

Dark Matter Tools: Status & Prospects



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The (Inconvenient) Truth about DM

We have many hints DM exist, **but no direct evidence!**

If particle DM exists, **what do we know about it?**

Dark Matter:

1. Mass = ???
2. Spin = ???
3. Decays = ???
4. Interactions = Gravity, ???
5. Elementary = ???
6. ...

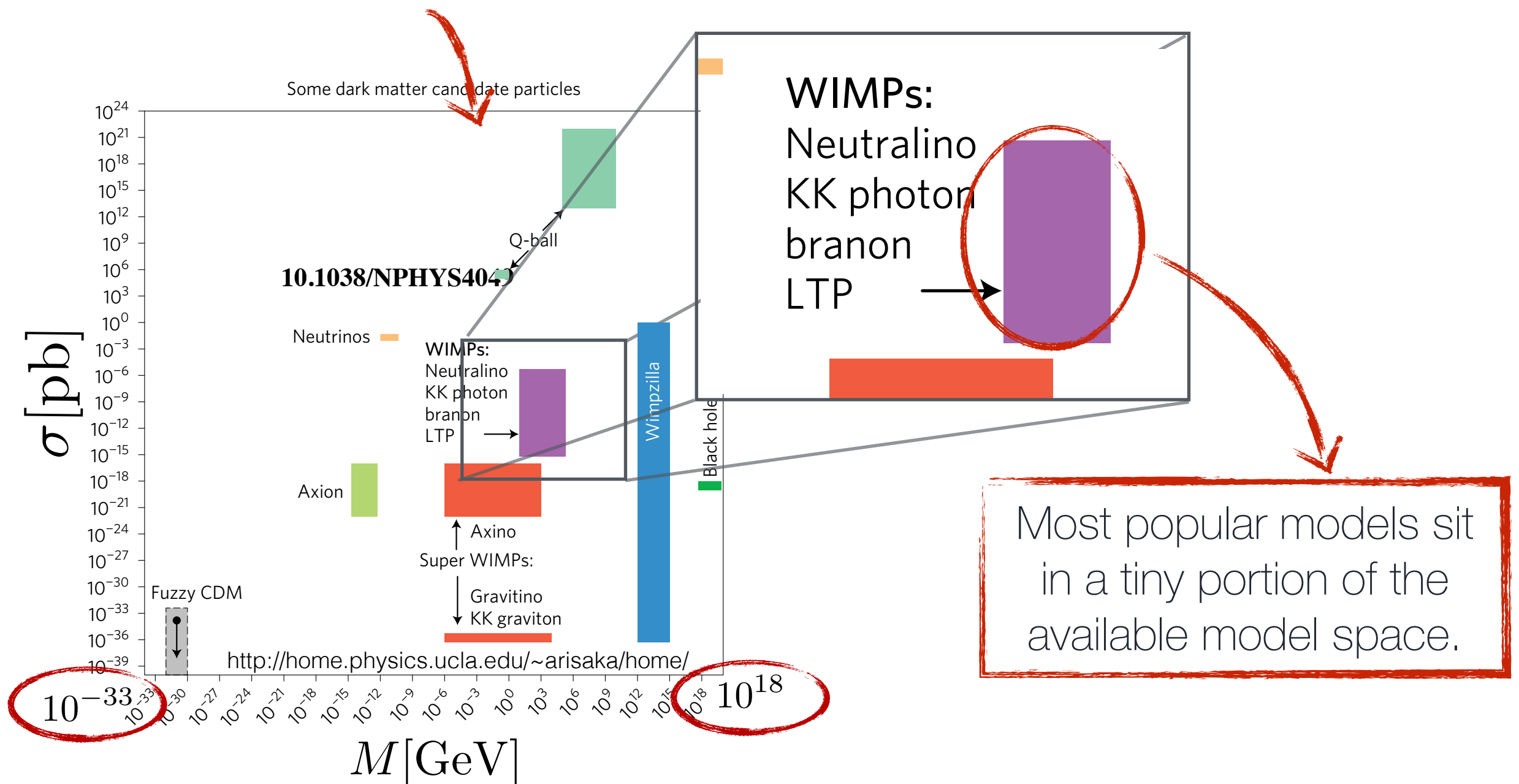
DM could in principle only interact gravitationally...

... **in which case, the rest of
this talk is completely useless**

The (Inconvenient) Truth about DM

We **do not have any sense of scale** associated with dark matter!

Large number of viable models, spanning **many orders of magnitude** in dark matter mass and interaction strength.



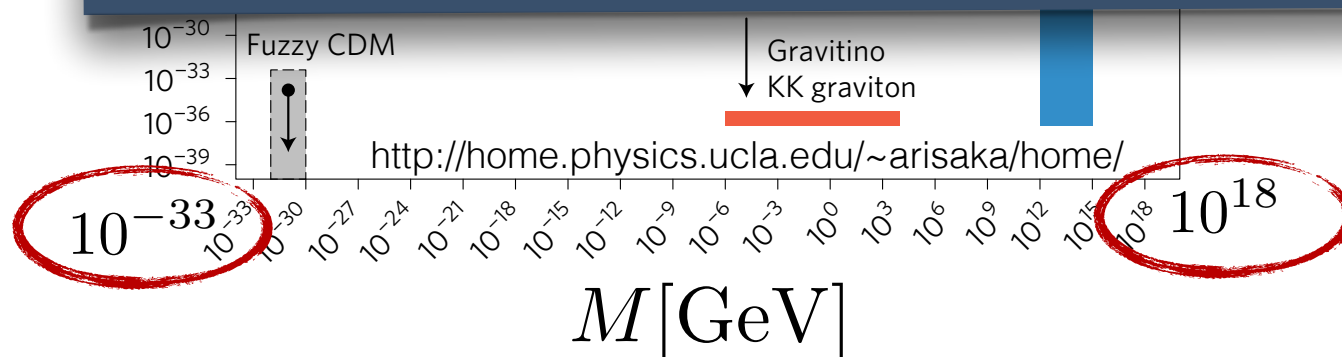
The (Inconvenient) Truth about DM

We **do not have any sense of scale** associated with dark matter!

For **rapid progress on the theory side**

DM tools need to be:

1. Comprehensive
2. Integrated (Inheritance)
3. Accurate/Precise (NLO)



In a tiny portion of the available model space.

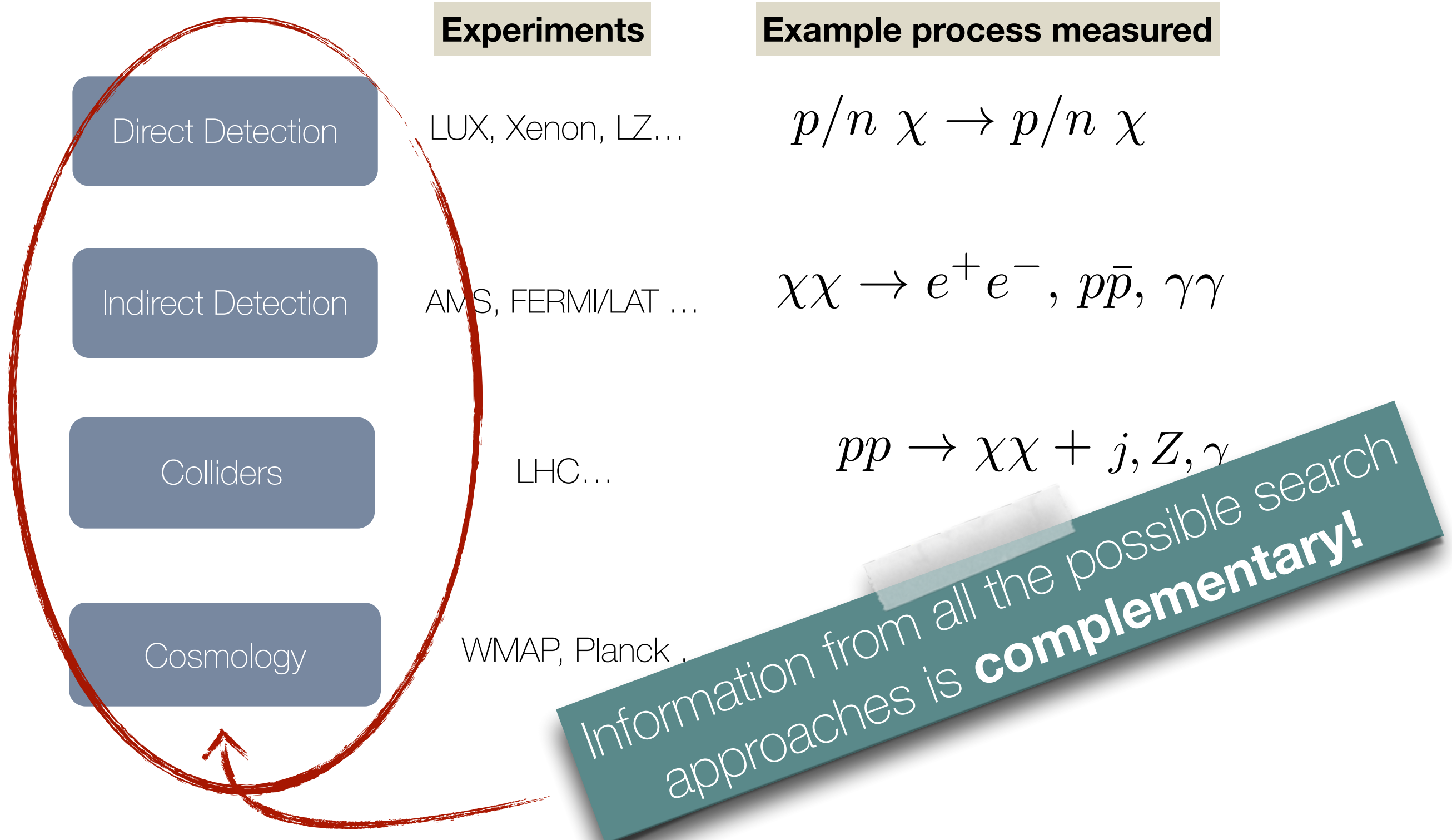
Comprehensive DM tools

You can “attack” dark matter from many directions...

	Experiments	Example process measured
Direct Detection	LUX, Xenon, LZ...	$p/n \chi \rightarrow p/n \chi$
Indirect Detection	AMS, FERMI/LAT ...	$\chi\chi \rightarrow e^+e^-, p\bar{p}, \gamma\gamma$
Colliders	LHC, beam dump...	$pp \rightarrow \chi\chi + j, Z, \gamma...$
Cosmology	WMAP, Planck ...	$\chi\chi \rightarrow \text{all}$

Comprehensive DM tools

You can “attack” dark matter from many directions...



Comprehensive DM tools

Comprehensive DM tools need to be able to calculate **all possible signatures** while taking into account **complex parameter spaces!**

Indirect Detection

AMS, FERMI/LAT ...

$$\chi\chi \rightarrow e^+e^-, p\bar{p}, \gamma\gamma$$

Colliders

LHC...

$$pp \rightarrow \chi\chi + j, Z, \gamma$$

Cosmology

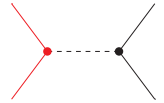
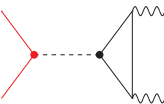
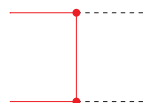
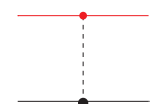
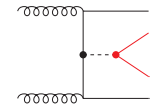
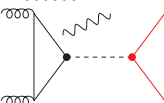
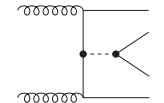
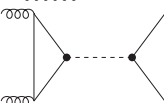
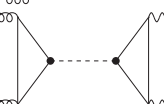
WMAP, Planck ...

Information from all the possible search approaches is **complementary!**

Example: Top-philic DM simplified model

$$\mathcal{L}_{t,X}^{Y_0} = - \left(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X \right) Y_0$$

Plethora of signatures:

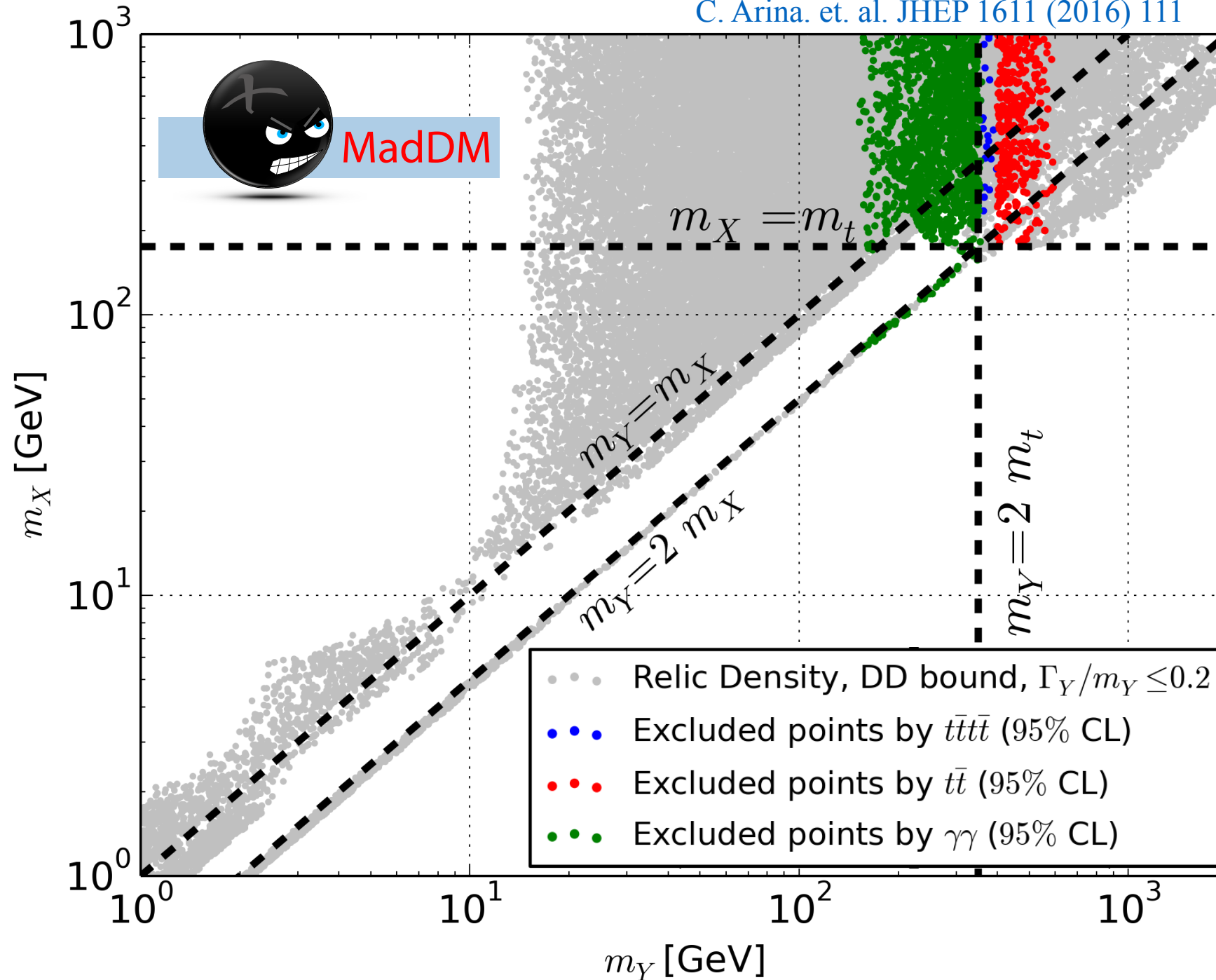
Cosmology	relic indirect		$m_X > m_t$	Planck, FermiLAT
			$m_X < m_t$	
Astrophysics			$m_X > m_Y$	
	direct		$m_X > 1 \text{ GeV}$	LUX, CDMSLite
Colliders	\cancel{E}_T		$m_Y > 2m_X$	$+t\bar{t}$
			$m_Y > 2m_X$	$+j, +Z, +h$
	no \cancel{E}_T	  	$m_Y > 2m_t$ $m_Y > 2m_t$ $m_Y < 2m_X, 2m_t$	$4t$ $t\bar{t}$ $jj, \gamma\gamma$

Scan over four free parameters (non-trivial): g_t, g_X, m_X, m_Y

Example: top-philic DM

LHC constraints on top-philic dark matter

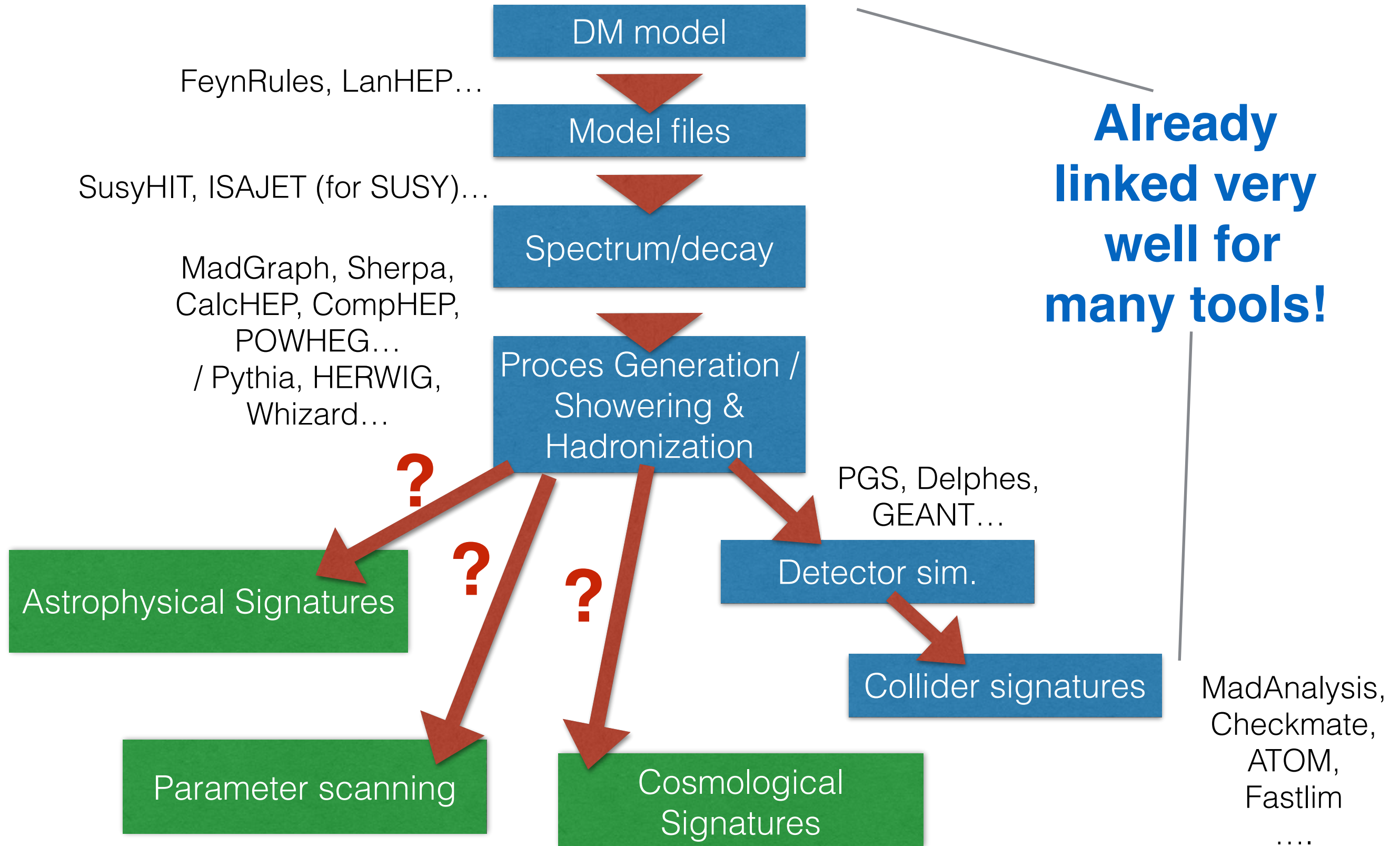
C. Arina. et. al. JHEP 1611 (2016) 111



darkBit now
doing something
similar

This study is an **proof of principle** that **automated comprehensive studies** of dark matter models **are within reach!**

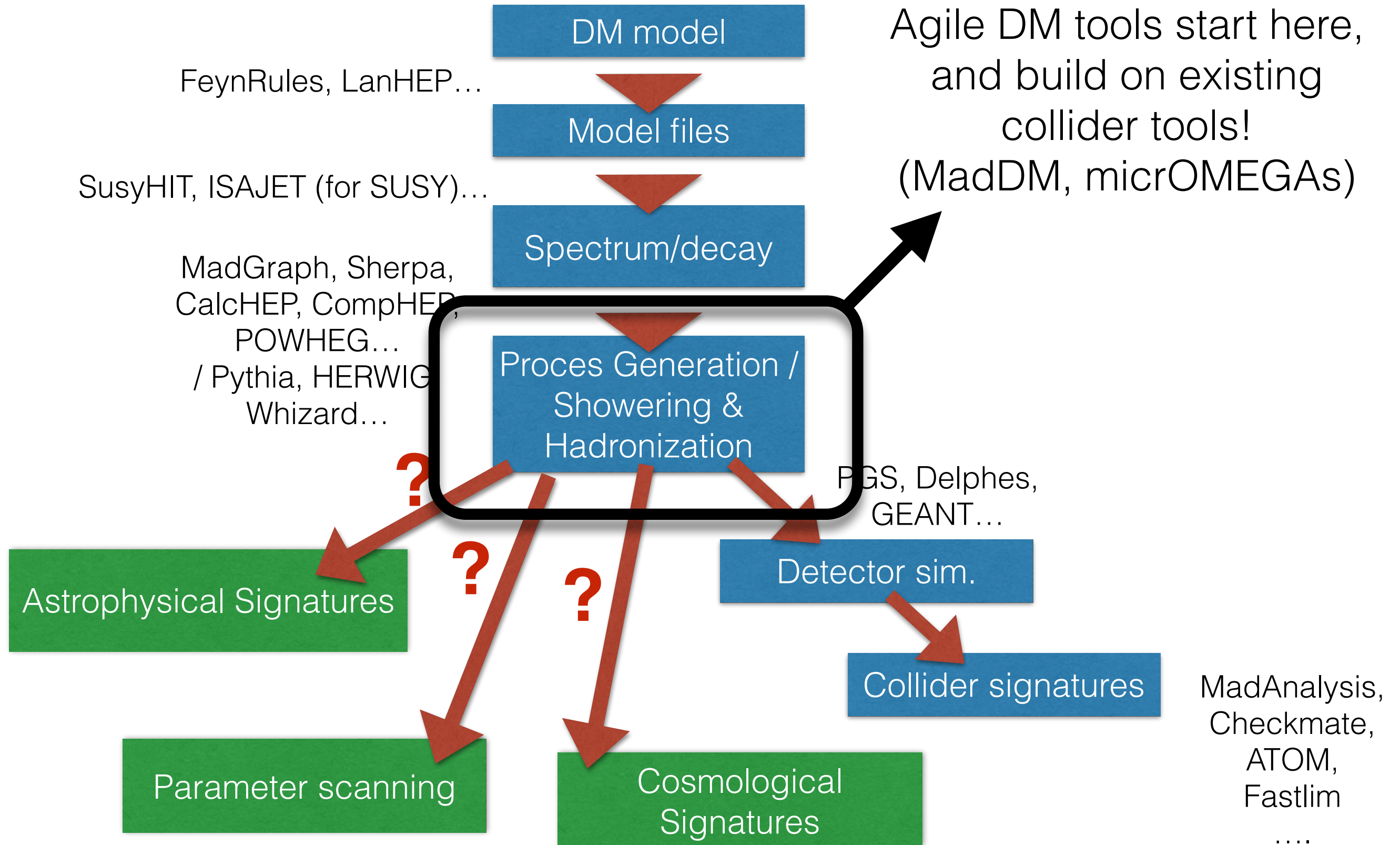
DM Tool Integration



**Already
linked very
well for
many tools!**

What about these?!

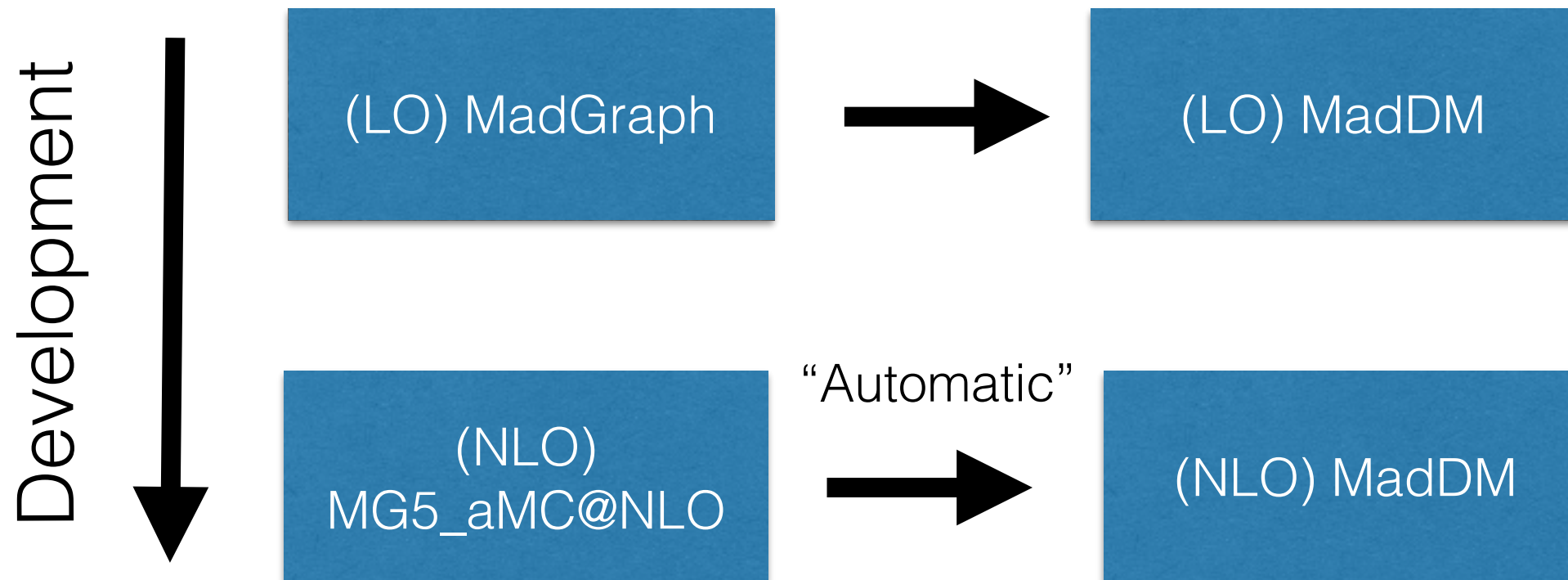
DM Tool Integration



What about these?!

DM Tool Integration

DM tools **can and should inherit** features of collider tools (e.g. MadDM and micrOMEGAs):



- typically requires a **high degree of tool integration**
- demands that we **rethink how to code the tools.**

Example issue: Does the divergence subtraction scheme / matrix element integration work for initial states with $v \sim 10^{-6}$?

Integration of MadDM w/ MG5_aMC@NLO

MadDM is now a **MG5 plugin** (took a long time and required some structural changes both in MadDM and MG5_aMC@NLO)

This means that you can install it using the MG5 interface

```
MG5_aMC> install maddm
```

It also means that MadDM now **inherits the features of MG5**

★ **Automatic resonance width computation**

```
DECAY 54 AUTO # WY0 (set up in param_card.dat)
```

★ **Integrated parameter scans**

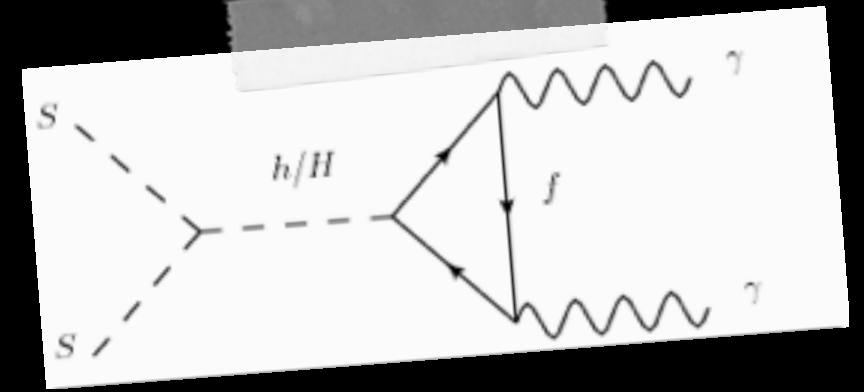
```
54 scan:range(100, 1000, 100) # MY0 (set up in param_card.dat)
```

★ **Ability to do calculations at NLO / Loop induced!**

Integration of MadDM w/ MG5_aMC@NLO

We also **completely revamped the interface**

```
import model DMsimp_spin0_LO_UFO
define darkmatter xd
generate relic_density
generate direct_detection
generate indirect_detection b b~
add indirect_detection a a
...
output DMsimp
launch
```



← Will do loop induced annihilation!!
← Collider signatures here soon!!

We still need to finish the astro-physical part for the ID (cosmic ray flux/propagation)!

Integration of MadDM w/ MG5_aMC@NLO

The result of **launch** feels and looks like a MG5 run:

Here is the current status of requested run :

* Enter the name/number to (de-)activate the corresponding feature

1. Compute the Relic Density relic = ON

2. Compute Direct Detection direct = ON

3. Compute Directional Detection directional = ON

4. Compute Indirect Detection indirect = ON

You can also edit the various input card:

* Enter the name/number to open the editor

* Enter a path to a file to replace the card

* Enter set NAME value to change any parameter to the requested value

4. Edit the model parameters [param]

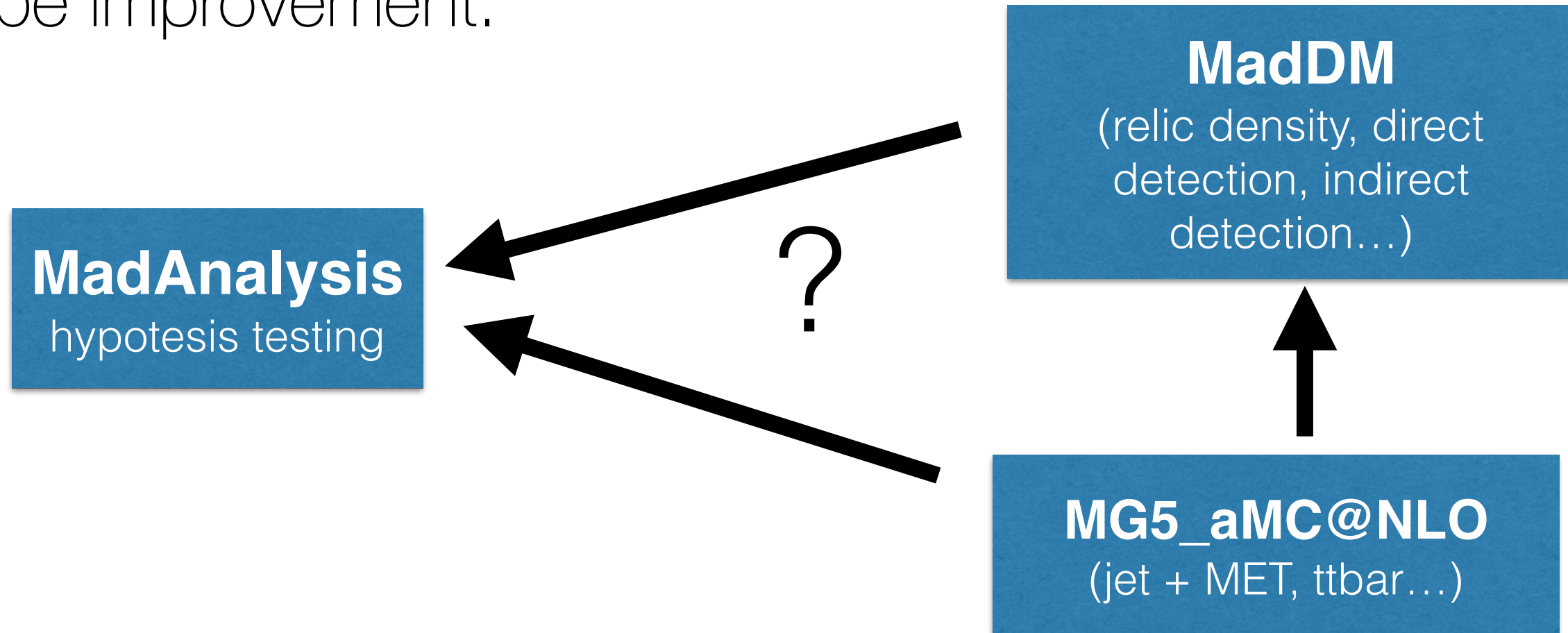
5. Edit the MadDM options [maddm]

A standard output:

```
INFO: *** RESULTS ***
INFO: relic density : 8.69e+04 Model excluded (relic not in range [0,0.12])
INFO: x_f : 5.00
INFO: sigmav(xf) : 1.35e-15 GeV^-2 = 5.25e-07 pb
INFO: sigmaN_SI_p : 2.74e-19 GeV^-2 = 1.07e-10 pb
INFO: sigmaN_SI_n : 2.81e-19 GeV^-2 = 1.09e-10 pb
INFO: sigmaN_SD_p : 4.17e-34 GeV^-2 = 1.62e-25 pb
INFO: sigmaN_SD_n : 2.01e-33 GeV^-2 = 7.82e-25 pb
INFO: Nevents : 1
INFO: smearing : 0.00e+00
INFO: Indirect detection cross section at v = 1e-03: 2.33e-09+-4e-12
```

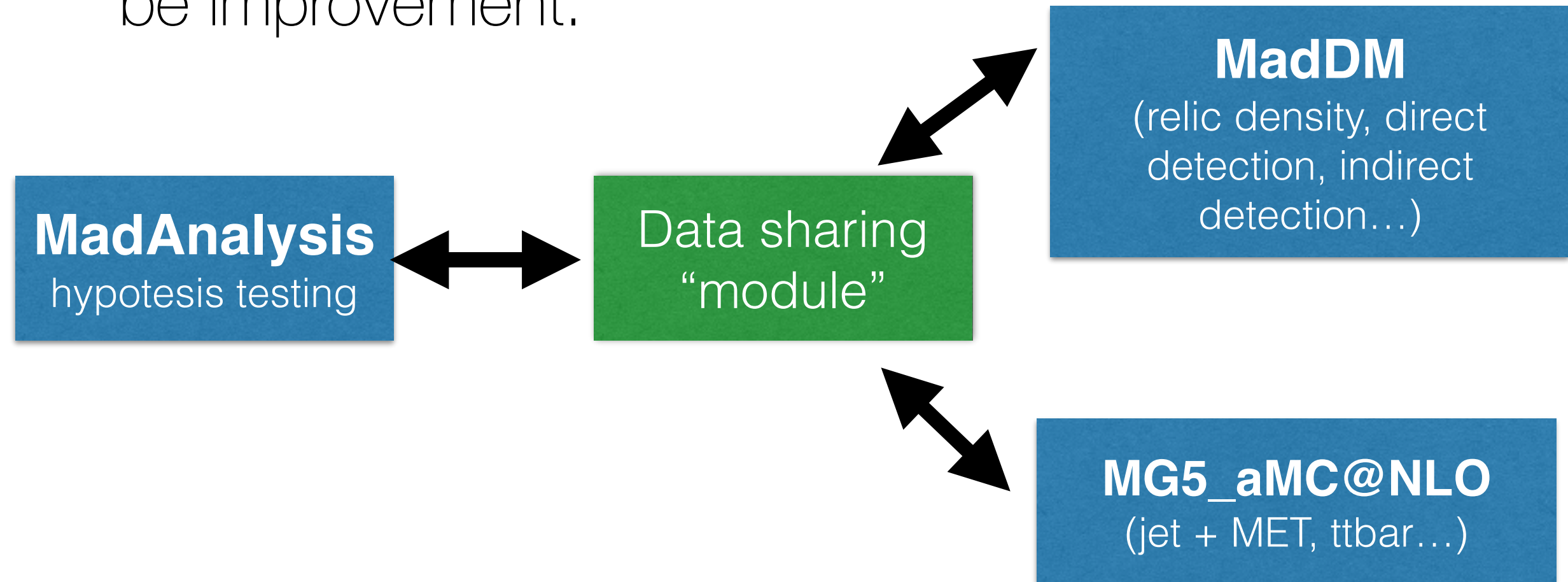
DM Tool Integration

MG **plugins are great**, but the framework could be improved.



DM Tool Integration

MG **plugins are great**, but the framework could be improved.



Different plugins/codes should be able to
“communicate” efficiently!

DM at Higher Order

There are **currently** two leading (but not only) reasons to go to higher order in perturbation theory in DM physics:

- 1) **Precision**

(at the moment) mostly for colliders

- 2) **Loop induced processes**

relevant for colliders, relic density, indirect detection...

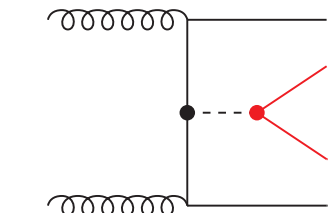
DM at Higher Order

1) Precision

Mostly studied in the context of **simplified models**. (NLO in QCD)

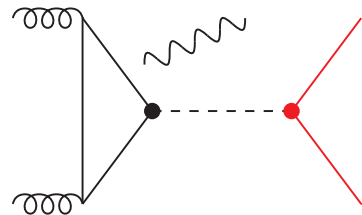
e.g. SM+DM+mediator 

\cancel{E}_T



$$m_Y > 2m_X$$

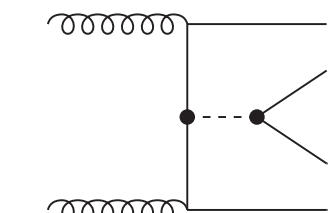
$$+t\bar{t}$$



$$m_Y > 2m_X$$

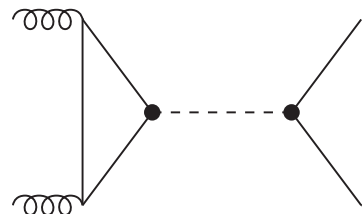
$$+j, +Z, +h$$

no \cancel{E}_T



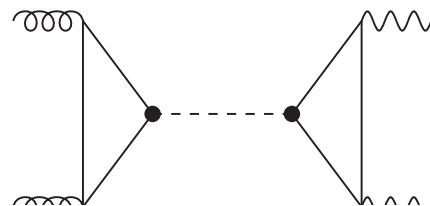
$$m_Y > 2m_t$$

$$4t$$



$$m_Y > 2m_t$$

$$t\bar{t}$$



$$m_Y < 2m_X, 2m_t$$

$$jj, \gamma\gamma$$

DM at Higher Order

1) Precision

Mostly studied in the context of **simplified models**. (NLO in QCD)

e.g. SM+DM+mediator

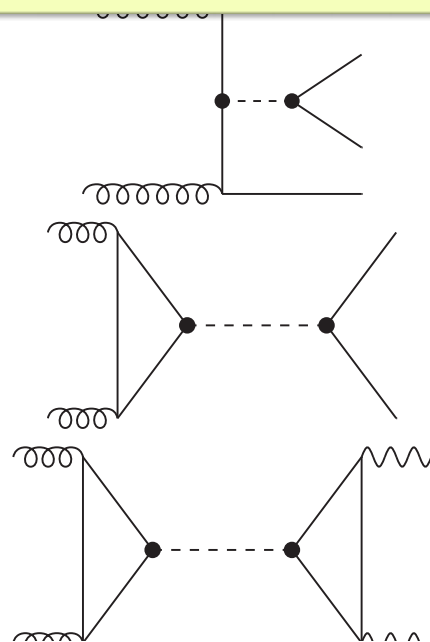


\cancel{E}

Precision **not paramount for relic density and indirect detection**

(very large systematic uncertainties from cosmology and astro-physics)

no \cancel{E}_T



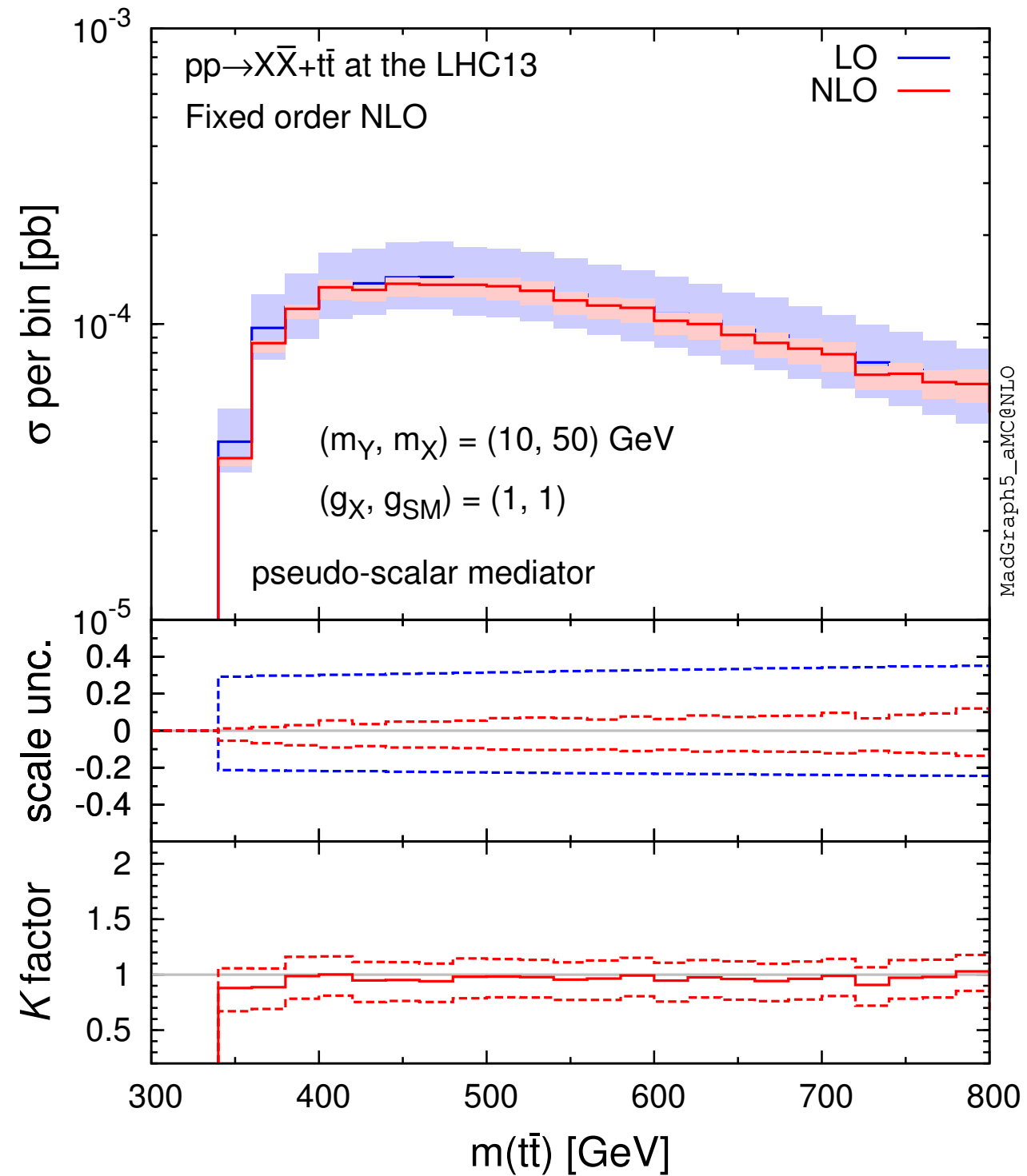
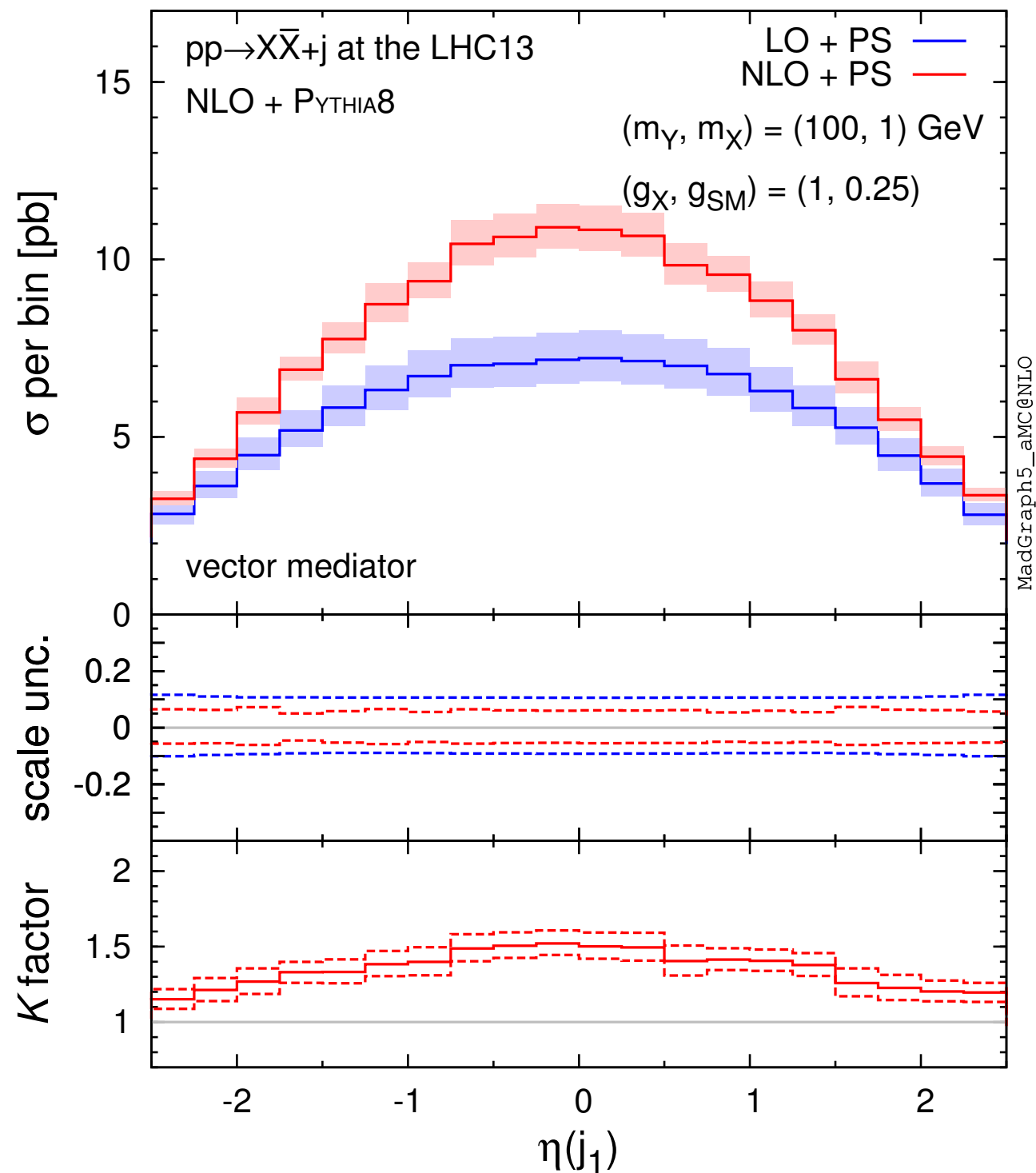
$$m_Y > 2m_t \quad 4t$$

$$m_Y > 2m_t \quad t\bar{t}$$

$$m_Y < 2m_X, 2m_t \quad jj, \gamma\gamma$$

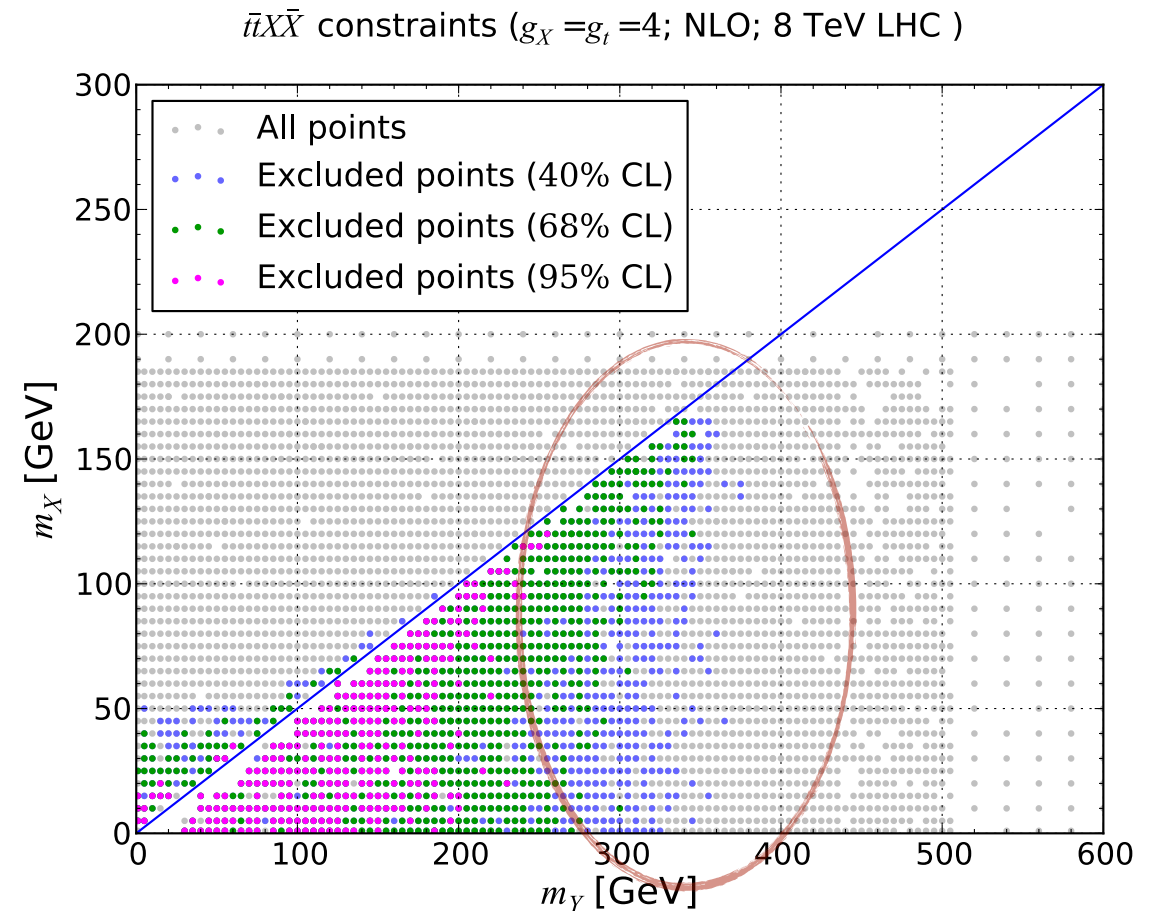
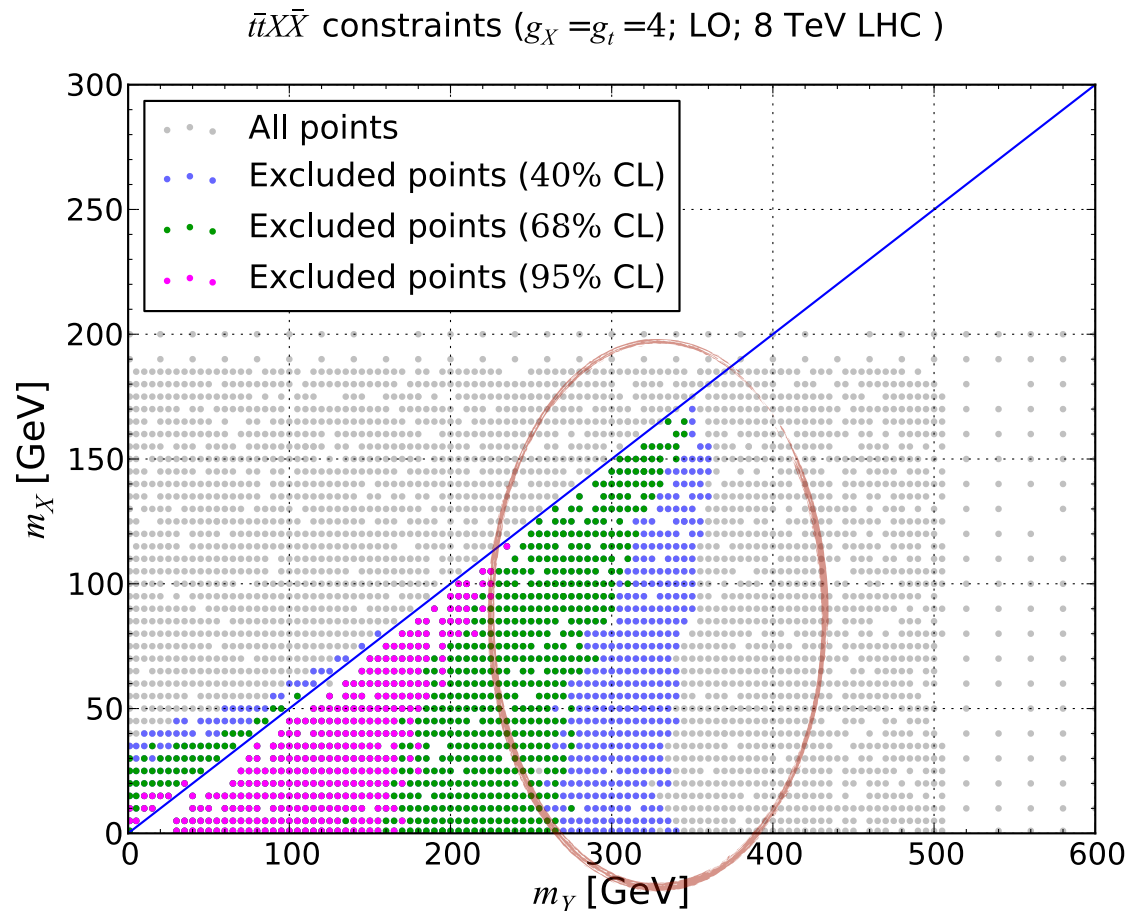
DM at Higher Order

Higher order corrections affect **overall rates, distribution shapes and scale dependence:**



DM at Higher Order

Scale dependence is important for **interpretation** of the LHC dark matter searches!



	(m_Y, m_X)	σ_{LO} [pb]	CL_{LO} [%]	σ_{NLO} [pb]	CL_{NLO} [%]
I	(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$98.7^{+0.8\%}_{-13.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$	$95.0^{+2.7\%}_{-0.4\%}$
II	(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$74.7^{+19.7\%}_{-17.7\%}$	$0.926^{+5.7\%}_{-10.4\%}$	$84.2^{+0.4\%}_{-14.4\%}$
III	(240, 100) GeV	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$

DM at Higher Order

Mostly studied in the context of simplified models. (NLO in QCD)

Publication	Mediator (s-ch.)	DM	Interactions
arXiv:1508.05327 (Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen)	S, PS, V, PV	Dirac, Scalar, CScalar	q, t
arXiv:1508.00564 (Mattelaer, Vryonidou)	S, PS, V, PV	Dirac	b, t (loop induced)
arXiv:1509.05785 (Neubert,	S, PS, V, PV	Dirac, Cscalar	Z

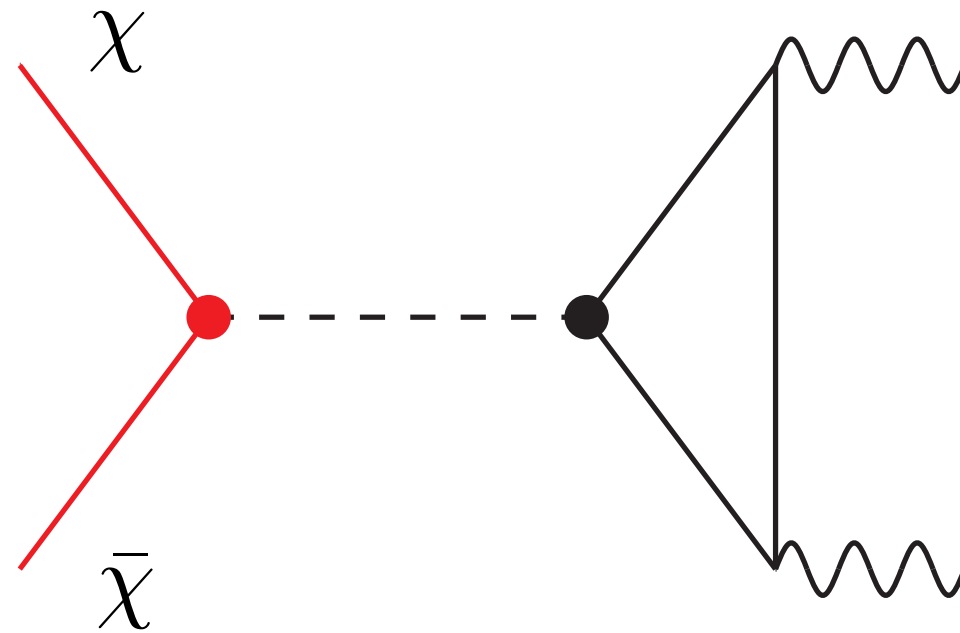


With the help of FeynRules+NLOCT
+MG5_aMC, all of these papers were
written within in a couple of months.

DM at Higher Order

2) Loop induced processes

Example:



Currently there is **no DM tool** which can calculate this process (in a generic model)!

Super relevant for **relic density and cosmic ray flux calculations** in some models

Current DM tools

There are a few existing tools on the market, but no tool can do everything yet!

<i>Tool</i>	<i>Relic Density</i>	<i>Direct Detection</i>	<i>Indirect Detection</i>	<i>Colliders</i>	<i>Advanced parameter scanning</i>	<i>Generic model</i>	<i>NLO</i>
MadDM/ MG5_aMC@NLO	Yes	Yes	No/Soon	Yes	No/Soon	Yes	Yes*
micrOMEGAs/ Calchep	Yes	Yes	Yes	Yes	No	Yes	No
darkSUSY***	Yes	Yes	Yes	No	Yes	No	No
DM@NLO	Yes	Yes	Yes	No	No	No	Yes**

* for relic density and ID.

** for colliders, soon for ID, maybe relic density

*** also Isatools, SSARD, Drees, Roskowski

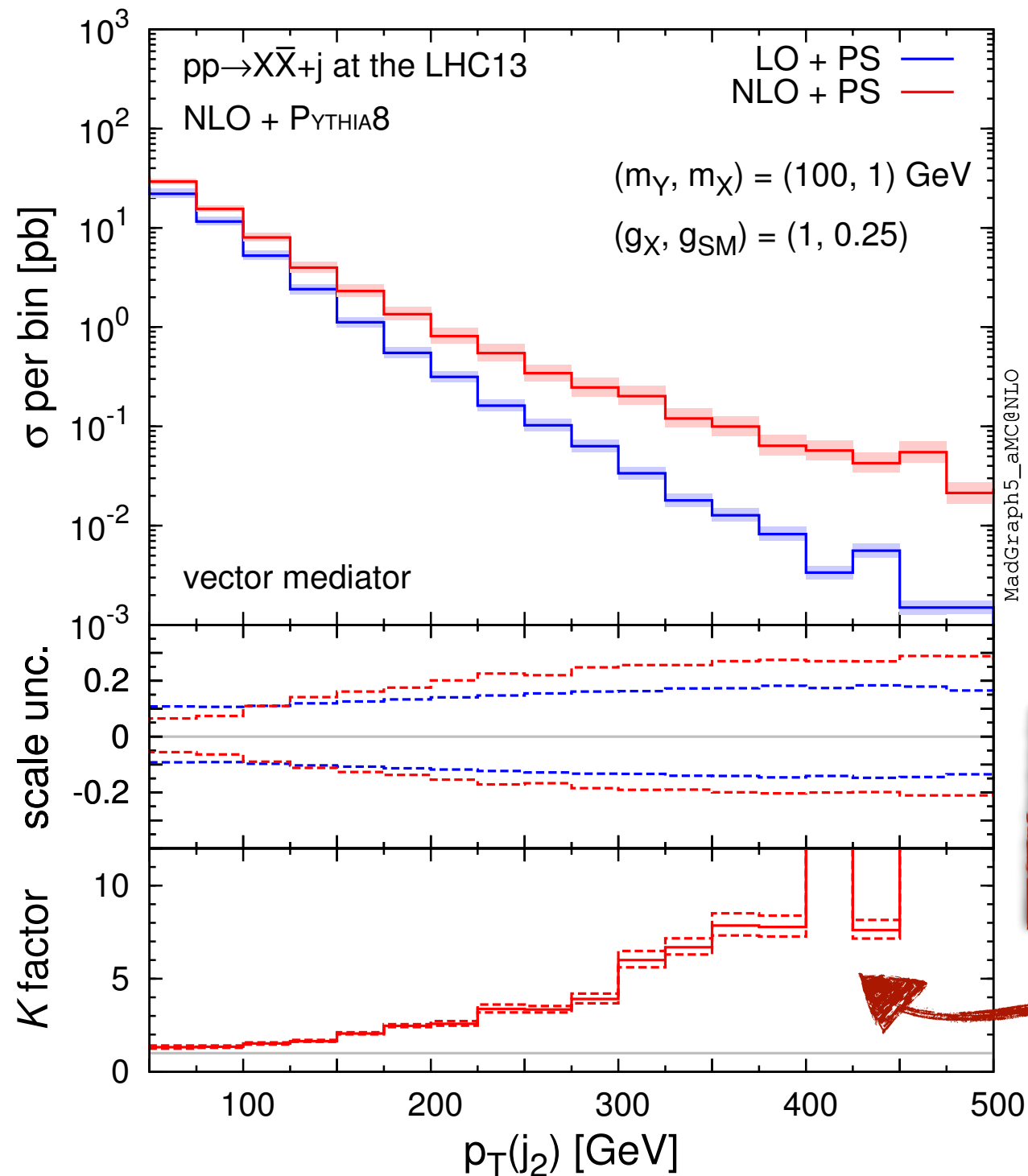
Red color means
no prospects in the
near future!

BACKUP

DM at Higher Order

Giant K-factors in simplified DM models

(Think W+jets with high jet pT at NLO)



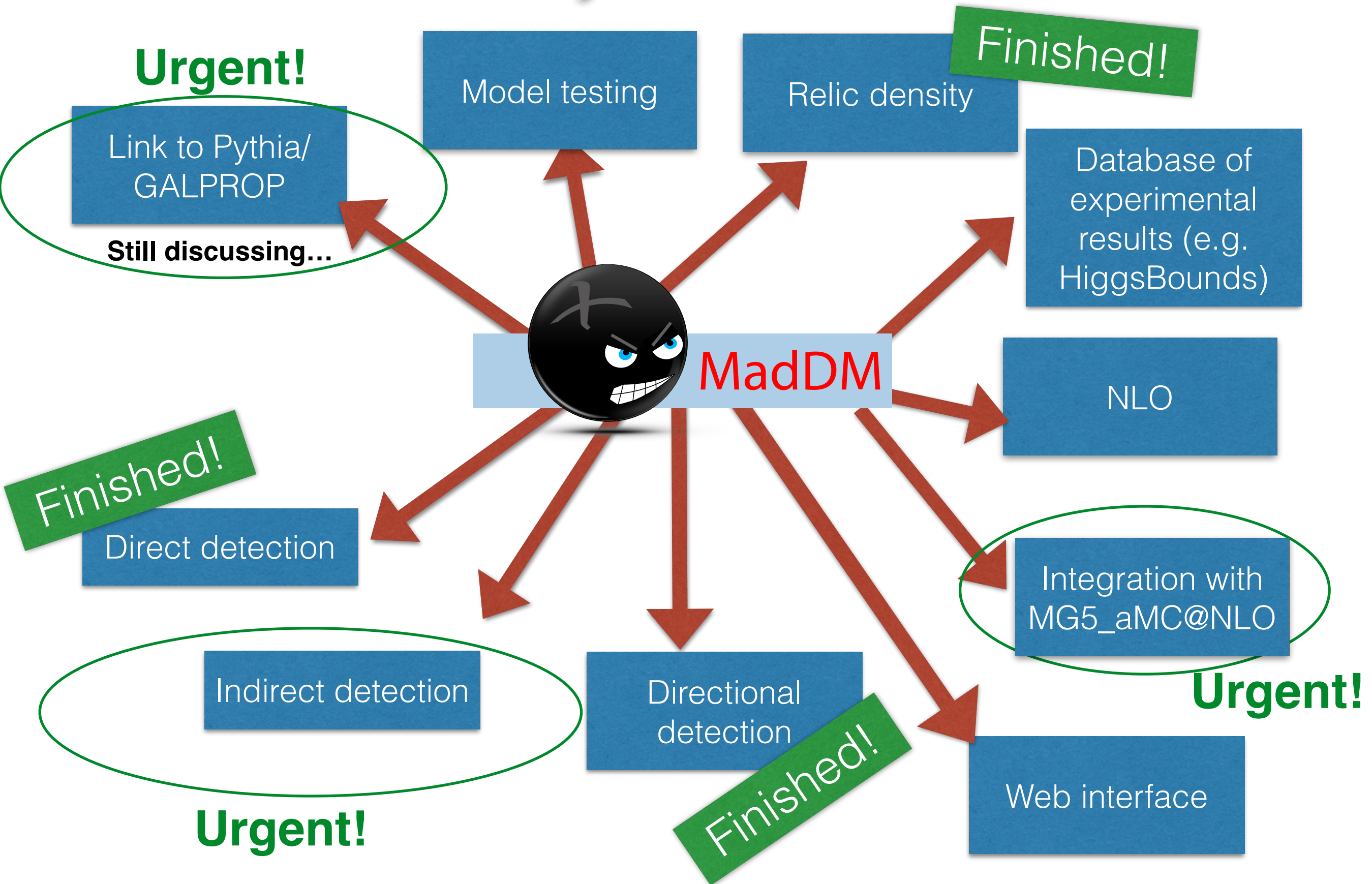
LO: $pp \rightarrow Y_1 + j$

NLO: $pp \rightarrow Y_1 + jj$ also

Relevant when $p_T^j \gg m_Y, m_X$

K-factor $\sim \alpha_s \log^2(p_T^j/m_Y)$

MadDM Status, MC4BSM 2015



MadDM Status, **NOW**

