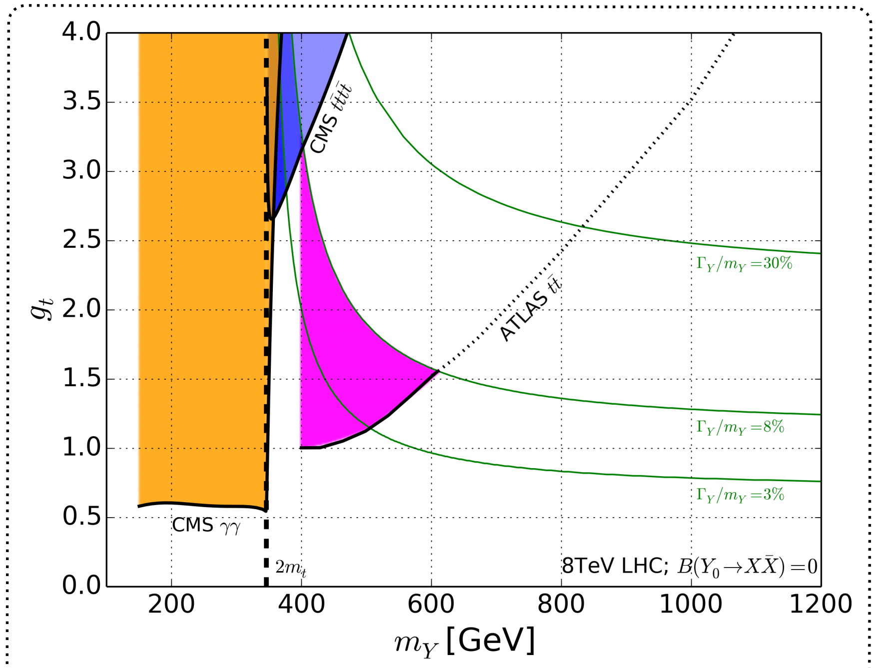
[Arina, Backovic, Conte, BF, Guo *et al.* (1605.09242)]

Non-MET searches are important

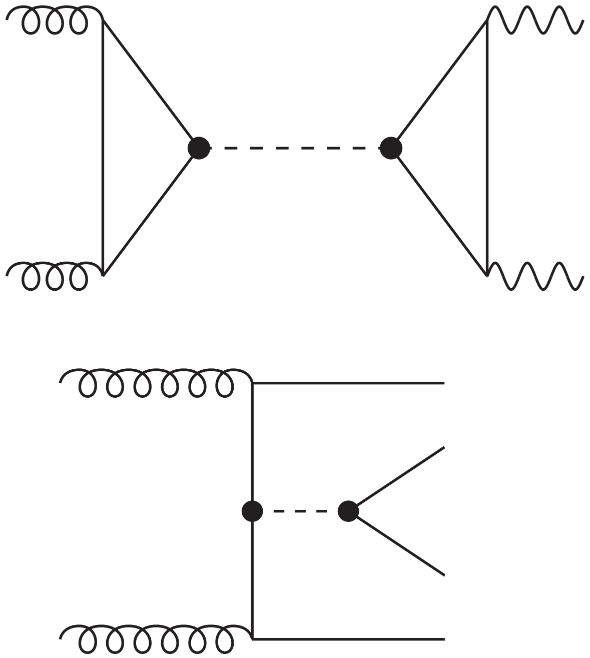
✦ The mediator can decay back to Standard Model particles

- ✤ Loop-induced dijet, digamma
- ✤ top-antitop resonances
- ✤ Four top production

No single top



[Arina, Backovic, Conte, BF, Guo *et al.* (1605.09242)]



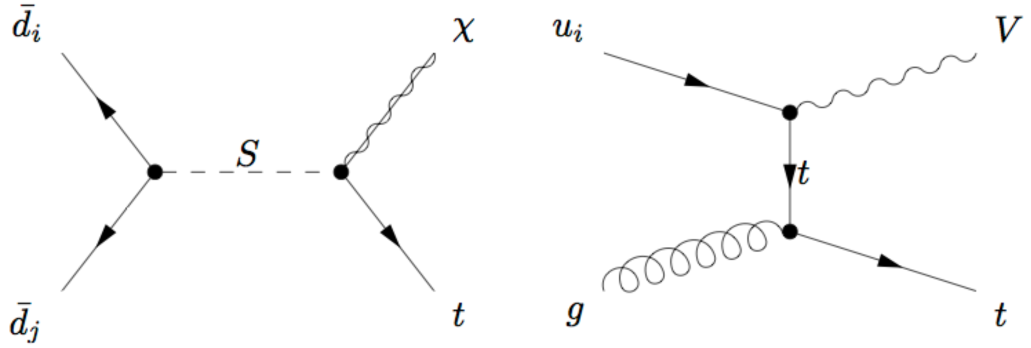
✤ Combining MET and resonance searches provide extra handles on the model

Monotops at hadron colliders: the general case

- The bottom-up strategy: we start from the final state signature and build a model
- Allows us to simultaneously analyze several new physics models, e.g.,
  - Supersymmetric compressed spectrum: undetected soft objects
  - Dark matter models with a mediator coupling to quarks in a flavor-violating way
  - *etc.*

[Andrea, BF, Maltoni (PRD '11)]

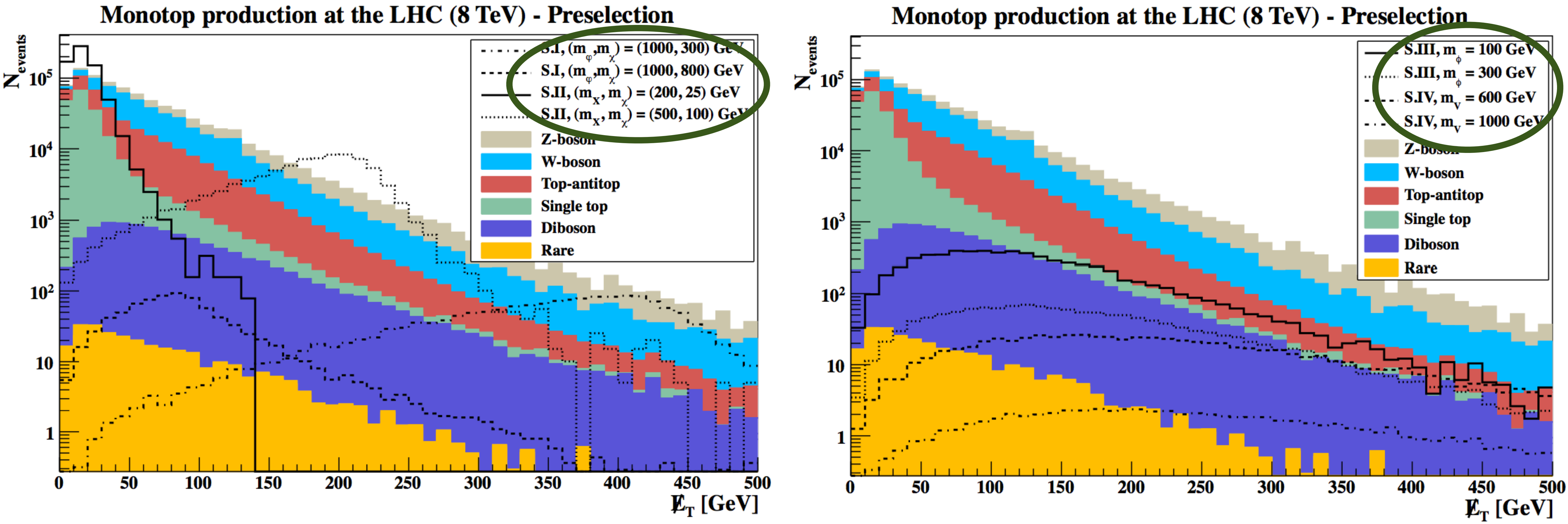
- Generic monotop production
  - Missing energy (dark matter candidate or mediator decaying to dark matter particles)
    - Bosonic or fermonic state
    - One-particle or n-particle state
    - Neutral, weakly-interacting, long-lived/stable/invisible
  - Initial state: two possibilities
    - A down-type (anti)quark pair → baryon-number-violating process
    - An up-type quark / gluon associated pair → flavor-changing neutral interactions



Two classes of models

Monotops with 20 fb^{-1} of 8 TeV LHC data (1)

✦ Missing energy spectrum for resonant (left) and non-resonant (right) monotop production



Resonant mode

The position of the (distorted) edge depends on the resonant and invisible particle masses.

Flavor-changing mode

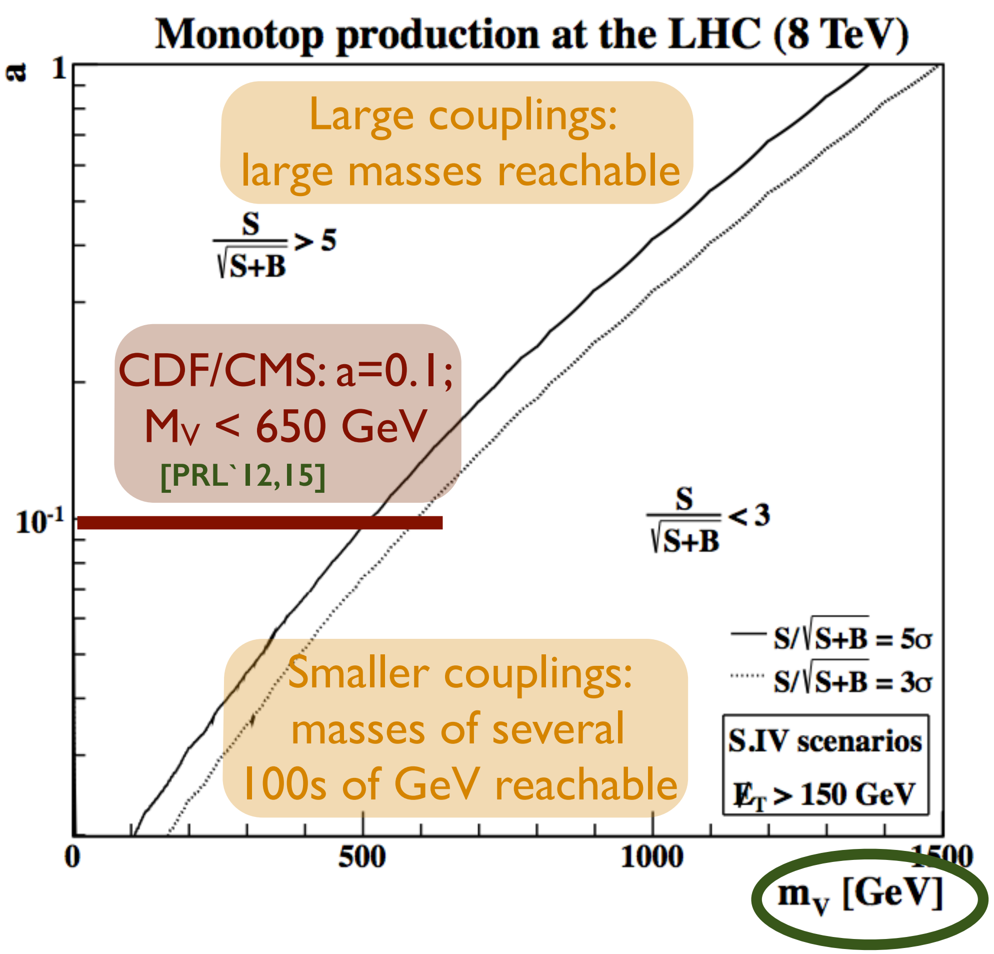
The peak position depends on the invisible particle mass. Signal spectra exhibit large tails.

Not much sensitivity to light monotops

[Agram, Andrea, Buttignol, Conte, BF (PRD'14)]

Monotops with 20 fb^{-1} of 8 TeV LHC data (2)

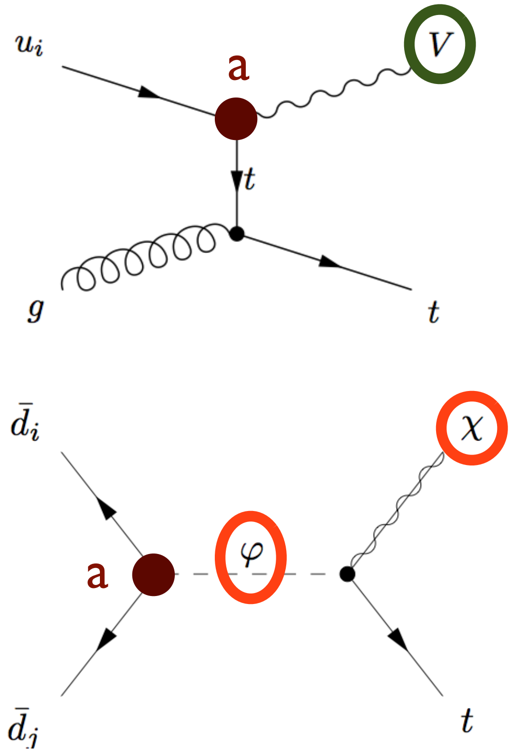
[Agram, Andrea, Buttignol, Conte, BF (PRD'14)]



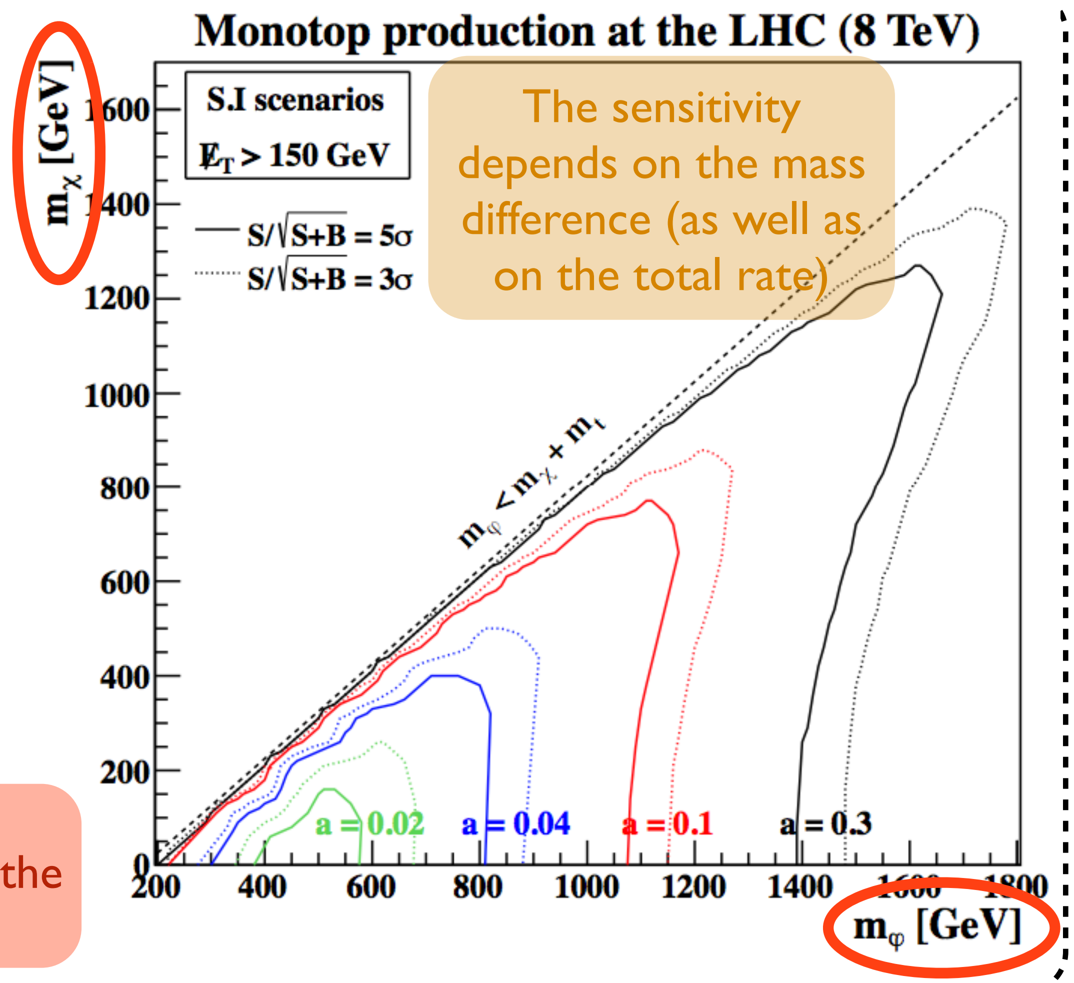
Large couplings: large masses reachable

CDF/CMS: a=0.1; M_V < 650 GeV [PRL`12,15]

Smaller couplings: masses of several 100s of GeV reachable



BR($\varphi \to u\chi$) = 100%
→ results independent of the related coupling.



The sensitivity depends on the mass difference (as well as on the total rate)

✦ Hadronic monotop selection (similar results for the leptonic case)

- ✤ Lepton veto
- ✤ 2 light jets and 1 b-tagged jet
- ✤ $\not{E}_T > 150 \text{ GeV}$
- ✤ M_{jj} and M_W compatible
- ✤ M_{bjj} and M_t compatible
- ✤ Non-collinear top and missing energy

The LHC can largely access the monotop mot general parameter space

Towards UV completion: the EW symmetry (1)

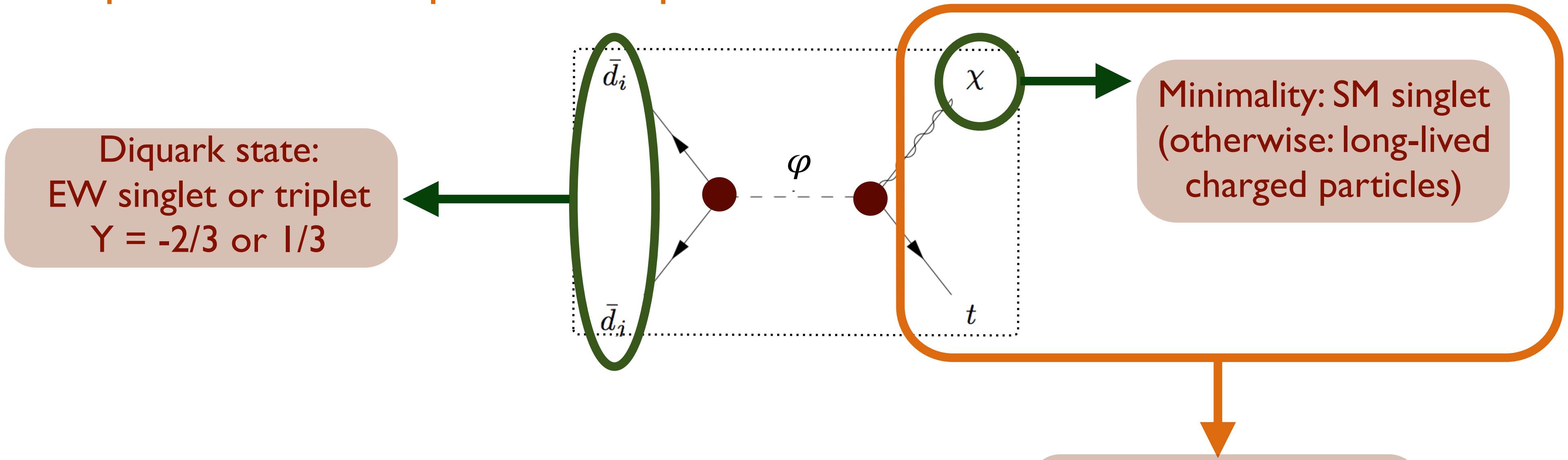
[Boucheneb, Cacciapaglia, Deandrea, BF (JHEP '15)]

✦ What about the electroweak symmetry?

✤ The new states should be part of EW singlets/doublets ➢ extra signals

✤ We impose the monotop probe to be the dominant way to test the model

- ★ Simplification of the parameter space



Diquark state:
EW singlet or triplet
Y = -2/3 or 1/3

Minimality: SM singlet
(otherwise: long-lived
charged particles)

Monotop system:
EW singlet or doublet
Y = 2/3 or 1/6

✤ One single model and four parameters

- ★ Two masses (resonance + invisible fermion)
- ★ Two coupling strengths

$$\mathcal{L} = \lambda_s^{ij}\ \varphi_s\, \bar d^C_{R,i} d_{R,j} + y_s\ \varphi_s^\dagger\, \bar\chi t_R + \text{h.c.}$$

- ★ The resonance and is a scalar that couples to a pair of right-handed quarks
- ★ The invisible fermion is a SM singlet and couples to right-handed quarks

Towards UV completion: the EW symmetry (2)

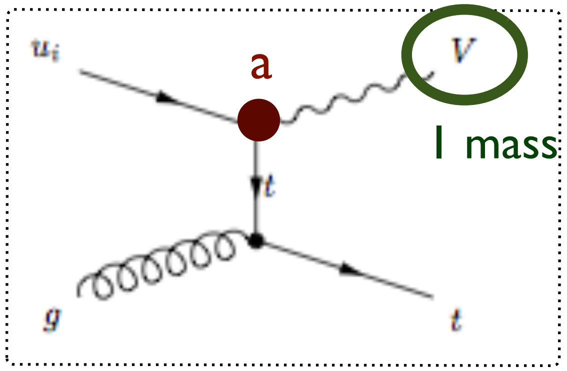
[Boucheneb, Cacciapaglia, Deandrea, BF (JHEP '15)]

✦ Same exercise for the flavor changing case

- We impose the monotop signal to be the key way to probe the model
  - ★ The mediator and is a vector state
  - ★ It couples to the right-handed quarks only

$$\mathcal{L} = a_R^{ij}\ V_\mu \bar{u}_{R,i}\gamma^\mu u_{R,j}$$

- One single model and two parameters
- Other cases (scalar mediator, different couplings): New physics should appear in other channels first



✦ Is V invisible?

- The V state can decay back into a top quark and a jet
  - ★ Addition of a dark sector strongly coupled to V

$$\mathcal{L}_{V-\text{decay}} = V_\mu \Big(g_{R\chi}\ \bar{\chi}_R\gamma^\mu\chi_R + g_{L\chi}\ \bar{\chi}_L\gamma^\mu\chi_L \Big)$$

- More parameters
- Dark matter considerations can constrain them

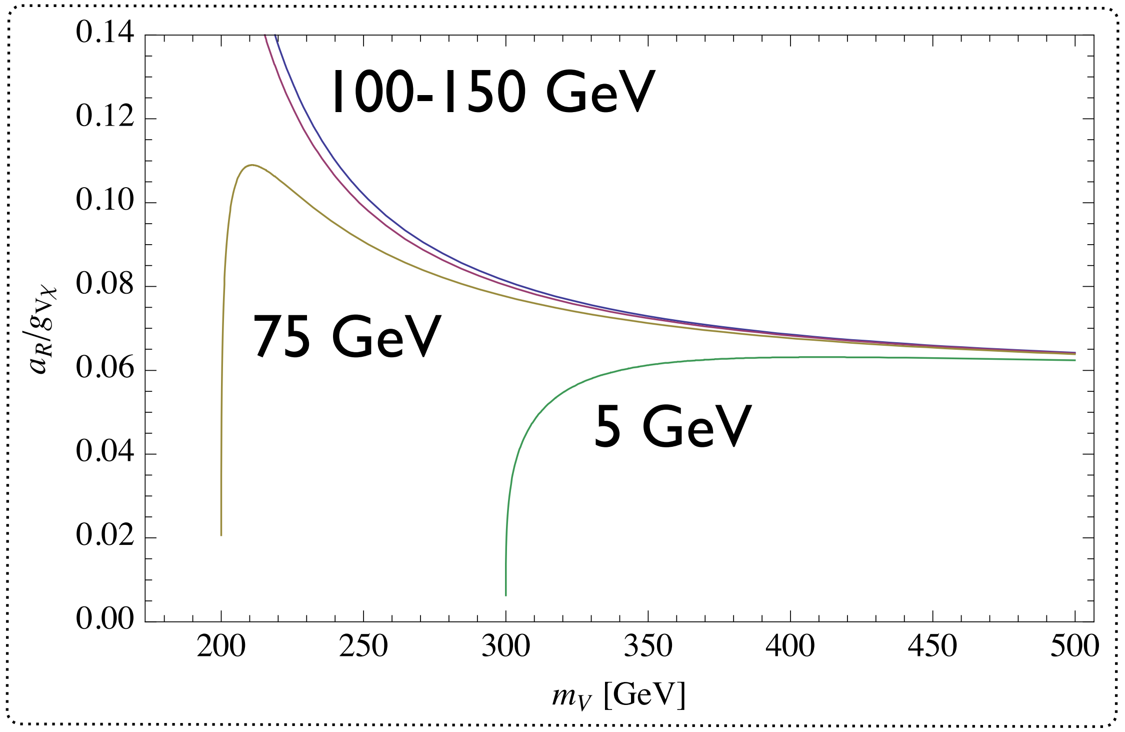
The same holds for the resonant model

Pinning down the flavor changing monotop model

[Boucheneb, Cacciapaglia, Deandrea, BF (JHEP '15)]

✦ Dominant V invisible decays (BR= 99%)

- ✤ Constrains the maximum ratio a / g_V



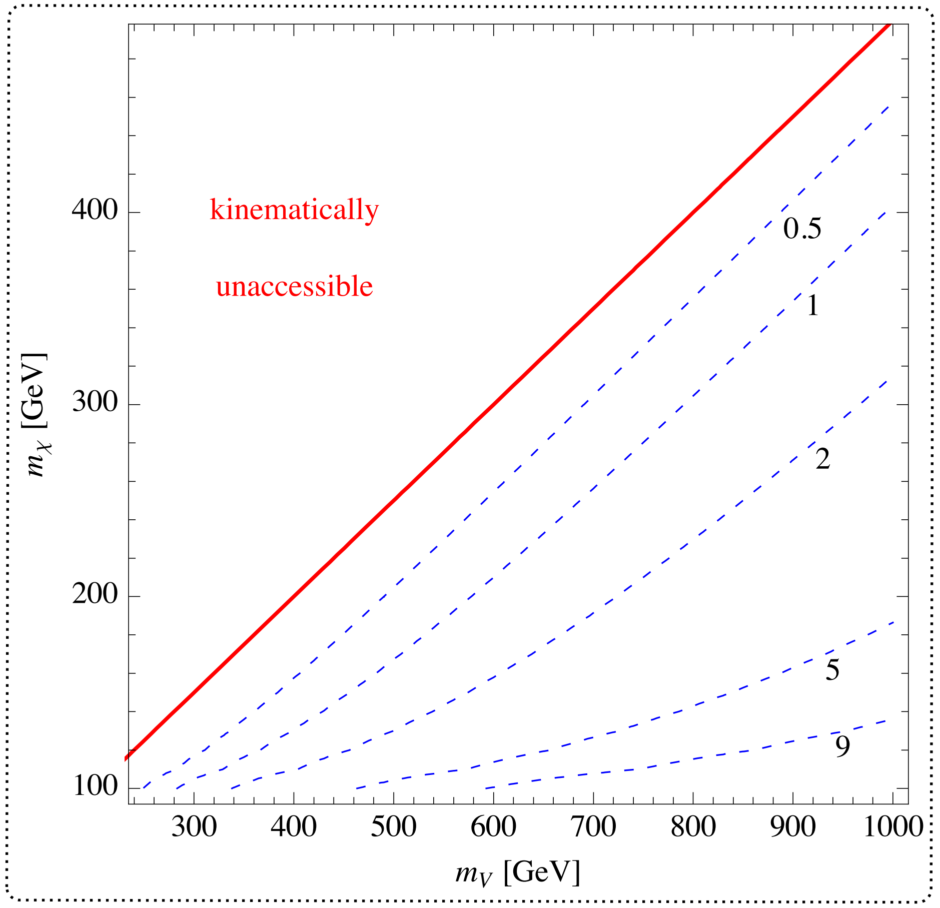
Possible choice

- ★ g_V of order 1
- ★ a of order 0.1

✦ We need a good DM candidate

- ✤ Constrains the minimum product a x g_V

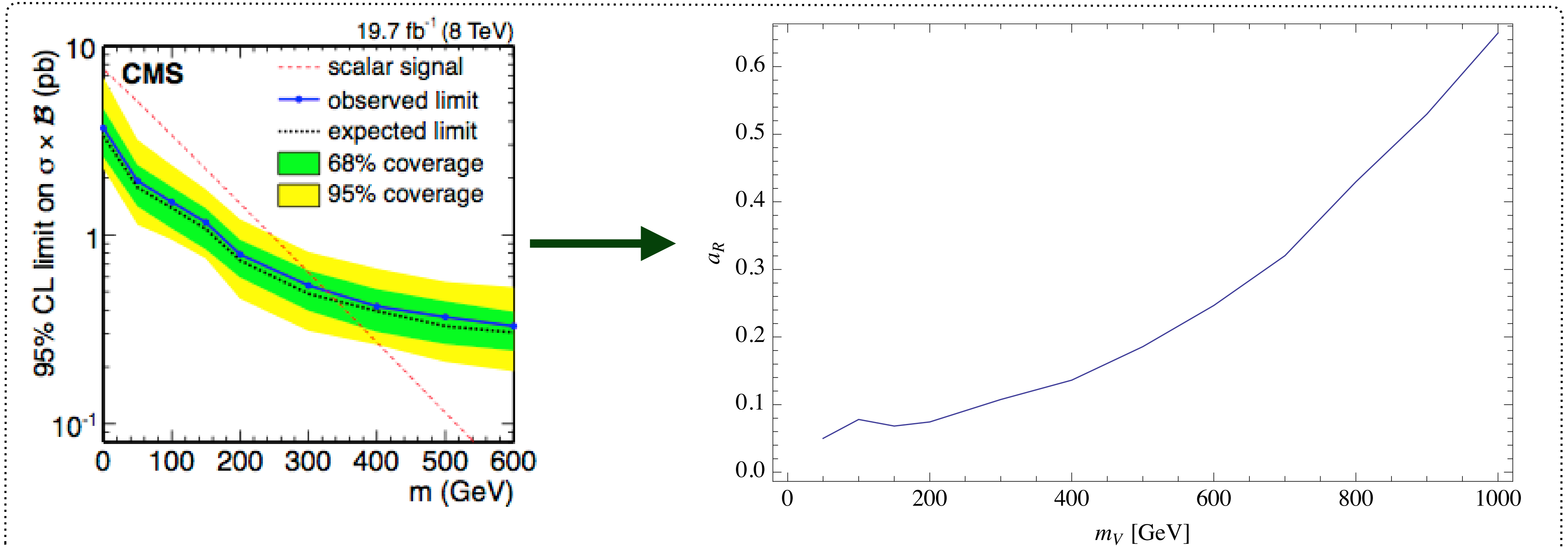
Both: we can deduce a lower bound on g_V



Combining collider and dark matter constraints

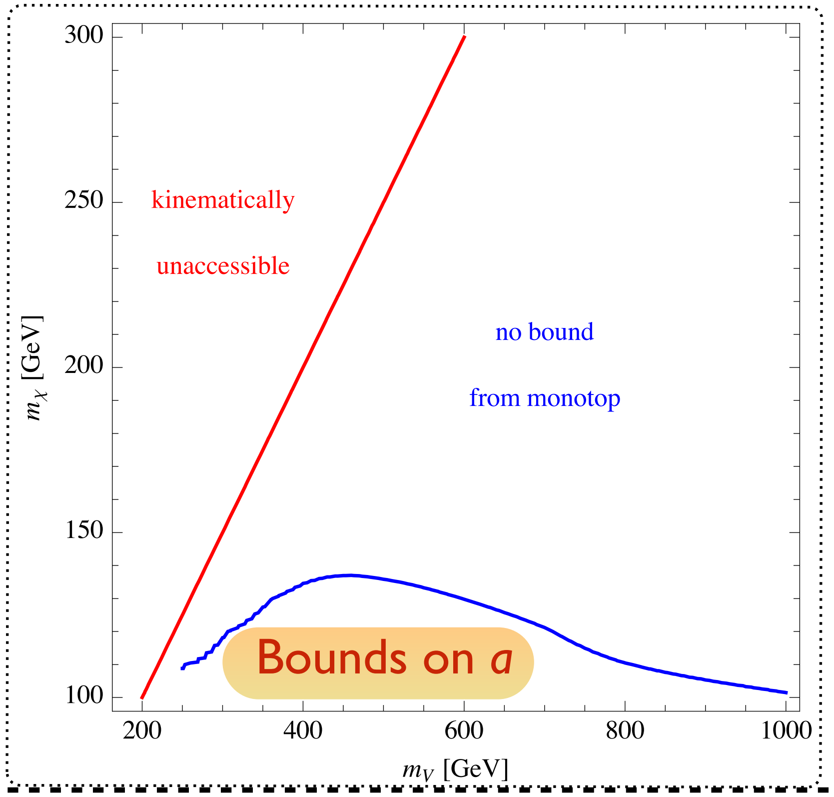
[Boucheneb, Cacciapaglia, Deandrea, BF (JHEP '15)]

✦ CMS hadronic monotop results & constraints on *a* as a function of m_V



✦ Combining with dark matter results

★ A large fraction of the parameter space is already well constrained



Conclusions (before the next topic)

- ✦ There is a clear gain in combining constraints from many sources
  - ✤ Astrophysics - cosmology
  - ✤ Collider (MET searches, resonance searches)
  - ✤ Gravitational anomalies
  - ✤ *etc.*
- ✦ Two considered examples
  - ✤ Top-philic dark matter models
  - ✤ Monotop models

Outline

1. Simplified models for top-philic dark matter

2. Monotop models and their constraints

3. Effects of next-to-leading-order predictions

NLO calculations in a nutshell

✦ Contributions to an NLO result in QCD

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

$$\sigma_{NLO} = \underbrace{\int d^4\Phi_n \mathcal{B}}_{\text{Born}} + \underbrace{\int d^4\Phi_{n+1} \mathcal{R}}_{\text{Reals: one extra power of } \alpha_s \text{ and divergent}} + \underbrace{\int d^4\Phi_n \ \mathcal{V}}_{\text{Virtuals: one extra power of } \alpha_s \text{ and divergent}}$$

✤ KLN theorem: the divergences cancel for infrared-safe observables

- ★ If no distinction between soft-and-collinear emission from the no-emission case

The virtual contributions

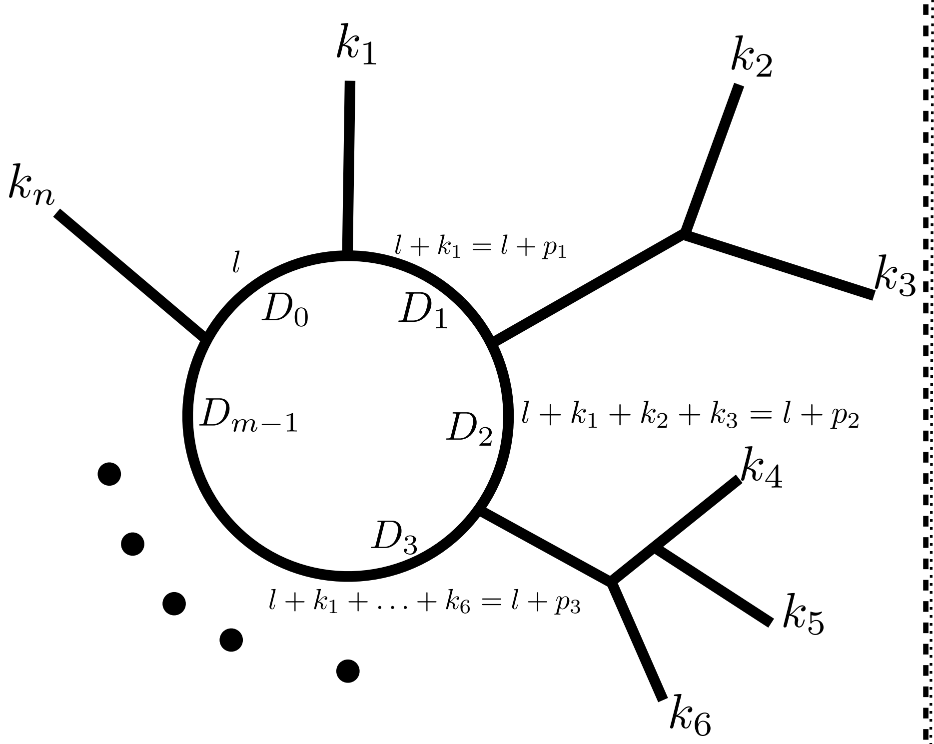
✦ Loop diagram calculations

- ✤ Calculations should be done in *d*=*4*-*2ε* dimensions
  - ★ Divergences made explicit (1/ε^2, 1/ε)
  - ★ Numerical methods: work in four dimensions
- ✤ Rewriting the loop integral with scalar integrals

$$\int \mathrm{d}^d\ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int \mathrm{d}^d\ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

  - ★ Involves integrals with up to four denominators
  - ★ The decomposition basis is finite

m-point diagram with *n* external momenta



Reduction in four dimensions - the rational terms

- The loop momentum lives in a *d*-dimensional space
  - The reduction should be done in *d* dimensions and not in 4 dimensions

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

  - Need to compensate this!

- The R_1 terms originates from the denominator

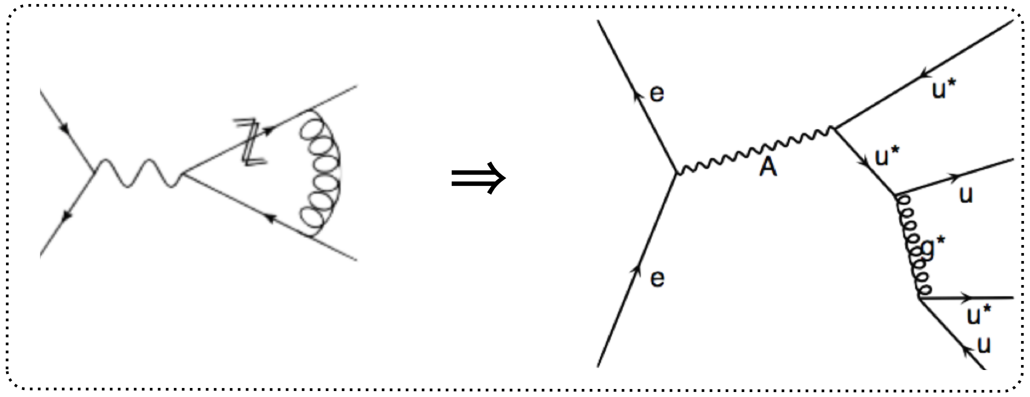
$$\frac{1}{\bar{D}} = \frac{1}{D}\left(1 - \frac{\tilde{\ell}^2}{\bar{D}}\right)$$

  - These extra pieces can be calculated generically (3 integrals in total)

- The R_2 terms originates from the numerator
  - Process-dependent contributions proportional to l^2 can arise
  - In a renormalizable theory, there is a finite number of such R_2 pieces
    - ★ They can be calculated once and for all for a specific model (R_2 counterterm Feynman rules)

Loop calculations with MADLOOP

- MADLOOP uses MADGRAPH tree-level capabilities for loop calculations
  - Loop-diagrams with *n* external legs are cut: tree-level diagrams with *n*+2 external legs



  - ★ All diagrams with two extra partons in the final states are generated
  - ★ A first filter removes the non-necessary ones (including permutations, mirror graphs, *etc.*)
  - ★ A second filter removes the external-line tadpoles and bubbles graphs

- MADLOOP then calculates the virtual contributions
  - Contraction with Born diagrams, color traces calculations, *etc.*
  - Internal propagator denominators are removed
    - ★ We have the loop integrand numerator
    - ★ It can be reduced and evaluated
  - UV and R_2 counterterm diagrams added

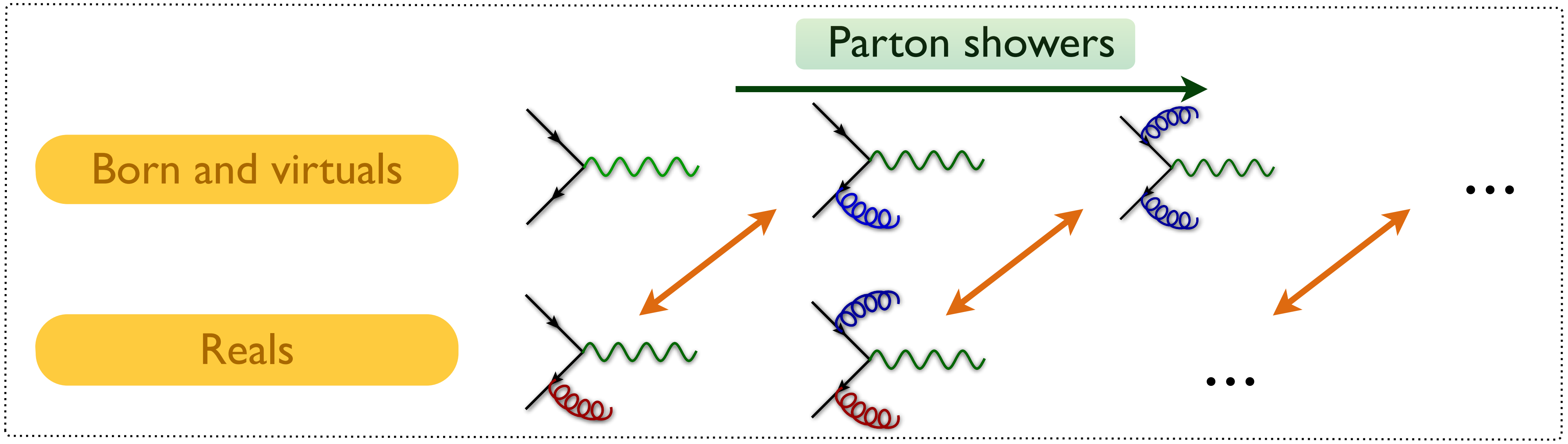
Matching NLO calculations to parton showers

✦ Subtracting the poles

- ✤ The structure of the poles appearing at NLO is known ➢ subtraction methods
  - ★ $\mathcal{C}$ subtracted from the reals ➢ makes them finite
  - ★ $\mathcal{C}$ integrated and added back to the virtuals ➢ makes them finite
  - ★ Integrals can be made numerically in four dimensions

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

✦ Double counting when matching to parton showers



- ✤ Two sources of double counting that compensate each other (shower unitarity)
  - ★ Radiation: both at the level of the reals and of the shower
  - ★ No radiation: both in the virtuals and in the no-emission probability

Counterterms and master formula (MC@NLO)

✦ Two series of subtraction terms: NLO and Monte Carlo

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

S-events

H-events

★ $\mathcal{I}_{\mathrm{MC}}^{(n)}$ represents the shower operator for a (*n*)-body final state

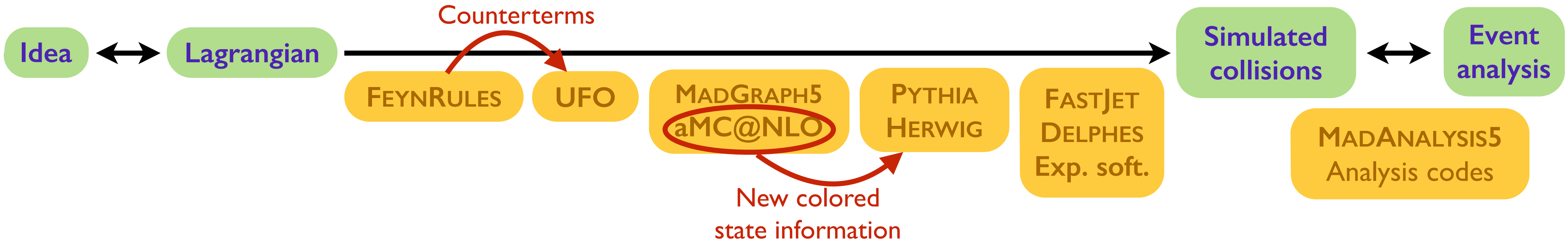
✤ The MC counterterms match the real emission IR behavior (by definition)
  - ★ They describe: how the shower gets from an (n)-body to a (n+1)-body final state
  - ★ Same kinematics as the reals: pole cancelation

✤ The MC counterterms cannot be integrated numerically
  - ★ Using simultaneously the NLO and MC counterterms in the virtuals

✤ In practice, S-events and H-events are generated separately
  - ★ The related contribution can carry a negative weight
  - ★ The sign of the weight has to be included in the unweighting procedure

Automating NLO event generation

✦ 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)
  - ★ Restrictions on the parton shower code to employ (PYTHIA 8, HERWIG++)

SUS-13-011: NLO effects on an exclusion limit

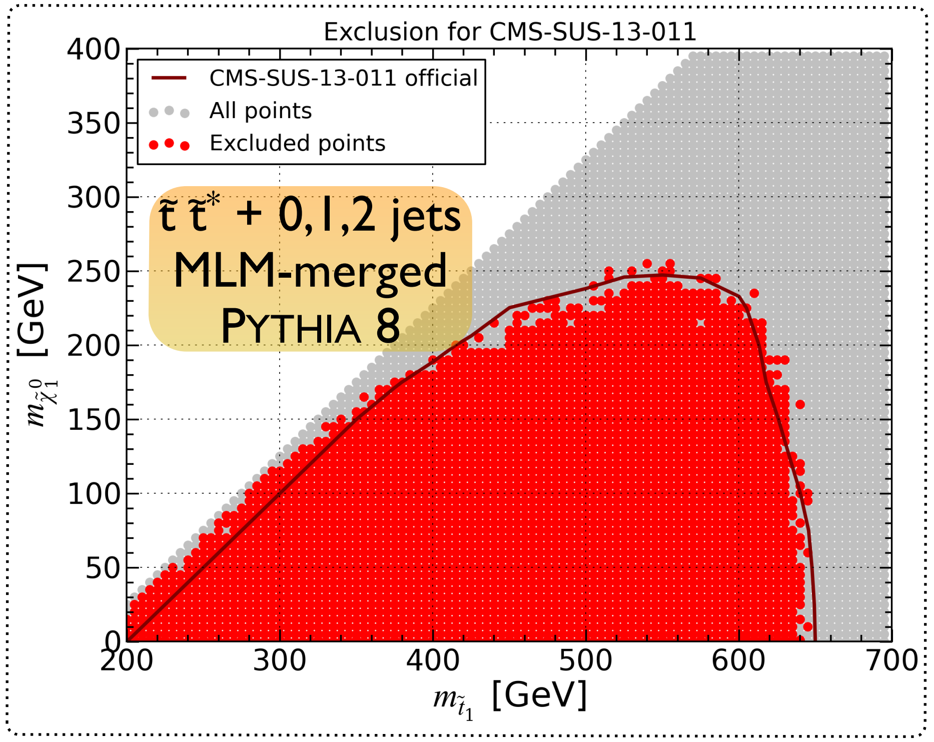
[Ambrogi, Conte, BF, Kulkarni & Molter (in preparation)]

✦ LO and NLO

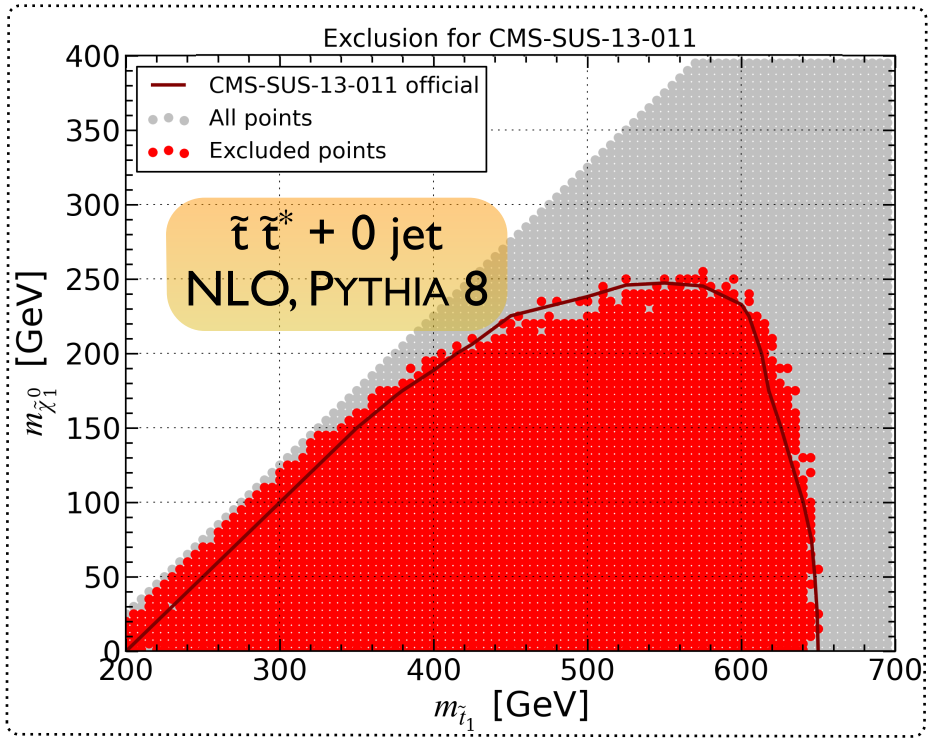
1. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0,1,2 jets @LO ; PYTHIA 8 with the MONASH tune
2. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0 jet @NLO ; PYTHIA 8 with the MONASH tune

✦ How are the limits changing (with MADANALYSIS 5)?

- ✤ Stable constraints (due to the many jets already there at the LO)



$\tilde{t}\,\tilde{t}^*$ + 0,1,2 jets
MLM-merged
PYTHIA 8



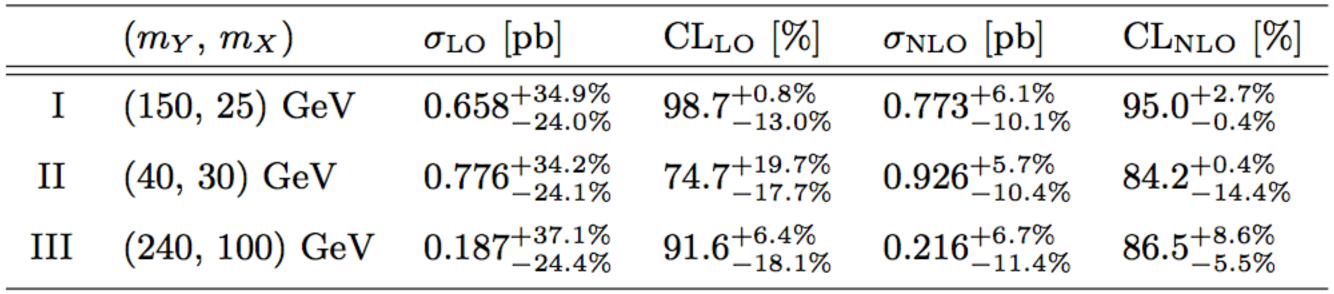
$\tilde{t}\,\tilde{t}^*$ + 0 jet
NLO, PYTHIA 8

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

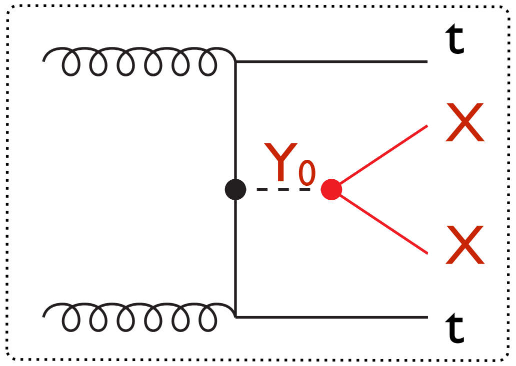
B2G-12-002: top-antitop + missing energy search

[Arina, Backovic, Conte, BF, Guo *et al.* (1605.09242)]

- ✦ There is a theoretical uncertainty on a CLs number



	(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]	$\mathrm{CL}_{\rm LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\mathrm{CL}_{\rm NLO}$ [%]
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 that excluded !
  - ✤ The CLs number can increase / decrease at NLO

- ✦ Monotop NLO models under development (help needed!)

(Final) conclusions

✦ There is a clear gain in combining constraints from many sources

- Astrophysics - cosmology
- Collider (MET searches, resonance searches)
- Gravitational anomalies
- *etc.*

✦ Two considered examples

- Top-philic dark matter models
- Monotop models

✦ NLO simulations become available

- Many effects: cross sections, differential distributions, efficiencies, CLs
- Number of available models increasing with time

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