3.2.4 Experimental strategies

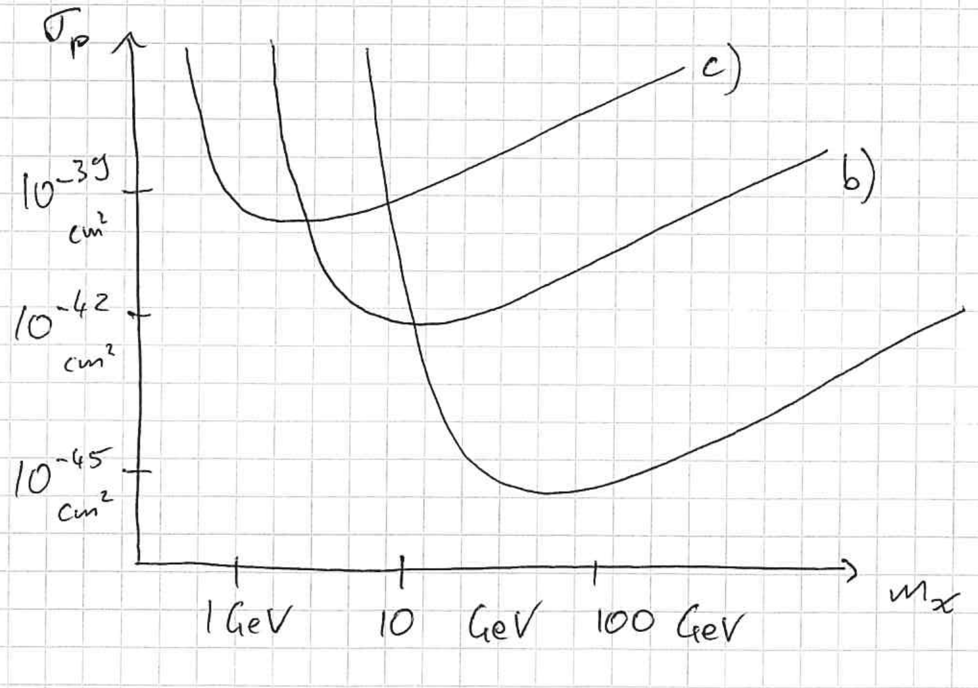
Three possibilities to detect $E_R \sim keV$:

1) Ionization (detect free charges)
2) Scintillation (detect light)
3) Heat (detect phonons)

To identify a DM signal, at least 2 channels should be detected.

Main strategies:	Channels	Threshold	Mas
a) Nobel gas detectors:	1 + 2	~10 keV	to
b) Cryogenic semiconductors:	1 + 3	~1 keV	kg
c) Cryogenic scintillators:	2 + 3	~0.1 keV	g

Typical result:



3.3 Collider searches

Idea: Collide SM particles to invert annihilation processes in the Early Universe and produce DM

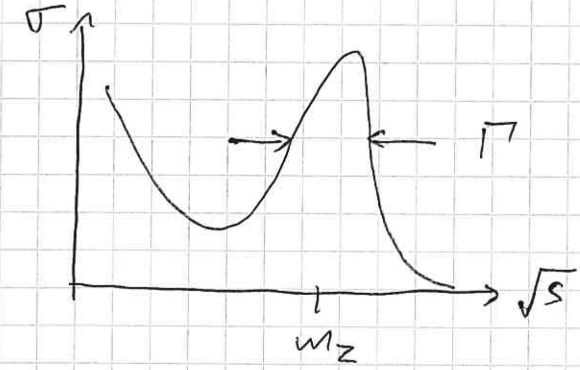
Problem: Impossible to detect DM particles produced at colliders

$\Rightarrow$ Search for invisible particles

3.3.1 Invisible width

We can measure total width $\Gamma = \tau^{-1}$ of certain particles

Example: Z boson



$$\Gamma = \sum_{\substack{\text{final} \\ \text{states}}} \Gamma(Z \to \text{f.s.})$$

Known contributions

$$\Gamma(Z \to q\bar{q}) \sim 1.75 \text{ GeV}$$
$$\Gamma(Z \to e^+e^-) \sim 0.25 \text{ GeV}$$
$$\Gamma(Z \to \nu\bar{\nu}) \sim 0.50 \text{ GeV}$$

Measured: $\Gamma = 2.495 \pm 0.002$ GeV

$\Rightarrow \Gamma(Z \to \chi\chi) < 1.5$ MeV

↳ Excludes e.g. additional active neutrino

Note: The decay $Z \to \chi\chi$ is possible only if

$$m_\chi < \frac{m_Z}{2}$$

$\Rightarrow$ No constraint for heavier DM

3.3.2 Invisible branching ratio

If $\Gamma < \sigma_E$ (← energy resolution) width cannot be measured directly

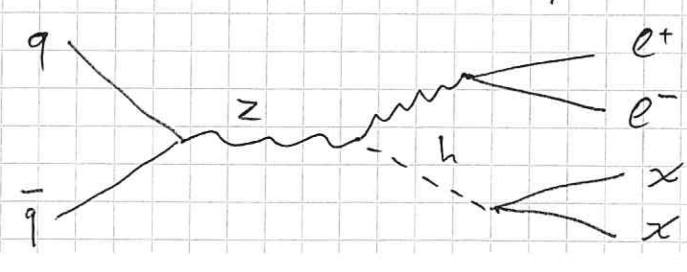
Example: H boson ($\Gamma_{SM} \sim 4$ MeV)

$\Rightarrow$ Need different approach

Consider associated production

→ easy to measure

and invisible decay



→ hard

Momentum distribution of initial state is given by parton distribution functions $f_q(x_1)$, $f_{\bar{q}}(x_2)$

centre-of-mass energy ↙

$$p_q = \begin{pmatrix} x_1 \sqrt{s}/2 \\ 0 \\ 0 \\ x_1 \sqrt{s}/2 \end{pmatrix} \qquad p_{\bar{q}} = \begin{pmatrix} x_2 \sqrt{s}/2 \\ 0 \\ 0 \\ -x_2 \sqrt{s}/2 \end{pmatrix}$$

=> Partonic centre-of-mass energy

$$\sqrt{s_*} = \sqrt{(p_q + p_{\bar{q}})^2} = \sqrt{x_1 x_2}\,\sqrt{s}$$

is unknown in a given collision

But transverse momentum

$$\vec{p_T} = p_x \vec{e_x} + p_y \vec{e_y}$$

is always zero for initial state

=> Final state must also have zero total $\vec{p_T}$!

If $\vec{p_T}(\ell^+) + \vec{p_T}(\ell^-) \neq 0$

=> invisible particles present!

Experiments measure separately

$$\sigma_{vis} = \sigma(pp \to h(\to b\bar{b}) + Z(\to \ell^+\ell^-))$$

and

$$\sigma_{inv} = \sigma(pp \to h(\to inv) + Z(\to \ell^+\ell^-))$$

Construct ratio: $R = \frac{\sigma_{inv}}{\sigma_{vis}} = \frac{\Gamma(h \to inv)}{\Gamma(h \to vis)}$

$\Rightarrow$ Can be used to calculate Higgs invisible branching ratio

$$BR(h \to inv) = \frac{\Gamma(h \to inv)}{\Gamma}$$

$$= \frac{\Gamma(h \to inv)}{\Gamma(h \to inv) + \Gamma(h \to vis)}$$

$$= \frac{1}{R + 1}$$

LHC experiments give upper bound on $BR(h \to inv)$:

$$BR(h \to inv) \lesssim 0.25$$

(constantly getting better)

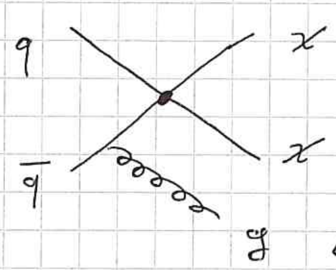
$\Rightarrow$ Important constraint on DM models with $m_\chi < m_h/2$

3.3.3 Missing energy searches

Define $\not{E}_T = \left| \sum_{\substack{\text{visible} \\ \text{final} \\ \text{states}}} \vec{p_T} \right|$

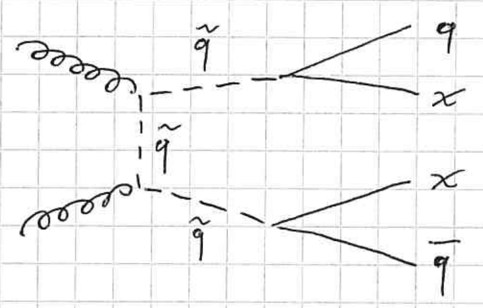
$\Rightarrow$ Search for events with $\not{E}_T > 0$

Examples: EFT



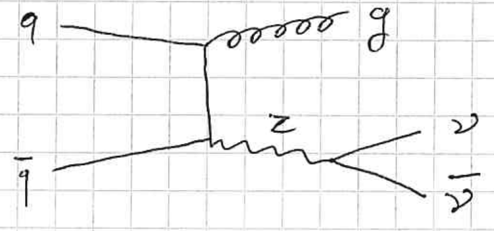
initial state radiation

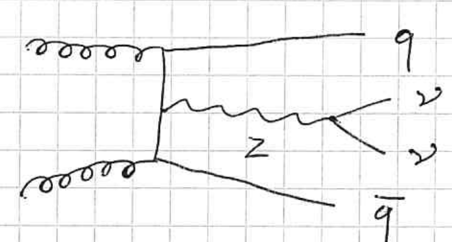
SUSY



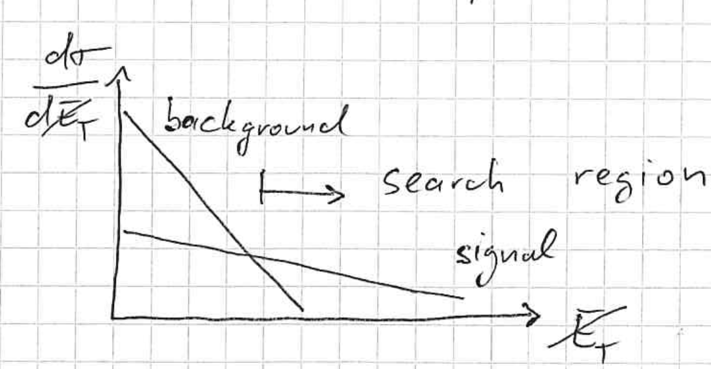
$\Rightarrow$ decay of heavy squark

Problem: $\not{E}_T > 0$ can also arise in the SM





$\Rightarrow$ Need to study kinematic distributions



3.4 Case study: Scalar singlet DM

↳ Arguably simplest WIMP model

Consider scalar boson s with no SM charges (singlet)

⇒ No couplings to SM fermions or gauge bosons

But: Can couple to SM Higgs boson

$$\mathcal{L} \supset \frac{1}{2}\mu_s^2 s^2 + \frac{1}{2}\lambda_{hs} s^2 |H|^2 + \frac{1}{2}\partial_\mu s \partial^\mu s$$

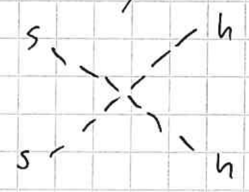
Electroweak symmetry breaking:

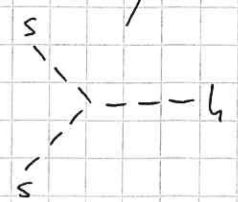
$$H \rightarrow \frac{1}{\sqrt{2}}(h + v)$$

h: Higgs boson; v: vacuum expectation value

$$\Rightarrow \mathcal{L} \supset \frac{1}{2} m_s^2 s^2 + \frac{1}{4}\lambda_{hs} s^2 h^2 + \frac{1}{2}\lambda_{hs} s^2 h v$$

$$m_s^2 = \mu_s^2 + \frac{1}{2}\lambda_{hs} v^2$$





No vertices involving a single scalar boson

⇒ $\mathcal{L}$ is symmetric under $s \rightarrow -s$

⇒ s is stable

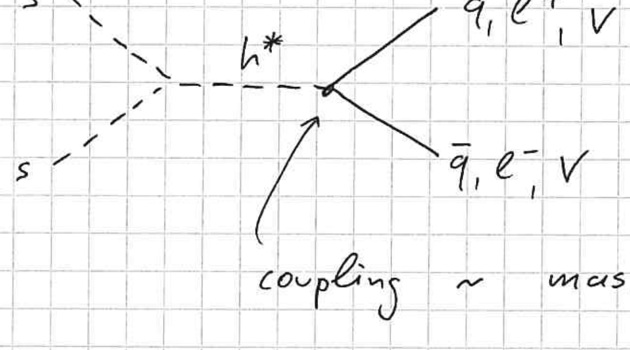
Two relevant parameters :

m_s : singlet mass

λ_{hs} : Higgs coupling

3.4.1 Relic density

Relevant diagrams :

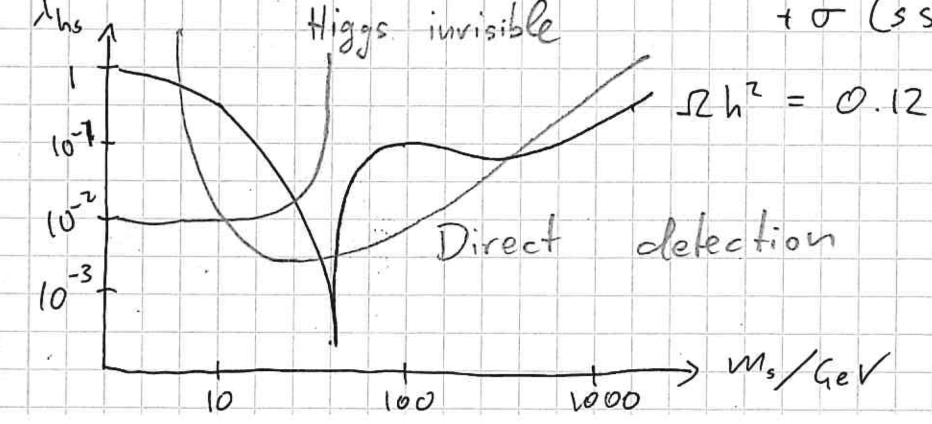


For $m_s \lesssim m_W$: $\sigma \approx \sigma(ss \to b\bar{b})$

Note: $\sigma \sim \dfrac{1}{(E_{cm}^2 - m_h^2)^2 + \Gamma_h^2 m_h^2}$, where $E_{cm}^2 \sim 4 m_s^2$

$\Rightarrow$ Strong enhancement for $m_s \approx \frac{m_h}{2}$

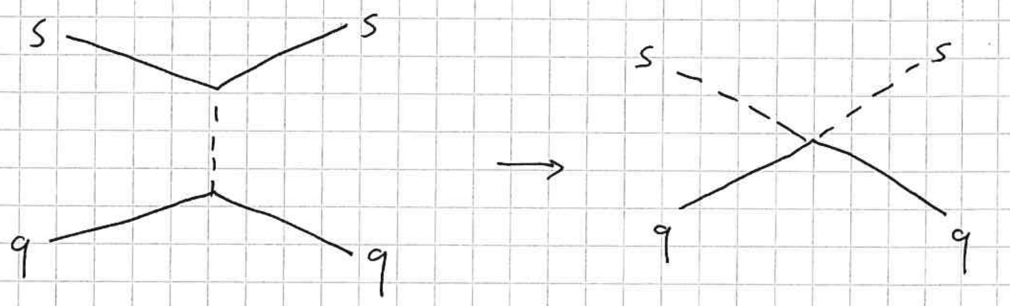
For $m_s \gtrsim m_h$: $\sigma \approx \sigma(ss \to W^+W^-) + \sigma(ss \to ZZ) + \sigma(ss \to hh)$



3.4.2 Direct detection

Since $m_h \gg m_s \cdot v$ (with $v \sim 10^{-3}$)

we can "integrate out" the Higgs boson



$$\mathcal{L} = \frac{1}{2}\lambda_{hs}\, s^2 h v + \frac{\sqrt{2}\, m_q}{v}\,\bar{q} q h \rightarrow \mathcal{L}_{eff} = \frac{m_q}{\Lambda^2} s^2 \bar{q} q$$

$$\text{with } \Lambda^2 = \frac{\sqrt{2}\, m_h^2}{\lambda_{hs}}$$

$$\sigma_p = \frac{m_p^2\, \mu^2\, f_p^2}{2\pi\, m_s^2\, \Lambda^4} \leftarrow f_p \approx 0.3 \quad (\text{see § 3.2.3})$$

Experimental bound: $\sigma_p < 10^{-46}\,\text{cm}^2$
for $m_s \sim 30$ GeV

$$\Rightarrow \lambda_{hs} < 5 \cdot 10^{-3}$$

3.4.3 Invisible Higgs decays

→ See problem 15

$$\Rightarrow \lambda_{hs} < 0.02 \quad \text{for} \quad m_s < \frac{m_h}{2}$$

3.4.4 Summary

Two viable regions

1) $m_s \approx m_h/2$ & $\lambda_{hs} \ll 1$

↳ difficult to probe

↳ fine-tuning necessary

2) $m_s \gtrsim 1\,\text{TeV}$ & $\lambda_{hs} \sim 1$

↳ probed by future direct detection experiments

⇒ Even simple WIMP models are still viable, but experiments are closing in!