Dark matter @ LHC

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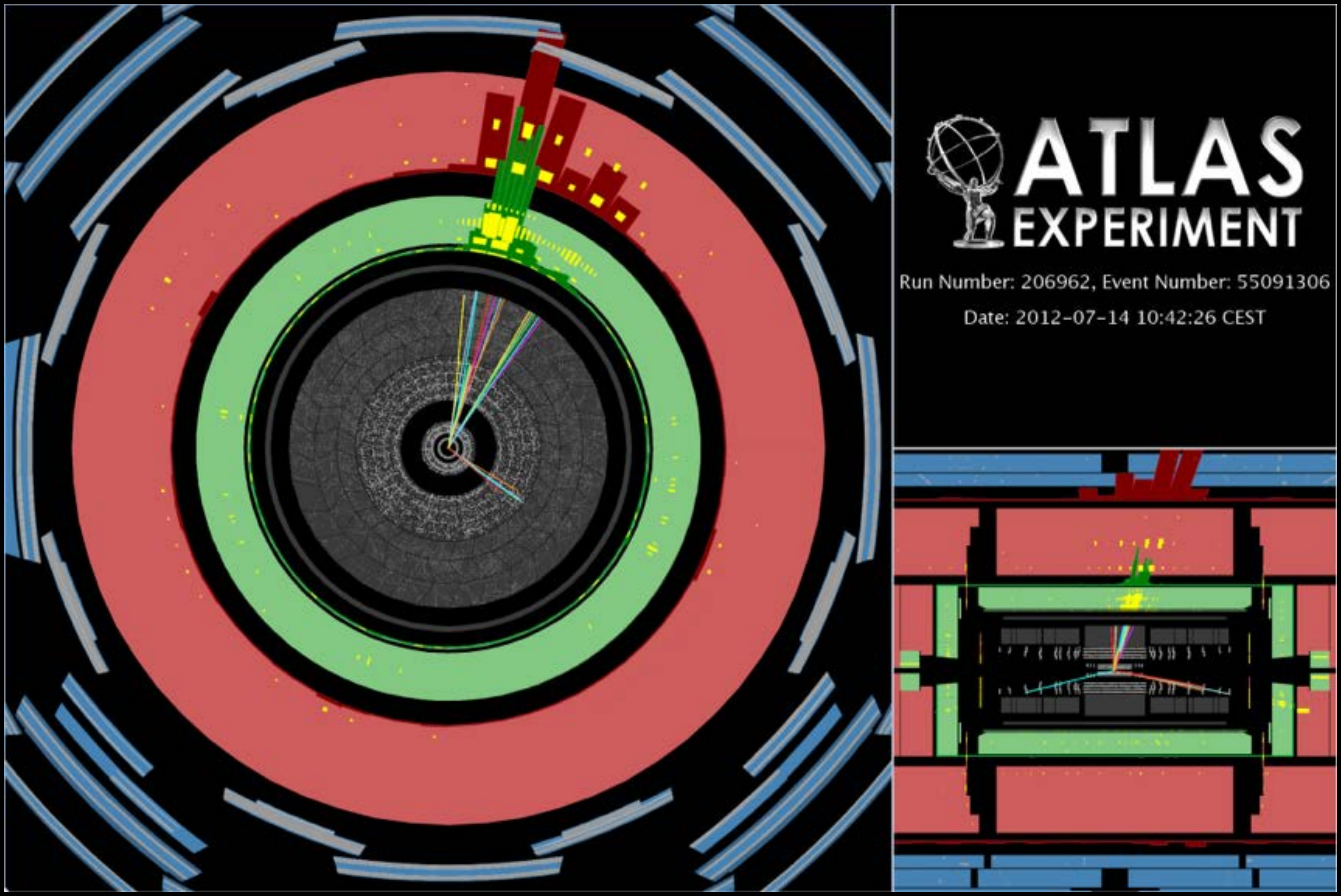
50th Rencontres de Moriond EW 2015, La Thuile

How to see invisible?



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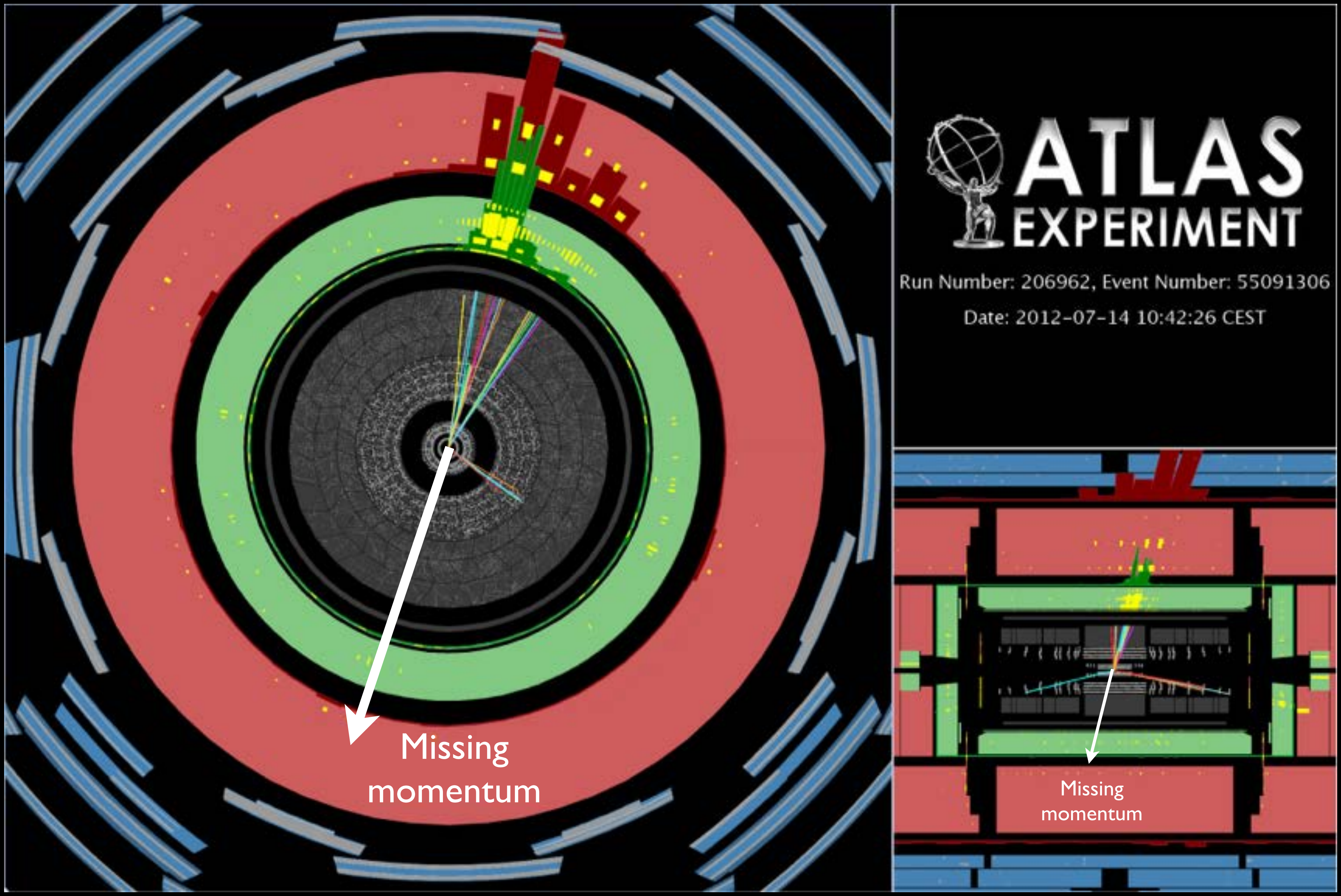
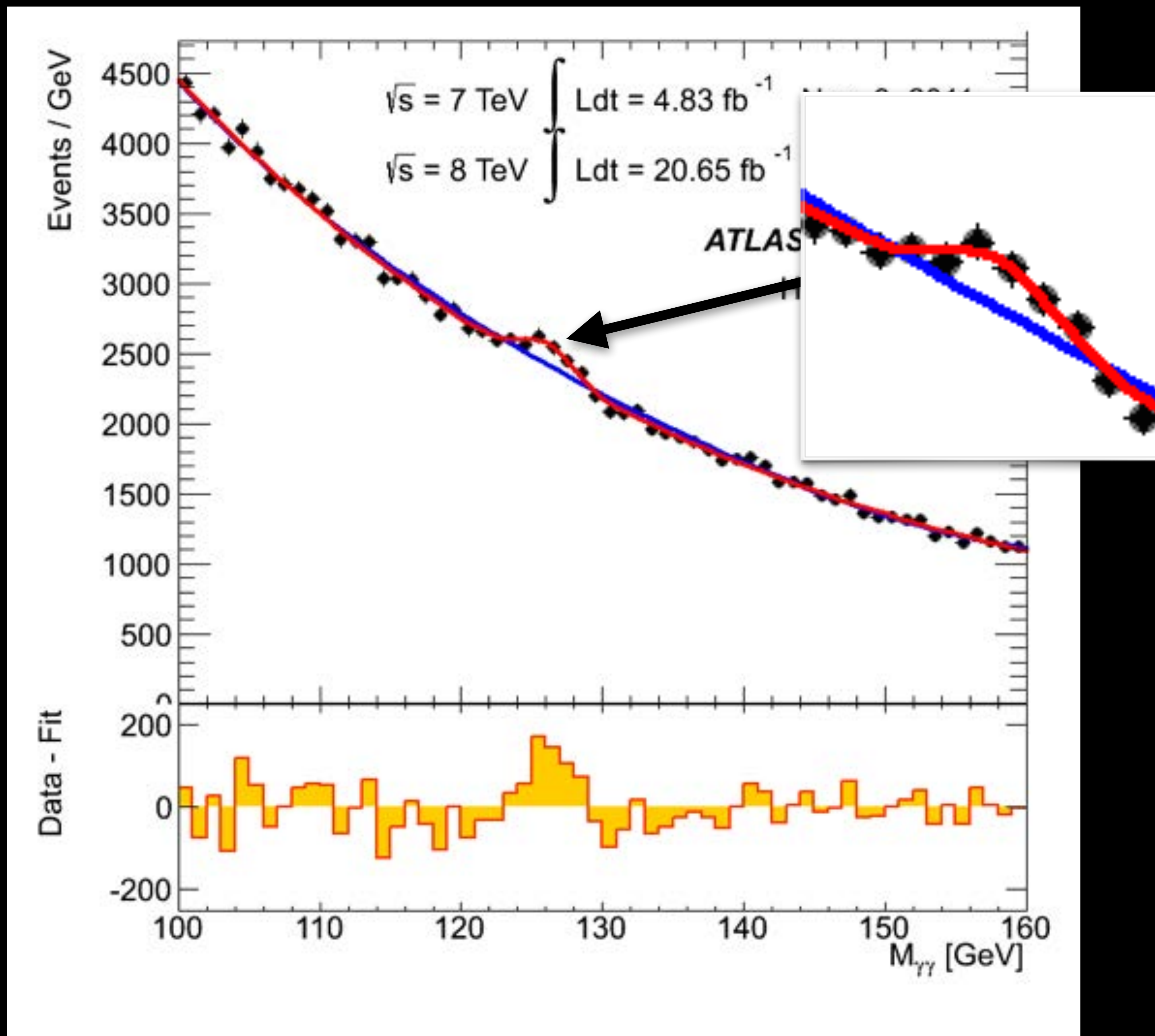


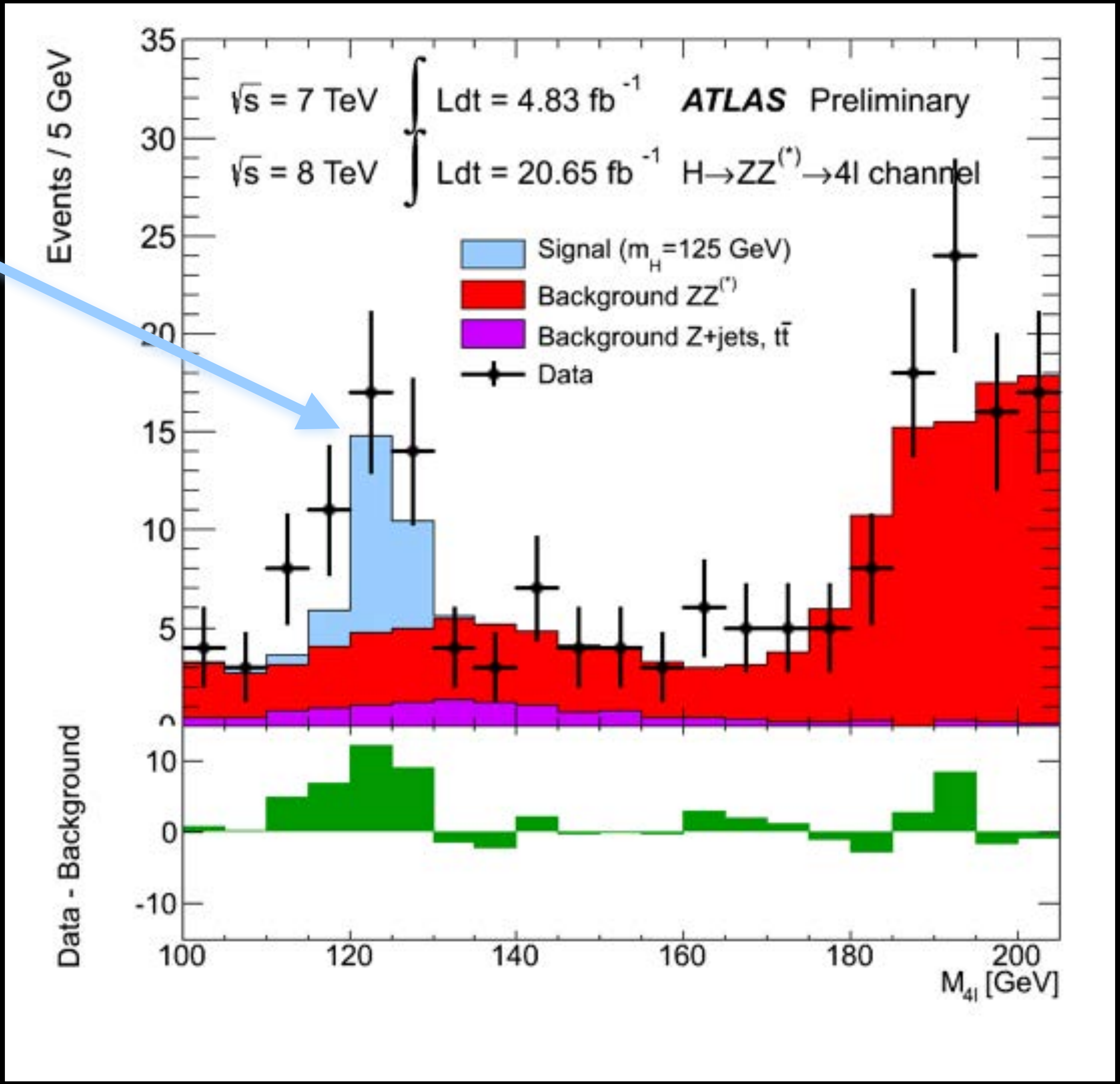
“Bump hunting” for Higgs



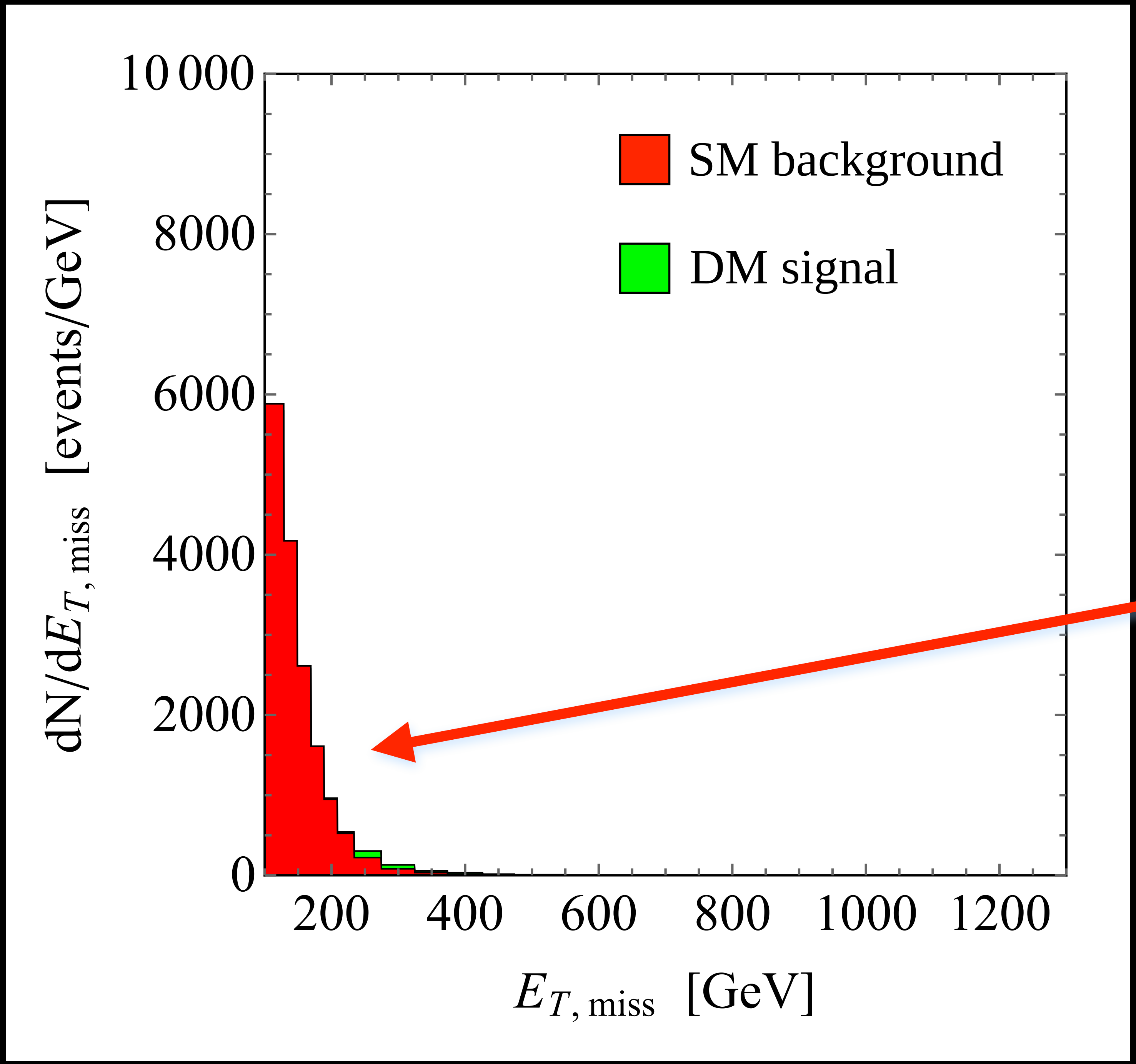
Di-photon decay of Higgs leads to a nice bump in invariant mass distribution

“Bump hunting” for Higgs

To see bump for Higgs decaying to two Z bosons, one does not even have to zoom in

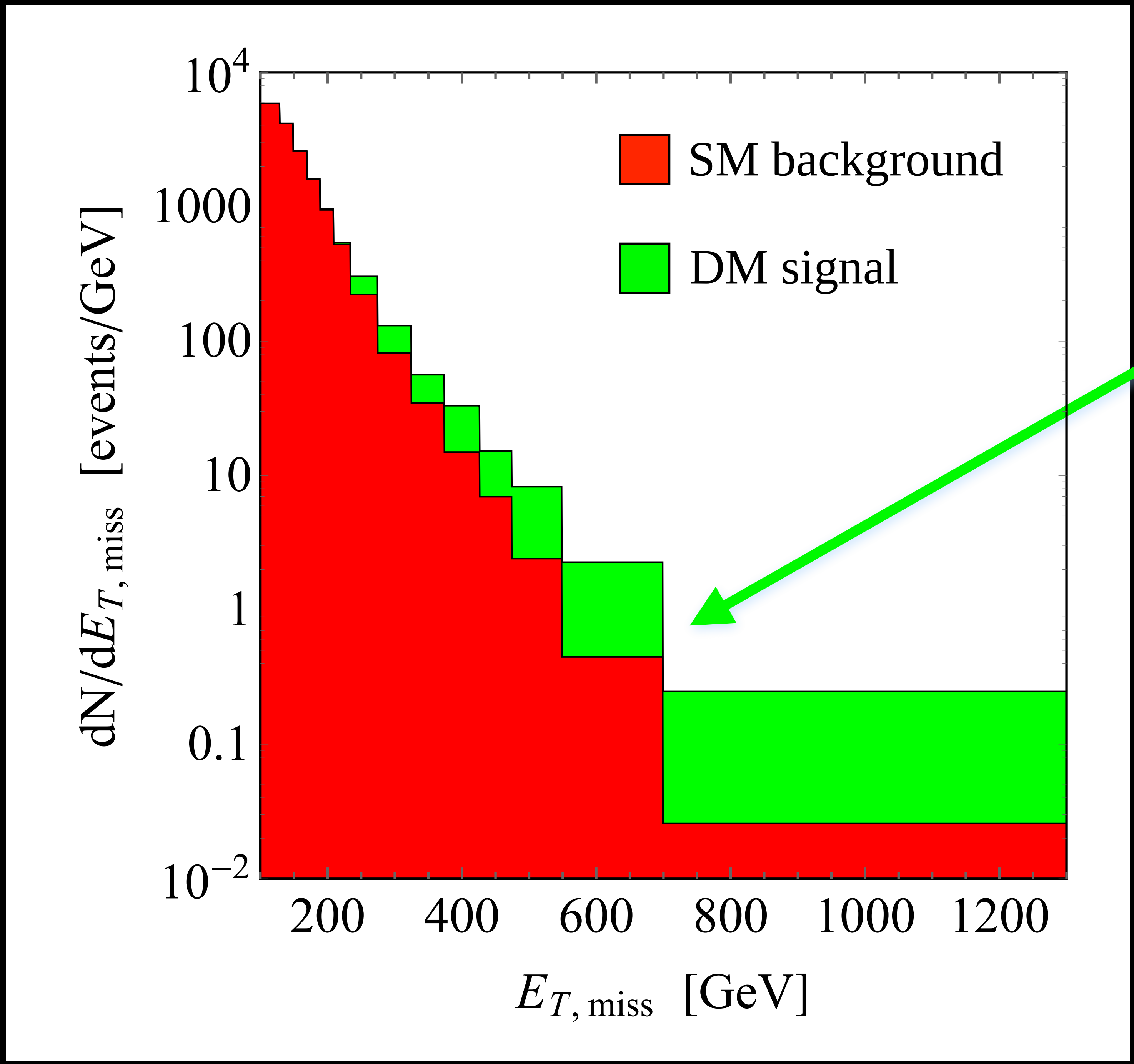


"Tail surgery" for dark matter



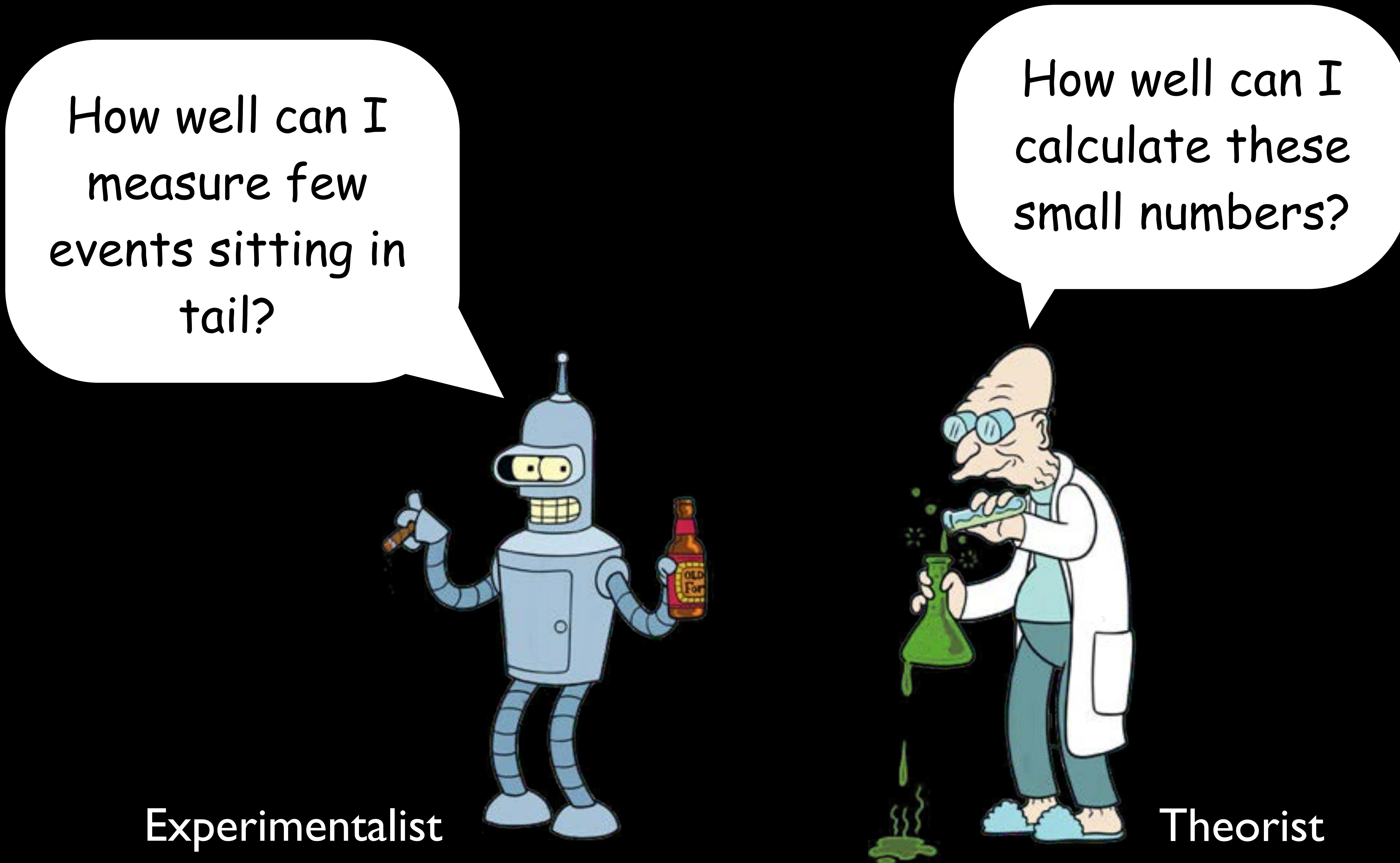
Overwhelming SM background, that arises in case of mono-jet searches from Z + jet production with Z boson decaying to neutrinos

“Tail surgery” for dark matter

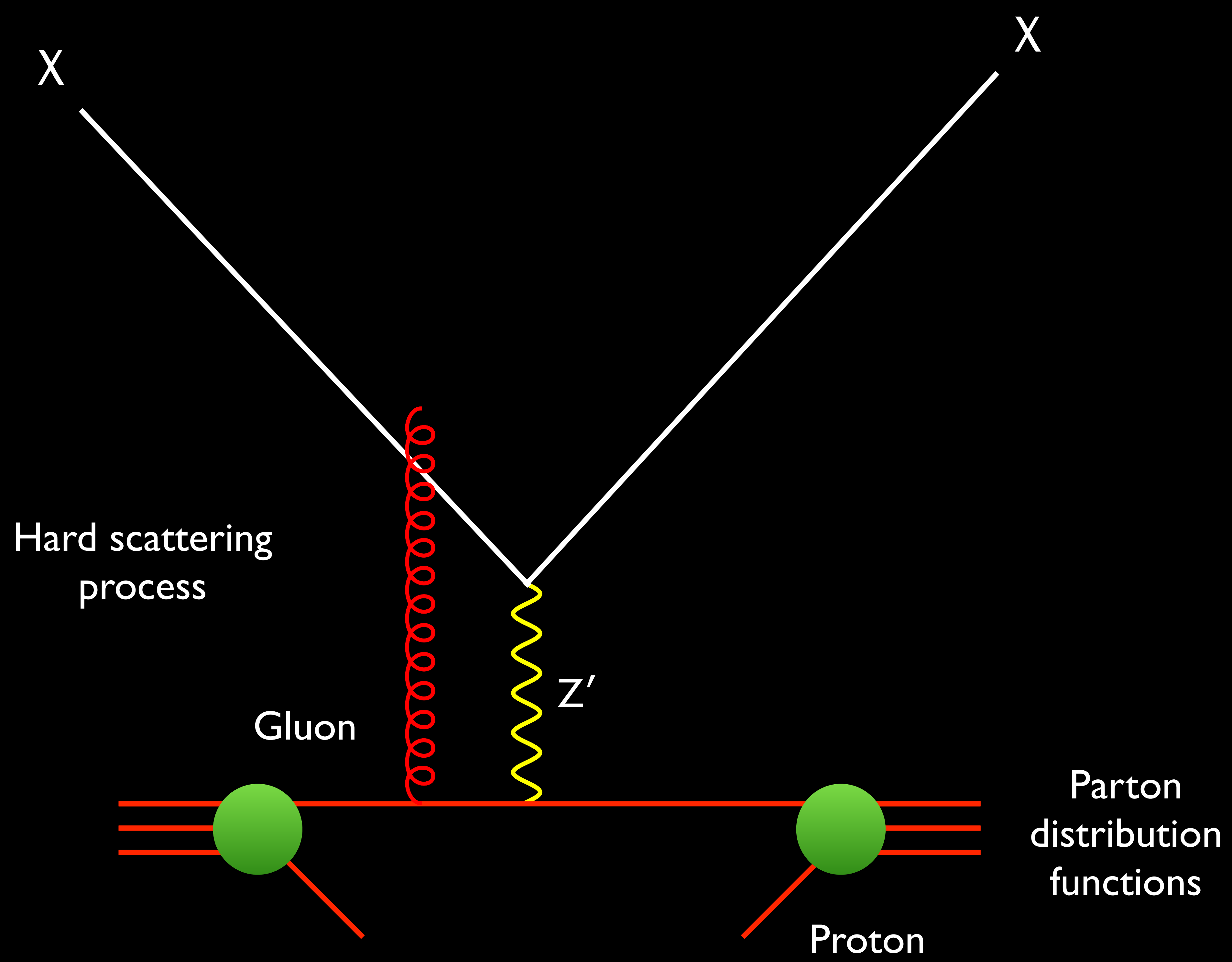


Presence of dark matter (DM) manifests itself in a small enhancement in tail of missing energy ($E_{T,miss}$) distribution

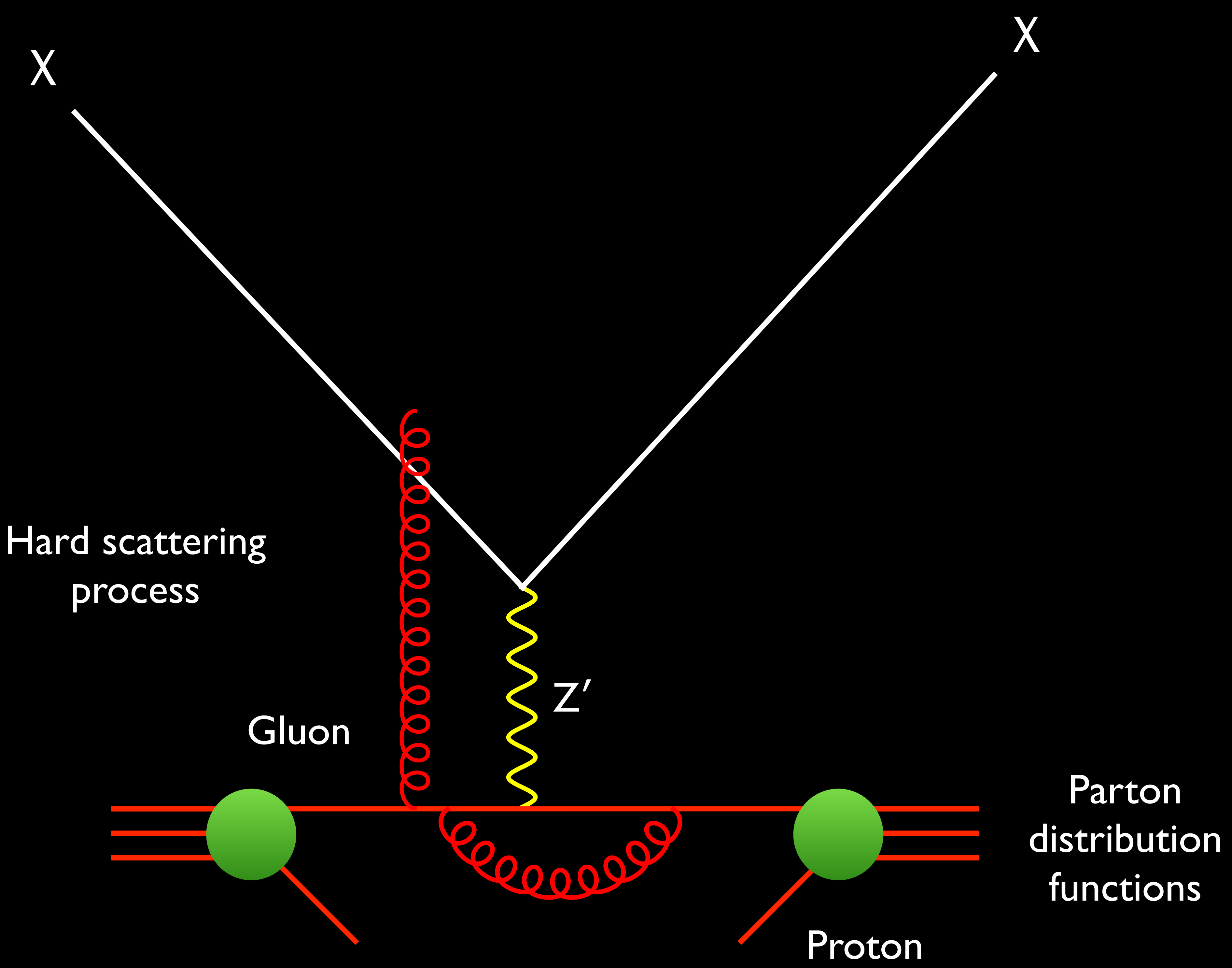
A big challenge indeed



Precision mono-jet predictions

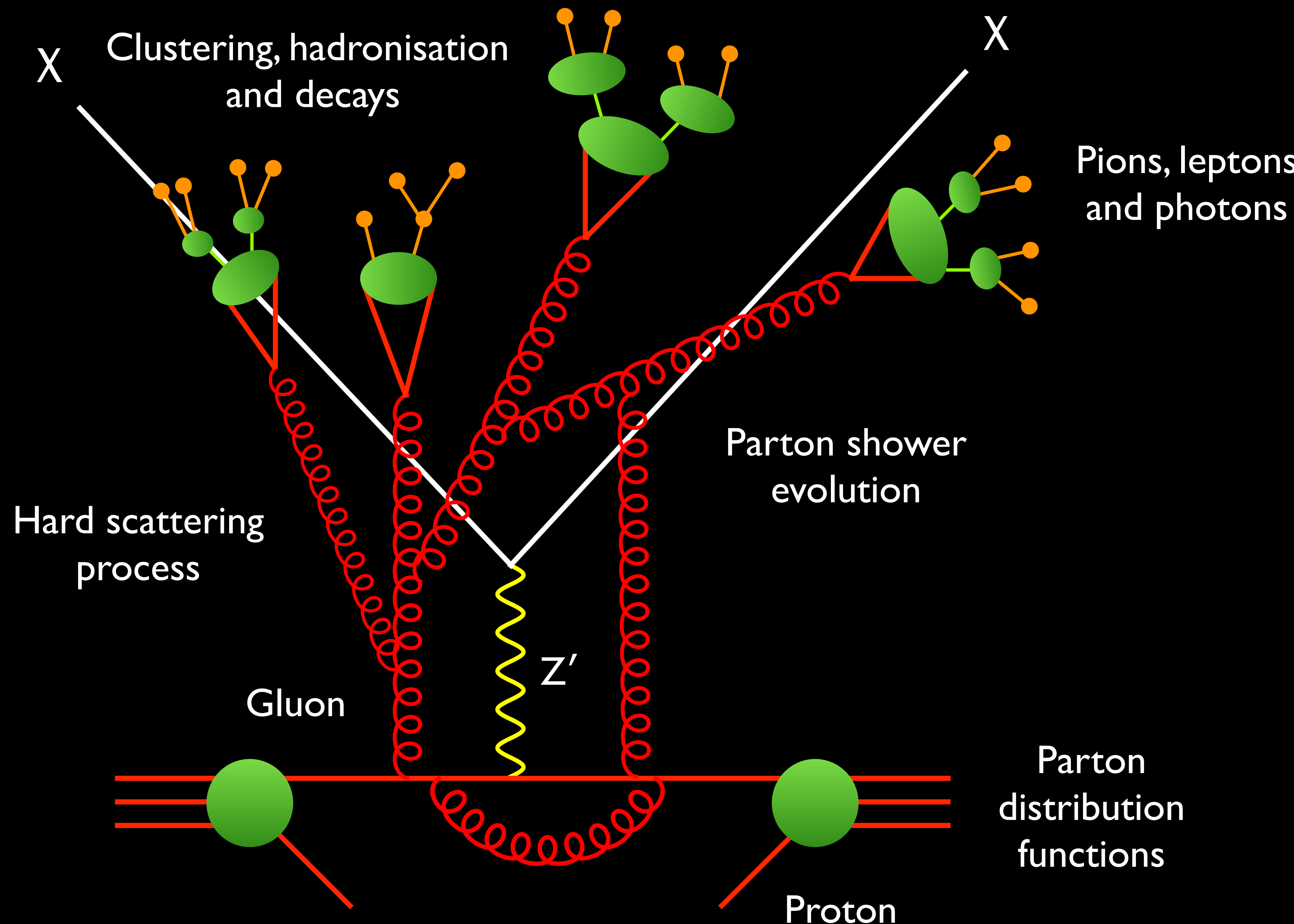


Precision mono-jet predictions



[NLO in MCFM, Fox & Williams, 1211.6390]

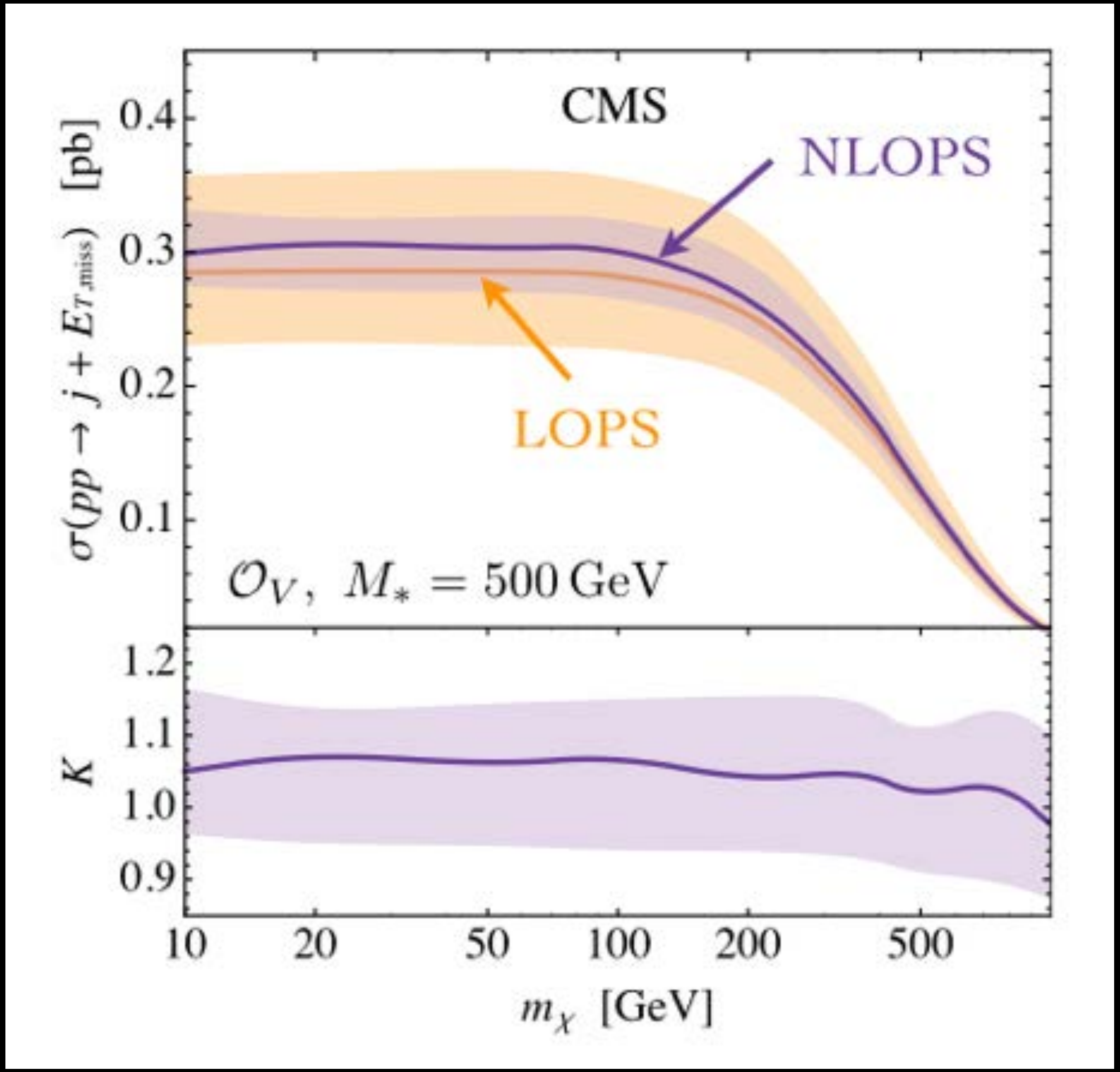
Precision mono-jet predictions



[NLOPS in POWHEG BOX, UH, Kahlhoefer & Re, 1310.4491]

NLO effects in spin-1 case

[UH, Kahlhoefer & Re, 1310.4491]



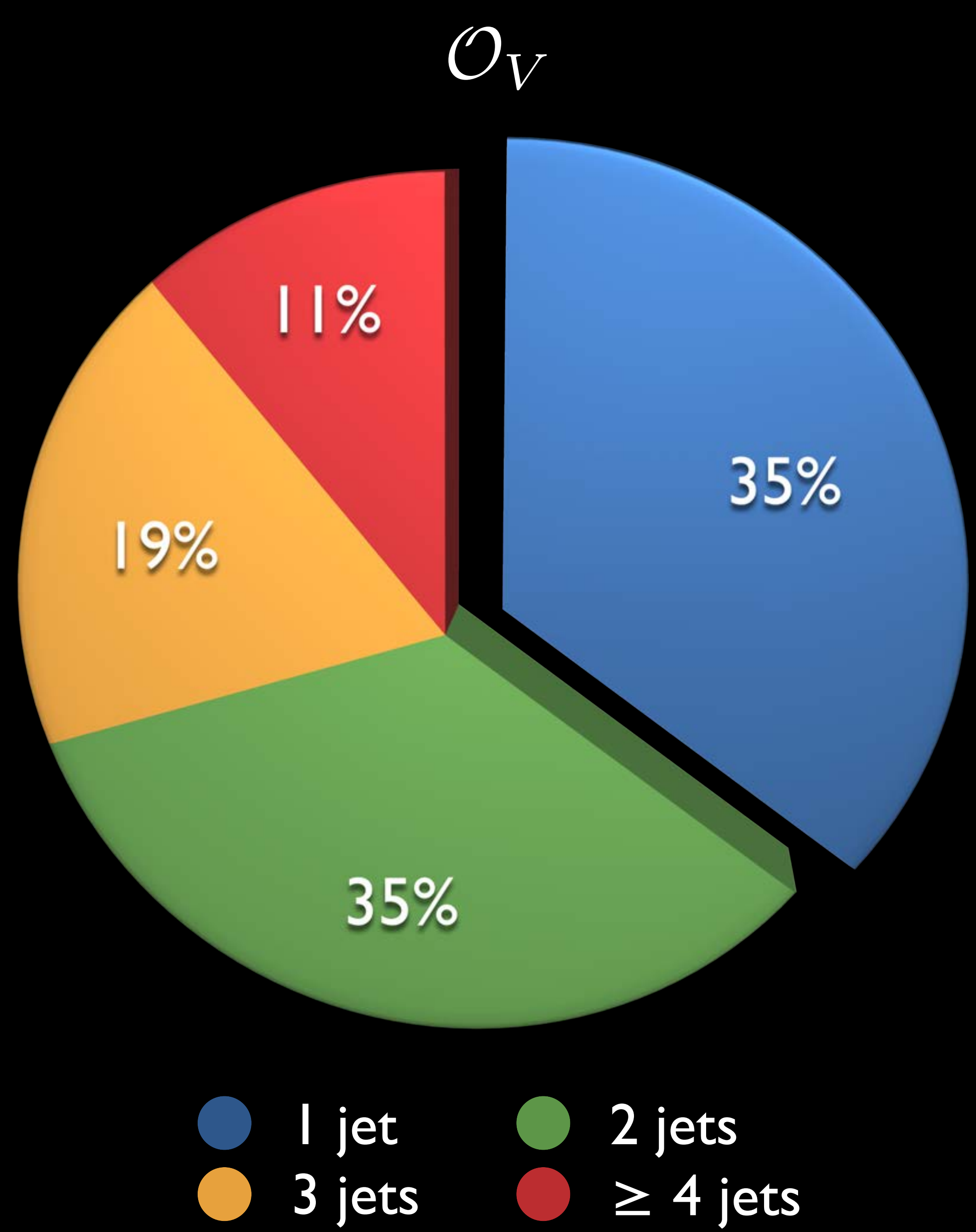
Inclusion of NLO effects leads only to slight enhancement of mono-jet cross section, but uncertainties reduced by about 2

Why are NLO effects small?

- LHC searches require large $E_{T,miss}$ & one hard jet with e.g. $p_{T,j1} > 110$ GeV. Events with a 2nd jet of $p_{T,j2} > 30$ GeV are also included, but a 3rd jet is vetoed

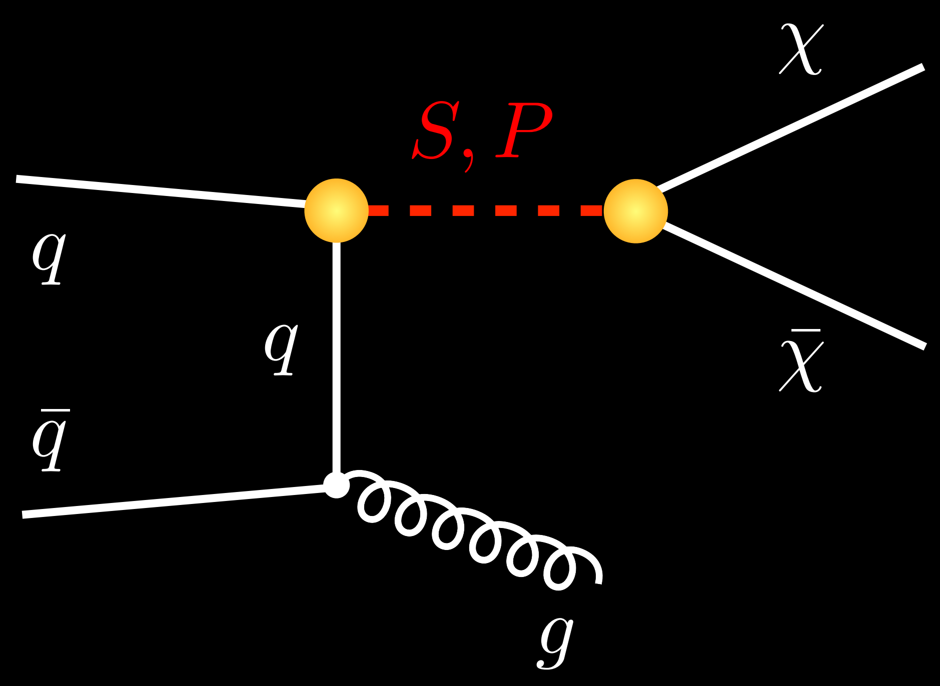
- In pp collisions at $\sqrt{s} = 8$ TeV, fraction of 2j + $E_{T,miss}$ events is large. This reduces impact of NLO corrections

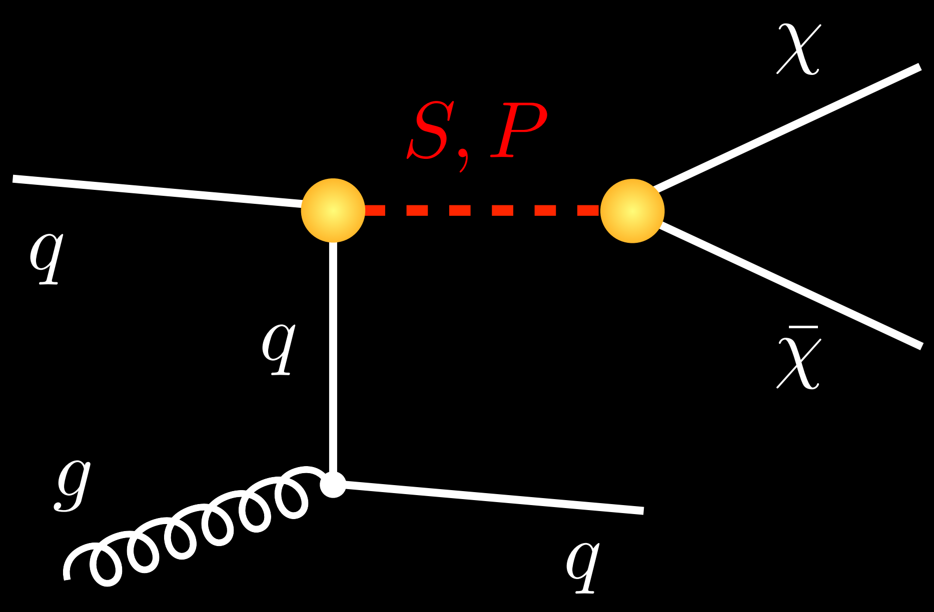
[UH, Kahlhoefer & Re, 1310.4491]



Spin-0 interactions

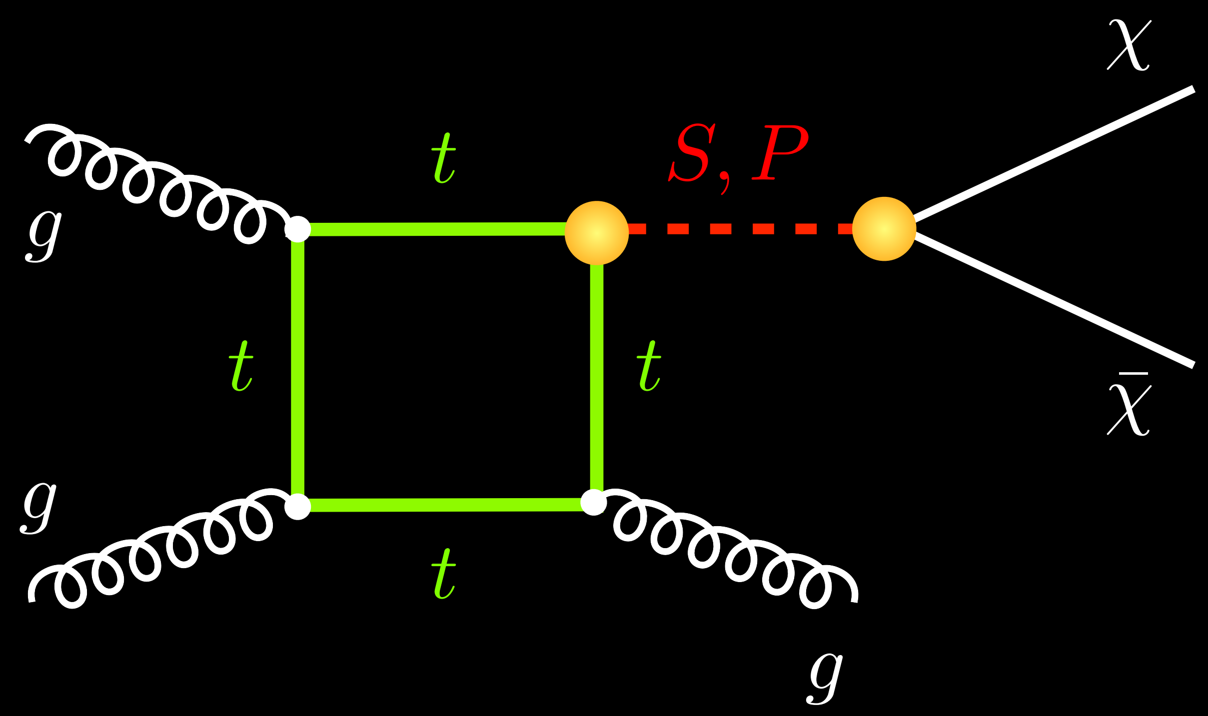
- For spin-1 DM-standard model (SM) interactions loop corrections do not play important role. Is this a generic feature?
- In spin-0 case with Higgs-like couplings, tree-level cross section is small since heavy-quark luminosities are tiny & light quarks suffer Yukawa suppression





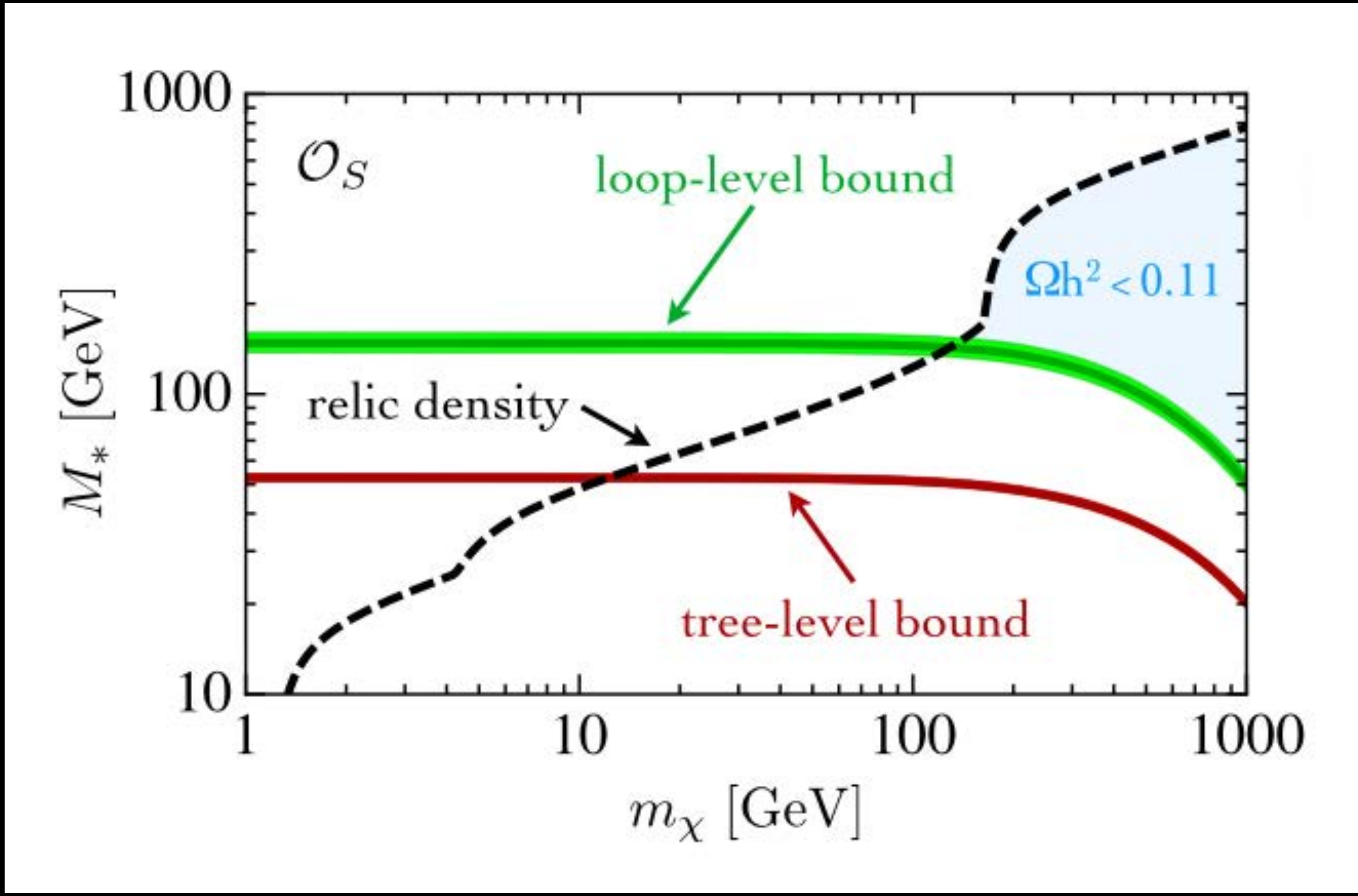
Spin-0 interactions

- For spin-1 DM-standard model (SM) interactions loop corrections do not play important role. Is this a generic feature?
- At 1-loop level heavy-quark loops start to contribute to mono-jet cross section & expected to lift Yukawa suppression



How big is this effect?

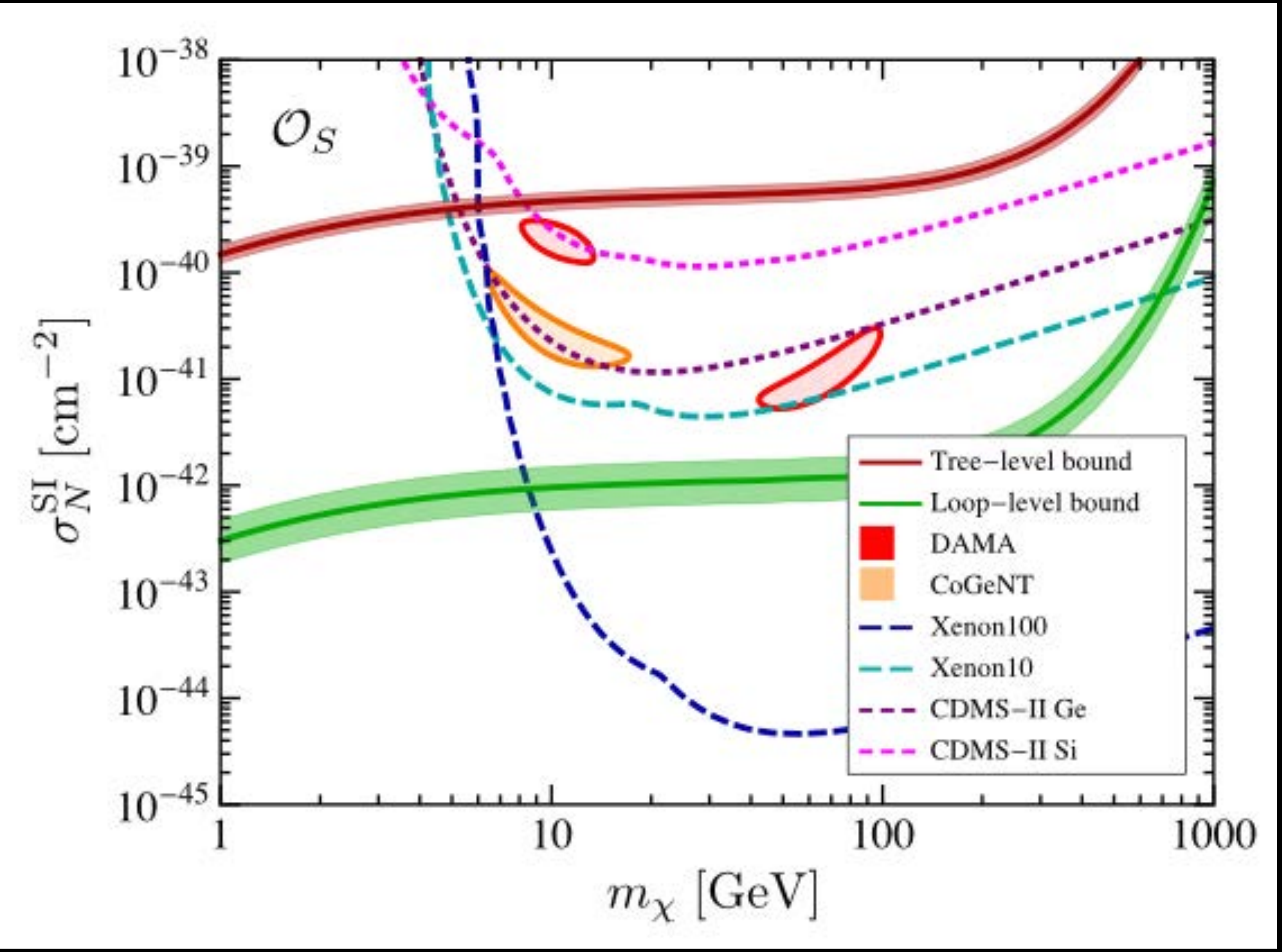
[UH, Kahlhoefer & Unwin, 1208.4605]



Inclusion of top-quark loops increases mono-jet cross section (bound on M_*) by a factor of around 500 (3)

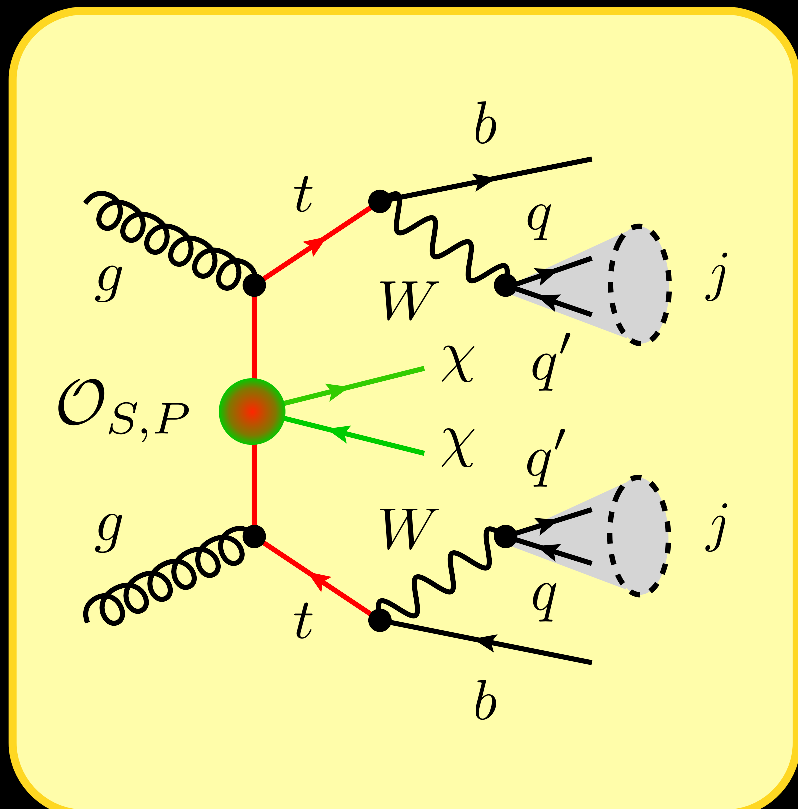
LHC & direct detection bounds

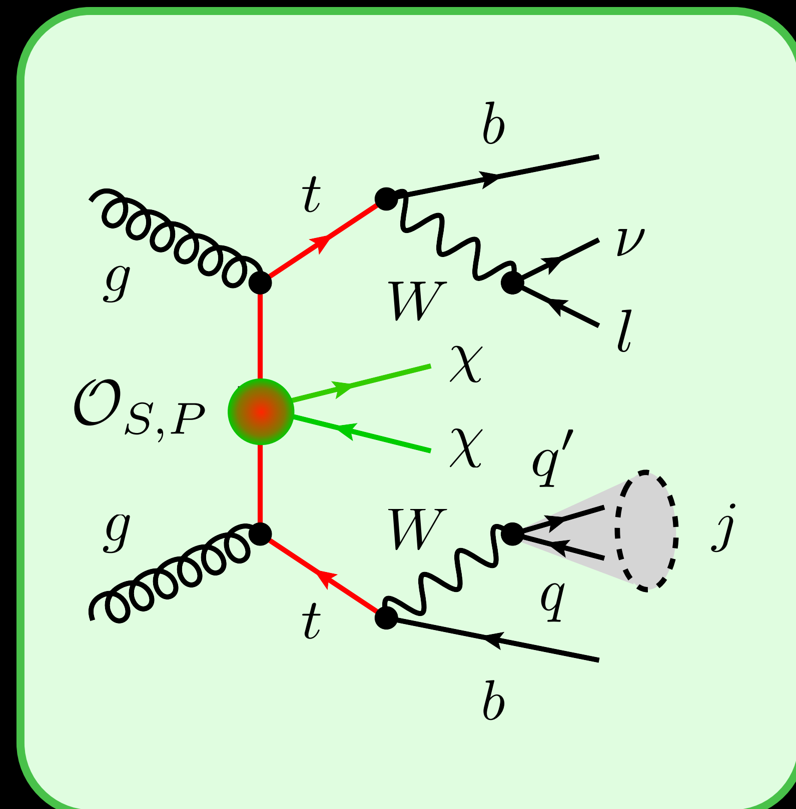
[UH, Kahlhoefer & Unwin, 1208.4605]

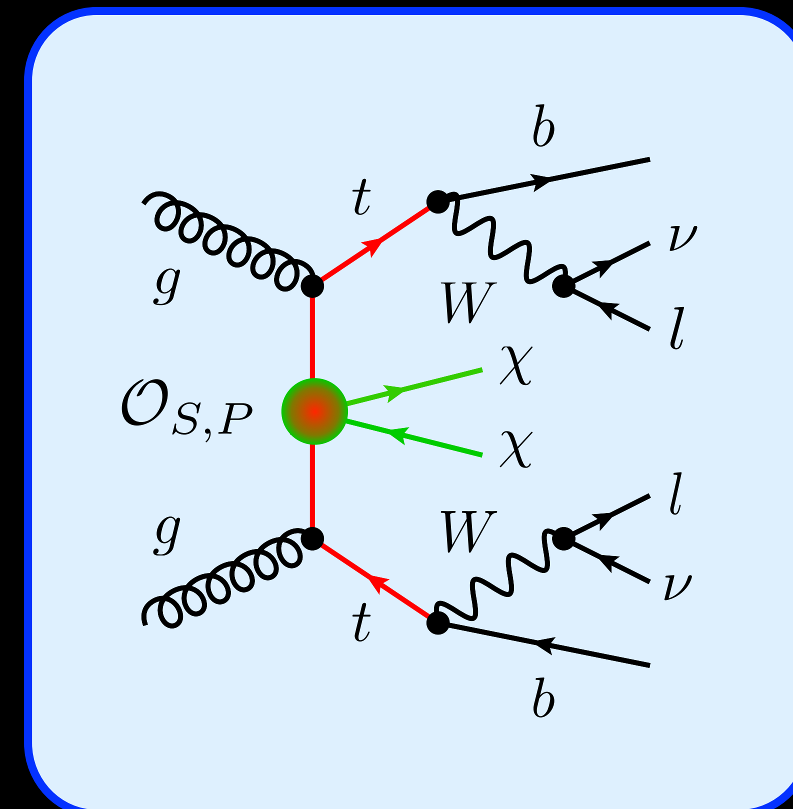


Parameter regions favoured by DAMA & CoGeNT (hinting to DM of order 10 GeV) clearly excluded by loop-level bound

Heavy-quark pairs & $E_{T,\text{miss}}$







$2b2j + E_{T,\text{miss}}$

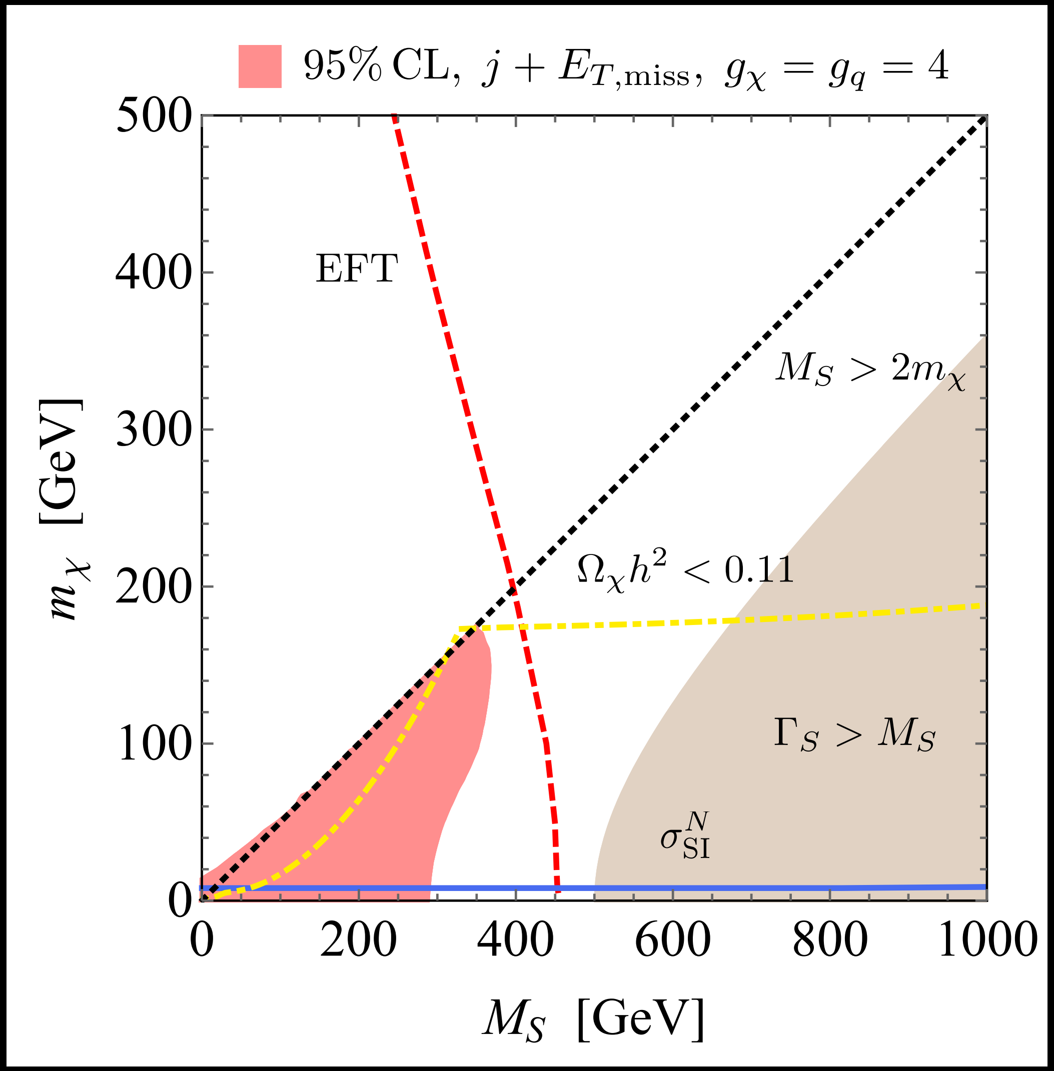
$2bj\ell + E_{T,\text{miss}}$

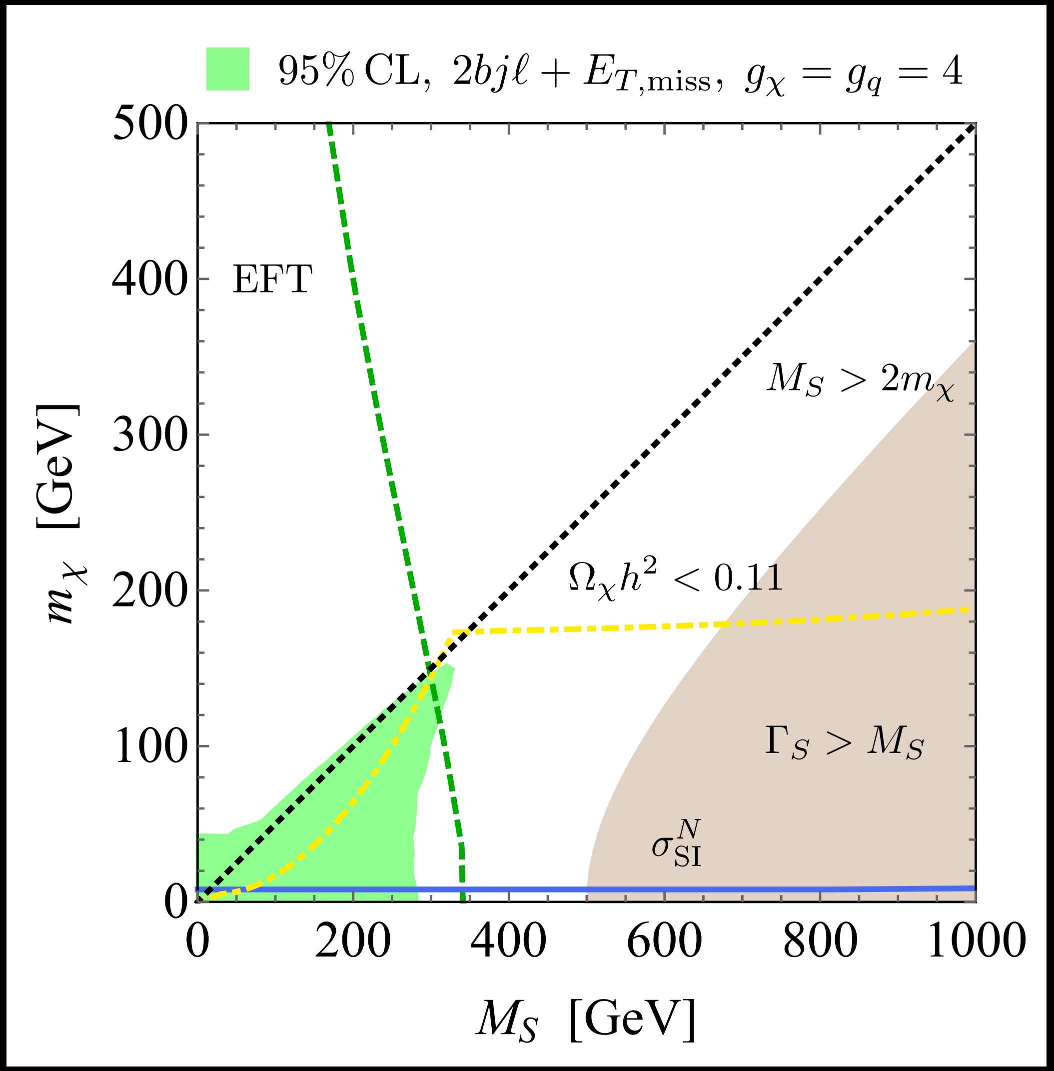
$2b2\ell + E_{T,\text{miss}}$

[Lin et al., 1303.6638; Artoni et al. 1307.7834; CMS PAS B2G-13-004; CMS-B2G-13-004; ATLAS, 1410.4031; Buckley et al., 1410.6497; UH & Re, 1503.00691; also Deborah in YSF2]

j + $E_{T,\mathrm{miss}}$ vs. $t\bar{t}$ + $E_{T,\mathrm{miss}}$

[UH & Re, 1503.00691]





Depending on specific simplified model realisation either search can provide strongest constraints. Strategies are thus complementary

[see also Buckley et al., 1410.6497; Harris et al., 1411.0535]

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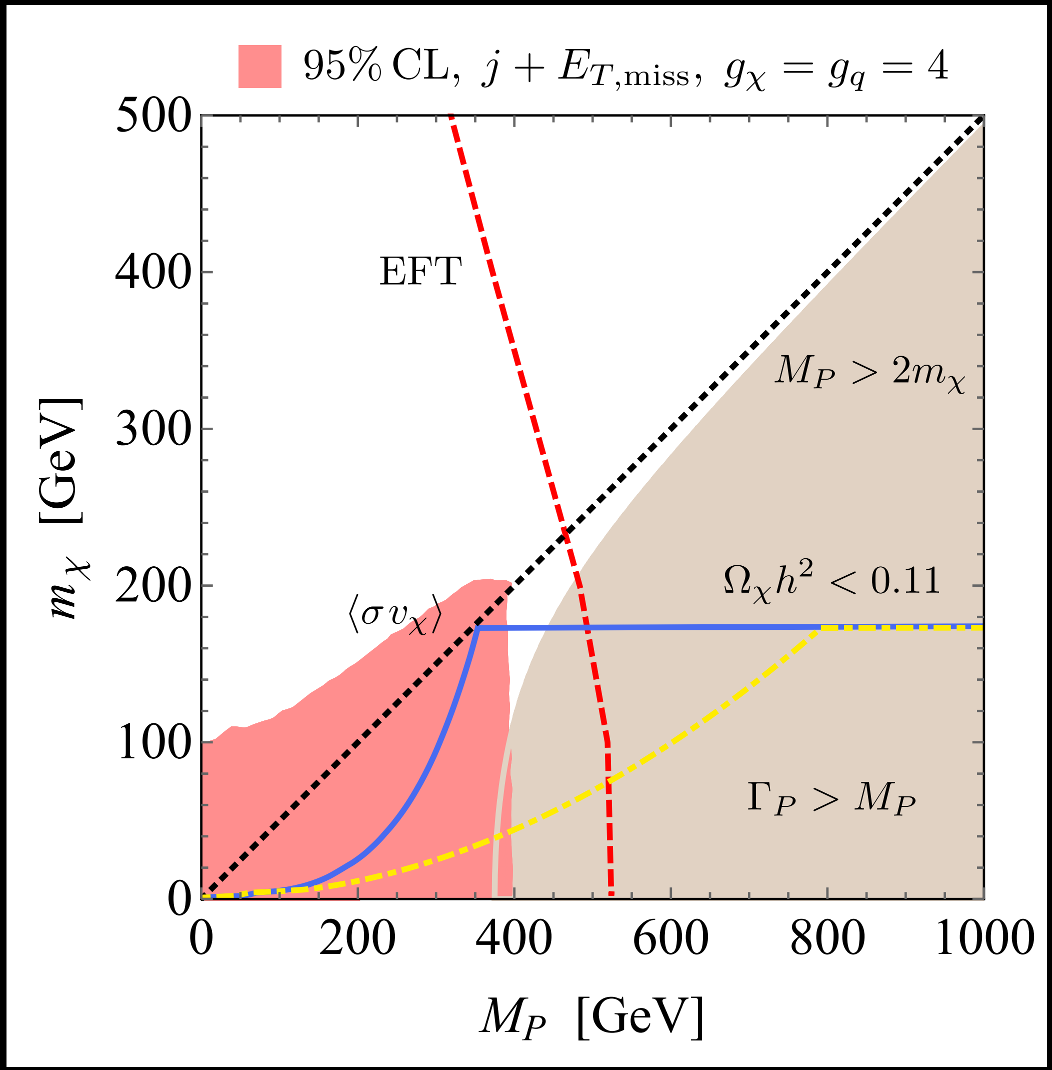

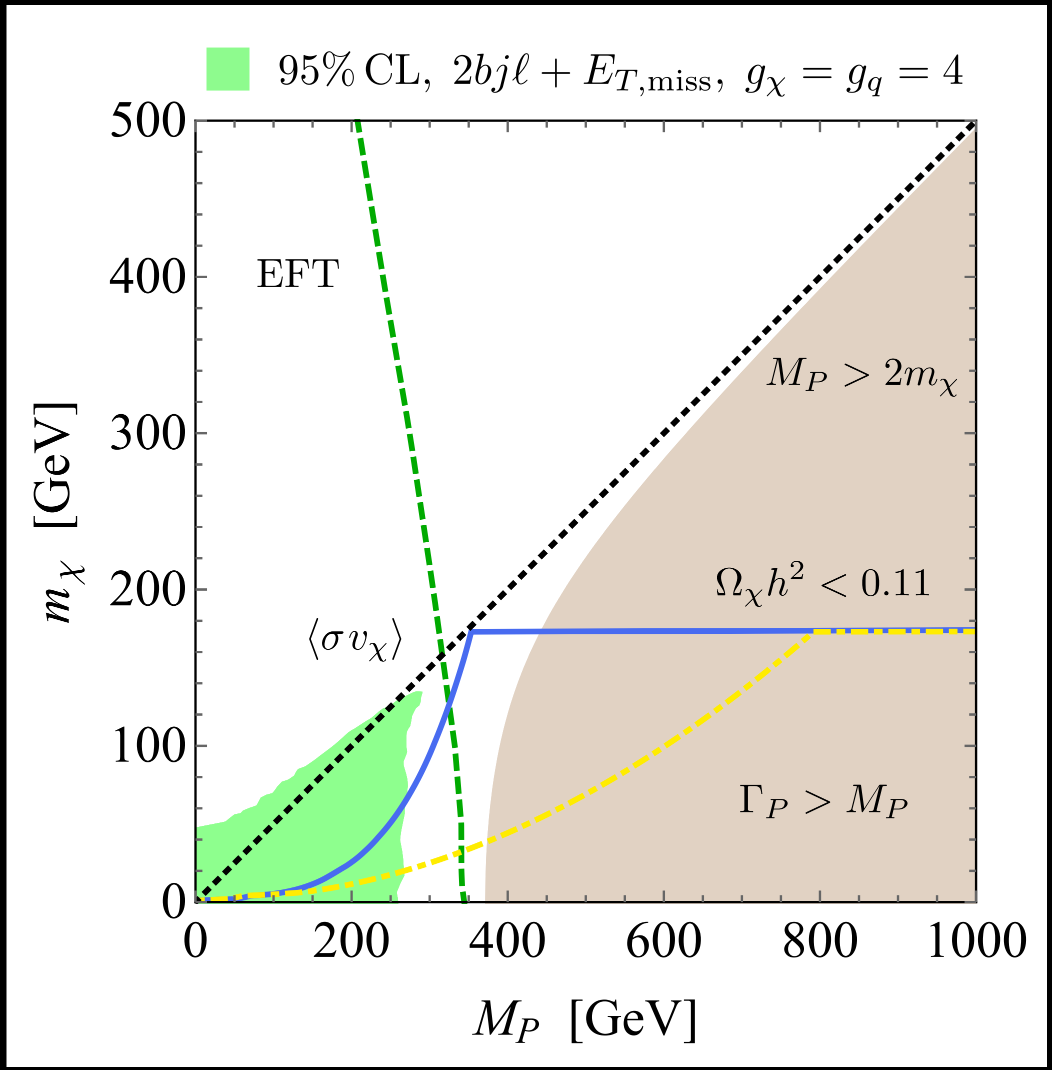

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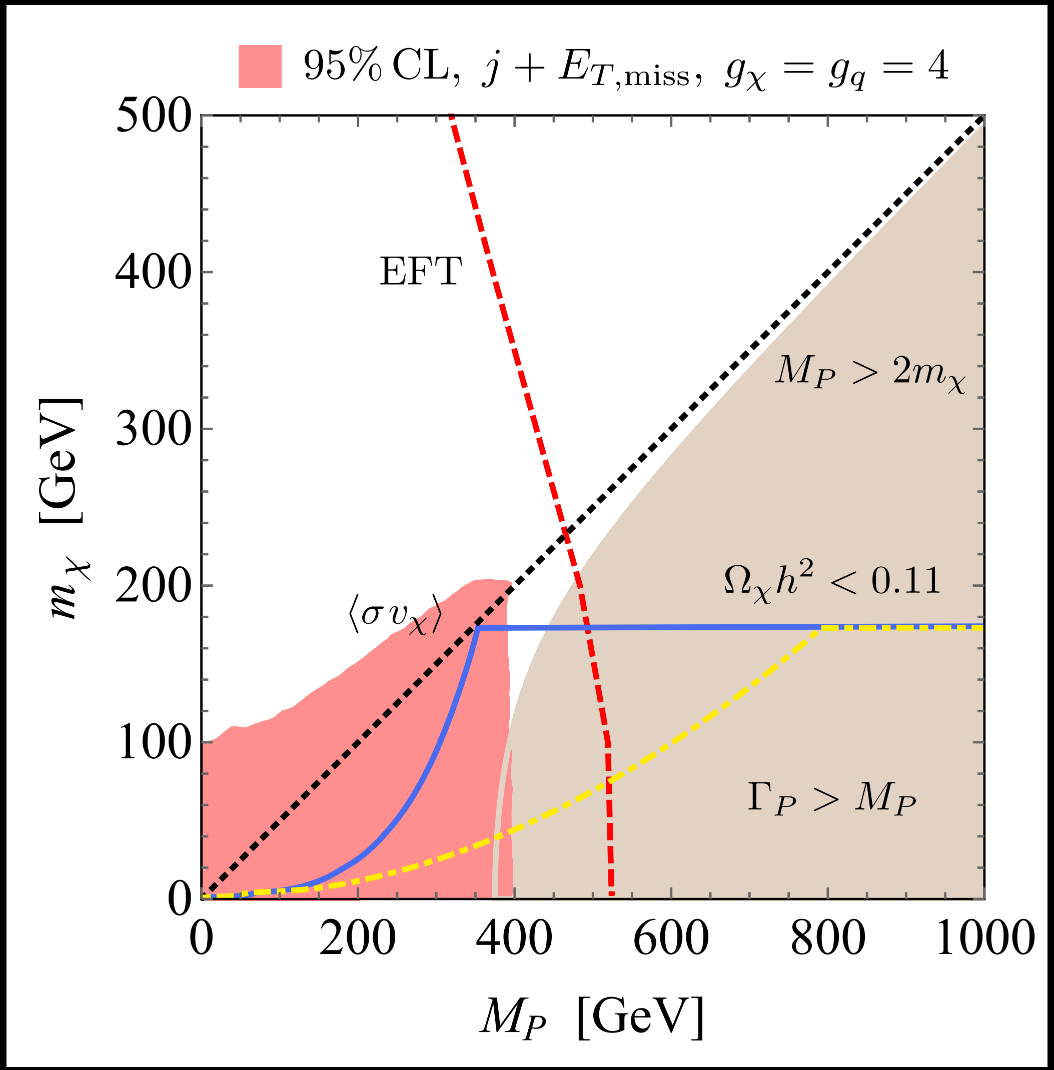
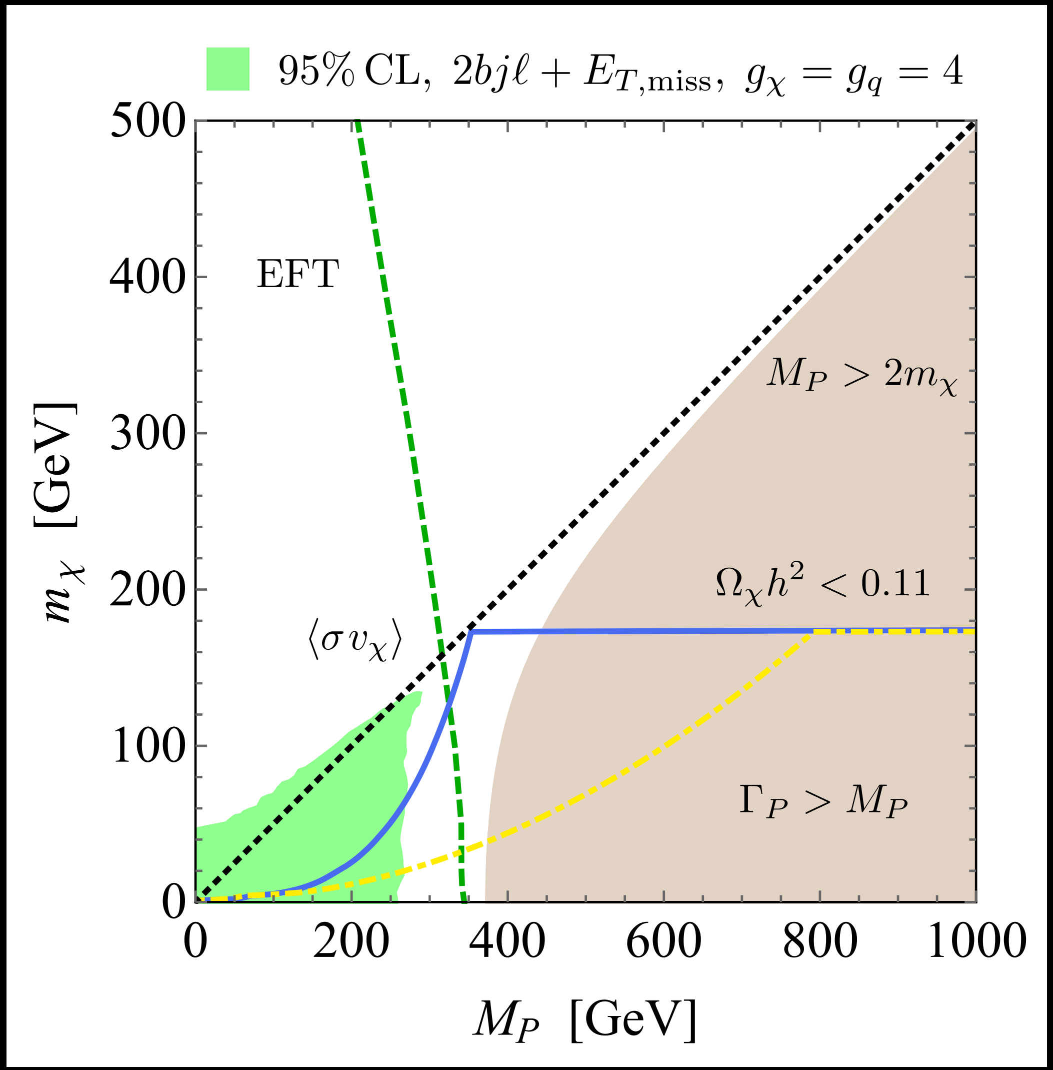
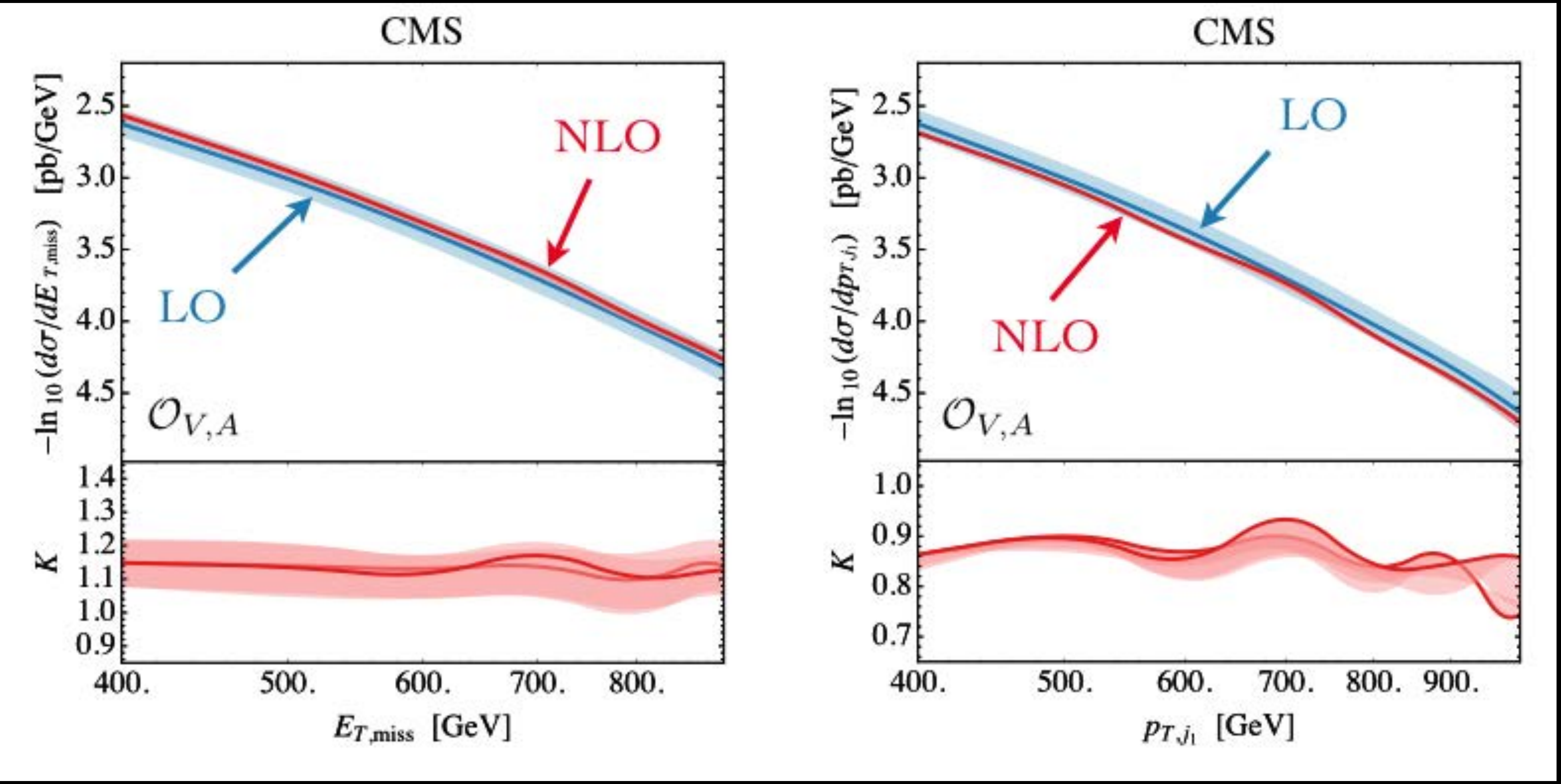




LHC search strategies for spin-0 interactions considered so far allow to probe only mediators with couplings larger 1 & weak scale masses

[see also Buckley et al., 1410.6497; Harris et al., 1411.0535]

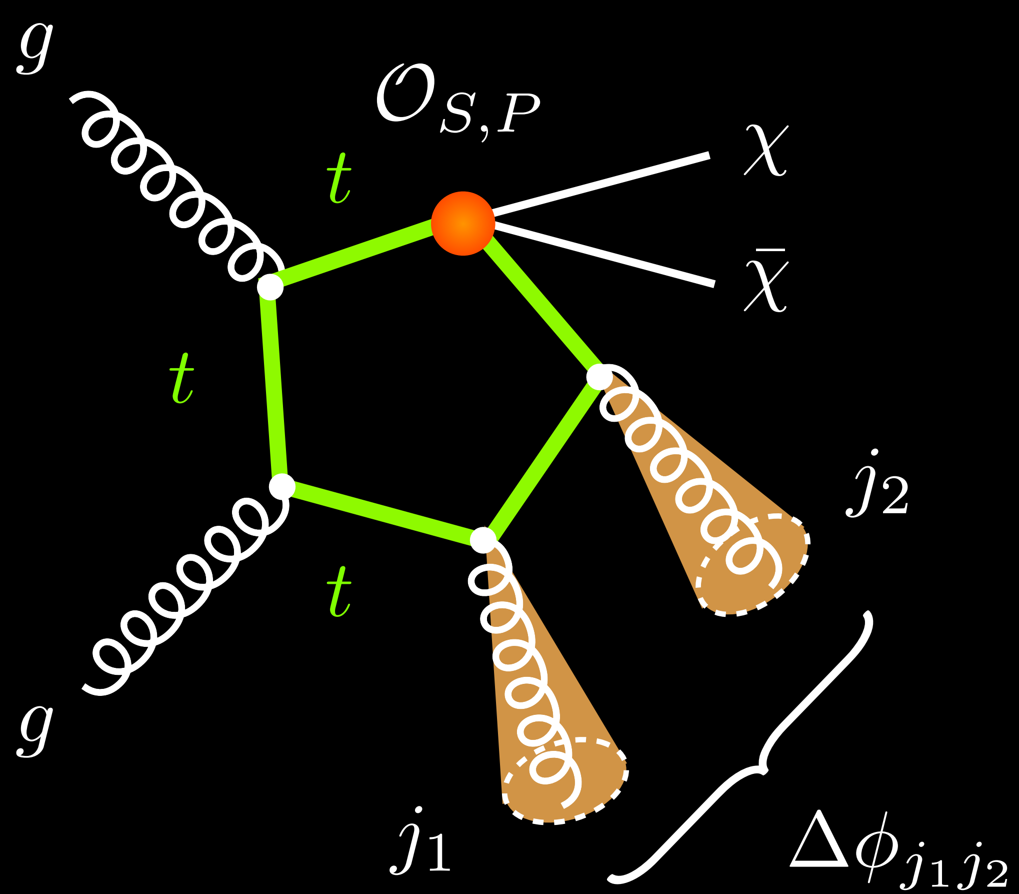
Properties beyond mass scale?

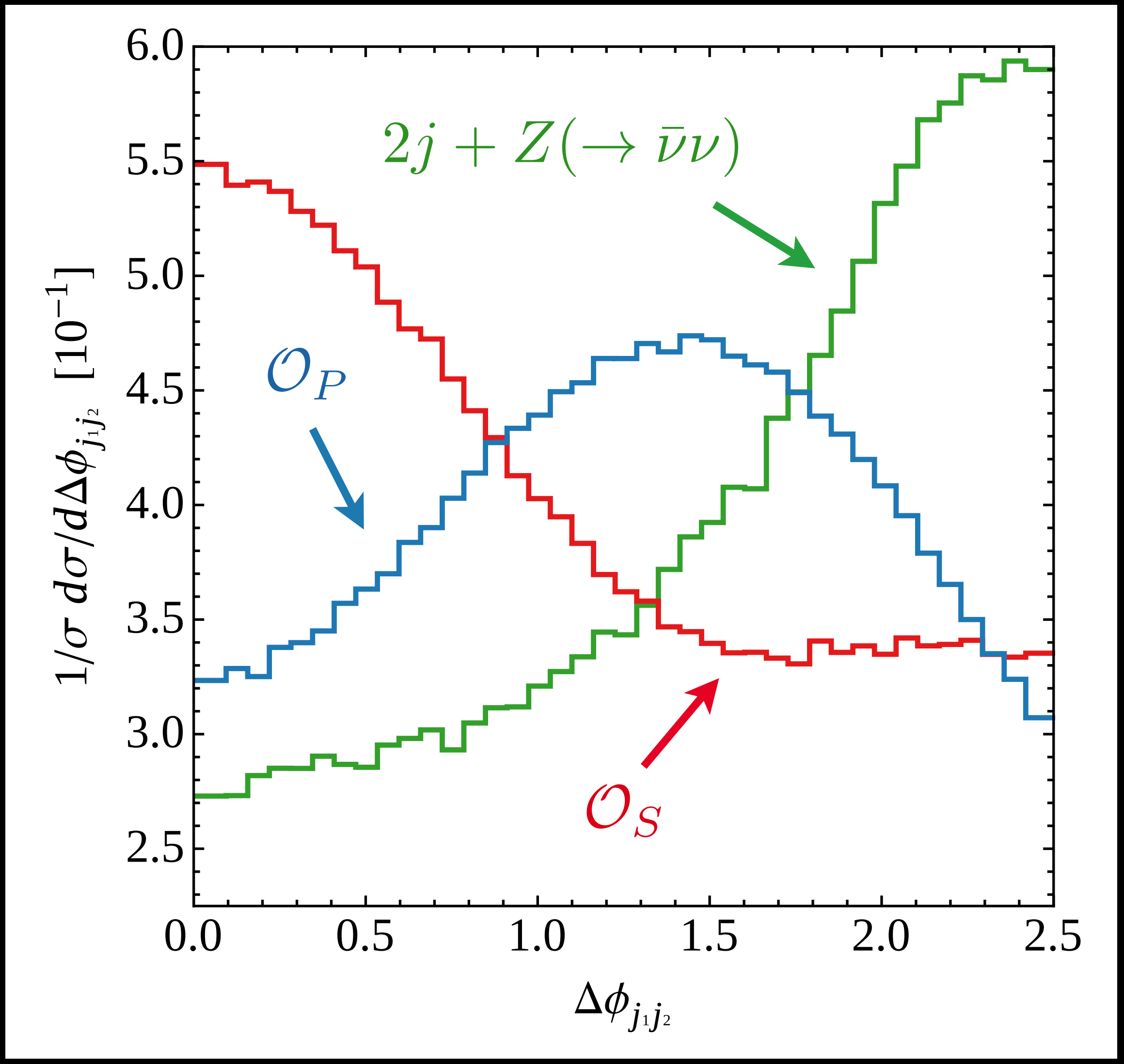


$E_{T,miss}$ & $p_{T,j1}$ spectra for vector & axial operators identical.
Mono-jet searches not sensitive to chirality of interactions

DM-pair production & 2 jets

[UH, Hibbs & Re, 1311.7131]





Azimuthal angle difference $\Delta\phi_{j1j2}$ in 2j + $E_{T,miss}$ events gold-plated observable to probe structure of DM-SM interactions

[cf. Cotta et al., 1210.0525 for related ideas]

How general is method?

“Darkness” of DM could be a natural consequence of DM having only irrelevant interactions with “light”. In Majorana case, dimension-5 dipole interactions vanish, so that leading effects arise at dimension 7

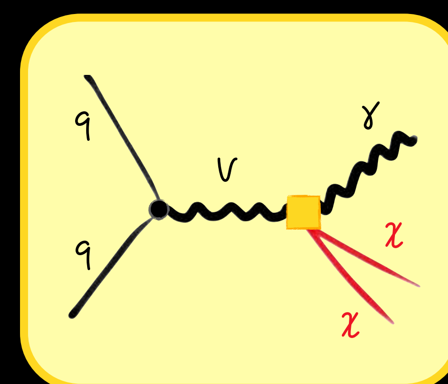
$$\mathcal{O}_B = \bar{\chi}\chi\, B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_W = \bar{\chi}\chi\, W^i_{\mu\nu} W^{i,\mu\nu}$$

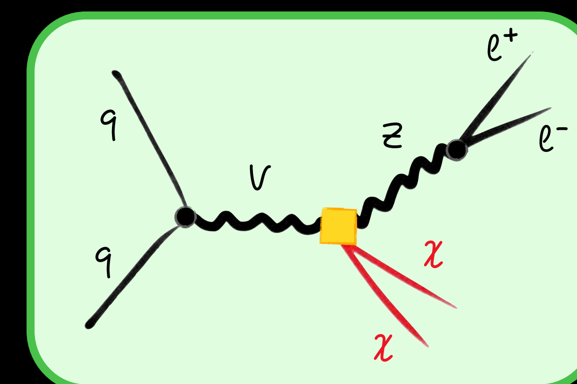
$$\mathcal{O}_{\tilde{B}} = \bar{\chi}\gamma_5\chi\, B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_{\tilde{W}} = \bar{\chi}\gamma_5\chi\, W^i_{\mu\nu} \tilde{W}^{i,\mu\nu}$$

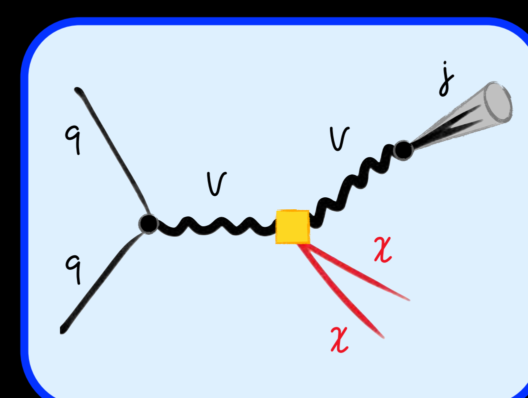
$$\vdots$$



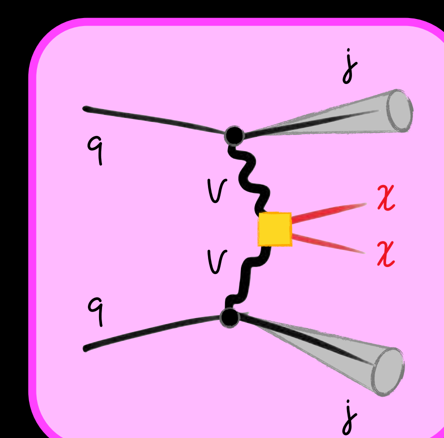
mono-photon



mono-Z



mono-W



mono-jet

[see e.g. Weiner & Yavin 1206.2910, 1209.1093; Liu et al. 1303.4404]

LHC 14 TeV prospects

Imposed VBF cuts:

$$\Delta\eta_{j_1 j_2} > 2$$

$$m_{j_1 j_2} > 1100\,\mathrm{GeV}$$

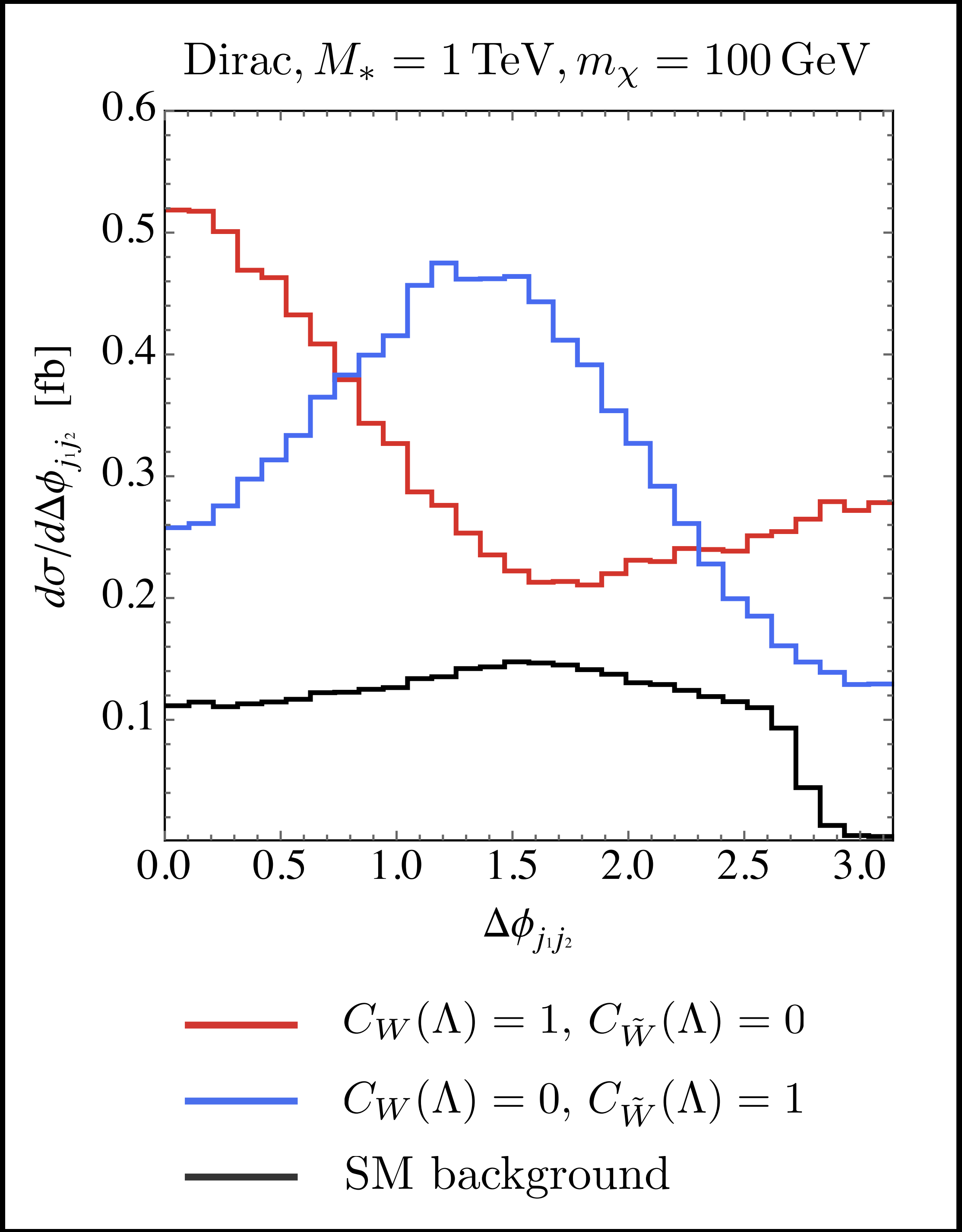
⇩

$$\sigma_{\rm fid}\,(pp \to E_{T,\rm miss} + 2j) = 1.0\,\mathrm{fb}$$

$$\sigma_{\rm fid}\,(pp \to Z\,(\to \bar{\nu}\nu) + 2j) = 0.35\,\mathrm{fb}$$

$$S/\sqrt{B} = 8.4\ (25\,\mathrm{fb}^{-1})$$

$$S/\sqrt{B} = 29\ (300\,\mathrm{fb}^{-1})$$



[Crivellin, UH & Hibbs, 1501.00907]

LHC 14 TeV prospects

Angular decomposition:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi_{j_1j_2}} = \sum_{n=0}^{2} a_n \cos\left(n\Delta\phi_{j_1j_2}\right)$$

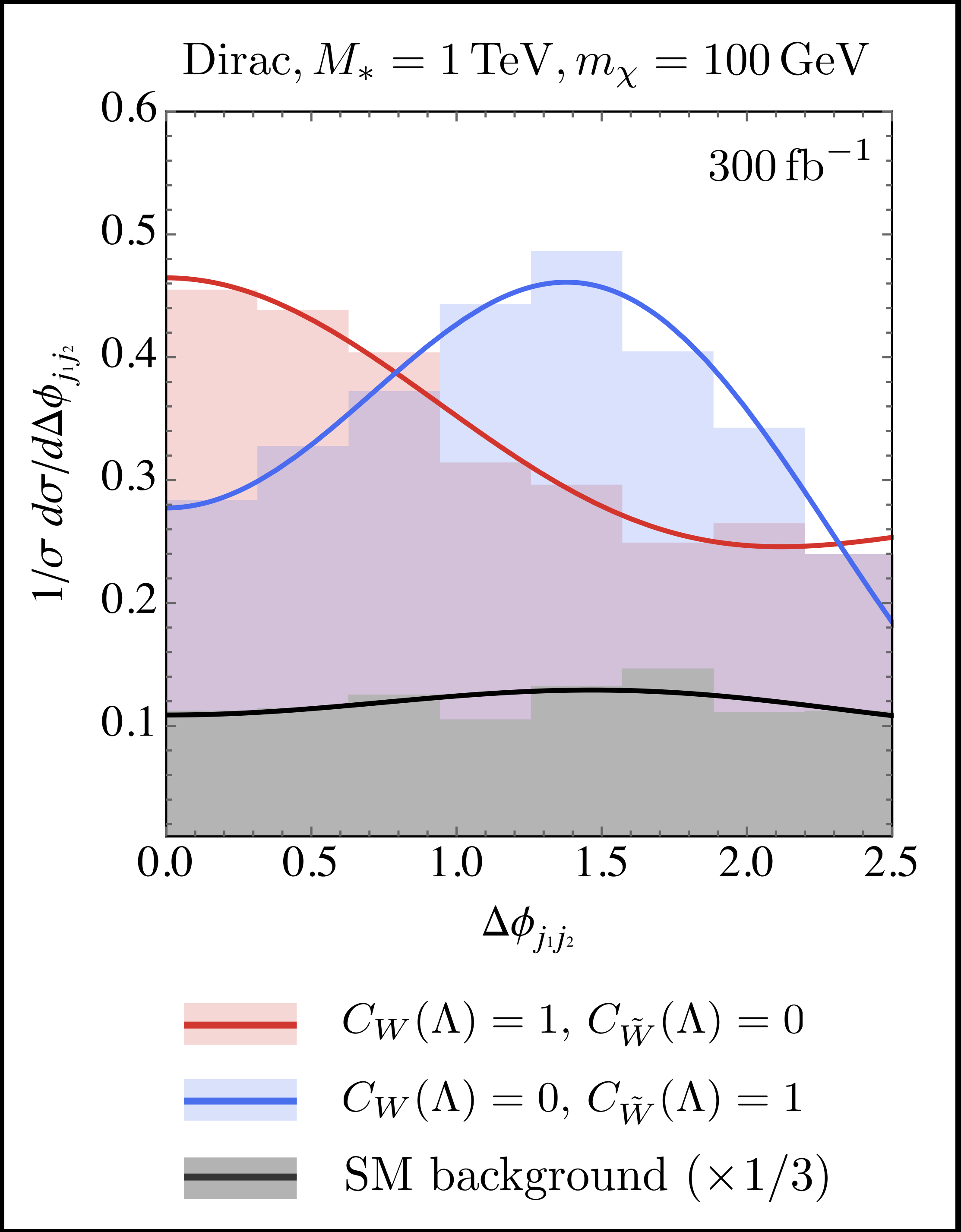
⇓ $300\,\text{fb}^{-1}$

$$(a_2/a_0)_{W+\text{SM}} = 0.15 \pm 0.10$$

$$(a_2/a_0)_{\tilde{W}+\text{SM}} = -0.45 \pm 0.14$$

$$(a_2/a_0)_{\text{SM}} = -0.12 \pm 0.22$$

significance: 2.7, 2.4, 5.1



[Crivellin, UH & Hibbs, 1501.00907]

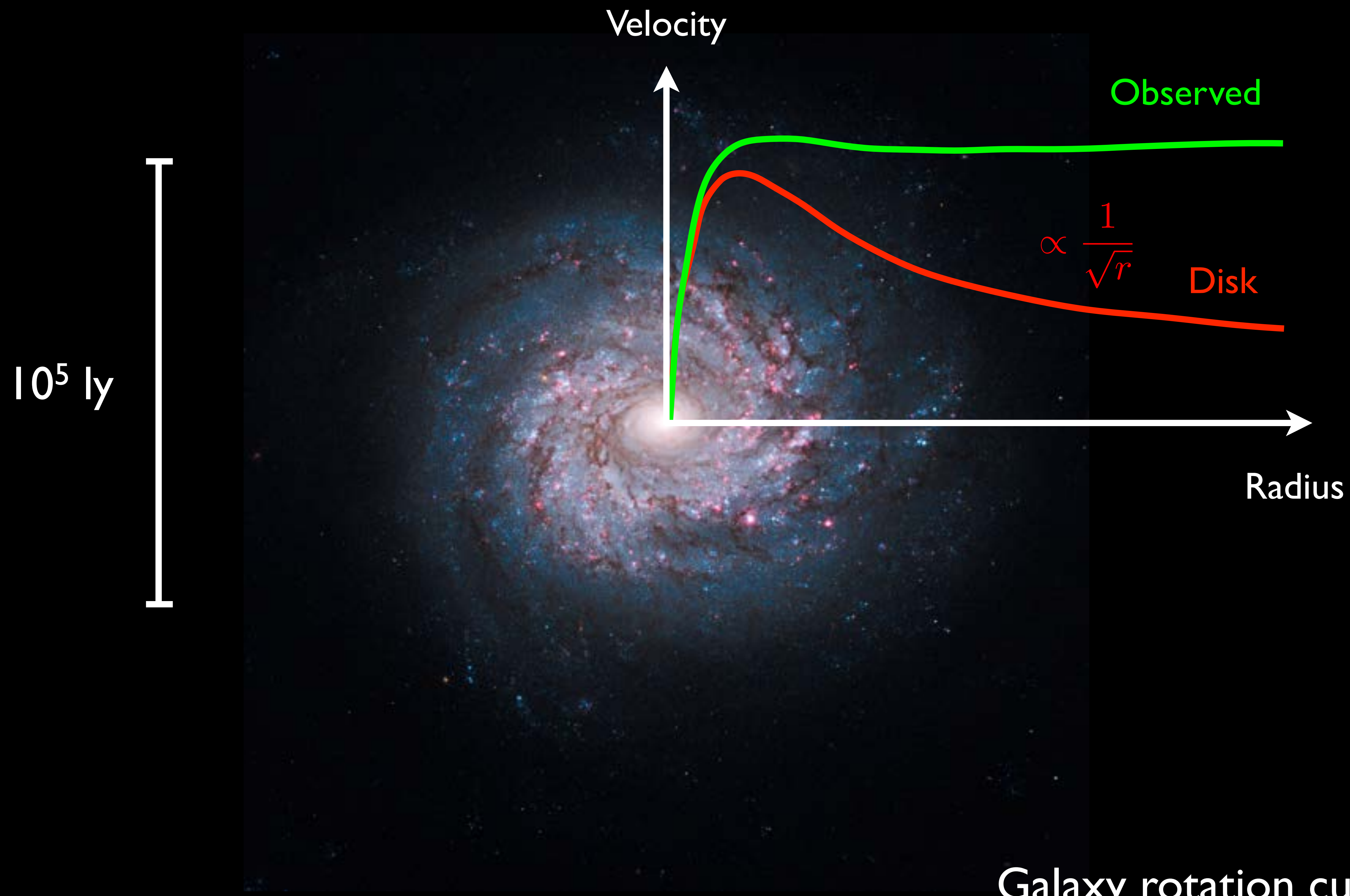
Conclusions

- With start of LHC run-2, collider searches for $E_{T,miss}$ signatures are soon to explore new territory & large statistics expected at phase-1 & -2 upgrades at 14 TeV have potential to revolutionise our understanding of DM

- New theoretical developments that allow for a better description of signals both in context of DM effective field theory & simplified models will help to exploit full physics potential of LHC

- Studies of 2-particle correlations in 2j + $E_{T,miss}$, $t\bar{t}$ + $E_{T,miss}$, etc. can provide information on structure of DM-SM couplings. Important to harness these ideas at LHC run-2

Evidence for dark matter



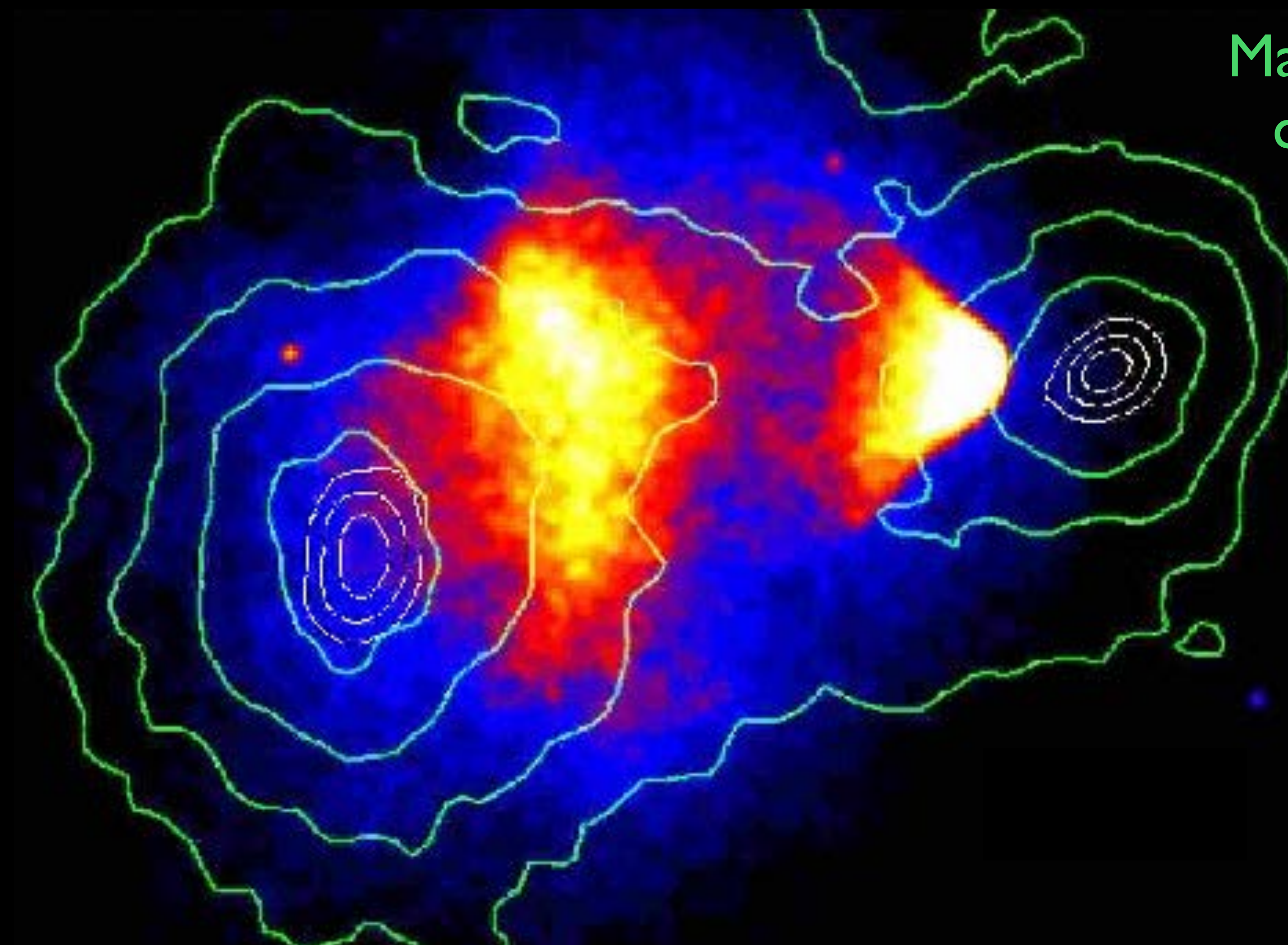
Galaxy rotation curves

Evidence for dark matter

Bullet cluster

10^7 ly

Mass density contours

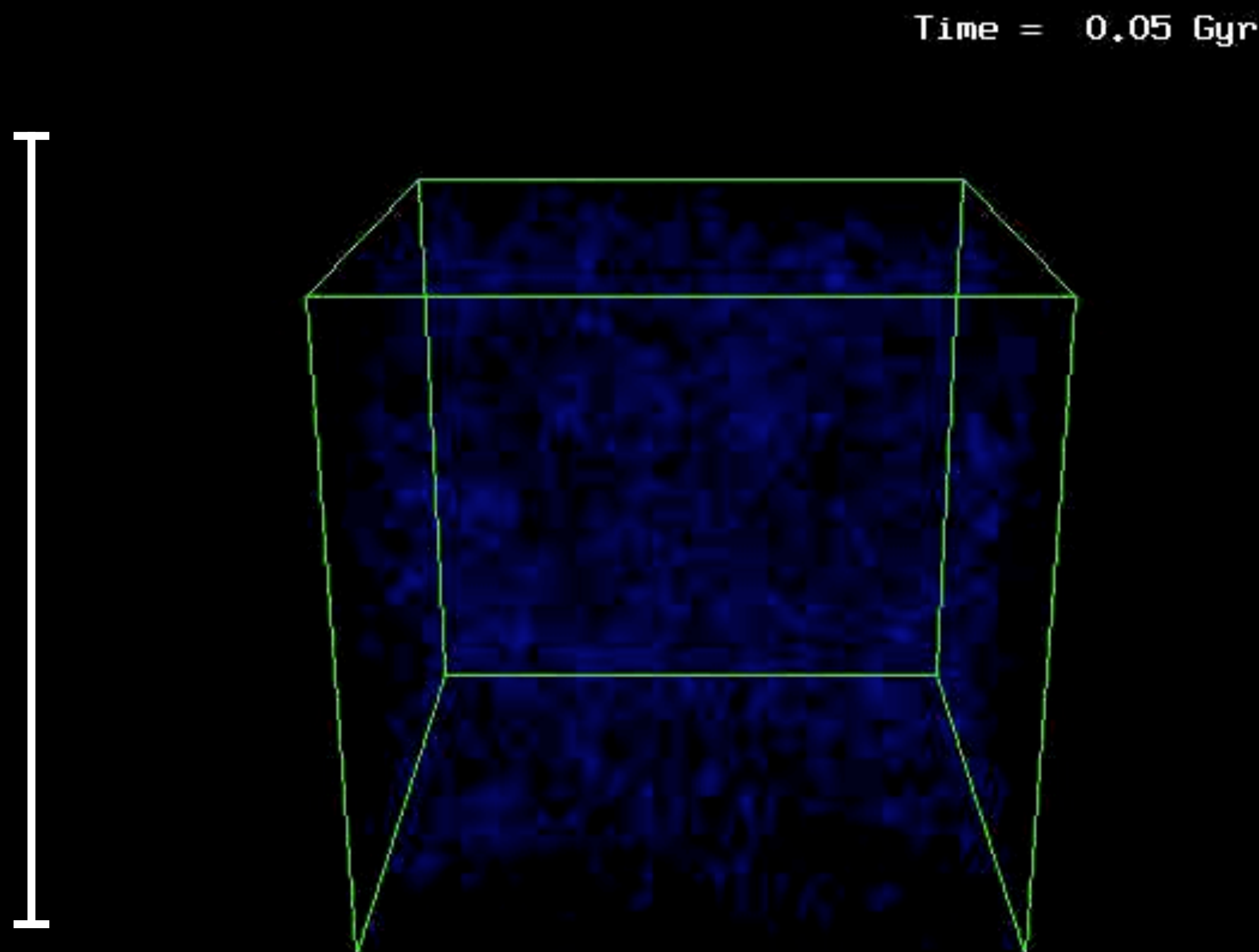


X-ray image

Gravitational lensing

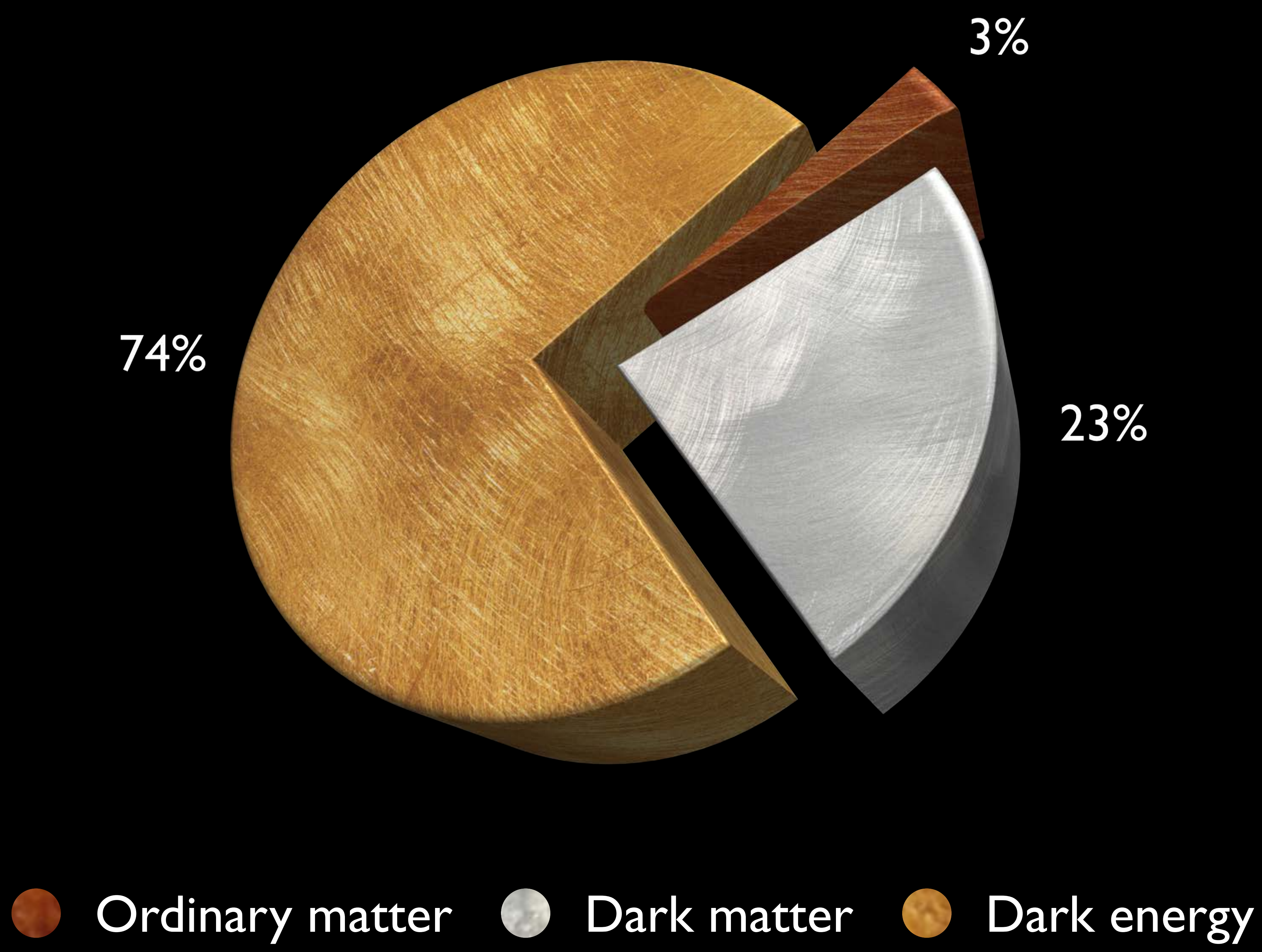
Evidence for dark matter

10^9 ly



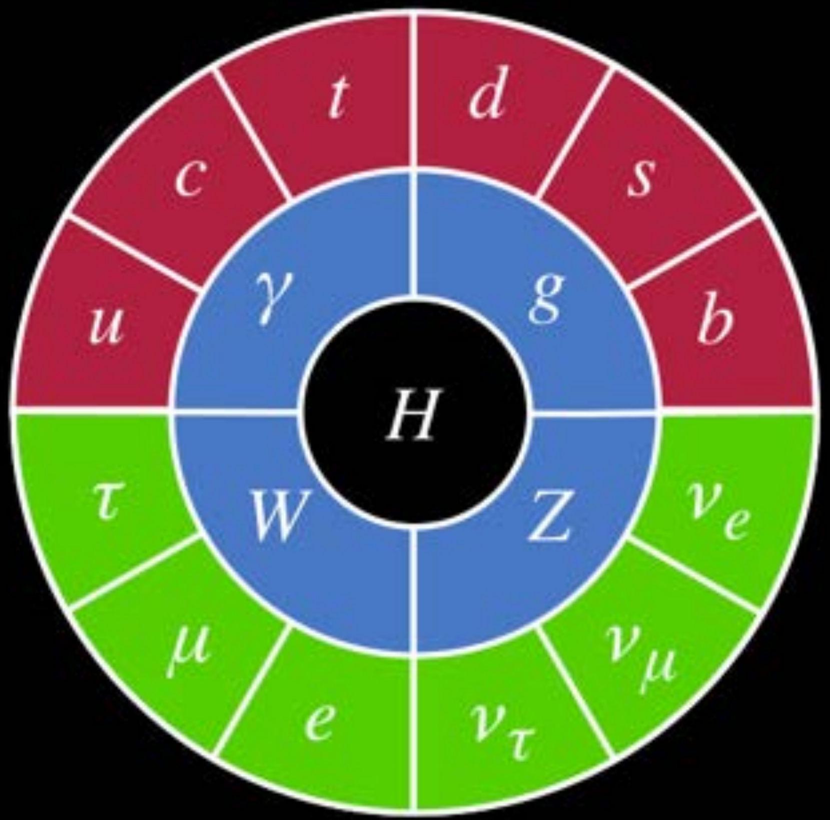
Structure formation

Content of Universe



But what is dark matter?

- As a particle physicist I want to know how dark matter (DM) fits into a particle description
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime exceeding the age of the Universe)
- Nothing in the Standard Model of particle physics fits the profile



Standard Model (SM)

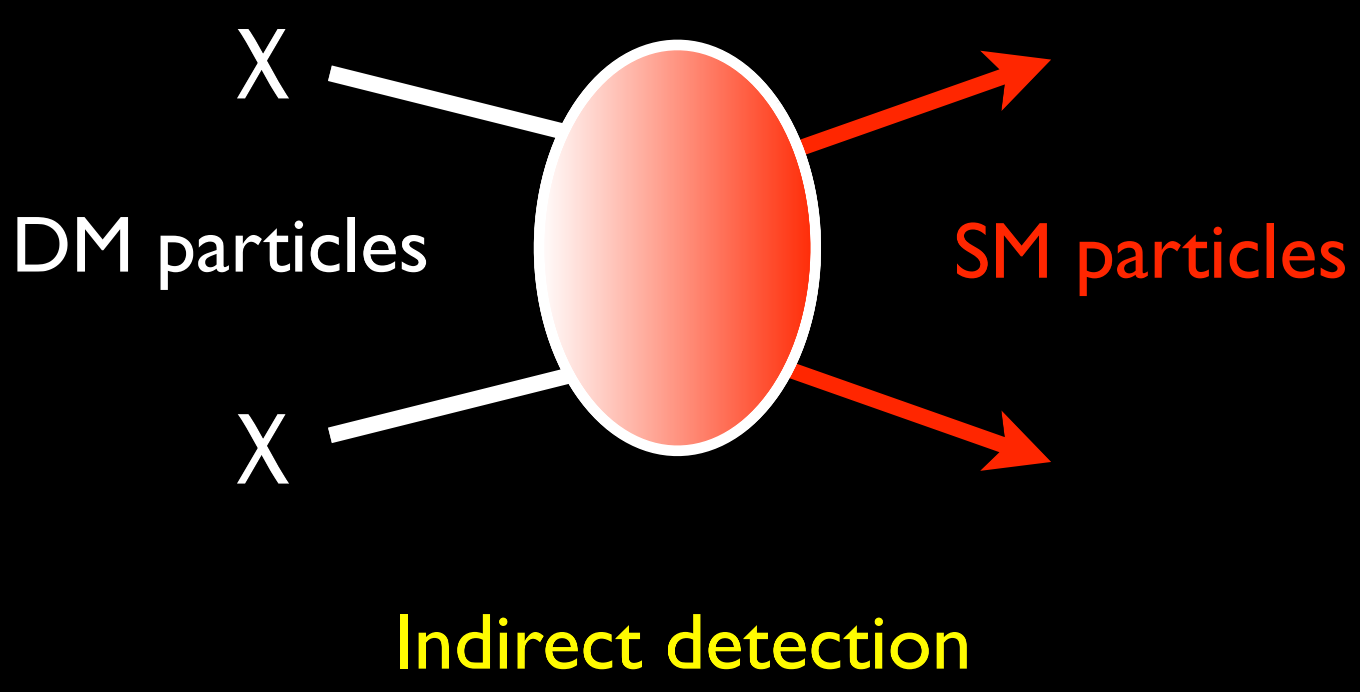
DM questionnaire

- [ ] Mass: ________
- [ ] Spin: ________
- [ ] Lifetime: ________

Couplings:

- [x] Gravity
- [ ] Weak interaction?
- [ ] Higgs?
- [ ] Quarks/gluons?
- [ ] Leptons?
- [ ] Thermal relic?
    - [ ] Yes
    - [ ] No

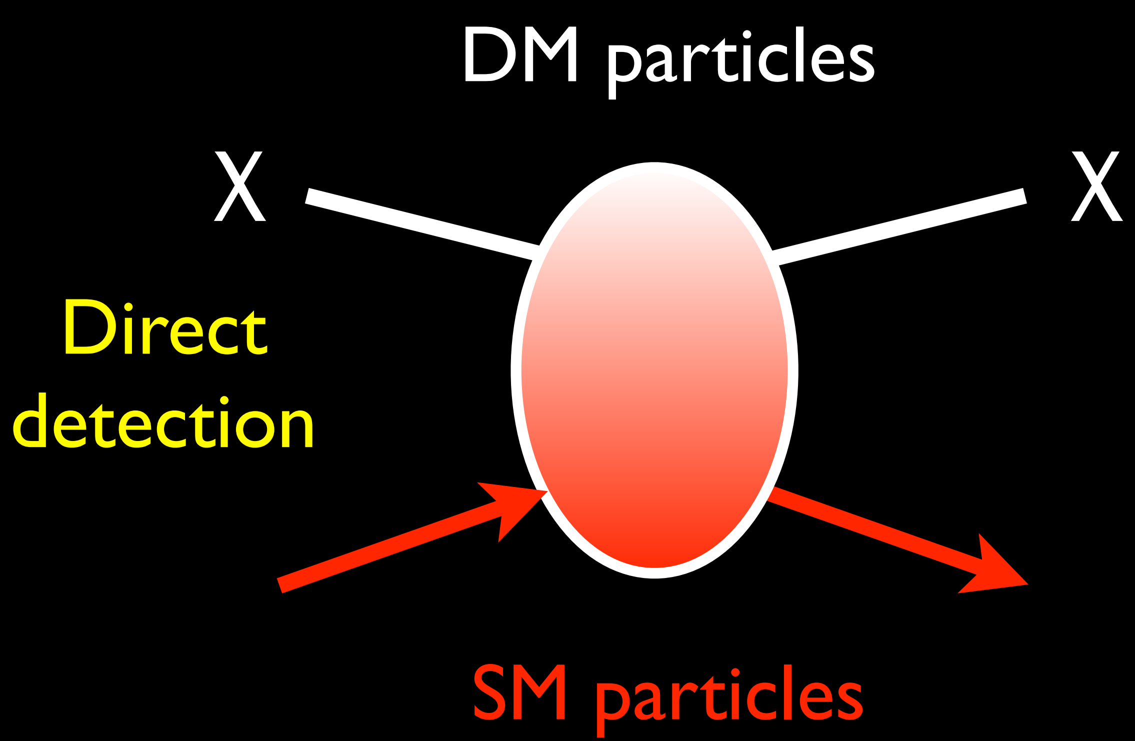
Particle probes of DM



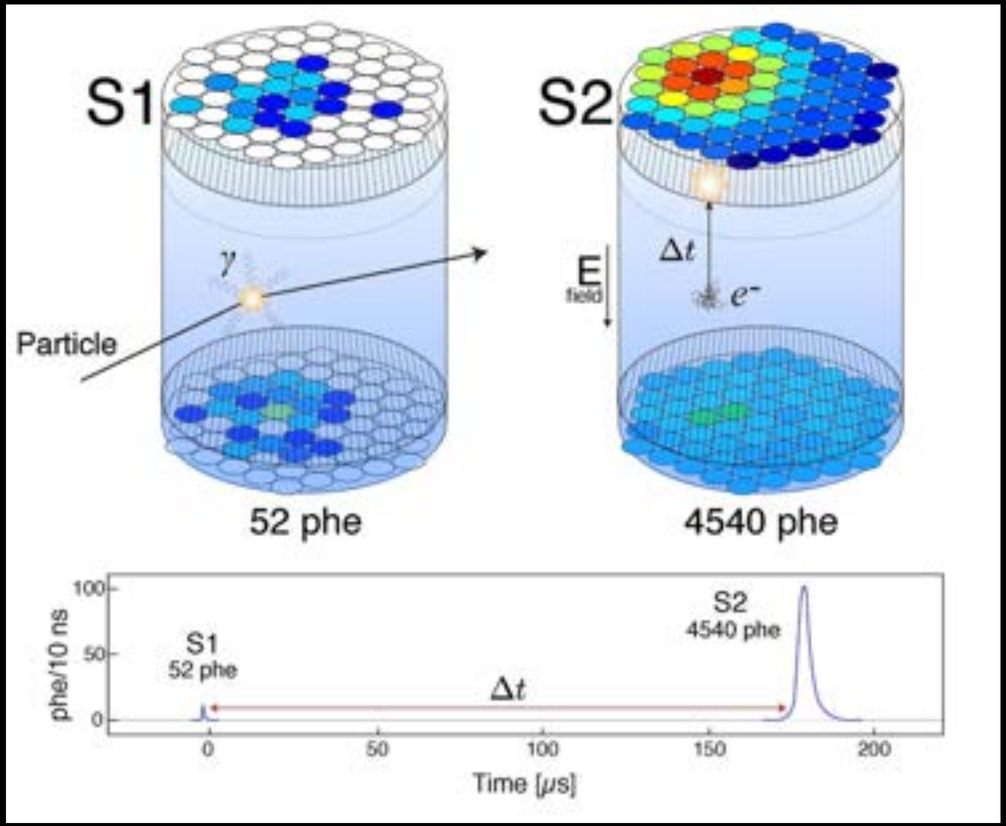
Fermi telescope

- The common theme of searches for DM is that all methods are determined by how the DM particles interact with the SM

Particle probes of DM



LUX detector



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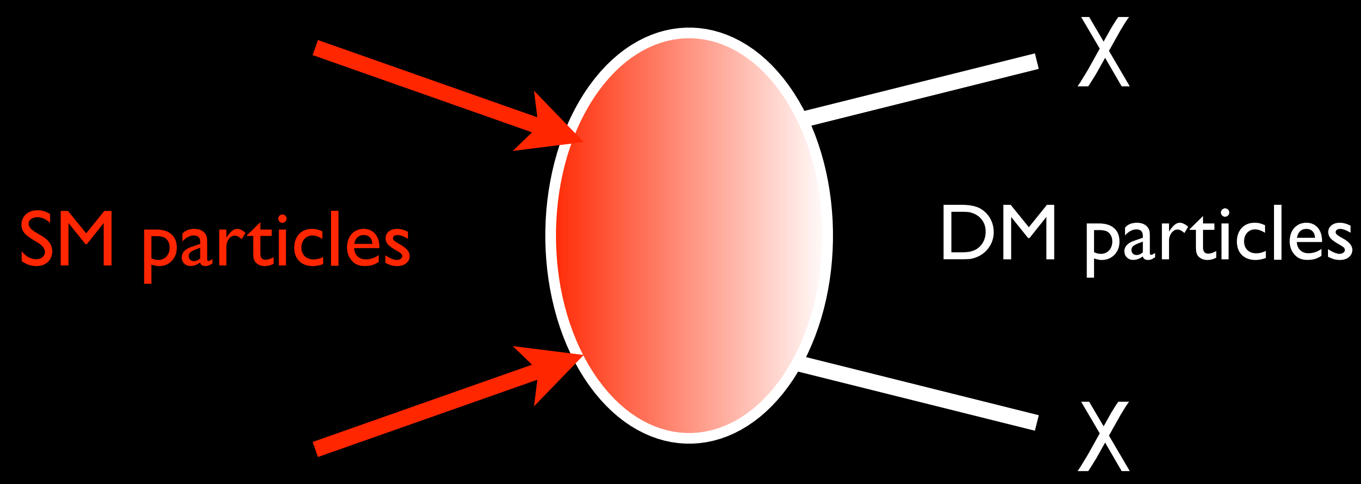
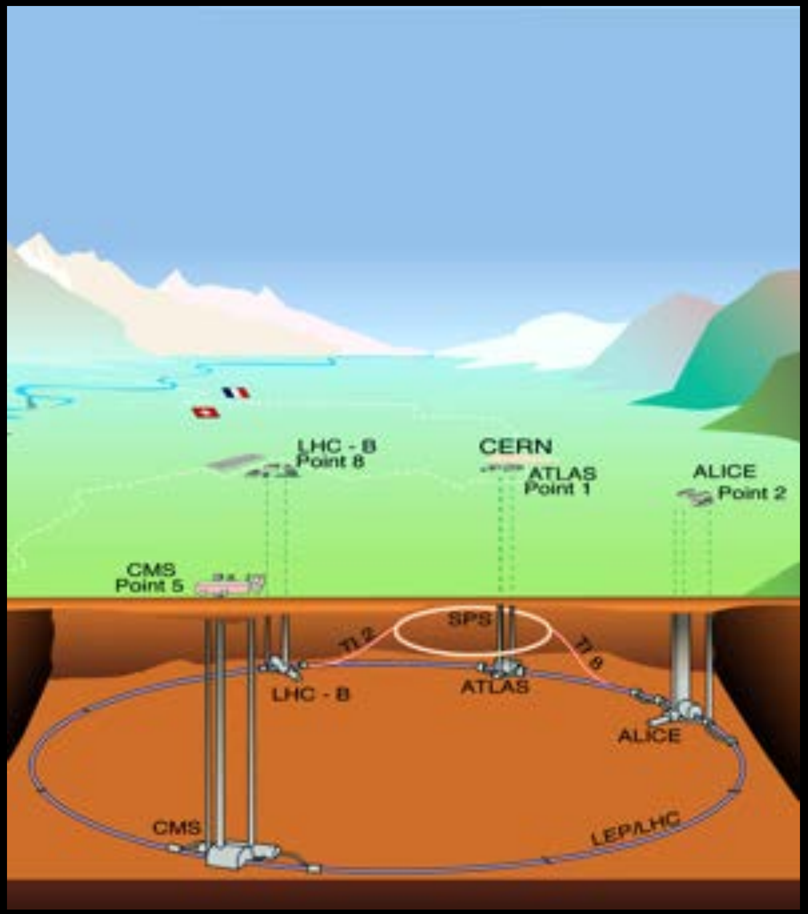
Particle probes of DM



Collider searches

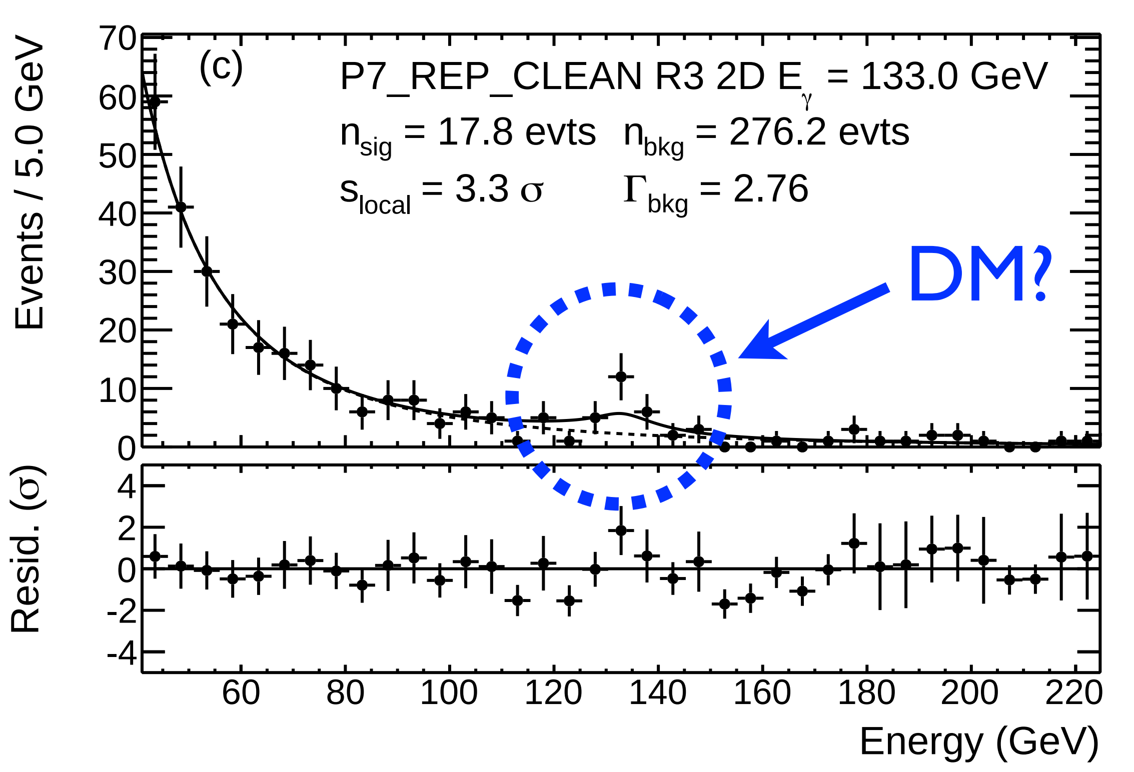
LHC at CERN



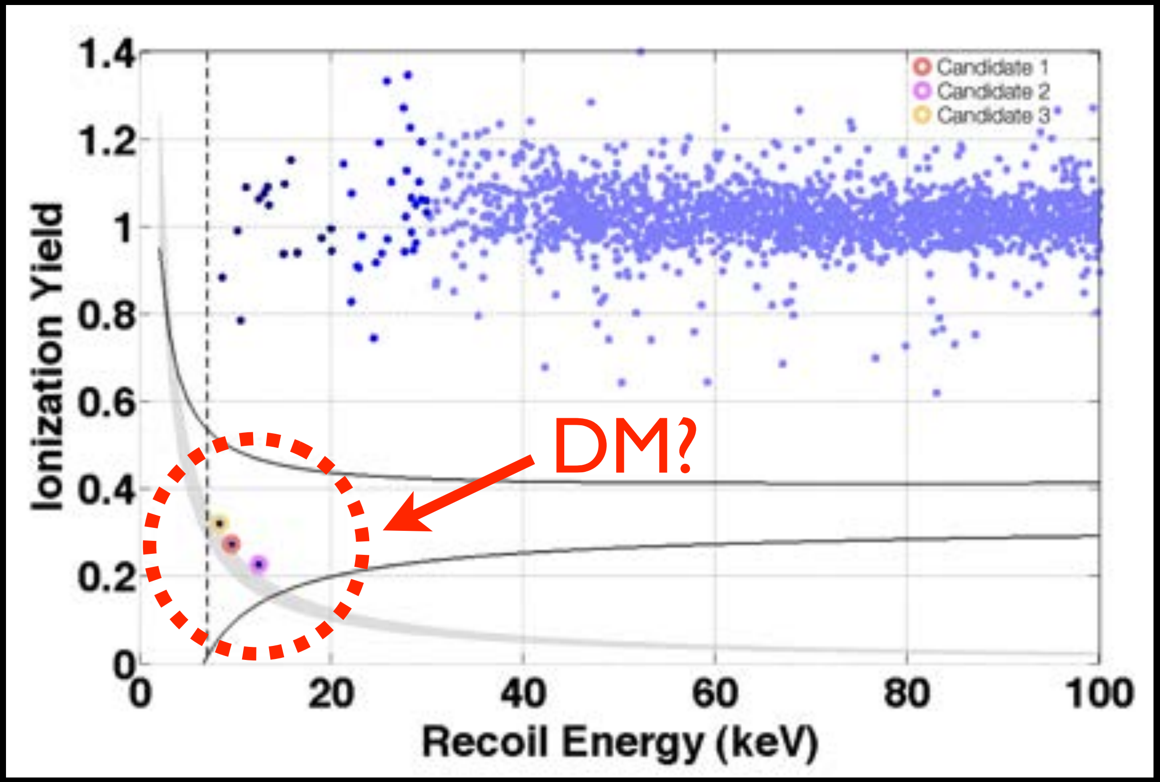
- The common theme of searches for DM is that all methods are determined by how the DM particles interact with the SM

Has DM already been seen?

Fermi-LAT



CDMS II

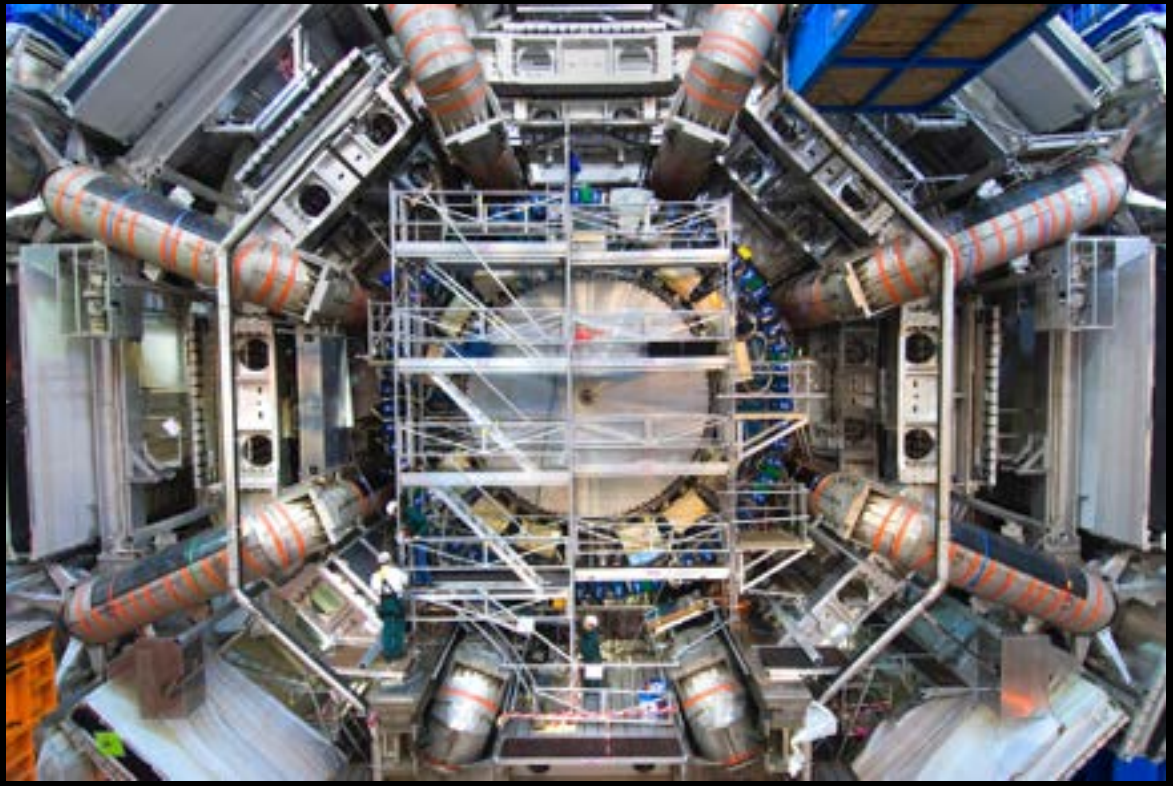


- Claims for DM discovery have been made based on the results of indirect and direct detection experiments. Since the backgrounds in both cases are large and uncertain (and given that we have no control over the signal), claims remain unsubstantiated

DM production at the LHC

- If DM particles are sufficiently light and couple to quarks or gluons, we should be able to produce them at the LHC
- By studying DM production in proton-proton collisions, we are testing the inverse of the process that kept DM in thermal equilibrium in the early Universe
- LHC may allow us to produce other states of "dark sector", which are no longer present in the Universe today

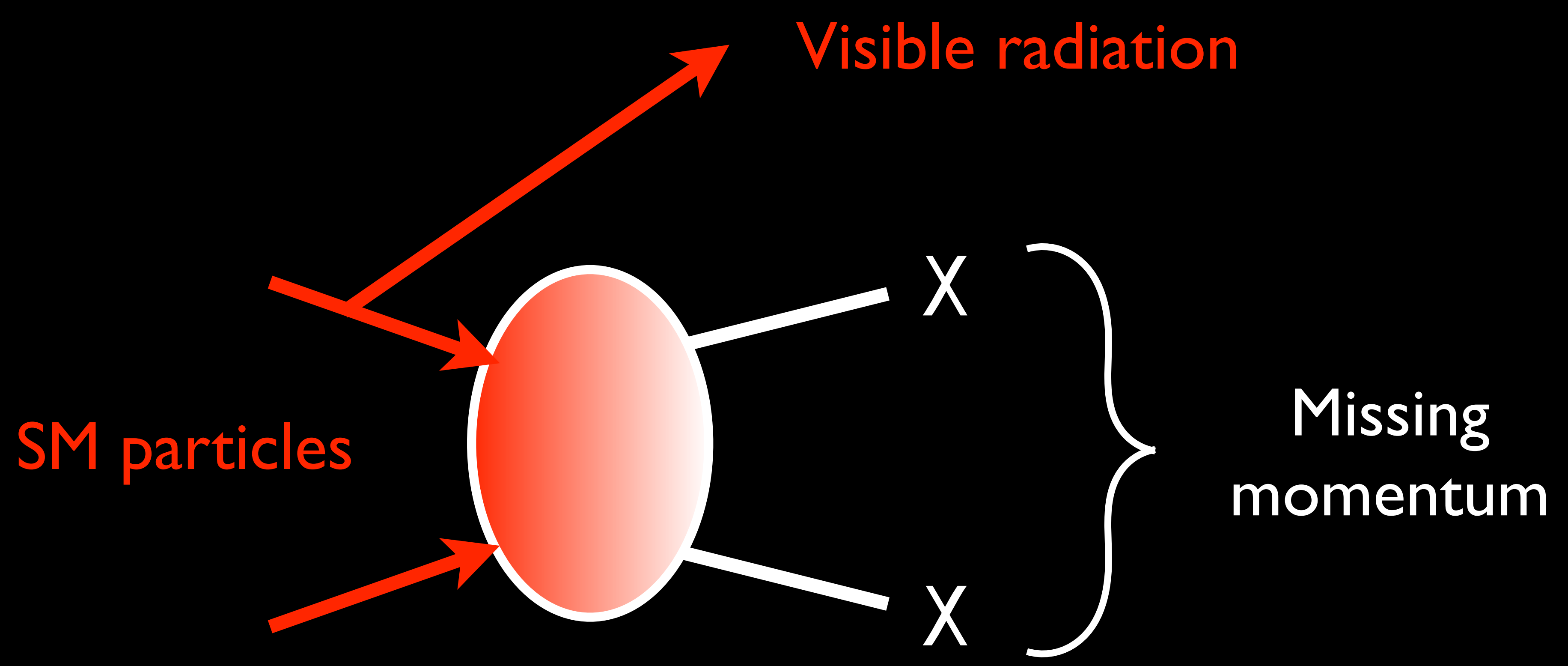
ATLAS detector



46 m $\times$ 25 m,
7000 t,
3000 km of cables, …

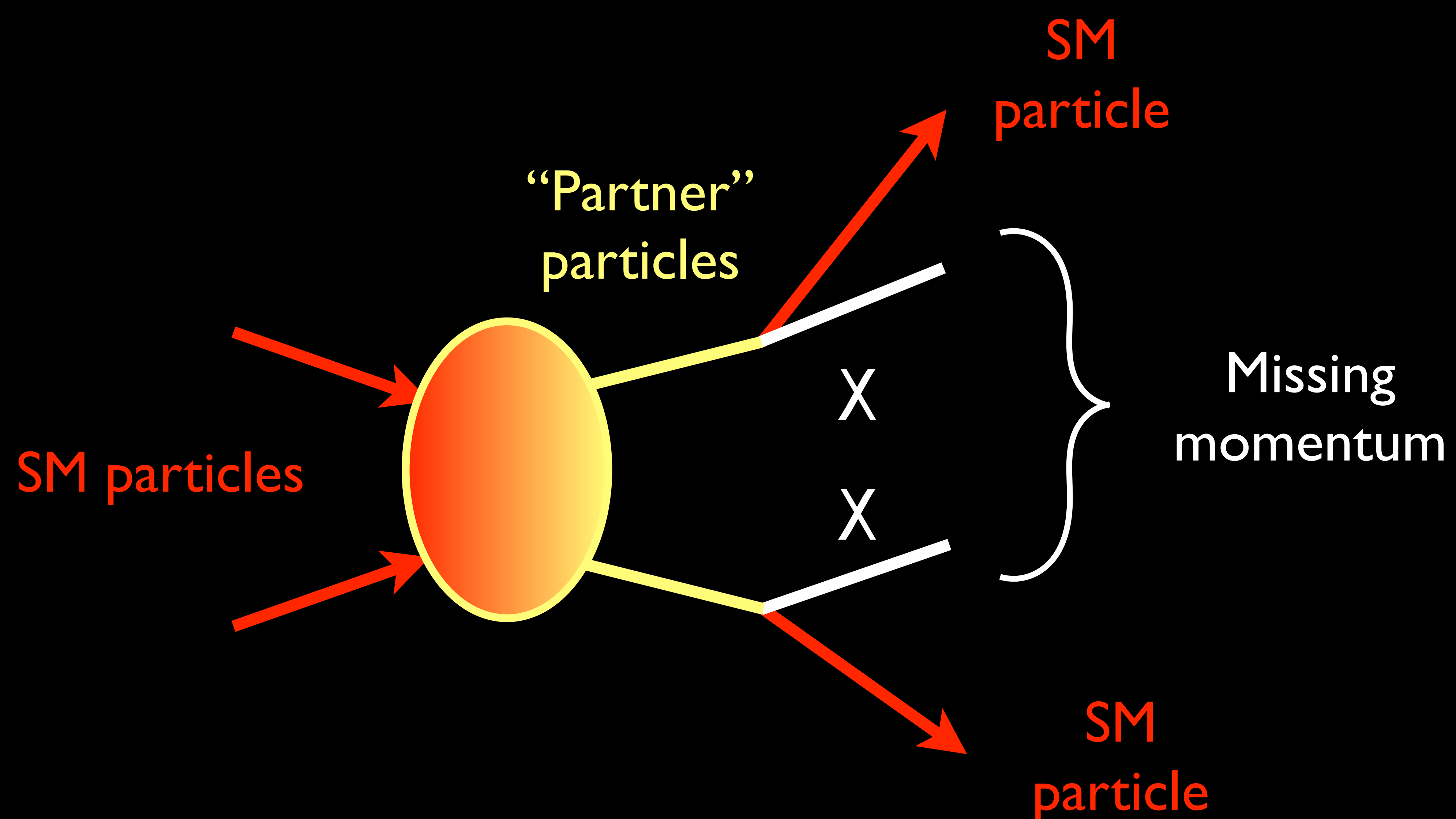
How to see the invisible?

- The DM particles interact so weakly that they are expected to pass out of the detector components without any significant interaction, making them effectively invisible (much like neutrinos)
- One way to “see” DM particles nonetheless, works by looking for “missing momentum” and additional SM radiation



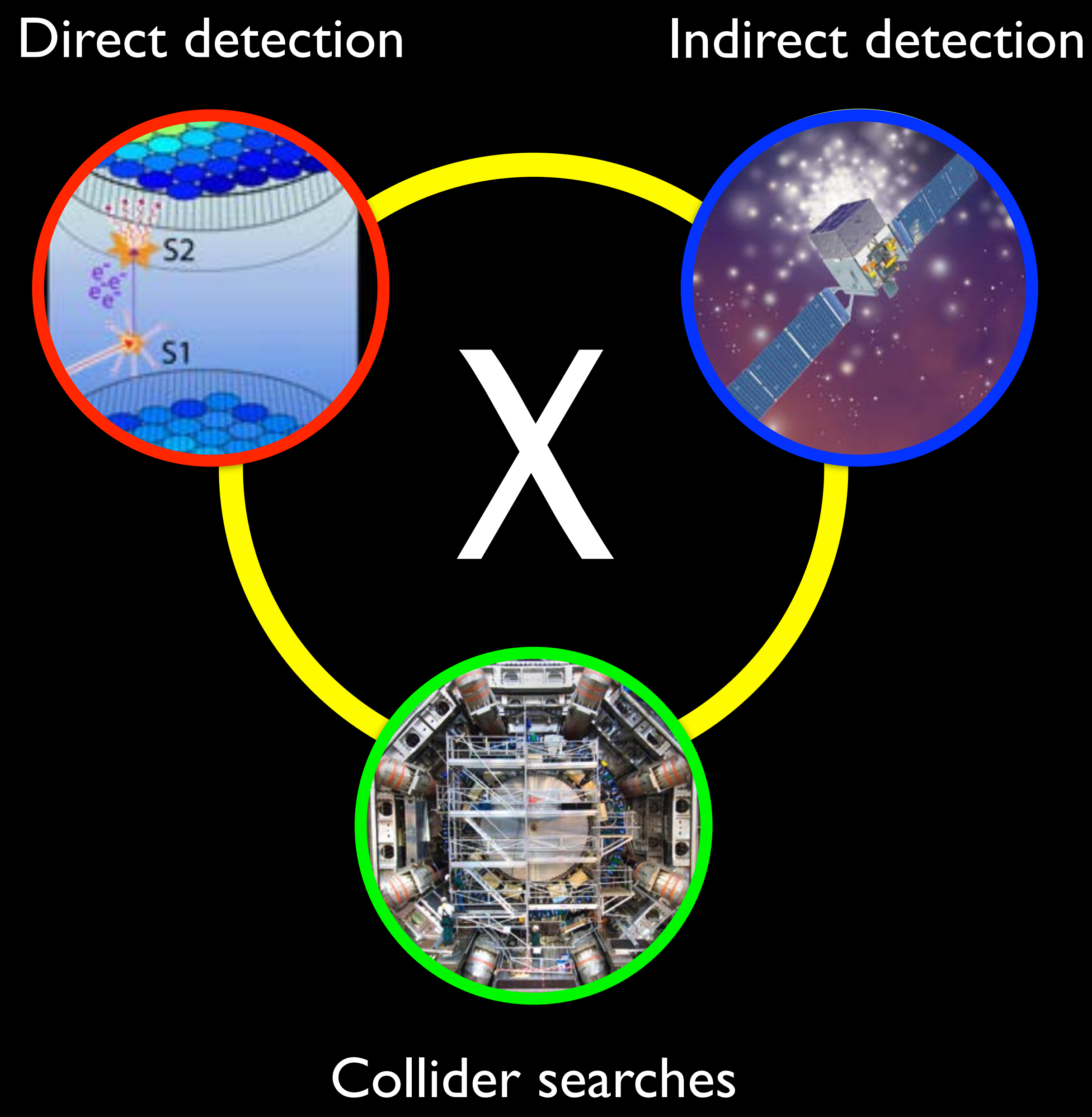
How to see the invisible?

- Second way to try to detect SM, based on production of "partner" particles that decay to DM and SM particles

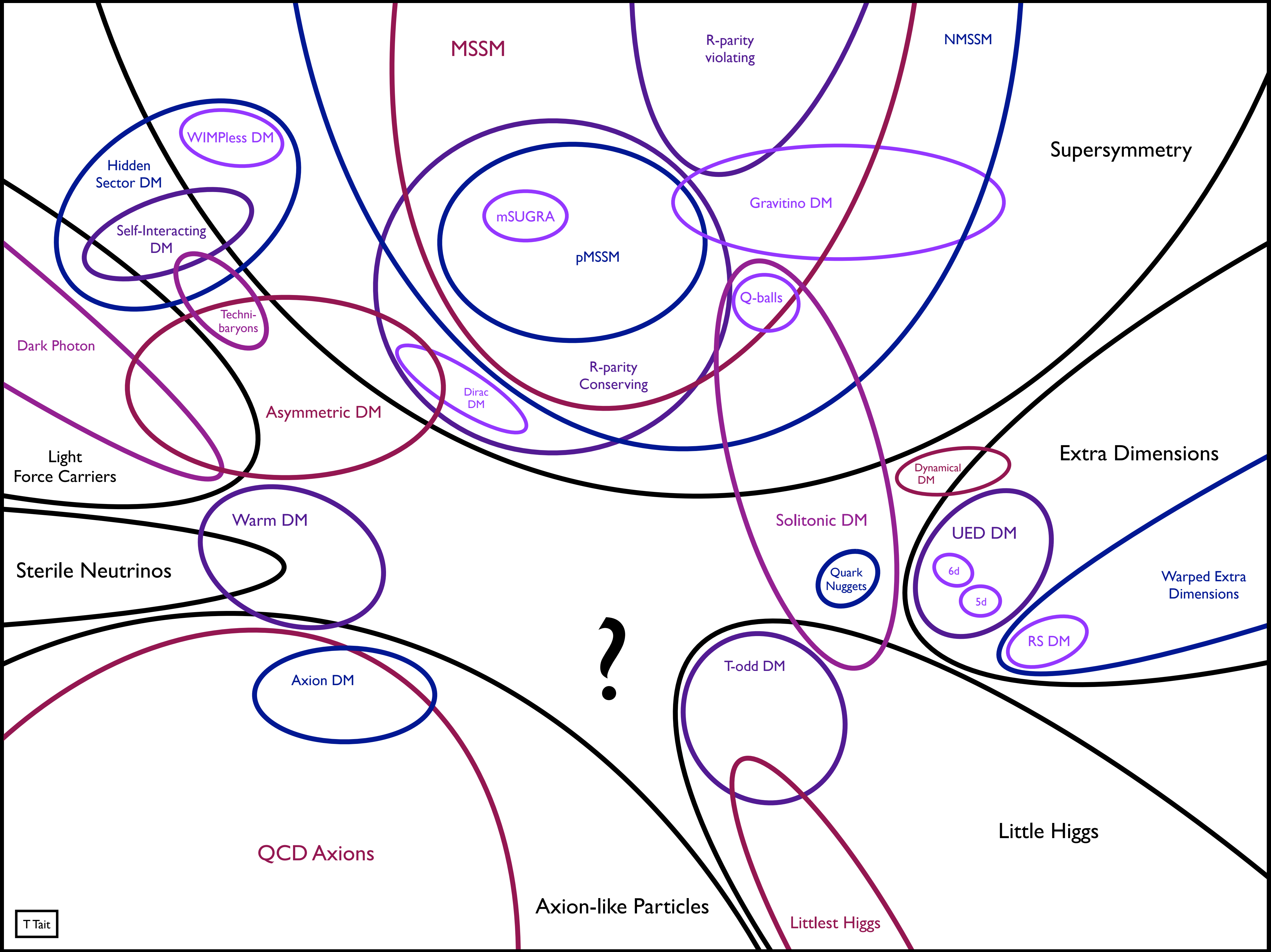


But we also need a DM theory

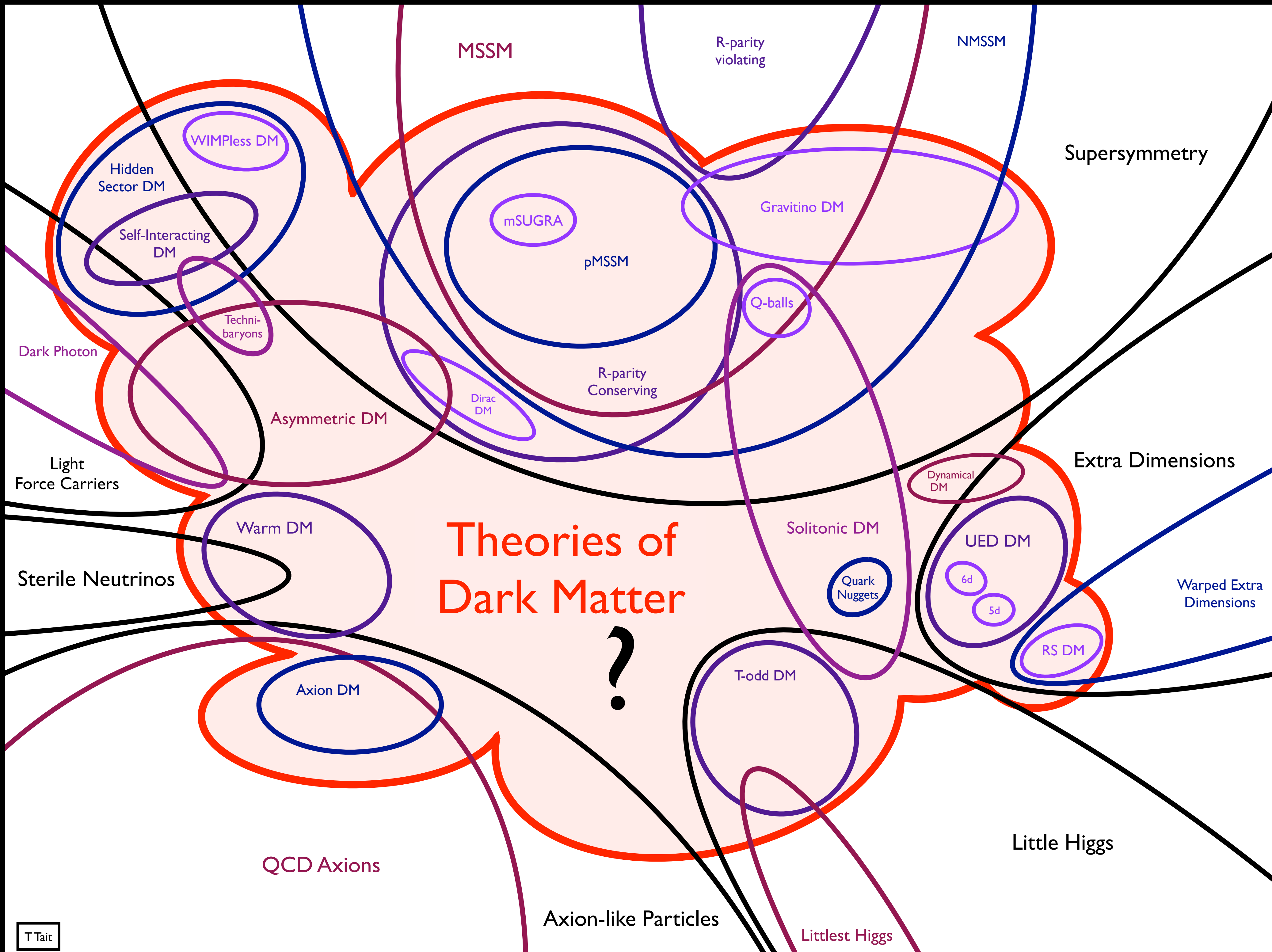
- The three main search strategies perform quite different measurements. Without a theoretical model of DM, we cannot compare the results
- If evidence for DM is found in one type of search, we can predict in a given model the signals that should be seen in other searches



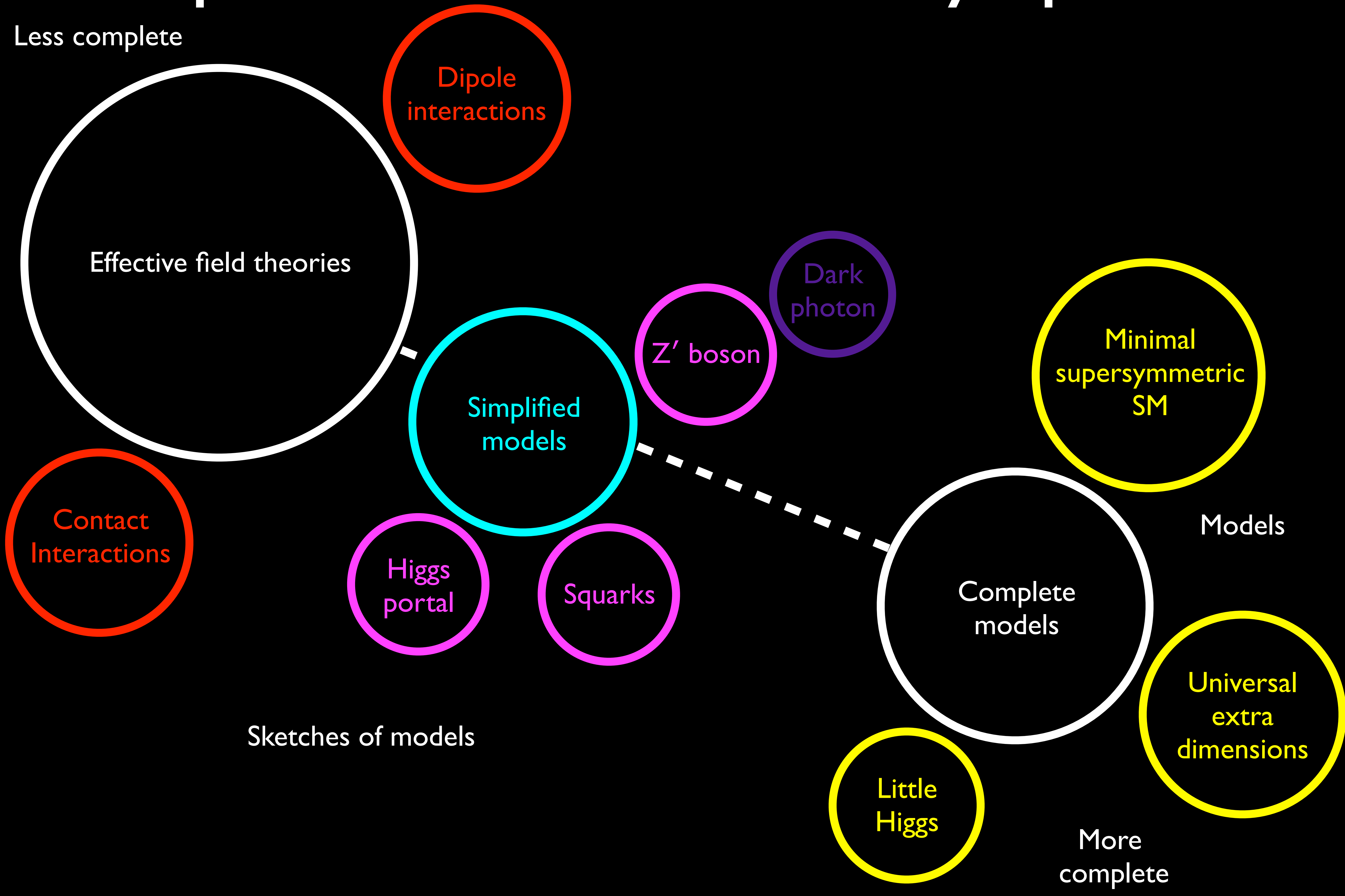
No lack of theoretical models



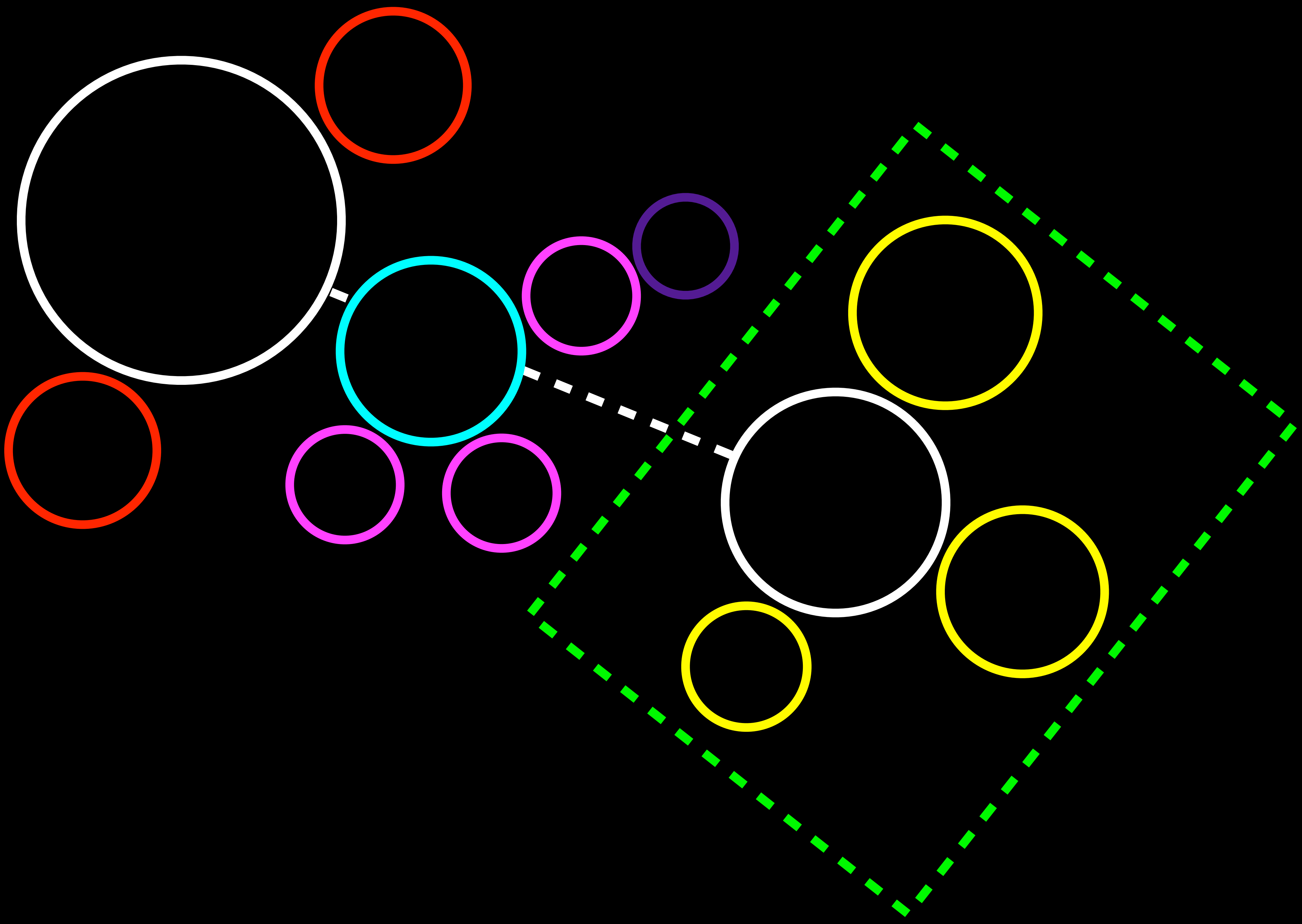
No lack of theoretical models



Spectrum of DM theory space

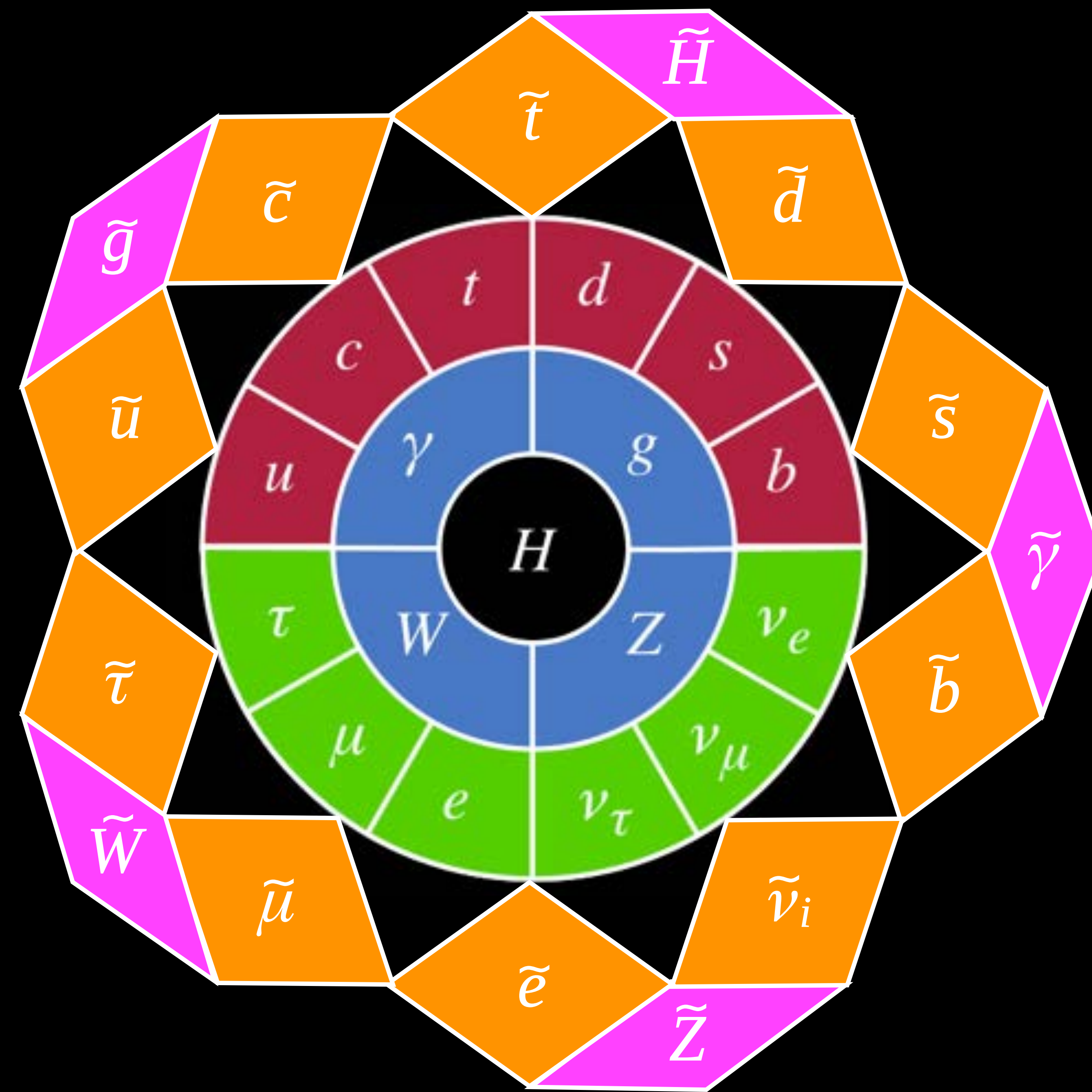


Complete DM theories



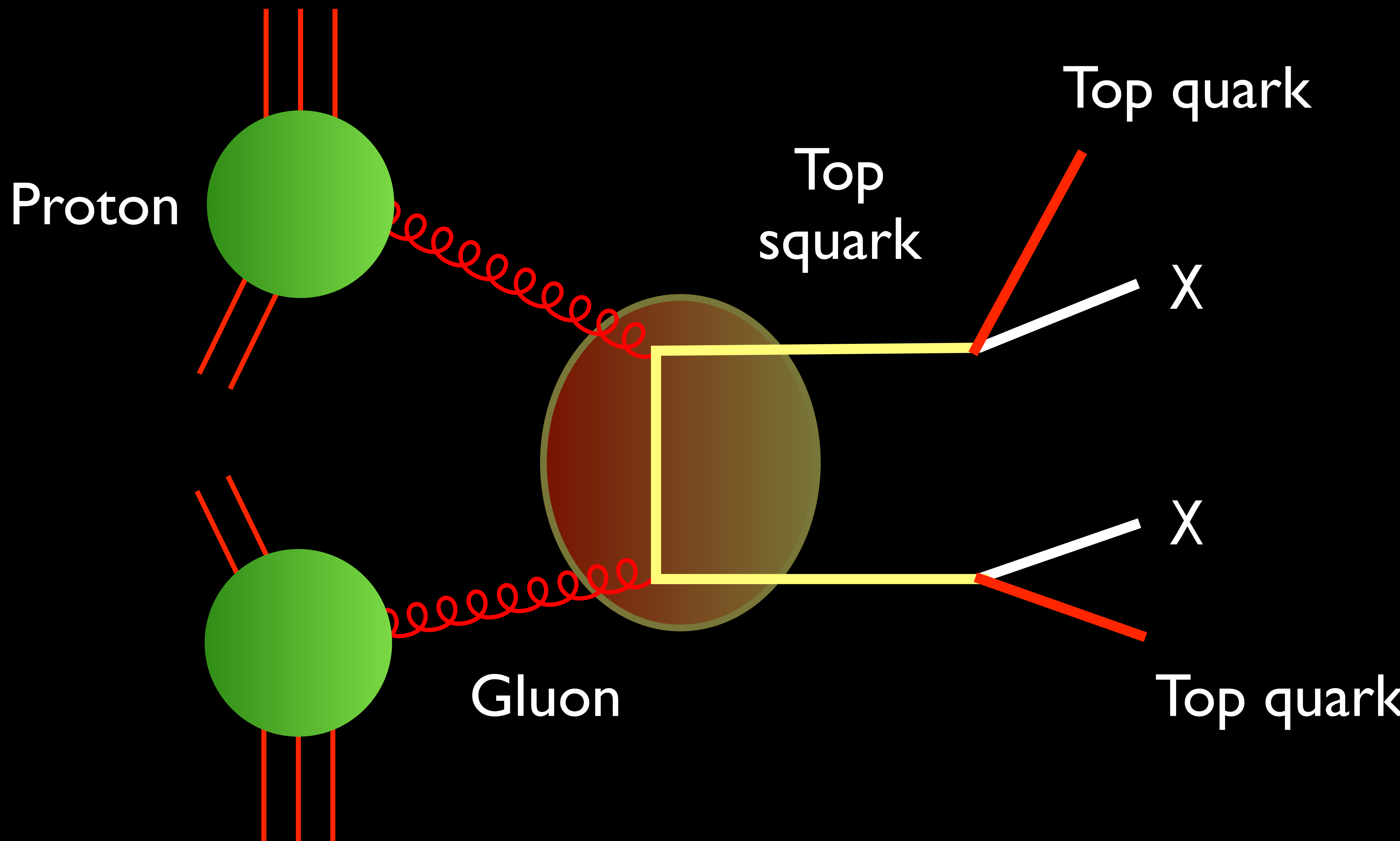
Complete = complicated

- All complete DM models add more particles to the SM, most of which are not viable DM candidates
- The classical example is the MSSM, in which each SM particle gets its own “superpartner”
- In the case of the MSSM there are 20 additional parameters that can be relevant for DM physics

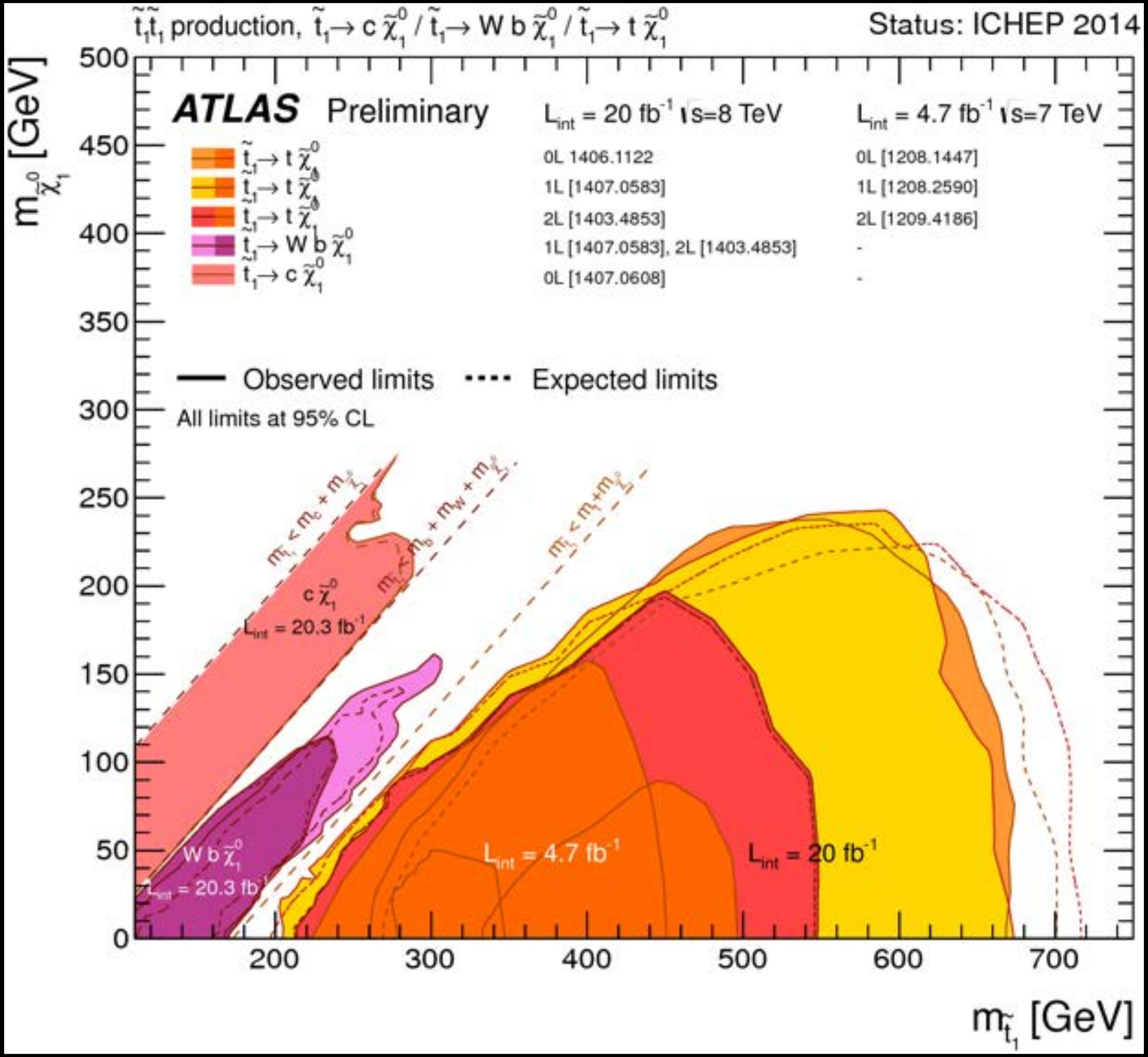


Minimal supersymmetric SM (MSSM)

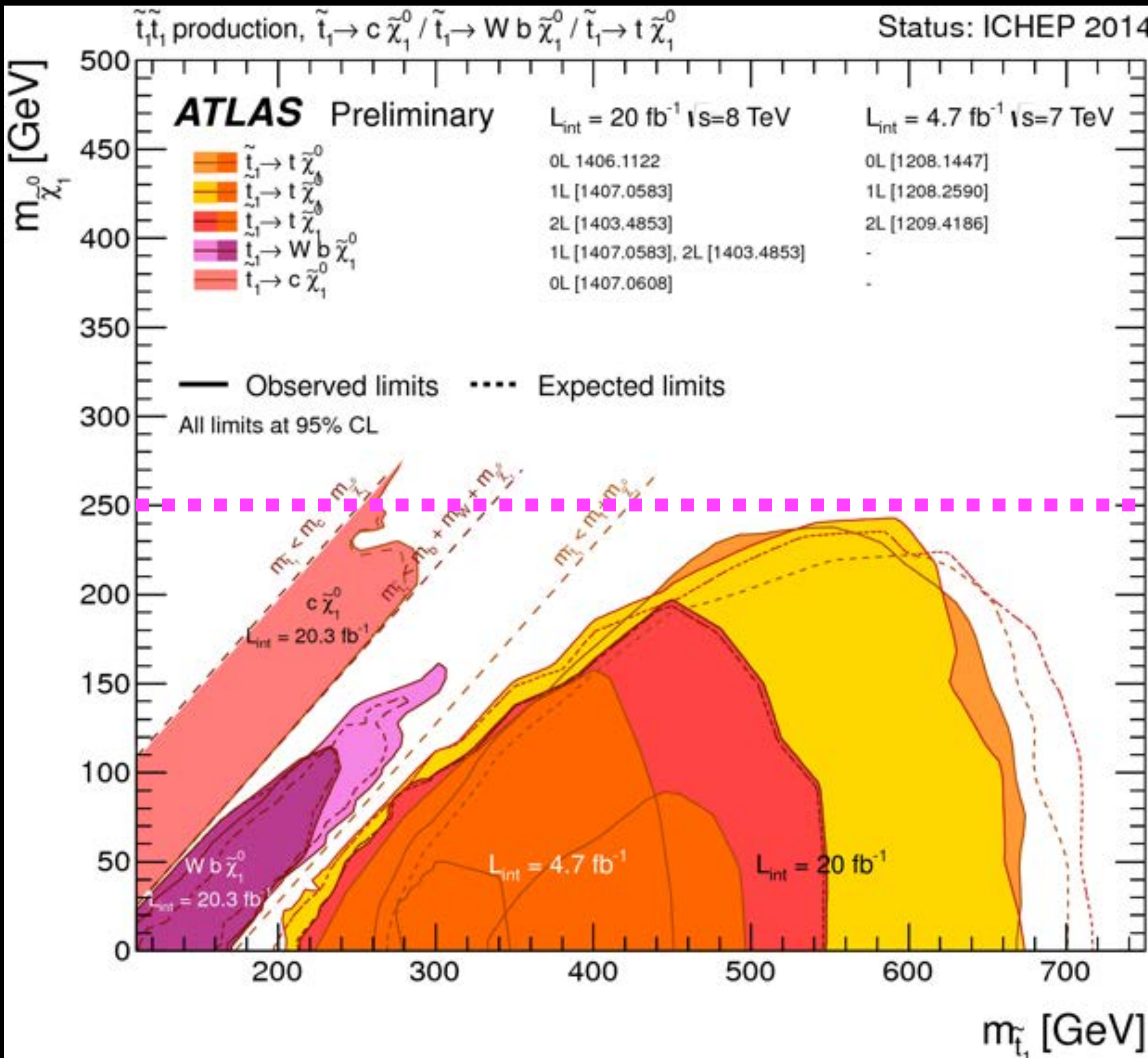
One way to produce DM in MSSM



LHC limits on DM mass in MSSM



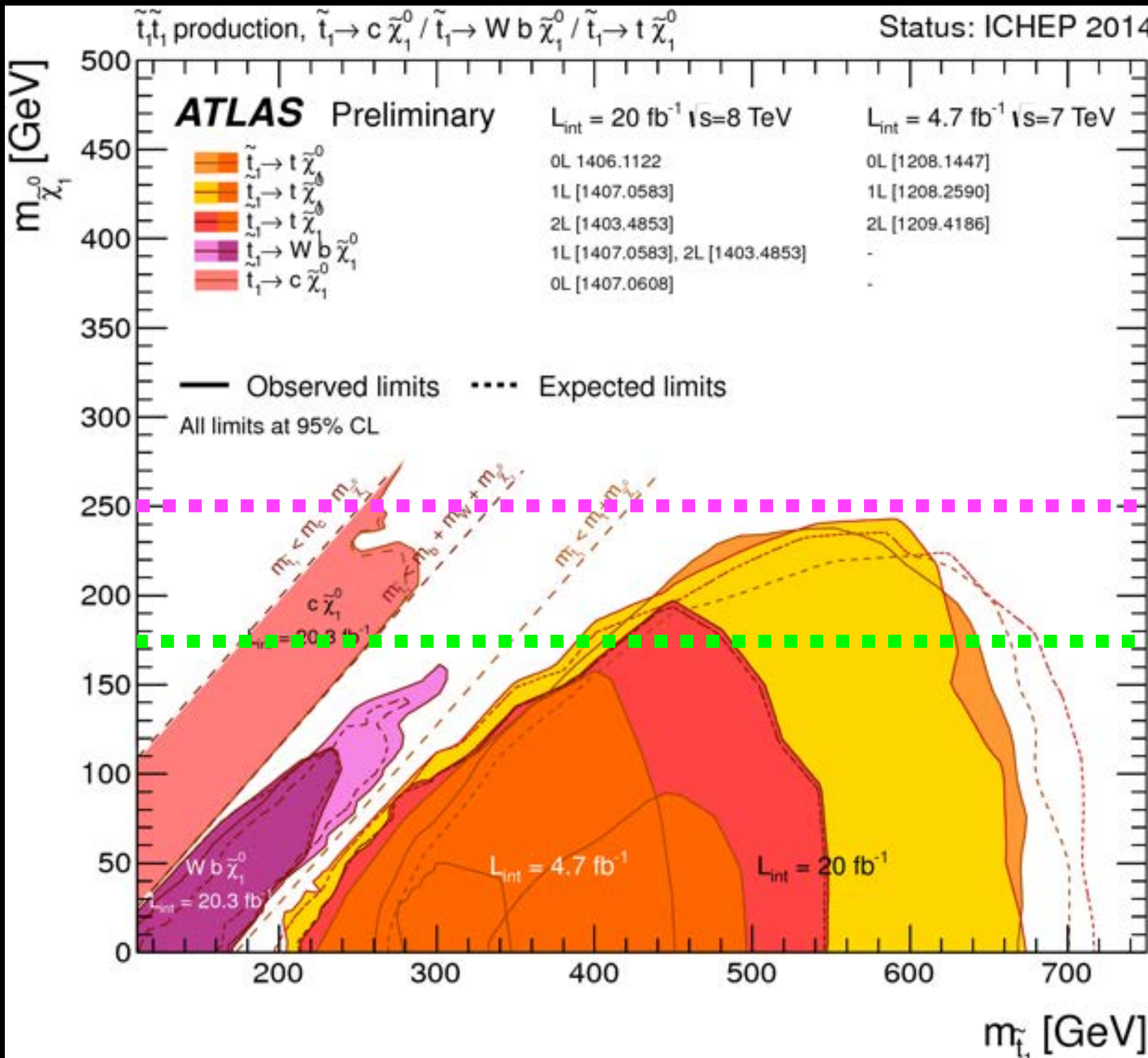
LHC limits on DM mass in MSSM



Range of DM masses unexplored by the first LHC run

250 GeV

LHC limits on DM mass in MSSM



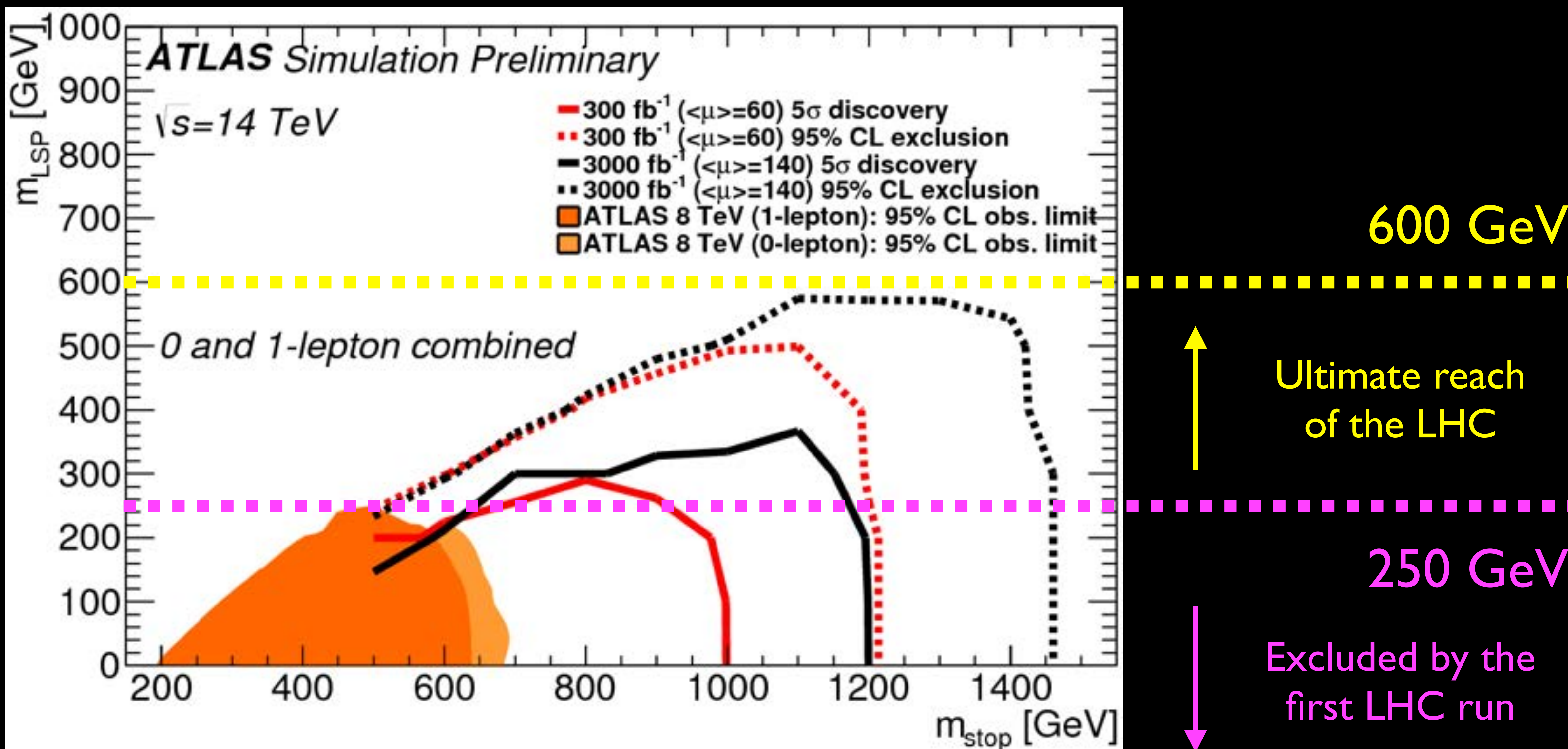
Range of DM masses unexplored by the first LHC run

250 GeV

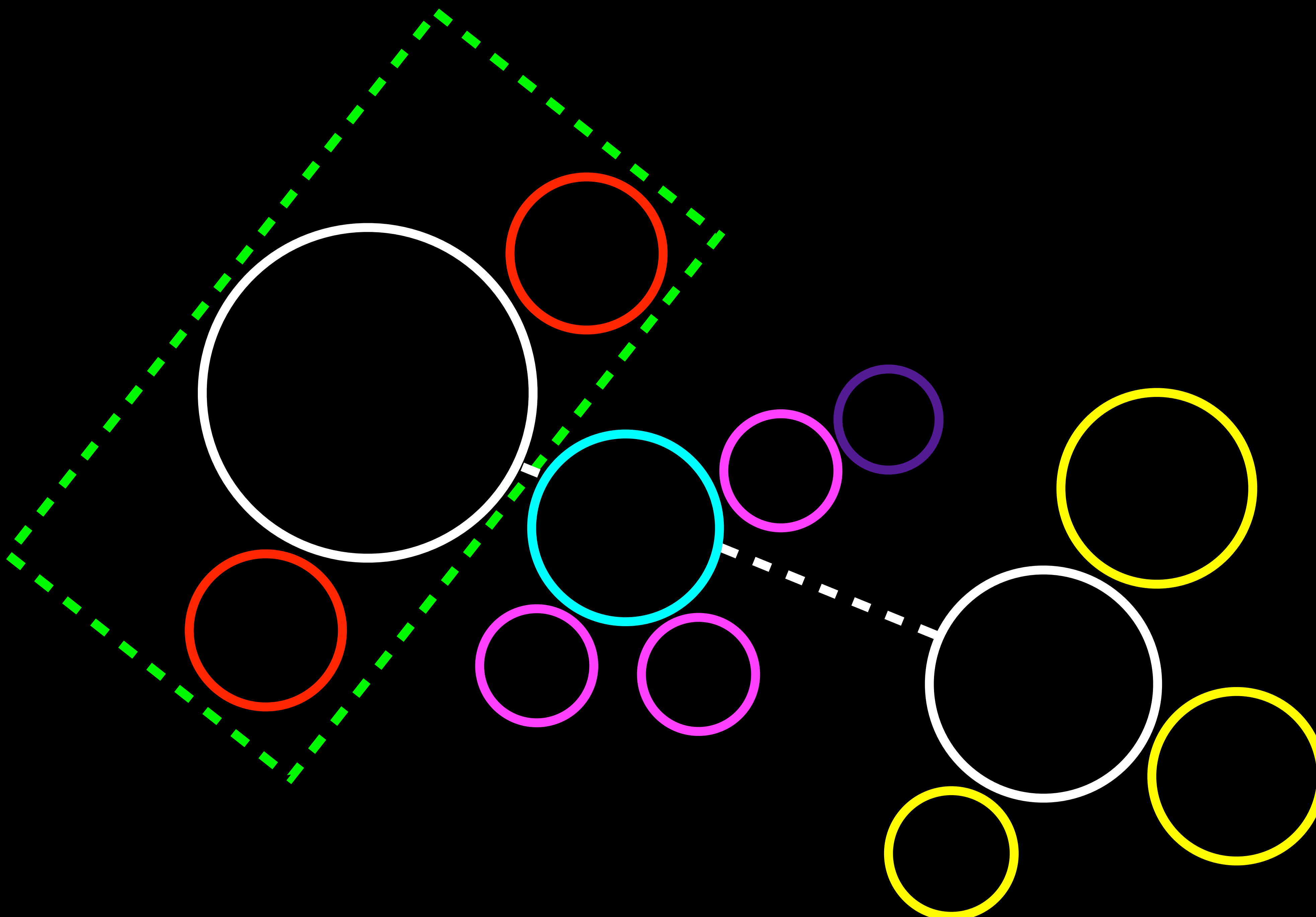
175 GeV

Masses of all the SM particles: top quark, Higgs, Z boson, …

LHC limits on DM mass in MSSM



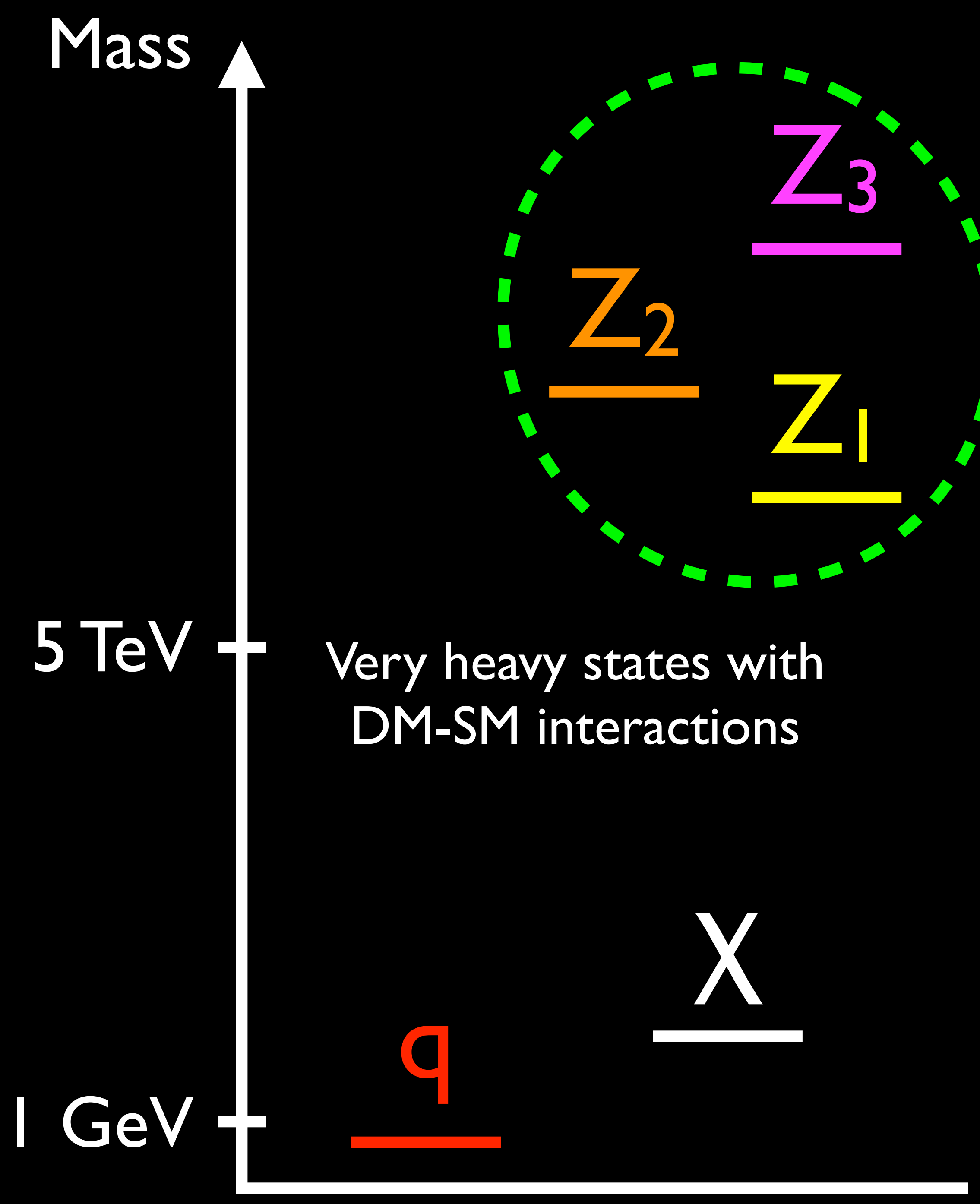
DM effective field theories



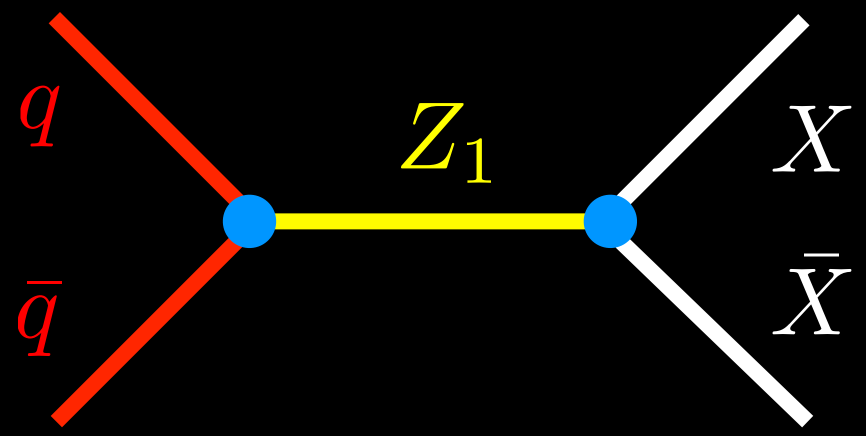
Effective = easy

- At the other end of complexity are models in which the DM particles are the only new states that can be produced at the LHC

- In such cases, effective field theory allows us to describe the DM-SM interactions mediated by all heavy particles in a simple and universal way



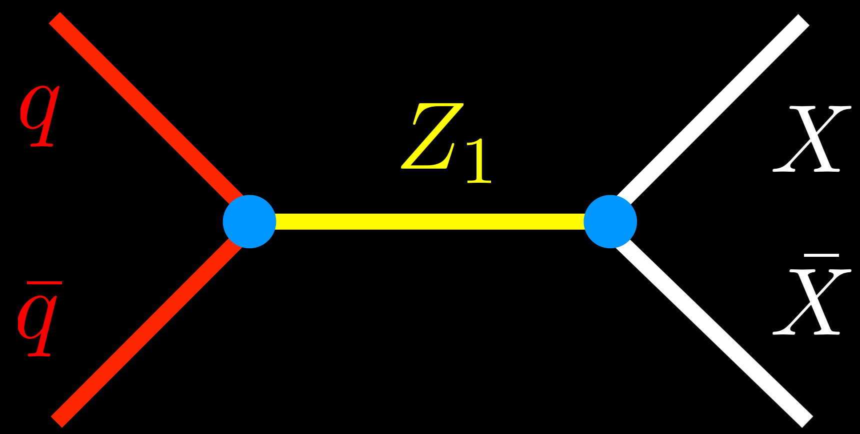
Effective field theory primer



$$= \frac{g^2}{p^2 - M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

$$p = p_{\bar{q}} + p_q = p_{\bar{X}} + p_X$$

Effective field theory primer



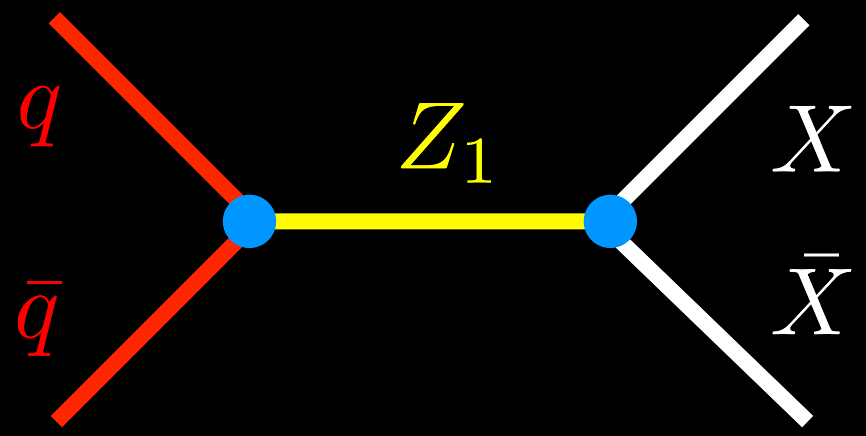
$$= \frac{g^2}{p^2 - M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

$$p = p_{\bar{q}} + p_q = p_{\bar{X}} + p_X$$

$$p^2 \ll M_{Z_1}^2$$

$$-\frac{g^2}{M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

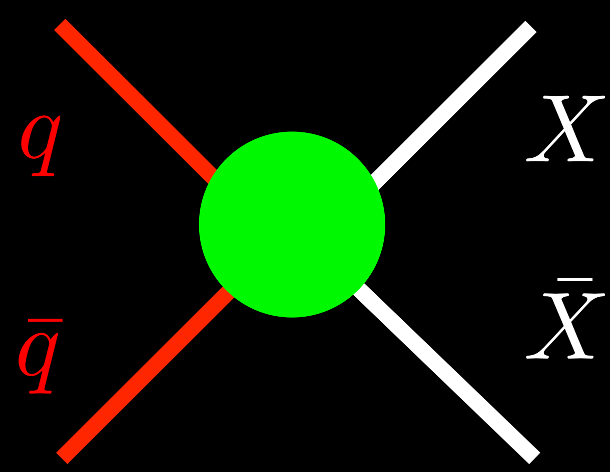
Effective field theory primer



$$= \frac{g^2}{p^2 - M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

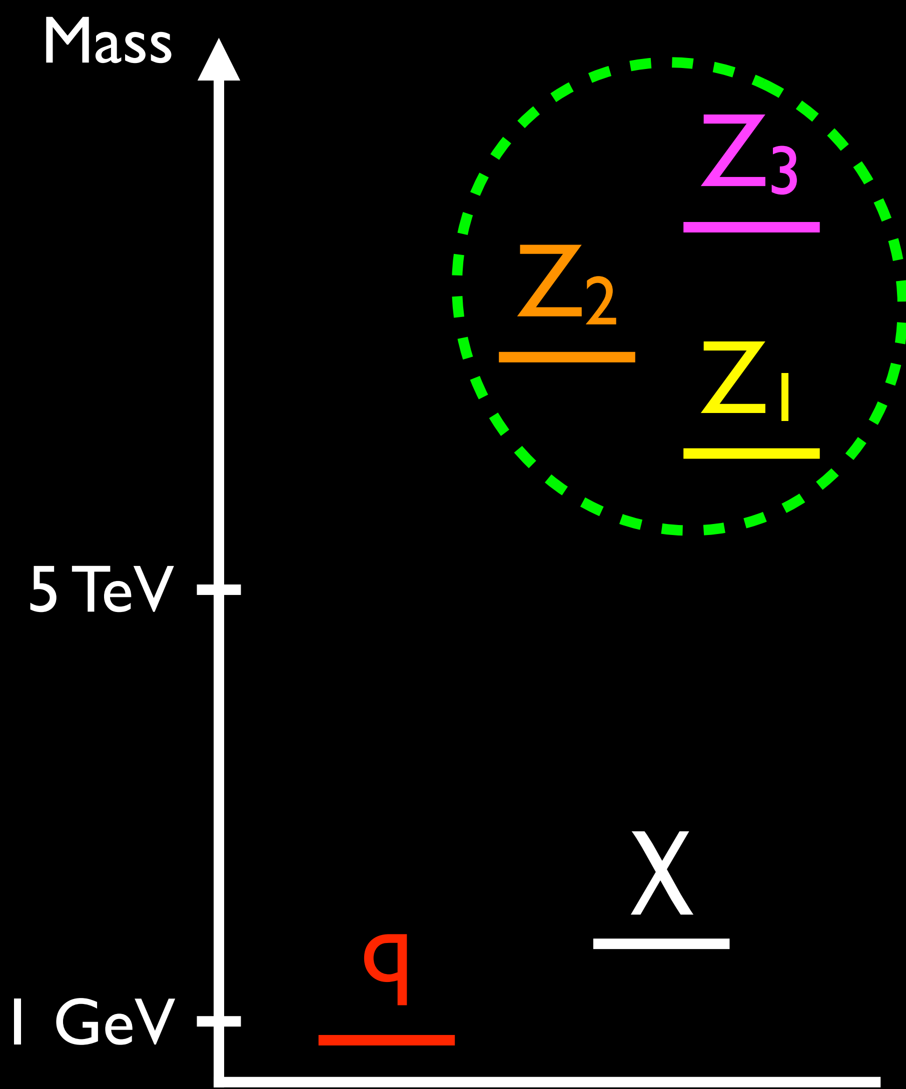
$$p^2 \ll M_{Z_1}^2$$

$$-\frac{1}{M_*^2}$$



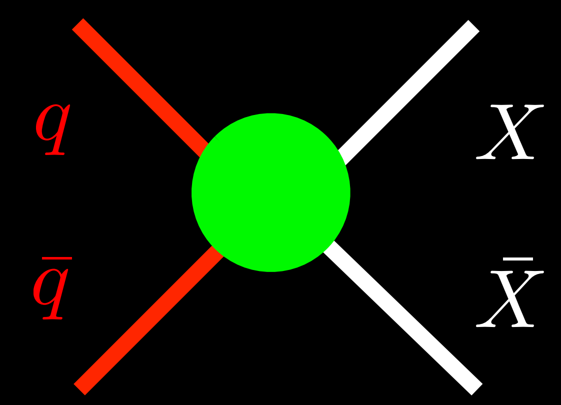
$$= -\frac{g^2}{M_{Z_1}^2} (\bar{q}\Gamma q)(\bar{X}\Gamma X)$$

Effective field theory primer



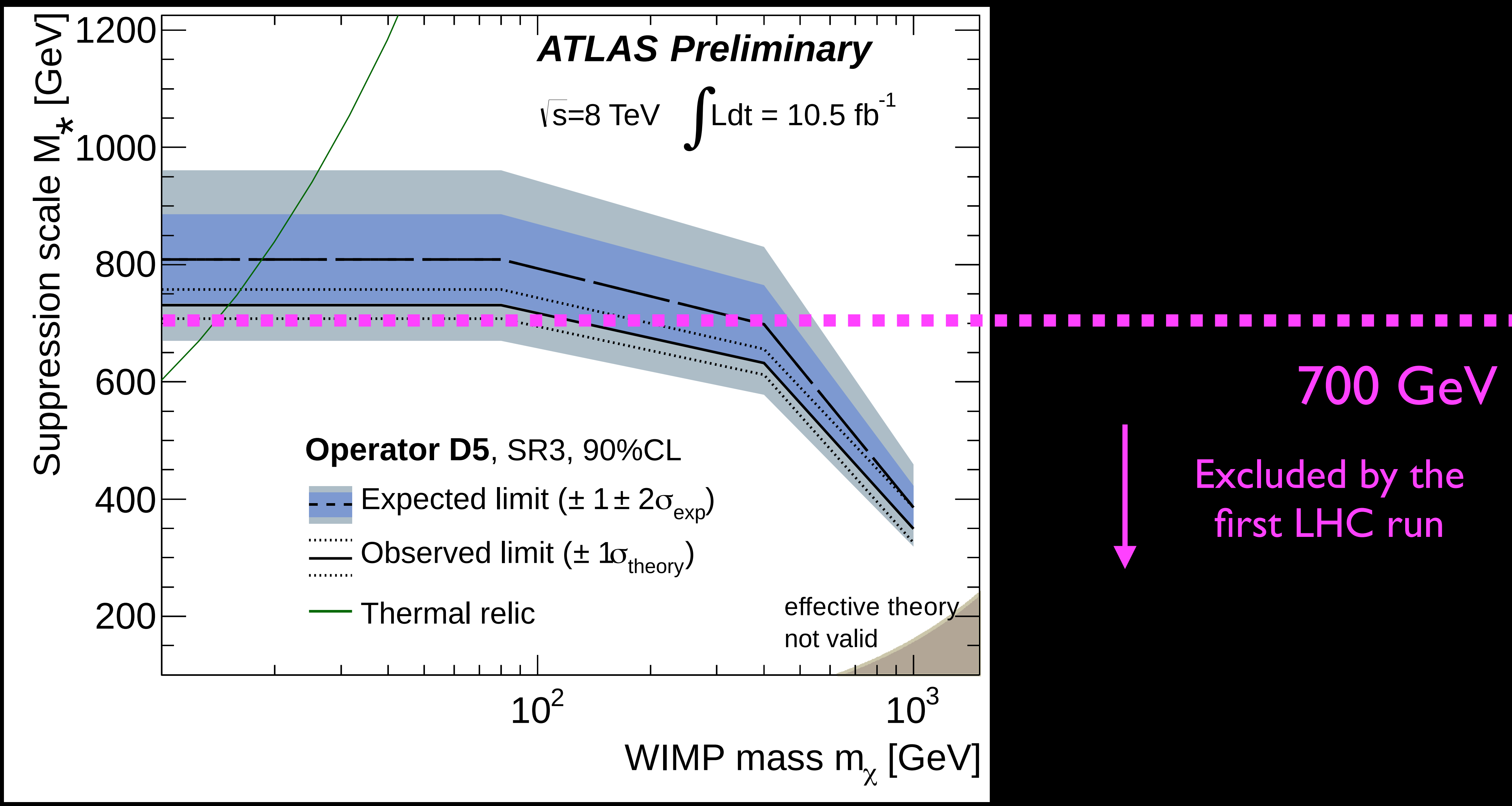
Information on heavy states encoded in a single coupling

$$\frac{1}{M_*^2} = \frac{g^2}{M_{Z_1}^2}$$

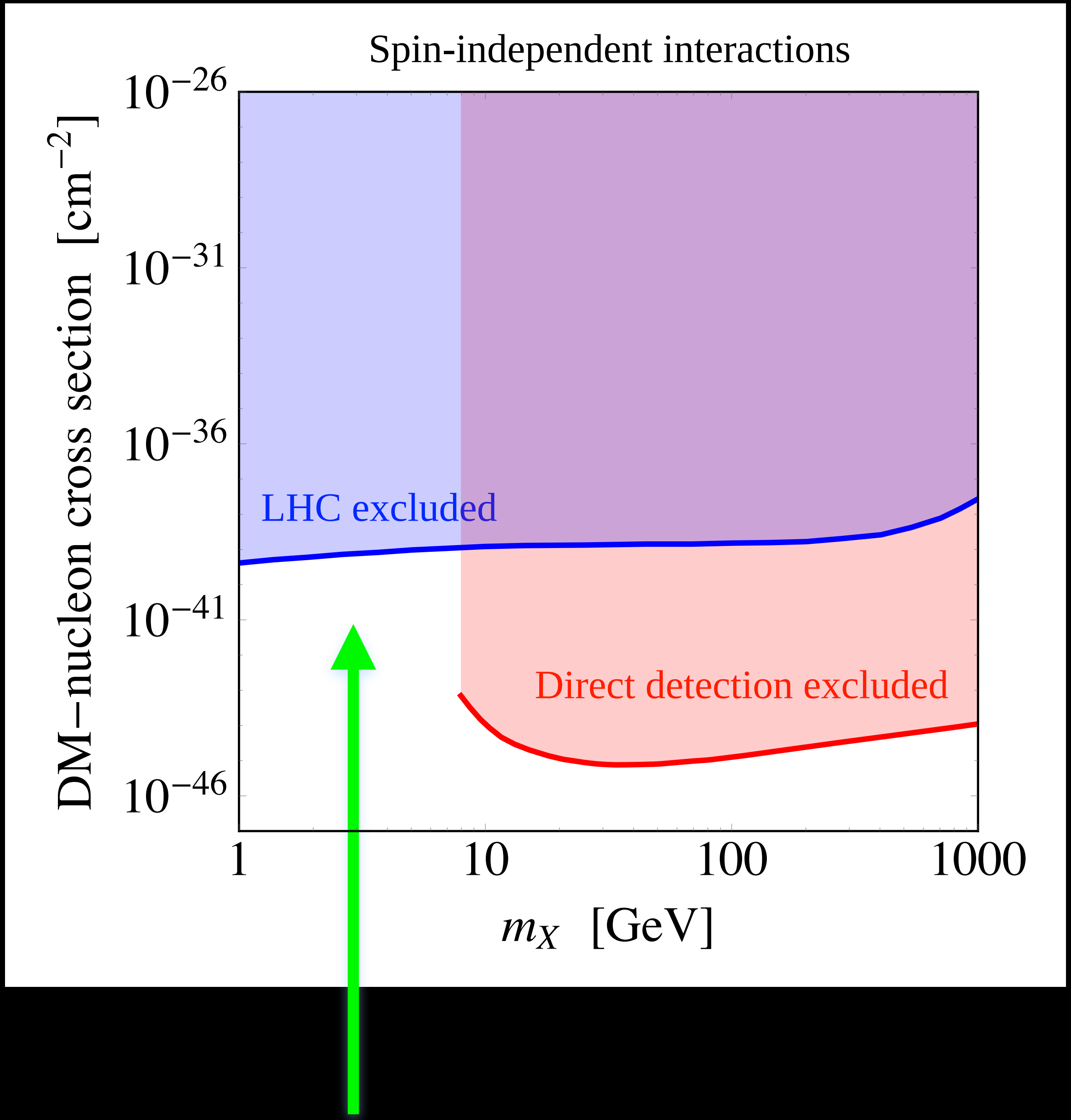


Independent of heavy physics

LHC limits on suppression scale

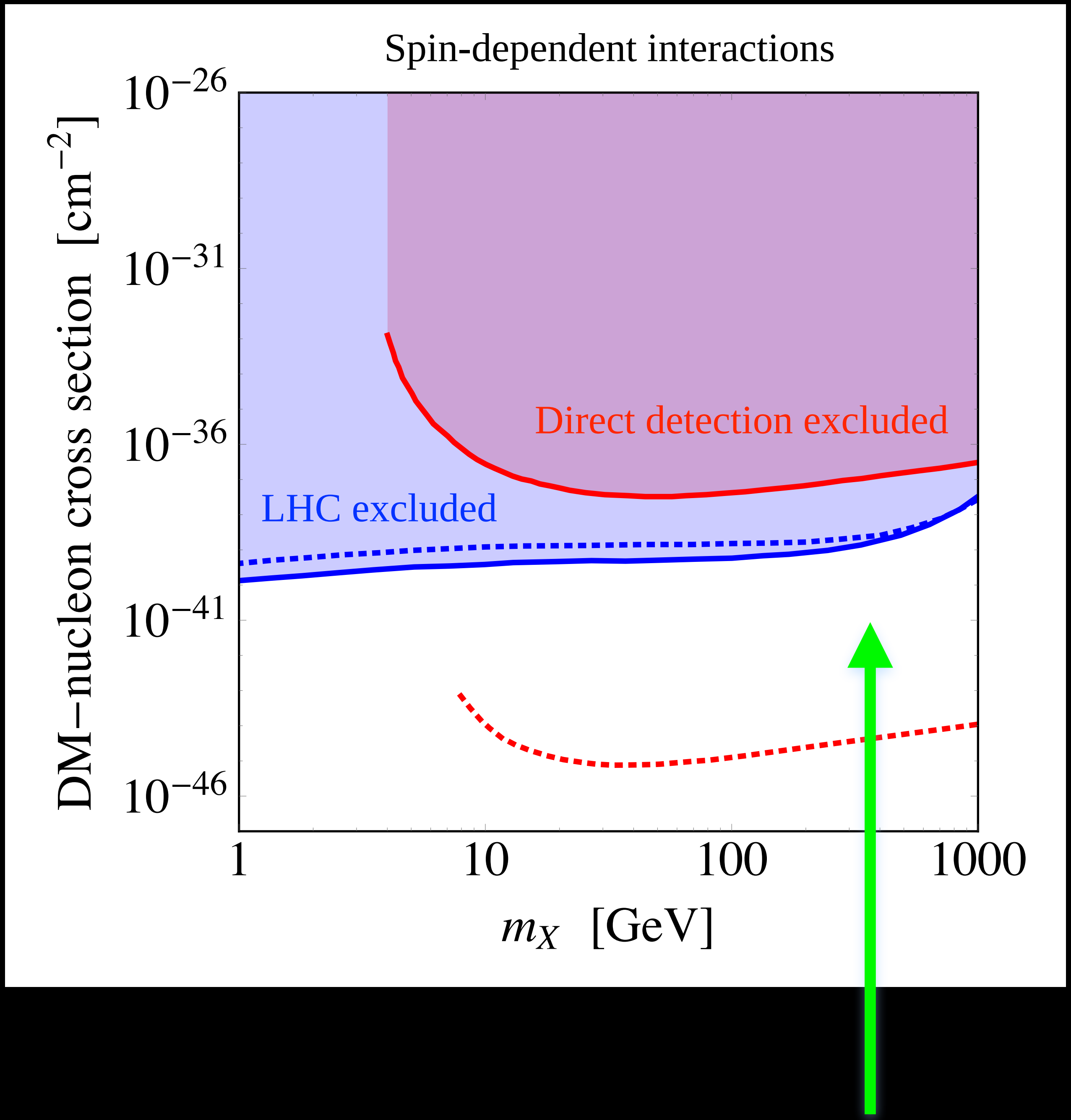


Comparison with direct detection



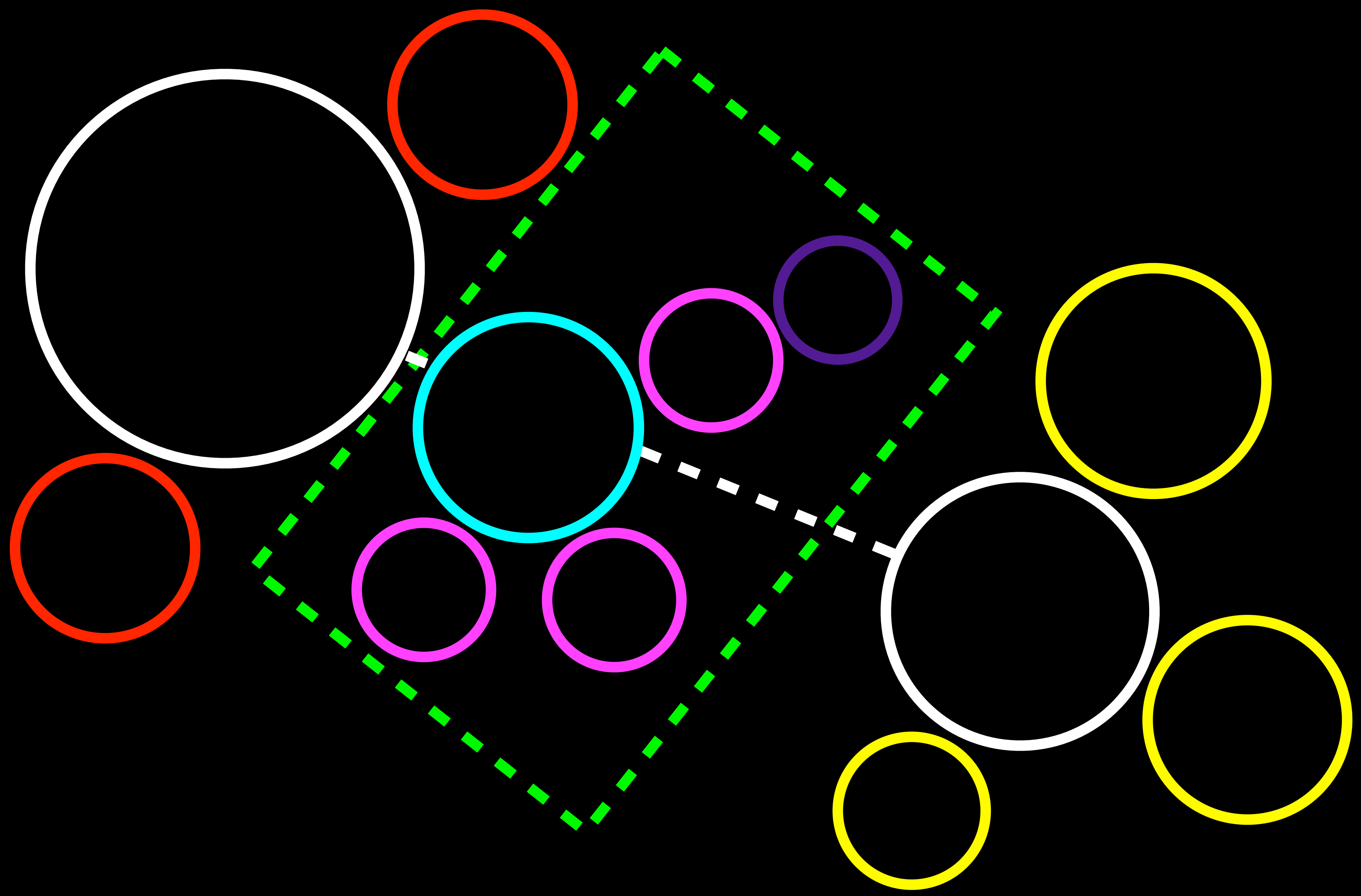
The LHC constraints are strongest at low DM mass, where direct detection is challenging due to the small nuclear recoil

Comparison with direct detection



The LHC is superior to any spin-dependent search for all DM masses, since DM-nucleon scattering is incoherent in this case

Simplified DM models



Simplified = in-between

- Another interesting option is to consider models that contain DM and the most important state mediating its interactions with the SM

- Unlike the effective field theories, these simplified models can describe the full kinematics of DM production at the LHC

- Simplified DM models have typically a few parameters