Dark Matter @ Colliders

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LPTHE / Sorbonne Université

10th IDPASC school

Nazaré (Portugal) - 06-17 September 2021

Outline

1. Collider simulations in a nutshell

2. Dark matter from a collider perspective

3. Interpretation of dark matter collider search results

4. Summary

Monte Carlo simulations & new physics

- ✦ Towards the characterisation of new physics
  - ✤ About the nature of an observation
    - ★ Fitting (and interpreting) deviations
    - ★ Leading order Monte Carlo tools and techniques good enough
  - ✤ Final words on the nature of any potential new physics
    - ★ Accurate measurements
    - ★ More precise predictions mandatory

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- ✦ Monte Carlo tools play a key role at each step
  - ✤ Prospective collider studies (*a priori* preparation)
    - ★ Study of various new physics signals
  - ✤ Reinterpretation of existing results (*a posteriori* reactions)
    - ★ LHC recasting in new contexts

New physics simulations crucial

From Lagrangians to events

✦ Simulating new physics is standard

- ✤ 20−25 years of developments ↝ LO simulations ≡ bread and butter
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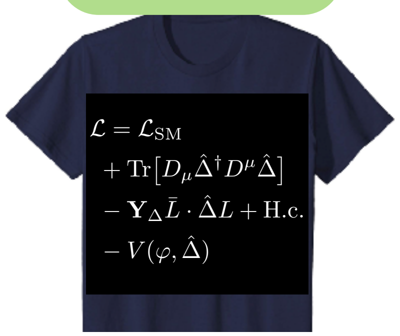
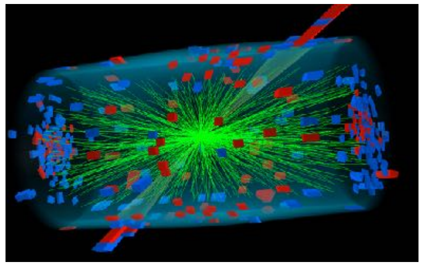
✦ Streamlining the connection of a physics models to events

- ✤ Any new physics model can be implemented
- ✤ Easy to validate and maintain

Idea Lagrangian → Chain of tools → Simulated collisions → Other tools → Event analysis





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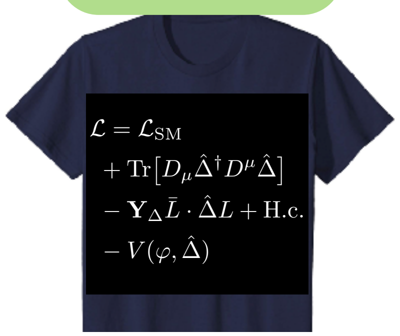
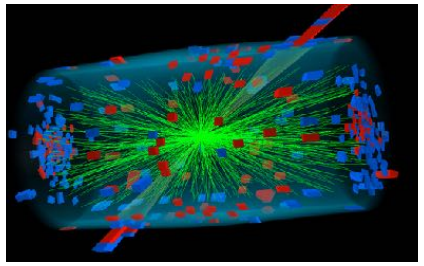
Chain of tools

Other tools

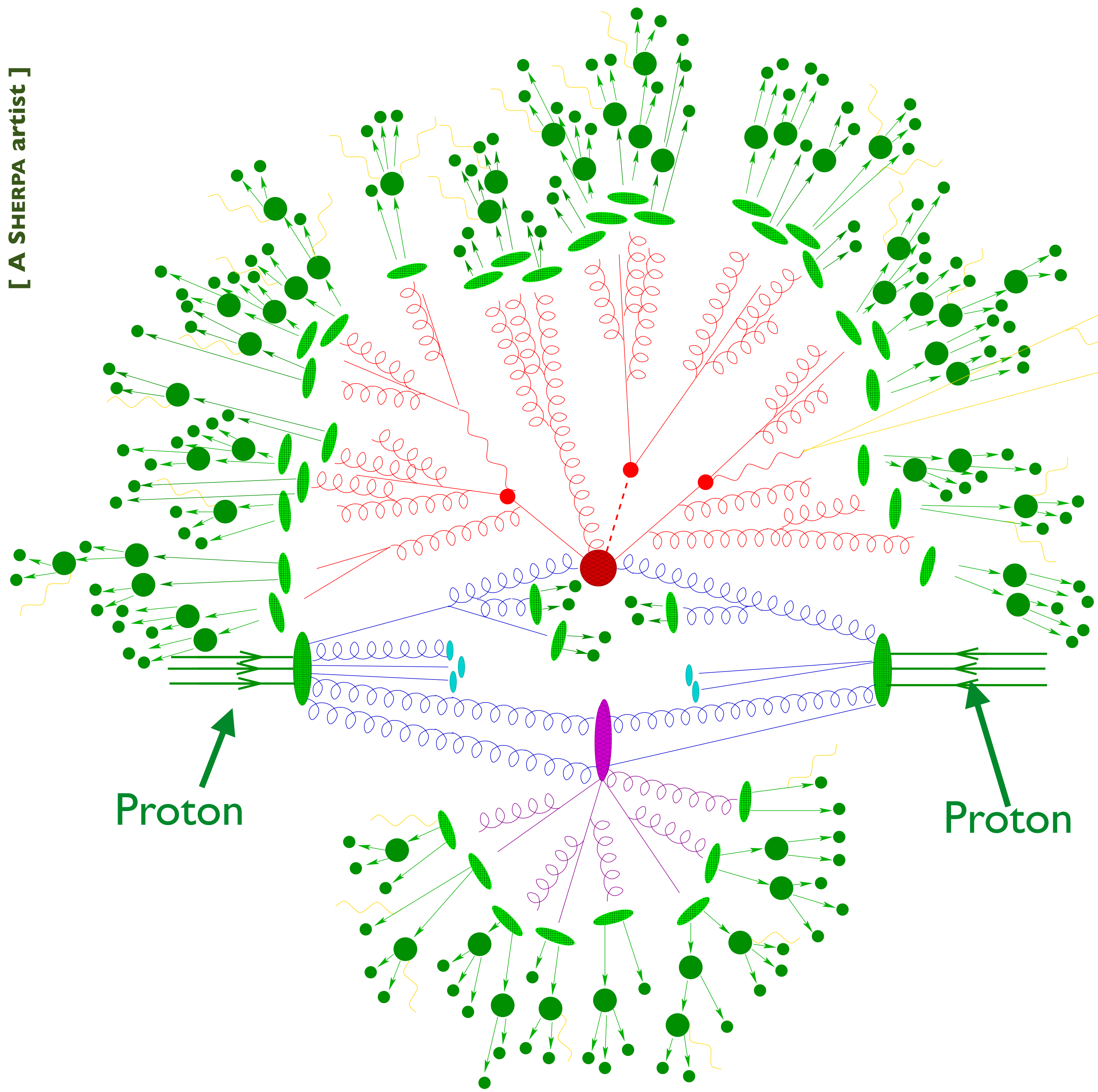




✦ A chain of several tools?

- ✤ Phenomena at different scales ⇝ factorisation

Deciphering a proton-proton collision



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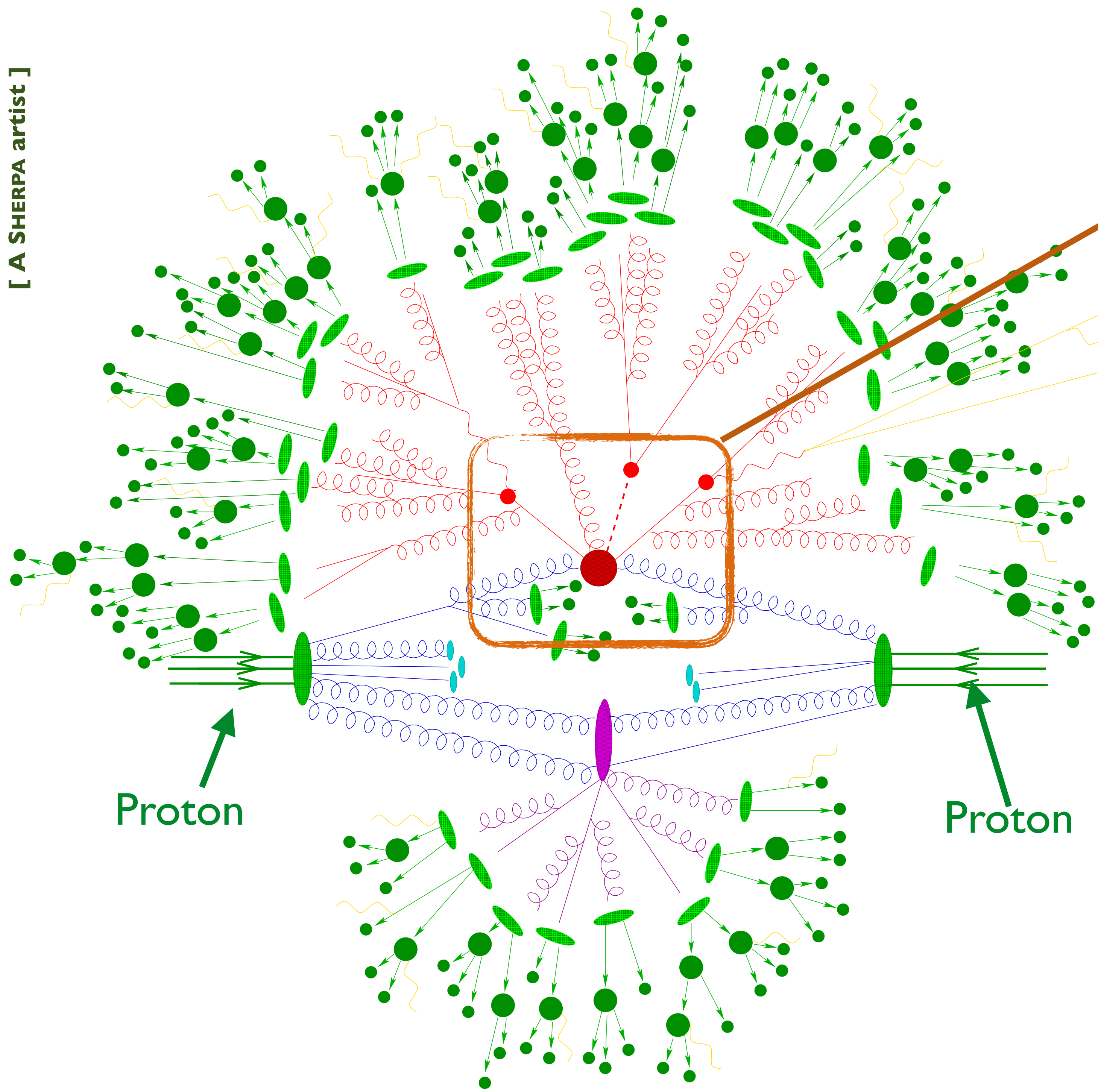

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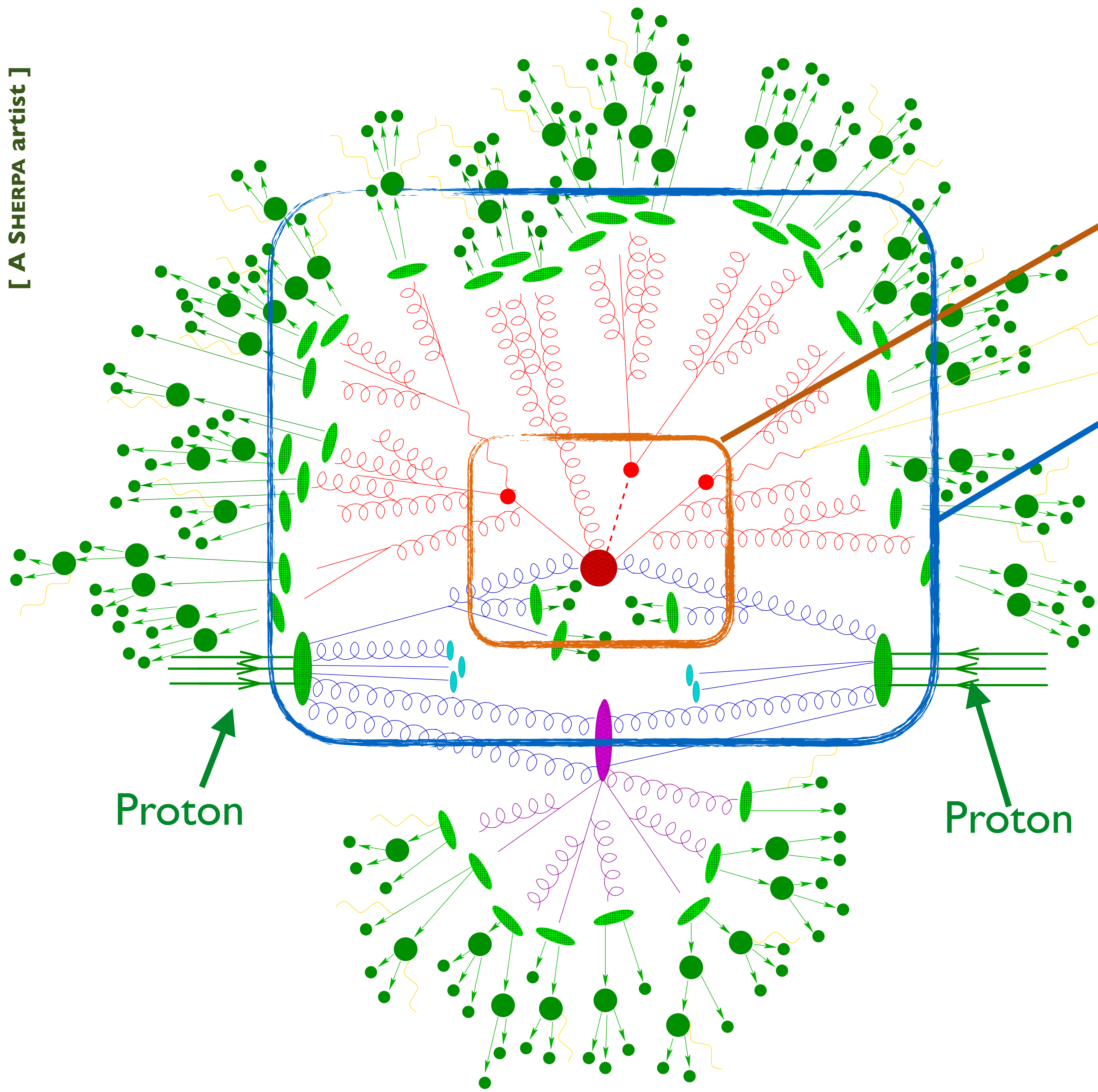

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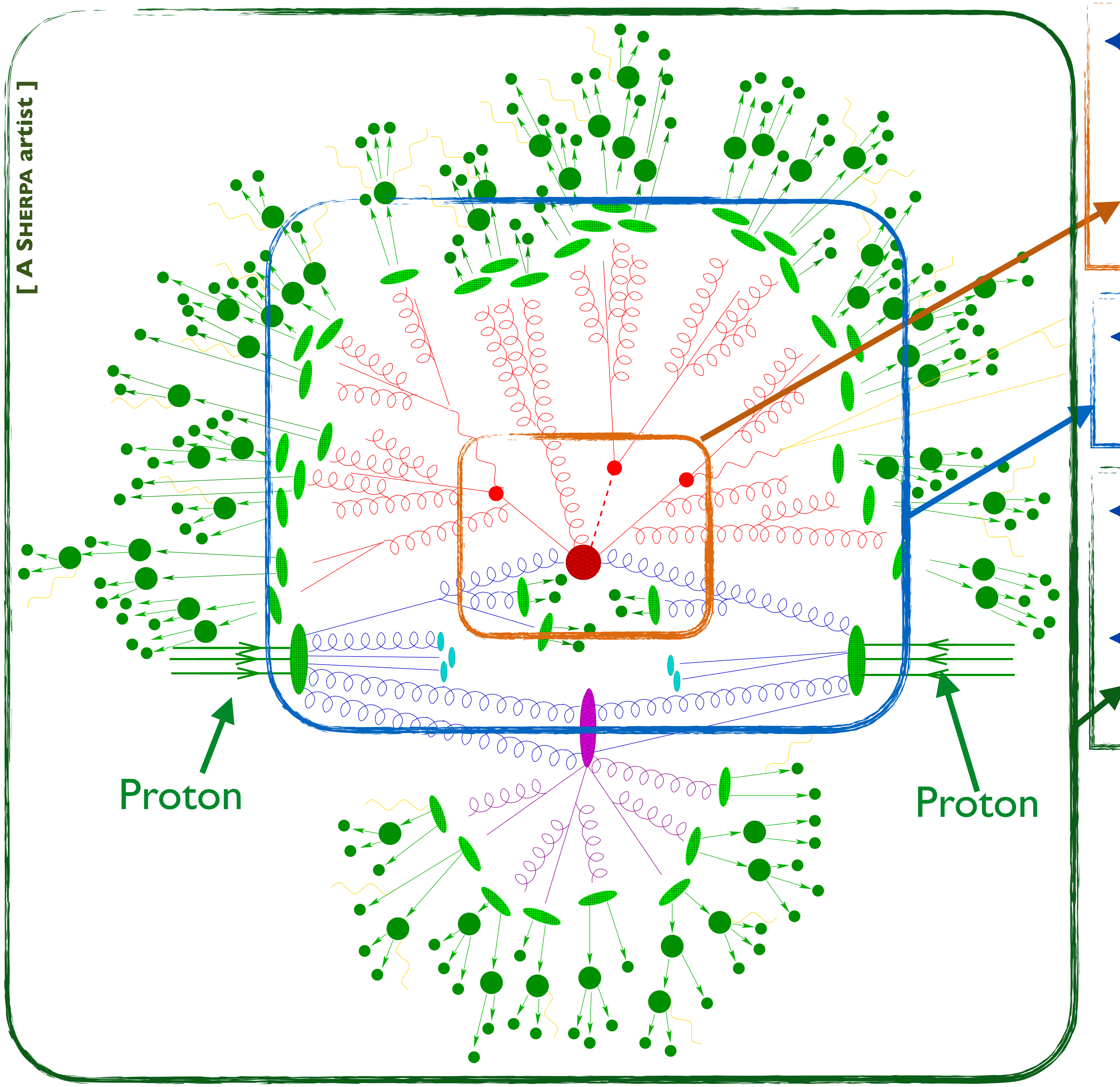

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  - ✤ Model-based, universal
- ✦ Underlying event
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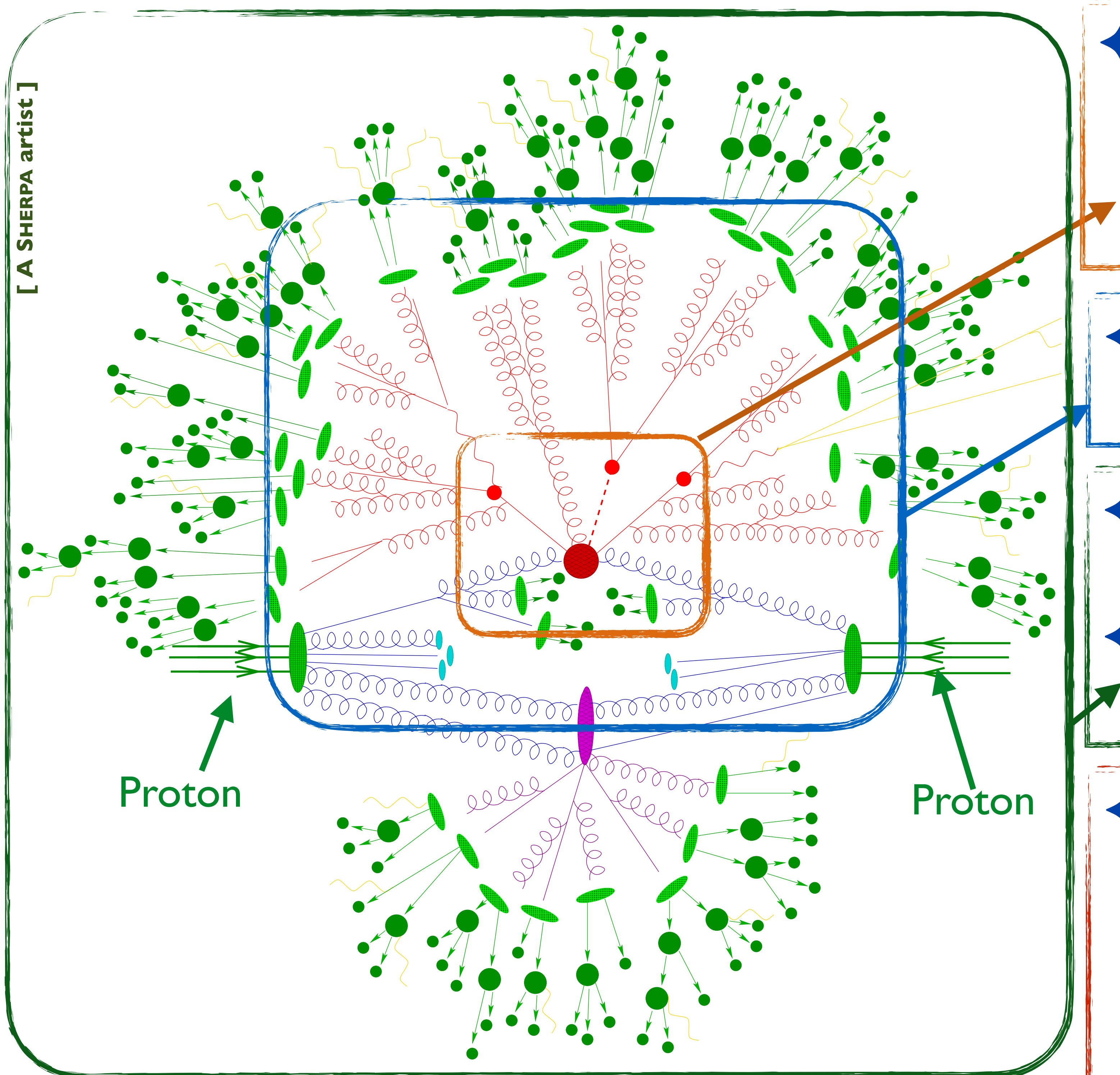

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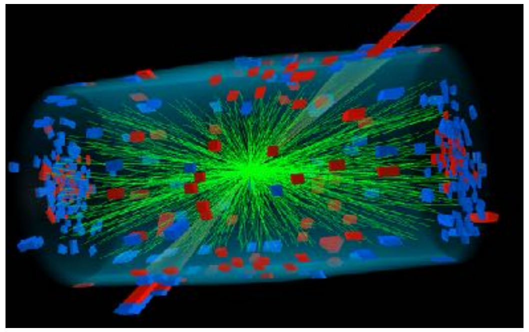
✦ Detector simulation

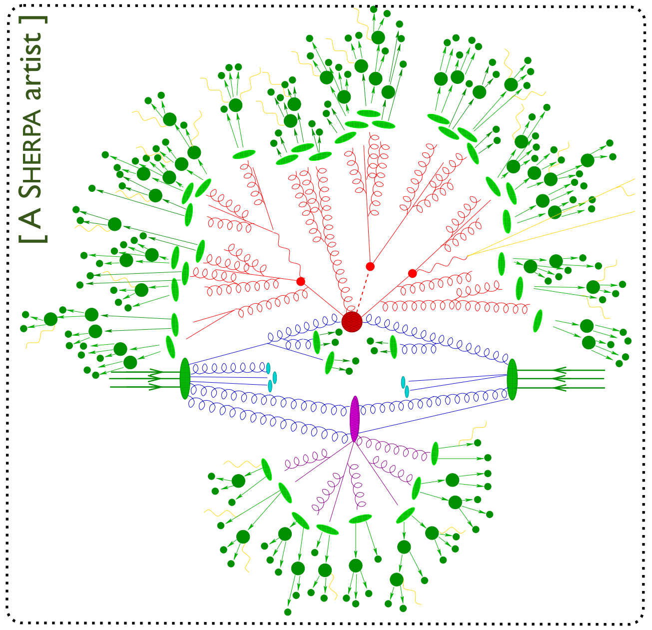


Monte Carlo simulations for proton collisions

✦ Multi-scale problem ↝ factorisation

- ✤ TeV scale: hard scattering (new physics?)
- ✤ Down to $\Lambda_{\rm QCD}$: QCD environment
- ✤ Down to sub-MeV: interactions with a detector

Tools and methods for each step



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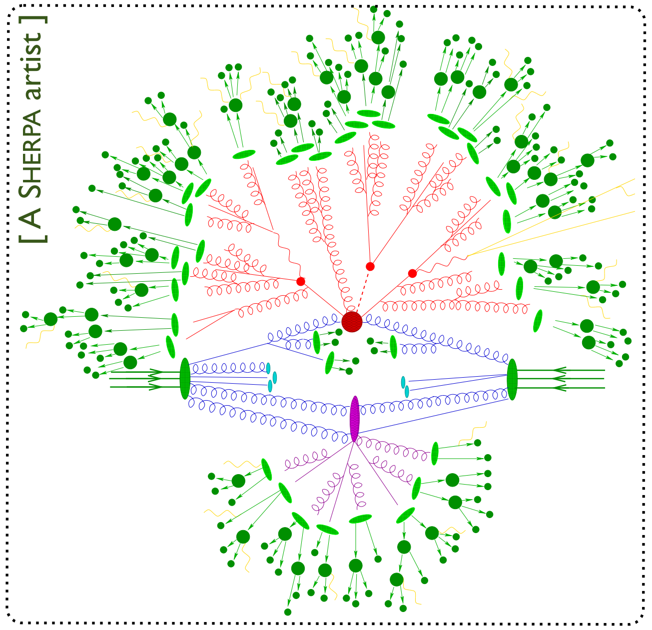

✦ Tools development: a very intense activity

- ✤ Matrix-element generation (CALCHEP, HERWIG, MG5_AMC, SHERPA, WHIZARD, *etc.*)
- ✤ Higher-order computation techniques (MC@NLO, POWHEG, NNLO)
- ✤ Parton showering / hadronisation (PYTHIA, HERWIG, SHERPA)
- ✤ Matrix element - parton shower matching
- ✤ Merging techniques (MLM, CKKW, FxFx, UNLOPS, *etc.*)
- ✤ Detector simulators (DELPHES, RIVET, MADANALYSIS 5)

SM and BSM simulations: the status

- ✦ Standard Model simulations under good control
  - ✤ Relevant LHC processes: known with a very good precision
  - ✤ Further improvements expected in the next few years

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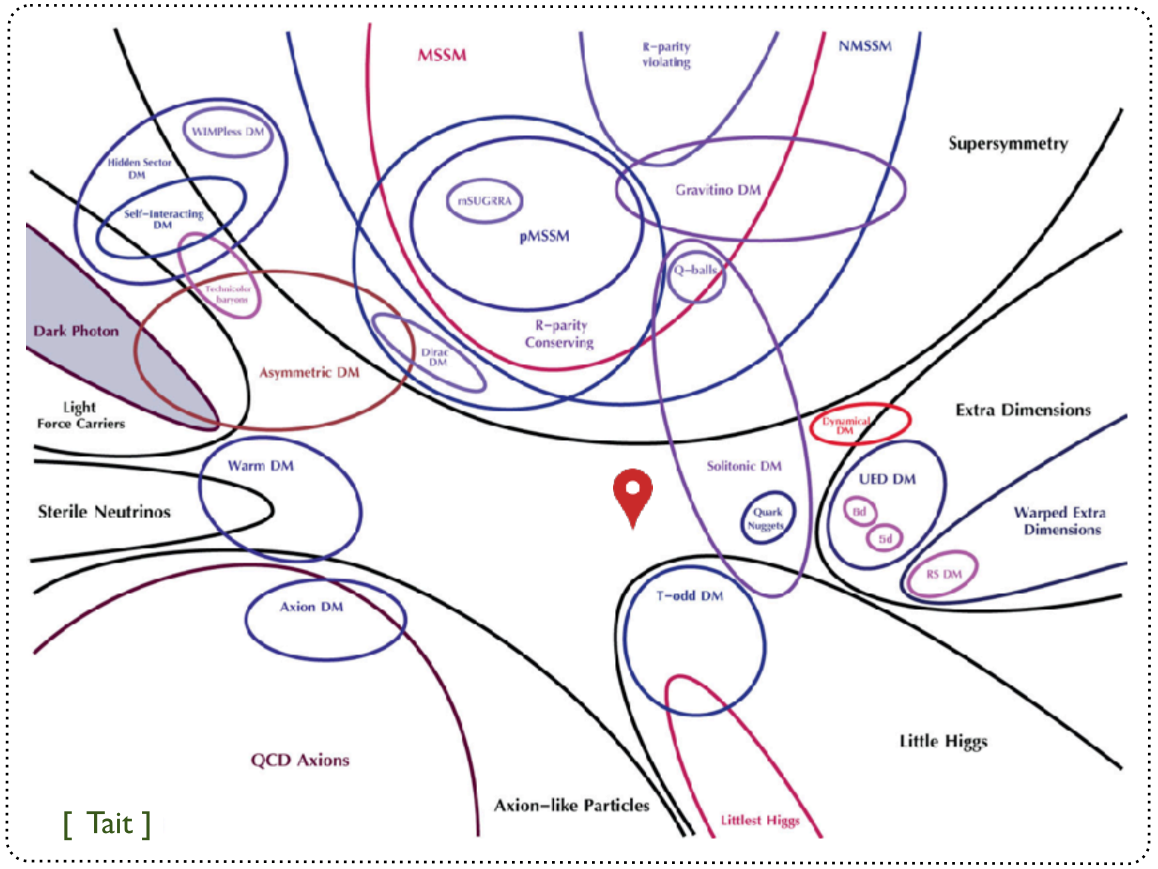
✦ Different challenges for new physics

- ✤ No sign of new physics
- ✤ SM-like measurements
  - ↝ no leading candidate theory
- ✤ Plethora of models to consider
  - ↝ many implementations in tools

Despite of this, new physics is standard today

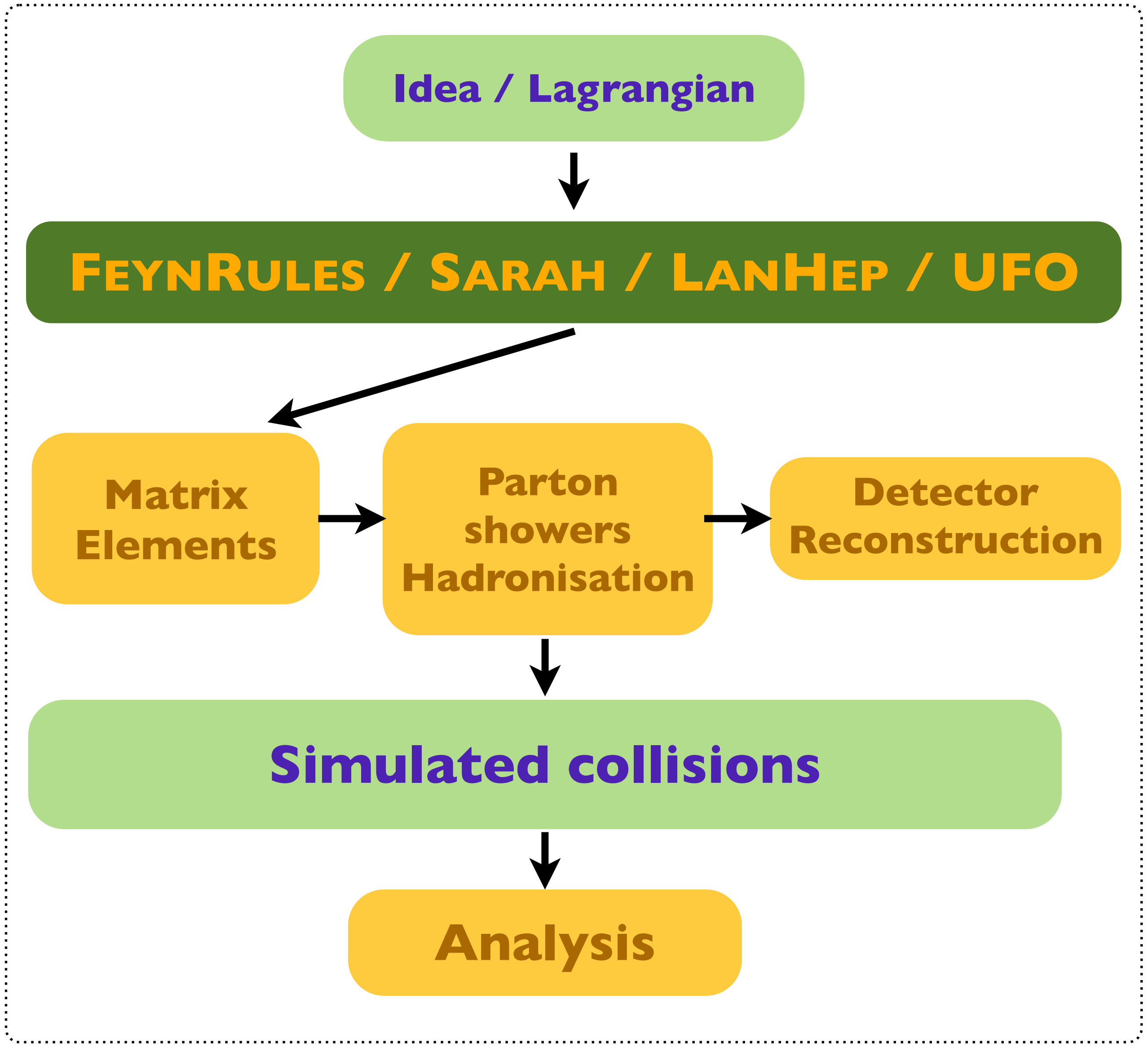


[Tait]

A comprehensive approach to MC simulations

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

✦ Tools connecting an idea to simulated collisions



- Model building
- Hard scattering
  - Feynman diagram and amplitude generation
  - Monte Carlo integration
  - Event generation
- QCD environment
  - Parton showering
  - Hadronisation
  - Underlying event
- Detector simulation
  - Simulation of the detector response
  - Object reconstruction
- Event analysis
  - Signal/background analysis
  - LHC recasting

QCD calculations and Monte Carlo simulations for colliders

QCD 101: predictions at the LHC

✦ Distribution of an observable ω: the QCD factorisation theorem

$$\frac{d\sigma}{d\omega} = \sum_{ab} \int dx_a \, dx_b \, \mathbf{f}_{\mathbf{a}/\mathbf{p_1}}(x_a;\mu_F) \, \mathbf{f}_{\mathbf{b}/\mathbf{p_2}}(x_b;\mu_F) \, \frac{d\sigma_{\mathbf{ab}}}{d\omega}(\ldots,\mu_F)$$

✤ Long distance physics: the parton densities

✤ Short distance physics: the differential parton cross section $d\sigma_{ab}$

✤ Separation of both regimes ⇝ the factorisation scale μ_F
  ★ Choice of the scale ⇝ theoretical uncertainties

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✦ Short distance physics: the partonic cross section

- ✤ Order by order in perturbative QCD: $d\sigma = d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)} + \ldots$
  - ★ More orders ⇝ more precision
  - ★ Truncation of the series and α_s ⇝ theoretical uncertainties

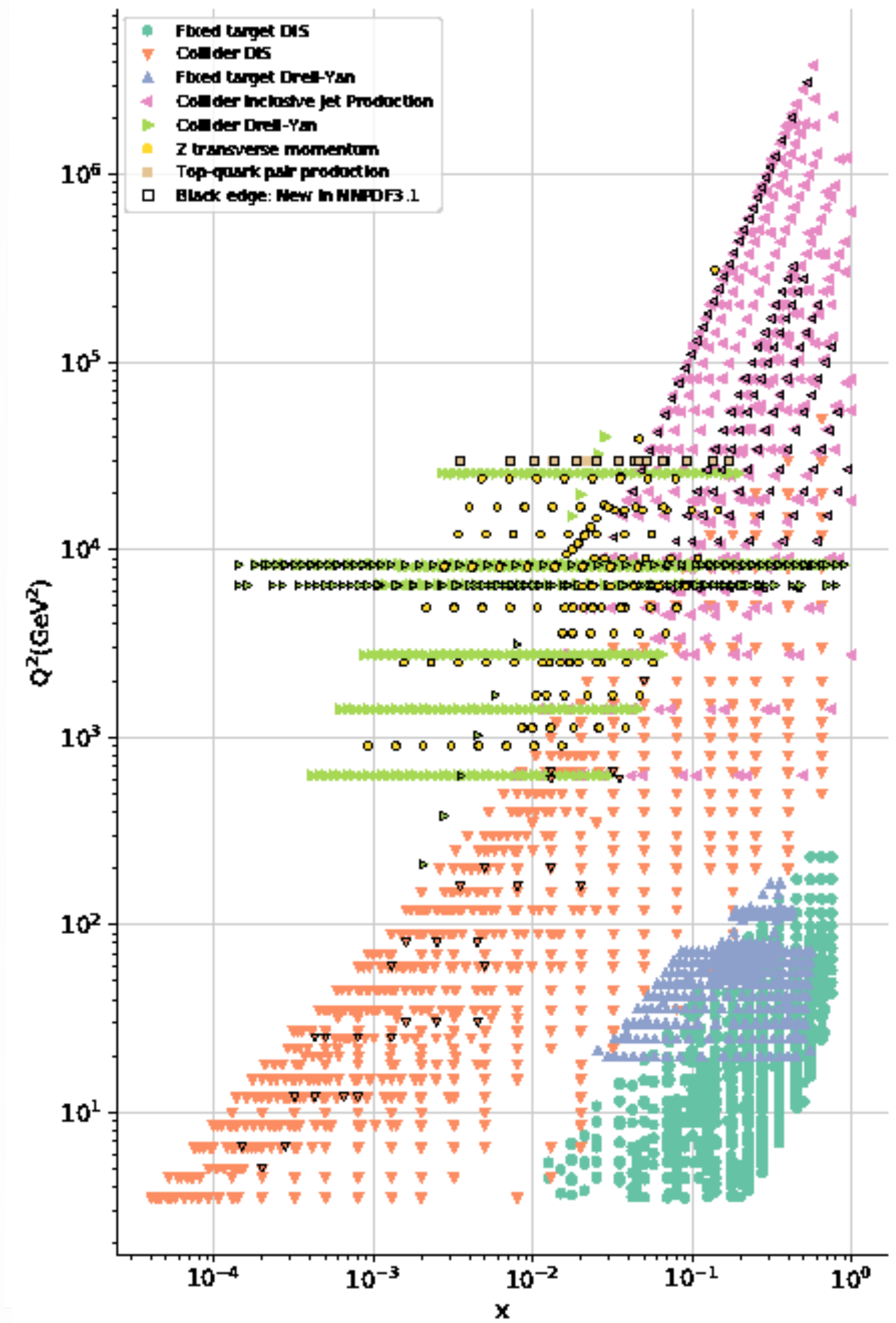
Feynman diagrams (depend on the physics model)

Parton densities

✦ Long distance physics: parton densities

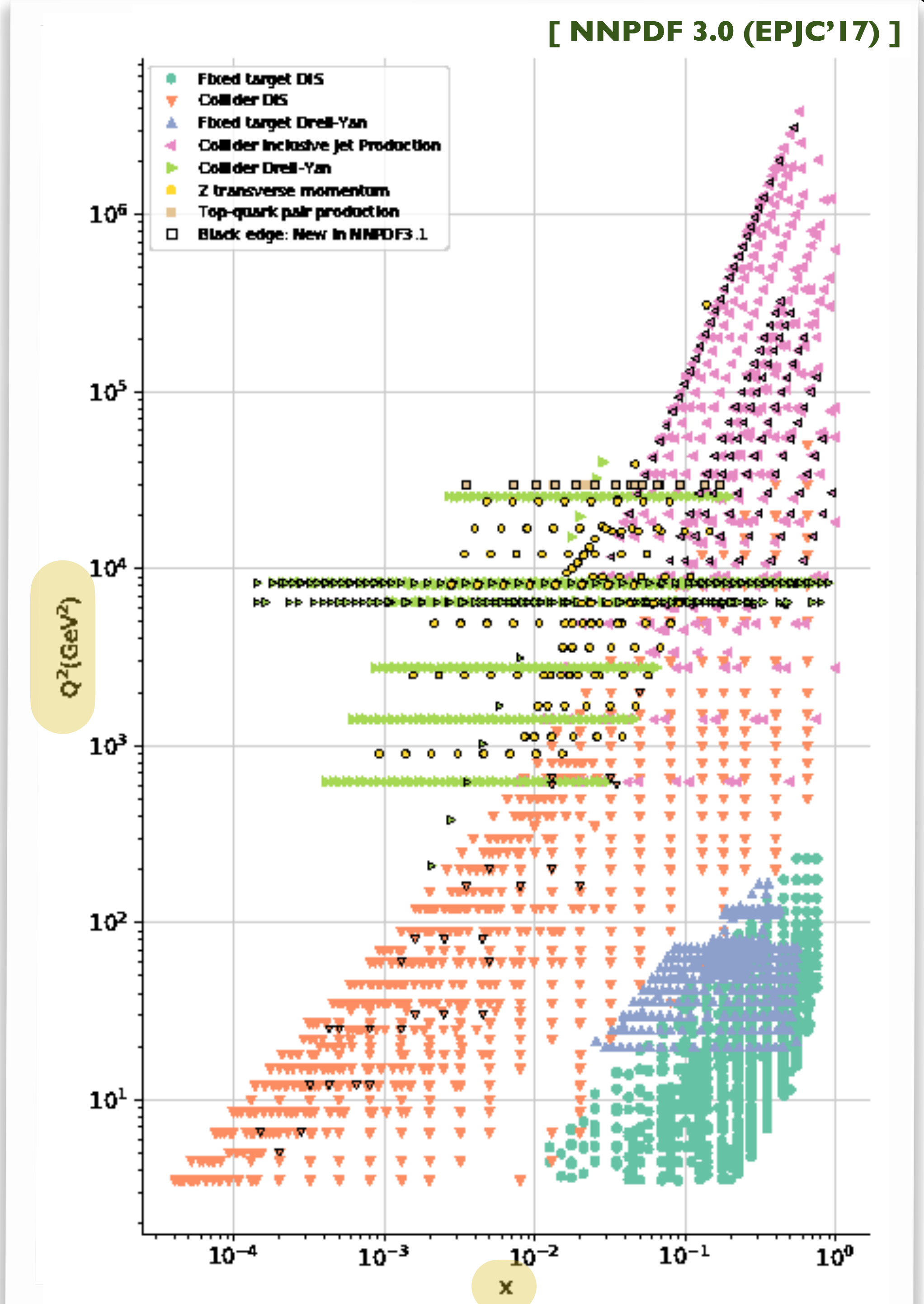
✤ Relate hadrons to their content

[NNPDF 3.0 (EPJC'17)]



Parton densities

- ✦ Long distance physics: parton densities
  - ✤ Relate hadrons to their content
  - ✤ Depend on the momentum fraction *x* of the parton in the proton
  - ✤ Depend on a scale Q



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✤ Depend on the momentum fraction *x* of the parton in the proton

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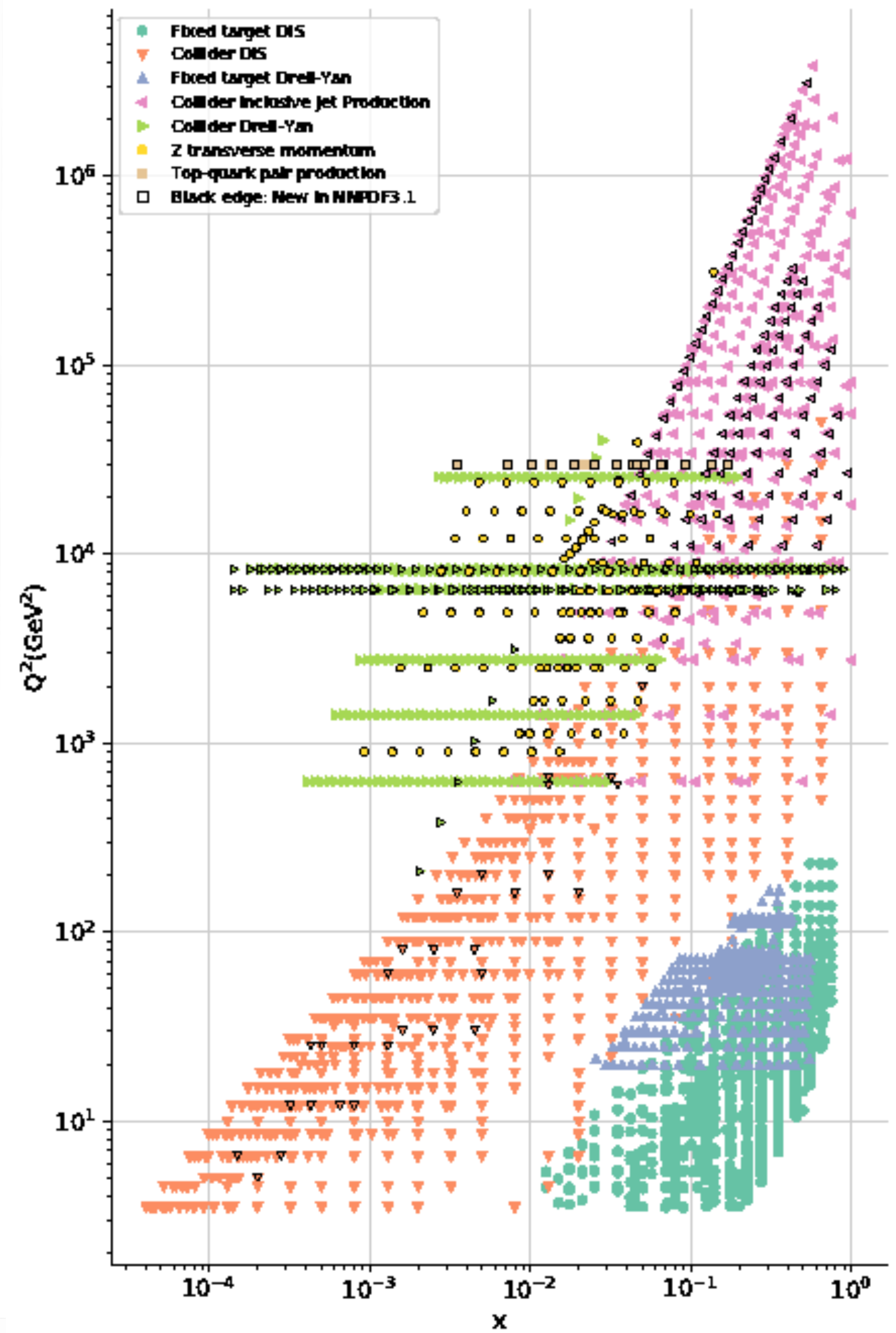
✤ Fitted from experimental data [in some kinematical regimes (x,Q)]

✤ Evolution driven by QCD (DGLAP/BFKL)

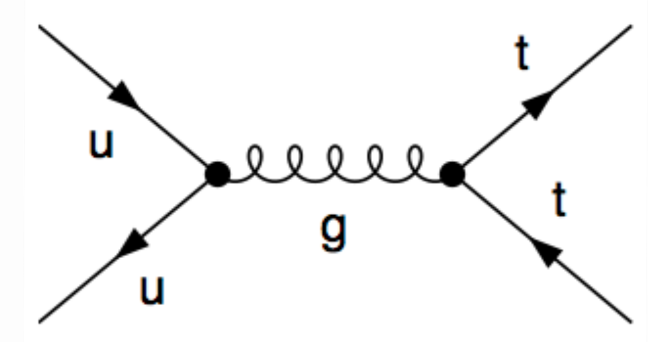
[NNPDF 3.0 (EPJC'17)]



Feynman diagram calculations

- **Direct squared matrix element computations**
  - Extraction of the amplitude from the Feynman rules

$$i\mathcal{M} = i g_s^2 \Big[\bar{v}_2 \gamma^\mu u_1\Big] \frac{\eta_{\mu\nu}}{s} \Big[\bar{u}_3 \gamma^\nu v_4\Big] T^a_{c_2 c_1} T^a_{c_3 c_4}$$



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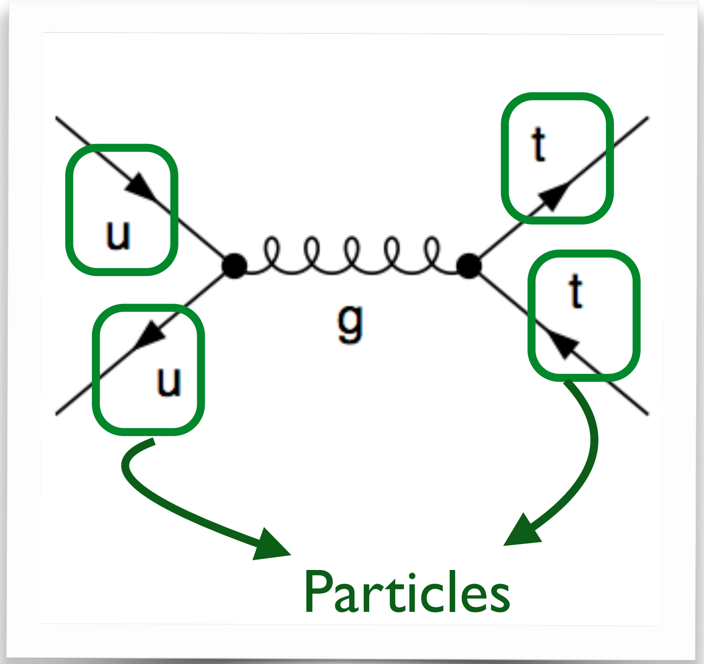

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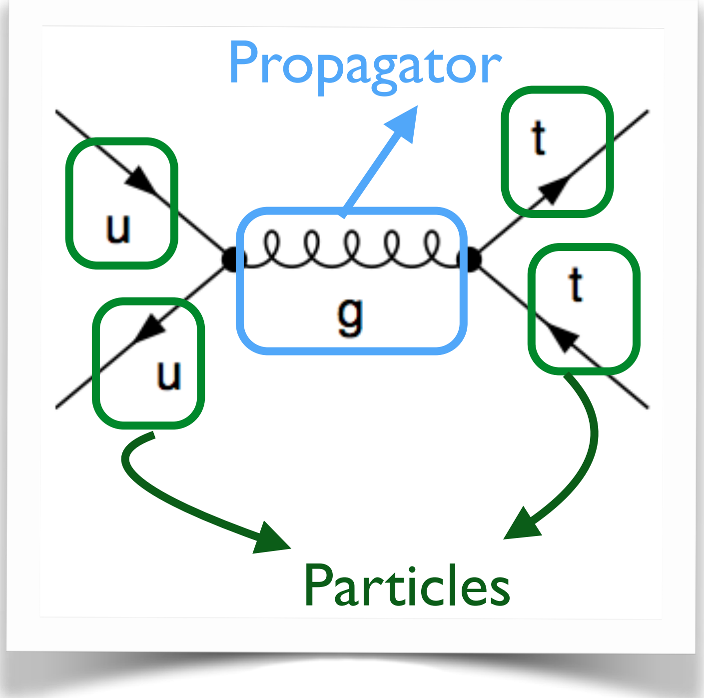

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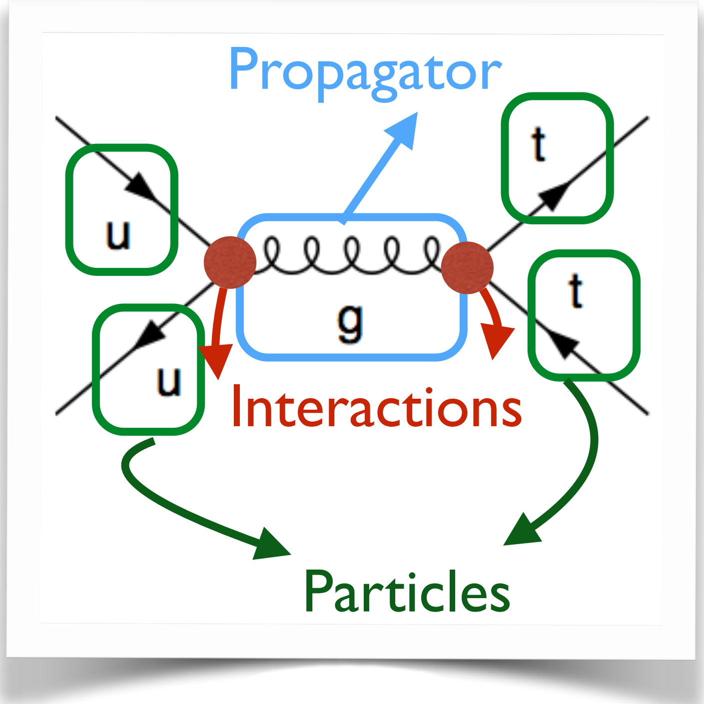

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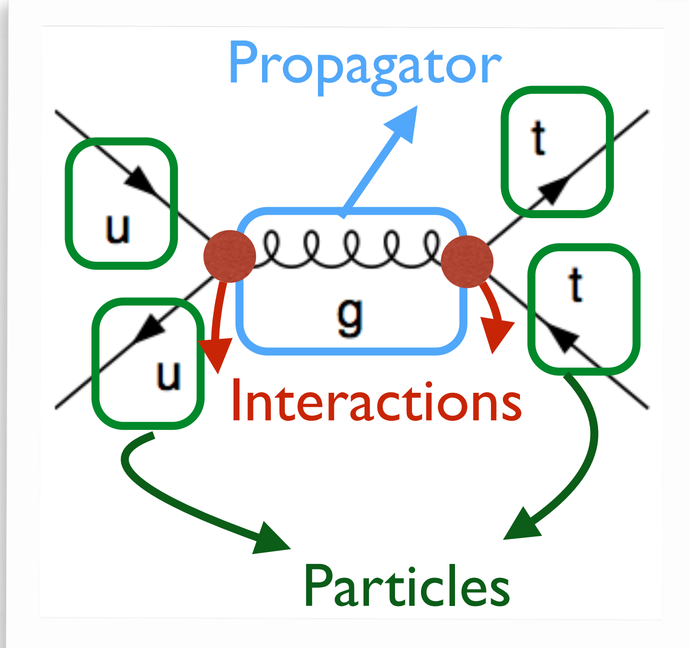
✤ Squaring with the conjugate amplitude

✤ Algebraic calculation (colour and Lorentz structures)

✤ Sum/average over the external states

$$\begin{aligned}\overline{|\mathcal{M}|^2} &= \frac{1}{36}\frac{2g_s^4}{s^2}\mathrm{Tr}\left[\not{p}_1\gamma^\mu\not{p}_2\gamma^\nu\right]\left[\not{p}_3\gamma_\mu\not{p}_4\gamma_\nu\right] \\ &= \frac{16g_s^4}{9s^2}\left[(p_1\cdot p_3)(p_2\cdot p_4)+(p_1\cdot p_4)(p_2\cdot p_3)\right]\end{aligned}$$



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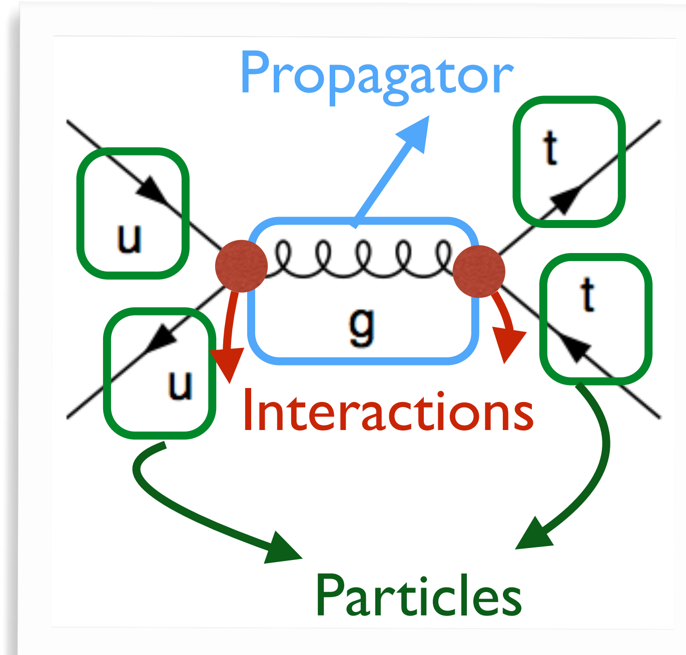

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✦ The number of diagrams increases with the number of final-state particles

✤ The complexity rises as N^2

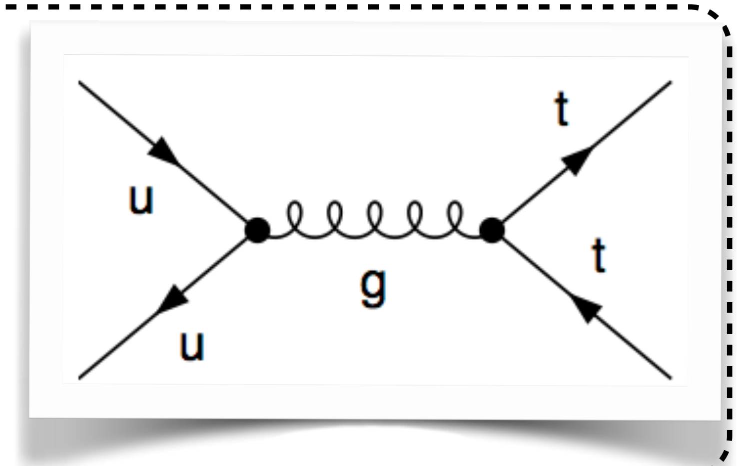
✤ Any calculation beyond 2-to-3 becomes a problem

➢ **Helicity amplitudes**

Helicity amplitudes

✦ Principle

- ✤ Evaluation of the amplitude for fixed external helicities
- ✤ Add all amplitudes (we get complex numbers)
- ✤ Squaring
- ✤ Sum/average over the external states



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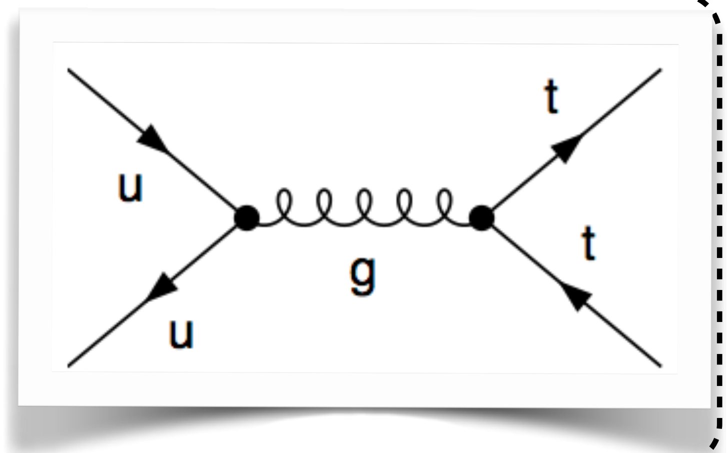
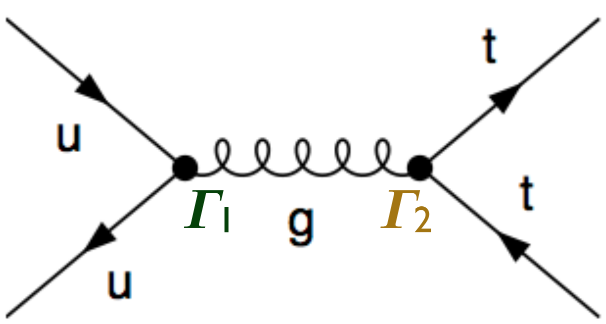


✦ Practical example



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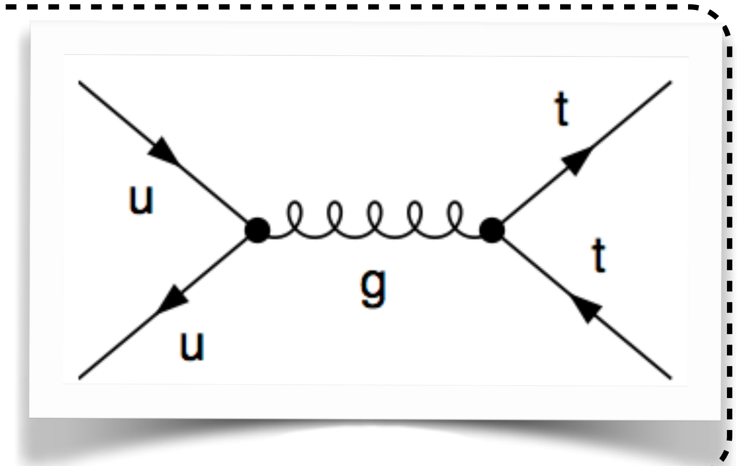

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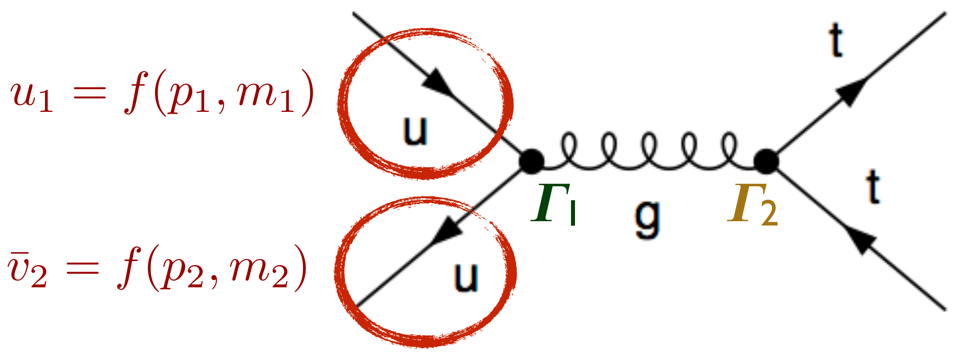

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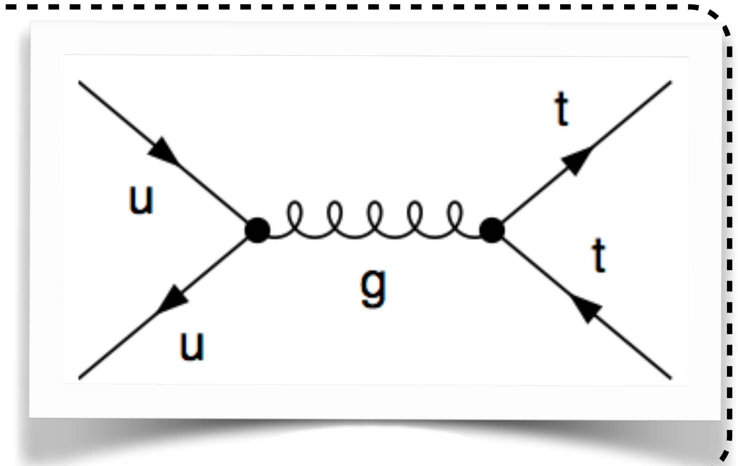

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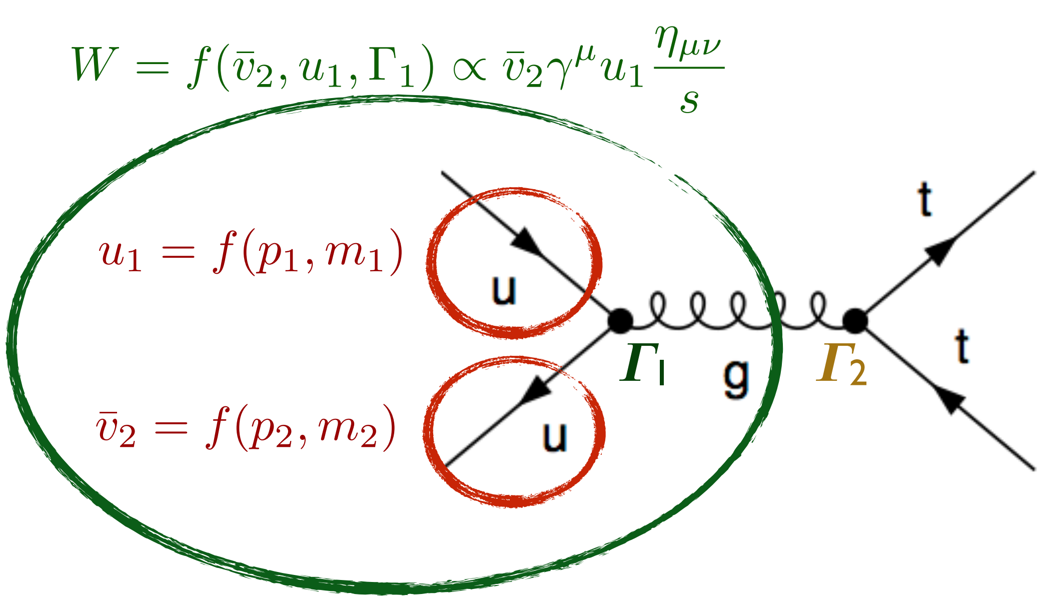

1. External incoming particles (numbers)
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2. Wave function of the gluon propagator

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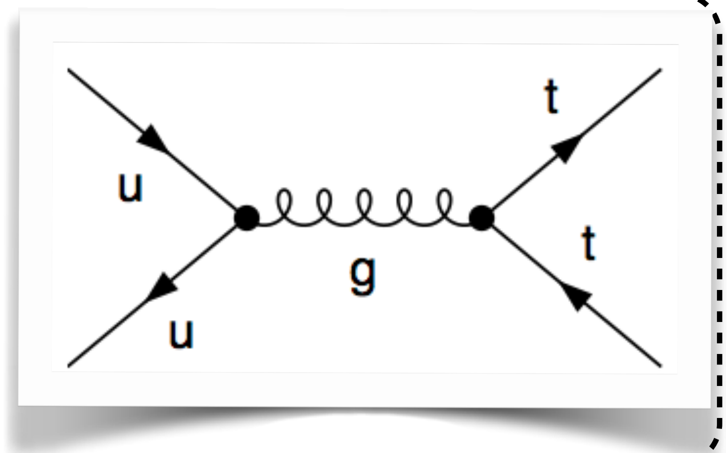

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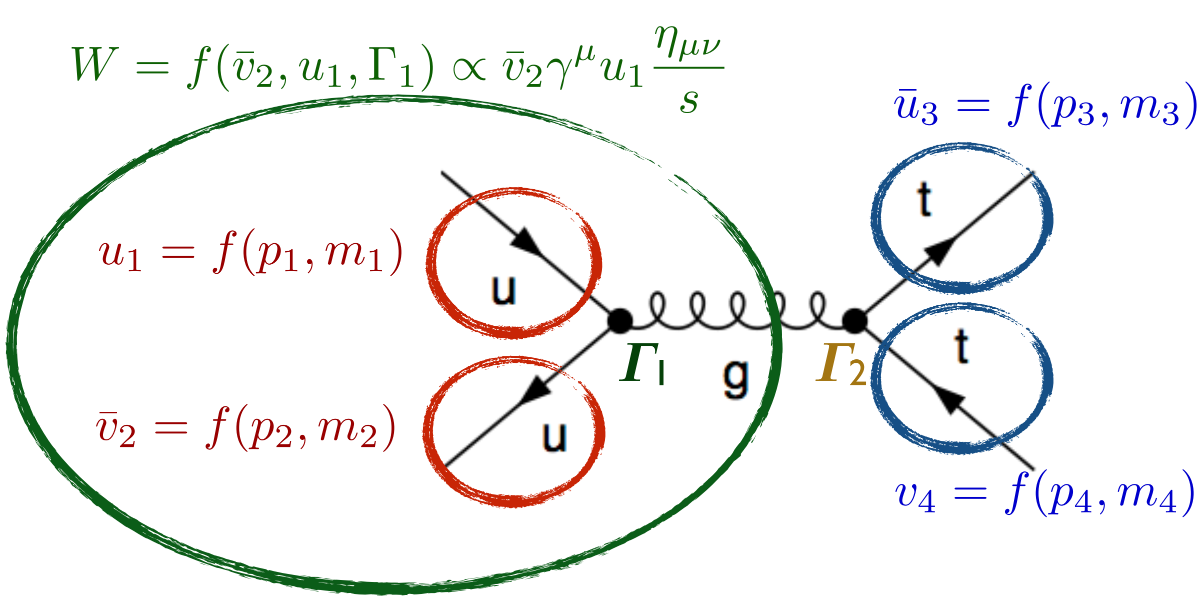

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3. External outgoing particles

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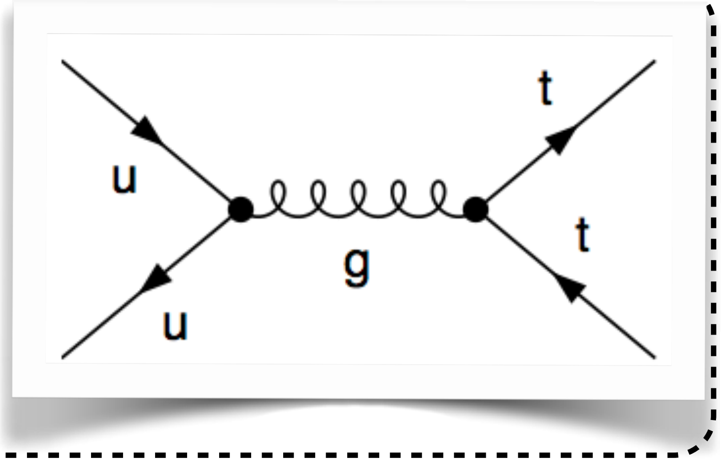

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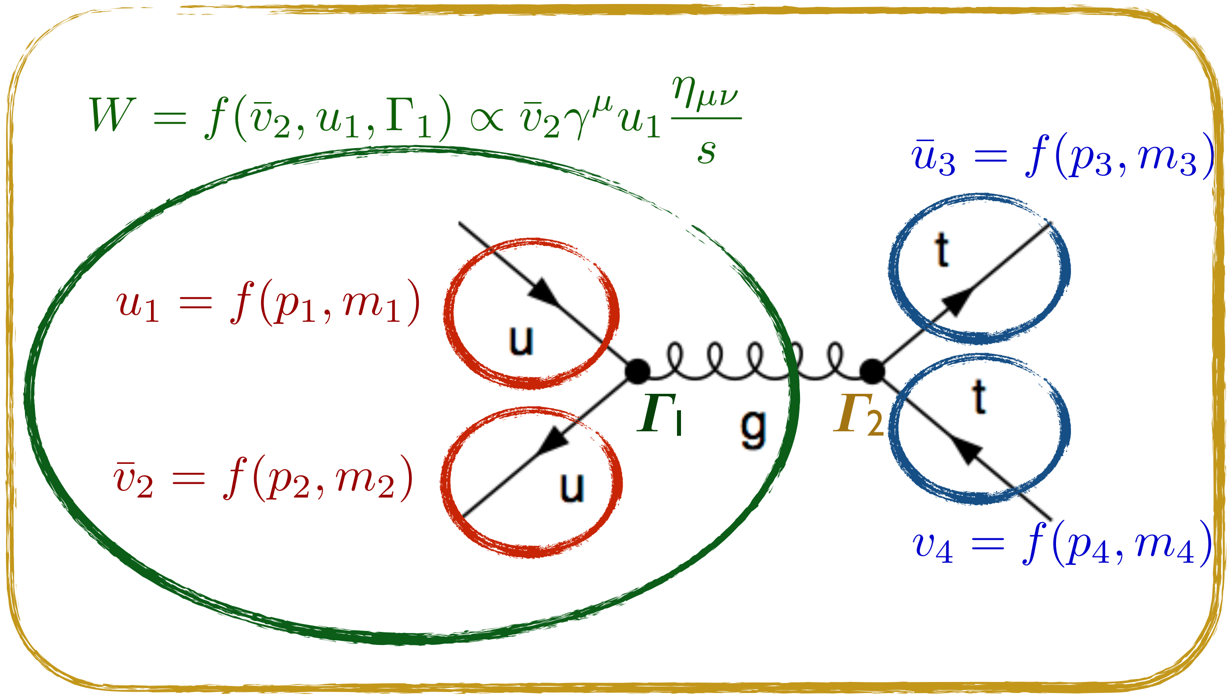
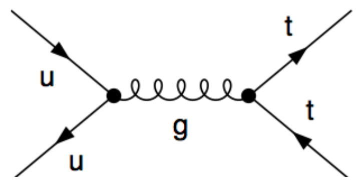


$i\mathcal{M} = f(\bar{u}_3, v_4, W, \Gamma_2)$

1. External incoming particles (numbers)
   - ★ For fixed helicity and momentum
2. Wave function of the gluon propagator
3. External outgoing particles
4. Full amplitude (complex number)

HELAS

✦ The building blocks of the amplitude are the so-called HELAS functions



$$u_1 = f(p_1, m_1)$$
$$\bar{v}_2 = f(p_2, m_2)$$
$$\bar{u}_3 = f(p_3, m_3)$$
$$v_4 = f(p_4, m_4)$$
$$W = f(\bar{v}_2, u_1, \Gamma_1)$$
$$i\mathcal{M} = f(\bar{u}_3, v_4, W, \Gamma_2)$$

- HELAS ≡ HELicity Amplitude Subroutine
- One specific routine for each Lorentz structure (Γ_i)
- Not generic for any model
  - ★ SM [Murayama, Watanabe & Hagiwara (KEK-91-11)]
  - ★ MSSM [Cho, Hagiwara, Kanzaki, Plehn, Rainwater & Stelzer (PRD`06)]
  - ★ HEFT [Alwall et al. (JHEP`07)]
  - ★ Spin 2 [Hagiwara, Kanzaki, Li &Mawatari (EPJC`08)]
  - ★ Spin 3/2 [Mawatari & Takaesu (EPJC`11)]

Sufficient for many models
→ very useful for numerical calculations

HELAS

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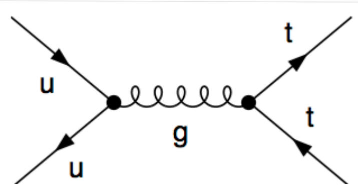

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$$W = f(\bar{v}_2, u_1, \Gamma_1)$$
$$i\mathcal{M} = f(\bar{u}_3, v_4, W, \Gamma_2)$$

- ✤ HELAS ≡ HELicity Amplitude Subroutine
- ✤ One specific routine for each Lorentz structure (Γ_i)
- ✤ Not generic for any model
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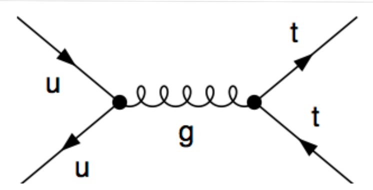

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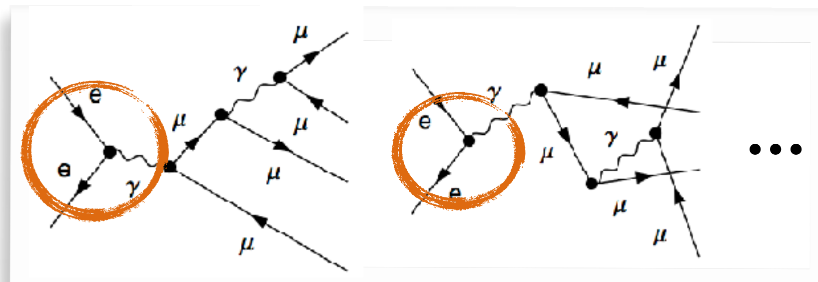
✦ Recycling: reusing pieces across diagrams

- ✤ Gain in computing time



Efficiencies of the methods

	For M diags	For N particles	$2 \rightarrow 6$ example
Analytical	M^2	$(N!)^2$	10^9
Helicity	M	$N!\ 2^N$	10^7
Recycling	M	$(N-1)!\ 2^{N-1}$	5×10^5

Observable calculations

✦ The QCD factorisation theorem

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \mathrm{d}\Phi_n \mathbf{f_{a/p_1}}(x_a, \mu_F)\ \mathbf{f_{b/p_2}}(x_b, \mu_F)\ \left|\mathcal{M}\right|^{\mathbf{2}} \mathcal{O}_\omega(\Phi_n)$$

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General and flexible numerical methods
→ Monte Carlo simulations

Parton evolution - generalities

✦ Accelerated charges radiate

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- ✦ Highly energetic coloured particles radiate
  - ✤ Each parton is dressed with an arbitrary number of partons (multiple radiation)
    - ➢ Radiated partons also radiate
  - ✤ One ends up with a cascade of radiations ➢ parton showers

Hadronisation / detector simulations

✦ Generalities

- ✤ Perturbative QCD breaks down at scales around 1 GeV
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✦ Detector simulations and reconstruction (see below)

- ✤ Transfer functions or 'tracks and hits'
- ✤ Pile-up (very relevant for the future)

What about NLO simulations?

To be discussed later

Outline

1. Collider simulations in a nutshell
2. **Dark matter from a collider perspective**
3. Interpretation of dark matter collider search results
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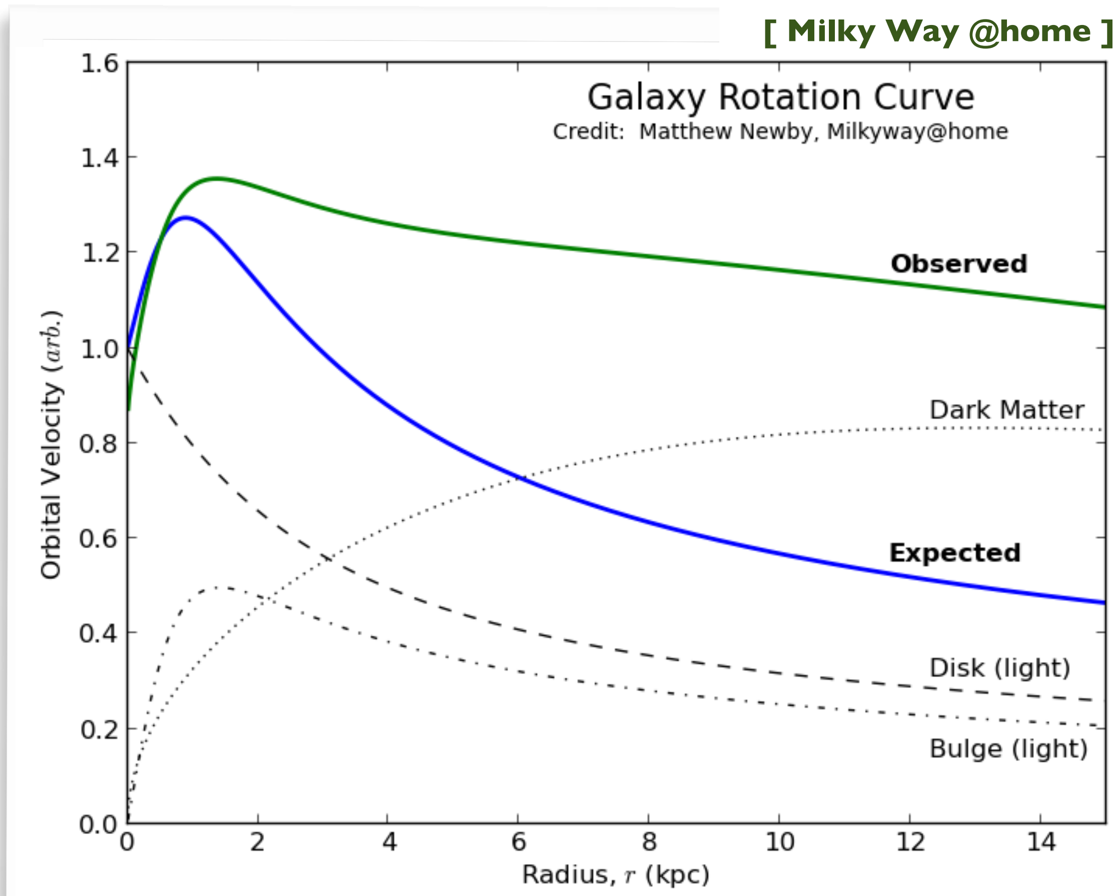
New physics and dark matter

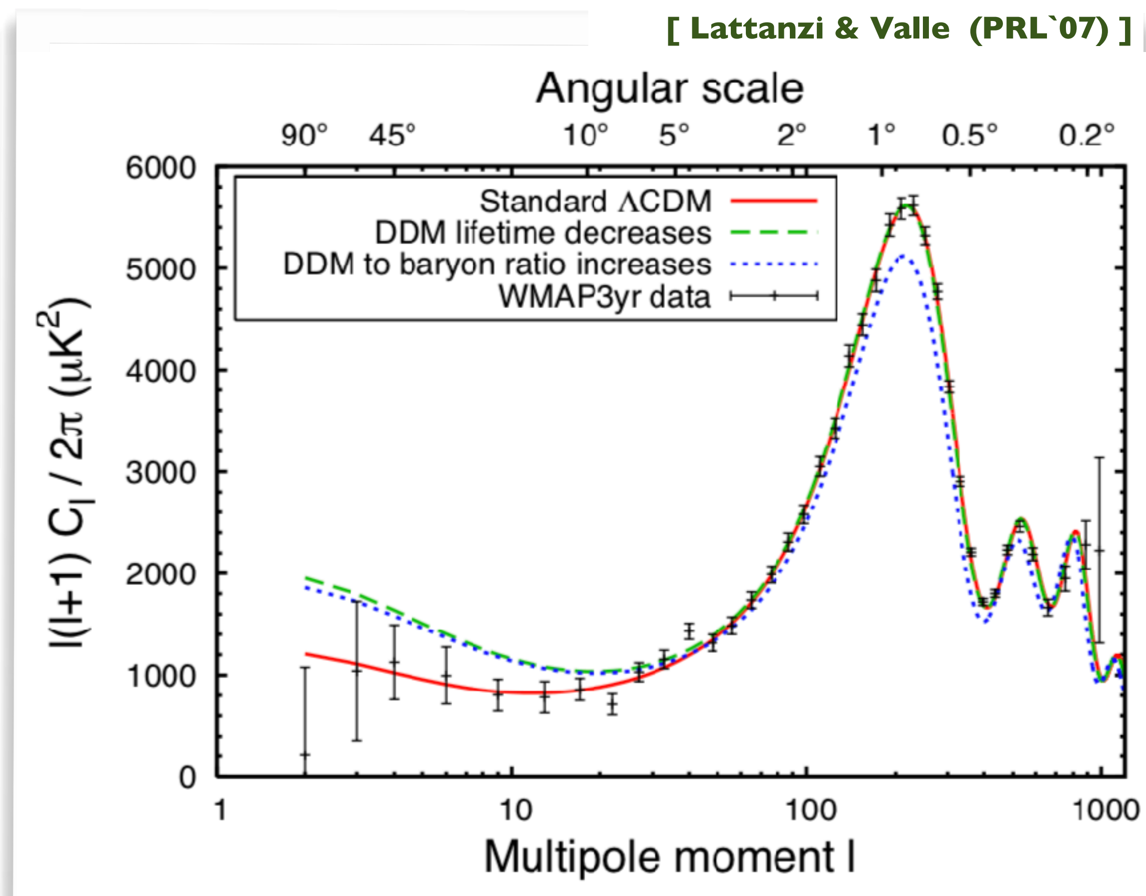
- ✦ Dark matter is an important motivation for new physics
  - ✤ Flattening of the galaxy rotation curves
  - ✤ Gravitational lensing
  - ✤ Cosmic microwave background
  - ✤ Structure formation

Enormous endeavour to detect dark matter

[Milky Way @home]



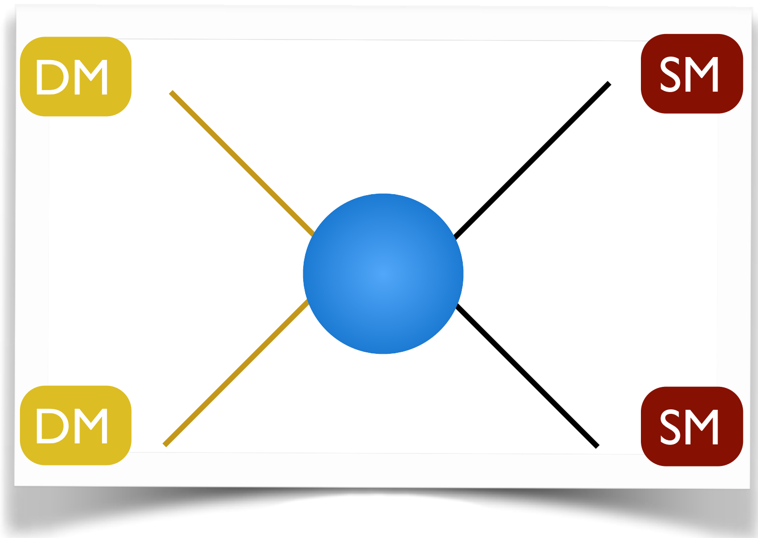
[Lattanzi & Valle (PRL`07)]

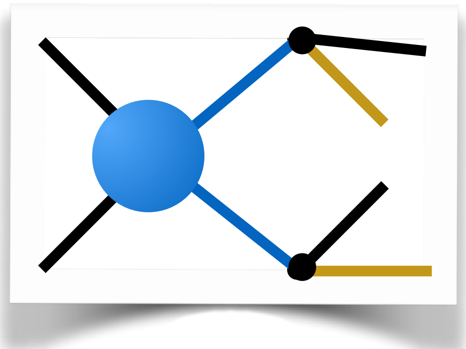


Dark matter in cosmology and at colliders

- ✦ Dark matter is searched for directly, indirectly and at colliders
  - ✤ This huge experimental effort offers a strategy to constrain models

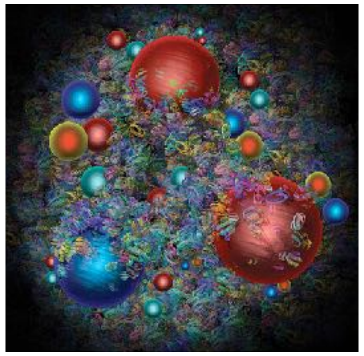
- ✦ Complementary between colliders and cosmology
  - ✤ Dark matter relic abundance must be reproduced
  - ✤ Dark matter direct/indirect detection constraints
  - ✤ Direct production at (hadron) colliders (or from the decay of heavier states)





From dark matter to missing transverse energy

✦ Hadron collisions: scattering of the proton constituents



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  - ★ Larger $\sqrt{s}$ ➢ heavier new particles
- ✤ Unknown longitudinal momenta
  - ★ Use of quantities invariant under longitudinal boosts (p_T, *etc.*)

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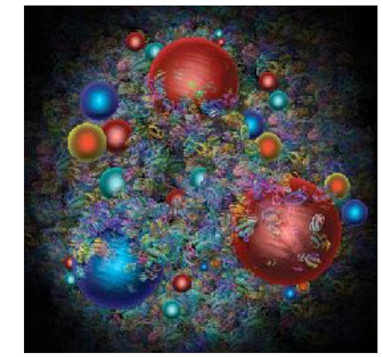

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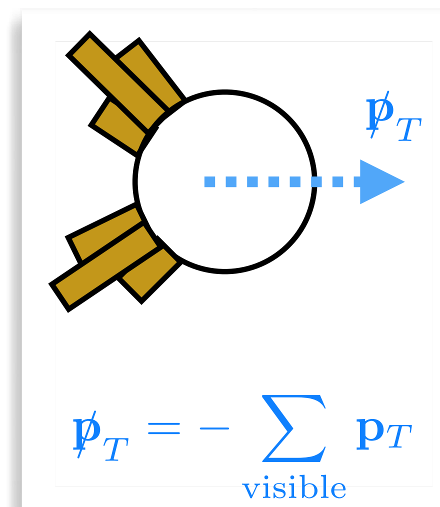

- ✤ The initial-state total transverse momentum is zero
  - ➢ the final-state total p_T is zero
- ✤ Invisible particles (DM in particular) ≡ missing momentum
  - ★ Weakly interacting and neutral ➢ detector is transparent
  - ★ Presence inferred from momentum imbalance

$$\not{E}_T = ||\not{p}_T|| = \left|\left| -\sum_{\text{visible}} \mathbf{p}_T \right|\right|$$

- ✤ Beware: MET ≠ DM
  - ★ MET could originate from neutral long-lived states, or even neutrinos
  - ★ DM may not yield large MET (if light or from a compressed spectrum)

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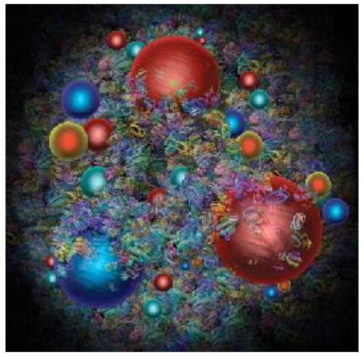

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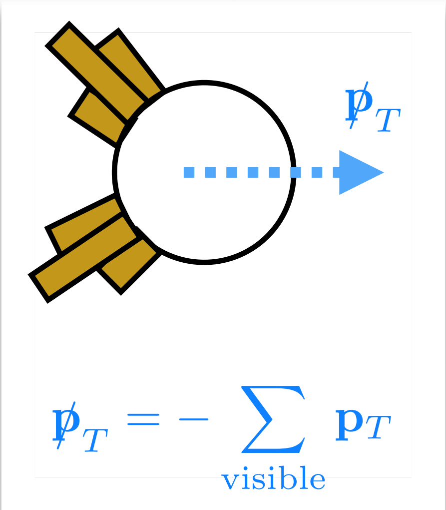

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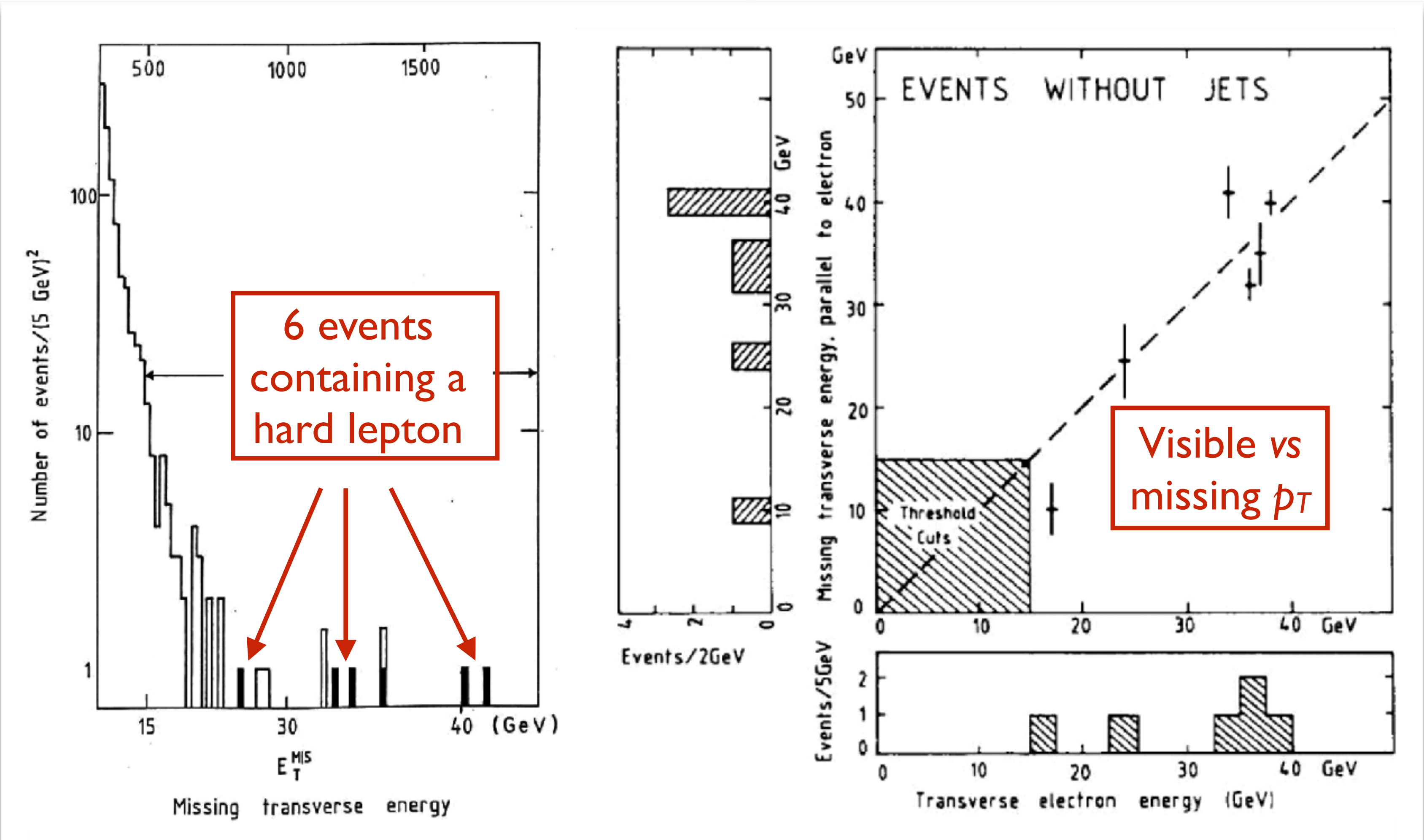
How to detect missing energy?

Detecting missing energy at colliders (I)

✦ Missing transverse energy detection 40 years ago

- ✤ This neither new nor typical of modern colliders
- ✤ W-boson discovery in 1983 (with 6 events) ➢ $M_W = 81 \pm 5\ \mathrm{GeV}$

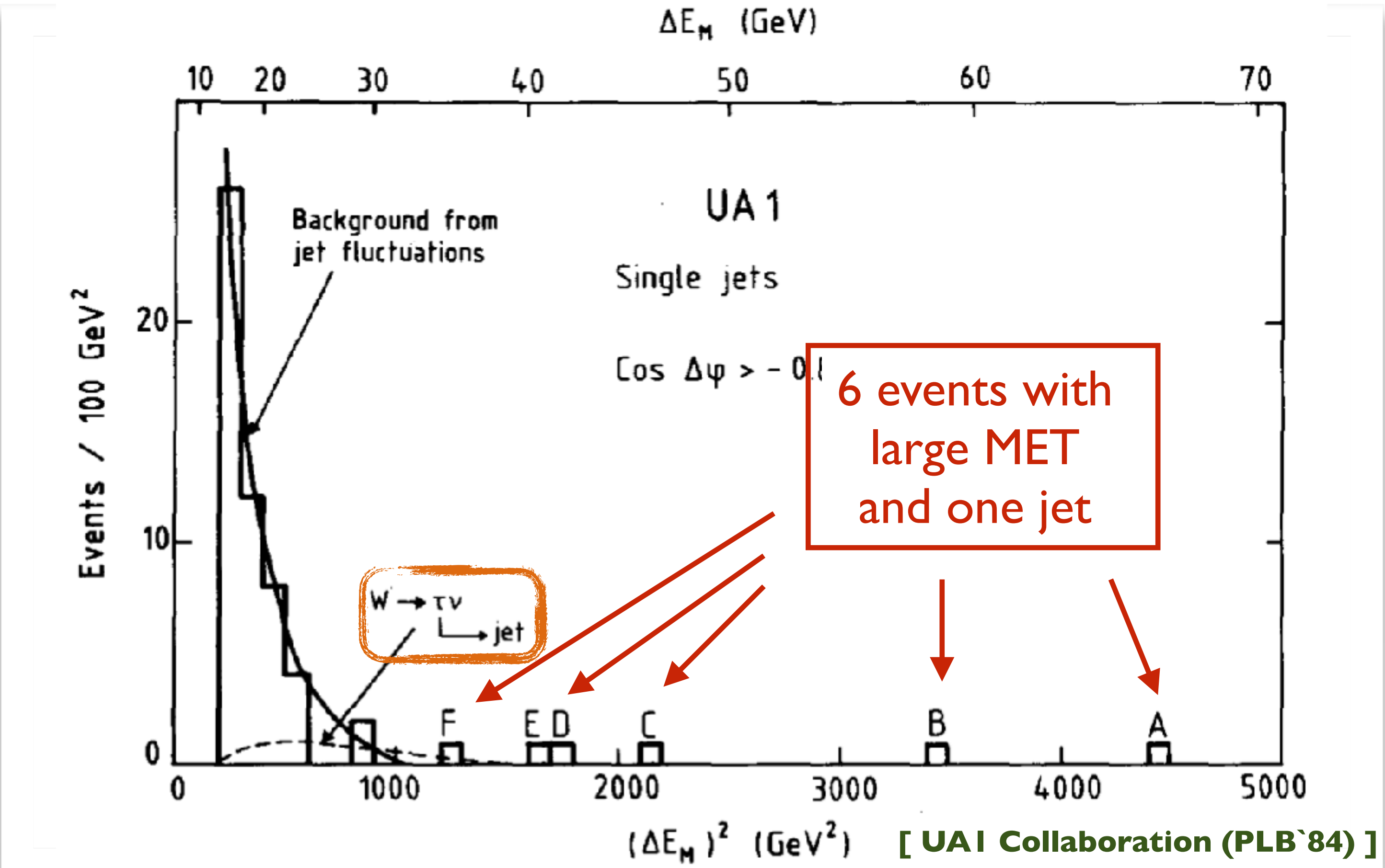


[UA1 Collaboration (PLB`83)]

Detecting missing energy at colliders (2)

✦ Missing transverse energy detection 40 years ago

- ✤Jets and missing energy in UA1
- ✤Not called DM-related at that time
- ✤No SM explanation → *W*+jets (in orange) , invisible *Z*+jets, *etc.*

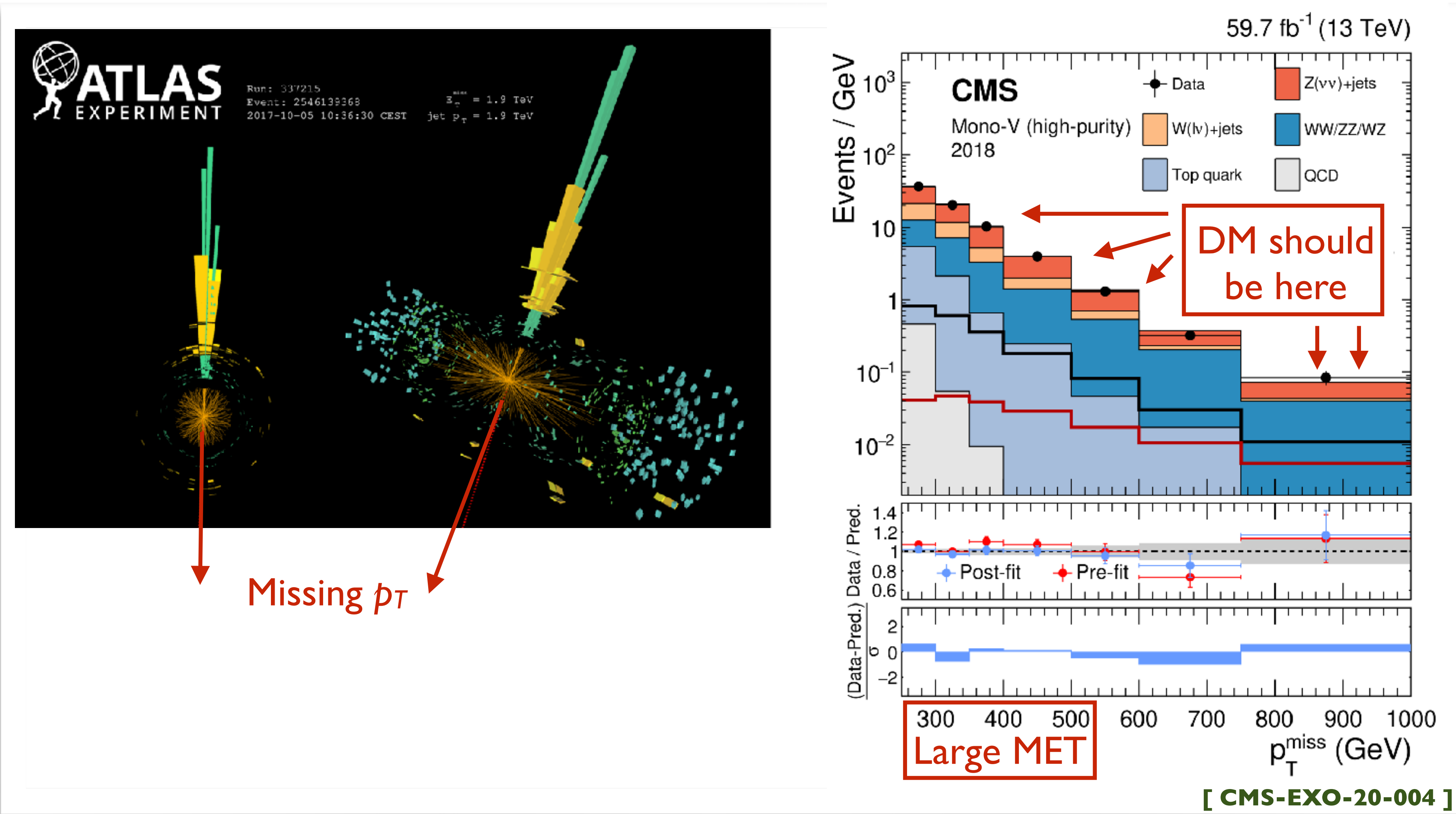


[UA1 Collaboration (PLB`84)]

Detecting missing energy at colliders (3)

✦ Missing transverse energy at the LHC: 40 years fast forward

- Searching for a signal with a lot of missing energy
- The missing momentum recoils against visible objects



[CMS-EXO-20-004]

Dark matter signatures at the LHC

- ✦ Dark matter signatures
  - ✤ Missing transverse energy (carried away by the DM particles)
  - ✤ Visible stuff (triggers, handles for background rejection, *etc.*)
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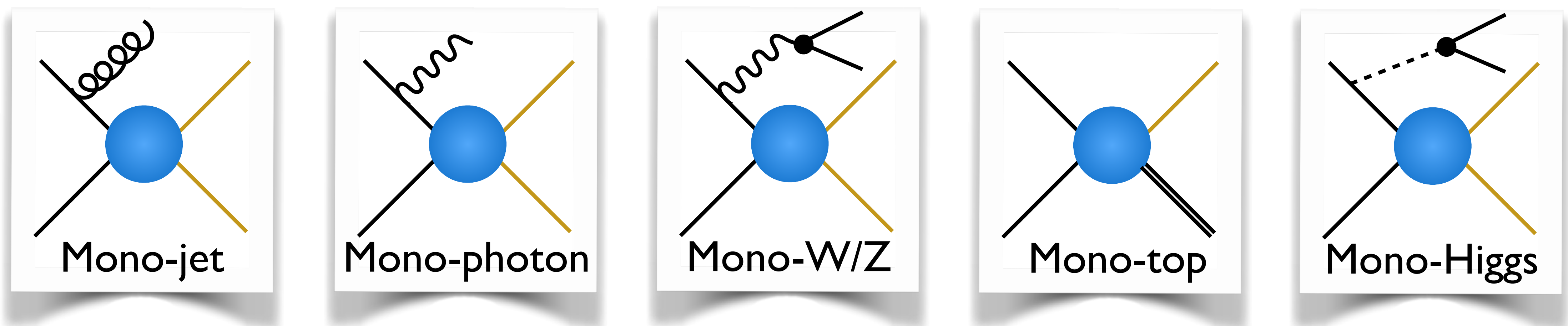

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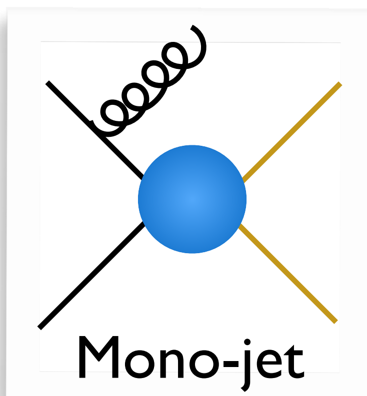
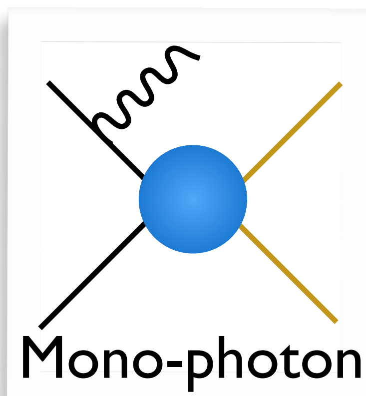
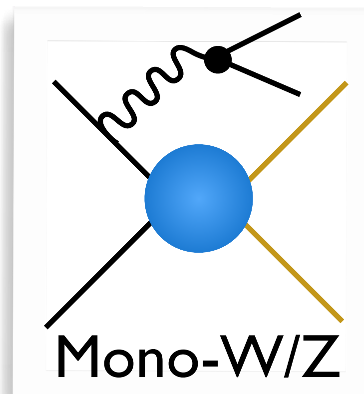
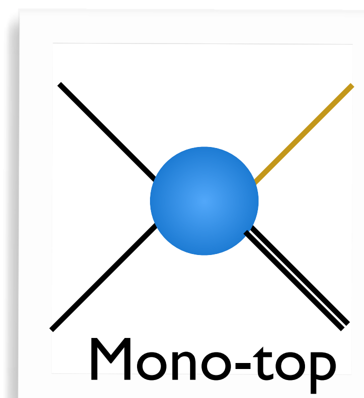
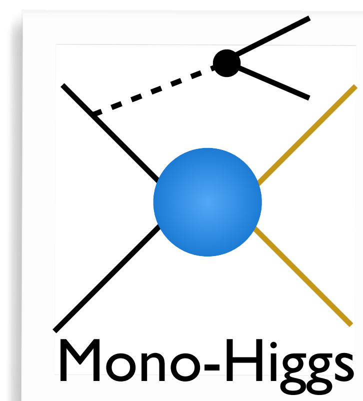


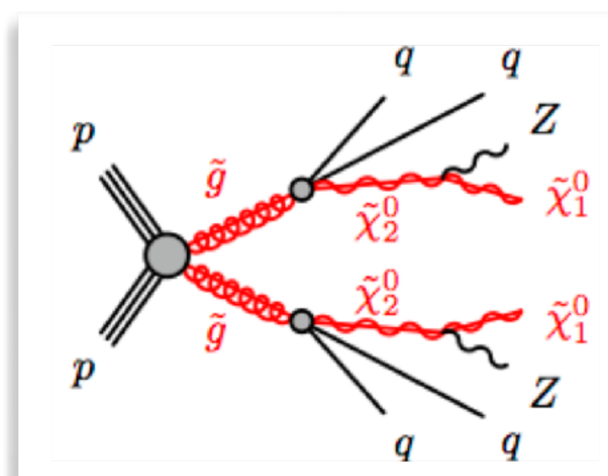








- ✤ More complicated signals also considered
  - ★ Multi-jets and missing energy
  - ★ Multiple leptons, jets and missing energy
  - ★ Top-antitop pair and missing energy
  - ★ *etc.*



Almost two decades of mono-X searches…

✦ The mono-X (DM) story is almost 20 years old

- ✤ The problem was to trigger on DM signals → need for a visible object
- ✤ Introduced first as mono-photons in lepton collisions **[Birkedal, Matchev & Perelstein (PRD`04)]**
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✦ Colliders meet direct detection

- ✤ Applied to the LEP and Tevatron case
- ✤ Limits set in the same parameter space
- ✤ Light DM becomes accessible through mono-jets and mono-photons

[Bai, Fox & Harnik (JHEP`10)]

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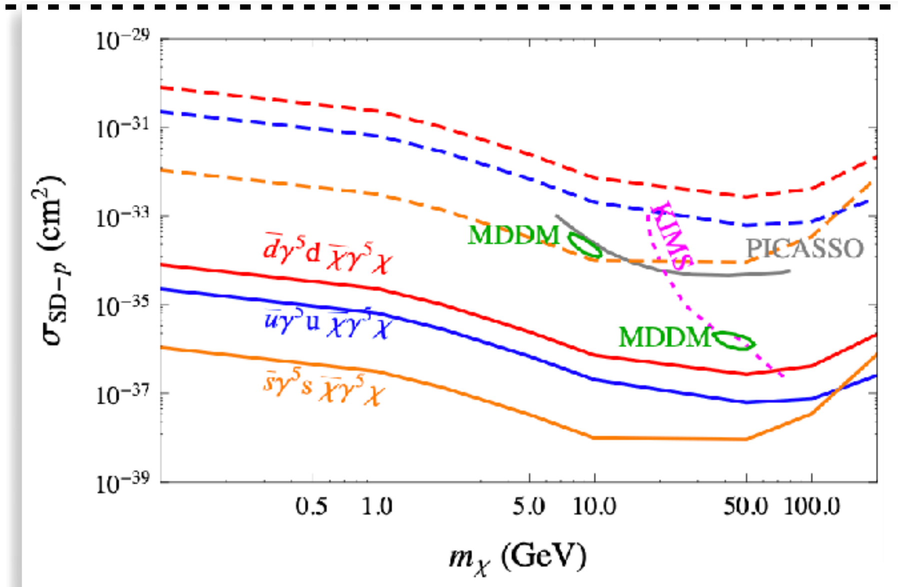

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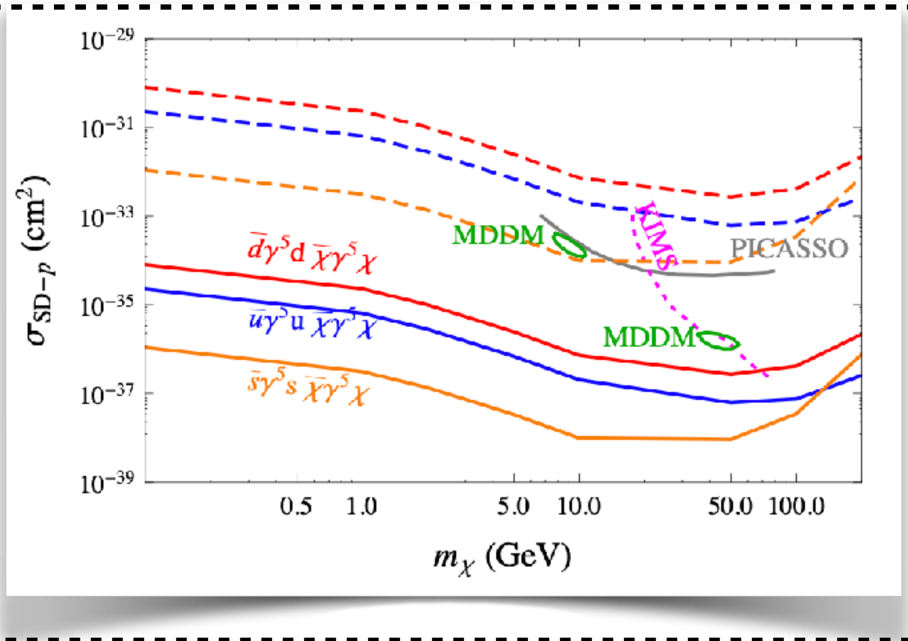

✦ Towards the modern epoch

- ✤ New dark signals: mono-top, mono-Z, mono-lepton & mono-Higgs

[Andrea, BF & Maltoni (PRD`11); Bell, Dent, Galea, Jacques, Krauss & Weiler (PRD`12); Bai & Tait (PLB`13); Petrov & Shepherd (PLB`14)]

- ✤ First experimental studies: CDF, and then ATLAS/CMS

A dark matter search strategy at the LHC

✦ A typical LHC dark matter search strategy

- ✤ Requirement of a significant amount of missing transverse energy
- ✤ Requirement of a significantly hard visible object (jet, di-lepton pair, photon, *etc.*)
- ✤ Extra constraints (angular correlations, vetoes, *etc.*) to reduce the backgrounds
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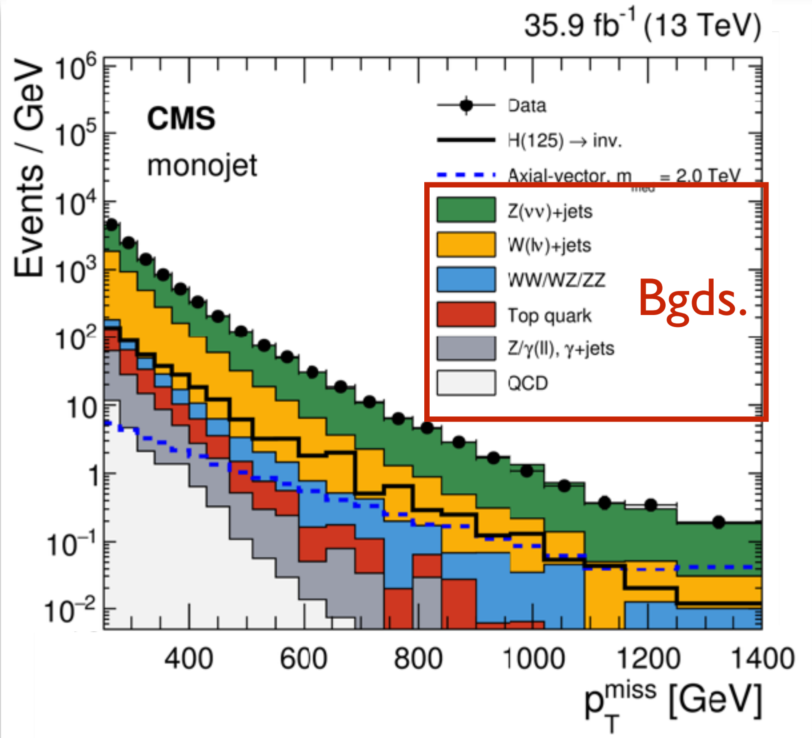
✦ Backgrounds - the mono-jet case

- ✤ Invisible *Z* decays
  - → irreducible backgrounds
- ✤ W decays with a lost lepton
  - → not very frequent but large (total) rate
- ✤ Mis-measurements in multi-jet production
  - → rare, but huge QCD total rate
  - → steeply falling with the MET value



[CMS-EXO-16-048]

Outline

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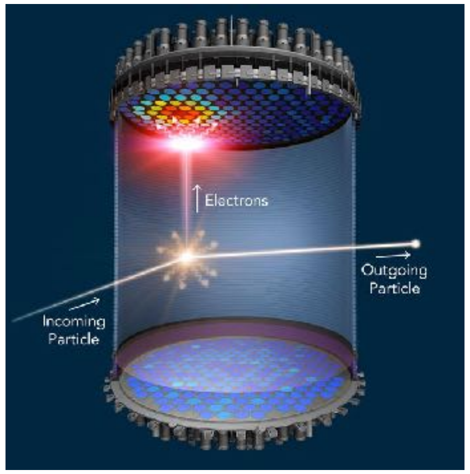
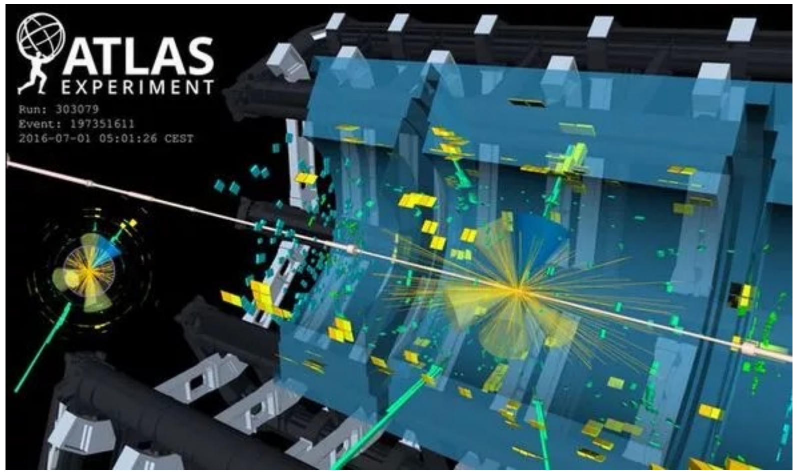
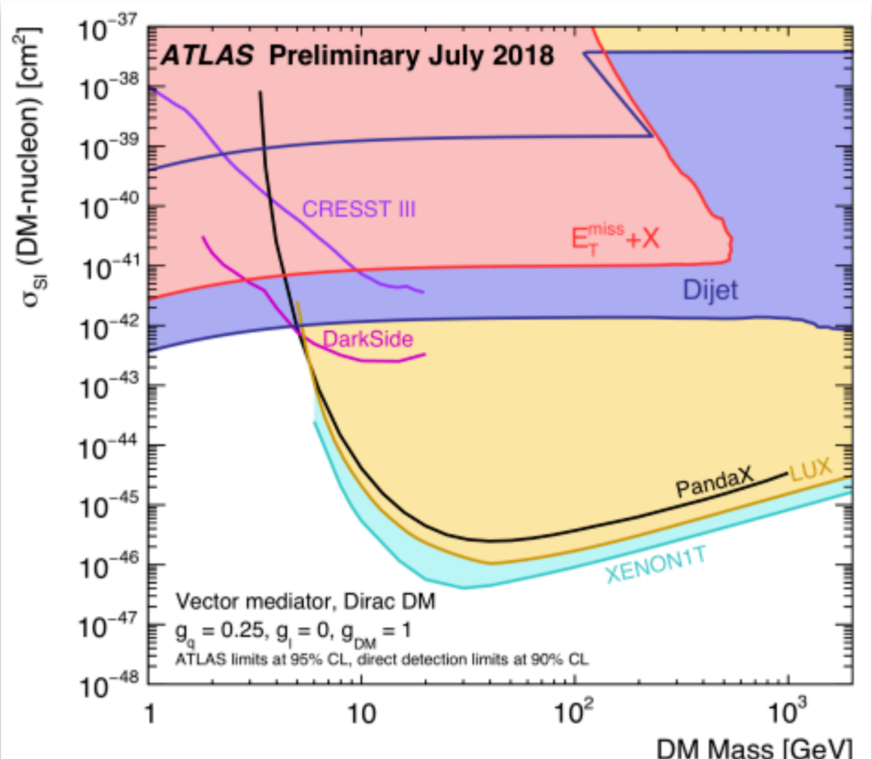
An EFT interpretation

Connecting direct detection and colliders

✦ No mono-X excess wrt the SM background
- ✤ Limits can be set on DM and its properties
  - ➢ in the same plane as for direct detection







[ATLAS-EXOT-2017-32]

✦ Direct detection in a nutshell (see H. Araujo's lectures for details)
- ✤ Cross sections ⇔ nucleon-DM couplings ⇔ nucleon-quark/gluon couplings
- ✤ Effective field theory approach
  - ★ LHC constraints on the effective couplings and scale

Constraining direct detection with LHC data

✦ Effective field theory to model DM-nucleon interactions

$\mathcal{L}_\chi = f_N \ \bar{\chi}\chi\bar{N}N$	or	$\mathcal{L}_\phi = f_N \ \phi^2\bar{N}N$	or	$\mathcal{L}_X = f_N \ X_\mu X^\mu\bar{N}N$
Majorana DM		Real scalar DM		Real vector DM

✤ f_N originates from nucleon matrix elements and the underlying new physics

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✦ Ingredients in the DM-nucleon scattering cross section (through f_N)

(1) Nucleon matrix elements

(2) Effective interactions between dark matter and quarks/gluons

→ EFT-derivation from the initial particle physics model

✤ Connection of the direct detection cross section to the physics parameters

[Drees & Nojiri (PRD`93); Hisano, Nagai & Nagata (JHEP`15)]

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✦ LHC constraints on the underlying physics models

→ Translation in terms of the effective theory parameters

→ Translation in terms of the direct detection cross section

DM direct detection in a nutshell

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✦ Connection with the UV: Wilson coefficients

✤ Integration out of heavy UV states → DM-quark/gluon effective interactions

$$\begin{aligned}
\mathcal{L}_{\rm EFT,\chi} &= \frac{C^q_\chi}{\Lambda^2}\big[\bar\chi\chi\big]\big[m_q\bar q q\big] + \frac{C^q_{\chi,\rm AV}}{\Lambda^2}\big[\bar\chi\gamma_\mu\gamma_5 q\big]\big[\bar q\gamma^\mu\gamma_5 q\big] + \ldots\\
\mathcal{L}_{\rm EFT,\phi} &= \frac{C^q_\phi}{\Lambda^2}\phi^2\big[m_q\bar q q\big] + \frac{C^g_\phi}{\Lambda^2}\frac{\alpha_s}{\pi}\phi^2\big[G_{\mu\nu}G^{\mu\nu}\big] + \ldots\\
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\end{aligned}$$

The Wilson coefficients depend on the UV physics

Complementary constraints

✦ Constraints from both directions

Dark matter direct detection cross section ⟷ **DM EFT** $\mathcal{L}_{\rm EFT} = \frac{C}{\Lambda^2}\,\mathcal{O}(q,g,{\rm DM})$ ⟷ **UV model (with heavy states)**

- ✤ Direct detection constraints translated into bounds on the UV parameters
- ✤ LHC bounds on the UV model translated into bounds on C/Λ^2 (and DD rates)

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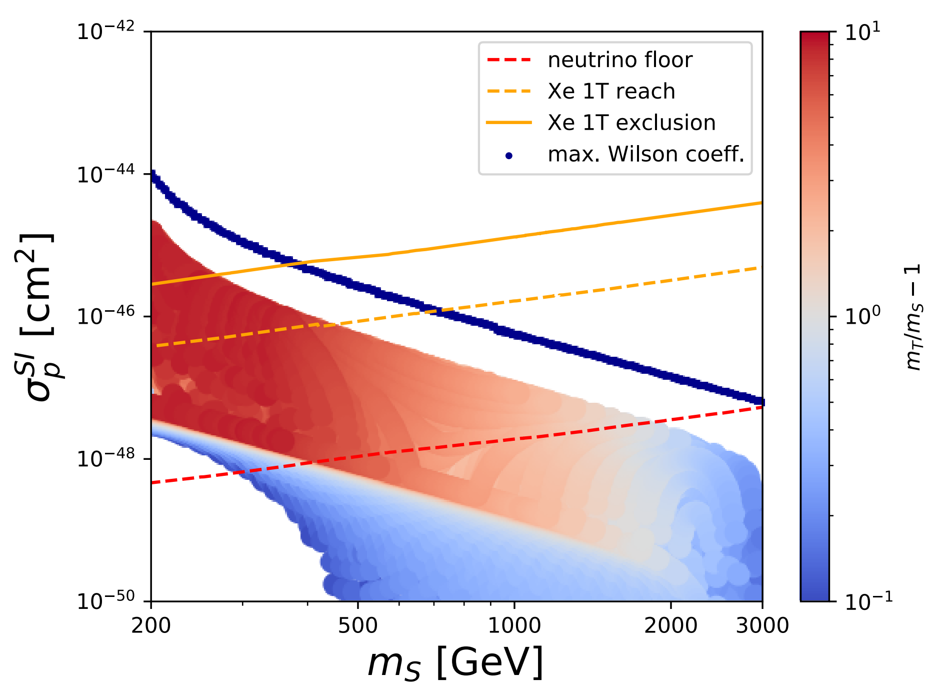
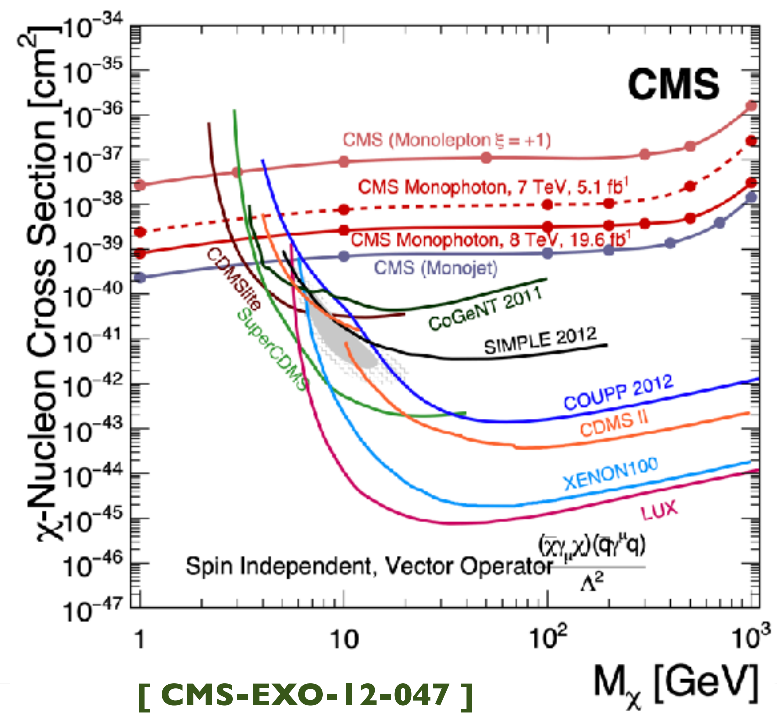
✦ Illustration of the complementarity

- ✤ Top-philic scalar DM from direct detection to bounds on the UV model
- ✤ Direct detection bounds from mono-photon searches at the LHC (run 1)



[Cornell, Deandrea, Flacke, BF & Mason (JHEP`21)]



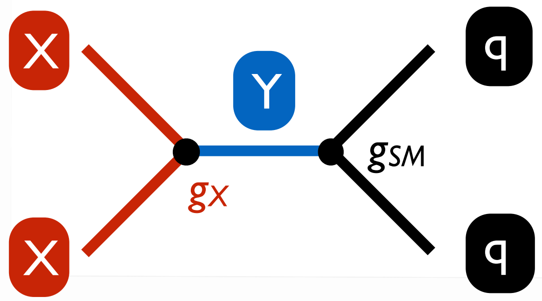
[CMS-EXO-12-047]

The failure of the EFT interpretation

✦ Using an EFT

✤ Integration out of heavy UV states → relating UV parameters to the EFT scale Λ

✤ Example: *s*-channel axial-vector mediator *Y* coupling to a dark matter *X*



$$\Rightarrow \frac{C}{\Lambda} \bar{X}\gamma^\mu\gamma_5 X \; \bar{q}\gamma_\mu\gamma_5 q \qquad \text{with} \qquad \frac{\Lambda}{C} = \frac{m_Y}{g_X\, g_{\rm SM}}$$

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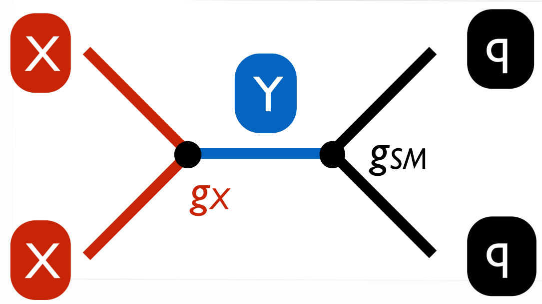

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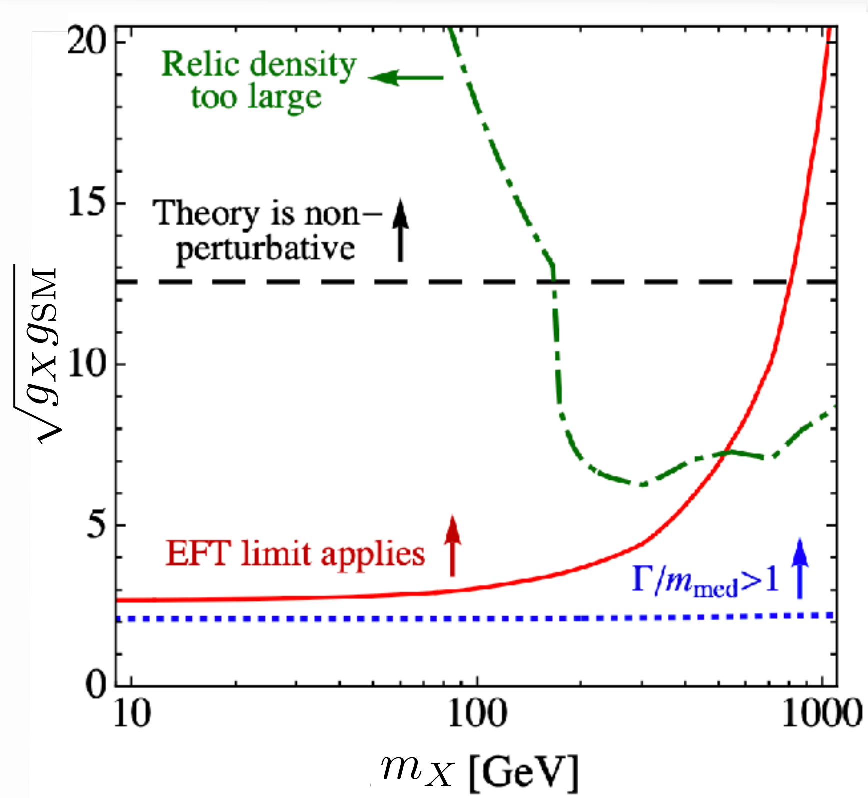

[Buchmueller, Dolan & McCabe (JHEP`14)]

✦ An ill-defined interpretation

- m_Y is fixed for the EFT to be valid
  → $m_Y \gg$ typical LHC momentum transfer
- Derivation of minimum couplings (red line)
  → from LHC run I mono-jet searches
- The mediator is not even a particle ($\Gamma > m_Y$)
  ★ Large (not extreme) widths interesting too
- Perturbativity issues for $m_X > 800$ GeV
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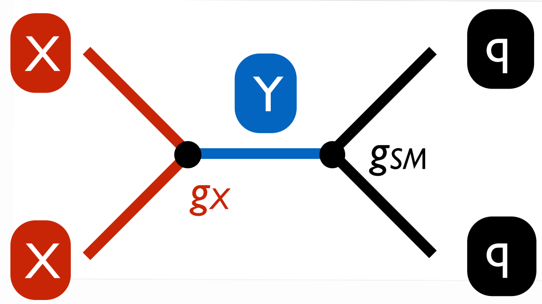

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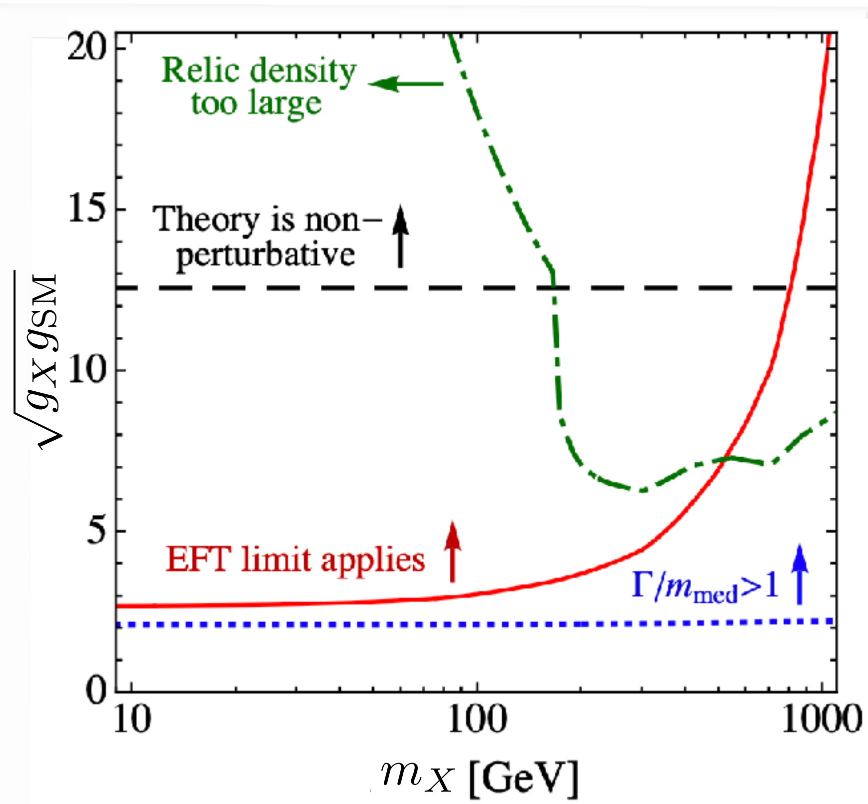

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Constraints on baroque setups

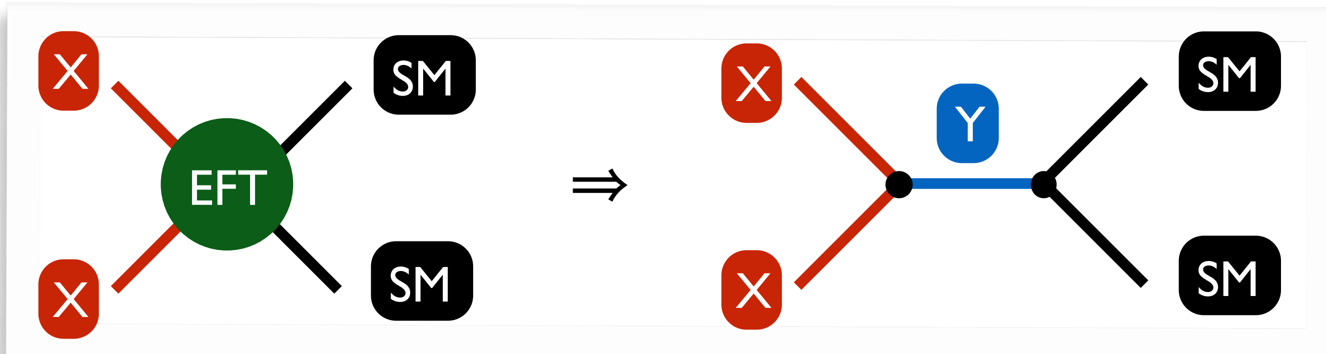
Dark Matter simplified models

The *s*-channel case

From EFT to simplified model interpretations

✦ Resolution of the EFT interactions in a minimal way

- ✤ Simplified models as a tool for generic DM search interpretations
- ✤ Sizeable LHC rates, few assumptions on the model
- ✤ A small number of free parameters



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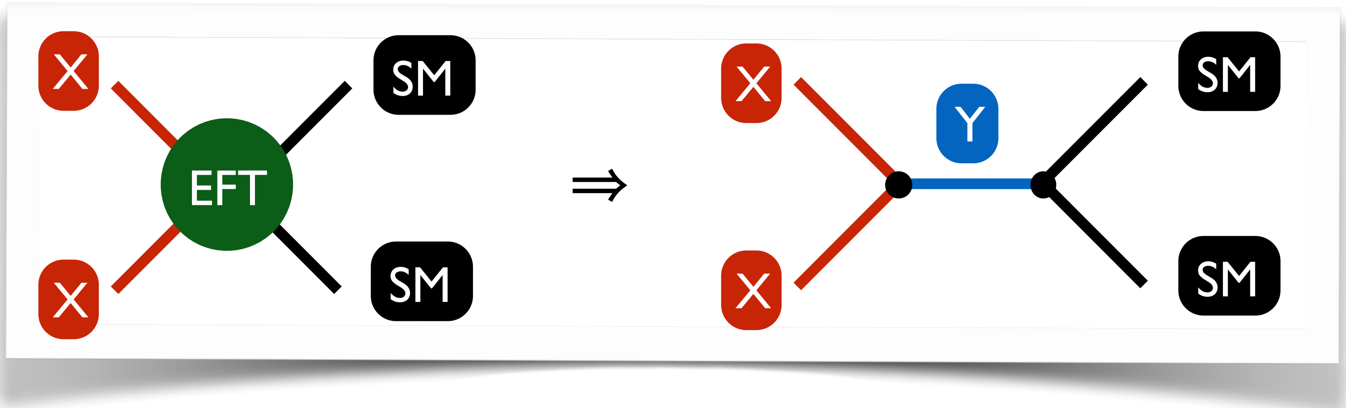


✦ Generic simplified models for dark matter @ LHC

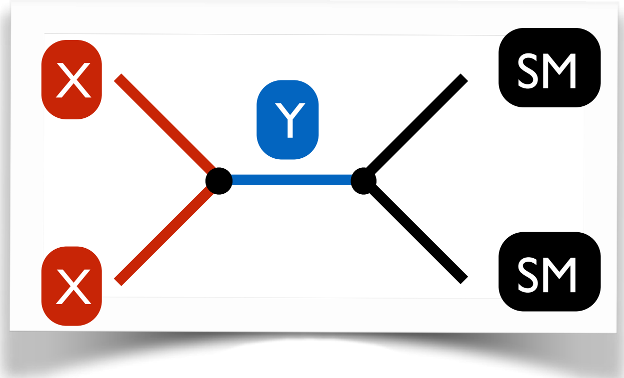
- ✤ Minimality: SM + 1 DM candidate + 1 mediator (coupling to quarks and gluons)
  - ★ Representative of different theoretically-motivated new physics scenarios
  - ★ Lack non-minimal features (multiple mediators, multi-component DM, *etc.*)
  - ★ Beware: non-minimality can change the picture

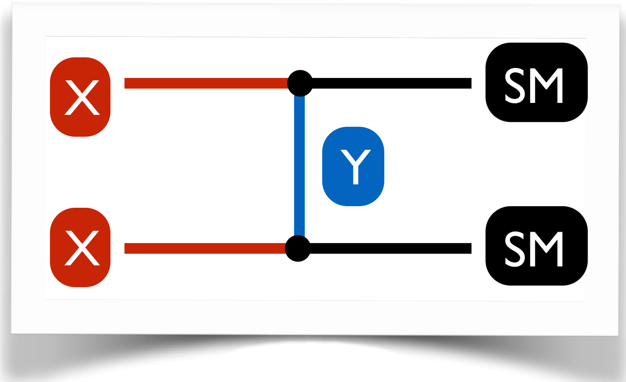
Simplified dark matter models @ LHC

✦ Basic properties of the simplified DM models

✤ DM (X) is stable
- ⤳ Odd under some $\mathbb{Z}_2$ discrete symmetry
- ⤳ SM states even under the same symmetry

✤ The mediator (Y) connects DM to quarks/gluons
- ★ $\mathbb{Z}_2$-even: *s*-channel models ⤳ colour singlet and electrically neutral
- ★ $\mathbb{Z}_2$-odd: *t*-channel models ⤳ colour triplet and electrically charged





[Arina, BF & Mantani (EPJC`20)]
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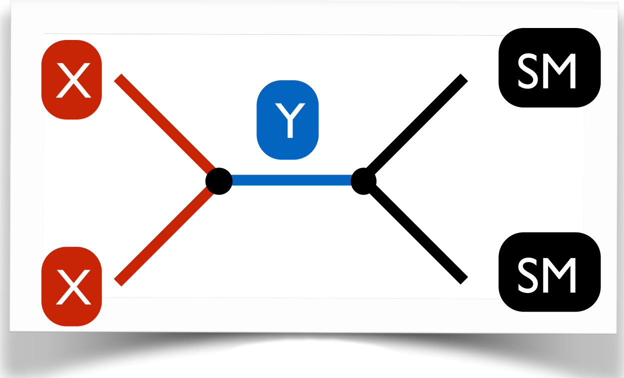

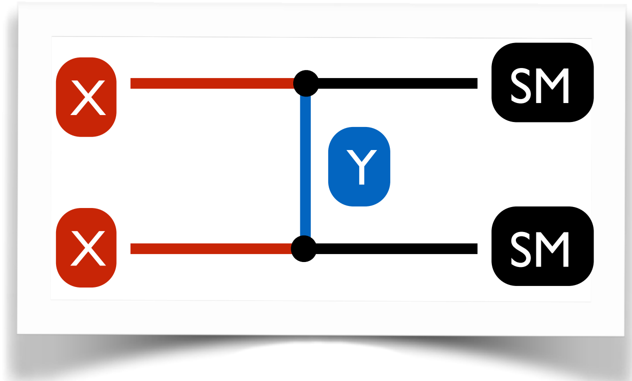

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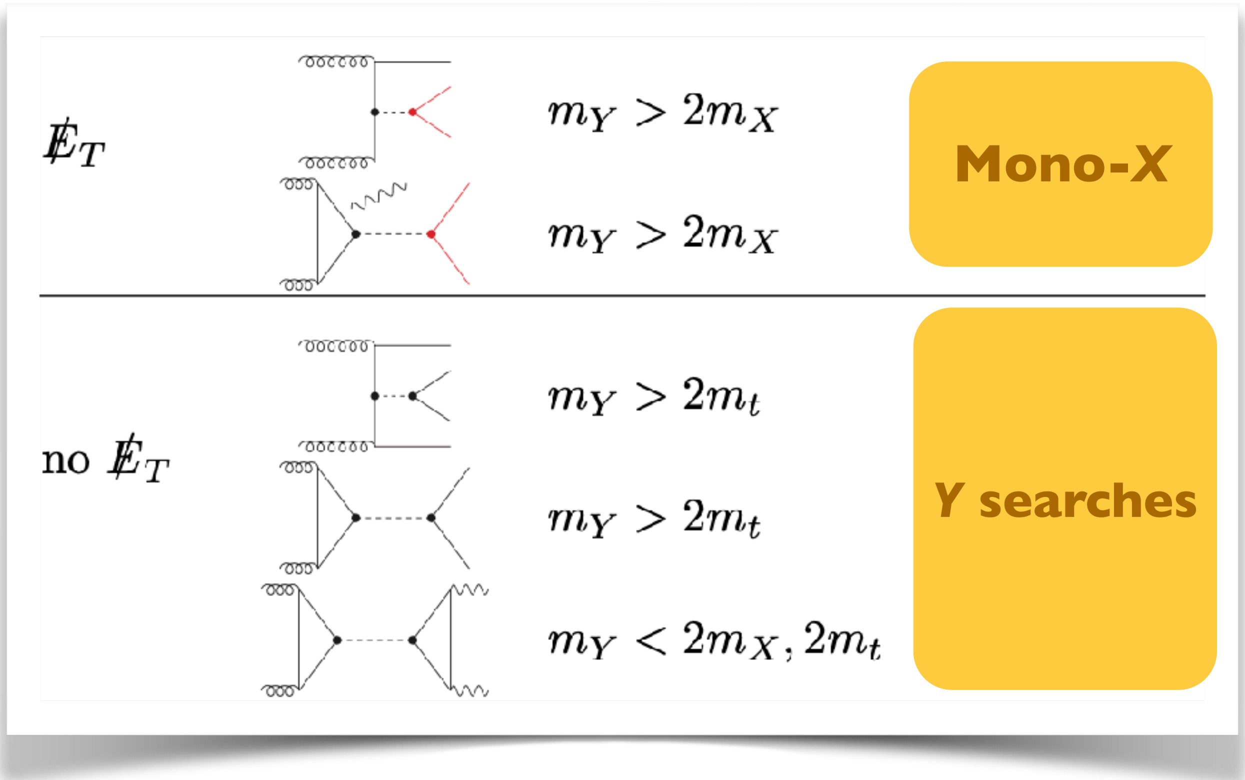
✦ Free parameters

- ✤ 2 spins: J_X, J_Y
- ✤ O(10) masses
  - ★ 1 DM mass: m_X
  - ★ Several mediators (coupling to different SM generations)
- ✤ Many couplings in the flavour space

s-channel models at colliders

✦ Simplified models ⇔ richer phenomenology than expected



- ✤ Two classes of processes
  - ★ With missing energy (mono-X)
  - ★ Without missing energy (mediator)
- ✤ Tree-level / loop-induced processes
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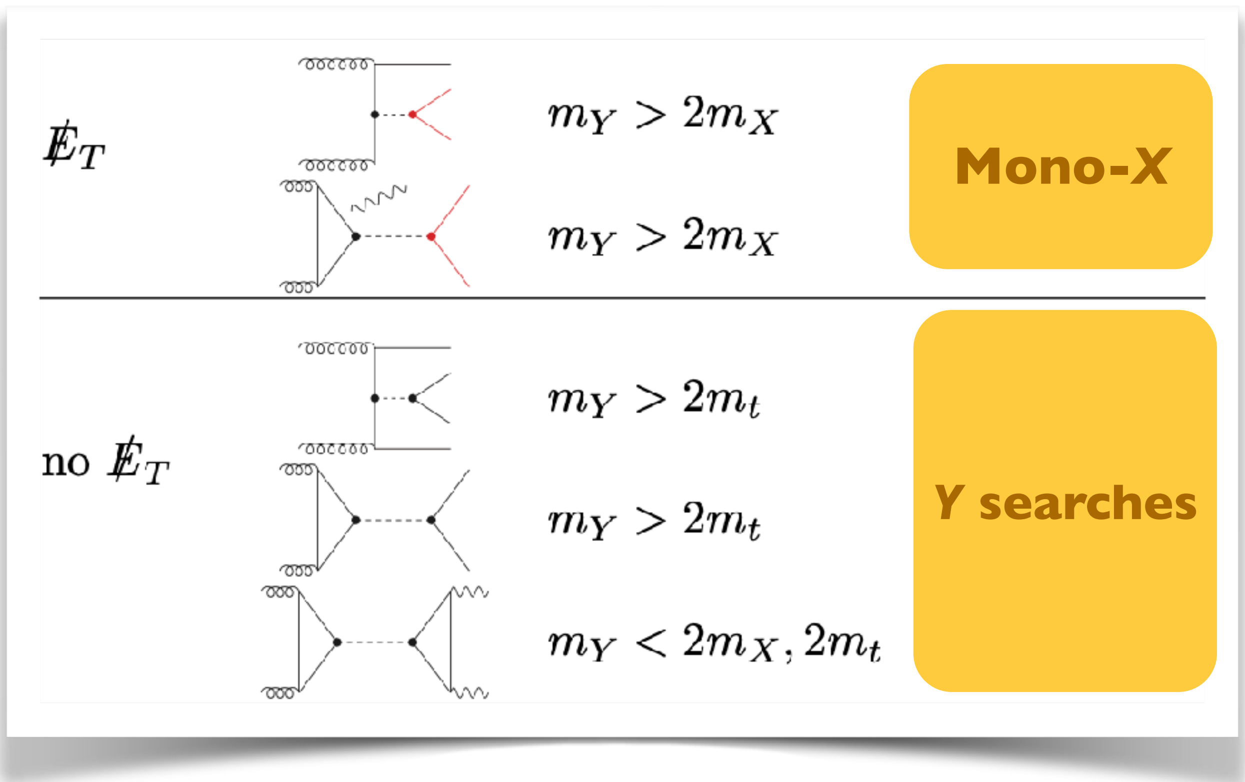

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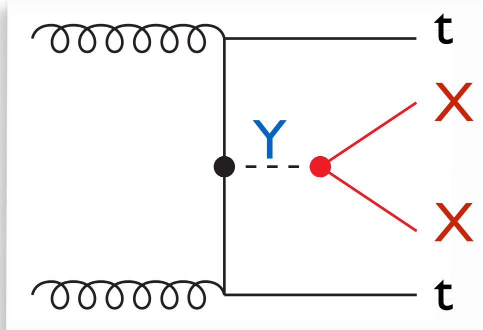
✦ Complementary DM model probes at colliders

- ✤ With DM searches
- ✤ Through resonance searches
- ✤ Several ways to constrain the parameter space (at the LHC)

Example: top-philic fermion DM / scalar mediator

✦ A simplified model for top-philic dark matter

- A dark sector with a fermionic dark matter candidate X
- A (scalar) mediator Y linking dark matter and the top
  - ★ MFV ≡ fermion-Y couplings proportional to the SM Yukawas



$$\mathcal{L} = -\frac{g_t y_t}{\sqrt{2}} \; [\bar{t}t] \; Y - g_X \; [\bar{X}X] \; Y$$

4 parameters: 2 masses and 2 couplings

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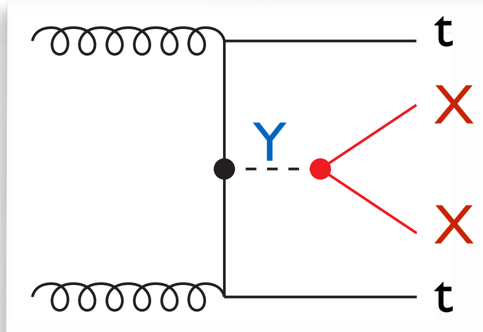

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✦ Scanning procedure

- Masses
  - ★ 1 GeV < m_Y < 5 TeV
  - ★ 1 GeV < m_X < 1 TeV
- Perturbative couplings: 0.01 < g_X, g_t < 2π
- Flat likelihood functions in all dimensions
- LHC Run 1 constraints are imposed, no cosmology bounds

Collider constraints on top-philic *s*-channel DM

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

- Points excluded by run 1 data
  - Mediator masses of 100-600 GeV
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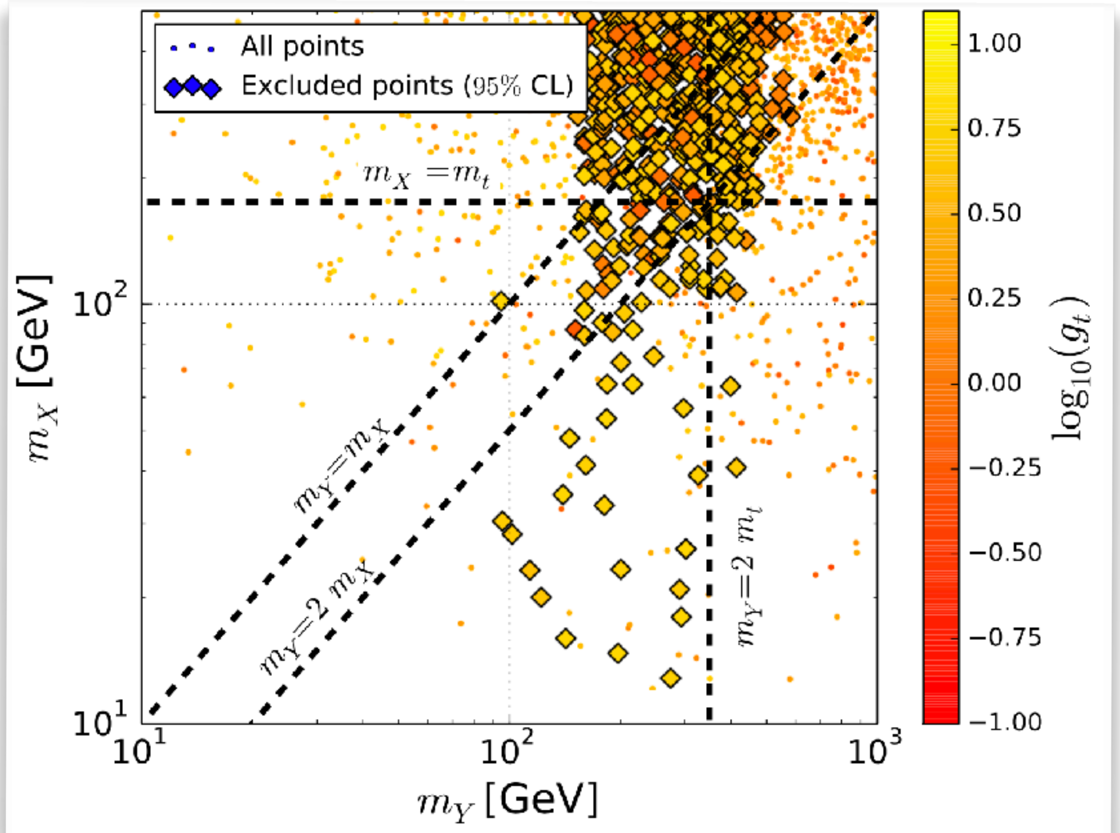

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  - Large MET at the LHC
    - Dark Y decays open
    - Y decays in tops closed
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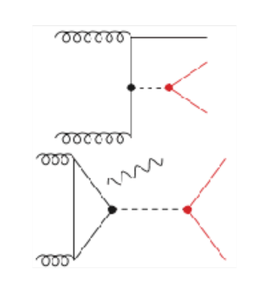

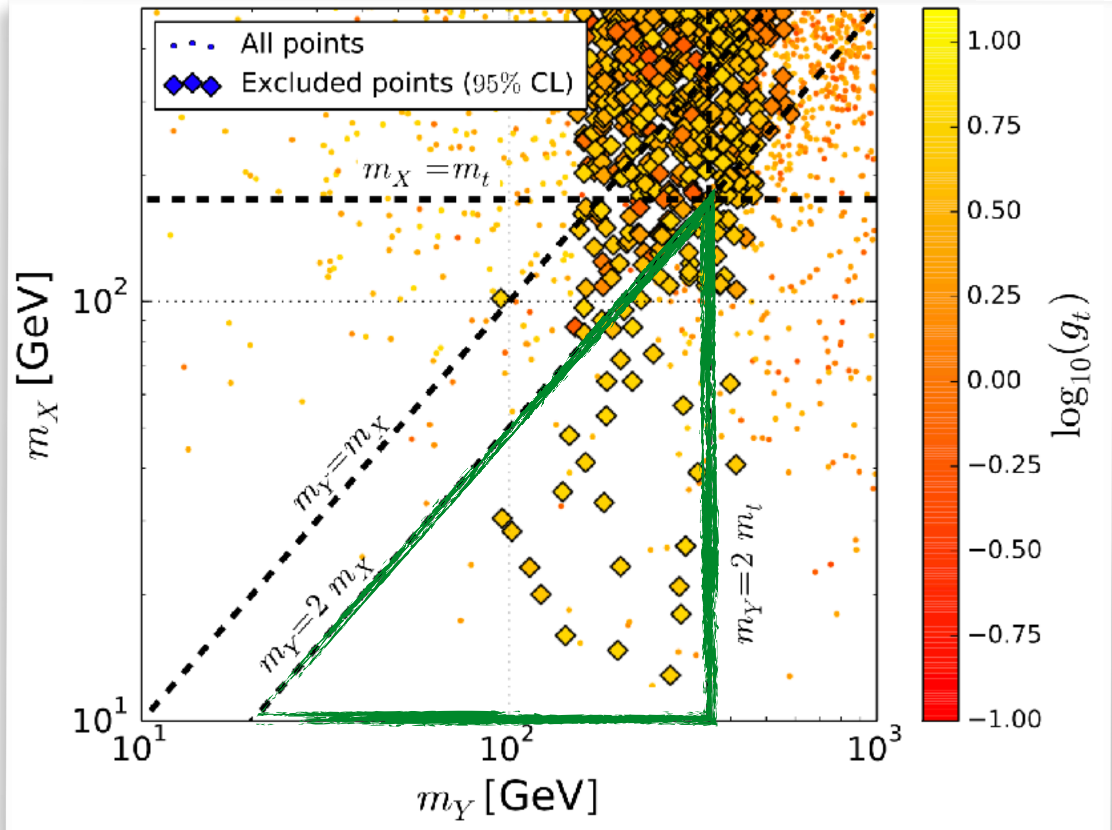

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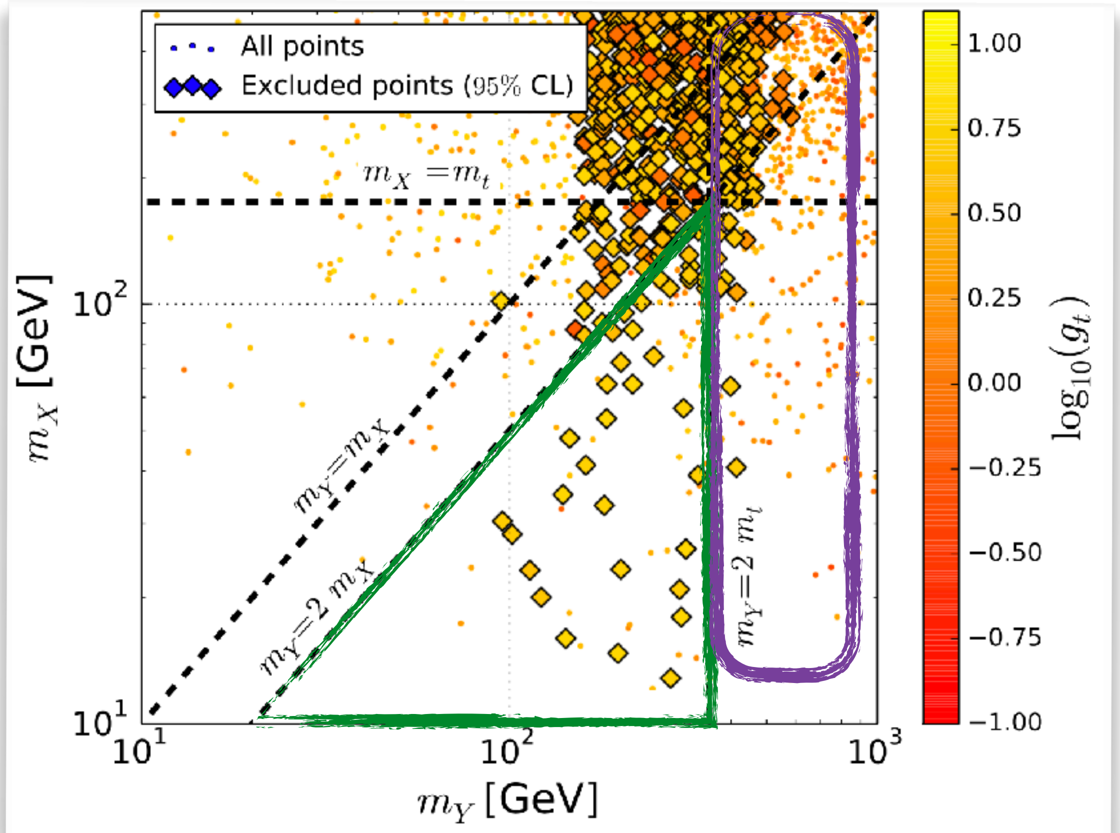

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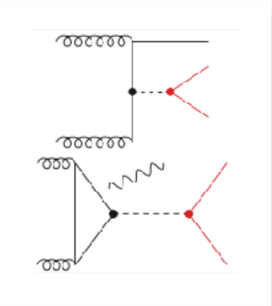

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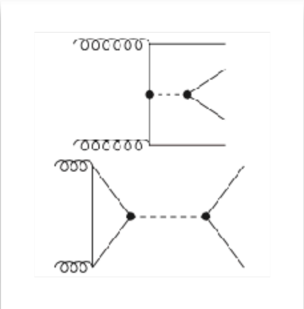

- ✤ *Y* decays in tops open and dominant
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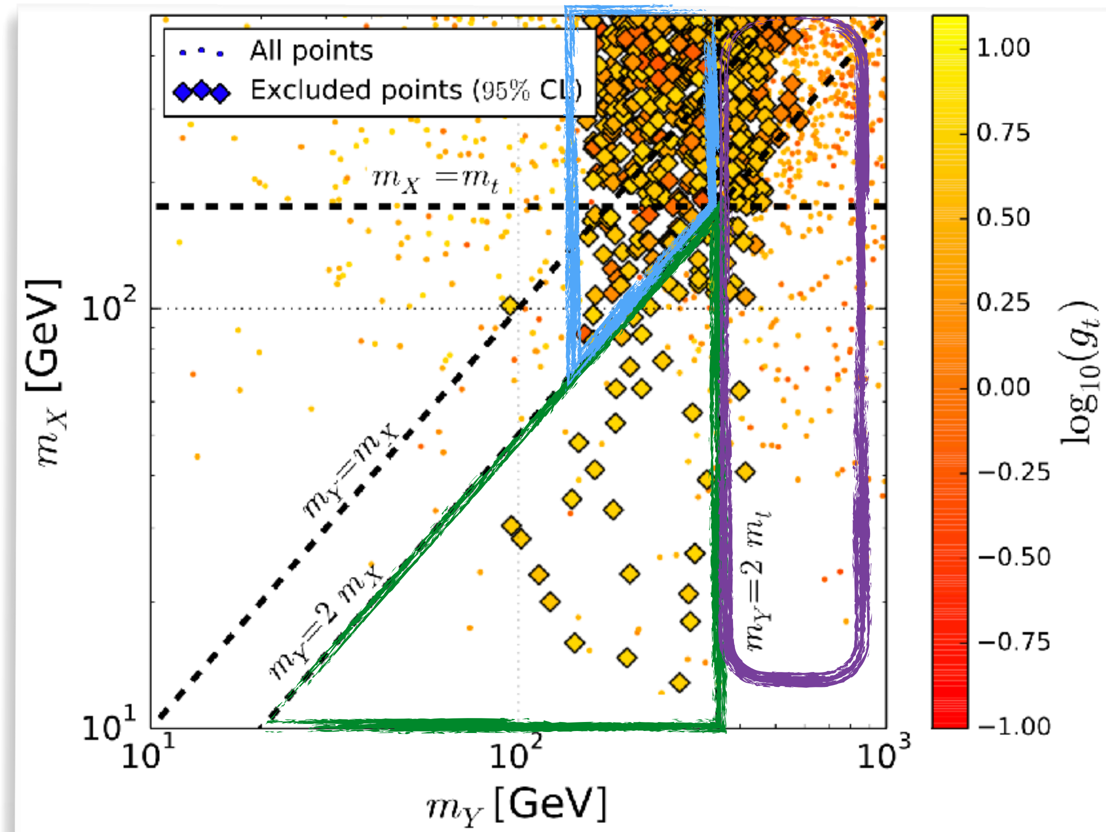

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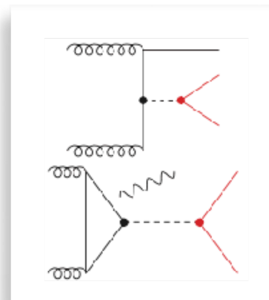

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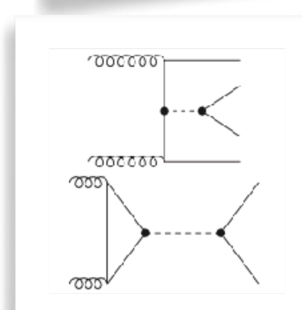

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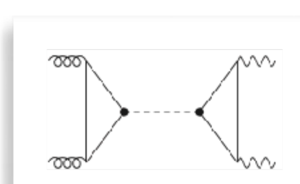
✦ Diphoton resonance searches



- ✤ Y decays in tops DM closed
- ✤ O(0.1) g_t couplings excluded

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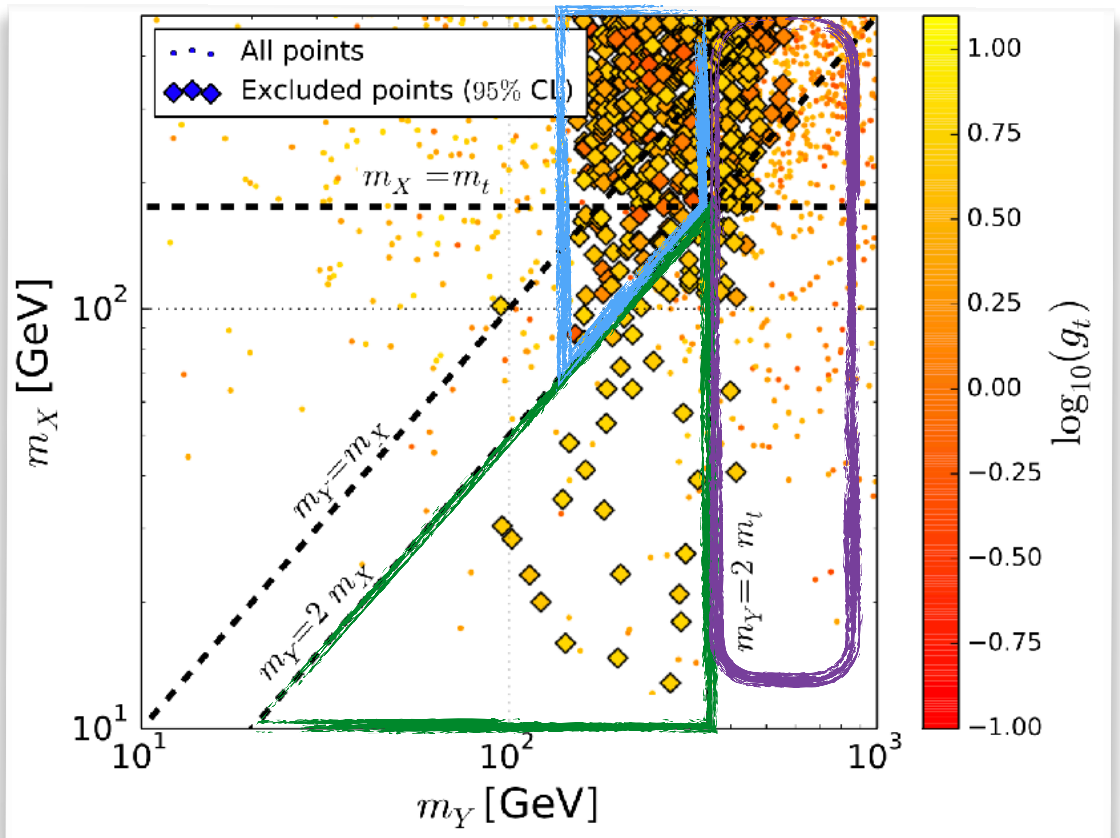

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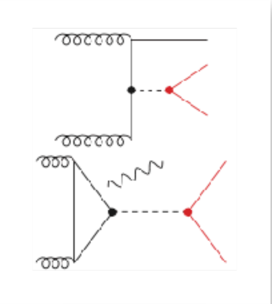
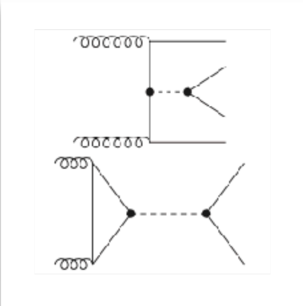
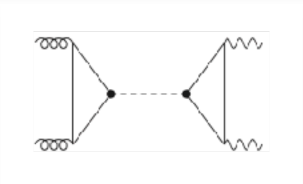
  - Mediator masses of 100-600 GeV
    - $m_Y < 2\,m_t$ or $m_Y > 2\,m_t$
  - Large sets of DM masses
    - $m_Y < m_X$ or $m_Y > m_X$
    - $m_t < m_X$ or $m_t > m_X$
- **Mono-jet / $t\bar{t}$+MET**
  - Large MET at the LHC
    - Dark Y decays open
    - Y decays in tops closed
  - O(10) g_t couplings excluded



- **$t\bar{t}/t\bar{t}t\bar{t}$ production**
  - Y decays in tops open and dominant
  - O(1) g_t couplings excluded



- **Diphoton resonance searches**
  - Y decays in tops DM closed
  - O(0.1) g_t couplings excluded



Large complementarity between all LHC searches

Details on the simulations

- ✦ Several key aspects behind the previous results
  - ✤ Simulations at the NLO-QCD accuracy → precision predictions
  - ✤ Recasting with public tools
    - ★ Many ATLAS and CMS searches for new physics
    - ★ Interpretation within popular frameworks and simplified models
    - ★ Need for interpretations in all kind of models

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A (not too) technical interlude on NLO simulations & LHC recasting

Interlude 1

NLO simulations in a nutshell

A few words on NLO computations

✦ Dissecting an NLO calculation in QCD

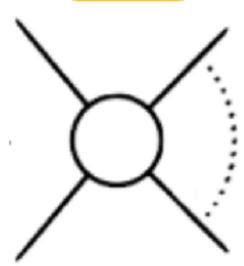
✤ Three ingredients: the Born, virtual loop and real emission contributions

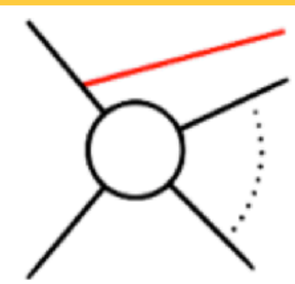
$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \mathcal{B} \quad + \quad \int \mathrm{d}^4\Phi_n \int_{\text{loop}} \mathrm{d}^d\ell \, \mathcal{V} \quad + \quad \int \mathrm{d}^4\Phi_{n+1} \, \mathcal{R}$$

Born

Virtuals: one extra power of α_s and divergent

Reals: one extra power of α_s and divergent

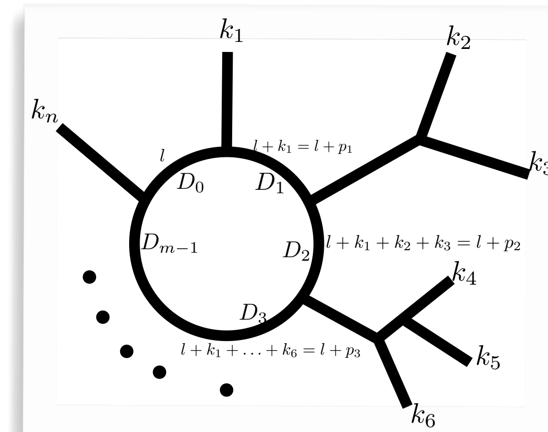




Loop calculations

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

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



[Ossola, Papadopoulos & Pittau (NPB'07)]
[Ossola, Papadopoulos & Pittau (JHEP'08)]

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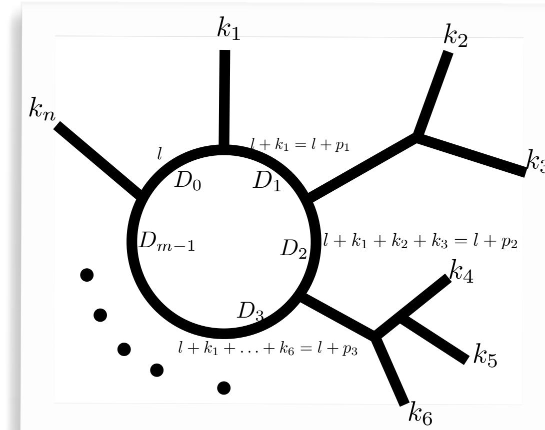

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- ✦ R_1 terms originate from denominators

$$\frac{1}{\bar{D}} = \frac{1}{D}\left(1 - \frac{\tilde{\ell}^2}{\bar{D}}\right) \quad \Rightarrow \quad \text{3 generic non-vanishing integrals}$$

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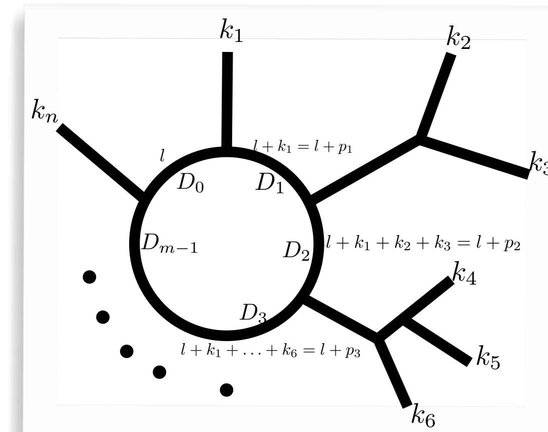

$$\int \mathrm{d}^d\ell \frac{N(\ell,\tilde{\ell})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}} \quad \text{with } \bar{\ell} = \ell + \tilde{\ell}$$

D-dim 4-dim (-2ε)-dim

[Ossola, Papadopoulos & Pittau (NPB'07)]
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✦ R_2 terms originate from numerators

✤ Process-dependent contributions proportional to $\tilde{\ell}^2$

✤ Renormalisable theory: finite number of R_2's → *R_2 Feynman rules*

Subtraction of the IR divergences

✦ Subtracting the poles

✤ The structure of the poles is known ➢ subtraction methods

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

★ $\mathcal{C}$ 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)

FKS subtraction

✦ Example: 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

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★ $\mathcal{S}_{ij} \to 0$ for all other infrared limits

✦ Regulators: events and counter-events

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

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

$$d\sigma^{(n+1)}_{ij} = \left[\frac{1}{\xi_i}\right]_c \left[\frac{1}{1-y_{ij}}\right]_\delta \Sigma_{ij}(\xi_i, y_{ij}) d\xi_i \, dy_{ij}$$

$$= \int_0^{\xi_{\max}} d\xi_i \int_{-1}^{+1} dy_{ij} \frac{1}{\xi_i(1-y_{ij})} \Big[\underbrace{\Sigma_{ij}(\xi_i, y_{ij})}_{\text{Event}} \underbrace{- \Sigma_{ij}(\xi_i, 1)\Theta(y_{ij} - 1 + \delta)}_{\text{Counter-event}}$$

$$\boxed{- \Sigma_{ij}(0, y_{ij})\Theta(\xi_{\text{cut}} - \xi_i) + \Sigma_{ij}(0,1)\Theta(y_{ij} - 1 + \delta)\Theta(\xi_{\text{cut}} - \xi_i)} \Big]$$

Matching with parton showers

✦ Parton shower

- ✤ 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 various fixed-order instabilities (unweighting, peak-dip structures, *etc.*)

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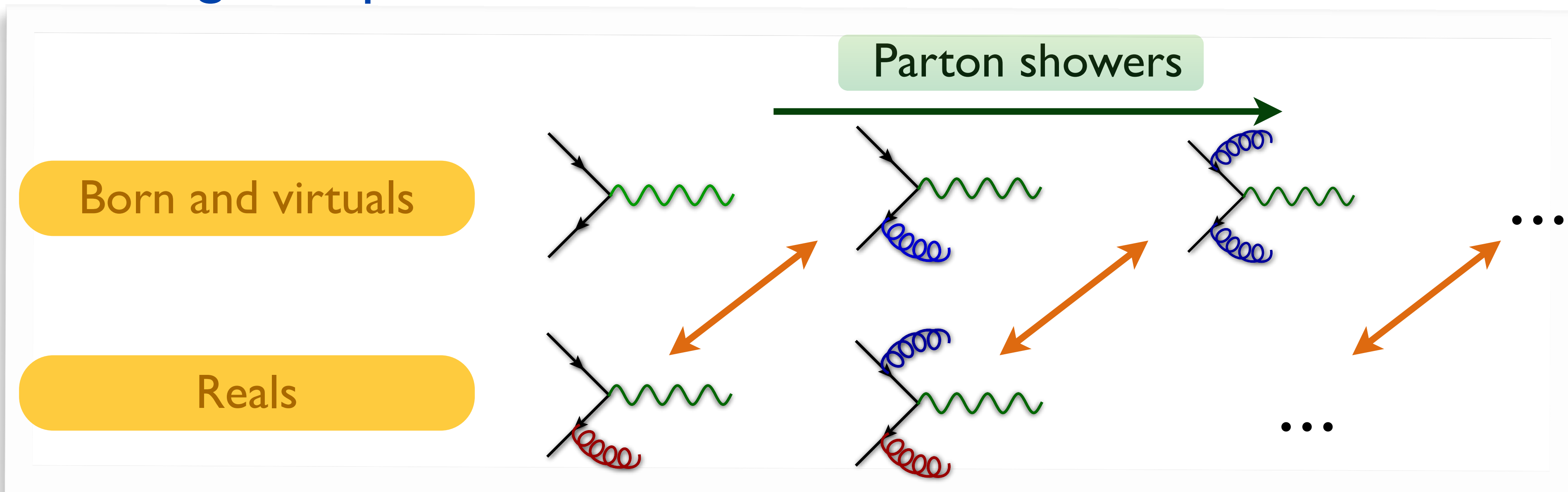


- ✤ Two sources of double counting
  - ★ Radiation: reals *vs.* shower
  - ★ No radiation: virtuals *vs.* no-emission probability

aMC@NLO simulations

[Frixione, Webber (JHEP'02); Alwall, Frederix, Frixione, Hirschi, Mattelaer, Shao, Stelzer, Torrielli & Zaro (JHEP'14)]

✦ Inclusion of Monte Carlo counterterms

✤ Simultaneous usage of FKS and MC counterterms

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

S-events H-events

✤ Definition: MC counterterms match the reals in the IR

★ Same kinematics: no need for reshuffling (as for fixed order) → 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: $\mathcal{MC} \approx 0, \quad \mathcal{I}_{\rm MC}^{(n)} \approx 0, \quad \mathcal{I}_{\rm MC}^{(n+1)} \approx 1$ ↝ hard-radiation-dominated

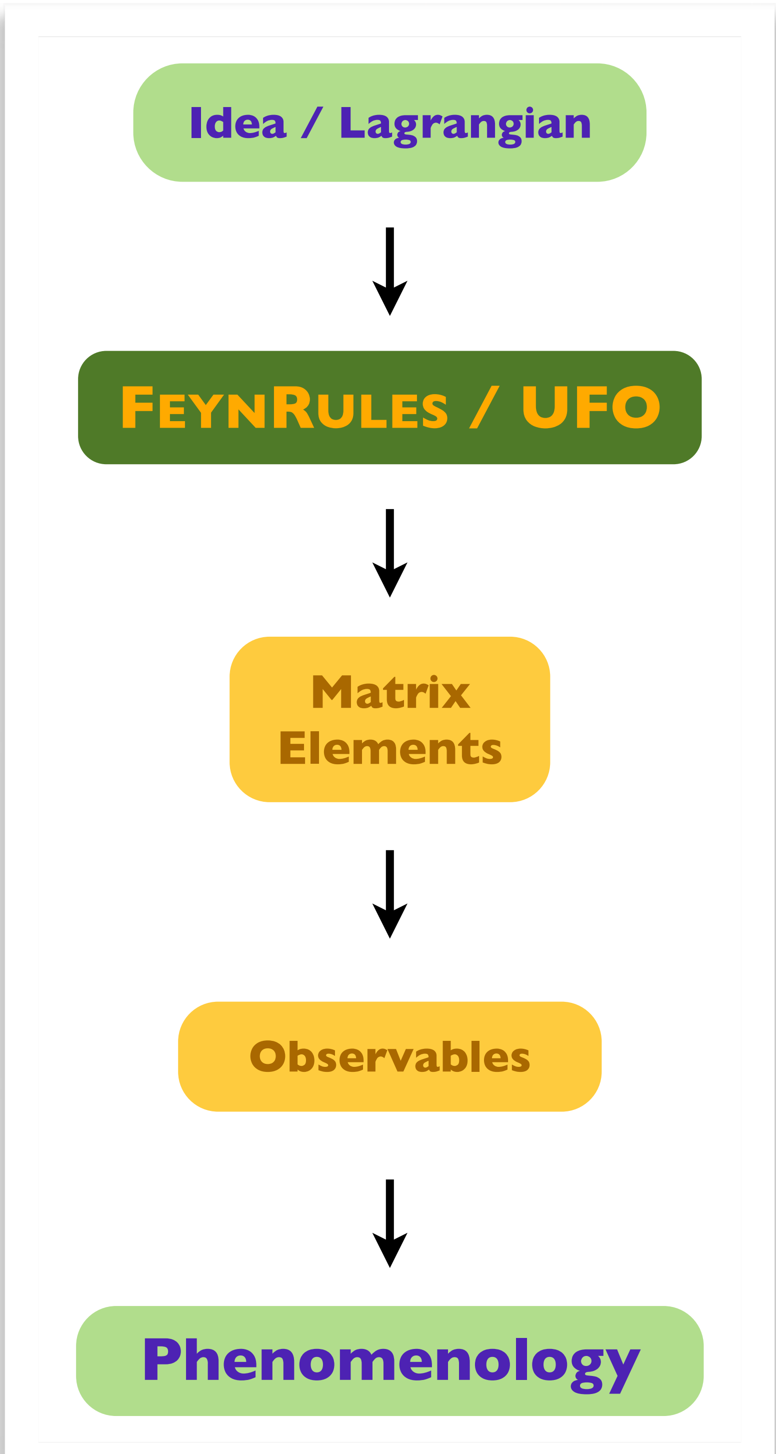
✤ The MC counterterms are shower-dependent

✤ Separate generation of the S-events and H-events

↝ Negative weights

A comprehensive approach to new physics simulations

[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 (JHEP`19)]

✦ Hard scattering

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

[Alwall et al. (JHEP'14)]

✦ BSM phenomenology @ colliders with MG5_aMC

- ✤ Matching matrix elements with parton showers

[Alwall et al. (JHEP'14)]

Precision simulations at colliders: is it needed?

- Collider simulations at the NLO-QCD easily achieved
  - All previous results include NLO-QCD corrections
  - Are those relevant for DM @ colliders?
  - Example: tt+MET at the LHC for g_X=g_t=4

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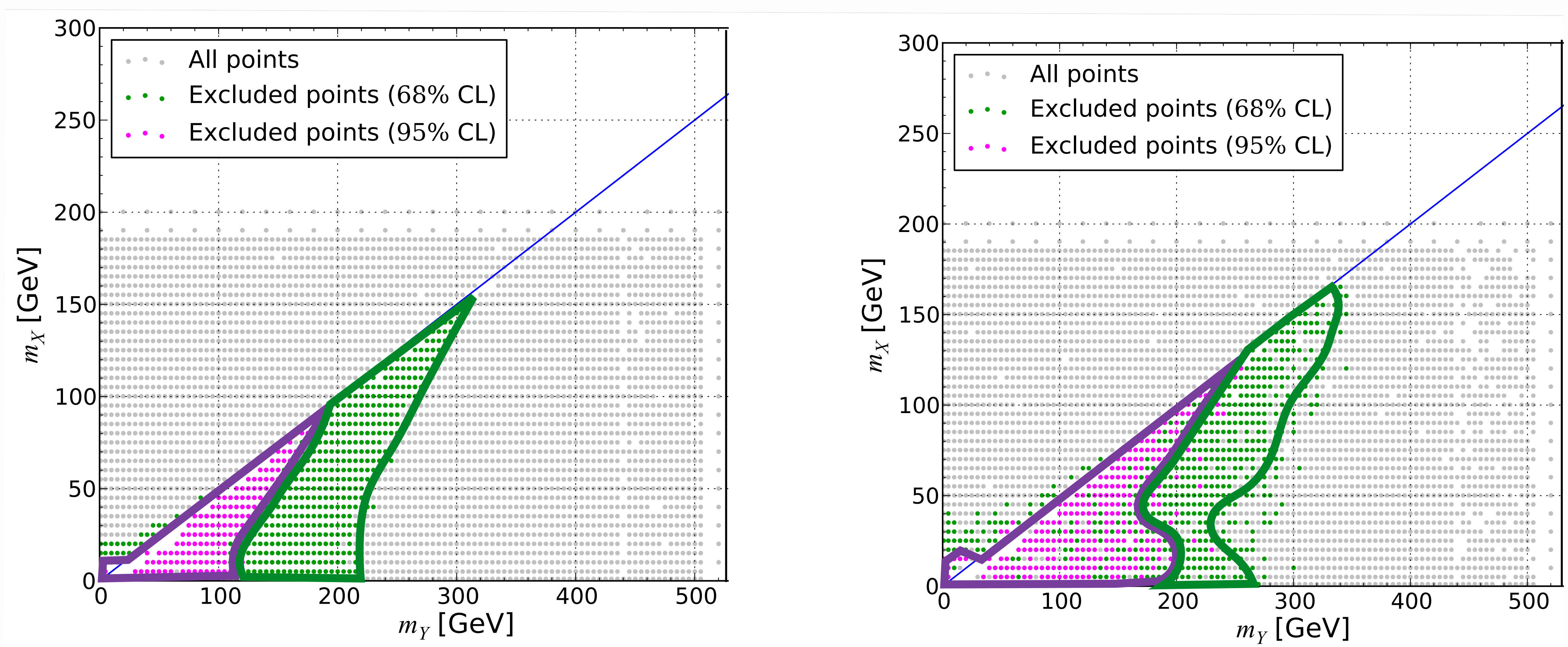


[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

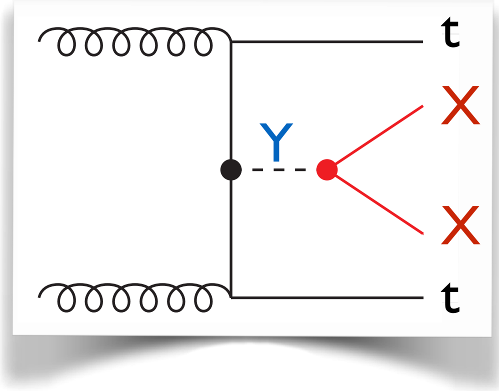
- Non-triangular shape of the exclusion: mediator width effects
- Mild *K*-factors (~ 1.10) & mild impact on the kinematic → mild NLO effect…

NLO effects on an exclusion

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



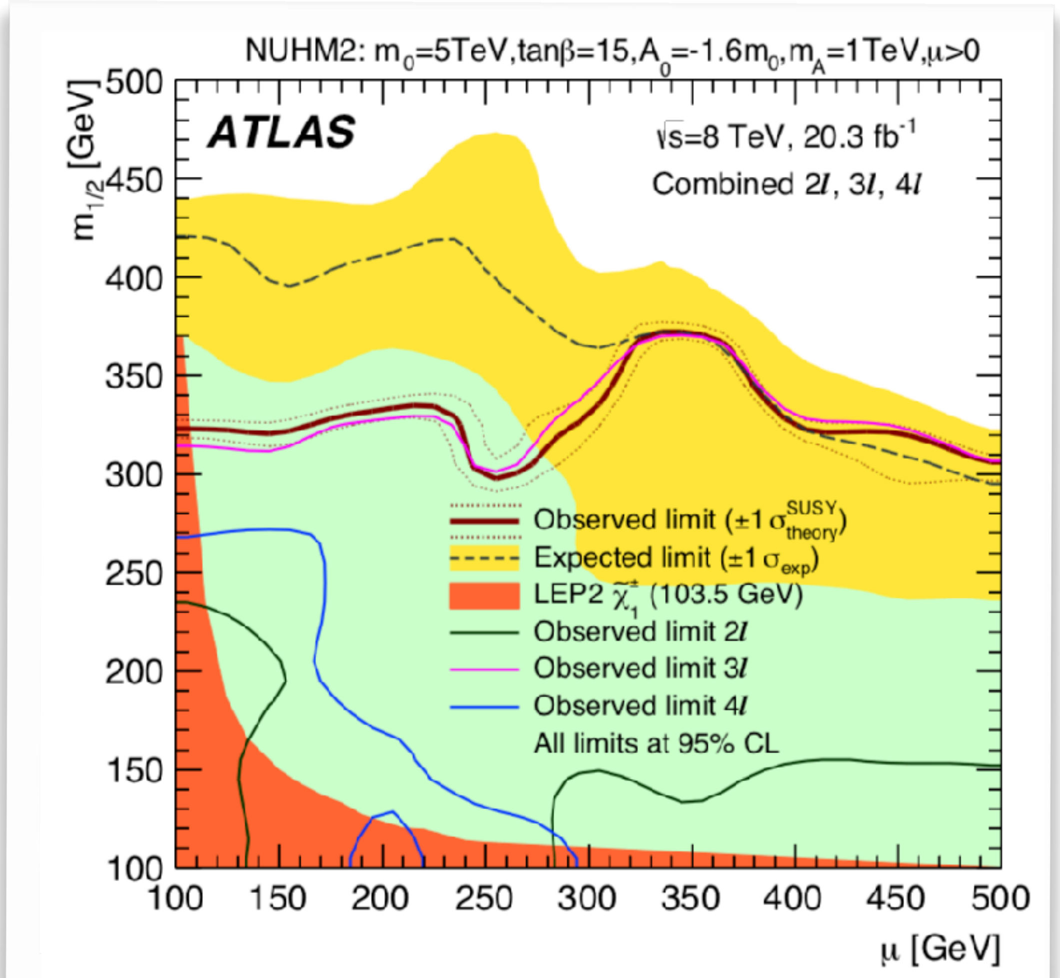
- ✤ At NLO, uncertainties are reduced significantly here
  - ★ An excluded point may not be excluded when accounting for uncertainties
- ✤ The CLs number can increase / decrease at NLO
  - ★ Impact of the kinematic and the rate
- ✤ The error band around the CLs is reduced

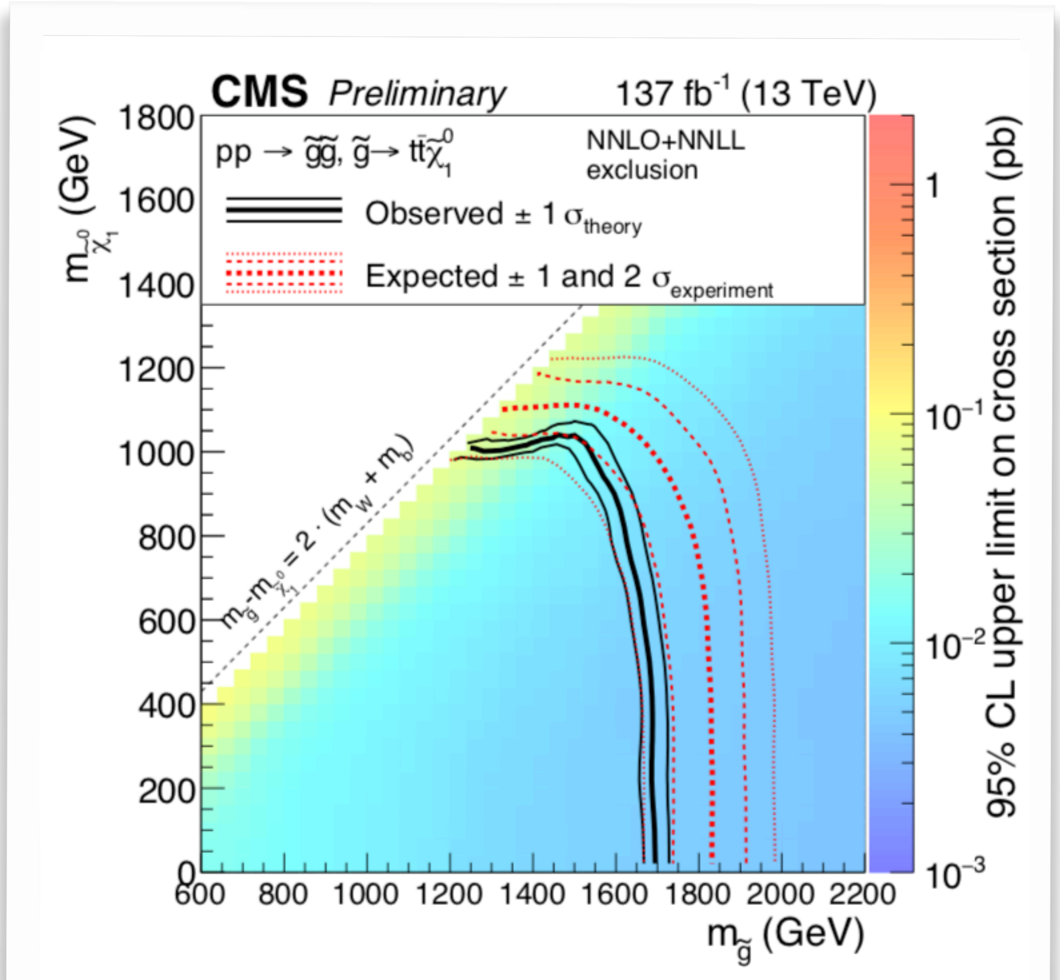
Interlude 2

LHC recasting in a nutshell

New physics results at the LHC

- ✦ LHC ≡ discovery machine
  - ✤ Many ATLAS and CMS searches for new physics
  - ✤ Interpretation within popular frameworks and simplified models (SMS)





- ✦ Need for reinterpretations in all kinds of models

Simplified Model Spectra (SMS)

✦ The SMS-based reinterpretation framework

- ✤ Decomposition of all signatures of a theory into SMS signatures
- ✤ Fiducial cross sections are calculated on the basis of public efficiency maps
- ✤ Comparisons to published upper bounds are made

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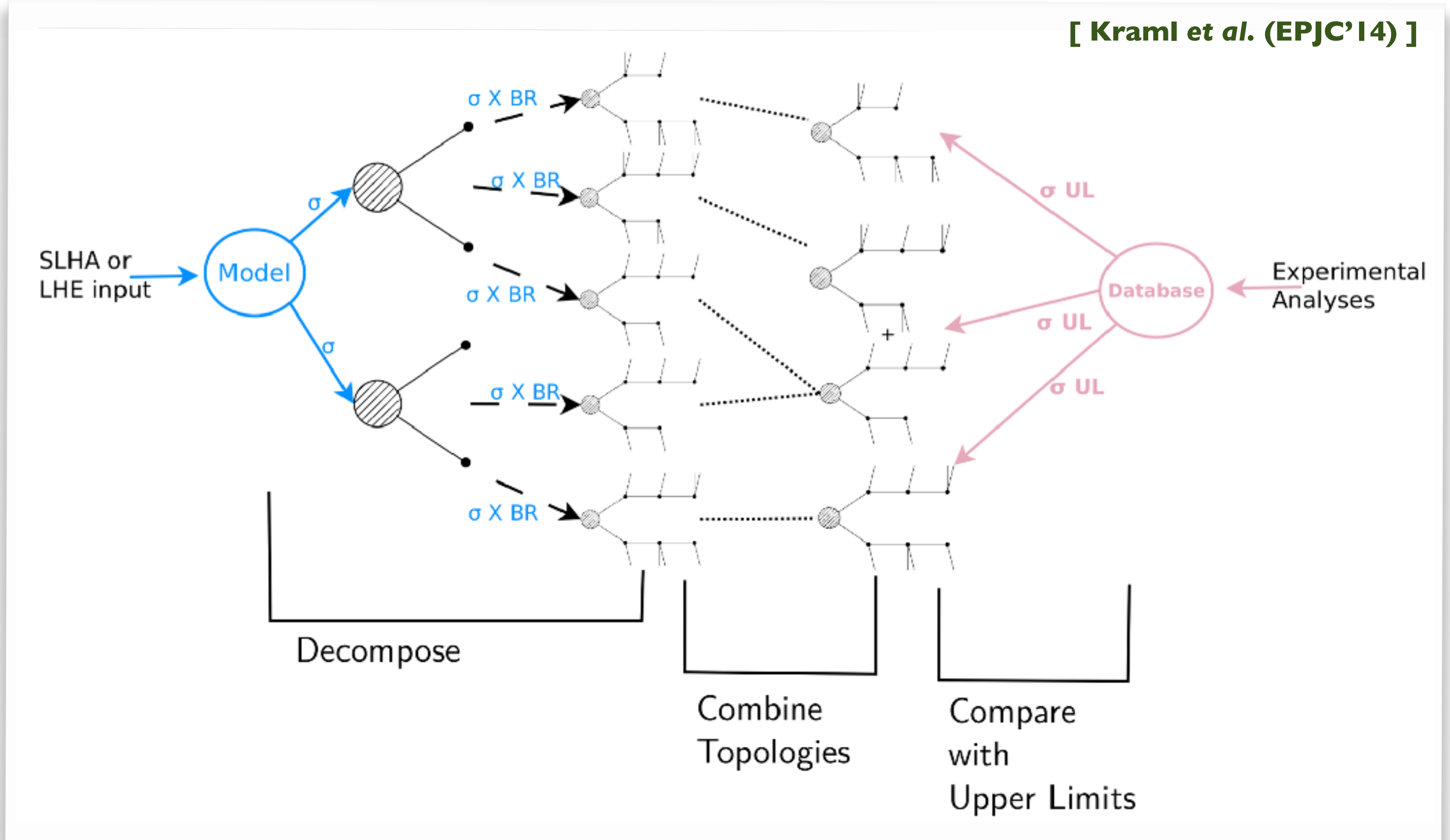
✦ Main features



- ✤ Extremely fast
- ✤ Often conservative
  - ★ Different kinematics
  - ★ Asymmetric decays

Beyond the SMS approach

- Plethora of new physics realisations deserving to be studied
  - Experimentalists cannot study all options
  - SMS often not sufficient
    - → Detector simulator mimicking ATLAS and CMS
    - → Framework for LHC analysis re-implementations

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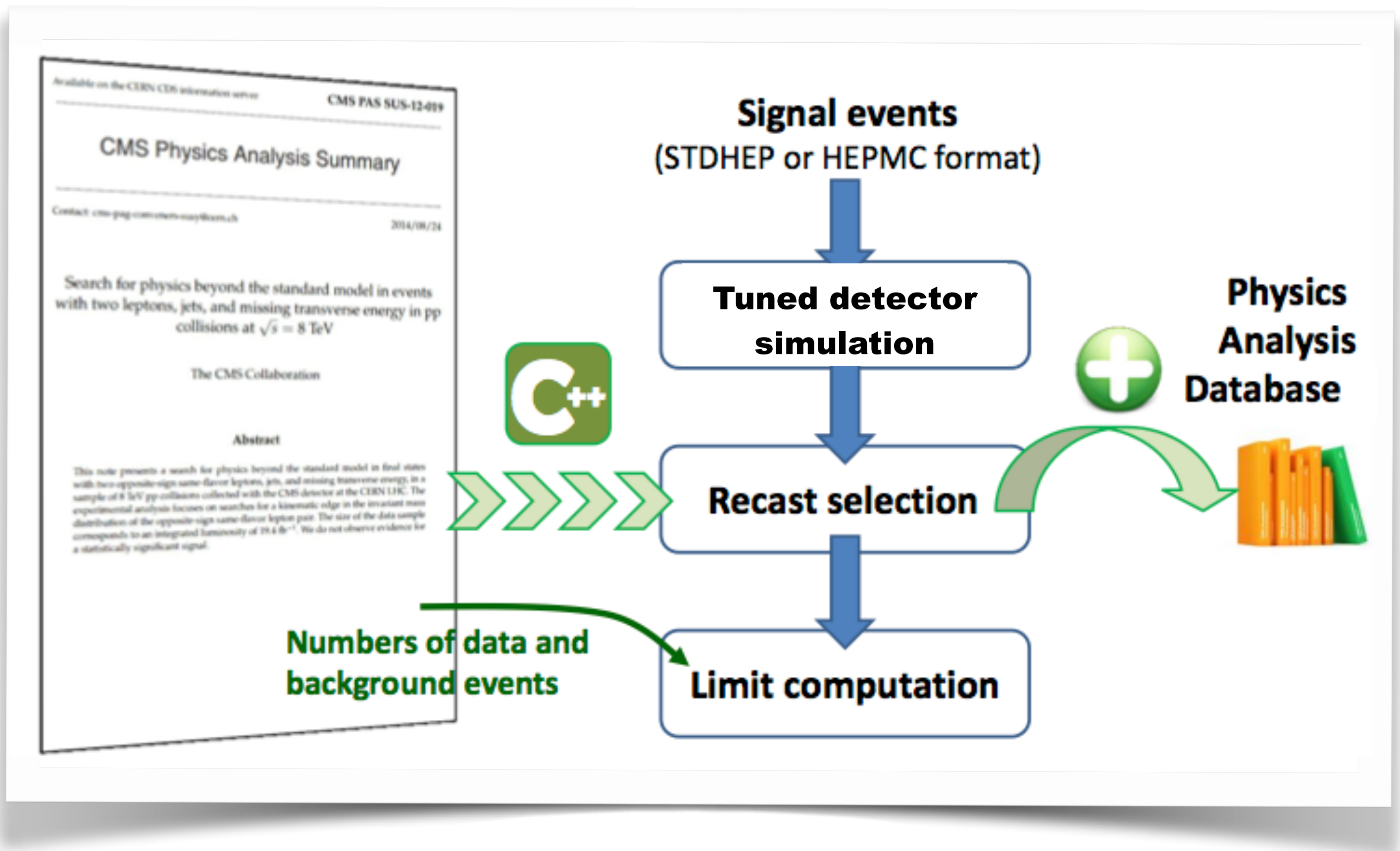
- ✦ Another recasting strategy



- ✤ 3 options for detector effects
  - ★ DELPHES 3
    - ↝ from particles to tracks/hits
    - ↝ resolutions, efficiencies, ...
  - ★ Transfer functions
    - ↝ From the MC particles
    - ↝ resolutions, efficiencies, ...
  - ★ Unfolding
    - ↝ No need for a detector

Public tools to recast new physics searches

✦ Generic SMS-recast program: SMODELS
- ✤ O(100) available run 1 and 2 analyses ~ largest library today
- ✤ Includes prompt and long-lived decays

[Kraml *et al.* (EPJC'14; LHEP'20)]

✦ Detector simulation based on (customised) DELPHES 3
- ✤ CHECKMATE 2 [Derks et al. (CPC`17)]
  - ★O(50) run 1 and 2 analyses, including some LLP searches
- ✤ MADANALYSIS 5 [Dumont, BF, Kraml et al. (EPJC`15); Conte & BF (IJMPA`19)]
  - ★O(50) run 1 and 2 analyses, including 1 LLP search

✦Transfer functions for the detector simulation
- ✤ COLLIDERBIT [Balász et al. (EPJC`17)]
  - ★O(40) run 1 and 2 analyses
- ✤ MADANALYSIS 5 - SFS [Araz, BF & Polykratis (EPJC`21)]
  - ★3 run 2 analyses
- ✤ RIVET [Buckley et al. (2010); Bierlich et al. (SciPost`20)]
  - ★O(30) run 1 and 2 analyses

Validation of the CMS B2G-14-004 search

✦ Search for dark matter in the top-antitop + MET channel

- ✤ Implementation in MADANALYSIS 5
- ✤ Validation: comparison of cut-flows and differential distributions
  - ★ MADANALYSIS 5 predictions *vs* CMS results

[BF & Martini (MA5 Dataverse `16)]

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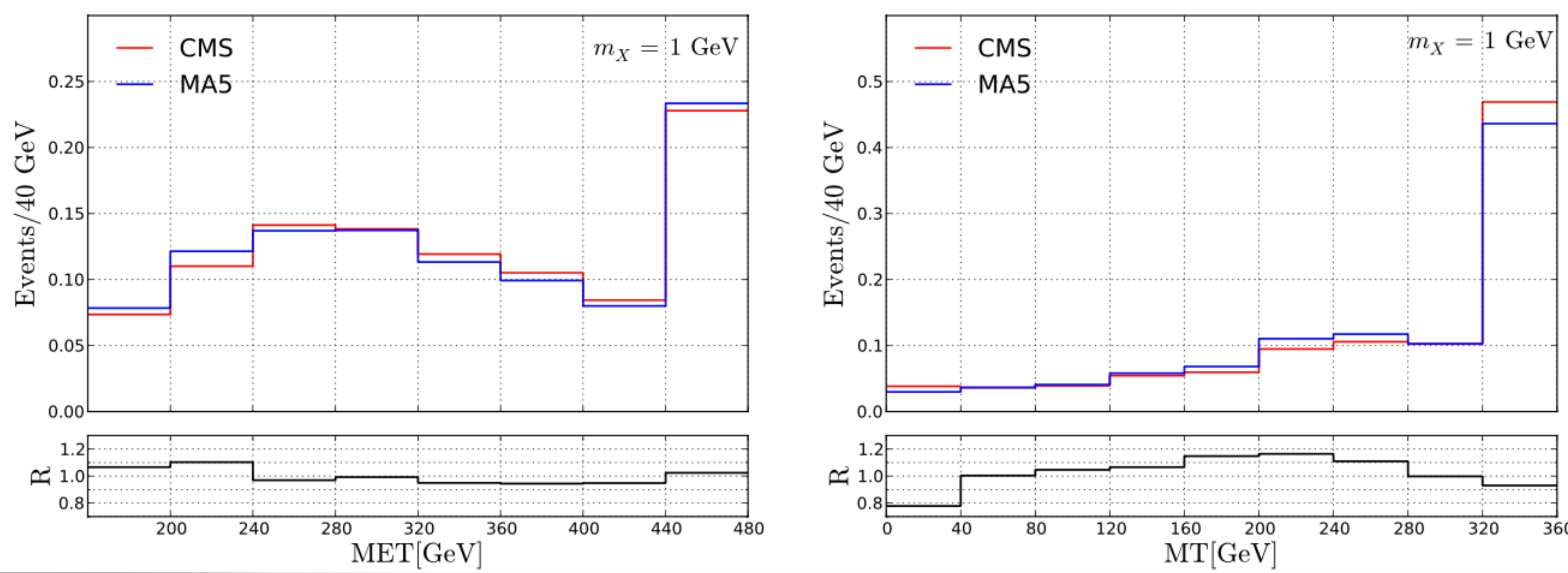
[BF & Martini (MA5 Dataverse `16)]

✦ Constraining ttXX contact interactions (m_X = 1 GeV)

	Selection step	CMS	$\epsilon_i^{\rm CMS}$	MA5	$\epsilon_i^{\rm MA5}$	$\delta_i^{\rm rel}$
0	Nominal	224510		224510		
1	Preselection			15468.5	0.069	
2	$\not{E}_T > 320$ GeV	4220.8		4579.8	0.296	
3	$M_T > 160$ GeV	3390.1	0.803	3648.2	0.797	0.75%
4	$\Delta\Phi(j_{1,2}, \not{E}_T) > 1.2$	2963.5	0.874	3124.3	0.856	2.06%
5	$M_{T2}^W > 200$ GeV	2267.6	0.765	2403	0.769	-0.52%

Agreement @ 2-3 %

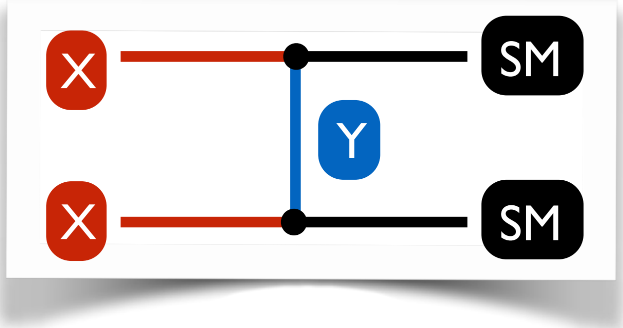


Back to DM simplified models

The *t*-channel case

t-channel models at colliders

- Very different from s-channel models
  - The mediator couples to one DM and one SM particle
    - Y decay into one invisible (→ MET) and one visible state
  - Relevant for the LHC: couplings to (light) quarks



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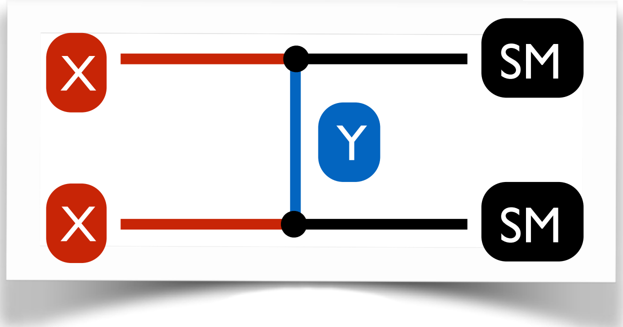
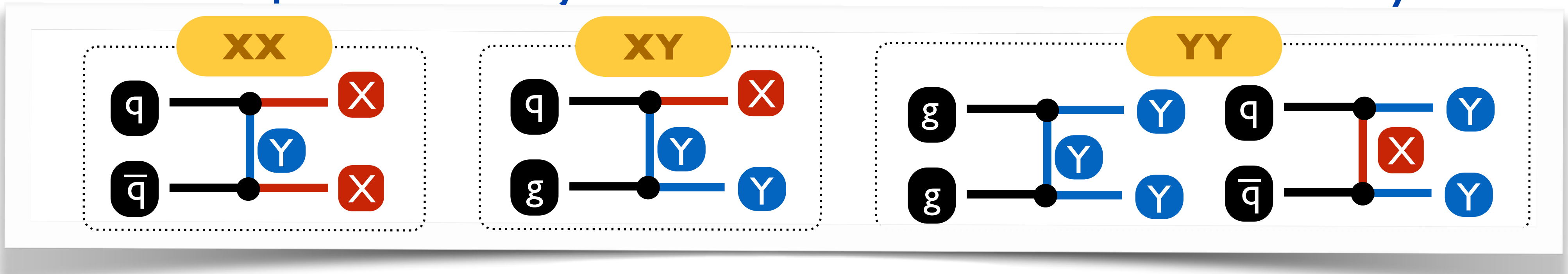


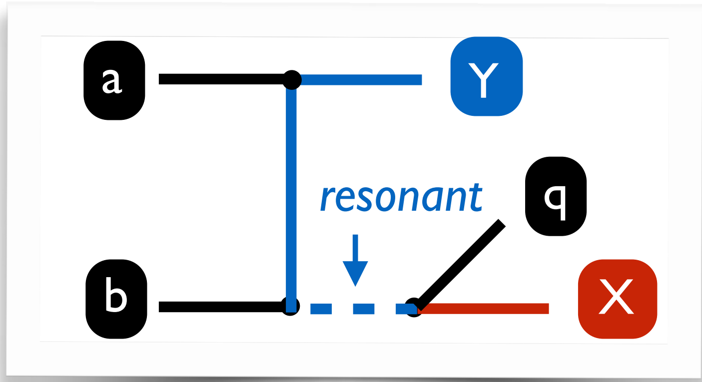
- 3 classes of processes ↝ jets from radiation or mediator decays



  - Signal less naive than considering XX production only
    - ★ DM pair production
    - ★ DM/mediator associated production (with mediator decays into DM+jet)
    - ★ Mediator pair production (with mediator decays into DM+jet)
  - Mediator pair-production: *t*-channel and QCD contributions
    - ★ Model-dependent relative dominance → couplings, masses
    - ★ Mixed order situation → to be simulated separately (at NLO)
    - ★ Interference issue → re-weighted LO simulations

Resonance subtraction: generalities

✦ NLO computations are not trivial



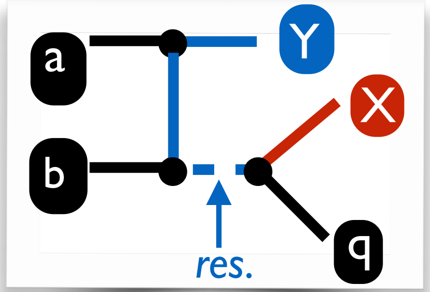
- ✤ Overlap
  - ★ YY @ LO ⊗ Y → Xq decay
  - ★ YX @ NLO (real emission)
- ✤ Possible (huge) enhancement w.r.t. LO (if YY dominates over XY)
  - ★ Spoiling the perturbative expansion for the original process
- ✤ All three subprocesses need to be considered separately to avoid double counting
  - ★ Resonances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

Resonance treatment in practice

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

✦ Matrix element: resonant and non-resonant pieces

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

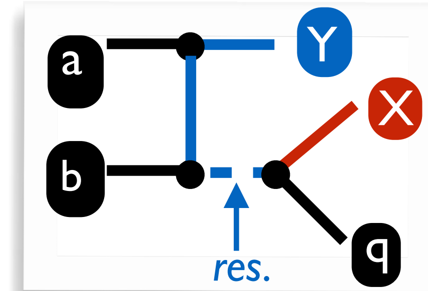


Resonance treatment in practice

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

✦ Matrix element: resonant and non-resonant pieces

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



✦ Diagram removal

- ✤ Removal of the resonant diagrams
- ✤ Interferences can be kept (or not)

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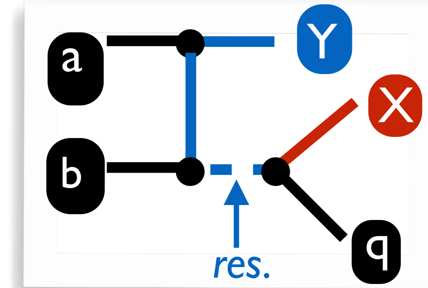

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✦ Projection of the kinematics on the resonance

$$\left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi \quad \Rightarrow \quad \left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi - f(m^2)\ \mathbb{P}\left(\left|\mathcal{A}^{(\text{res.})}\right|^2 \mathrm{d}\Phi\right)$$

t-channel example: $m = m_{Xq} \sim m_Y$

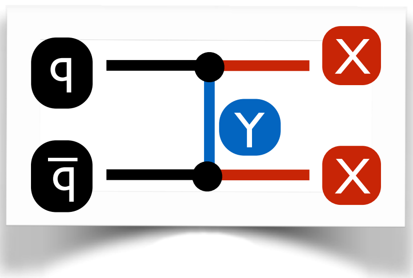
- ✤ The projector operator $\mathbb{P}$
  - ★ From an *n*-body kinematics to an (*n*-1) ⊗ (1→2) kinematics

$$\left|\mathcal{A}^{(\text{res.})}(ab \to XYq)\right|^2 = \left|\mathcal{A}(ab \to YY)\right|^2 \otimes \left|\mathcal{A}(Y \to Xq)\right|^2$$

- ✤ The pre-factor *f* is arbitrary (tends to 1 in the resonant limit)

A fivefold signal event generation procedure

XX @ NLO



★ Jet activity ↝ QCD radiation

★ Resonance: XY prod. + decay

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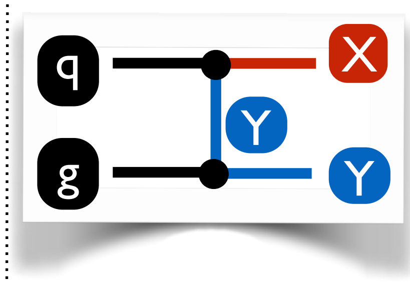
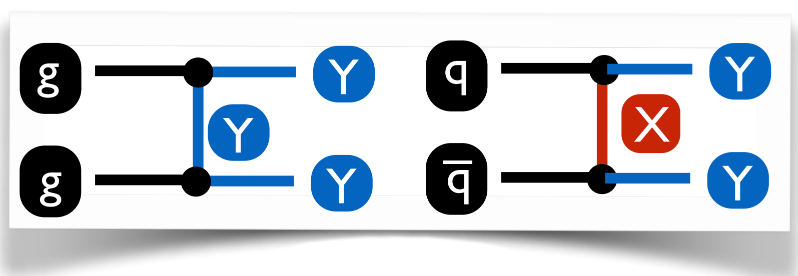


★ Jet activity ↝ QCD radiation
↝ mediator decay

★ Resonances: YY/XX prod. + decay (benchmark dependent)

YY @ NLO



★ Jet activity ↝ QCD radiation and mediator decay

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★ 2 interfering channels (from qqbar initial states)

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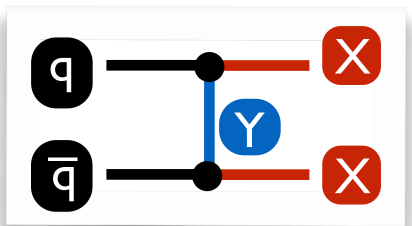

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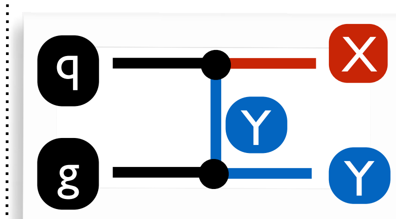

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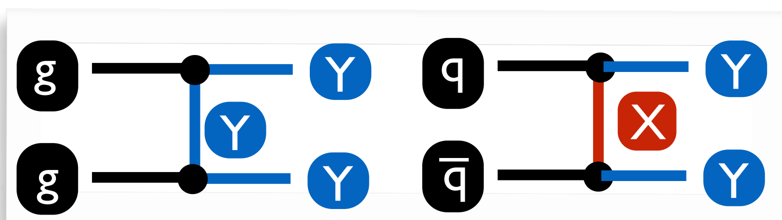

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Is all of this needed (NLO, *etc.*)?

Recasting ATLAS mono-jet search (36/fb)

✦ CLs exclusion from the best region (1 TeV mediator; 150 GeV DM)

Process	CL_s [LO]	$E_T^{\rm miss}$ constraint	CL_s [NLO]	$E_T^{\rm miss}$ constrtaint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
XX	$0.7^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV	$3.6^{+0.3}_{-0.6}$ %	≥ 900 GeV
XY	$62.7^{+12.3}_{-10.4}$ %	$\in [500, 600]$ GeV	$83.9^{+2.9}_{-4.3}$ %	$\in [700, 800]$ GeV
YY [total]	$24.0^{+3.1}_{-3.1}$ %	≥ 900 GeV	$58.1^{+2.2}_{-3.1}$ %	≥ 900 GeV
YY [QCD]	$10.7^{+4.4}_{-2.6}$ %	≥ 900 GeV	$17.0^{+2.1}_{-2.1}$ %	≥ 900 GeV
YY [t-channel]	$29.6^{+3.3}_{-2.6}$ %	≥ 900 GeV	$38.9^{+1.2}_{-1.8}$ %	≥ 900 GeV

[Arina, BF & Mantani (EPJC`20)]

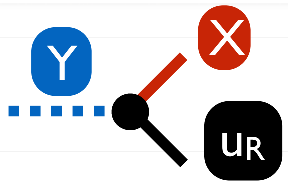
- ✤ NLO simulations are crucial
  - ★ Modification of the rates (larger yields) and shapes (different best region)
  - ★ Better control of the theory errors
- ✤ Considering all signal components is crucial
  - ★ One component alone is not sufficient to exclude the scenario

I[st] gen. mediator & Majorana DM

✦ Majorana DM coupling to the right-handed up quark

X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{\chi}$	1/2	yes	φ_{u_1}	0

$$\mathcal{L}_{\mathrm{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \mathrm{h.c.}\right]$$



✤ Fixed λ = 1 coupling

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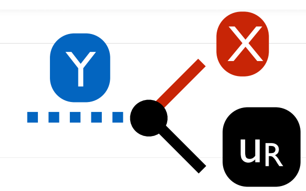

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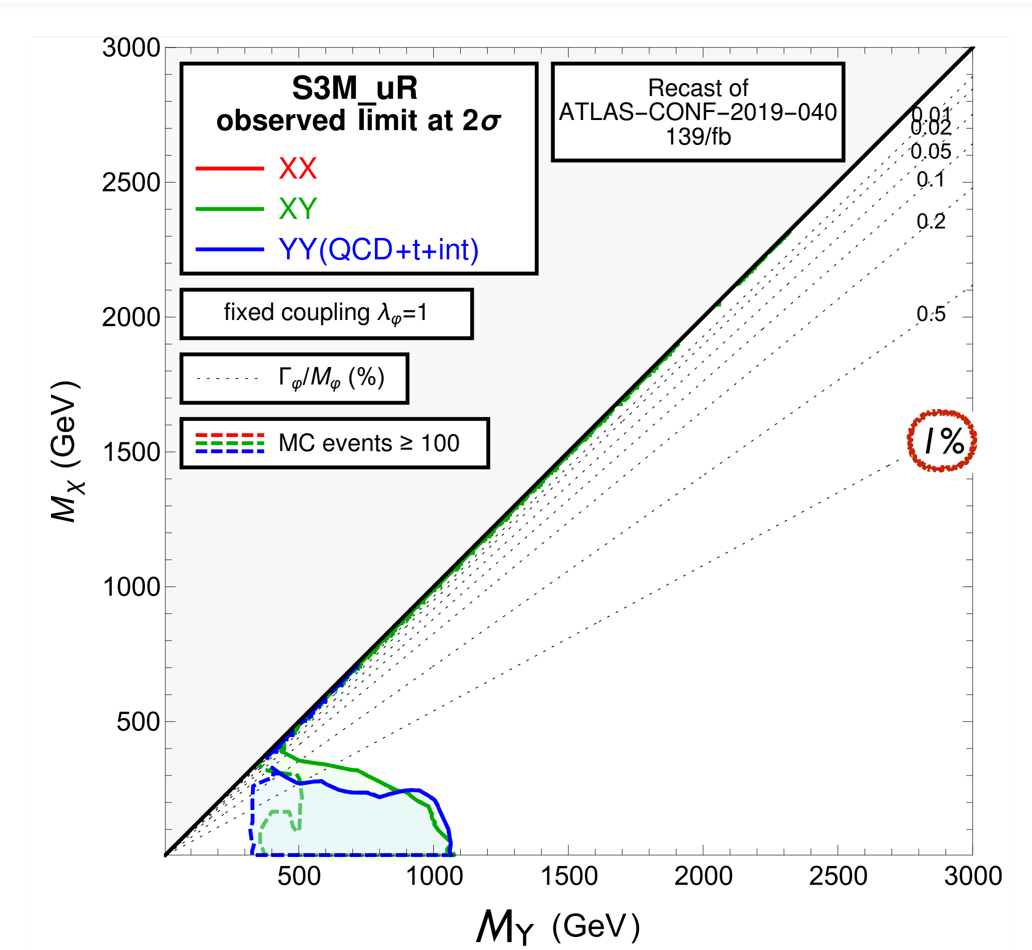


[Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20)]

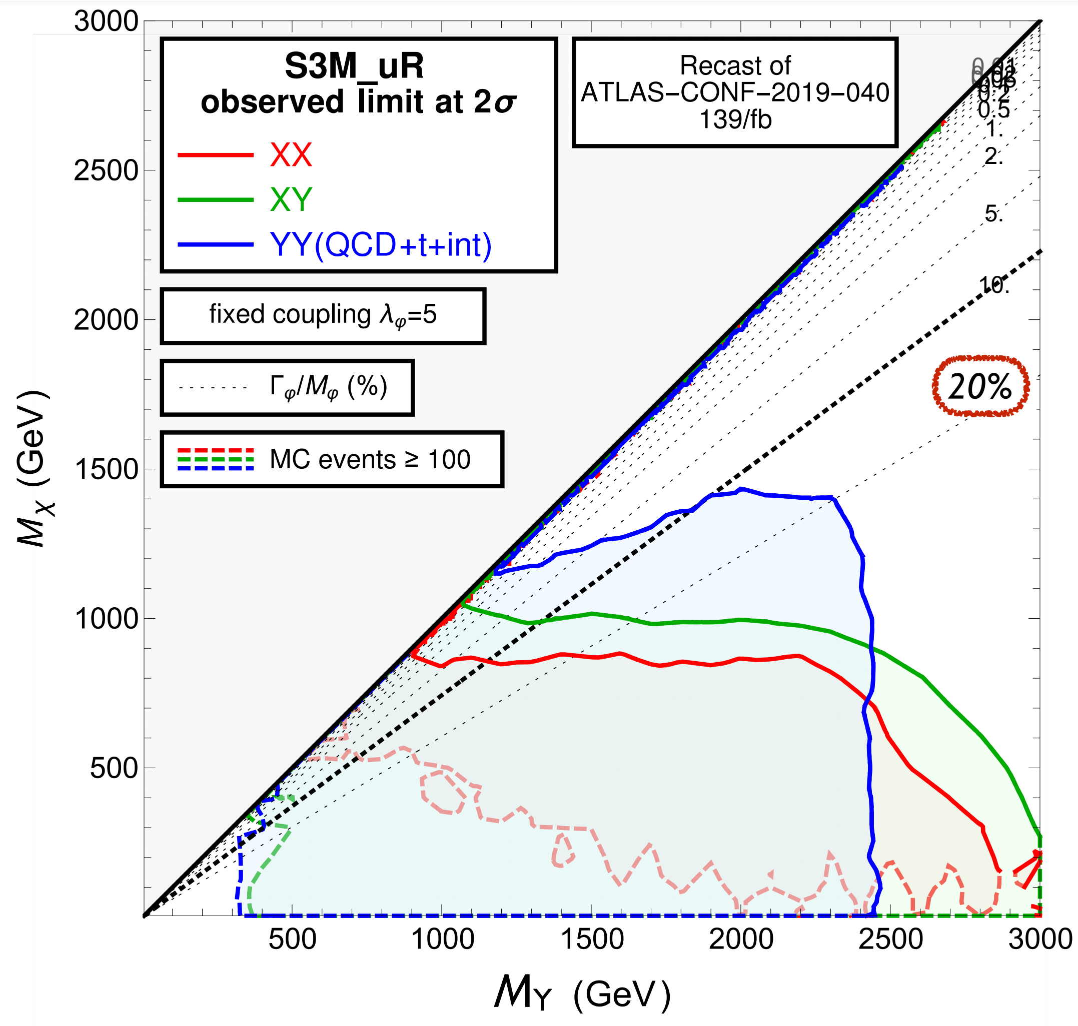
✦ Recast: ATLAS multi-jet + MET search

- ✤ 139/fb
- ✤ Mono-jet-like and multi-jet + MET regions

✦ Signal component complementarity

- ✤ DM production is irrelevant
- ✤ YY and XY production: comparable reach
  - ↝ M_Y below 1 TeV
  - ↝ M_X below few hundred GeV
  - ↝ Mild coverage of the parameter space
- ✤ The width of the mediator can play a role
  - ↝ especially for larger λ values

More strongly coupled dark matter



[Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20)]

- $\lambda = 5$
  - All channels contribute (larger rates)
    - ★ $XX \sim \lambda^4$
    - ★ $XY \sim \lambda^2$
    - ★ $YY \sim \lambda^4 + \lambda^2 + \lambda^0$

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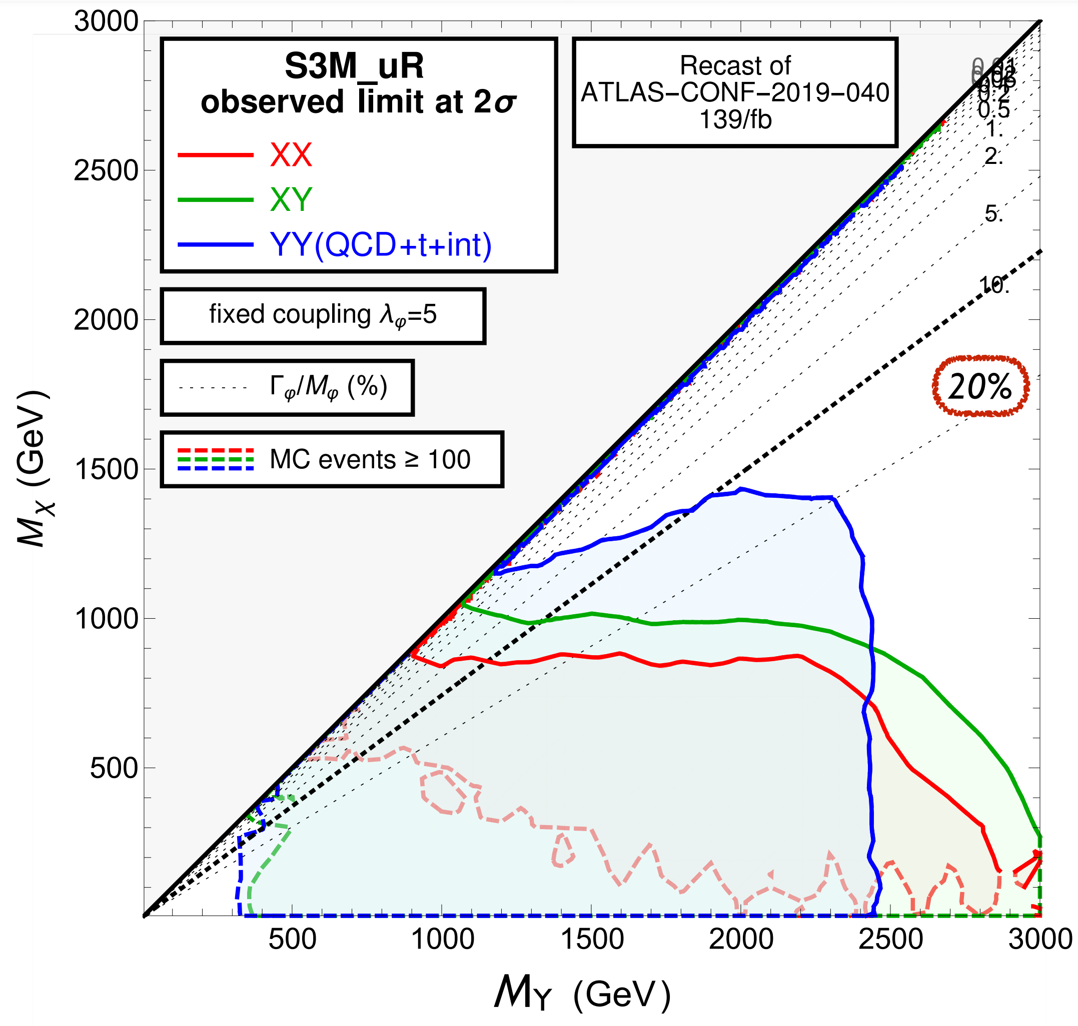

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  - ★ XX ~ λ^4
  - ★ XY ~ λ^2
  - ★ YY ~ $\lambda^4 + \lambda^2 + \lambda^0$
- Simulations unreliable
  - ★ The NWA breaks down
  - ★ Γ_Y/M_Y >10% or compressed spectrum
  - ★ Most 'excluded' points inconclusive
- Γ_Y plays a role for large λ values

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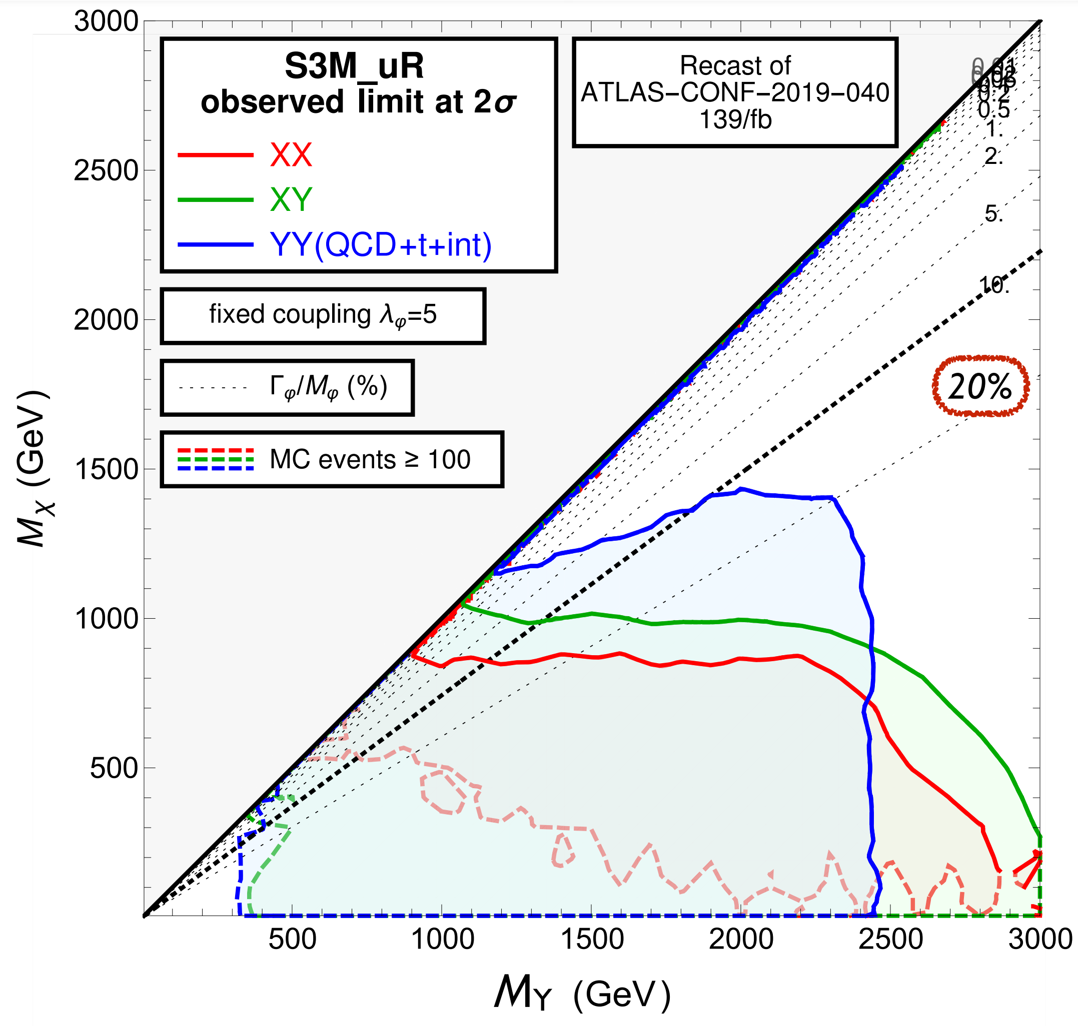

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    - ★ $\Gamma_Y/M_Y > 10\%$ or compressed spectrum
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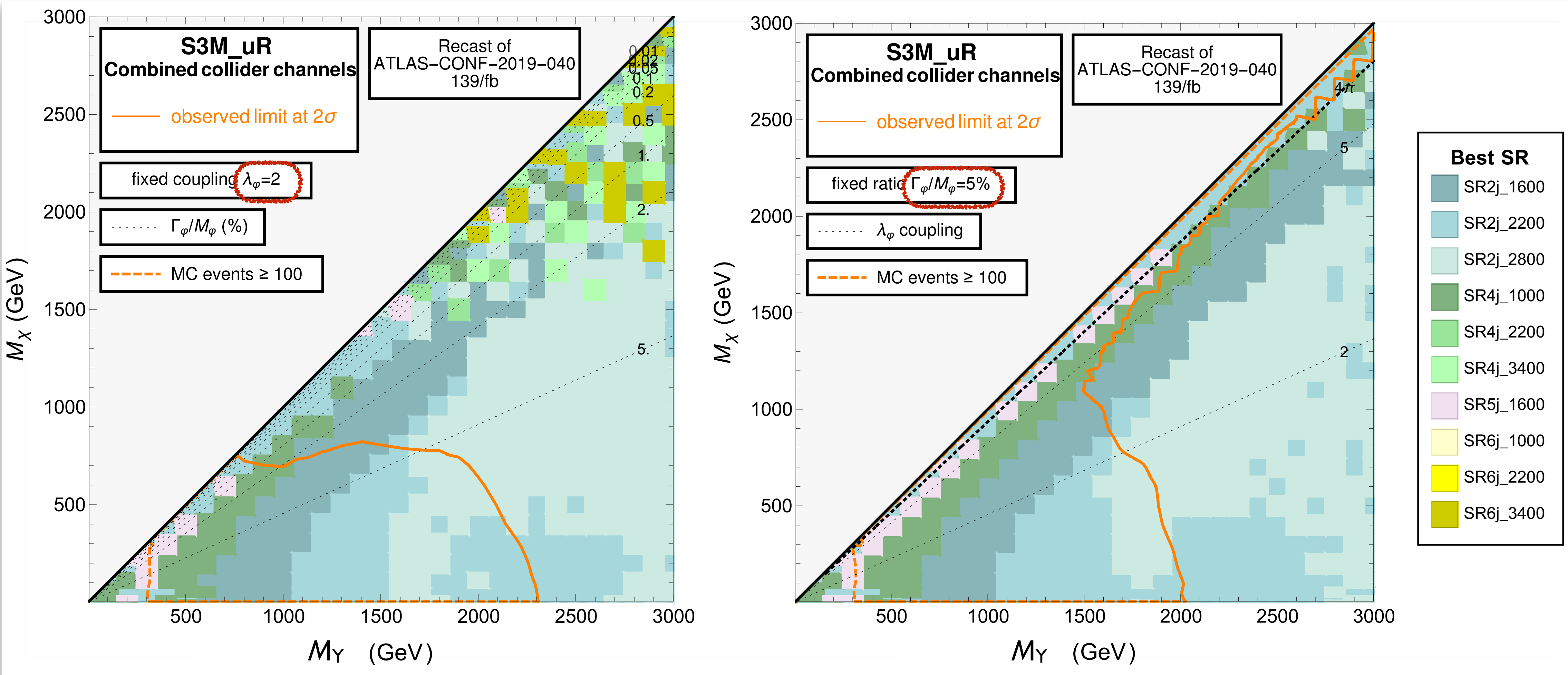
  - Γ_Y plays a role for large λ values
- Sensitivity to all channels
  - Different jet properties
    - → XX: small N_j, mostly soft jets
    - → XY: medium N_j, hard and softer jets
    - → YY: large N_j, hard jets
  - Dedicated regions for all cases

Fixed coupling *vs* fixed width

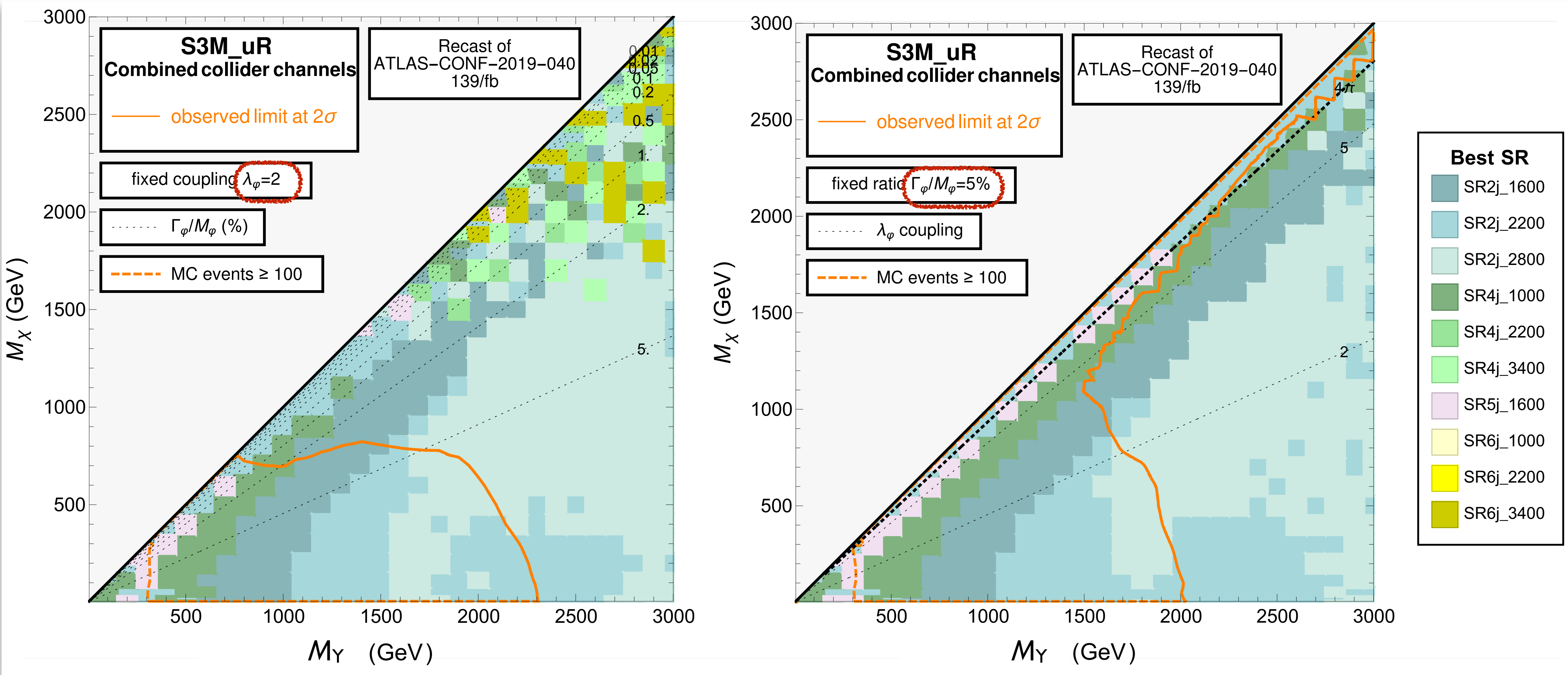
[Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20)]



- $\lambda = 2$ vs $\Gamma_Y/M_Y = 5\%$
  - Signal ≡ XX + XY + YY
  - Regions with 2 very hard jets (SR2j) ↝ YY production and decay
  - Regions with more not so hard jets (SR4j, SR5j, SR6j) ↝ compressed regime
  - Reliability of the simulations
    - ★ Fixed Γ_Y/M_Y: compressed spectrum ≡ non-perturbative regime
    - ★ Fixed λ: split spectrum ≡ broad mediator

Fixed coupling *vs* fixed width

[Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20)]



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✤ Reliability of the simulations

★ Fixed Γ_Y/M_Y: compressed spectrum ≡ non-perturbativ

★ Fixed λ: split spectrum ≡ broad mediator

Care to be taken with baroque setups

Beyond simplified models

Benchmark models

- ✦ More complex than simplified models
  - ✤ A large set of models exist → focus on few benchmarks (e.g. supersymmetry)
  - ✤ Dedicated searches for those specific benchmarks
    - ★ Simplified models encapsulate characteristics of varied theories

- ✦ 3 (subjective) examples
  - ✤ The Higgs portal model (very few parameters a one new state)
  - ✤ Dilaton-induced DM (very few parameters and two new states)
  - ✤ Supersymmetry (lots of parameters and new states)
- ✦ There are many more: dark photons, axions, *etc.* (not covered here)

1. The Higgs portal

[Arcadi, Djouadi & Raidal (PhysRept`19)]

✦ The Higgs boson connects DM to the SM

- ✤ DM interacts with the Higgs boson via effective couplings
- ✤ The Higgs can decay into a pair of DM particles
  - ★ For instance, Majorana DM:

$$\mathcal{L}_\chi = i\bar{\chi}\partial\!\!\!/\chi - \frac{m_\chi}{2}\bar{\chi}\chi - \frac{1}{4}\frac{C}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi$$

Economical (few states and params)
Simplest way to connect DM to the SM

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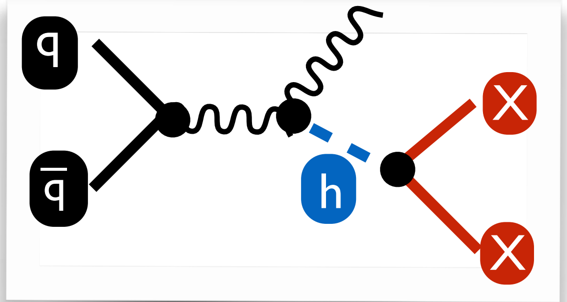
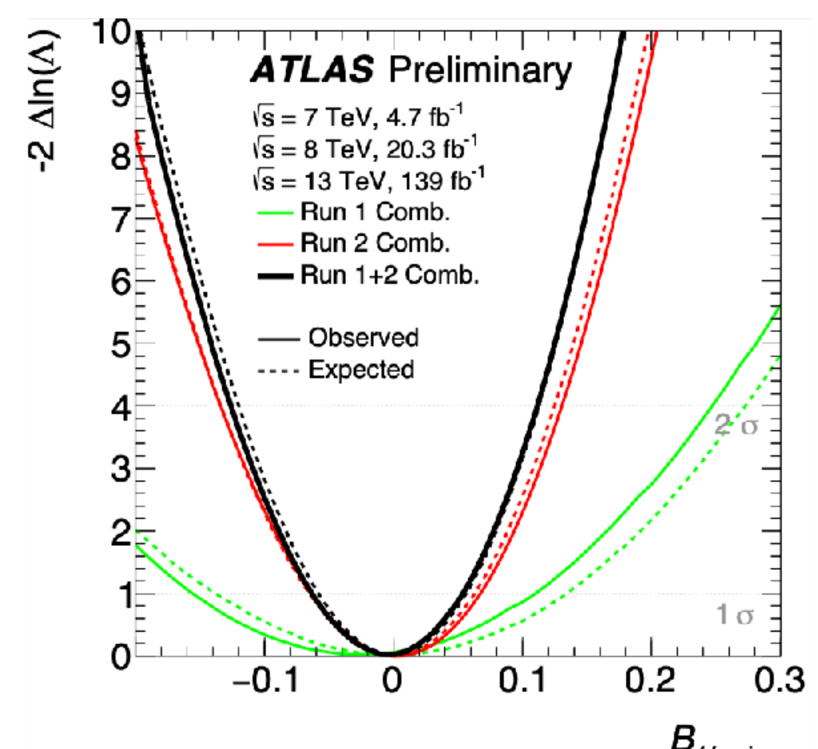
✦ LHC searches for invisible Higgs decays

- ✤ No sign of new physics
- ✤ All SM production modes considered (VBF, VH,…)
- ✤ BR(H→ inv) < 0.11 @ 95%CL
  - ★ Full run 2 dataset





[ATLAS-CONF-2020-052]

2. Dilaton induced DM

[Bai, Carena & Lykken (PRL`09)]

✦ A dilaton portal between the SM and dark sector

- ✤ Scale invariance is imposed → compensator field → dilaton
- ✤ Dilaton couplings proportional to the mass
  - ★ 3 parameters: the dilaton and DM masses, scale invariance breaking scale f
  - ★ Example: vector DM

$$\mathcal{L}_\sigma = \left(\frac{\sigma}{f} + \frac{\sigma^2}{2f^2}\right) m_V^2 X_\mu X^\mu$$

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Economical (few states and params)

✦ Mono-X searches apply

- Solid exclusions (hashed = HL-LHC)

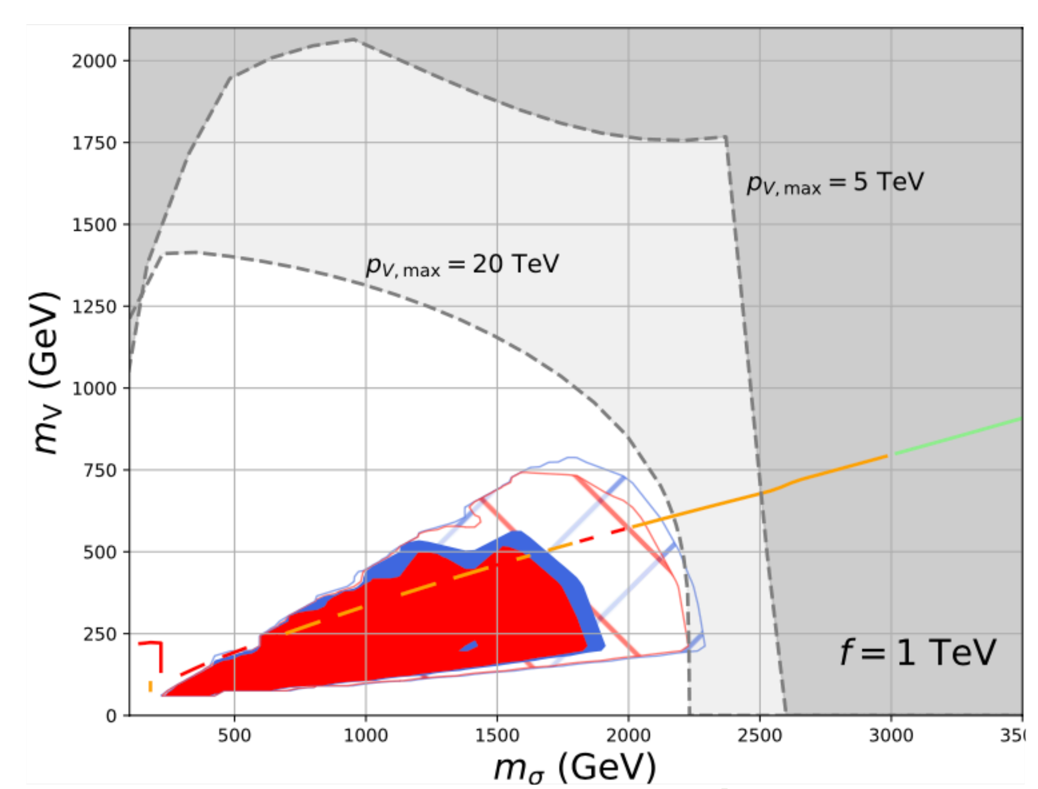
✦ Heavy Higgs searches & correct relic

- Orange line (excluded)
- Green line (allowed)

✦ The EFT must be valid

- Cutoff on the momentum transfers
- Grey exclusions

f=1 TeV is ruled out!

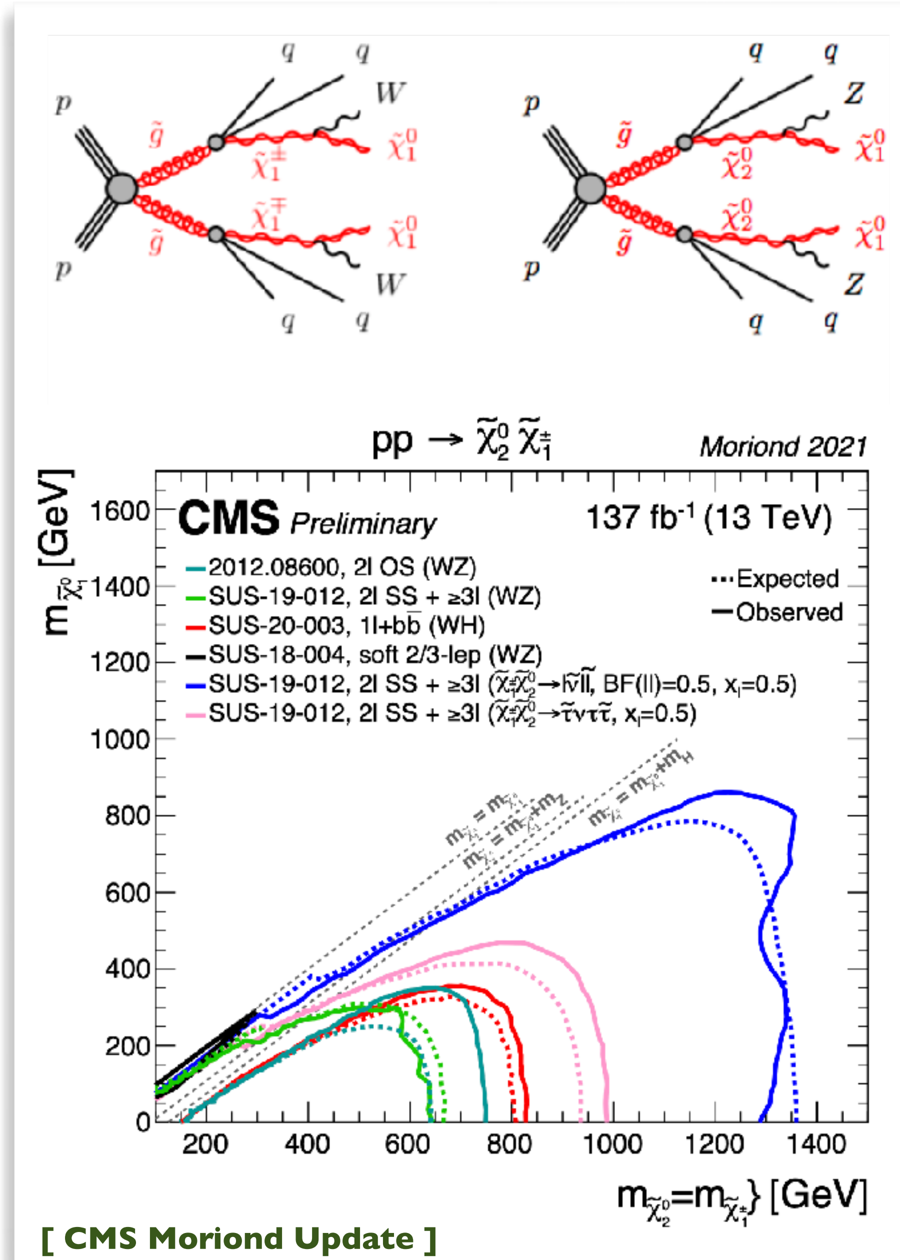


[BF, Goodsell, Kang, Ko, Lee, & Utsch (JHEP`20)]

3. Supersymmetry (I)

- Pair production of heavy states cascade-decaying into leptons, jets and MET
  - Inspiring many simplified model searches
  - Neutralino ≡ typical WIMP candidate
  - Strong limits exist
  - Holes in the SUSY space exist too

- Specific variables
  - Transverse variables (M_{T2}, …)
  - Hadronic quantities (H_T, $m_{\rm eff}$, …)
  - *etc.*



[CMS Moriond Update]

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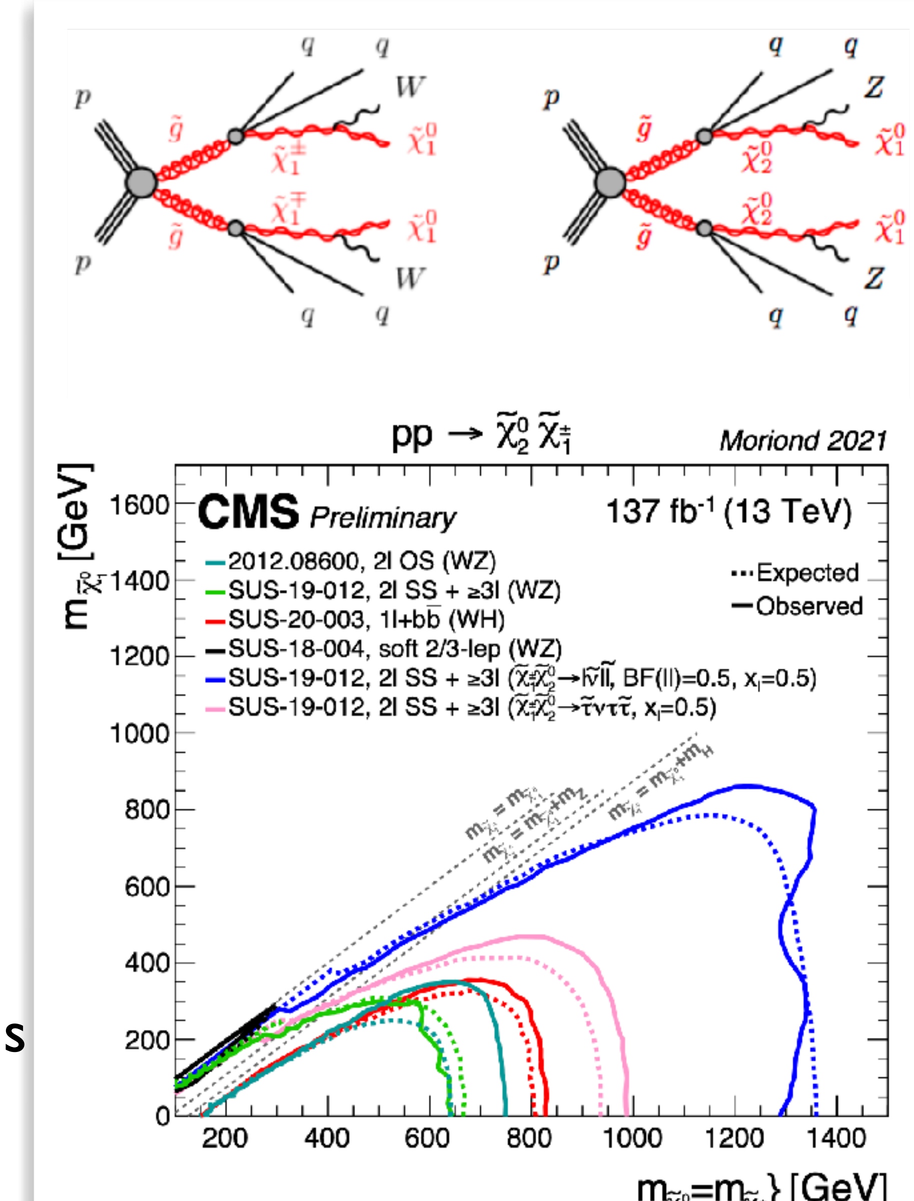

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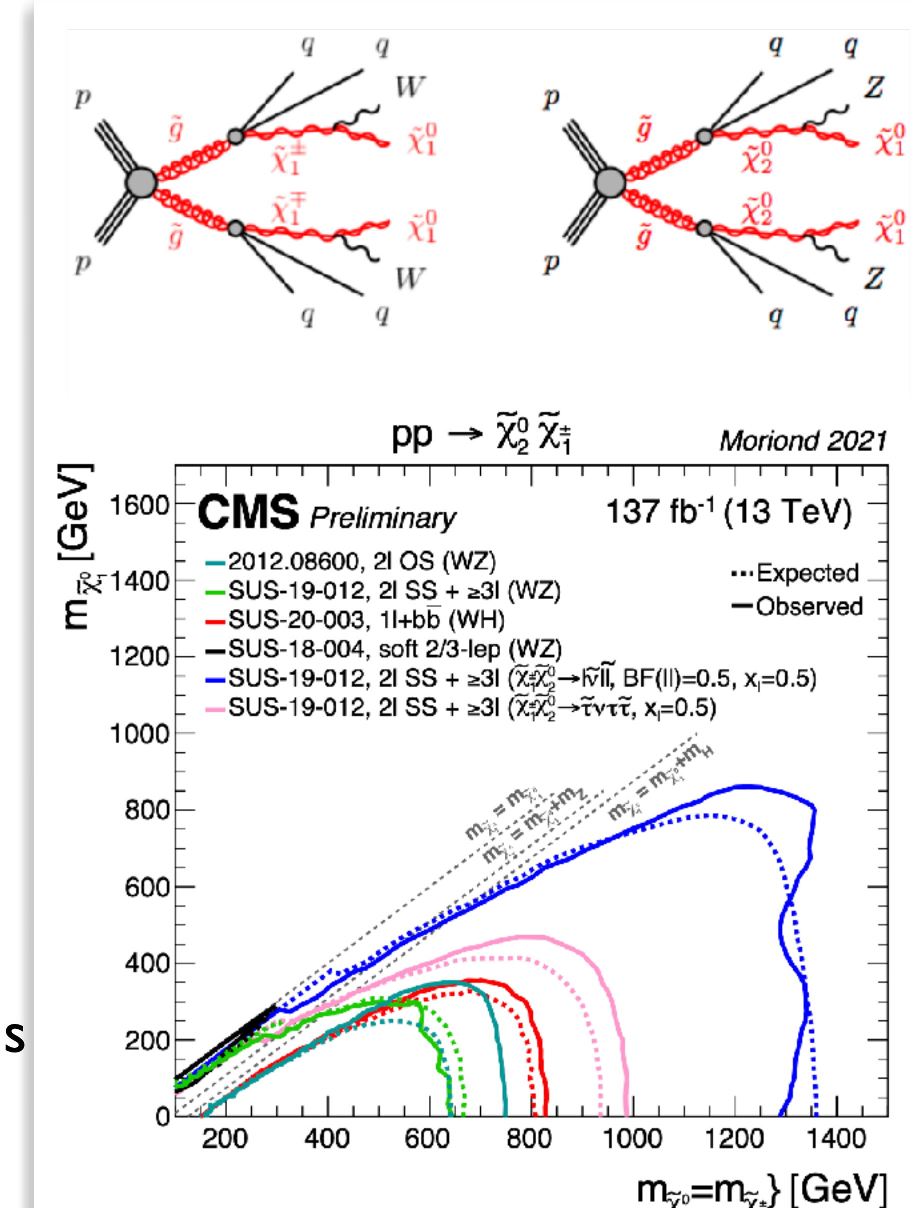
Is SUSY ruled out? NO…
But will it ever be? 😀



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3. Supersymmetry (2)

- Supersymmetry could be non-minimal
  - Left-right SUSY, SUSY VLQ, SUSY GUTs, sneutrino DM, *etc.*
- Non-minimal supersymmetry ≡ great playground to test new signals
  - Example: UMSSM (SUSY + Z')

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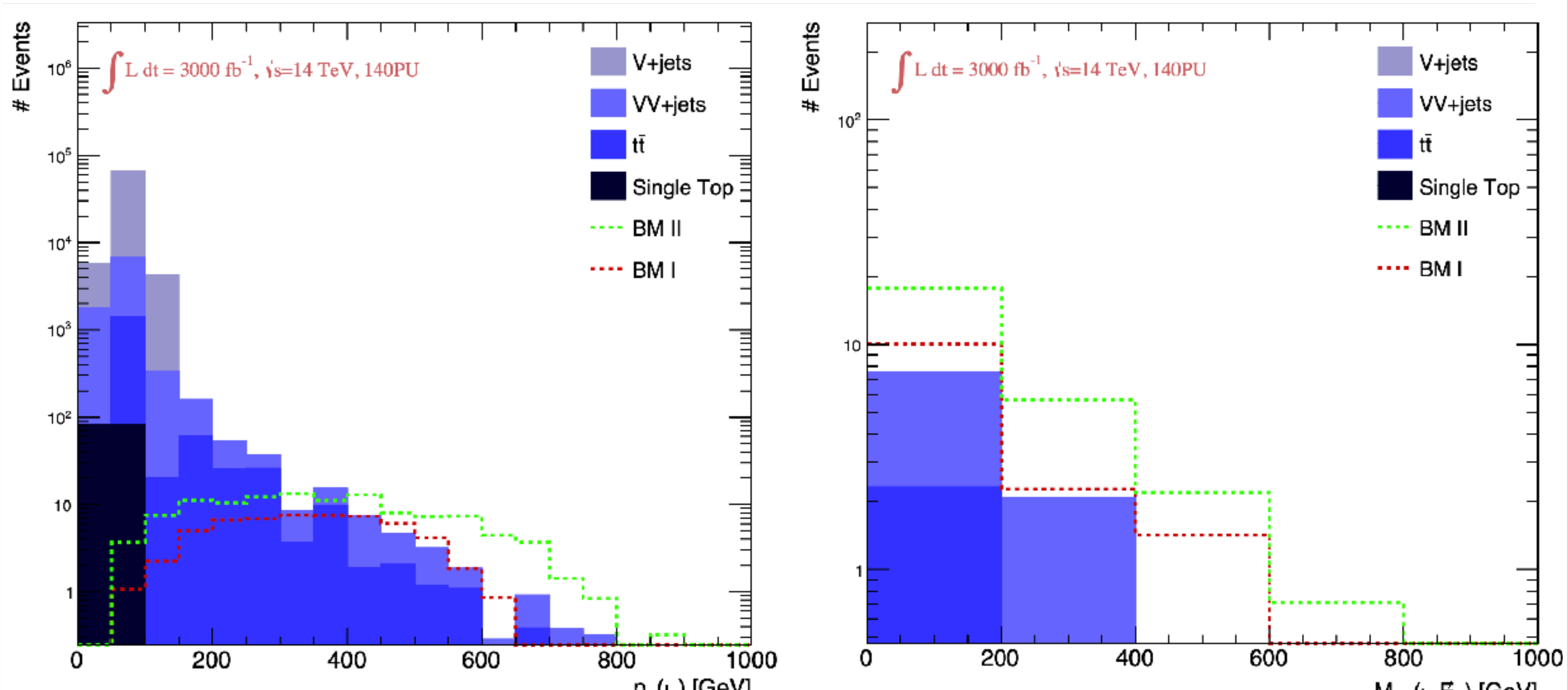
- Hard to miss signals



[Araz, Corcella, Frank & BF (JHEP 18)]

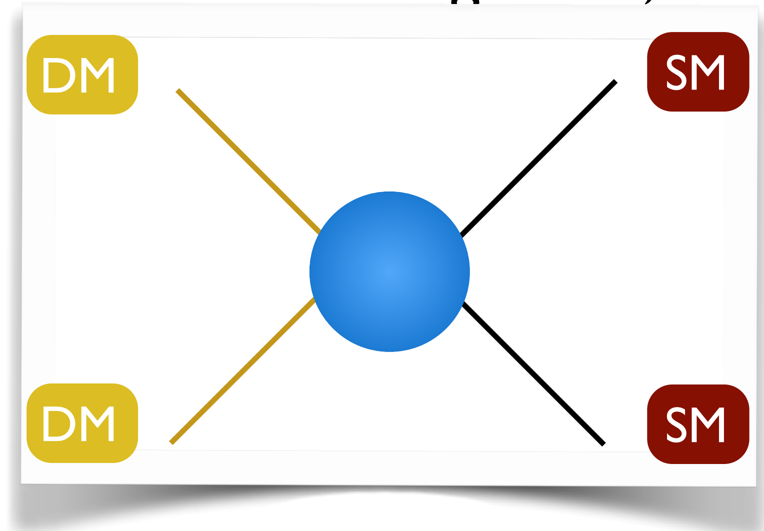
- Very hard probes
- Special variables
- Visible at HL-LHC

Outline

1. Collider simulations in a nutshell
2. Dark matter from a collider perspective
3. Interpretation of dark matter collider search results
4. **Summary**

New physics and dark matter

- ✦ Dark matter is an important motivation for new physics
  - ✤ Galaxy rotation curves, gravitational lensing, cosmic microwave background, …
- ✦ Searched for in a complementary way
  - ✤ Dark matter relic abundance must be reproduced
  - ✤ Dark matter direct/indirect detection constraints
  - ✤ Production at (hadron) colliders



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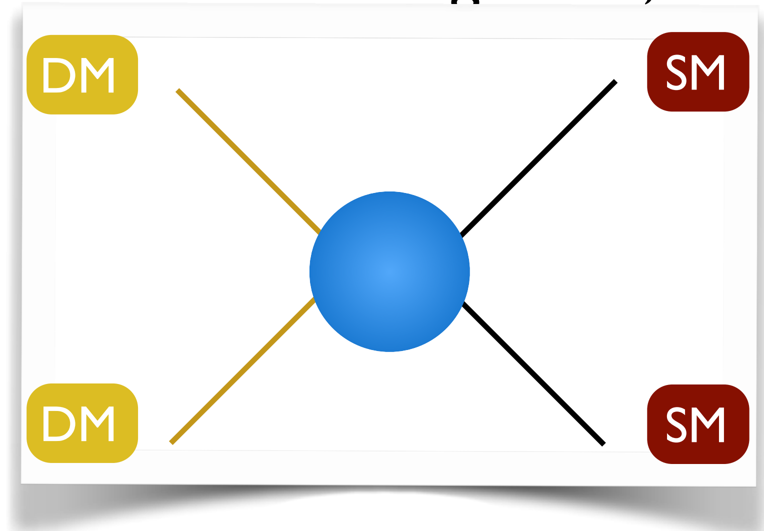

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A lot of fun is planned for the next decades