Some Questions about that Dawn

Tilman Plehn

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Heidelberg, April 2018

Questions

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Status

SUSY

EFT

Mono-X

LHC

Where we stand

What we know about dark matter

- it is particles   [axions to black holes]
- it's global density is $\Omega_\chi h^2 \approx 0.12$ [Planck]
- it is cold   [structure formation]
- it interacts (at least) gravitationally   [bullet cluster, structure formation, etc]
- neutrinos contribute, but explain nothing
- ⇒ more data the key, DM ready to be solved?

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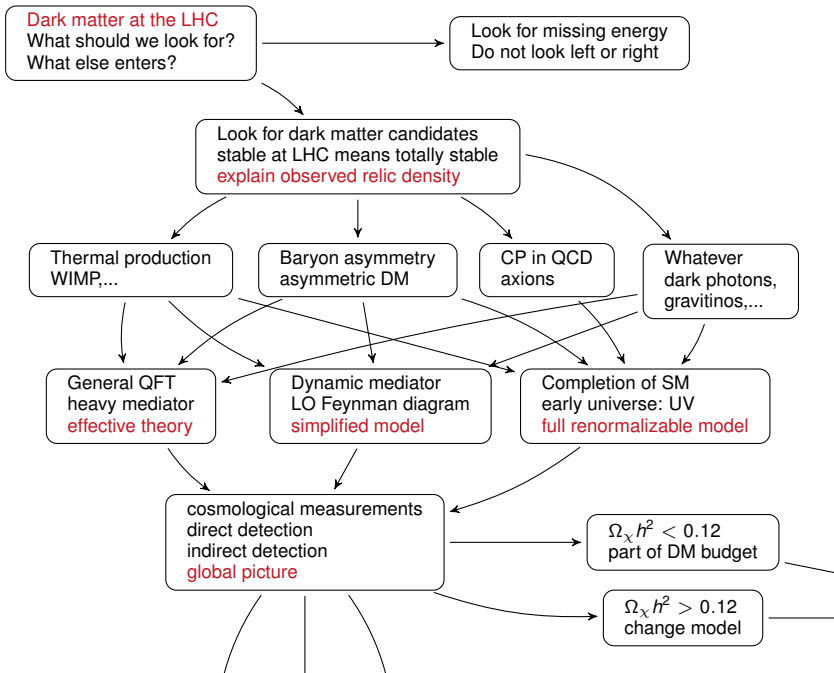
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How we search for dark matter

– direct detection: scattering in earth-based detectors
– indirect detection: annihilation products from high densities
– collider searches: 'invisible' particles
– cosmological experiments: thermal history
– astrophysics: micro-lensing

  ...
⇒ all-physics-and-astronomy effort!
⇒ are we missing something?

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Being an LHC dark matter person

Dark matter at the LHC
What should we look for?
What else enters?

→ Look for missing energy
Do not look left or right

Look for dark matter candidates
stable at LHC means totally stable
explain observed relic density

Thermal production
WIMP,...

Baryon asymmetry
asymmetric DM

CP in QCD
axions

Whatever
dark photons,
gravitinos,...

General QFT
heavy mediator
effective theory

Dynamic mediator
LO Feynman diagram
simplified model

Completion of SM
early universe: UV
full renormalizable model

cosmological measurements
direct detection
indirect detection
global picture

$\Omega_\chi h^2 < 0.12$
part of DM budget

$\Omega_\chi h^2 > 0.12$
change model

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Thermal production

Our one measurement

– annihilation rate from Boltzmann equation

$$\Omega_\chi h^2 \approx 0.12 \; \frac{x_{\text{dec}}}{28} \; \frac{\sqrt{g_{\text{eff}}}}{10} \; \frac{4 \cdot 10^{-9} \; \text{GeV}^{-2}}{\langle \sigma_{\chi\chi} v \rangle}$$

– literal WIMP

$$\langle \sigma_{\chi\chi} v \rangle = \frac{\pi \alpha^2 m_\chi^2}{s_w^4 m_W^4} \quad \Rightarrow \quad \Omega_\chi h^2 \approx 0.12 \; \left(\frac{50 \, \text{GeV}}{m_\chi} \right)^2$$

– light mediator

$$\langle \sigma_{\chi\chi} v \rangle \approx \frac{g^4}{16\pi m_\chi^2} \quad \Rightarrow \quad \frac{m_\chi}{g^2} \approx 2.2 \, \text{TeV}$$

– heavy mediator

$$\langle \sigma_{\chi\chi} v \rangle \approx \frac{g^4 m_\chi^2}{16\pi \, m_{\text{med}}^4} \quad \Rightarrow \quad \frac{m_{\text{med}}^2}{g^2 m_\chi} \approx 2.2 \, \text{TeV}$$

– Higgs portal

$$\sigma_{\chi\chi} \propto \begin{cases} \dfrac{\lambda_3^2 m_b^2}{m_H^4} & m_S \ll \dfrac{m_H}{2} & \lambda_3 \approx 0.2 \\[2mm] \dfrac{\lambda_3^2 m_b^2}{m_H^2 \Gamma_H^2} & m_S = \dfrac{m_H}{2} & \lambda_3 \approx 10^{-5} \\[2mm] \dfrac{\lambda_3^2}{m_S^2} & m_S > m_Z, m_H & \lambda_3 \approx 0.05 \end{cases}$$

⇒ universal framework including relic density?

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Supersymmetry

Still the mother of models

– solving the hierarchy problem, if it's a problem   [ask philosophers?]

– allowing for gauge coupling unification

– linking to string theory in the UV

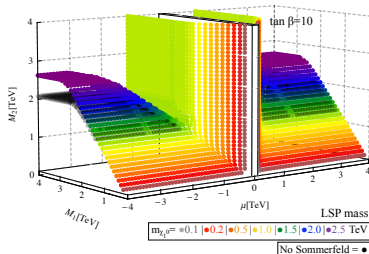– only BSM model still making sense after Run I

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At least the leading thermal DM model

– electroweakinos with TeV-scale upper mass limit

– define DM through $SU(2)_L$ representation
  singlet, doublet, triplet

– allow for general mixing

– add co-annihilation partners, if needed

– add light NMSSM mediator, if needed

⇒ relic neutralino surface

tan β=10

M_2[TeV]

M_1[TeV]

μ[TeV]

LSP mass

m_{χ_0}= •0.1 •0.2 •0.5 •1.0 •1.5 •2.0 •2.5 TeV

No Sommerfeld = •

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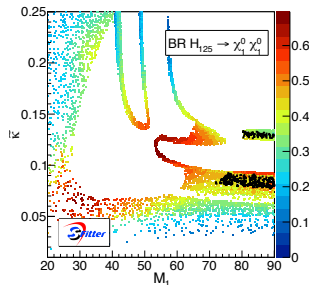
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LSP mass

$m_{\chi_0} = \bullet 0.1 \mid \bullet 0.2 \mid \bullet 0.5 \mid \bullet 1.0 \mid \bullet 1.5 \mid \bullet 2.0 \mid \bullet 2.5$ TeV

No Sommerfeld = $\bullet$
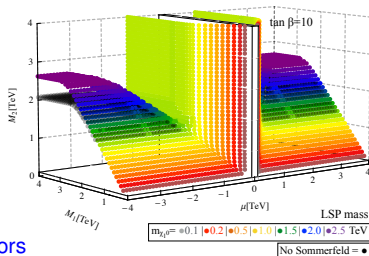
Majorana (or Dirac) neutralino, different mediators

– SM Z-boson $\chi\chi \to Z \to$ jets

– SM-like Higgs $\chi\chi \to h \to b\bar{b}$

– heavy Higgs $H, A \to b\bar{b}, t\bar{t}$

– t-channel chargino $\chi\chi \to WW \to$ jets

– chargino co-annihilation $\chi^0\chi^\pm \to W$

– stau co-annihilation $\tilde{\tau}\chi \to \tau + X$

– light singlet-singlino channel $\chi\chi \to a \to$ SM

⇒ many simplified models, properly defined

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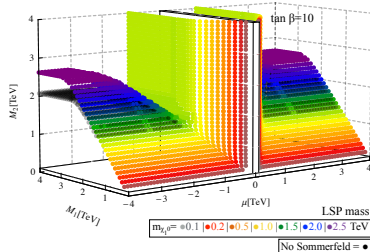
Inspiring signatures

– jets/leptons plus missing energy

– charged tracks

– photons from late decays

– combination of very soft and very hard objects

– invisible Higgs decays

– ????

– ????

⇒ QFT of simplified models?

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Effective theory

Decoupled mediator $m_{med} \gtrsim 2m_\chi$

– direct detection fine [non-relativistic]

– indirect detection, annihilation today fine [very non-relativistic]

– remember relic density $\quad \dfrac{m_{med}^2}{g^2 m_\chi} = \dfrac{m_{med}}{g^2} \dfrac{m_{med}}{m_\chi} \approx 2.2\,\text{TeV} \quad \overset{m_{med} > 2m_\chi}{\Rightarrow} \quad \dfrac{m_{med}}{g^2} < 1.1\,\text{TeV}$

– LHC constraints: $m_{med} \gtrsim$ TeV

$\Rightarrow$ big problem, and it's not the LHC

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Representing models? [lesson from EFT for Higgs@LHC]

- tree-level colored t-channel mediator [squark-neutralino in MSSM]
- tree-level vector s-channel mediator [Z' mediator]
- loop-mediated scalar s-channel mediator [heavy Higgs-neutralino in MSSM]
- loop-mediated scalar t-channel mediator [stop-neutralino in MSSM]
- ⇒ can we imagine sensible UV completions of DM-EFT?

Questions

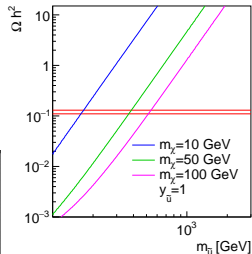Tilman Plehn

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Effective theory vs models

Tree-level scalar in *t*-channel [squarks]

– relic density for small $m_{\tilde{u}}$

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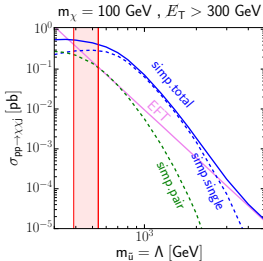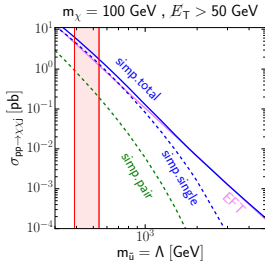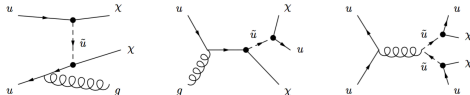
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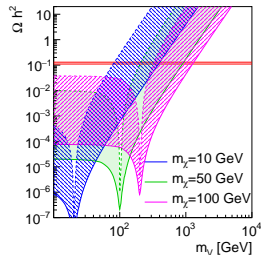

Tree-level scalar in *t*-channel [squarks]

– relic density for small $m_{\tilde{u}}$
– two effective Lagrangians

$$\mathcal{L}_{\text{eff}} \supset \frac{c_{u\chi}}{\Lambda^2} \, (\bar{u}_R \chi) \, (\bar{\chi} u_R) \qquad \mathcal{L}_{\text{eff}} \supset \frac{c}{\Lambda^3} (\bar{\chi}\chi) \, G_{\mu\nu} G^{\mu\nu}$$

– EFT not valid for correct relic density...

$m_\chi = 100$ GeV , $E_T > 50$ GeV

$m_\chi = 100$ GeV , $E_T > 300$ GeV

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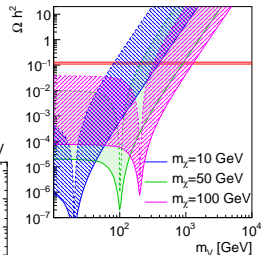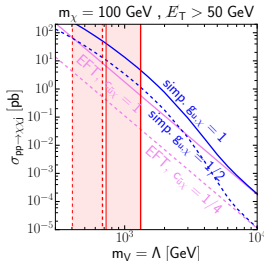
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Tree-level vector in *s*-channel

– relic density for small m_V or on-shell mediator

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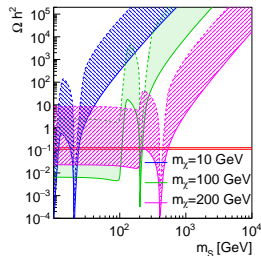
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Tree-level vector in s-channel

– relic density for small m_V or on-shell mediator
– only 4-fermion operator
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EFT

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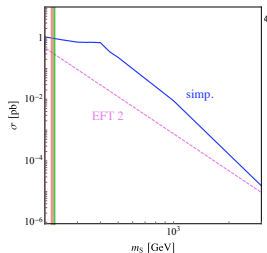– EFT not valid for correct relic density...

Loop-mediated scalar in *s*-channel

– relic density around pole

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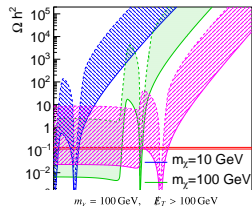– EFT not valid for correct relic density...

Loop-mediated scalar in *s*-channel

– relic density around pole

– two good effective Lagrangians

$$\mathcal{L}_{\text{eff}} \supset \frac{c_S^t}{\Lambda^2} (\bar{t} t) \, (\bar{\chi} \chi) \qquad \mathcal{L}_{\text{eff},3} \supset \frac{c_\chi^g}{\Lambda^3} (\bar{\chi} \chi) \, G_{\mu\nu} G^{\mu\nu}$$

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⇒ does a global DM-EFT framework make any sense?

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Signatures: mono-X-itis

DM signatures with measurable recoil
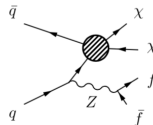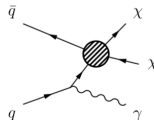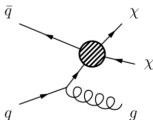
– mono-jet(s) signature from 80s

– ISR with Z' mediator

$$pp \to Z'X \to \chi\chi\, X \qquad \text{with} \quad X = j, \gamma, Z$$

– ratio of signal rates known, nothing to learn

$$\frac{\sigma_{\chi\chi\gamma}}{\sigma_{\chi\chi j}} \approx \frac{\alpha}{\alpha_s} \frac{Q_q^2}{C_F} \approx \frac{1}{40} \qquad\qquad \frac{\sigma_{\chi\chi\ell\ell}}{\sigma_{\chi\chi j}} \approx \frac{\alpha}{\alpha_s} \frac{Q_q^2 s_w^2}{C_F} \, \mathrm{BR}(Z \to \ell^+\ell^-) \approx \frac{1}{2000}$$

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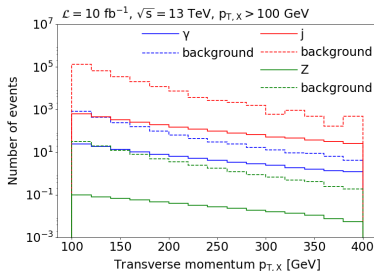$$pp \to Z' X \to \chi\chi\, X \qquad \text{with} \quad X = j, \gamma, Z$$

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Signal vs background

– background $Z \to \nu\nu$ [and a little $W \to \ell\nu$]

– statistical significance

$$n_{\sigma,\gamma} \approx \frac{1}{6.3} \sqrt{\frac{\epsilon_\gamma}{\epsilon_j}}\; n_{\sigma,j}$$

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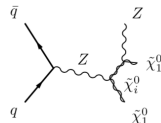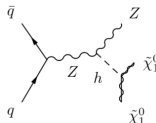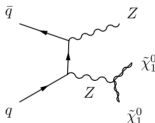## Signal vs background

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- beyond ISR: final state decays [SUSY, 2HDM, Z'?]

⇒ does mono-X make sense beyond few models?

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Power of the LHC

Kinematics of missing transverse momentum

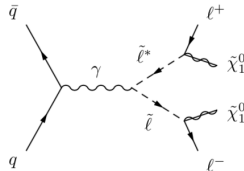- transverse mass with observable edge $[t \to W_\ell b]$

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- the glory of m_{T2}

$$m_{T2}(\hat{m}_{\text{miss}}) = \min_{\vec{p}_T = q_1 + q_2} \left[\max_j \ m_{T,j}(q_j; \hat{m}_{\text{miss}}) \right] \qquad m_{T2}(m_{\text{miss}}) \subset [m_{\text{light}} + m_{\text{miss}}, m_{\text{heavy}}]$$

- many advanced mass constructions

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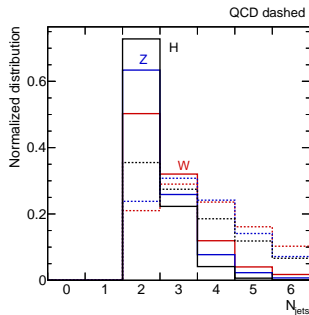
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Magic of QCD

– $pp \to Hjj$ vs $pp \to Zjj$ vs $pp \to Wjj$
– number of (central) jets different for H, Z, W

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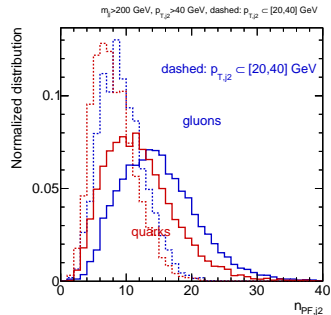$$m_T^2 = \left(E_{T,\text{miss}} + E_{T,\ell}\right)^2 - \left(\vec{p}_T + \vec{p}_{T,\ell}\right)^2 < m_W^2$$

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– number of (central) jets different for H, Z, W
– quark vs gluon tagging jets

$m_j > 200$ GeV, $p_{T,j2} > 40$ GeV, dashed: $p_{T,j2} \subset [20,40]$ GeV

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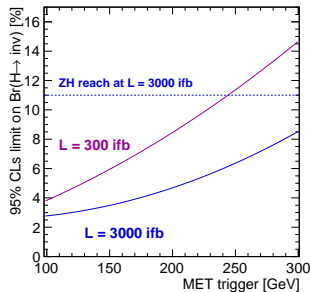
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– $pp \to Hjj$ vs $pp \to Zjj$ vs $pp \to Wjj$

– number of (central) jets different for H, Z, W

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– trigger is the limit

$\Rightarrow$ how far can we push the LHC?

ZH reach at L = 3000 ifb

L = 300 ifb

L = 3000 ifb

Questions

Aspects to discuss before Dawn

Is DM ready to be solved?

Are we missing something?

Is a universal (thermal) DM framework possible?

What are the QFTs of simplified models?

Can we imagine sensible UV completions of DM-EFT?
Does a global DM-EFT framework make any sense?

Does mono-X make sense beyond few models?

How far can we push for example the LHC?