Optimal Bounds on Heavy-Mediator Dark Matter

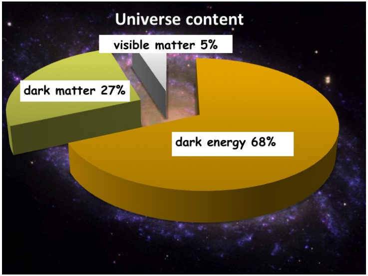
Federico Pobbe

35th IMPRS Workshop

28th June 2016

Heavy-Mediator Dark Matter

- Particles not included in the Standard Model
- Production in the early Universe
- WIMP-miracle



Dark-matter sterile neutrinos in models with a gauge singlet in the Higgs sector

Kalliopi Petraki and Alexander Kusenko

Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA

Asymmetric WIMP Dark Matter in the presence of DM/anti-DM Oscillations

Gabrijela Zaharijas

The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, I-34014 Trieste, Italy

Neutralino Dark Matter and the Curvaton

Martin Lemoine* and Jérôme Martin†

Institut d'Astrophysique de Paris, UMR 7095-CNRS, Universit... Pierre et Marie Curie, 98bis boulevard Arago, 75014 Paris, France

Dark Matter in Split SUSY with Intermediate Higgses

Kingman Cheung[a,b,c], Ran Huo[d], Jae S... Lee[e], Yue-...in Sming Tsai[d]

WIMP Dark Matter in Composite Higgs Models and the Dilaton Portal

Manki Kim*

Department of Physics, Korea ...nced Institute of Science and Technology, 335 Gwahak-ro, ...seong-..., Daejeon 305-701, Korea

The 750 GeV Diphoton Excess from a Pseudoscalar in Fermionic Dark Matter Scenario

Karim Ghorbani*

Physics Department, Faculty of Sciences, Arak University, Arak 38156-8-8349, Iran

Top Quark Mediated Dark Matter

Yue Zhang

...al Center for Theoretical Physics, Trieste 34014, Italy

Effective Field Theory

- Heavy-Mediator models $\rightarrow$ **Effective Field Theory**

Effective Field Theory

- Heavy-Mediator models $\rightarrow$ **Effective Field Theory**
- Approximation for the low energy regime

Effective Field Theory

- Heavy-Mediator models $\rightarrow$ **Effective Field Theory**
- Approximation for the low energy regime
- Free Lagrangian:

$$\mathcal{L}_X = \frac{1}{2}\bar{X}(i\partial\!\!\!/ - m_{DM})X$$

Effective Field Theory

- Heavy-Mediator models $\rightarrow$ **Effective Field Theory**
- Approximation for the low energy regime
- Free Lagrangian:

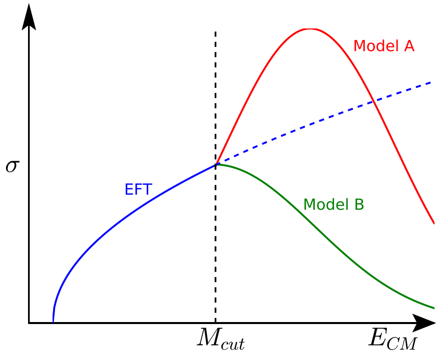
$$\mathcal{L}_X = \frac{1}{2}\bar{X}(i\partial\!\!\!/ - m_{DM})X$$

- Interaction Lagrangian:

$$\mathcal{L}_{int} = -\frac{1}{M_*^2}(\bar{X}\gamma^\mu\gamma^5 X)(\sum_q \bar{q}\gamma_\mu\gamma^5 q)$$

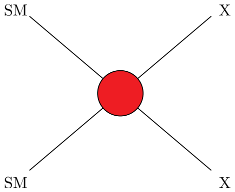
Effective Field Theory

- Limited range of validity: Parameter $\mathbf{M_{cut}}$



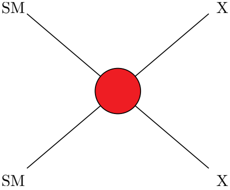
Experimental Approach

- Dark Matter production in colliders

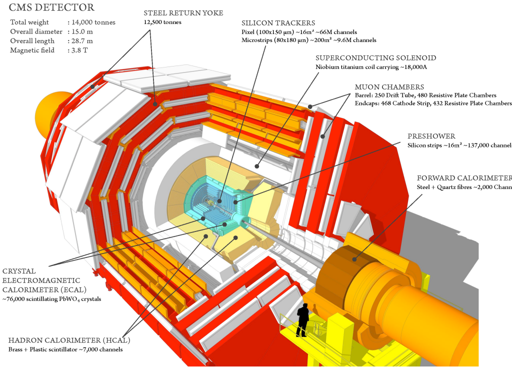


Experimental Approach

- Dark Matter production in colliders



- CMS experiment as benchmark



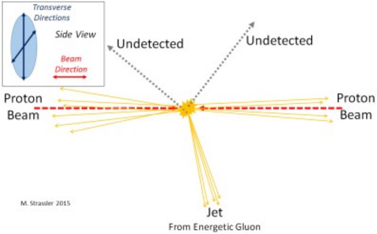
Mono-jet

- Dark Matter particles do not interact with the detector.

Mono-jet

- Dark Matter particles do not interact with the detector.
- **Mono-jet**: events with a high transverse momentum ($\mathbf{p}_T$) jet, balanced by "missing transverse energy" $\not{E}_T$.

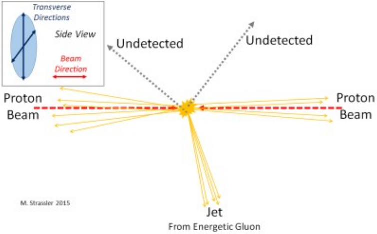
Mono-jet

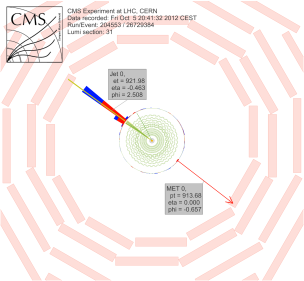


- Dark Matter particles do not interact with the detector.
- **Mono-jet**: events with a high transverse momentum ($\mathbf{p}_T$) jet, balanced by "missing transverse energy" $\not{E}_T$.

Mono-jet

- Dark Matter particles do not interact with the detector.
- **Mono-jet**: events with a high transverse momentum ($\mathbf{p}_T$) jet, balanced by "missing transverse energy" $\not{E}_T$.





Statistical Analysis

Basic Principle

The number of events, or the cross section, predicted by the EFT is always lower or equal to the complete model prediction.

$$\sigma_{EFT} \leq \sigma_{true}$$

Calculation of bounds on the parameters of the theory.

Statistical Analysis

Cut & Count

- Select an optimal region of the phase space ($\not{E}_T > \not{E}_T^{min}$)

Statistical Analysis

Cut & Count

- Select an optimal region of the phase space ($\not{E}_T > \not{E}_T^{min}$)
- Impose $\sigma_{EFT} \leq \sigma_{exc}$

Statistical Analysis

Cut & Count

- Select an optimal region of the phase space ($\not{E}_T > \not{E}_T^{min}$)
- Impose $\sigma_{EFT} \leq \sigma_{exc}$

  $\sigma_{EFT} = \left[\frac{1\,TeV}{M_*}\right]^4 \cdot \bar{\sigma}(M_* = 1\,TeV) \cdot \epsilon(m_{DM}, M_{cut}, \not{E}_T^{min})$

  σ_{exc} = maximum cross section compatible with the background at 95% C.L.

Statistical Analysis

Cut & Count

- Select an optimal region of the phase space ($\not{E}_T > \not{E}_T^{min}$)
- Impose $\sigma_{EFT} \leq \sigma_{exc}$

  $\sigma_{EFT} = \left[\frac{1\,TeV}{M_*}\right]^4 \cdot \bar{\sigma}(M_* = 1\,TeV) \cdot \epsilon(m_{DM}, M_{cut}, \not{E}_T^{min})$

  σ_{exc} = maximum cross section compatible with the background at 95% C.L.
- Chi-square test: $\chi^2 = \frac{(\mathcal{O}-(\bar{B}+S))^2}{\delta\nu^2\bar{B}^2+\bar{B}+S} \leq \chi^2_{95}(1) \simeq 4$

Statistical Analysis

Cut & Count

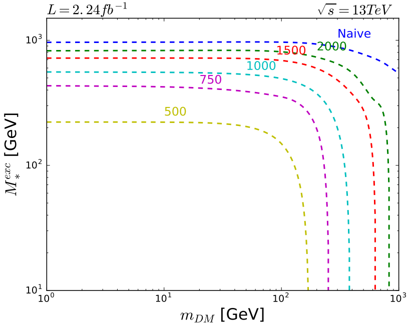
- Select an optimal region of the phase space ($\not{E}_T > \not{E}_T^{min}$)
- Impose $\sigma_{EFT} \leq \sigma_{exc}$

  $\sigma_{EFT} = \left[\frac{1\,TeV}{M_*}\right]^4 \cdot \bar{\sigma}(M_* = 1\,TeV) \cdot \epsilon(m_{DM}, M_{cut}, \not{E}_T^{min})$

  σ_{exc} = maximum cross section compatible with the background at 95% C.L.
- Chi-square test: $\chi^2 = \frac{(\mathcal{O}-(\bar{B}+S))^2}{\delta\nu^2\bar{B}^2+\bar{B}+S} \leq \chi^2_{95}(1) \simeq 4$
- Lower Bound: $M_* \geq M_*^{exc} = \sqrt[4]{\frac{\bar{\sigma}\cdot\epsilon}{\sigma_{exc}}}$

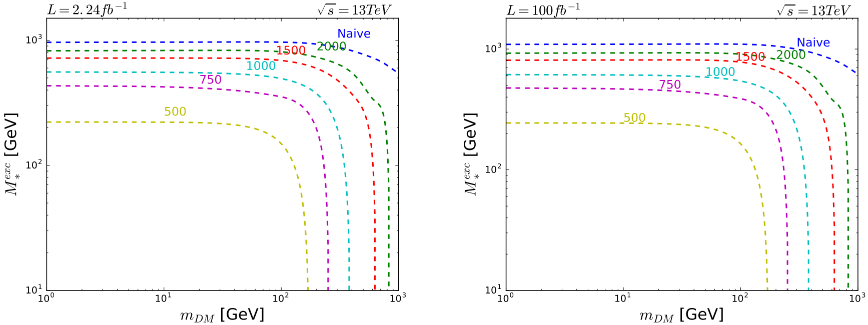
Cut & Count

The region below the curve is excluded.



Cut & Count

The region below the curve is excluded.



- We choose to study the $\not{E}_T$ distribution of events.

Statistical Analysis
Modified Shape Analysis

- We choose to study the $\not{E}_T$ distribution of events.
- We define a *likelihood* for each bin:

$$\mathcal{L}_i(\delta\nu_i, S_i, \Delta S_i) = \frac{1}{2\pi\sqrt{\bar{B}_i + S_i + \Delta S_i}} \frac{1}{\delta\nu_i} e^{-\frac{1}{2}\frac{(\bar{B}_i + S_i + \Delta S_i - \mathcal{O}_i)^2}{\bar{B}_i^2 \delta\nu_i^2 + \bar{B}_i + S_i + \Delta S_i}}$$

Statistical Analysis

Modified Shape Analysis

- We choose to study the $\not{E}_T$ distribution of events.
- We define a *likelihood* for each bin:

$$\mathcal{L}_i(\delta\nu_i, S_i, \Delta S_i) = \frac{1}{2\pi\sqrt{\bar{B}_i + S_i + \Delta S_i}}\frac{1}{\delta\nu_i}e^{-\frac{1}{2}\frac{(\bar{B}_i+S_i+\Delta S_i-\mathcal{O}_i)^2}{\bar{B}_i^2\delta\nu_i^2+\bar{B}_i+S_i+\Delta S_i}}$$

- ΔS_i: signal not predicted by the EFT ($\Delta S_i \geq 0$)

Statistical Analysis

Modified Shape Analysis

- We choose to study the $\not{E}_T$ distribution of events.
- We define a *likelihood* for each bin:

$$\mathcal{L}_i(\delta\nu_i, S_i, \Delta S_i) = \frac{1}{2\pi\sqrt{\bar{B}_i + S_i + \Delta S_i}} \frac{1}{\delta\nu_i} e^{-\frac{1}{2}\frac{(\bar{B}_i + S_i + \Delta S_i - \mathcal{O}_i)^2}{\bar{B}_i^2 \delta\nu_i^2 + \bar{B}_i + S_i + \Delta S_i}}$$

- ΔS_i: signal not predicted by the EFT ($\Delta S_i \geq 0$)
- Total likelihood of the system:

$$\mathcal{L}_{tot}(\mathbf{S}, \mathbf{\Delta S}) = \prod_{i=1}^{n} \mathcal{L}_i$$

Obtain a limit valid for any ΔS_i value.

Statistical Analysis

Modified Shape Analysis

Obtain a limit valid for any ΔS_i value.

- Test Statistic:

$$\chi^2(M_*) = \sum_{i=1}^{n} \frac{(\bar{B}_i + S_i + \Delta S_i - \mathcal{O}_i)^2}{\bar{B}_i^2 \delta\nu_i^2 + \bar{B}_i + S_i + \Delta S_i}$$

Statistical Analysis
Modified Shape Analysis

Obtain a limit valid for any ΔS_i value.

- Test Statistic:

$$\chi^2(M_*) = \sum_{i=1}^{n} \frac{(\bar{B}_i + S_i + \Delta S_i - \mathcal{O}_i)^2}{\bar{B}_i^2 \delta\nu_i^2 + \bar{B}_i + S_i + \Delta S_i}$$

- $S_i = \left[\frac{1\,TeV}{M_*}\right]^4 \cdot \bar{\sigma}(M_* = 1\,TeV) \cdot \epsilon_i(m_{DM}, M_{cut}, i) \cdot L$

Obtain a limit valid for any ΔS_i value.

- Test Statistic:

$$\chi^2(M_*) = \sum_{i=1}^{n} \frac{(\bar{B}_i + S_i + \Delta S_i - \mathcal{O}_i)^2}{\bar{B}_i^2 \delta\nu_i^2 + \bar{B}_i + S_i + \Delta S_i}$$

- $S_i = \left[\frac{1\,TeV}{M_*}\right]^4 \cdot \bar{\sigma}(M_* = 1\,TeV) \cdot \epsilon_i(m_{DM}, M_{cut}, i) \cdot L$

Lower Bound on M_*

The minimum value of M_* at 95 % C.L. is obtained solving:

$$\chi^2(M_*) < \chi^2_{95}(n)$$

Minimise χ^2 with respect to ΔS_i. Two possible cases:

Minimise χ^2 with respect to ΔS_i. Two possible cases:

- $\bar{B}_i + S_i \geq \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = 0$

Statistical Analysis
Modified Shape Analysis

Minimise χ^2 with respect to ΔS_i. Two possible cases:

- $\bar{B}_i + S_i \geq \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = 0$
- $\bar{B}_i + S_i < \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = \mathcal{O}_i - \bar{B}_i - S_i$

Statistical Analysis

Modified Shape Analysis

Minimise χ^2 with respect to ΔS_i. Two possible cases:

- $\bar{B}_i + S_i \geq \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = 0$
- $\bar{B}_i + S_i < \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = \mathcal{O}_i - \bar{B}_i - S_i$

Statistical Reason

Principle of Maximum Likelihood.

Statistical Analysis

Modified Shape Analysis

Minimise χ^2 with respect to ΔS_i. Two possible cases:

- $\bar{B}_i + S_i \geq \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = 0$
- $\bar{B}_i + S_i < \mathcal{O}_i \quad \rightarrow \quad \Delta S_i = \mathcal{O}_i - \bar{B}_i - S_i$

Statistical Reason

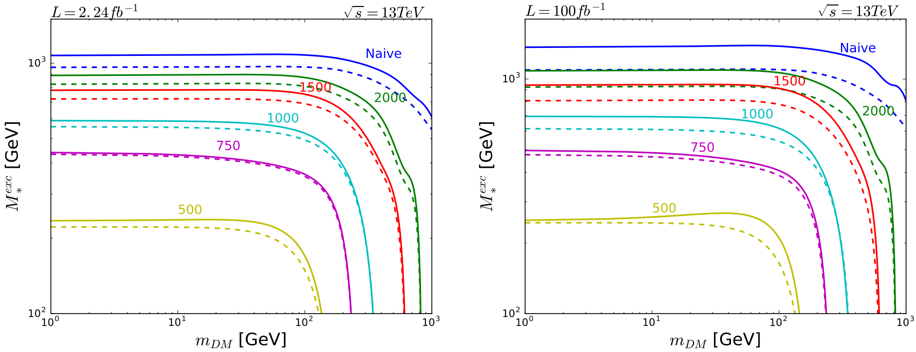
Principle of Maximum Likelihood.

Physical Reason

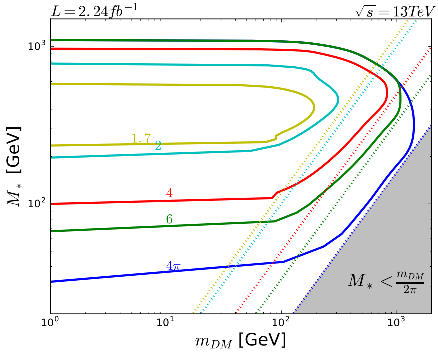
Underestimation of the signal.

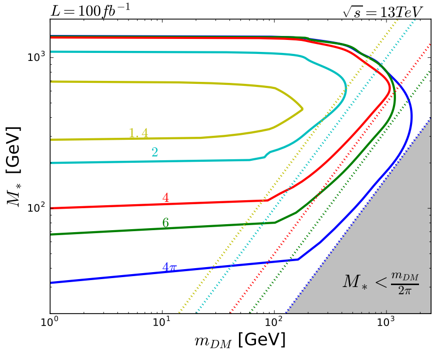
Results

Comparison between MSA and C&C.



Re-write the limit using: $M_{cut} = g_* M_*$.





Conclusions

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;
- We developed a method to combine the EFT approach with a shape-based statistical analysis;

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;
- We developed a method to combine the EFT approach with a shape-based statistical analysis;
- Method applicable to similar situations;

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;
- We developed a method to combine the EFT approach with a shape-based statistical analysis;
- Method applicable to similar situations;
- Possible extensions:

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;
- We developed a method to combine the EFT approach with a shape-based statistical analysis;
- Method applicable to similar situations;
- Possible extensions:
  - NON-gaussian Likelihood

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;
- We developed a method to combine the EFT approach with a shape-based statistical analysis;
- Method applicable to similar situations;
- Possible extensions:
    - NON-gaussian Likelihood
    - Systematics and errors correlated

Conclusions

- The EFT approach allows us to study Dark Matter production in a model-independent way;
- Solid and reliable limits;
- We developed a method to combine the EFT approach with a shape-based statistical analysis;
- Method applicable to similar situations;
- Possible extensions:
    - NON-gaussian Likelihood
    - Systematics and errors correlated
    - Application to different final states

Thank you for your kind attention