Dark Portals ... to Dark Matter

mainly based on collaborations with S. Colucci, B. Fuks, F. Giacchino, A. Ibarra, M. Tytgat, J. Vandecasteele and S. Wild

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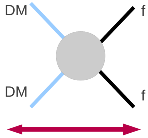
IAP (final) meeting -Brussels

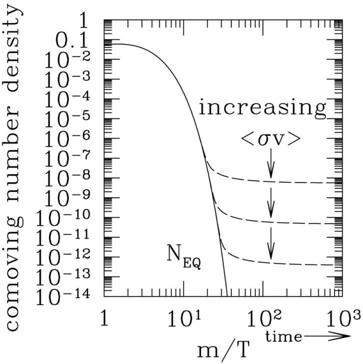
Belgian Science Policy Office belspo Fundamental .be Interactions

Dark Matter as a WIMP

- WIMP relic abundance is driven by processes:



Freeze-out mechanism:
$\rightsquigarrow \Omega h^2 \propto 1/\langle\sigma v\rangle$



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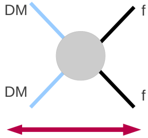

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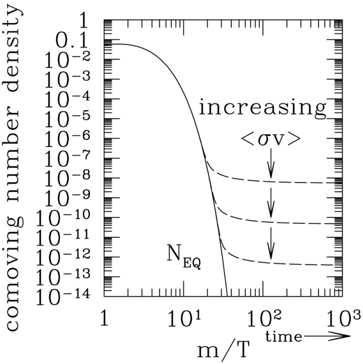
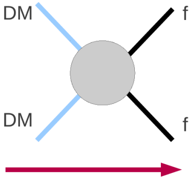


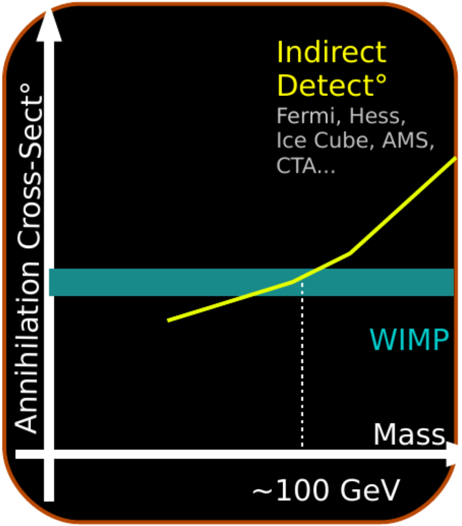
- Cosmo observations ($\Omega h^2 \sim 0.11$) can be interpreted as

$$\langle\sigma v\rangle \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$\rightsquigarrow$ target value for detection experiments looking for annihilation products

Testing WIMPS: the “simple” picture





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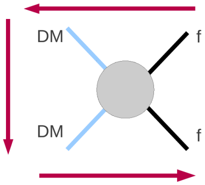
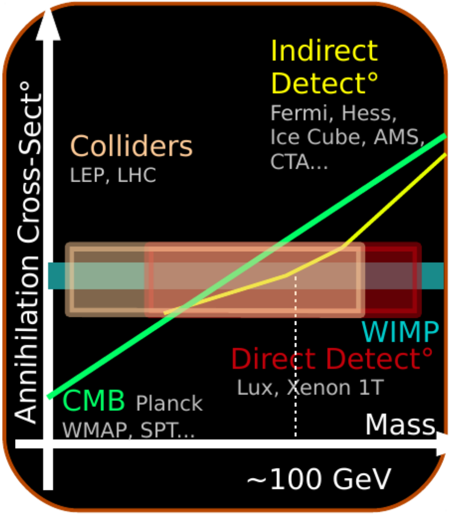


[see also D. Dobur, S. Lowette and I. Mariş talk]



Beyond the simple picture

ways to break $\langle\sigma v\rangle_{\rm fo} \leftrightarrow \langle\sigma v\rangle_{\rm today} \leftrightarrow \sigma_{\rm direct,coll}$??

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- Depending on the DM properties (odd Z_2 assumed) and on the portal:
  - velocity dependent annihilation
  - richer DM sector with coannihilations [Griest & Seckel '90]
  - annihilation near thresholds and resonances [Griest & Seckel '90]
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    (Sommerfeld enhancement [Hisano '04, Cirelli '05], secluded DM [Pospelov '07])

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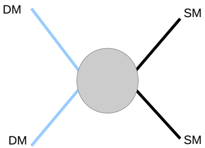
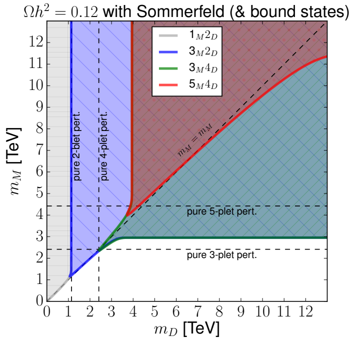
- non WIMP, non "standard" Freeze-out or stability other than Z_2:
  FIMP (freeze-in, ...), SIMP, semi-annihilating DM, asymmetric dark matter, ALP, dark freeze-out, reannihilation, sterile neutrinos (non) resonantly [see next talk by M. Drewes], co-annihilation without chemical equilibrium...

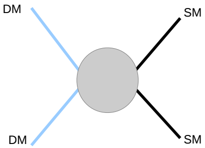
Portals to Dark Matter



Portals to Dark Matter

- SM portals
  - H portal
  - SM gauge bosons portal





Higgs coupled Minimal DM

[LLH,Tytgat, Tziveloglou, Zaldivar'17]

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  - *H* portal
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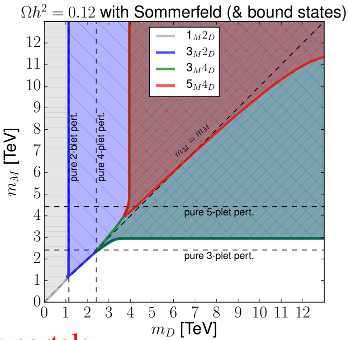
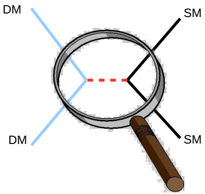
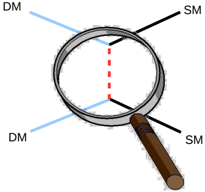




- Dark portals
  - Dark gauge bosons: Z', W'
  - Dark scalars
  - Dark Fermions

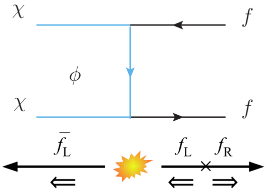


Simplified Models
t-channel mediators: Scalar vs Fermion DM

Why t-channel mediators?

[Bergstrom'89, Flores et al'89 and also Bringmann '08+, Ciafaloni '11, Garny '11+]

Majorana DM with $\mathcal{L} \supset y\phi^\dagger \chi f_R + h.c.$



Annihilation $\sigma v = a + bv^2$

- a term :s-wave chirally suppressed $\propto (m_f/m_\chi)^2$
- b terms :p-wave v suppression $\langle v^2 \rangle_{fo} \sim 0.2$ while $\langle v^2 \rangle_{\rm GC} \sim 10^{-6}$

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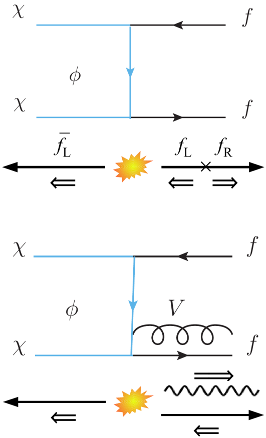

Not hopeless! Can get significant signal from $\chi\chi \to V\bar{f}f$!!

The emmission of an extra vector V lifts the chiral suppression

... but suppressed by 3bdy & extra coupling

What about real Scalar DM ?

[Bergstrom '89+, Bringmann '08+, Ciafaloni '11, Garny '11+,Toma '13, Giacchino'13,...]

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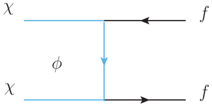
$$Z_2 \,:\, \chi \to -\chi, \Phi \to -\Phi$$



$$r = \frac{M_\phi}{M_\chi}$$

$$\sigma v_{ff}|_\chi = \frac{g_l^4}{48\pi} \frac{v^2}{M_\chi^2} \frac{1+r^4}{(1+r^2)^4}$$

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$$\mathcal{L} \supset y\, S\, \bar{\psi} f_R + h.c..$$

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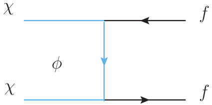

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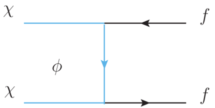

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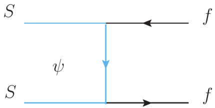

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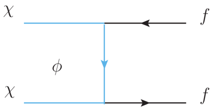

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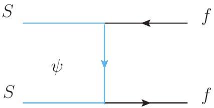

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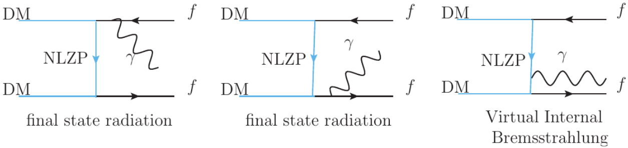
- At f.o. $\langle \sigma v \rangle_{\bar{f}f}|_S / \langle \sigma v \rangle_{\bar{f}f}|_\chi \lesssim 0.16 \rightsquigarrow$ larger Yukawas for S to match $\Omega_{\rm dm}$
- In addition, in general, higher order effects are more importants in the scalar case, ie $\sigma v^\chi_{V\bar{f}f} < \sigma v^S_{V\bar{f}f}$ and $\sigma v^\chi_{VV} < \sigma v^S_{VV}$, for $M_{\rm dm}, y$ fixed & $V = \gamma$, g

[Toma '13, Giacchino'13 & '14, Ibarra'14]

Coupling to light leptons: Significant gamma ray spectral features

[Giacchino, Lopez-Honorez,Tytgat'13& 14]

Sharp spectral feature



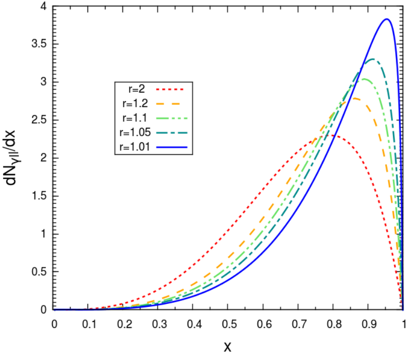
The γ spectrum

$$\frac{dN_{\gamma ll}}{dx} = \frac{M_{\rm dm}}{\sigma_{\gamma ll}} \frac{d\sigma_{\gamma ll}}{dE_\gamma}$$

as a fn of $x = \frac{E_\gamma}{M_{\rm dm}}$ and $r = \frac{M_{\rm NLZP}}{M_{\rm dm}}$

- peaked at $E_\gamma \sim M_{\rm dm}$ for $r \to 1$
- Identical for Scalar & Majonana

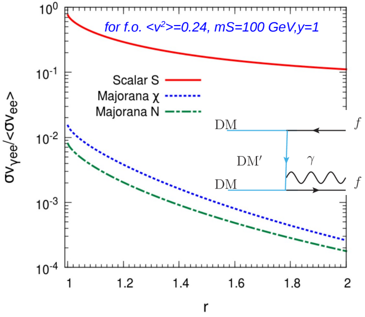
[see also Barger'11]

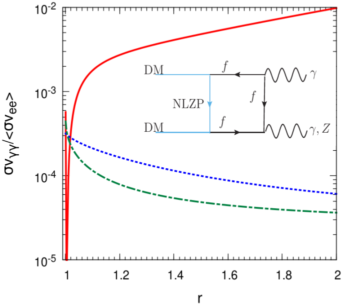


$\rightsquigarrow$ "γ line"-like feature with Bremsstrahlung emission

Enhanced radiative processes for Scalars

see [Giacchino, LLH & Tytgat '13 &'14]
see also [Toma'13 & Ibarra'14]





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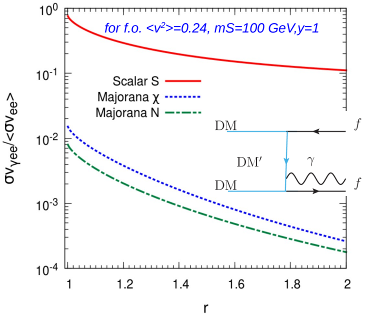
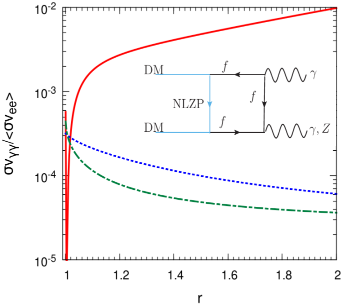
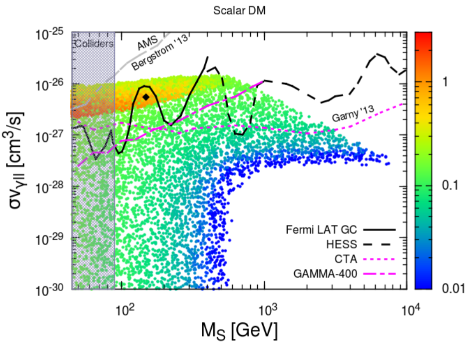




Relative enhancement min ∼ 50 of the Bremsstrahlung signal for scalar DM !!
Radiative processes $\gamma\gamma$, γee always more relevant for Real Scalar DM

Allowed $\langle\sigma v\rangle_{\gamma ll}$ for relic abundance



- when $\sigma v \propto y^4$ dominates $\rightsquigarrow$ larger y for S (due to $d-$wave) $\rightsquigarrow$ larger $\langle\sigma v\rangle_{\gamma ll}$ (modulo the r suppression).
- Majorana DM: $\langle\sigma v\rangle^{max}_{\gamma ll}$ well beyond current and future experimental limits, need extra boost [see also Bringmann'12,Bergstrom'12]
- Scalar DM: $\langle\sigma v\rangle^{max}_{\gamma ll}$ can be larger by up to 2 orders of magnitude

Coupling to light quarks:
Complementarity: Direct, Indirect and Collider searches

[Giacchino, Ibarra, Lopez-Honorez,Tytgat, Wild'15]

Viable param. space for coupling to light quarks

$$\mathcal{L} \supset yS\bar{\psi}q_R + h.c.$$

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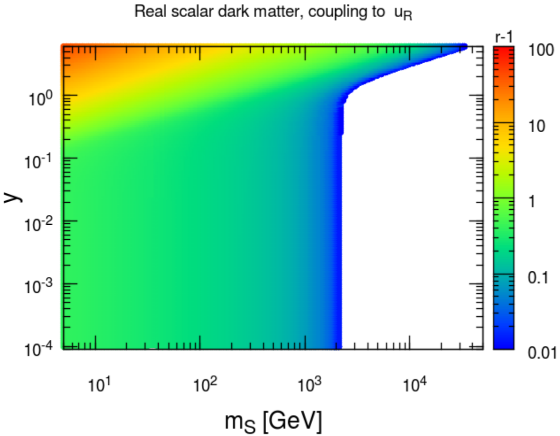
- σv_{VV} & $\sigma v_{V\bar{q}q}$ included and $\langle\sigma_{gg}\rangle$ and $\langle\sigma_{g\bar{q}q}\rangle$ important at f.o. (away from coann.)
- Sommerfeld corrections for mediator annihilation included
  $\rightsquigarrow$ up to max 15% effect on Ωh^2



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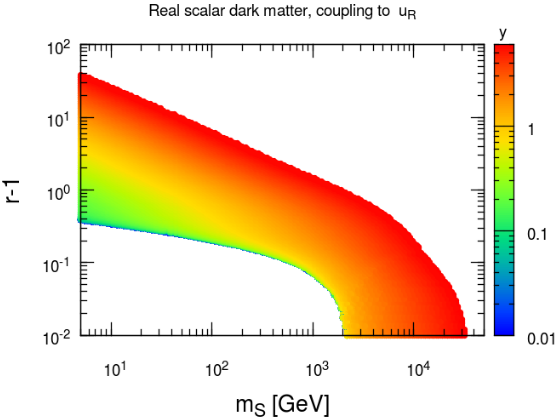
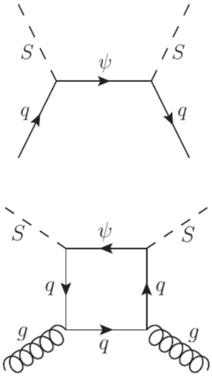
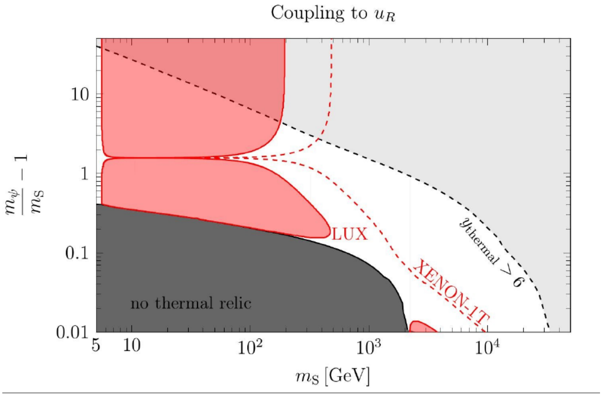


Direct, indirect and collider searches

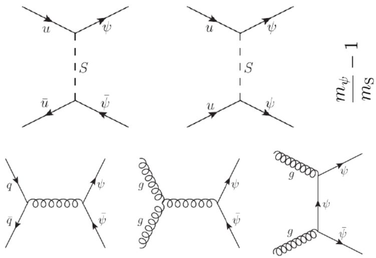
Direct detection

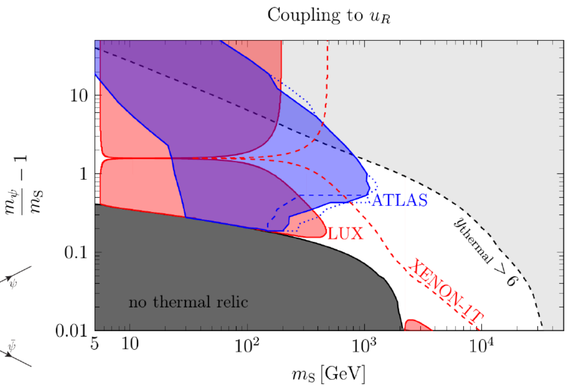




Direct, indirect and collider searches

Collider Searches for mediator multi-j+ MET





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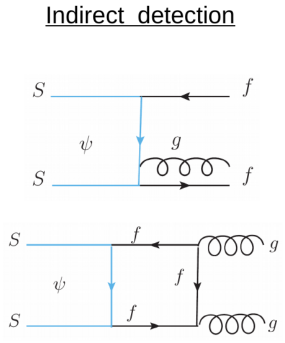

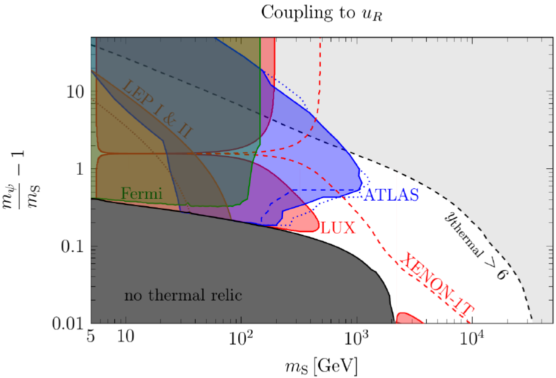

$SS \to gg$ dominates at large $r = m_\Psi/m_D$ while $SS \to \bar{q}qg$ dominates at smaller r

Coupling to top quarks

[to be published: Colucci, Fuks, Giacchino, Lopez-Honorez,Tytgat, VandeCasteele'17 (or '18?)]

From light to heavy quarks

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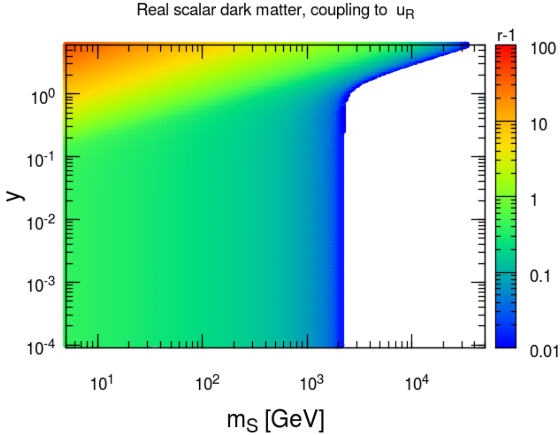

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- $\sigma v_{V\bar{q}q}$ has to be carrefully evaluated in the $m_t \neq 0$

[Colucci, Giacchino, Tytgat, VandeCasteele'17]

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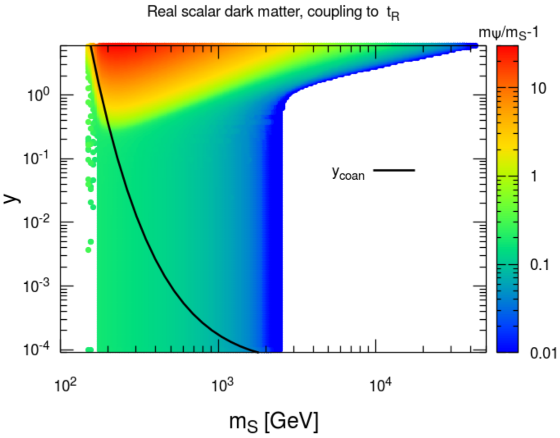

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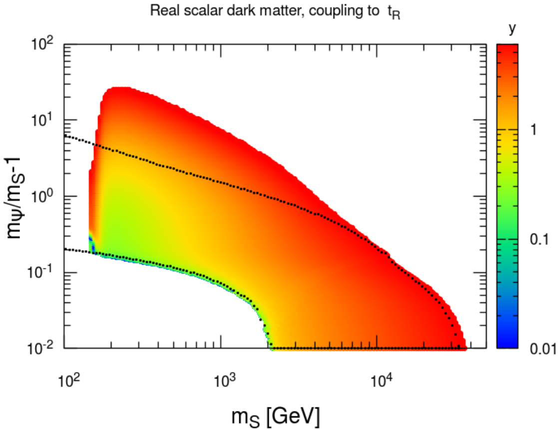
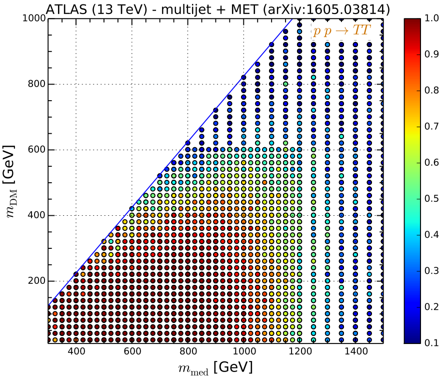
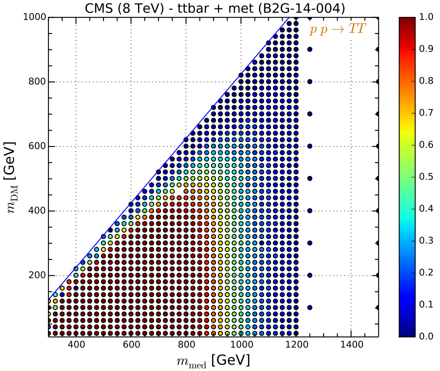
  contribs. for $m_S > 5$TeV
- Larger r values allowed for $m_S \sim m_t$ than for light quarks



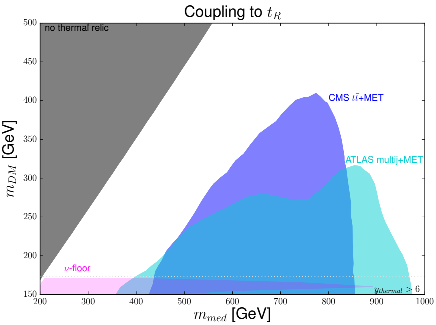
Largely unconstrained parameter space

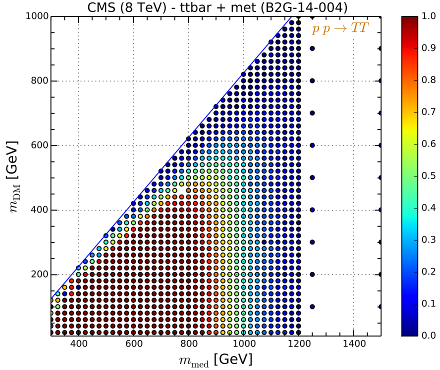




- Main probe: production of mediator at colliders

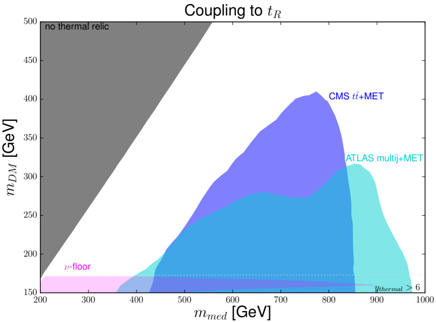
Largely unconstrained parameter space

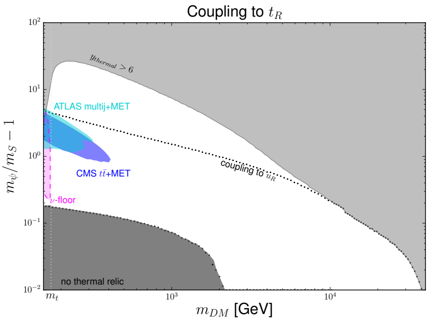




- Main probe: production of mediator at colliders
- Direct Detection: loop suppressed
- Indirect Detection: $\sigma v^{full}_{t\bar{t}g}$ below Fermi reach at $m_{DM} > 150$ GeV

Largely unconstrained parameter space





- Main probe: production of mediator at colliders
- Direct Detection: loop suppressed
- Indirect Detection: $\sigma v^{full}_{t\bar{t}g}$ below Fermi reach at $m_{DM} > 150$ GeV

Real Scalar DM with t-channel fermionic mediator

$\mathcal{L} \supset y\, S\, \bar{\Psi} f_R + h.c.$: simple SM extension with very rich phenomenology:

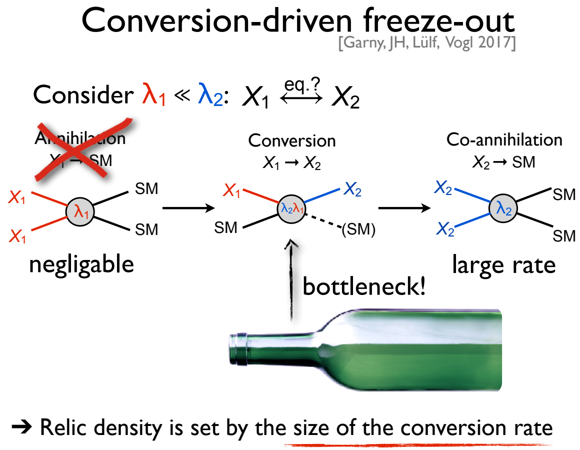
- Coupling to light fermions:
  - d-wave 2-body $\sigma v_{\bar{f}f}$ in the chiral limit
    $\rightsquigarrow$ pheno driven by $SS \to VV, V\bar{q}q$
  - Coupling to l_R: $\langle\sigma v\rangle_{\gamma\gamma}$ & $\langle\sigma v\rangle_{\gamma ll}$
    $\rightsquigarrow$ significant spectral features relevant gamma ray searches
  - Coupling to q_R:$\langle\sigma_{gg}\rangle$ & $\langle\sigma_{g\bar{q}q}\rangle$ are (may be) the dominant contribution today (at f.o) and nice indirect/direct and collider searches complementarity.
- Coupling to t_R: largely unconstrained by direct searches/ indirect searches, best probe so far: collider searches

Thank you for your attention !!!

Backup

Long lived particles in the Majornana scenario

[stolen from Heisig talk'17]



Long lived particles in the Majornana scenario

[stolen from Heisig talk'17]

General back-of-the-envelope estimate:

Conversion rate (just) efficient at freeze-out:

$$\Gamma_{\rm conv} = \Gamma_{\rm decay} + \Gamma_{\rm scatter} \sim H(x \simeq 30)$$

$$\Rightarrow \Gamma_{\rm decay} \lesssim H(x \simeq 30) \sim ((1\text{–}100)\,{\rm cm})^{-1}$$

for masses 100GeV to few TeV

X_2 decay-length:

$$c\tau \gtrsim (1\text{–}100)\,{\rm cm}$$

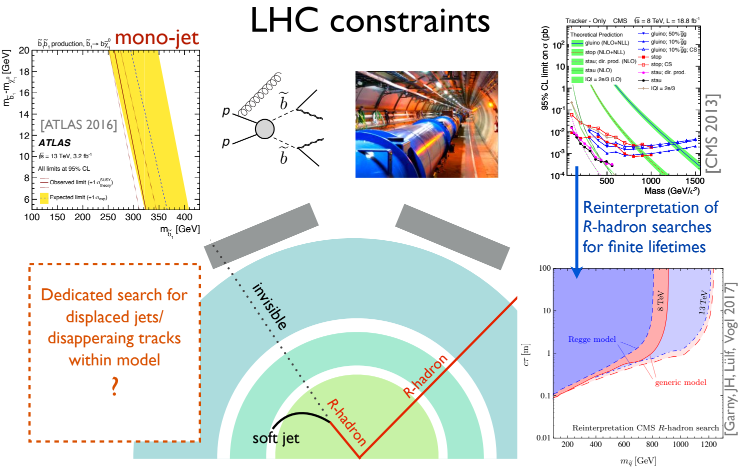
⇒ Long-lived particles at LHC!

"LLP-miracle"

cf. Thomas' talk

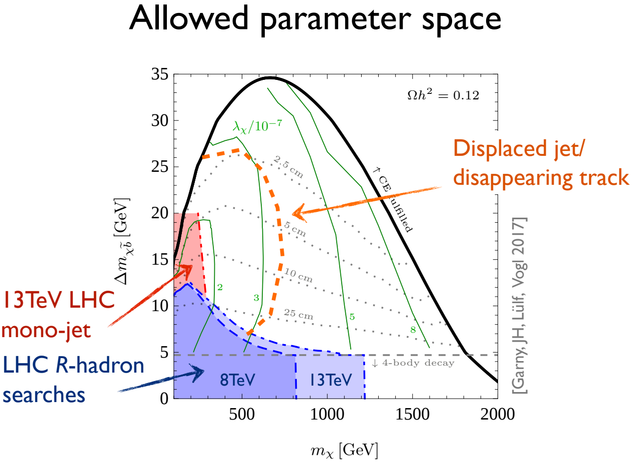
Long lived particles in the Majornana scenario

[stolen from Heisig talk'17]



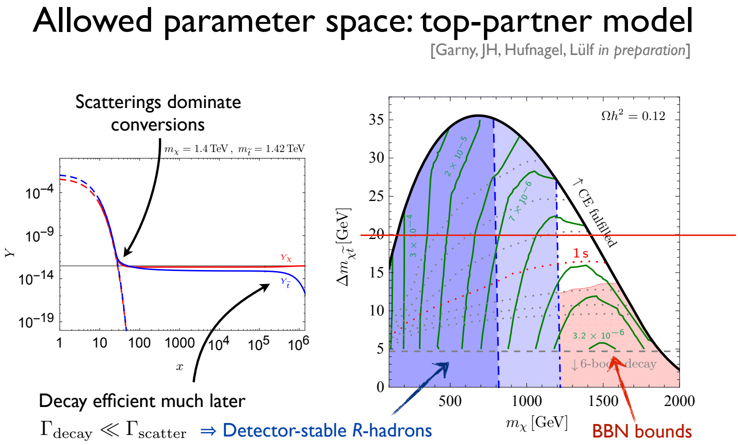
Long lived particles in the Majornana scenario

[stolen from Heisig talk'17]



Long lived particles in the Majornana scenario

[stolen from Heisig talk'17]

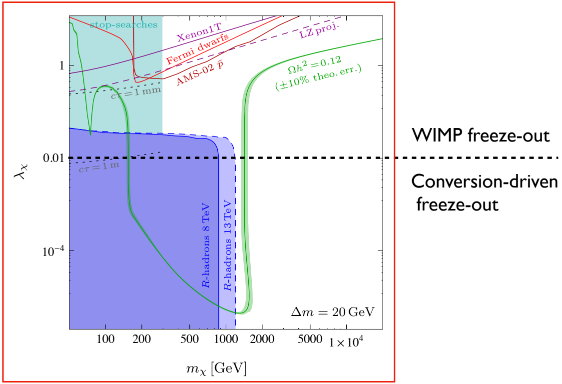


Long lived particles in the Majornana scenario

[stolen from Heisig talk'17]

Allowed parameter space: top-partner model

[Garny, JH, Hufnagel, Lülf *in preparation*]



Flavour

flavour anomalies: deficit in R(K*)

$$H_{\text{eff}} \ni \mathcal{O}_{b_L \mu_L} = \frac{1}{\Lambda^2}(\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$$

Model and low-energy effective theory. We introduce a Dirac fermionic DM particle S, a vectorlike heavy quark Ψ that carries SM color and hypercharge, and a

	SU(3)	SU(2)$_L$	U(1)$_y$	U(1)$_{\text{em}}$	Z_2
Ψ	3	1	2/3	2/3	−1
S	1	1	0	0	−1
ϕ	1	2	−1/2	(0, −1)	−1

$$\tilde{\lambda}_i \bar{Q}_{i,a} \phi^a \Psi + \lambda_i \bar{S} \phi^*_a L^a_i + \lambda |H|^2 |\phi|^2$$

Flavour

flavour anomalies: deficit in R(K*) [Cline '17]

$$H_{\rm eff} \ni \mathcal{O}_{b_L\mu_L} = \frac{1}{\Lambda^2}(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$$

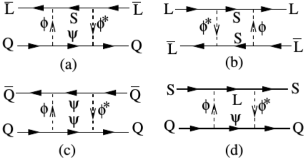


Figure 1. Diagrams leading to (a) $b \to s\mu\mu$, (b) $\tau \to 3\mu$, (c) B_s-$\bar{B}_s$ mixing and (d) dark matter scattering on quarks.

$$\tilde{\lambda}_i \bar{Q}_{i,a}\phi^a\Psi + \lambda_i\bar{S}\phi^*_a L^a_i + \lambda|H|^2|\phi|^2$$

Flavour

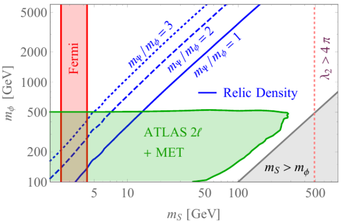


Figure 3. The blue curves show the values of m_S and m_ϕ that give the correct relic density. The red region is excluded by searches by the Fermi-LAT for DM annihilation in dwarf spheroidal galaxies [24] when the local dark matter density is rescaled by the calculated relic density, and in the grey region S can decay, preventing it from being the DM. The green region is a rough estimate of the region of parameter space excluded by an ATLAS slepton search [25]. For all points in this parameter space, λ_2 is set to the minimum value that allows for explanation of the flavor anomalies while avoiding B_s mixing constraints (see text for more details). The dotted

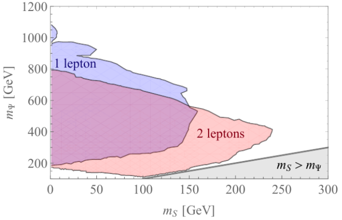
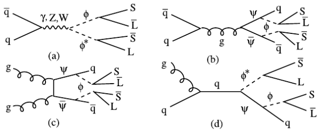
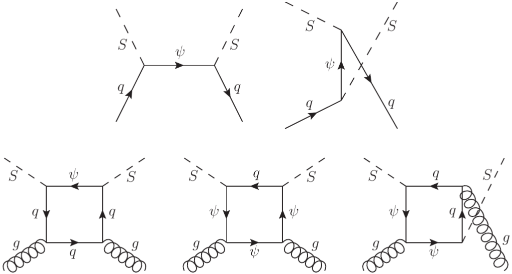


Figure 6. Shaded regions in the m_S-m_Ψ plane are excluded at 95% c.l. by ATLAS run 2 searches for one (blue) or two leptons (red), jets, and missing energy [30, 31]. For each point, m_S and the couplings are set as described in text to satisfy flavor and DM relic density constraints.



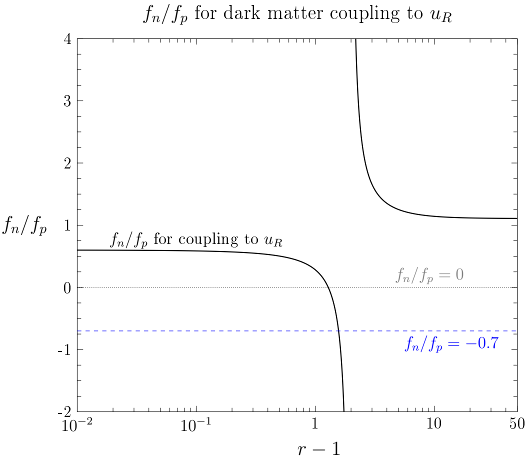
Direct Detection searches

- effective DM coupling to q (scalar and twist-2 [Drees'93]) and g [Hisano'15] included



Direct Detection searches

- effective DM coupling to q (scalar and twist-2 [Drees'93]) and g [Hisano'15] included
- effective DM coupling to nucleons $f_p \neq f_n \rightsquigarrow$ max. isospin violation at r =2.6, (3.3) for $q = u,(d)$

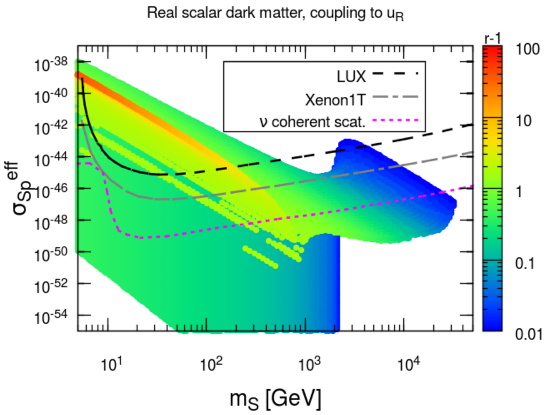


$$\sigma_p^{\text{eff}} = \sigma_p \cdot \frac{\sum_{i \in \text{isotopes}} \xi_i (Z + (A_i - Z) f_n/f_p)^2}{\sum_{i \in \text{isotopes}} \xi_i A_i^2}$$

Direct Detection searches

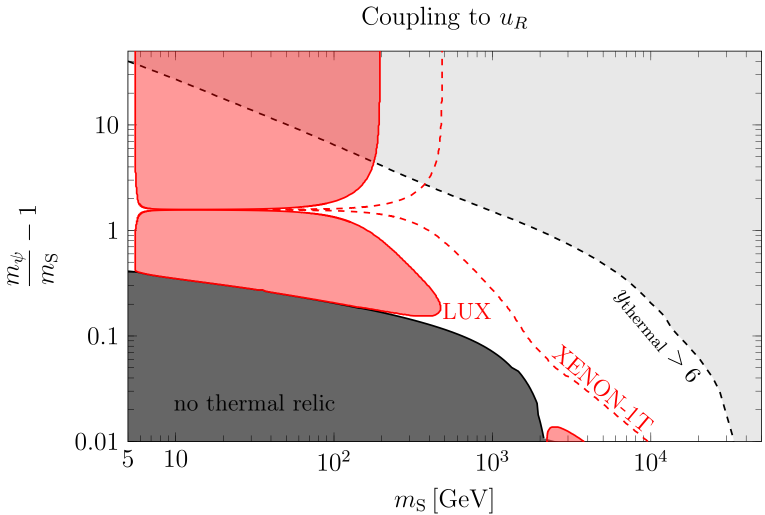
- effective DM coupling to q (scalar and twist-2 [Drees'93]) and g [Hisano'15] included
- effective DM coupling to nucleons $f_p \neq f_n \rightsquigarrow$ max. isospin violation at r =2.6, (3.3) for $q = u,(d)$

- LUX probes $m_S \lesssim 200 - 300$ GeV + an island around $m_S \sim 2$ TeV
- At all masses, viable parameter space out of reach Direct DM searches.



$$\sigma_p^{\rm eff} = \sigma_p \cdot \frac{\sum_{i\in \rm isotopes} \xi_i (Z+(A_i - Z) f_n/f_p)^2}{\sum_{i\in \rm isotopes} \xi_i A_i^2}$$

Projection of direct-detection constraints

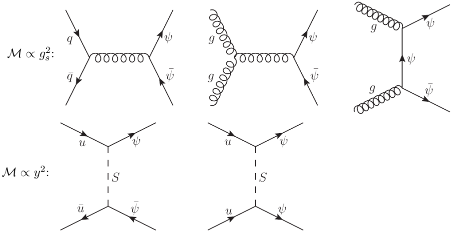


Collider constraints

Production of colored mediator at the LHC $\rightsquigarrow$ n-jets+MET ($n > 2$)

at r small: $n > 2$ enhance visibility for too soft $\psi \to uS$ jets

at r large: $n > 2$ S/Bgd can be larger for $n > 2$



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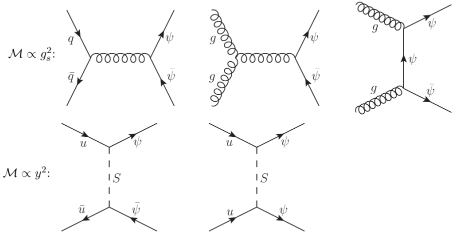
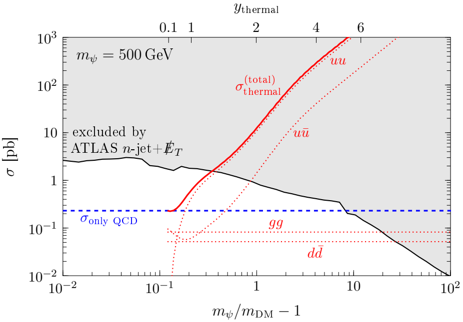
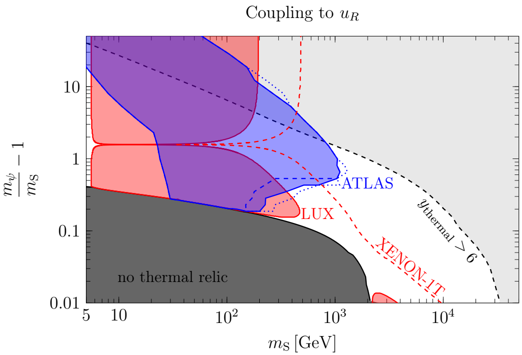




$\rightsquigarrow$ Enhanced production σ including $y = y_{thermal}$

Constraints derived from ATLAS multijet analysis

- We use : ATLAS-CONF-2013-047 for 2-6 jets +MET at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3fb^{-1}$ $\rightsquigarrow$ limits on the number of signal events S
- We recompute $\sigma^{excl}(r, m_{DM})$ evaluating efficiencies $\epsilon = N^{cut}/N^{events}$ using Madgraph & CheckMATE

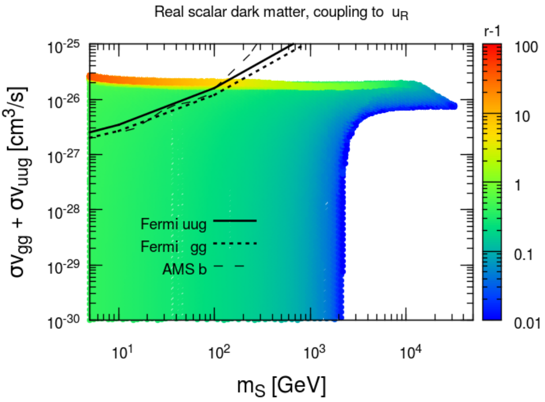


- We get $\sigma(r, m_{DM}, y_{thermal})$ (tree-level) using calchep and compare to $\sigma^{excl}(r, m_{DM})$

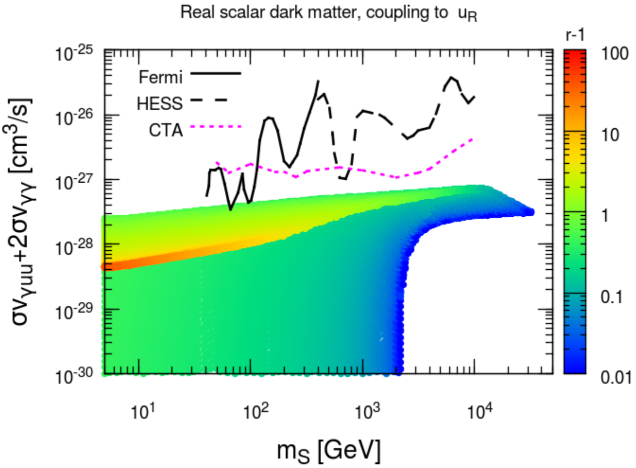
$\rightsquigarrow$ Can exclude DM models up to ~ 1 TeV for the large $r - y_{thermal}$ region

Indirect detection constraints

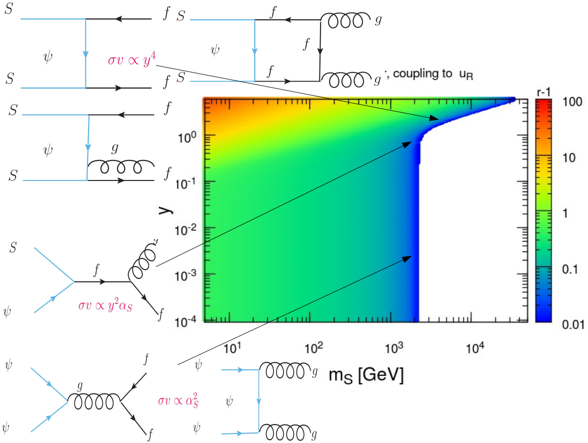
- $\langle\sigma_{gg}\rangle + \langle\sigma_{g\bar{q}q}\rangle \equiv 95 - 100\%\, \sigma v_{tot}$ today $\rightsquigarrow \gamma$ & $\bar{p}$ constraints
- rough estimation of Fermi dSphs bound on $\langle\sigma_{gg}\rangle$ & $\langle\sigma_{g\bar{q}q}\rangle$ using integrated specra for $E_\gamma = [0.5, 500]$ GeV
- Typically probe the $r > 1.2$ & $m_S < 150$ GeV $\rightsquigarrow$ complement direct detection and collider searches at low DM mass



Cross-section relevant for gamma-ray line searches



Relic abundance relevant processes



Sharp gammma ray spectral features & Focus on Yukawa coupling to leptons

see [Giacchino, LLH & Tytgat '13 &'14]
see also [Toma'13 & Ibarra'14]

Looking for smoking gun evidence for DM?

like e.g. sharp spectral features, such as lines, in the gamma ray spectrum:

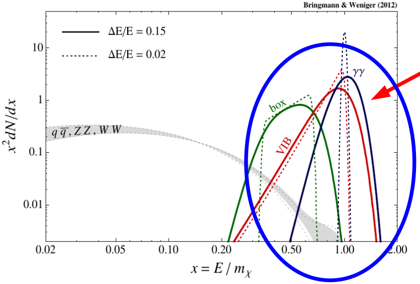
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{8\pi}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\mathrm{l.o.s}} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \times \boxed{\left(\frac{\langle\sigma v\rangle_{\mathrm{ann}}}{m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}\right)}$$

Particle physics input

Looking for smoking gun evidence for DM?

like e.g. sharp spectral features, such as lines, in the gamma ray spectrum:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{8\pi}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\rm l.o.s} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \times \left(\frac{\langle\sigma v\rangle_{\rm ann}}{m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}\right)$$



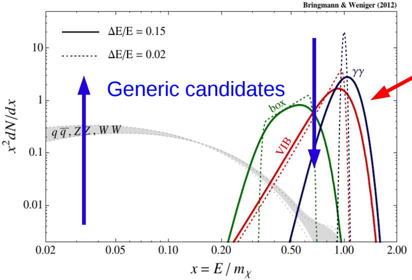
Possibly including pronounced spectral features

More easily discriminated from backgrounds

Looking for smoking gun evidence for DM?

like e.g. sharp spectral features, such as lines, in the gamma ray spectrum:

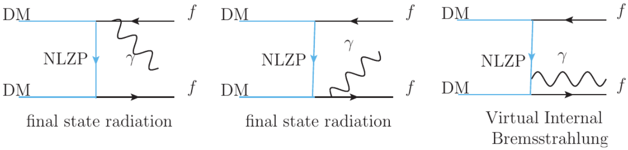
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{8\pi}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\rm l.o.s} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \times \left(\frac{\langle\sigma v\rangle_{\rm ann}}{m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}\right)$$



Careful!!

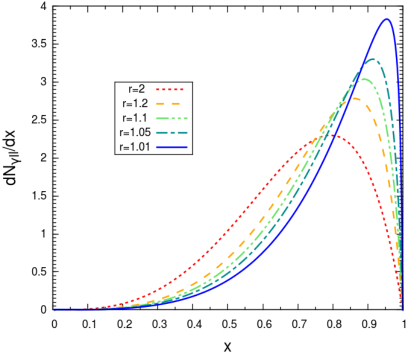
The importance of the "line" compared to the continuum depends on their relative contribution to the total annihilation cross-section

Sharp gamma ray spectral features

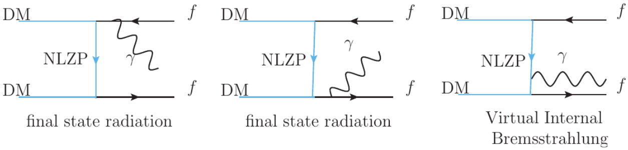


- From 3bdy process:
  Virtual Internal Bremsstrahlung
  - peaked at $E_\gamma \sim M_{\rm dm}$ for $r \to 1$
  - Identical for Scalar & Majonana

  [Barger'11]



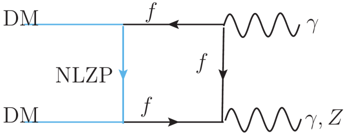
Sharp gamma ray spectral features



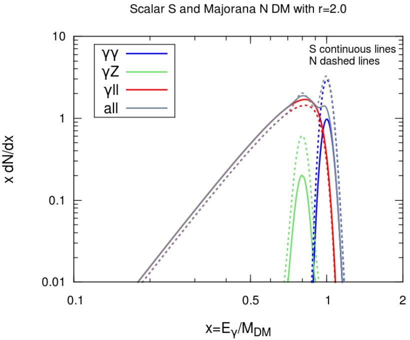
- From 3bdy process:
  Virtual Internal Bremsstrahlung
  - peaked at $E_\gamma \sim M_{\rm dm}$ for $r \to 1$
  - Identical for Scalar & Majonana

  [Barger'11]

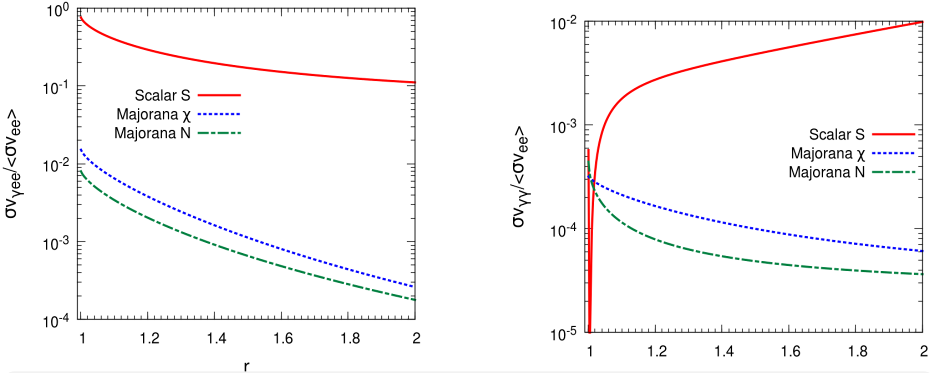
- From loop process: gamma line



[Rudaz '89, Bergstrom'89+, Bern'97& Bertone'09, Giacchino'14& Ibarra'14]



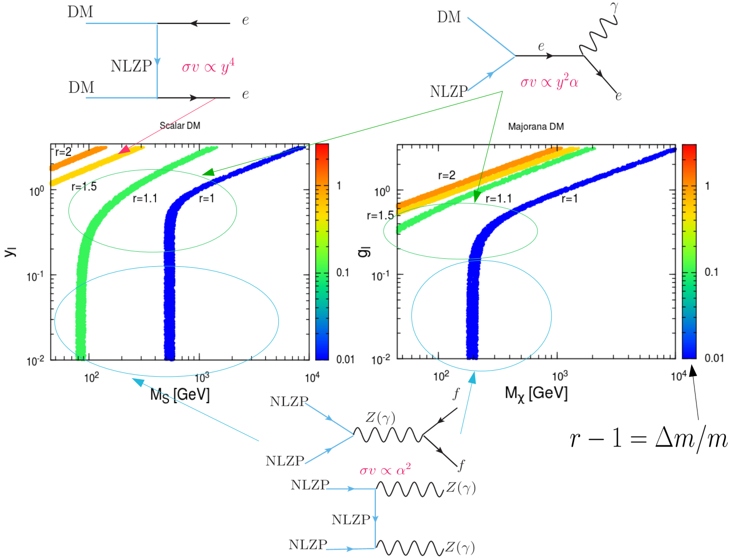
Enhanced $\langle \sigma v \rangle_{\gamma ll}$ and $\langle \sigma v \rangle_{\gamma\gamma}$ for Scalar DM



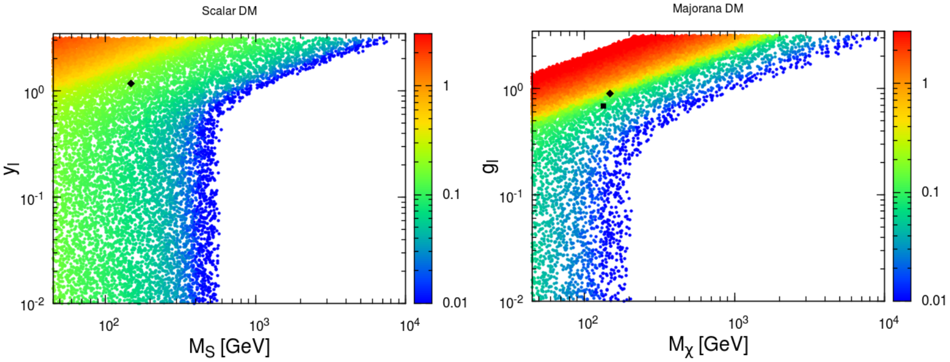
- at f.o. for Real Scalar DM: $\langle \sigma v \rangle_{\gamma ll} \sim \langle \sigma v \rangle_{ll}$
- in general, higher order effects are more important for scalar DM: $\langle \sigma v \rangle^{\chi}_{\gamma ll} < \langle \sigma v \rangle^{S}_{\gamma ll}$ and $\langle \sigma v \rangle^{\chi}_{\gamma\gamma} < \langle \sigma v \rangle^{S}_{\gamma\gamma}$

see [Toma'13,Giacchino'13, Giacchino'14& Ibarra'14]

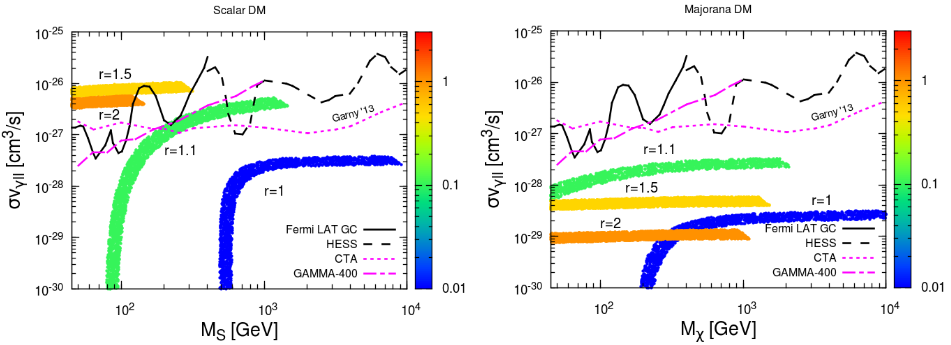
Viable param. space for coupling to e_R



Viable param. space for coupling to e_R

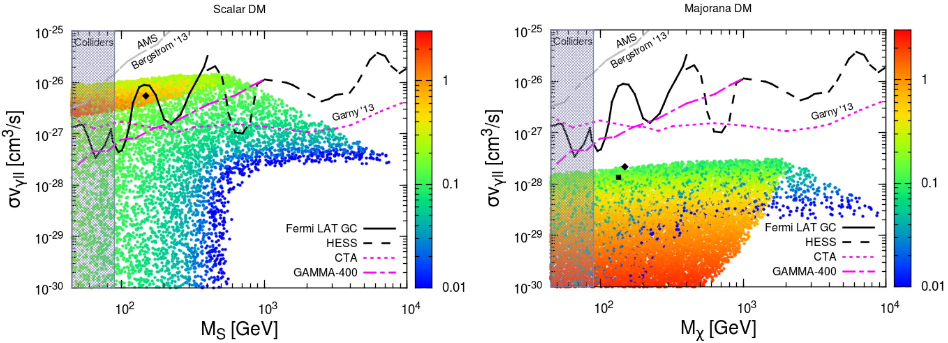


Allowed $\langle \sigma v \rangle_{\gamma ll}$ for relic abundance



- when $\sigma v \propto y^4$ dominates $\rightsquigarrow$ larger y for S (due to $d-$wave) $\rightsquigarrow$ larger $\langle \sigma v \rangle_{\gamma ll}$ (modulo the r suppression).

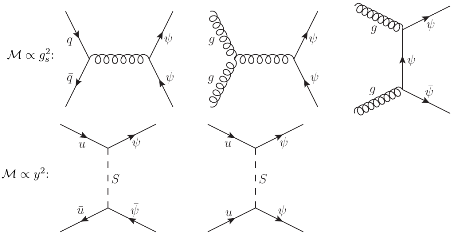
Allowed $\langle \sigma v \rangle_{\gamma ll}$ for relic abundance



- when $\sigma v \propto y^4$ dominates $\rightsquigarrow$ larger y for S (due to $d-$wave) $\rightsquigarrow$ larger $\langle \sigma v \rangle_{\gamma ll}$ (modulo the r suppression).
- Majorana DM: $\langle \sigma v \rangle_{\gamma ll}^{max}$ well beyond current and future experimental limits, need extra boost [see also Bringmann'12,Bergstrom'12]
- Scalar DM: $\langle \sigma v \rangle_{\gamma ll}^{max}$ can be larger by up to 2 orders of magnitude

Collider constraints

Production of colored mediator at the LHC $\rightsquigarrow$ MET+jets



Collider constraints

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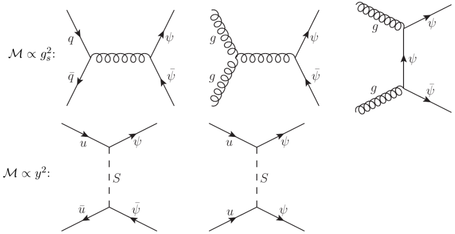
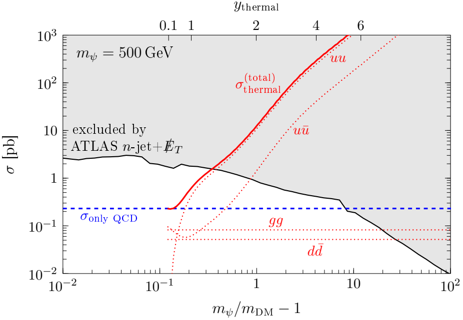




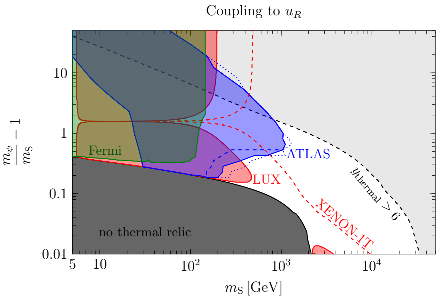
enhanced production σ

- for large $y = y_{thermal}$ with $\bar{u}u \to \bar{\psi}\psi$ & $uu \to \psi\psi$
- dominating $uu \to \psi\psi$ at large r (y) due to large u PDF in the p
- destructive y-g_s interference for $\bar{u}u \to \bar{\psi}\psi$

Constraints derived from ATLAS multijet analysis

Why Multijet (>2) analysis (ie consider extra jets from q or g in the initial state)

- for $m_\psi - m_S < 50 - 100$ GeV, jets from $\psi \to uS$ too soft, additional jet necessary for visibility
- at large r, S/Bgd can be larger for $n - jets + MET$ signal with $n > 2$



- We use :ATLAS-CONF-2013-047 for 2-6 jets +MET at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3 fb^{-1}$ $\rightsquigarrow$ Comparing to bgd expectation no significant excess observed $\rightsquigarrow$ limits on the number of signal events S
- We recompute $\sigma^{excl}_{95\%CM}(r, m_{DM})$ evaluating $S_i = \sigma \epsilon_i \mathcal{L}$ or more precisely the efficiency ϵ_i that depends on the DM model generating events in Madgraph and apply cuts using CheckMATE
- We compare $\sigma^{excl}_{95\%CM}(r, m_{DM})$ to $\sigma(r, m_{DM}, y_{thermal})$ using calchep

Worked example: Real Scalar DM and $E_\gamma \sim 130$ GeV signal

- Hint for γ-ray signal at $E_\gamma \sim 130$ GeV at the GC could correspond to
  - $M_{\rm dm} \sim 130$ GeV $\gamma\gamma$ signal [Weniger'12]
  - $M_{\rm dm} \sim 150$ GeV $\gamma \bar{f} f$ signal [Bringmann et al'12]
- First $\gamma \bar{f} f$ analysis [Bringmann et al'1203] concluded that thermally produced DM could not account for a signal involving $\sigma v \sim 6\,10^{-27}{\rm cm}^3/{\rm s}$

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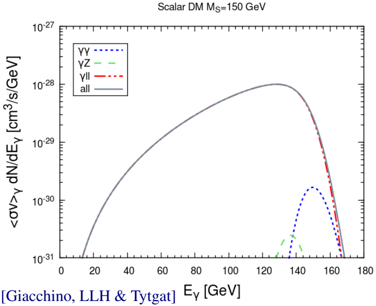
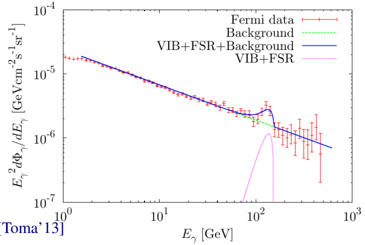
This is indeed the case for Majorana DM, but real scalar DM can do the job

[Toma'13, Giacchino, LLH & Tytgat '13]



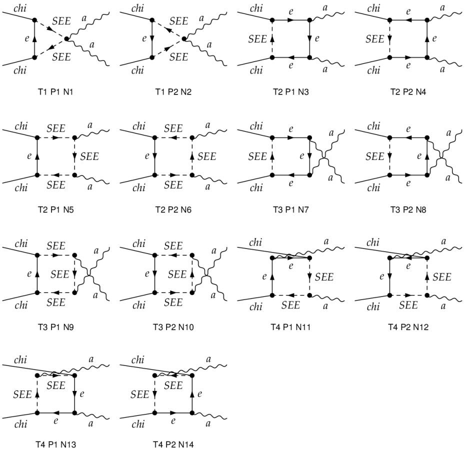
[Giacchino, LLH & Tytgat]



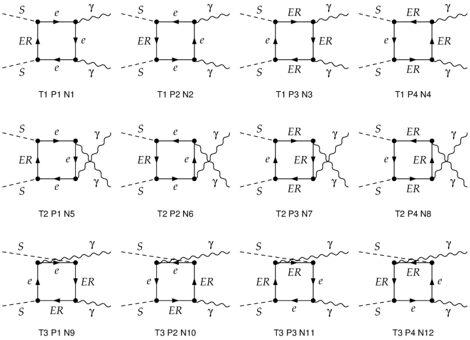
[Toma'13]

Contributions to $\langle \sigma v \rangle_{\gamma\gamma}$

chi chi $\rightarrow$ *a a*

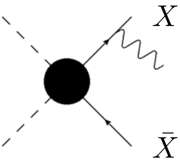


$SS \rightarrow \gamma\gamma$

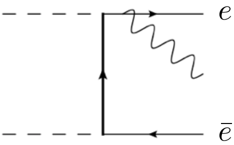


VIRTUAL INTERNAL BREMSSTRAHLUNG?

annihilation of DM into charged particles



e.g.



→ Final State Radiation (FSR)

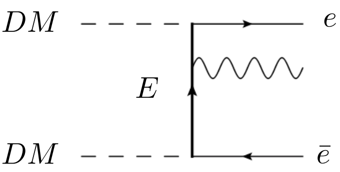
$$\frac{d\sigma(\chi\chi \to X\bar{X}\gamma)}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right) \sigma(\chi\chi \to X\bar{X})$$

IR dominated, collinear emission
universal feature encoded in splitting function

Birkedal, Matchev, Perelstein and Sprey (2005)

[M. Tytgat - Scalars 13]

VIRTUAL INTERNAL BREMSSTRAHLUNG



$$\mathcal{M} \propto ((p_{DM} - p_{\bar{e}})^2 - M_E^2)^{-1} \sim (M_{DM}^2 - M_E^2 - 2 M_{DM} E_{\bar{e}})^{-1}$$

POTENTIALLY **VERY LARGE** ENHANCEMENT IF $M_{DM} \sim M_E$

FOR $E_{\bar{e}} \sim 0$ CORRESPONDING TO $E_\gamma \sim M_{DM}$

Bergstrom
Phys.Lett. B **225** (1989), 372

Bergstrom, Bringmann & Edsjo
JHEP 0801 (2008) 049

[M. Tytgat - Scalars 13]

Any (not very new) idea of how to break the links ... ?

Sure!!

We need to break $\langle\sigma v\rangle_{\rm fo} \leftrightarrow \langle\sigma v\rangle_{\rm today} \leftrightarrow \sigma_{\rm direct,coll}$

- velocity dependent annihilation
- richer DM sector with coannihilations [Griest & Seckel '90]
- annihilation near thresholds and resonances [Griest & Seckel '90]
- annihilation into light mediators
  (Sommerfeld enhancement [Hisano '04, Cirelli '05], secluded DM [Pospelov '07])
- Non WIMPS: FIMP, asymmetric dark matter, axions
- ...

This is really the end