DARK MATTER SEARCHES AT ATLAS

OLEG BRANDT
on behalf of the ATLAS Collaboration
29/5/2019
DARK MATTER

15% SM matter

85% Dark matter

M33 rotation curve

observed

expected from luminous disk

v (km/s)

R (kpc)
Dark Matter detection

Indirect detection

Collider production

Direct detection

This presentation
Dark Matter detection

- Indirect detection
- Direct detection
- Collider production

Bright prospects for next decade(s)!

This presentation
**Dark Matter (DM) at Colliders**

Collider production

(controlled experimental environment!)

**Generic signature:**
SM particles, e.g., jet(s), Higgs boson, etc

**MET [1]**

[1] MET: missing transverse momentum
MODELS FOR DM SEARCHES @ LHC

1) Effective field theory
2) Simplified models
3) Simplified, consistent, & UV-complete models
4) Complete models

Richer kinematics + phenomenology

V/AV mediator model
arXiv:1507.00966

2HDM+a model
JHEP 05 (2017) 138
arXiv:1507.00966

DMF recommendations
arXiv:1507.00966
2HDM+a: MOTIVATION

Focus of this presentation

1) Effective field theory
2) Simplified models
3) Simplified, consistent, & UV-complete models
4) Complete models

Richer kinematics + phenomenology

V/AV mediator model

\[
\begin{align*}
\text{White Papers of LHC DM WG/DMF} & \\
\text{arXiv:1507.00966} & \\
\end{align*}
\]

2HDM+a model

arXiv:1507.00966

JHEP 05 (2017) 138

DMF recommendations

arXiv:1507.00966
**Motivation:**

1) Mediator that couples to SM and to Dark Sector particles
2) Generic signatures that are present in complete models
Motivation:
- Simplified model with generic signatures
- s-channel mediator: interplay between signatures

Work horse model:
- Assume vector (V) or axial vector (AV) mediator (Z'_{V/A})
  - Easy to calculate for m_{Z'} > 200 GeV
- LHC Dark Matter WG: coherence across ATLAS & CMS
  - arXiv:1507.00966 (DMF report)
OVERVIEW OF X+MET AND RESONANCE SEARCHES

- X+MET searches:
  - Mono-jet 36 fb\(^{-1}\), JHEP 01 (2018) 126
  - Mono-photon 36 fb\(^{-1}\), EPJC 77 (2017) 393
  - Mono-Z(\(\ell\ell\)) 36 fb\(^{-1}\), PLB 776 (2017) 318
  - Mono-V(qq) 36 fb\(^{-1}\), JHEP 10 (2018) 180
  - Mono-top 36 fb\(^{-1}\), JHEP 05 (2019) 41

- Resonance searches:
  - Dijet resonances 139 fb\(^{-1}\), ATLAS-CONF-2019-007
  - Angular dijet resonances 37 fb\(^{-1}\), PRD 96 (2017) 052004
  - Resolved dijet+ISR (+bjet) 80 fb\(^{-1}\), 1901.10917
  - Di-b-jet resonances 36 fb\(^{-1}\), PRD 98 (2018) 032016
  - Dijet Trigger-Level Analysis 29 fb\(^{-1}\), PRL 121 (2018) 081801
  - Boosted dijet+ISR 36 fb\(^{-1}\), PLB 788 (2019) 316
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  - Hadronic tt resonances 36 fb\(^{-1}\), EXOT-2016-24
  - Dilepton resonances 139 fb\(^{-1}\), EXOT-2018-08

All 2015+2016 (36 fb\(^{-1}\)) results in DM summary arXiv:1903.01400
**JET+DM: STRATEGY**

- **Analysis strategy:**
  - Require MET > 250 GeV
  - Require jet with $p_T > 250$ GeV
  - Inclusive selection: up to 3 extra jets
  - Look for excess at high MET:

  {\begin{align*}
  \log N_{\text{events}} &= \text{MET} \\
  250 \text{ GeV} &\quad \text{MET}
  \end{align*}}

  **Shape fit:** 10 bins in MET
**JET+DM: STRATEGY**

- **Analysis strategy:**
  - Require MET > 250 GeV
  - Require jet with $p_T > 250$ GeV
  - **Inclusive selection: up to 3 extra jets**
  - Look for excess at high MET:

  ![Graph](image)

  **Shape fit: 10 bins in MET**
**JET+DM: Backgrounds**

- **Backgrounds:**
  - SM $Z(vv)+$jets (dominant), $W+$jets, Diboson, $tt + rest$

- **Strategy:**
  - Constrain major backgrounds:

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<td>Constrain $W(\nu\nu)+$jets and $Z(vv)+$jets</td>
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![Diagram](image)
**Backgrounds:**
- SM Z(\(\nu\nu\)) + jets (dominant), W+jets, Diboson, tt + rest

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ATLAS:
- \(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
- Signal Region \(p_T^{\ell1}>250 \text{ GeV}, \slashed{E}_T^{miss}>250 \text{ GeV}\)

**post-fit**

Data 2015+2016
- Standard Model
- Z(\(\nu\nu\)) + jets
- W(\(\nu\nu\)) + jets
- Z(\(\ell\ell\)) + jets
- t\(\bar{t}\) + single top
- Diboson
- multijets + ncb
- m\(\ell\ell\), \(\ell^\tau\), \(\ell^\tau\) + 500, 495 GeV
- \(m_{\mu\mu}, M_{\mu\mu}\) = 400, 1000 GeV
- ADD, n=4, \(M_{\mu}\)=6400 GeV

ATLAS:
- \(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
- Z(\(\mu\mu\)) Control Region \(p_T^{\ell1}>250 \text{ GeV}, \slashed{E}_T^{miss}>250 \text{ GeV}\)

**post-fit**

Data 2015+2016
- Standard Model
- Z(\(\nu\nu\)) + jets
- W(\(\nu\nu\)) + jets
- Z(\(\ell\ell\)) + jets
- t\(\bar{t}\) + single top
- Diboson

Data / SM
- Stat. + Syst. Uncertainties
Backgrounds:
- SM $Z(\nu\nu)$+jets (dominant), $W$+jets, Diboson, $tt$ + rest

Strategy:
- Constrain major backgrounds:

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Challenge: $BR(Z \rightarrow \nu\nu) \approx 20\%$ $BR(Z \rightarrow \mu\mu) \approx 3\%$
**JET+DM: BACKGROUNDS**

- **Backgrounds:**
  - SM Z(\(\nu\nu\))+jets (dominant), W+jets, Diboson, tt + rest

- **Strategy:**
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**ATLAS**

- \(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
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*post-fit*

**ATLAS**

- \(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
- W(\(\rightarrow \nu\nu\)) Control Region: \(p_T(1)>250\) GeV, \(E_T^{miss}>250\) GeV

*post-fit*

\(\times\) anti-ID
**JET+DM: BACKGROUND**

- **Ansatz:**
  - Constrain $Z(\nu\nu)+\text{jets}$ using $W+\text{jets}$!
  - Benefit: $BR(W \rightarrow \mu\nu) \approx 10\% \times 2 \ (e\nu)$

- **Challenge:**
  - $Z+\text{jets}$ and $W+\text{jets}$ related, but different!

- **Solution:**
  - Calculate $Z+\text{jets}$ vs $W+\text{jets}$ difference at NNLO($\alpha_S$)+NNLL($\alpha_S$), NLO($\alpha_{\text{EW}}$)}
**Results:**

\[\begin{align*}
\text{ATLAS} & \quad \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \\
& \quad \text{Vector Mediator} \\
& \quad g_q = 0.25, \ g_\chi = 1.0 \\
& \quad 95\% \ CL \ limits
\end{align*}\]

\[\begin{align*}
\text{Expected limit} & \pm 2 \sigma_{\text{exp}} \\
\text{Expected limit} & \pm 1 \sigma_{\text{exp}} \\
\text{Observed limit} & \pm 1 \sigma_{\text{theory}} \\
\text{Perturbativity Limit} \\
\text{Relic Density (MadDM)}
\end{align*}\]
Overview of X+MET and Resonance Searches

- **X+MET searches:**
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All 2015+2016 (36 fb$^{-1}$) results in DM summary arXiv:1903.01400
**Dijet Resonances: Strategy**

- **Analysis strategy:**
  - Require \( \geq 2 \) of jets with \( p_T > 150 \text{ GeV} \)
  - Reduce SM \( t \)-channel dijets:
    \[
    |y^*| = \frac{1}{2}|y_1 - y_2| < 0.6
    \]
  - \( M_{jj} > 1.1 \text{ TeV} \)
  - Look for excess in \( m_{jj} \) distribution:

  ![Diagram of dijet resonances]

  **Background from data**
m_{jj} = 8.02 \, \text{TeV}!
**Results:**

\[
f(x) = p_1 (1 - x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}
\]

\[x \equiv m_{jj} / \sqrt{s} \quad \text{Nominally: } p_5 = 0\]
**Results:**

\[ f(x) = p_1 \left( 1 - e^{-x} \right) \]

\[ x \equiv m_{jj} / \sqrt{s} \quad \text{Nominally: } p_5 = 0 \]

**Challenge:** trigger limitations below \( m_{jj} < 1 \text{ TeV} \! \)
**TRIGGER LEVEL DIJET RESONANCES: STRATEGY**

- **Analysis strategy:**
  - Jets reconstructed by high-level trigger
  - Require $\geq 2$ of jets with $p_T \approx 220$ GeV
  - $|y^*| = \frac{1}{2}|y_1 - y_2| < 0.6$ (also 0.3)
  - $M_{jj} > 450$ GeV
  - Look for excess in $m_{jj}$ distribution:
**Triger Level Dijet Resonances: Strategy**

- **Ansatz:**
  - Reconstruct jets using High Level Trigger
  - Storage: one 4-vector per jet $\rightarrow$ larger bandwidth!

- **Challenge:**
  - Calibration of jets in High Level Trigger:

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**Trigger level analysis**

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**PRL 121 (2018) 081801**
Results:

TRIGGER LEVEL DIJET RESONANCES: STRATEGY

ATLAS

95% CL upper limits

PRL 121 (2018) 081801
**Overview plot from the Dark Matter Summary Paper:**
- using 2015+2016 data only – expect improvements!

JET RESONANCE SEARCHES: OVERVIEW

acc’d by JHEP, arXiv:1903.01400
**Dilepton resonances: strategy**

- **Analysis strategy:**
  - Require $ee$ or $\mu\mu$ pair with $p_T \gtrsim 220$ GeV
  - $m_{\ell\ell} > 225$ GeV
  - Look for excess in $m_{\ell\ell}$ distribution:

```
subm. to PLB, arXiv:1903.06248
```
DILEPTON RESONANCES

$m_{ee} = 4.06$ TeV!

Run Number: 336852, Event Number: 1440436043
Date: 2017–09–29 11:44:35 CEST

subm. to PLB, arXiv:1903.06248
Background parametrisation:

\[ f_{ee}(m_{ee}) = f_{BW,Z}(m_{ee}) \cdot (1 - x^e)^b \cdot x^{3\sum_{i=0}^{3} p_i \log(x)^i}, \]

Generic resonance limits for Breit-Wigner \( \otimes \) resolution

\[ Z'_{SSM} \quad (\Gamma/m = 3.0\%) \]
DARK MATTER V/AV model: PIECING IT ALL TOGETHER
Objective: summarise DM searches using 2015+2016 data:

- LHC DM WG recommendation:
  - Explore complementarity between X+MET & resonance searches
  - \( \rightarrow 4 \) representative scenarios!

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**JHEP, arXiv:1903.01400**
Objective: summarise DM searches using 2015+2016 data:

- **LHC DM WG recommendation:**
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  - → 4 representative scenarios!

### Table: Overviews

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*arXiv:1703.05703*

*JHEP, arXiv:1903.01400*
**Objective:** summarise DM searches using 2015+2016 data:

- **LHC DM WG recommendation:**
  - Explore complementarity between X+MET & resonance searches
  - \( \rightarrow \) 4 representative scenarios!

**Very strong dilepton limits if \( g_\ell \simeq g_q \):**

**Axial-vector mediator, Dirac DM**

- \( g_q = 0.1, g_\ell = 0.1, g_\chi = 1 \)
- All limits at 95% CL

**Coupl.**

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**JHEP, arXiv:1903.01400**

**arXiv:1703.05703**
Objective: summarise DM searches using 2015+2016 data:

Challenging for hadronic & leptonic final states!

LHC DM WG recommendation:
Explore complementarity between X+MET & resonance searches
→ 4 representative scenarios!

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arXiv:1703.05703

JHEP, arXiv:1903.01400
Complementarity of ATLAS results and direct detection experiments

**Summary Paper: Overview**

JHEP, arXiv:1903.01400

**Coupl.** | V1 | V2 | A1 | A2
---|---|---|---|---
$g_q$ | 0.25 | 0.1 | 0.25 | 0.1
$g_\ell$ | 0 | 0.01 | 0 | 0.1
$g_\chi$ | 1 | 1 | 1 | 1

**Dark Matter Summary Paper: Overview**
Complementarity of ATLAS results and direct detection experiments

**Summary Paper: Overview**

JHEP, arXiv:1903.01400

**ATLAS**

- Complementarity of ATLAS results and direct detection experiments

**Dijet**

Dijet $\sqrt{s} = 13$ TeV, $37.0$ fb$^{-1}$

PRD 96, 052004 (2017)

Dijet TLA $\sqrt{s} = 13$ TeV, $29.3$ fb$^{-1}$

PRL 121 (2018) 0818016

Dijet + ISR $\sqrt{s} = 13$ TeV, $15.5$ fb$^{-1}$

Preliminary ATLAS-CONF-2016-070

**Dibjet**

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

EPJC 78 (2018) 565

**$E_T^{miss} + X$**

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

PRD 98 (2018) 032016

**Axial-vector mediator, Dirac DM**

$g_q = 0.25$, $g_l = 0$, $g_X = 1$

ATLAS limits at 95% CL, direct detection limits at 90% CL

**Coupl.**

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**LUX**

PRL 118, 021303 (2017)

**What if?**

- Interpretations shown focus on s-channel mediator case:

- What if…
  - Nature thought differently?
  - E.g. **t-channel mediators?**
    - *t-channel mediators to dark sector are equally motivated as s-channel*

Dramatic difference, → **no resonances!**
Results:

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

95% CL limits

Coloured scalar mediator

$g = 1$

**But:** no coherency across the LHC...
LHC DM WG: WG on Dark Matter Searches at the LHC

- **Role:**
  - Provide *open, collaborative, and friendly* environment for:
    - Discuss new Dark Matter signatures
    - Devise future searches for Dark Matter
    - Provide recommendations for interpretation of Dark Matter searches
  - **Your** ideas very welcome:
    - E.g. t-channel mediators, dark photon models, you name it!
  - Suggestions for future topics you would like to tackle very welcome!
  - **Facilitate exchange of ideas** through meetings etc:
Dark Matter Models with $t$-Channel Mediators & @LHC & B-factories

26 April 2019 • 13:00-18:00 • CERN 40-S2-C01 (Salle Curie) • Vidyo

& Going Beyond?

Consolidating Existing Work

Experimental + Theory Workshop
https://indico.cern.ch/e/tChannelDM

LHC Dark Matter Working Group
Organisers: Oleg Brandt • Ulrich Haisch • Philipp Harris • Christian Ohm
• Tim Tait • Xabier Cid Vidal
Work towards White Paper started!
Expressions of interest being collected in document linked from workshop page
https://indico.cern.ch/event/806526/
Motivation: 1) Mediator that couples to Higgs, SM and Dark Sector typically: Higgs sector extension, 2HDM
2) Higgs coupling to new particles (hierarchy problem)
**Higgs**(bb)**)+**DM: **STRATEGY**

- **Signal proxy:**
  - Z’+2HDM model →

- **Analysis strategy:**
  - Require MET
  - Look for excess in m_{bb} distribution:

![Diagram showing signal and analysis strategy](image)

- Events × (1, 2 b-tags)
- × 4 MET bins
**HIGGS(bb)+DM: STRATEGY**

- **Signal proxy:**
  - $Z'+2$HDM model

- **Analysis strategy:**
  - Require MET
  - Look for excess in $m_{bb}$ distribution:

\[
\begin{align*}
\text{events} & \quad \text{(1, 2 b-tags)} \\
& \quad \times 4 \text{ MET bins}
\end{align*}
\]

**Talk on track-assisted reclustered jets by Fabrizio Napolitano**

**Combined mass (tracker + calorimeter)**
**Higgs(bb)+DM: Backgrounds**

- **Backgrounds:**
  - SM $Z(\nu\nu)h(bb)$, resonant
  - $Z(\nu\nu)+jets$, $W+jets$, $tt$, +rest

- **Strategy:**

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![Diagram showing Higgs(bb)+DM backgrounds and strategies](image-url)

- $Z(\nu\nu)+jets$
- $Z(\ell\ell)+jets$
**Backgrounds:**
- SM $Z(vv)h(bb)$, resonant
- $Z(vv)$+jets, $W$+jets, $tt$, +rest

**Strategy:**

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**Graphs:**

- **0 lepton signal region:**
  - Events/bin vs. $E_T^{miss}$ [GeV]
  - Data, $Z$+jets, $W$+jets, Diboson, SM $Vh$

- **1 lepton control region:**
  - Events/bin vs. $E_T^{miss}$ [GeV]
  - Data, $Z$+jets, $tt$ + single top, $W$+jets, Diboson, SM $Vh$

- **2 lepton control region:**
  - Events/bin vs. $p_T$ [GeV]
  - Data, $Z$+jets, $tt$ + single top, $W$+jets, Diboson, SM $Vh$
**Higgs**(bb)**)+DM: Backgrounds**

- **Backgrounds:**
  - SM Z(vv)h(bb), resonant
  - Z(vv)+jets, W+jets, tt, +rest

- **Strategy:**

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</table>

**PRL 119 (2017) 181804**

**ATLAS Simulation Preliminary**

- **W+jets**
- **Top-antitop**
**HIGGS**(bb)**+DM**: **RESULTS**

- **Interpretation:**
  - Z’+2HDM model

- **Alternative new models?**
  - → provide generic limits on Higgs + DM production!
Generic limits on $h+\text{DM}$

- Assume SM-like Higgs boson ($m_h \approx 125$ GeV, $\text{BR}(h \rightarrow bb) \approx 58\%$)
- Assume back-to-back topology of Higgs and MET

Set limits on visible cross section:

$$\sigma_{\text{vis}, h+\text{DM}} \equiv \sigma_{h+\text{DM}} \times \text{BR}(h \rightarrow bb) \times \mathcal{A} \times \varepsilon$$

- Can translate limits on $\sigma_{\text{vis}, h+\text{DM}}$ to parton level $\sigma_{h+\text{DM}}$ using $\mathcal{A} \times \varepsilon$

Easy to check exclusion of a new model! → next slides
**2HDM+a: MOTIVATION**

1) Effective field theory

DMF recommendations

arXiv:1507.00966

2) Simplified models

V/AV mediator model

arXiv:1507.00966

2HDM+a model

JHEP 05 (2017) 138

arXiv:1507.00966

3) Simplified, consistent, & UV-complete models

White Papers of LHC DM WG/DMF

4) complete models

Richer kinematics + phenomenology

Supersymmetry

Tuesday session

Tommaso et al.

OLEG BRANDT  CAVENDISH LABORATORY
**2HDM+a: SIGNATURES**

- Future benchmark for DM searches @ LHC:
  - 2HDM+a model [JHEP 05 (2017) 138]
    - Simplified, but UV-complete

- Diverse palette of signatures
  - Experimentally exciting interplay!

![Graph showing projections for 40 fb⁻¹](image)

- Mono-Higgs
- Mono-Z
- Di-top
- Mono-jet
- $tt + E_T, \text{miss}$

+ other signatures
2HDM+$\alpha$: FEATURES

- **Pseudoscalar DM mediator**
  - Weak constraint from direct detection experiments
  - No tree-level coupling

- **2HDM (II) extension of Higgs sector**
  - Well motivated
  - Avoid Higgs constraints in alignment limit
  - Avoid issues of pure pseudoscalar models

- **Predictiveness:**
  - Minimal particle content for a complete theory
  - Simple enough to parametrise on simple grids

- **Diverse palette of signatures**
  - Confront, combine complementary channels
  - Mono-Z, mono-h play special role

Particle content:
- CP even: $h, H$
- CP odd: $A, a$
- Charged: $H^\pm$
- Dirac DM: $\chi$

$a_0$ (before mixing) couples to $\chi$

Simplified scalar models from LHC DM WG exist (arXiv:1603.04156) that map directly to 2HDM for some final states, e.g. monojet, $tt+H$
2HDM+a: IMPLEMENTATION (ATLAS + LHC)

- **Identify relevant regions of parameter space** (see spares)
  - Diverse experimental signatures
  - Phenomenology-inspired
- **Identify “interesting” regions:**
  - NOT clearly excluded
  - NOT clearly beyond reach
- Define MC request

Use generic limits derived in h+DM analysis!

Estimate from generic limits
2HDM+a: Implementation (ATLAS + LHC)

- Identify relevant regions of parameter space (previous slides)
  - Diverse experimental signatures
  - Phenomenology-inspired

- Identify “interesting” regions:
  - NOT clearly excluded
  - NOT clearly beyond reach

Define MC request

Use generic limits derived in h+DM analysis!

Estimate from generic limits

Limits with full analysis (4+ months):

- $h(b\bar{b})+DM$
- $h(\gamma\gamma)$
- $h^{miss}+Z(q\bar{q})$
- $E_T^{miss}+Z(\ell\ell)$
- $E_T^{miss}+h(b\bar{b})$
- $E_T^{miss}+h(\gamma\gamma)$

\[ E_T^{miss}+Z(\ell\ell) \]

\[ E_T^{miss}+h(b\bar{b}) \]

\[ E_T^{miss}+h(\gamma\gamma) \]

\[ h(b\bar{b})+DM \]
2HDM+a: RESULTS IN ALL CHANNELS (ATLAS)

- Overlay of results in different channels:

![Diagram showing overlay of results in different channels](image)
2HDM+a: RESULTS IN ALL CHANNELS (ATLAS)

- Overlay of results in different channels:

**ATLAS**
\[ t \bar{t} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]
Limits at 95% CL

- Observed
- Expected

2HDM+a, Dirac DM
- \( m_\chi = 10 \text{ GeV}, g_1 = 1 \)
- \( m_A = m_H = m_{h^\pm} = 600 \text{ GeV} \)
- \( \sin(\theta) = 0.35 \)

\[ \Gamma/m_\chi > 20\% \]

\[ \tan \beta = 1 \]

\[ m_a \text{ [GeV]} \]

\[ \tan \beta \]

arXiv:1903.01400

h(bb) + DM

\[ h + \text{DM} \]

\[ Z + \text{DM} \]

Di-top

\[ t t + \text{DM} \]

Jet + DM

+ other signatures

\[ h(bb) + \text{DM} \]

\[ h + \text{DM} \]

\[ \chi \]

\[ \tilde{\chi} \]

\[ A \]

\[ a \]

\[ t \]

\[ t \]

\[ g \]

\[ g \]

\[ g \]
**2HDM+a: RESULTS IN ALL CHANNELS (ATLAS)**

- **Overlay of results in different channels:**

- **Important parameter $\sin\theta$**
  (mixing angle $A_0 / a_0$):
  - Balance of signatures with and w/o MET:
    $\Gamma(A \rightarrow ah) \propto \sin \theta \cos \theta$
  - Balance of (non-) resonant
    $\Gamma(a \rightarrow \chi\chi) \propto \cos^2 \theta$
    $\Gamma(a \rightarrow ff) \propto \sin^2 \theta$

---

**Graphical Elements:**

- **Diagram 1:**
  - Balance of (non-) resonant
  - $\Gamma(A \rightarrow ah) \propto \sin \theta \cos \theta$
  - $\Gamma(a \rightarrow \chi\chi) \propto \cos^2 \theta$
  - $\Gamma(a \rightarrow ff) \propto \sin^2 \theta$

---

**Equations:**

- $\sin^\beta = \frac{50}{6}$
- $\tan \beta = 0.5$: $E_{\text{miss}}^{+}\text{b}\overline{b}$
- $\tan \beta = 1$: all others

---

**References:**

- arXiv:1903.01400
**Motivation:**

1) Higgs Yukawa coupling to massive Dark Sector particles → appealing fundamental interaction!

2) Higgs coupling to new particles (hierarchy problem)
**Higgs \(\rightarrow\) Invisible: Overview**

- **Motivation:**
  - Higgs couples to massive particles
  - Dark Matter particles massive...
  - \(H \rightarrow \chi\chi\) possible if \(M_\chi \leq M_H\)

- **Competitive – Higgs production as tag:**

<table>
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<tr>
<th>ggF H [49 pb]</th>
<th>VH [2.3 pb]</th>
<th>VBF H [3.8 pb]</th>
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<td>+ ISR jet</td>
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<td>(\chi)</td>
<td>(W/Z^*)</td>
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<td>H(125)</td>
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- \(ggF+V(\text{had})H(\text{inv}): 0.83 (0.58) [1]\)
- \(Z(\ell\ell)H(\text{inv}): 0.67 (0.39) [2]\)

**New**

- \([1] JHEP 10 (2018) 180\)
- \([2] PLB 776 (2017) 318\)
- \([3] PLB 04 (2019) 024\)
**VBF HIGGS → INVISIBLE: STRATEGY**

- **Analysis strategy:**
  - Require MET > 180 GeV
  - Require high $|\Delta \eta_{jj}| > 4.8$
  - No 3rd jet with $p_T > 25$ GeV
  - Look for excess at high $m_{jj}$:

  ![Graph](image)

  **Shape fit: 3 bins in $m_{jj} > 1$ TeV**

  ![Diagram](image)

  **two forward jets
  no other jets at LO**

  **PLB 04 (2019) 024**
Constrain $Z(vv)+jets$, $W+jets$ in signal region (SR) using control regions (CR):

<table>
<thead>
<tr>
<th></th>
<th>0 lepton SR</th>
<th>1 lepton CR</th>
<th>2 lepton CR</th>
</tr>
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<td>Signal + constrain $Z(vv)+jets$ etc. at low $m_{jj}$</td>
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<td>Constrain $Z(vv)+jets$ using $Z(\ell\ell)+jets$</td>
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$Z(vv)+jets$  

$Z(\ell\ell)+jets$
Constrain $Z(vv)+\text{jets}$, $W+\text{jets}$ in signal region (SR) using control regions (CR):

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- **VBF Higgs $\rightarrow$ INVISIBLE: CONSTRAIN BACKGROUNDS**

- **0 lepton SR**: Signal + constrain $Z(vv)+\text{jets}$ etc. at low $m_{jj}$
- **1 lepton CR**: Constrain $W+\text{jets}$
- **2 lepton CR**: Constrain $Z(vv)+\text{jets}$ using $Z(\ell\ell)+\text{jets}$
Results:

$$BR(h \rightarrow \text{inv.}) < 0.37 \ (0.28^{+0.11}_{-0.08})$$
Results:

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Blue: V(had)H
- Green: Z(lep)H
- Red: VBF
- Black: Combined

**ATLAS**

\( \sqrt{s} = 7 \text{ TeV}, 4.7 \text{ fb}^{-1} \)  
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)  
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Green: Run 1 combined
- Red: Run 2 combined
- Black: Run 1+2 combined

**arXiv:1904.05105 → Poster by Sascha Dreyer**
H→INVISIBLE COMBO: RESULTS

- Results:

\[ \mathcal{B}_{H \rightarrow \text{inv}} < 0.26 \ (0.17^{+0.07}_{-0.05}) \]

arXiv:1904.05105  → Poster by Sascha Dreyer
H→INVISIBLE COMBO: COMPARISON TO DIRECT DETECTION

- Results:

\[ B_{\text{H→inv}}^{\text{observed}} < 0.24 \]

All limits at 90% CL

**ATLAS**

- \( \sqrt{s} = 7 \text{ TeV}, 4.7 \text{ fb}^{-1} \)
- \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
- \( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

Higgs portals
- Scalar WIMP
- Fermion WIMP

Other experiments
- Cresst-III
- DarkSide50
- LUX
- PandaX-II
- Xenon1T

\[ \sigma_{\text{WIMP-N}} \text{[cm}^2] \]

\[ 10^{-40} \quad 10^{-42} \quad 10^{-44} \quad 10^{-46} \]

\[ m_{\text{WIMP}} \text{[GeV]} \]

\[ 1 \quad 10 \quad 10^2 \quad 10^3 \quad 10^4 \]

[arXiv:1904.05105] → Poster by Sascha Dreyer
**Motivation:**
- New physics may affect Higgs production and visible decays

**Ansatz:**
- Combined fit with visible Higgs decay channels in $\kappa$ framework [1]:

\[
\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H} \quad \text{with} \quad \kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}
\]

\[
\Gamma_H(\kappa, B_{inv}, B_{undet}) = \frac{\kappa_H^2(\kappa)}{(1 - B_{inv} - B_{undet})} \Gamma_H^{SM}
\]

**Results:** (including Run 2 invisible searches)

- Maximum granularity for $\kappa_{SM}$

- Free $\kappa_\gamma$ and $\kappa_g$:

  ![Graph](image)

  - $B_{inv} = B_{undet} = 0$
  - $B_{inv} = B_{undet} = 0$, $p_{SM} = 88$

  - $< 0.46 (0.23)$
  - $< 0.12 (0.32)$
CONCLUSION + OUTLOOK

- **Bottom line:**
  - Dark Matter a fact, but particle nature not clear
  - Higgs boson at the centre of SM + extensions

- **Turn every stone:**
  - Consider simplified models with generic signatures
  - s-channel mediator addressed, t-channel targeted
  - Generic limits: useful and powerful tool

- **Higgs as a probe:**
  - Direct probe of interaction with DM
  - Co-dominant in 2HDM+a model

- **Higgs $\to$ invisible decays:**
  - Probe Yukawa-like couplings of Higgs to DM
  - Combination: $\mathcal{B}_{H \to \text{inv}} < 0.26 \left(0.17^{+0.07}_{-0.05}\right)$
  - Single-digit precision with 140 fb$^{-1}$ (full Run 2)

- **Exciting times ahead:**
  - One order of magnitude more data at HL-LHC!
Thank you!
The Standard Model (SM) of Particle Physics

SM is beautiful:
- Locally gauge invariant quantum field theory
- Underlying symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$

BUT it is massless!
- QED: simple mass term
  \[ \Delta \mathcal{L} = \frac{1}{2} m^2 A_\mu A^\mu \]
  - breaks gauge invariance
  \[ A_\mu \rightarrow A_\mu - \frac{1}{e} \partial_\mu \alpha \]

Solution:
- Mass term via Yukawa coupling to Higgs field:
  \[ \Delta \mathcal{L} = y_e \bar{e}_R (\phi^+, \phi^0) \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \]
  - If $\langle \phi^0 \rangle = v \neq 0$:
    \[ \Rightarrow m_e = y_e v \]

The Higgs boson has a central role in the SM! → also in SM extensions?

N.B.: ignoring gravitational interaction
Naturalness problem:
- $m_h = 125 \text{ GeV}$ seems unnaturally small

$m_p > m_n$  \hspace{2cm}  $m_n - m_p > \text{nuclear binding energy}$

- Loop corrections to $m_h$ from all particle types:
  
  - Corrections numerically large:
    - Fine-tuning at $\approx 1\%$ level to get $m_h$ “right” already for $\Lambda = 5 \text{ TeV}$
    - $\Lambda = 5 \text{ TeV} \ll \Lambda_{\text{Planck}}$!

- If New Physics to make $m_h$ more natural:
  - $\rightarrow$ Corrections to $m_h$ from New Physics
    - $\rightarrow$ New Physics likely to couple to Higgs!
- Also provide generic limits in inclusive bins of MET:

<table>
<thead>
<tr>
<th>Selection</th>
<th>$\langle \sigma \rangle_{\text{obs}}^{95}$ [fb]</th>
<th>$S_{\text{obs}}^{95}$</th>
<th>$S_{\text{exp}}^{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM1</td>
<td>531</td>
<td>19135</td>
<td>11700$^{+4400}_{-3300}$</td>
</tr>
<tr>
<td>IM2</td>
<td>330</td>
<td>11903</td>
<td>7000$^{+2600}_{-2600}$</td>
</tr>
<tr>
<td>IM3</td>
<td>188</td>
<td>6771</td>
<td>4000$^{+1400}_{-1100}$</td>
</tr>
<tr>
<td>IM4</td>
<td>93</td>
<td>3344</td>
<td>2100$^{+770}_{-590}$</td>
</tr>
<tr>
<td>IM5</td>
<td>43</td>
<td>1546</td>
<td>770$^{+280}_{-220}$</td>
</tr>
<tr>
<td>IM6</td>
<td>19</td>
<td>696</td>
<td>360$^{+130}_{-100}$</td>
</tr>
<tr>
<td>IM7</td>
<td>7.7</td>
<td>276</td>
<td>204$^{+74}_{-57}$</td>
</tr>
<tr>
<td>IM8</td>
<td>4.9</td>
<td>178</td>
<td>126$^{+47}_{-35}$</td>
</tr>
<tr>
<td>IM9</td>
<td>2.2</td>
<td>79</td>
<td>76$^{+29}_{-21}$</td>
</tr>
<tr>
<td>IM10</td>
<td>1.6</td>
<td>59</td>
<td>56$^{+21}_{-16}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inclusive (IM)</th>
<th>IM1</th>
<th>IM2</th>
<th>IM3</th>
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<th>IM5</th>
<th>IM6</th>
<th>IM7</th>
<th>IM8</th>
<th>IM9</th>
<th>IM10</th>
</tr>
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<tbody>
<tr>
<td>$E_{T}^{\text{miss}}$ [GeV]</td>
<td>&gt; 250</td>
<td>&gt; 300</td>
<td>&gt; 350</td>
<td>&gt; 400</td>
<td>&gt; 500</td>
<td>&gt; 600</td>
<td>&gt; 700</td>
<td>&gt; 800</td>
<td>&gt; 900</td>
<td>&gt; 1000</td>
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</tbody>
</table>
Data 2016, $\sqrt{s} = 13$ TeV
anti-$k_t$, $R = 0.4$, EM+JES + relative in situ correction
Data 2016, \( \sqrt{s} = 13\text{ TeV} \)

\( \text{anti-}k_t \), \( R = 0.4 \), EM+JES + \textit{in situ} correction

\( \eta = 0.0 \)

**Fractional JES uncertainty**

- Total Uncertainty, Trigger
- Total Uncertainty, Offline
- Absolute \textit{in situ} JES, fitted
- Relative \textit{in situ} JES
- Trigger Flav. composition, dijet events
- Trigger Flav. response, dijet events
- Trigger Pileup, average 2016 conditions
- Trigger data-derived correction

\( p_T^{\text{jet}} \) [GeV]
LHC Dark Matter Working Group:

Next-generation spin-0 dark matter models

Abstract. Dark matter (DM) simplified models are by now commonly used by the ATLAS and CMS Collaborations to interpret searches for missing transverse energy ($E_T^{\text{miss}}$). The coherent use of these models sharpened the LHC DM search program, especially in the presentation of its results and their comparison to DM direct-detection (DD) and indirect-detection (ID) experiments. However, the community has been aware of the limitations of the DM simplified models, in particular the lack of theoretical consistency of some of them and their restricted phenomenology leading to the relevance of only a small subset of $E_T^{\text{miss}}$ signatures. This document from the LHC Dark Matter Working Group identifies an example of a next-generation DM model, called 2HDM+$\alpha$, that provides the simplest theoretically consistent extension of the DM pseudoscalar simplified model. A comprehensive study of the phenomenology of the 2HDM+$\alpha$ model is presented, including a discussion of the rich and intricate pattern of mono-$X$ signatures and the relevance of other DM as well as non-DM experiments. Based on our discussions, a set of recommended scans are proposed to explore the parameter space of the 2HDM+$\alpha$ model through LHC searches. The exclusion limits obtained from the proposed scans can be consistently compared to the constraints on the 2HDM+$\alpha$ model that derive from DD, ID and the DM relic density.
2HDM+\(\alpha\): PARAMETERS

\[ M_H = M_A = M_{H^\pm}, \quad m_\chi = 10 \text{ GeV}, \]
\[ \cos(\beta - \alpha) = 0, \quad \tan \beta = 1, \quad \sin \theta = 0.35, \]
\[ y_\chi = 1, \quad \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3. \]

Convenience

Resonant enhancement

\[ \sin \theta \]
\[ \text{excluded} \]

\[ \lambda_3 \]
\[ \text{excluded} \]
Executive Experimental summary on model pheno:
- 14 parameters to start with
  - 7 parameters fixed:
    - symmetry, EW-precision measurements, Higgs properties,...
  - 7 “free” parameters:
    - \[ A/a \text{ mixing angle } \sin \theta \text{ important, e.g.} \]
      \[
      \begin{align*}
      \Gamma(A \to \chi \chi) & \propto \sin^2 \theta & \Gamma(a \to \chi \chi) & \propto \cos^2 \theta \\
      \Gamma(A \to ff) & \propto \cos^2 \theta & \Gamma(a \to ff) & \propto \sin^2 \theta \\
      \Gamma(A \to ah) & \propto \sin \theta \cos \theta
      \end{align*}
      \]
      [1] can change shapes if u/d-type couplings process-relevant
      [2] statement true if decay mediator on-shell

More details in talk by Johanna Gramling
https://indico.cern.ch/event/665524/sessions/260090/
2HDM+$\alpha$: (NON-) RESONANT SIGNATURES

Resonant

Non-Resonant

$\begin{array}{c}
\text{h + DM} \\
\text{Z + DM} \\
\text{Wt + DM}
\end{array}$

$\begin{array}{c}
\text{h + DM} \\
\text{Z + DM} \\
\text{Wt + DM}
\end{array}$

+ many other signatures
2HDM+$a$: $h + \text{DM}$

- **General:**
  - Can be resonantly enhanced
    - $\rightarrow$ driving sensitivity for 2HDM+$a$
  - $h + E_{T}^{\text{miss}}$ dominant over $Z + E_{T}^{\text{miss}}$ if

$$M_{H} = M_{H^\pm} = M_{A}$$

**Graphs:**
- **Mono-Higgs, $M_{a} = 200$ GeV**
- **Mono-Higgs, $M_{a} = 700$ GeV**
2HDM+α: Z + DM

- General:
  - Can be resonantly enhanced
  - $Z + E_T^{\text{miss}}$ dominant over $h + E_T^{\text{miss}}$ if

$$\Rightarrow M_H = M_{H^\pm} = M_A$$

\begin{align*}
M_H &\quad \quad \quad \quad \quad M_A
\end{align*}

\begin{align*}
\text{mono–Z, } M_a = 200 \text{ GeV} \\
\text{mono–Z, } M_H = 700 \text{ GeV}
\end{align*}
Higgs → INVISIBLE: OVERVIEW

- **Motivation:**
  - Higgs couples to massive particles
  - Dark Matter particles massive...
  - $H \rightarrow \chi\chi$ possible if $M_\chi \leq M_H$

- **Competitive – Higgs production as tag:**

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**ATLAS**
- ggF+V(had)H(inv): 0.83 (0.58) [1]
- $Z(\ell\ell)H$ (inv): 0.67 (0.39) [2]

**CMS**
- ggF+V(had)H(inv): 0.53 (0.40) [5]
- $Z(\ell\ell)H$ (inv): 0.40 (0.42) [6]

**Combo**
- ggF+V(had)H(inv): 0.53 (0.40) [5]
- $Z(\ell\ell)H$ (inv): 0.40 (0.42) [6]

Feynman diagrams: Christian Ohm

**Analysis strategy:**
- Require MET
- Look for excess in $m_{qq}$ distribution:

1) **Merged:**
   \[ \text{MET} > 250 \text{ GeV} \]

2) **Resolved:**
   \[ \text{MET} > 150 \text{ GeV} \]

\( \times \sim 10 \text{ MET bins} \)
\( \times (0, 1, 2 \text{ b-tags}) \)
\( \times \sim \text{merged/resolved} \)
VH Higgs \rightarrow INVISIBLE: STRATEGY

- Analysis strategy:
  - Require MET
  - Look for excess in $m_{qq}$ distribution:

\[ \begin{align*}
\times & \sim 10 \text{ MET bins} \\
\times & (0,1, 2 \text{ b-tags}) \\
\times & \sim \text{merged/resolved}
\end{align*} \]

1) Merged:
MET > 250 GeV

\[ \begin{align*}
\chi & \rightarrow W, Z \\
\text{New combined mass} & \text{(tracker + calorimeter)}
\end{align*} \]

\[ \begin{align*}
\text{ATLAS} & \text{ Simulation Preliminary} \\
\sqrt{s} & = 13 \text{ TeV, WZ} \rightarrow qqqq \\
\text{anti-k, R} & = 1.0 \text{ jets, } |\eta| < 2.0 \\
\text{Trimmed} & = (f_{out} = 0.05, R_{sub} = 0.2) \\
\text{LCW + JES + JMS calibrated}
\end{align*} \]
Constrain $Z(vv)+\text{jets}$, $W+\text{jets}$ in signal region using control regions
- Similar to VBF $Higgs \rightarrow \text{invisible}$

Representative signal region (SR) plots:

Higgs $\rightarrow \text{invisible}$ interpretation:

$BR(h \rightarrow \text{inv.}) < 0.83 \left( 0.58^{+0.23}_{-0.16} \right)$
**V + MET: RESULTS**

s-channel (V/AV) mediator model

arXiv:1507.00966

(White Paper of LHC DM WG/DMF)

---

**ATLAS**

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

Mono-\(W/\Z qq\): Vector, Dirac

$g_{SM} = 0.25$, $g_{DM} = 1.0$

---

Observed 95% CL

Expected 95% CL

($\pm 1\sigma$ and $\pm 2\sigma$)

Relic density

---

**JHEP 10 (2018) 180**
**Strategy:** change the mass hypothesis in V+MET

- For $m_{Z'} \geq 100$ GeV only resolved regime

First search for $Z'+\text{DM}$!
Generic limits on $W/Z + \text{DM}$ production:

$$\sigma_{\text{vis, } W+\text{DM}}(E_T^{\text{miss}}) \equiv \sigma_{W+\text{DM}}(E_T^{\text{miss}}) \times \mathcal{B}_{W \rightarrow q'q} \times (A \times \varepsilon)(E_T^{\text{miss}})$$

Provided in paper → limits on partonic $\sigma_{W/Z+\text{DM}}$
**Analysis strategy:**
- Require $Z(\ell\ell)$ candidate
- Look for excess in $E_{T}^{\text{miss}}$ distribution:

\[ Z(\ell\ell)h(\text{INVISIBLE}) \]
**Backgrounds:**
- Irreducible (dominant):
  - $Z(\ell\ell)Z(\to\nu\nu)$ [60%]
- Reducible:
  - $WZ(\ell\ell)$ [25%]
  - $Z(\ell\ell)$+jets [10%]
  - Rest [10%]

**Overview of signal regions and control regions:**

<table>
<thead>
<tr>
<th>2 lepton signal region</th>
<th>3 lepton control region</th>
<th>2 lepton control region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>Constrain $WZ(\ell\ell)$, Propagate using lepton inefficiency scale factor</td>
<td>Constrain $Z(\ell\ell)$+jets, Estimate $E_T^{\text{miss}}$ rate from jet $p_T$ mis-measurements</td>
</tr>
</tbody>
</table>
Estimate $WZ(\ell\ell)$ in 3 lepton control region:

$$N_{WZ}^{SR} = N_{WZ, MC}^{SR} \times f_{WZ}$$

$$f_{WZ} = 1.25 \pm 0.04 \text{(stat)} \pm 0.05 \text{(syst)}$$

- Trigger:
  - Easy (single leptons, $\varepsilon=98\%$)

- Selection:
  - Z mass window, no b-jets
  - topological requirements: $Zh$ back-to-back, $|\Delta\phi(E_T^{miss}, \text{jets})|$  

- Challenge:
  - MET resolution
$Z(\ell\ell)h(\text{invisible})$: Results

**ATLAS** Run I, all channels **combined**:
BR($h \rightarrow \text{inv}$) = 0.25 obs. (0.27 exp.) [1]

**CMS** Run I+2015 data, all channels **combined**:
BR($h \rightarrow \text{inv}$) = 0.24 obs. (0.23 exp.) [2]

Z(ll)h(INVISIBLE): RESULTS

- Interpretation:
  - Stringent limits for
    \[ M_{\text{WIMP}} \lesssim \frac{M_h}{2} \]
  - Complementary to direct detection experiments

\[ \sqrt{s} = 7 \text{ TeV}, \ 4.5-4.7 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, \ 20.3 \text{ fb}^{-1} \]

Vis. & inv. Higgs boson decay channels

[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_c, \kappa_\mu, \kappa_\tau, \kappa_\gamma, \kappa_{Z\gamma}, \text{BR}^{-1}] \]

No \kappa_{W,Z} assumption: \text{BR}^{-1} < 0.22 at 90\% CL

WIMP mass [GeV]

- DAMA/LIBRA (99.7\% CL)
- CRESST II (95\% CL)
- CDMS SI (95\% CL)
- CoGeNT (99\% CL)
- CRESST II (90\% CL)
- SuperCDMS (90\% CL)
- XENON100 (90\% CL)
- LUX (90\% CL)

ATLAS 90\% CL in Higgs portal model:
- Scalar WIMP
- Majorana WIMP
- Vector WIMP
Improvement strategies #1 (VBF):
- Re-optimise VBF selections in view of experimental uncertainties:
  - Jet energy scale + resolution, lepton ID, etc.
- Lower MET threshold $\rightarrow$ dedicated VBF trigger!
- More $V+$jets (QCD) MC simulations (leading systematic uncert.)
- Improved theory predictions for $V+$jets

Improvement strategies #2 (ZH, not shown):
- $Z(\ell\ell)Z(\nu\nu)$ background estimation
- Lower MET threshold

Improvement strategies #3 (VH):
- Benefit from improved $V+$jets theory for jet+MET
- Further improve $W \rightarrow qq$ identification:
  - Include tracking information (better jet substructure resolution)
  - Design custom multivariate discriminant for boosted $W \rightarrow qq$
H→INVISIBLE OUTLOOK (RUN 2, 140 FB⁻¹)

- **Improvement for Run 2 combination (technical):**
  - Orthogonality by construction
  - Design analyses with future combo in mind
  - More coherent treatment of systematic uncertainties

- **Improvement for Run 2 combination (more channels):**
  - VBF H(inv)
  - Z(II)H(inv)
  - V(qq)H(inv)
  - ttH(inv)
  - ggF H(inv)

Aim for single-digit expected limit on B_{H→inv}!

Evidence for B_{H→inv} ≠ 0 possible if same central value

\[ s = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

ATLAS

\[ m_\phi = 1 \text{ GeV}, \text{ Dirac DM} \]

Expected

\[ E_{\text{miss}} + bb \text{ 0L} [EPJC 78 (2018) 18] \]
\[ E_{\text{miss}} + tt \text{ 0L} [EPJC 78 (2018) 18] \]
\[ E_{\text{miss}} + tt \text{ 1L} [JHEP 06 (2019) 108] \]
\[ E_{\text{miss}} + tt \text{ 2L} [EPJC 78 (2018) 18] \]
**Orthogonality checks**
- < 1% overlap (use sensitivity-ranked orthogonal selections in the future!)

**Input checks:**
- Individual analyses represented correctly

**Correlation scheme:**
- Detector uncertainties straightforward (exception: jet uncertainties)

<table>
<thead>
<tr>
<th>Source</th>
<th>name</th>
<th>VBF</th>
<th>ZH</th>
<th>VH</th>
</tr>
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<tbody>
<tr>
<td>Luminosity</td>
<td>Lumi</td>
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<td>✓</td>
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<tr>
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<td>MUON_EFF_TrigStatUncertainty</td>
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<td>–</td>
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<td>Muon trigger</td>
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<tr>
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<td>MUON_EFF_SYS</td>
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<td>✓</td>
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</table>

- Theory uncertainties “tricky”
  - Lots of talking to analysers + deciphering nuisance parameter names
  - Combination with Run 1 results → more detective work

*arXiv:1904.05105 → Poster by Sascha Dreyer*
### VBF Higgs $\rightarrow$ INVISIBLE: SYSTEMATIC UNCERTAINTIES

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mathcal{B}<em>{\text{inv}}$ improve. [%] using all $m</em>{jj}$ bins</th>
<th>Yields, $\alpha$ changes (%) in $1 &lt; m_{jj} &lt; 1.5$ TeV</th>
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<td>Experimental (†)</td>
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<td>Jet energy resol.</td>
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<td>$E^\text{miss}_T$ soft term</td>
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<td>Lepton id., veto</td>
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<td>Pileup distrib.</td>
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<td>Theoretical (‡)</td>
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<tr>
<td>All ‡ sources</td>
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<td>Combine †, ‡, ★</td>
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AND NOW FOR SOMETHING COMPLETELY DIFFERENT
GRAND UNIFIED THEORY OF AMBULANCE CHASING
GRAND UNIFIED THEORY OF AMBULANCE CHASING

#Run2Seminar and subsequent γγ-related arXiv submissions

2016/08/03 19:00:02: Submissions: 542
A Theory of Ambulance Chasing

Mihailo Backović

(Submitted on 3 Mar 2016)

Ambulance chasing is a common socio-scientific phenomenon in particle physics. I argue that despite the seeming complexity, it is possible to gain insight into both the qualitative and quantitative features of ambulance chasing dynamics. Compound-Poisson statistics suffices to accommodate the time evolution of the cumulative number of papers on a topic, where basic assumptions that the interest in the topic as well as the number of available ideas decrease with time appear to drive the time evolution. It follows that if the interest scales as an inverse power law in time, the cumulative number of papers on a topic is well described by a di-gamma function, with a distinct logarithmic behavior at large times. In cases where the interest decreases exponentially with time, the model predicts that the total number of papers on the topic will converge to a fixed value as time goes to infinity. I demonstrate that the two models are able to fit at least 9 specific instances of ambulance chasing in particle physics using only two free parameters. In case of the most recent ambulance chasing instance, the ATLAS $\gamma$ excess, fits to the current data predict that the total number of papers on the topic will not exceed 310 papers by the June 1, 2016, and prior to the natural cut-off for the validity of the theory.

Comments: 9 pages, 4 figures
Cite as: arXiv:1603.01204 [physics.soc-ph]
(or arXiv:1603.01204v1 [physics.soc-ph] for this version)
GRAND UNIFIED THEORY OF AMBULANCE CHASING

II. AMBULANCE CHASING AS A POISSON PROCESS

\[ P(N, T) = \prod_{t=1}^{T} P(n, t) \]
\[ = \prod_{t=1}^{T} \frac{e^{-\mu(t)}}{n(t)!} \mu(t)^{n(t)} \]
\[ = \exp \left[ -\sum_{t=1}^{T} \mu(t) \right] \left[ \sum_{t=1}^{T} \mu(t) \right]^{N(t)} \]

\[ \mu(t) = \begin{cases} 
\sum_{k=1}^{\infty} \frac{a_k}{t^k} & \text{model 1} \\
A \exp \left( -\sum_{k=1}^{\infty} B_k t^k \right) & \text{model 2}
\end{cases} \]

"Experimental" data

<table>
<thead>
<tr>
<th>Result</th>
<th>Announcement Date</th>
<th>arXiv number</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS ( \gamma \gamma )</td>
<td>15 Dec. 2015</td>
<td>N/A</td>
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<td>ATLAS VV</td>
<td>2 Jun. 2015</td>
<td>1506.00962</td>
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<td>BICEP2</td>
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<td>1403.3985</td>
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<td>Fermi 130 GeV</td>
<td>12 Apr. 2012</td>
<td>1204.2797</td>
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<td>OPERA</td>
<td>22 Sep. 2011</td>
<td>1109.4897</td>
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<td>CDF ( W + 2j )</td>
<td>4 Apr. 2011</td>
<td>1104.0699</td>
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<td>( A_{FB} )</td>
<td>30 Dec. 2010</td>
<td>1101.0034</td>
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<td>PAMELA e+</td>
<td>8 Oct. 2008</td>
<td>0810.4995</td>
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<td>Unparticles</td>
<td>23 Mar. 2007</td>
<td>0703260</td>
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</tbody>
</table>

arXiv:1603.01204
GRAND UNIFIED THEORY OF AMBULANCE CHASING

ATLAS $\gamma \gamma$

$\mu(T) = 77.9 \, H(0.104/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

Fermi 130 GeV

$\mu(T) = 161.0 \, H(0.00246/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

ATLAS $VV$

$\mu(T) = 316.7 \, H(0.00131/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

BICEP2

$\mu(T) = 401.3 \, H(0.012/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

OPERA

$\mu(T) = 61.3 \, H(0.122/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

CDF W+2j

$\mu(T) = 36.9 \, H(0.02699/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

$A_{FB}$

$\mu(T) = 206.6 \, H(0.00189/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

PAMELA $e^+$

$\mu(T) = 679.5 \, H(0.00111/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

Unparticles

$\mu(T) = 193.7 \, H(0.00208/\text{day} \, T)$

 Cumul. num. of papers

T (Days)

arXiv:1603.01204