SUSY 2024
Theory meets Experiment


# LHC Constraints on Dark Matter Models with SModelS v3

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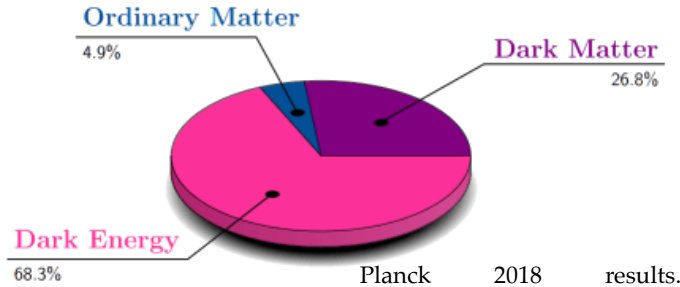
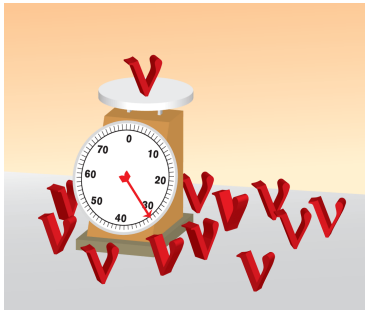
*The SM cannot explain the existence of DM*

## SM Unresolved Issues:



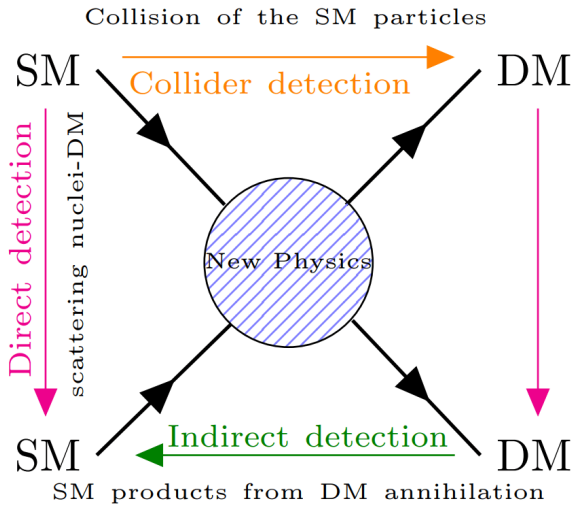

Planck 2018 results. Astronomy & Astrophysics 641 (2020) A6



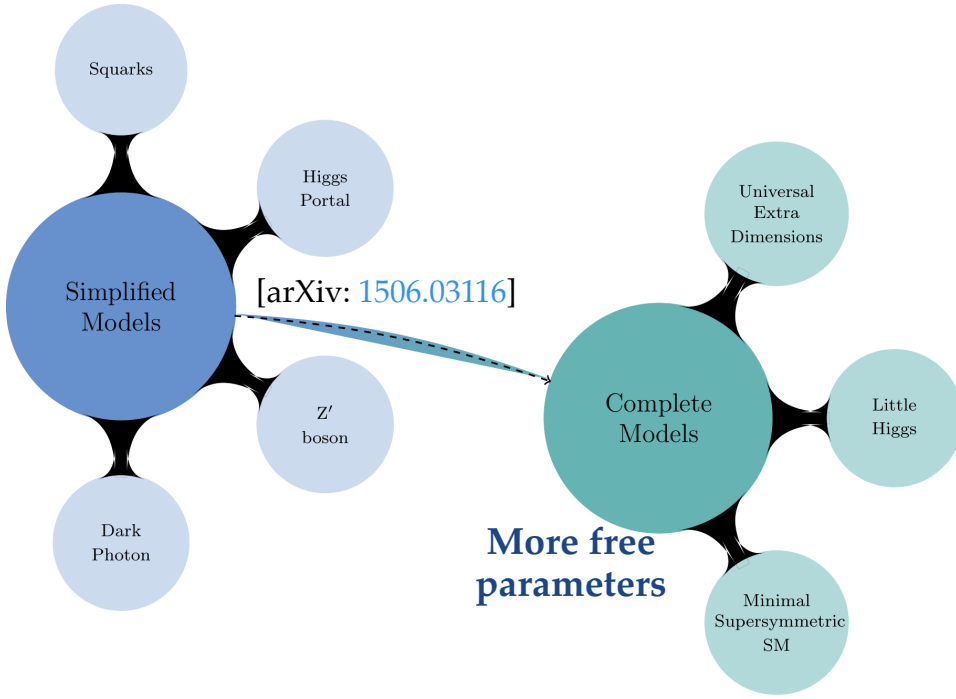
\+

...

**Commonality:**
**New Extensions to the SM?**

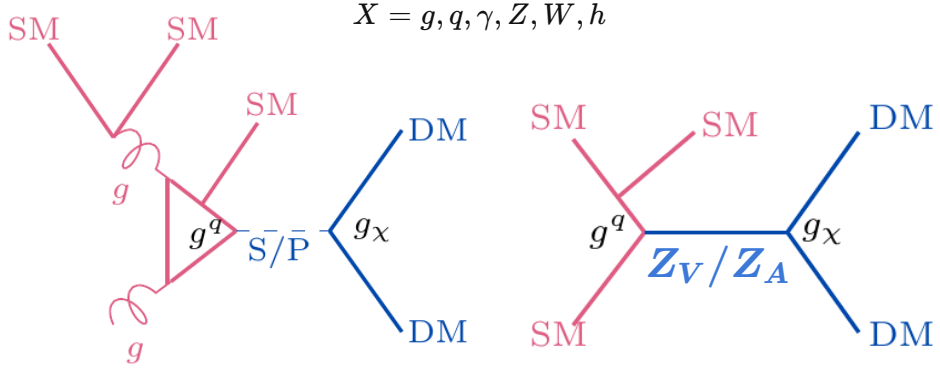



*In collider physics, the search for dark matter is promising through* ***effective field theories and simplified models****. For instance, simplified models can create a favorable channel for pair production of invisible particles from a proton-proton collision [10.1146/annurev-nucl-101917-021008]*

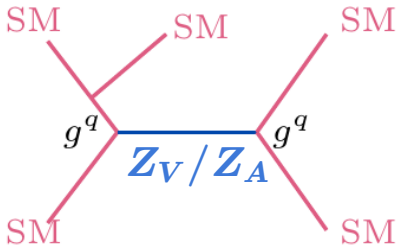



## Mono-X+$E^T_{miss}$

$X = g, q, \gamma, Z, W, h$




## Visible

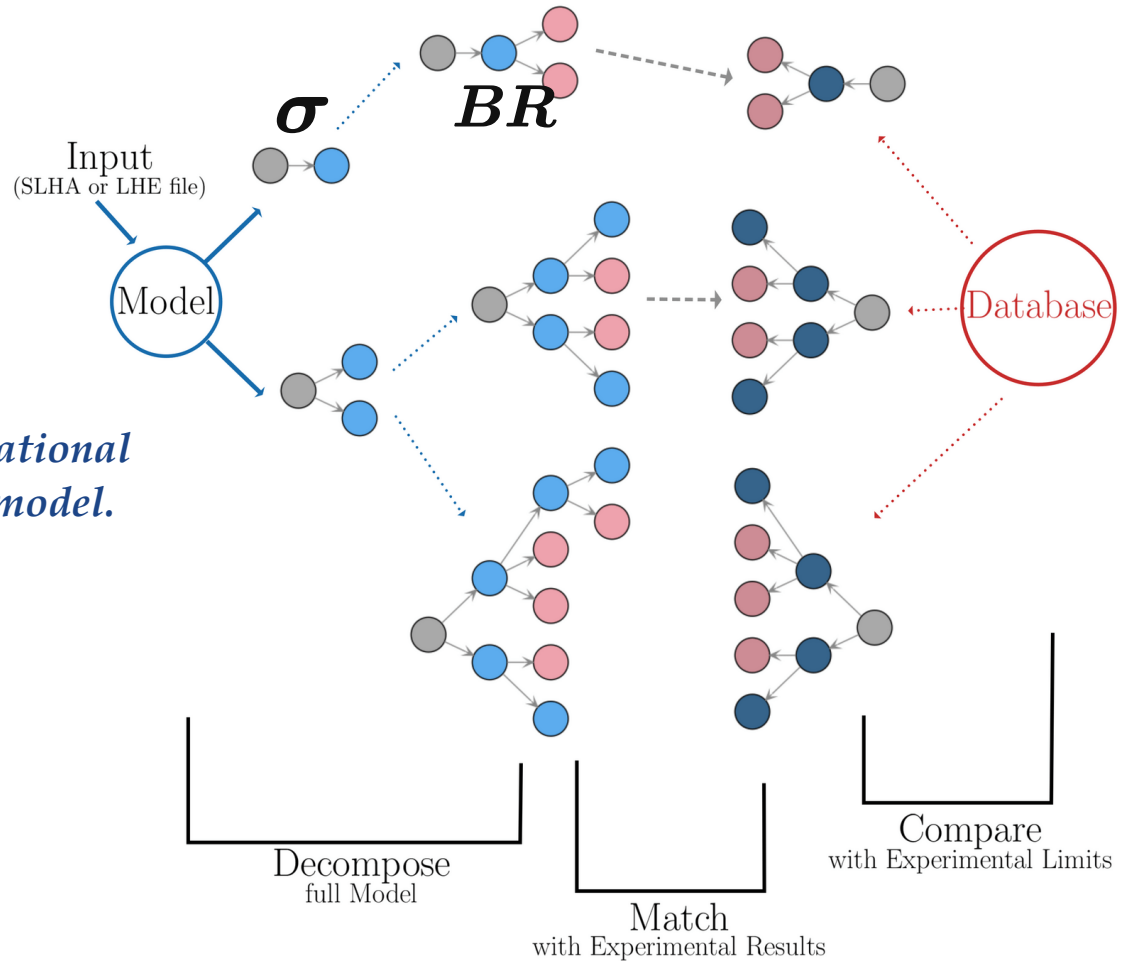



# *SModelS*

***SMS*** **(**Simplified Model Spectra)


## SModelS v1-v2 could only deal with SUSY-like topologies (no resonances)

## SModelS working principle




### A tool for interpreting simplified-model results from the LHC

Mohammad AlTakach, Sabine Kraml, Andre Lessa, Sahana Narasimha, Timothée Pascal, Humberto Reyes-González, Wolfgang Waltenberger

Previously involved in SModelS: Gaël Alguero, Federico Ambrogi, Jan Heisig, Charanjit K. Khosa, Juhi Dutta, Suchita Kulkarni, Ursu Laa, Veronika Magerl, Wolfgang Magerl, Philipp Neuhuber, Doris Proschofsky, Jory Sonneveld, Michael Traub, Matthias Wolf, Alicia Wongel

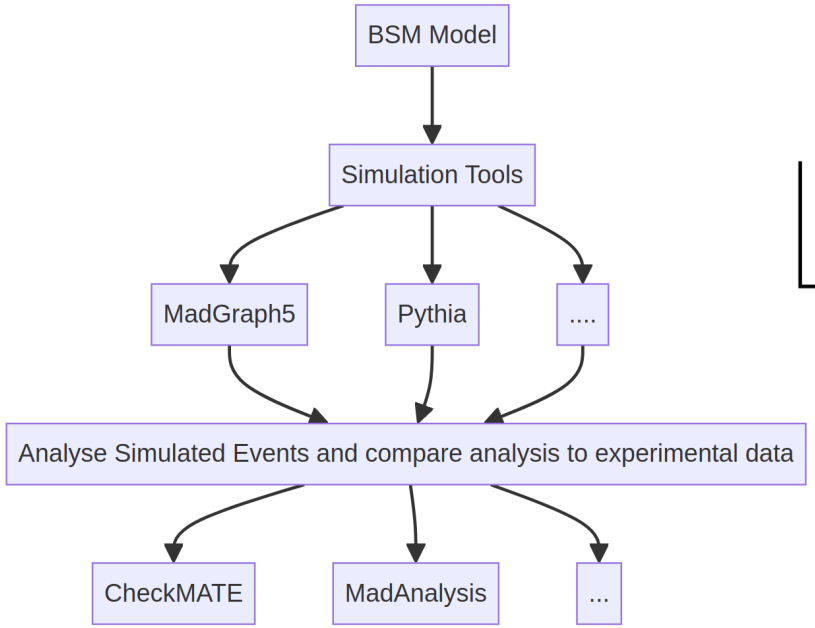
GitHub | pypi package 2.3.3 | Open in Colab | docs main

**19 December 2023: SModelS version 2.3.3 available (what's new)**

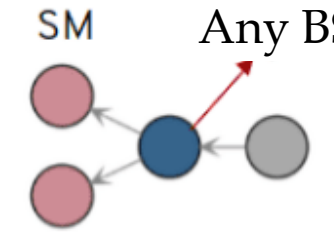
**Paper for version 2.3: arXiv:2306.17676**

- ☑ We can reinterpret the results of simplified models
  - ➔ BSMs with multiple free parameters can be tested.
- ☑ With or without a dedicated Monte Carlo simulation
  - ➔ Faster
- ☑ Large number of analyses: 111

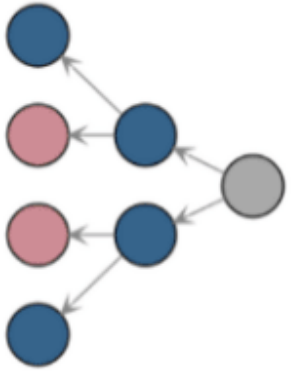
*There are several computational tools for testing a BSM model.*




*SModelS compares the decomposed topologies with the compatible experimental constraints.*

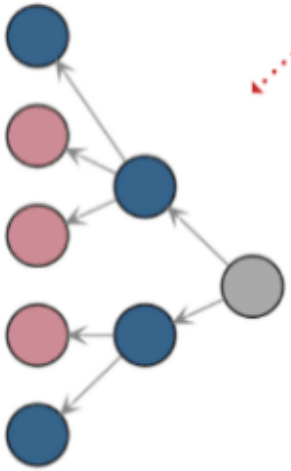



Efficiencies Map type:
$A \times \epsilon$



Database
Storage

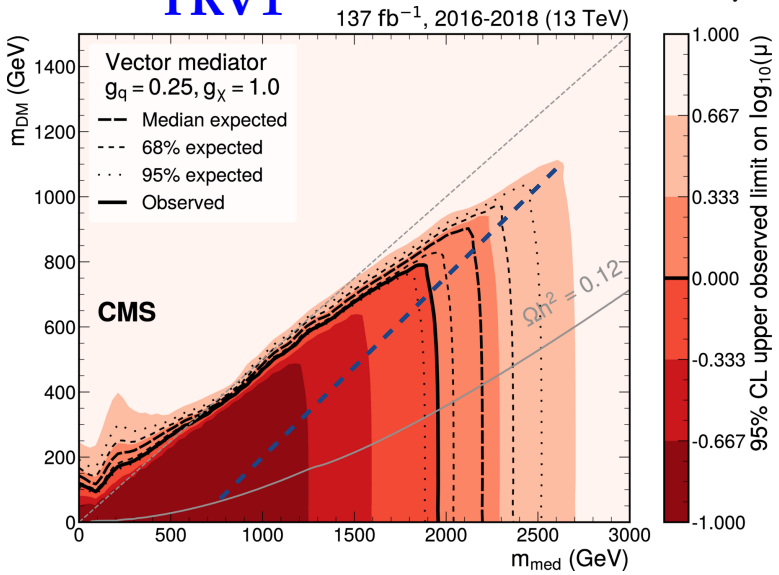
Upper Limit type:
$\sigma \times BR$



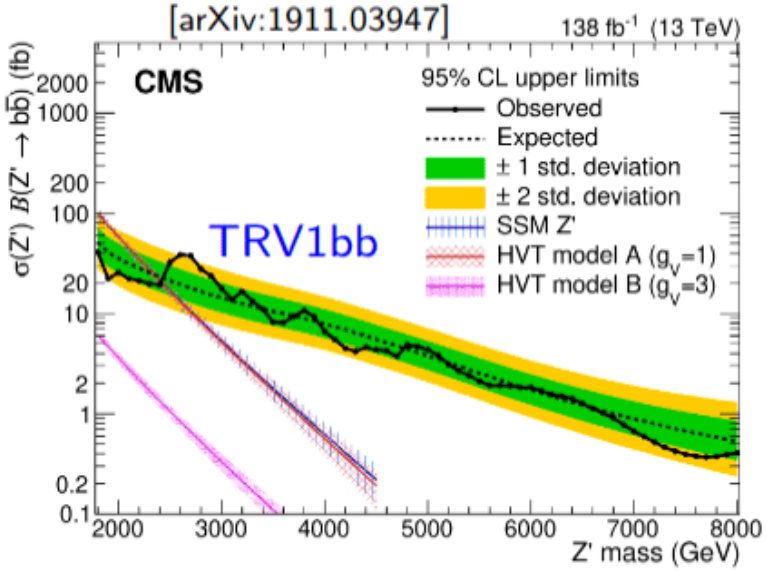
- SModelS allows storing SMS results (CMS and ATLAS)

CMS-EXO-20-004
[arXiv:2107.13021]

**TRV1**

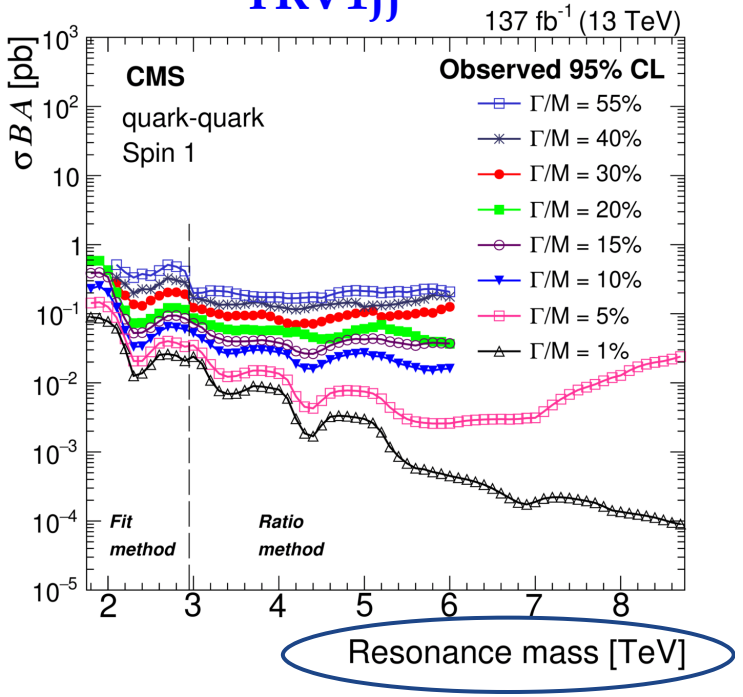



Signal strength
$\mu = \sigma_{obs} / \sigma_{theo}$




CMS-EXO-19-012
[arXiv:2205.01835]

**TRV1jj**



Update of the SModelS Database V3.0 with simplified model results from ATLAS and CMS searches

| ID | Signature | Luminosity | SMS Topology | Type |
|---|---|---|---|---|
| | Run II - 13 TeV | | | |
| ATLAS-EXOT-2019-03 [arXiv:1910.08447] | Dijet resonance | 139 $fb^{-1}$ | $pp \to Z' \to jj$ | UL |
| ATLAS-EXOT-2018-48 [arXiv:2005.05138] | $t\bar{t}$ resonance | 139 $fb^{-1}$ | $pp \to Z' \to t\bar{t}$ | UL |
| CMS-EXO-19-012 [arXiv:1911.03947] | Dijet resonance | 138 $fb^{-1}$ | $pp \to Z' \to j\bar{j}$ | UL |
| CMS-EXO-20-008 [arXiv:2205.01835] | b-jet resonance | 138 $fb^{-1}$ | $pp \to Z' \to b\bar{b}$ | UL |
| CMS-EXO-20-004 [arXiv:2107.13021] | Jets plus $E_T^{miss}$ | 138 $fb^{-1}$ | $pp \to Z', \phi \to \chi\bar{\chi}$ | EM |
| ATLAS-SUSY-2018-22 [arXiv:2010.14293] | Multi-jet plus | 139 $fb^{-1}$ | $pp \to Z' \to \chi\bar{\chi}, \ldots$ | EM |
| ATLAS-SUSY-2018-13 [arXiv:2301.13866] | Displaced jets | 139 $fb^{-1}$ | $pp \to \tilde{\chi}\tilde{\chi} \to jjj.jjj, \ldots$ | EM |
| | Run I - 8 TeV | | | |
| CMS-EXO-16-057 [arXiv:1802.06149] | b-jet resonance | 19.7 $fb^{-1}$ | $pp \to Z' \to b\bar{b}$ | UL |
| CMS-EXO-12-059 [arXiv:1501.04198] | Dijet resonance | 19.7 $fb^{-1}$ | $pp \to Z' \to jj$ | UL |
| ATLAS-EXOT-2013-11 [arXiv:1407.1376] | Dijet resonance | 20 $fb^{-1}$ | $pp \to Z' \to q\bar{q}$ | UL |

The column SMS Topology displays the topologies constrained by the search included in the database, while the column Type shows if the result contains upper limits or efficiency maps.

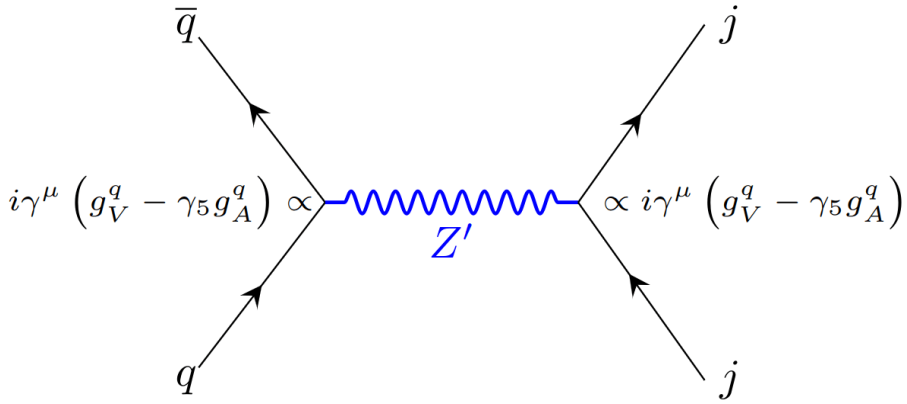
- In some analyses on the SModelS v3 database, only the NWA is considered valid. However, when the NWA is invalid, the CMS-EXO-19-012 analysis includes upper limits for the mediator's width-to-mass ratio values

# Two-Mediator Dark Matter (2MDM) *model*

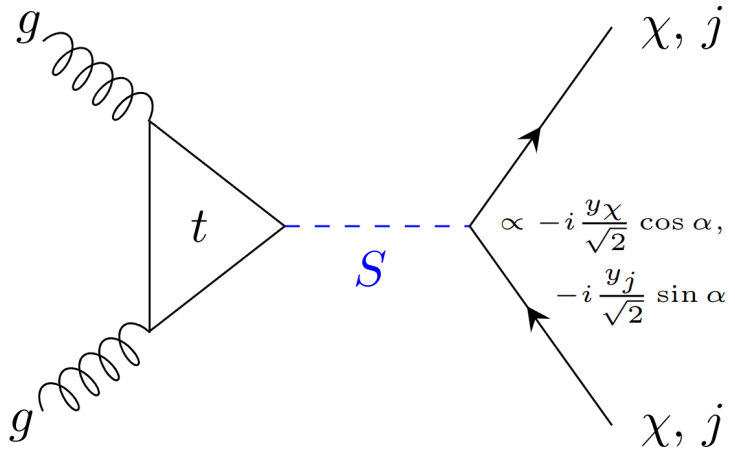
This model extends the Standard Model by incorporating a local gauge symmetry known as U(1)′, and it was documented in arXiv: 1606.07609, arXiv: 2109.13597 and arXiv: 1701.08780. We have made some modifications to this model.

The Two-Mediator Dark Matter (2MDM) model represents an extension to the SM by incorporating a local gauge symmetry denoted as U(1)'. The common way to generate a mass for the Z' boson through the introduction of a scalar singlet field is as follows,

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'_X$$
$$\downarrow m_{Z'} \equiv 2 g_\chi v_2$$
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$
$$\downarrow$$
$$SU(3)_c \otimes U(1)_Q$$




$$\mathcal{L}_{(2MDM)} \supset -g_\chi Z'^\mu \overline{\chi}\gamma^5\gamma_\mu\chi - \overline{\chi} m_\chi \chi - \overline{\chi}\frac{y_\chi}{2\sqrt{2}} S\chi\cos\alpha + \frac{1}{2}M\overline{\chi}\chi$$
$$+ \sum_q \bar{\psi}_q \gamma^\mu \left(g_V^q - \gamma_5 g_A^q\right)\psi_q Z'^\mu - 3\frac{Y_q}{\sqrt{2}}\bar{q}qS\sin\alpha$$




**Free parameters of the 2MDM model are:**

$$\{m_\chi, m_{Z'}, m_S, g_\chi, g_q^V/g_q^A, y_\chi, \sin\alpha\},$$

where $m_{Z'}$ is the mass of the $Z'$ boson, $g_q^V/g_q^A$ and $g_\chi$ are the coupling constants, $m_S$ is the scalar mass, $\alpha$ is the mixing angle $(-\pi/4 < \alpha < \pi/4)$ between the doublet and singlet scalars, $m_\chi$ is the dark fermion mass, and $y_\chi$ is the Yukawa coupling

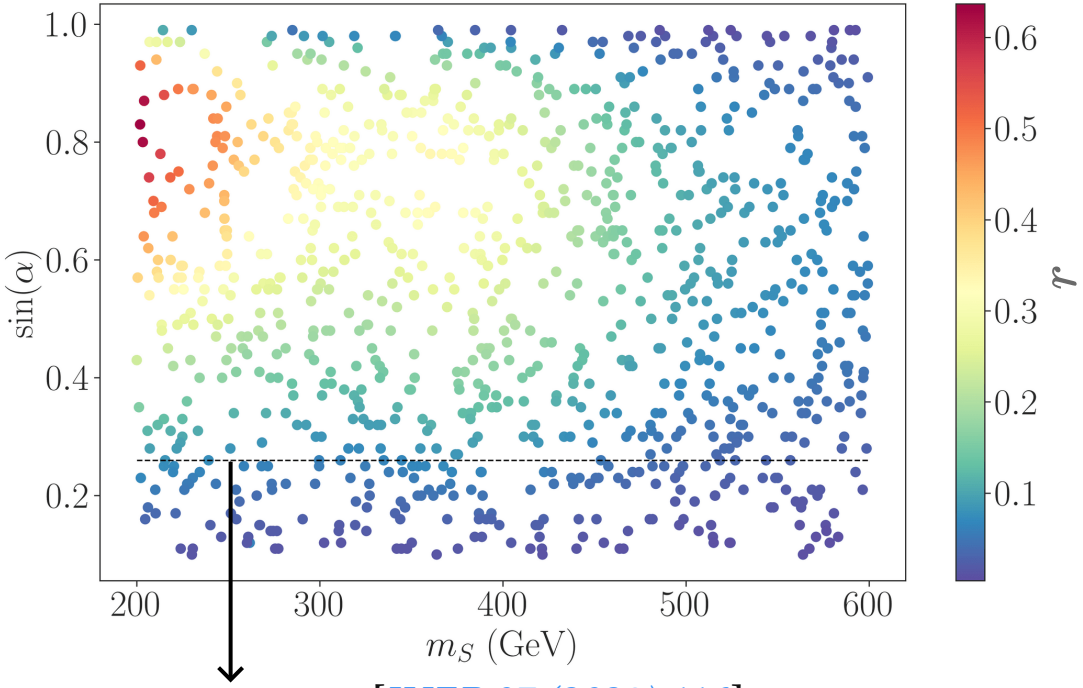
$$g_A^q = 0,$$
$$m_{Z'} = 1 - 3 \text{ TeV}$$
$$m_s = m_{Z'}/2$$

- $m_{Z'/s} > 2m_\chi$ (allow decay in $2\chi$)


# Preliminary Results of the 2MDM Model Analysis Using SModelS

We implemented the Two-Mediator Dark Matter Model (2MDM) using SModelS v3.

Scan over $\sin\alpha$ vs. $m_S$ for 2MDM model using SModelSv3.

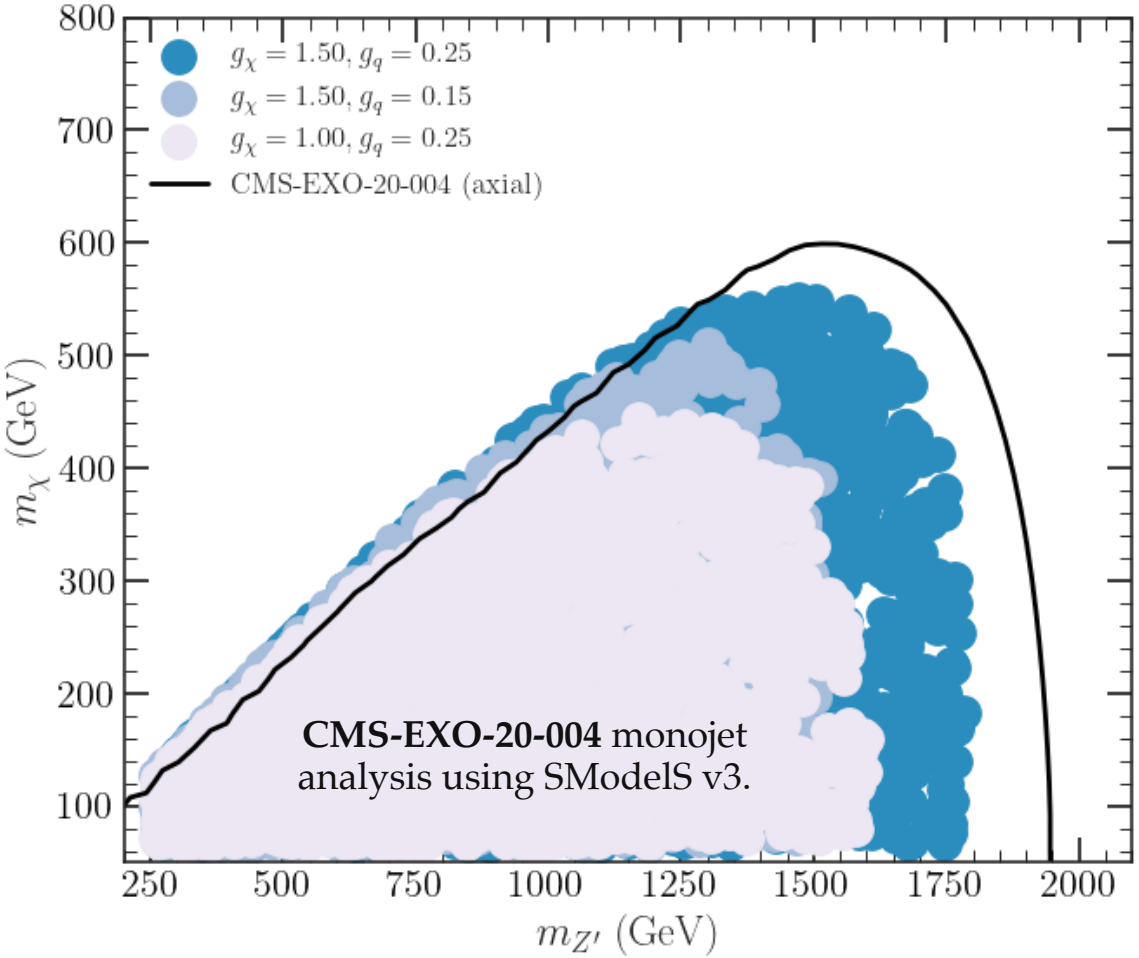



$\sin\alpha < 0.27$ [*JHEP 07 (2023) 116*]

No Higgs decay into the dark sector

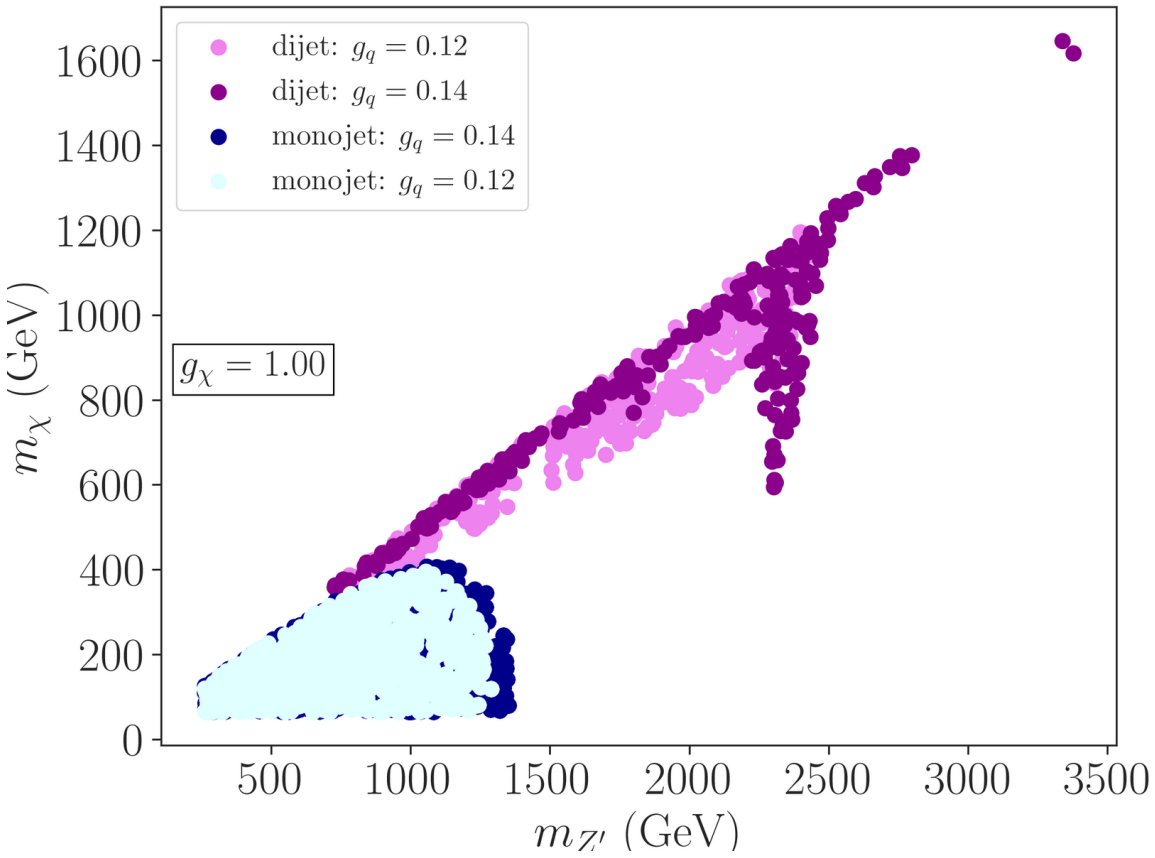
The scalar will not impact monojet searches due to angle limit; it will be suppressed.

$y_\chi = 1,\ g_\chi = 1,\ m_\chi = 65.0GeV$



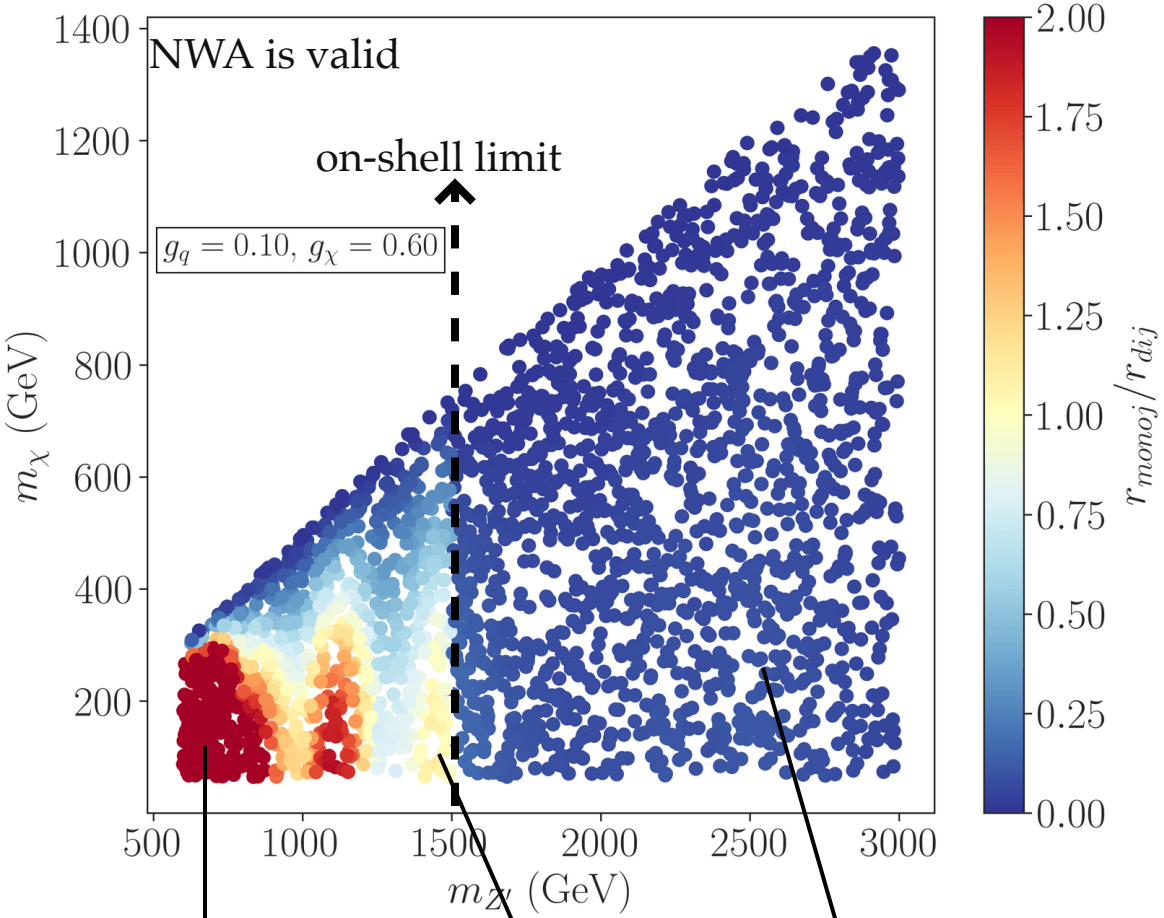

- $r > 1$ excluded
- $r < 1$ allowed

- s-channel production cross-section for the DM pair (spin-1 mediator) is proportional to $(g_q g_\chi)^2$.




Exclusion regions on scan over $m_\chi$ vs. $m_{Z'}$ for the 2MDM model for different analyses with $\sqrt{s} = 13$ TeV.

Comparison between $r$ from monojet analysis (CMS-EXO-20-004), denoted by $r_{monoj}$ and dijet analyses, or $r_{dij}$




Monojet more important

More sensitive dijet (run 2)

r values are comparable from both methods.


**version 3.0**
to be released soon

https://smodels.github.io/

❖ The new version was built for topologies containing resonant decays.

❖ We have updated the SModelS database with new analyses from CMS and ATLAS experimetal searches for spin-1 resonances with decays to jets, b-jets, top quarks, or DM, and the resonant production of a scalar that decays into a pair of DM particles.

❖ We implemented the Two-Mediator Dark Matter Model (2MDM) using SModelS v3.

For our analyses of the **2MDM model**

- We have constrained the 2MDM model considering the new data included in SModelS for resonant processes of $pp \to Z'/S \to jj, \chi\chi$ at ATLAS and CMS.

New topologies are being added to the database, such as $pp \to Z' \to \ell^+\ell^-$

SUSY 2024

Theory meets Experiment

Madrid
10-14 June 2024

SUSY24: The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions

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# Thank you so much for your attention!

**Acknowledgement**

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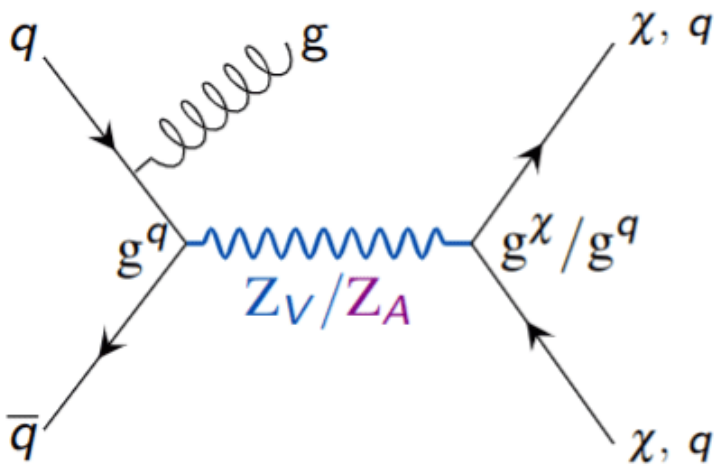
# *Backup slides*

The leptophobic model is one of the most common BSM models. A DM candidate, $\chi$, interacts with the SM via a spin 1 or Spin 0 mediator [arXiv: 1507.00966].

- Spin 1: DM production through vector/vector-axial (V/A) mediator

$$\mathscr{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

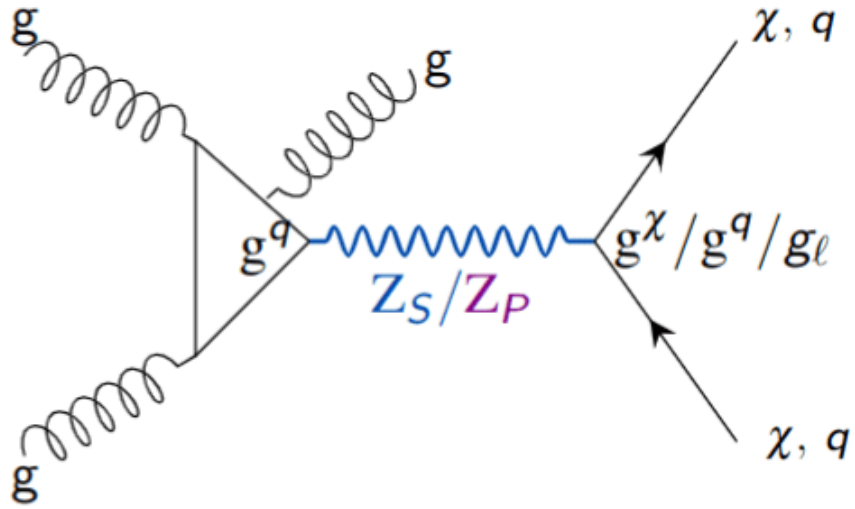
$$\mathscr{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$




- Spin 0: DM production through scalar/pseudoscalar (S/P) mediator

$$\mathscr{L}_S = g_X S\chi\bar{\chi} + \frac{S}{\sqrt{2}}\sum_i (g^u_{ii} u_i \bar{u}_i + g^d_{ii} d_i \bar{d}_i + g^\ell_{ii} \ell_i \bar{\ell}_i)$$

$$\mathscr{L}_P = i g_X P\chi\bar{\chi} + i\frac{P}{\sqrt{2}}\sum_i (g^u_{ii} u_i \bar{u}_i + g^d_{ii} d_i \bar{d}_i + g^\ell_{ii} \ell_i \bar{\ell}_i)$$



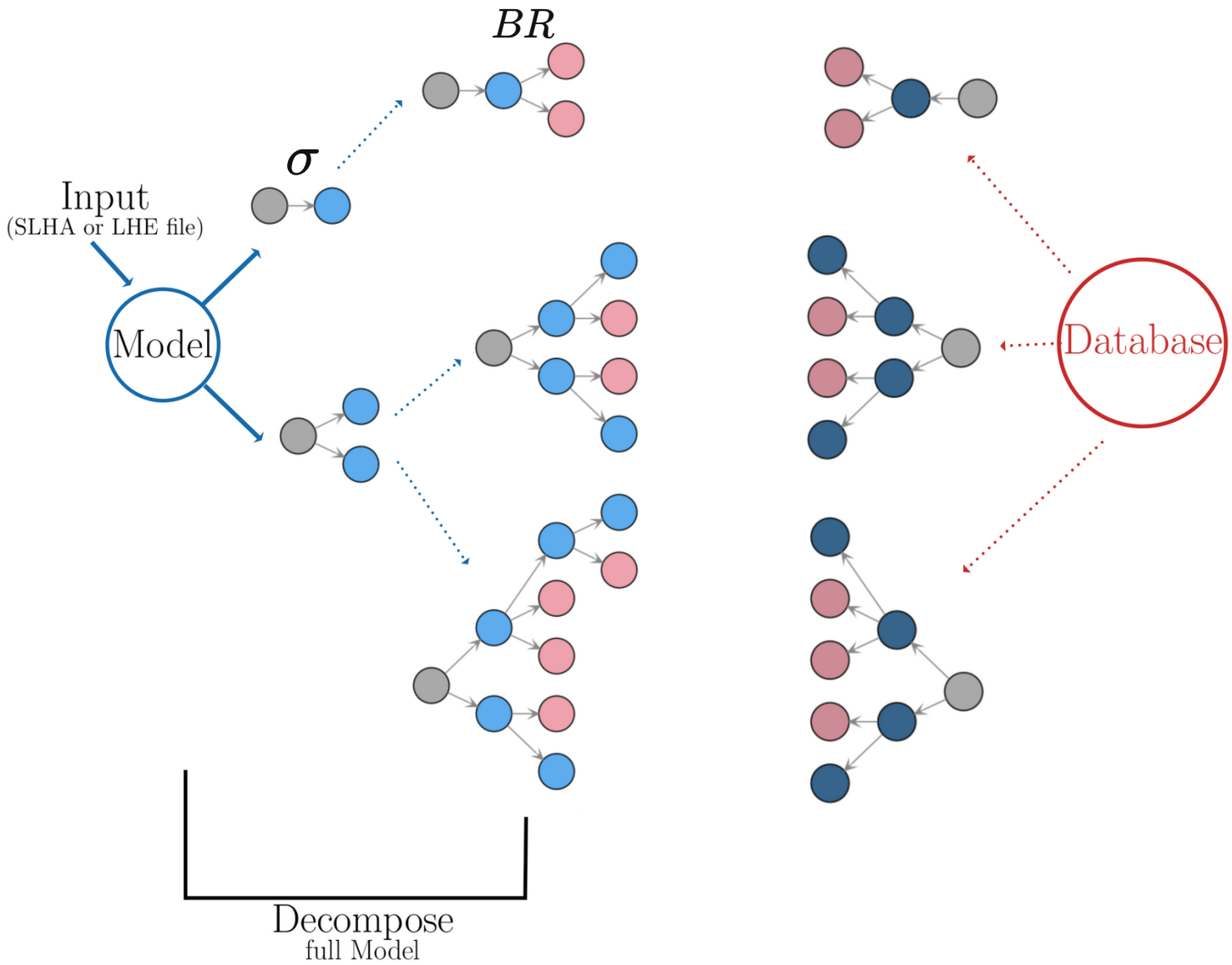

Free parameters: $\{m_\chi, m_{S/P}$ or $mZ_{A/V} = M_{\text{med}}, g_X, g_q\}$

- Any BSM model as an input
- Inputs can be defined in terms of the spectrum, decay and cross-section information.

SLHA FILE

MASS
QUANTUM NUMBERS
DECAY
XSECTION

- SModelS decomposes the full BSM model into individual topologies or SMS, representing the production and decay of new particles.



```
#####################################
## INFORMATION FOR MASS
#####################################
BLOCK MASS #
...
      5000001 2.500000e+03 # my1
      5000521 1.000000e+00 # mxd
```

```
#####################################
## INFORMATION FOR QNUMBERS 5000521
#####################################
BLOCK QNUMBERS 5000521 #    xd
      1 0 # 3 times electric charge
      2 2 # number of spin states (2s+1)
      3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
      4 1 # particle/antiparticle distinction (0=own anti)
#####################################
## INFORMATION FOR QNUMBERS 5000001
#####################################
BLOCK QNUMBERS 5000001 #    y1
      1 0 # 3 times electric charge
      2 3 # number of spin states (2s+1)
      3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
      4 0 # particle/antiparticle distinction (0=own anti)
```

```
#####################################
## INFORMATION FOR DECAY
#####################################
DECAY   5000001    1.140599e+02
#  BR             NDA   ID1     ID2    ...
   5.814006e-01    2     5000521  -5000521 # 66.31449595965601
   6.976814e-02    2     1   -1 # 7.957747154594769
   6.976814e-02    2     3   -3 # 7.957747154594768
   6.976814e-02    2     2   -2 # 7.957747154594768
   6.976814e-02    2     4   -4 # 7.95774715459159
   6.976814e-02    2     5   -5 # 7.957747153998318
   6.975870e-02    2     6   -6 # 7.956670548466599
#
#      PDG          Width
DECAY   5000521    0.000000e+00
```

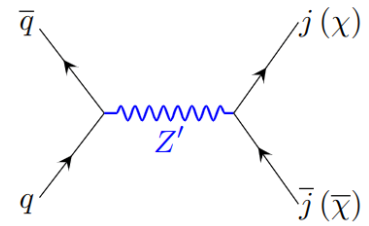
$\Gamma_{\text{total}}$

$BR(Z' \to \bar{\chi}\chi)$
$BR(Z' \to \bar{d}d)$
$BR(Z' \to \bar{s}s)$
$BR(Z' \to \bar{u}u)$
$BR(Z' \to \bar{c}c)$
$BR(Z' \to \bar{b}b)$
$BR(Z' \to \bar{t}t)$

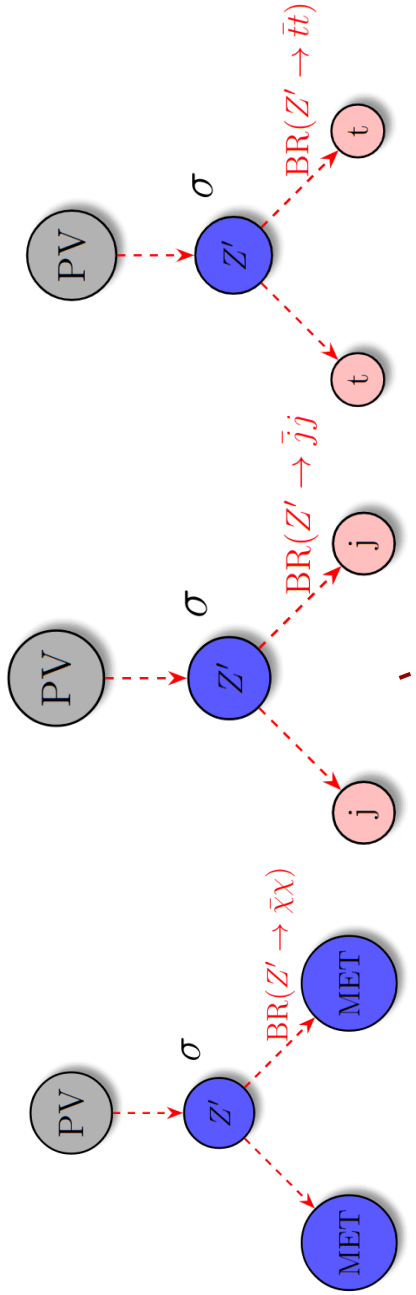
$\sqrt{S}$ in GeV — PDGs of incoming partons — # outgoing partons — PDG of outgoing partons

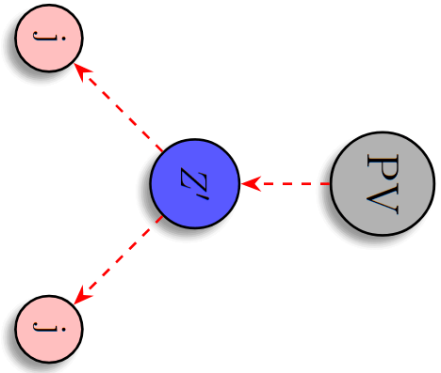
```
XSECTION  1.30E+04  2212 2212 1 5000001 # 10000 events, [pb]
 0   0   0   0   0   230000    0.12013604 SModelS 3.0.0-beta
```

PDF ID — $\sigma_{Z'}$ in pb




$$w = \sigma \times BR(Z' \to \ldots)$$




CMS-EXO-12-019

Database

$TRV1jj$

SModelS provides information on whether the model is excluded or not.

$j = u, d, c, s, b$

# Example output of SModelS

```
Decomposition output status: 1 #decomposition was successful

================================================================================
#Analysis   Sqrts   Cond_Violation   Theory_Value(fb)   Exp_limit(fb)   r   r_expected

     CMS-EXO-19-012   1.30E+01     0.0   4.191E+01   3.722E+01   1.126E+00   9.651E-01
 Signal Region:  (UL)
 Txnames:  TRV1jj
```

$$\sigma \times BR(Z' \to jj)$$

$$r = \frac{\sigma \times BR(Z' \to jj)}{\sigma_{UL}}$$

from SLHA file

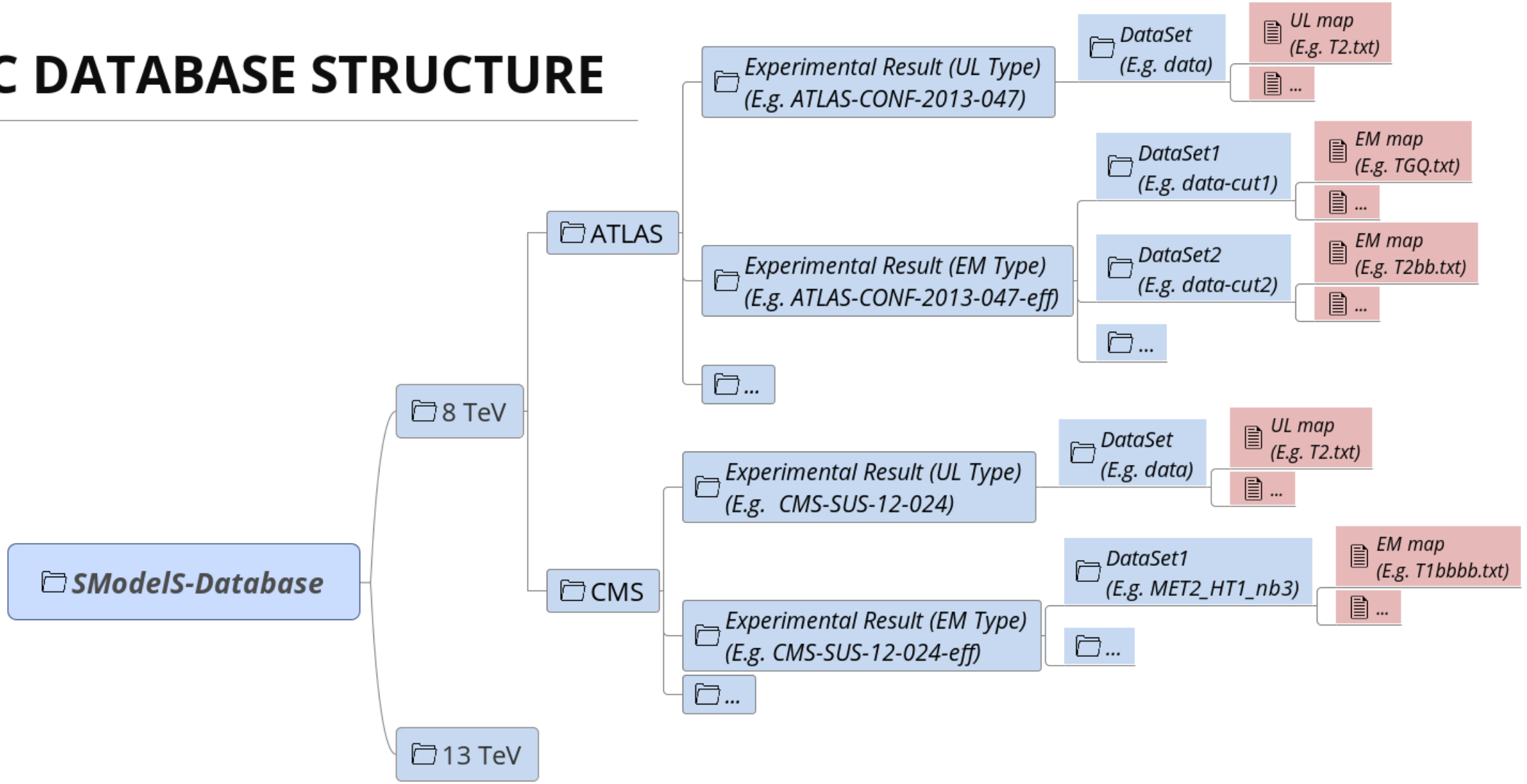
From upper limits in the database

```
================================================================================
The highest r value is = 1.12599 from CMS-EXO-19-012 (r_expected=0.96507)
CMS analysis with highest available r_expected: CMS-EXO-19-012, r_expected=0.96507, r_obs=1.1

Total cross-section for missing topologies (fb):  7.823E+01
Total cross-section for missing topologies with displaced decays (fb):  0.000E+00
Total cross-section for topologies outside the grid (fb):  0.000E+00

#Full information on unconstrained cross sections
================================================================================
missing topologies with the highest cross sections (up to 10):
Sqrts (TeV)   Weight (fb)                SMS description
 13.0          6.985E+01    #                                        PV > (MET)
 13.0          8.381E+00    #                                        PV > (t,t)
================================================================================
No missing topologies with displaced decays found
```

$r > 1$ Excluded

$r < 1$ Allowed

# BASIC DATABASE STRUCTURE



# Input file using SModelS for the 2MDM model

```
BLOCK MASS #
...
      9000006 5.394134e+02 # mchi
      9900026 2 9.518278e+02 # msd
      9900032 1.903656e+03 # mzp
...


###################################
## INFORMATION FOR DECAY
###################################
...

BLOCK QNUMBERS 9900032 #   zp
      1 0 # 3 times electric charge
      2 3 # number of spin states (2s+1)
      3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
      4 0 # particle/antiparticle distinction (0=own anti)

BLOCK QNUMBERS 9900026 #   sd
      1 0 # 3 times electric charge
      2 1 # number of spin states (2s+1)
      3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
      4 0 # particle/antiparticle distinction (0=own anti)

BLOCK QNUMBERS 9000006 #   chi
      1 0 # 3 times electric charge
      2 2 # number of spin states (2s+1)
      3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
      4 0 # particle/antiparticle distinction (0=own anti)
#
```

```
DECAY  9900026    3.796677e+01
#  BR             NDA  ID1    ID2    ...
   4.465895e-01   2    -24    24 # 16.955561233344973
   2.589817e-01   2    25     25 # 9.832698435454121
   2.204410e-01   2    23     23 # 8.369432341202666
   7.398455e-02   2    6      -6 # 2.8089541663607336
   3.247222e-06   2    15     -15 # 0.00012328653720425622

#       PDG            Width
DECAY  9900032    9.295477e+01
#  BR             NDA  ID1    ID2    ...
   3.889047e-01   2    9000006  9000006 # 36.15054668395339
   1.018561e-01   2    5      -5 # 9.468008198329535
   1.018561e-01   2    4      -4 # 9.468008198329535
   1.018561e-01   2    3      -3 # 9.468008198329535
   1.018561e-01   2    2      -2 # 9.468008198329535
   1.018561e-01   2    1      -1 # 9.468008198329535
   1.018149e-01   2    6      -6 # 9.464180310317941
```

| QUARKS | |
|---|---|
| $d$ | 1 |
| $u$ | 2 |
| $s$ | 3 |
| $c$ | 4 |
| $b$ | 5 |
| $t$ | 6 |
| $b'$ | 7 |
| $t'$ | 8 |

| LEPTONS | |
|---|---|
| $e^-$ | 11 |
| $\nu_e$ | 12 |
| $\mu^-$ | 13 |
| $\nu_\mu$ | 14 |
| $\tau^-$ | 15 |
| $\nu_\tau$ | 16 |
| $\tau'^-$ | 17 |
| $\nu_{\tau'}$ | 18 |

| GAUGE AND HIGGS BOSONS | |
|---|---|
| $g$ | (9) 21 |
| $\gamma$ | 22 |
| $Z^0$ | 23 |
| $W^+$ | 24 |
| $h^0/H_1^0$ | 25 |

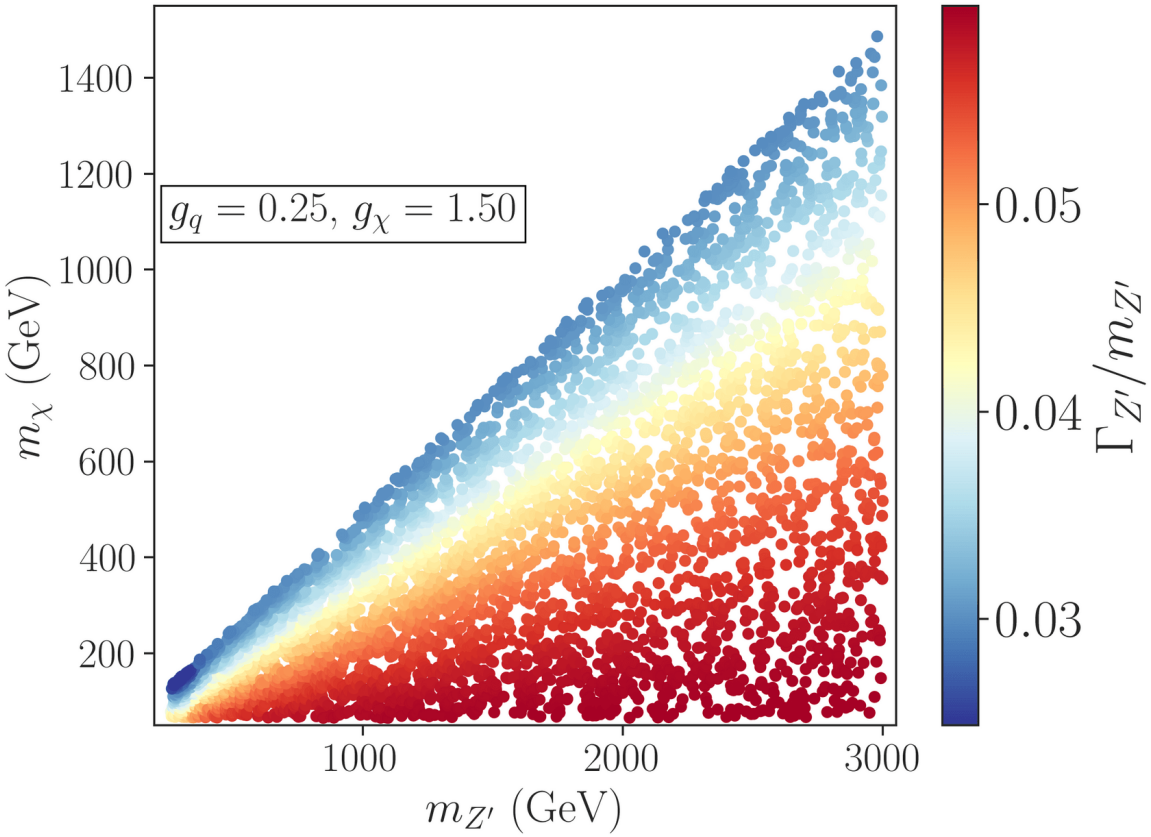
$\sqrt{S}$ in GeV

PDG of outgoing partons

```
XSECTION 1.300e+04 2212 2212 1 9900032 # xsec unit: pb xsec error: 2.329e-03
  0   0   0   0   0   303600   9.6462e-01 madgraph 3.5.1
```

$\sigma_{Z'}$ in pb

```
================================================================================
#Analysis  Sqrts  Cond_Violation  Theory_Value(fb)  Exp_limit(fb)  r  r_expected

 ATLAS-EXOT-2019-03  1.30E+01    0.0  4.913E+02  4.859E+01  1.011E+01  8.341E+00
 Signal Region:  (UL)
 Txnames:  TRV1jj
--------------------------------------------------------------------------------
     CMS-EXO-20-008  1.30E+01    0.0  9.825E+01  2.242E+01  4.383E+00  2.430E+00
 Signal Region:  (UL)
 Txnames:  TRV1bb
--------------------------------------------------------------------------------
 ATLAS-EXOT-2018-48  1.30E+01    0.0  9.821E+01  3.881E+01  2.530E+00  4.412E+00
 Signal Region:  (UL)
 Txnames:  TRV1tt
--------------------------------------------------------------------------------
     CMS-EXO-19-012  1.30E+01    0.0  4.913E+02  2.054E+02  2.392E+00  3.996E+00
 Signal Region:  (UL)
 Txnames:  TRV1jj
--------------------------------------------------------------------------------
     CMS-EXO-20-004  1.30E+01    0.0  2.243E+01  3.017E+01  7.436E-01  1.387E+00
 Signal Region:  (combined)
 Txnames:  TRV1


================================================================================
The highest r value is = 10.11029 from ATLAS-EXOT-2019-03 (r_expected=8.34142)
CMS analysis with highest available r_expected: CMS-EXO-19-012, r_expected=3.99572, r_obs=2.39192
ATLAS analysis with highest available r_expected: ATLAS-EXOT-2019-03, r_expected=8.34142, r_obs=10.11029

Total cross-section for missing topologies (fb):  0.000E+00
Total cross-section for missing topologies with displaced decays (fb):  0.000E+00
Total cross-section for topologies outside the grid (fb):  0.000E+00

#Full information on unconstrained cross sections
================================================================================
No missing topologies found
================================================================================
```

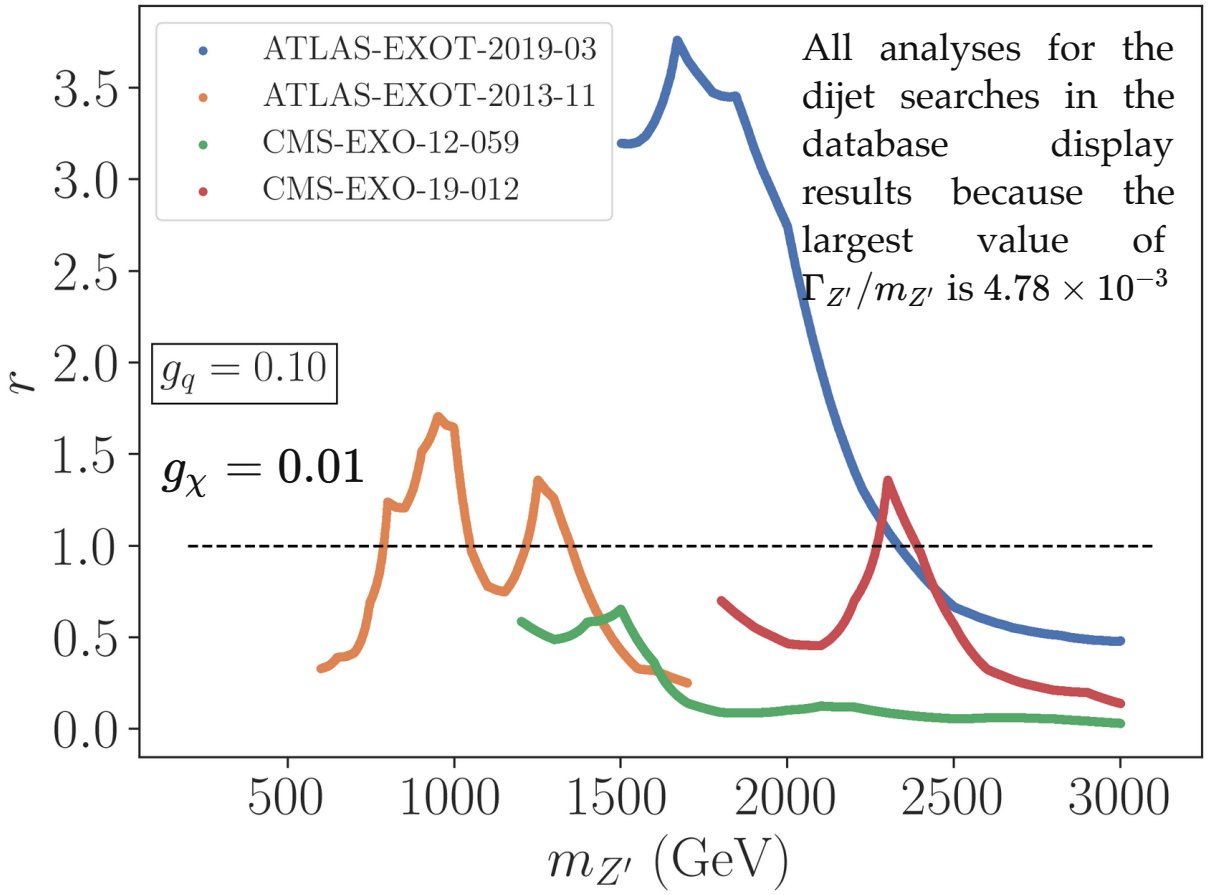


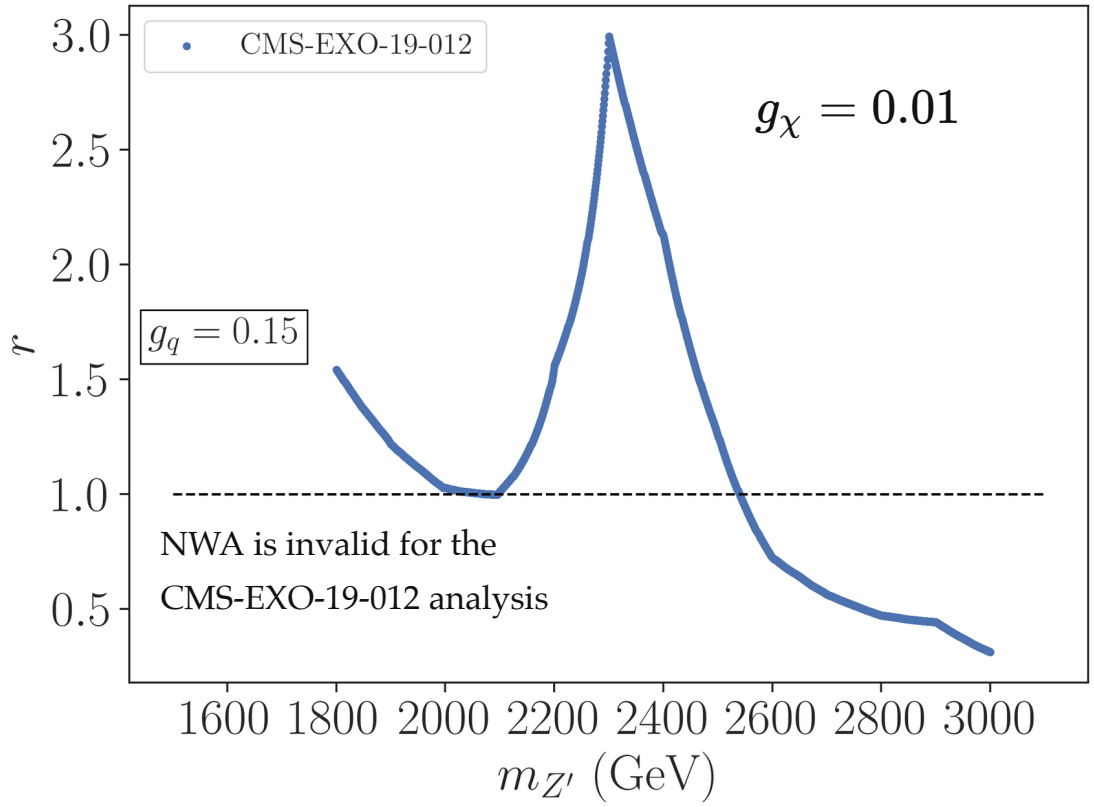

$$\frac{\Gamma_{Z'}}{m_{Z'}} \simeq 0.0477 g_q^2 + 0.013 g_\chi^2$$

$$m_{Z'} \gg m_\chi, m_q$$

- NWA regime: $\frac{\Gamma_{Z'}}{m_{Z'}} < 0.01$

The NWA holds for monojet processes in regions where $\Gamma_{Z'}/m_{Z'} < 0.05$, primarily when $m_{Z'} >$ 2000GeV and low dark matter masses.




- In some analyses on the SModelS v3 database, only the NWA is considered valid. However, when the NWA is invalid, the CMS-EXO-19-012 analysis includes upper limits for the mediator's width-to-mass ratio values

- $r > 1$ excluded
- $r < 1$ allowed