Direct Detection of Dark Matter: Precision Predictions in a Simplified Model Framework

Christoph Borschensky

[arXiv:2008.04253]

in collaboration with Gabriele Coniglio, Barbara Jäger, Josef Jochum, and Vincent Schipperges

DESY Theory Workshop

Virtual Theory Forum 2020

25 September 2020

Eberhard Karls
Universität
Tübingen

Outline

1. Dark Matter Models
2. Direct Detection of Dark Matter at NLO-QCD
3. Phenomenological Analysis
4. Summary

The dark matter model space

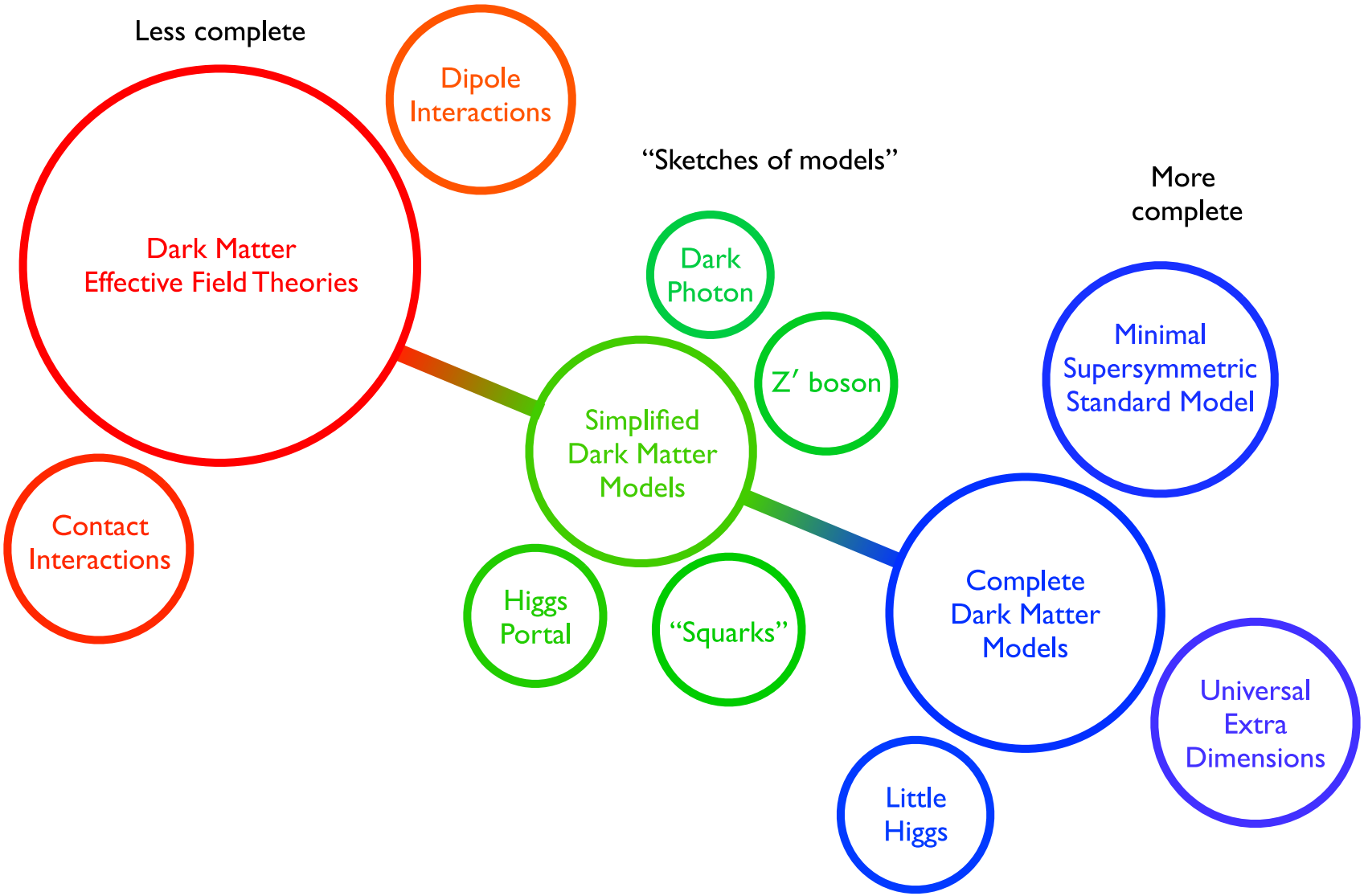


Figure taken from *[Abdallah et al. '15, arXiv:1506.03116]*

The dark matter model space

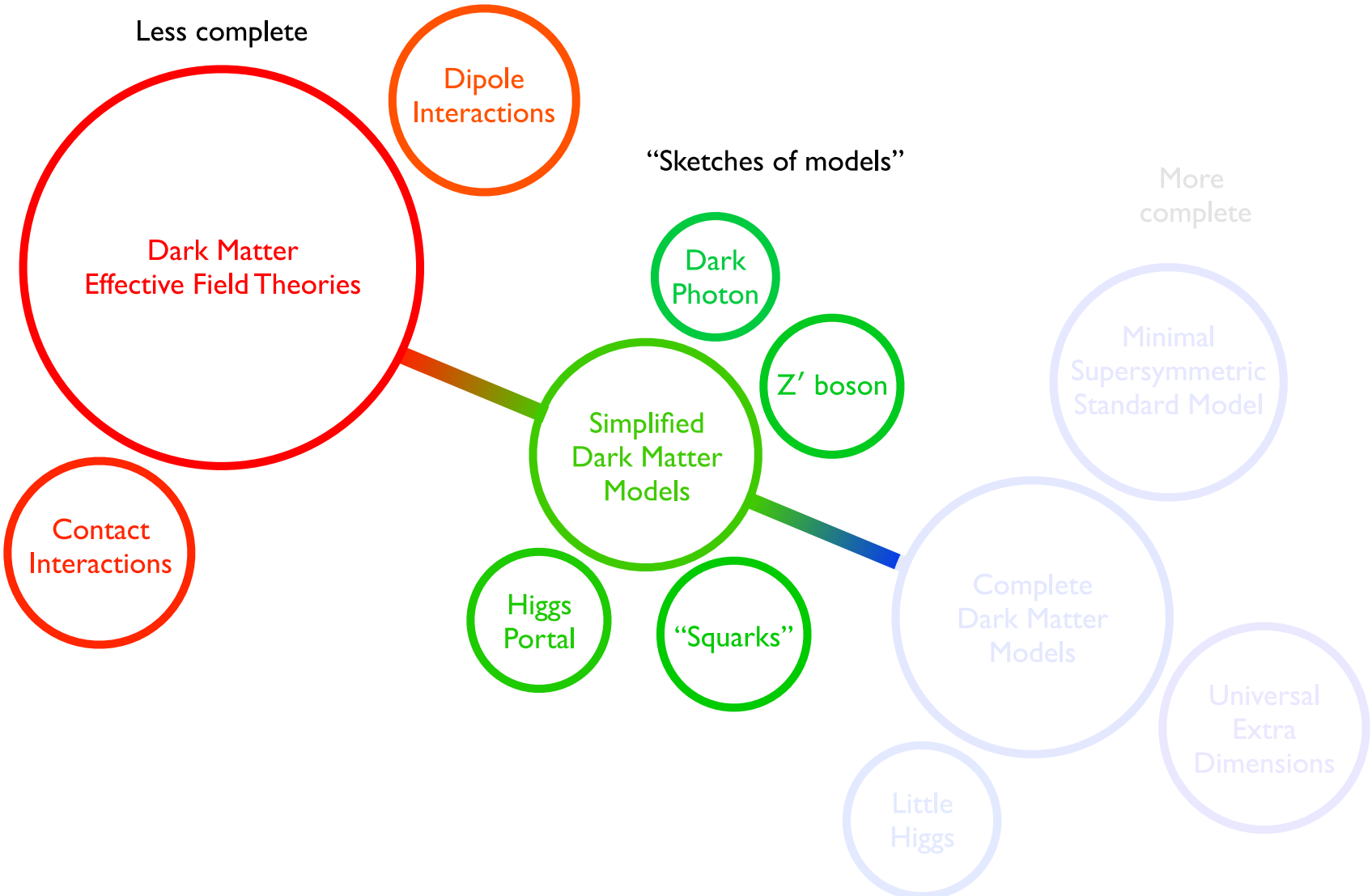
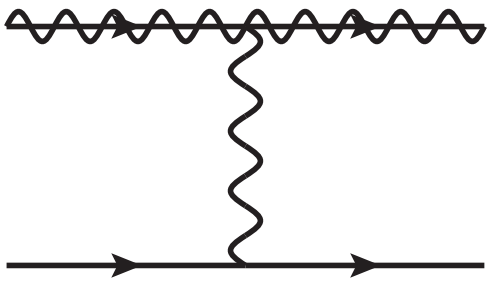


Figure taken from *[Abdallah et al. '15, arXiv:1506.03116]*

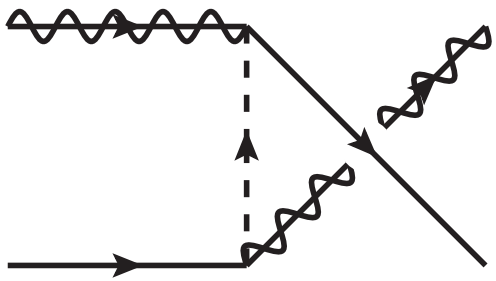
Simplified s- and t-channel models

Choice: DM χ is a Dirac fermion and singlet under the SM gauge group

s-channel model



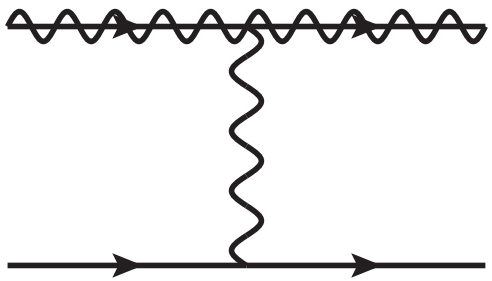
t-channel model



Simplified s- and t-channel models

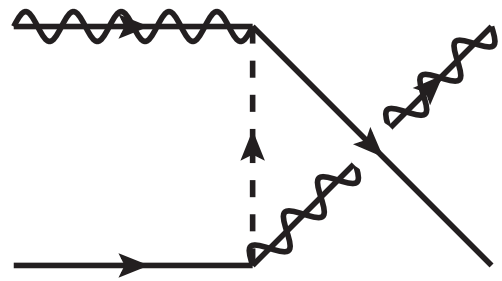
Choice: DM χ is a Dirac fermion and singlet under the SM gauge group

s-channel model



$$\mathcal{L}_V^{\text{int}} = \bar{\chi}\gamma^\mu \left[g_\chi^V - g_\chi^A \gamma_5\right] \chi V_\mu + \sum_q \bar{q}\gamma^\mu \left[g_q^V - g_q^A \gamma_5\right] q V_\mu$$

t-channel model

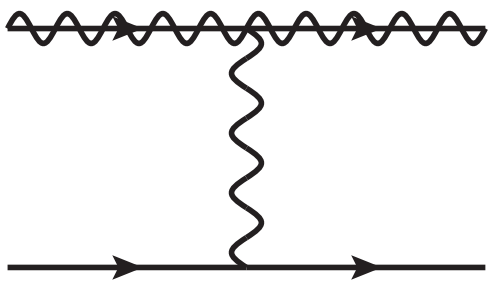


$$\mathcal{L}_{\tilde{Q}}^{\text{int}} = -\lambda_{Q_L}\left(\tilde{Q}^*_{u_L}\bar{\chi}u_L + \tilde{Q}^*_{d_L}\bar{\chi}d_L\right) - \lambda_{u_R}\tilde{Q}^*_{u_R}\bar{\chi}u_R - \lambda_{d_R}\tilde{Q}^*_{d_R}\bar{\chi}d_R + \text{h.c.}$$

Simplified s- and t-channel models

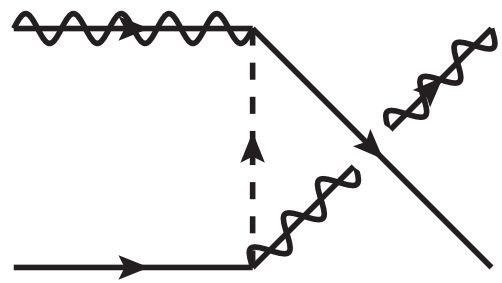
Choice: DM χ is a Dirac fermion and singlet under the SM gauge group

s-channel model



$$\mathcal{L}_V^{\text{int}} = \bar{\chi}\gamma^\mu \left[g_\chi^V - g_\chi^A \gamma_5\right] \chi V_\mu + \sum_q \bar{q}\gamma^\mu \left[g_q^V - g_q^A \gamma_5\right] q V_\mu$$

t-channel model



$$\mathcal{L}_{\tilde{Q}}^{\text{int}} = -\lambda_{Q_L}\left(\tilde{Q}_{u_L}^* \bar{\chi} u_L + \tilde{Q}_{d_L}^* \bar{\chi} d_L\right) - \lambda_{u_R} \tilde{Q}_{u_R}^* \bar{\chi} u_R - \lambda_{d_R} \tilde{Q}_{d_R}^* \bar{\chi} d_R + \text{h.c.}$$

Vector mediator

- Mass M_V; uncolored
- Decays only into SM/DM pairs

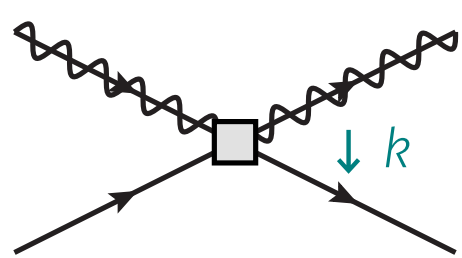
Scalar mediator

- Mass $M_{\tilde{Q}}$; colored & flavored
- $M_{\tilde{Q}} > m_\chi$ to allow decay $\tilde{Q} \to q\chi$

Elastic DM-nucleon scattering

Rate of events dR per recoil energy interval dE:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim \sum_{i\text{: nuclear species}} D_i \cdot A_i \cdot \sigma_i$$



k: exchanged momentum between DM and nucleon

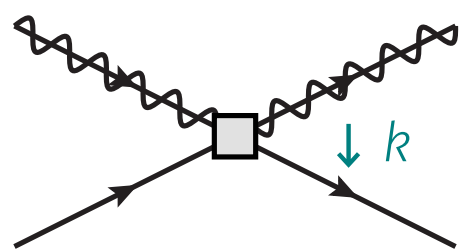
- D_i: detector material
- A_i: astrophysical input (local DM density, relative DM velocity)
- σ_i: **elastic DM-nucleus scattering cross section**

(Experimental limits typically given as limits on DM-nucle**on** cross section σ_N)

Elastic DM-nucleon scattering

Rate of events dR per recoil energy interval dE:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim \sum_{i\text{: nuclear species}} D_i \cdot A_i \cdot \sigma_i$$



k: exchanged momentum between DM and nucleon

- D_i: detector material
- A_i: astrophysical input (local DM density, relative DM velocity)
- σ_i: **elastic DM-nucleus scattering cross section**

(Experimental limits typically given as limits on DM-nucle**on** cross section σ_N)

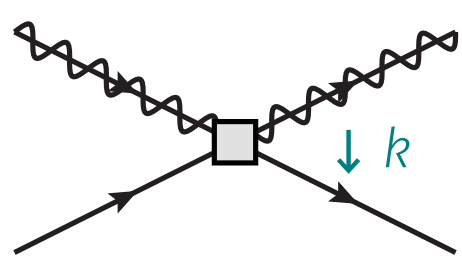
Non-relativistic regime $k \to 0$: use effective field theory (EFT):

$$\mathcal{L}_{\mathrm{EFT}}^{\mathrm{int},\chi q} = c_S\,\mathcal{O}_S + c_V\,\mathcal{O}_V + c_A\,\mathcal{O}_A + c_T\,\mathcal{O}_T$$

Elastic DM-nucleon scattering

Rate of events dR per recoil energy interval dE:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim \sum_{i\text{: nuclear species}} D_i \cdot A_i \cdot \sigma_i$$



k: exchanged momentum between DM and nucleon

- D_i: detector material
- A_i: astrophysical input (local DM density, relative DM velocity)
- σ_i: **elastic DM-nucleus scattering cross section**

(Experimental limits typically given as limits on DM-nucle**on** cross section σ_N)

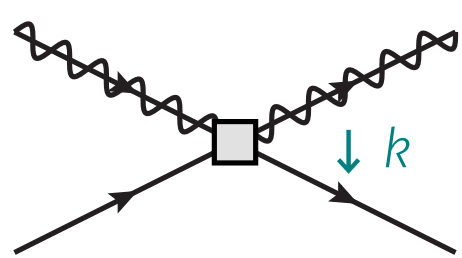
Non-relativistic regime $k \to 0$: use effective field theory (EFT):

$$\mathcal{L}_{\mathrm{EFT}}^{\mathrm{int},\chi q} = c_S \left[\bar{\chi}\chi\,\bar{q}q\right] + c_V \left[\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q\right] + c_A \left[\bar{\chi}\gamma^\mu\gamma_5\chi\,\bar{q}\gamma_\mu\gamma_5 q\right] - \frac{1}{2} c_T \left[\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\sigma_{\mu\nu}q\right]$$

Elastic DM-nucleon scattering

Rate of events dR per recoil energy interval dE:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim \sum_{i\text{: nuclear species}} D_i \cdot A_i \cdot \sigma_i$$



k: exchanged momentum between DM and nucleon

- D_i: detector material
- A_i: astrophysical input (local DM density, relative DM velocity)
- σ_i: **elastic DM-nucleus scattering cross section**

(Experimental limits typically given as limits on DM-nucle**on** cross section σ_N)

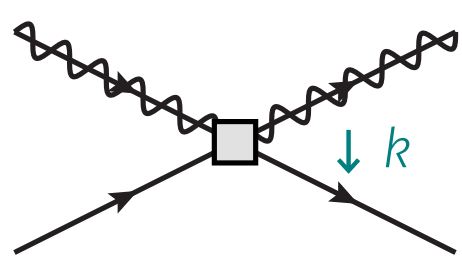
Non-relativistic regime $k \to 0$: use effective field theory (EFT):

$$\mathcal{L}_{\mathrm{EFT}}^{\mathrm{int},\chi q} = \underbrace{c_S \left[\bar{\chi}\chi\, \bar{q}q\right] + c_V \left[\bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu q\right]}_{\text{spin independent = SI}} + \underbrace{c_A \left[\bar{\chi}\gamma^\mu\gamma_5\chi\, \bar{q}\gamma_\mu\gamma_5 q\right] - \frac{1}{2} c_T \left[\bar{\chi}\sigma^{\mu\nu}\chi\, \bar{q}\sigma_{\mu\nu} q\right]}_{\text{spin dependent = SD}}$$

Elastic DM-nucleon scattering

Rate of events dR per recoil energy interval dE:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim \sum_{i\text{: nuclear species}} D_i \cdot A_i \cdot \sigma_i$$



k: exchanged momentum between DM and nucleon

- D_i: detector material
- A_i: astrophysical input (local DM density, relative DM velocity)
- σ_i: **elastic DM-nucleus scattering cross section**

(Experimental limits typically given as limits on DM-nucle**on** cross section σ_N)

Non-relativistic regime $k \to 0$: use effective field theory (EFT):

$$\mathcal{L}_{\mathrm{EFT}}^{\mathrm{int},\chi q} = c_S\left[\bar{\chi}\chi\,\bar{q}q\right] + c_V\left[\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q\right] + c_A\left[\bar{\chi}\gamma^\mu\gamma_5\chi\,\bar{q}\gamma_\mu\gamma_5 q\right] - \frac{1}{2}c_T\left[\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\sigma_{\mu\nu}q\right]$$

From $\mathcal{L}_{\mathrm{EFT}}$, derive non-rel. DM-nucleon scattering cross section σ_N:

$$\sigma_N^{\mathrm{SI}} = \frac{\mu_N^2}{\pi}\left|g_{\mathrm{SI}}^N\right|^2, \quad \sigma_N^{\mathrm{SD}} = \frac{3\mu_N^2}{\pi}\left|g_{\mathrm{SD}}^N\right|^2$$

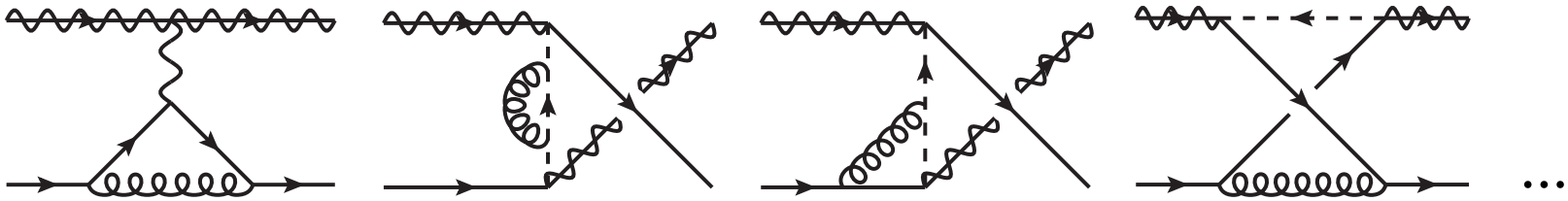
with $g_j^N = \sum_q f_{j,q}^N c_{j,q}$, $j = S, V, A, T$

$f_{j,q}^N$: nucleonic matrix elements

μ_N: reduced DM-nucleon mass

Higher-order corrections and matching

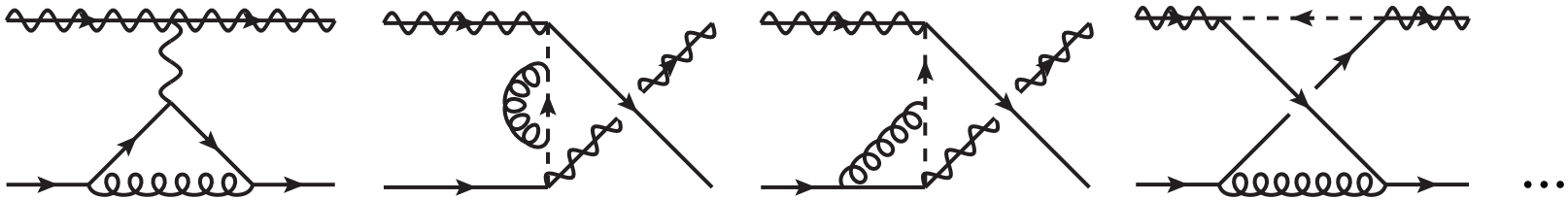
One-loop diagrams in the full theory (simplified models):



(No real contributions in the elastic and non-relativistic limit)

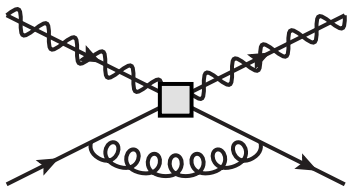
Higher-order corrections and matching

One-loop diagrams in the full theory (simplified models):



(No real contributions in the elastic and non-relativistic limit)

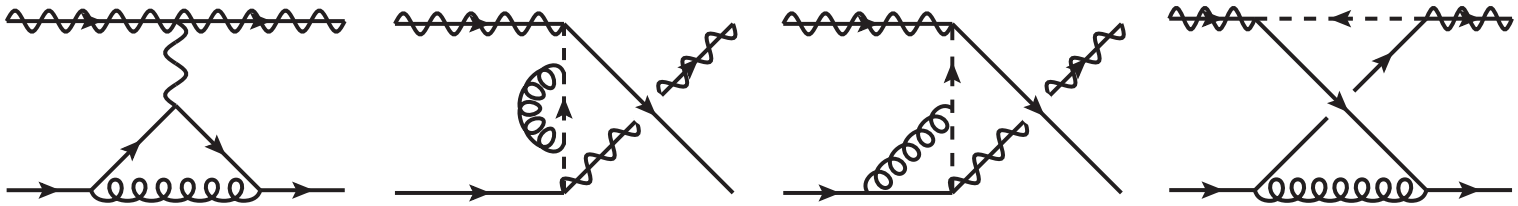
One-loop diagrams in the EFT are also required:



(Only one diagram for each operator)

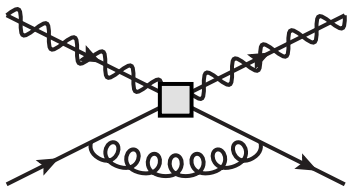
Higher-order corrections and matching

One-loop diagrams in the full theory (simplified models):



(No real contributions in the elastic and non-relativistic limit)

One-loop diagrams in the EFT are also required:

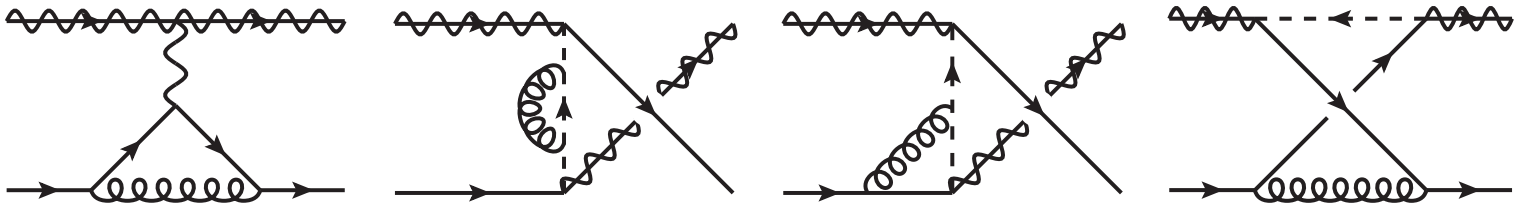


(Only one diagram for each operator)

+ counterterm diagrams!

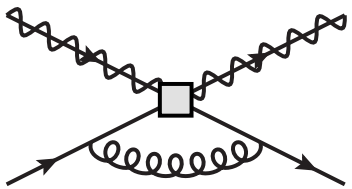
Higher-order corrections and matching

One-loop diagrams in the full theory (simplified models):



(No real contributions in the elastic and non-relativistic limit)

One-loop diagrams in the EFT are also required:



+ counterterm diagrams!

(Only one diagram for each operator)

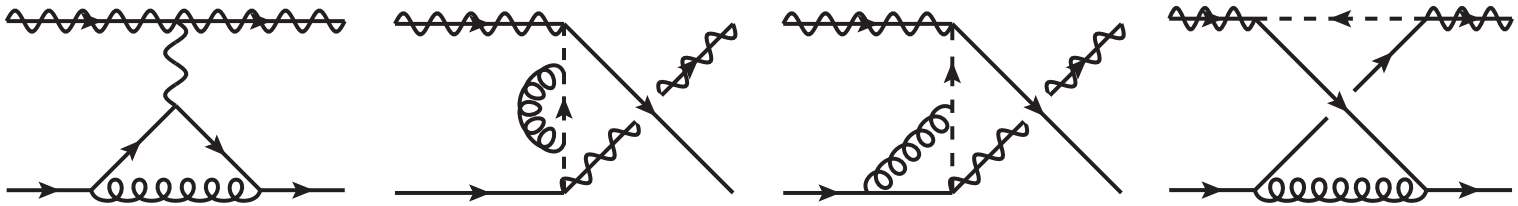
Match the matrix elements $\mathcal{M}$ from full theory to EFT: $\mathcal{M}_{\text{sim}} \stackrel{!}{=} \mathcal{M}_{\text{EFT}}$

LO matching

$$\mathcal{M}_{\text{sim}}^{\text{tree}} \stackrel{!}{=} c_V^{\text{tree}} \mathcal{O}_V^{\text{tree}} + c_A^{\text{tree}} \mathcal{O}_A^{\text{tree}}$$

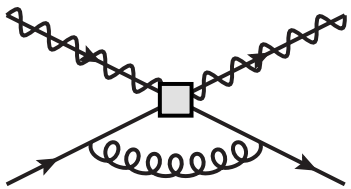
Higher-order corrections and matching

One-loop diagrams in the full theory (simplified models):



(No real contributions in the elastic and non-relativistic limit)

One-loop diagrams in the EFT are also required:



+ counterterm diagrams!

(Only one diagram for each operator)

Match the matrix elements $\mathcal{M}$ from full theory to EFT: $\mathcal{M}_{\text{sim}} \stackrel{!}{=} \mathcal{M}_{\text{EFT}}$

LO matching

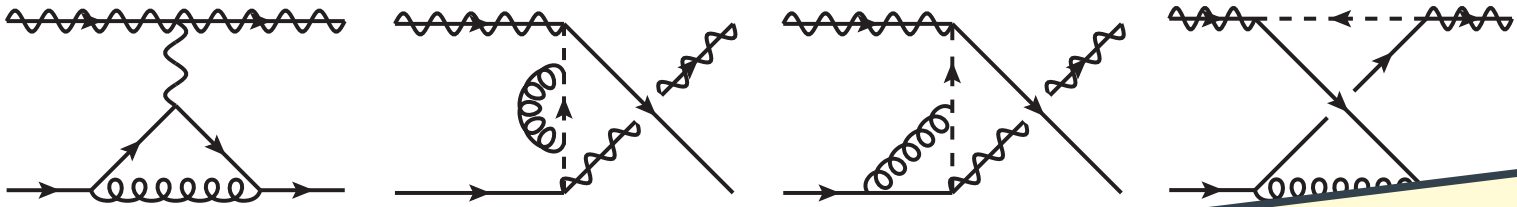
$$\mathcal{M}_{\text{sim}}^{\text{tree}} \stackrel{!}{=} c_V^{\text{tree}} \mathcal{O}_V^{\text{tree}} + c_A^{\text{tree}} \mathcal{O}_A^{\text{tree}}$$

NLO matching

$$\mathcal{M}_{\text{sim}}^{\text{1-loop}} - c_V^{\text{tree}} \mathcal{O}_V^{\text{1-loop}} - c_A^{\text{tree}} \mathcal{O}_A^{\text{1-loop}} \stackrel{!}{=} c_S^{\text{1-loop}} \mathcal{O}_S^{\text{tree}} + c_V^{\text{1-loop}} \mathcal{O}_V^{\text{tree}} + c_A^{\text{1-loop}} \mathcal{O}_A^{\text{tree}} + c_T^{\text{1-loop}} \mathcal{O}_T^{\text{tree}}$$

Higher-order corrections and matching

One-loop diagrams in the full theory (simplified models):



(No real contributions in the elastic and non-rel...

One-loo... ...grams!

+ coun...

No one-loop corrections to the Wilson coefficients in the pure s-channel model

⇒ Focus on the t-channel and the combined s+t-channel models

(Only one diagram for each operator)

Match the matrix elements $\mathcal{M}$ from full theory to EFT: $\mathcal{M}_{\text{sim}} \stackrel{!}{=} \mathcal{M}_{\text{EFT}}$

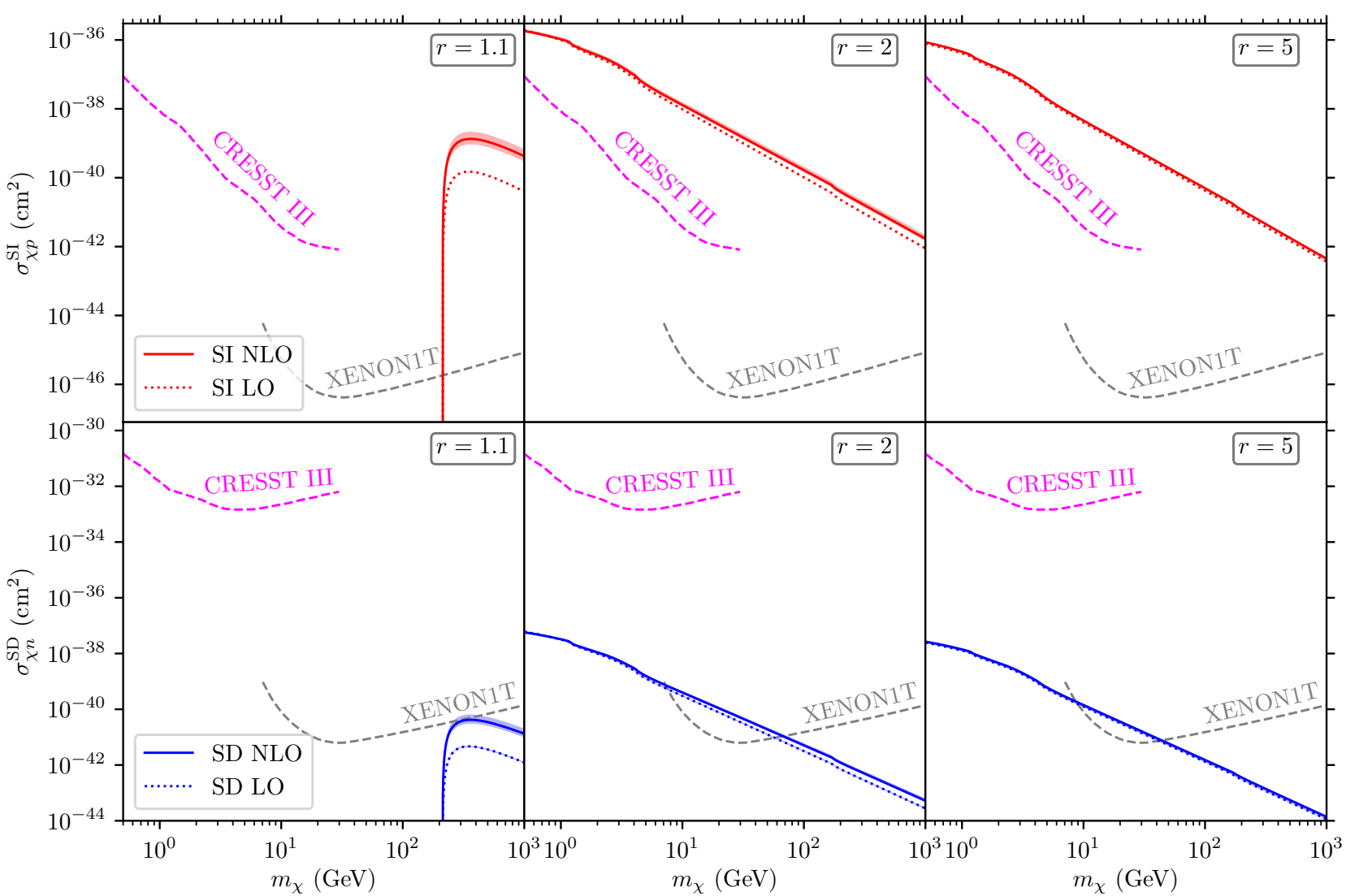
LO matching

$$\mathcal{M}_{\text{sim}}^{\text{tree}} \stackrel{!}{=} c_V^{\text{tree}} \mathcal{O}_V^{\text{tree}} + c_A^{\text{tree}} \mathcal{O}_A^{\text{tree}}$$

NLO matching

$$\mathcal{M}_{\text{sim}}^{\text{1-loop}} - c_V^{\text{tree}} \mathcal{O}_V^{\text{1-loop}} - c_A^{\text{tree}} \mathcal{O}_A^{\text{1-loop}} \stackrel{!}{=} c_S^{\text{1-loop}} \mathcal{O}_S^{\text{tree}} + c_V^{\text{1-loop}} \mathcal{O}_V^{\text{tree}} + c_A^{\text{1-loop}} \mathcal{O}_A^{\text{tree}} + c_T^{\text{1-loop}} \mathcal{O}_T^{\text{tree}}$$

t-channel model: NLO-QCD effects on cross sections



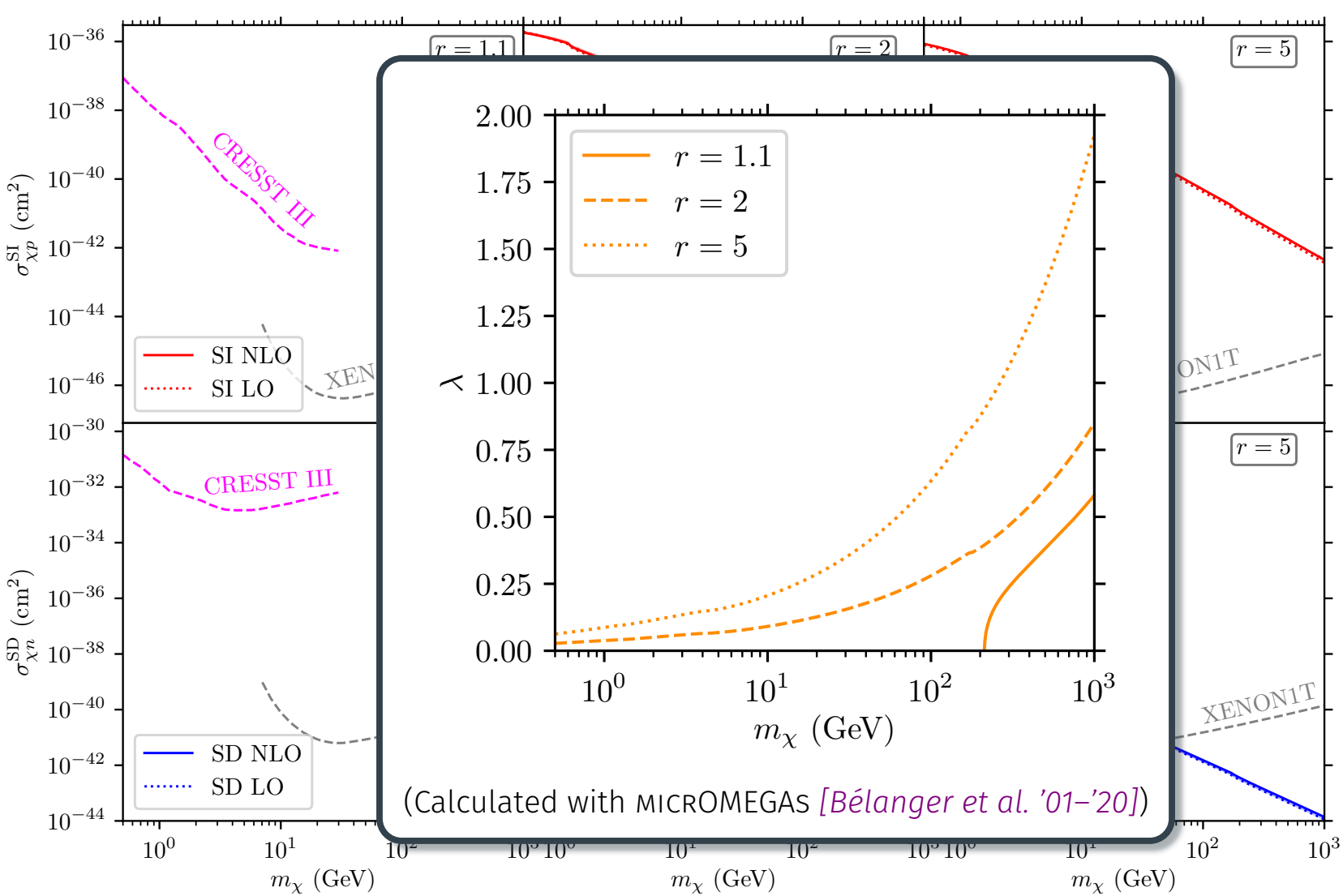
$$r = \frac{M_{med}}{m_\chi}$$

← $\sigma^{SI}_{\chi p}$

← $\sigma^{SD}_{\chi n}$

Coupling $\lambda \equiv \lambda_{Q_L}$ adapted point-by-point to match observed DM relic abundance

t-channel model: NLO-QCD effects on cross sections



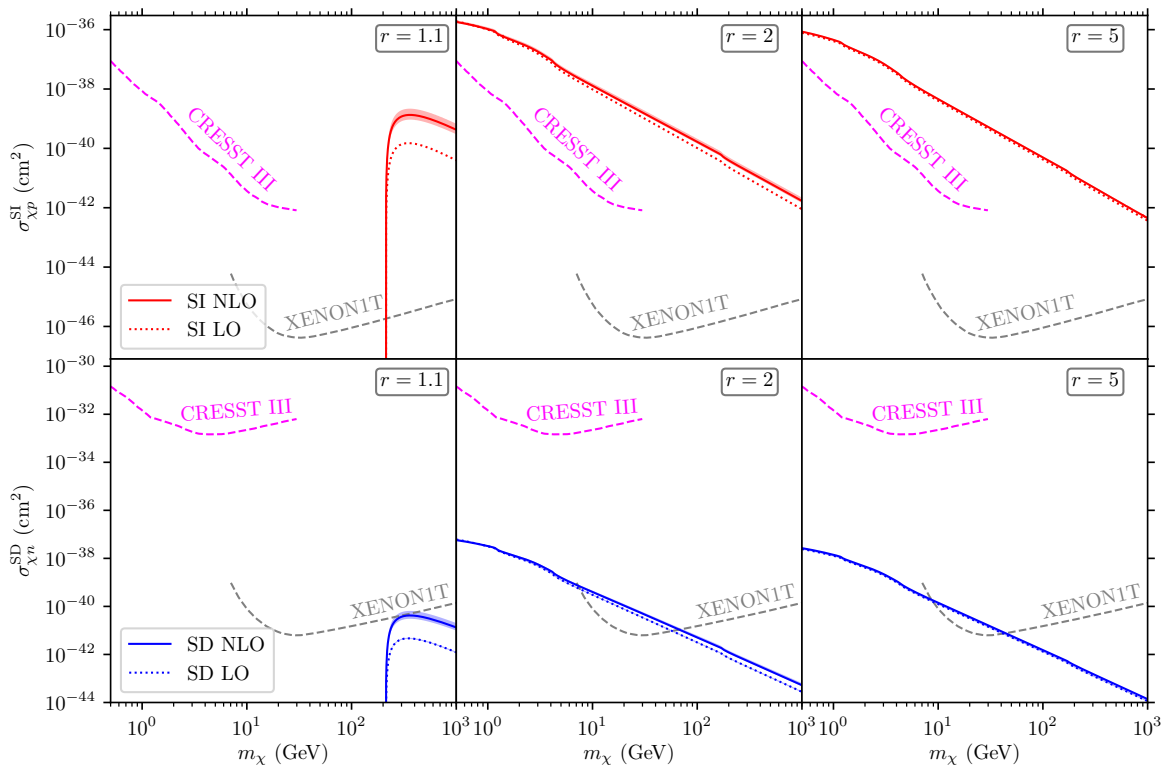
$$r = \frac{M_{\mathrm{med}}}{m_\chi}$$

← $\sigma^{\mathrm{SI}}_{\chi p}$

← $\sigma^{\mathrm{SD}}_{\chi n}$

Coupling $\lambda \equiv \lambda_{Q_L}$ adapted point-by-point to match observed DM relic abundance

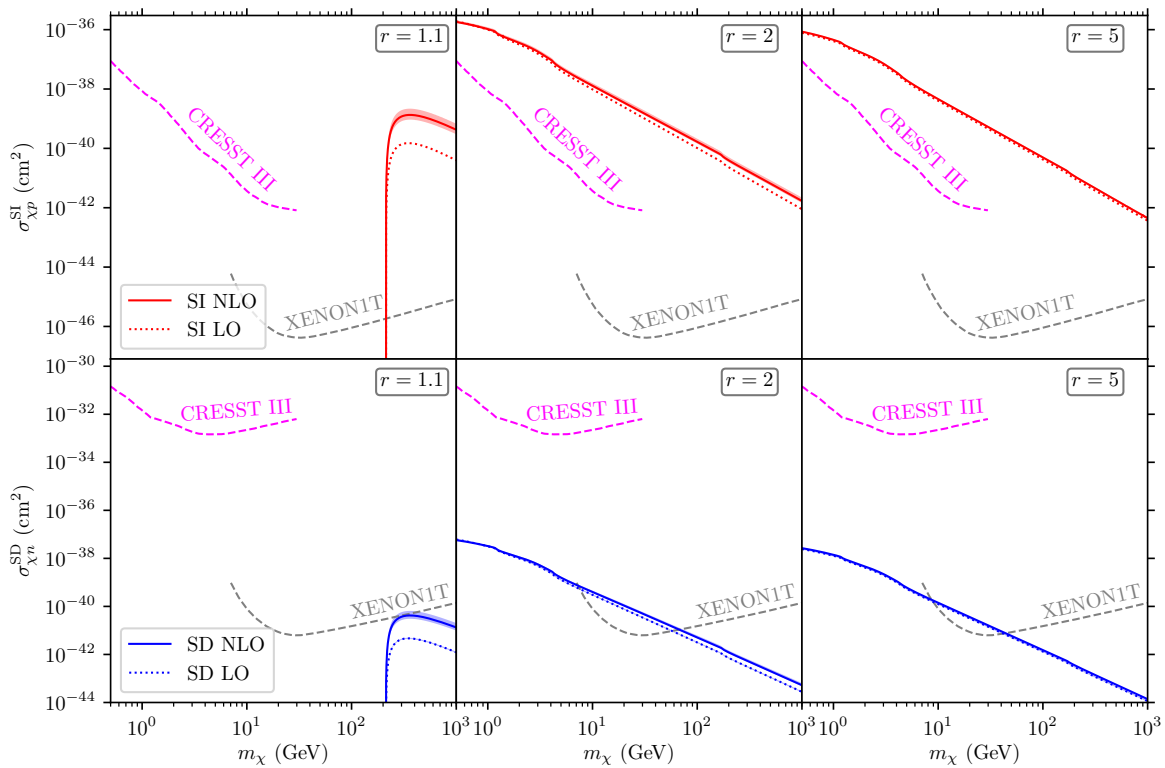
t-channel model: NLO-QCD effects on cross sections



$$r = \frac{M_{\mathrm{med}}}{m_\chi}$$

- CRESST III limits from *[Abdelhameed et al. '19]*, XENON1T limits from *[Aprile et al. '18, '19]*
- NLO-QCD effects more relevant for small $r \approx 1$

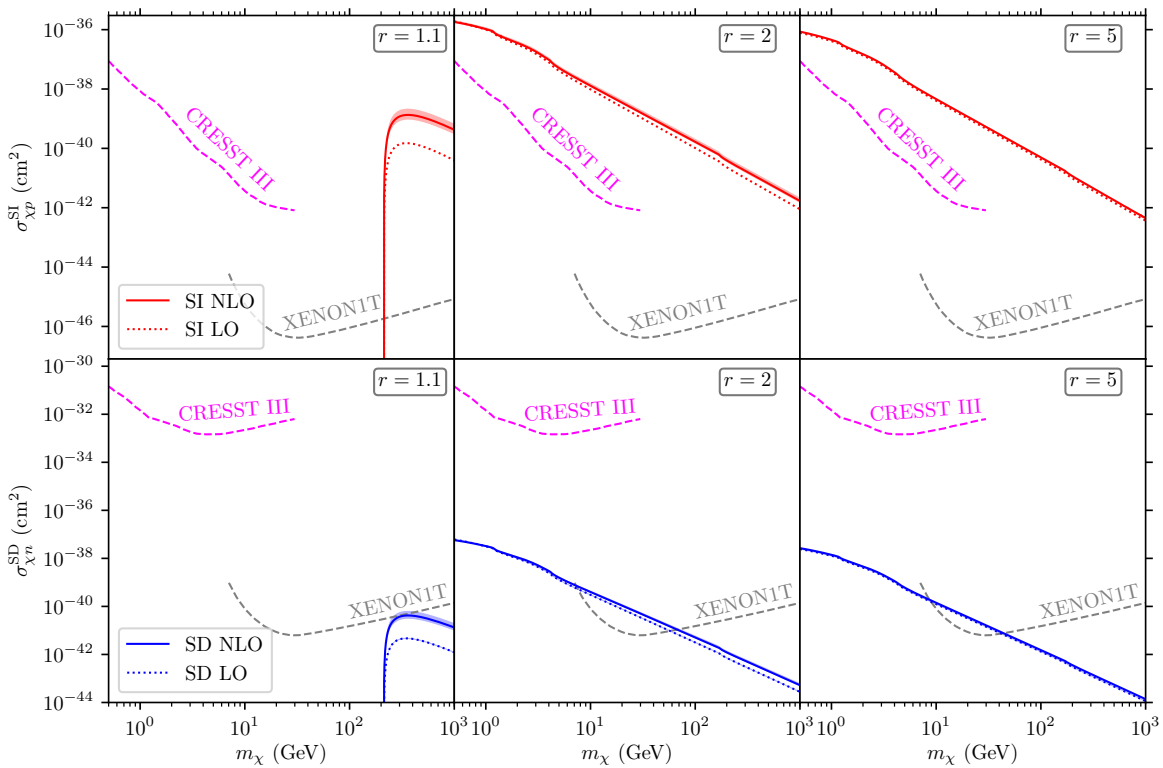
t-channel model: NLO-QCD effects on cross sections



$$r = \frac{M_{\mathrm{med}}}{m_\chi}$$

- CRESST III limits from *[Abdelhameed et al. '19]*, XENON1T limits from *[Aprile et al. '18, '19]*
- NLO-QCD effects more relevant for small $r \approx 1$
- Size of NLO-QCD effects similar for SI and SD

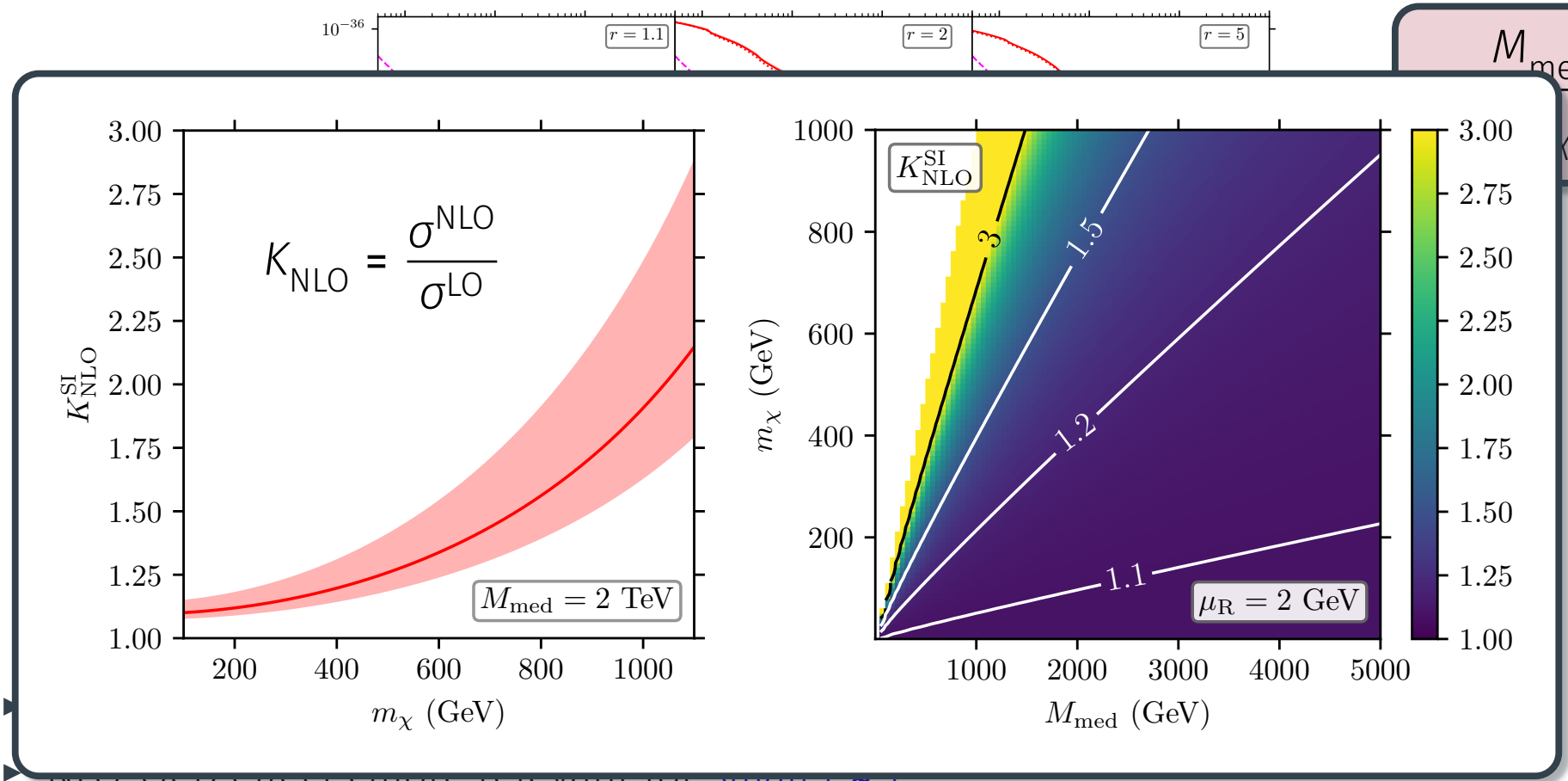
t-channel model: NLO-QCD effects on cross sections



$$r = \frac{M_{\text{med}}}{m_\chi}$$

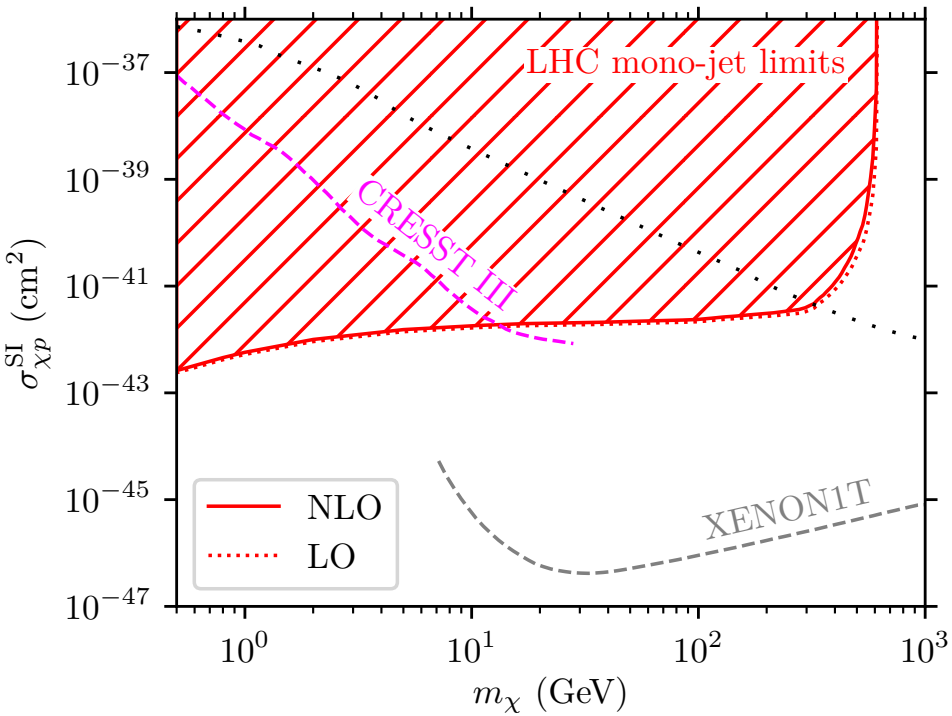
- CRESST III limits from *[Abdelhameed et al. '19]*, XENON1T limits from *[Aprile et al. '18, '19]*
- NLO-QCD effects more relevant for small $r \approx 1$
- Size of NLO-QCD effects similar for SI and SD
- Theoretical uncertainties from varying renormalization scale $\mu_R \in \{1, 2, 4\}$ GeV
- μ_R dependence smaller than NLO-QCD effects

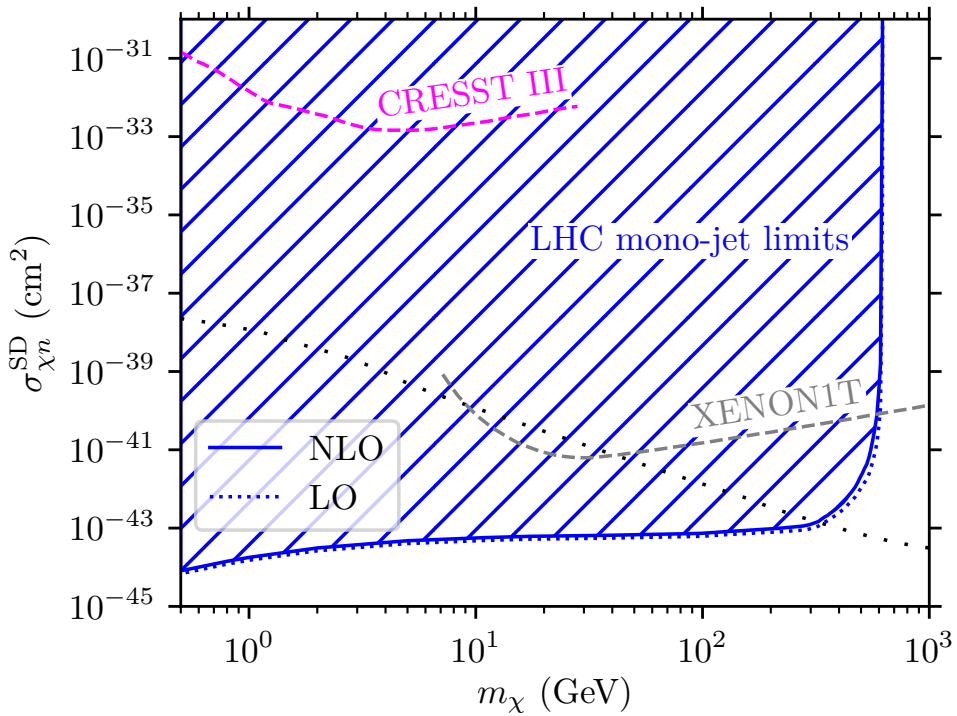
t-channel model: NLO-QCD effects on cross sections



- NLO-QCD effects more relevant for small $r \sim 1$
- Size of NLO-QCD effects similar for SI and SD
- Theoretical uncertainties from varying renormalization scale $\mu_R \in \{1, 2, 4\}$ GeV
- μ_R dependence smaller than NLO-QCD effects

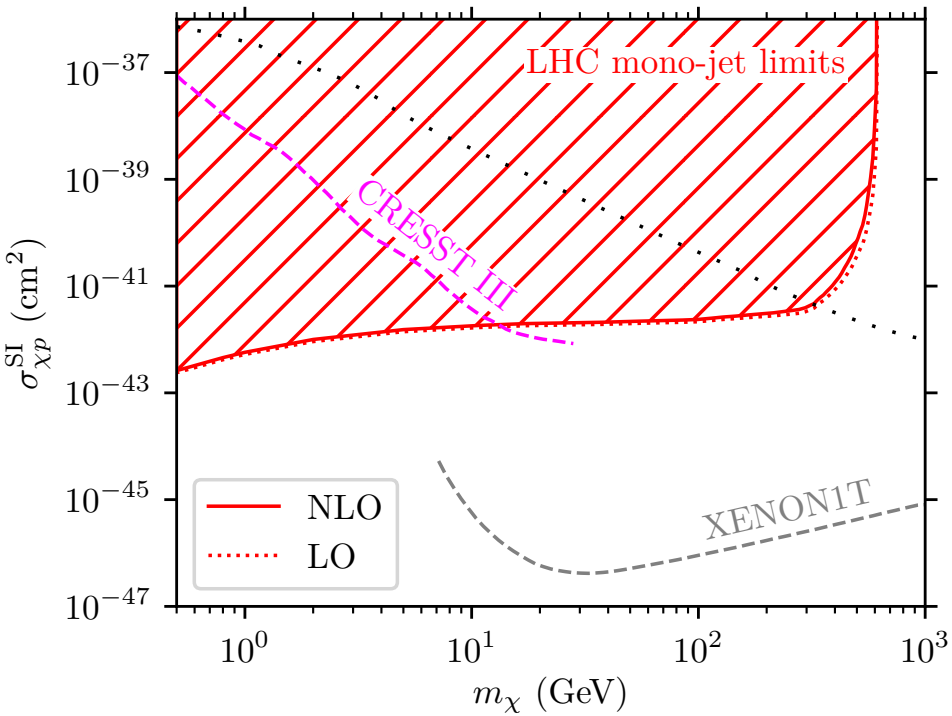
t-channel model: NLO-QCD effects on LHC limits

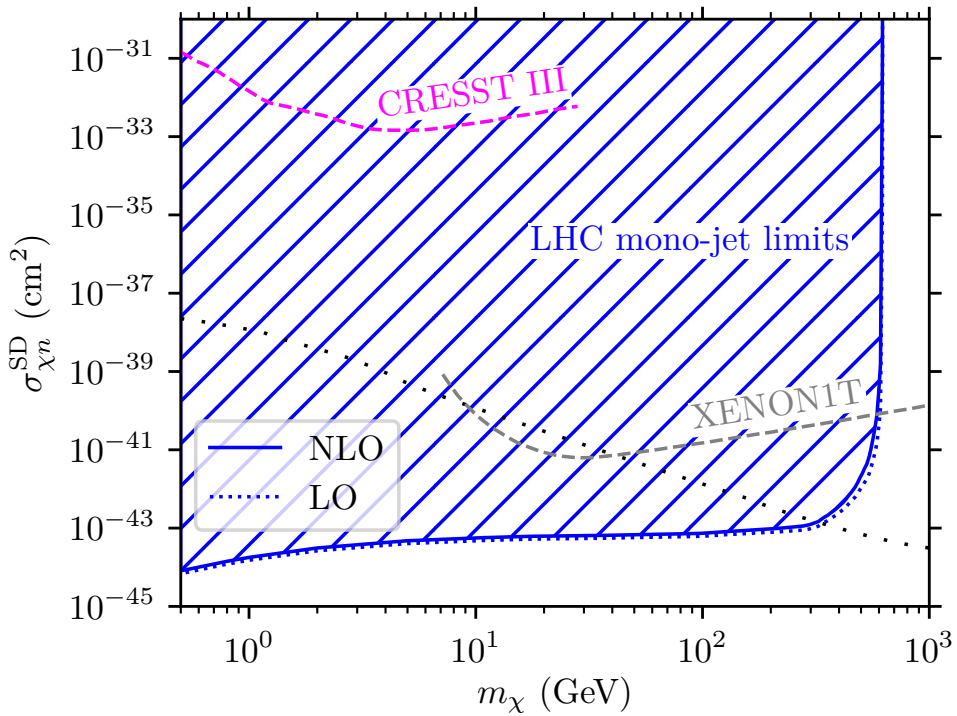




- Mono-jet limits from ATLAS *[Aaboud et al. '18]* for $\lambda_{Q_L} = 1$, $\lambda_{u_R} = \lambda_{d_R} = 0$
- LHC limits affected by NLO-QCD corrections and strongly model dependent!

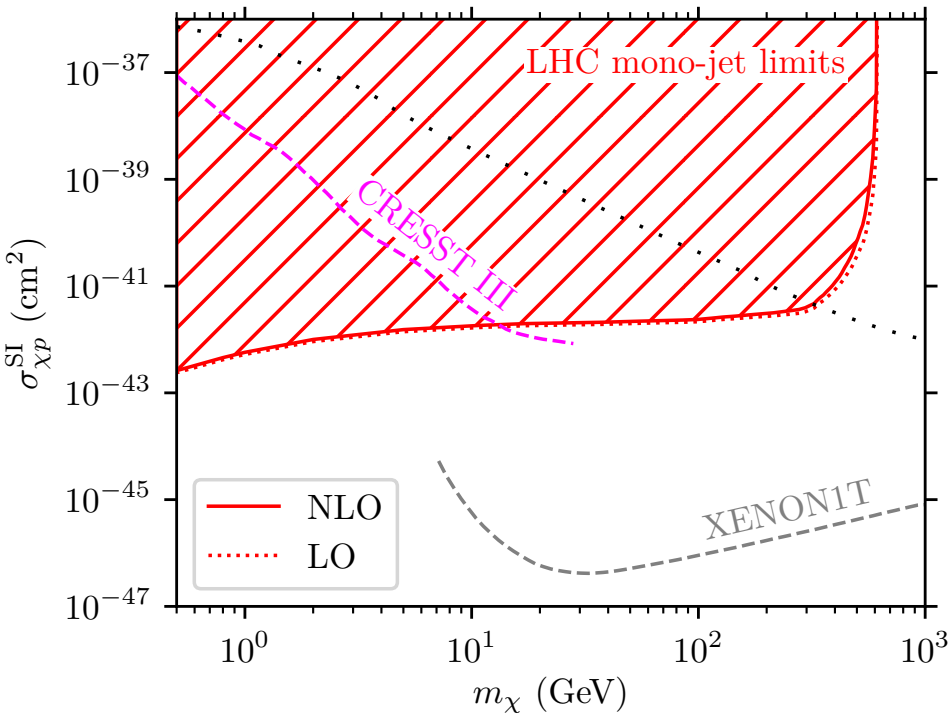
t-channel model: NLO-QCD effects on LHC limits

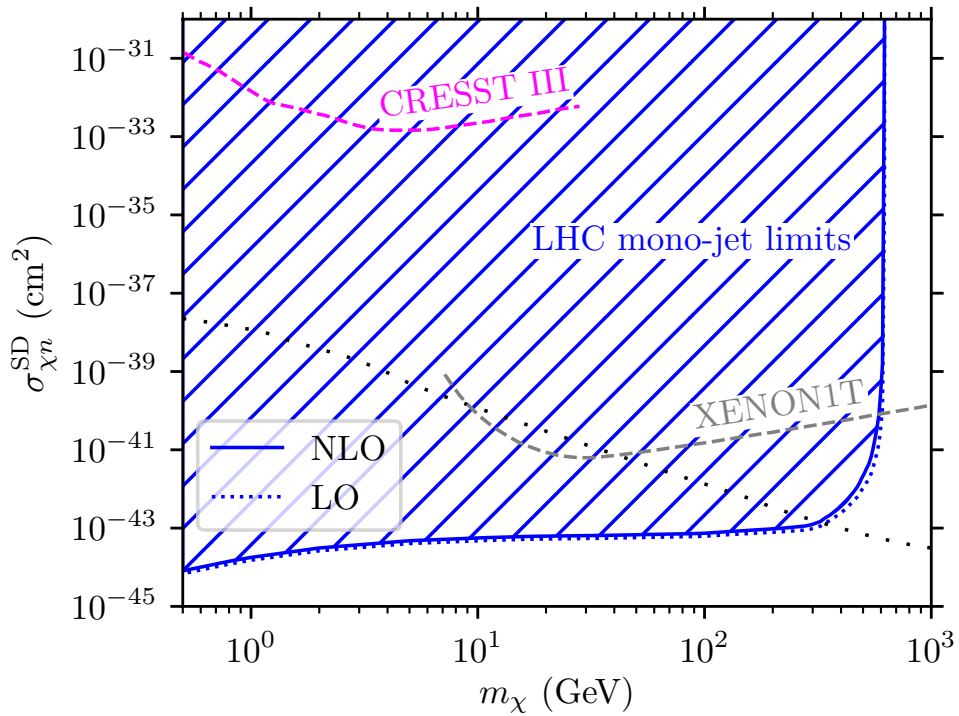




- Mono-jet limits from ATLAS *[Aaboud et al. '18]* for $\lambda_{Q_L} = 1$, $\lambda_{u_R} = \lambda_{d_R} = 0$
- LHC limits affected by NLO-QCD corrections and strongly model dependent!
- Black dotted line shows points that match the observed DM relic abundance

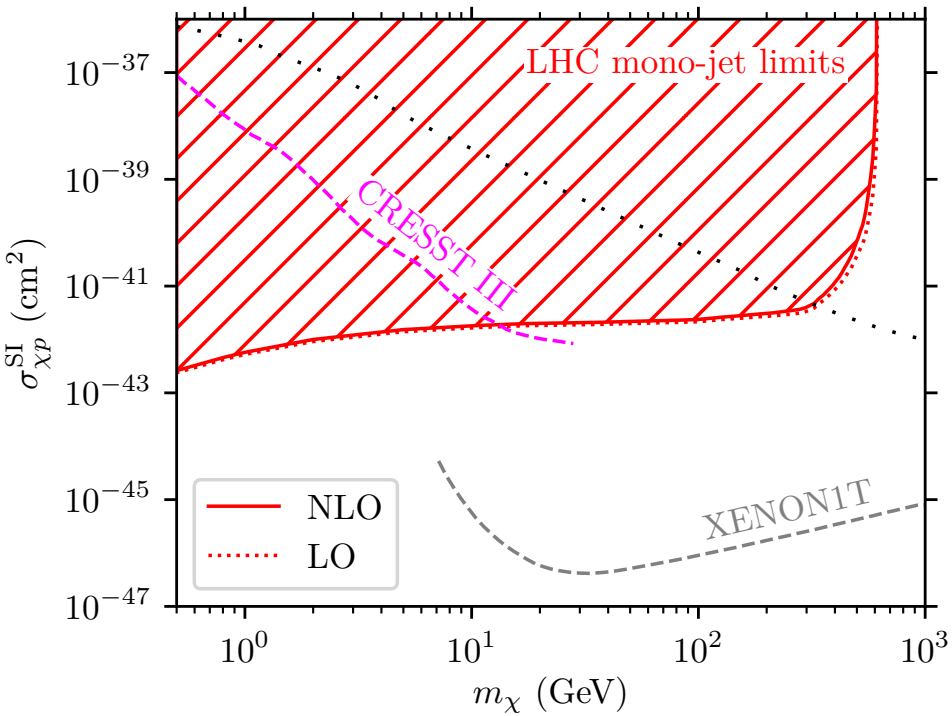
t-channel model: NLO-QCD effects on LHC limits

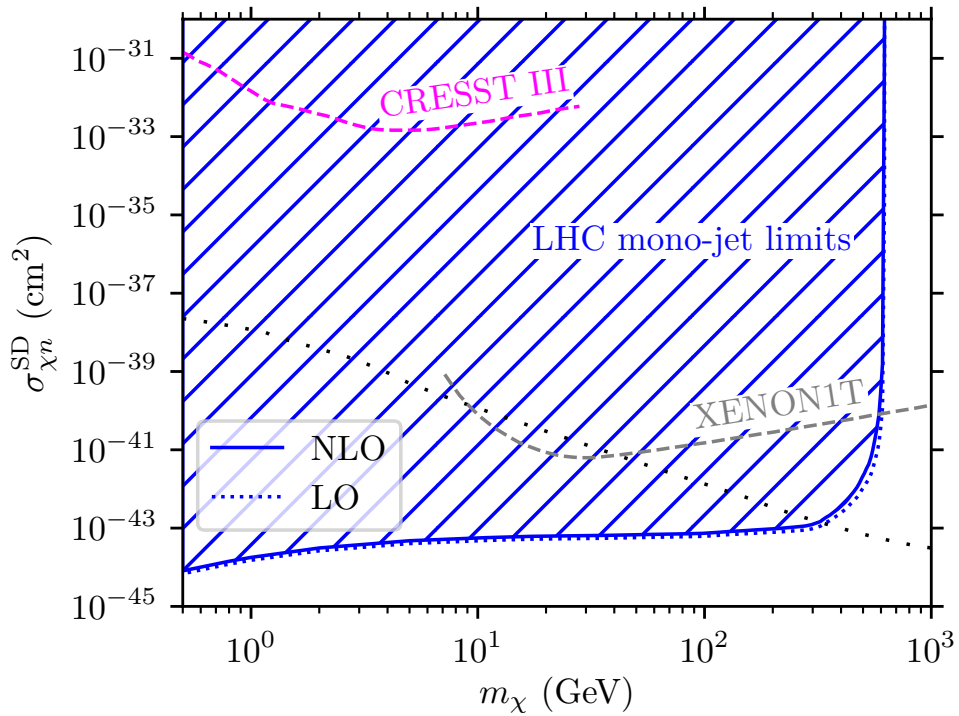




- Mono-jet limits from ATLAS *[Aaboud et al. '18]* for $\lambda_{Q_L} = 1$, $\lambda_{u_R} = \lambda_{d_R} = 0$
- LHC limits affected by NLO-QCD corrections and strongly model dependent!
- Black dotted line shows points that match the observed DM relic abundance
- Sharp cut-off for highest probed m_χ due to $\mathcal{M} \sim 1/(m_\chi^2 - M_{\mathrm{med}}^2)$
- NLO-QCD effects enhanced at this threshold due to additional logarithms

t-channel model: NLO-QCD effects on LHC limits

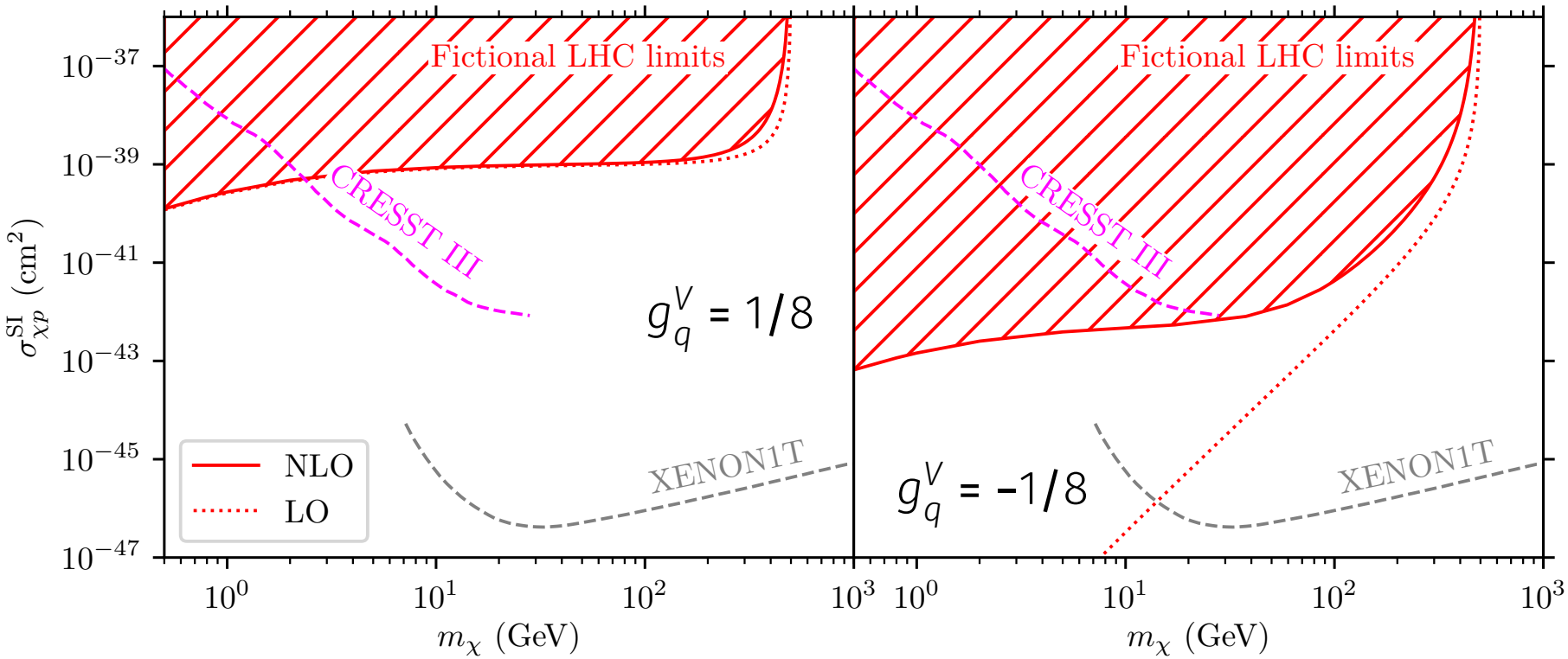




- Mono-jet limits from ATLAS *[Aaboud et al. '18]* for $\lambda_{Q_L} = 1$, $\lambda_{u_R} = \lambda_{d_R} = 0$
- LHC limits affected by NLO-QCD corrections and strongly model dependent!
- Black dotted line shows points that match the observed DM relic abundance
- Sharp cut-off for highest probed m_χ due to $\mathcal{M} \sim 1/(m_\chi^2 - M_{\mathrm{med}}^2)$
- NLO-QCD effects enhanced at this threshold due to additional logarithms
- Generally, however, NLO-QCD corrections affect the LHC limits only marginally

Effects for a combined s + t-channel model

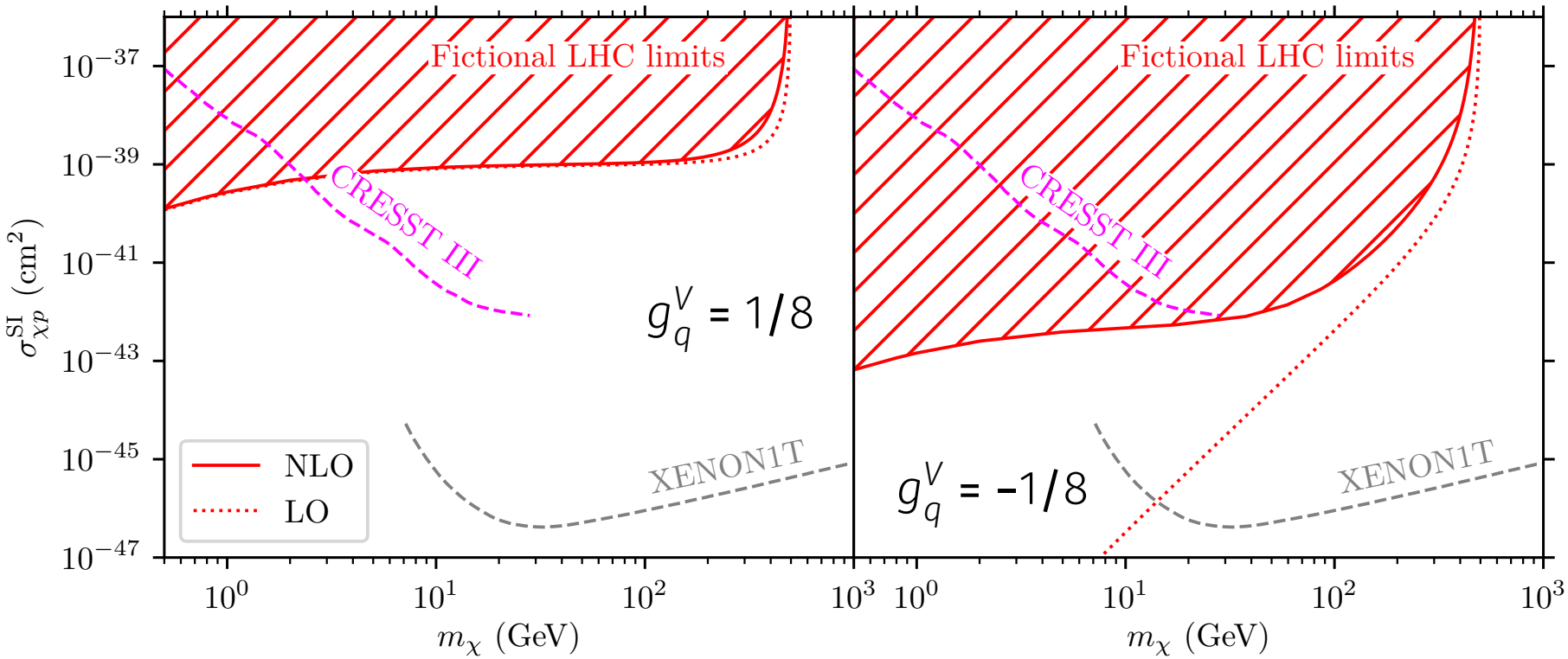
Adding the interaction Lagrangians of both s- and t-channel models:



- Model parameters: $\lambda_{Q_L} = 1$, $\lambda_{u_R} = \lambda_{d_R} = 0$, $M_V = M_{\tilde{Q}}$, $g_\chi^V = 1$, $g_q^V = \pm 1/8$
- "Fictional" limits assuming all mediator masses up to 500 GeV being excluded

Effects for a combined s + t-channel model

Adding the interaction Lagrangians of both s- and t-channel models:



- Model parameters: $\lambda_{Q_L} = 1$, $\lambda_{u_R} = \lambda_{d_R} = 0$, $M_V = M_{\tilde{Q}}$, $g_\chi^V = 1$, $g_q^V = \pm 1/8$
- "Fictional" limits assuming all mediator masses up to 500 GeV being excluded
- $\sigma^{\mathrm{pert}} \propto \left|c^{s,\mathrm{tree}} + c^{t,\mathrm{tree}}\right|^2 + 2\,\mathrm{Re}\left[\left(c^{s,\mathrm{tree}} + c^{t,\mathrm{tree}}\right)\left(c^{s+t,\text{1-loop}}\right)\right] + \left|c^{s+t,\text{1-loop}}\right|^2 + \ldots$
- If LO is suppressed, $\left|c^{s,\mathrm{tree}} + c^{t,\mathrm{tree}}\right| \approx 0$, the $\mathcal{O}(\alpha_s, \alpha_s^2)$ terms become dominant

Summary

Dark Matter: a puzzle with many missing pieces

NLO-QCD corrections to direct detection of DM

- Two simplified models: the t-channel and s + t-channel models
- NLO-QCD results in the elastic and non-relativistic scattering limit matched to EFT to obtain one-loop Wilson coefficients
- Dependence on μ_R, appearing first at NLO, generally smaller than the size of the NLO-QCD effects

Summary

Dark Matter: a puzzle with many missing pieces

NLO-QCD corrections to direct detection of DM

- Two simplified models: the t-channel and s + t-channel models
- NLO-QCD results in the elastic and non-relativistic scattering limit matched to EFT to obtain one-loop Wilson coefficients
- Dependence on μ_R, appearing first at NLO, generally smaller than the size of the NLO-QCD effects

Impact on exclusion limits

- LHC and direct searches are complementary, cover different regions of the parameter space
- Effect of the corrections on the LHC limits generally mild, can however be large for specific choices of the model parameters

Summary

Dark Matter: a puzzle with many missing pieces

NLO-QCD corrections to direct detection of DM

- Two simplified models: the t-channel and s + t-channel models
- NLO-QCD results in the elastic and non-relativistic scattering limit matched to EFT to obtain one-loop Wilson coefficients
- Dependence on μ_R, appearing first at NLO, generally smaller than the size of the NLO-QCD effects

Impact on exclusion limits

- LHC and direct searches are complementary, cover different regions of the parameter space
- Effect of the corrections on the LHC limits generally mild, can however be large for specific choices of the model parameters

THANK YOU FOR YOUR ATTENTION! ☺