DESY Theory Workkshop 2015 - Hamburg, 29.09.2015

LHC prospects for Dark Matter

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$[q,p]=i\hbar$

invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

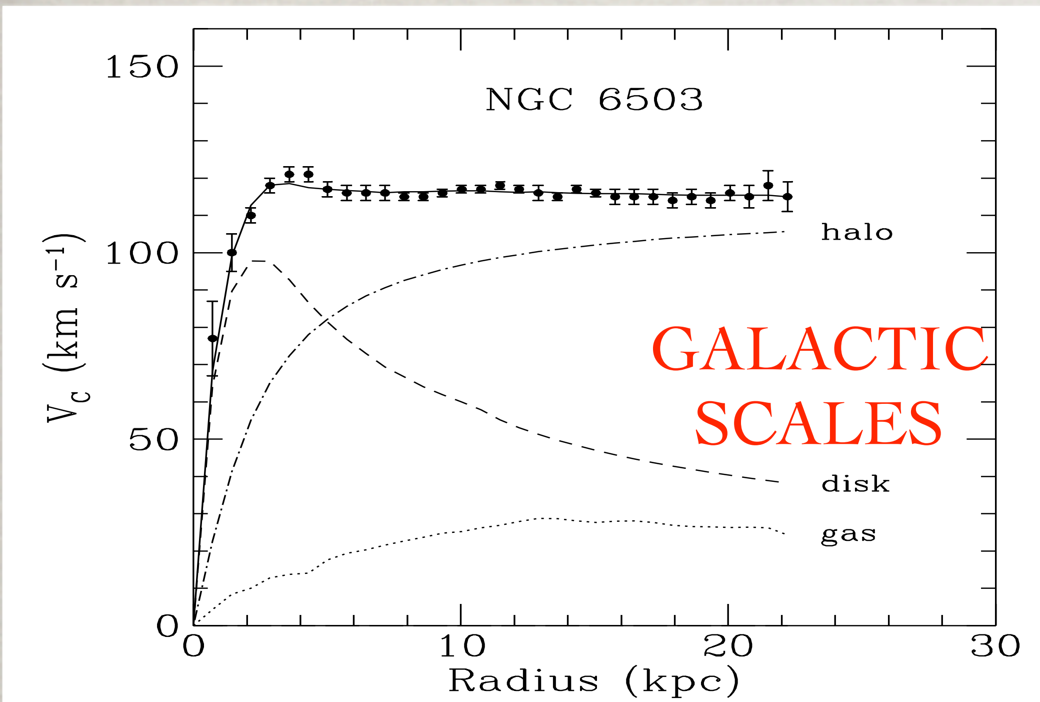
MARIE CURIE ACTIONS

Outline

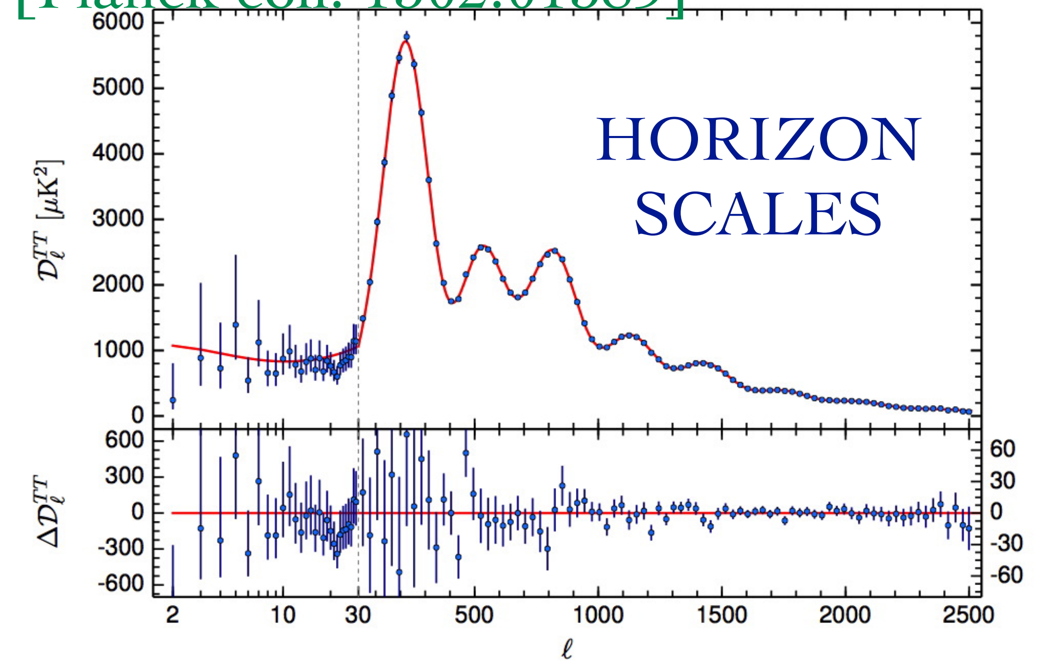
- Introduction:
  From DM production to the LHC
- Mono-X searches and EFT @ LHC
- Simplified/Minimal Models @ LHC
- pMSSM DM confronts LHC
- Outlook

From DM production to the LHC

DARK MATTER EVIDENCE



[Planck coll. 1502.01589]



Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.11-13	Cold

THE WIMP PARADIGM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X \rightarrow \text{anything}) v \rangle \left(n_{eq}^2 - n_X^2 \right)$$

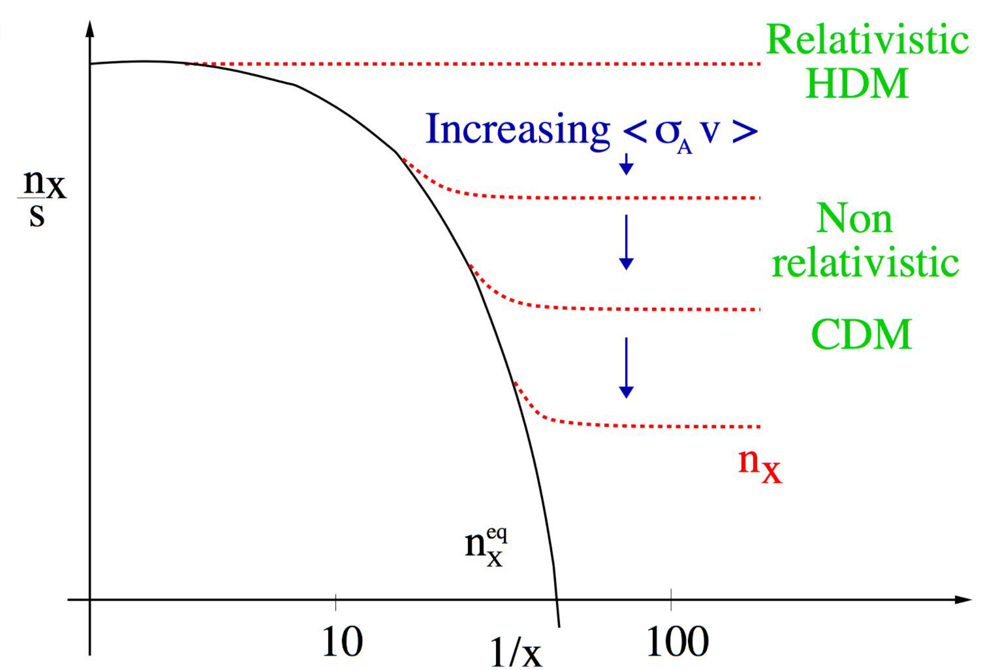
Hubble expansion Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X / T_f$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives

$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties



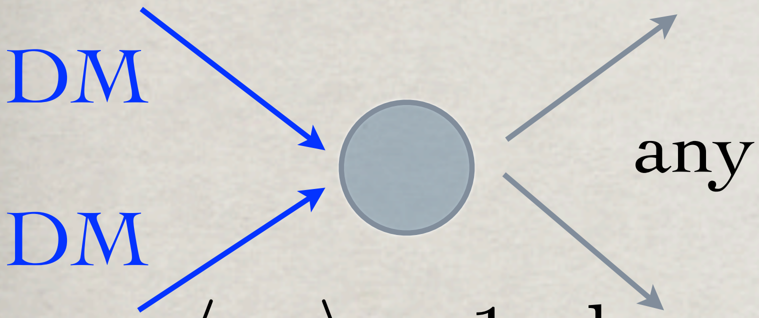
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

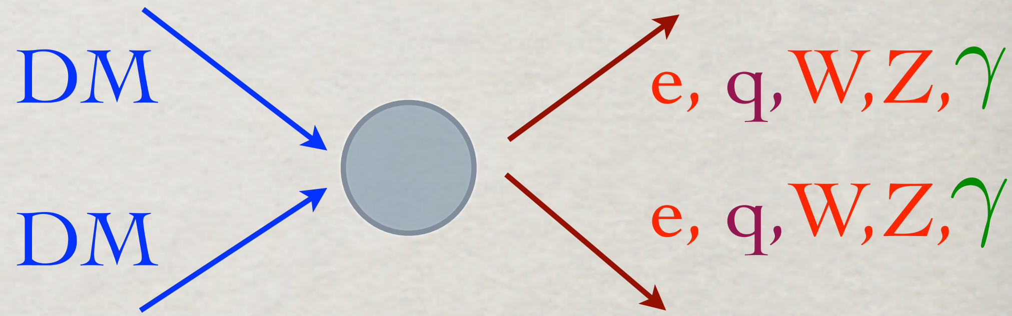
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$

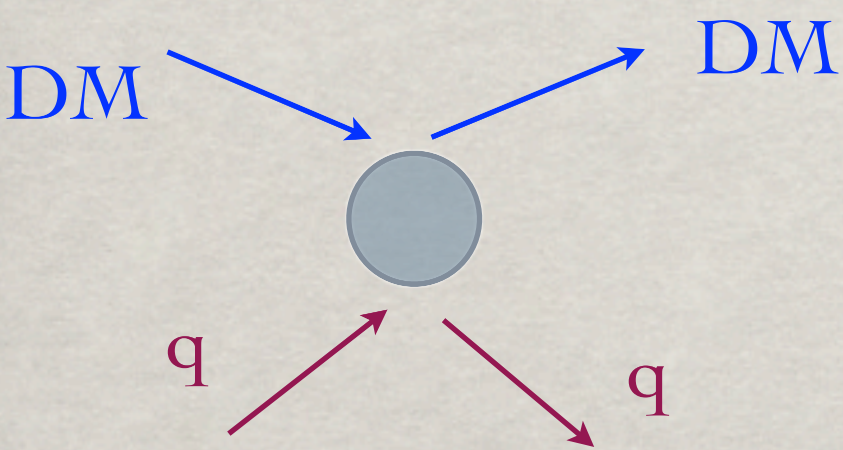


$\langle \sigma v \rangle \sim 1$ pb

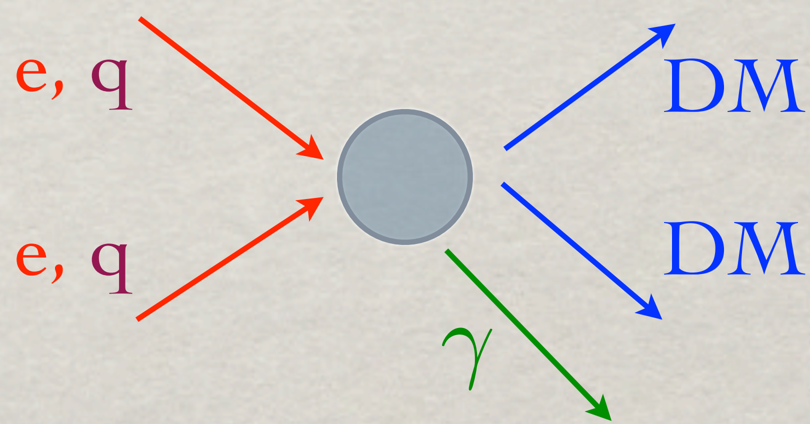
Indirect Detection:



Direct Detection:



Colliders: LHC/ILC



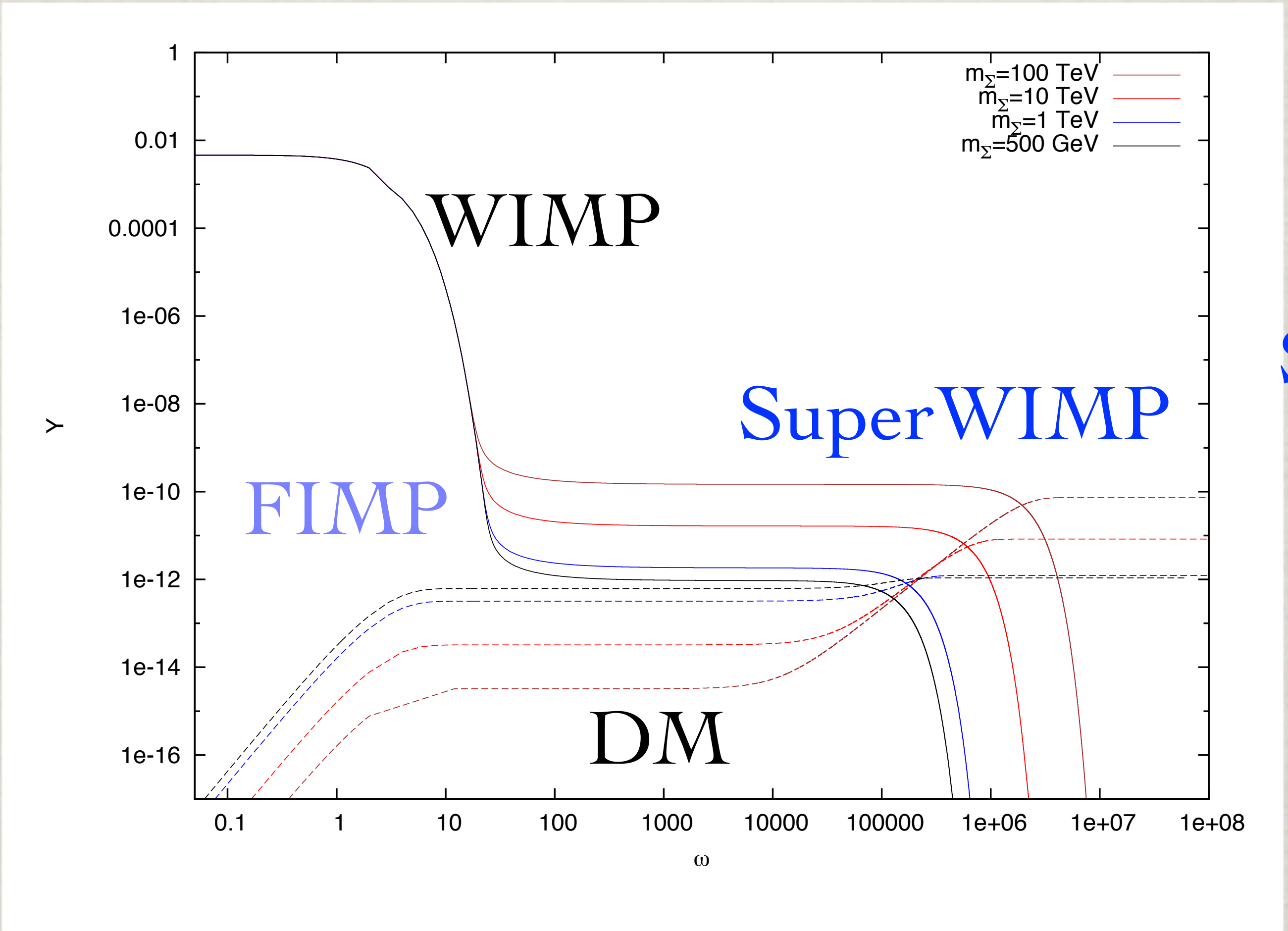
3 different ways to check this hypothesis !!!

SuperWIMP/FIMP paradigms

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



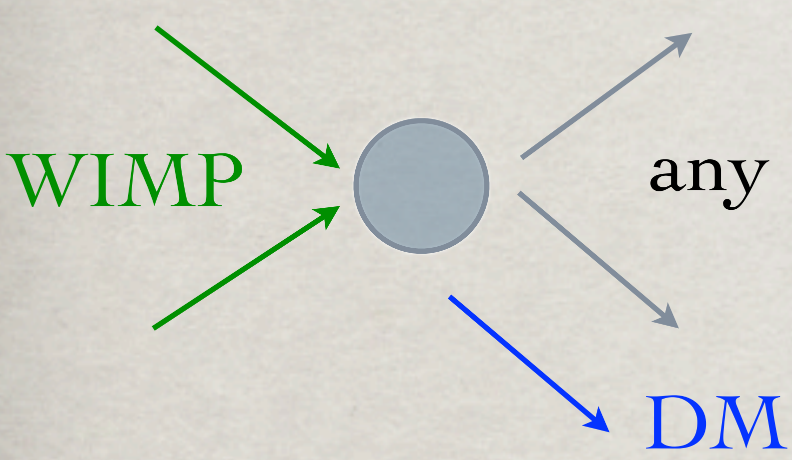
[Feng et al 04]

SuperWIMP DM produced by WIMP decay after freeze-out

Two mechanism naturally giving "right" DM density depending on WIMP/DM mass & DM couplings

F/SWIMP CONNECTION

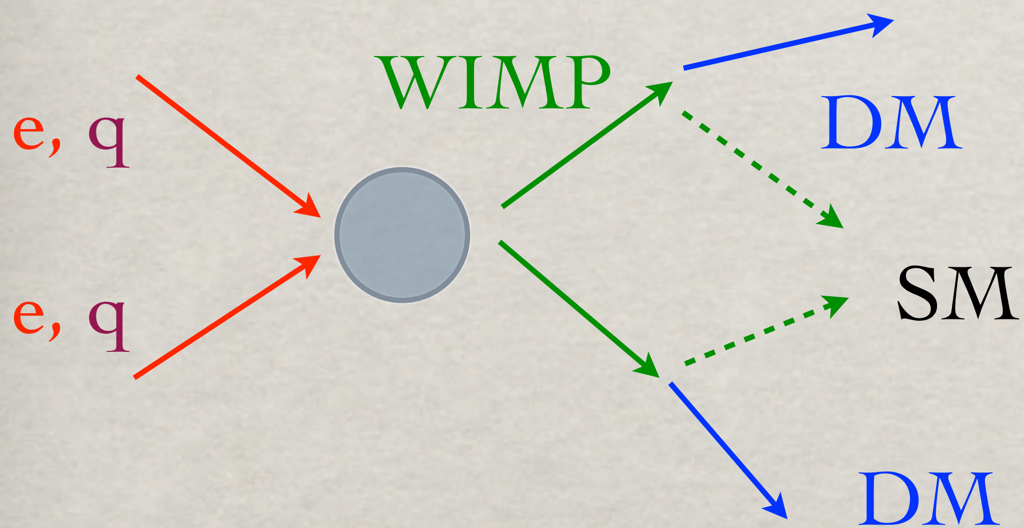
Early Universe: $\Omega_{CDM} h^2$



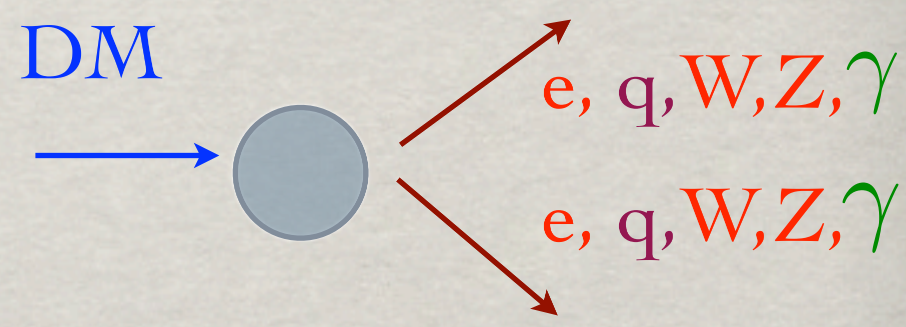
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

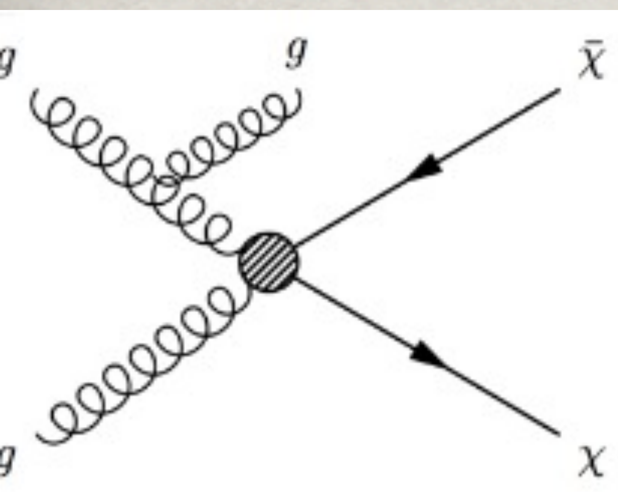
3 different ways to check this hypothesis !!!

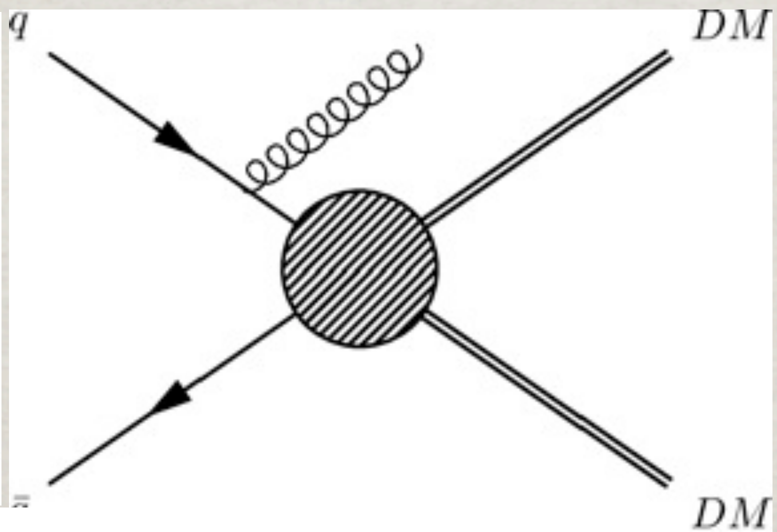
Mono-X Searches and EFT @ LHC

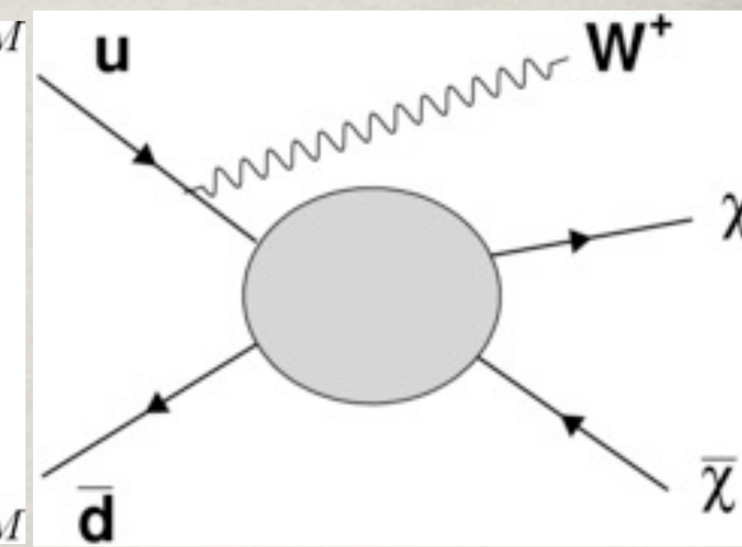
EFT for Dark Matter

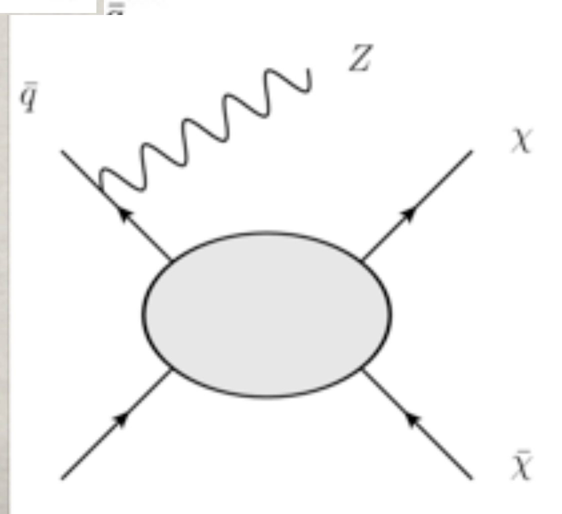
[Beltram et al 2000, Goodman et al 2000 & 2001, Bai et al 2001,....]

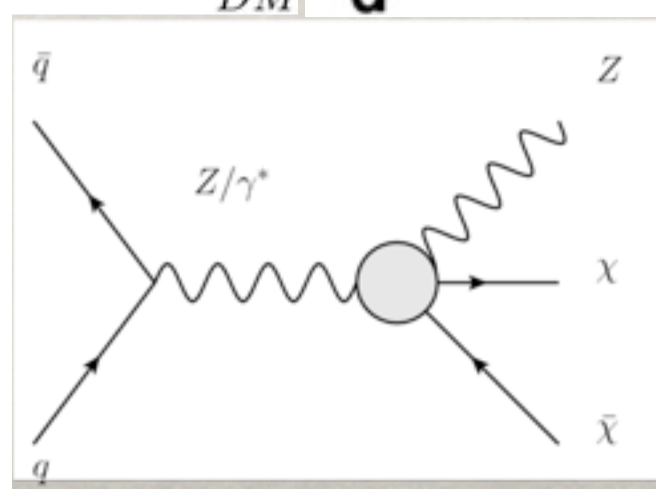
Consider the production of a pair of DM particles together with ISR of a SM particle: gluon, photon, W/Z, top, etc...
Many different effective operators are possible:





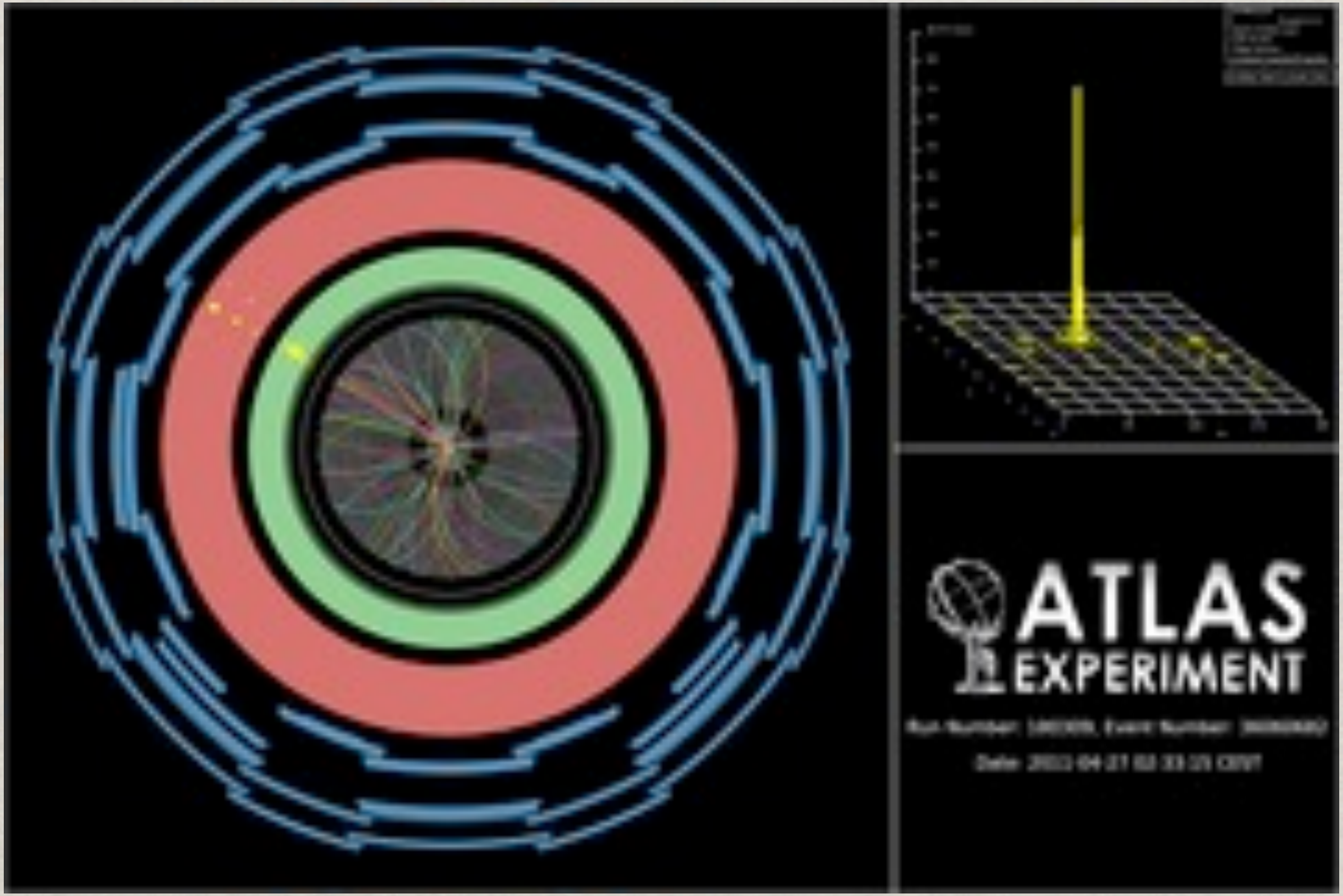






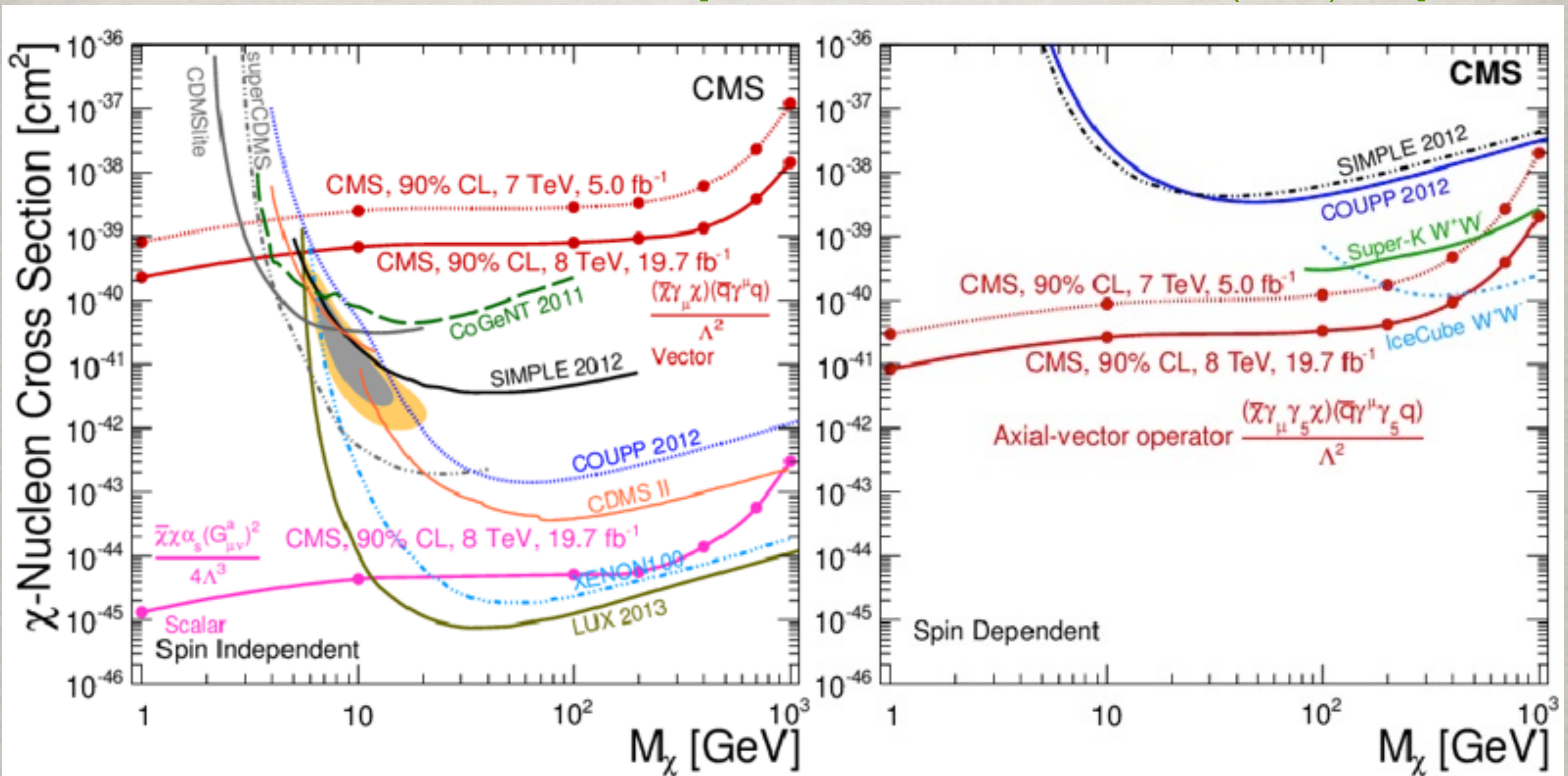
LHC: Monojets

Clear signal: single jet recoiling against nothing !



LHC monojet limits

[CMS collaboration, EPJC 75 (2015) 235]

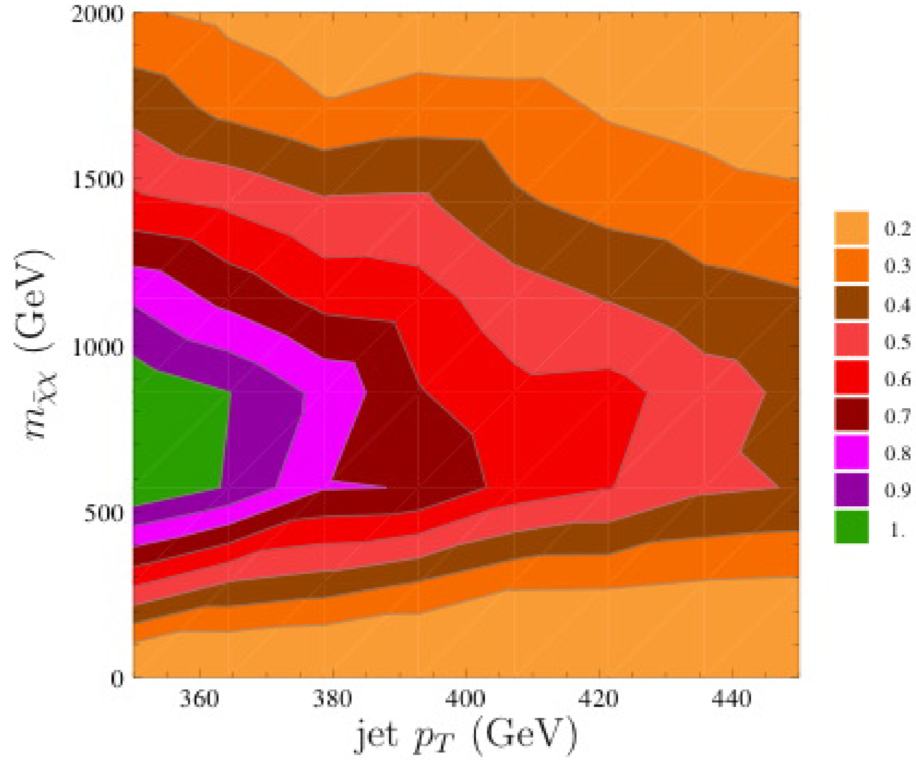


Limits competitive with DD at low mass and for the spin-dependent case.

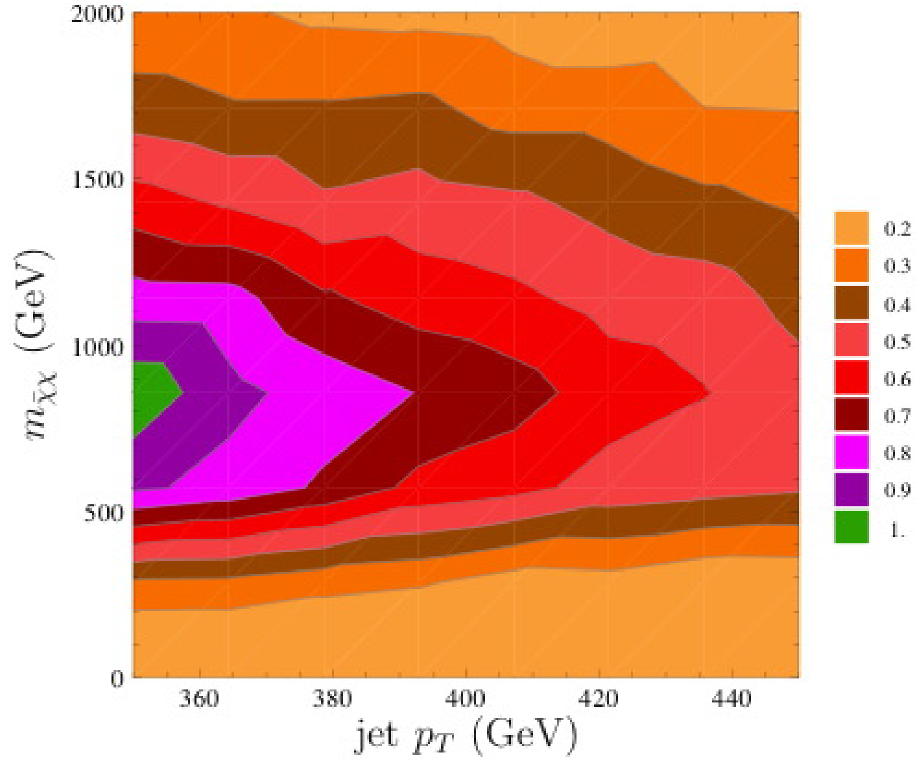
Jet substructure for DM

In case of a positive signal, the jet substructure could help to disentangle the operator and type of coupling:

[Agrawal & Rentala 1312.5325]



(a) Event kinematic distribution for $\mathcal{O}_q$.



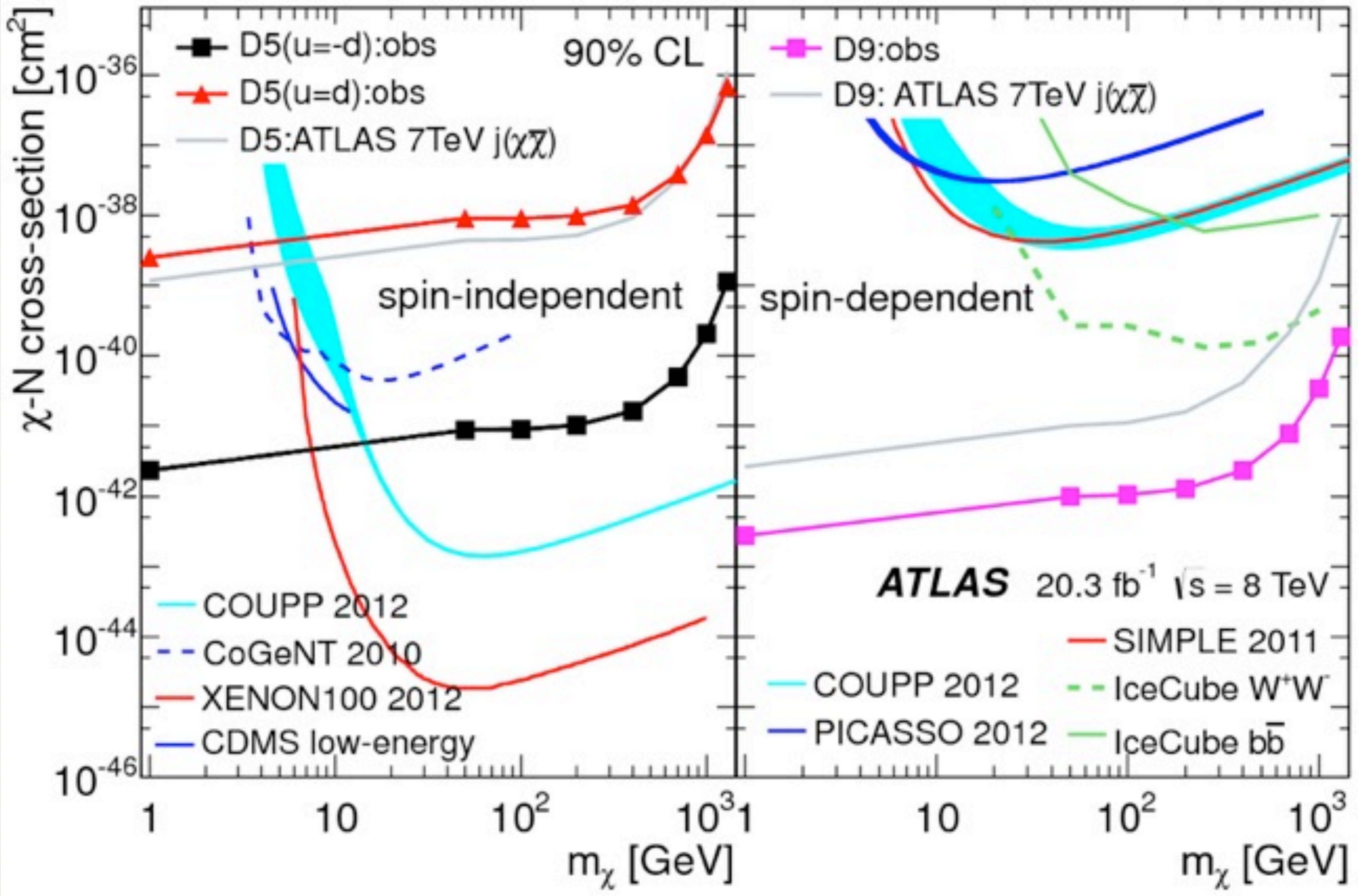
(b) Event kinematic distribution for $\mathcal{O}_g$.

Di-jet angular distribution could also vary for loop operators !

[Haisch et al 1311.7131]

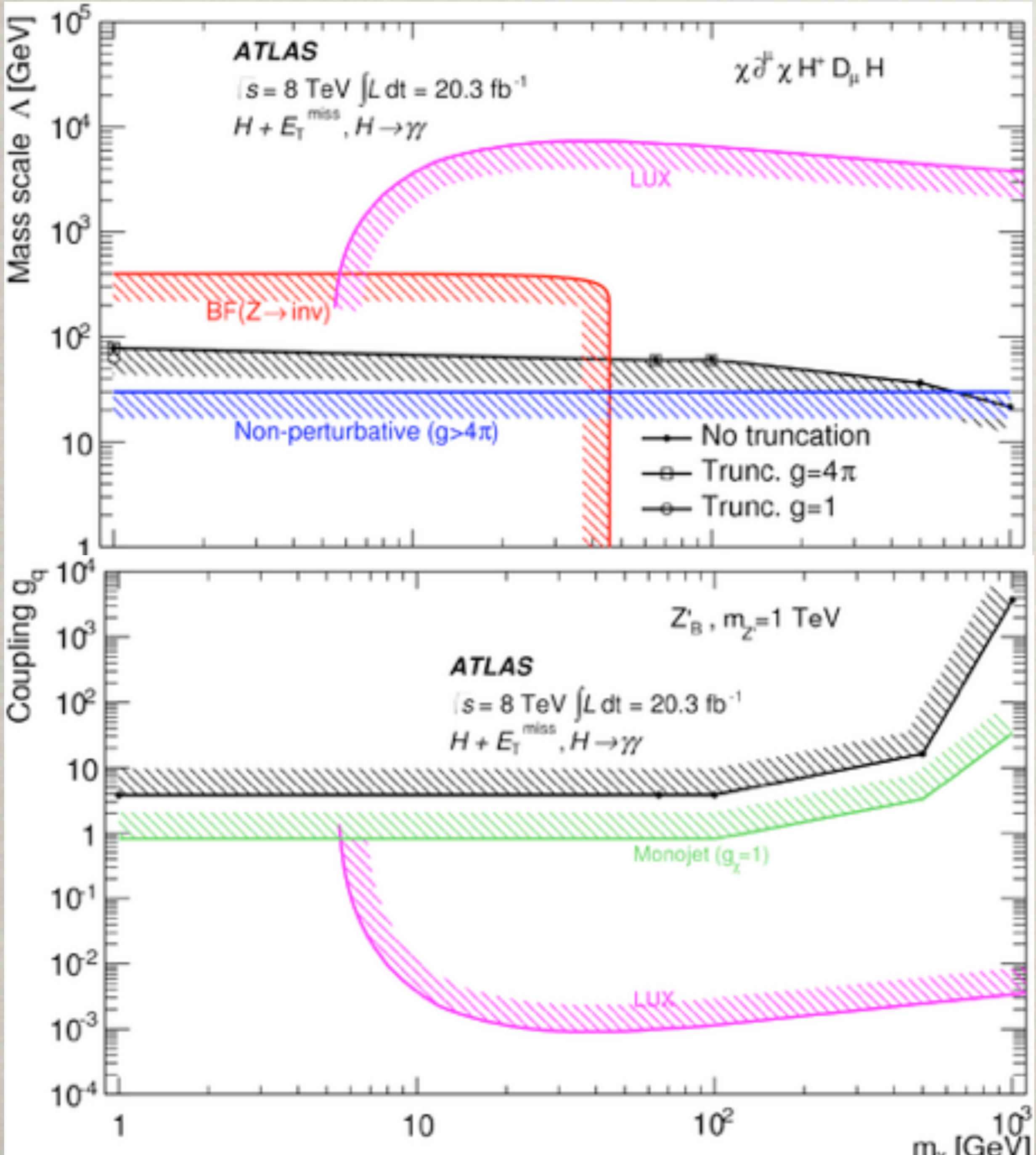
Mono- W/Z channels

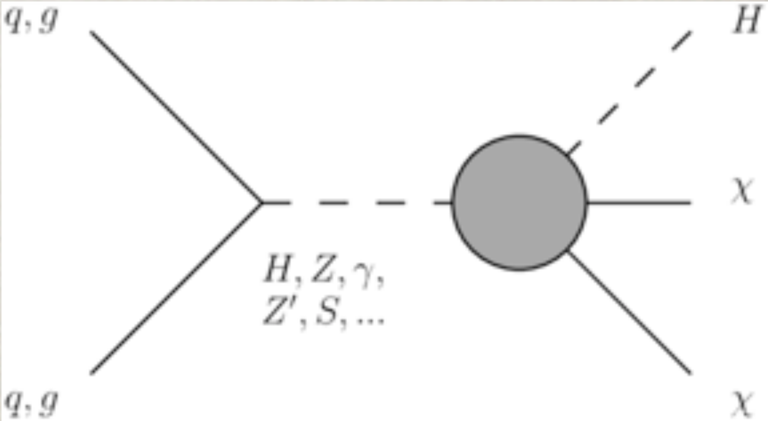
[ATLAS, PRL 112 (2014) 041802]



Mono-Higgs channel

[ATLAS, PRL 115 (2015) 131801]





Limits can be stronger than the monojet limits for models with Z' !

Effective Theory for DD

[Riccardo Catena WIN-2015]

- Only 14 linearly independent operators can be constructed, if we demand that they are at most linear in $\hat{\mathbf{S}}_N$, $\hat{\mathbf{S}}_\chi$ and $\hat{\mathbf{v}}^\perp$

- The most general Hamiltonian density is therefore

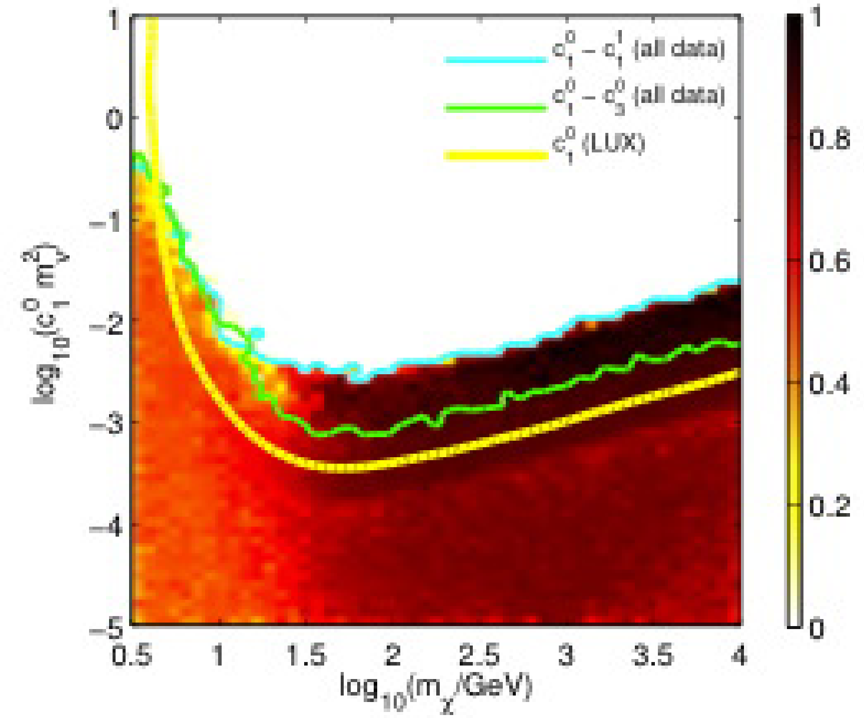
$$\hat{\mathcal{H}}(\mathbf{r}) = \sum_k c_k \, \hat{\mathcal{O}}_k(\mathbf{r})$$

[Fitzpatrick et al. 2012]

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

Effective Theory for DD

Interference matters !

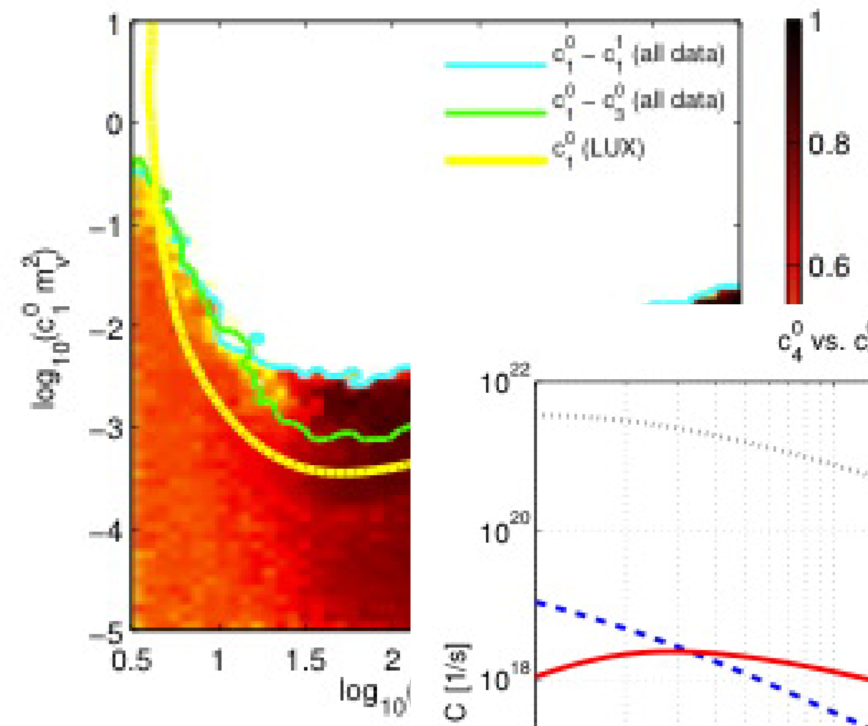


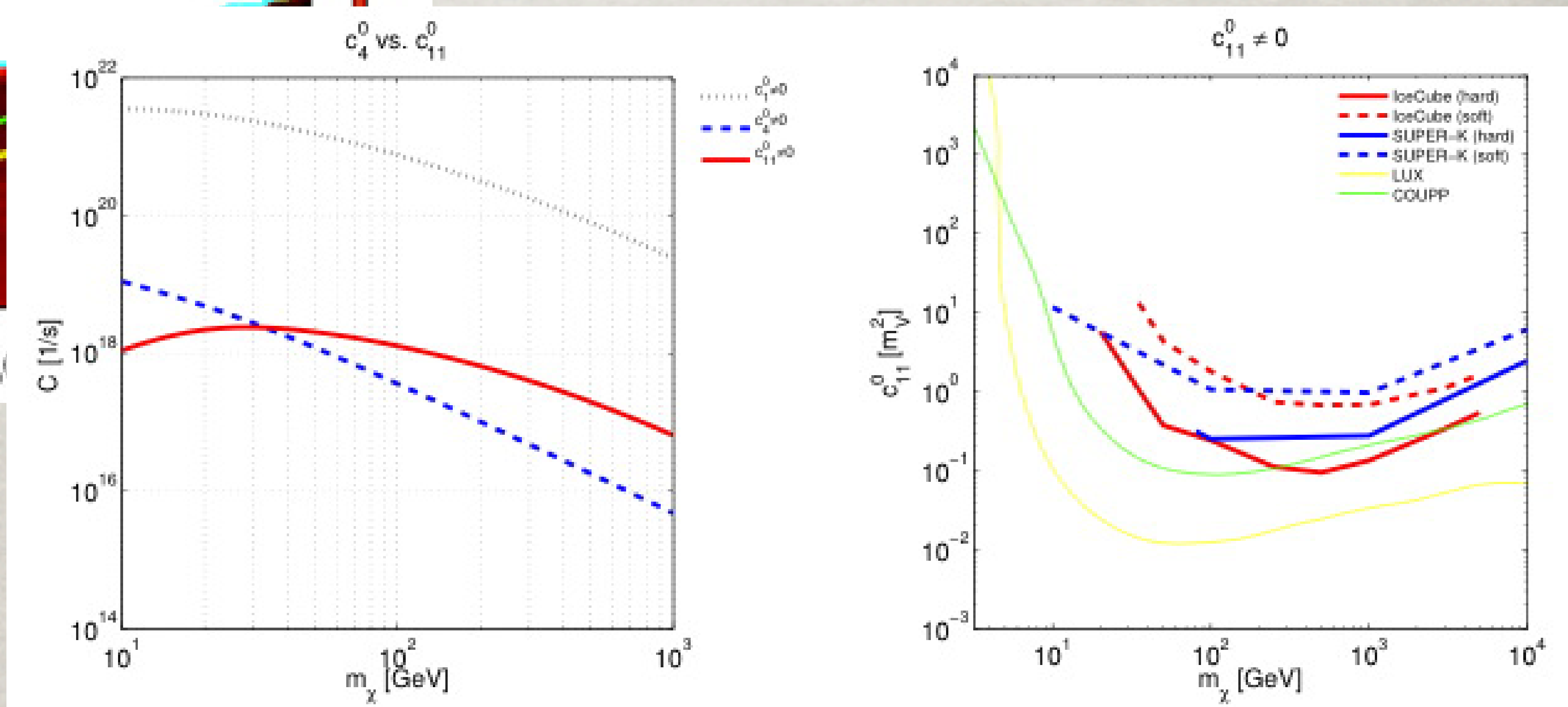
[Catena & Gondolo 2015]

Effective Theory for DD

Interference matters !

[Catena & Gondolo 2015]





[Catena 2015]

More Ops can contribute to solar capture:

- $\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$, $\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$

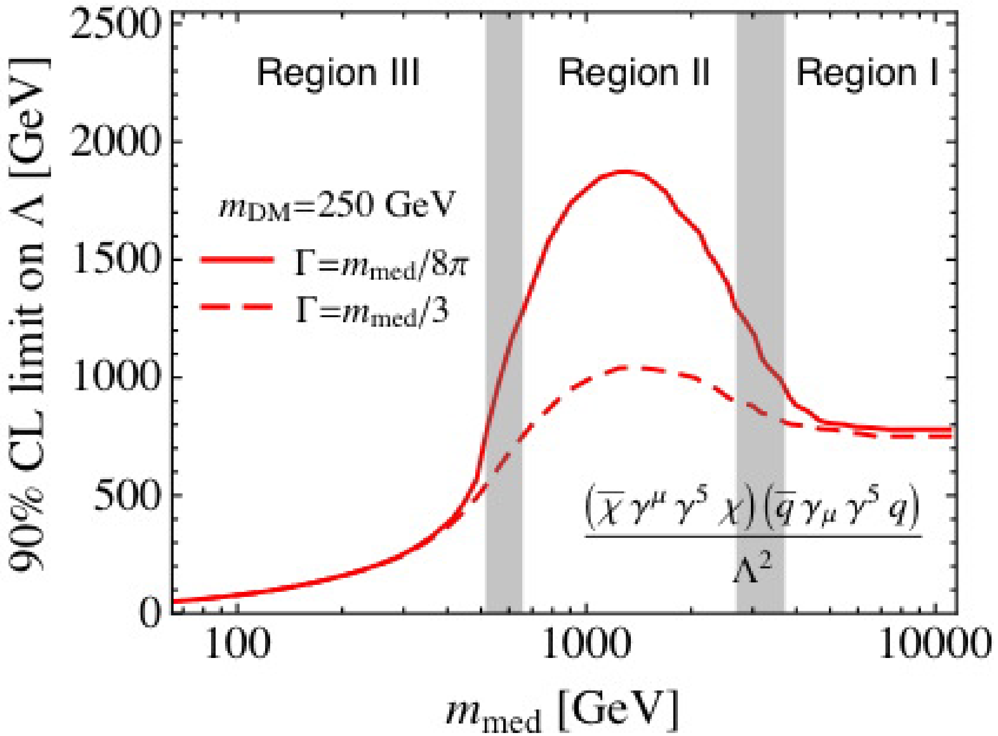
Simplified/Minimal models @ LHC

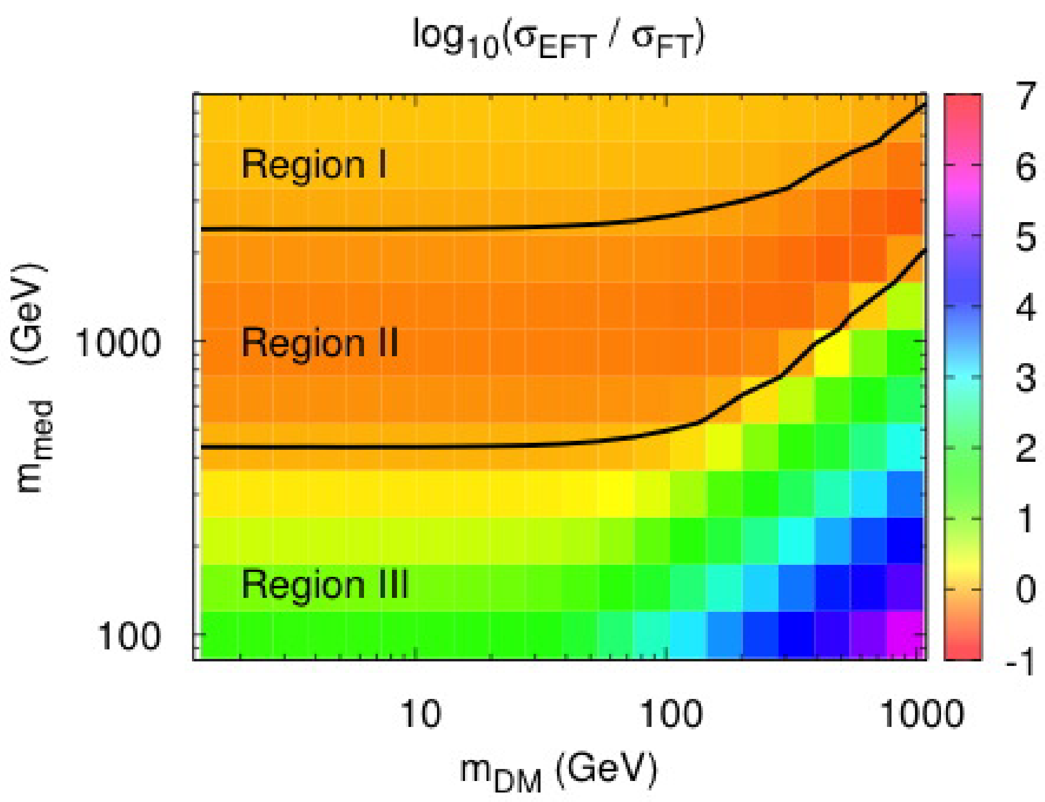
Caveat for the EFT: s

While the use of EFT for the case of non-relativistic scattering with matter in DM direct detection is well-justified, at LHC energies one has to be more careful...

[Fox et al 11, Busoni et al 13, O.Buchmuller et al 13, ...]

[O.Buchmuller et al 1308.6799]

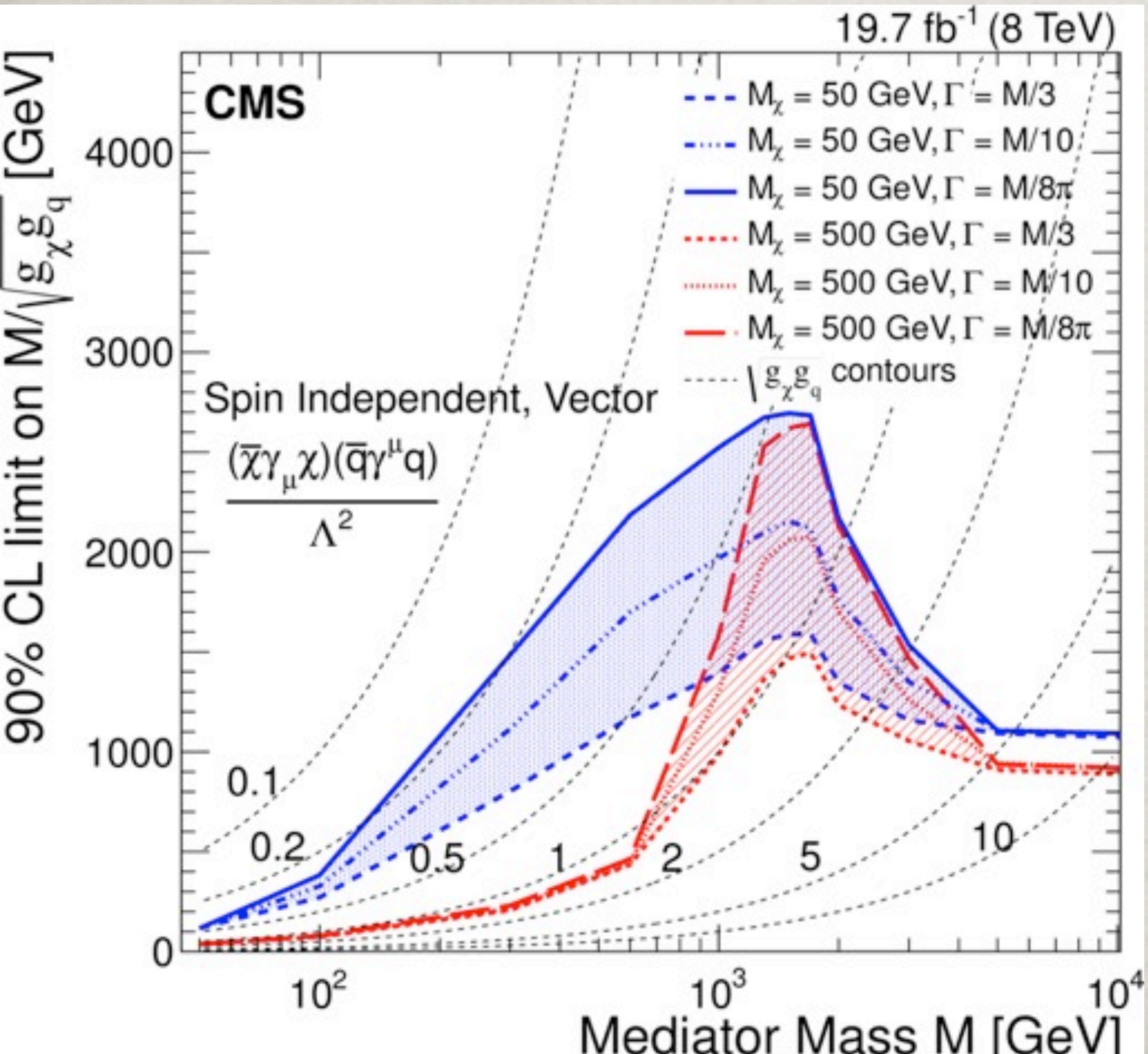




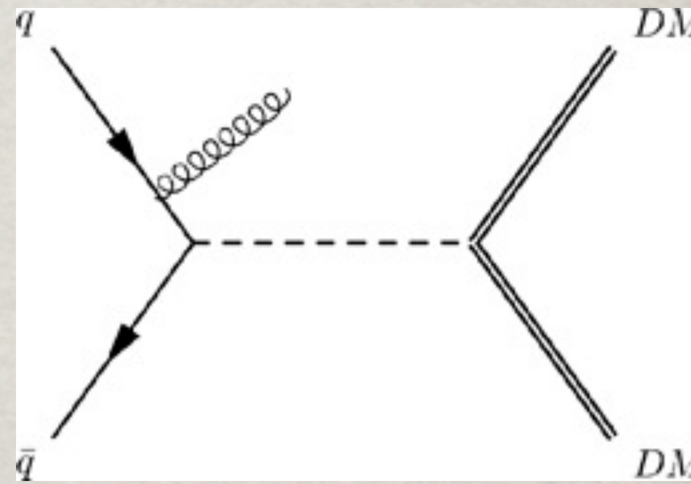
The bound is valid only for large mediator mass !

LHC: SIMPLIFIED MODELS

[CMS collaboration, EPJC 75 (2015) 235]



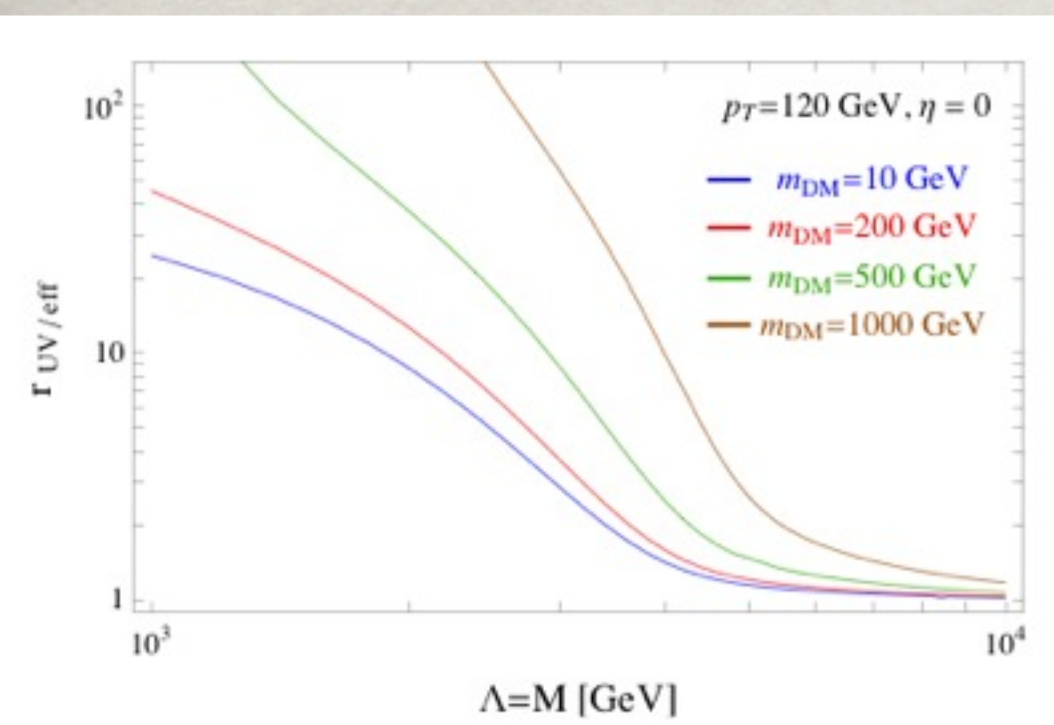
Vector mediator

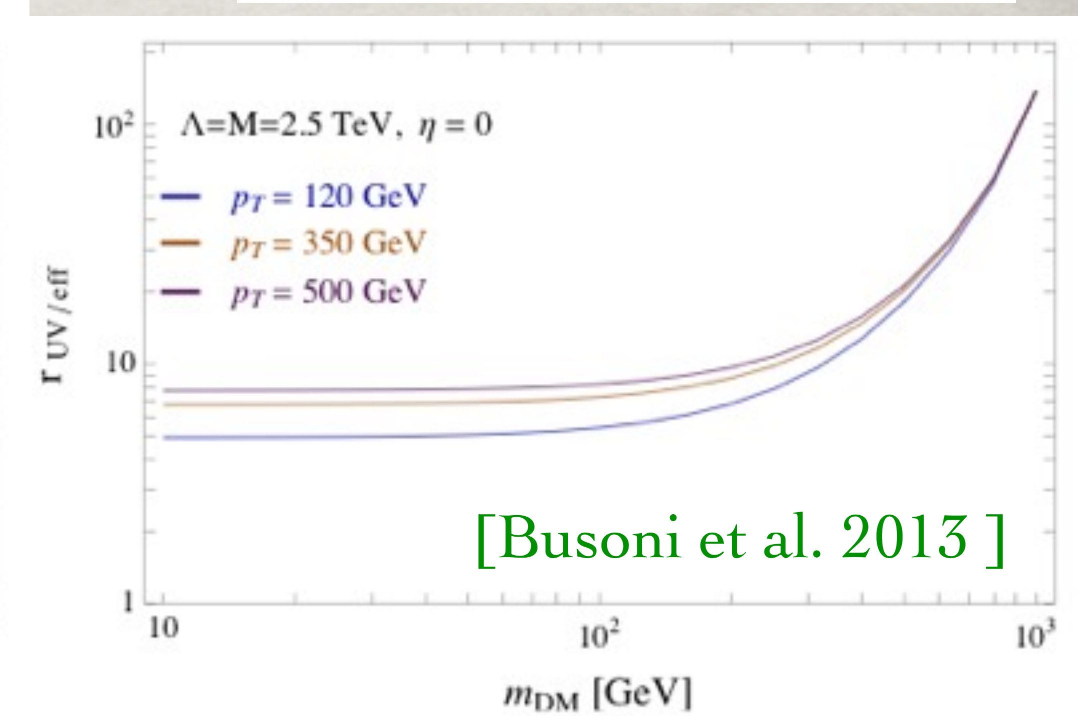


Caveat for the EFT II: s

How much one can trust the EFT, depends on the momentum transfert and therefore as well DM mass, p_T of emission.

$$r_{\mathrm{UV/eff}} \equiv \frac{\left.\dfrac{\mathrm{d}^2\sigma_{\mathrm{UV}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}\right|_{Q_{\mathrm{tr}}<M}}{\left.\dfrac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}\right|_{Q_{\mathrm{tr}}<\Lambda}}\,.$$





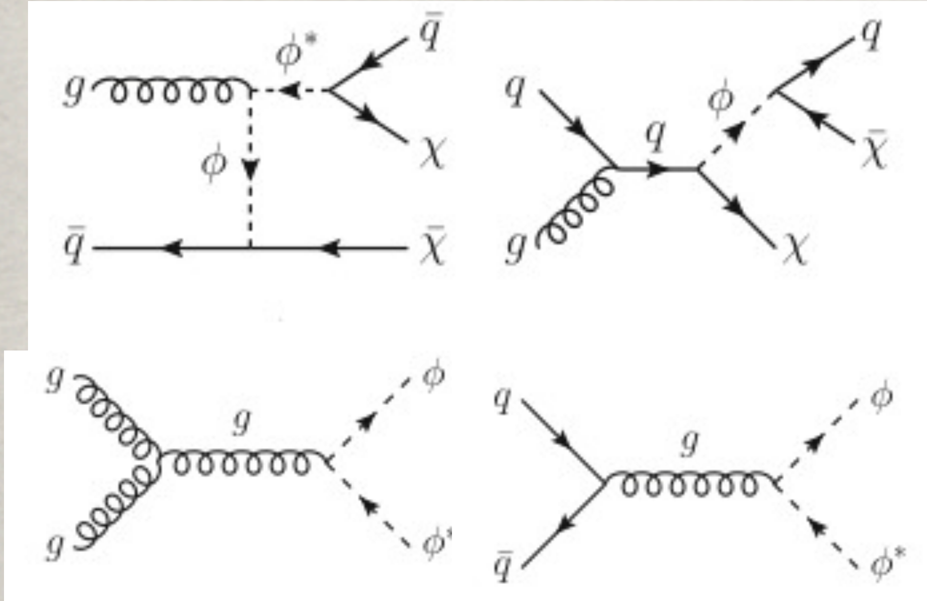
[Busoni et al. 2013]

Small DM mass, small p_T give better agreement!

Caveat for the EFT III: t

In the case of t-channel mediation, there is no resonant enhancement, but instead more channels for monojets as well as dijets show up, e.g. for scalar mediator:

[An et al. 2013, Papucci et al 2014]



Mono-jet without ISR

Dijet and MET

Complementary limits from Mono-jets & Di-jets !

In some cases direct searches for the mediator or di-jets can be more effective than monojets (i.e. also for Z').

[Fradsen et al. 2012, Chala et al. 2015]

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

Consider a simple model where the Dark Matter, a Majorana SM singlet fermion, is coupled to the colored sector via a renormalizable interaction and a new colored scalar Σ :

$$\lambda_\psi \bar{\psi} d_R \Sigma + \lambda_\Sigma \bar{u}_R^c d_R \Sigma^\dagger$$

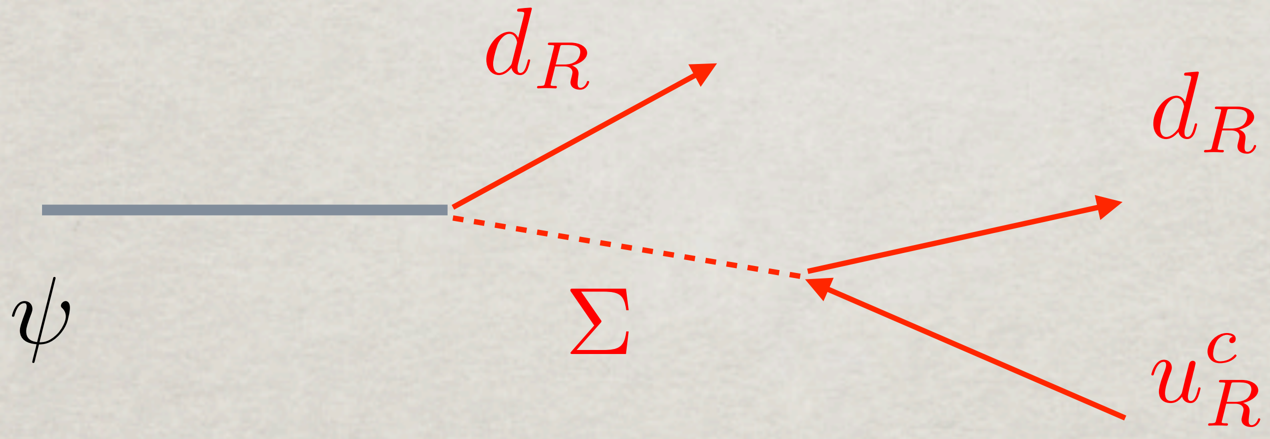
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

$\longrightarrow$ FIMP/SWIMP connection

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

No symmetry is imposed to keep DM stable, but the decay is required to be sufficiently suppressed. For $m_\Sigma \gg m_\psi$:

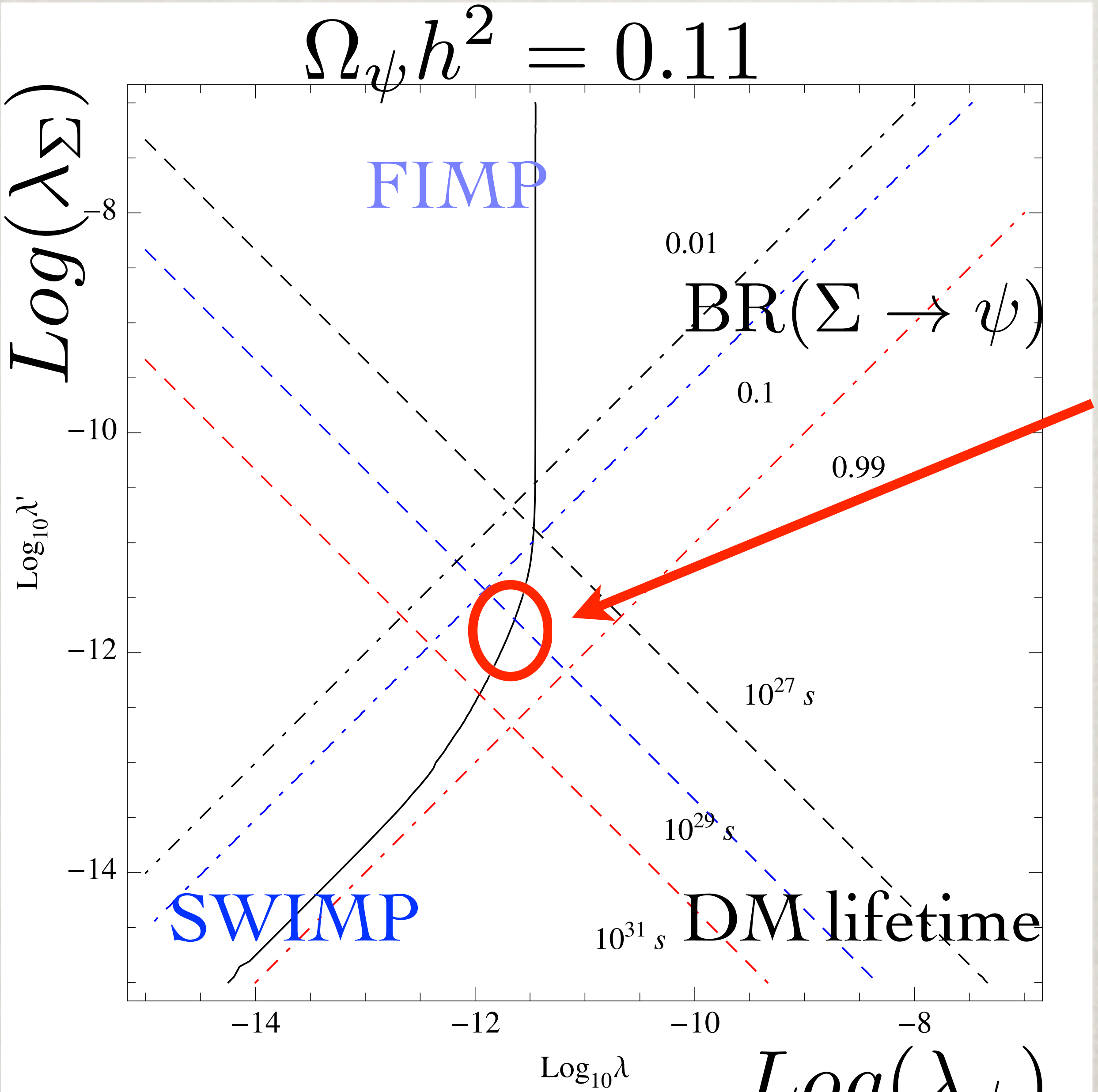


Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

A simple WIMP/SWIMP model



[G. Arcadi & LC 1305.6587]

DM decay observable
in indirect detection
& right abundance
& sizable BR in DM

$$\lambda_\psi \sim \lambda_\Sigma$$

But unfortunately
Σ decays outside
the detector @ LHC!
Perhaps visible
decays with a bit of
hierarchy...

FIMP/SWIMP AT LHC

At the LHC we expect to produce the heavy charged scalar Σ, as long as the mass is not too large... In principle the particle has two channels of decay with very long lifetimes.
Fixing the density by FIMP mechanism we have:

$$l_{\Sigma,DM} = 2.1 \times 10^5 \mathrm{m}\, g_\Sigma x \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-1} \left(\frac{\Omega_{CDM} h^2}{0.11}\right)^{-1} \left(\frac{g_*}{100}\right)^{-3/2}$$

Very long apart for small DM mass, i.e. $x = \frac{m_{DM}}{m_{\Sigma_f}} \ll 1$

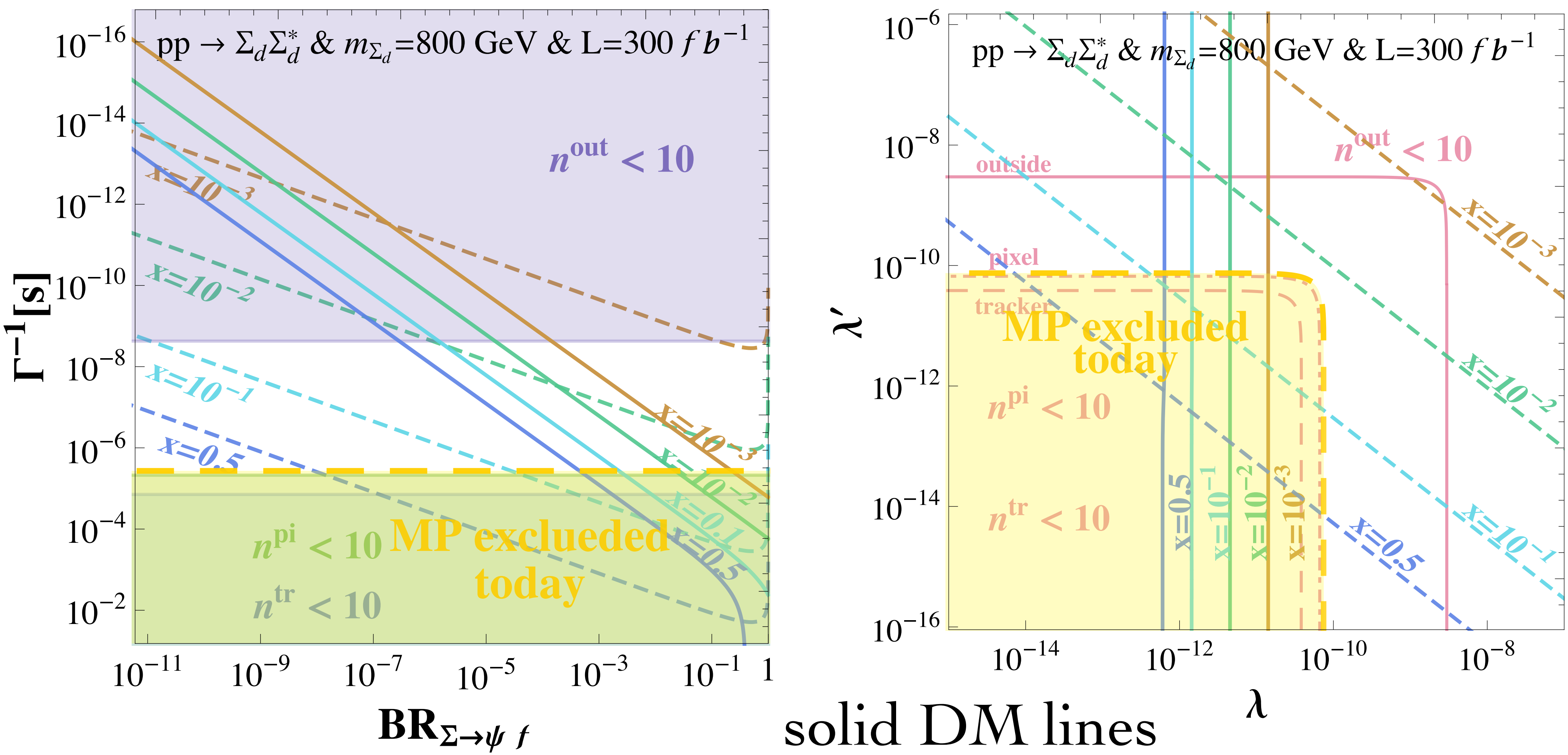
Moreover imposing ID "around the corner" gives

$$l_{\Sigma,SM} \simeq 55\,\mathrm{m} \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\mathrm{GeV}}\right)^4 \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right) \left(\frac{\Omega_{CDM} h^2}{0.11}\right) \left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

FIMP/SWIMP & COLORED Σ

[G. Arcadi, LC & F. Dradi 1408.1005]



solid DM lines

Practically pure FIMP production: both displaced vertices & "stable" charged particle @ LHC possible...

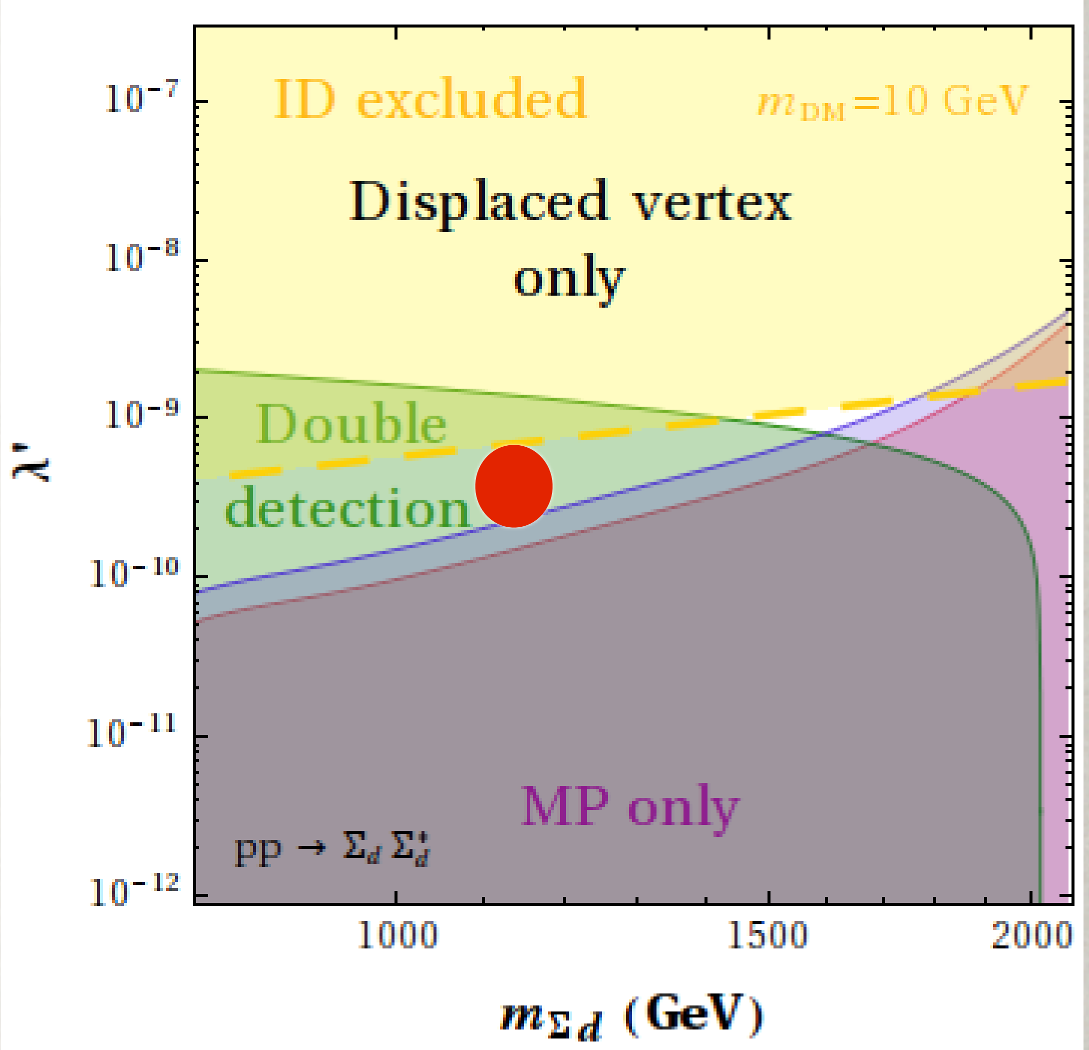
Σ Combined detection

Still possible to have multiple detection of

- DM decay:
  $m_\psi \quad \Gamma_\psi \to \lambda\lambda'$
- displaced vertices
  $m_\Sigma \quad \Gamma_{\Sigma,SM} \to \lambda'$
- metastable tracks
  $m_\Sigma \quad \Gamma_{\Sigma,SM} < X \to \lambda'$

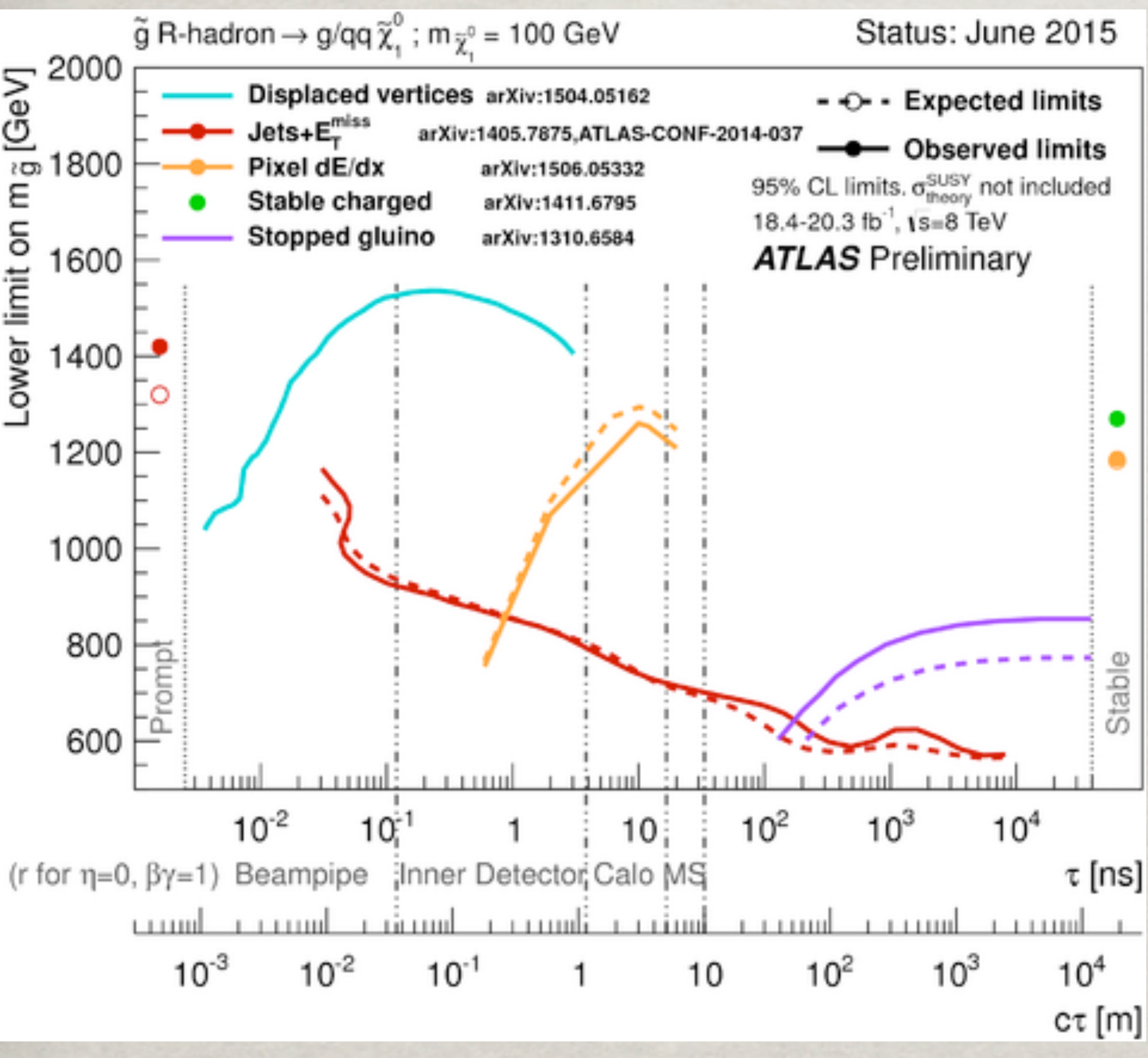
with stopped tracks maybe both $\Gamma_{\Sigma,SM}, \Gamma_{\Sigma,DM}$

[G. Arcadi, LC & F. Dradi 1408.1005]



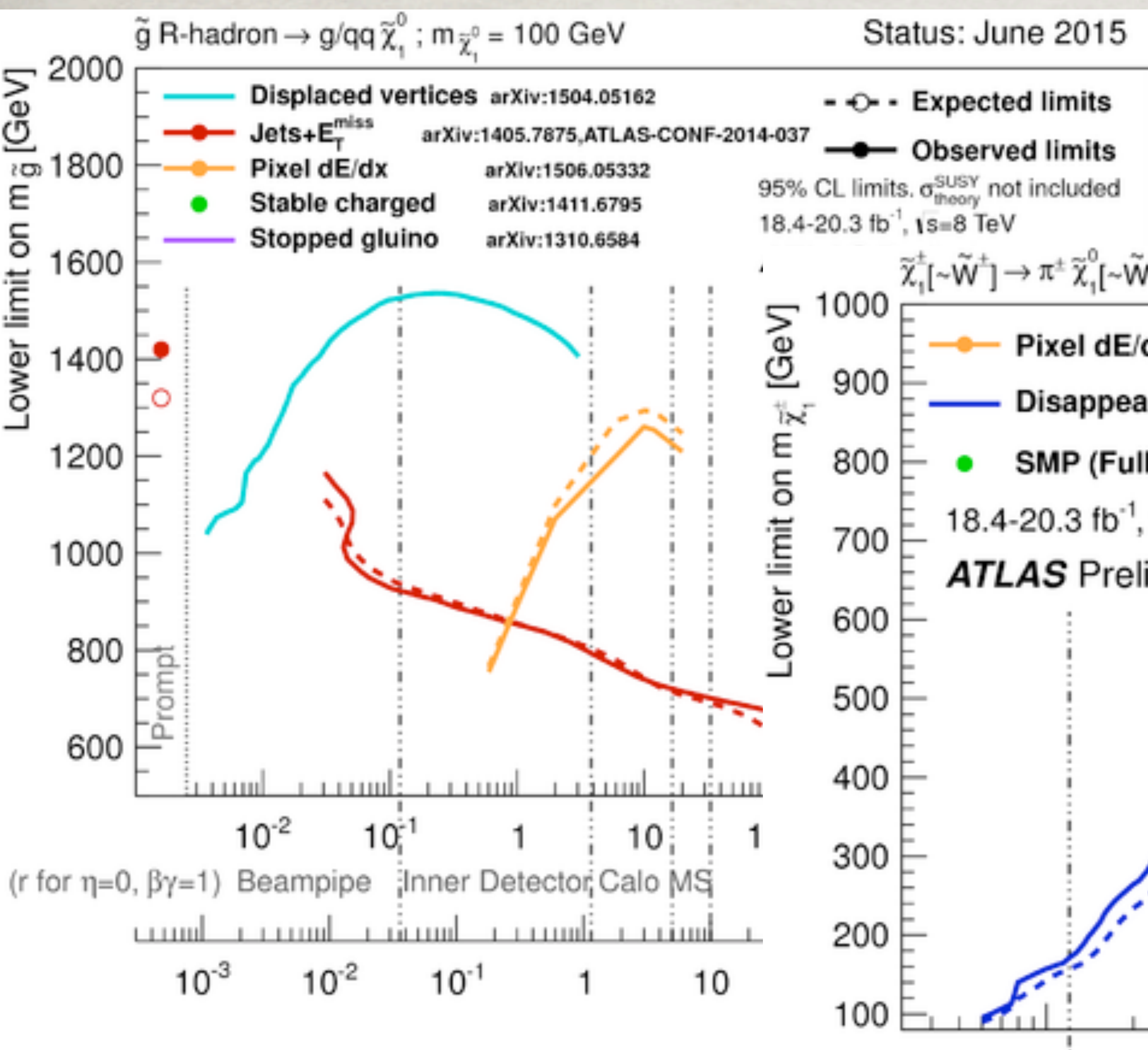
It is possible to over-constraint the model and check the hypothesis of FIMP production !

Long-lived particles @ LHC

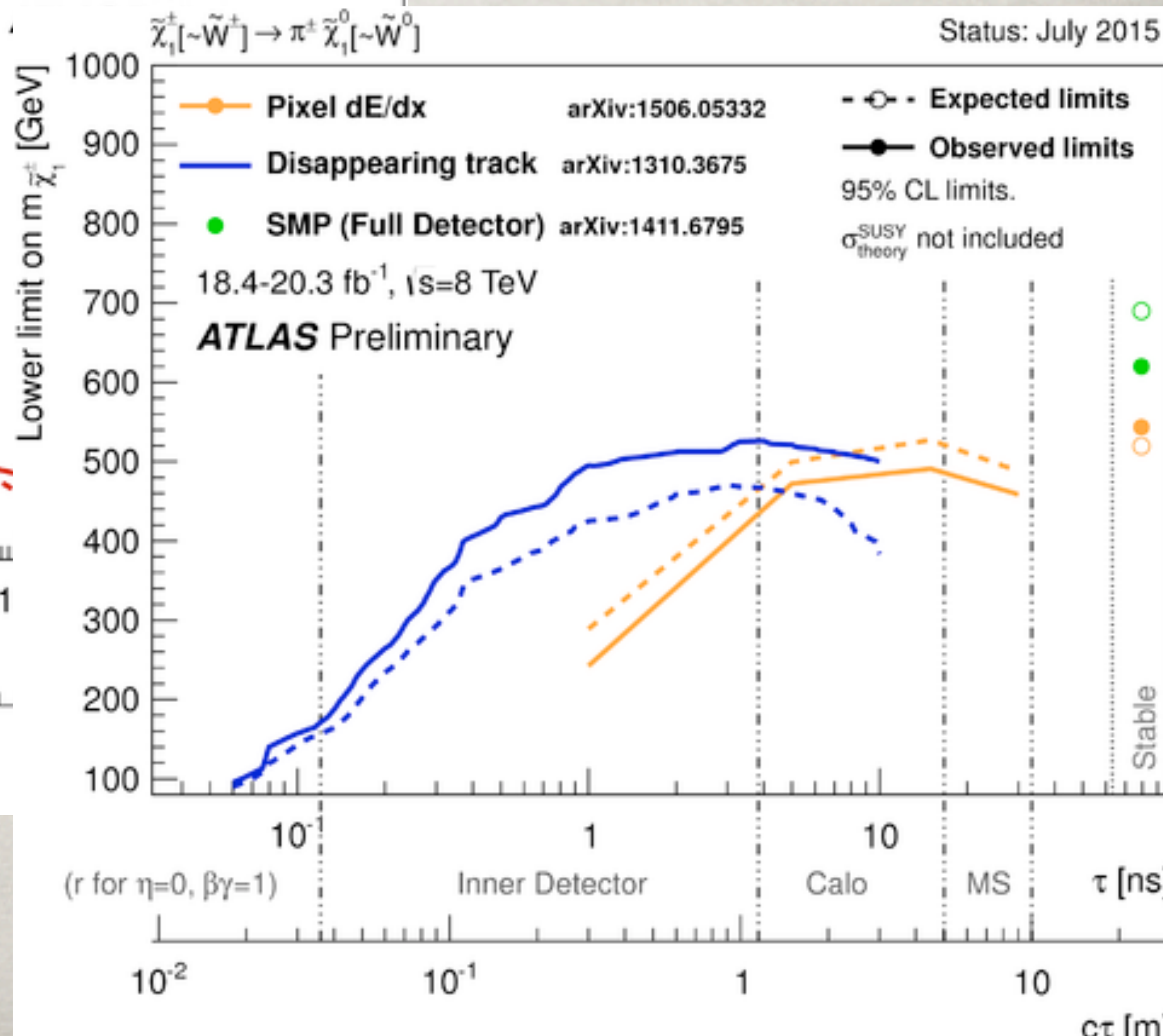


[ATLAS combination]

Long-lived particles @ LHC



[ATLAS combination]

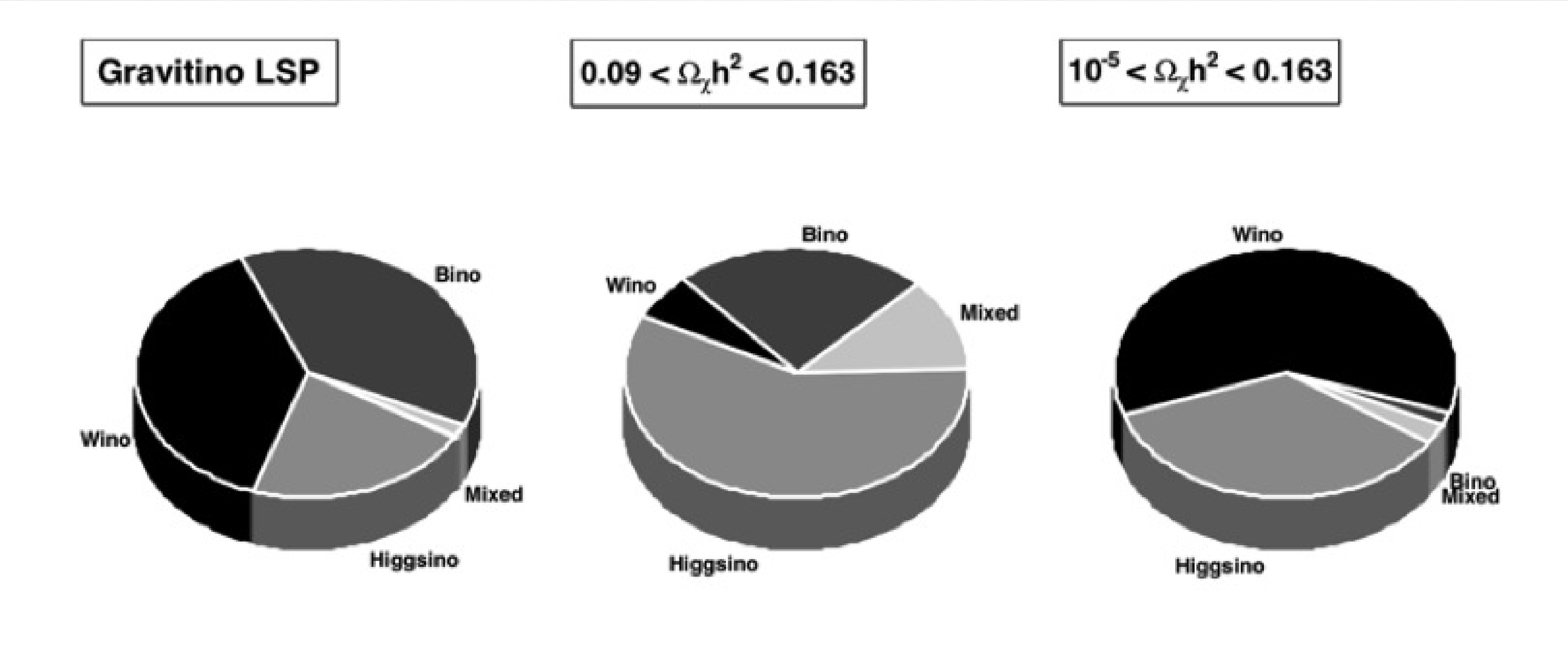


pMSSM DM confronts LHC

DM in pMSSM

[Arbey et al. 1505.04595]

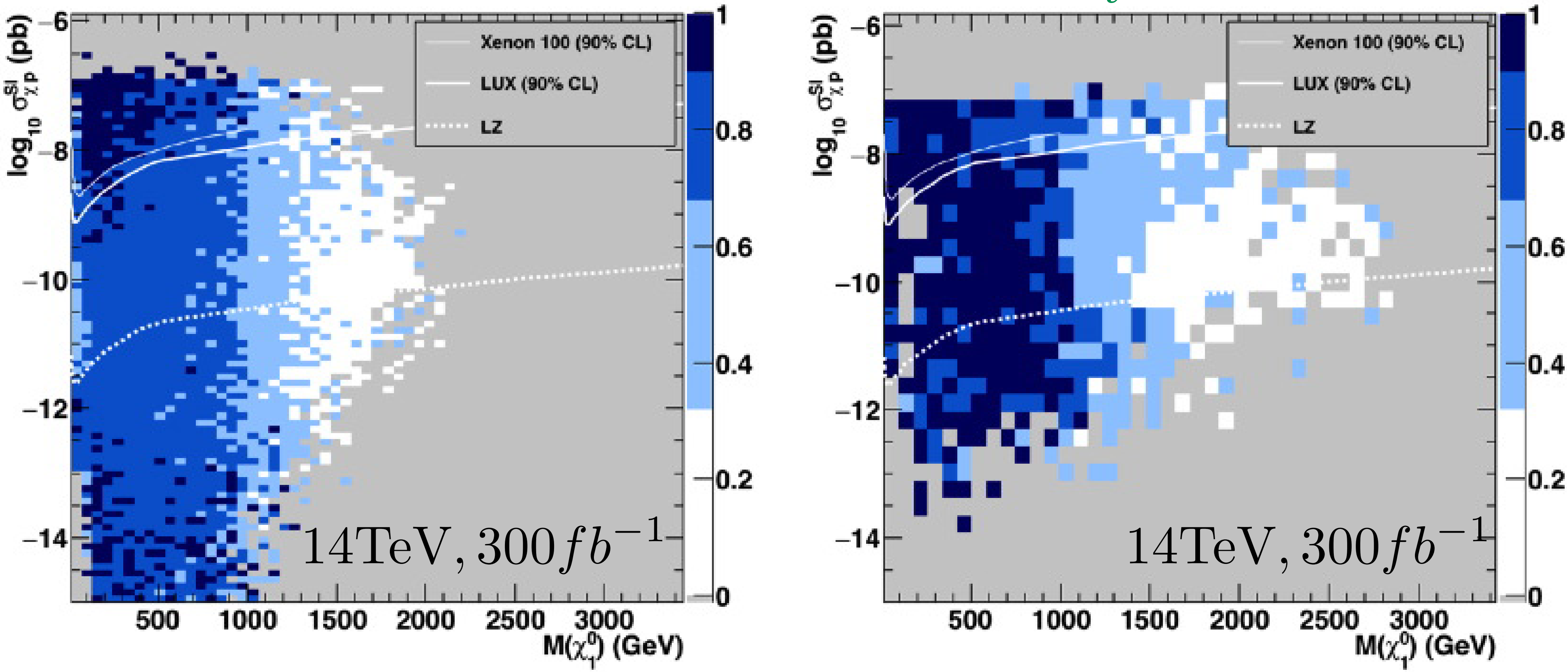
Take neutralino DM or gravitino DM with neutralino NLSP within the RPC pMSSM with 19+1 parameters, i.e. no unification assumption, flavour & CP conserving SUSY breaking. Impose all constraints from low energy, flavour observables, LHC SUSY searches and monojets, as well as DM density and BBN limits on neutralino NLSP…



Gravitino vs neutralino

The neutralino compositions in the two scenarios is very different and so also the LHC reach in the next run: only half the neutralino DM points will be excluded, while 75% of the gravitino DM points...

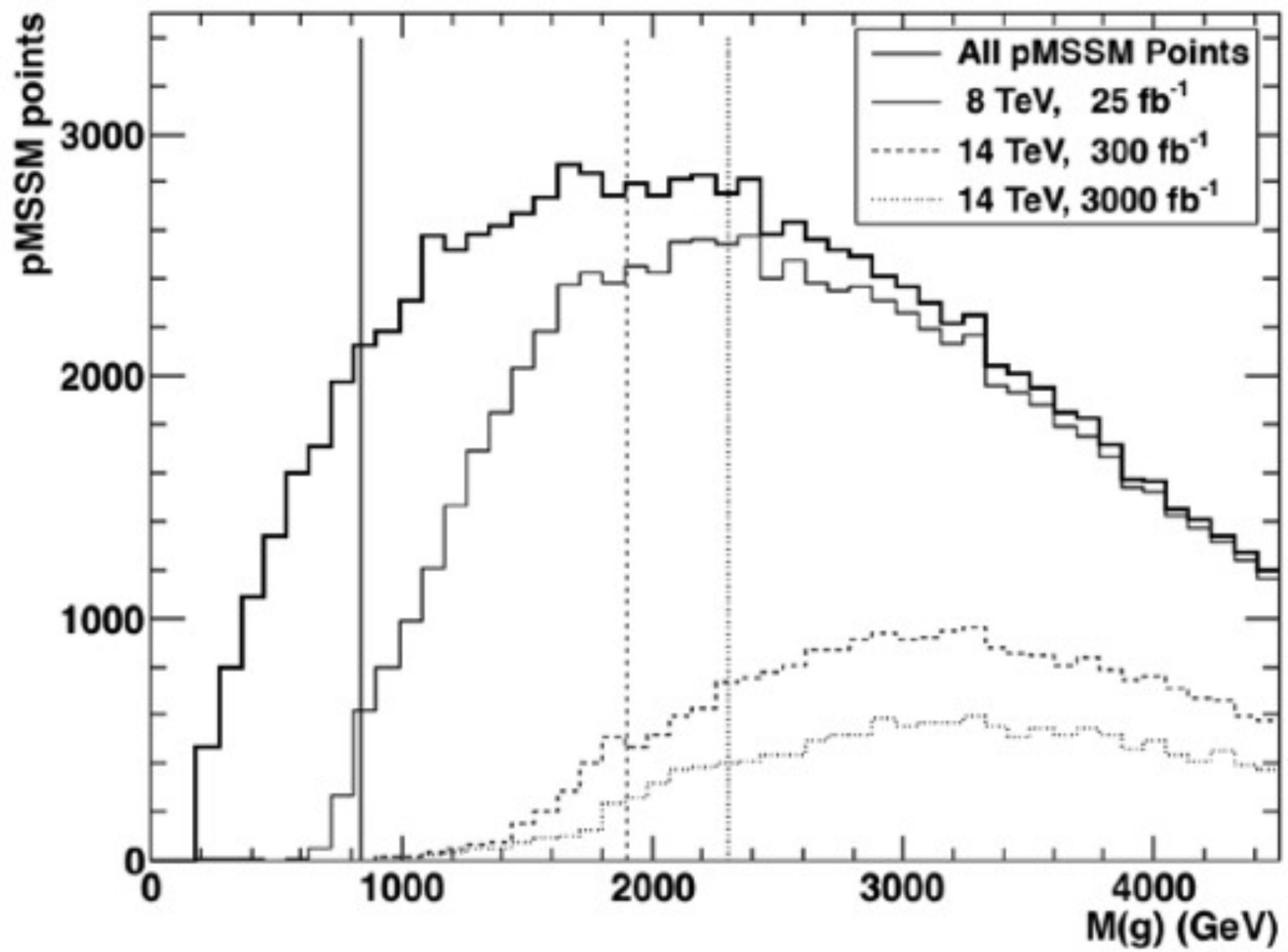
[Arbey et al. 1505.04595]



Gluino mass in pMSSM

In the generic pMSSM limits on the gluino mass are less strong than in constrained models !

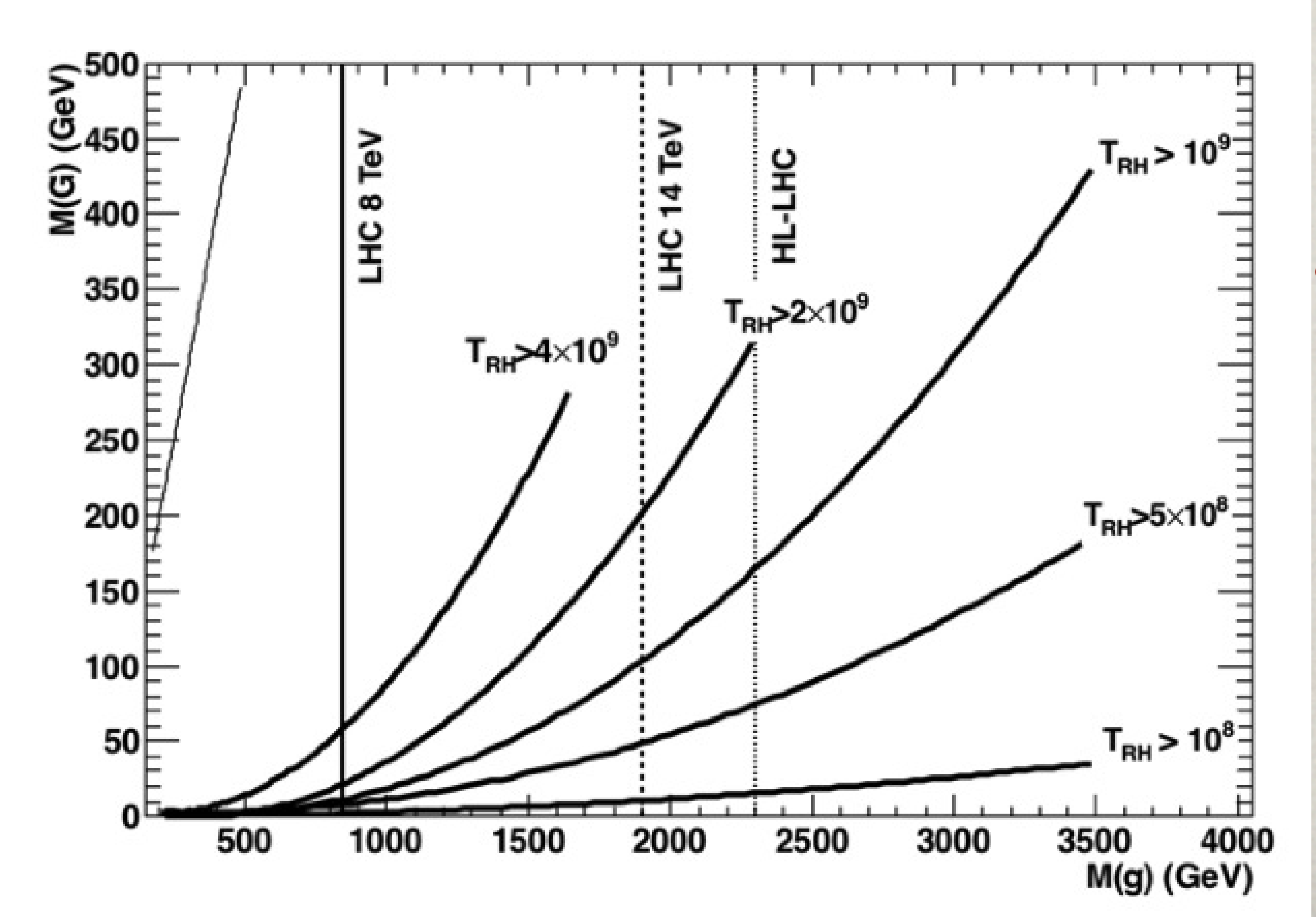
[Arbey et al. 1505.04595]



Gravitino DM & gluino

[Arbey et al. 1505.04595]

Gluino mass is an important parameter in gravitino thermal production: the next LHC run will probe the parameter space compatible with classical (no-flavour) thermal leptogenesis.



Minimal gravitino mass such that $\Omega_{\tilde{G}} h^2 < 0.12$ is given by

$$m_{\tilde{G}} \propto m_{\tilde{g}}^2$$

Stop NLSP

Try to reduce the NLSP density to evade BBN bounds:

- require a strongly interacting NLSP to increase the annihilation cross-section, including as well the Sommerfeld enhancement

→ colored NLSP like stop & gluino

- for naturality reasons and to keep the Higgs light, concentrate on the lightest stop

→ stop NLSP scenario

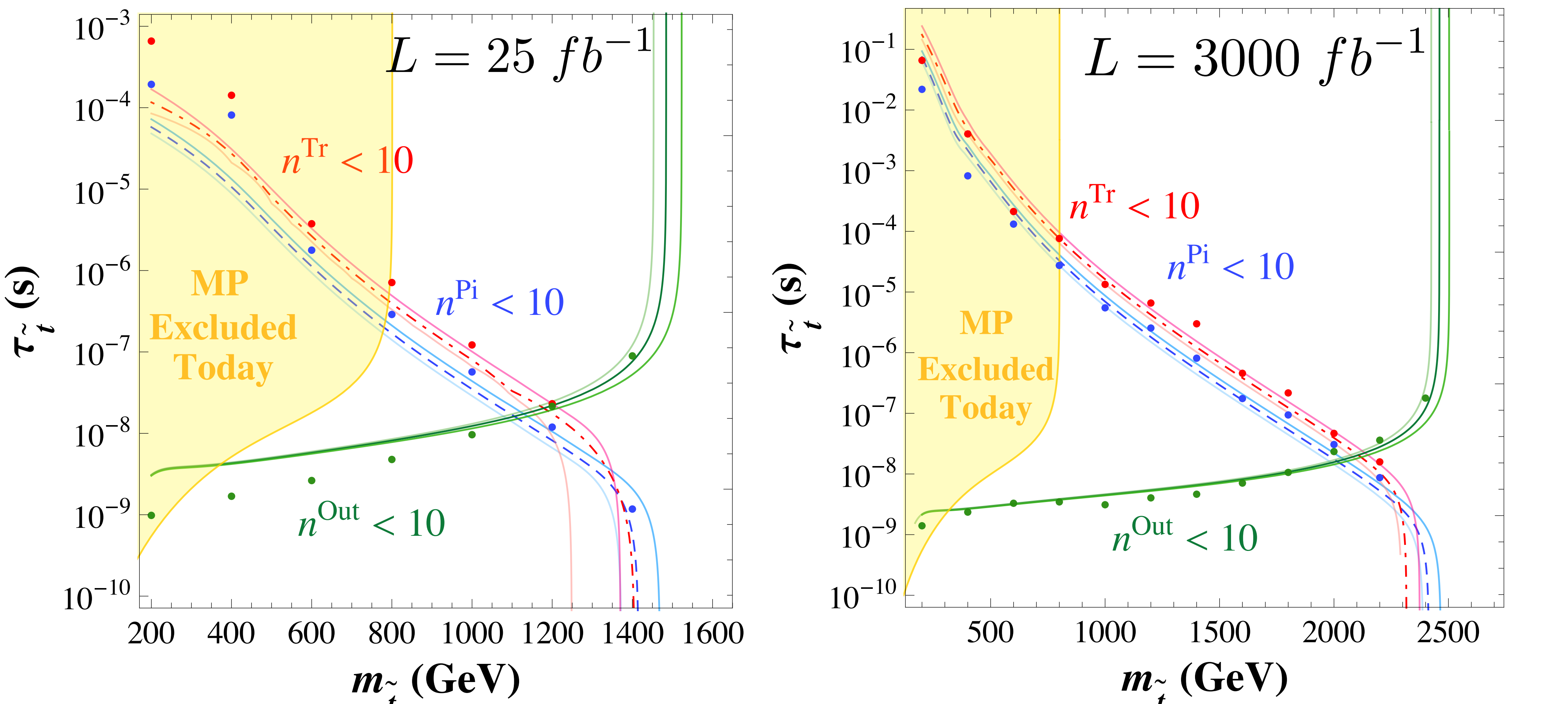
[LC & Federico Dradi 1403.4923]

Of course stop has also the advantage of a relatively small production cross-section compared to gluinos/other squarks such that the LHC bounds are weaker...

LHC: LONG-LIVED STOP

Best strategy: combine searches for metastable particles (out) and displaced decay vertices in tracker or pixel CMS detector. Draw the lines for 10 events of any type to be conservative:

[LC & F. Dradi 1403.4923]

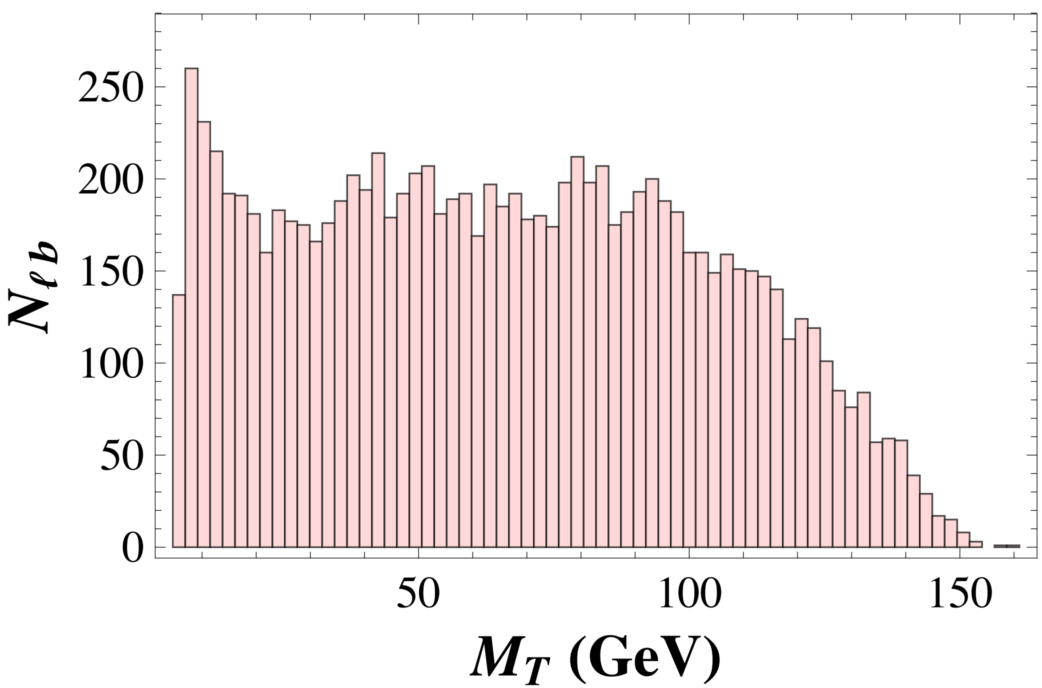


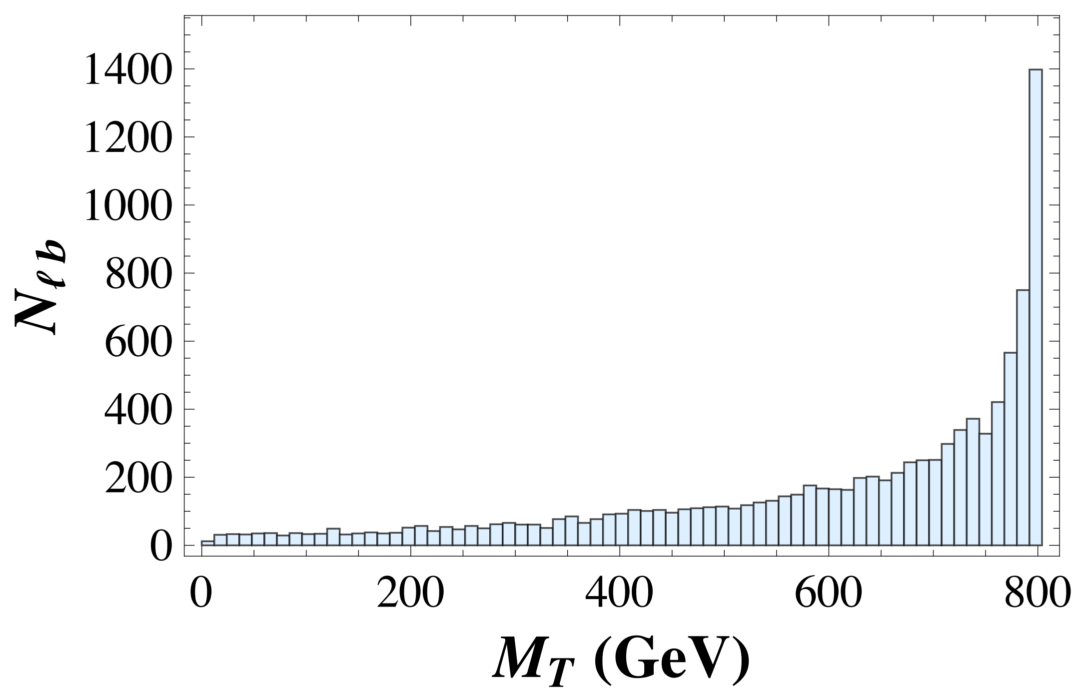
Band is the +/- 1 sigma fluctuation for a Poisson distribution..

LHC: WHICH DECAY ?

If the stop decays inside the detector, the momentum distributions allow to distinguish RPC and RPV decays...

[LC & F. Dradi 1403.4923]





It should be easy to disentangle 2-body from 4-body decay !

Outlook

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- The search for a DM particle continues on all fronts: the LHC is one of the most important probes for WIMP and FIMP/SuperWIMP Dark Matter !
- For generic WIMP DM searches via EFT are being improved and complemented by simplified model searches.
- The FIMP/SuperWIMP framework is quite general and may point to heavy metastable particles & displaced vertices at LHC ! A combined detection is still possible in the next run for a colored scalar.
- pMSSM with Gravitino DM: it will be tested in the next LHC run, especially in the parameter region compatible with high T_{RH} and large gravitino mass.