Determining the masses of invisible particles: Application to Higgs boson invisible decay

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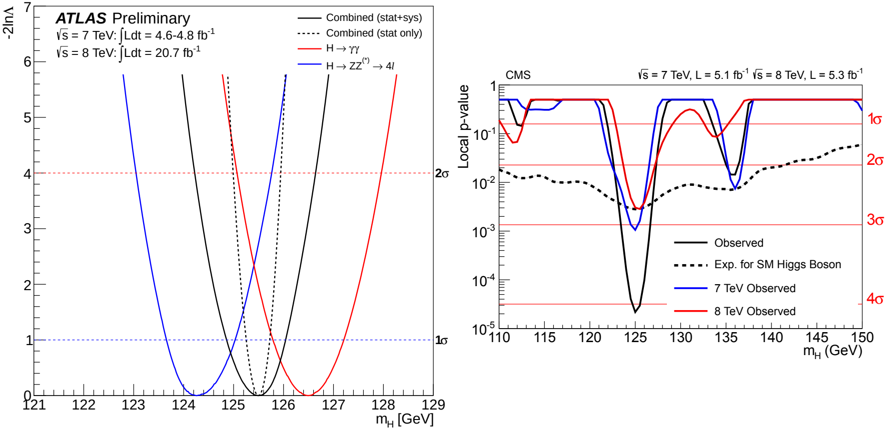
Outline

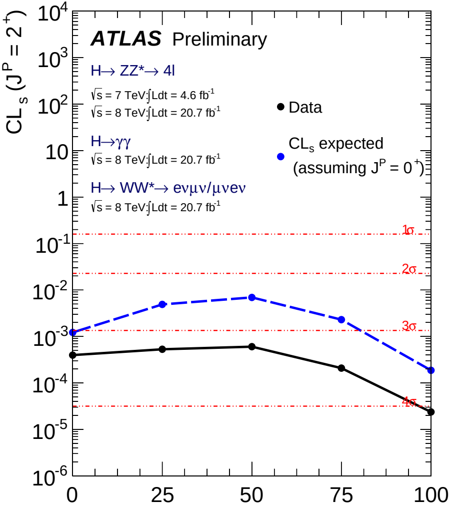
About Higgs boson

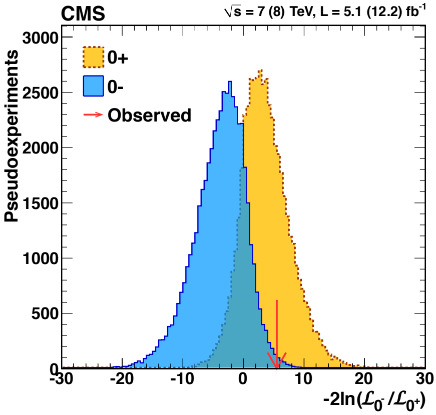
The Higgs boson is the last block of the Standard Model. It is crucial to precisely measure its properties.

Higgs boson mass

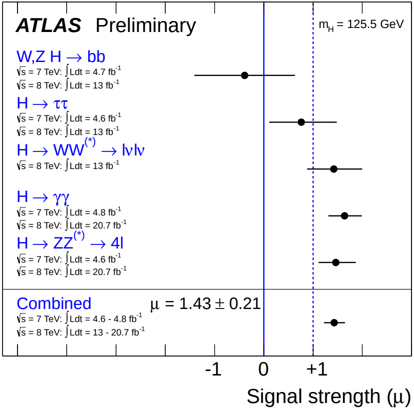


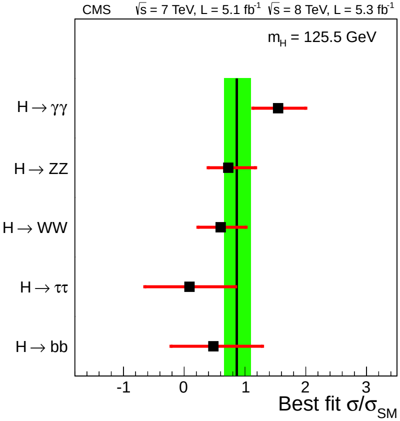
Higgs boson spin





Higgs boson couplings





Higgs boson total width

- The line shape method can not be applied in determining the Higgs boson total width.
- It can be obtained by fitting and sum over the various decay channels, shown to be $6.1^{+7.7}_{-2.9}$ MeV, assuming that the Higgs boson has no other decays beyond those in the Standard Model [1].
- An upper limit, $\Gamma_H < 22\mathrm{MeV}$ is set by measurement of the on-shell and off-shell rates in $gg \to H \to ZZ$ [2].

[1] Vernon Barger et al., PRL 108, 261801 (2012)
[2] CMS Collaboration, arXiv:1405.3455

Higgs boson invisible decay

- The idea can be traced back to 1982. $H \to aa, MM, \nu\bar{\nu}$ [3].
- At the theory side, the signals of invisible Higgs boson decay are investigated in different channels, $pp \to jH, jjH, VH$.
- At the experiment side, the data of the LEP have excluded the Higgs boson mass range below 114.4 GeV via the Higgs-strahlung process $e^+e^- \to HZ$ [4]. The ATLAS results constrain the invisible branching fractions to be less than 65% at the 95% confidence level [5].

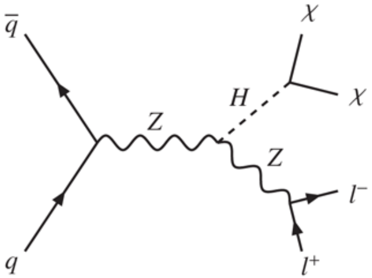
[3] Mahiko Suzuki et al., PLB110,250,1982
[4] arXiv:hep-ex/0107032
[5] ATLAS-CONF-2013-011

Question on Higgs boson invisible decay

If some deviation from the SM expectation is observed in the future as the integrated luminosity of the LHC is increased, then can we determine the invisible decay width of the Higgs boson?

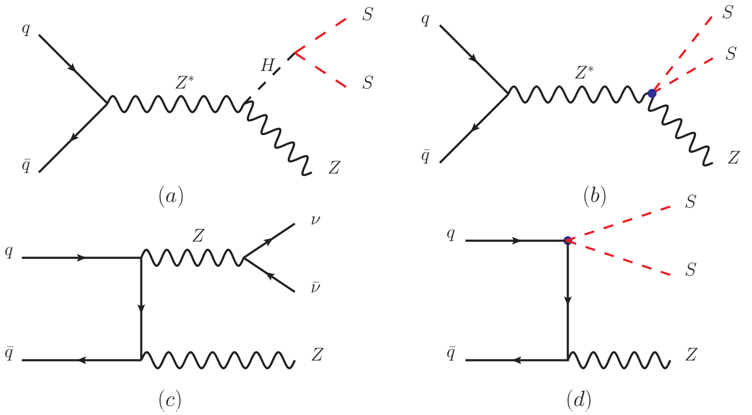
Question on Higgs boson invisible decay

The signal observed is a charged lepton pair and missing energy.



Question on Higgs boson invisible decay

It is likely that some dark matter (DM) can interact with the Z boson or quarks.



Higgs portal model

- Higgs boson invisible decay can be explained in a Higgs portal model.
- It can be realized in a renormalizable extension of SM, by adding to the SM a new real scalar S with the Lagrangian given by [6]

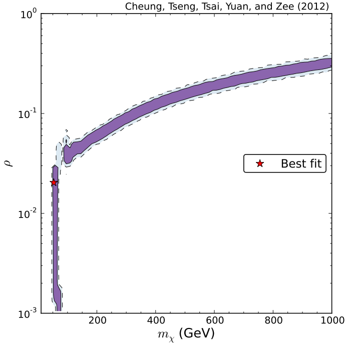
$$\mathcal{L}_{\rm min} = \mathcal{L}_{\rm SM} + \frac{(\partial_\mu S)^2}{2} - \frac{m_0^2}{2} S^2 - \lambda S^2 |H|^2 - \frac{\lambda_S}{4!} S^4. \qquad (1)$$

- The new real scalar S can account for the observed dark matter density after an global Z_2 symmetry is imposed. And it is possible for $H \to SS$ if $m_S < m_H/2$.

[6] Vanda Silveira and A. Zee. Phys.Lett., B161:136, 1985.

Higgs portal model

Given that the Higgs boson mass is around 125 GeV, this model receives strong constraint after considering the results of searching for Higgs boson at the LHC, cosmological relic density and the DM direct detection [7].



[7] Kingman Cheung, et al., JCAP 1210 (2012) 042

Effective operators

In more complex models more particles are included. They are perhaps heavy since a lighter particle is often much easier to be found either in the decay product or direct production at colliders. In this case, the role played by these particles can be described by effective operators:

$$\mathcal{O}_Z = \frac{m_Z^2}{4\Lambda_Z^2} Z^\mu Z_\mu S^2, \qquad \mathcal{O}_q = \frac{m_q}{2\Lambda_q^2} \bar{q} q S^2, \tag{2}$$

$$\mathcal{O}_Z^{(6)} = \frac{\kappa}{\Lambda^2} (D^\mu H)^\dagger (D_\mu H) S^2, \mathcal{O}_q^{(6)} = \frac{\kappa \lambda_q}{\Lambda^2} \bar{Q}_L H q_R S^2 + H.c \tag{3}$$

They can induce the production processes described by the Feynman diagrams (b) and (d) in Fig.**??**.
Priority is given to power counting rather than gauge invariance.

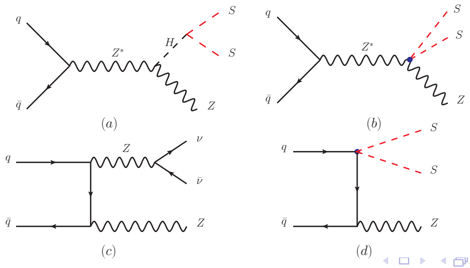
Effective operators

The main difference between the Feynman diagrams (a) and (b) is whether the missing particles have a fixed invariant mass.

The candidate for the Higgs boson decay products should have a mass lower than one half of the Higgs boson mass.

It is essential to extract more information about the missing energy.

In this work, we perform such a study toward this direction, focusing on the mass of the missing particles.



Parameter space

First, we have to find the allowed parameter space of $(\Lambda_{Z/q}, m_S)$.
In the following, we will discuss

1. dark matter relic abundance
2. direct detection experiment XENON100 and LUX
3. Z boson and missing energy associated production at the LEP and LHC

relic abundance

The DM relic abundance is a precision observable in cosmology and impose constraint on any dark matter model. It is determined by the annihilation cross section of DM to SM particles, given by [8]

$$\Omega_{\mathrm{DM}} h^2 \approx \frac{1.07 \times 10^9 \mathrm{GeV}^{-1} x_f}{M_{\mathrm{Pl}} g_*^{1/2} (a + 3b/x_f)}, \quad (4)$$

g_* is the number of relativistic degrees of freedom available at the freeze-out epoch x_f.
a and b are the coefficients in the partial wave expansion of the dark matter annihilation cross section,

$$\sigma_{\mathrm{an}} v_{\mathrm{Møl}} = a + b v_{\mathrm{Møl}}^2 + O(v_{\mathrm{Møl}}^4). \quad (5)$$

[8] Edward W. Kolb and Michael S. Turner. The Early Universe.1990

relic abundance

$v_{\mathrm{M\o l}}$ is called Møller velocity, defined as [9]

$$v_{\mathrm{M\o l}} = \sqrt{|\mathbf{v}_1 - \mathbf{v}_2|^2 - |\mathbf{v}_1 \times \mathbf{v}_2|^2}, \qquad (6)$$

where $\mathbf{v}_1$ and $\mathbf{v}_2$ are the velocities of colliding DMs in the cosmic comoving frame.
It is proved that

$$\langle \sigma v_{\mathrm{M\o l}} \rangle = \langle \sigma v_{\mathrm{lab}} \rangle^{\mathrm{lab}} \neq \langle \sigma v_{\mathrm{cm}} \rangle^{\mathrm{cm}}, \qquad (7)$$

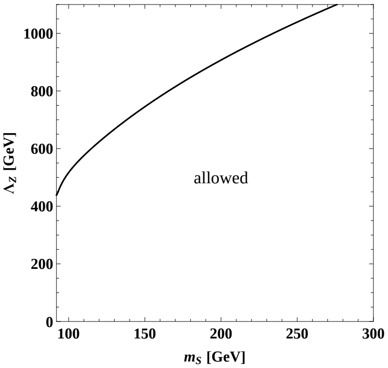
in which $v_{\mathrm{lab}} = |\mathbf{v}_{1,\mathrm{lab}} - \mathbf{v}_{2,\mathrm{lab}}|$ is the relative velocity in the rest frame of one of the incoming particles.
In the expansion, we should use $s \approx 4m_S^2 + m_S^2 v^2 + 3m_S^2 v^4/4$.

[9] Paolo Gondolo and Graciela Gelmini. Nucl.Phys., B360:145, 1991.

relic abundance

The latest WMAP data give the constraint [10]

$$\Omega_{\rm DM} h^2 = 0.1157 \pm 0.0023. \quad (8)$$



[10] G. Hinshaw et al. Astrophys.J.Suppl., 208:19, 2013.

direct detection

DM around the earth can scatter elastically with atomic nuclei, resulting in recoiling movements of nuclei.

The most stringent limit on the spin independent elastic scattering cross section comes from the XENON100 and LUX experiments [11].

The DM-proton spin independent elastic scattering cross section is given by

$$\sigma_{Sp}^{SI} = \frac{m_p^2}{4\pi(m_S + m_p)^2}[f_{Sp}^{(p)}]^2, \tag{9}$$

where

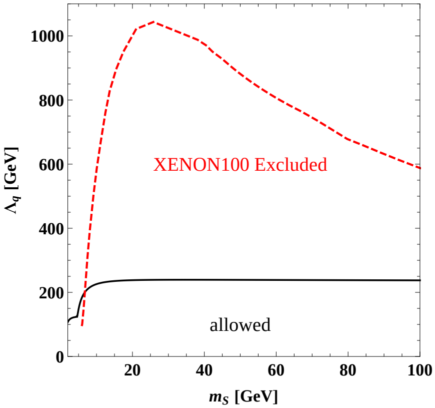
$$f_{Sp}^{(p)} = \sum_{q=u,d,s} f_{T_q}^{(p)} C_{Sq} \frac{m_p}{m_q} + \frac{2}{27} f_{T_g}^{(p)} \sum_{q=c,b,t} C_{Sq} \frac{m_p}{m_q}. \tag{10}$$

In our case, $C_{Sq} = m_q/\Lambda_q^2$.

[11] Phys.Rev.Lett., 109, 181301 (2012), Phys.Rev.Lett. 112, 091303 (2014)

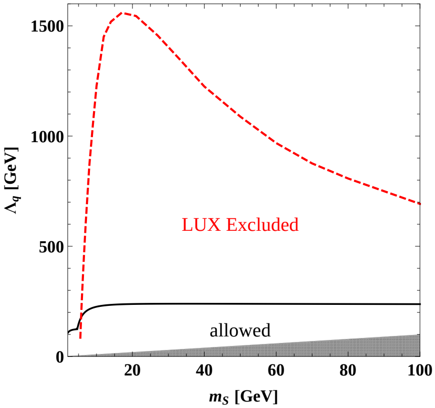
direct detection

After comparing with the XENON100 data, we obtain the allowed parameter region.



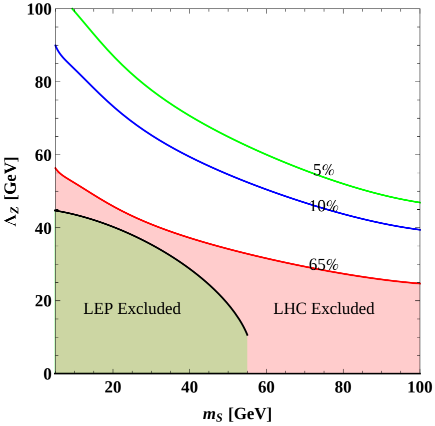
direct detection

After comparing with the LUX data, we obtain the allowed parameter region.



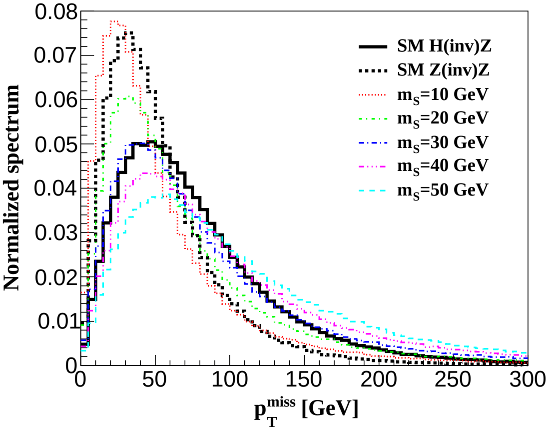
Z boson and missing energy associated production

Z boson and missing energy associated production at the LEP and LHC, $e^+e^-(pp) \to Z^* \to SSZ$.



missing transverse momentum distribution

At the 8 TeV LHC,



missing transverse momentum distribution

Two handles of the distributions:

$$R_1 \equiv \frac{\sigma(p_T^{\mathrm{miss}} < p_T^{\mathrm{peak}})}{\sigma(p_T^{\mathrm{miss}} > p_T^{\mathrm{peak}})}, \tag{11}$$

$$R_2 \equiv \frac{\sigma(p_T^{\mathrm{miss}} < p_T^{\mathrm{cut}})}{\sigma(p_T^{\mathrm{miss}} > p_T^{\mathrm{cut}})}. \tag{12}$$

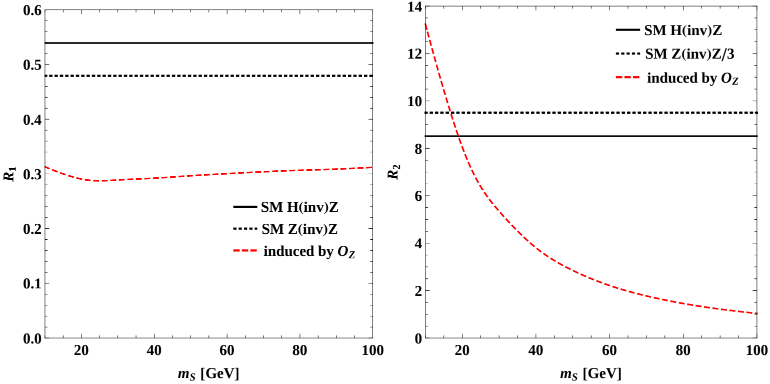
where the peak positions are set by

$$p_{T,Z}^{\mathrm{peak}} = 15.83\ \mathrm{GeV} + 6.67\ \mathrm{GeV}\frac{m_S}{10\ \mathrm{GeV}}. \tag{13}$$

The coefficients in the operators are canceled, thus they are functions of only the DM mass.

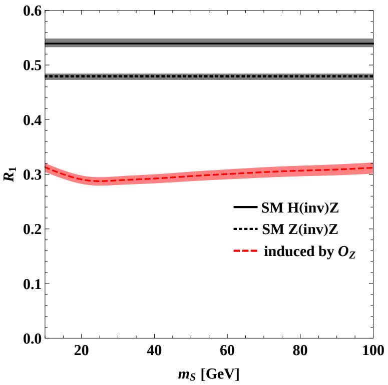
missing transverse momentum distribution

The dependence of R_1 and R_2 on the dark matter mass:



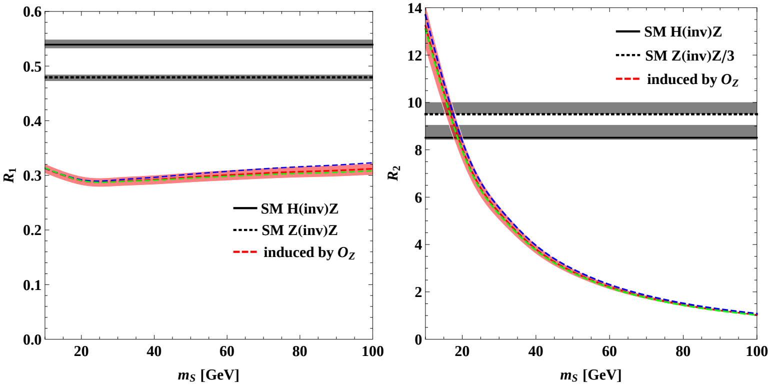
missing transverse momentum distribution

Uncertainties from scale variations:



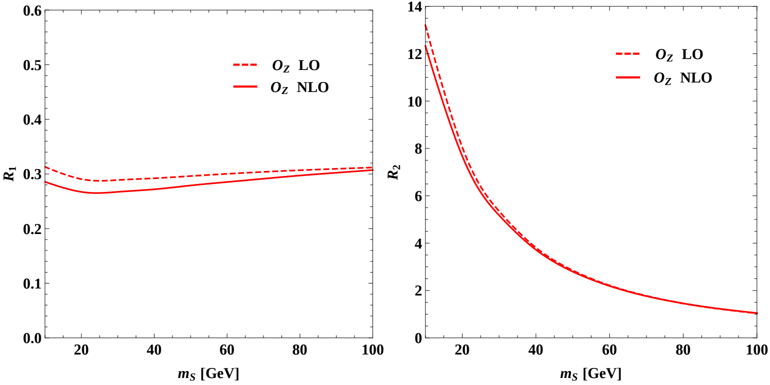
missing transverse momentum distribution

Uncertainties from PDF sets (red for CTEQ6ll, blue for CT10, green for MSTW2008):



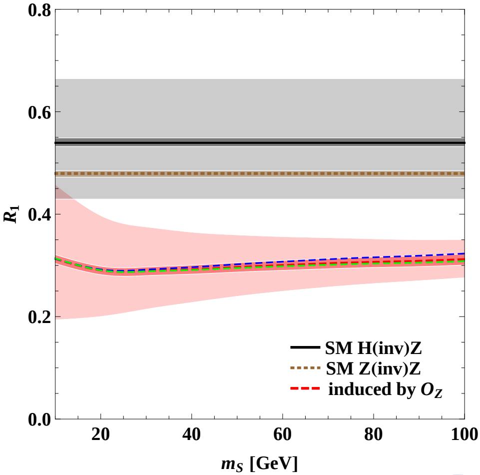
missing transverse momentum distribution

Uncertainties from QCD corrections:



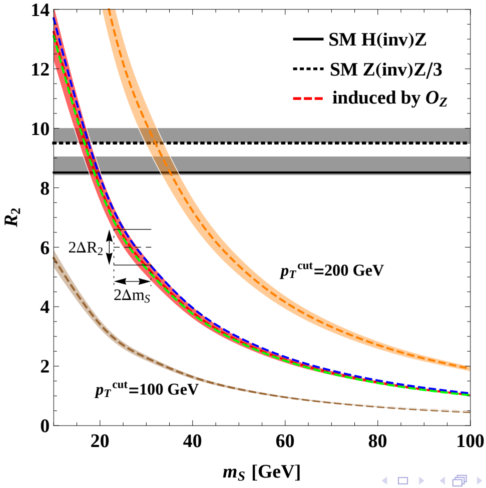
missing transverse momentum distribution

Uncertainties from peak positions:



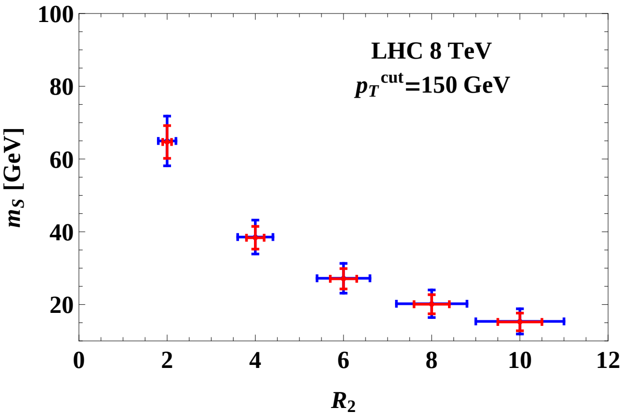
missing transverse momentum distribution

Uncertainties in determining the DM mass:



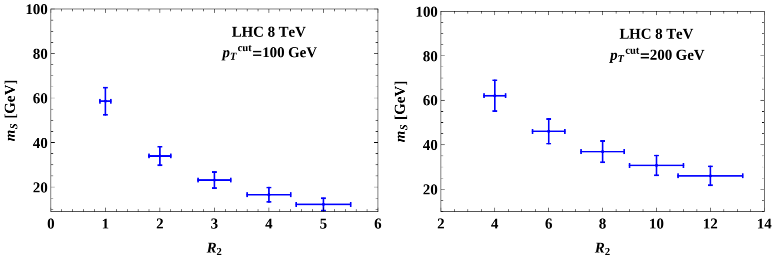
missing transverse momentum distribution

Uncertainties in determining the DM mass:



missing transverse momentum distribution

Uncertainties in determining the DM mass:



Conclusion

- It is important to measure the invisible decay width of the Higgs boson in order to know the total width.
- The signal for this measurement at the LHC has to be carefully treated because of dark matter interactions.
- We consider the relic abundance, the XENON100 and LUX direct detection experiment and the result of searching for Higgs boson invisible decay at the LEP and LHC.
- The interaction of DM-quarks is stringently constrained while the DM-Z couplings are still possible.
- Two observables (ratios based on $p_T^{\rm miss}$) are proposed that can be used to distinguish the different underlying processes.
- Uncertainties are estimated.

Outlook

- We only consider the Higgs boson invisibly decaying into scalar dark matter, inspired by the possible renormalizable extension of the SM.
- We also assume the Z boson and quarks also interact with this kind of dark matter.
- But it is likely the dark matter coupling with the Z boson and quarks differs from that with Higgs boson.
- For example, the Z boson and quarks connect with fermionic dark matter while the Higgs boson decays into scalar dark matter.
- More general questions arise as well: How to distinguish the missing energy of graviton (spin-2), neutralino (spin-1/2), Higgs invisible decay (spin-0) and dark matter (spin-0,1/2,1)?

Thank you !