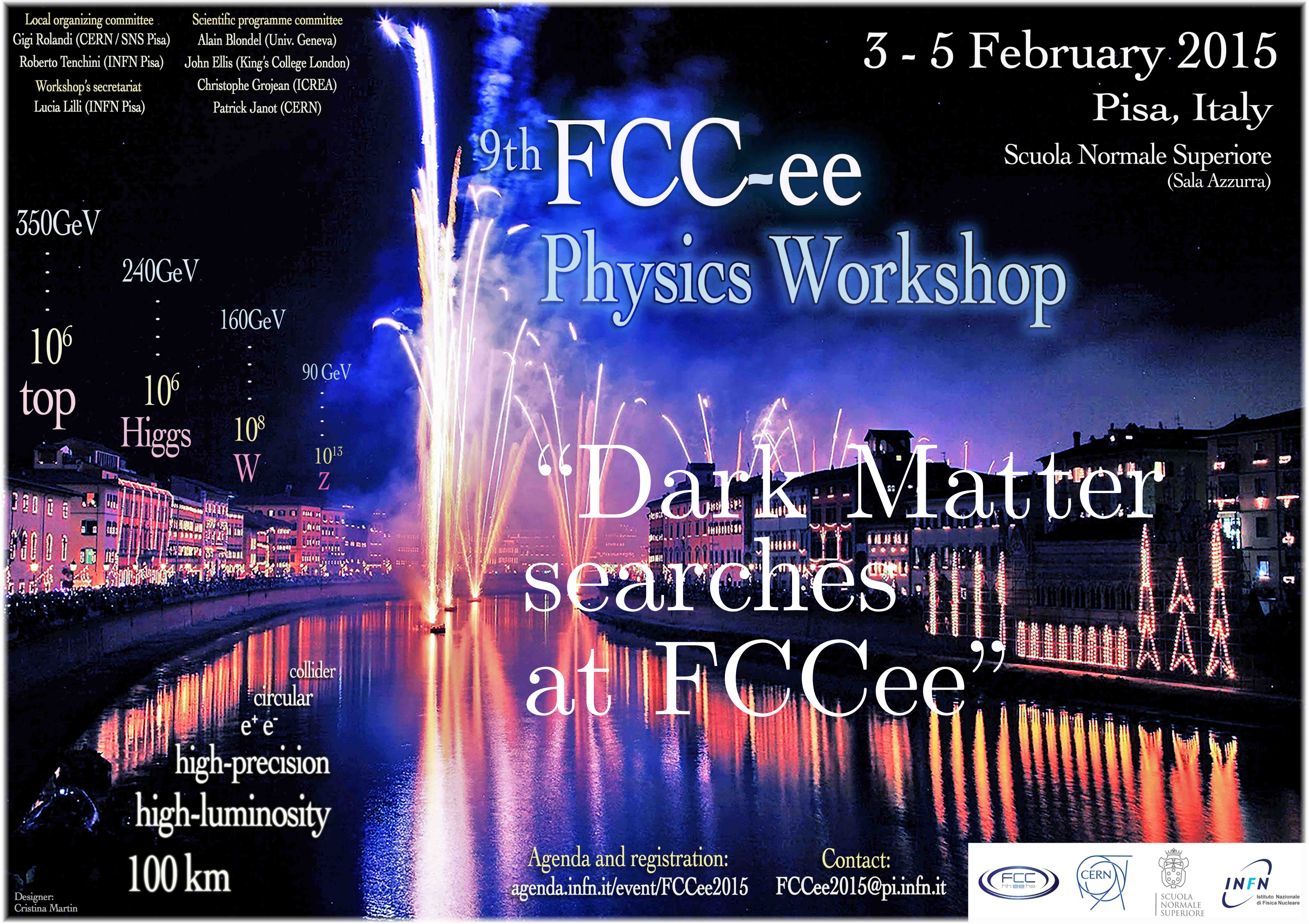


Alessandro Strumia, TLEP9 workshop, Pisa, February 5, 2015

My little paper about DM searches

Alessandro Strumia, TLEP9 workshop, Pisa, February 5, 2015

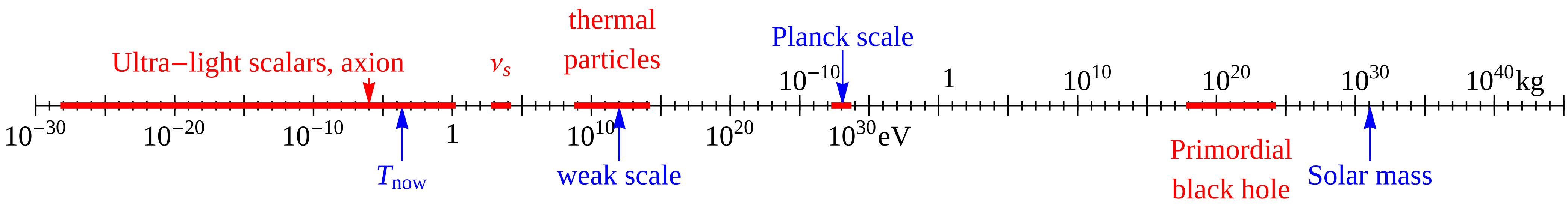
Trivia

Difficult to go beyond well known simple statements:

- DM is probably stable thanks to a Z_2 symmetry: **DM produced in pairs**.
- DM behaves like ν: DM carries away **missing transverse momentum** $\not{p}_T$.
- Maybe DM comes alone giving $\not{p}_T j$ and $\not{p}_T \gamma$ from initial state radiation.
- Maybe DM comes with other particles giving better signals.

It would be wise to stop here.

Theory: $M_{\rm DM}$ = (weak scale) $\times 10^{\pm 40}$



Two great arguments favour weak scale DM:

1) Dark Matter as a thermal relic
2) Naturalness of the Higgs mass!

SUSY-DM aka neutralino would have given great signals. But

1) Bullets are finishing
2) Naturalness of the Higgs mass?

Abandoning the natural SUSY scenario it becomes difficult to tell something useful: building DM models is too easy and the literature is a mare magnum.

Collider experiments (ATLAS, CMS) followed an effective-operator approach.

Effective operators for DM at colliders?

Assume that the unknown physics that couples DM to SM is so heavy that it can be integrated out leaving effective operators of the form

$$\frac{[\bar{\Psi}_{\rm DM}\gamma_\mu\Psi_{\rm DM}][\bar{\Psi}_{\rm SM}\gamma^\mu\Psi_{\rm SM}]}{\Lambda^2}$$

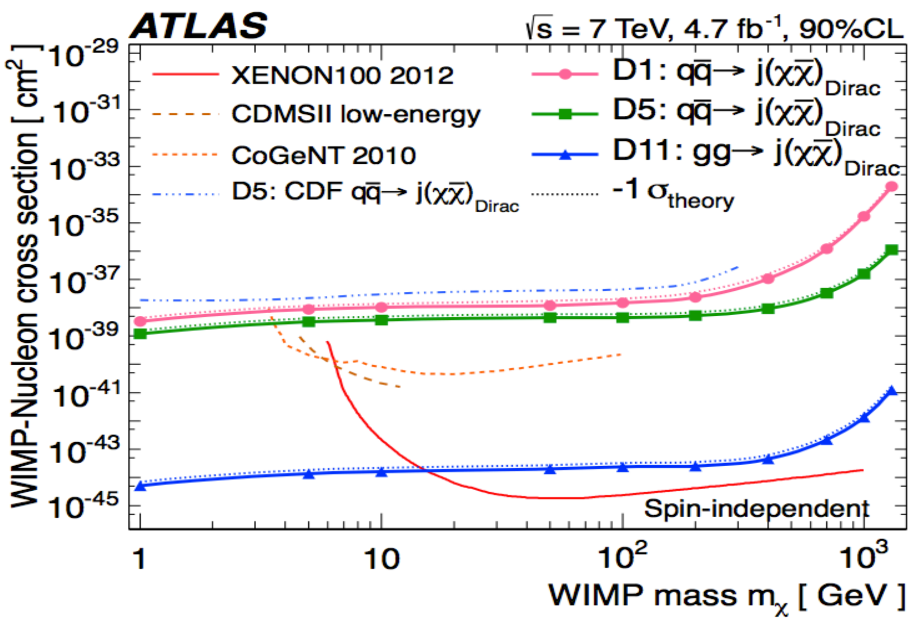
General framework where everything is computed in terms of Λ and $M_{\rm DM}$:

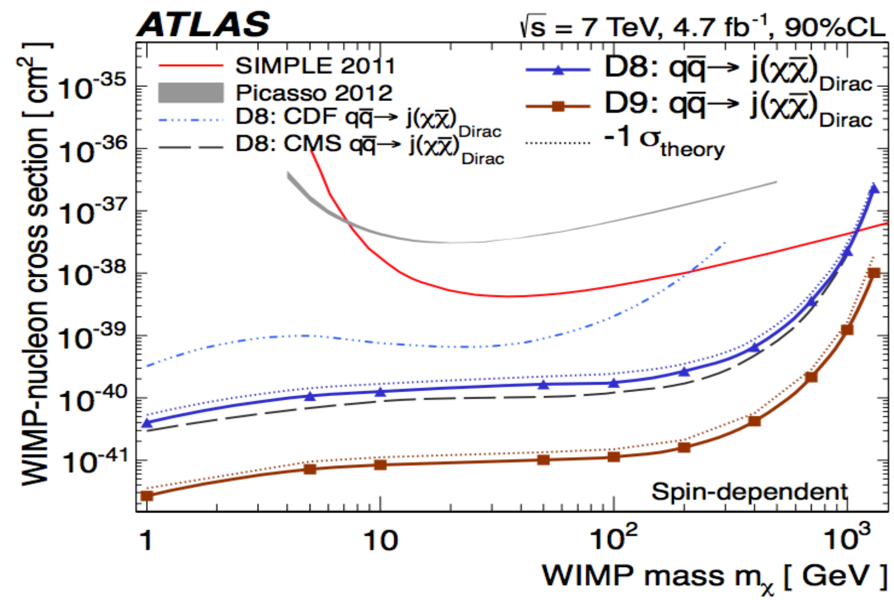
- **Thermal DM abundance**: $\dfrac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm exp}} = \dfrac{(\Lambda/700\,{\rm GeV})^4}{(M/150\,{\rm GeV})^2}$.

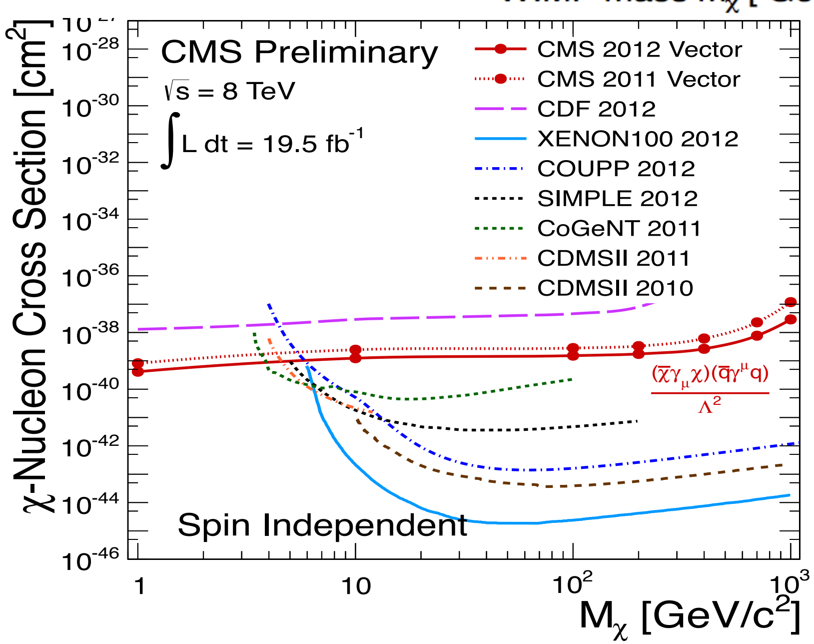
- **Direct detection**, $\sigma_{\rm SI} \approx 5\ 10^{-39}\,{\rm cm}^2 \left(\dfrac{M}{m_N+M}\right)^2 \left(\dfrac{700\,{\rm GeV}}{\Lambda}\right)^4$.

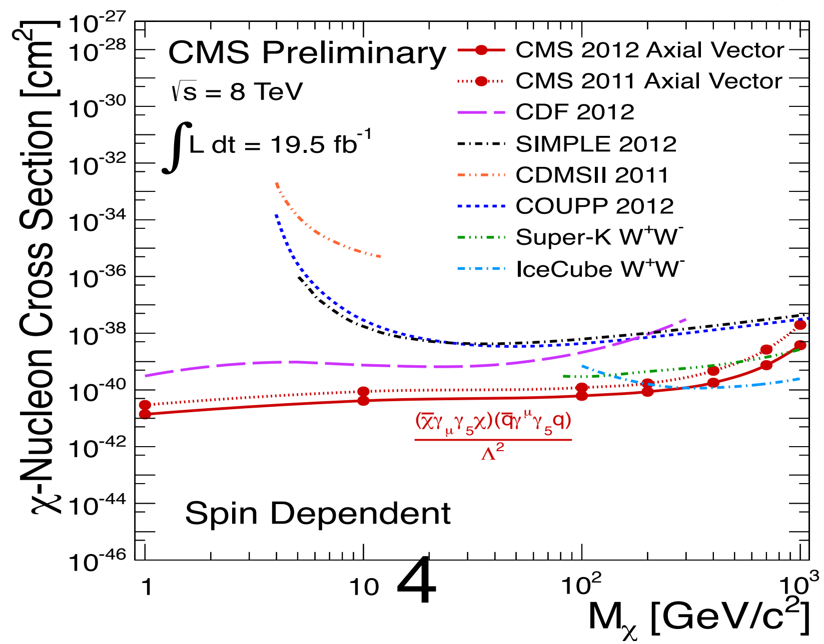
- **Collider**: $j\not{E}_T$ and $\gamma\not{E}_T$ searches at LHC imply $\Lambda > 700\,{\rm GeV}$ for $M_{\rm DM} \ll \Lambda$.

LHC competes with direct detection?









But

1. **In-validity of the effective operator approximation.**

   Effective operators hold at low energy. For any collider the limit will be $\Lambda \ll \sqrt{s}$, because tagging the invisible signal needs extra j or γ: small σ.

2. **Effective operators could mislead to miss the missing energy signal.**

   The assumed growth of $\sigma \sim E^2/\Lambda^4$ is crucial in getting competitive collider "bounds" on $\sigma_{\rm SI}$. In models where $1/\Lambda^2 \approx g^2_{\rm mediator}/M^2_{\rm mediator}$, such growth stops at the mediator mass: the signal is no longer at the highest E.

3. **What LHC would really see is the heavy mediator particle**.

   Not missing energy. Even using "simplified models" the casistics is tedious. The basic possibilities are a colored mediator in t-channel (signal: QCD pair production) or a neutral mediator in s-channel (signal: $pp \to jj$).

   (There is now a vast literature on all of this, with many mediators)

SM mediators

[An attempt from Giudice, De Simone, Strumia, arXiv:1402.6287]

Don't add a speculative mediator with unknown couplings to DM and to SM. Since the mediator must be seen first, assume that it is a known particle. Explore the possibility that

- DM is either a fermion $\psi_{\rm DM}$ or a scalar $s_{\rm DM}$

- The mediator is either the Higgs h

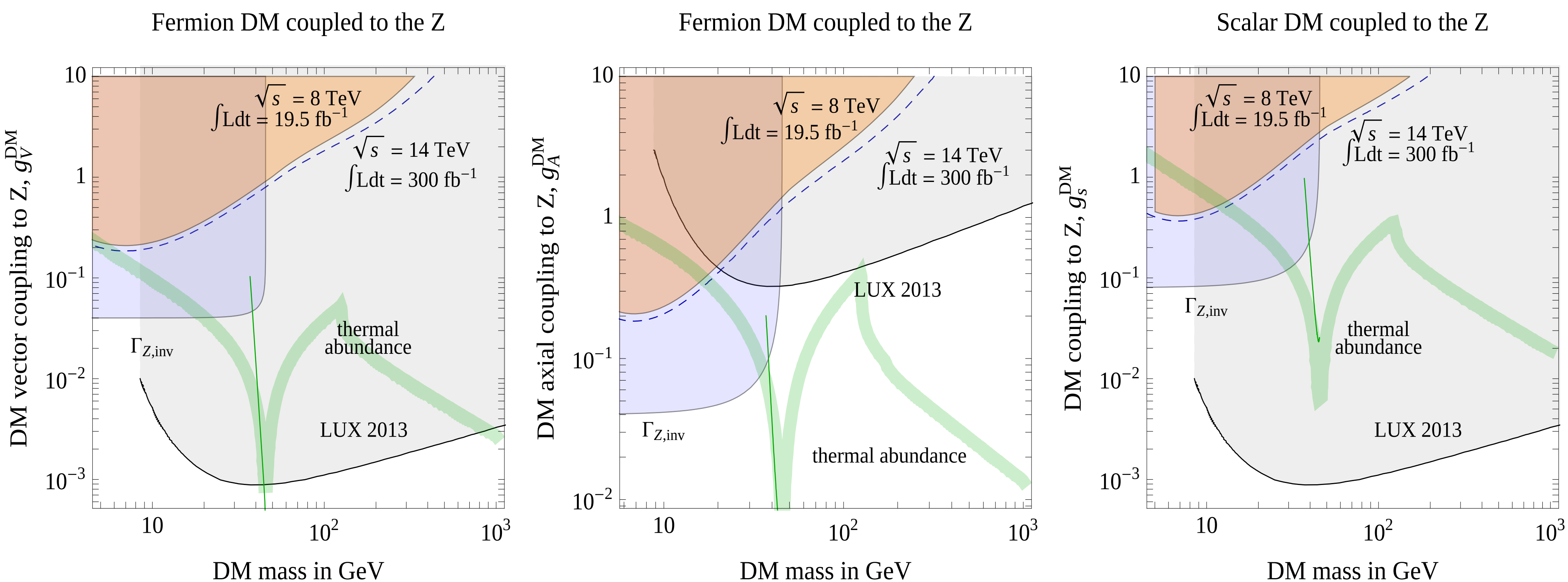
$$\frac{h}{\sqrt{2}}\left[\bar{\psi}_{\rm DM}(y_{\rm DM}+iy^P_{\rm DM}\gamma_5)\psi_{\rm DM}+\frac{\lambda_{\rm DM}v}{2}s^2_{\rm DM}\right].$$

  or the Z

$$\frac{g_2 Z_\mu}{\cos\theta_{\rm W}}\left[[\bar{\psi}_{\rm DM}\gamma_\mu(g_V^{\rm DM}+\gamma_5 g_A^{\rm DM})\psi_{\rm DM}]+\sum_s g_s[s^*_{\rm DM}(i\partial_\mu s_{\rm DM})-(i\partial_\mu s^*_{\rm DM})s_{\rm DM}]\right]$$

They act as s-channel mediators.

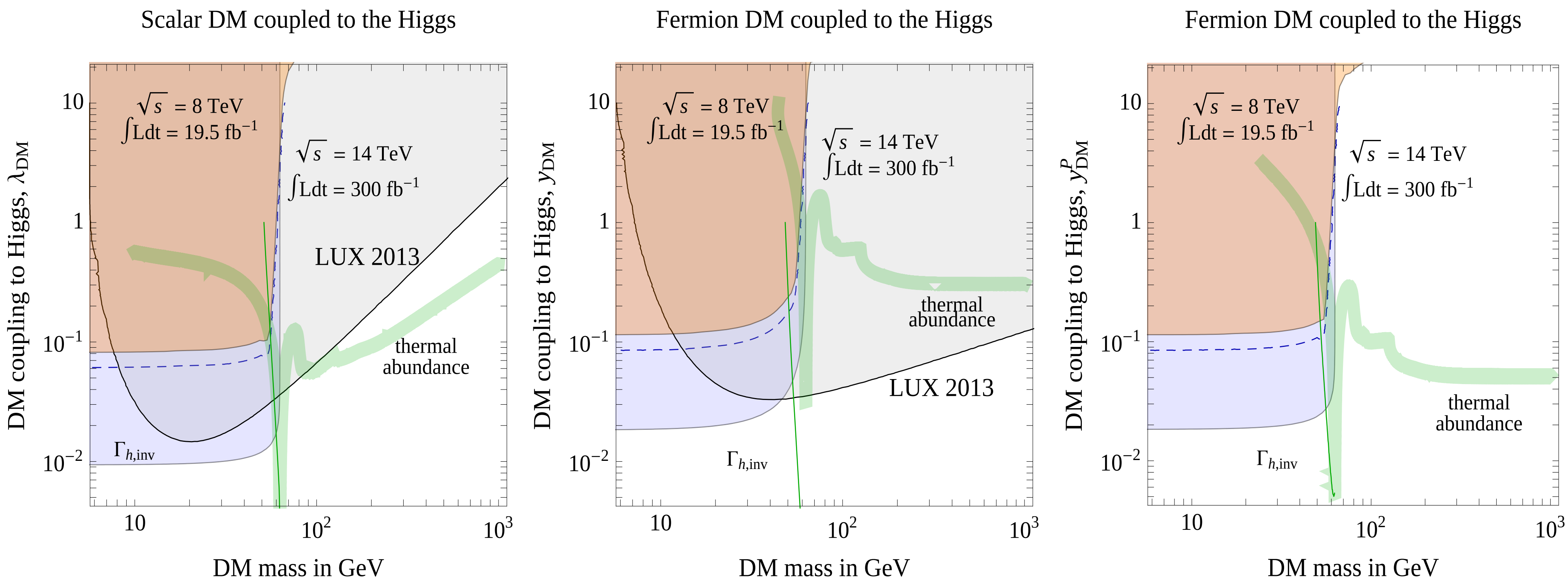
DM coupled to the Z



Red: LHC8 bound. Blue: Γ_Z^{inv} bound. Gray: direct detection bound.

Green: estimated band where the DM abundance is reproduced thermally.

DM coupled to h



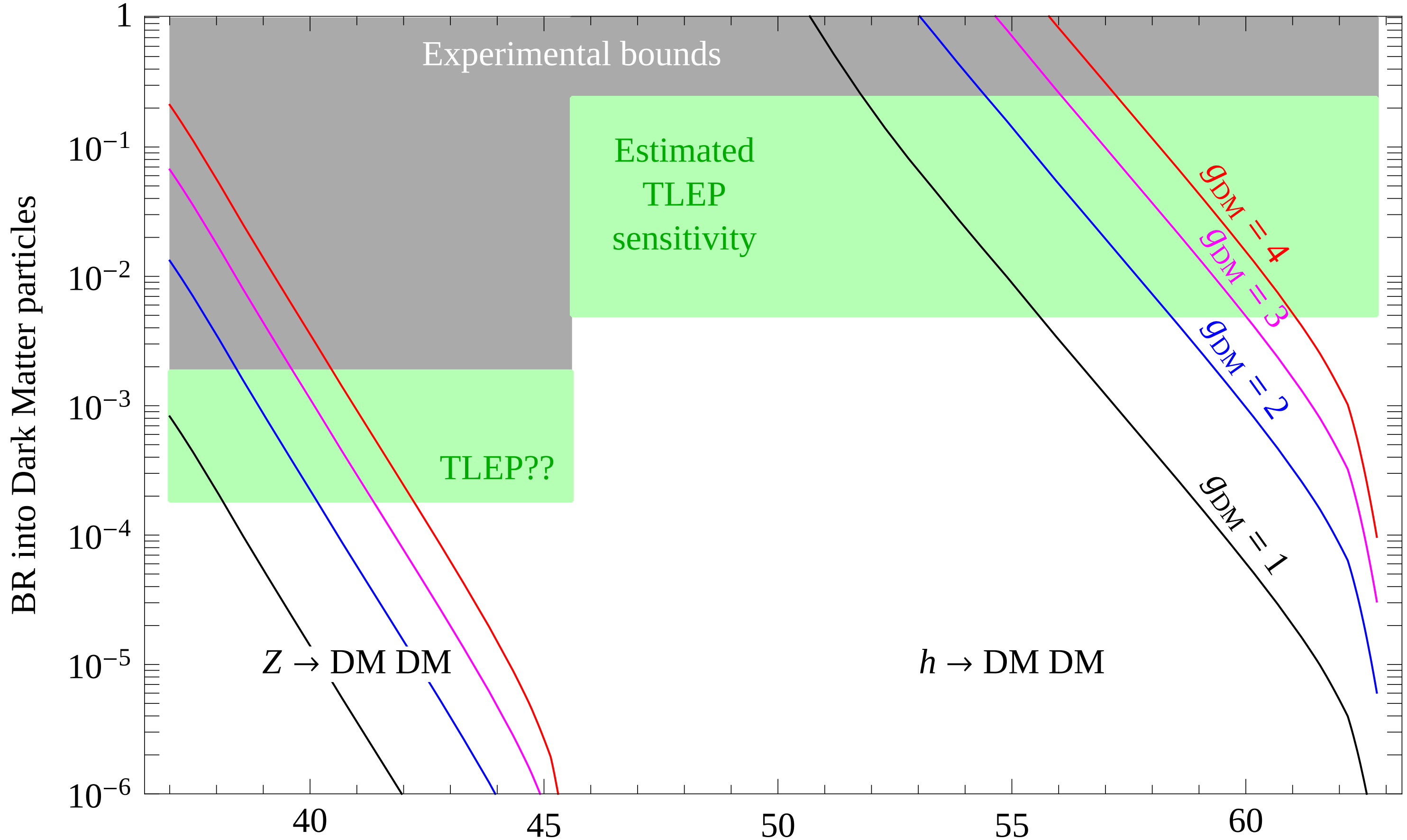
In both cases the message is that:

- If $M_{\rm DM} > \frac{1}{2}M_{Z,h}$ LHC cannot improve (signal much below backgrounds).
- If $M_{\rm DM} < \frac{1}{2}M_{Z,h}$ better measurements of $\Gamma^{\rm inv}_{Z,h}$ can help

DM freeze-out via decays

Usually DM freeze-out fixes $\sigma v \approx 3\ 10^{-26}\text{cm}^3/\text{sec}$. It M_{DM} is just below $\frac{1}{2}M_{Z,h}$ DM freeze-out is dominated by resonant exchange of Z, h and it fixes $\Gamma^{\text{inv}}_{Z,h}$

Invisible BR suggested by DM thermal relic abundance



DM mass in GeV

A specific model: Minimal DM

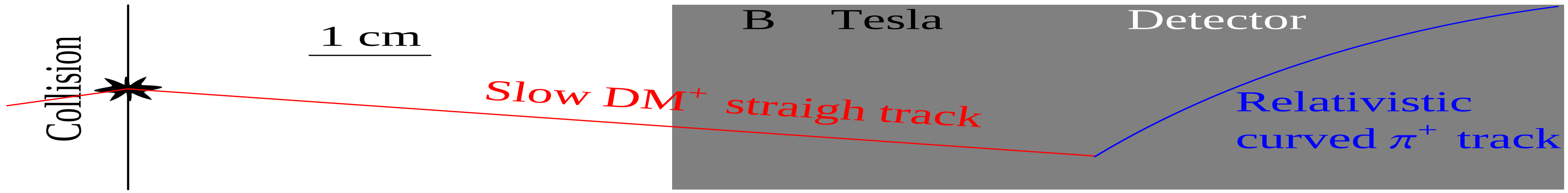
Assume that DM is **one** electroweak n-plet containing a neutral DM particle with **only gauge** interactions. DM as a thermal relic predicts a too large mass.

Quantum numbers $\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{\mathrm{DM}^\pm} - m_{\mathrm{DM}}$ in MeV	Naturalness bound in TeV	σ_{SI} in $10^{-46}\,\mathrm{cm}^2$
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(2.3 \pm 0.3)\, 10^{-2}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(2.5 \pm 0.8)\, 10^{-2}$
3	0	0	HH^*	2.5	166	$0.22 \times \sqrt{\Delta}$	0.60 ± 0.04
3	0	1/2	LH	2.7	166	$1.0 \times \sqrt{\Delta}$	0.60 ± 0.04
3	1	0	HH, LL	$\gtrsim 1.6$	540	$0.22 \times \sqrt{\Delta}$	0.06 ± 0.02
3	1	1/2	LH	$\gtrsim 1.9$	526	$1.0 \times \sqrt{\Delta}$	0.06 ± 0.02
5	0	0	(HHH^*H^*)	9.4	166	$0.10 \times \sqrt{\Delta}$	5.4 ± 0.4
5	0	1/2	stable	10	166	$0.4 \times \sqrt{\Delta}$	5.4 ± 0.4
7	0	0	stable	$8 \to 25$	166	$0.06 \times \sqrt{\Delta}$	22 ± 2

The neutral component is $166 - 500\,\mathrm{MeV}$ lighter than the charged component.

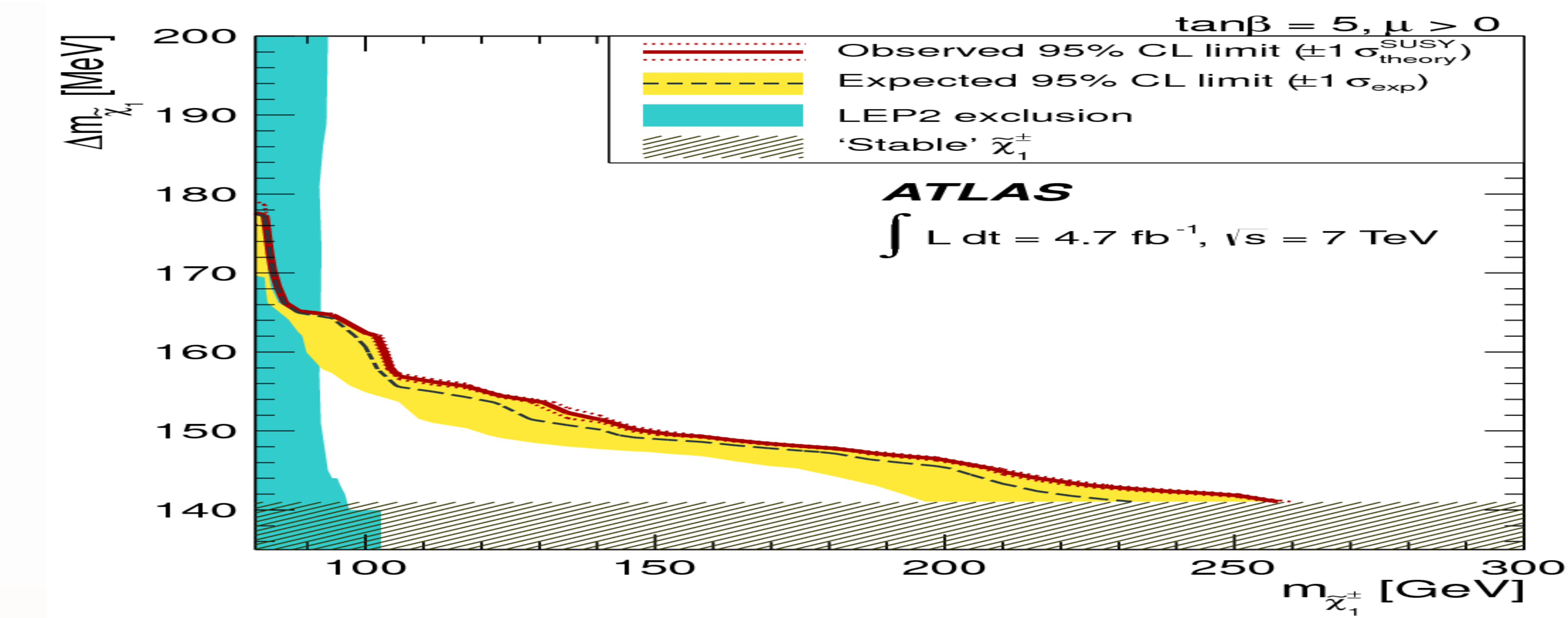
$$1/\Gamma(\mathrm{DM}^\pm \to \mathrm{DM}^0 \pi^\pm) = 44\,\mathrm{cm}/(n^2 - 1)$$

Wino/MDM searches



Trigger on initial state radiation and missing energy.

Difficult but not impossible at LHC for low ΔM, maybe FCCee can do better.



Conclusions / last slide

Better measurements of the invisible widths of the Z and of the Higgs are the best collider option to test DM lighter than $M_h/2$ that couples via SM mediators.