Decoding the nature of Dark Matter
at current and future experiments

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ACAT2019

19th International Workshop on Advanced Computing and Analysis Techniques in Physics Research

10-15 March 2019

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Southampton University & Rutherford Appleton Laboratory

Moscow State University 1993 graduation

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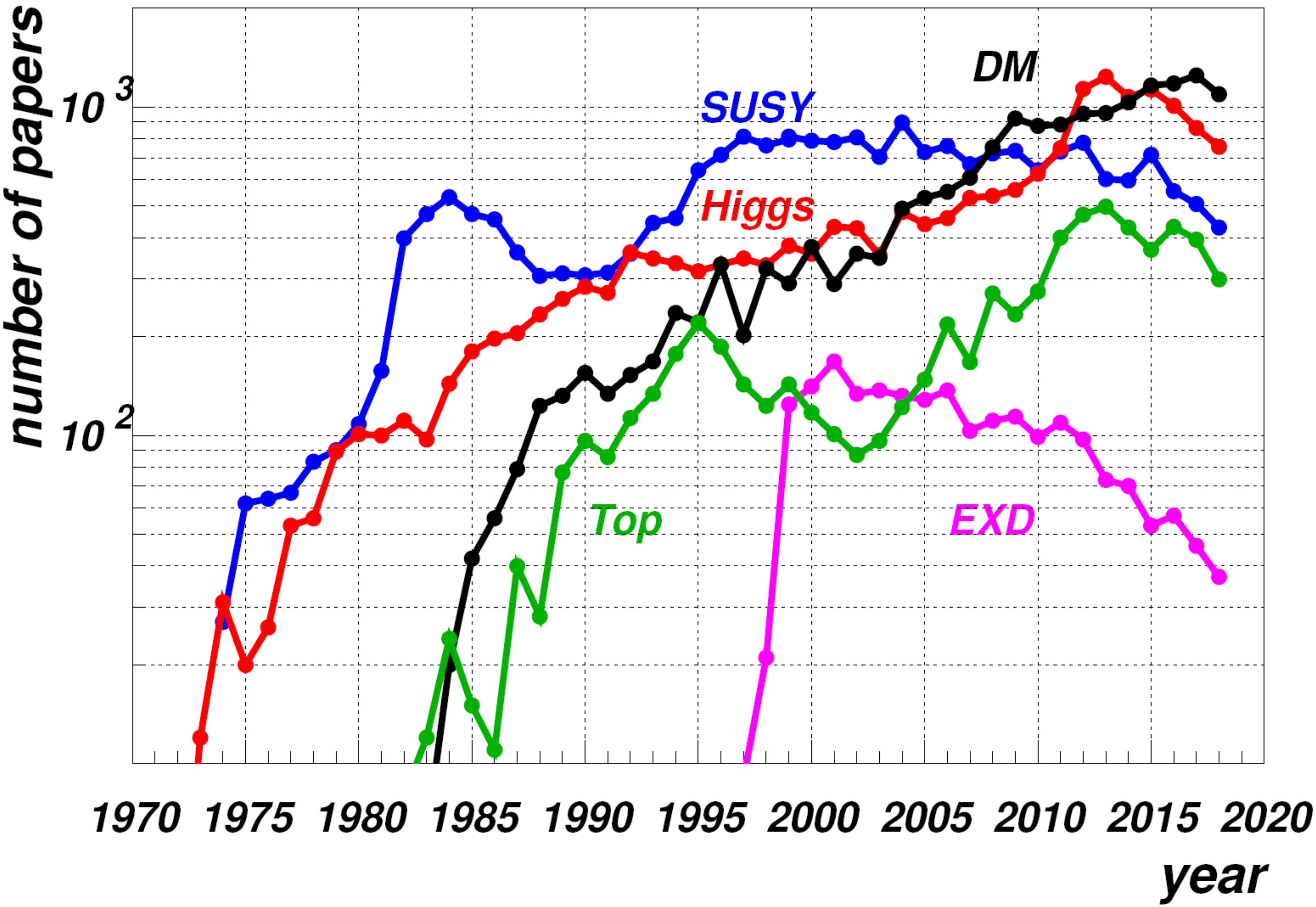
Dark Matter is in the main focus after Higgs discovery
(statistics of publications based on inSPIRE database)



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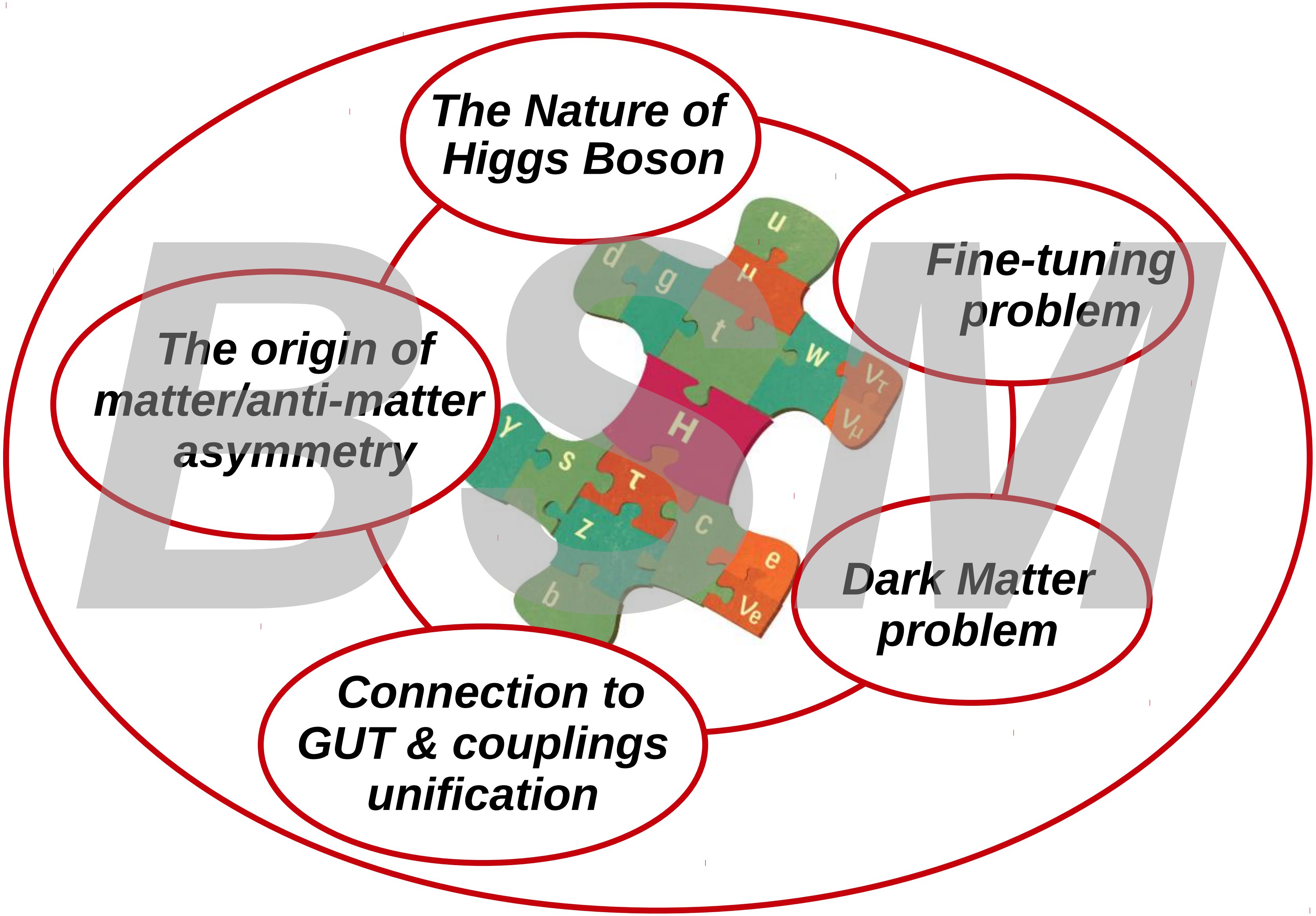
it became obvious that the SM itself is the piece of some (more) complete and consistent BSM theory



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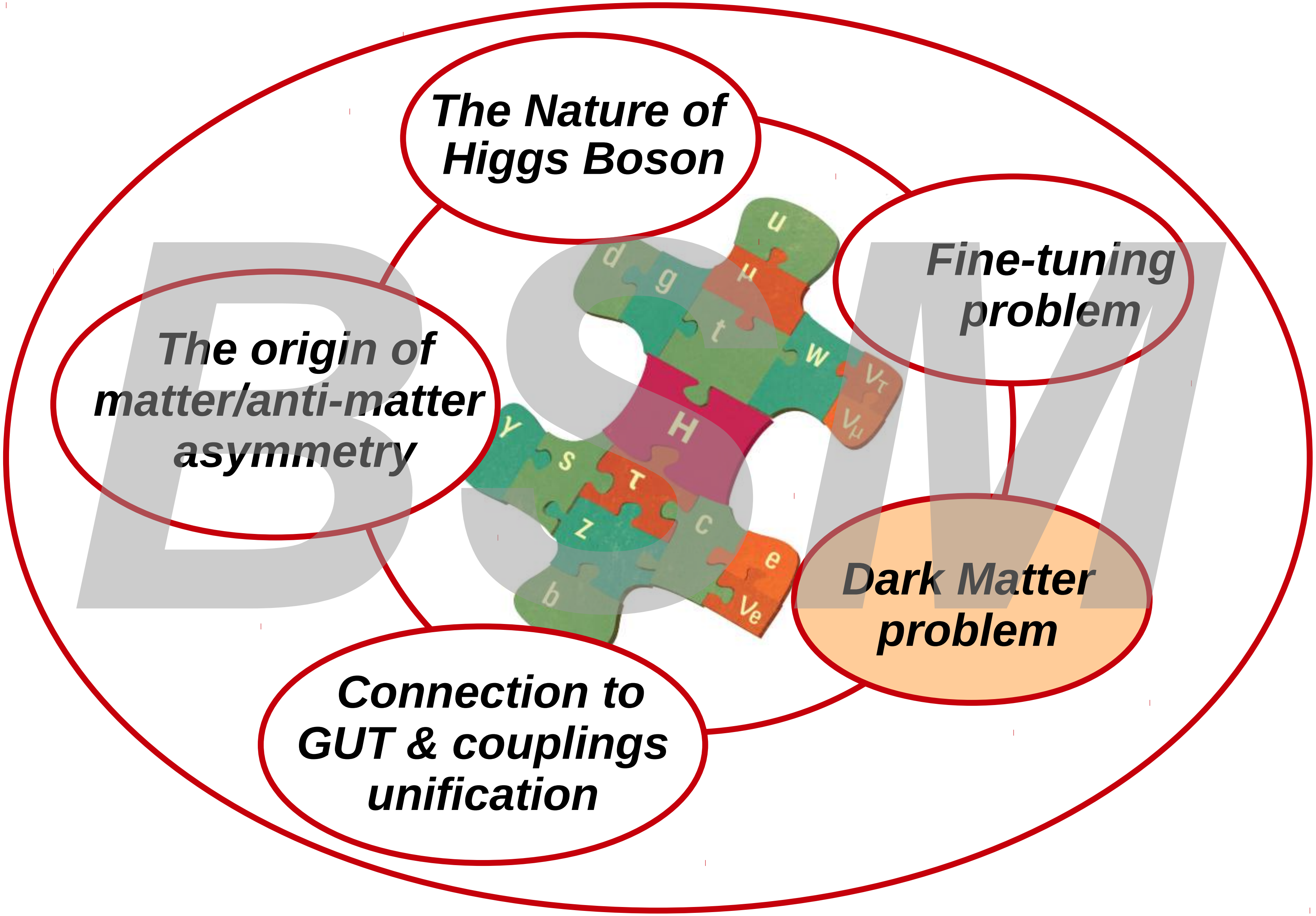
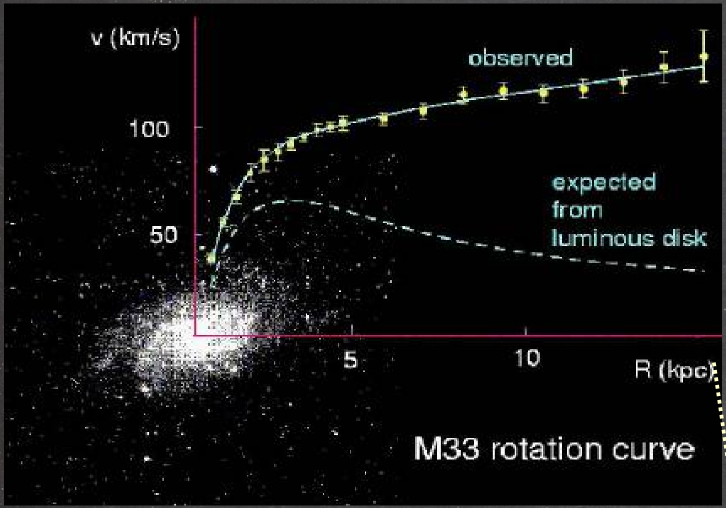
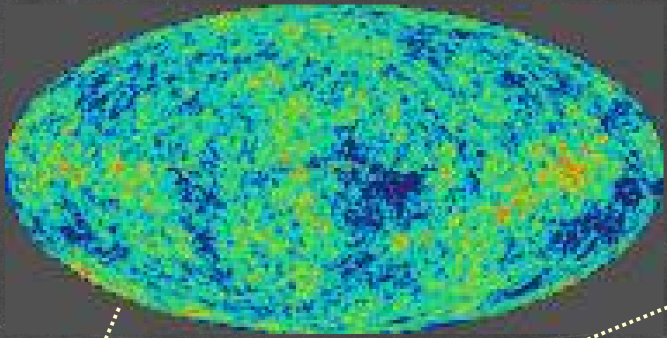


And DM is strong and very appealing evidence for BSM!

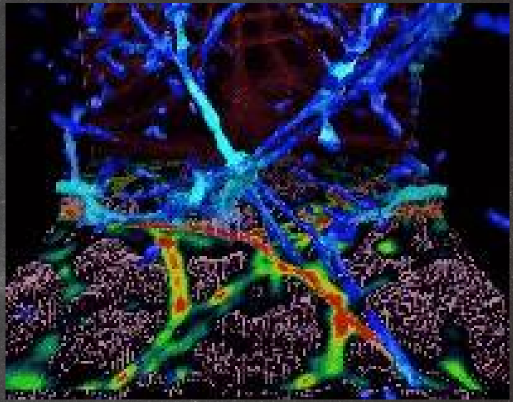
Galactic rotation curves

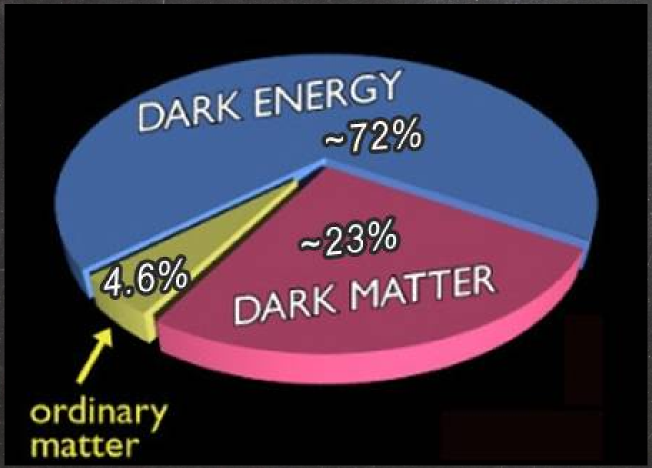


CMB: WMAP and PLANCK



Large Scale Structures





Gravitational lensing

Bullet cluster

DM is very appealing even though we know almost nothing about it!

Spin ?

Mass ?

Stable

Yes ? *No* ?

symmetry behind stability ?

Couplings

gravity	V
Weak	?
Higgs	?
Quarks/gluons	?
Leptons	?
New mediators	?

Thermal relic

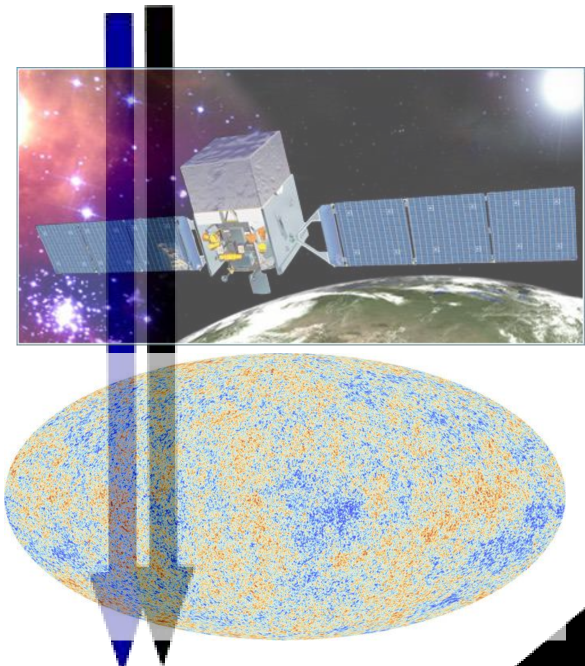
Yes ? *No* ?

How do we probe Dark Matter?

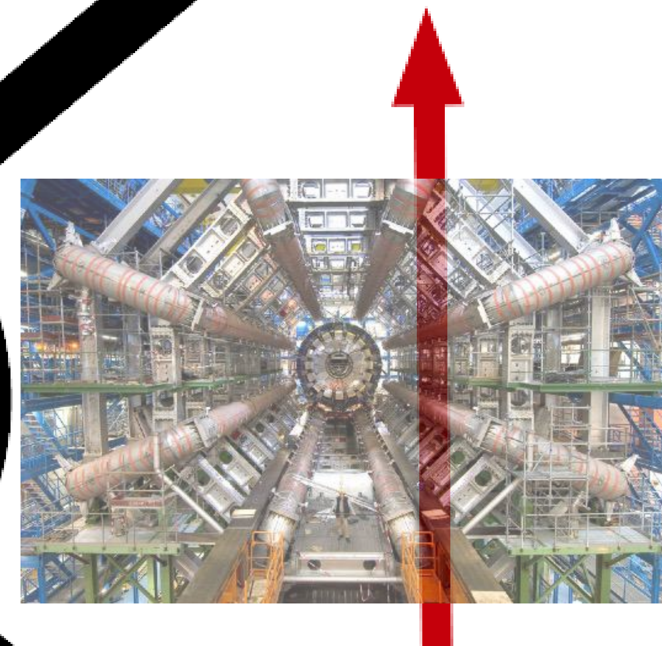
DM DM

Correct Relic density: efficient (co) annihilation at the time of early Universe

Efficient annihilation now: Indirect Detection



Dark Matter (DM) Signatures

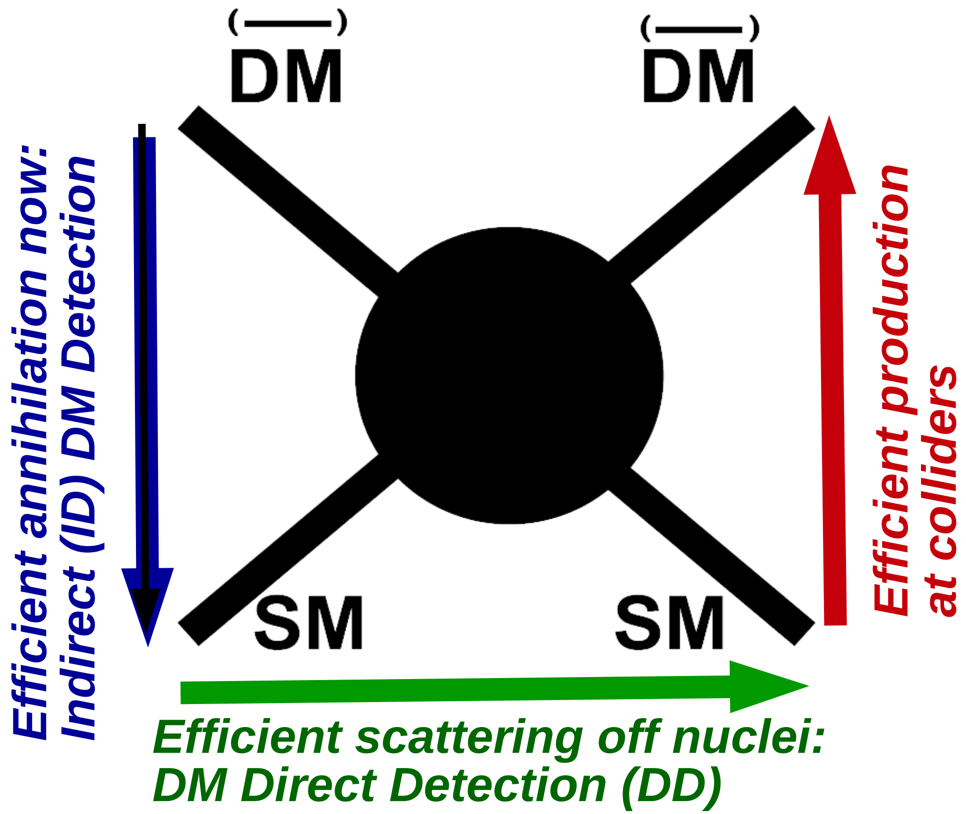


Efficient production at colliders

SM SM

Efficient scattering off nuclei: Direct Detection

Complementarity of DM searches

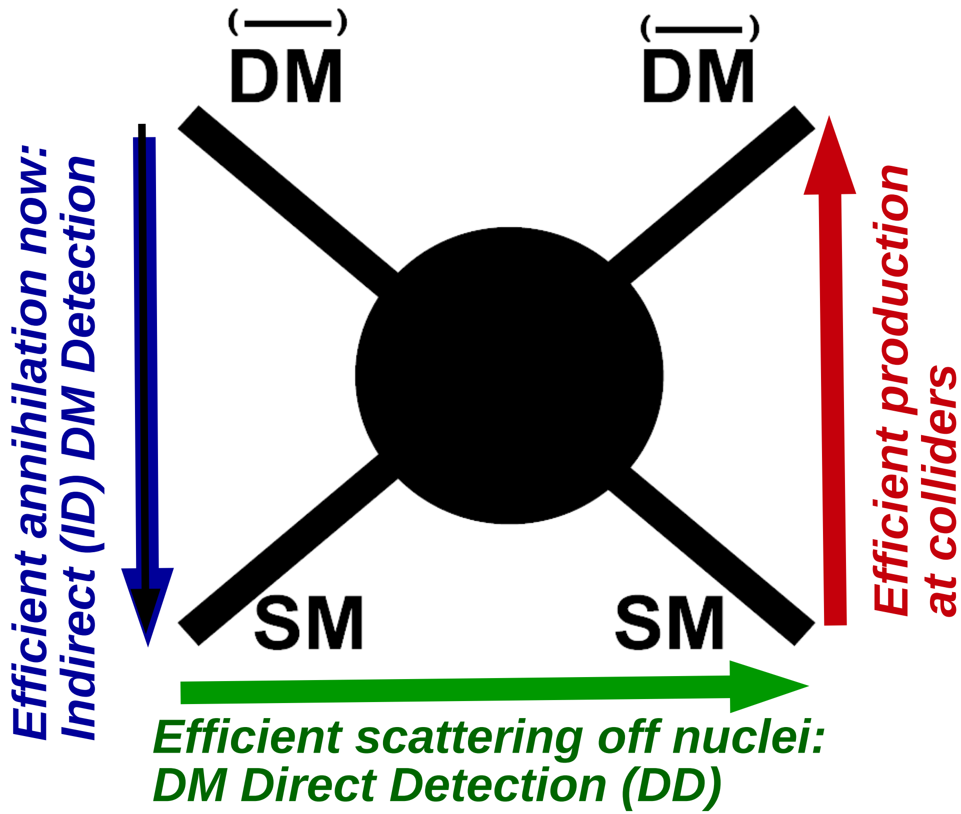


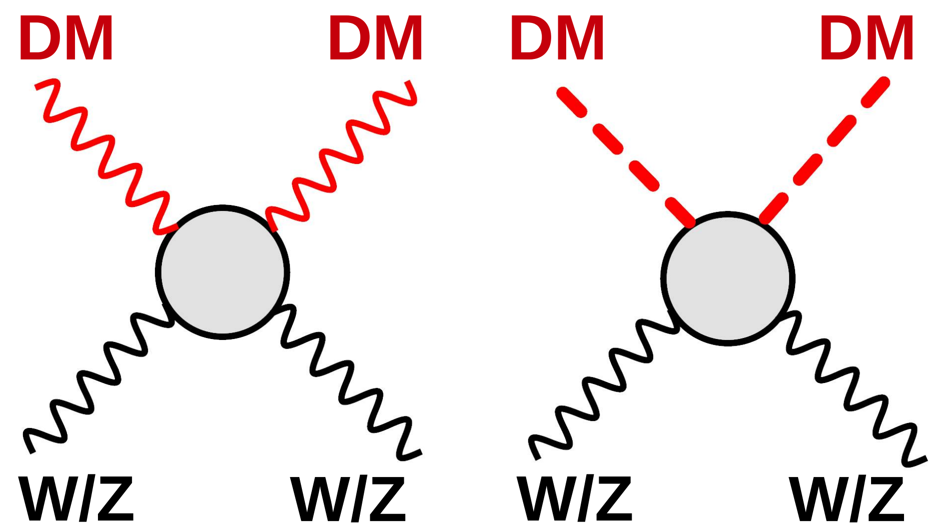
Important: **there is no 100%correlation between signatures above. E.g. the high rate of annihilation does not always guarantee high rate for DD!**

Actually there is a great complementarity in this:

- **In case of NO DM Signal – we can efficiently exclude DM models**
- **In case of DM signal – we have a way to determine the nature of DM**

Complementarity of DM searches





Example of DM interactions with negligible/suppressed DD rates

Important: **there is no 100%correlation between signatures above. E.g. the high rate of annihilation does not always guarantee high rate for DD!**

Actually there is a great complementarity in this:

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- **In case of DM signal – we have a way to determine the nature of DM**

How we can decode the fundamental nature of Dark Matter?

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We need a DM signal first!

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But at the moment we can:

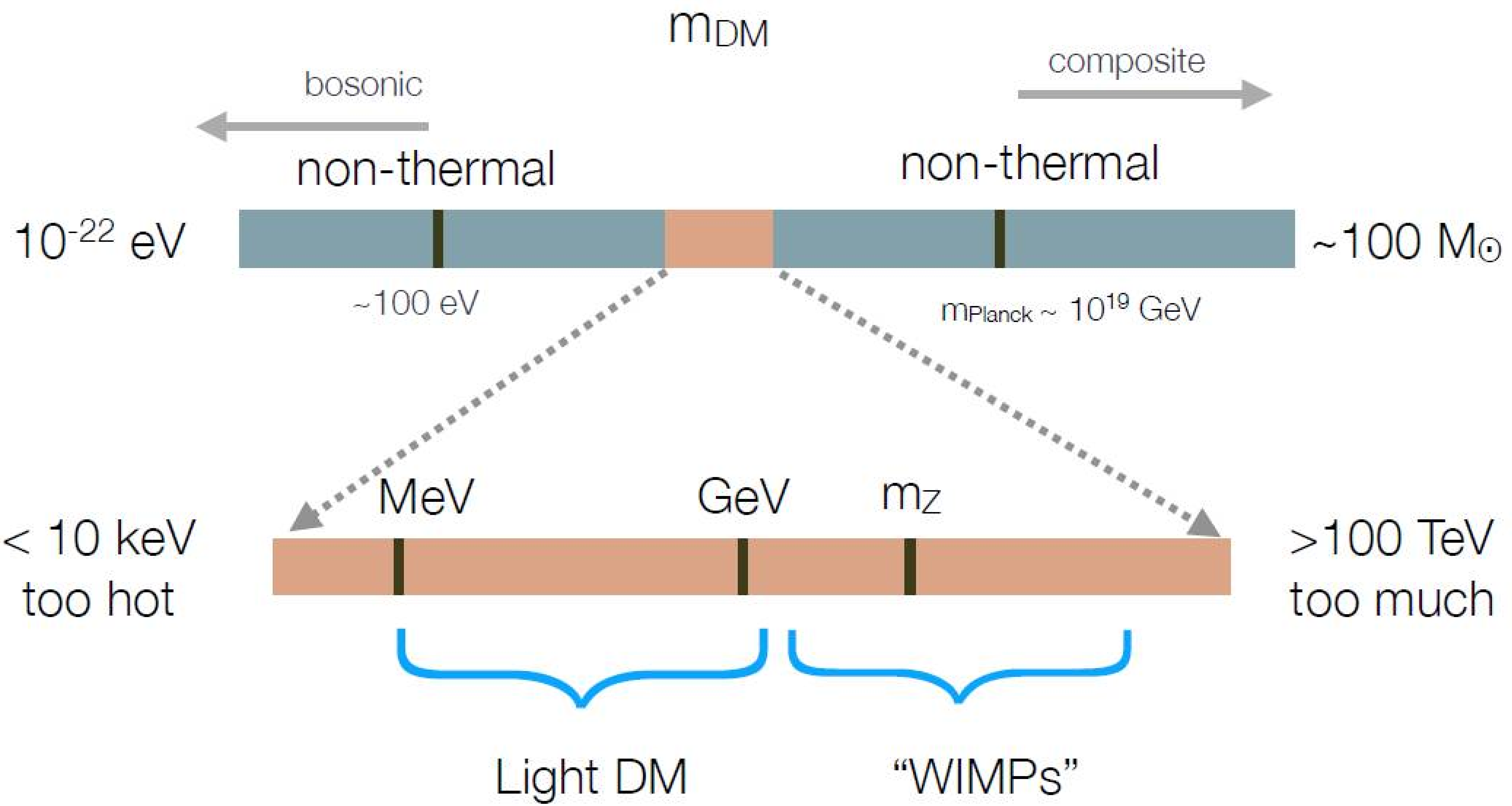
- ➩ understand what kind of DM is already excluded
- ➩ create framework for mapping theory → signatures space (using effective multiple top→ down simulation)
- ➩ using [theory→ signatures] mapping data, perform
- ➩ [signatures→ theory] identification using machine learning

We should prepare for DM discovery and identification!

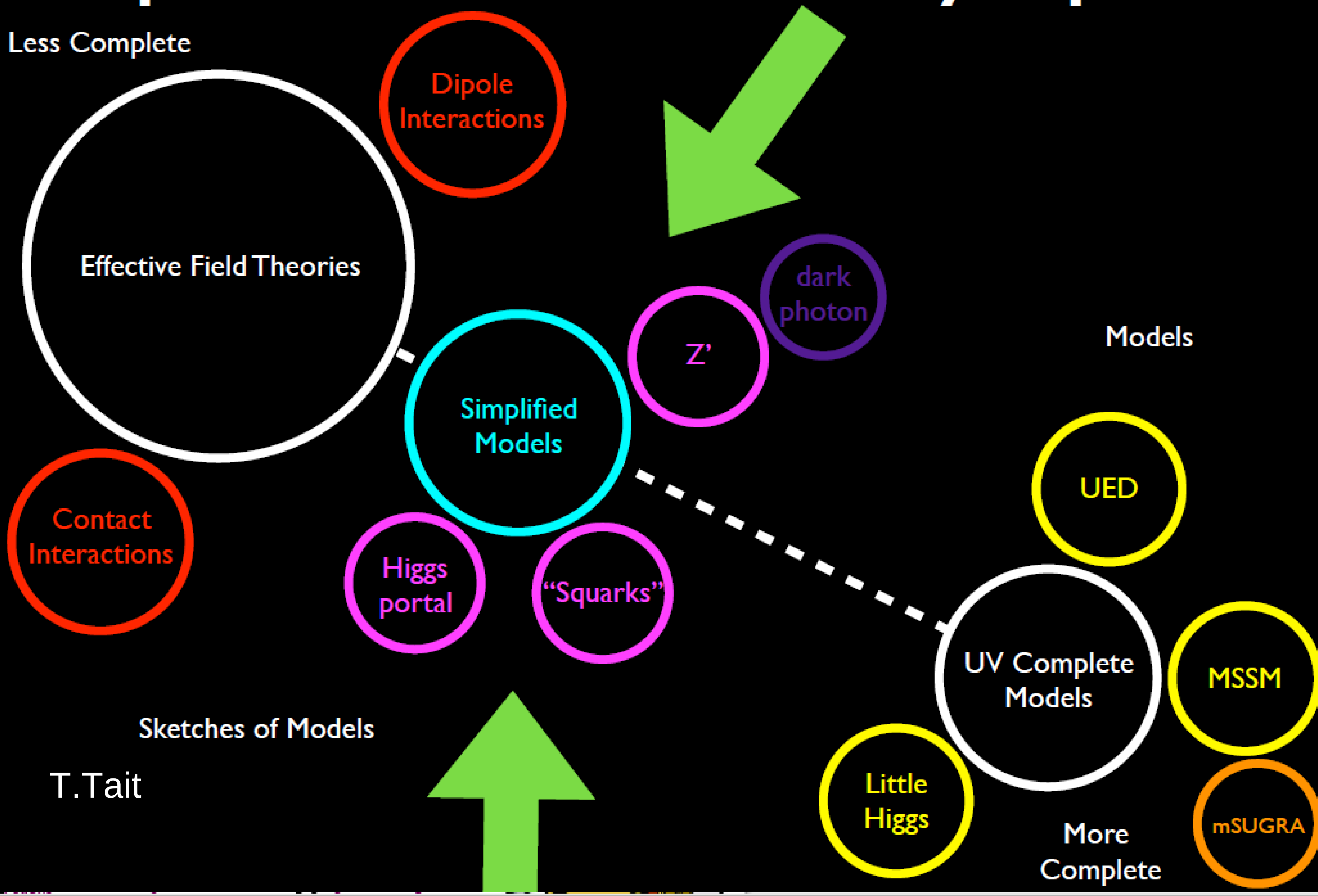
Collaborators & Projects

- I.Ginzburg, D.Locke, A. Freegard, T. Hosken, A.Pukhov,AB   to appear
- S.Novaes, P.Mercadante, C.S. Moon,T.Tomei,
  S. Moretti, M.Tomas, L. Panizzi, AB   arXiv:**1809.00933**
- G.Cacciapaglia, J.McKay, D. Marin, A.Zerwekh, AB   arXiv:**1808.10464**
- E.Bertuzzo, C.Caniu, G. di Cortona, O.Eboli,
  F. Iocco, A.Pukhov, AB   arXiv:**1807.03817**
- T. Flacke, B. Jain, P. Schaefers, AB   arXiv:**1707.07000**
- G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB   arXiv:**1612.00511**
- I. Shapiro, M. Thomas, AB   arXiv:**1611.03651**
- L. Panizzi, A. Pukhov, M.Thomas, AB   arXiv:**1610.07545**
- D. Barducci, A.Bharucha, W. Porod, V. Sanz, AB   arXiv:**1504.02472**

DM Mass range

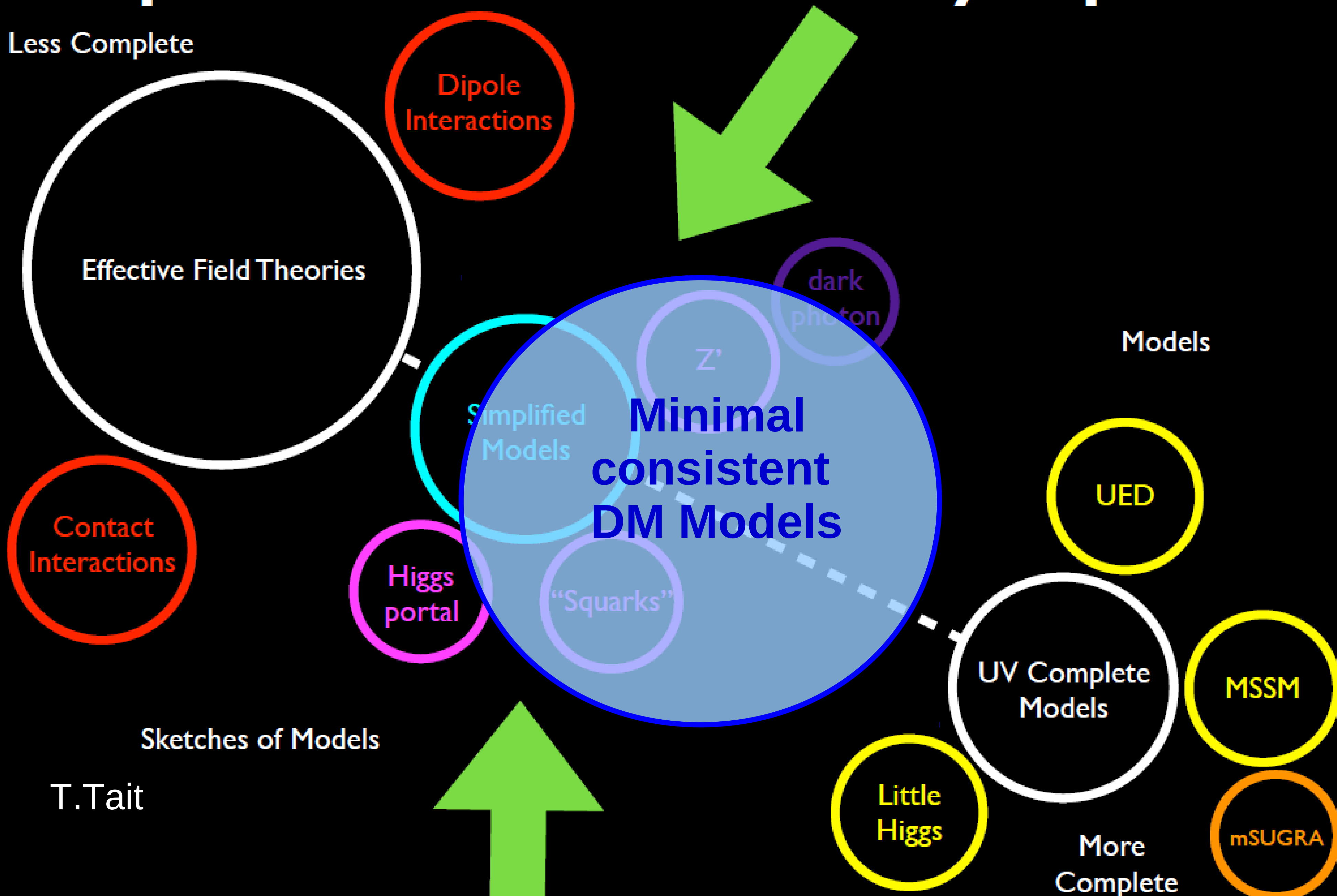


Spectrum of Theory Space

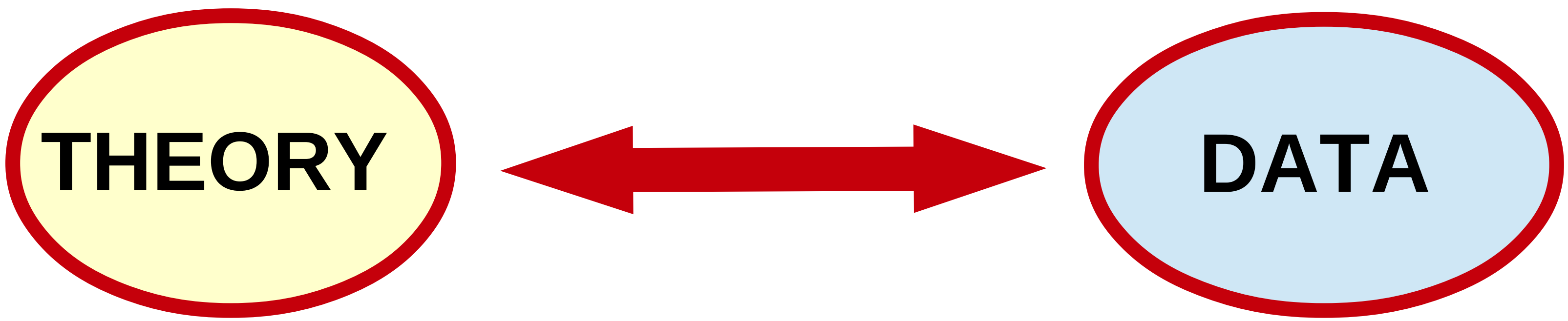


T.Tait

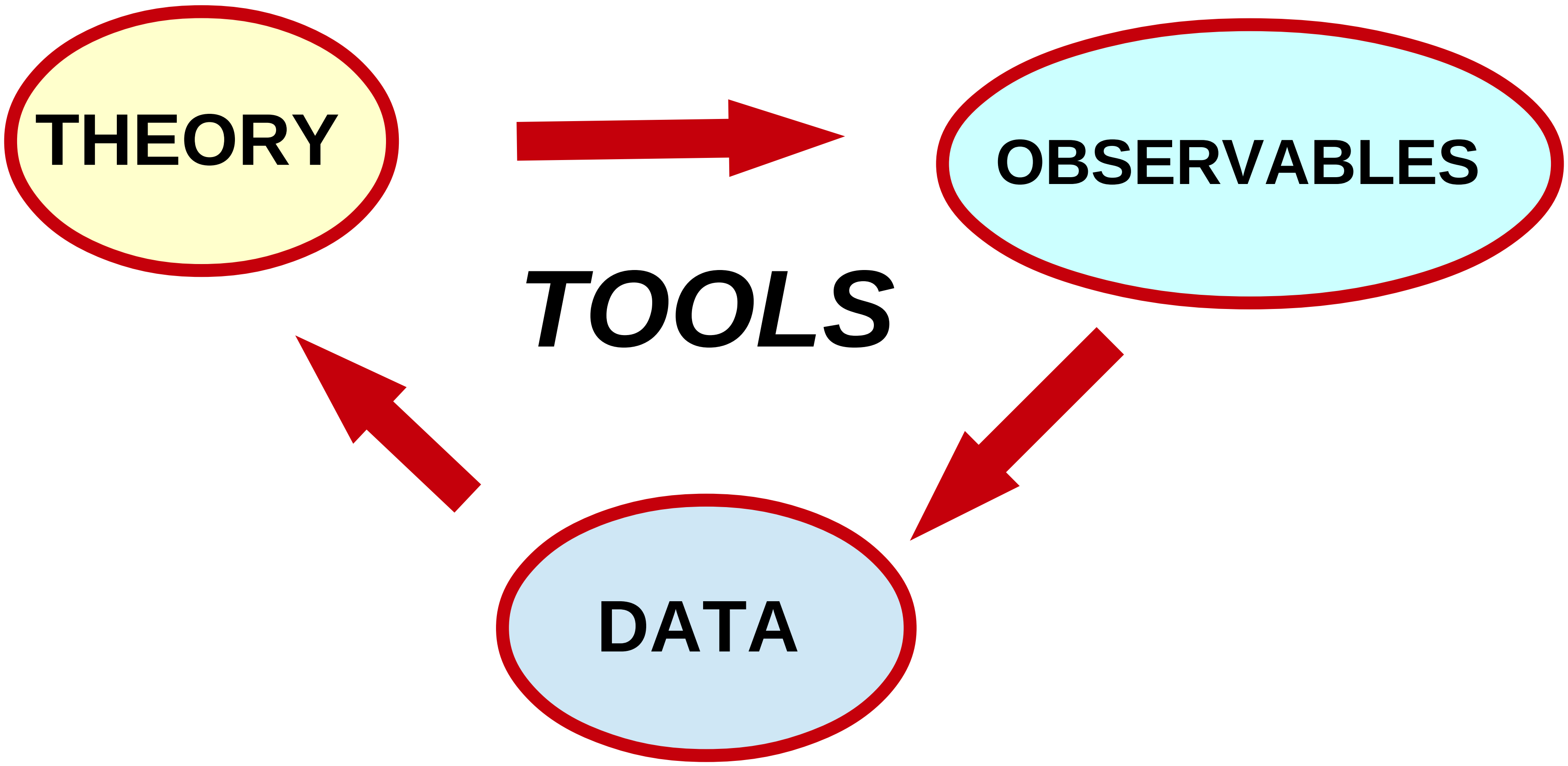
Spectrum of Theory Space



To test DM theory we need to realise theory ↔ data link which is a non-trivial story

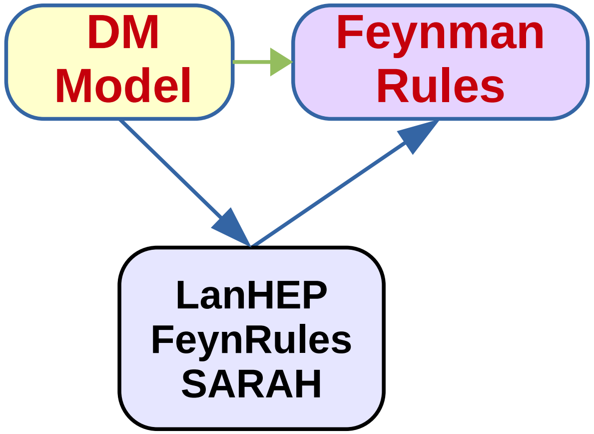


theory ↔ data requires observables to be compared with data



TOOLS

Tools for theory → observables link



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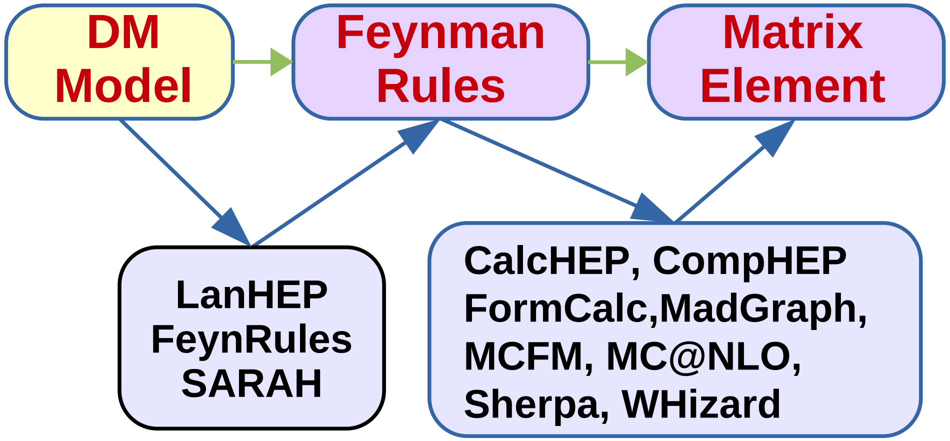

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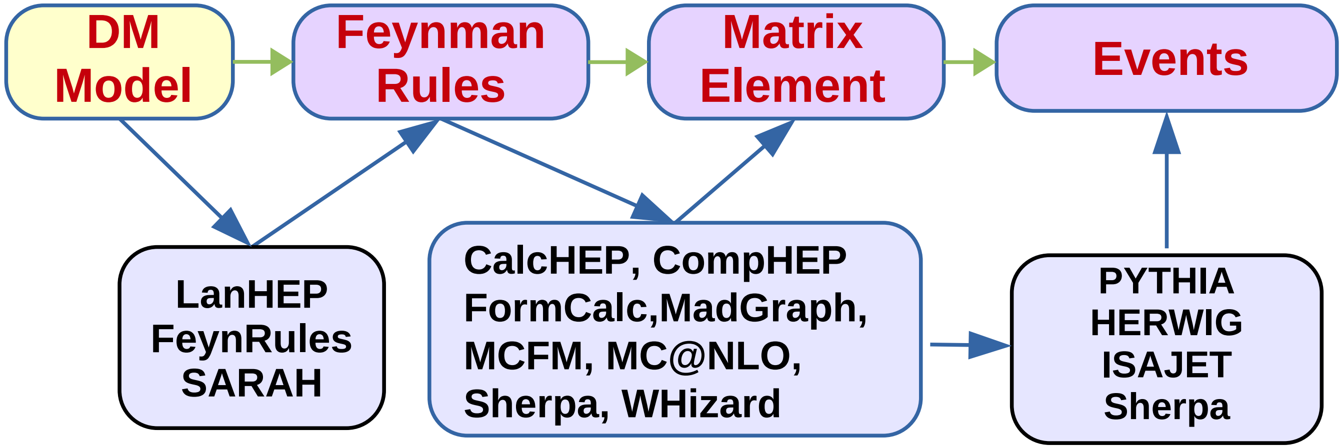

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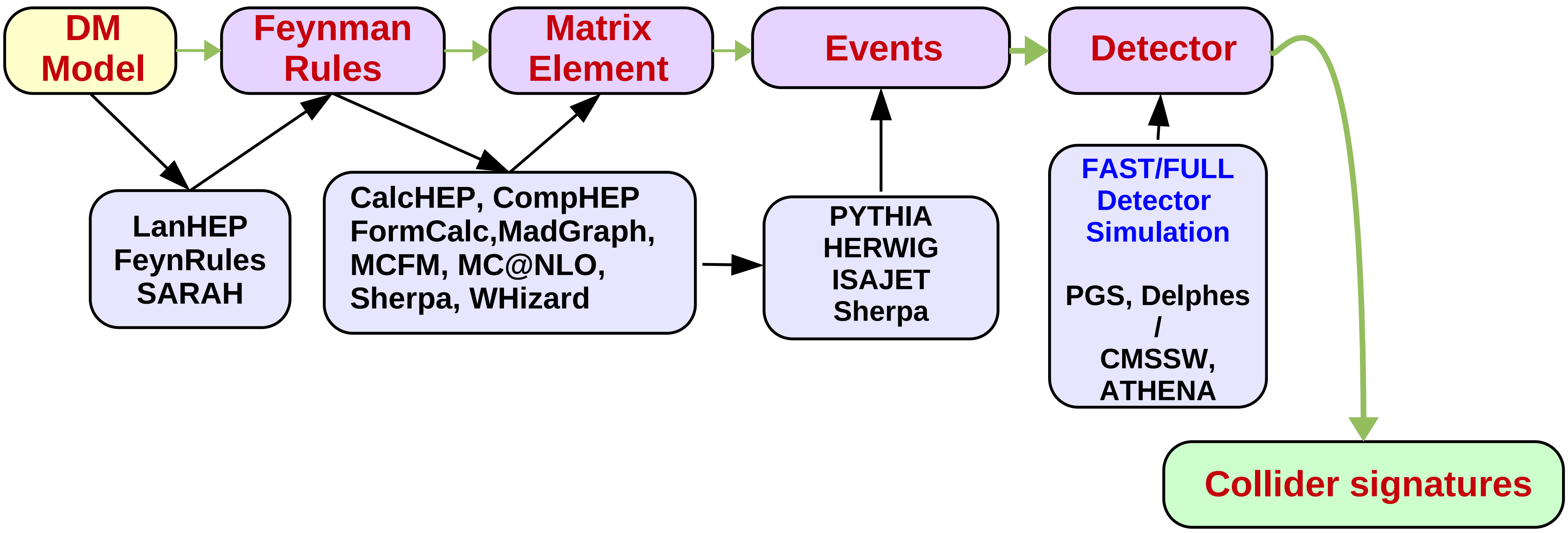

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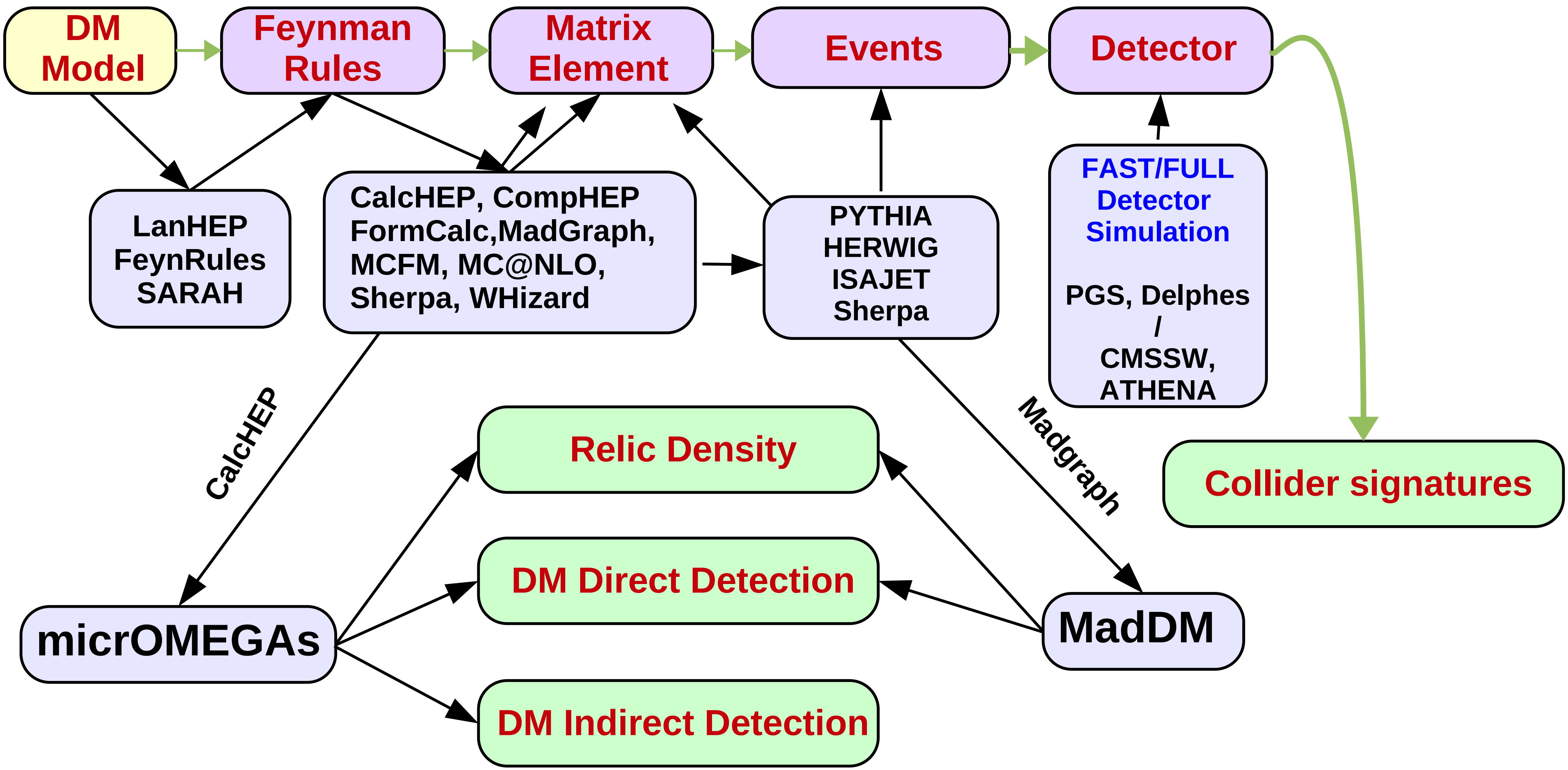

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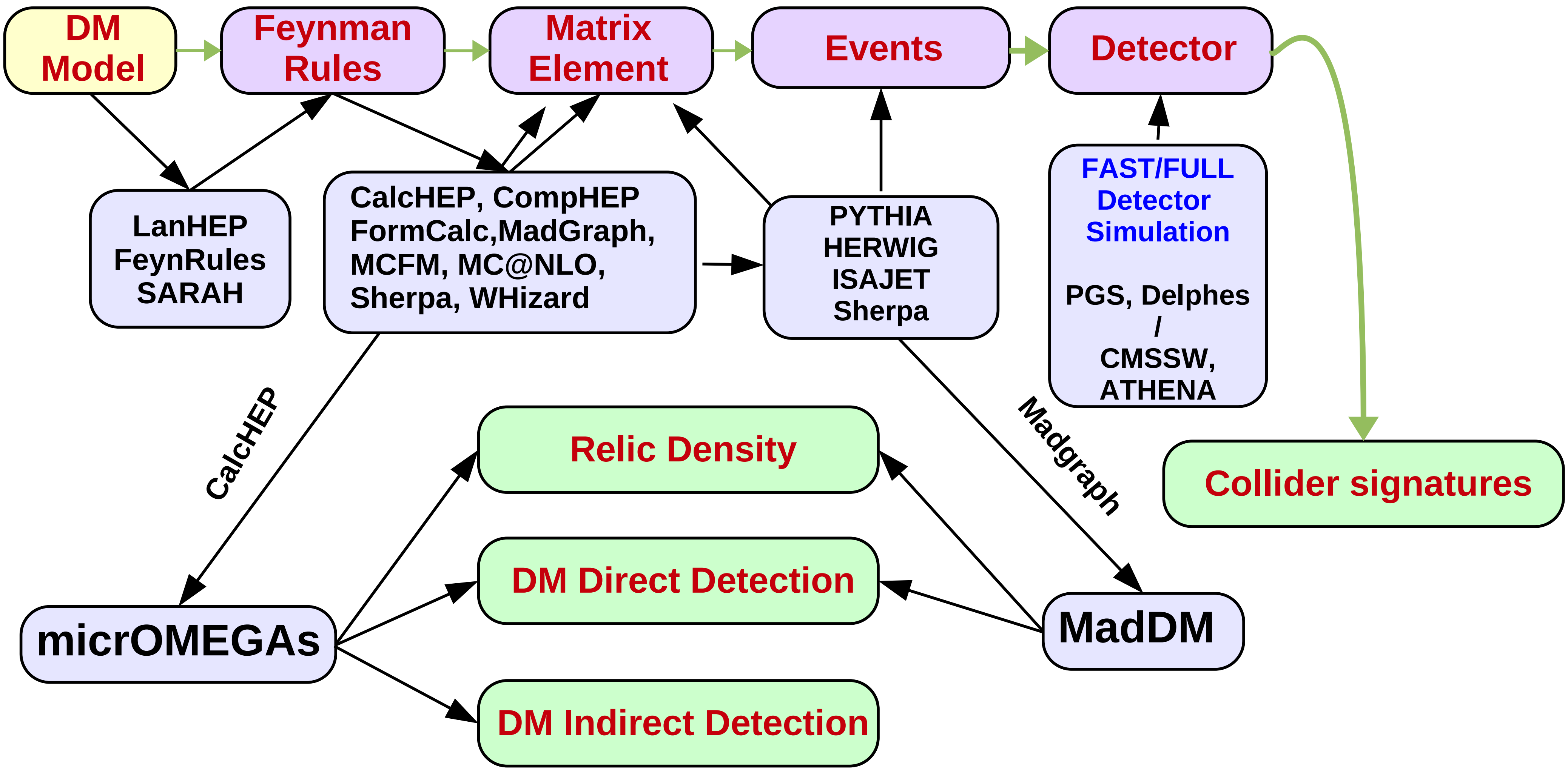

? **CMB constraint on <σv>**

“CMB constraints on Dark Matter models with large annihilation cross-section”
'09 Gallia, Iocco,Bertone, Melchiorri

MicrOMEGAs

http://lapth.in2p3.fr/micromegas
Belanger, Boudjema, Pukhov, Semenov
Goudelis, Zaldivar v5.0.8

hep-ph/0112278, hep-ph/0405253, hep-ph/0607059, arXiv:0803.2360, arXiv:1305.0237, arXiv:1407.6129, arXiv:1801.03509

- Comprehensive tool for dark matter studies : precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays
- Comes with models: MSSM, NMSSM,CPV-MSSM, RH-neutrino, Littlest Higgs, Inert doublet+singlet Z3,Z4; many more models are available at ***hepmdb.soton.ac.uk***

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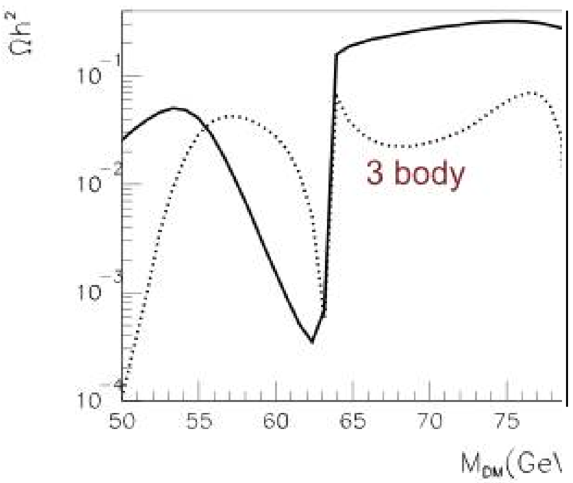
- **Recent features**
  - **Neutrino signal** from DM capture (for SuperKamiokande, IceCube), both neutrino flux and muon flux are computed
  - **Higgs 3-body decays** and loop-induced decays are included – a good agreement with HDECAY (Djouadi et al) for SM-like Higgs
  - Links to **external packages**: HiggsSignals/HiggsBounds(Bechtle et al), Smodels(Kraml et al)
  - Includes **3/4-body processes** with one/two virtual W/Z
  - Z2,Z3,Z4,Z5 symmetries and **two DM candidates**
  - **Asymmetric DM:** option to define $\Delta Y = Y^{+} - Y$
  - Collider limits for Z' on-shell mediator (Barducci et al)
  - **Freeze-in DM scenario:** from v 5.0



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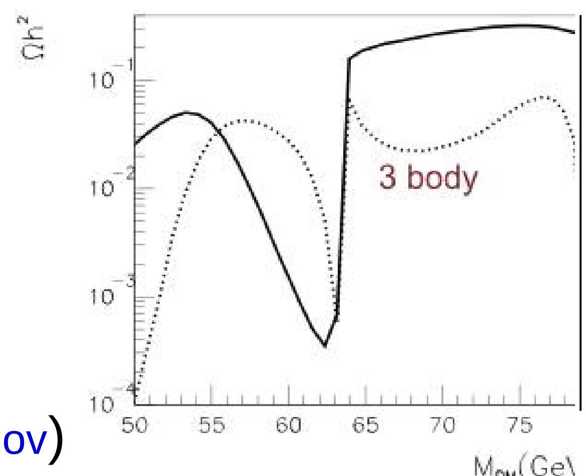


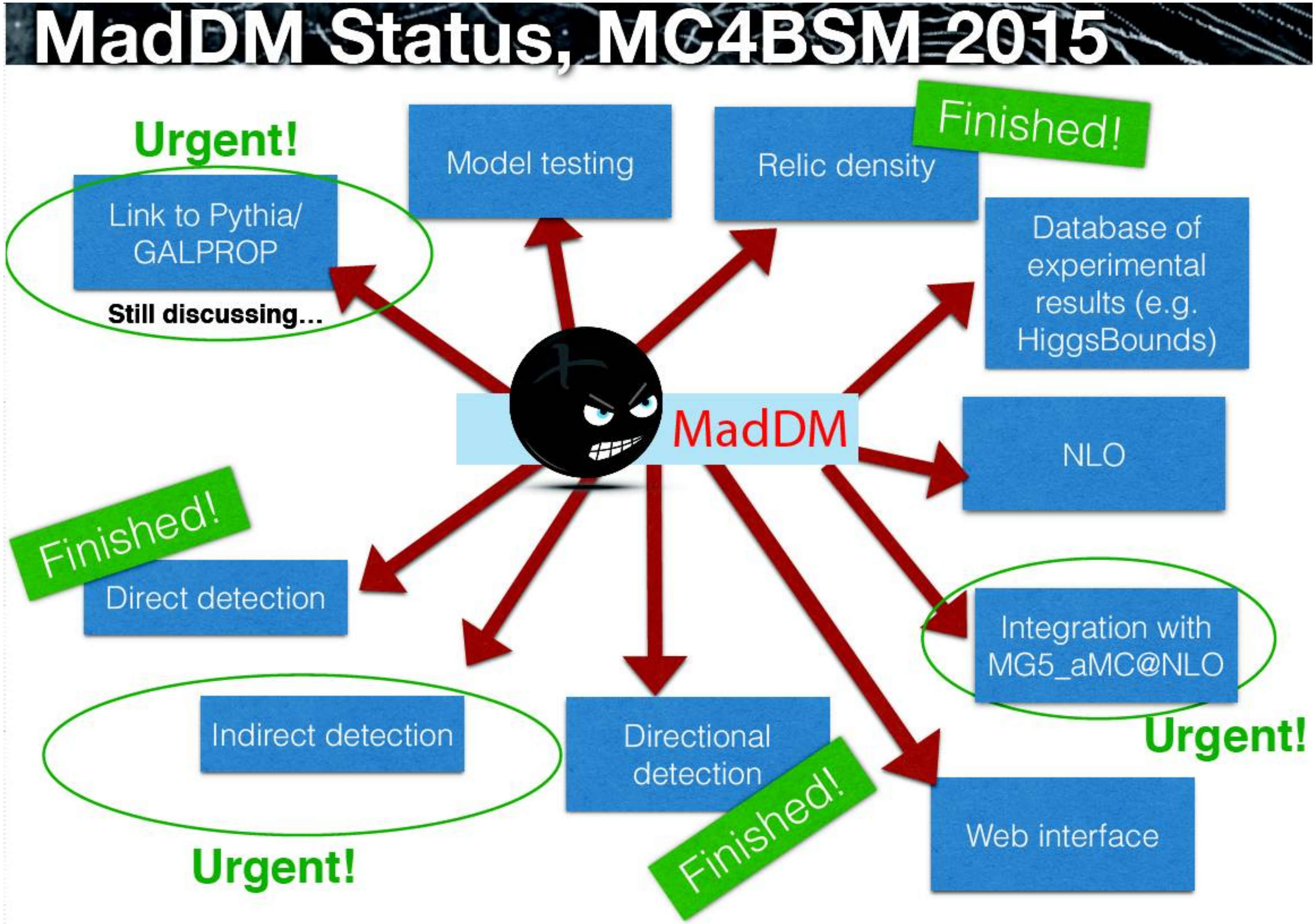
- **Prospects**
  - Collider limits for any DM model (Belanger, Barducci, AB, Pukhov)
  - Improved propagation for ID DM signals, interface to USINE, GALPROP
  - $DMDM \to \gamma\gamma/\gamma Z$ with FormCalc (AB, Hahn, Pukhov, Semenov)

MadDM

http://susy.phsx.ku.edu/~mihailo/index.html
https://launchpad.net/maddm
Backovic, Martini, Kong, Mattelaer, Mohlabeng

arXiv:1509.03683
arXiv:1308.4955

- Was born in 2013, version 2.1: DM relic density, DM direct and directional detection



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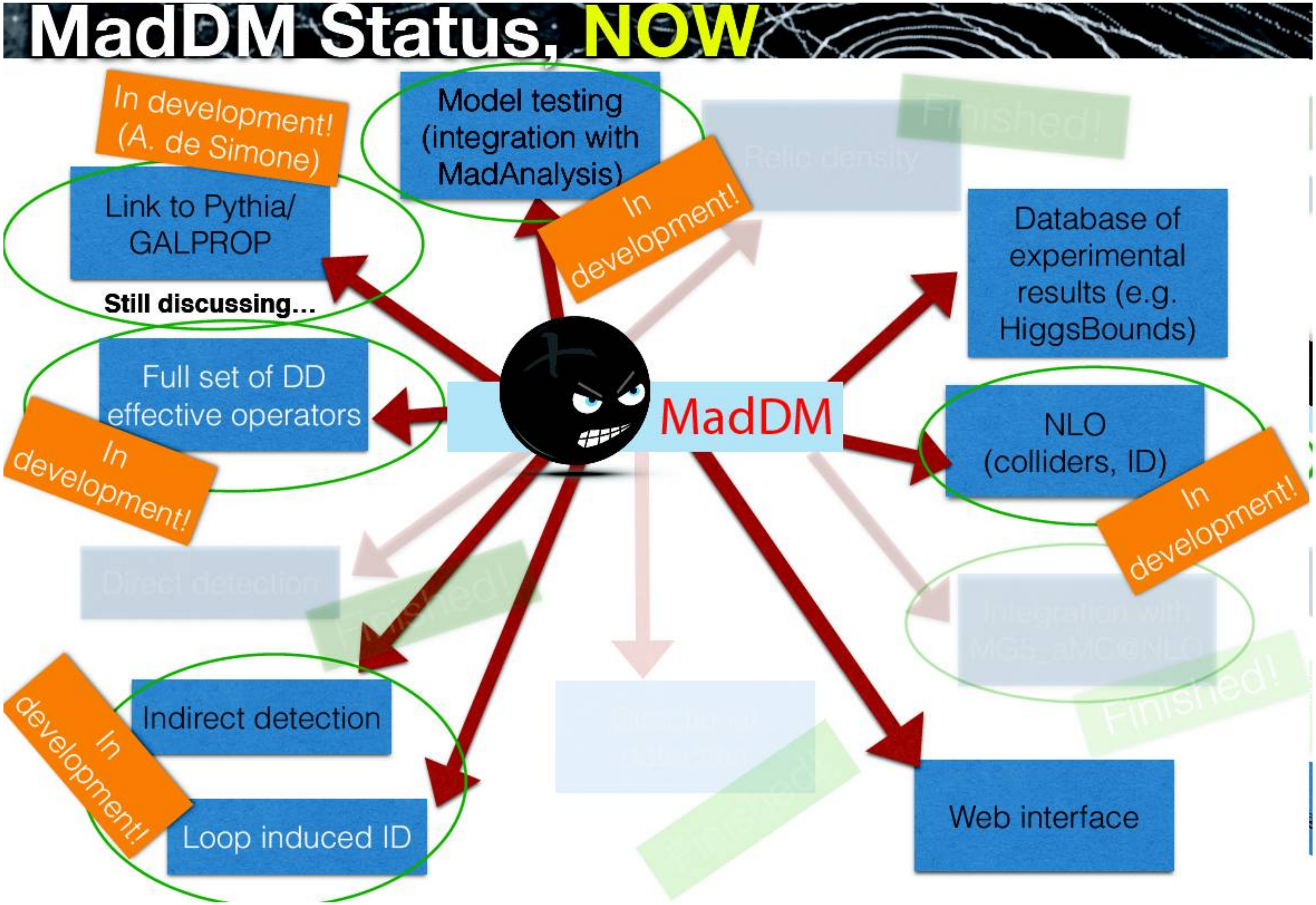
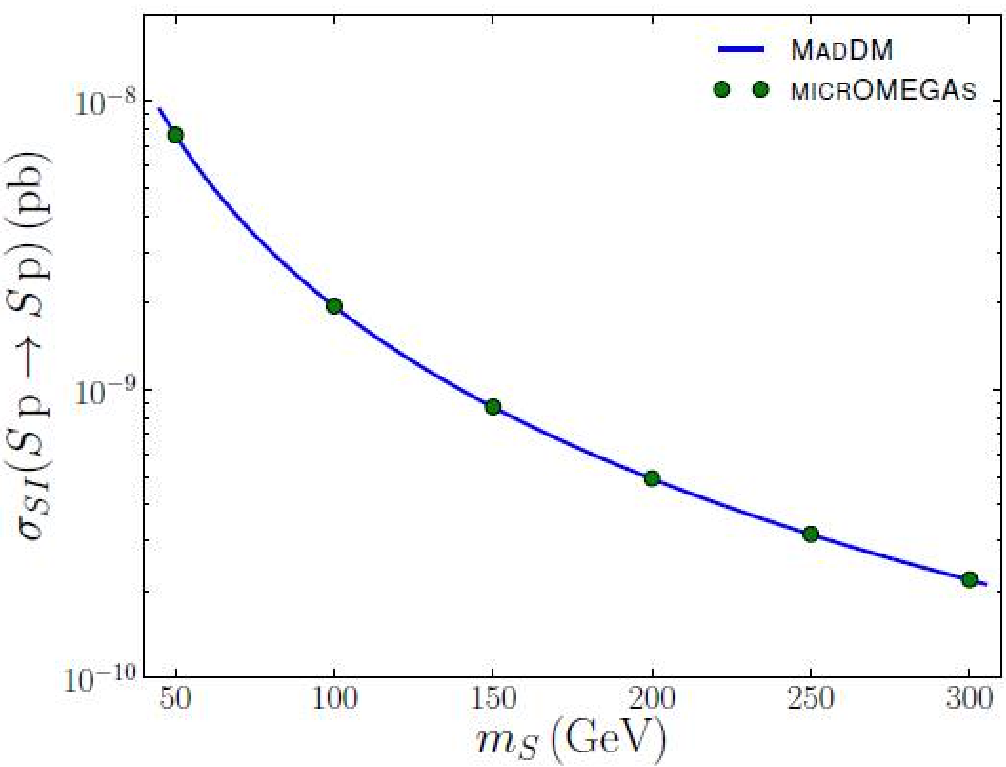


MicroMEGAs – MadDM comparison: DM DD

arXiv:1509.03683

	DM spin	Even	Odd
SI		scalar current	vector current
	0	$2M_\chi S S^* \bar{\psi}_q \psi_q$	$i\left(\partial_\mu S\, S^* - S\,\partial_\mu S^*\right)\bar{\psi}_q \gamma^\mu \psi_q$
	1/2	$\bar{\psi}_\chi \psi_\chi \bar{\psi}_q \psi_q$	$\bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_q \gamma^\mu \psi_q$
	1	$2M_\chi A^*_{\chi\mu} A^\mu_\chi \bar{\psi}_q \psi_q$	$i\left(A^{*\alpha}_\chi \partial_\mu A_{\chi\alpha} - A^\alpha_\chi \partial_\mu A^*_{\chi\alpha}\right)\bar{\psi}_q \gamma_\mu \psi_q$
SD		axial-vector current	tensor current
	1/2	$\bar{\psi}_\chi \gamma^\mu \gamma^5 \psi_\chi \bar{\psi}_q \gamma_\mu \gamma_5 \psi_q$	$-\frac{1}{2}\bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_q \sigma^{\mu\nu} \psi_q$
	1	$\sqrt{6}\left(\partial_\alpha A^*_{\chi\beta} A_{\chi\nu} - A^*_{\chi\beta} \partial_\alpha A_{\chi\nu}\right)\epsilon^{\alpha\beta\nu\mu}\bar{\psi}_q \gamma_5 \gamma_\mu \psi_q$	$i\frac{\sqrt{3}}{2}\left(A_{\chi\mu} A^*_{\chi\nu} - A^*_{\chi\mu} A_{\chi\nu}\right)\bar{\psi}_q \sigma^{\mu\nu} \bar{\psi}_q$



- There is a good agreement between spin-Independent (SI) and spin-dependent (SD) rates

Importance of the MicroMEGAs – MadDM comparison

- Actually the main message here is the importance of the fact that two independent tools exist and are being cross checked!

Importance of the MicroMEGAs – MadDM cross-check

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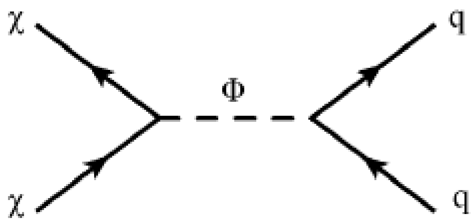

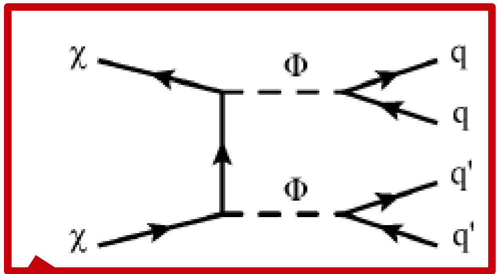

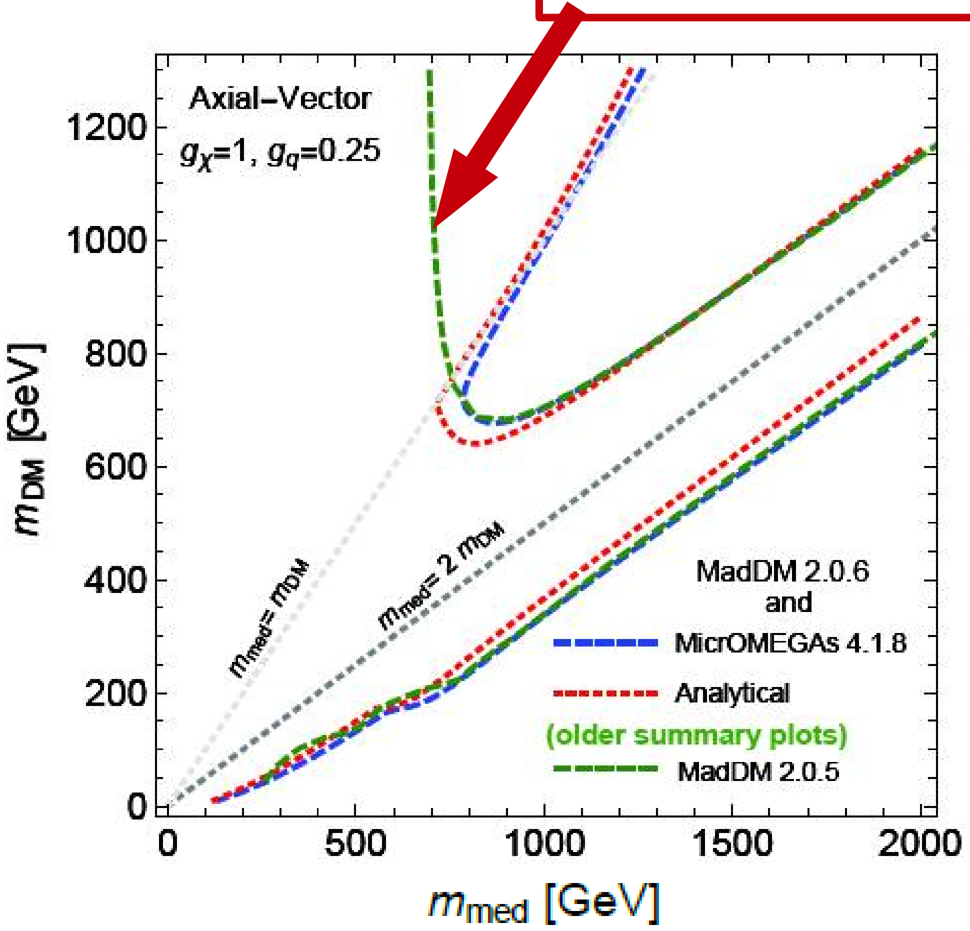

a recent example of this importance are the results for the S-mediated model used with MadDM 2.0.5 in arXiv:1603.08525 and brought at DM LHC forum

t-channel diagram was missed in MadDM 2.0.5, leading to the erroneous results

CalcHEP for DM studies at colliders

A.Pukhov, AB, N.Christensen
http://theory.sinp.msu.ru/~pukhov/calchep.html

hep-ph/9908288
arXiv:1207.6082

- Some highlights
  - *the “engine” of micOMEGAs*
  - ***has convenient graphical interface***
  - *evaluates particle widths 'on the fly'*
  - ***allows to select diagrams** (inducing squared diagram level) – important for the dedicated interference studies*
  - *allows easily modify an existing model (GUI) or to implement the new one (LanHEP, FeynRules)*
  - ***powerful batch interface** – connects production and decay processes, allows to perform multidimensional scan and produce LHE files in one run*
  - *adopted to HPC cluster, symbolic and numerical evaluations/simulations are **threads parallelized***
  - *exports plots to GNUPLOT, PAW and ROOT*
  - *numerous models are implemented, see CalcHEP's site and HEPMDB database*
  - ***modular structure, used in GAMBIT***

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hep-ph/9908288
arXiv:1207.6082

- DM Models:
  at CalcHEP, HEPMDB (hepmdb.soton.ac.uk) and FeynRules(feynrules.irmp.ucl.ac.be) sites
  - **Extra dimensions :** 5D UED (MUED) with 2KK and 4KK layers, 6D UED with 2KK layers
  - **SUSY :** CMSSM, MSSM, NMSSM, left-right symmetric MSSM, MSSM with CP violation, E6MSSM
  - **Technicolor & Composite Higgs models:** TC with DM, VLQ with scalar DM
  - **Little Higgs:** Littlest higss model with T-parity
  - **DM EFT operators:** The complete set of DIM5&6 operators with spin 0,1/2,1 DM

MadGraph5_aMC@NLO for DM studies at colliders

A.J. Alwall, R. Frederix, S. Frixione, M. Herquet, V. Hirschi,
F.Maltoni, O. Mattelaer, H.-S. Shao, T. J. Stelzer, P. Torrielli, M. Zaro

arXiv:1106.0522
arXiv:1405.0301

http://madgraph.hep.uiuc.edu/
https://launchpad.net/mg5amcnlo

- the “engine” of MadDM
- has been most intensively used by ATLAS and CMS
- can perform NLO QCD corrections (not a generic for arbitrary model) but works for SM and NLO models located at FeynRules web site
- Includes matching to parton showers

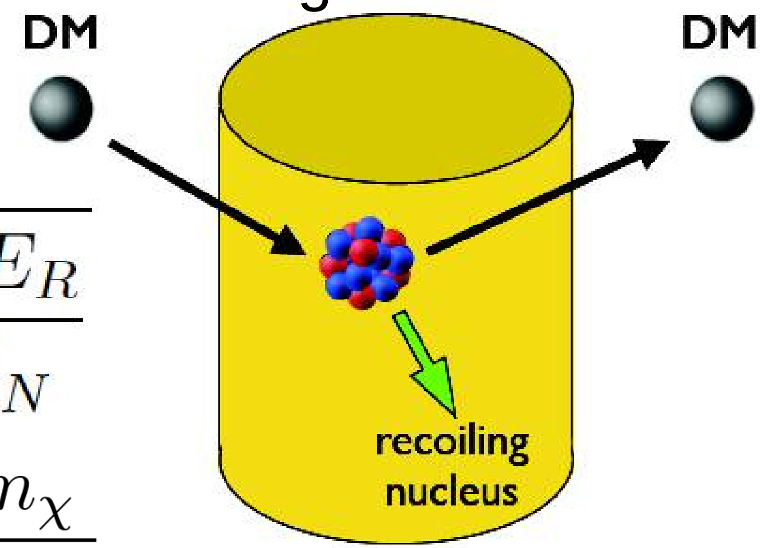
- DM models: at FeynRules and HEPMDB sites
  - **Extra dimensions :** 5D UED (MUED)
  - **SUSY :** MSSM NMSSM
  - **DM EFT operators:** The complete set of DIM5&6 operators with spin 0,1/2,1 DM
  - **NLO models at *feynrules.irmp.ucl.ac.be/wiki/NLOModels***
    - DM simplified models (s-channel spin 0,1,2), SUSY-QCD
- DM models at https://github.com/LHC-DMWG/model-repository
  - **2HDM, EFT, …** → MG models more specific to LHC-DMWG activity

We need models for both Magraph and CalcHEP for the cross-check& validation!

DM Direct detection interplay with colliders

Direct Dark Matter Detection

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP



Elastic recoil energy

$$E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N}\cos^2\theta \qquad v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

- Minimum WIMP speed required to produce a recoil energy - **limitation in low DM mass region**

$$\mu_\chi = \frac{m_N \cdot m_\chi}{m_N + m_\chi}$$

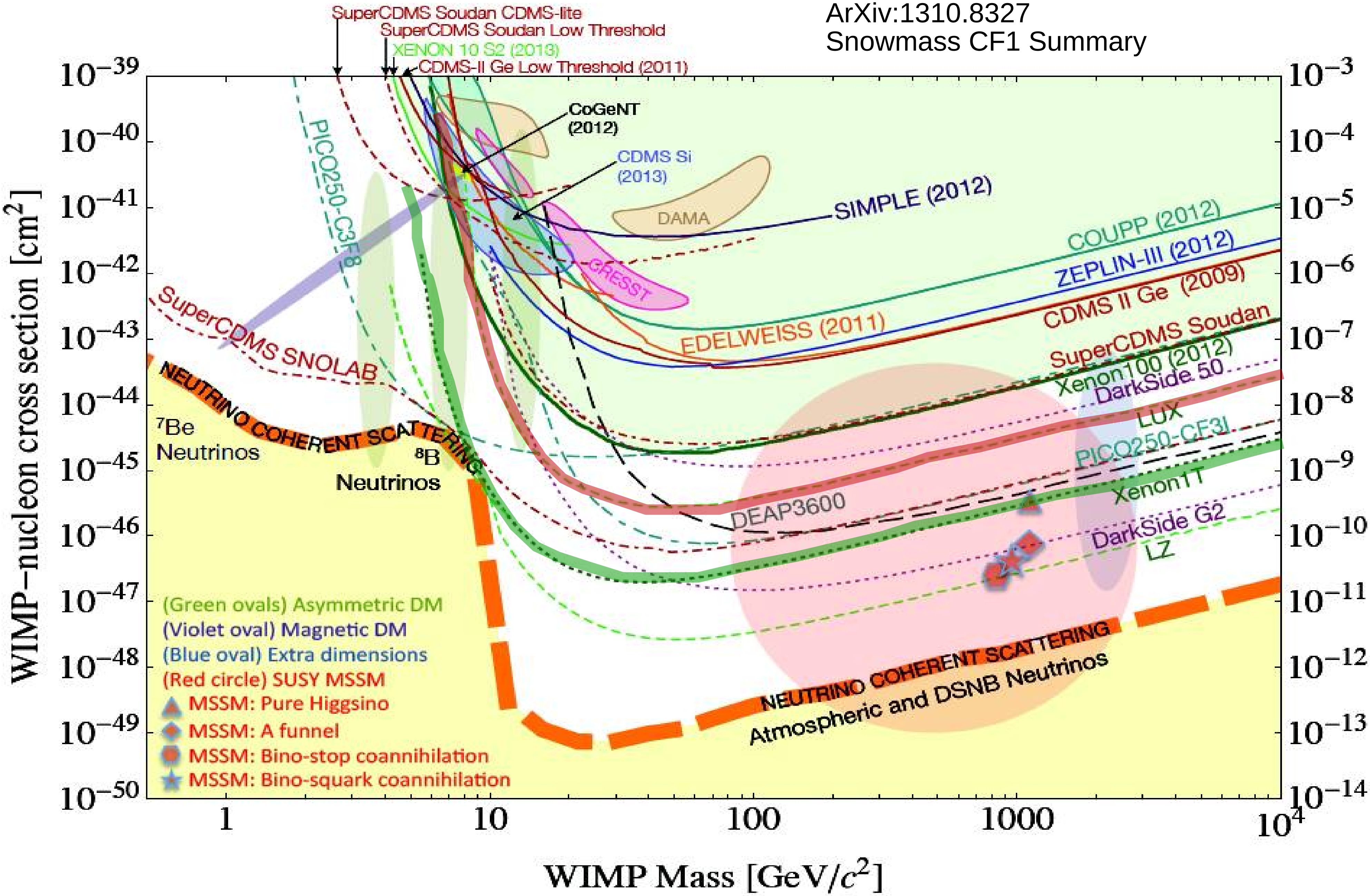
- The differential event rate (per unit detector mass):

$$\frac{dR}{dE_R} = \frac{\sigma_0 F^2(E_R)}{2m_\chi \mu_{\chi N}^2}\,\rho_\chi \underbrace{\eta(v_{\min}, t)}$$

particle physics — astrophysics — halo integral

Power of DM DD to rule out theory space

ArXiv:1310.8327
Snowmass CF1 Summary

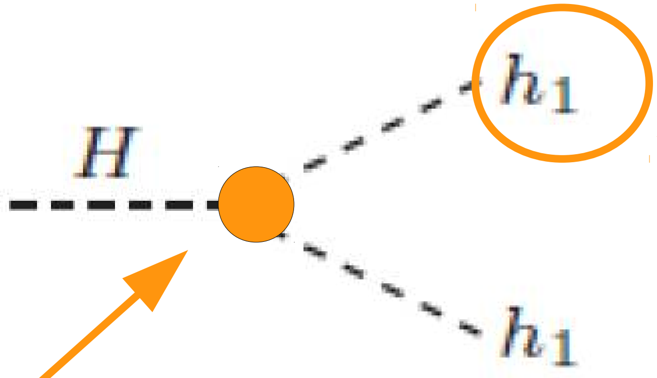


Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} h^+ \\ h_1 + i h_2 \end{pmatrix}$$

$$\begin{aligned} V &= -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2\right] \end{aligned}$$



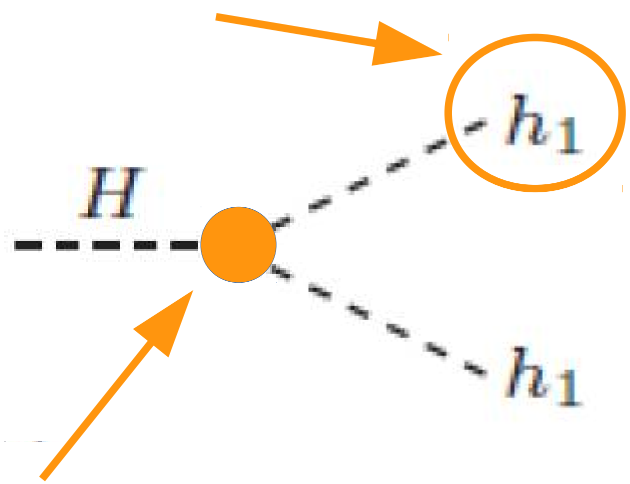
scalar DM

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

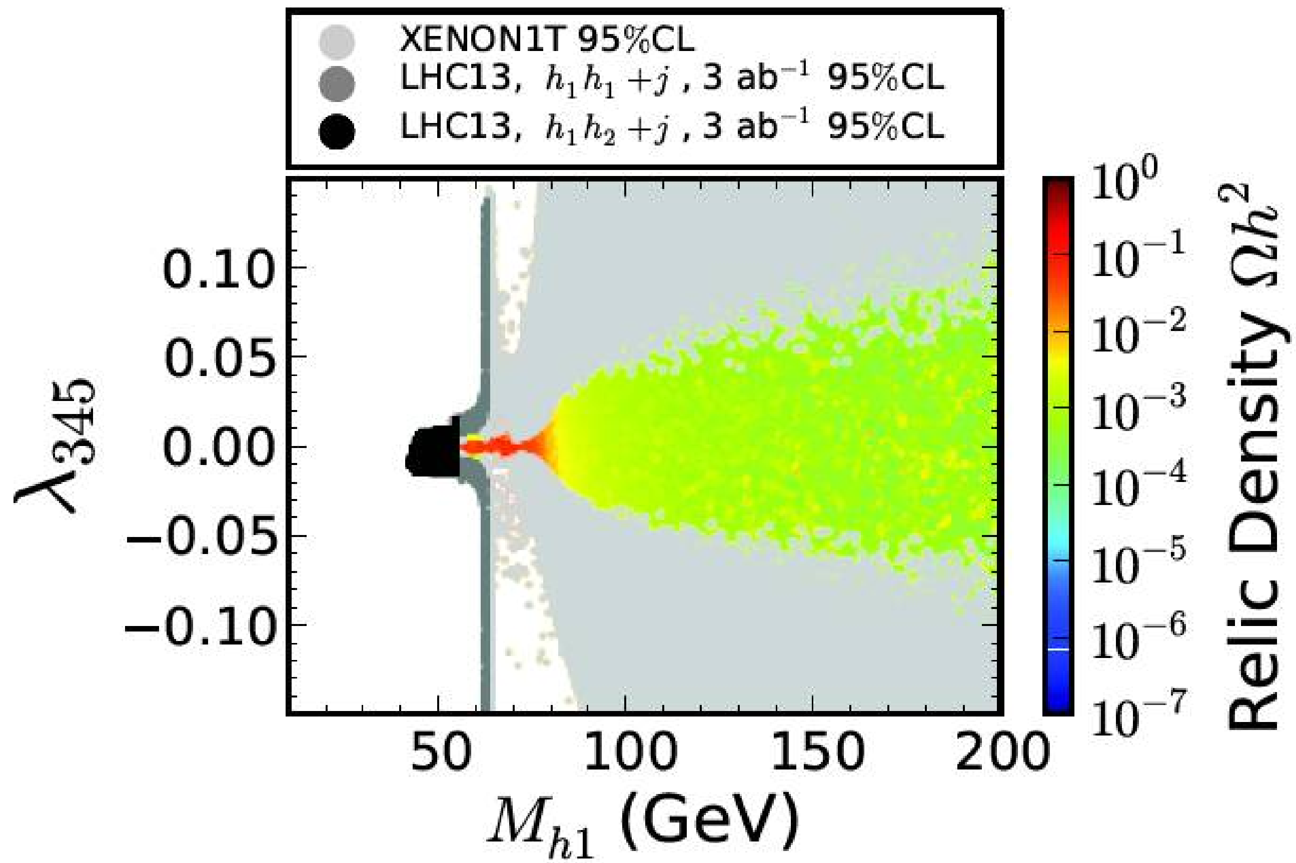
Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

scalar DM

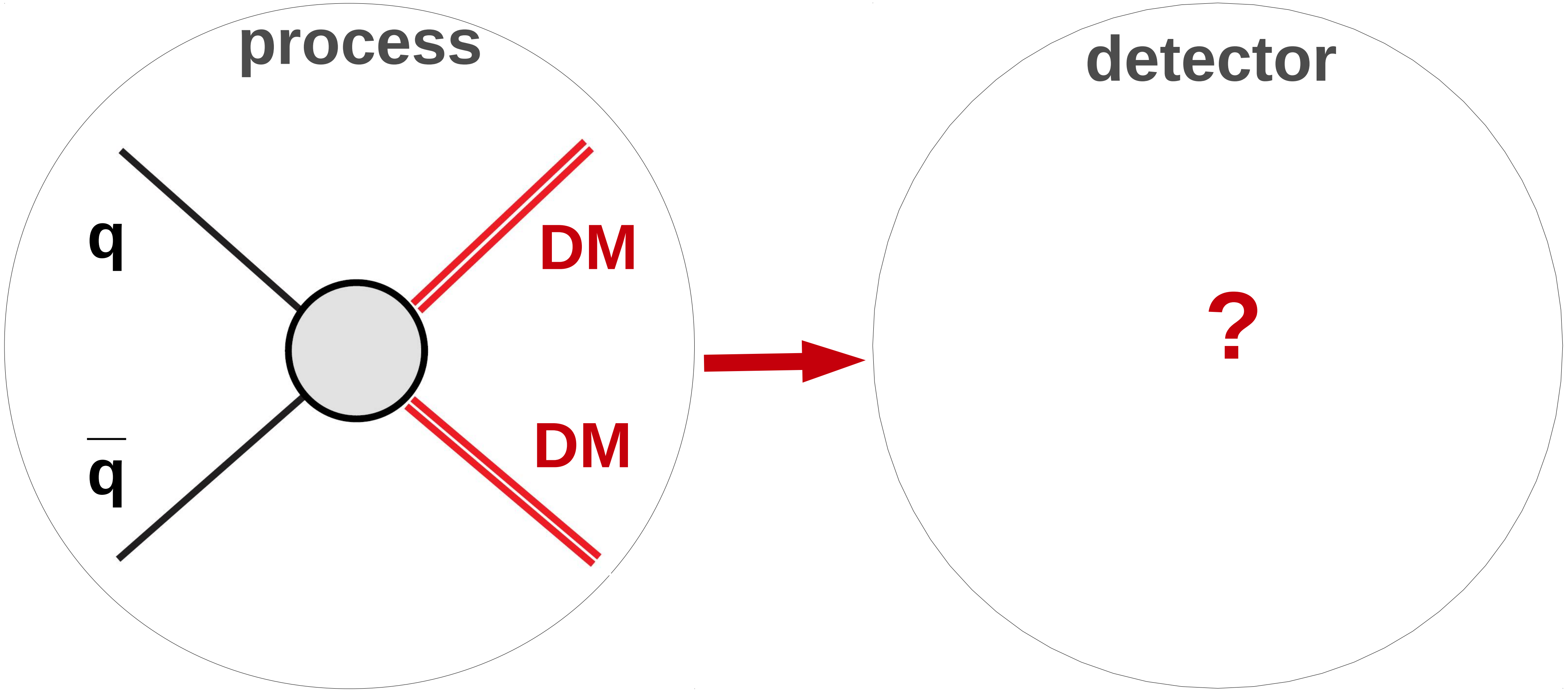


$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

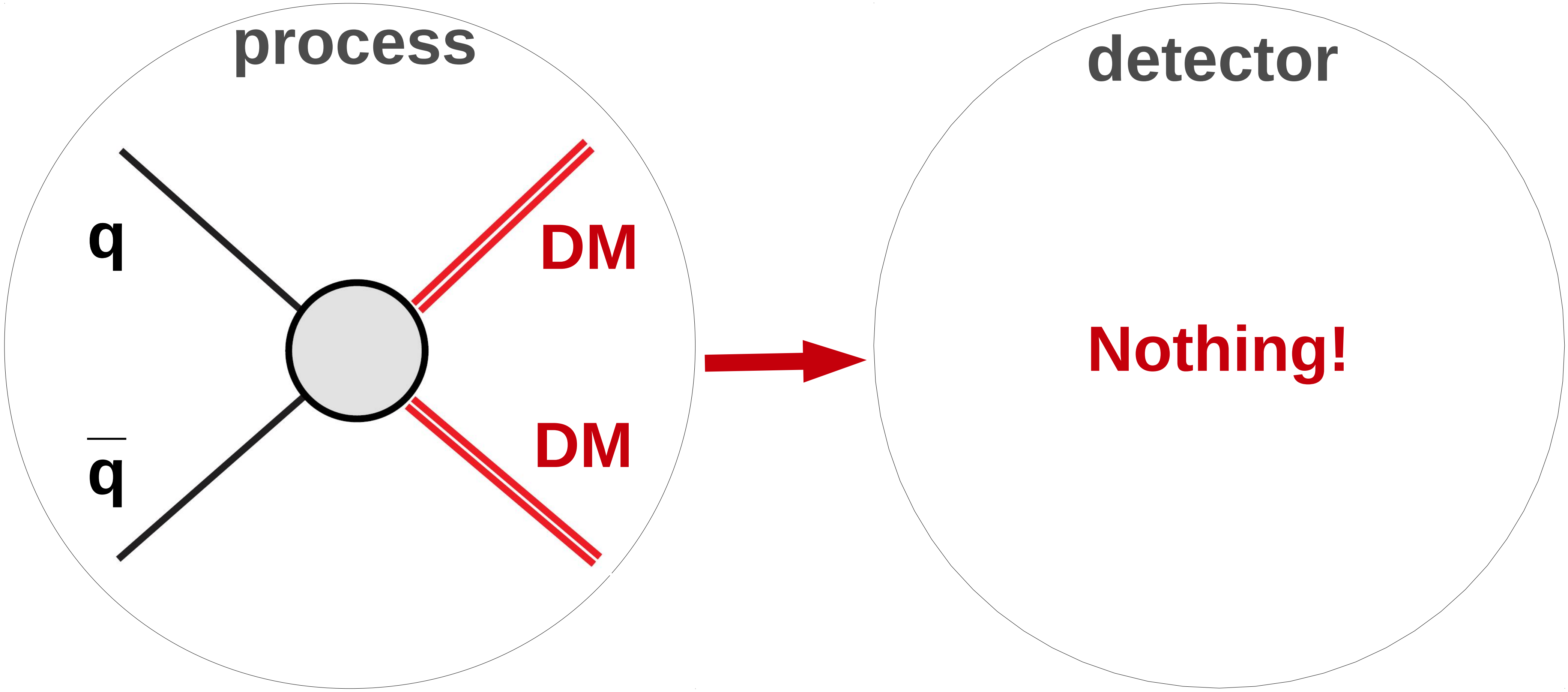


Cacciapaglia, Ivanov, Rojas, Thomas, AB arXiv:**1610.07545**
Novaes, Mercadante, Moon,Tomei, Moretti,Tomas, Panizzi, AB arXiv:**1809.00933**

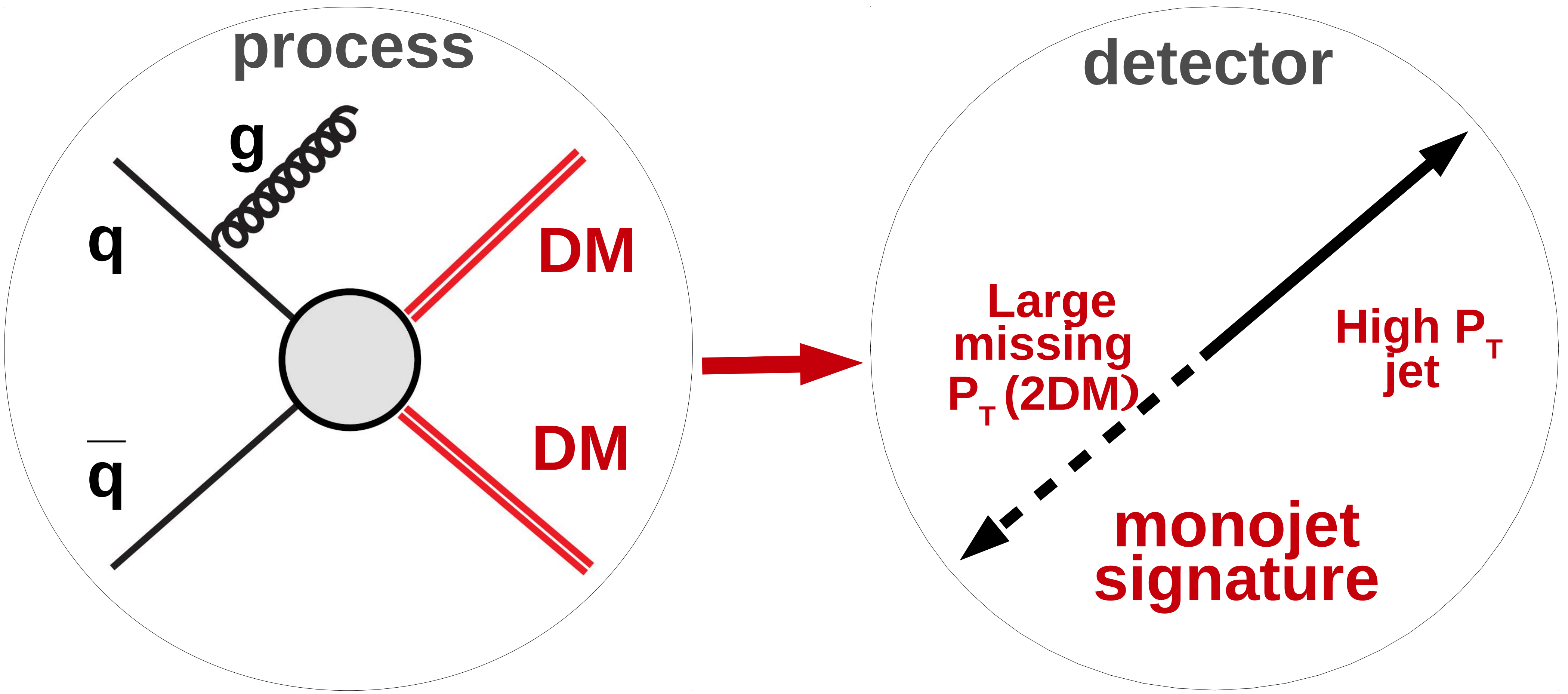
Collider Searches



Collider Searches



Collider Searches

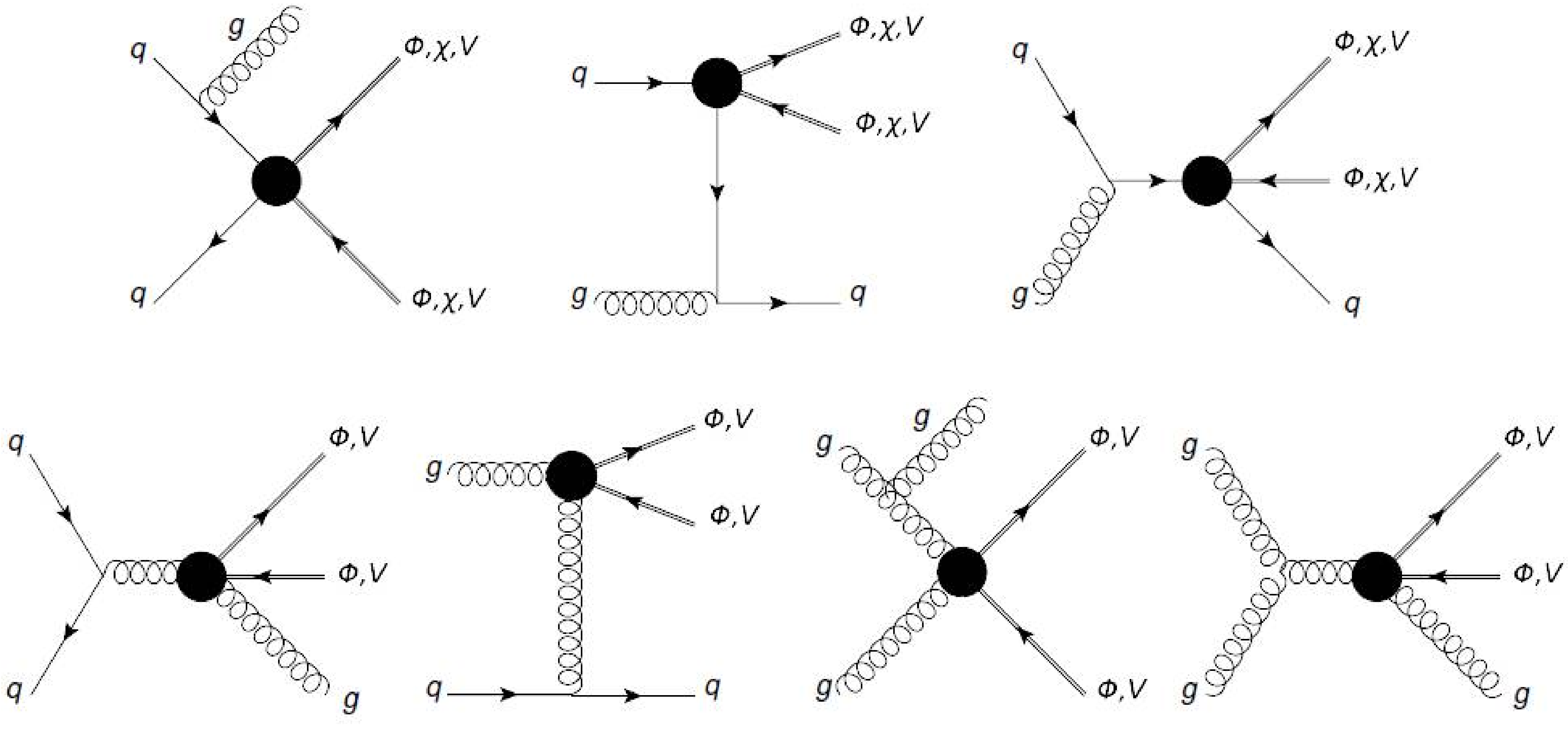


Can we test DM properties at the LHC?

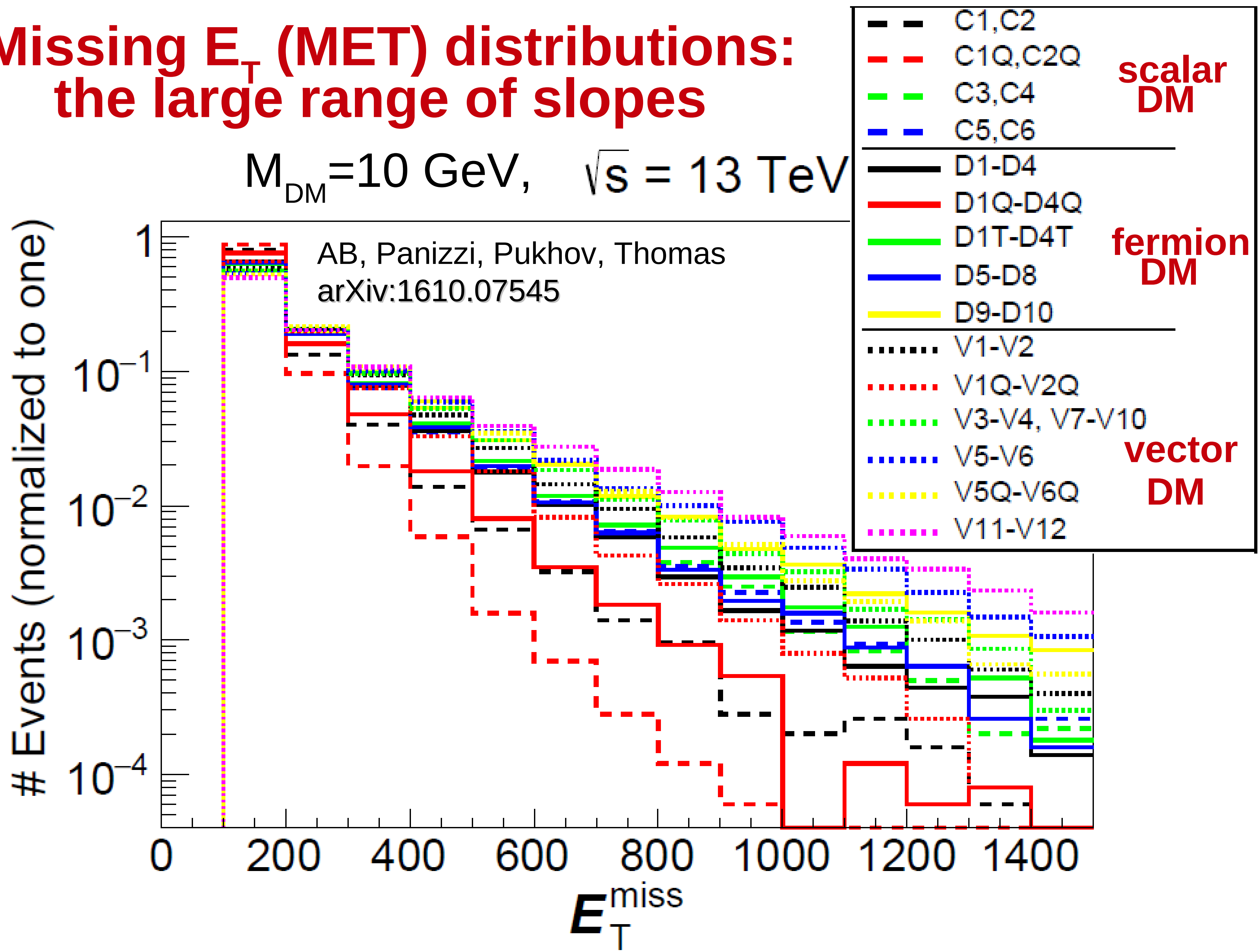
To explore the LHC potential to probe DM operators with different DM spin using the shape missing transverse momentum **(MET)**

- we use the EFT approach: simplicity and model independence
- explore the complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
- consider DM with spin=0, 1/2, 1
- use mono-jet signature at the LHC

Mono-jet diagrams from EFT operators

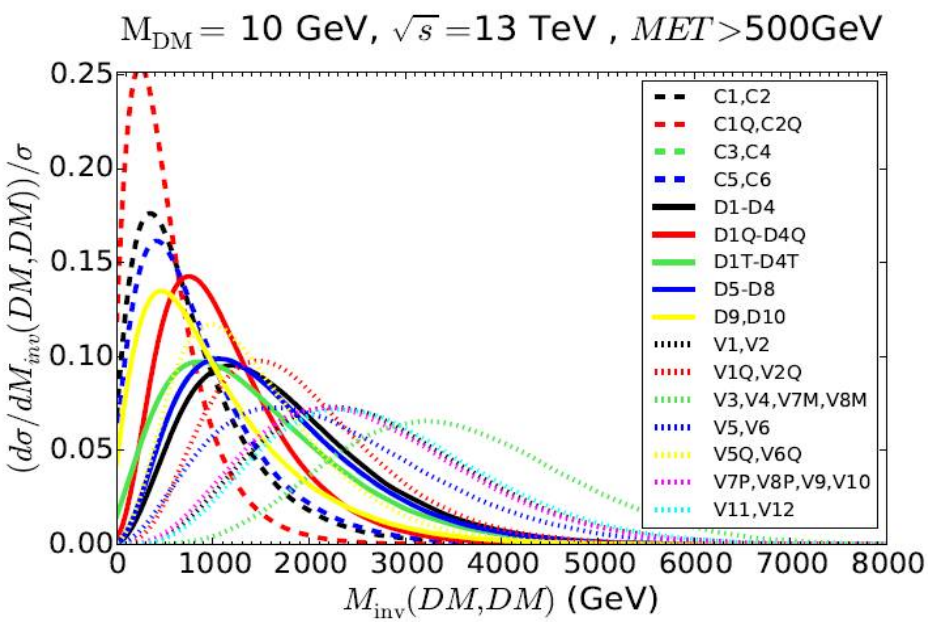


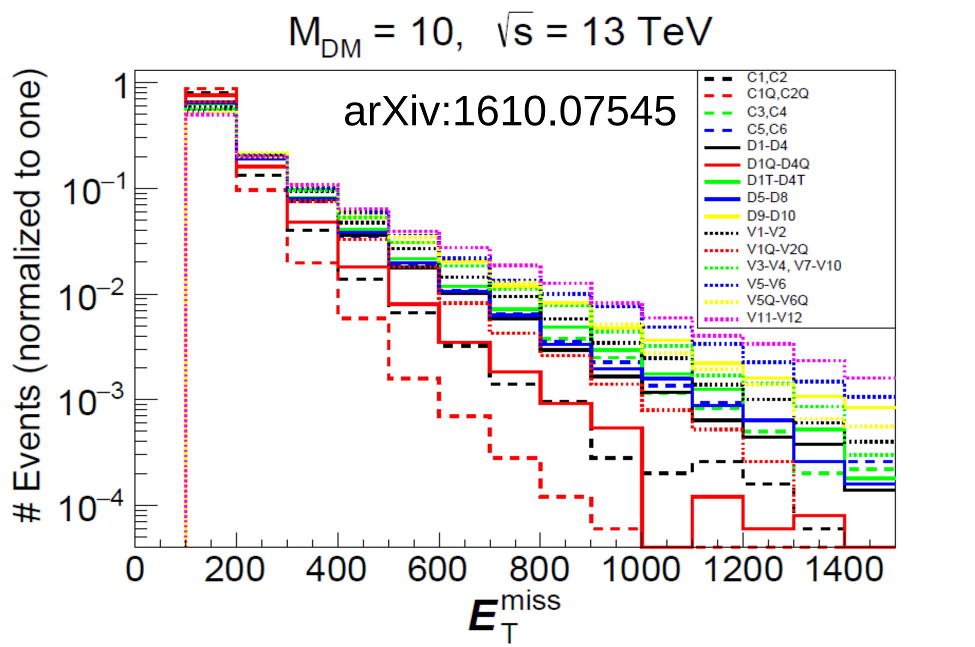
Missing E_T (MET) distributions: the large range of slopes



Distinguishing DM operators/theories

The harder M(DM,DM) distributions ⟷ **The flatter MET shapes**





operator energy dependence → M_{DMDM} shape → MET shape

➪ projection for 300 fb^{-1}: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other

➪ Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

Distinguishing the DM operators: χ^2 for pairs of DM operators

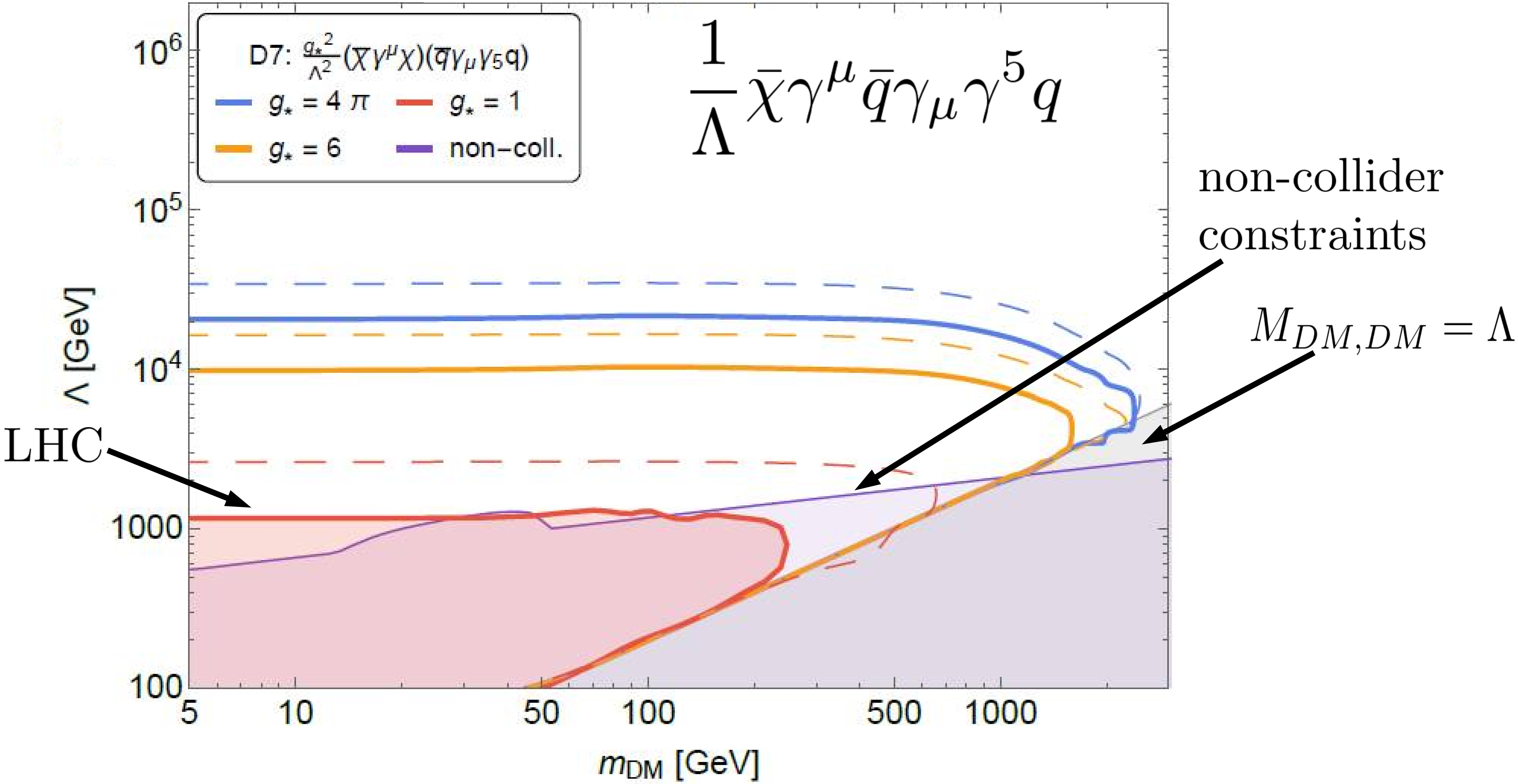
$$\chi^2_{k,l} = \min_{\kappa} \sum_{i=3}^{7} [(\frac{1}{2} N_i^k - \kappa \cdot N_i^l)/(10^{-2} BG_i)]^2$$

: if χ^2>9.48 (95%CL for 4 DOF) – operators can be distinguished!

			Complex Scalar DM				Dirac Fermion DM			
			100 GeV		1000 GeV		100 GeV		1000 GeV	
			C1	C5	C1	C5	D1	D9	D1	D9
Complex Scalar DM	100 GeV	C1	0.0	**19.7**	**25.54**	**74.63**	**11.73**	**41.79**	**25.78**	**52.58**
		C5	**15.74**	0.0	0.37	**16.25**	1.11	3.93	0.74	7.35
	1000 GeV	C1	**19.89**	0.36	0.0	**11.82**	2.33	2.09	0.27	4.58
		C5	**50.86**	**13.86**	**10.34**	0.0	**21.03**	3.7	**11.18**	1.53
Dirac Fermion DM	100 GeV	D1	**9.88**	1.17	2.52	**25.99**	0.0	9.23	2.4	**14.17**
		D9	**30.49**	3.59	1.96	3.96	7.99	0.0	2.71	0.52
	1000 GeV	D1	**20.31**	0.73	0.27	**12.92**	2.25	2.93	0.0	5.42
		D9	**37.38**	6.54	4.18	1.6	**11.96**	0.5	4.89	0.0

DM DD ↔ Collider interplay

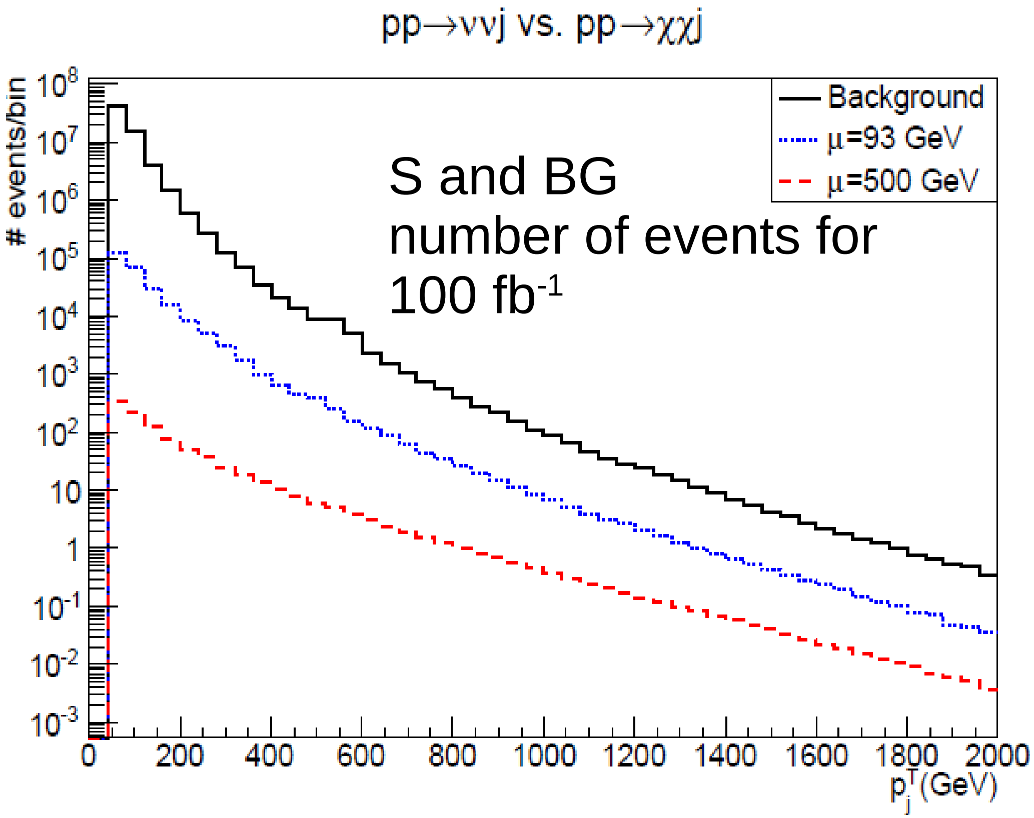
AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018

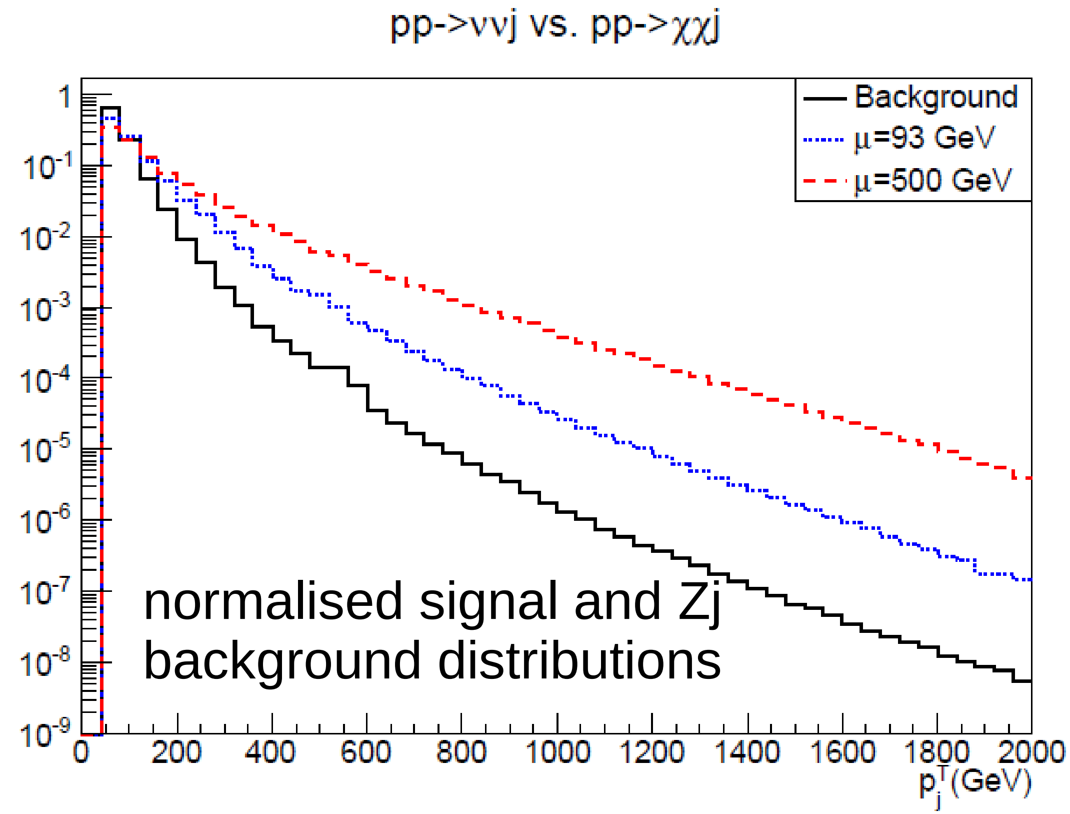


Beyond the EFT: SUSY

Signal vs Background: SUSY scenario

- difference in rates is pessimistic ...
- but the difference in shapes is encouraging: large DM mass → bigger M(DM,DM) → flatter MET

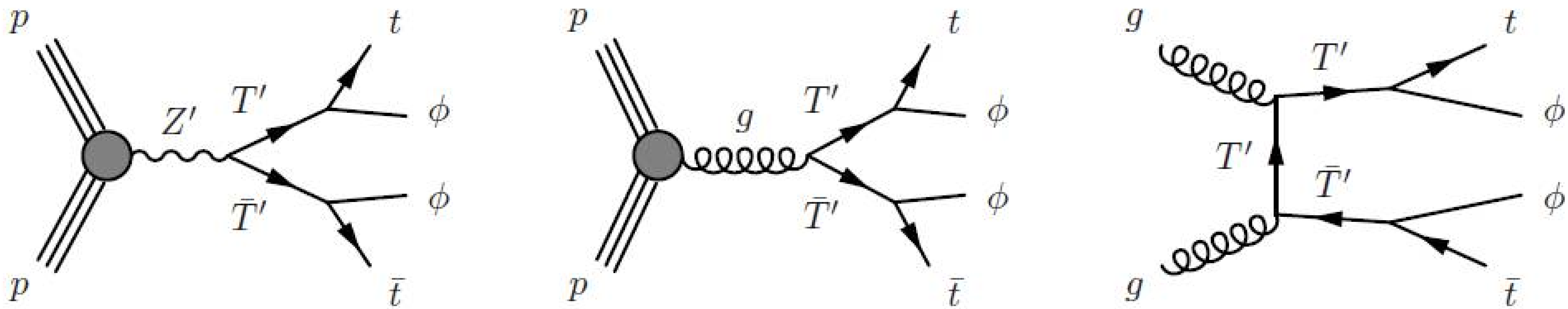


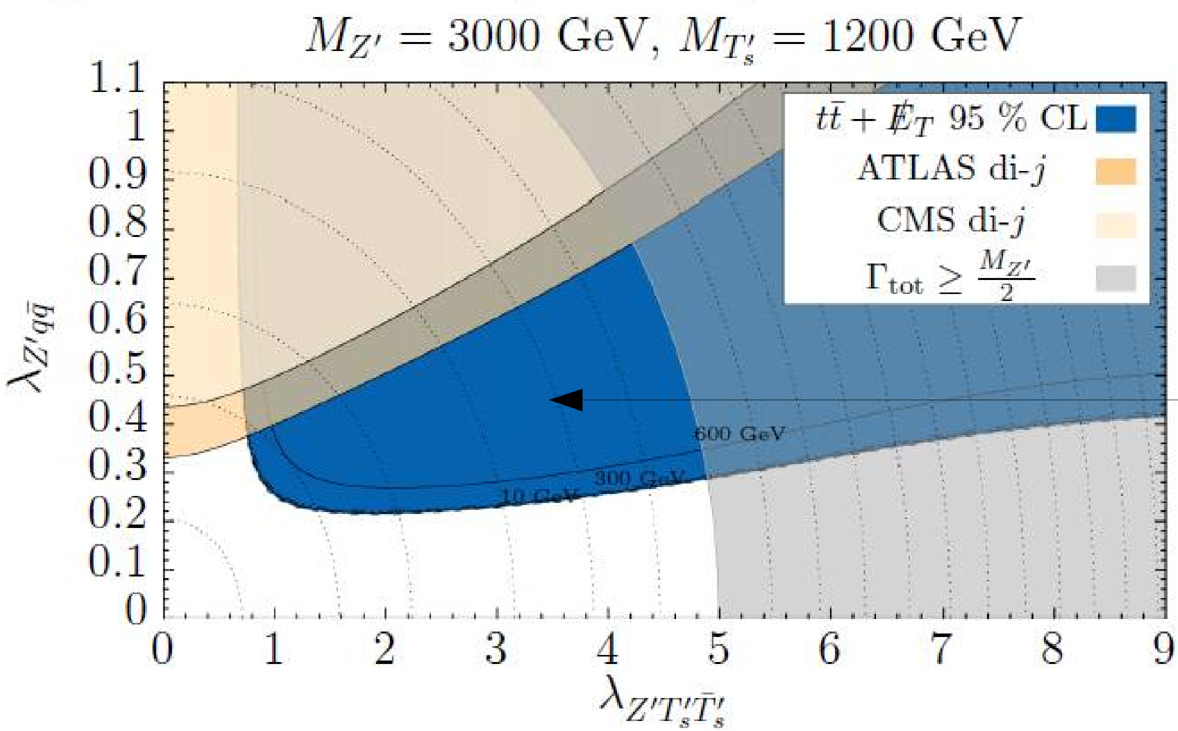


Signal and Zj background p_T^j distributions for the 13 TeV LHC

Beyond the mono-jet signature

Example of the vector resonance in the Composite Higgs model:
Z'→ TT→ t t DM DM signature





Current LHC reach with **tt+ MET signature** based on ATLAS_CONF_2016_050 results

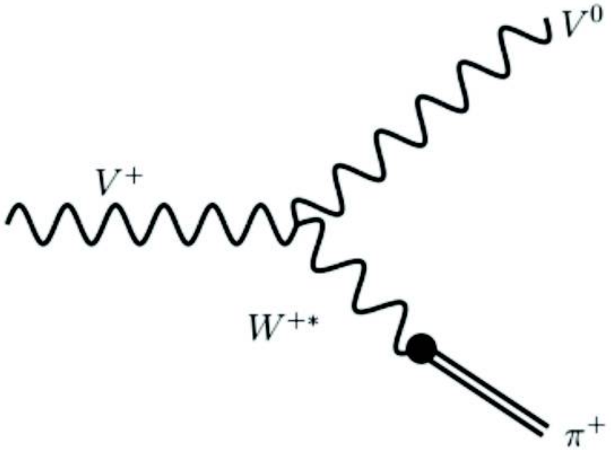
Flacke, Jaine, Schaefers, AB, 2017

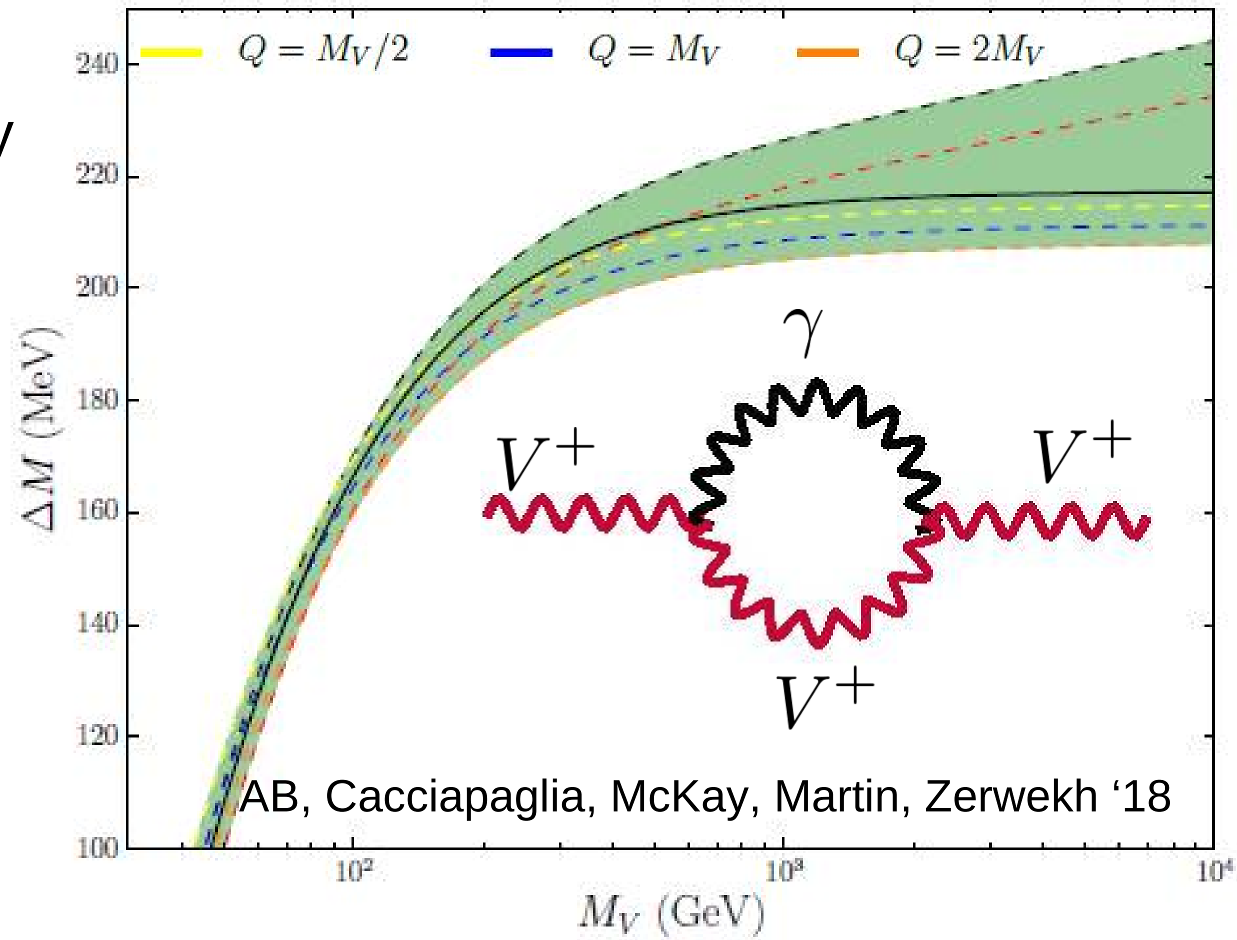
Disappearing Charged Tracks (DCT): VDM as an example

$$\mathcal{L} = \mathcal{L}_{SM} - Tr\{D_\mu V_\nu D^\mu V^\nu\} + Tr\{D_\mu V_\nu D^\nu V^\mu\}$$
$$-\frac{g^2}{2} Tr\{[V_\mu, V_\nu][V^\mu, V^\nu]\}$$
$$-igTr\{W_{\mu\nu}[V^\mu, V^\nu]\} + \tilde{M}^2 Tr\{V_\nu V^\nu\}$$
$$+a\left(\Phi^\dagger\Phi\right) Tr\{V_\nu V^\nu\}$$

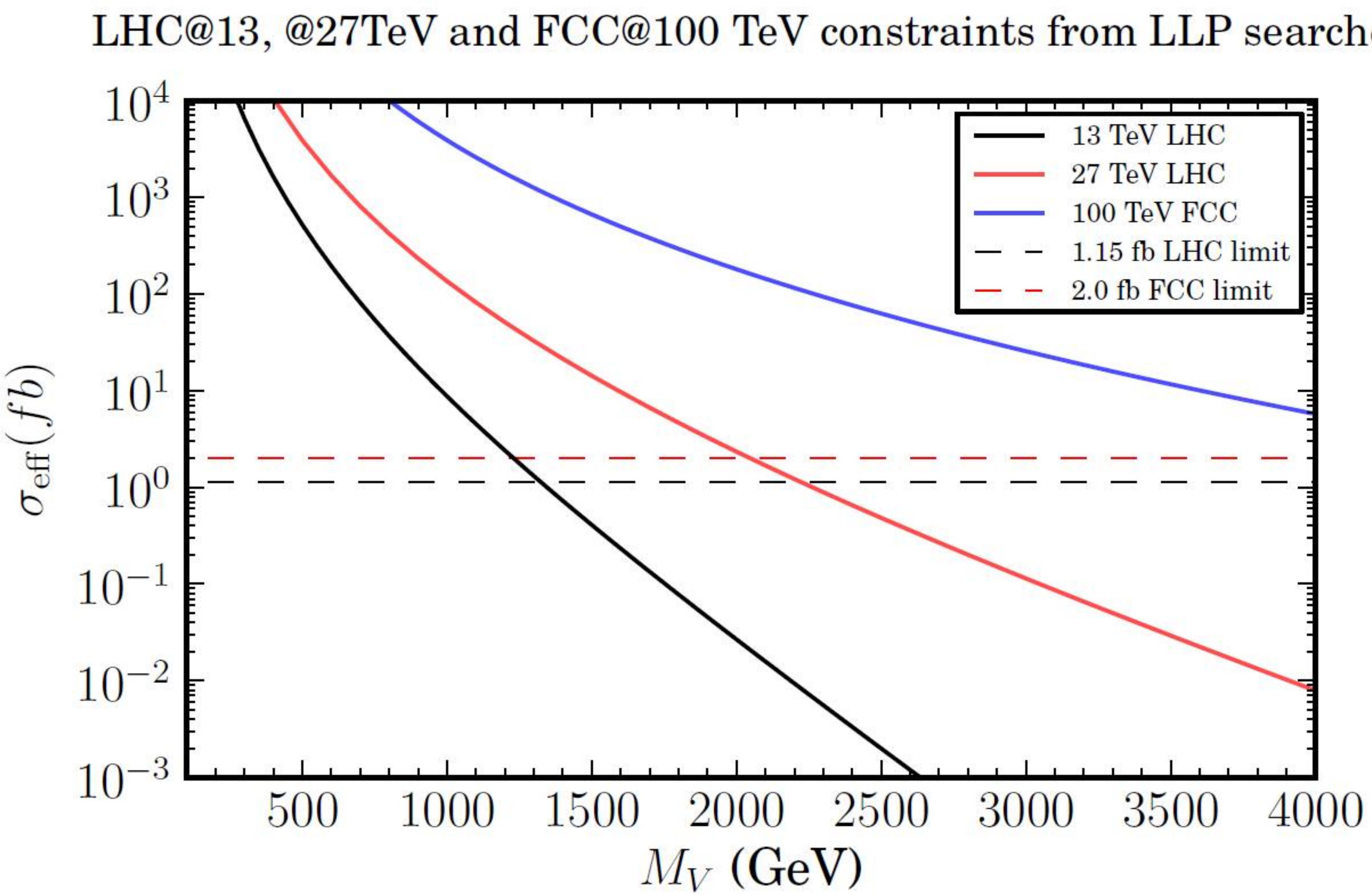
The small mass gap (~ pion mass) between DM and its charged partner will lead to the disappearing charge tracks signatures

The life-time should be properly evaluated using W-pion mixing (otherwise overestimated by factor of 10)





DCT allows to probe TeV DM at colliders



AB, Cacciapaglia, McKay, Martin, Zerwekh arXiv:**1808.10464**

Current bound from LHC on DM mass from the minimal vector triplet model: **1.3 TeV** !

100 TeV FCC will cover DM mass **beyond 4TeV:**
will discover or close the model

Frameworks for observables → data link

- **CheckMATE** V2 (**checkmate.hepforge.org**)
  arXiv:1312.2591, arXiv:1503.01123, arXiv:1611.09856
  Drees, Schmeier,Dercks,Desai,Kim ,Rolbiecki,Tattersall, Weber

- **MadAnalysis** (**madanalysis.irmp.ucl.ac.be**)
  arXiv:1206.1599, arXiv:1405.3982, arXiv:1509.03639
  Conte,Dumont,Fuks,Schmitt,Kraml,Bein,Chalons

  - quickly developing support from users (analysis validation)
  - relies on Delphes fast simulation
  - Incorporates projection analysis
  - Great potential in creating **public library of the analysis**
  - **Needs validation of more DM searches and boosted objects analysis**

- **GAMBIT** the Global and Modular Beyond-Standard Model Inference Tool
  https://gambit.hepforge.org/collaboration
  about 20 authros, see Andy Buckley's talk
  is a global fitting code for generic Beyond the Standard Model theories, designed to allow fast and easy definition of new models, observables, likelihoods, scanners and backendphysics codes

The problem of data → theory link

- We have studied a lot of models, identified many potential signatures of DM, have powerful tools for theory → data exploration

- But **the inverse problem of decoding of the underlying theory from signal** remains remains unexplored
- Its solution requires
  - database of models, database of signatures
  - framework with machine learning **aiming to connect theory and signature space**
  - effective creation of multidimensional set of signatures data in models space and in parameter space for each model
  - **your input!**

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  - **your input!**

- **HEPMDB (High Energy Physics Model Database) hepmdb.soton.ac.uk** created in 2011 to make the first step for decoding (AB, Daniel Locke at present)
  - has a status of the permanent server at Southampton
  - convenient centralized storage environment for HEP models
  - **linked to IRIDIS 5 HPC** cluster at Southampton, 20K cores, 1.3 Petaflops
  - it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database via web interface
  - users can upload their own model and perform simulation – became a very attractive feature for all range of researchers
  - **database of signatures is under development – your input is important!**

HEPMDB: models list

HEPMDB

High Energy Physics Models DataBase

Login | Register

Home News Calculate Tools Signatures Wiki Contact Us

Search in HEPMDB | Show All Models

Search Models :: Results for [MSSM]

1. **MSSM** [2011-06-21 10:54:07] hepmdb:0611.0028

   CalcHEP/MicrOMEGAs groups

   We present MSSM with SUGRA and AMSB scenario as well as MSSM with low energy input. Read file INSTALLATION for model installation and file CITE for references on scientific publications which pre...

2. **MSSM with bilinear R-Parity violation** [2011-11-17 20:00:51] hepmdb:1111.0036

   Florian Staub

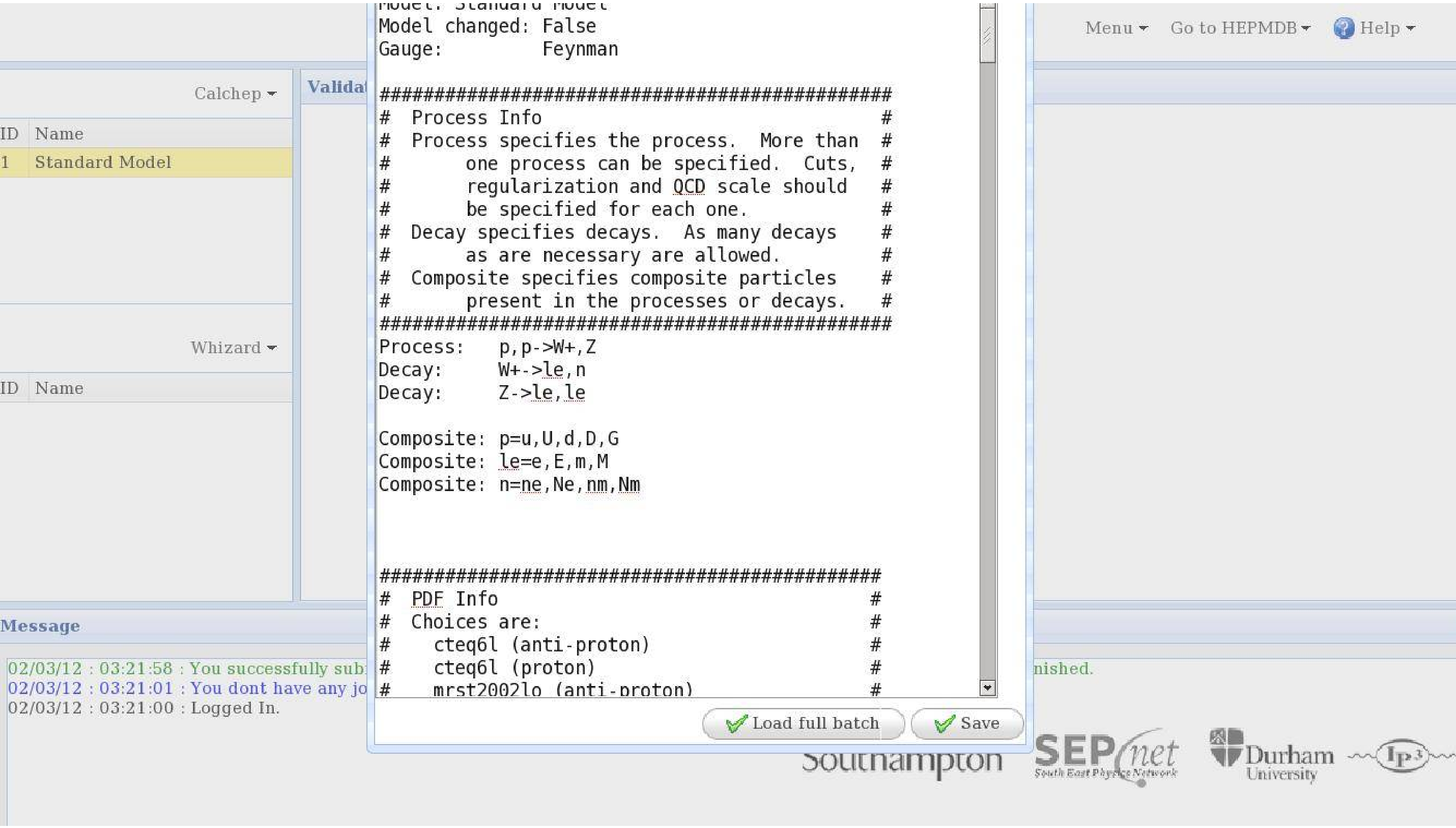
   The MSSM with bilinear R-Parity violating terms in the superpotential and for the soft-breaking terms. Model files created by SARAH 3.1.0 Support of SLHA+ functionality to read spectrum files...

3. **TMSSM** [2011-11-17 20:06:23] hepmdb:1111.0037

   Florian Staub

   Triplet extended MSSM (including possibility of flavor violation) Model files created by SARAH 3.1.0 Support of

HEPMDB: setting batch file



HEPMDB: getting results

Menu ▾ Go to HEPMDB ▾ Help ▾

Calchep

Calchep ▾

ID	File Name
1	Standard Model(CKM=1)

Whizard

Madgraph 5

Validation

Job #1628195.blue30=============Wednesday 01st of August 2012 09:55:37 PM=====================

CalcHEP Numerical Details

Done!

Scans	sigma (fb)	Running	Finished	Time (hr)	N events
Mh120	9.8870e+02	0/13	13/13	0.01	10000
Mh125	9.7740e+02	0/13	13/13	0.01	10000
Mh130	9.6810e+02	0/13	13/13	0.02	10000
				0.04	

Mh120.txt CalcHEP Numerical Details

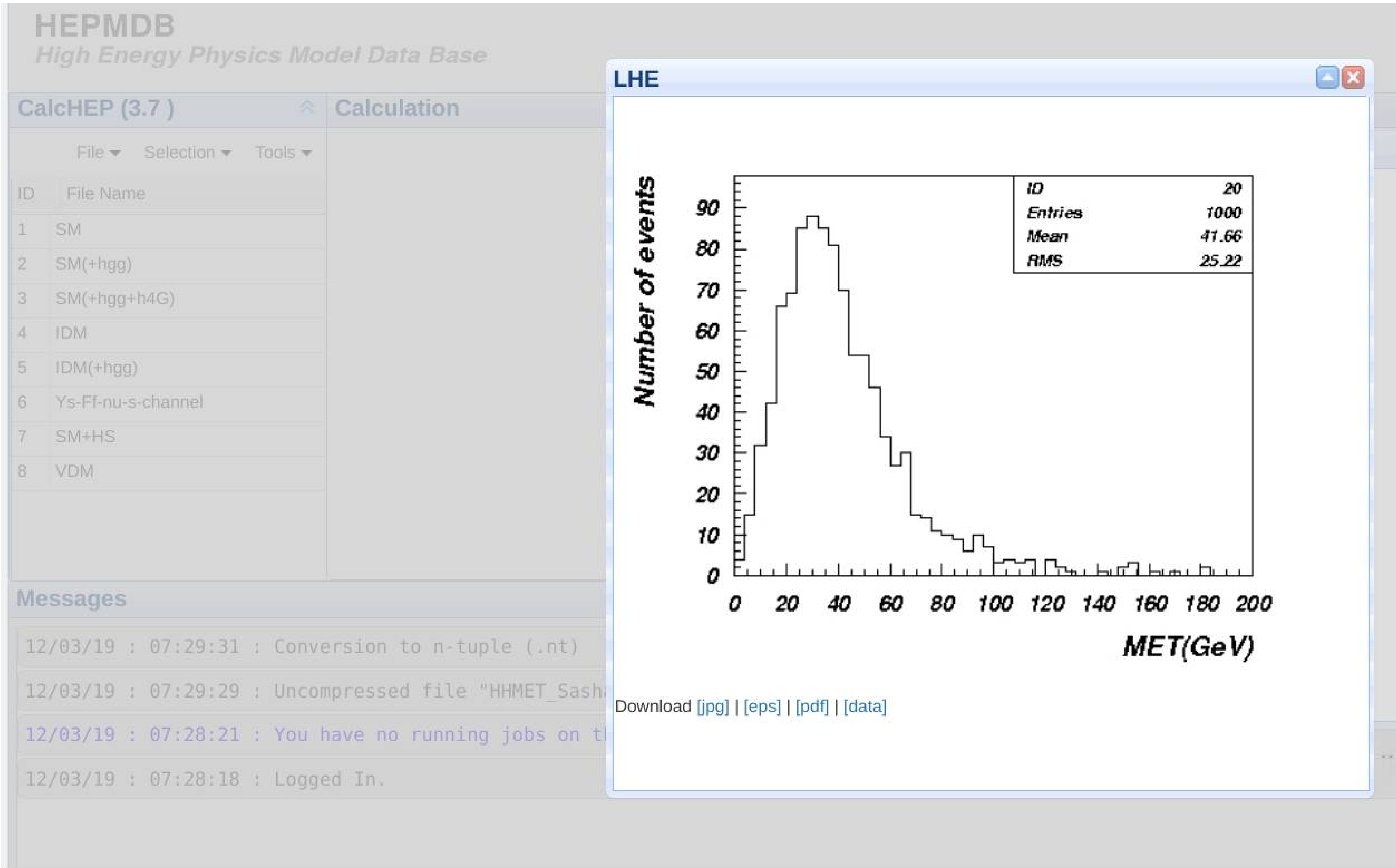
Done!

Processes	sigma (fb)	unc (%)	PID	Time (hr)	N events
u,D->W+,b,B	1.3296e+03	4.59e-01	0	0.00	3258/3258
U,d->W-,b,B	7.2163e+02	5.03e-01	0	0.00	1822/1822
d,U->W-,b,B	7.1638e+02	4.39e-01	0	0.00	1810/1810

Message

01/08/12 : 21:56:05 : Nt_maker test-Mh120.lhe
01/08/12 : 21:56:04 : gunzip file test-Mh120.lhe.gz
01/08/12 : 21:55:38 : Job 1628195.blue30 was finished.
01/08/12 : 21:38:29 : You successfully submitted a job on HPCx : #1628195.blue30 . You will be notified by email when the job is finished.

HEPMDB: distributions from lhe files



HEPMDB: geo and stats

last year activity: 200 users, 70M events, ~2K visits from over 60 countries

Summary

- ➪ we have powerful tools to explore complementarity of collider and non-collider signatures and perform top-down exploration for theory → data link

- ➪ there are observables to decode DM nature from the signal which we hope to observe soon (slopes of MET- beyond EFT approach, cross sections, beyond mono-X signatures, DCT, …)

- ➪ not only tools but also models should be public - this will help us to validate and improve them - HEPMDB and FeynRules are good examples

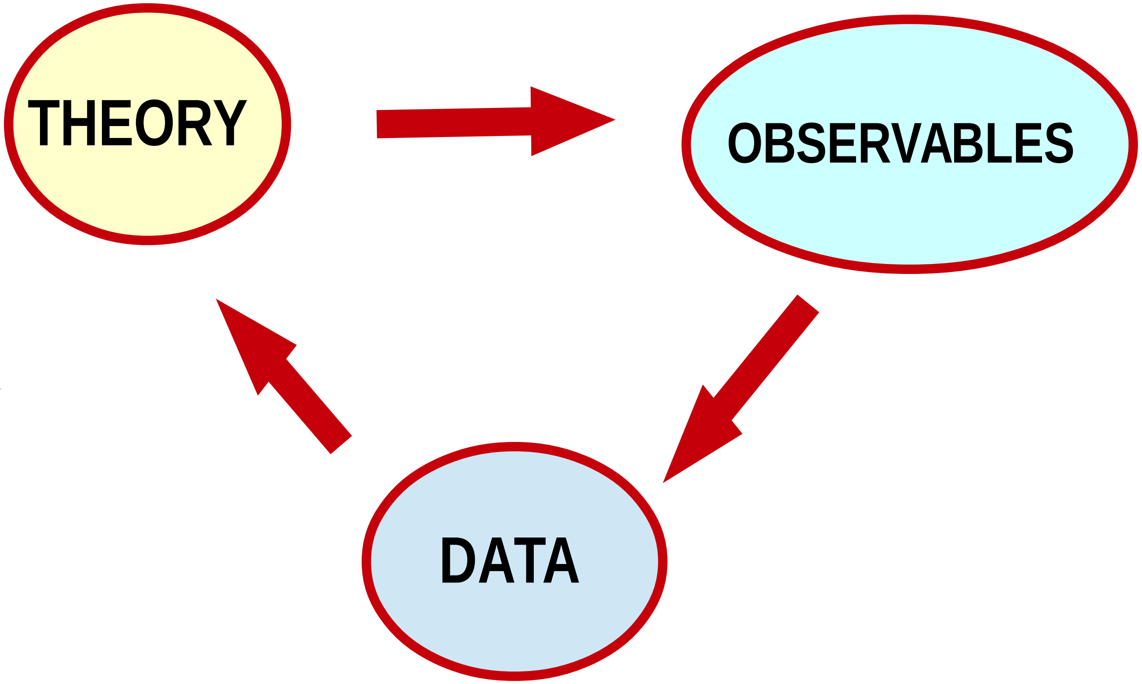
- ➪ model → signatures → data link is well explored, it is time to start tackling **data → model** problem
  - ➤ requires machine learning framework over theory-signature space
  - ➤ database of models and signatures (e.g. HEPMDB)
  - ➤ **your participation!**

Thank you!

Backup Slides

We need HEP/DM "tools" first

- **Theory → Signature link**
  - MicrOMEGAs and MadDM
  - CalcHEP & MadGraph
  - models and repositories
  - Signatures,examples, remarks
- **Signature → Data link**
  - Checkmate, MadAnalysis, Gambit
- **Data → Theory link**
  - The inverse problem of decoding of the underlying theory from signal



DIM5/6 operators (spin 0,1/2,1)

Complex scalar DM†	
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	$[C1]^*$
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}i\gamma^5 q$	$[C2]^*$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	$[C3]$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma^5 q$	$[C4]$
$\frac{1}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	$[C5]^*$
$\frac{1}{\Lambda^2}\phi^\dagger\phi\tilde{G}^{\mu\nu}G_{\mu\nu}$	$[C6]^*$

Dirac fermion DM†	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	[D1]*
$\frac{1}{\Lambda^2}\bar{\chi}i\gamma^5\chi\bar{q}q$	[D2]*
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}i\gamma^5 q$	[D3]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	[D4]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	[D5]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	[D6]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	[D7]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	[D8]
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	[D9]*
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}i\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	[D10]*

Complex vector DM‡	
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}q$	[V1]*
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}i\gamma^5 q$	[V2]*
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}\gamma^\mu q$	[V3]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[V4]
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}i\sigma^{\mu\nu}q$	[V5]
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}\sigma^{\mu\nu}\gamma^5 q$	[V6]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu q$	[V7P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu q$	[V7M]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu\gamma^5 q$	[V8P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[V8M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu q$	[V9P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu q$	[V9M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu\gamma^5 q$	[V10P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu\gamma^5 q$	[V10M]
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu G^{\rho\sigma}G_{\rho\sigma}$	$[V11]^*$
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu\tilde{G}^{\rho\sigma}G_{\rho\sigma}$	$[V12]^*$

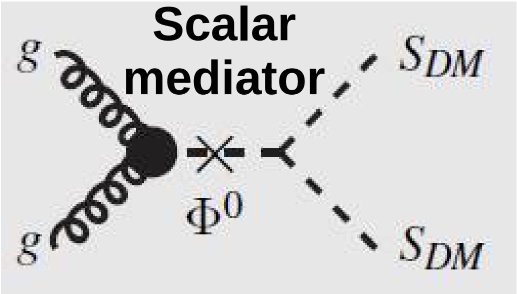
* operators applicable to real DM fields, modulo a factor 1/2

† Listed in J. Goodman *et al.*, *Constraints on Dark Matter from Colliders*, Phys.Rev. **D82** (2010) 116010, [arXiv:1008.1783]

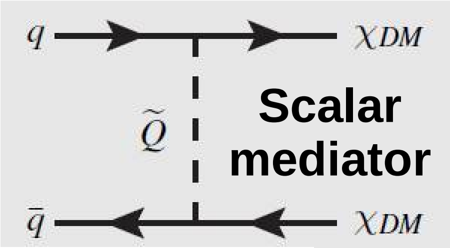
‡ All but V11 and V12 listed in Kumar *et al.*, *Vector dark matter at the LHC*, Phys. Rev. **D92** (2015) 095027, [arXiv:1508.04466]

Mapping EFT operators to simplified models

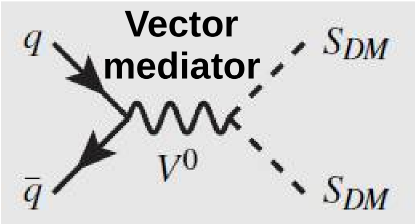
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ $\longrightarrow$



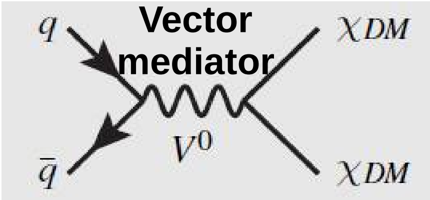
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ $\longrightarrow$

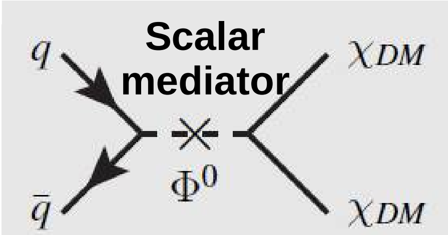


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ $\longrightarrow$

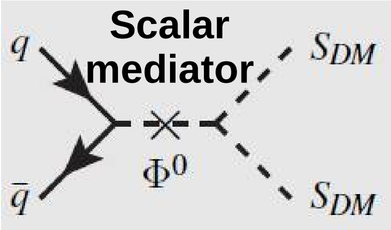


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ $\longrightarrow$





C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ $\longrightarrow$



D9,D10 $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \longrightarrow \frac{8}{\Lambda^2}\left[\bar{\chi}q\bar{q}\chi - \frac{1}{4}\left(\bar{\chi}\chi\bar{q}q + \bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q + \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q - \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q\right)\right]$

Distinguishing the DM operators: χ^2 for pairs of DM operators

$$\chi^2_{k,l} = \min_{\kappa} \sum_{i=3}^{7} [(\frac{1}{2} N_i^k - \kappa \cdot N_i^l)/(10^{-2} BG_i)]^2$$

: if χ^2>9.48 (95%CL for 4 DOF) – operators can be distinguished!

			Complex Scalar DM				Dirac Fermion DM				Complex Vector DM							
			100 GeV		1000 GeV		100 GeV		1000 GeV		100 GeV				1000 GeV			
			C1	C5	C1	C5	D1	D9	D1	D9	V1	V3	V5	V11	V1	V3	V5	V11
Complex Scalar DM	100 GeV	C1	0.0	19.7	25.54	74.63	11.73	41.79	25.78	52.58	22.97	32.89	54.35	73.34	25.18	34.61	52.34	80.85
		C5	15.74	0.0	0.37	16.25	1.11	3.93	0.74	7.35	0.18	1.53	8.2	15.73	0.44	1.9	7.24	19.13
	1000 GeV	C1	19.89	0.36	0.0	11.82	2.33	2.09	0.27	4.58	0.06	0.45	5.29	11.41	0.06	0.68	4.42	14.36
		C5	50.86	13.86	10.34	0.0	21.03	3.7	11.18	1.53	11.57	6.82	1.26	0.01	10.84	6.1	1.61	0.14
Dirac Fermion DM	100 GeV	D1	9.88	1.17	2.52	25.99	0.0	9.23	2.4	14.17	1.85	5.09	15.34	25.37	2.29	5.85	13.85	29.81
		D9	30.49	3.59	1.96	3.96	7.99	0.0	2.71	0.52	2.49	0.62	0.73	3.69	2.31	0.39	0.56	5.36
	1000 GeV	D1	20.31	0.73	0.27	12.92	2.25	2.93	0.0	5.42	0.32	0.82	6.33	12.58	0.08	1.18	5.08	15.7
		D9	37.38	6.54	4.18	1.6	11.96	0.5	4.89	0.0	4.98	2.02	0.06	1.44	4.56	1.61	0.04	2.55
Complex Vector DM	100 GeV	V1	18.06	0.17	0.06	13.34	1.72	2.68	0.32	5.5	0.0	0.77	6.25	12.9	0.1	1.06	5.34	16.03
		V3	24.86	1.45	0.44	7.57	4.57	0.65	0.79	2.14	0.74	0.0	2.68	7.25	0.57	0.03	2.04	9.59
		V5	38.36	7.24	4.79	1.3	12.86	0.7	5.67	0.06	5.61	2.5	0.0	1.14	5.24	2.04	0.13	2.13
		V11	50.03	13.43	10.0	0.01	20.55	3.45	10.89	1.39	11.2	6.54	1.11	0.0	10.52	5.83	1.49	0.16
	1000 GeV	V1	19.73	0.43	0.06	12.46	2.13	2.48	0.08	5.02	0.1	0.59	5.83	12.09	0.0	0.89	4.78	15.14
		V3	25.96	1.78	0.65	6.72	5.21	0.4	1.12	1.7	1.01	0.03	2.17	6.41	0.85	0.0	1.65	8.6
		V5	37.33	6.47	4.04	1.68	11.72	0.55	4.59	0.04	4.84	1.93	0.14	1.55	4.34	1.57	0.0	2.72
		V11	54.48	16.14	12.42	0.13	23.85	4.95	13.43	2.41	13.74	8.55	2.03	0.16	13.01	7.73	2.57	0.0

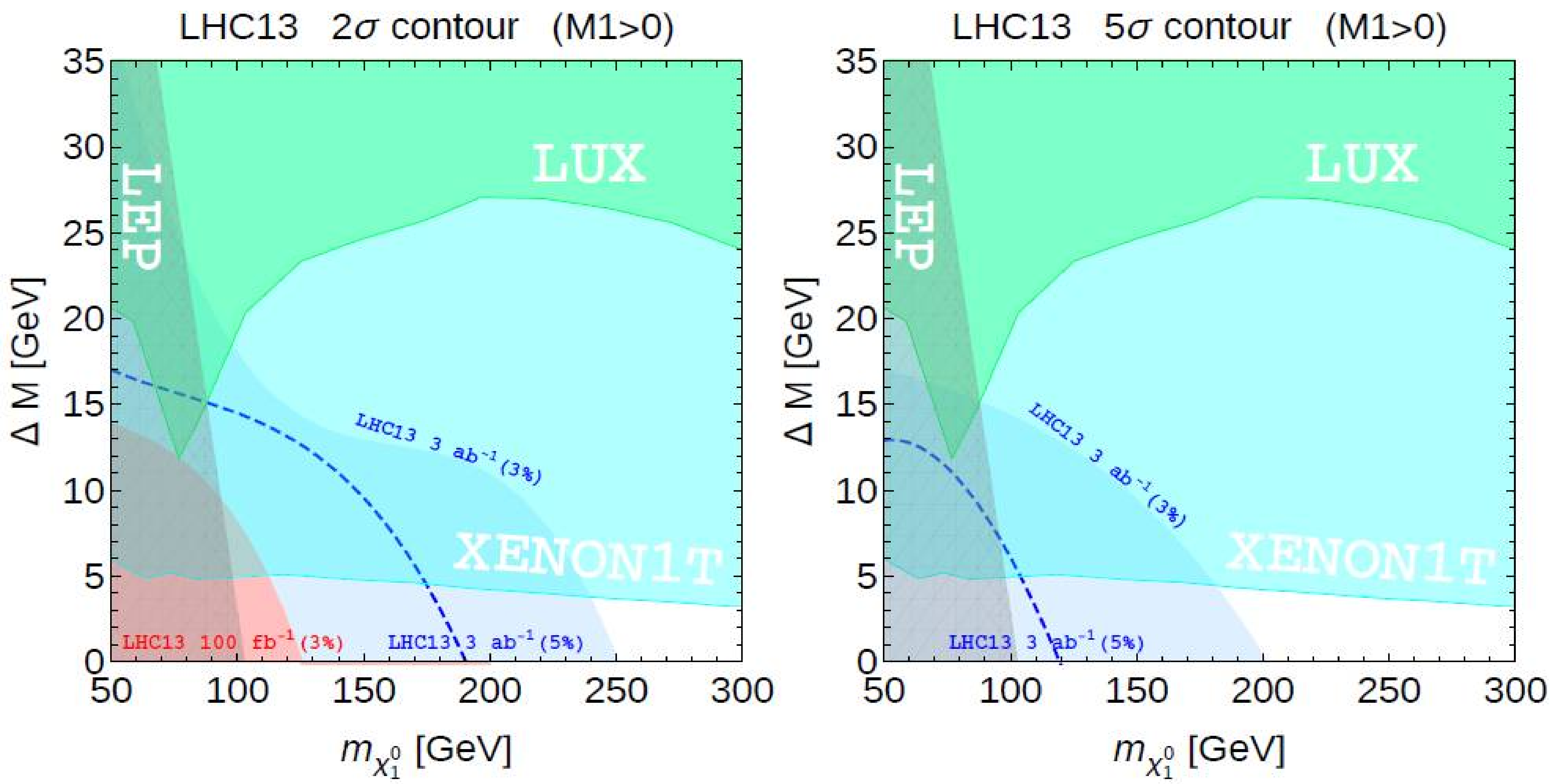
LHC@13TeV Reach for spin 0 and ½ DM

	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Scalar DM	C1 & C2	$1/\Lambda$	456	424	98	1168	1115	267
	C3 & C4	$1/\Lambda^2$	750	746	400	1134	1131	662
	C5 & C6	$1/\Lambda^2$	1621	1576	850	2656	2611	1398
Dirac Fermion DM	D1 & D3	$1/\Lambda^2$	931	940	522	1386	1405	861
	D2 & D4	$1/\Lambda^2$	952	936	620	1426	1399	1022
	D1T & D4T	$1/\Lambda^2$	735	729	476	1217	1199	780
	D2T	$1/\Lambda^2$	637	638	407	1053	1052	670
	D3T	$1/\Lambda^2$	586	625	391	969	938	644
	D5 & D7	$1/\Lambda^2$	1058	967	721	1580	1591	1190
	D6 & D8	$1/\Lambda^2$	978	1050	579	1608	1585	955
	D9 & D10	$1/\Lambda^2$	1587	1592	958	2613	2619	1580

LHC@13TeV Reach for spin 1 DM

	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Vector DM	V1 & V2	M_{DM}^2/Λ_D^3	831	833	714	1162	1161	997
	V3 & V4	M_{DM}^2/Λ_D^4	930	931	833	1196	1193	1070
	V5 & V6	M_{DM}^2/Λ_D^3	784	791	711	1095	1104	993
	V7M & V8M	M_{DM}^2/Λ_D^4	930	926	882	1195	1193	1130
	V7P & V8P	M_{DM}/Λ_D^3	796	791	652	1112	1102	911
	V9M & V10M	M_{DM}/Λ_D^3	796	799	737	1109	1114	1027
	V9P & V10P	M_{DM}/Λ_D^3	794	782	609	1110	1089	850
	V11 & V11A	M_{DM}^2/Λ_D^4	1435	1442	1309	1844	1850	1683

LHC/DM direct detection sensitivity



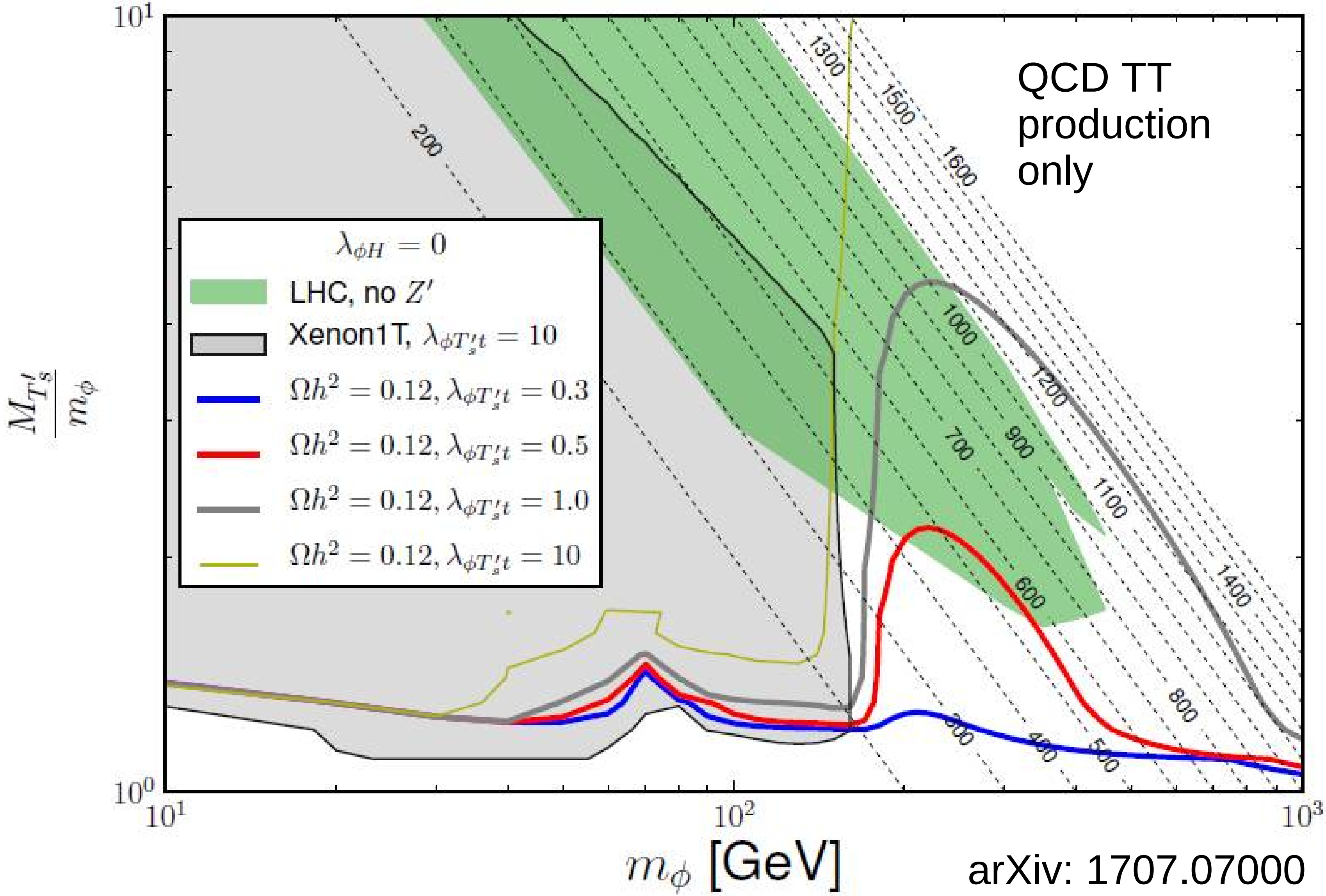
AB, Barducci,Bharucha,Porod,Sanz JHEP, 1504.02472

- SUSY DM, can be around the corner (~100 GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small DM (NSUSY) region

Complementarity of LHC and non-LHC DM searches

for the model with Vector Resonances, Top Partners and Scalar DM

TT → t t DM DM



arXiv: 1707.07000