Semi-visible jets: where do we go from here?

Deepak Kar (with others)

University of Witwatersrand (South Africa)
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University of Glasgow (UK)

Dark Interactions 2024

Vancouver, Oct. 16-18

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

University of Glasgow

THE ROYAL SOCIETY

ATLAS EXPERIMENT

Prologue:

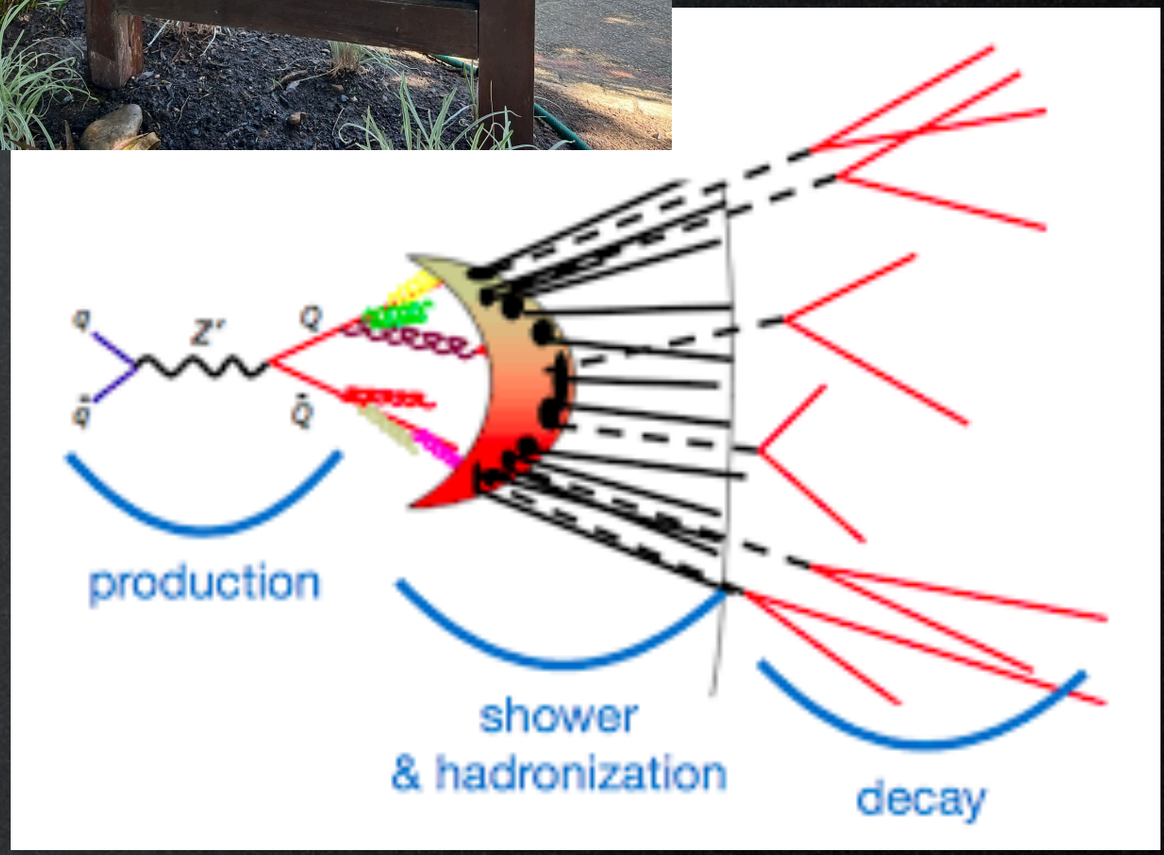

Papers wth SVJ in their title
6
4
2
0
2016
2018
2020
2022
2024


SEMI-VISIBLE
JETS!
imgflip.com

Dark QCD/Strongly Interacting Dark Sector

- A simple replica of standard QCD!
- Hadronisation in hidden sector, off-diagonal dark hadrons, invisible and stable while diagonal ones can decay back to SM quarks.
- The fraction decaying back to SM determines if we get a visible, invisible or semi-visible jet!

Not a model, more like a Topology-generator



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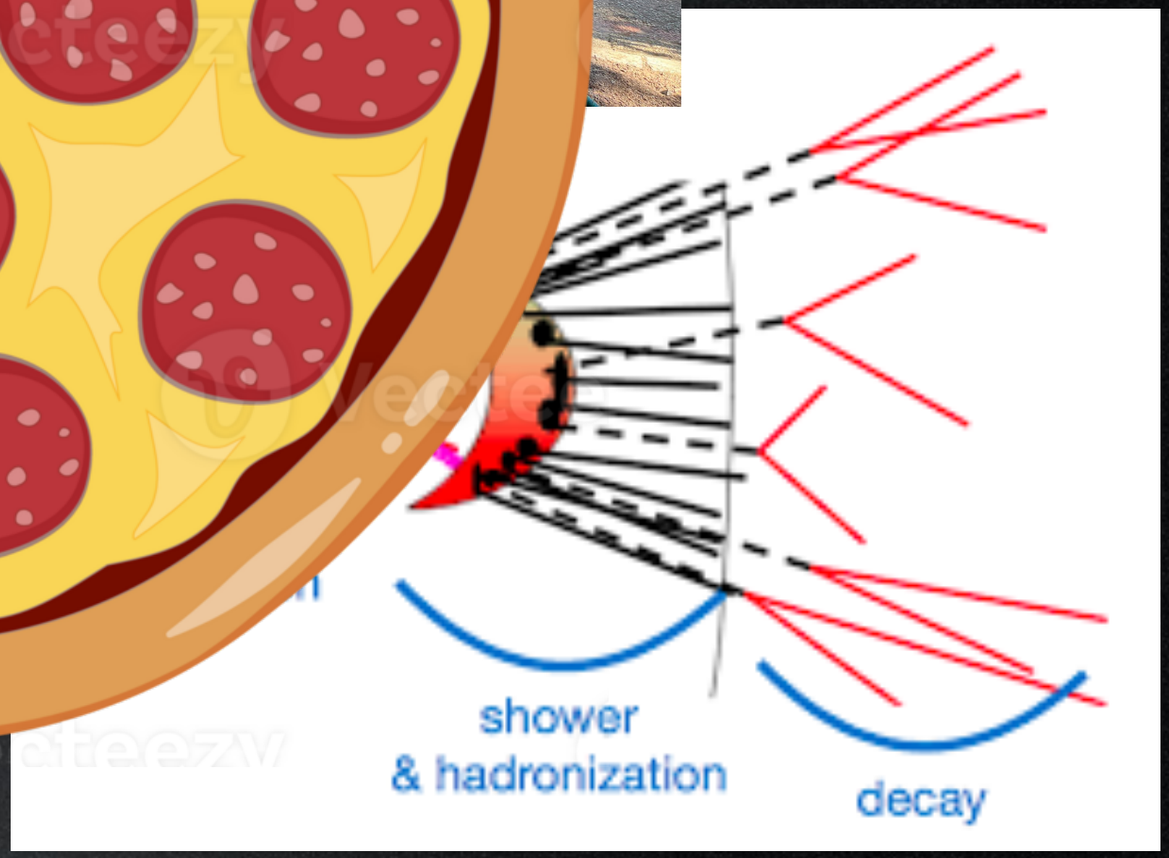

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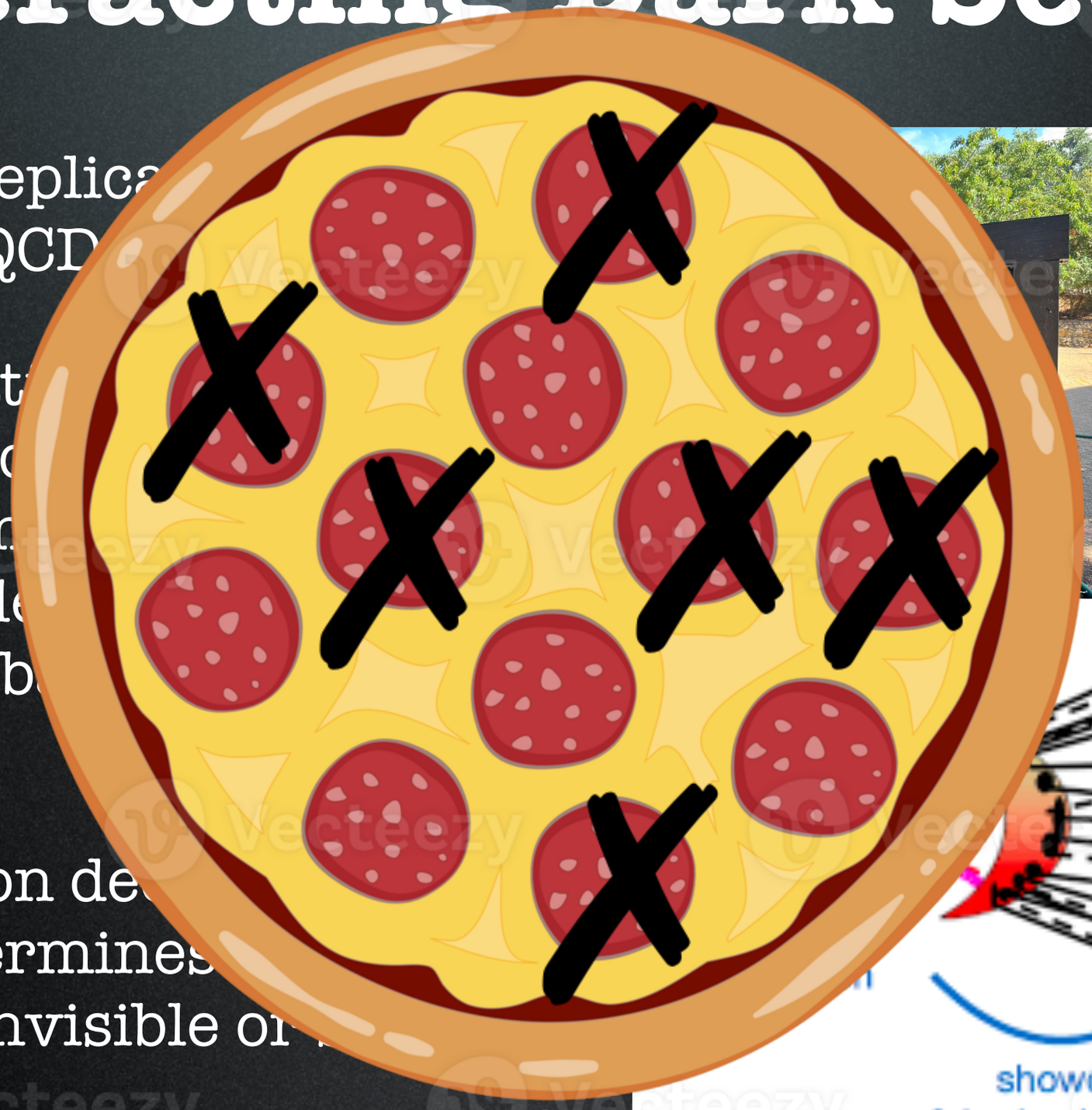

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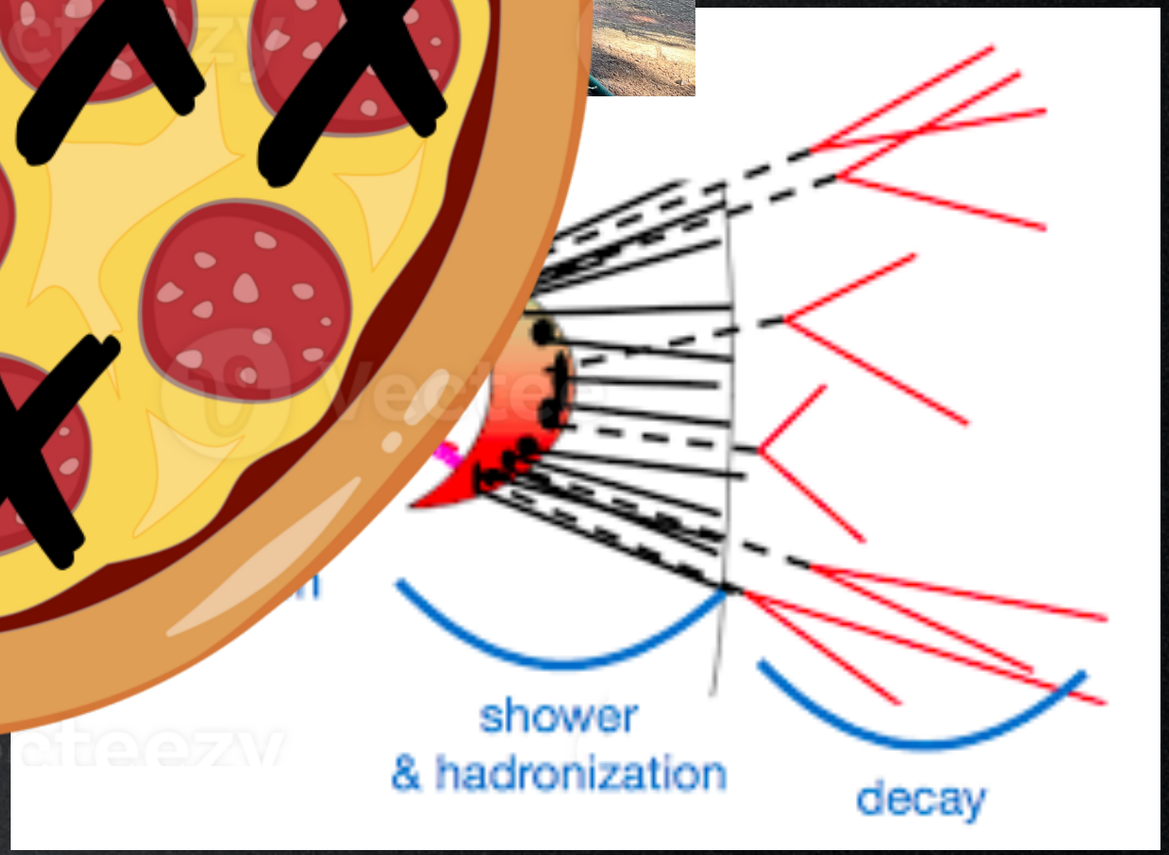

Sabine Hossenfelder
@skdh

That's basically what it is. The "dark sector" or "hidden sector" is a name for increasingly contrived and complex collections of particles (and their interactions) which physicists have invented and that no one has ever seen.

> **Benjamin Titus** @Benny_Switch · Feb 14
>
> Replying to @WKCosmo
>
> Please tell me what “Dark Sector” means. I thought I was well read enough, but I’ve been seeing this phrase thrown around and all I get from it is “additional Dark things that may or may not be there”

Will Kinney
@WKCosmo

There's a very good reason why the default assumption is that dark matter consists of a single type of particle: Dark matter must be stable, and only the lightest particle in a mass hierarchy is stable. For example, the only stable baryon in the Standard Model is the proton.

2:36 AM · Feb 15, 2023 · **72.4K** Views

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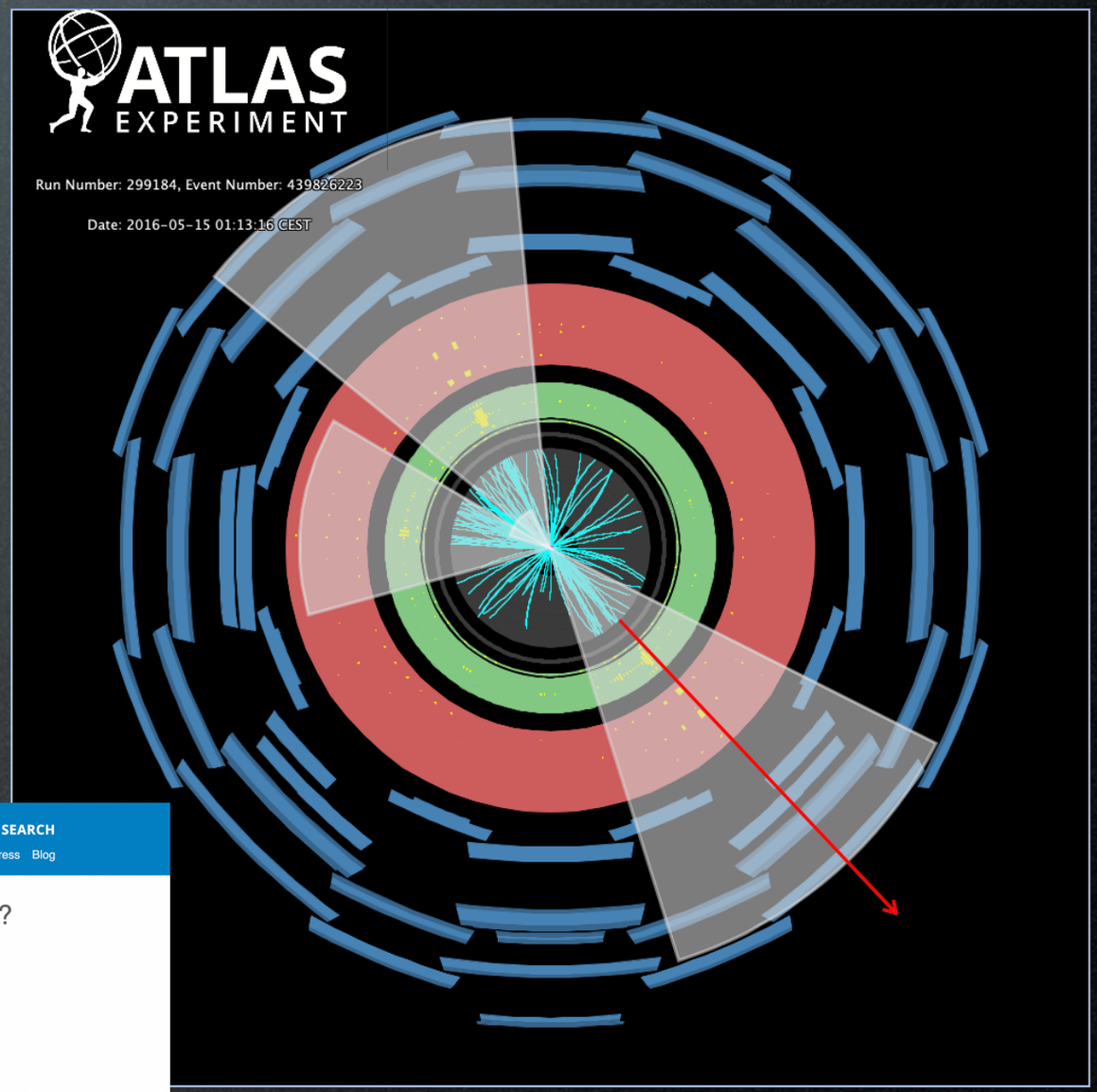
Experimental Results (so far ...)

- CMS s-channel search
- ATLAS t-channel search
- ATLAS (s-channel) dark-jets search



ATLAS EXPERIMENT

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Physics Briefing

Tags:
LHCP 2023,
new physics,
dark matter,
physics results

Not a jet all the way: is dark matter hiding in plain sight?

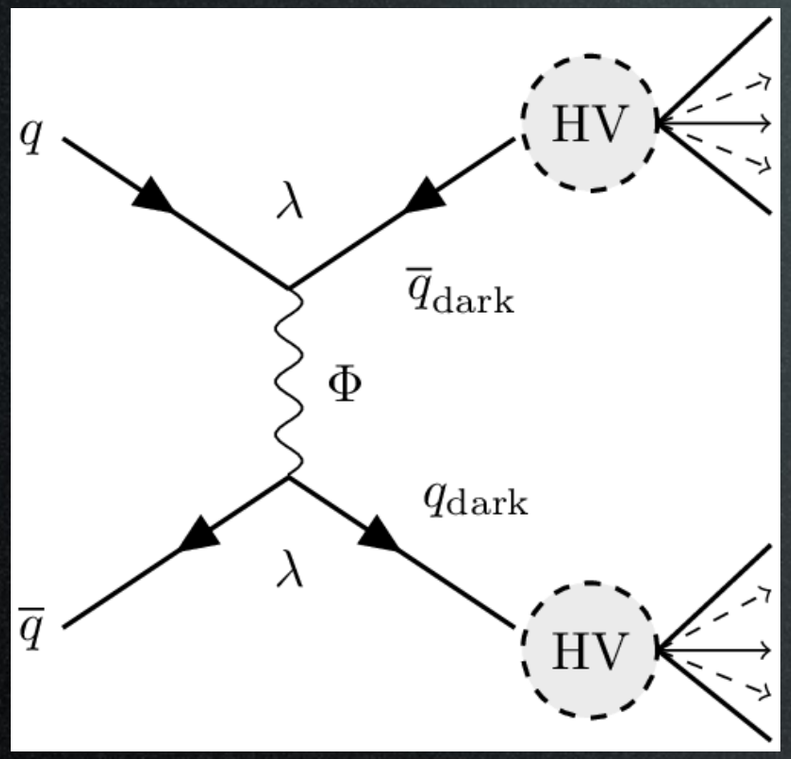
26 May 2023 I By ATLAS Collaboration

What happens if dark-matter particles are produced inside a jet of Standard-Model particles? This leads to a novel detector signature known as semi-visible jets! The ATLAS Collaboration has come up with the first search for semi-visible jets, looking for them in a general production mode where two protons interact by exchanging an intermediate particle, which is then converted into two jets.

The elusive nature of dark matter remains one of the biggest mysteries in particle physics. Most of the searches have so far looked for events where a “weakly interacting” dark-matter particle is produced alongside a known Standard-Model particle. Since the dark-matter particle cannot be seen by the ATLAS detector, researchers look for an imbalance of transverse momentum (or “missing energy”). However, some theoretical models predict a “strongly interacting” dark sector, with dark quarks and gluons as replicas of Standard-Model quarks and gluons. Semi-visible jets would arise when dark quarks decay partially to Standard-Model quarks and partially to stable dark hadrons (the “invisible fraction”). Since they are produced in pairs, typically along with additional Standard-Model jets, the missing energy arises when all the jets are not fully balanced. The direction of the missing energy is often aligned with one of the semi-visible jets, as can be seen in the event display above.

Phys. Lett. B 848 (2024) 138324

ATLAS SVJ Search



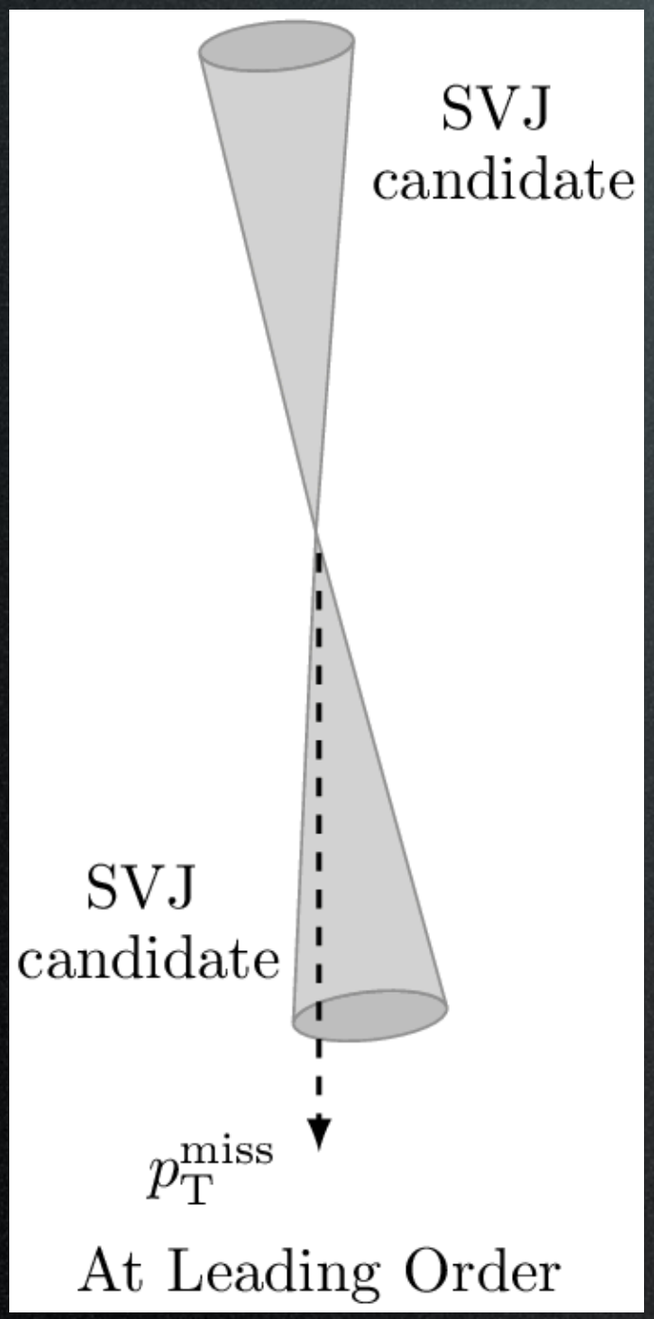
Results in jets interpersed with dar
hadrons, with missing transve
momentum direction alig with one of
the SVJs in leading Not so for
events with ext and large boost.

Unique collider topology - mostly overlooked in searches!

Events with two central j ET trigger, leading jet p_T > 250 GeV, H_T > 600 GeV, MET 600 > G closest to MET with $\Delta\Phi$<2

Define: S uon veto), and three CRs, 1L, 1L1B, 2L (with muons and b-tag ts)

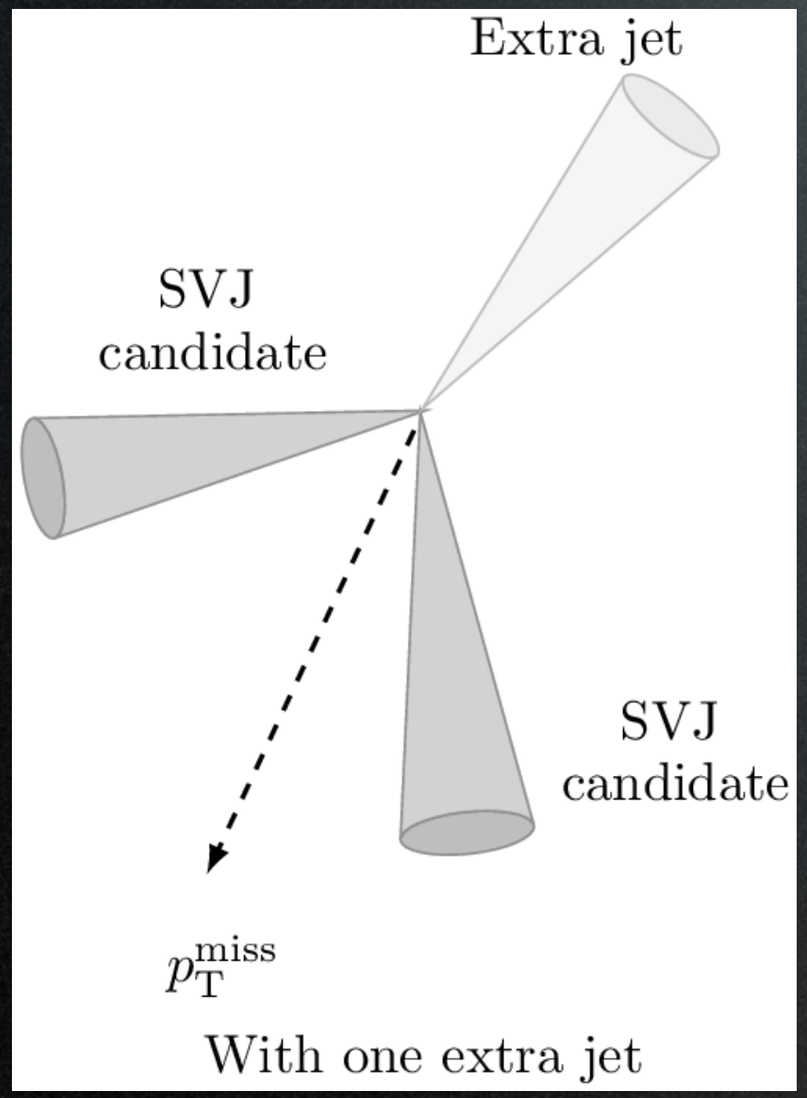
The topology and the challenges



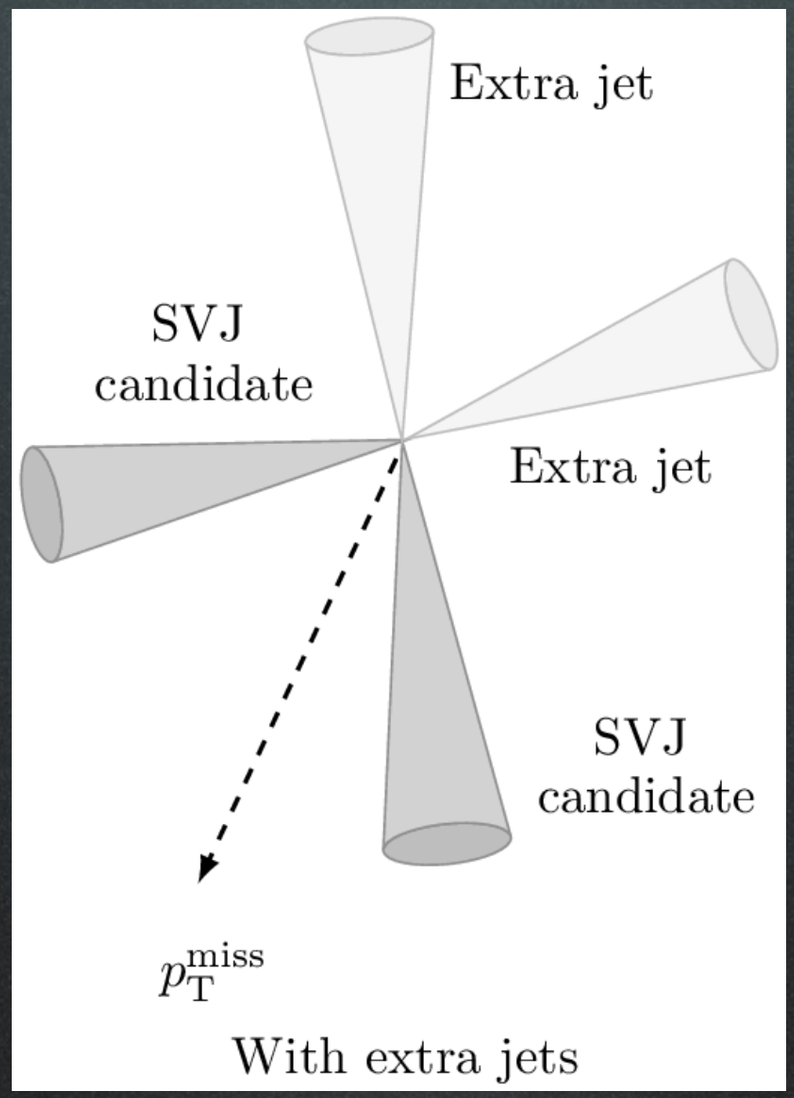
Same fraction
of dark hadrons
In each jet

Why any MET?

The topology and the challenges



With one extra jet



With extra jets

A real event will look like this!

Quantum fluctuations, and boost by extra jets

Therefore MET

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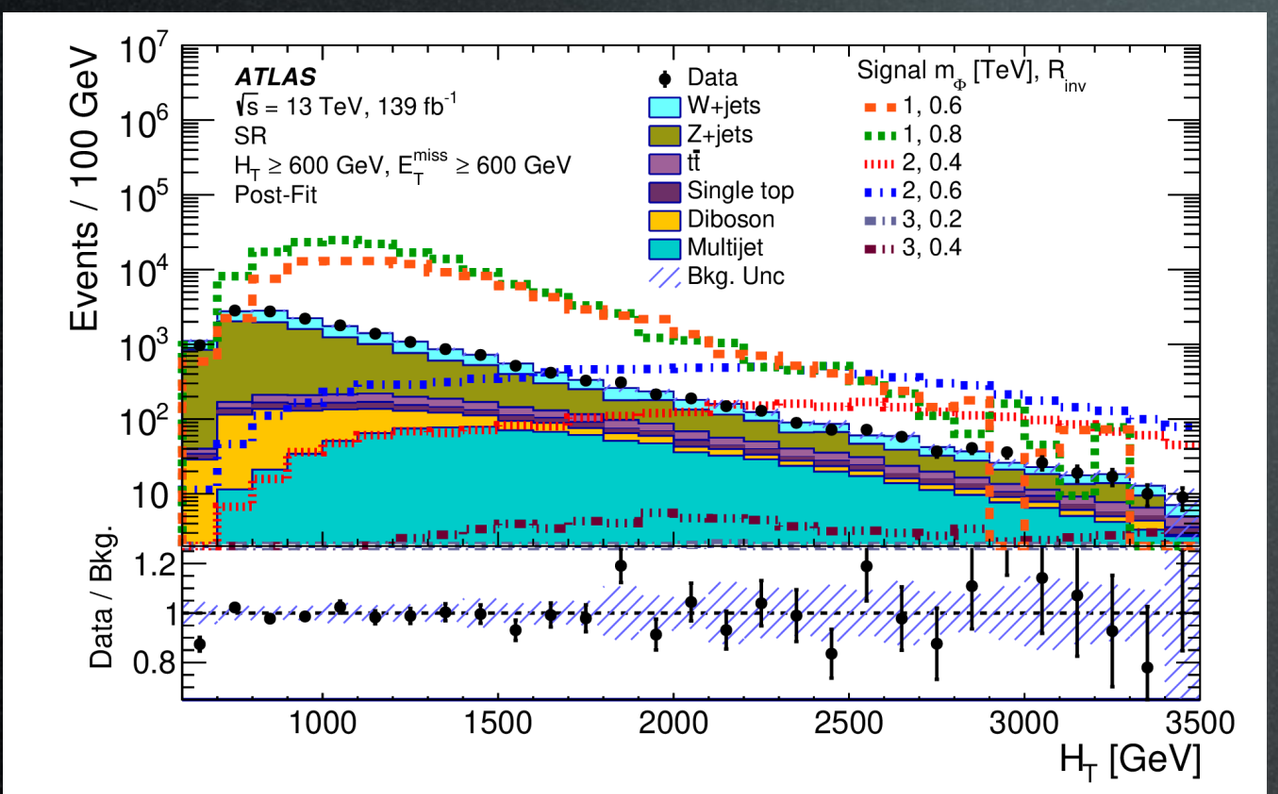
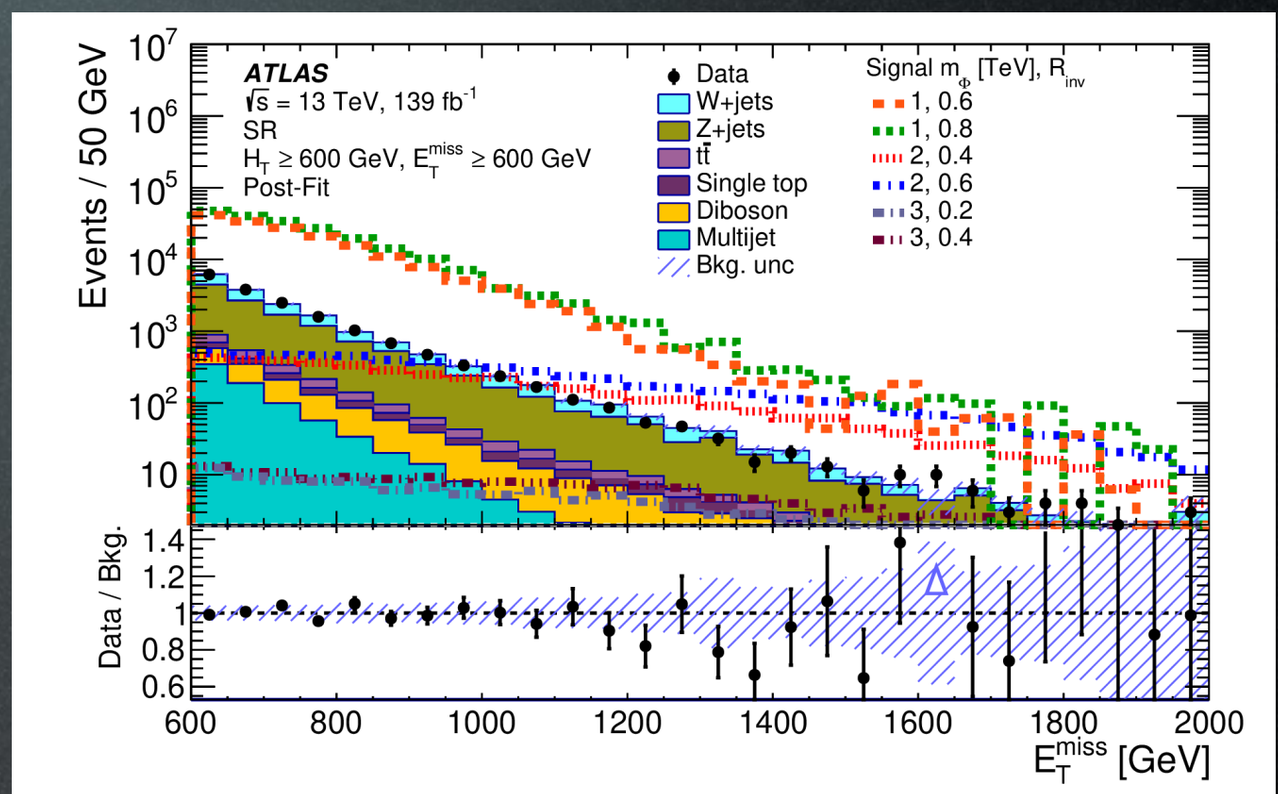
Results

Sukanya Sinha:
former PhD student,
now in UofM





Excellent agreement between data and background prediction:
H_T and MET

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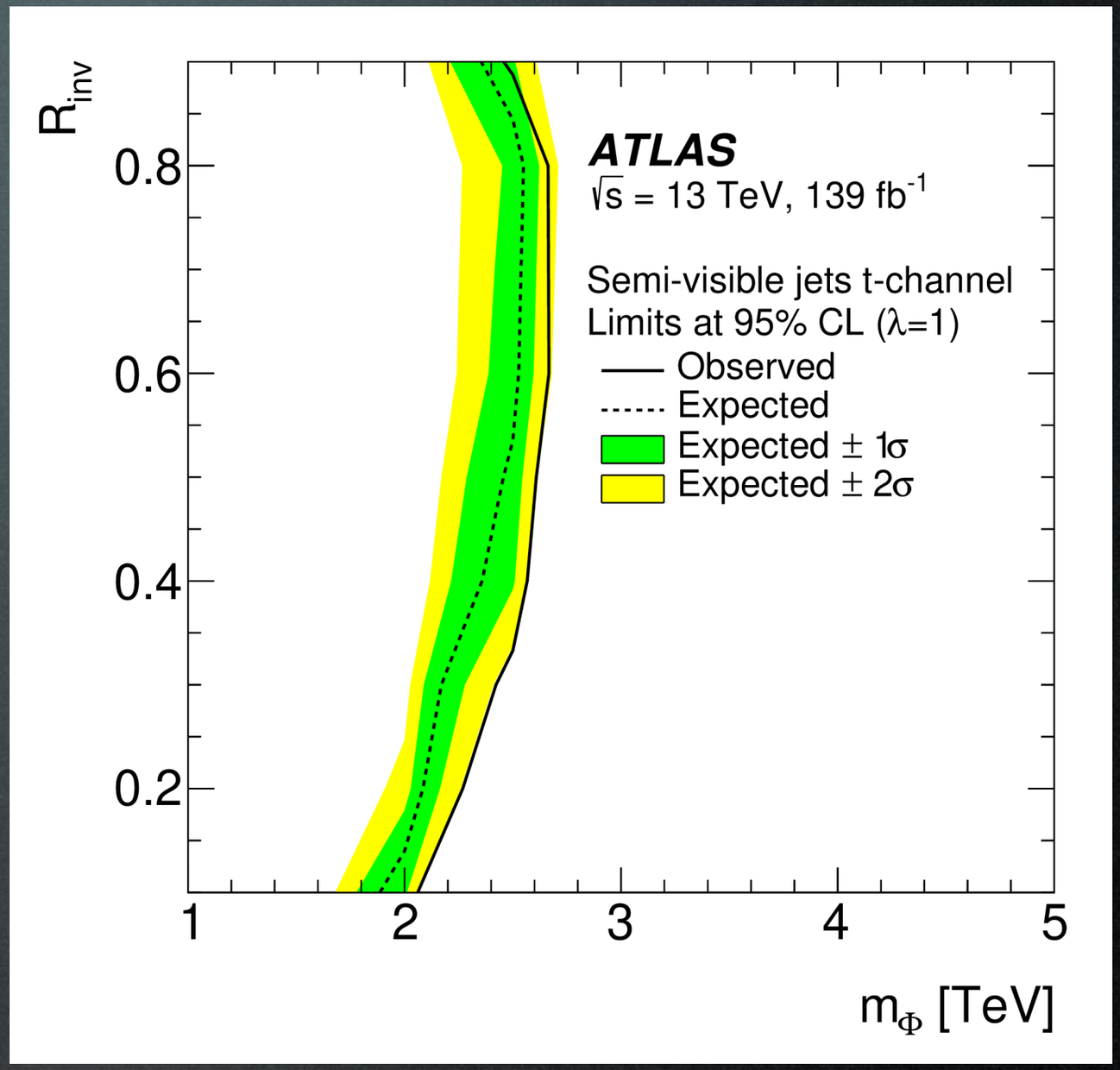
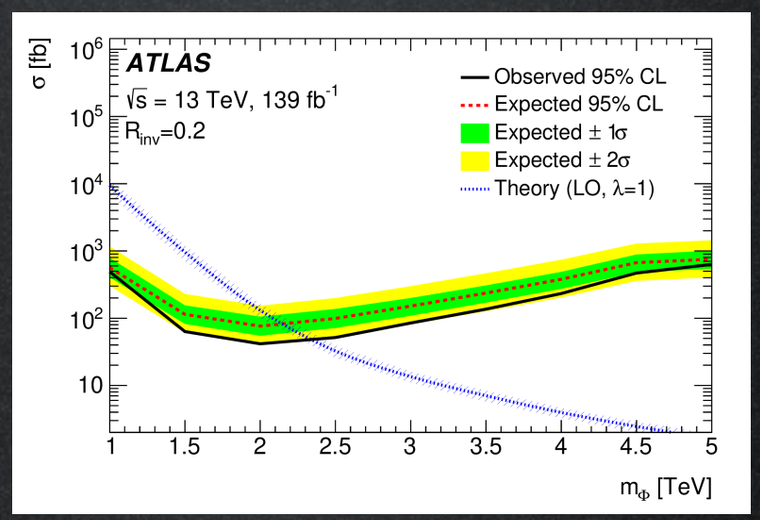
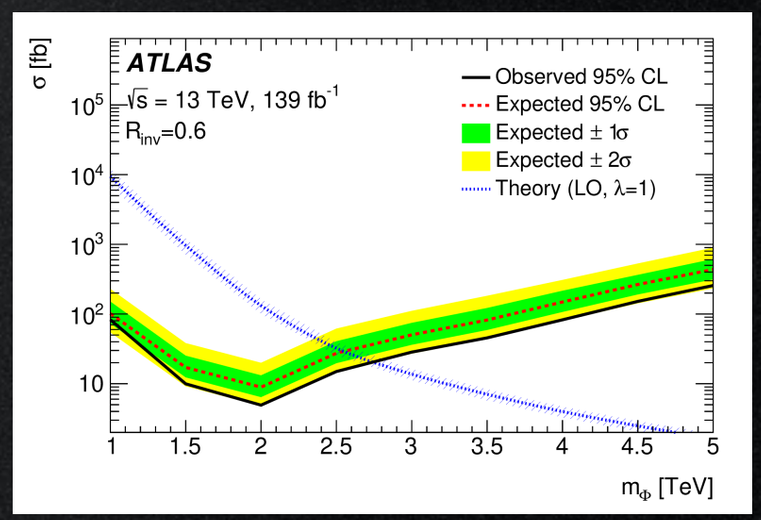
Results

- Limits on mediator mass separately for each R_{inv}
- Data yield in SR, proxy for model independent limit with this SR selections: 17388







What's next for SVJ?

- Diverse signatures
- Reviewing/benchmarking the models: alternate approaches, checking constraints from other collider and non-collider results
- Better discriminating observables including Machine-learning based approaches

Make best use of our data ;-)
This is all we are going to have!

Leptons lurking in semi-visible jets at the LHC

Cesare Cazzaniga [a,1], **Annapaola de Cosa** [b,1]

[1] ETH Zürich Institute for Particle Physics and Astrophysics, CH-8093 Zürich, Switzerland

Uncovering tau leptons-enriched semi-visible jets at the LHC

Hugues Beauchesne[a,1], **Cesare Cazzaniga**[b,2], **Annapaola de Cosa**[c,2], **Caterina Doglioni**[d,3], **Tobias Fitschen**[e,3], **Giovanni Grilli di Cortona**[f,4,5], **Ziyuan Zhou**[g,2,6]

[1]Physics
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Phenomenology of photons-enriched semi-visible jets

Cesare Cazzaniga[a,1], **Alessandro Russo**[c,2], **Emre Sitti**[d,1], **Annapaola de Cosa**[b,1]

[1] ETH Zürich,
[2] Stanford Uni

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Semi-visible jets + X: Illuminating Dark Showers with Radiation

Bingxuan Liu[a] **Kevin Pedro**[b]

[a] *School of Science, Sun Yat-sen University, 66 Gongchang Road, Shenzhen, Guangdong 518107, PRC*

[b] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*

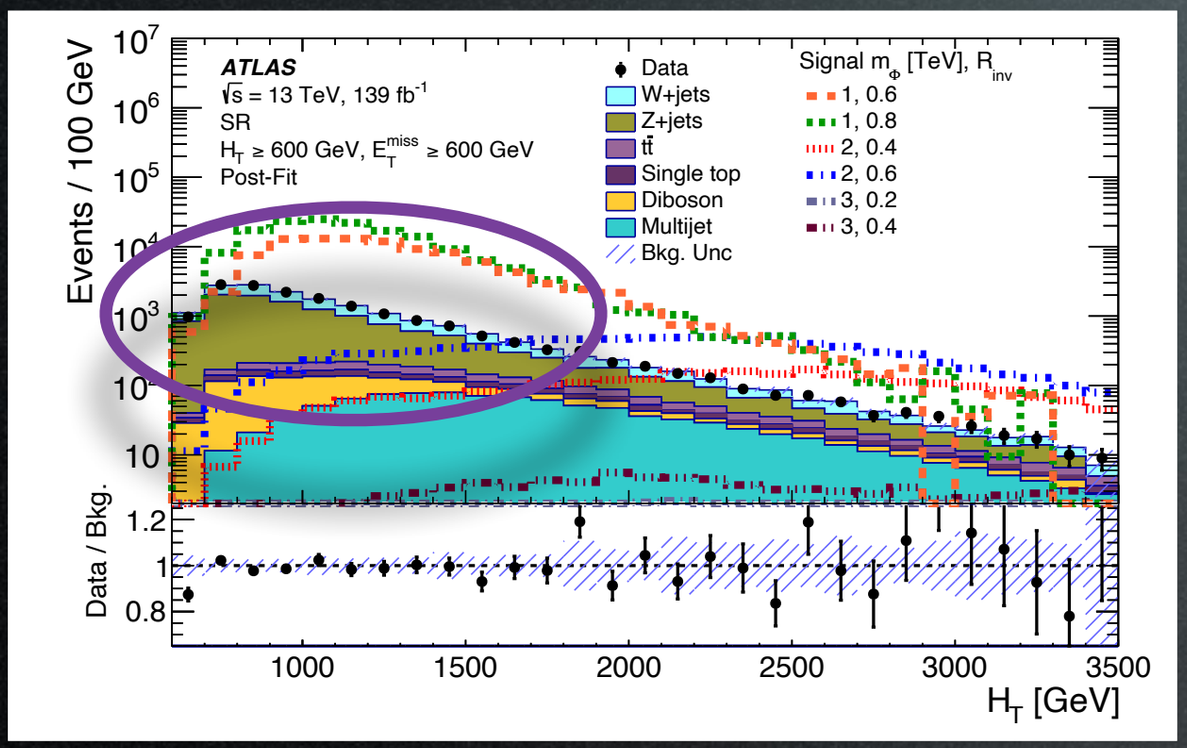
Abstract: We investigate the potential to search for semi-visible jets (SVJs) at the LHC using initial-state radiation (ISR). Both photon ISR and jet ISR channels are considered, using a benchmark signal model with the decay of a leptophobic Z' mediator forming two SVJs. We compare and extend several techniques to decompose the missing transverse

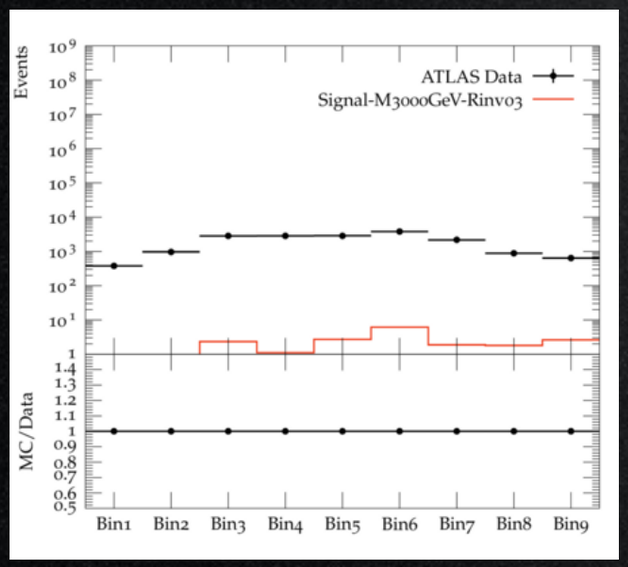
https://arxiv.org/abs/2207.01885

B-philic SVJ

with: Sukanya Sinha and Wandile Nzuza

Wandile Nzuza:
current masters student



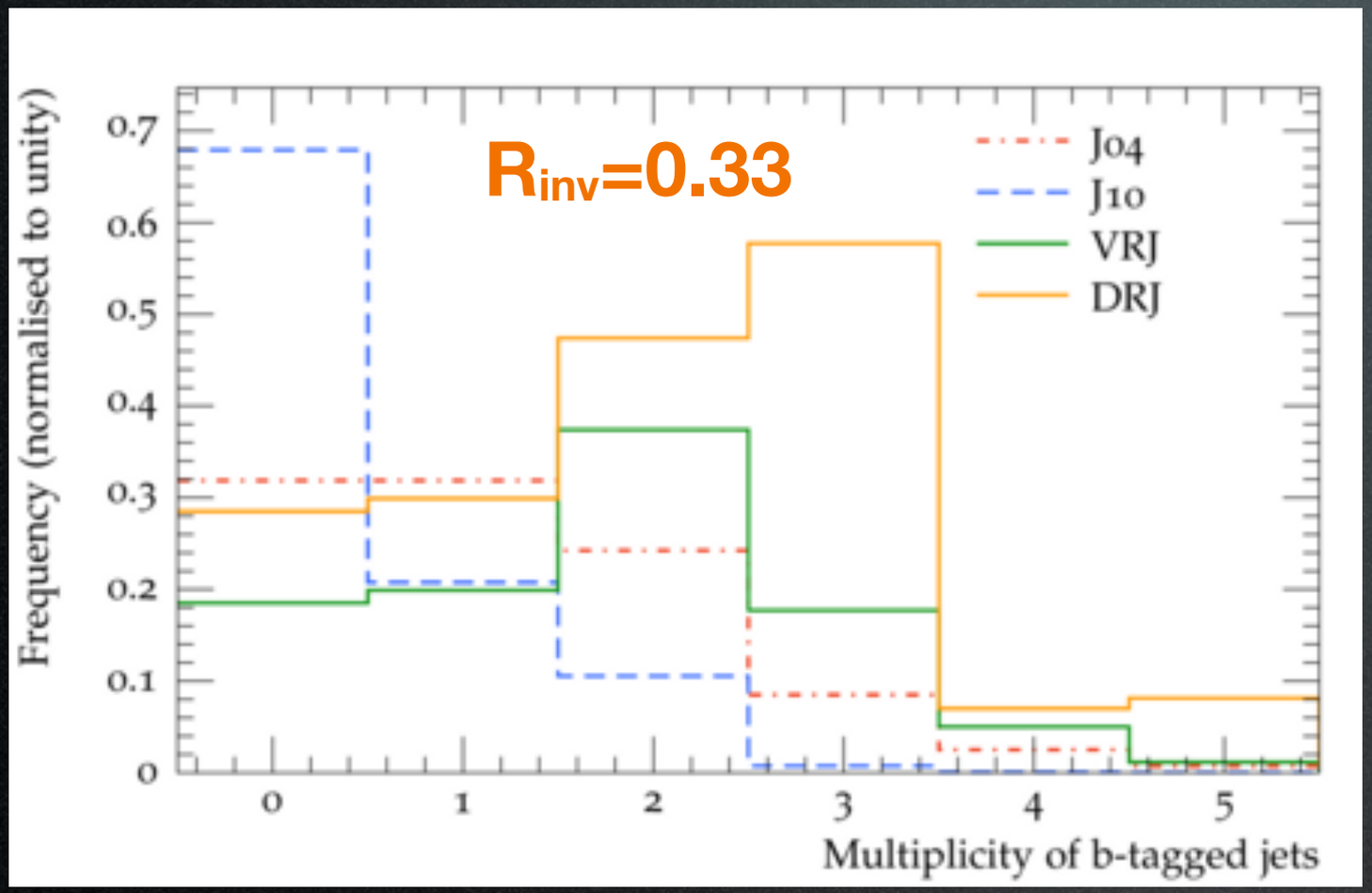


Not excluded by the above result!

- Can we reduce our dominant background in the most signal-rich region?
- Theoretically: well motivated, helicity flipping suppression can force the dark ρ to go to $b\bar{b}$.
- The advantage: the SVJ candidate can be better identified by the presence of b-hadrons.

https://arxiv.org/abs/2207.01885

Jets to use:



Selection	Selection Efficiency in % Signal R_{inv} = 0.33	Signal R_{inv} = 0.67
J04	33	12
J10	11	3
VRJ	60	35
DRJ	81	66

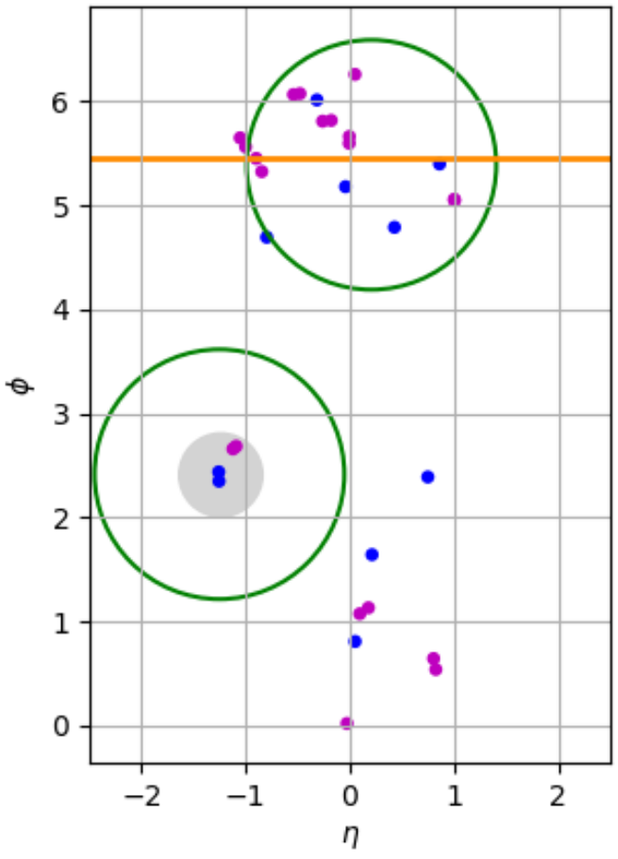
Jet multiplicity: indicative of signal selection efficiency

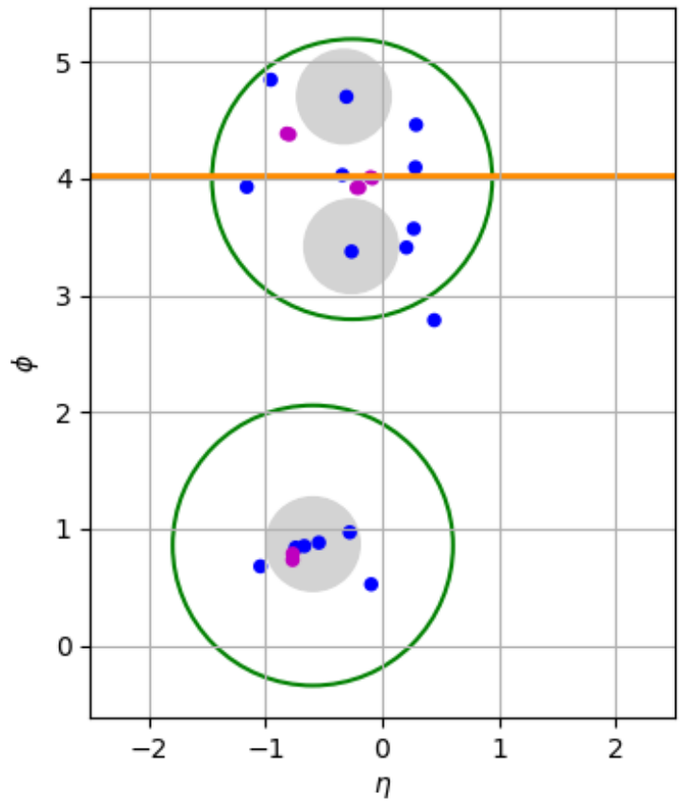
- J04: typically SVJs have a larger spread
- J10: higher pT threshold
- VRJ: expanded radius based on a mass-like parameter ρ/p_T of the jet (used j04 as inputs)
- DRJ: allows the radius by an additional term, which captures the p_T-weighted standard deviation of the distances between pairs of constituents.

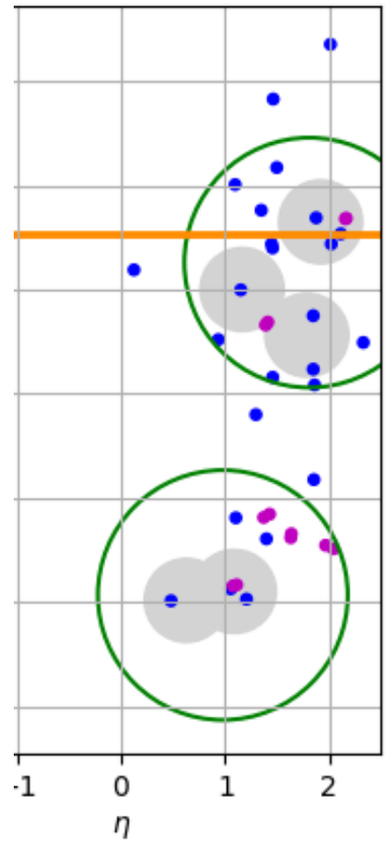
https://arxiv.org/abs/2207.01885

Example Events

Shows the advantage of using VR jets







J04

VRJ

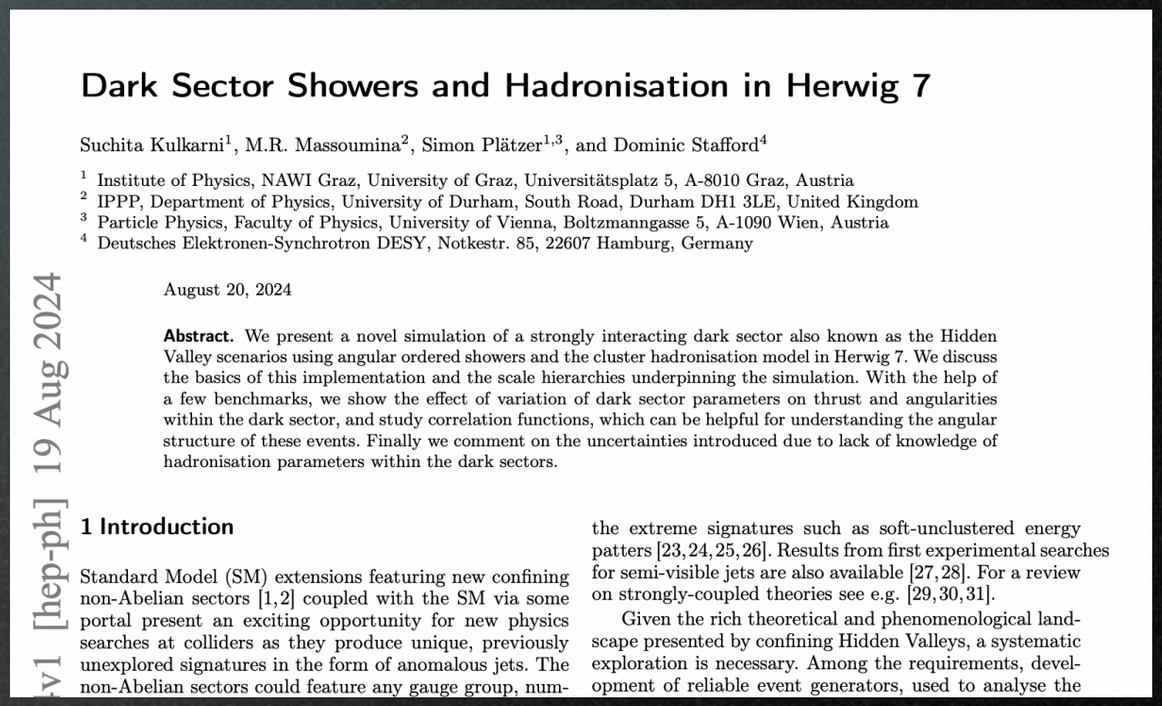
MET

Dark hadrons

B-hadrons

Signal Models

- Only Pythia8 HV model so far, and the model parameters are still being discussed* ...
- Herwig7 dark shower model, almost there ...
- A simplified approach:



Dark Sector Showers and Hadronisation in Herwig 7

Suchita Kulkarni[1], M.R. Massoumina[2], Simon Plätzer[1,3], and Dominic Stafford[4]

[1] Institute of Physics, NAWI Graz, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria
[2] IPPP, Department of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom
[3] Particle Physics, Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Wien, Austria
[4] Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

August 20, 2024

Abstract. We present a novel simulation of a strongly interacting dark sector also known as the Hidden Valley scenarios using angular ordered showers and the cluster hadronisation model in Herwig 7. We discuss the basics of this implementation and the scale hierarchies underpinning the simulation. With the help of a few benchmarks, we show the effect of variation of dark sector parameters on thrust and angularities within the dark sector, and study correlation functions, which can be helpful for understanding the angular structure of these events. Finally we comment on the uncertainties introduced due to lack of knowledge of hadronisation parameters within the dark sectors.

1 Introduction

Standard Model (SM) extensions featuring new confining non-Abelian sectors [1,2] coupled with the SM via some portal present an exciting opportunity for new physics searches at colliders as they produce unique, previously unexplored signatures in the form of anomalous jets. The non-Abelian sectors could feature any gauge group, number

the extreme signatures such as soft-unclustered energy patters [23,24,25,26]. Results from first experimental searches for semi-visible jets are also available [27,28]. For a review on strongly-coupled theories see e.g. [29,30,31].

Given the rich theoretical and phenomenological landscape presented by confining Hidden Valleys, a systematic exploration is necessary. Among the requirements, development of reliable event generators, used to analyse the

* Single dark QCD flavour, one loop running of dark QCD coupling, confinement scale o
6.5 GeV, coupling between dark and SM sector taken to be unity.

The idea:

with: Nishita Desai

Let dark quarks split into stable and unstable dark hadrons by R_{inv} fraction:

- The unstable dark hadron decays back to SM quarks -> SM hadrons.
- The stable dark hadrons are the invisible components.

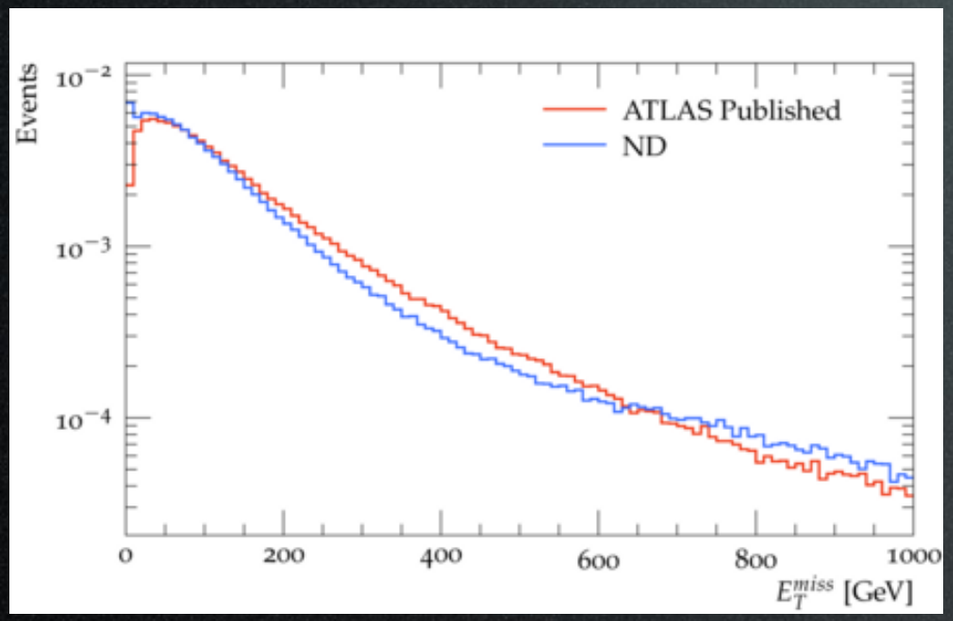
The splitting is determined by: Average Number of Dark hadrons (N_{avg}) and energy distribution by:

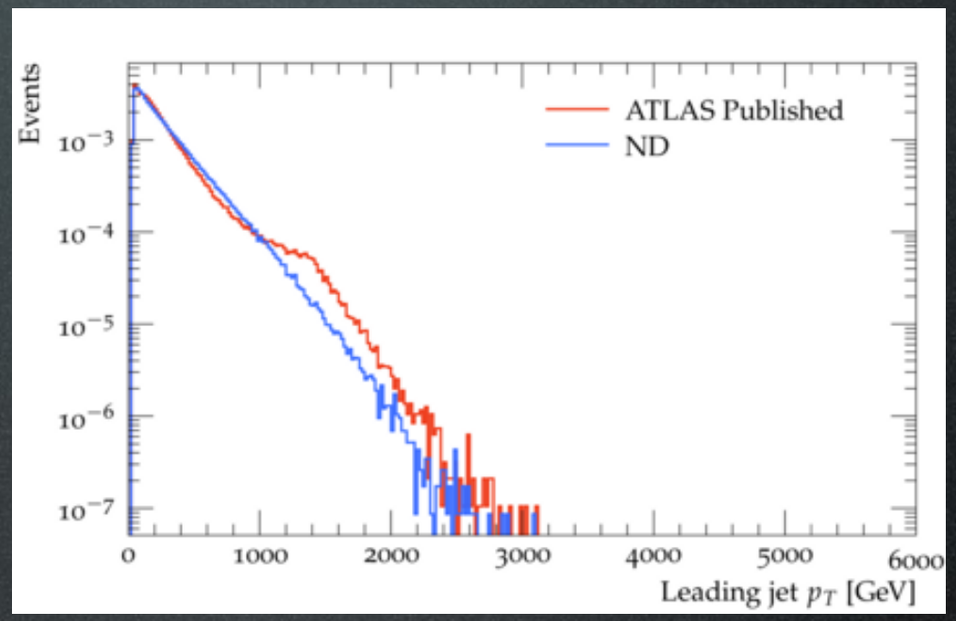
$$f(r) = \frac{1 - a^{2r}}{1 - a^{2r_{\max}}}$$

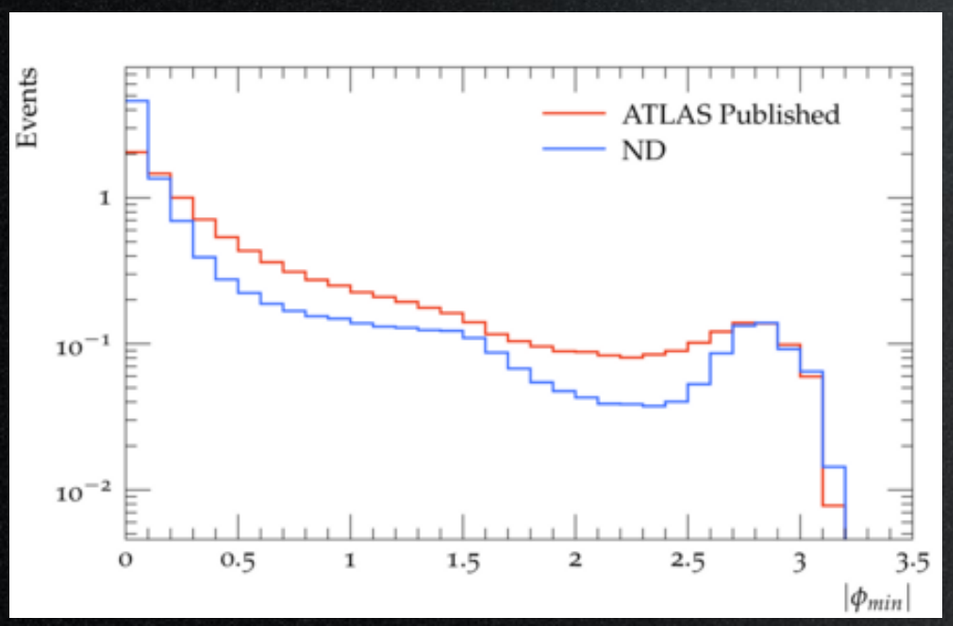
Less Free Parameters!

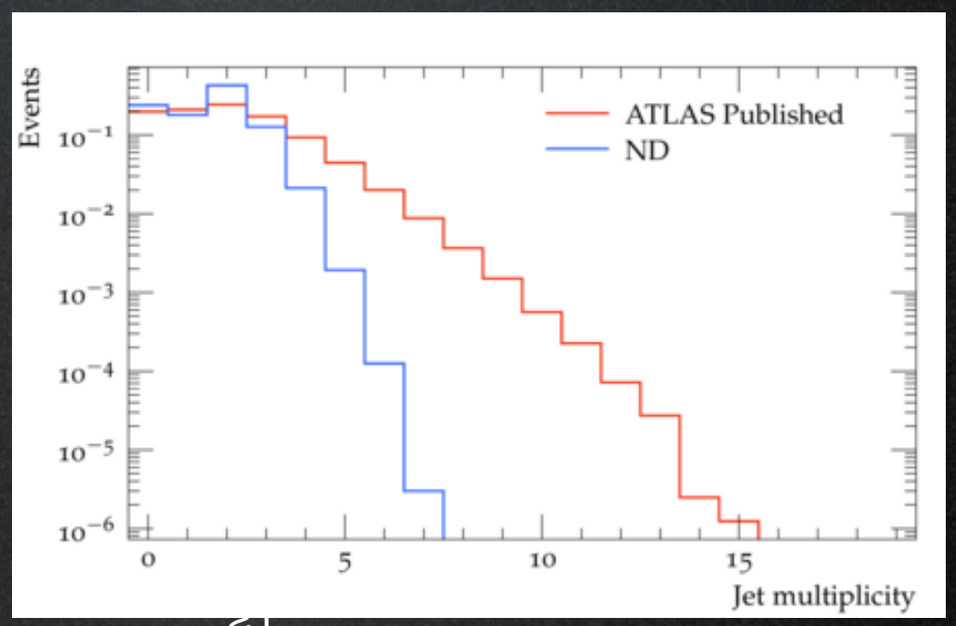
Exact number of hadrons in each event will be different so splitting in each event will be different. It depends on number of hadrons (which is in turn set by N_{avg} value)

WiP: Looking at the kinematic distributions









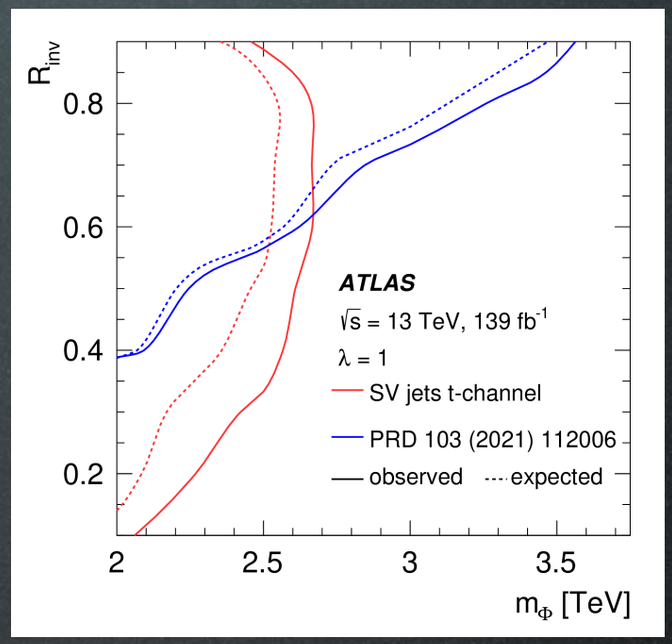
... with a specific parameter choice, fairly insensitive to reasonable variations

WiP: Estimating constraints from current results/Reinterpretation

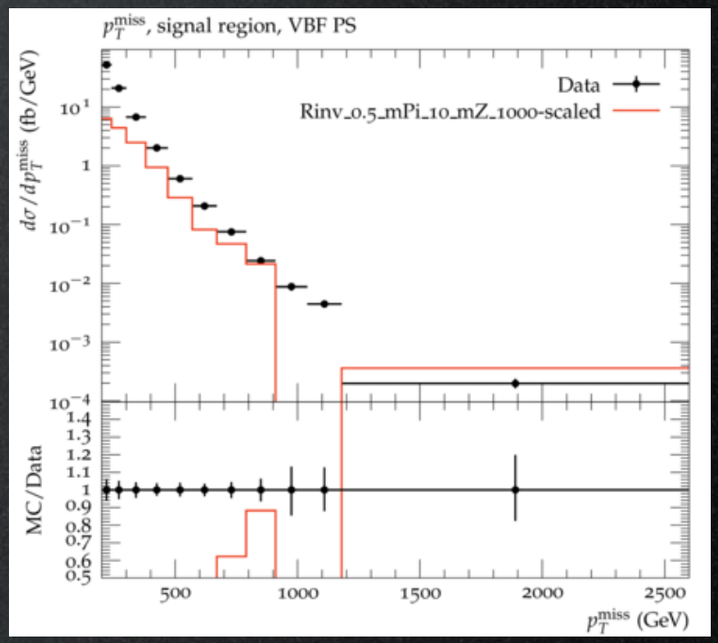
Clarisse Prat
current masters
student

with: Clarisse Prat, Sukanya Sinha, Suchita Kulkarni, Jon Butterworth, Andy Buckey

- The CONTUR (Constraints On New Theories Using Rivet) approach
- Proof of principle: ATLAS JET+MET measurement almost excludes Z' SVJ-s signal for 1 TeV mass
- SVJ-t study in progress!



Expected and observed exclusion contours at 95% CL for semi-visible jets signal, using the mono-jet analysis selection.

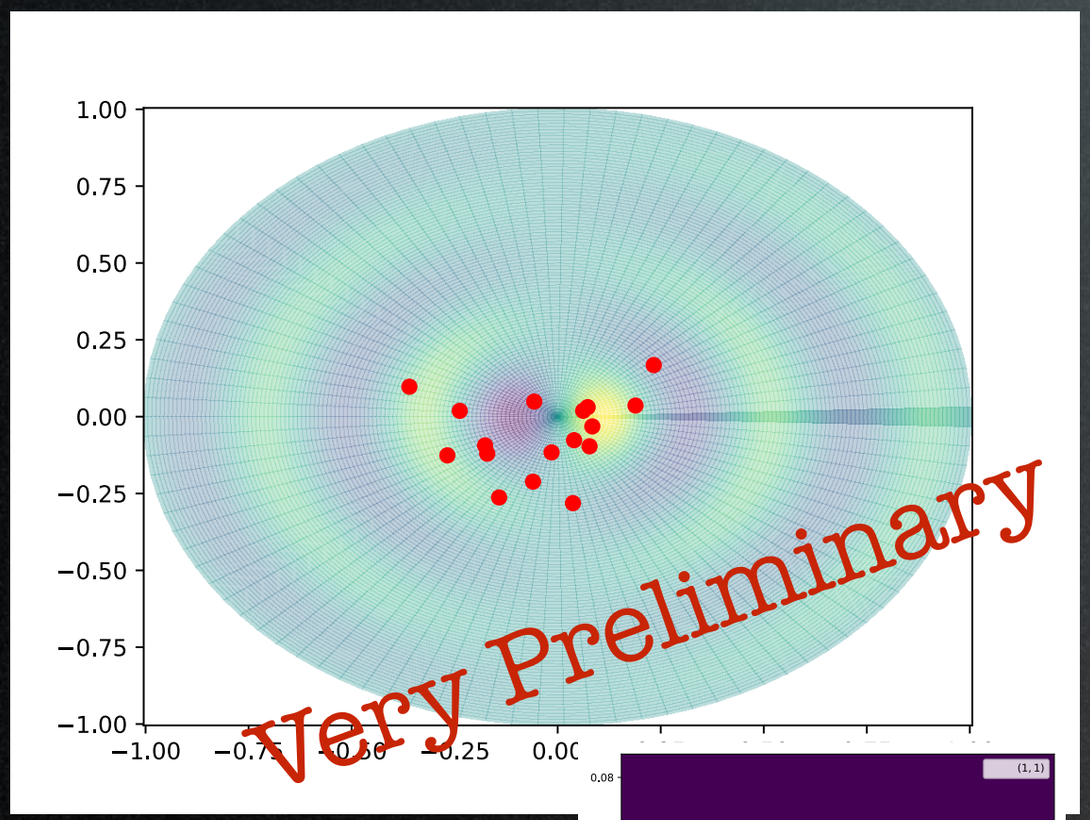


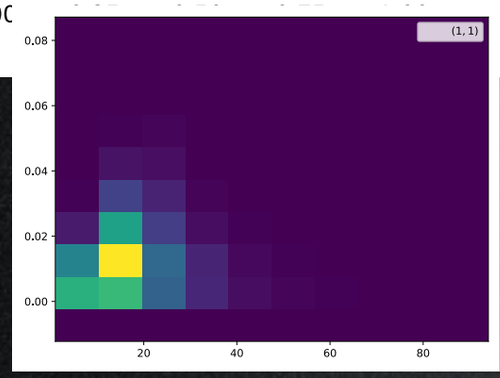
WiP: New Observables

with: Andy Buckey

SVJs rather than having prongs like top-quarks, have holes.

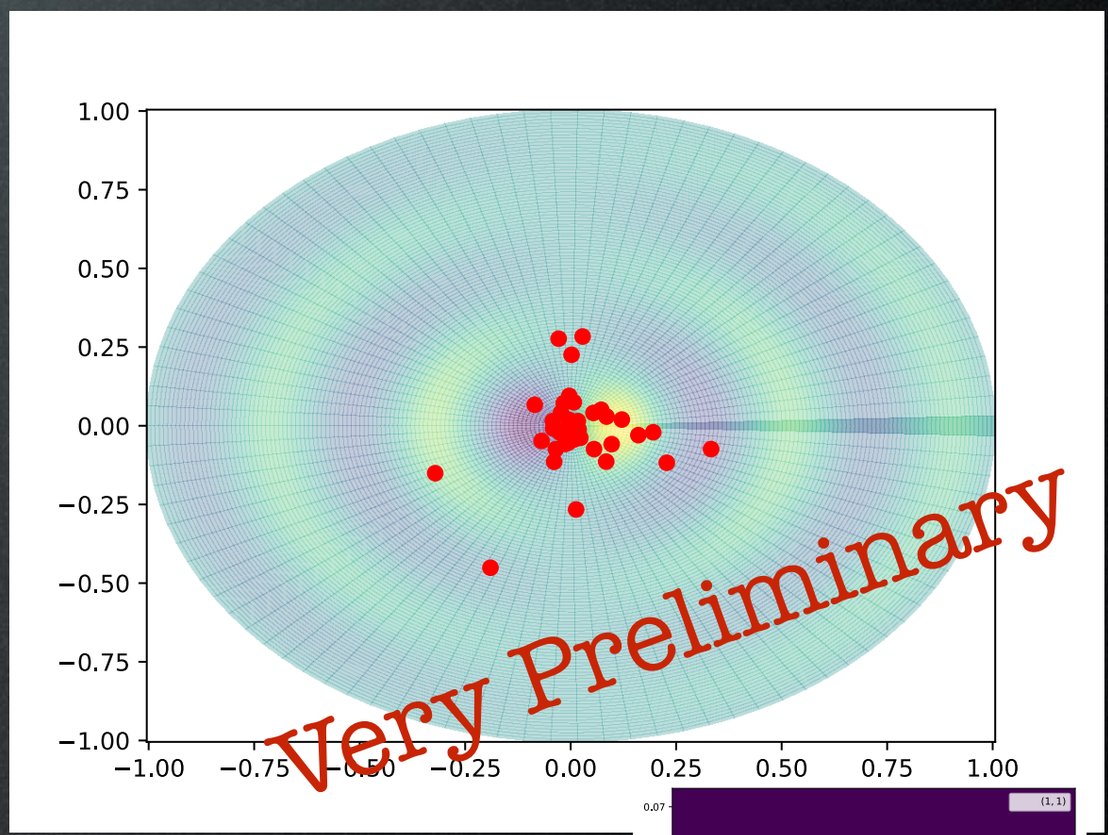
Can we calculate overlap with cylindrical Bessel functions?

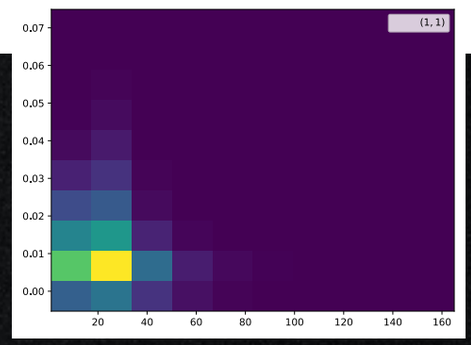




SVJ

vs





Q/G Jet

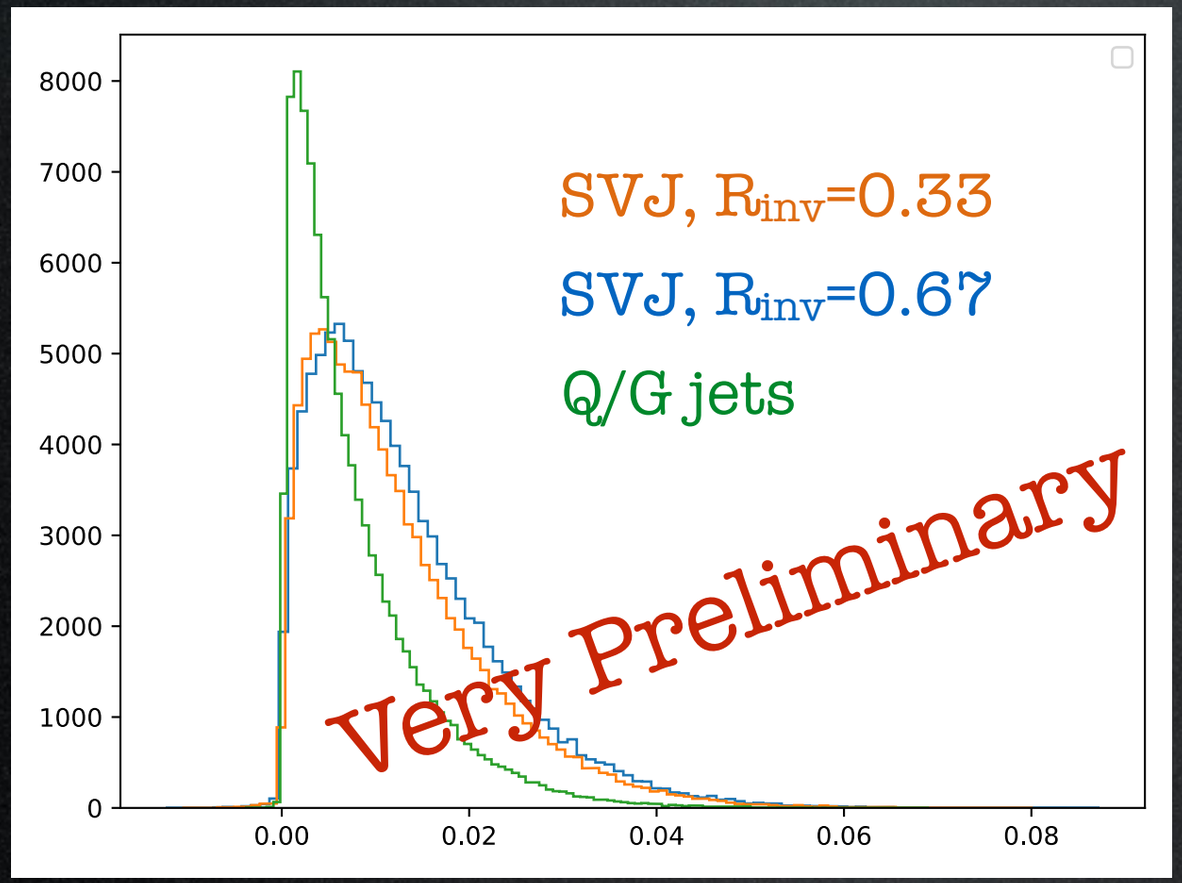
WiP: New Observables

with: Andy Buckey

SVJs rather than having prongs like top-quarks, have holes.

Can we calculate overlap with cylindrical Bessel functions?

We can, somewhat ...

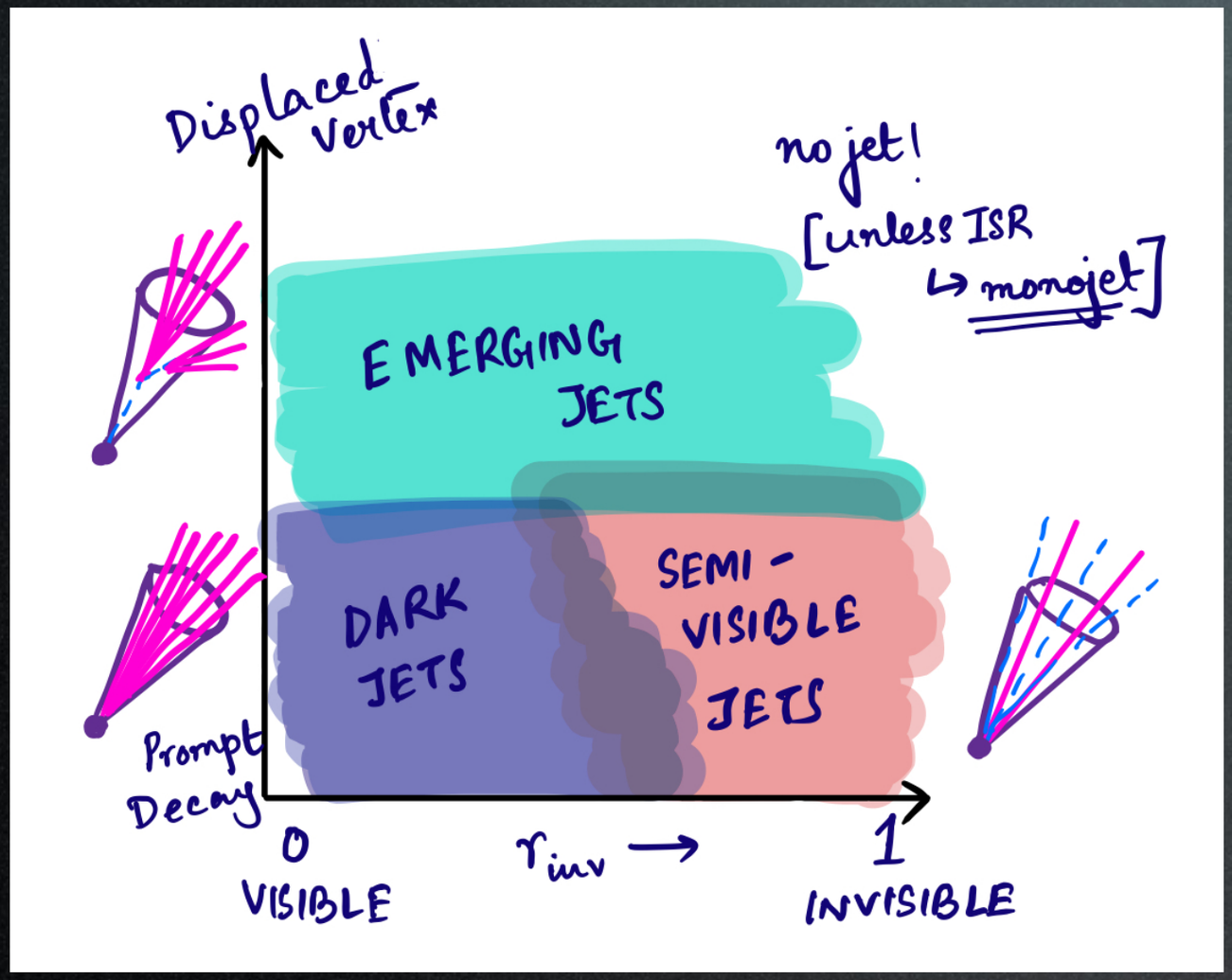


Summary

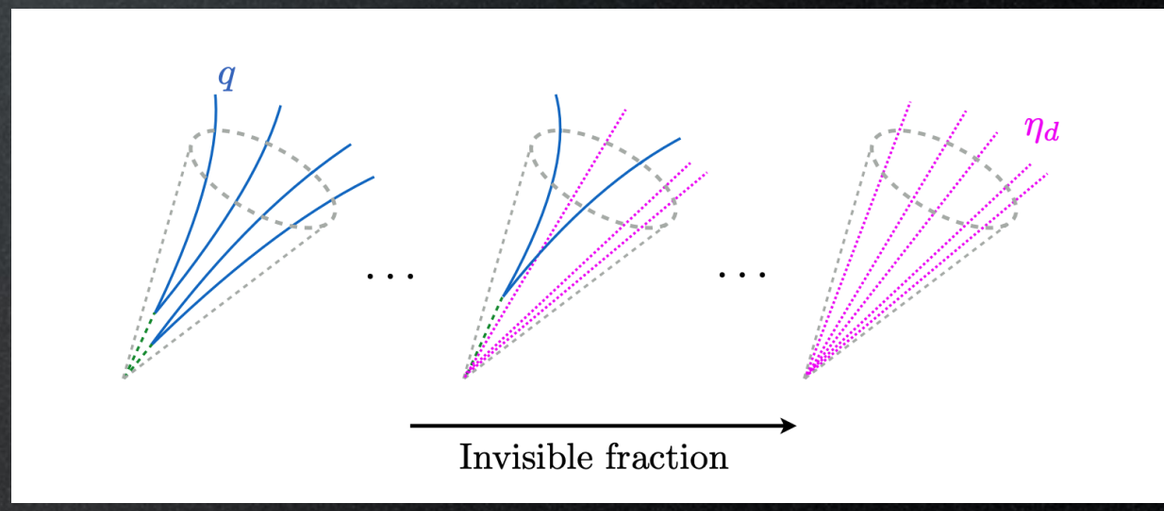
- Novel signatures (i.e SVJ!) are fun!
- Perhaps we need more a bottom up/ signature driven approach than a top down/model driven approach?
- Unless we search for them, can't really rule them out, can we?

Backup

Semi-visible jets!



Dark hadrons decaying in a QCD-like fashion, fully (dark jets) or partially back to visible sector (semi-visible jets, based on Cohen et al)



R_{inv} = Ratio of stable dark hadrons over number of hadrons

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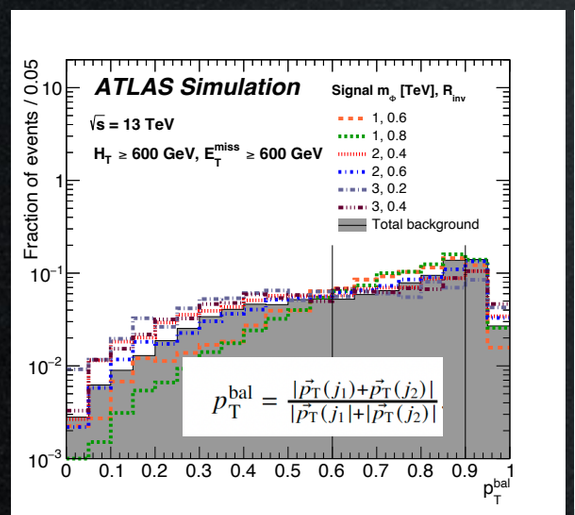
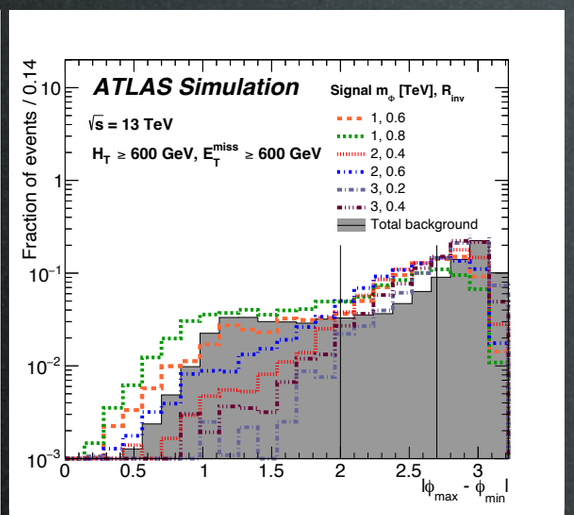
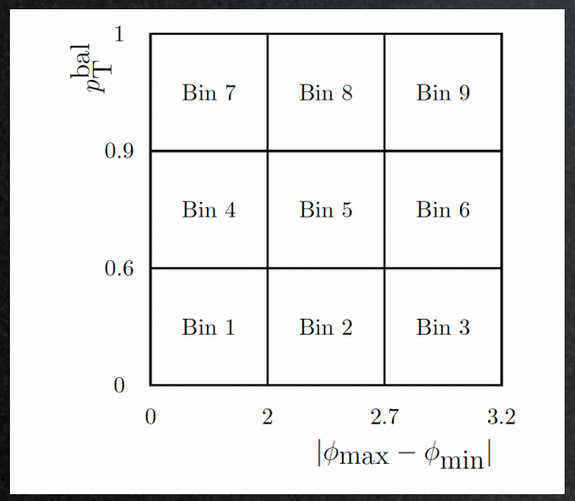
Background Estimate

Two sensitive observables:

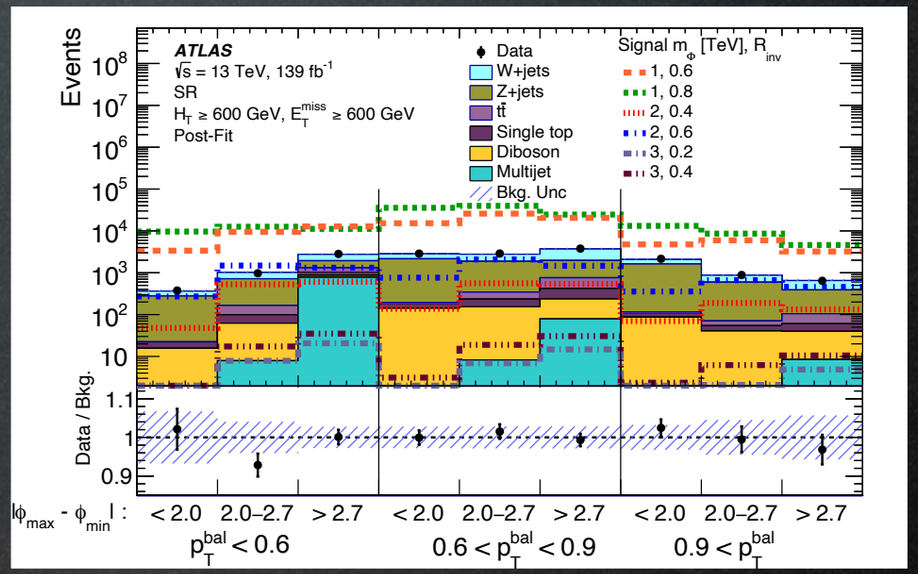




Used to Form a 9-bin grid, with yields in each bin treated as observables:



Partially data-driven method, simultaneously fit SR and three CRs to obtain scale factors for each bg process:



Process	k^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

Absence of signal, good postfit agreement :(

Multijet reweighed in using a dedicated VR given by MET within 250 to 300 GeV, then fitted

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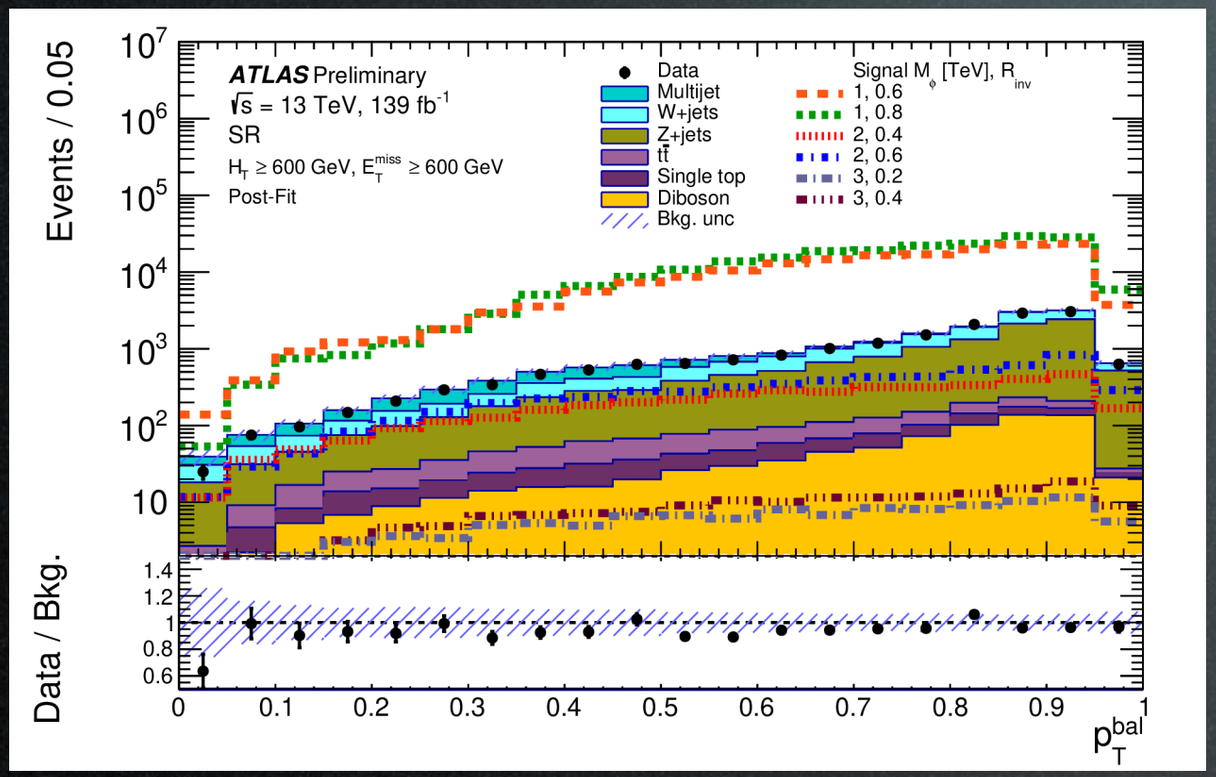
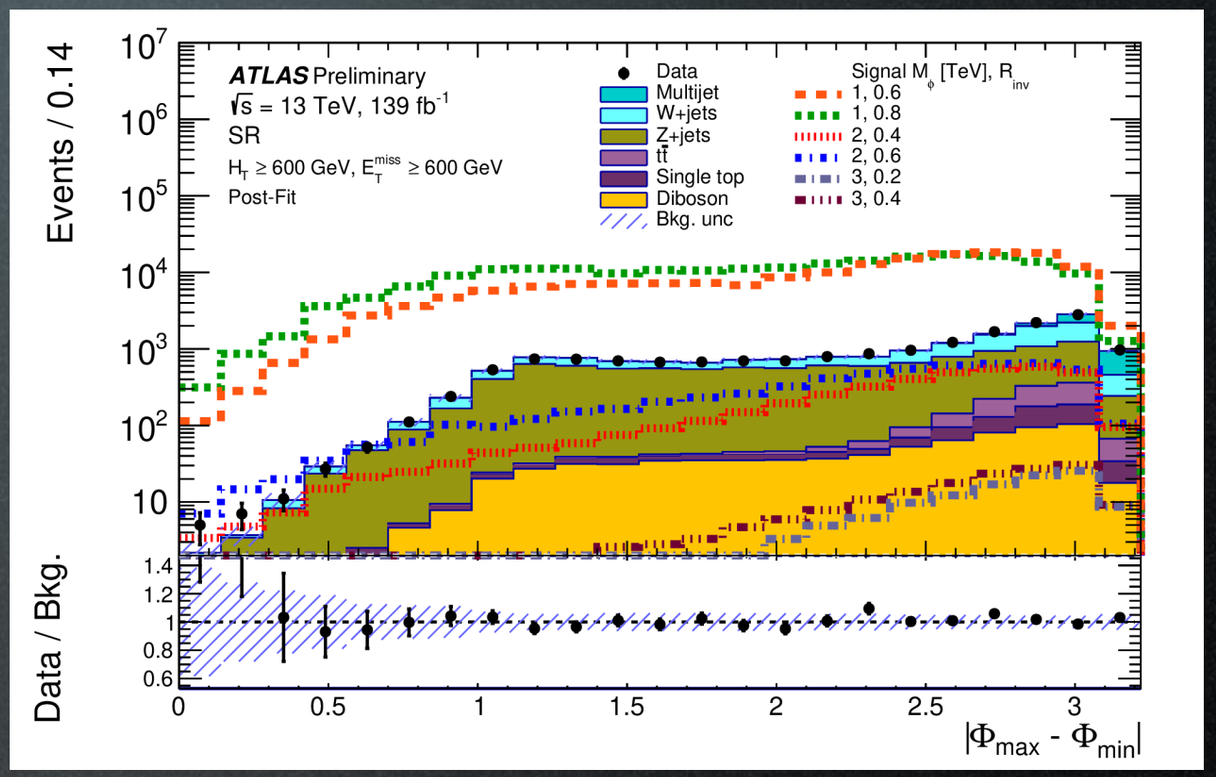
ATLAS SVJ-t Results





Excellent agreement between data and background prediction: $P_T^{balance}$ and max-min ϕ

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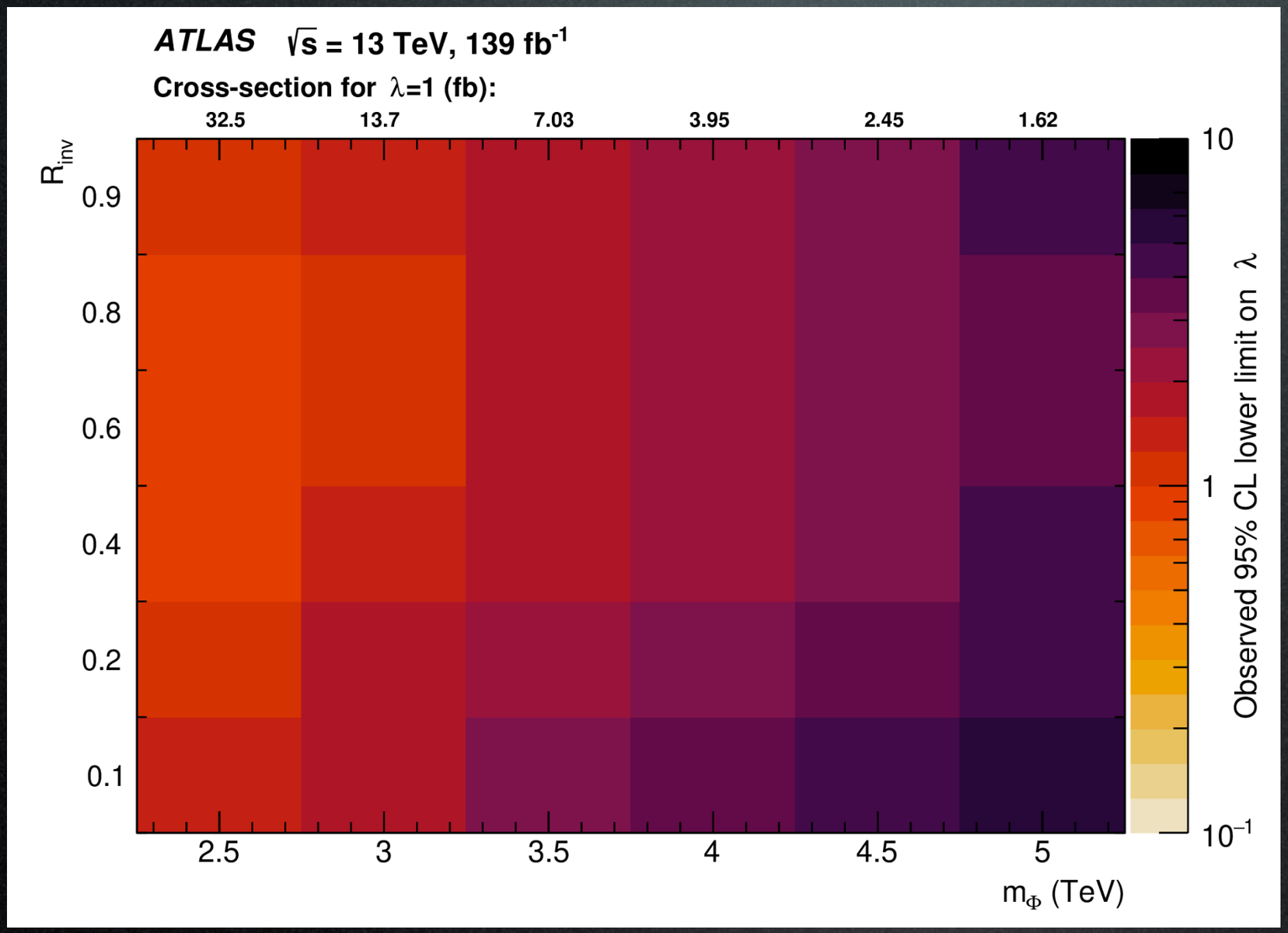
ATLAS SVJ-t Results



For mediator mass of 2.5 TeV or higher can also express the limits in terms of the q-q_d-ϕ vertex coupling strength λ, with the XS scaling as λ^4